Elettra 2.0

Preliminary Conceptual Design Report (Mk. I)

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CONTENTS

0. INTRODUCTION
   0.1 ELETTRA in 2016

1. EXPECTED IMPACT OF DLSR SOURCES ON RESEARCH
   1.1 MICRO- AND NANO-X-RAY ABSORPTION SPECTROSCOPY (XAS) IN 2 AND 3 DIMENSIONS
   1.2 PHOTOELECTRON SPECTROSCOPY (PES) – TOWARDS NANO-PES USING DLSRs
      1.2.1 NANOSCALE ANGULAR-RESOLVED PHOTOELECTRON SPECTROSCOPY (NANO-ARPES)
      1.2.2 NANO-AMBIENT PRESSURE PHOTOELECTRON SPECTROSCOPY (NANO-APPES)
   1.3 RESONANT INELASTIC X-RAY SCATTERING (RIXS)
   1.4 INELASTIC ULTRAVIOLET SCATTERING – RESONANT RAMAN SCATTERING
   1.5 NANO-INFRARED SPECTROSCOPY (NANO-IRS)
   1.6 TECHNIQUES BASED ON COHERENT BEAMS: COHERENT DIFFRACTION IMAGING (CDI), PYCHOGRAPHY AND X-RAY PHOTON CORRELATION SPECTROSCOPY (XPCS)
   1.7 CRYSTALLOGRAPHY AND TOMOGRAPHY
      1.7.1 TOWARDS MICROPROBE AND HIGH-THROUGHPUT CRYSTALLOGRAPHY
      1.7.2 X-RAY POWDER DIFFRACTION
      1.7.3 HARD X-RAY IMAGING AND TOMOGRAPHY

2. THE ELETTRA 2.0 CONCEPT: FRAMEWORK AND BASIC CONSTRAINTS

3. DESIGN CONSIDERATIONS
   3.1. MAGNET LATTICE
      3.1.1. LATTICE DESCRIPTION
   3.2. DYNAMIC APERTURE OF THE BARE LATTICE
   3.3. CLOSED ORBIT CORRECTION AND DA INCLUDING ERRORS
   3.4. APERTURE REQUIREMENTS, GOOD FIELD REGION
   3.5. VIBRATIONS AND ORBIT DISTORTIONS
   3.6. INJECTION INTO THE STORAGE RING
   3.7. EFFECTS OF INSERTION DEVICES AND OF SUPER BENDS
   3.8. LIGHT SOURCE PROPERTIES

4. BEAM STABILITY AND LIFETIME
   4.1. IMPEDANCES
      4.1.1. BROAD BAND IMPEDANCES AND SINGLE BUNCH INSTABILITIES
      4.1.2. NARROW BAND IMPEDANCES AND MULTI BUNCH IN-
STABILITIES
4.2. SCATTERING PROCESSES AND LIFETIME
  4.2.1. TOUSCHEK SCATTERING
  4.2.2. INTRABEAM SCATTERING
  4.2.3. ION TRAPPING AND FAST ION INSTABILITY

5. MAGNET DESIGN
  5.1. BENDING MAGNETS
  5.2. QUADRUPOLES
  5.3. SEXTUPOLES
  5.4. CORRECTORS
  5.5. MAGNET POSITIONING
  5.6. MAGNET HEAT LOAD
  5.7. DIPOLE PERMANENT MAGNET

6. RADIOFREQUENCY

7. DIAGNOSTICS
  7.1 BEAM POSITION MONITORS
  7.2 FILLING PATTERN MEASUREMENTS
  7.3 TRANSVERSE FEEDBACK PICKUP
  7.4 TUNE MEASUREMENT SYSTEM
  7.5 DC CURRENT TRANSFORMER
  7.6 FAST CURRENT TRANSFORMER
  7.7 SYNCHROTRON RADIATION PROFILE MONITOR (SRPM)
  7.8 TEMPERATURE MONITOR
  7.9 ANNULAR ELECTRODE
  7.10 GLOBAL ORBIT FEEDBACK
  7.11 FAST ORBIT INTERLOCK
  7.12 BEAM-BASED ALIGNMENT (BBA)
  7.13 FLUORESCENT SCREENS
  7.14 SCRAPERS
  7.15 BEAM DUMP SYSTEM

8. LAY-OUT, NAMING AND INSTALLATIONS
  8.1 MACHINE LAY-OUT
  8.2 OVERALL LAYOUT, NAMING, AND INSTALLATION
    8.2.1 NOMENCLATURE CRITERIA
    8.2.2 “TYPE” FIELD
    8.2.3 “AREA” FIELD
    8.2.4 ABBREVIATIONS

9. VACUUM CHAMBER AND SUPPORTS
  9.1 MACHINE LAY-OUT
  9.2 THE ABSORBERS
  9.3 MATERIALS
  9.4 MANUFACTURING
9.5 SUPPORTS
9.6 VIBRATION ANALYSIS OF THE SUPPORTS

10. VACUUM SYSTEMS
10.1 GENERAL REQUIREMENTS
10.2 CONDITIONING AND PRESSURE
10.3 THE PUMPING SYSTEM
10.4 CHOICE OF VACUUM MATERIAL
10.5 SIMULATIONS
10.6 VACUUM COMPONENTS
   10.6.1 FLANGES AND JOINTS
   10.6.2 PRESSURE GAUGES
   10.6.3 VALVES
   10.6.4 RACKS

11. FRONT-ENDS

12. MAGNET POWER SUPPLIES

13. CONTROLS AND SCIENTIFIC DATA MANAGEMENT
13.1 CONTROL AND FEEDBACK SYSTEMS
   13.1.1 CONTROL SYSTEM ARCHITECTURE AND TECHNOLOGIES
   13.1.2 FEEDBACK SYSTEM
   13.1.3 EQUIPMENT PROTECTION AND PERSONNEL SAFETY SYSTEMS
13.2 SCIENTIFIC DATA ACQUISITION, ANALYSIS AND MANAGEMENT
   13.2.1 EXPERIMENT CONTROL, AUTOMATION
   13.2.2 DATA ACQUISITION, PROCESSING AND MANAGEMENT SYSTEMS
   13.2.3 REMOTE OPERATIONS AND E-INFRASTRUCTURE

14. RADIATION PROTECTION
14.1 BEAM LOSSES SCENARIOS
   14.1.1 BEAM LOSS MONITORING (BLM) SYSTEMS IN THE RING TUNNEL
14.2 RING SHIELDING
14.3 BEAMLINES SHIELDING
   14.3.1 RADIATION PROTECTION ISSUES TIED TO GAS BREMS-STRAHLUNG RADIATION
   14.3.2 RADIATION PROTECTION ISSUES TIED TO SYNCHROTRON RADIATION
14.4 PERSONNEL SAFETY SYSTEMS (PSSs)
   14.4.1 RING PSS
   14.4.2 BEAMLINES PSS
14.5 ENVIRONMENTAL RADIATION MONITORING SYSTEM OUTSIDE THE RING SHIELDING
14.6 RING DECOMMISSIONING
14.7 AUTHORIZATION PROCESS
14.8 PSSs AND SHIELDING ACCEPTANCE TESTS
15. TIMING AND SYNCHRONIZATION
   15.1 BEAM LOSSES SCENARIOS
   15.2 TIMING AND SYNCHRONIZATION

16. INJECTION
   16.1 CURRENT SCHEME AND PARAMETERS
   16.2 PROPOSED LAYOUT FOR ELETTRA 2.0
       16.2.1 GEOMETRY AT THE SEPTUM 2 EXIT POINT
       16.2.2 KICKERS GEOMETRY AND MAIN PARAMETERS
       16.2.3 SEPTA GEOMETRY AND OPERATING PARAMETERS
   16.3 ALTERNATIVE INJECTION SCHEMES

17. ALIGNMENT

18. ENERGY EFFICIENCY

19. INFRASTRUCTURE
   19.1 MECHANICAL SYSTEMS
       19.1.1 PRIMARY COOLING SYSTEM
       19.1.2 SECONDARY COOLING CIRCUIT
       19.1.3 AIR CONDITIONING SYSTEM FOR EXPERIMENTAL HALL
       19.1.4 AIR CONDITIONING SYSTEM FOR SERVICE AREA
       19.1.5 AIR CONDITIONING SYSTEM FOR STORAGE RING
       19.1.6 COMPRESSED AIR PLANT
   19.2 ELECTRICAL INSTALLATIONS
       19.2.1 ELECTRICAL CABINET-BUILDING X
       19.2.2 TECHNOLOGICAL BUILDINGS (R,V,S05)
       19.2.3 EXPERIMENTAL HALL
       19.2.4 SERVICE AREA AND STORAGE RING
       19.1.5 AIR CONDITIONING SYSTEM FOR STORAGE RING
       19.1.6 COMPRESSED AIR PLANT
   19.3 CIVIL ENGINEERING
       19.3.1 EXPERIMENTAL HALL
       19.3.2 SERVICE AREA
       19.3.3 STORAGE RING
       19.3.4 TECHNOLOGICAL BUILDINGS

20. AUXILIARY SPACES

21. INSERTION DEVICES
   21.1 PERFORMANCE OF CURRENT IDs IN ELETTRA 2.0
   21.2 PERFORMANCE OF FUTURE IDs
   21.3 ADJUSTABLE PHASE UNDULATOR

22. IMPACT ON THE CURRENT PHOTON SOURCES
23. BEAMLINE SIMULATIONS

24. IMPACT ON SCIENCE
   24.1 CONDENSED MATTER
      24.1.1 CORRELATED SYSTEMS AND MAGNETISM
      24.1.1.a NANO-ARPES AND SPIN-ARPES
      24.1.1.b XPEEM AND COHERENT SOFT X-RAY SCATTE RING – XPCS
      24.1.1.c NANO-RIXS
      24.1.1.d VUV RAMAN and NANO-IR
      24.1.2 FUNCTIONAL MATERIALS FOR CATALYSIS, ENERGY CONVERSION AND ENERGY STORAGE
      24.1.2.a AMBIENT PRESSURE NANO-SPEM
      24.1.2.b NANO-SXM AND PTYCHOGRAPHY
      24.1.2.c NANO-IR
   24.2 ATOMIC, MOLECULAR, AND NANOPARTICLE SCIENCE
   24.3 LIFE SCIENCES
      24.3.1 FROM PROTEIN SCIENCE TO CELLULAR BIOLOGY
      24.3.2 FROM A SINGLE ORGANISM TO A COMMUNITY
   24.5 SCIENCE OPPORTUNITIES COMPLEMENTARY TO FEL

25. INDUSTRIAL IMPACT
   25.1 BACKGROUND
   25.2 PERSPECTIVES FOR PROPRIETORY INDUSTRIAL RESEARCH
      25.2.1 MATERIALS SCIENCE APPLICATIONS
      25.2.1.a CHEMICAL AND BIO SENSORS
      25.2.1.b CATALYSTS
      25.2.1.c NOVEL NANOMATERIALS
      25.2.1.d SEMICONDUCTOR INDUSTRY
      25.2.2 LIFE SCIENCES APPLICATIONS
      25.2.2.a ANTIBIOTIC RESISTANCE
      25.2.2.b BIOFUELS
      25.2.2.c MICROBIAL
   25.3 TECHNOLOGY PLATFORM
      25.3.1 MAGNETIC DEVICES AND POWER SUPPLIES
      25.3.2 RF SYSTEMS
      25.3.3 DIAGNOSTICS
      25.3.4 CONTROL SYSTEMS
      25.3.5 BIG DATA
      25.3.6 DETECTORS

26. IMPLEMENTATION
    (OMITTED)

27. DISMANTLING AND INSTALLATIONS
    (OMITTED)
28. COMMISSIONING
   (OMITTED)
29. PRELIMINARY COST AND MANPOWER ESTIMATES
   (OMITTED)
0. INTRODUCTION

The key parameters to perform synchrotron experiments with a given spatial, temporal, and energy resolution are the brightness (high X-ray power in small area) and the degree of transverse coherence (X-rays with uniform transverse wavefront) of the X-rays. Recent developments and new concepts for generating synchrotron light using multi-band achromat lattices have led to dramatically improved parameters and have gained momentum during the last few years. MAX IV in Sweden (inaugurated on the 21st of June 2016) and the SIRIUS project in Brazil (operative 2018) have been the first low-emittance machines. Upgrade plans have been approved and preparation work is ongoing at many of the existing storage rings, such as ESRF in France (operative ~ 2020), APS and ALS (operative ~ 2022) in the USA, SPring-8 in Japan (operative ~ 2021). Initial design steps for upgrades have been made at PETRA III in Germany, which operates at 5-7 GeV, Soleil in France and Diamond in the U.K., both operating at 3 GeV, BESSY-2 in Germany and SLS in Switzerland, operating at 1.9 and 2.4 GeV, respectively.

What is expected from diffraction-limited storage rings (DLSRs) is that they will provide transversely coherent beams with uniform phase maintaining high flux and stability and nearly cw operation for handling the radiation damage. As shown in Figure 0.1, the brightness of the next generation DLSRs increases by about two orders of magnitude as compared to previous third-generation light sources, nonetheless the total photon flux delivered at the sample location remains practically the same. Another revolutionary aspect is the high degree of transverse coherence in both horizontal and vertical directions. With such parameters there is a significant improvement in flux for investigation of smaller and dilute samples without beam tailoring.

![Figure 0.1. Beam size-brightness improvement with advances in storage ring technology.](image)

We should also outline some recent important developments and other considerations that add to the expected performance of DLSR-generated photon beams for experiments. First, novel insertion devices (IDs) with both stronger magnetic fields and smaller gap and shorter period for a given energy range can lead to further enhancement of coherent flux by a factor of three to four, as recently demonstrated by the four-fold symmetric Delta IDs developed at Cornell. Smaller and lighter adjustable-phase IDs have simpler
movement mechanisms, so additionally there is an economic ‘cost savings’ impact. Consequently, one can increase the number of beamlines using the short straight sections, or chicane long straight sections to accommodate two insertion devices. Secondly, the optical elements for photon transport at DLSRs, that should preserve the coherence, can be made with reduced sizes. This will make it easier to meet the stringent requirements for fabrication of mirror surfaces with very high precision to secure very small slope errors. In parallel, the development of more efficient and faster photon and electron detectors will be the key for making full use of the opportunities offered by DLSRs.

The small source size in DLSRs is very advantageous for mirror focusing optics and for monochromator design, in particular when higher energy resolution is required. The combination of reduced beam dimensions and increased coherence also leads to improved performance of diffractive optics, pushing the spatial resolution to the sub-10 nm range and allowing coherent scattering methods where diffraction-limited spatial resolution can be approached.

Improved lateral resolution has been one of the major driving force for development of so-called DLSR technology, responding to the growing request for addressing intrinsic heterogeneity and dynamic variations in chemical composition, geometric, electronic or magnetic structure of all types of materials at their natural spatial lengths and - when possible - combined with temporal resolution at relevant time scales. The envisaged comprehension of the function of individual constituents in complex natural and man-made materials is a prerequisite for breakthroughs in many disciplines related to energy, micro-electronics, environment, biology and bio-medicine.

In this respect, thanks to the coherence of the DLSRs one expects performance enhancement of key tools such as nanospectroscopy, coherent imaging and photon correlation spectroscopy for solving technological problems in design and fabrication of new materials with targeted properties.

0.1 ELETTRA in 2016

At present the Elettra storage ring operates at 2.0 (75% of the user time) and 2.4 GeV (25% of the user time) with beam currents of 310 mA and 160 mA, respectively. The total operating time is about 6400 hours/year of which 5000 are dedicated to the users on a 24/7 basis. The storage ring has 12 long straight sections, 11 of which with IDs, including 3 wigglers (1 superconducting, 1 permanent magnet and 1 electromagnetic elliptical) and 8 undulators (3 sections host Apple-II type of undulators). Another undulator is also installed in an additional short straight section. There are also 10 beam lines using the radiation of 6 dipole bending magnets. Currently there are 28 independently operating beamlines. Since 2010 Elettra operates in a top-up mode, injecting 1 mA of current every 6 or 20 min at 2 GeV and 2.4 GeV, respectively.

All of the most important X-ray based techniques in the areas of spectroscopy, spectro-microscopy, diffraction, scattering and lithography are currently present at Elettra. Versatile experimental stations area available for research in diverse fields and disciplines offering a variety of experimental tools: (i) Photon-in/electron-out spectroscopies (PES, ARPES, spin-resolved ARPES, and XAS), including spectro-microscopy and chemical or magnetic imaging; (ii) Photon-in/photon-out spectroscopy (XAS, FS, IUVS, Raman and IR), including X-ray and IR microscopy; (iii) XRD diffraction and SAXS. The sup-
porting laboratories provide access to atomic probe methods (AFM and STM), a cell culture room, a protein production facility, etc. Users of all continents apply for beamtime. The average beamlines oversubscription is currently ~ 1.8. Figure 0.2 shows the number of approved user proposals and user publications in the different science fields for 2013-2015.

Distinguishing features of the Elettra facility and of its user community include:

- Using routinely two different operating energies to cater to both the EUV user community and the X-ray user community;
- Emphasizing spectromicroscopy techniques and applications in a variety of complementary facilities and fields;
- Allowing complementary experiments on a third generation synchrotron radiation source and on a seeded FEL source;
- ISO 9001:2008 quality certification and BS OHSAS 18001:2007 safety certification to facilitate measurements for industrial concerns;
- Catering to the most international user community of all national facilities, with some 50% of the Elettra user community and 66% of the FERMI user community coming from abroad;
- Hosting major user communities from Eastern European and Central European countries;
- Hosting major user communities from developing countries in collaboration with UNESCO and IAEA.

Investigations performed using the Elettra storage ring span over all classes of materials: metals, semiconductors, superconductors, catalysts, ceramics, glasses, polymers, magnetic materials, materials for energy, electronic and bio-medical appliances, biomaterials, etc. ([http://www.Elettra.trieste.it/science/science.html](http://www.Elettra.trieste.it/science/science.html)). Elettra has one of the most extensive programs worldwide in the development and applications of all types of photoelectron spectroscopies (PES), which are used at 12 out of 28 of Elettra beamlines. They include high resolution PES, time-resolved PES, nano-ARPES, spin-resolved ARPES, scanning and full-field imaging photoelectron microscopy and imaging (SPEM and
PEEM). Experiments using photon-in/electron out techniques span over 2D materials, strongly correlated electron systems, magnetism, surface and interface phenomena relevant to catalysis and electrochemistry. In particular, the response to operating conditions and external stimuli – temperature, radiation, electric and magnetic fields are the main targets. In the field of life sciences, along with protein crystallography experiments, rather extended programs have been focused in the few years on assessing potential health hazards of nano-materials and pollutants on living organisms by means of photon-in/photon-out spectroscopies (XRF, XAS) and IR and Soft X-ray Microscopy.

After 23 years of faithful service to the user community with excellent results, Elettra should undergo a major upgrade preferably towards what it is called an “ultimate” light source, i.e., a DLSR, in order to remain competitive by enabling new science and the development of new methodologies to overcome the present limits. In particular, the science case supporting the Elettra 2.0 storage ring and beamlines upgrade represents a major step forward in synchrotron research, which complements and integrates the new possibilities offered by the FERMI free-electron laser (FEL) facility.

The main features of the new DLSR Elettra 2.0 source will be a substantial increase in the brilliance and coherence fraction of the source as compared to the X-ray radiation offered by the present 3rd generation ring. The Elettra 2.0 conceptual design under consideration will keep the same building and ring circumference, and is based on a six-bend achromat scheme for a beam energy of 2 GeV and a beam current of 400 mA. This will allow us to use the existing top-up injection system, maintain the same number of straight sections, have additional shorter straight sections for each quadrant and still reduce by a factor of about 5 the beam size and divergence and by a factor of about 28 (from 7 nmrad to about 0.25 nmrad) the emittance.

1. EXPECTED IMPACT OF DLSR SOURCES ON RESEARCH

The implementation of a DLSR storage ring, including new beamlines and beamlines upgrades, will require a major financial effort. However, the expanded spatial and temporal range of all photon-based techniques resulting from the availability of DLSR will allow new classes of experiments in many disciplines, beneficial to science and technology to such an extent that the project will lead to a significant positive social impact.

The coherent flux produced by DLSR on the sample per square nanometer will be comparable with that from existing third-generation sources per square micrometer. Hence, X-ray spectroscopy experiments on individual meso/nano-sized constituents can be envisioned even without the use of sophisticated focusing optics. In such experiments, using the most appropriate spectroscopic methods, information can be obtained about the local coordination environment of different types of atoms in such sub-units on the surface, at the interface or in the bulk, about the size and shape of the individual mesoscopic units, and about the overall structure. In addition details about the interactions or real-time changes in the chemical state constituent units can be obtained.

In all experiments using photon focusing optics, the increased brightness of the DLSR beam will translate directly into a corresponding increase in focal flux density. This will ensure sufficiently high photon density in a much smaller microprobe, pushing the lateral resolution in all X-ray imaging modes down to the 1-5 nm range. With the progress
in detector developments, all available spectroscopic techniques complementing X-ray absorption-scattering imaging, namely X-ray absorption spectroscopy (XAS), photoelectron spectroscopy (PES), X-ray fluorescence (XRF), resonant X-ray emission (XES) and resonant X-ray inelastic scattering (RIXS), will provide information on a scale approaching the X-ray imaging spatial resolution of a few nm, thus connecting structure to function. Combining nano-scale XAS, PES, XRF, XES and RIXS, complemented with nano-scale IR and VUV microscopy, will allow unprecedented investigations of structure and dynamics in three and four dimensions with variable probing depths.

All such improvements in methodology are a prerequisite for cutting-edge applications to processes, controlling properties and performance in functional heterogeneous materials from fabrication to operation.

In brief the main benefits expected from the introduction of a DLSR Elettra 2.0 in the soft to moderate hard X-ray range are:

1. Increasing the brightness of the source by 28 times and providing a 5-fold reduced beam size of equal dimensions in the horizontal and vertical planes will lead to significant gains in the emitted or transmitted signals from the objects under investigation. It will be profitable for all types of spectroscopies and X-ray scattering techniques in terms of reduced acquisition time or monitoring very weak signals. It will be especially advantageous for photon-hungry experiments such as: (i) high pressure experiments with anvil cells and dilute samples (ii) Q-resolved resonant inelastic X-ray scattering (RIXS) and (iii) spin-resolved ARPES.

2. Increasing the brightness and coherence will have particular impact on pushing the lateral resolution to the nanoscale range using focusing optics – introducing the possibility of performing all types of spectroscopies with nano-sized photon beams (e.g., nano-PES, nano-ARPES, nano-RIXS, nano-XAS).

3. The high coherence of the source will open unique opportunities for coherence-hungry experimental methods, such as: (i) 3D coherent diffraction imaging (CDI) of bulk samples with chemical specificity and closely related X-ray photon correlation spectroscopy (XPCS) experiments, monitoring fluctuations with nanosecond to second time resolution and nanometer to micrometer spatial resolution. For all coherent x-ray scattering techniques, including ptychography, the improved coherence will allow us to approach the wavelength-limited spatial resolution with chemical specificity and improved temporal resolution.

4. Increasing the brightness will have a direct impact on the temporal resolution achievable, e.g., in XPCS, where the fluctuations of the speckle pattern encode stimulus-driven (e.g., temperature- or field-induced) changes in the geometric, electronic and magnetic structure of heterogeneous samples. Major gains will derive from the coherence of DLSR beam, since the time resolution - proportional to the square of the coherent flux - will be limited only by the electron bunch length (~ 100 ps) of the DLSR.

It should also be noted that although the 21st century has seen major developments in the area of high-harmonic generation (HHG) and X-ray free-electron laser (XFEL) sources, DLSR sources remain essential. This derives not only from capacity considerations - i.e., the limited number of beamlines that HHG and XFEL sources can serve as compared to DLSR sources - but also from quality considerations.
Using DLSRs is not only complementary but also absolutely necessary because of the significantly higher repetition rate (>100 MHz) available at DLSRs as compared to HHG and FELs, including those based on superconducting technology, the higher stability in intensity, wavelength and bandwidth from pulse to pulse are the main assets of DLSR sources. The high average flux distributed over many electron bunches is, on one the hand, highly beneficial for photon- and coherence-hungry techniques such as RIXS, coherent scattering, photon correlation spectroscopy, phase imaging etc. On the other hand, it allows handling of undesired effects in high ionization rate experiments, for example space-charge problems in electron detection and sample radiation damage, problems that cannot be overcome using the full power of FEL pulses.

In the following sub-sections we will illustrate some of the main improvements in spectroscopic and imaging techniques that will derive from the availability of the ultrabright, coherent and high-repetition rate EUV and X-rays pulses from DLSR opening new science opportunities by overcoming the current limits in spectral, spatial and time resolution.

1.1. MICRO- AND NANO-X-RAY ABSORPTION SPECTROSCOPY (XAS) IN 2 AND 3 DIMENSIONS

XAS includes extended X-ray absorption fine structure (EXAFS) and near-edge absorption fine structure (NEXASF) and provides detailed information about the chemical state and bonding configuration of elemental constituents. The first imaging and micro-spectroscopy experiments at synchrotron facilities used X-ray absorption spectroscopy - in X-ray transmission or electron and fluorescence emission modes - for mapping the local chemical or magnetic structure with lateral resolution that has reached lately 20-30 nm both in scanning X-ray and full-field imaging transmission or photoemission electron emission microscopes (SXM, TXM, XPEEM), which monitor transmitted X-rays, emitted X-rays or photoelectrons.

Micro-XAS has already achieved excellent performance in spectral resolution using a transmission measurement mode. For example, using SXM micro-NEXAFS, the evolution of oxidation state of individual catalyst nanoparticles was followed in operating Fischer-Tropsch reactor, batteries and fuel cells. Another field of interest is magnetometry in three dimensions of ferromagnetic, ferrimagnetic, and antiferromagnetic samples with chemical sensitivity. Performed using X-ray magnetic circular and linear dichroism (XMCD/XMLD) at the nanoscale, it will allow mapping the vector magnetization in magnetic nanostructures. Compared to Lorentz Transmission Electron Microscopy (LTEM), which measures stray transverse fields around inhomogeneous textures, the great advantage of magnetic nano-XAS is the X-ray penetration depth that enables us to probe thicker structures in various environments measuring directly the magnetic signal. With the availability of DLSR sources further improvements in lateral resolution, further gains in the intensity of the emission signals and further reductions in the required measurement time will open more in-operando opportunities.

DLSRs will also allow for optimizing the design and performance of X-ray photoemission electron microscope (XPEEM) beamlines and experimental stations. The reduced beam divergence of the new machine will permit us to obtain a larger horizontal demagnification of the source, which will produce, in turn, an increased flux density at the
sample and thus faster acquisition times. The improvement in the illumination efficiency implies that space charge effects will become less important, with beneficial effects in terms of both energy and lateral resolution. The new XPEEM beamlines will be able to exploit also several recent advances in detector technology. CMOS imaging detectors represent a significant step forward as compared to channelplates, thanks to their superior efficiency and versatility. For instance, they will greatly facilitate the development of time-resolved and in-operando methods, owing to the relative ease of implementing gating and synchronization with external stimuli.

Expected benefits deriving from the use DLSRs for nano-XAS in the soft X-ray range include: (1) higher throughput; (2) improvement in lateral resolution to sub-10 nm range; (3) higher sensitivity to light elements. The higher signal and the faster data collection will allow ‘serial imaging’ for:

(i) making movies to follow catalytic processes, magnetic switching and phase transitions of complex materials in real time;
(ii) 3D reconstructions using big set of high-resolution 2D chemical images, each taken at different sample orientations within seconds rather than minutes;
(iii) performing 3D imaging with chemical specificity down to a nm resolution in scanning XAS microscopy using coherent ptychography;
(iv) implementing photon-hungry spin-filtering techniques in XPEEM both imaging (XMC/LD) and complementary diffraction (microprobe-APRES) experiments.

It should also be considered the possibility offered by DLSRs of achieving focal spots at the sample well below 1 µm² with conventional mirror optics. This will pave the way to combining a mesometric X-ray beam with the bulky sample environment required for most XMCD experiments - including typically a magnet capable of producing fields in the range of several Teslas and a cryostat reaching temperatures in the sub-Kelvin range - that cannot be integrated in common X-ray microscopes. Moreover, concentrating the currently available photon flux into an area of the order of 100x100 nm² would open up the possibility to performing scanning tunneling microscopy (STM) detection in XMCD. This would couple the atomic spatial resolution of the STM with the chemical and magnetic sensitivity of XMCD, thus combining in a single experiment the two of the most advanced techniques for the study of the electronic and magnetic properties of individual atoms or very small clusters.

1.2 PHOTOELECTRON SPECTROSCOPY (PES) – TOWARDS NANO-PES USING DLSRs

High flux, high brightness and tunability are the three fundamental requests for performing state-of-the-art spatially-resolved PES, a photon-in/electron-out technique with different operation modes that provides indispensable information about surface and near-surface composition, electronic structure and correlations in condensed matter.

1.2.1 NANOSCALE ANGULAR-RESOLVED PHOTOELECTRON SPECTROSCOPY (NANO-ARPES)

ARPES is the most direct methods for analysis of the electronic structure of solids. This technique provides a detailed picture of the electronic bands and Fermi surface, which contain the essential information for understanding the macroscopic properties of the
materials. ARPES has been very popular for studies of low dimensional and magnetic materials and can reach the energy and angular resolution of 1 meV and 0.1 degrees using the new DLSRs. Such high spectral and angular resolution opens new opportunities for very accurate gap mapping with full control of beam polarization to exploit ARPES selection rules. We should stress here that the signal level is still one of the limits in electron spin detection and a real step ahead in this respect is expected using DLSR sources.

The physics of emerging new quantum materials, such as spin-orbitronics and topological systems, Fe-based superconductors and 2-D materials, poses the challenge of assessing a manifold of novel properties arising over fast time scales or intrinsically associated to spatial inhomogeneities. Shedding light on the intrinsic electronic inhomogeneity and their ‘single particle’ response to external stimuli also needs us to improve the spatial resolution to at least the 10-nm scale, but nano-ARPES becomes feasible only with a DLSR source, which will provide all means for the realization of SPEM/µ-ARPES, including: (i) sufficiently high photon flux in a submicron spot on the sample; (ii) stability of the beam focusing during x,y scanning of the sample and especially during spectrum acquisition from the selected micro-spot; (iii) necessity to acquire three dimensional (k_x, k_y, E) band structure maps with spectral quality comparable to that of classical ARPES experiments.

Acquisition of ARPES and spin-resolved ARPES with resolution in space and time will be achieved with unprecedented efficiency at Elettra 2.0 by means of a recently developed momentum microscopes where the angular distribution of the emitted electrons originating from a given real space region are imaged for in k_x and k_y directions and it is possible to switch from real space imaging to k-space imaging [1]. This is particularly useful for the investigation of spatially inhomogeneous samples, where areas in the order of a 1 mm^2 could be selected using only modest focusing and a simple focusing optics at Elettra 2.0. The advantages of momentum microscopes are manifold – they can also implement a spin-detector as already done at the NanoESCA beamline at Elettra.

Time-of-flight (ToF) momentum microscopes could be used to perform time-resolved ARPES experiments using few-bunch modes or suitably tuned hybrid modes of Elettra 2.0. The best energy and momentum resolution so far obtained in this field, with a time-resolution of the DLD of 150 ps, are 19 meV and 0.01 Å, although faster detectors are expected to become available in the next future. The bunch length of Elettra 2.0 (12.5 ps with the third-harmonic cavity off) along with repetition rates in the range of 1-10 MHz will allow us to perform time-resolved micro-ARPES experiments on time scales complementary to those available at FERMI.

Compared to the present synchrotron sources the expected gain in the photoelectron signal intensity using DLSR light sources is expected to be at most one order of magnitude, since increasing the photon flux density undesired events (briefly described below) impose some limitations. However, nano-PES and nano-ARPES could still be realized with relatively modest-sized insertion devices.

1.2.2 NANO-AMBIENT PRESSURE PHOTOELECTRON SPECTROSCOPY (NANO-APPES)

One of the distinctive strengths of core-level PES, in particular when combined with NEXAFS, is in the study of physical and chemical phenomena at surfaces and interfaces. Processes occurring at solid surfaces in contact with gaseous or liquid ambient are of extreme importance in heterogeneous catalysis and energy device technology, two fields where Elettra 2.0 is expected to have a strong impact. After decades of model surface science studies, which have provided deep fundamental knowledge, the advent of ambient pressure PES (APPES) and the development of environmental reaction cells have been major steps towards overcoming the pressure gap and shedding light on surface phenomena under more realistic operating conditions.

The smaller source size with preserved flux is an advantage since one can use the beam demagnification to reduce the sample aperture size that will allow for approaching atmospheric pressure. However, we should also overcome the ‘material gap’ since most of the functional systems are complex and inherently heterogeneous. This requires implementing new methodologies for in-operando APPES using nanoprobes opening new possibilities to realize nano-APPES. Adapting the present SPEMs and XPEEMs to experiments at ambient pressures and pushing farther the available spatial resolution will open the route to exploring chemical states and their evolution under working conditions at the scale of individual catalyst nano-particles, probing mass transport processes and local charge fluxes, etc. Having such tools in place and reaching resolution down to 5 nm for radiation damage-resistant materials could revolutionize fabrication processes and result in novel smart solutions in all fields where nano-particulate materials are used.

However, being a photon-in/electron-out technique PES is applicable mostly for characterization of electrically conductive specimens and even using ‘hard X-rays’, sensitivity to the bulk properties remains limited. Thus, in order to obtain true complementary information about properties and processes controlling certain complex functional materials we should count also on photon-in/photons-out resonant X-ray spectroscopies, such as fluorescence-yield XAS, X-ray emission (XES), RIXS or Raman scattering.

1.3 RESONANT INELASTIC X-RAY SCATTERING (RIXS)

Resonant Inelastic X-ray Scattering (RIXS), an X-ray analog of resonant Raman scattering, is a bulk-sensitive method where low-energy excitations of the electronic system, created by inelastic X-ray scattering from sample constituents, can be characterized as a function of momentum transfer (q) and incident X-rays energy loss \(^{[2]}\). The involvement of a core-hole localizes the scattering event at a specific site allowing one to probe selectively atomic species in different chemical environments. As dipole selection rules apply for both the photon-in and photon-out processes, one can select specific orbitals and probe their symmetry with polarized incident radiation. With current state-of-the-art RIXS instruments it is possible to probe with very high sensitivity and resolving power different excitations - vibrational (or phonon), charge, magnetic and orbital. In explor-

ing electronic phase transitions of strongly correlated electron systems RIXS comple-
ments XAS and surface-sensitive ARPES.

However, at present storage rings the signal-to-noise ratio available for RIXS exper-
iments is limited and there is at the moment no RIXS beamline at Elettra. The expected
improvements in brightness and beam shape afforded by Elettra 2.0 are a major motiva-
tion for proposing construction of a new RIXS beamline. Employing proper beam
shaping optical schemes and novel spectrometer concepts for parallel detection of inci-
dent and emitted photon energies in a single shot will open new opportunities for sophi-
sticated RIXS experiments \[^1\] exploring dilute systems, performing in-operando studies
in liquid or gaseous sample environments, using reaction cells (catalysts, energy devi-
ces), liquid jets etc. By designing more robust high-temperature/high-pressure reactors,
experiments in the liquid state or under a gaseous atmosphere will become realistic. For
example, the detection of the elemental, valence-selective and charge-transfer excita-
tions within a working catalyst system will require much higher signal strength than
achievable today at third-generation synchrotron sources. Using liquid jet sample envi-
nronments RIXS experiments on metal centers in proteins, which are of particular inter-
est in biology and biochemistry, will become routine, providing important preliminary
information for future experiments planned at XFELs.

The sub-10 meV spectral resolution, achievable in RIXS at DLSRs, will make possible
to monitor very low energy losses relevant to vibrations, spin, charge and magnetic ex-
citations in molecules and complex materials. For low-dimensional metal oxides, pro-
bing the evolution of the superconducting gaps at the relevant energy scale will provide
a wealth of information on the unknown aspects of electronic and spin transitions. As
for transition metal oxides, also the properties of coordination complexes, transition met-
al ions in solution and transition metals in proteins depend on the dominant effects of
spin-orbit, and charge-transfer excitation. By using core-hole clock analysis methods
the time-dependent decay channels can be determined. Soft X-ray core spectra can be
measured with sub-lifetime resolution using the coherent excitation and decay, shedding
light on the nature of the core excited states and of the different decay channels and
about their interference as well.

The signal gain will also make possible to use microprobes pushing the later resolutio-
to the sub-50 nm region. This will allow probing systems that are electronically or
structurally inhomogeneous and the expected input from nano-RIXS will complement
nano-XAS, nano-XES and nano-ARPES studies for better understanding the nature and
functions of complex systems, where phase transitions occur in heterogeneous fashion
involving nucleation phenomena as well.

1.4. INELASTIC ULTRAVIOLET SCATTERING – RESONANT RAMAN SCAT-
TERING

The importance of extending the unique capabilities of Raman spectroscopy to the VUV
domain lies essentially in the possibility of covering the whole range of outer electronic
shells in matter (up to ~ 10-15 eV) by selective and resonant excitation of specific orbit-
als and bands, opening new research opportunities in many fields. It is worth to outline
the potential contributions of this technique in two research topics of condensed matter

1076
physics, namely nanotubes and semiconductors. Furthermore possible important developments might be envisioned in biochemistry.

Resonant Raman experiments can provide general information on the electronic structure of the nano-tubes, as demonstrated by recent studies of double-wall carbon nanotubes (DWNT’s) and C60-single wall nanotube (SWNT) peapods. Such measurements in the UV/VUV region have appeared crucial to characterize DWNT’s grown with very small inner tube diameter and also for the study of boron nitride, boron carbide, and carbon nitride tubes, which have resonances in this wavelength region. Other possible applications of resonant VUV Raman scattering on carbon-based systems include: i) surface-enhanced Raman scattering on SWNT where an enhancement of up to 14 orders of magnitude can be obtained; ii) Raman spectroscopy of polyconjugated molecules and materials, revealing confinement effects in one and two dimensions; iii) Raman spectroscopy of hydrocarbons; iv) study of amorphous, nano-structured, diamond-like carbon, and nano-diamond.

Pushing the excitation wavelength of Raman spectroscopy to the VUV domain has opened new opportunities to study wide gap semiconductors and semiconductor nanostructures: for instance, the presence of an hexagonal phase in BN thin films is characterized by an enhancement of the Raman cross section at 5.4 eV, and its complete characterization would require higher excitation energies. In general, VUV resonant Raman scattering appears as a powerful tool to study higher lying conduction band electronic states of semiconductor alloys and relative nanostructures, as indicated by the first measurements performed in the UV on GaP$_{1-x}$N$_x$ and GaAs$_{1-x}$N$_x$.

Resonant Raman scattering is a powerful technique to study the fermiology of highly correlated electronic materials, presenting several characteristics complementary to other widespread methods such as photoelectron spectroscopy. Being a photon in – photon out technique, it allows the study of insulators; furthermore, its probing depth is considerably larger as compared to techniques using photoelectrons, so that surface effects can be neglected. In addition, being a second order technique, it makes it possible to observe transitions forbidden by dipole transition rules. Therefore, it can provide important information - with high energy resolution - on the fundamental parameters involved in electron-electron or electron-phonon interactions, while monitoring, for example, metal-insulator transitions or the opening of the superconducting gap in a superconductor.

VUV Raman scattering can also have an impact on many issues of biochemical interest. Recent publications demonstrated the great potential of this technique for providing molecular insight into complex phenomena, including: (i) determining the properties of hydrogels, promising materials to be used as scaffolds for tissue engineering, in regenerative medicine and for drug delivery; (ii) monitoring rapid changes in the oxidation of DNA, opening opportunities for diagnostic applications; (iii) probing protein folding and providing direct structural details with sufficient time resolution, key challenges in structural molecular biology today.

Resonant Raman Scattering in the VUV is currently available at the state-of-the-art IUVS beamline at Elettra that has allowed the study of many open issues in different scientific domains, but the increased brightness of the DLSR sources and the possibility
of using new IDs (in vacuum undulators) would greatly improve signal-to-noise levels and possibly add lateral resolution capabilities as well.

1.5. NANO-INFRARED SPECTROSCOPY (NANO-IRS)

The non-damaging nature of the studies that can be performed using infrared synchrotron radiation (IRSR) has allowed measurements of the vibrational, phononic, electronic and many other low-energy excitations for a wide variety of materials. Moreover, the pulsed nature (over nearly a 100 ps scale), of the IRSR radiation provides the possibility of performing time-resolved studies in many systems. Applications cover a wide range of research fields, including surface and materials science, superconductivity, plasmonics, high-pressure materials science and chemistry, graphene and 2D materials, cultural heritage, forensics, geology, polymer-science, biochemistry, in-vitro live cell analysis, biomedical diagnostics, etc.

Extracting IRSR radiation from a bending magnet in next-generation DLSR is somewhat challenging. For instance, the Multi-Bend Achromat (MBA) lattice of Elettra 2.0 will be more tightly packed, significantly reducing the available space for photon extraction ports. Moreover, since IRSR extraction ports have larger vertical aperture than X-ray extraction chambers and require extraction mirrors very close to the source point, special designs should be implemented for minimizing the contribution to the chamber impedance. Nonetheless, the scientific programs of worldwide IR beamlines, and SISSI as well, are very productive and synergic efforts between machine, optics, engineering and scientific communities are ongoing at several facilities (ALS, NSLS-II, SOLEIL, SIRIUS, etc.) for finding satisfactory solutions.

The increase in the beam current up to 0.4 A, combined with the expected higher beam stability of DLSRs, offers advantages in terms of IR flux and brilliance that should increase significantly the S/N ratio. This is also important for further promoting synchrotron-based IR nanospectroscopy and nano-imaging, derived from the use of near-field approaches. Indeed, IR nanospectroscopy programs are already active or under development in several third generation SR facilities worldwide and they will potentially benefit from DLSRs for the aforementioned S/N ratio advantage.

Implementing Nano-IR at the SISSI beamline would fit perfectly within the scientific mission of Elettra 2.0, that aims at responding to the growing request of improving the lateral and temporal resolution for addressing intrinsic heterogeneity and dynamic variations in chemical composition, geometric, electronic or magnetic structure of matter at their natural spatial and time scales. IRSR nanospectroscopy end station at DLSRs will provide a unique opportunity for covering the gap in lateral resolution that exist today between X-ray and IR microspectroscopy beamlines, adding the non-damaging vibro-electronic complement to the wide array of X-ray based approaches that will be further pushed toward nano-resolution in DLSRs.

DLSR will provide a unique opportunity for complementing state-of-the-art X-ray nano-probes with both microscopic and nanoscopic IR probes. Nano-IRSR at SISSI, complemented by nano-Raman at IUVS, would be a unique tool to study the chemistry of organic matter and biological specimens, since they will provide the necessary chemical information without concerns for radiation damage.
1.6 TECHNIQUES BASED ON COHERENT BEAMS: COHERENT DIFFRACTION IMAGING (CDI), PTYCHOGRAPHY AND X-RAY PHOTON CORRELATION SPECTROSCOPY (XPCS)

Today all synchrotron experiments using methods that rely on beam coherence need to use an aperture to select the coherent portion of the beam. Most studies are exploring time-dependent phenomena in heterogeneous functional materials. Typical examples are reaction-diffusion processes in systems such as: i) metal-organic framework compounds that have been functionalized to achieve high catalytic selectivity; ii) nanostructured solids designed for chemical sensors; iii) soil particles immersed in a contaminated ground water plume; iv) nano-porous separator membranes deployed in a battery or a fuel cell; (v) magnetic materials etc. All these need tools to perform measurements on the relevant spatial/time scale, probing sample volumes comparable with the size of the coherent beam. Therefore all coherence-hungry X-ray scattering methods will derive substantial benefits from the use of DLSRs.

CDI, being diffraction-limited, overcomes the spatial resolution limitations imposed by focusing optics, replacing them with mathematical algorithms that reconstruct the real space image of the object from the speckle pattern of the scattered coherent light from the object [1]. Today CDI is one of the most used methods at XFEL facilities where images of non-periodic nano-objects were acquired with a single FEL pulse in a shot-destroy mode. However, a great number of investigations require preservation of sample integrity and do not require the femtosecond temporal resolution afforded by FELs. Ptychography is a scanning X-ray microscopy (SXM) variant of CDI that provides more flexibility when extended objects have to be studied. However, because it needs to record a large number of speckle patterns from overlapping regions, scanning over the sample in steps of a fraction of the coherent microprobe size, ptychography tends to be quite time-consuming. The CDI based methods can also be used for 3D imaging, but the experiment may take a whole day or more.

Both CDI and ptychography will greatly benefit from the high brightness of DLSRs by reducing the acquisition time by at least 50 times. In particular, we expect real gain using resonant CDI and ptychography to access to chemical and magnetic information as well, through absorption and scattering at atomic electron resonances. Consequently, we would be able to obtain scattering-imaging-speciation information with diffraction-limited lateral resolution adding also temporal resolution as in following.

X-ray photon correlation spectroscopy (XPCS) probes dynamics in disordered systems by analyzing the temporal correlations between photons scattered by the sample. XPCS can be considered as complementary to RIXS, since the speckle patterns map sample fluctuations in the time domain \((q, t)\) at a length scale \(2p/q\), complementing the RIXS information in the energy domain \((q, w)\).

Figure 1.1 The principle of XPCS experiments and the ranges of $Q$ and $\omega$ typically accessible with spatiotemporal methods, indicating the extended range for XPCS at DLSRs [From O. G. Shpyrko, J. Synchrotron Rad. (2014). 21, 1057–1064].

An important advantage of using grazing incidence geometry is that choosing appropriate incidence angles one can enhance the surface sensitivity to distinguish between bulk and surface dynamics. For studies of thin films information about the interior of the film can be obtained by selecting proper incident angle to create standing waves within the film. Recent XPCS studies have shed light on the surface dynamics of polymer films, buried structures and interfaces, and - using resonant magnetic X-ray scattering - about spin fluctuations in magnetic films [5].

However, XPCS experiments are very challenging at present storage rings and the coherence-hungry nature of the method limits the time resolution to the millisecond range. Since the temporal resolution scales as the square of the coherent flux, the 28-fold increase in the Elettra 2.0 brightness as compared to Elettra today will provide a $10^3$ increase in dynamic range. This will allow us to sample processes in the microsecond regime with diverse samples and environments, all of these monitored under extremely reproducible, tunable conditions, and with spatiotemporal and chemical sensitivity. For reaching the sub-microsecond range the pulsed nature of the ring could be used, which would require a very fast and quantum efficient 2D detectors with single-photon detection capability.

Fast XPCS would make possible dynamic experiments for probing incoherent processes that control the evolution of complex nanostructured functional materials, such as spontaneous phase nucleation, reaction-diffusion and Turing instabilities. Another field of high interest for fast XPCS concerns processes driven by the application of external stimuli: magnetic, electric fields, light, temperature etc. Here, experiments at DLSRs could complement those performed at FELs, exploiting the higher repetition rate and reduced radiation damage as compared to FELs and with some advantages in count rate for coincidence experiments probing chemical dynamics and extending the observation window of phonon driven structural transitions into the ns and $\mu$s domain, which is important for understanding charge transfer in photosensitizing molecules with implications for energy materials.

XPCS would be performed at DLSRs in normal or grazing angle-incidence geometry with dedicated set-ups using hard X-rays at a new high-brilliance beamline and using soft X-rays with the upgraded instrument at the Nanospectroscopy beamline. For the first (SAXS), Elettra 2.0 with its specification is a necessity for the implementation of an in-vacuum undulator in the lower hard X-ray regime. The soft X-ray set-up would allow complementary PEEM and XPCS experiments with resonant contrast, which will yield both surface and in-depth information, simplify reconstruction procedures and provide a unique tool for exploring nanoscale kinetic phenomena in chemistry, magnetism, etc.

Figure 1.2 Schematic of Time-resolved X-ray solution scattering experiment. The sample e.g., protein in solution is excited by an optical laser (pump) pulse. After a well-defined time delay (t), an X-ray (probe) pulse generated from a synchrotron is delivered to the photo-excited sample and the scattering patterns are measured at various time delays. By taking the difference between scattering patterns measured before the laser excitation (i.e., at a negative time delay) and after the laser excitation (i.e., at a positive time delay), the transient structural change of the sample can be obtained selectively. (From Kim JG Acc.Chem.Res.2015, 48, 2200-220, DOI: 10.1021/acs.accounts.5b00198).

Elettra 2.0 with its optical quality would facilitate the research program presently conducted, e.g., at the Austrian SAXS beamline implementing a ps to µs pump-probe set-up or grazing incidence studies by a factor of 100 gain in intensity and a $10^3$ order gain in brilliance compared to the present situation. Fig. 5 shows the typically set-up of such pump probe experiments.

The splitting of SAXS into two scattering beamlines will allow for a specialization into a new high-brilliance branch for cutting edge science with the scope of grazing incidence, coherent scattering, scanning SAXS, XPCS/cross correlation spectroscopy and an existing, more classical, high throughput branch allowing for structural characterization of bio-polymers, structural biology, chemical synthesis, e.g., MOF’s synthesis or following in-operando energy storage applications [6]

1.7 CRYSTALLOGRAPHY AND TOMOGRAPHY

1.7.1. TOWARDS MICROPROBE AND HIGH-THROUGHPUT CRYSTALLOGRAPHY

Macromolecular crystallography (MX) is a powerful technique based on X-ray diffraction that is used to encode with atomic resolution the 3D structure of molecules involved in biochemical processes, such as proteins, nucleic acids (RNA and DNA), and viruses. This information is not only essential for understanding the working mechanisms of the biomolecules in the cells but also is a prerequisite to modify their properties via attaching of properly selected smaller molecules. Such modifications are playing crucial role in the structure-based rational drug design or in biotechnology for enhancing their activity and/or specificity.

However, the difficulties in the production and crystallization of a great number of macromolecules of medical and industrial interest are pushing the MX beamlines to face smaller and smaller samples. DLSR sources fulfill the strong needs of high flux, high brightness and tunability to perform state-of-the-art measurements in many fields, but this is especially true for the soft and medium hard X-ray range. In particular, the features of a 2.0 GeV Elettra 2.0 combined with the use of an in-vacuum undulator open the possibility to build a microfocus MX beamline optimized for the moderate hard X-rays (4-8 keV).

The foreseen X-ray beam flux and dimensions (8x10^{12} ph/s and 10 x 10 micron^2) would allow the characterization of small crystalline samples (impossible to be probed at the present XRD beamlines at Elettra) and surely will reduce the measurements time of medium-size samples. Elettra 2.0 also opens the possibility to implement modern data collection strategies with the aim of increasing data quality and limiting the radiation damage (severe in this energy range): helicoidal sample scan and serial crystallography which is the new paradigm in MX sciences as well as crystallization plate screening or data collection are the most important among the possible examples.

Another advantage of using the 4-8 keV energy range at a new Elettra 2.0 beamline is that the longer wavelengths have become attractive on the rational base of the increased anomalous scattering signal and the large number of atomic K and L edges of relevant elements as Ca, Mn, Fe, I, Cs, Xe in this energy range. In fact, the beamlines recently designed for MX measurements offer high photon flux also at lower energies and most of them start from 5 keV to fulfill the user needs to exploit the anomalous signal from lighter elements naturally present in the native protein or RNA/DNA crystals, both to solve the phase problem and to answer to specific biological questions. In some cases (as beamline I 23 of Diamond synchrotron, UK) the beamline is fully dedicated to this kind of measurements.

The beamline would gain from the small sizes and divergence of source providing 10x10 mm^2 probe at the sample with the intrinsic Si(111) bandpass, permitting also MAD experiments. Further-on, implementing a Kirkpatrick Baez focusing system, would allow variable spot dimensions in order to fit best to the samples size.
This longer-wavelength macromolecular crystallography beamline will also cope very well with the new generation of very fast single photon counting detectors, increasing substantially the data acquisition speed.

In summary, Elettra 2.0 represents a unique opportunity, offering to the scientific community a real breakthrough, increasing the quality of the data collected and opening to the characterization of samples today impossible to probe due to their size. At the same time, exploiting the longer wavelengths spectrum, it would catch the new scientific trends to face technical and scientific (especially biological) problems. The spectral range of the new beamline would perfectly complement the existing XRD2 beamline (7.5 up to 35 keV) also dedicated to MX.

1.7.2 X-RAY POWDER DIFFRACTION

The MCX beamline offers the characterization of ordered solid state samples in ambient and non-ambient conditions. The beamline is equipped for stress-strain analysis on alloys and in situ characterization of dynamic processes such as phase transition (e.g., lithium batteries).

In the context of Elettra 2.0 the MCX beamline could exploit the possibility to upgrade the X-ray source using, e.g., a high field wiggler or superbend, gaining 1-2 orders of magnitude in flux and a shift of the critical energy towards higher energies, opening to new scientific possibilities and industrial applications.

The shift of the spectrum would allow to perform experiments at 30 keV, extending the beamline activity to the study of higher absorbing materials (e.g., bismuth containing multiferroics), or residual stress analysis on iron containing alloys (e.g., steel) as a result of the higher penetration depth. The availability of high energy photons would also permit the implementation of modern methods for disordered materials as PDF.

The flux improvement will bring considerable advantages for in situ experiments thanks to the reduced exposures times, improving the time resolution and the characterization of dynamical phenomena.

The new opportunities resulting from this upgrade will attract new scientific communities and open to new experiments now unfeasible.

1.7.3 HARD X-RAY IMAGING AND TOMOGRAPHY

Hard X-ray imaging using synchrotron radiation has widespread applications in a variety of research fields spanning over Life, Materials Sciences and Cultural Heritage. The potentials of imaging techniques are beneficial not only for visualization microstructure building blocks of matter in two and three dimensions, but also provide essential quantitative information that can be retrieved using image analysis algorithms.

Recent achievements at several synchrotron laboratories highlighted the importance for increasing the source spatial coherence and X-ray fluxes in order to (i) shorten the acquisition time and open the route to real time studies and (ii) increase the spatial resolution using multiscale/multi resolution phase contrast techniques as well. The requests with respect to spatial resolution should integrate several length scales from mm to submicrometer depending on the sample sizes and properties of interest.
Being fed by a bending magnet source, the present hard X-ray imaging SYRMEP beamline has several limitations regarding the available flux and the photon energy range. The planned superconducting superbend as a source at Elettra 2.0 would open new opportunities for cutting edge research, keeping SYRMEP competitive with other beamlines operated at higher energy synchrotrons.

For research in materials and life science, including geomaterials and biomaterials, the possibility of extending the energy range would allow to expand the range of characterized materials, both in terms of composition and sizes (rocks, metallic alloys, innovative materials, industrial components, etc.). The higher photon flux would enable reducing the acquisition time in order to perform in-situ and in-operando real time microCT experiments (the so-called 4D microCT). Using 4D microCT one can investigate the temporal evolution of specific characteristics of the sample that can be subject to different treatments (temperature, strains, etc.). The time resolution depends on the X-ray flux that determines the scan duration (typically ~1 sec for acquiring several hundreds of projections in white beam mode).

Recently, 4D microCT is one of the most interesting developments of synchrotron-based hard X-ray imaging and it has still unexplored potentials, particularly for biological research. In this respect the reduction of the exposure time has also important advantages for sample sensitive to radiation damage.

Another application field is volcanology where the challenge is dynamical studies of bubbles formation and crystal nucleation and growth in magmatic systems. From a quantitative morphological and textural analysis of their microstructure, better understanding of the volcanic eruption mechanisms and of the system explosive potential can be assessed. These studies are typically performed during in-situ treatment of the samples at high temperature (up to ca 1200ºC) monitoring in real time their morphological evolution.

The expected SYRMEP improvements will have strong positive impact on preclinical research where the typical photon energy range for is 22-40 keV. As an example, the tomography of small living animals can allow to perform functional studies or to monitor the change of a given feature as a function of time. In-vivo low dose phase contrast CT protocols can be efficiently applied for monitoring lung function in allergic airway inflammation mouse models. Thanks to the effectiveness of propagation based phase contrast imaging, high quality images can be obtained at low radiation doses and longitudinal studies to evaluate the effects of different therapeutic approaches can be performed. Similar protocols can be used also for other lung diseases. Phase contrast imaging protocols can also be applied at different time intervals to monitor osteoarthritis in rats and rabbit models.

Since many years, SYRMEP beamline in collaboration with Trieste University and Public Hospital executes a program of clinical mammography with patients. After the first clinical trial of planar imaging, the activity is evolving towards a protocol of breast CT. Presently, the possibility to use higher X-ray energies, (i.e. 50-60 keV) instead the highest available today energy range of 32-40 keV combined with propagation based phase contrast modality would be essential in view to further reducing the doses to the
level of a single exposure of a conventional mammography (Ultra low dose phase contrast breast CT).

Furthermore, the new beamline parameters open opportunities for new clinical studies, e.g., the planar or CT protocol for the study of cartilages and joints. Feasibility experiments carried out at ESRF and Elettra already showed the higher sensitivity of phase contrast modalities for detecting early signs of cartilages degeneration due to osteoarthritis, with respect to MRI. Finally, the availability of an sufficient flux at X-ray energies of 70-80 keV would allow to open new prospects for phase contrast imaging of lungs in humans.

In the field of Cultural Heritage, several classes of samples of cultural and historical interest (fossilised teeth and bones, ceramic and metal manuafacts, etc.) require photon energies and flux not achievable with the present SYRMEP parameters. The implementation of the "superbend solution" would push-up both the energy and flux values, with the requested spatial coherence, beam size and spot dimension.

2. THE ELETTRA 2.0 CONCEPT: FRAMEWORK AND BASIC COSTRAINTS

The main characteristics of this new generation of storage ring based X-ray sources, is a substantial increase of the brilliance and coherence fraction of the source as compared to today’s X-ray beams. This objective should be reached without compromising the stability and reliability of Elettra, without increasing the total radiated power as well as not increasing the operational, instrumentation development and electricity costs.

The driving concept for this “ultimate” machine is the substantial reduction of the emittance of the stored electron beam, targeting emittance levels capable of providing a diffraction limited X-ray source also in the horizontal plane while such a limit has already been achieved at Elettra for the vertical plane. However, as the challenge is to implement it also for the horizontal plane, the new machine, Elettra 2.0 aims to provide intense nano-beams in the range of VUV to X-rays for the analytical study of matter with very high spatial resolution.

Development in accelerator technologies during the last twenty years has led to many important results featuring new magnet design, innovative vacuum technology, and revolutionary beam monitoring and orbit feedback systems. These new capabilities and technologies, which were not available or were at their infancy when the present Elettra storage ring was conceived, provide today a solid basis for the realization of the new machine.

A new compact lattice that will replace the existing double-bend achromat has been identified [1, 2], which should meet the following requirements, most of them defined during a workshop dedicated to the future of Elettra held in Trieste in the Spring of 2014:

- Maintain the existing building
- Maintain the existing ID straight sections in their current state
- Maintain the free space available
- Operating energy 2 GeV
• Increase the brilliance at 1 keV by more than one order of magnitude
• Preserve the time structure operation with a multi-bunch intensity of 400 mA
• Keep the present injection scheme and injection complex
• Minimize operation costs and electric power consumption.
• Limit the downtime for installation and commissioning to about one year.

The realisation of the new lattice requires the substitution of the 12 arcs of the existing storage ring with 12 new arcs of almost identical length. The new magnetic lattice reduces the present horizontal emittance of 7 nm-rad down to 0.24-0.28 nm-rad increasing the brilliance and coherence of the X-ray beam by a factor of 20, whilst preserving the injection system and the 12 straight sections of the existing ring.

The experience already gained with the continuing efforts to improve the existing facility (still in progress), sets a privileged starting point for the complete renewal of the storage ring. The technology of the RF Solid-State Amplifiers (SSA) to be installed in the Booster and subsequently in the storage ring will guarantee that the requirements for high availability will be met in the future. The expertise acquired in state-of-the-art vacuum technology during the last decade, especially in the long straight-section vacuum chambers, represents a solid basis for the design of a new vacuum system in the achromats.

The ultra-low vertical emittance under study for implementation, the orbit stability provided by the forthcoming new beam position detectors, the fast orbit-feedback, the third harmonic cavity, the superconducting wiggler as well as some of the insertion devices are already compatible with the specifications of the new generation of storage rings.

3.0 DESIGN CONSIDERATIONS

3.1 MAGNET LATTICE

The performance of a synchrotron radiation source is predominantly determined by the design of the storage ring magnet lattice. The design of the lattice for ultra-low emittance rings is mainly based on an intensive use of undulators, although one cannot exclude use of wigglers and dipoles as radiation sources inherited from the third generation of synchrotrons. However, the maximum benefit comes from the use of undulators. The insertion devices may have a deleterious effect on emittance, and to minimize emittance the dispersion function should be low and preferably zero in the straight section where the majority of the insertion devices are located. To obtain high brilliance requires a small beam emittance, giving small beam sizes and divergences.

The emittance is given by:

$$\varepsilon_x = C \frac{E^2}{N_d^3}$$

where C is a lattice constant, E the electron energy and N_d the number of dipoles. It is then obvious that the emittance is a strong function of the number of dipoles, and by increasing the dipole number the emittance is strongly reduced. However, in addition to the low emittance the lattice must provide adequate space for insertion devices. The lattice of Elettra is a double bend achromat having in total 24 dipoles with an emittance of
7 nm-rad at 2 GeV. By simply scaling with the number of dipoles for the same energy and almost same lattice constant for a six bend lattice (72 dipoles), one could obtain a reduction of the order \((72/24=3)^3 = 27\) or an emittance of about 0.26 nm-rad and allow for the same free space for insertion devices as in the present Electra lattice. This new lattice, the six bend achromat (6-BA), is proposed for Elettra 2.0.

### 3.1.1 LATTICE DESCRIPTION

The design lattice consists of 12 cells with 6-BA structure and with a total length almost equal to that of the present Elettra, i.e., 259.2 m, giving the right balance between available free space (both in dispersion-free and dispersive areas) and emittance requirements. Each cell of Elettra 2.0 includes 6 dipoles with vertical field gradient, 16 normal quadrupoles and 20 normal sextupoles. In addition, at least two skew quadrupole magnets per cell are foreseen to control betatron coupling. The magnets will be powered independently, although they will be grouped in families.

The lattice provides triplet focusing in the straight sections to compensate for any optical distortions produced by the insertion devices (IDs). In general IDs with a magnetic field up to 1 T (undulators) are very well tolerated, but for higher fields (usually wigglers) corrections are necessary. Similarly, the nonlinear effects of the IDs will be minimized by reducing the vertical beta function (at least for planar devices and especially for in-vacuum devices).

At 2 GeV of beam energy and at the design vacuum pressure of one pbar, the beam lifetime is expected to be Touschek-scattering limited. The effect can be reduced by maintaining the momentum acceptance at 3% and reusing the third harmonic cavity already in operation at Elettra. Furthermore, the new lattice must fit into the existing facility (in terms of ring circumference, periodicity and beam-line source point positions). A 7-bend achromat cell was also studied that gave an emittance of 0.18 nm-rad, but there was insufficient space in the short straights for installing the radio frequency cavities (as they are at Elettra) without sacrificing a long straight section already occupied by a beamline.

The two main configurations examined are displayed in Figs. 3.1.1.1 and 3.1.1.2. The first configuration contains two lateral free spaces in the arc of about 1.3 m long whereas in the second configuration there is a central free space of 1.6 m while the lateral ones are reduced to 0.4 m. The solutions are equivalent from the point of view of lattice properties, and the choice is based on the study of interferences between the light exits with the magnetic elements and the minimization of the source point shifts.

Both solutions come with a triple option for the second and fifth bending magnet. In the first option all bends are combined-function electromagnets with a field of about 0.8 T and a gradient of 14-20 T/m. In that case, some dipole beamlines may receive their radiation from a short wiggler with the implication of shifting the corresponding beamline by about 7 degrees. In the second option the second and fifth dipoles are replaced by strong permanent magnets of about 1.4 T with a bending angle of about 5.6 degrees, enough to serve a single dipole beam line with minimal position shift. A large variation of this configuration is studied whereby it can be exchanged by a three-piece electromagnet with its central section of high field without gradient. Those configurations give achromatic solutions with emittances 0.24 to 0.28 nm-rad respectively.

The permanent magnet (PM) solution (the third option) could consist of either a short strong permanent magnet without gradient therefore accompanied by two defocusing quadrupoles at each end of the magnet or by a series of permanent magnets, a concept
that has been developed at Elettra [3], as the “short PM dipole series concept”. This configuration is a series of 7 short permanent magnets of about 13 cm each with one anti-bend, two strong 1.4 T dipoles without gradient while the others have a field of 0.8 T and gradient of about 18 T/m.

The optics of the Elettra 2.0 for the short PM dipole series concept configuration (shown in Figure 3.1.1.1a, using the OPA code [4]) has a long dispersion-free section of 4.84 m and two dispersive sections of 1.33 m. The beam dimensions assuming 1% coupling are shown in the next figure 3.1.1.1b:

![Figure 3.1.1.1a: Lattice functions for the first configuration](image)

![Figure 3.1.1.1b: Beam dimensions](image)

The optics of the Elettra 2.0 for the second configuration (shown in Figure 3.1.1.2) has a long dispersion-free section of 4.95 m, two short dispersive sections of 0.40 m and a large central dispersive section 1.55 m long.
Since the dispersion is generally very low (60 mm maximum), the beam dimensions in
the dispersive short straight sections remain comparable to those without dispersion
(long straights) making the possibility of installing short undulators there very attractive.

In the first configuration only the right dispersive section 1.33 m long can be used since
the left one interferes with the light exit of the undulators of the long straight sections. In
the second configuration all dispersive central sections about 1.6 m long can be used,
making this configuration more attractive. In both cases, four sections will be occupied
by the four RF cavities, leaving 8 dispersive, short straight sections available for inser-
tion devices.

The second configuration is better as compared with the first one with respect interfe-
rences point while also minimizing the shift of the dipole beam lines. Therefore although
all options are valid, all of the following analysis is based on the second configuration as
in figure 3.1.1.3 corresponding to the optics shown in figure 3.1.1.2.

As it can be seen in Fig. 3.1.1.3, the arc consists of 6 gradient dipole magnets that also
provide vertical focusing by having at each end one horizontally focusing quadrupole.
The configuration “quadrupole, dipole, quadrupole” creates six unitary cells (UC) with
the optics being invariant to distance changes between UCs, a very useful property, but
very sensitive to distance changes between the dipole and the quadrupoles within the UC.
The lattice is not isomagnetic, since the bending angles vary (two 0.75 m long dipoles
with bending angles of 3.6 degrees and four 0.84 m long dipoles with bending angles of
5.7 degrees, while their normalized strengths are -1.91 m\(^{-2}\) and -2.03 m\(^{-2}\) respectively).
The quadrupoles come in 8 families, and their maximum normalized strength is 6.8 m\(^{-2}\).
It is well known that low-emittance lattices result in large natural chromaticities that have to be compensated by the sextupoles in the ring to avoid tune shifts to resonances that are dangerous for beam stability. The nonlinear effects of strong sextupoles can reduce the dynamic aperture (DA) if they are not compensated adequately. Therefore, a sufficiently large DA must be attained for efficient beam injection and proper lifetime.

The nonlinear effects due to the sextupoles may be reduced by a suitable phase advance between the sextupole locations that, in general, is sensitive to the choice of tunes. The sextupoles come in nine families positioned where the beta functions/dispersion are largest, including 2 families of harmonic sextupoles (instead of octupoles) in the dispersion-free region to help increase the DA by reducing the amplitude of the tune shift without affecting the chromaticity and providing as well Landau damping to control the coherent bunch instabilities [5]. In the tune diagram, shown below, the preferred tune area \((33 < Q_x < 33.3\) and \(9 < Q_y < 9.3\)) shows a preference towards the upper part of the 2nd order line:

![Tune diagram showing the resonance lines up to 11th order](image)

Figure 3.1.1.4: Tune diagram showing the resonance lines up to 11th order
Figures 3.1.1.5 and 3.1.1.6 show the horizontal and vertical tune shifts with relative momentum deviation (±3%) – to identify potential crossing of integer or half-integer resonances – and with horizontal and vertical initial amplitudes at the injection point, which provide an indication of the oscillation amplitude at which the particle motion may remain stable.
Figure 3.1.1.7: Left: horizontal and vertical tune vs. horizontal amplitude in m. Right: horizontal and vertical tune vs. vertical amplitude in m.

To keep the free space as large as that of the existing Elettra lattice, the intra-magnet distances were reduced. The magnet-to-magnet free space distance is 50-70 mm; additionally the magnets will have magnetic length equal to the physical length to avoid interferences of the coils.

A list of the optics and RF-related functions is given in the following table 3.1.1:

<table>
<thead>
<tr>
<th>Table 3.1.1: Elettra 2.0 parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
</tr>
<tr>
<td>Energy (GeV)</td>
</tr>
<tr>
<td>Number of cells</td>
</tr>
<tr>
<td>Geometric emittance (nm-rad)</td>
</tr>
<tr>
<td>Horizontal tune</td>
</tr>
<tr>
<td>Vertical tune</td>
</tr>
<tr>
<td>Betatron function in the middle of straights (x, y) m</td>
</tr>
<tr>
<td>Horizontal natural chromaticity</td>
</tr>
<tr>
<td>Vertical natural chromaticity</td>
</tr>
<tr>
<td>Horizontal corrected chromaticity</td>
</tr>
<tr>
<td>Vertical corrected chromaticity</td>
</tr>
<tr>
<td>Momentum compaction</td>
</tr>
<tr>
<td>Momentum compaction second order</td>
</tr>
<tr>
<td>Energy loss per turn (no IDs) (keV)</td>
</tr>
<tr>
<td>Energy spread</td>
</tr>
<tr>
<td>$J_x$</td>
</tr>
<tr>
<td>$J_y$</td>
</tr>
<tr>
<td>$J_{\delta}$</td>
</tr>
<tr>
<td>Horizontal damping time (ms)</td>
</tr>
<tr>
<td>Vertical damping time (ms)</td>
</tr>
<tr>
<td>Longitudinal damping time (ms)</td>
</tr>
<tr>
<td>Dipole field (T)</td>
</tr>
<tr>
<td>Quadrupole gradient in dipole (T/m)</td>
</tr>
<tr>
<td>Quadrupole gradient (T/m)</td>
</tr>
<tr>
<td>Sextupole gradient (T/m²)</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
</tr>
<tr>
<td>Beam revolution frequency (MHz)</td>
</tr>
<tr>
<td>Harmonic number</td>
</tr>
<tr>
<td>Orbital period (ns)</td>
</tr>
</tbody>
</table>
3.2 DYNAMIC APERTURE OF THE BARE LATTICE

The DA is defined as the maximum initial betatron amplitude that can be tolerated for particles in the lattice before an unbounded growth of the oscillation amplitude occurs. An amplitude growth of the oscillation of a particle is caused by nonlinear magnetic fields either introduced on purpose such as the sextupoles to compensate the chromaticity or that are present accidentally due to unavoidable magnet errors.

To avoid instabilities of the head-tail type that make the beam unusable and to avoid exciting resonances, sextupoles are introduced into the lattice to compensate the natural chromaticity defined as the change in tune for off-momentum particles; i.e.,

$$\xi = \frac{\Delta Q}{\Delta p/p}.$$

A low-emittance lattice produces large natural chromaticities that have to be compensated by sextupoles, to avoid tune shifts to resonances dangerous for beam stability. Furthermore, the sextupoles introduce nonlinear fields and a coupling between the transverse planes of motion that naturally lead to a reduction of the DA. Nonetheless, a sufficiently large DA is essential for efficient beam injection and sufficiently large lifetime. The nonlinear effects due to the sextupoles may be reduced by choosing a suitable phase advance between the sextupole locations. In general the effects are sensitive to the tunes.

These undesirable effects, which are already quite strong in third generation machines, now become even stronger. Achieving very small beam dimensions requires the use of strong, combined-function magnets. For example, the dipoles – in spite of having a field of about 0.8 T (which is less than the nominal 1.2 T of the existing Elettra dipoles at 2 GeV) – must have a quadrupole gradient of about 14 T/m as compared with the 3 T/m of the present dipoles.

Similarly, the quadrupoles have 3 times higher gradients that increase the chromaticity of the machine by a factor of 2-3. To correct for the chromaticity, stronger sextupoles are needed that naturally reduce further the DA of the accelerator thereby introducing other nonlinear effects. As previously indicated, the proposed lattice contains 20 sextupoles per achromat. Of those 20, four sextupoles are located in the dispersion-free region (harmonic) to increase the dynamic aperture by reducing the tune shift with amplitude without affecting the chromaticity and also to provide Landau damping to control coherent bunch instabilities.

As a rule of thumb, the DA for a given machine scales inversely with the number of dipoles, thus Elettra 2.0 will have about 3 times smaller DA than the present Elettra for which the DA is 60x40 mm (bare lattice without errors). One then would expect a 20x13 mm DA for Elettra 2.0. To optimize the DA even further proves to be non-trivial, as strong sextupoles in the low-emittance lattice can affect the motion of beam particles with large betatron amplitude and, in turn, reduce the DA that may be further decreased by various machine errors. For the optimization of the DA, the harmonic sextupoles are very important since they counteract the shifts with amplitude.
To investigate the DA, 6-dimensional (6-D) particle tracking was performed, including both betatron and synchrotron oscillations in the presence of classical synchrotron radiation emission and radiofrequency (RF) acceleration. Beam energy was held constant, and the beam was assumed to be stored at equilibrium. Tracking was done by simulating particle motion up to the third order in the particle coordinates in the 6-D phase space. DA was then calculated on the basis of particle tracking. When a particle was not lost for 2000 turns, it was assumed that its initial amplitudes in the transverse phase space continuously remained in stable motion. The DA was therefore defined as the maximum initial amplitude for which the motion is stable over 2000 turns or about 10% of the horizontal damping time. As the amplitude of particle oscillations is damped by synchrotron radiation, it was assumed that 2000 turns are sufficient condition for stable motion at equilibrium. The DA was studied for the bare lattice (no errors) on-momentum, off-momentum, and on-momentum with machine errors (see next section) using the code ELEGANT [6].

Figure 3.2.1 shows the area of the DA as a function of the working point, in a specific region of the tune diagram. A general trend favors relatively low values of the fractional tune. Hereafter, the nominal working point for the bare lattice maybe fixed to (33.10 to 33.30, 9.20).

Figure 3.2.1: On-momentum dynamic aperture in mm² for the bare lattice, as a function of the working point.

Figure 3.2.2 shows the DA for the on-momentum bare lattice. The colour scale codes the tune diffusion coefficient, which remains very low within a physical region of ~ (± 5 mm) × (± 3 mm) around the reference closed orbit.
Figure 3.2.2: Dynamic aperture over 2000 turns, for the on-momentum bare lattice. Color scale codes the tunes diffusion coefficient. The DA is calculated in the vicinity of the injection point.

Figure 3.2.3 shows the value of the coherent horizontal and vertical tune as a function of the beam position at injection inside the DA. The fractional part of the tune remains close to the nominal working point within ±0.05 for a region of ~ (± 5 mm) × (± 3 mm) around the closed orbit, consistently with the evaluation of the diffusion coefficient in the figure. Figure 3.2.4 and 3.2.5 shows the DA for on- and off-momentum bare lattice; the fractional momentum was set to ±4%.

Figure 3.2.3: Frequency map (zoomed on right plot) calculated over 2000 turns, for the on-momentum bare lattice. Colour scale codes the tunes’ diffusion coefficient.
Figure 3.2.4: Dynamic aperture calculated over 2000 turns, for the on-momentum bare lattice. Color scale codes the fractional part of the horizontal (top) and vertical tune, as a function of the beam position inside the DA at the injection point.

Figure 3.2.5: Dynamic aperture calculated over 2000 turns, for the bare lattice on-momentum, and for ± 4% off-momentum.

The impact of resonances on the stability of the particle motion can be inferred by looking at the single particle motion in phase space. Figure 3.2.6 shows the horizontal, vertical and longitudinal phase space for the on-momentum, bare lattice. The most evident limitation to stability is the third-order sextupole resonance in the horizontal plane. The Fourier analysis of the motion in the longitudinal phase space provides a synchrotron frequency of 0.005 Hz.

Figure 3.2.6: Tracking of single particle motion in the horizontal (left), vertical (centre) and longitudinal phase space over 500 turns, including high order transport, RF focusing and synchrotron radiation. A fourth-order resonance deforms the horizontal betatron motion at large amplitudes.
3.3 CLOSED ORBIT CORRECTION AND DA INCLUDING ERRORS

Closed orbit errors are produced mainly by quadrupole misalignments, dipole field errors and dipole rotation errors. The correction of induced closed orbit distortions is essential to reduce the effects of non-linearities that are large because of the increased field gradients. The correction schemes are well established in the present Elettra machine. They include global and local orbit correction with a corrector strength minimiser, as well as slow and fast orbit feedbacks with excellent performance.

In implementing a correction scheme, it is important to define the number and position of the beam position monitors (BPMs) and correctors. From Shannon’s sampling theorem and the given tunes, the minimum number of BPMs for the orbit reconstruction was determined to be 72 for the horizontal position and 24 for the vertical. However, the higher the number of BPMs used, the more accurate is the reconstruction of the orbit. The present Elettra ring has 92 BPMs for both planes, while a plausible minimum for this machine would be 36 horizontal and 24 vertical. For Elettra 2.0, it is proposed to use 14\times12=168 BPMs for both planes close at quadrupole locations when possible for beam based alignment, attached on the girder.

Correctors should have a maximum kick of 2 mrad. Some will be located in the sextupole magnets with separate coils that could be used also for creating skew quadrupole fields. There will be 72 combined independent correctors that might be used also as skew quadrupoles. There will be 16 correctors/section, in total 192. There will also be a large number of fast correctors of a few gauss-meter (0.1 mrad kick) for the fast orbit feedback.

For the correction of the orbit there are available many programs locally developed having all possible methods such as SVD, most effective, local bumps both symmetric and asymmetric and a combined method for global orbit minimization that at the same time performs corrector strength minimisation using eigenvalues. While in the past such programs were stand-alone, nowadays with MML and Matlab orbit optimization is performed using the machine model.

Figure 3.3.a: BPM and Corrector positioning in one section
Orbit corrections were possible assuming errors as shown in the Table 3.3.1. Given the error budget of Tab.3.3.1, the results of the error runs were filtered to eliminate those error sets that provide difficult orbit control, i.e., beam positions exceeding 1 mm along the whole ring. As a result, a conservative scenario is provided in which at least approximately 70% of the error sets can be easily managed with the implemented correction scheme. All the results in the present sub-section refer to this “good” ensemble of data. In the selected runs, the maximum corrector’s kick to be provided is 200 µrad with an rms value of 50 µrad. When including also largely distorted orbits, the maximum kick required for correction is 1 mrad.

All errors are assumed to be standard deviations of Gaussian distributions with a 3-sigma cutoff. Twenty independent error runs were used to determine a statistically meaningful ensemble of DA. The closed orbit distortion was corrected with 13 BPMs per cell, 11 horizontal and 11 vertical corrector magnets. BPMs were placed close to quadrupoles. Figure 3.3.2 shows the distribution of correctors and BPMs along the ring, as a function of the betatron phase advance in the horizontal and vertical plane.

<table>
<thead>
<tr>
<th>Element Type</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>Δx</td>
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<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δy</td>
<td>20</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δz</td>
<td>300</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Roll angle</td>
<td>100</td>
<td>µrad</td>
</tr>
<tr>
<td></td>
<td>ΔBl/Bl</td>
<td>0.01</td>
<td>%</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>Δx</td>
<td>20</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δy</td>
<td>20</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δz</td>
<td>300</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Roll angle</td>
<td>100</td>
<td>µrad</td>
</tr>
<tr>
<td></td>
<td>ΔBl/Bl</td>
<td>0.01</td>
<td>%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>Δx</td>
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<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δy</td>
<td>20</td>
<td>µm</td>
</tr>
<tr>
<td></td>
<td>Δz</td>
<td>300</td>
<td>µm</td>
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<tr>
<td></td>
<td>Roll angle</td>
<td>100</td>
<td>µrad</td>
</tr>
<tr>
<td></td>
<td>ΔBl/Bl</td>
<td>0.01</td>
<td>%</td>
</tr>
<tr>
<td>Corrector</td>
<td>Δz</td>
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<td>µm</td>
</tr>
<tr>
<td></td>
<td>Roll angle</td>
<td>100</td>
<td>µrad</td>
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<tr>
<td>BPM</td>
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<tr>
<td></td>
<td>Roll angle</td>
<td>100</td>
<td>µrad</td>
</tr>
</tbody>
</table>

Values refer to the standard deviation of a Gaussian distribution with a 3-sigma cutoff. Approximately 70% error runs (corresponding to 20 selected files) generated by this budget were post-processed and shown in the following figures.

For each error run, the closed orbit distortion was corrected, the tunes were corrected to the nominal values by two families of quadrupoles, and the linear chromaticities were corrected to the nominal value of +1 in both planes by two families of sextupoles. The
closed orbit correction was performed by imposing a maximum kick angle of 2 mrad by the correctors, and assuming random noise in the reading of the BPMs of 0.1 µm rms.

As will be discussed later, off-axis injection of the beam is thought to be compatible with a 8 mm horizontal aperture at the septum location. Figure 3.3.1 shows the DA on-momentum, both for the bare lattice and with the machine errors listed in Tab.3.3.1.

![Figure 3.3.1: Dynamic aperture for the bare lattice (named transverse acceptance in the legend), and in the presence of machine errors plus corrections, for 20 independent error seeds (see error budget in Table 3.3.1).](image)

Figure 3.3.2 shows the perturbed closed orbit, before and after correction. Figure 3.3.3 shows the perturbed closed orbit, before and after correction. Figure 3.3.4 shows average and extreme values of the dispersion and betatron functions along the ring, in the presence of errors and correction.
In addition to machine errors (Tab.3.3.1), transverse misalignments of the girders and beam-based alignment orbit correction were simulated as an equivalent 100 µm lateral displacement of elements that placed on the same girder. The alignment errors are correlated for elements on the same girder, and uncorrelated girder-to-girder. By doing so, the horizontal DA reduces further from approximately ±9 mm (see Fig.3.3.1) to ±7 mm. Certainly, it may be laborious to inject off-axis into a ±7 mm horizontal aperture, especially as far as top-up efficiency is concerned, but this difficulty does not render the optics unfeasible because once the injected beam is stored, the DA still corresponds to 200 σ of the beam size (compared with 100 σ in Elettra).

3.4 APERTURE REQUIREMENTS, GOOD FIELD REGION

The required horizontal aperture $A_x$ is determined by the injection process and by the requirement to accommodate scattered electrons with large momentum deviation (Touschek scattering). The half-aperture required for injection may be given by:

$$A_x = \frac{\sqrt{\beta_{x,\text{max}}}}{\sqrt{\beta_x \text{ inj}}} \left( 2 \sqrt{\epsilon_x \beta_x \text{ inj} + 2 \sqrt{\epsilon_x \text{ inj} \beta_x \text{ ib} + \text{Sept} } } + C. O, \right)$$

where

$\beta_{x,\text{max}} = 16 \text{ m}$ maximum horizontal beta value

$\beta_x \text{ inj} = 11 \text{ m}$ beta value at the injection point

$\beta_x \text{ ib} = 11 \text{ m}$ beta value of the injected beam
\[ \varepsilon_x = 0.3 \text{ nm-rad} \quad \text{emittance of the stored beam (conservative)} \]
\[ \varepsilon_{x\text{ inj}} = 100 \text{ nm-rad} \quad \text{emittance of the injected beam} \]
Sept = 3.0 mm effective septum thickness
C.O. = 2.0 mm peak value of closed orbit error

The injection point is placed in the middle of the straight section as it is presently. Assuming for now that the injection will be the same as with the present Elettra, then \( A_x = \pm 7.7 \text{ mm} \) for an injected beam of 100 nm rad.

Furthermore, for the aperture requirements for Touschek scattering, a Touschek scattered particle with a momentum change of 3% must be stable within the aperture of the ring or suffer lifetime reduction. If the scatter occurs at the position of the maximum dispersion of 0.06 m, the new closed orbit will be shifted by \( 0.06 \times 0.03 = 1.8 \text{ mm} \) and a betatron oscillation of the same amplitude may be excited. The half aperture due to this effect is 3.6 mm.

Thus the aperture for injection should be \( A_x = \pm 7.7 \text{ mm} \) and then for a stored beam it should be \( > \pm 3.6 \text{ mm} \). Adding the two numbers, the absolute total \( A_x \) becomes \( \pm 11.3 \text{ mm} \). However, this aperture is the absolute maximum to be on the safe side.

The vertical aperture requirement come from the quantum lifetime and is defined by the relation of the half vertical aperture:
\[ A_y = n \sqrt{\varepsilon_y \beta_y + \text{c.o}} \]
where \( \varepsilon_y \) is the vertical emittance \( \beta_y \) the maximum vertical beta =16 m and \( n=10 \) the number of standard deviations for good lifetime. Assuming a fully coupled, round beam \( \varepsilon_x = \varepsilon_y = \varepsilon_0 / (1 + t_x / t_y) = 0.25 / (1 + 15/23) = 0.15 \text{ nm rad} \) where \( t_x \) and \( t_y \) are the horizontal and vertical damping times. \( A_y \) becomes \( \pm 2.5 \text{ mm} \) whereas for a 1% coupling its value is \( \pm 2.2 \text{ mm} \).

The good field region represents the horizontal and vertical space in the magnet where the field is required to be within the defined error tolerance, usually of the order of 10 ppm (i.e. \( 10^{-6} \)) or less.

According to the above derivations, the minimum circular cross section may be at 23 mm diameter. A more conservative vacuum chamber might have a rhomboidal shape of height x width = 35 mm x 20 mm, providing a larger horizontal physical aperture and a lower horizontal chamber impedance. However, a cylindrical shape may have a better vacuum conductance; therefore we are presently inclined toward using a round vacuum chamber of 26 mm external and 23 mm internal diameter.

### 3.5 Vibrations and Orbit Distortions

Vibrations of the storage ring lattice lead to closed orbit distortions and can be approximated as being generated by constant displacements of magnets with quadrupole gradient. Sources of vibration include seismic waves, traffic, external works, cooling water flow, eigen-frequencies of the girder, etc. Closed orbit distortions have also many other causes in addition to vibrations; such sources are temperature and ground variations, insertion devices, power supplies. The effects that produce orbit distortions may be distinguished between slow and fast. Slow effects have frequencies below 10 Hz and can be
managed using slow feedback systems. Instead faster effects should be mitigated as much as possible before applying fast feedback systems.

In the following table the main vibration sources and their amplitude on the electron beam are shown:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Magnitude</th>
<th>Dominant cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td>10 µm ptp</td>
<td>Ground motion / temperature long fluctuations / see motion / wind</td>
</tr>
<tr>
<td>days</td>
<td>5 µm ptp</td>
<td>Day / night temperature variation / bpm detectors AD conversion</td>
</tr>
<tr>
<td>Hours - minutes</td>
<td>1-2 µm rms</td>
<td>Steerer hysteresis / feed forward /</td>
</tr>
<tr>
<td>0.1 to 300 Hz</td>
<td>1-4 µm rms</td>
<td>ID movements, water flow vibrations, air blast coolers vibrations, air condition, 50 Hz noise, ps ripple, feed forward errors</td>
</tr>
</tbody>
</table>

Elettra is constructed on a very solid bedrock and is largely insensitive to disturbances. In addition, a fast global orbit feedback corrects very efficiently any source of vibrations. The figure 3.5.2 shows the beam amplitude spectrum in the 0 to 500 Hz range without (red spectrum) and with feedback (blue spectrum) while in the following table the various amplitudes in relation to frequency are shown:

Table 3.5.1: Amplitudes in relation to frequency with feedback on and off

<table>
<thead>
<tr>
<th>I=320mA</th>
<th>0 - 5 Hz</th>
<th>0 - 5 Hz</th>
<th>0 - 200 Hz</th>
<th>0 - 200 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=2GeV</td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>FB off</td>
<td>0.4</td>
<td>0.15</td>
<td>3.5</td>
<td>2.1</td>
</tr>
<tr>
<td>FB on</td>
<td>0.1</td>
<td>0.06</td>
<td>1.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
The above data demonstrate that the only significant source of vibrations (apart from the 50 Hz and their harmonics originating from the mains) is in the range 16-38 Hz due to the magnet cooling water pumps, air conditioning, cooling blasters. However those effects can be reduced to about 0.3 µm. In general, all vibrations can be reduced to about 1 µm. Although this performance is excellent for the present Elettra ring, special care should be taken for vertical beam stability in Elettra 2.0. Thus while 1 µm is below 10% of the horizontal beam size (45 µm) the vertical stability should be increased to stay within the 10% rule. The minimum vertical beam size of Elettra 2.0 is about 3 µm (1% coupling). Therefore the vibration amplitude with feedback on should be reduced down to 0.3 µm. To mitigate sources of vibrations, the magnets of Elettra 2.0 will be air cooled. Special care should also be taken to decrease the mains noise.

Magnet vibrations generate orbit variations that generally have larger rms amplitudes than the vibrations of the magnets themselves. The ratio of the rms orbit distortion to rms random misalignments of the magnets, for each plane, is a measure of the enhancement effect and is called the amplification factor. This factor depends on the particular machine optics and can be computed numerically. For the Elettra 2.0 lattice with WP (33.3,9.2) it reads 107 for the horizontal and 77 for the vertical plane (for comparison the present Elettra machine has 49 and 23) meaning that with random vibrations of 10 µm of all magnetic elements the orbit may be disturbed as much as about 1 mm horizontally and 0.77 mm vertically. Such condition, however, is not very probable and residuals can be compensated by the orbit correction system. In any case we will strive to reduce drastically all sources of vibration. To this end, special care should be taken for the girder design that may introduce a correlation in the random vibration of the magnetic elements. A properly designed girder can reduce vibrations to a large extent.
3.6 INJECTION INTO THE STORAGE RING

The electron beam accelerated to 2.0 GeV by the inner booster ring is assumed to be injected horizontally into Elettra 2.0 in a dispersion-free, long, straight section of the ring (S12), where the horizontal betatron function is approximately 10 m. We assume standard off-axis injection with 4 fast kickers and one or two of septum magnets, configuration similar to the actual Elettra injection scheme.

As shown in section 3.4 the half aperture required for injection is 7.7 mm. Since the injection occurs from the inside of the ring, a bump amplitude of -8 mm from the stored beam center should be sufficient for off-axis injection while a -9 mm bump would relax tolerances on the beam injection position and angular divergence in the presence of machine errors. A front view of the injection geometry is shown in Fig.3.6.1 with the corresponding beam/septum sizes.

![Front view of the injection geometry for Elettra 2.0, based on a standard 4-kickers + septum injection. The large injected beam (in orange) has an rms horizontal beam size of 1 mm. The stored beam in green has an rms horizontal beam size of 50 µm. The septum thickness is assumed to be 3 mm.](image)

The injection efficiency may be maximized as the horizontal bump of the injected beam is within the transverse acceptance of the main ring at the point of injection. However, injection experiments performed at Elettra indicate that injection is also possible when the injection bump lies outside of the DA although at lower efficiency. The following discussion assumes no physical restrictions to the horizontal motion, so that the transverse acceptance coincides with the DA. A preliminary optimization of the DA as a function of the working point indicates a stable motion up to a horizontal amplitude of 9 mm at the point of injection, as shown in Figure 3.2.3.

![Filamentation in the horizontal phase space of a beam tracked through the ring for 500 turns, in the presence of an horizontal offset of 8 mm at the injection point.](image)

Figure 3.6.2 shows the filamentation in the horizontal phase space of a beam tracked through the ring for 500 turns, in the presence of an horizontal offset of 8 mm at the injection point. The worst-case scenario considered is an injected beam as the one found at the exit of the current Elettra booster, i.e., 100 nm rad (10 nm rad) horizontal (vertical) emittance, 0.8% rms relative energy spread and 10 mm rms bunch length. The same figure shows the motion of the centre of mass of the particles distribution. The particles transmission after 500 turns is 100% for the bare lattice. For an injection offset equal to -8 mm and -9 mm, the injection efficiency is reduced to 92% and 81%, respectively.
Figure 3.6.2 Left: Filamentation in the horizontal phase space of 200 macro-particles beam tracked over 500 turns, with initial offset of 8 mm at the injection point, in the presence of high-order transport, RF focusing and synchrotron radiation (color legend is arbitrary, one color per turn in the ring). Right: motion of the beam centroid in the horizontal phase space, sampled every 10 turns, over 500 turns in total.

The above analysis assumed a bare lattice, including errors as specified in Table 3.3.1. The injection efficiency is shown in figure 3.6.3 versus the horizontal beam bump position. Thus a 5 mm bump will have 100% injection efficiency while an 8 mm bump will have 97% efficiency.

Figure 3.6.3: Injection efficiency versus the horizontal beam bump amplitude

3.7 EFFECTS OF INSERTION DEVICES AND OF SUPERBENDS

The presence of the IDs in a synchrotron gives rise to various effects on beam dynamics. Firstly, IDs modify the radiation equilibrium through quantum excitation and damping, resulting in a change in the beam emittance, energy spread and damping times. IDs influence the linear and non-linear optics producing distortions of the optics functions (e.g., beta beats and tune shifts) via edge focusing of the magnetic blocks, and additional resonance excitations that can reduce the DA. Usually these effects can be corrected to a large extent using the dispersion-free quadrupoles and by careful choice of the working point.

The emittance and energy spread are given by:

\[ \varepsilon_x = A \frac{I_3}{I_2 - I_4} \quad \sigma_x^2 = A \frac{I_3}{2I_2 + I_4} \]
where $A$ is a constant and $I_{1,5}$ are the synchrotron radiation integrals. The IDs introduced in the lattice give an extra contribution to the integrals thus modifying the above expressions. In general the emittance and energy spread will decrease with moderate ID fields. However, for very strong fields and/or long period devices the small dispersion created by those devices (since all of them are a sequence of dipoles) may first compensate and subsequently invert the effect. Some inverted effect (i.e., emittance increase) will be produced also by IDs that are installed in dispersive regions.

In the present configuration of Elettra the influence of the IDs has been studied and measured. The IDs currently present at Elettra are shown in the table 3.7.0:

Table 3.7.0: Current insertion devices at Elettra

<table>
<thead>
<tr>
<th>ID</th>
<th>type</th>
<th>section</th>
<th>Period (mm)</th>
<th>Nper</th>
<th>gap (mm)</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>U5.6</td>
<td>PM/Linear</td>
<td>12 short</td>
<td>56</td>
<td>18</td>
<td>23</td>
<td>operating</td>
</tr>
<tr>
<td>EU10.0</td>
<td>PM/Elliptical</td>
<td>1</td>
<td>100</td>
<td>20–20</td>
<td>13.5</td>
<td>operating</td>
</tr>
<tr>
<td>U4.6</td>
<td>PM/Linear</td>
<td>2</td>
<td>46</td>
<td>2 x 49</td>
<td>13.5</td>
<td>operating</td>
</tr>
<tr>
<td>U12.5</td>
<td>PM/Linear</td>
<td>3</td>
<td>125</td>
<td>3 x 12</td>
<td>32.0</td>
<td>operating</td>
</tr>
<tr>
<td>EEW</td>
<td>EM/Elliptical</td>
<td>4</td>
<td>212</td>
<td>16</td>
<td>18.0</td>
<td>operating</td>
</tr>
<tr>
<td>W14.0</td>
<td>HYB/Linear</td>
<td>5</td>
<td>140</td>
<td>3 x 9.5</td>
<td>22.0</td>
<td>operating</td>
</tr>
<tr>
<td>U12.5</td>
<td>PM/Linear</td>
<td>6</td>
<td>125</td>
<td>3 x 12</td>
<td>29.0</td>
<td>operating</td>
</tr>
<tr>
<td>U8.0</td>
<td>PM/Linear</td>
<td>7</td>
<td>80</td>
<td>19</td>
<td>26.0</td>
<td>operating</td>
</tr>
<tr>
<td>EU4.8</td>
<td>PM/Elliptical</td>
<td>8</td>
<td>48</td>
<td>44</td>
<td>19.0</td>
<td>operating</td>
</tr>
<tr>
<td>EU7.7</td>
<td>PM/Elliptical</td>
<td>8</td>
<td>77</td>
<td>28</td>
<td>19.0</td>
<td>operating</td>
</tr>
<tr>
<td>EU6.0</td>
<td>PM/Elliptical</td>
<td>9</td>
<td>60</td>
<td>36</td>
<td>19.0</td>
<td>operating</td>
</tr>
<tr>
<td>EU12.5</td>
<td>PM/Elliptical/QP</td>
<td>9</td>
<td>125</td>
<td>17</td>
<td>18.6</td>
<td>operating</td>
</tr>
<tr>
<td>FEU</td>
<td>PM/Figure-8</td>
<td>10</td>
<td>140</td>
<td>16-16</td>
<td>19.0</td>
<td>operating</td>
</tr>
<tr>
<td>SCW</td>
<td>SC/Linear</td>
<td>11</td>
<td>64</td>
<td>24.5</td>
<td>10.7</td>
<td>operating</td>
</tr>
</tbody>
</table>

The biggest impact on the optics and emittance of Elettra 2.0 is expected from the 3.5 T superconducting wiggler. In the following figure shows the emittance and energy spread change versus the wiggler field:
Figure 3.7.0: Emittance and energy spread change versus the wiggler field

As it can be seen, the net effect is a small reduction of the emittance at maximum field. In Figure 3.7.1 the emittance, energy spread and energy loss per turn is shown versus the number of IDs at operating gap.

Figure 3.7.1: Emittance, energy spread and energy loss per turn versus the number of insertion devices at minimum gap / max phase.

The net effect also in this case is a reduction on the emittance when all other IDs are at minimum gap/maximum phase, since the fields of the other IDs are below 1.5 T and do not create spurious dispersion and/or strong optical asymmetries. Undulators number 4,
11, 12 and 13 are of the APPLE II type, whereas the number 14 is the superconducting wiggler.

IDs in general can produce optical distortions that may reduce the dynamic aperture if the distortions are not corrected due to resonance excitations. In Figs. 3.7.2 and 3.7.3 the optical distortion of the wiggler are shown for various fields:

Figure 3.7.2: Optics with wiggler at 0.5 T, no distortions are evident.

Figure 3.7.3: Optics with wiggler at 2.5 T, distortions are evident.

The resulting asymmetries are easily corrected using the quadrupole triplets of the long straight section as shown in Fig. 3.7.4 below.
Figure 3.7.4: Symmetry restoration after only one set of iterations for about 10% change in the quadrupole strengths.

The effects of the IDs on the DA including alignment errors at 3 $\sigma$ are shown in Figs. 3.7.5 and 3.7.6. In this case the symmetry was not restored. Correcting the optical asymmetries will help increasing the DA.

Figure 3.7.5: On-energy dynamic aperture with all IDs (with the exception of the wiggler) at functioning settings with and without alignment errors.
Figure 3.7.6: On-energy dynamic aperture with all IDs at functioning settings with alignment errors and the induced optical asymmetries. The wiggler was set to 3.5 T.

As mentioned previously, IDs introduce a change in the equilibrium parameters (i.e., emittance and energy spread). For moderate fields the emittance is decreased, which, in turn, has a favourable effect on the brilliance. For IDs with long period and/or high fields, however, the effect is inverted due to the self-dispersion generated by those devices. Wigglers also produce a considerable effect on the linear optics that can be compensated by the quadrupole triplets in the long straight sections. On the other hand, short wigglers at 2T are well tolerated and do not produce evident distortions.

The nonlinearities induced by the IDs are inversely proportional to the square of the period length. Hence, the APPLE II type undulators generally have a stronger nonlinear effect than the wigglers. Nevertheless tracking has shown that the reduction of the DA due to the present insertion devices is minimal provided that the optical asymmetries induced are corrected. Thus the DA with all IDs at functioning settings, the superconducting wiggler at 3.5 T, with alignment errors and the induced optical asymmetries corrected, is ±7.5 mm in the horizontal and ±3.0 mm in the vertical plane.

Next the effects of short 3-pole wigglers to replace some of dipole source points are investigated. There are 10 beam-lines using 6 dipole magnets. There will be 7 available free spaces in the arc to accommodate the 2 T short wigglers. Six 3-pole wigglers are considered to be installed in dispersive regions (D=60 mm) that will increase the emittance as shown in the next figure 3.7.7
In Fig. 3.7.8 below we show the emittance change with all six short wigglers at 2T versus the superconducting wiggler field.

Similarly the energy spread increases from the value of $6.67 \times 10^{-4}$ in the bare optics to $6.76 \times 10^{-4}$ when all six short wigglers are at 2T and further to $8.31 \times 10^{-4}$ with the addition of the superconducting wiggler at 3.5 T. However not all dipole beam lines can use short wigglers, for example the SYRMEP (mammography) beam line that uses a horizontally long beam. Therefore the possibility of installing some superbends and their impact on the optics has been investigated.
The field profile assumed for the simulations is shown in figure 3.7.9. Note that the central field of 3.5 T yields a 9.3 keV critical energy for a 3.0 degree fan. The effect on the emittance and energy spread is shown in figure 3.7.10 for up to 5 pairs of superbends. As it can be observed, each pair of superbends increases the original emittance by 4%.

3.8 LIGHT SOURCE PROPERTIES

As explained in Section 1, the new generation light sources aim at increasing the brilliance and the coherence fraction of the radiation as well as providing a smaller radiation spot size with smaller divergence. An increase in flux is also possible, either by increasing the intensity of the stored beam or by changing the characteristics of the IDs.

The two main figures of merit characterizing a synchrotron light source, i.e., brilliance and coherence fraction are given as follows:

$$Brilliance = \frac{Flux}{(2\pi)^2 \sigma T_x \sigma T_y \sigma T'_x \sigma T'_y}$$
Coherence fraction = \frac{\left(\frac{\lambda}{4\pi}\right)^2}{\sigma T_{x} \sigma T_{y} \sigma T'_{x} \sigma T'_{y}}

where \(\sigma T_{x,y}\) and \(\sigma T'_{x,y}\) are the convolutions of the electron beam emittances and the photon beam emittance, \(\lambda/4\pi\). Thus

\[\sigma T_{x,y} = \sqrt{\varepsilon_{x,y} \beta_{x,y} + \sigma_{r}^2}\]
and

\[\sigma T'_{x,y} = \sqrt{\varepsilon_{x,y} \beta_{x,y} + \sigma_{r'}^2}\]

with \(\sigma_{r, r'} = \lambda/4\pi\). A source is diffraction limited for a wavelength \(\lambda\) if the electron emittance obeys the condition:

\[\varepsilon < \frac{\lambda}{4\pi}\]

For a well-matched undulator the spectral brilliance for each wavelength, \(\lambda_n\), given by

\[\lambda_n = \frac{l_{x}}{2n^2}(1 + \frac{K_{peak}^2}{2})\]

becomes:

\[B_n = \frac{F_n}{4\pi^2 (\varepsilon_x + \lambda_n/4\pi)(\varepsilon_y + \lambda_n/4\pi)}\]

Using the above formulas for the six bend lattice of Elettra 2.0, one can easily appreciate that the peak brilliance and the coherence fraction and subsequently the coherent flux will increase by more than one order of magnitude at 1 keV as shown in the next Figures 3.8.1 and 3.8.2

Figure 3.8.1: Brilliance of Elettra and Elettra 2.0 for the already existing IDs
Figure 3.8.2: Coherence fraction for Elettra and Elettra 2.0 for a well matched undulator. At 1keV this fraction is 0.8% for Elettra and 28% for Elettra 2.0

The increase of a factor of 35 in the coherent flux ratio between the two machines at 1keV assumes IDs similar to those currently present at Elettra. If shorter period IDs are introduced with a smaller magnetic gap, an additional improvement by a factor of 10 can easily be obtained. In that case the coherent flux ratio between the two machines will increase by a factor of 350 at 1 keV.

Table 3.8.1 summarizes the main parameters of Elettra 2.0 as compared with the present Elettra machine characteristics.

<table>
<thead>
<tr>
<th>Table 3.8.1: Elettra and Elettra 2.0 main parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>Circumference</td>
</tr>
<tr>
<td>Horizontal Emittance (1% coupling)</td>
</tr>
<tr>
<td>Vertical Emittance</td>
</tr>
<tr>
<td>Beam size @ ID (σx,σy)</td>
</tr>
<tr>
<td>Beam size @ short ID</td>
</tr>
<tr>
<td>Beam size @ Bend</td>
</tr>
<tr>
<td>Bunch length</td>
</tr>
<tr>
<td>Energy spread DE/E</td>
</tr>
<tr>
<td>Bending angle (per half achromat - 1/24)</td>
</tr>
<tr>
<td>Coherence fraction @ 100 eV</td>
</tr>
<tr>
<td>Coherence fraction @ 1 keV</td>
</tr>
</tbody>
</table>
The above studied optics have a momentum compaction factor of about $3 \times 10^{-4}$, i.e. an order of magnitude smaller than that of the present Elettra – meaning that the zero current bunch length will be 3 times smaller or about 2 mm (9 ps) at 2 GeV. Nevertheless, this reduced bunch length is large compared to that of FEL pulses (<1 ps). In general, the ultra low emittance lattices need longer bunches for stabilization and lifetime. This objective usually is achieved by employing a higher harmonic rf-system (already existing at Elettra). If also short bunches are requested, one can think of a double higher harmonic rf-system or crab cavities to create short and long bunches – an approach similar to the schemes proposed by BESSY (BESSY-VSR) or SPEAR3. In this case both short and long bunches may be available at the same time.

If a larger repetition rate is required (the present RF-system operates at 500 MHz) one can consider RF-systems at a higher frequency such as the 2 GHz systems designed for CLIC.

Finally it is interesting to note that the proposed lattice can be easily detuned to give the “low alpha” option. In that case the emittance becomes large, about 5 nm-rad, but the bunch length may be reduced down to 1 ps or even less (for low intensity).

4. BEAM STABILITY AND LIFETIME

It is well known that collective effects should be studied during the design stage of an accelerator and the evaluation of the impedance is necessary in controlling the total impedance of the ring to prevent the occurrence of beam instabilities. The interaction between the electron beam and its environment, i.e., the vacuum chamber, is described in terms of the impedance that can generate instabilities and deteriorate both beam lifetime and beam quality. In addition to the impedance, scattering processes, i.e., scattering between the electrons within a bunch or between electrons and the residual gas in the vacuum chamber, may play a very important role in determining beam quality and lifetime.

4.1 IMPEDANCES

The beam interacting with its environment generates electromagnetic fields (known as wake fields) which act back on the beam. Those fields can generate instabilities whereby a small deviation of the beam position and/or energy creates an additional field in phase that produces further deviations thereby leading to beam deterioration and even beam loss.

The beam environment (e.g., sections of the vacuum chamber) can be approximated in the frequency domain as an RLC resonant circuit with an impedance having a real (resistive) and an imaginary (reactive) part. The resistive part is responsible for energy losses and determines thus the growth or damping of an instability, whereas the reactive part causes frequency phase shifts and potential well distortions.

In general the impedance of a section of a vacuum chamber [7] for longitudinal (∥) and transverse (⊥) modes can be written as:
\[
Z_{||}(\omega) = \frac{R_s}{1 + jQ \left( \frac{\omega}{\omega_R} - \frac{\omega_R}{\omega} \right)} \quad Z_{\perp}(\omega) = \frac{\omega R}{1 + jQ \left( \frac{\omega}{\omega_R} - \frac{\omega_R}{\omega} \right)}
\]

The impedance can be divided into two parts: Narrow-band impedances with high quality factor (Q), which induce coupled bunch instabilities, i.e. multi-bunch effects, and broad-band impedances with low Q (usually of order 1) that are responsible for single-bunch effects. The main sources of the narrow band impedances are the RF cavities and their higher order parasitic modes, although also passive, resonating elements can also have an influence. The broadband impedance arises from the vacuum chamber material and its geometry including its associated elements including the RF cavities.

The vacuum chamber of Elettra 2.0 will have a circular cross section with an internal diameter of 23 mm. For the long straight sections the current vertical dimension of 9 mm was assumed. The material will be stainless steel for light exits and straight chambers, copper for the curved pipes while the long and maybe some of the short straight sections will be Al coated with NEG.

4.1.1 BROAD BAND IMPEDANCES AND SINGLE BUNCH INSTABILITIES

The main sources of impedance are the resistive wall, transitions and tapers, bellows, BPMs, strip lines, RF higher modes, flanges, antechamber, and kickers. Due to the small dimensions of the beam pipe, the wall impedance is expected to dominate. The effective wall impedance for a smooth chamber is given by [8, 9, 10 and 11]:

\[
\frac{Z_\parallel}{n} = Z_0 \frac{(1 + i) \delta}{2} \frac{L}{b} \frac{L}{2\pi R} \quad Z_{\perp} = Z_0 (1 + i) \frac{\delta}{b} \frac{L}{2\pi}
\]

where \(b\) is the chamber radius, \(\delta\) the skin depth, \(Z_0\) the free space impedance and \(L\) the length of the chamber. From the above considerations on the vacuum chamber material, we can produce the following table indicating the dimensions and material of the chambers as well as the corresponding impedances at the cut-off frequency:

<table>
<thead>
<tr>
<th>total length / achromat (m)</th>
<th>Number of pieces</th>
<th>Chamber height (m)</th>
<th>material</th>
<th>(Z_{\perp}) kohm/m both H and V</th>
<th>(Z_\parallel/n) ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>12</td>
<td>0.023</td>
<td>S.Steel</td>
<td>13</td>
<td>0.11</td>
</tr>
<tr>
<td>12.5</td>
<td>12</td>
<td>0.023</td>
<td>Cu</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.009</td>
<td>Al+NEG</td>
<td>42</td>
<td>0.06</td>
</tr>
</tbody>
</table>

For Al+NEG we have assumed a resistivity five times higher than that of Aluminum. From the above table one sees that the transverse wall impedance will be about 60 kohm/m for both planes while the longitudinal impedance is \(\sim0.22\) ohm

Transitions also contribute to the impedance (via geometric effects); therefore, they must be tapered. The transverse impedance of a taper is given by:
While for the longitudinal impedance one can use:

\[ Z_\perp = iZ_0 \frac{l \tan \theta}{4} \left( \frac{1}{b^2} - \frac{1}{d^2} \right) \]

where \( \omega_0 \) is the revolution frequency, \( l \) is the length, \( b \) and \( d \) the vertical full sizes and \( \theta \) the angle of the slope. It should be noted that the geometric impedance does not result in energy losses. The following table shows the estimated impedances.

<table>
<thead>
<tr>
<th>type</th>
<th>D1(m)</th>
<th>D2(m)</th>
<th>L (m)</th>
<th>( Z_\perp ) kohm/m</th>
<th>( Z_{\parallel} ) ( \omega_0 ) tan ( \theta ) / ( 4\pi c ) ohm</th>
<th>Number of tapers</th>
<th>( Z_\perp ) tot kohm/m</th>
<th>( Z_{\parallel} ) /n tot ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>0.1</td>
<td>0.023</td>
<td>0.070</td>
<td>7.2</td>
<td>0.22</td>
<td>8</td>
<td>58</td>
<td>0.18</td>
</tr>
<tr>
<td>IDs</td>
<td>0.023</td>
<td>0.09</td>
<td>0.070</td>
<td>6.9</td>
<td>7e-4</td>
<td>20</td>
<td>138</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Other cross section transitions should be avoided and the chamber should be as smooth as possible. Bellows can have a large contribution to the impedance if unshielded. For shielded bellows of length \( l \) the only impedance is that of the openings (\( w \)) between the RF-fingers that can be described by:

\[ \frac{Z_{\parallel}}{n} = i \frac{Z_0 \omega_0}{4\pi c b^2} w^2 \left( \frac{0.1814 - 0.0344}{l} \right) \]

\[ Z_\perp = i \frac{Z_0}{\pi_2 b^4} w^2 \left( \frac{0.1814 - 0.0344}{l} \right) \]

Those formulas are also valid for the openings for pumping or radiation extraction. In the following table all bellows, extraction opening and instrumentation (bpms) impedance are summarised.

Note that the BPM button impedance is given by:

\[ \frac{Z_{\parallel}}{n} = i \frac{2Z_0 r_b}{R} \left( \frac{\theta}{\pi} \right) \]

With \( Z_c=11 \) ohm and \( r_b = 5.5 \) mm (button radius) and \( \theta = r_b / b \) the effective semi-angular aperture with \( b \) the chamber radius 11.5 mm, contributions to the impedance are

<table>
<thead>
<tr>
<th>type</th>
<th>Radius (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th># of items</th>
<th>( Z_{\parallel} ) ohm</th>
<th>( Z_\perp ) ohm/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF bellows</td>
<td>0.011</td>
<td>0.085</td>
<td>0.0015</td>
<td>144</td>
<td>9e-3</td>
<td>91.48</td>
</tr>
<tr>
<td>Cham. blw</td>
<td>0.011</td>
<td>0.05</td>
<td>0.0015</td>
<td>60</td>
<td>1.45e-2</td>
<td>15.160</td>
</tr>
<tr>
<td>Pump slots</td>
<td>0.011</td>
<td>0.05</td>
<td>0.003</td>
<td>30</td>
<td>1.353-2</td>
<td>14.090</td>
</tr>
<tr>
<td>open.</td>
<td>0.011</td>
<td>0.05</td>
<td>0.01</td>
<td>192</td>
<td>4.2e-3</td>
<td>28.55</td>
</tr>
<tr>
<td>BPMs</td>
<td>0.011</td>
<td>0.01</td>
<td>0.01</td>
<td>192</td>
<td>4.2e-3</td>
<td>28.55</td>
</tr>
</tbody>
</table>
Finally there is contribution from the RF cavities, due to the high order modes (HOMs) that introduce a considerable contribution to the broad band ring impedance. This impedance can be extracted from the measured higher order modes of the cavities (see the RF part of this document) according to the formula:

\[
\frac{Z_{//}}{n} = i\omega_b \sum_{k=2}^{N} \frac{R_k}{Q_k \omega_k} \frac{R_k}{n}
\]

Using the measured values of the higher harmonics up to the cut-off frequency one obtains

<table>
<thead>
<tr>
<th>RF cavity</th>
<th># of cavities</th>
<th>(Z_{//}/n) (ohm)</th>
<th>(Z_{\perp}) (kohm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive wall</td>
<td>4</td>
<td>0.24</td>
<td>8</td>
</tr>
<tr>
<td>Transitions</td>
<td></td>
<td>0.19</td>
<td>196</td>
</tr>
<tr>
<td>RF</td>
<td></td>
<td>0.24</td>
<td>8</td>
</tr>
<tr>
<td>Bellows+slots+openings</td>
<td></td>
<td>-0.037</td>
<td>-38</td>
</tr>
<tr>
<td>BPMs and other</td>
<td></td>
<td>0.004</td>
<td>2.8</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>0.22</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.61</td>
<td>230</td>
</tr>
</tbody>
</table>

Thus \(| Z_{//}/n| = 0.65\, \text{ohm}\), the inductive part of the transverse impedance is 230\, \text{kohm/m} and \(| Z_{\perp}| = 240\, \text{kohm/m}\).

From the above impedances one can now estimate the bunch lengthening, mode coupling and tune shift with current. From the microwave criterion the expected bunch lengthening with single bunch current is shown in the next figure using the known formula:

\[
\left| \frac{Z_{//}}{n} \right| \leq \frac{8 \ln 2}{2\pi} \frac{hV_{cf} \cos(\phi_s)}{\sqrt{2\pi} I_b} \left( \frac{\sigma}{R} \right)^3
\]

with \(R\) the ring radius, \(h\) the harmonic number, \(\phi_s\) the synchronous phase angle, \(\sigma\) the bunch length and \(I_b\) the single bunch current.
Thus while the zero current bunch length is 6 ps, at 0.92 mA/bunch (giving 400 mA total) the bunch length will be already 16 ps. Similarly, the energy spread ΔE/E will increase from 6.65x10^{-4} to 1.9x10^{-3} while at 10 mA it will be 4x10^{-3}.

The analytic expression for the detuning of the zero mode is given by:

\[ \frac{df}{dl} = -\frac{c}{8\pi^{3/2} \sigma E/e} <\beta_\perp> \text{Im}(Z_\perp)_{\text{eff}} \]

For the quoted 230 kohm/m a frequency shift of -0.9 kHz/mA is predicted being 50% larger than that measured for the present Elettra machine (-0.6 kHz/mA).

The transverse mode coupling current threshold is given by:

\[ I_b = \frac{4\nu_s E/e}{|Z_\perp|} b \frac{b}{R} \]

where \(\nu_s\) is the synchrotron tune. For the above estimated transverse impedance, the single bunch current threshold before a transverse mode coupling instability occurs is estimated to be at 6 mA.

In general we observe that the largest contributors of the impedance are the resistive wall and transitions, but in any case no large performance limitations are seen.

4.1.2 NARROW BAND IMPEDANCES AND MULTI BUNCH INSTABILITIES

The main source of narrow band impedances is the rf cavities. Since the same cavities will be used for Elettra 2.0, we don’t expect changes. All HOMs of the cavities have been measured (see RF chapter), and an analysis of their impact on the beam stability was made. The technique of avoiding those dangerous modes by their detuning by using high order mode (HOM) shifters and/or changing their temperature is a well-established method at Elettra.

The figure below depicts the graphical display of a program [12] that analyses and shows the high order multi-bunch modes that can be eliminated using the technique described above.
Additionally a multi-bunch feedback is used that completely eliminates any remaining unstable modes. For longitudinal stability there is also a third harmonic cavity that helps to eliminate the longitudinal multi-bunch modes by adding Landau damping into the system and increasing the bunch length by a factor 3.5, also increasing the lifetime by the same factor.

4.2 SCATTERING PROCESSES AND LIFETIME

The beam contained transversely by the vacuum chamber and longitudinally by the RF-bucket suffers from many interactions. The beam scatters with the residual gases within the vacuum chamber either via elastic or inelastic (bremsstrahlung) collisions, resulting in particle losses that reduce the lifetime of the beam. The beam may also ionize the gases leading to ion trapping that, in principle, can alter the accelerator performance producing emittance growth, instabilities and other unwanted effects.

At the same time, when the electrons emit radiation, the interaction of the emitted photons with the electrons of the beam can also result in losses especially in the longitudinal dimension if the RF acceptance is not sufficient (quantum effect). Electrons may also interact with one another either via large-angle scattering (Touschek effect), which has a large influence on the lifetime, or through small-angle scattering (intra-beam effect), which usually influences the particle distribution in the beam (emittance effect).

In general the total lifetime is given by:

\[
\frac{1}{r} = \frac{1}{r_{\text{elastic}}} + \frac{1}{r_{\text{inelastic}}} + \frac{1}{r_{\text{quantum}}} + \frac{1}{r_{\text{Touschek}}}
\]

The quantum lifetime can be neglected since the beam dimensions are very small and the RF-acceptance is large (3%), resulting in very large values of the reciprocal lifetime in all three planes. The formulas for elastic and inelastic scattering processes can be
found in most textbooks, and the calculation results are a usual output from the most accelerator design programs. For sake of completeness the quantum lifetime formula is shown below. One can easily confirm that for the Elettra 2.0 parameters (also for actual Elettra) the exponent is very large.

\[
\tau_{\text{quantum}} = \tau_{\text{rad-}x,y,j} \frac{\sigma_{x,y,j}^2}{a_{x,y,j}^2} \exp\left(\frac{a_{x,y,j}^2}{2\sigma_{x,y,j}^2}\right)
\]

For example, in the longitudinal plane \(\sigma_l = 7e^{-4}\) is the energy spread and \(a_l = 3\%\) is the RF-acceptance (whereas in the \(x, y\) plane are the beam dimensions and physical acceptance) the exponent becomes \(e^{918}\) and with the longitudinal damping time \(\tau_{\text{rad}}=15\text{ms}\) the result is \(\tau_{\text{quantum}}=10^{-5} e^{918}\). Even if the RF-acceptance were 0.45% the quantum lifetime would be 127 h.

Assuming 3 nTorr of \(\text{N}_2\), the dynamic pressure in the vacuum chamber that can certainly be achieved in a 23 mm diameter chamber with NEG and lateral pumping for 400 mA is \(\tau_{\text{elastic}}=2409\) h and \(\tau_{\text{inelastic}}=52\) h; thus the gas lifetime at 400 mA would be \(\tau_{\text{elastic+inelastic}}=51\) h. The following section examines the issues of the Touschek effect, intrabeam scattering and ion trapping.

### 4.2.1 TOUSCHEK SCATTERING

The Touschek effect is a single large-angle Coulomb scattering within a bunch. When the relative momentum deviation (\(\Delta p/p\)) of a particle exceeds the acceptance imposed longitudinally by the RF-bucket momentum or transversely by the transverse aperture (dynamic or physical) the particle is lost and the lifetime is reduced.

Assuming same conditions as in the present Elettra ring, 3 nTorr of \(\text{N}_2\) dynamic pressure, 1% coupling, but a 400 mA stored beam intensity and a 2.4 MV effective RF voltage, the Touschek lifetime is 12 hours and including elastic (1286 h) and inelastic scattering (26 h) the total linear lifetime becomes 8 hours. Elettra 2.0 is therefore Touschek scattering dominated as the present Elettra machine. Note that in this calculation the bunch length is the “zero current” bunch length (1.78 mm for 2.4 MV). Continuing to investigate the Touschek effect with a 4-D tracking using OPA, whereby particles start on axis, but with momentum deviation \(\Delta p/p\), the total lifetime is found to be reduced to 6 hours for 1% coupling, while it becomes 12.4 hours for 10% coupling.

![Figure 4.2.1.1: Momentum acceptance from RF (green) and from apertures (brown)](image-url)

A similar tracking study was carried out with ELEGANT for the bare lattice and no physical restrictions; the momentum aperture was evaluated at the sextupoles’ locations,
as shown in Figure 4.2.1.2. On the other hand using the third harmonic cavity one expects a threefold increase in lifetime.

![Figure 4.2.1.2: Momentum acceptance from 6-D particle tracking, evaluated at the sextupoles locations.](image)

The momentum acceptance was found to be about 7% as shown from the graphs above.

The above results assume the “zero current” bunch length. Using the third harmonic cavity a threefold increase in lifetime is expected according to current experience with Elettra. It is also necessary to increase the effective voltage of the RF system from 1.7 to 2.4 MV.

4.2.2 INTRABEAM SCATTERING

Intrabeam scattering (IBS) refers to multiple, small-angle Coulomb scattering within a beam that leads to excitation of betatron and synchrotron oscillations, producing a diffusion process in both longitudinal and transverse phase space. The result is a redistribution of emittances, and the 6-D emittance ellipsoid acquires a new equilibrium. The most usual effect is a blow-up of the horizontal emittance since in the horizontal plane dipoles generate dispersion. Therefore the emittance increases in both the longitudinal and the horizontal planes.

In a perfectly aligned storage ring, in which there is no vertical dispersion and no betatron coupling, IBS can shrink the vertical emittance to infinitesimal values, but in reality, there is a significant amount of vertical emittance generated by both vertical dispersion and betatron coupling. In general, any growth in the horizontal emittance appears in the same proportion in the vertical emittance. The growth scales in inverse proportion to the emittance, i.e., the smaller the emittance the larger is the blow-up. IBS starts being a problem for electron emittances below 1 nm-rad. Therefore, it was not considered in the design of the majority of the 3rd generation light sources.

The following graph shows the emittance growth for Elettra 2.0 (assuming an initial value 0.26 nm-rad) for up to 400 mA and for two cases: assuming the natural bunch length (3HC off) and assuming a bunch lengthening factor 3.5 (3HC on):
Figure 4.2.2.1: Emittance increase due to IBS for both natural bunch length (triangles) and a bunch 3.5 times lengthened (x).

In the case of bunch lengthening the emittance increase is 46% at 400 mA (0.38 nm-rad) whereas without lengthening it is 92 % (0.5 nm-rad). Hence, the existing third harmonic cavity of Elettra should be used also for Elettra 2.0.

4.2.3 ION TRAPPING AND FAST ION INSTABILITY

Trapped ions in the beam can produce many side effects because they act as an additional optic element, thereby changing the optics of the accelerator in a way that can render the beam unstable. Usually a gap in the bunch train solves the problem since the gap gives time for the ions to move away from the beam. If a gap cannot be employed, one can equip the accelerator with clearing electrodes that remove the ions from the beam path.

Ion trapping occurs if the following condition [13] is satisfied:

$$\left| \cos(\omega_l t) - \frac{1}{2} \omega_l G_{\tau} \sin(\omega_l \tau) \right| \leq 1$$

where $\omega_l$ is the ion frequency (usually in the range of hundreds of MHz), $l$, the bunch train in time and $G_{\tau}$ the gap in time. For an ion of 300 MHz frequency and a minimum gap of 10 ns and assuming multi-bunch train of 830 ns, the left hand side becomes 1.6 therefore no ion trapping will occur. In the present Elettra configuration a beam gap of 5% is used (i.e., 43 ns) and the left-hand side of the above inequality becomes 6.5. In any case ion trapping has only being observed in Elettra when for the sake of experimenting a higher pressure was allowed with an almost non existing bunch train gap.

However, even if ions are not trapped, they can interfere with the electron beam. The effect arises during a single pass of a train of electron bunches that start mutually driven transverse oscillations producing the so called fast ion instability. The growth rate of this instability is given by

$$\tau_{inst}^{-1}[s^{-1}] = 6P[Torr] \frac{N_b^{3/2} n_b^2 r_p^{1/2} l_{sep}^{1/2}}{\gamma \sigma_z^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2} \omega_e}$$
where $N_b$ denotes the number of particles per bunch, $n_b$ the number of bunches, $r_e$ and $r_p$ the classical electron and proton radius, $L_{sep}$ is the bunch spacing, A is the atomic mass number of the ions and $w_b=1/b_y$.

For the present Elettra lattice the fast ion instability was not an issue due to the relatively large beam dimensions. Since Elettra 2.0 will have much smaller beam dimensions one must evaluate whether the fast ion instability will be important. Assuming 4 nTorr of CO (A=28) with the data from Elettra 2.0 one obtains a growth time of 30 ms (for the actual Elettra it is 3 sec) being easily dumped by the natural radiation damping and/or the multi-bunch feedback system.

Section references


5. MAGNET DESIGN

As stated in section 3.1.1 the Electra 2.0 magnets will be in general stronger that those of the actual Elettra. The next tables summarises the iron-dominated electromagnets needed and their main parameters:

### Dipoles

<table>
<thead>
<tr>
<th>name</th>
<th>$L_{mag}$ (m)</th>
<th>$k$</th>
<th>$B0$ (T)</th>
<th>$B1$ (T/m)</th>
<th>Angle (°)</th>
<th>$\rho$ (mm)</th>
<th>$N$</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF1</td>
<td>0.75</td>
<td>-1.91</td>
<td>0.5585</td>
<td>12.7</td>
<td>3.6</td>
<td>11937</td>
<td>24</td>
<td>72</td>
</tr>
<tr>
<td>BF2</td>
<td>0.84</td>
<td>-2.03</td>
<td>0.7896</td>
<td>13.5</td>
<td>5.7</td>
<td>8444</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

### Quadrupoles

| name | $L_{mag}$ (m) | $k$ | $B1$ (T/m) | $\Theta$ (mm) | $|B_{pole}|$ (T) | $N$ | sum |
|------|---------------|-----|------------|----------------|-----------------|-----|-----|
| Q1   | 0.13          | -2.840 | 18.93    | 26         | 0.246           | 24  | 192 |
To reduce vibrations all electromagnets are designed having air cooled coils with the same maximum current and the same conductor section as if water cooled. For each magnet family, the gaps and bore diameters are optimized considering the vacuum chamber and the beam line exits dimensions. The possibility to reduce the vacuum chamber diameter (now 25 mm) further could allow a more compact magnet design, but the limit is set by the photon exit dimensions.

5.1 BENDING MAGNETS

The dipoles will be iron dominated magnets with an integrated quadrupole component. These field components will be obtained by shaping the pole profile geometry. The goal is to obtain the smallest yoke with the requested frame stiff. The adopted solution employs one back-leg c-type, two cornered coils, two separable pole extensions and one insert of nonmagnetic bricks between them at the minimum gap chamfering. The spacer could be use also for the poles positioning. The coils are made of solid copper and are cooled naturally by air. The bending types are two: BF1 and BF2. The main parameters and the models are listed and showed in the table and figure below.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>BF1</th>
<th>BF2</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature angle</td>
<td>3.6</td>
<td>5.7</td>
<td>deg</td>
</tr>
<tr>
<td>Magnetic arc length</td>
<td>750</td>
<td>840</td>
<td>mm</td>
</tr>
<tr>
<td>Overall length</td>
<td>830</td>
<td>920</td>
<td>mm</td>
</tr>
<tr>
<td>Central gap</td>
<td>30</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Good field region radius</td>
<td>10</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Coil turns</td>
<td>2 x 144 = 288</td>
<td>2 x 200 = 400</td>
<td>#</td>
</tr>
<tr>
<td>Coil turns on width</td>
<td>6</td>
<td>8</td>
<td>#</td>
</tr>
<tr>
<td>Conductor square section side</td>
<td>7</td>
<td>7</td>
<td>mm</td>
</tr>
<tr>
<td>Conductor cross section area</td>
<td>48.1</td>
<td>48.1</td>
<td>mm²</td>
</tr>
<tr>
<td>Conductor total length</td>
<td>2 x 255 = 510</td>
<td>2 x 401 = 802</td>
<td>m</td>
</tr>
<tr>
<td>Conductor total electric resistance</td>
<td>2 x 90 = 180</td>
<td>2 x 140 = 280</td>
<td>mΩ</td>
</tr>
<tr>
<td>Nominal current</td>
<td>47.3</td>
<td>48.1</td>
<td>A</td>
</tr>
<tr>
<td>Nominal current density</td>
<td>0.98</td>
<td>1.00</td>
<td>A/mm²</td>
</tr>
<tr>
<td>Nominal magnet power</td>
<td>422</td>
<td>690</td>
<td>W</td>
</tr>
</tbody>
</table>

**Figure 5.1.1: Bending electromagnet models**

The figure below shows the assembled and exploded parts of the bending BF1.

**Figure 5.1.2: BF1 main parts**
All parts of the yoke are made of solid iron. The pole extensions have the longitudinal length equal to the bending region length ($L_{\text{eff}}$) and a pseudo-Rogowski longitudinal chamfering. Also the back-leg part could be made of two parts (upper and lower), this solution could increase the yoke transversal homogeneity.

5.2 QUADRUPOLES

Different quadrupole designs were made in order to cover all the optic and layout specifications and requirements. Since the optics layout has very short drifts between the magnetic lengths, a novel kind of magnet has been developed in order to obtain a magnetic length equal or very close to the magnet overall length. Those quadrupoles have asymmetric pole terminations to mainly resolve possible transversal interferences with the beam line exits and yoke made of two separated parts. Note that the field longitudinal extension inside the magnetic circuit required a yoke made of solid iron. Also the quadrupole types are only two: Q10T9 and Q3T5.

The main parameters and the models are, respectively, listed and showed in the table and figure below.

Table 5.2.1: Quadrupole electromagnet parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Q3T9</th>
<th>Q10T8</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gradient</td>
<td>30.0</td>
<td>49.3</td>
<td>T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>130</td>
<td>220</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum integrated gradient</td>
<td>3.90</td>
<td>10.85</td>
<td>T</td>
</tr>
<tr>
<td>Overall length</td>
<td>130</td>
<td>230</td>
<td>mm</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>26</td>
<td>26</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum gap between the poles</td>
<td>9</td>
<td>9</td>
<td>mm</td>
</tr>
<tr>
<td>Good field region radius</td>
<td>10</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Number of turns for coil</td>
<td>$24 + 20 = 44$</td>
<td>$28 + 24 + 20 = 72$</td>
<td>#</td>
</tr>
<tr>
<td>Number of turns on width</td>
<td>4</td>
<td>6</td>
<td>#</td>
</tr>
<tr>
<td>Conductor cross section</td>
<td>$5 \times 9 = 45$</td>
<td>$5 \times 9 = 45$</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>Conductor length for coil</td>
<td>18.8</td>
<td>46.0</td>
<td>m</td>
</tr>
<tr>
<td>Conductor electric resistance for coil</td>
<td>7.3</td>
<td>17.7</td>
<td>mΩ</td>
</tr>
<tr>
<td>Maximum current</td>
<td>50</td>
<td>50</td>
<td>A</td>
</tr>
<tr>
<td>-----------------</td>
<td>----</td>
<td>----</td>
<td>---</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>1.11</td>
<td>1.11</td>
<td>A/mm²</td>
</tr>
<tr>
<td>Magnet maximum power</td>
<td>13.5 x 4 = 68</td>
<td>45 x 4 = 178</td>
<td>W</td>
</tr>
</tbody>
</table>

Figure 5.2.1: Quadrupole electromagnet models
The pole extensions have the longitudinal tapering inside the coils that have a special winding with semi-reversed steps. The figure below shows the quadrupole Q10T9 exploded plus the coil winding.

Concerning the magnetic performance, the pole longitudinal extensions allow very low iron saturation on the pole terminations, because the longitudinal tapering increases the iron section reducing the magnetic reluctance. The figure below show the iron field distribution calculated by VF Opera Tosca at the current excitation of 50 A. The simulated model is 1/8 of the total magnet.
5.3 SEXTUPOLES

The sextupole magnets have the higher design issues. Similar to the quadrupoles, in order to optimize the overall length, also these magnets have been designed with special pole and coil shapes. In order to resolve the most part of the possible transversal interferences, the poles are asymmetric and the bore diameter has been increased from 26 mm (the minimum required) to 32 mm. The sextupole types are 4 (four).

Table 5.3.1: Sextupole electromagnet parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sx120</th>
<th>Sx150</th>
<th>Sx180</th>
<th>Sx240</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gradient</td>
<td>3986</td>
<td>4640</td>
<td>4880</td>
<td>5009</td>
<td>T/m²</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>121</td>
<td>151</td>
<td>181</td>
<td>240.6</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum integrated gradient</td>
<td>326</td>
<td>701</td>
<td>878</td>
<td>1202</td>
<td>T/m</td>
</tr>
<tr>
<td>Overall length</td>
<td>121</td>
<td>164</td>
<td>194</td>
<td>254</td>
<td>mm</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>mm</td>
</tr>
<tr>
<td>Field at the pole tip radius</td>
<td>0.348</td>
<td>0.594</td>
<td>0.625</td>
<td>0.641</td>
<td>T</td>
</tr>
<tr>
<td>Minimum gap between the poles</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Good field region radius</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Number of turns for coil</td>
<td>32</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>#</td>
</tr>
<tr>
<td>Number of turns on width</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>#</td>
</tr>
<tr>
<td>Conductor cross section</td>
<td>5 x 9 = 45</td>
<td>5 x 9 = 45</td>
<td>5 x 9 = 45</td>
<td>5 x 9 = 45</td>
<td>mm²</td>
</tr>
<tr>
<td>Conductor length for coil</td>
<td>12.5</td>
<td>26.7</td>
<td>31.3</td>
<td>38.3</td>
<td>m</td>
</tr>
<tr>
<td>Conductor electric resistance for coil</td>
<td>4.81</td>
<td>10.3</td>
<td>12.1</td>
<td>14.8</td>
<td>mΩ</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Maximum current</th>
<th>50</th>
<th>50</th>
<th>50</th>
<th>50</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum current density</td>
<td>1.11</td>
<td>1.11</td>
<td>1.11</td>
<td>1.11</td>
<td>A/mm²</td>
</tr>
<tr>
<td>Magnet maximum power</td>
<td>73</td>
<td>155</td>
<td>182</td>
<td>222</td>
<td>W</td>
</tr>
</tbody>
</table>

Figure 5.3.1: Sextupole electromagnet models

The main parameters and the models are, respectively, listed and showed in the table and figure above. The figure below show the iron field distribution calculated by VF Opera Tosca at the current excitation of 50 A. The simulated model is 1/12 of the total magnet.

Figure 5.2.3: Sextupole yoke field distributions at 50 A (Colour bars from 0 to 2 Tesla)

### 5.4 CORRECTORS

The comb correctors will be embedded in the sextupoles magnets and different solutions are evaluated. There are also 76 single correctors with the same longitudinal dimension (12 cm) to the ones lately installed at Elettra (8th correctors). A single corrector with multiple poles option to serve also as skew quadrupole is under study.
5.5 MAGNET POSITIONING

As the required specifications involve a design of iron dominated quadrupoles and sextupoles with a yoke transversally large and longitudinally short, this topology requires a very stiff closing and support system, it will be most practical to realize, in two different types, a common support nonmagnetic system (or 3D frame) whose task will be to support and position all the magnets, also in the case of yokes made by separated parts. This 3D frame will be made by two parts, bottom and upper parts, that allow the simultaneous opening of all the magnets (with the exception of the dipoles that will be C-Type) for a comfortable vacuum chamber installation, maintenance and bake-out. The possibility to have, for each magnet, a dynamic positioning of the separated yoke parts is under evaluation. The figure below shows the magnets positioning in the 1/2 of the acromat (1/12).

![Magnets layout](image)

Figure 5.6.1: Magnets layout

5.6 MAGNET HEAT LOAD

As said above we are opting for air-cooled magnets; in this way vibrations due to the water circulation can be avoided. If all magnets will be air-cooled the air heating power is calculated to be 5.4 kW / section giving 12x5.4 = 65 kW total. Considering the EM bending magnets to be water-cooled the power from the remaining air-cooled magnets is 3.5 kW/ section or 42 kW total.

5.7 DIPOLE PERMANENT MAGNET

There are certain advantages using permanent magnet dipoles. There are versions of the optics allowing the use of those magnets in the lattice. Although the present CDR is based on electromagnets it is useful to try and develop a permanent magnet design. The R&D work concerning the permanent magnet dipoles is in progress. A scaled prototype has already being constructed showing the necessary characteristics and giving a 1.6 T field as shown below.
Open issues that are being studied for this kind of permanent magnet dipole are the temperature dependence, the magnet opening – closing and the introduction of gradient by shaping the poles.

6.0 RADIOFREQUENCY

The installed RF system at Elettra is a normal conducting, single fed accelerating cavity operating at 500 MHz. One RF station is installed in the Booster\(^7\) and four independent stations are installed in the storage ring.

This design although is more than 20 years old, the operating experience has shown its high level of reliability and operability \([1]\). Some main characteristics of the present system are:

- The single cell has been installed in short straight section allowing to dedicate all eleven available long straight section to the insertion devices (the 12\(^{th}\) is dedicated to injection)

\(^7\) Normal conduction five cells cavity is installed in the Booster
• The normal conducting system waistes a large amount of energy as dissipated power, leading to elevated electric grid energy consumption.

• Independent RF feeds for each cavity have improved the MTBF (mean time between failures), allowing fixing a failure on one station while running the machine at lower intensity.

• The simple cell shape with no dedicated HOM dampers forced us to dedicate efforts and tools to fine-tune the higher order modes in order to mitigate multibunch instabilities.

The design of the RF system for Elettra 2.0 shall consider several options:

• **Frequency choice**: the same RF acceptance can be achieved with less accelerating voltage (thus less power consumption) lowering the frequency, and at the same time longer bunch lengths are achieved. Moreover lowering the frequency requires adding the proper phase modulation in the full energy injector or “forcing” the injected beam into the new RF bucket.

• **Superconducting technology**: superconducting cells have been chosen in recent synchrotrons because of the large stored current and the related stability issue. The HOM damping is achieved by means of dedicated couplers and the cryogenic temperature allows achieving a good accelerating gradient even if the profile of the cell is not optimized for large shunt impedance. But the saved energy in terms of RF power is balanced by the cryogenic plant consumption, so no significant energy saving is obtained. The cryogenic module is quite cumbersome and needs the installation of a longer section. Moreover the operational experience for these devices is not very satisfactory in terms of reliability and costs.

• **Power Source**: the typical RF power requirement for a 2.0 GeV machine is few hundreds of kW. In late 90's this power demand was fulfilled with klystron tubes. Nowadays the huge improvement in the thermal power capability and high voltage standoff of the new transistor, LDMOS SI and GaN, has lead to the design of scientific dedicated transmitter based on a solid state amplifier (SSA). Even if not yet operating at 500 MHz, the successfully implementation of this technology at SOLEIL and its operational behaviour has already validated this choice [2]. The discontinuance of the klystron production in the several tens of kW range and the concern about tube production in general is no longer an issue. A project is currently in progress at Elettra for the implementation of a SSA in the Booster, 500 MHz and 18 kW [3]. This project aims at replacing the obsolete Booster transmitter as well as at testing the new solid-state technology at 500 MHz. In terms of power consumption, the solid-state technology has a 50% efficiency (from electrical grid plug to RF) which is better than the typical klystron based transmitter efficiency of 38% [4, 5]. Moreover the SSA solution can provide a high degree of modularity and operational redundancy thanks to the modular (and therefore slow) degradation of the output power in case of failures, matching the high reliability requirement of the light sources.

• **Cost**: any new system costs in terms of design, procurement and know-how.

To decide the best RF choice for Elettra 2.0 the first step was to check out if the present 500 MHz system would be appropriate.
An interesting fact about Elettra 2.0 is the lower energy loss/turn value that can reduce the RF power budget and consequently the operating costs. The Elettra 2.0 RF parameters keeping the same Elettra 500 MHz cavity system can be estimated:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>2.0</td>
</tr>
<tr>
<td>Current [mA]</td>
<td>400</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>3.0 $10^{-4}$</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>433</td>
</tr>
<tr>
<td>Energy losses [keV]</td>
<td>500</td>
</tr>
<tr>
<td>Beam Power [kW]</td>
<td>200</td>
</tr>
<tr>
<td>Accelerating voltage [MV]</td>
<td>2.2 MV</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>4</td>
</tr>
<tr>
<td>RF acceptance</td>
<td>± 6%</td>
</tr>
<tr>
<td>Synchrotron frequency [kHz]</td>
<td>5.4</td>
</tr>
<tr>
<td>Synchrotron Tune $Q_s$</td>
<td>$4.71 \times 10^{-3}$</td>
</tr>
<tr>
<td>Cavity voltage [kV]</td>
<td>800</td>
</tr>
<tr>
<td>Cavity $R_{shunt}$ [MΩ]</td>
<td>3.3</td>
</tr>
<tr>
<td>Cavity losses (Cu) [kW]</td>
<td>50</td>
</tr>
<tr>
<td>Total cavity power [kW]</td>
<td>100</td>
</tr>
</tbody>
</table>

The above data show that, even for an overestimated energy loss scenario, the four 500 MHz cavities can easily manage the energy loss budget. The estimated RF acceptance is quite large and entails a quite low synchrotron frequency. But this is just an indication of the conceivable values.

The main issue of the Elettra cavity is the interaction of HOMs with beam. Any instability could spoil the high brilliance achieved by the emittance reduction.

The HOM frequencies can interact with the electron beam up to the cut off frequency of TM and TE modes of the cavity beam port:

- $f_{c_{TM01}} = 2.297$ GHz
- $f_{c_{TE_{11}}} = 1.758$ GHz

A preliminary and rough simulation of a quarter of a cavity is used to evaluate the impedance from the HOMs frequencies and parameters of the following tables [6]:

---

8 Estimated largest value
9 The cavity beam ports behave like a circulating waveguide
10 HFSS v15.0 run: 1 hour C.P.U. time, 16000 tetrahedra on the cavity volume, rms mesh size 24 mm
The longitudinal impedance is evaluated from the shunt impedance \((R/Q)’\) computed at the beam port radius, that is \(r = 50\,\text{mm}\) for the Elettra cavity [7].

The transverse impedance of the dipole modes is calculated from the off-axis longitudinal shunt impedance.

The high quality factor \(Q\) of the Elettra cavity HOMs allows the approximation of the impedance frequency behavior\(^{11}\) with the narrow band resonance of a lumped RLC parallel circuit.

\(^{11}\)This is a simplified model. For the multibunch instabilities, that is when bunch talks to each other due to long decay mode of the narrow band resonances, the impedance should be evaluated from the Sacherer integral equation, at frequencies \(\omega_r \approx q\hbar\omega_{rev} \mp p\omega_{rev} \mp \omega_{syn}\), see for example “Lecture Notes” K.Y. Ng, USPAS, FNAL 2000 or “Beam Instabilities”, M. Furman, J. Byrd, S. Chattopadhyay, Ch 2 of “Synchrotron Radiation Source”, A Primer, World Scientific 1994
The beam stability is ensured when the growth rate of the multi bunch instability is less than the radiation damping rate. Elettra and Elettra 2.0 have the following parameters:

<table>
<thead>
<tr>
<th></th>
<th>Elettra</th>
<th>Elettra 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>I beam [mA]</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Synchrotron tune $Q_s$</td>
<td>$9.8 \times 10^{-3}$</td>
<td>$4.710^{-4}$</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$1.6 \times 10^{-3}$</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Longitudinal damping time [ms]</td>
<td>8.0</td>
<td>10.9</td>
</tr>
<tr>
<td>H transverse damping time [ms]</td>
<td>10.4</td>
<td>12.9</td>
</tr>
<tr>
<td>V transverse damping time [ms]</td>
<td>13.6</td>
<td>17.7</td>
</tr>
</tbody>
</table>

According to these data, the threshold current for almost all the HOMs is below the rated one for both the machines, so that the frequency detuning needed to have a stable beam will be estimated under the assumption that the HOM frequencies of each cavity are equal and that there is the maximum overlap between the beam spectrum and the HOM frequencies [8]. For the longitudinal high order modes we obtain:

<table>
<thead>
<tr>
<th>Mode</th>
<th>F [MHz]</th>
<th>$\Delta f$ shift [kHz]</th>
<th>$\Delta f$ shift [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>957</td>
<td>234</td>
<td>197</td>
</tr>
<tr>
<td>L2</td>
<td>1063</td>
<td>35</td>
<td>29</td>
</tr>
<tr>
<td>L3</td>
<td>1430</td>
<td>153</td>
<td>129</td>
</tr>
<tr>
<td>L4</td>
<td>1524</td>
<td>149</td>
<td>126</td>
</tr>
<tr>
<td>L5</td>
<td>1607</td>
<td>247</td>
<td>208</td>
</tr>
<tr>
<td>L6</td>
<td>1891</td>
<td>54</td>
<td>45</td>
</tr>
<tr>
<td>L7</td>
<td>1960</td>
<td>123</td>
<td>103</td>
</tr>
<tr>
<td>L8</td>
<td>2070</td>
<td>56</td>
<td>46</td>
</tr>
<tr>
<td>L9</td>
<td>2137</td>
<td>282</td>
<td>237</td>
</tr>
</tbody>
</table>

The lowest value of the threshold transverse impedance occurs in the H-plane for both the machines, for Elettra $Z_T$ (threshold) = $2.12 \times 10^5$ $\Omega$, for Elettra 2.0 $Z_T$ (threshold) = $1.22 \times 10^5$ $\Omega$. 

79
<table>
<thead>
<tr>
<th>Mode</th>
<th>F [MHz]</th>
<th>Δf shift [kHz]</th>
<th>Δf shift [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>747.6</td>
<td>32</td>
<td>42</td>
</tr>
<tr>
<td>D2</td>
<td>750.6</td>
<td>59</td>
<td>77</td>
</tr>
<tr>
<td>D3</td>
<td>1122.8</td>
<td>98</td>
<td>130</td>
</tr>
<tr>
<td>D4</td>
<td>1229.9</td>
<td>Not required</td>
<td>4</td>
</tr>
<tr>
<td>D5</td>
<td>1249.6</td>
<td>64</td>
<td>86</td>
</tr>
<tr>
<td>D6</td>
<td>1312.8</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>D7</td>
<td>1548.1</td>
<td>Not required</td>
<td>Not required</td>
</tr>
<tr>
<td>D8</td>
<td>1652.4</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>D9</td>
<td>1728.6</td>
<td>54</td>
<td>72</td>
</tr>
<tr>
<td>D10</td>
<td>1730.2</td>
<td>24</td>
<td>33</td>
</tr>
</tbody>
</table>

The scenario for Elettra 2.0 seems better as compared to Elettra in the longitudinal plane and the maximum frequency shift needed to stabilize the beam for Elettra 2.0, that is 237 kHz, is well within the plunger frequency range and frequency tuning system range. Although Elettra 2.0 appears somehow worse in the transverse plane, the required frequency shift is affordable.

The above estimates come from simulations. The next step is to carefully measure the shunt impedance (The HOM impedances were measured in 1990 and 1997 and should be repeated today on the new Elettra cavities with the new available instrumentation) on the real cavity fully equipped and to repeat this evaluation. However based on our experience it is plausible to assume that the present Elettra RF system can still be a good candidate also from the stability point of view.

It should also be mentioned that Elettra 2.0 will be equipped with a third harmonic cavity and a longitudinal and transverse multibunch feedback system that will bring additional stability to the beam.

The implementation of the 500 MHz cavities for Elettra 2.0 seems possible without major complications while the cost saving by using the same accelerating structures along with all the operational experience and know how gained during all those years of operation makes this choice very attractive.

Four Elettra cavities can cover the RF acceptance requirements, while they need only 1.4 m each for installation in the ring. In the new layout they may be installed in the short straight sections where no dipole beam lines exist, namely sections 1, 2, 3 and 4.

The layout of each RF plant could follow the present scheme: an independent transmitter for each cavity. A 100 kW RF power transmitter is easily available also in solid-state power source technology that is becoming the state of the art choice for most synchrotron light sources. Thus the Elettra 2.0 RF system will be composed by a common RF distribution and four independent RF power stations.

In each station the following sections are identified:
1. RF signal conditioning and interlock at Low Level signal (LLRF)
2. RF power amplification stage
3. High power RF distribution
4. Accelerating section

Figure 7.3: Cartoon of the RF power station

Section references:
1. C. Pasotti et all, “Twenty Years of Operation of the Elettra RF System”, IPAC2014, Dresden – Germany
3. C. Pasotti, “RF Power for Elettra”, Elettra Project P2013096

7. DIAGNOSTICS

Non-destructive Diagnostics:
1. Beam Position Monitor: to measure the transverse position of the beam
2. Filling pattern: to measure the ring filling
3. Transverse feedback pick-up: to measure the transverse position of the beam bunch by bunch to be used for the feedback system that eliminates beam oscillations
4. Tune Measurement System
5. DC Current Transformer (DCCT): to measure current and lifetime.
6. Fast Current Transformer (FCT): for the measurement of variations in current and for the current measurement bunch by bunch
7. Synchrotron Radiation Profile Monitor (SRPM)
8. Temperature monitor (vacuum chamber, magnets, environment)
9. Annular electrode
10. Global orbit feedback
11. Fast orbit interlock
12. Beam based alignment (BBA)

Destructive Diagnostics:

13. Fluorescent Screens: Used for the measurement of position, shape and size of the beam. Useful for first turn diagnostics
14. Scrapers: Control the horizontal and vertical aperture at a certain position in the accelerator
15. Fast beam dump system

7.1 BEAM POSITION MONITORS

The beam position monitors (BPMs) are the most important diagnostic system in the machine. It assures the position measurement of the beam with the desired precision and is used for feedback and interlock purposes. For Elettra 2.0 we will need to measure the beam position in at least 16 points per acromat for a total of about 200 points along the entire orbit; to do this 200 electromagnetic button pickups are needed whose signal is processed by the same number of electronic units that will provide the control system with the orbit data (first turn mode, turn-by-turn mode, etc.). Furthermore they will interface with the interlock system for the protection of the vacuum chamber and with the orbit feedback system for maintaining the desired orbit. The system will have to ensure a position measurement resolution of some tens of nm at 10 kHz repetition rate.

Since the space between magnets is of the order of 50 to 70 mm the BPM system (BPM and bellows) must have a similar length. Alternatively one could design BPM integrated in the vacuum chamber in order to minimize the mechanical interference with the other components of the machine. In any case the bpm's will not be mechanically connected on the quadrupoles but will have their own dedicated supports on the girders preferably equipped with a very precise coordinate positioning system.

The acquisition electronics equipment will be hosted in temperature controlled racks in the SR service area.
Special BPM: 3 BPMs are needed to measure Tune, Transverse Feedback and Machine Filling. They has to be similar to the Orbit bpm (chamber and button shape). Their position will be chosen in accordance with the new lattice optics (beta function value).

7.2 FILLING PATTERN MEASUREMENTS

The filling pattern measurement is needed in order to determine the charge of each bucket relative to the charge of the whole beam. The relative charge measurement can be done using different pickups like a strip-line (sensitive also to beam position) or a fast current transformer. The signal from the pickup can be displayed by an oscilloscope or acquired by a dedicated acquisition system.

7.3 TRANSVERSE FEEDBACK PICKUP

One of the BPM pickups will provide signals to drive the bunch by bunch fast transverse feedback system. It measures the transverse position of each bunch to obtain the signal used by the feedback for the correction. The signal is fed back to the beam by strip-lines as shown in the next picture.

7.4 TUNE MEASUREMENT SYSTEM

To measure the fractional part of the tune, the beam is excited by a strip-line while the beam amplitude after the excitation is detected using a dedicated BPM. Two pairs of strip-lines, each 15 cm long are needed for the horizontal and vertical tune. The four strip-lines have the same shape of the underlying vacuum chamber and each one has two entries one upstream and one downstream. The position of the strip-line will be chosen

Figure 7.1.1: Possible bpm shape and vacuum pass-through

Figure 7.3.1: Horizontal Strip-line (left) and its physical appearance as installed in section 7 of the actual Elettra.
accordingly to the needed beta function value. The next picture shows an example of excitation strip-lines.

Figure 7.4.1: excitation strip-line

7.5 DC CURRENT TRANSFORMER

This system is used to measure the current circulating in the ring. It must be sufficiently sensitive and immune to noise in order to measure also the lifetime and the injection rate with an appropriate refresh rate. It needs about 20 cm longitudinal space but it is advisable to be far from pulsed magnets and RF cavities.

7.6 FAST CURRENT TRANSFORMER

It is a system for the measurement of the current circulating in the ring with a high response speed which allows determining rapid changes in the overall current as well as the charge carried by each bunch. It is indispensable for operating in top-up. It needs about 20 cm longitudinal space but it is advisable to be far from pulsed magnets and RF cavities.
7.7 SYNCHROTRON RADIATION PROFILE MONITOR (SRPM)

SRPM uses the synchrotron radiation to obtain information on the characteristics of the photon beam and the related characteristics of the electron beam. The radiation usually comes from a bending magnet or in alternative from a dedicated mini id located in a “beam diagnostic” section where different diagnostic systems will be located. The expected measurements are transverse profile, emittance, high frequency transverse oscillations and using a streak camera the beam bunch length and longitudinal profile, for the longitudinal dynamic studies of the beam. The laboratory that houses these diagnostics is in Experimental Hall, it has to maintain its position.

7.8 TEMPERATURE MONITOR

It is planned to have a system for temperature monitoring that could accommodate different kind of sensors for various purposes (chamber, magnet, environment, etc). Each station will collect signals from tens of sensors and will send data using a standard field bus allowing the desired modularity.

7.9 ANNULAR ELECTRODE

This kind of sensor has to provide a signal independent from transverse beam position to study longitudinal beam dynamics.

7.10 GLOBAL ORBIT FEEDBACK

The orbit of the beam must be kept constant over time by an automatic feedback. It works on the corrector’s strength to keep constant the orbit measured by the bpm's. To do so, the response matrix that measures the effect of each corrector on the position measured by each BPM is obtained. Then the inverse of this matrix is used to change the corrector’s strength to obtain the desired orbit. This system shares resources from diagnostics (BPM), power supplies (for the required corrector kick) and control system for real-time data processing at high speed to ensure the effectiveness at frequencies in the order of hundreds of Hz.

7.11 FAST ORBIT INTERLOCK

The photon beam produced by the insertion devices has enough power to damage seriously the vacuum chamber in a short time if the orbit of the electron beam is not good. This may happen due to human mishandling or due to a power supply fault, so an automatic interlock system must be constructed able to kill fast the beam before damage is caused. The interlock system uses the bpm electronics that will generate an alarm signal if the measured position exceeds a programmable limit (position's interlock) or if this happens for appropriate pairs of position values (angle interlock).

7.12 BEAM-BASED ALIGNMENT (BBA)

In order minimize geometric coupling and therefore maintain high photon beam brilliance, care must be taken in the stability and reliability of the beam position measure-
ment, so the widely used technique of BBA to calibrate the electrical center offset of the bpms with respect to the magnetic center of the closest quadrupole must be implemented. By correlating the magnetic centre of a quadrupole or sextupole with a nearby beam position monitor via the beam, the true centre of the bpm can be physically established to high precision. To apply a BBA system, the current through a given magnet is perturbed and any resulting shift of the beam orbit is observed. An orbit shift implies that the beam does not pass through the centre of the perturbed magnet. The beam can be aligned through both the centre of the magnet and an adjacent bpm by adjusting the position of the orbit in the magnet until no orbit shift is observed. For efficient BBA measurements each magnet should be powered by a dedicated power supply. If that is not possible shunts must be installed at each magnet, a technique presently used in Elettra. The BBA system can also be used to measure the amplitude of the lattice functions by measuring the tune shifts resulting from magnet perturbation.

7.13 FLUORESCENT SCREENS

This is a destructive diagnostic system to obtain information on the location and shape of the beam, very useful for first turn diagnostics during machine commissioning and to validate the bpm system measurement in first turn mode. A 20 cm length flange to flange is needed and it requires a nearby free space for maintenance (i.e., CCD substitution).

7.14 SCRAPERS

They consist of two pairs of blades that can be inserted, horizontally or vertically in the vacuum chamber to change its physical aperture. They can be used as a diagnostic tool by analyzing their interaction with the beam (e.g., dynamic aperture measurements) or as a dedicated beam loss point in case of a beam dump. A 30 cm length flange-to-flange for each scraper (Horizontal and Vertical) is needed plus a minimum connection chamber between the two in the order of 20 cm as well as a free space for maintenance (i.e. interlock switch calibration and substitution).

7.15 BEAM DUMP SYSTEM

Various systems may require a beam dump in order get protected. Presently in Elettra this is achieved by interrupting the RF-drive signal for 4 ms, this way the beam looses energy and after some hundreds of turns it is lost at some position in the inward-facing center part of the vacuum chamber. It has been observed that although this technique is rather robust, it may create problems at the point of loss especially if there are vacuum seals or ion pumps. For Elettra 2.0 it is recommended to have a dedicated beam dump system consisting of a fast vertical kicker and a beam dump.

8. LAY-OUT, NAMING AND INSTALLATIONS

8.1 MACHINE LAY-OUT

As we have seen that the lay-out should meet the following requirements:

- Keep the existing tunnel / building
- Keep the position and source point positions of the insertion devices beam lines
The objective in this first phase of layout is to control in 3D that the above requirements are met. The first step was to start from the coordinates of the actual Elettra and super-impose Elettra 2.0.

![Coordinates of the present Elettra ring](image1)

![Elettra 2.0 coordinates](image2)

On those coordinates now the optical elements of Electra 2.0 (dipoles, quadrupoles and sextupoles) are positioned:
Figure 8.1.3: Elettra 2.0, layout of the magnetic elements in one section.

Figure 8.1.4: As above in 3D view. It may be noticed the central 1.6 m long dispersive space in the arc.

Figure 8.1.5: Layout and the 500 MHz cavity as positioned in the long dispersive straight section.
Eight of those sections can be used for installing insertion devices.

Next was to check the Elettra 2.0 optical elements in relation to the existing machine. In the next Figure 8.1.6 a half achromat of actual Elettra is shown with the injection line.

![Figure 8.1.6: Half achromat of Elettra and corresponding front end together with the injection line for controlling the interferences.](image)

Concerning front-ends a longitudinal shift for all front ends will be necessary. The front ends replacing the dipole front ends of the actual Electra will have to be shifted also transversely outwards by at most 3.5 degrees.

In the next figures 3D views of Elettra 2.0 situated in the old tunnel on the supports of the actual Elettra are shown:

![Figure 8.1.7: Present Elettra - mini ID section.](image)
Continuing the analysis, the next step is to verify the real space between magnets, the
positioning of the front-ends, the shape of the vacuum chamber, the positioning of the
diagnostics, the positioning of the vacuum pumps, the interface between the support sys-
tem and the existing girders and the magnet support system.

![Figure 8.1.9: Elettra 2.0 - valves and pumps preliminary layout](image)

The maximum bore diameter in the quadrupoles and sextupoles is defined to be 26 mm;
therefore the vacuum chamber is supposed to have an external diameter of 25 mm.

### 8.2 OVERALL LAYOUT, NAMING, AND INSTALLATION

The optimization of the Elettra 2.0 design goes beyond the accelerator and the equip-
ment directly connected to it – e.g., magnet power supplies, control electronics, vacuum
system, etc. These devices, in fact, are supported by a network of “conventional” plants –
AC mains distribution system, cooling water system (including flow meters, thermom-
eters…), air conditioning – that are fundamental for the operation and performance of
the accelerator and are to be considered as a relevant part of the “Elettra 2.0 System”.

The design of the “conventional systems” will be *harmonized* with the design of the ac-
ccelerator in order to be more energy-efficient, avoiding under-dimensionalizing and exces-
sive over-dimensionalizing, and taking in account “contemporary factors”. At the same time,
the design of the “conventional systems” will be fully integrated in the overall layout of
the plant, sharing common naming rules to identify objects both in the field (labels and
tags) and from the MPS (Machine Protection System), PPS (Personnel Protection Sys-
tem), and RCS (Remote Control System).

The adoption of common naming rules will facilitate the installation operations as well,
providing uniform criteria to identify – at every level of detail – the components, their
position, and the interconnections among them.

The nomenclature criteria are required to allow clear and unique identification of a given
object, primary in the configuration file “date_elettra2_CM.xls”, as well as in the layout
drawings, in the control system, in the cabling lists and so on. The nomenclature criteria
will include a first field related to the function of the object, a second field related to the
area in which the object is located while a third field gives the relative position of simi-
lar objects located in the same area.
8.2.2 NOMENCLATURE CRITERIA

The general nomenclature criteria to be used in order to identify a given object are the following:

- **type_area.progressive**

with the following meaning of the fields:

- The **“type”** field identifies the function of the object, e.g. “B” for Bending magnet, “Q” for Quadrupole magnet, “RV” for Rack of vacuum.
- “_” is the separation character between “type” and “area”.
- The **“area”** field identifies the area in which the object is located, e.g. “S01” for Achromat section 1 and so on;
- “.” is the separation character between “area” e “progressive”
- The **“progressive”** field identifies the relative position of recurring objects of the same “type”, in the same “area”. By definition, the “progressive” field is a two-figure number: 00, 01, 02, ..., 09, 10, 11...

8.2.3 “TYPE” FIELD

The “type” field contains an abbreviation which allows unambiguous identification of each object. Objects are equipment, instruments, racks, supports, and so on.

8.2.4 “AREA” FIELD

The “area” field contains an abbreviation which allows unambiguous identification of each room, area or sector pertaining to the Elettra buildings.

8.2.5 ABBREVIATIONS

Abbreviations, for both “type” and “area” fields are listed in the Annex to Elettra 2.0 Naming Convention.

When new abbreviations are created, the related table in the Annex file will be updated or a new table will be created, as appropriate.

The Annex document will be updated exclusively by the Elettra2.0 Document Control and Configuration manager, who at the same time will take care of updating the configuration file “Elettra2.0_CM.xls”
Table 8.2.1: examples of abbreviations

<table>
<thead>
<tr>
<th>Tipo</th>
<th>OGGETTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCBT</td>
<td>RFCavity Accelerator</td>
</tr>
<tr>
<td>ACCH</td>
<td>RFCavity harmonic cavity</td>
</tr>
<tr>
<td>ACCT</td>
<td>RFCavity Accelerator</td>
</tr>
<tr>
<td>B</td>
<td>Magnet 2 poles magnet</td>
</tr>
<tr>
<td>BAM</td>
<td>Instrument Bunch arrival monitor</td>
</tr>
<tr>
<td>BPM</td>
<td>Monitor Beam position monitor</td>
</tr>
<tr>
<td>BST</td>
<td>Instrument Beam stopper</td>
</tr>
<tr>
<td>CBLM</td>
<td>Instrument Bunch length monitor</td>
</tr>
<tr>
<td>CBPM</td>
<td>Monitor Cavity beam position monitor</td>
</tr>
<tr>
<td>CH</td>
<td>Corrector Magnet correctors (channel H)</td>
</tr>
<tr>
<td>CHV</td>
<td>Corrector Magnet correctors (combined or not)</td>
</tr>
<tr>
<td>CID</td>
<td>Corrector Steerer coil</td>
</tr>
<tr>
<td>CM</td>
<td>Instrument Current monitor</td>
</tr>
<tr>
<td>CV</td>
<td>Corrector Magnet correctors (channel V)</td>
</tr>
<tr>
<td>D</td>
<td>Dump</td>
</tr>
<tr>
<td>DCAV</td>
<td>Instrument RF cavity deflector</td>
</tr>
<tr>
<td>DR</td>
<td>Drift Include all parts needed as vacuum chambers, ionoc pumps, valves, and so on..</td>
</tr>
<tr>
<td>EBPM</td>
<td>Instrument Energy Bmp</td>
</tr>
<tr>
<td>ECOL</td>
<td>Instrument Energy Collimator</td>
</tr>
<tr>
<td>EOS</td>
<td>Instrument Electric optical sampling</td>
</tr>
<tr>
<td>FC</td>
<td>Instrument Faraday cup</td>
</tr>
<tr>
<td>FLSC</td>
<td>Screen Fluorescent Screen</td>
</tr>
<tr>
<td>GBLM</td>
<td>Instrument Bunch length monitor</td>
</tr>
<tr>
<td>GCOL</td>
<td>Instrument Geometry collimator</td>
</tr>
<tr>
<td>GUN</td>
<td>Instrument Gun</td>
</tr>
<tr>
<td>ID</td>
<td>Instrument Insertion device (undulator)</td>
</tr>
<tr>
<td>MSCR</td>
<td>Screen Multiscreen (OTR+YAG)</td>
</tr>
<tr>
<td>PHSH</td>
<td>Magnet Phase shifter</td>
</tr>
<tr>
<td>Q</td>
<td>Magnet 4 poles magnet</td>
</tr>
<tr>
<td>SCRPH</td>
<td>Instrument Scraper</td>
</tr>
<tr>
<td>SOL</td>
<td>Magnet Solenoid</td>
</tr>
<tr>
<td>WSC</td>
<td>Instrument Wire scanner</td>
</tr>
<tr>
<td>YSCR</td>
<td>Screen YAG screen</td>
</tr>
</tbody>
</table>

Table 8.2.2: Examples of field codes “type”, Vacuum

<table>
<thead>
<tr>
<th>Tipo</th>
<th>Oggetto</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV</td>
<td>Rack Vuoto</td>
</tr>
<tr>
<td>VLV</td>
<td>Valvola Gate</td>
</tr>
<tr>
<td>VLVP</td>
<td>Valvola Prevuoto</td>
</tr>
<tr>
<td>FTVLV</td>
<td>Fast Valve</td>
</tr>
<tr>
<td>PSSIP</td>
<td>Power supply sputter ion pump</td>
</tr>
<tr>
<td>SIP</td>
<td>Sputter ion pump</td>
</tr>
<tr>
<td>TPG</td>
<td>Total Pressure Gauge</td>
</tr>
<tr>
<td>VGPI</td>
<td>Vacuum Gauge Pirani</td>
</tr>
<tr>
<td>VGPE</td>
<td>Vacuum Gauge Penning</td>
</tr>
<tr>
<td>IGC</td>
<td>Ionization Gauge Controller</td>
</tr>
<tr>
<td>VGBA</td>
<td>Vacuum Gauge Bayard Alpert</td>
</tr>
<tr>
<td>VGPI</td>
<td>Vacuum Gauge Pirani</td>
</tr>
<tr>
<td>RGA</td>
<td>Residual Gas Analyser</td>
</tr>
</tbody>
</table>
Prior to installation, a detailed summary of available power cables and cable trays will be prepared. This will allow the potential re-use of valuable power cables – in the orders of kilometers – for the installation phase.

### 9. VACUUM CHAMBER AND SUPPORTS

The circumference of the new storage ring will remain at about 259.2 m with a design current of 400 mA. The lattice is based on 12 6-bend achronats. Each cell includes 6 dipoles, 16 quadrupoles, 20 sextupoles and 6 skew quadrupoles. Elettra 2.0 will have 12 long straight sections of nearly 5000 mm, one dedicated to the injection and 11 reserved for undulators, and 12 short straight sections 1550 mm long, 4 reserved for the RF cavities and the rest for short undulators / wigglers.

#### 9.1 VACUUM CHAMBERS

Due to increased magnetic fields and the lack of space the gap and bore diameters of the magnets must be small. This also influences the vacuum chamber cross section and the required fabrication tolerances become tighter. The standard profile of the vacuum chamber consists of a pipe with inner diameter 22 mm and outer diameter 25 mm.

![Figure 9.1: drawing of the vacuum chamber cross section.](image)
However not all chambers will have the circular cross section shown above. The beam position monitor vacuum vessel will be octagonal (see section 8) or circular with buttons non following the chamber curvature, those of the long straight sections will be flat with vertical dimension of about or less than 10 mm and the light exits will have horizontal dimension of 20-30 mm and vertical dimension about 8-10 mm.

Non-evaporable getter (NEG) technology will allow distributed pumping being an essential technology for such a small cross section chambers hard to pump out. NEG coatings, developed by CERN, are based on thin films that coat the inner surfaces of vacuum chambers and have a chemical affinity for gas molecules.

9.2 THE ABSORBERS

The synchrotron radiation produced from the bending magnets will be absorbed in the vacuum chambers walls becoming an absorber distributed all over the ring. Cooling pipes soldered on the vessels will absorb the unused synchrotron radiation and reduce the thermal deformations. The total power from each dipole goes between 474 W and 1074 W. The maximum power density is 27.6 W/mrad² and the maximum surface power density (with normal incidence) is 143 W/mm².
A finite element analysis is performed to estimate the temperature on the cooled vacuum chambers from the bending radiation. The maximum temperature on the vacuum chamber is summarized in the following table.

Tab. 9.1 Maximum temperature according in the vacuum chamber due to bending unused radiation.

<table>
<thead>
<tr>
<th>Chamber-cooling channel materials</th>
<th>Tmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper – copper</td>
<td>27.42 C</td>
</tr>
<tr>
<td>Aluminum - copper</td>
<td>31.32 C</td>
</tr>
<tr>
<td>Steel – copper</td>
<td>79.86 C</td>
</tr>
</tbody>
</table>

The stainless steel chamber, due to the low thermal conductivity, leads to higher temperatures and although those temperatures are not critical will generate higher deformation on the vessels, conditions not always in compliance with a machine with so low longitudinal free available space to place enough bellows. This would also lead to a possible displacement of the BPMs that might not be easy to treat.

![Stainless steel vacuum chamber FE analysis](image)

Figure 9.3 Stainless steel vacuum chamber FE analysis.

For the light exit vessels, having special shapes, finite element analysis (FEA) will be performed to calculate their deformations under vacuum and heat load and ribs will be designed if necessary to reduce possible deformations at the slot region. A FEM analysis will allow a proper design of crotch absorbers that will protect the vacuum chambers.

9.3 MATERIALS

In third-generation light sources vacuum chambers are made of stainless steel, aluminium and copper alloys. Stainless steel has a low thermal conductivity and therefore using it one has to consider the problems connected with the radiation heat load. At the same time its high electrical resistivity contributes to the resistive wall impedance. However the low electrical conductivity helps reducing the eddy currents created by the fast orbit
feedback. It is easy to weld and is a corrosion resistance alloy with low magnetic permeability and high yield strength. It is an optimum material for high vacuum and has memory after a chamber venting meaning that needs less time to be conditioned for the second time.

Aluminium is easy to manufacture and extrude especially for long and complex chambers, it is also completely non magnetic. Aluminium has some disadvantages like weak mechanical properties and it is difficult to join it with other materials. On the other hand due to its low resistivity is attractive from the impedance point of view. However its greater disadvantage is its behaviour in the vacuum, after a venting does not have memory needing always about 100 Ah to be conditioned. Thus the aluminium chambers should be covered with NEG. At Electra the low gap chambers at long straight sections are made of aluminium with NEG.

The actual preference for Elettra 2.0 is in using vacuum chambers in oxygen-free copper, despite the increased complication for its production process and its cost. The main reasons are the following:

- high electrical conductivity of copper minimizes the impedance of the machine
- high thermal conductivity reduces the temperatures and deformations on the vacuum chamber
- high annealing temperature is convenient for NEG coatings because vacuum chambers need to be heated to a temperature of at least 200 C to activate the coating.

In order to minimize the shielding of the fast corrector fields of orbit feedback, the affected vacuum chambers will be made of steel AISI 316L.

The light exit vacuum chambers placed inside the bending magnet, that allow the electrons to follow their orbit and photons to exit from the storage ring will be made of AISI 316L. The undulator vacuum chambers will be manufactured in aluminium alloy with NEG and the design basically will not change from the current one. Stainless steel bellows with RF fingers will be placed between vacuum chambers to absorb the thermal expansion in the storage ring and to allow easy installation during assembly.

9.4 MANUFACTURING

Elettra 2.0 will use CF type connecting flanges made of stainless steel with copper gasket, a standard solution in several storage rings. Different manufacture processes will be used to join vacuum chambers avoiding annealing and distortions. Vacuum brazing will join short copper terminals to stainless steel flanges; TIG welding will weld copper elements to the vacuum vessel, while a less distortion inducer soldering will join the cooling pipes to the vacuum chambers. The complexity of the vacuum chambers in light exits makes the NEG coating challenging but not impossible.

9.5 SUPPORTS

It has already being verified that the designed supports can fit on the existing girders. The supports will be of a 3D type, a concept developed at Electra and its general description follows. As the required magnet specifications involve a design of iron dominated quadrupoles and sextupoles with a yoke transversally large and longitudinally
short, this topology requires a very stiff closing and support system; the idea is to realize, in two different types, a common support nonmagnetic system (or 3D frame) whose task will be to support and position all the magnets, also in the case of yokes made of separate parts. This 3D frame will be made in two parts, bottom and upper parts, that allow the simultaneous opening of all the magnets (except for the electromagnet bending dipole that will be C-Type) for convenient vacuum chamber installation, maintenance and bake-out. The upper part of the frame could be lifted by means of a crane and dowel pins allowing repositioning with very high accuracy. In this way, it will be easy to remove the vacuum chamber towards the inner part of the storage ring. There will be an early assembly area, where the magnetic elements will be assembled and aligned on girders to be later positioned in the storage ring building.

It is under investigation the possibility for dynamic positioning and alignment of the separated magnet yoke parts inside the girder. The investigation consists in designing a prototype that can move with accuracy by means of stepper motors and wedge mounts each magnet yoke. This system will allow the precise alignment of each magnet along its magnetic axis, with respect to the ideal beam axis given by the lattice. Each girder must be provided with fiducial marks referenced to the mechanical centre. The storage ring will contain twelve identical sectors and each sector will have four girders. For the positioning of the girders relative to the control network in the storage ring tunnel a laser tracker will be used.

![Girder preliminary design.](image)

Figure 9.4.1: Girder preliminary design.

Adjustment mechanisms will allow the alignment of the vacuum chambers and other machine components and its main design features are:

- Alignment precision and adequate positioning resolution
- Orthogonal adjustment, reduced crosstalk during adjustment motion
- Stability, when locked must be very stiff and accidental contact must not induce movement
- Low encumbrance, their footprint must be narrow in the beam direction, adjustment must be possible despite of being placed very close to other components
Vibration stiffness
Low sensitivity to thermal deformations

The undulator and light exit chambers will be supported by grouted pillars or stands, isolating the magnets from chamber vibrations. The standard vacuum chambers will be aligned by means of plate systems moved by screws. The girders will be moved vertically by means of levelling wedges. The other movements will be made by screws that will push rigid plates connected with the girder lower base. The screw aligned position will be blocked by locknuts.

9.5 VIBRATION ANALYSIS OF THE SUPPORTS

Displacements and relative vibrations of the girders lead to orbit deviations that can deteriorate the performance of the storage ring. The system must allow a high-precision alignment of the girders (±50µm), but at the same time must be stiff and insensitive to vibrations. However, a simultaneous easy high precision alignment and high mechanical stability is challenging. Easy alignment requires flexible and movable components but on the other hand, high stability requires a stiff design with multiple support points to reduce resonances and improve the vibration resistance.

Since Elettra is built on a very solid rock and relatively insensitive to disturbances, the vibration sources are mainly the flow of the cooling water, air conditioning, power supplies, actuator movements and mains disturbances.

Considering the self-excited vibration, it is necessary to study the dynamic characteristics and reduce the vibration eigenfrequencies of the system. A modal analysis based on the linear vibration theory and finite element method has been performed on a preliminary design of the girder. The dynamic characteristic of the girder are crucial to avoid the resonance phenomenon and decrease the vibratory displacements. The whole structure is a multi-degree-of-freedom system, and the vibration differential equation can be expressed by the formula:

$$MX'' + CX' + KX = F$$

where \(M\) is the system mass matrix, \(C\) and \(K\) are the damping and stiffness matrix, \(X''\) is the system acceleration matrix, \(X'\) and \(X\) are the velocity and displacement matrix. \(F(t)\) is the vibrating force matrix.

The natural frequency and vibration modes related to the system are the solution of the equation:

$$|K - \omega^2 M| = 0$$

The natural frequency \(\omega_i^2\) and main vibration modes \(\{\phi_i\}\) are obtained from the previous equations, where \(i=1, 2, \ldots, n\). The finite element calculation is the main method to simulation the dynamic characteristic of the structure.
A steel plate is grouted to concrete pedestals. The main structure of the girder is made of steel plates, direction adjustment systems, anchored to the basement, allowing for precise positioning. The dipole magnets are composed of steel sheets, steel plates and copper coils. A closed girder must withstand dipole magnets, quadrupoles and sextupoles.

Considering the results of the modal analysis, levelling wedges will be considered to make the structure stiffer.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Natural frequency [Hz]</th>
<th>Modal shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30,414</td>
<td>Beam direction bend</td>
</tr>
<tr>
<td>2</td>
<td>50,517</td>
<td>Beam direction torsion</td>
</tr>
<tr>
<td>3</td>
<td>52,966</td>
<td>Horizontal axis bend</td>
</tr>
<tr>
<td>4</td>
<td>67,388</td>
<td>Horizontal axis bend 2nd mode</td>
</tr>
<tr>
<td>5</td>
<td>70,297</td>
<td>Horizontal axis bend 3rd mode</td>
</tr>
<tr>
<td>6</td>
<td>100,7</td>
<td>Beam direction bend 2nd mode</td>
</tr>
</tbody>
</table>

The above eigenfrequencies referred to a prototype with three supporting points on the concrete pedestals indicating that their number should be increased.

The alignment jacks should be located under the girder and appropriately designed. Damping pads could be taken into consideration and installed between alignment jacks and grouting to prevent magnification of excitation by the weak elements of the support system. The damping pads will be simulated and optimized by using finite element modelling in future.
10. VACUUM SYSTEMS

10.1 GENERAL REQUIREMENTS

This new generation of synchrotron light sources with very small electron emittance beam requires a compact lattice with reduced magnet apertures, making the vacuum system design challenging.

The vacuum system of Elettra 2.0 should take into consideration the following constraints:

1. Small free distance between most of the magnets;
2. Heat load from synchrotron radiation (absorption, transmission, dissipation issues);
3. The dynamic pressure inside the vacuum chamber;
4. Compatibility with the present ID vacuum chambers and the present front-ends.

10.2 CONDITIONING AND PRESSURE

With the stored electron beam, a dynamic average pressure along the $e^-$ beam trajectory $< 2 \text{ pbar}$ and a local maximum pressure $<5\times10^{-9} \text{ mbar}$ have to be achieved in order to minimize the interactions between electrons and residual gas, i.e. to prevent the $e^-$ beam from producing an excess of bremsstrahlung, reducing its lifetime and increasing its emittance. The static (i.e. without any stored $e^-$ beam) pressure is expected to be in the $10^{-10} \text{ mbar}$ range. In order to achieve this target, the maximum allowed local leak is $8\times10^{-11} \text{ mbar/l/s}$ and no exception will be permitted.

Without beam the expected mass spectrum is mainly composed by hydrogen ($>80\%$ of the total pressure), carbon oxide ($<10\%$), carbon dioxide ($<2\%$), methane ($<5\%$). Oxygen and water should be reduced at negligible percentages. The peak intensity could be very different in different parts of the machine, depending on the vacuum chamber material and on the local pumping speed. The overall contribution to the total pressure should be largely reduced during the installation stage applying the proper bake out procedure. In fact, it reduces the specific thermal out gassing $q_T (\text{mbar}\text{l/s/cm}^2)$ for each component inside the vacuum.

All the vacuum chambers, valves, bellows and in vacuum diagnostics have to be baked out in situ at 180 to 220°C. Removable heating tapes and insulating blankets are necessary to obtain such a high temperatures. A set of programmable temperature controllers is employed during the bake out procedure to manage different components at the same time.

During machine operation, the pressure usually increases due to interaction between direct or scattered photons impinging the surfaces exposed to vacuum, stimulating the molecules desorption or their cracking and desorption. An effective beam scrubbing of the internal walls is expected, as usual, during the early stage of the machine conditioning, so the photon stimulated desorption (PSD), described by the desorption yield $\eta_{ph}$ (number of desorbed molecules/number of impinging photons), decreases during time. An empirical formula links $\eta$ (molecules/photons) and the integrated dose $D (\text{Ah})$ of machine rent: $\eta_{ph} = \eta_0 \cdot D^{-K}$, where $\eta_0$ and $K$ are constants, depending on the machine and the material. We expect to reduce the overall pressure to a “well conditioned” machine status...
that, at present, in Elettra, corresponds to a dynamic pressure of $1 \times 10^{-11}$ mbar mA. Different parts of the machine, made of different materials, are “well conditioned” after different doses. A maximum overall dose $D \leq 100$ Ah to complete the first conditioning is desirable.

Faster machine conditioning is then achieved taking into account three main stages:

1) Very good cleanliness of the components and much care during installation to keep them clean until in vacuum;
2) Bake out of components to reduce $q_T$ and $\eta_0$;
3) Capability of the vacuum pump system to remove as quickly as possible the gas inside the vacuum pipe.

The last point depends, of course, on the possibility of mounting locally high-speed pumps (i.e. ion and non evaporable getter pumps) and having a distributed pumping system (non evaporable getter stripes or coating) in a long, narrow, conductance limited vacuum system.

Finally, the result depends on the vacuum system design, according to constraints imposed by other machine subsystems, and on the operational conditions.

Studies of the heat load from synchrotron radiation and of the photon flux distribution on different components of the vacuum system have to be performed for the new machine; it will provide more precise information for the choice of the materials and for the optimization of the pumping system, including the possibility to understand if and where to employ NEG (non-evaporable getter) coating technology.

10.3 THE PUMPING SYSTEM

At the moment, in the achromat the first guess is to install conventional vacuum pumps where space permits it (Figure 11.3.1). On the first dipole vacuum chamber (UDL.1) where radiation generated by the previous undulator exits, a 500 l/s pump is mounted; three 200 l/s pumps are mounted on the following arc. A second light exit vacuum chamber (UDL.2) is foreseen in the position of the fourth bending magnet only in case of using the bending magnet or a short wiggler installed in the short section, as a radiation source for users. Only in these cases, the UDL.2 will be built as similar as possible to UDL.1, i.e. using stainless steel for the vacuum chamber and a conventional vacuum pump.

In the rest of the arc a simple, circular copper pipe internally coated with a non-evaporable getter acting as an effective, distributed pumping system is planned.

![Figure 10.3.1: Vacuum pumps position in the achromat](image_url)
As indicated in the figure 10.3.1, the main materials under investigation for the vacuum chambers in the achromat are stainless steel and copper. Copper should be used mainly as distributed heat sink and an internal NEG coating is applied to act as a distributed pumping system (see an example at the MAX IV facility in Figure 10.3.2). In this way the vacuum chamber design is much simplified and used to only transport the e⁻ beam in the middle of the bending magnets, where synchrotron radiation is generated and is mostly dissipated: just a circular tube with an external, small cooling circuit applied on the orbit plane.

Figure 10.3.2: Circular copper tube with cooling circuit at MAX IV (Lund, SE)

One could consider the same material for the light exits (UDL vacuum chambers) with many benefits in managing the heat load but, at the moment, it is preferred a more conventional solution using stainless steel. Stainless steel is having a more rigid structure enabling to host various components such as vacuum pumps, valves, a crotch absorber and a photon shutter.

A preliminary sketch is presented in Figure 10.3.3. At present, in Elettra, the dipole vacuum chambers (made of aluminium or stainless steel) are pumped by 400 l/s sputtered ion pumps and the pressure is easily kept below 1 pbar with stored e-beam. For the new dipole vacuum chambers, it could be possible to increase the pumping speed using a combined NEG+SIP pump up to 1000 l/s; moreover, a NEG strip could be used as a distributed pumping system applied to one side of the vacuum chamber.

Figure 10.3.3 The UDL vacuum chamber (left) and with the surrounding magnets (right)

The use of NEG + sputter ion pumps (SIPs) combined in one body and produced by SAES Getters, is under investigation (Figure 10.3.4). This solution would allow installing a very compact, high-speed vacuum pump (up to 200 l/s, DN40 mounting flange) in the very narrow space between magnets. Moreover, this kind of pump is very light compared to traditional SIPs with similar pumping speed, so it is possible to “upgrade” to large sizes, preserving ease of assembly. Depending on the chamber design, high-speed pumps (up to 1000 l/s or more, DN100 mounting flange) could be employed to absorb the large amount of gas produced in the dipole vacuum chamber, due to the synchrotron
radiation interaction with the crotch absorber, with the machine shutter and with the dipole vacuum chamber itself.

Figure 10.3.4: NEG+SIP combined pumps with different nominal pumping speeds, a) 200 l/s and b) 1000 l/s (SAES Getters).

A not-negligible part of the photon flux produced in the bending magnet will irradiate the downstream pipes, inducing photo desorption. The estimated contribution to the overall amount of gas present in the pipes suggests the use of a distributed pumping system, by means of the NEG coating, added to the discrete pumping.

We cannot exclude, however, reusing our traditional sputter ion pumps from Agilent (previously Varian) somewhere in the achromat to better pump the residual gases that are not efficiently (or not at all) pumped by NEGs. In fact, the aforementioned combined pumps cannot efficiently pump during the first stages of the conditioning, when a higher pressure is present in the storage ring. This is because are optimised in UHV conditions where the NEGs works better and also because their pumping speed (5-10 l/s) is small.

Another constraint that might occur in Elettra 2.0 is the possibility of reusing the insertion devices (ID, undulators and wigglers) and the corresponding low gap vacuum chambers of the actual Elettra, in the same original position, to reduce costs and not to waste well-earned knowhow on these systems. However it might be that lower gap chamber will be required and in this case new chambers must be constructed. If however the same gap but shorter chambers are required the raw extruded material (aluminium) already present in the warehouse may be used to be NEG coated.
In the present Elettra ring the long straight vacuum sections, all (except one) are already from aluminium NEG coated, while the ID stainless steel ones are not. A couple of 120 l/s sputter ion pumps, upstream and downstream the ID, help to keep the pressure in UHV conditions (Figure 10.3.5). With this setup, the pumping system is efficient in the long straight sections; the electron beam is not affected by the interaction with the residual gas and the gas bremsstrahlung production is reduced to acceptable levels. If needed to redesign the chambers of the long straight sections, it would be desirable to reuse the pumping system already installed.

Coming now to the machine front-ends and the related experimental beam-lines, the UDL.1 and UDL.2 exit cases are examined:

The beam-lines using the insertion devices as photon source through UDL.1 will keep their relative position in respect to the source itself, changing maybe only the vacuum chambers that are at the interface with the new machine and/or some components like photon shutters and stoppers. No relevant change in the pumping system is expected in that case.

The beam-lines receiving the synchrotron light from the bending magnets or a short wiggler through UDL.2 will have to move from 3.4 to 7 degrees with respect to the original one. As in the previous case, a new interface to the machine has to be designed, while no relevant change in the pumping system is expected.

The four radiofrequency (RF) cavities present in Elettra (Figure 10.3.6) could be upgraded, using 500 l/s NEG+SIP pumps.

Figure 10.3.6: RF cavity in the Elettra storage ring with 120 l/s SIP pump (left). The same RF cavity in laboratory with 500 l/s SIP+NEG pump (right).

This configuration has been tested on one RF cavity at full power in the laboratory (fig. 12.3.6), with very good results: the presence of the NEG ensures that pressure is kept at very low levels (<5×10⁻¹⁰ mbar) even when the ion pump power supply is switched off. A similar solution could be applied to the injection septum to preserve the vacuum in case of a power failure.
10.4 CHOICE OF VACUUM MATERIAL

Follows a material analysis from the vacuum point of view based also on the experience accumulated from Elettra. A very well cleaned 316L stainless steel could be a good candidate for further studies. With an initial specific out-gassing $q_0 < 5 \times 10^{-12}$ mbar/l/s/cm$^2$ at room temperature, considering a tube 2.5 m long (the maximum length we expect flange to flange, ID vacuum chambers apart), with 22-23 mm in diameter, and two pumps at its sides, the pressure in the middle would remain under $2 \times 10^{-9}$ mbar, without the stored beam. The initial photon desorption yield $\eta_0$ of the stainless steel is usually lower than that of other materials (Aluminium, Copper) and this fact promotes the initial conditioning. The beam scrubbing is very effective and lowers $q_T$ and $\eta_0$ run after run.

Aluminium shows higher dynamical pressure and this fact may be harmful to the beamline users because of the gas bremsstrahlung radiation, especially when the chambers are long and narrow where the pumping is not efficient; in this case a NEG coating is required otherwise such chambers need long conditioning time (100 Ah). On the contrary, when the chambers are as large as in the current bending magnet vacuum chambers, the conditioning time is comparable to stainless steel ones.

Copper is not used in the present storage ring except in the RF cavities that are usually pre-conditioned in the laboratory: they are large vessels and they are easy to pump to less than $5 \times 10^{-10}$ mbar. Other laboratories are using copper (better than aluminium) to make the narrow vacuum pipes a distributed heat sink. Internally, a NEG coating helps to keep the pressure low, because the initial copper photon desorption yield $\eta_0$ is not as good as the stainless steel one. The NEG coating acts as a pump and as a barrier for the molecules at the interface with the copper surface and allows a faster conditioning than stainless steel. The main issue of NEG technology, costs aside, is that it requires a local activation: compared to a “simple” bake out (12-16 hours but sometimes it is necessary only for ion pumps and only for few hours), the NEG activation takes up to 20 h of extra working time, i.e. about one day more of machine downtime. Moreover, the vacuum chambers must not suffer too many venting processes because of the limited number of NEG reactivations (few tens).

The NEG technology appears to be a very useful upgrade to be considered at the beginning of the vacuum system design but it is not mandatory to apply to the entire storage ring unless all the subsequent simulations about heat loads and pressure trends convince the engineering team to adopt it.

Magnets define the maximum dimensions of the vacuum chambers and their relative magnetic permeability $\mu_r$. As reported previously, the maximum external diameter will be 25 mm inside quadrupoles and sextupoles whereas the maximum height inside the bending magnets will be 35 mm. According to internal specifications, the relative magnetic permeability $\mu_r$ of the material used for tubes and flanges should be lower than 1.01. This requirement may be relaxed after further studies on the magnetic field propagation through the material, inside the vacuum chamber.

10.5 SIMULATIONS

Vacuum simulations are necessary to identify critical issues in the vacuum system design and to optimise each single component and entire vacuum sections. A Monte Carlo simulator like “Molflow +”, developed at CERN and freely distributed, is a great tool to com-
plete all indicated tasks. “Synrad”, a modified version of “Molflow +”, will be used to calculate flux and power distribution on a surface caused by synchrotron radiation. The results are easily transferred to the vacuum simulator to take into account not only the thermal out-gassing, the main contribution to the total pressure when the machine is at rest, but also the photon stimulated desorption when the machine is running.

In Figure 10.5.1 is shown the thermal out-gassing in a part of achromat (circular copper tube without NEG coating) for H₂.

![Pressure profile](image)

Figure 10.5.1: The simulated model (top, 2D section) and the corresponding pressure profile along the beam trajectory (bottom) for H₂, without PSD, at room temperature.

Due to low vacuum conductance, the tests indicate that good statistics, necessary to obtain a smooth pressure profile in the achromat chamber model, are achieved after 2-12 hours, depending on the model itself (geometry, number of facets, texture resolution, pumping speed, etc.).

10.6 VACUUM COMPONENTS

10.6.1 FLANGES AND JOINTS

In order to facilitate the coupling of flanges since the space between magnets is narrow, it is planned to use modified ConFlat flanges with tensioning chains and flat OHFC gaskets (fig. 11.6.1.1). All other less difficult couplings foresee normal CF flanges with bolts, nuts and flat OHFC gaskets. Silver plated copper gaskets could be taken into account to couple CF flanges in case of high temperatures during the bake-out of the vacu-
uum system. No Viton or other elastomers are allowed as permanent gasket in the storage ring.

Fig.10.6.1.1: CF flanges with different coupling configurations

10.6.2 PRESSURE GAUGES

The Elettra 2 vacuum system will keep the actual pressure monitoring system, based on the radiation resistant “Pirani” and “Penning” gauges and their controllers from Pfeiffer. New residual gas analysers (RGA) will be added to our mobile pumping stations, in order to be more flexible when necessary, instead of having an RGA in fixed positions around the storage ring.

10.6.3 VALVES

The Elettra vacuum valve system will be changed to fit with the new vacuum chamber dimensions and to divide the storage ring into more vacuum sections. That would help to manage the vacuum pipes that could be upgraded with a NEG coating or to replace them easily. All vacuum valves require RF contacts to guarantee electrical continuity. Only “all metal” type valves are considered.

Vacuum valves will be controlled by a dedicated PLC and operated remotely or by means of a local touch screen panel installed in the racks placed in the service area.

10.6.4 RACKS

An upgrade program of all racks dedicated to the vacuum system is ongoing and the new ones will also be used for Elettra 2.0. As previously reported, because of limited free spaces, many ion pumps from Varian (now Agilent) will be replaced with compact, combined SIP+NEG pumps from SAES Getters (at present, the only manufacturer marketing this kind of pump), but we plan to keep the ion pumps of the ID vacuum chambers. The racks will host all the pumps and gauges power supplies and the touch screen panel dedicated to the vacuum valves and to the vacuum interlock system.

One ion pump power supply can control up to 4 pumps, whereas each combined pump is controlled by a compact, single-channel power supply for the ion pump part and by a NEG pump controller, able to drive up to 4 NEG pumps. Each gauge controller can control up two “Penning” and two “Pirani” gauges. Considering the total provisional number of controllers, two racks per achromat will be sufficient for the vacuum system.
11. FRONT-ENDS

The front-ends of Elettra 2.0 will necessarily move from the previous position and one of the goals of the new machine design is to reduce the shift of the beamlines. According to the Elettra 2.0 design, the front-ends of the long straight sections IDs remain in the same line but since the angle between the new front-end and the machine section after a bending magnet is now smaller by about 5 deg, due to the smaller bending radius of the magnet housing the light exit, the front-end must be moved further downstream from 1.5 to 2.5 m according to the front-end design.

Observing Figures 11.1 and 11.2 one can immediately understand why in the Elettra 2.0 case the front-end should be longitudinally shifted. This might mean that the ID front-ends may have to be redesigned, but the space inside the protection wall should be sufficient to house them. However it might be quite challenging to place the XRD2 front-end without shifting the radiation shielding wall, considering the length of the masks necessary to absorb such a high heat load.
Concerning the current dipole beamlines the new source may be either a short wiggler of about 2T or a superbend and the corresponding front ends must be shifted both longitudinally and horizontally. In Figure 11.3 the present front-end is shown while in Figure 11.4 two different front-end configurations are shown for Elettra 2.0.

In the first case (Figure 11.4) the angle difference between the new front-end and the old one will increase by approximately 3.45°. The new origin of such beamline will be shifted by about 3.8 m upstream, but the pinhole could be shifted approximately 1 m downwards relative to the previous position. The front-end design as well as the position of the optical elements of the beamline will be affected by this change as well as the position of the beam-line optical elements. This configuration could lead to a change in the radiation shielding wall position.

In the second case (Figure 11.4), the theoretical radiation fan will be 5.7°, but considering the encumbrance of the sextupoles and quadrupoles that follow the bending magnet the effective radiation fan would become 3°. This angular range includes the actual light exit.
The new origin of such beamline will be placed approximately between 2.2 and 2.5 m upstream, but the pinhole could be moved approximately 2 m downwards relative to the previous position, because of the closer angle between the future machine and the front-end. The front-end design as well as the position of the optical elements of the beamline will be affected by this change, but this aspect may not lead to a change in the radiation shielding wall position.

Due to the different power density of the source, thermal simulations will be carried out on beam-stoppers, shutters, pinholes masks and slits both for ID and bending magnet beam-lines. The pinholes will have to be changed, while the stoppers and shutters should remain similar. The only change that could occur will be the absorber angle and cooling system.

The design of the outlet chamber of the synchrotron radiation need special attention: the shape of the chamber and the cooling system must be capable of absorbing the power density generated by the photons emitted from the bending magnet.

All utilities of the front-ends such as water cooling, compressed air, etc. should be regulated and controlled from the service or experimental area, thus minimising the accelerator downtime time necessary to restore those systems.

**12. MAGNET POWER SUPPLIES**

Magnets and their associated power supplies are not separated systems: the design of one part has a direct, strong influence on the other. One primary goal is to minimize, working in close collaboration with the magnet designer, the number of different types of power supplies for energizing the various typologies of magnets required by the machine optics design. Maintenance and spare parts management will benefit from such optimization. The choice of the power supply typology – custom, commercial ones (COTS – Commercial off the Shelf) or in-house design or a combination of them – will follow this optimization phase.

The interfacing with the Control and Protection (personnel and machine) systems is another critical issue. In the definition and design of the power supplies, a close collaboration with the control team is also mandatory for unifying as much as possible the control hardware (e.g., Ethernet interface with TCP-IP), interlock signals and software.

All magnets will be air-cooled. Also the power supplies will be air-cooled if their power ratings will allow this solution. Air-cooling reduces the complexity of the system (de-ionized water and the associated piping is not needed) and improves the reliability (no risk of water leakages). Realistic estimations of the dissipated power are needed for the correct dimensioning of the HVAC (Heat Ventilation Air Conditioning).

Power supplies have to be energized, both from “normal” mains and from UPS for the control part. Besides the “installed power”, it is planned to carry out accurate estimations of the “contemporary factors”, to define the actual power absorbed from the mains according to the optics, in collaboration with the Electrical Plant designers and machine physicists.

As the power supplies parameters (output current and voltage, ripple and stability) are not yet finalised, a tentative specification has been deployed. The following table summarizes few parameters.
From the most recent magnet data, it is possible to group the different types of magnets in order to reduce the number of different types of power supplies.

<table>
<thead>
<tr>
<th>Type of load</th>
<th>Nominal Current [A]</th>
<th>Stability 24h [ppm/FS]</th>
<th>Ripple [ppm/FS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Sextupole</td>
<td>50/20</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Corrector</td>
<td>20</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Notwithstanding the presence of 10 different types of magnets, the optimization of the system magnet power supplies (PS) has allowed us to reduce the number of PS types to three or four, depending on the energizing strategy of the dipoles. If each dipole in the achromat has its own power supply, one type of PS fits them all. Otherwise, creating three families of 24 dipoles in series each, two PS types are needed. In both cases, anyway, there are one type of PS for the quadrupoles and the “Big” sextupoles and one type of PS for the “Small” Sextupoles and the correctors. The following table summarizes the two cases.

<table>
<thead>
<tr>
<th>Type of load</th>
<th># of Magnets</th>
<th># of PS Types</th>
<th>Number of PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles</td>
<td>3 x 24</td>
<td>2 / 1*</td>
<td>3 / 72*</td>
</tr>
<tr>
<td>Quadrupoles &amp; “Big” Sextupoles</td>
<td>384</td>
<td>1</td>
<td>384</td>
</tr>
<tr>
<td>“Small” Sextupoles &amp; Correctors</td>
<td>336</td>
<td>1</td>
<td>336</td>
</tr>
</tbody>
</table>

* Depending whether the dipoles are grouped in three families of 24 magnets each or individually energised.

There are pros and cons in the two strategies. Grouping the dipoles in three families reduce the total number of power supplies by ~9% (723 instead of 792), but requires more powerful power supplies that are unique compared to the others. Having the dipole individually energized, as already normally done for the quadrupoles and sextupoles, provides additional flexibility in getting the optimal orbit. The increase in number is compensated by a smaller size and a possible standardization with the quadrupole and sextupole type, further reducing the number of PS types. This is also positive in terms of...
spare parts and maintenance. The performance and reliability aspects are the same in both cases, since the failure of any power supply in the Storage Ring would lead to the loss of the electron beam. Grouping the dipoles in families or not, the PS for the dipoles, quadrupoles and “big sextupoles” have to be finalized and designed.

For the “small sextupoles” and the correctors, there is already a “candidate PS”. Supported by the positive results of the bipolar power supplies realized for the Free Electron Laser FERMI, a new, more powerful version is developed, originally thought to replace the corrector power supplies in the actual storage ring. A standard 3U, 19” crate, hosts up to 4 independent units. With a maximum output current of 20 A at 50 V (1 kW Output Power), these bipolar DC/DC converters (named A2720) are naturally air-cooled for currents up to 16 A. [1] The first couple of power supplies is operational in the actual storage ring since March 2015. They were installed inside a cabinet hosting the original corrector power supplies (in use since 1993). The following pictures show a single channel and the two-channel installation inside the cabinet. It is remarkable that the whole 16-unit cabinet could be replaced by 4 crates with 4 channels each.

We plan to use the A2720 also at ESS for the corrector magnets of the Linac Warm Units [2], within the Italian In-Kind Contribution for the construction of the European Neutron Source.

Section references

13. CONTROLS AND SCIENTIFIC DATA MANAGEMENT

13.1 CONTROL AND FEEDBACK SYSTEMS

13.1.1 CONTROL SYSTEM ARCHITECTURE AND TECHNOLOGIES

The control systems will provide all the infrastructures and tools for controlling, managing and monitoring the accelerator and the experimental beam-lines in a unified, safe and coordinated way. It will be a distributed control system, made up of operator consoles, computing servers, storage servers, fronted computers and network-controlled devices. The latter will give access to most of the actual facility equipment; they will be interfaced to the external world by means of an Ethernet link, pursuing the “Internet of Things” model. Network controlled devices range from the simplest digital input/output controller to a whole plant or subsystem, for example an RF transmitter with its own control system provided by the supplier of the plant. Special requirements, such as very high sampling speeds or the integration of dedicated instrumentation, may be fulfilled by means of modular industrial platforms, for example MicroTCA.

All of the computers and the network controlled devices will be interconnected by a high speed Ethernet network, which will be the backbone of the control system. A proper choice of active network devices, their configuration and management will be adopted to guarantee a state of the art network security. Virtual LANs and routing will be used to minimize the interference of separated data traffic fluxes and also enhance network security.

The whole control system and data acquisition software will be based on Open Source technologies: their stability, scalability and economic convenience have already been demonstrated at Elettra. Special emphasis will be given to the standardization of hardware and software. The logical glue for building the control system from the assembly of thousands of different devices will be the TANGO distributed control system software. Extensive use of virtualization techniques will be used for configuring and deploying the control system computing and storage servers.

Feedback and feed-forward systems mitigating the beam distortion will allow the control of wigglers and IDs directly by the experimental stations. The possibility of performing continuous scans with the IDs will be provided according to the needs of the experimental stations, as it is becoming a standard feature of beam-lines in many light sources. Special care and emphasis will be put in the design of the IDs motion components, their interactions with the systems of the experimental stations (e.g., monochromators) and the integration of all these components into the control and data acquisition systems.

The control system will also acquire data from the utility plants (e.g., cooling water, air conditioning, electrical supply, etc.). These data will be available on line (it will be used for example to trigger alarms) and also stored in the historical database along with all the other relevant accelerator parameters.

13.1.2 FEEDBACK SYSTEMS

Feedback systems are essential for operating the light source and achieving the required beam stability; the most critical feedbacks are dedicated to damping multi-bunch instabilities and stabilizing the electron orbit. Transverse and longitudinal bunch-by-bunch feedback systems will be devoted to damping collective effects due to interaction of the beam with the vacuum chamber and other surroundings. They require very high analog bandwidths and fast digital processing, and will be managed by dedicated
hardware systems built in house or purchased as turnkey solutions. Characteristics and performance will be specified based on the new accelerator potential sources of instabilities, such as resistive wall or cavity high order modes. Some components of the current Elettra multi-bunch feedback systems such as amplifiers, kickers, etc., may be reused for Elettra 2.0.

The stabilization of the electron orbit will be handled by a fast orbit feedback system; its goal is to keep the beam position stable to less than one tenth (1/10) of the electron beam size and to reduce the disturbances of the beam orbit up the maximum bandwidths permitted by the fast corrector magnets (tens to hundreds of Hertz). The fast orbit feedback system will be based on a dedicated network infrastructure with fast links, which will allow hard real-time communication between the central processing servers and the peripherals interfacing the equipment involved in the feedback (electron and photon BPMs, magnet power supplies, etc.). The fast network infrastructure and the central processing servers have to guarantee a refresh rate of at least 10 kHz. The corrector magnet power supplies and the BPM detectors will have an interface capable of working at full speed.

The needs of the fast orbit feedback system must be kept in mind during the design of the accelerator lattice. An adequate number of sensors (BPM pick-ups and detectors) and actuators (corrector magnets) have to be placed in the proper positions according to the electron beam optics. They also have to guarantee the control of the source point in the undulators (position and angle) independently of the rest of the electron orbit.

Special control techniques will be evaluated to manage the very different dynamic performances of air and iron cored corrector magnets that will both be used as actuators in the orbit feedback system.

The possibility of installing photon BPMs or other photon diagnostics in the beamlines and integrating them in the fast orbit feedback must be taken into account. This will give us the capability of correcting the position of the delivered synchrotron light closer to the point where it is actually used, thus compensating also the relative motion of the beamline with respect to the storage ring.

The dedicated network infrastructure will also be used to integrate additional devices such as quadrupole magnets involved in other feedback/feed-forward loops. Examples are the real-time correction of the betatron tune, compensation of optics distortion induced by insertion devices and beam-based alignment.

13.1.3 EQUIPMENT PROTECTION AND PERSONNEL SAFETY SYSTEMS

Similarly to the existing facility, the personnel and equipment protection systems will be based on PLCs. The automation part (PLCs and peripherals) of the present systems have been renovated with Siemens S7 technology in 2012 and 2013 respectively; for Elettra 2.0 a further significant modification will be necessary possibly reusing part of the existing Siemens devices.

The existing equipment protection system will be significantly modified due to the important differences of Elettra 2.0 as compared to the existing facility, especially in the magnet and vacuum systems. The former will have new sensors such as flux-meters and thermo-switches matching the number of magnets and power supplies. The vacuum system will introduce a new type of ion pump controller that will likely be handled directly by the PLC. The operator interaction with the vacuum system will be done via local touch screens or via software modules for interfacing the PLCs with the control
system. Along with the refurbishing of the beam-lines the system in charge of the protection of beam-line components will also be renovated using the same PLC technologies.

The present personnel safety system is made of fail-safe PLCs and components, according to the IEC61508 international safety standards. Although no significant modification of the tunnel and safety hutches is foreseen, possible changes could be necessary due to different operating conditions and safety procedures to be adopted during run and shutdown periods.

The access control systems of the beam-line hutches, equipped in some cases with obsolete and not fail-safe PLCs, will all be renovated with the exception of the beam-lines recently upgraded. The new systems will have a web-based supervisor in order to allow monitoring from any PC. The present key dispenser will also be redesigned using modern concepts and technologies for better operations and maintenance.

13.2 SCIENTIFIC DATA ACQUISITION, ANALYSIS AND MANAGEMENT

The raw product of Elettra 2.0 will be scientific data from which, by means of different data analysis techniques and the experience of scientists, new knowledge will be derived. All modern synchrotron based light sources and FEL facilities have dedicated teams for data analysis software. The broad task of Data Analysis is multidisciplinary and in practice collaboration between mathematicians, software engineers, beam-line scientists and the user community is necessary. According to a recent survey in Nature [1] 45% of scientists spend more time today developing software than five years ago, 38% spend at least one fifth of the their time doing so but only 34% think that formal training in software development in important. The lack of specialized software engineering know-how and the use of sub-optimal mathematical methods, often result in software that rarely becomes standard and has very high hidden costs including that of rewriting the same software or making low performance systems that waste precious beam time and use costly data storage. This is well reported in established journals [1-5].

For the past half decade the community has been facing the problems of Big Data and Data Deluge [6,7]; where the growth of data is becoming bigger than our abilities in managing them. In order to manage this problem successfully and avoid the mistakes of the past, most facilities, including NSLS-II, ESRF, DLS, and AS, have included in their upgrade programs, strategies for creating dedicated teams for Data Analysis. In the case of the Elettra2.0 the improved light source will be coupled with upgraded systems as described in other sections of this document but the final result will be more data due to advances in detectors which will require more efficient analysis and more challenging archiving requirements.

13.2.1 EXPERIMENT CONTROL, AUTOMATION

The actual acquisition of data is a process of paramount importance. The beam-lines are complex instruments of interconnected components such as motors, pumps, and detectors. The experimental end-station acquisition software is an advanced system capable of controlling all these components while at the same time providing the user with an interface [8, 9].
End-station control systems will be implemented leveraging the recent experience of FERMI. The following estimates thus take into account our experience acquired by working on the FERMI beamlines and projected for Elettra 2.0 future beamlines. Currently Elettra beamlines are equipped with a working but obsolete control system named BCS. This control system has to be substituted by a modern control system based on TANGO. The same is valid for the data acquisition system of the end-station. Currently many Elettra beamline end-stations use a data acquisition system based on LabVIEW and the above-mentioned sub-optimal solutions. These data acquisition systems have to be substituted by a state of the art data acquisition system based on TANGO and prepared to allow the whole scientific data work-flow including fast on-line and off-line data analysis. The systems should be designed to permit the maximum level of automation and remote operations. This will imply costs for hardware upgrade and specialized manpower for software development. All the developments will incur a regular maintenance cost starting from the very first day after the development is complete and the beam-line is in operation.

The substitution and renewal of the obsolete beamlines control and data acquisition system can be carried out independently for each single beamline; it can be started before the construction of the new Elettra 2.0 control system and, if necessary, can continue after the commissioning of Elettra 2.0. An important constraint of these activities will be the availability of adequate manpower. The detailed design of the beam-lines control system will be tailored to the specific needs and configuration of each different beamline.

13.2.2 DATA ACQUISITION, PROCESSING AND MANAGEMENT SYSTEMS

Scientific computing for data analysis requires data processing and management. Tasks like data cataloging and storage require computer hardware that has to be maintained up to date. The above-mentioned data deluge problems results in major challenges, as we must take into serious consideration the Moore's law followed by the vast majority of components involved (but not all of them). A really crucial element is also that of specialized personnel called data scientists. For a successful activity, a multidisciplinary pool of knowledge at various levels (from students to experts) is required. Data analysis due to its research nature requires specialization; thus the personnel should be divided per technique (e.g., imaging). The requirements in term of personnel and purchases have been already taken into account in the previous paragraph.

13.2.3 REMOTE OPERATIONS AND E-INFRASTRUCTURE

Elettra has always been open to integration with available e-Infrastructures. Transferring data from Elettra to the National Storage Center located at CINECA or other external data center is under investigation. The challenges represented by Elettra 2.0 will require an update of the available computing, storage and wide area network infrastructures.

Section references

The dismantling of the existing storage ring and the mounting of the new lattice will have important implications as far as radiation protection is concerned. At present the storage ring is authorized to work with a stored beam of maximum energy 2.5 GeV and maximum power of 1000 Joule. Even if the maximum current (400 mA) and energy (2.0 GeV) foreseen for the new machine are within the authorization limits defined for the existing storage ring, nevertheless a complete revision of all the radiation protection aspects tied to the new project has to be done, especially in relation to the issues analyzed below.

14.1. BEAM LOSSES SCENARIOS

The new layout of the storage ring will necessarily imply a different beam loss distribution mainly due to the adoption of small aperture vacuum chambers (Ø 23 mm), but also to the re-positioning of components such as scrapers, stoppers, fluorescent screens, etc. utilized to intercept the electron beam for diagnostic purposes.

An in-depth analysis will be carried out with the machine physicists to understand the implications of the new ring lattice in terms of beam losses distribution both in “normal operation” and in correspondence to orbit mismatches. One of the points that has to be verified, taking into account the new ring lattice, is the possibility to extract a part of the electron beam through a beam-line photon port due to a magnetic device failure or mismatch during top-up operations.

The conclusions will be utilized to study, both through semi-empirical formulas and Monte-Carlo simulations, the radiation fields produced in the most critical scenarios both inside and outside the ring tunnel.

On the basis of these results, it will be evaluated the necessity of adding local shielding in the areas most affected by beam losses, or installing collimators or additional shielding in correspondence to the beam-line photon ports, to minimize the yield of radiation that can be transmitted towards the Experimental Hall. The possibility of installing permanent magnets at the beamline exits to prevent electron beam channelling outside the shielding will also be evaluated.
14.1.2 BEAM LOSS MONITORING (BLM) SYSTEMS IN THE RING TUNNEL.

The Elettra storage ring is equipped with two beam loss monitoring (BLM) systems, one based on Bergoz detectors (for electron losses) and the other on photodiode detectors (for bremsstrahlung radiation losses). They have already proved to be extremely useful in case of vacuum leakage, for regulating machine operation parameters during trajectory and transport optimization, and for a quick localization of the areas affected by beam losses. Therefore a study will be performed on how to integrate the actual BLM systems in the future Elettra 2.0 layout, taking into account the space constrains.

14.2. RING SHIELDING

At present the storage ring shielding consists of a 50 cm thick concrete wall on the internal side, and of 110 cm thick ordinary and 75 cm baritic concrete blocks on the external side. These blocks are dovetailing movable units that can be repositioned around the ring according to the needs. Taking into account the new ring layout and the consequent reorganization of the optics elements in the beam-line front-ends, which in some cases will produce a lengthening of the front-end itself, the necessity of re-designing part of the ring external shielding may occur.

A similar study will be carried out for the ring roof, which consists of movable ordinary concrete slabs. The compatibility of the actual slabs length with the ring lateral shielding structure will be checked and the need of constructing new slabs will be evaluated.

14.3. BEAMLINES SHIELDING

From the radiation protection point of view, the Experimental Hall of the actual Elettra is a “non-classified” area, which means that the level of radiation is within the limits foreseen by law for the public.

The beam-lines can be divided into two groups:
- low energy beamlines, working with synchrotron radiation in the range from infrared to soft X-rays, where only the initial part of the beam-line, hosting the first optical component, is enclosed in a shielding hutch
- high energy beam-lines, working with X-rays, where the entire beam-line is enclosed in one or more shielding hutches.

In general the actual beam-line shielding walls contain 2 mm of lead, and the hutches do not require a roof. The only exception is represented by the XRD2 beam-line that works with the synchrotron radiation produced by a super-conducting 3.5 T wiggler: in this case the first part of the beamline, upstream of the monochromator, is shielded with 5 and 6 mm lead walls, and is equipped with a 5 mm lead roof. The second part of the beamline (where the beam is monochromatic and confined within the stainless steel vacuum chamber) is shielded with 2 mm of lead and has no roof. The third part of the beam-line, where the beam is transported in air up to the sample, is shielded with 2 mm of lead and is equipped with a roof.

Also for Elettra 2.0, it is intened to maintain the characterisation of the Experimental Hall as “non-classified” area. The design of the beamline shielding structure will be re-evaluated taking into account the different beam loss distribution scenarios already described in point 14.1, together with the issues described in the following paragraphs.
14.3.1 RADIATION PROTECTION ISSUES TIED TO GAS BREMSSTRAHLUNG RADIATION

As far as the radiation protection is concerned, an important goal for the new machine will be the capability of reaching the same vacuum level in the storage ring chamber as the one of the present machine. The vacuum level, in fact, is strictly correlated to the intensity of the gas bremsstrahlung radiation produced inside the ring tunnel and partly channelled towards the beam-lines.

Radiation protection studies will be performed, both through semi-empirical formulas and Monte-Carlo simulations, to study different scenarios for bremsstrahlung production and transmission towards the Experimental Hall as a function of vacuum level.

The need to extend the front-end hutch to include also the second optic component will be evaluated in particular for the insertion device beam-lines, as they are aligned with the machine straight sections.

14.3.2 RADIATION PROTECTION ISSUES TIED TO SYNCHROTRON RADIATION

Elettra beamlines will be re-organized and upgraded in order to exploit at best the advantages offered by the adoption of the new machine layout. A study of these aspects has already started and is still in progress. A preliminary analysis seems to suggest the following possibilities:

- As far as the dipole beamlines are concerned, working with the higher energy component of the synchrotron radiation spectrum a part of them will probably utilize a 3.5 T superbend magnet installed in Elettra 2.0 storage ring or insertion devices (e.g., 2T wigglers) located in the short straight sections of the arcs.

- As far as the insertion devices beamlines are concerned, a part of them may probably maintains their actual insertion device with no substantial modifications.

- Another part of the insertion devices beamlines could decide to substitute their present in-line undulator and/or change configuration with a dual-canted undulator layout. The advantage of this configuration will be the possibility of simultaneous operation of two beam-lines fed by the same straight section, which will potentially double the time scheduled for the user research.

In all these cases the hutch shielding design will be revised taking into account both the possibility of re-using the actual shielding structure, or the need to completely substitute the present shielding walls with a structure containing a higher thickness of lead and equipped with a roof.

14.4. PERSONNEL SAFETY SYSTEMS (PSSs)

14.4.1 RING PSS.

Some machine components connected to the Personnel Safety System (PSS), such as the RF cavities, will be substituted with new models; therefore a revision of the safety signals exchanged with the PSS has to be provided. Also new modality of operation for the RF cavities will be evaluated. All the changes foreseen for the machine PSS will be dis-
cussed in advance with our National Regulators in view of the final authorization. A detailed description of the PSS will be inserted in the authorization documentation.

14.4.2 BEAMLINES PSS.
The beam-line Personnel Safety System will be upgraded, taking into account the obsolescence and aging of some components. At present different types of PLCs are in use for the accelerator and for the beam-lines PSSs. The idea of substituting the older ones and homogenizing the models will be taken into consideration.

14.5. ENVIRONMENTAL RADIATION MONITORING SYSTEM OUTSIDE THE RING SHIELDING
The actual environmental radiation monitoring system is based on pressurized ionization chambers for gamma radiation and BF$_3$ proportional counters for neutrons. The system will be upgraded, taking into account the obsolescence and aging of some components.

14.6. RING DECOMMISSIONING
Evaluation of expected induced radioactivity for the actual machine components will be an important task before the machine dismantling. At the beginning and during the whole shutdown period foreseen for the decommissioning, radiation protection measurements will be performed to characterize, in terms of induced radioactivity, all the dismantled machine components. This characterization will be necessary to evaluate the radiological risk for the personnel involved in the dismantling operations and to permit the transport to different locations of some parts of the machine, for warehousing or disposal.

14.7. AUTHORIZATION PROCESS
The relevant changes foreseen in the storage ring layout will require a complete revision of all the aspects related to radiation protection, and have implication both in the personnel safety systems and in the beam-lines/ring radiation shielding design. A technical documentation with the description of the new machine and a discussion of all the related radiation protection issues, including decommissioning aspects, will be prepared and presented to the National Regulators.

14.8. PSSs AND SHIELDING ACCEPTANCE TESTS
Once the mounting of the new storage ring is completed, a period for carrying out the acceptance tests both for the ring and for the beam-lines Personnel Safety Systems must be foreseen. At the end of the acceptance tests, the commissioning of the new storage ring with the electron beam will start and radiation protection surveys will be performed, both in the ring Service Area and in the Experimental Hall, to evaluate the impact of the new lattice on the machine and on the beam-lines shielding. The need for adding further local shielding will be evaluated on the basis of the measurements results.
15. TIMING AND SYNCHRONIZATION

15.1 CHOICE OF THE HARMONIC NUMBER

One of the requests for the new machine is to use the existing injectors. Thus the 100 MeV linac and the 2.5 GeV booster will be used to fill the storage ring. However, modification of the booster length and/or the booster to storage ring transfer line may be needed depending on the final length of the new storage ring so that the two machines can be synchronized.

The timing and synchronization system will provide trigger signals to synchronize the whole machine. It will provide trigger signals for the diagnostic systems and for the injection system whose goal is to inject the beam coming from the booster injector in the correct position of the storage ring. To satisfy this requirement we must take into account the effect of the physical and electrical length of the storage ring and the booster injector. Knowing the harmonic number of the present storage ring (432) and the value of the accelerating frequency (499.654 MHz) the orbit length for relativistic electrons is given by:

\[ C = h \times \frac{c}{F_{\text{rf}}} = 432 \times \frac{299792458}{499654000} = 259.2 \text{ m} \]

where \( c \) is the speed of light, \( h \) the harmonic number and \( F_{\text{rf}} \) the RF frequency.

The present length of the booster using the same RF frequency value is:

\[ C = 198 \times \frac{299792458}{499654000} = 118.8 \text{ m} \]

Since the maximum common divider of the two harmonic numbers is 18 the two machines to be in phase after \( 198/18 = 11 \) beam revolutions in the storage ring or \( 432/18 = 24 \) in the booster, i.e., every 15.5 \( \mu \text{s} \) being the coincidence period.

It is possible to change the length of the storage ring in steps of 1 bucket or in other words in steps of 0.6 m, but a variation in the storage ring length obviously affects the coincidence period. If the length increases by 60 cm (i.e., 1 bucket), the new harmonic number will be 433 (if keeping the same RF frequency) and being a prime number the two rings will be again in phase after 198 turns in the storage ring or 433 in the booster or 198*0.866 = 171.6 \( \mu \text{s} \) and may also have implications with the energy acceptance of the ring during injection.

At present supposing that the booster ramp is linear with a rise time of 0.2s from 100 MeV to 2 GeV, the energy step corresponding to 15.5 \( \mu \text{s} \) is about 0.150 MeV. If the coincidence period changes to 171.5 \( \mu \text{s} \) the energy step becomes about 1.6 MeV, i.e., injection with an energy error \( \Delta E/E = 8 \times 10^{-4} \) or 0.08\%, which may be still accepted. Please note that the above analysis applies only in case that one aims to fill the same bucket (like in single bunch and hybrid) and not for the multi-bunch fill case.

The following figure shows the beam energy during ramp in the Booster related to coincidence clock CRC for 432 and 433 buckets.
Now going to $h=434$, i.e., 260.4 m the storage ring length, the maximum common divider is 2 and therefore coincidence will occur every 99 turns in the storage ring and 217 turns in the booster. In this case the energy error is 0.04%. Going to $h=435$ the maximum common divider is 3 therefore coincidence occurs for 66 turns in the storage ring and 145 turns in the booster and the energy error is even less. Keeping the harmonic number of the booster at 198 the following table shows the maximum common dividers of the two harmonic numbers.

<table>
<thead>
<tr>
<th>Harmonic number storage ring</th>
<th>Max. common divider</th>
</tr>
</thead>
<tbody>
<tr>
<td>432</td>
<td>18</td>
</tr>
<tr>
<td>433</td>
<td>-</td>
</tr>
<tr>
<td>434</td>
<td>2</td>
</tr>
<tr>
<td>435</td>
<td>3</td>
</tr>
<tr>
<td>436</td>
<td>2</td>
</tr>
<tr>
<td>437</td>
<td>-</td>
</tr>
<tr>
<td>438</td>
<td>6</td>
</tr>
</tbody>
</table>

It is evident from the above analysis that small changes of the harmonic number, i.e., small changes in the storage ring circumference, are well tolerated especially for harmonic numbers 434, 435, 436 and 438. However at present it is preferred to let the circumference length of Electra 2.0 almost equal of that of the actual Elettra, i.e., 259.2 m with a margin of 26 mm or about 50 kHz. This means that one might change the RF frequency by at most 50 kHz, but let the harmonic number at 432. Changing the harmonic number might also imply to recreate all ramping curves of the booster, a cumbersome task.

15.2 TIMING AND SYNCHRONIZATION

The timing system must provide the following functionalities:
- Generate triggers for 100MeV linac pre-injector and gun system
- Generate triggers for Booster injection elements, kicker and septum
- Generate triggers for power supply to synchronize energy ramping in Booster
- Generate triggers for Booster extraction element, kickers and septum
- Generate triggers for Elettra injection elements, kicker and septum
- Generate triggers for diagnostic equipment and beam lines
- Give a supervision of all top-up process

The timing system is composed of three stations:
- Main station located in pre-injector area; this is the most important station and from there all main trigger is generated.
- Second station, located in booster, generates all signal triggers for ramping, injection, extraction purposes.
- Last station, located in Elettra, provides all signals for injection in storage ring, diagnostic, BPM, beam lines and TOP-UP current control.
- Other slave station can be placed everywhere in Elettra just for buffering trigger signals.

Class of signal
The timing system works on hierarchical cascade class of signal:
- First level signals is used for main synchronizations events
- Second level signals is derived from first level signal and used to drive physical element
- Third or more level can be used in cascade to obtain local delay between similar elements

Also every trigger can have different physically electrical interface:
- Fast speed optical or differential electrical output >1GB bandwidth, jitter lower than 50 ps
- Medium speed optical or electrical output 100 MHz bandwidth, jitter lower than 500ps
- Slow speed optical or electrical output 20 MHz bandwidth, jitter lower than 4 ns

Principle of work:
On the main station in pre-injector area, a 320 ms signal is generated from the 50 Hz main power supply frequency divider by 16. This is the repetition period between 2 consecutive injection and operative Booster period. This signal is called Injection request IRP.

The 499.654 MHz main RF oscillator in Elettra generates the following signals: Storage Ring Revolution clock called SRC, Booster revolution clock period called BRC, and coincidence between the two’s rings.

Assuming that the RF of Elettra is 499.654 MHz, the harmonic number is n=432 with a storage ring length is 259.2 m. Changing in main RF frequency produces a variation of the storage ring length as calculated by the formula L=1/RF*n*c. Instead, a variation of the harmonic number changes the ring length as well as the coincidence period between the two’s rings. Assuming the harmonic number n=432 for Elettra and n=198 for the booster, the coincidence period is 15.5 us.
Synchronization of IRC signal with coincidence clock CRC generates all first level class signal.

Timing Main station generates all triggers of first level class to be transmitted to the other stations:
- CRC coincidence clock between storage ring and booster
- SRC revolution period of Elettra
- BRC revolution clock of Booster
- GT Gun trigger from preinjector GUN
- SI start injection in Booster
- SE start extraction from Booster

Pros and cons of this design in order to inject in a selected bucket are:
- Cons: need to wait for the coincidence period to start the Booster injection and extraction cycle.
- Pros: has to move only one delay related to coincidence clock to move synchronously all injection and extraction delay (hierarchical class of the delay).

This timing system architecture permits to fill up the machine in any filling mode (single, multi, hybrid etc.). The high level software running on the main station also controls the top-up mode.
16. INJECTION

16.1 CURRENT SCHEME AND PARAMETERS

Currently the injection into the storage ring of Elettra takes place in a single straight section where the pulsed magnets dedicated for the task were installed. The beam comes from the Booster-to-Storage ring (BTS) transfer line with a horizontal angle of 8.6 deg which is compensated by two Septum magnets. The required closed orbit bump of 18 mm is generated by four kicker magnets acting on the beam in pairs. Both types of magnets are pulsed by capacitor discharging power circuits; the capacitors are chosen in order to produce the required pulse durations: 50 µs for the Septa and 5 µs for the kickers.

Four kicker magnets are paired and placed symmetrically with respect to the center of the straight section. The separation between the magnets within each pair is 1141 mm; this parameter is directly related to the closed orbit bump amplitude required for the injection process. Two Septum magnets produce a total deflection of 8.6 deg and place the beam to be injected on a trajectory parallel to the storage ring axis, with an offset of 29 mm to the right (looking in the direction of the stored beam). The core length of the magnets and their peak magnetic field have been optimized in order to keep the maximum operating parameters of the power circuits within safety limits. The following scheme shows the position of the electron beams at the exit point of Septum 2.

Considering a beam energy of 2.0 GeV, the working parameters of the injection magnets, as well as of the power circuits, are reported in the following tables.
### Kicker magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Hor. and ver. aperture</td>
<td>90 x 48 mm</td>
</tr>
<tr>
<td>Distance between core centers</td>
<td>1141 mm</td>
</tr>
<tr>
<td>Nominal bump (hor.)</td>
<td>18 mm</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>0.175 T</td>
</tr>
<tr>
<td>Peak current</td>
<td>6.7 kA</td>
</tr>
<tr>
<td>Current pulse duration</td>
<td>5 µs</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>13 kV</td>
</tr>
</tbody>
</table>

### Septum Magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>720 mm</td>
</tr>
<tr>
<td>Hor. and ver. aperture</td>
<td>30 x 15 mm</td>
</tr>
<tr>
<td>Total deflection</td>
<td>8.6 deg</td>
</tr>
<tr>
<td>Peak magnetic field (S1 – S2)¹</td>
<td>0.70 – 0.68 T</td>
</tr>
<tr>
<td>Peak current (S1 – S2)</td>
<td>8.4 – 8.2 kA</td>
</tr>
<tr>
<td>Current pulse duration</td>
<td>50 µs</td>
</tr>
<tr>
<td>Charging voltage (S1 – S2)</td>
<td>1.29 – 1.25 kV</td>
</tr>
</tbody>
</table>

16.2 PROPOSED LAYOUT FOR ELETTRA 2.0

The following proposal assumes that the same multi-turn injection process performed in Elettra will be reproduced in Elettra 2.0, adopting the same magnet configuration and taking into account the new parameters dictated by the beam dynamics.

16.2.1 GEOMETRY AT THE SEPTUM 2 EXIT POINT

The beam optics requirements call for a reduced bump produced by the kickers; given the data reported in sec. 3.4 and 3.6, the proposed close bump is 8 mm. The positions of the Septum sheet, as well as of the bumped and injected beams, are then shown in the following picture.

---

¹ S1 is the first magnet seen by the electron beam coming from the BTS transfer line and S2 follows.
The BTS-TL axis (the injected beam axis) is now offset by 13 mm from the SR axis (in Elettra the offset is 29 mm).

16.2.2 KICKERS GEOMETRY AND MAIN PARAMETERS

The performances of the kicker magnets will thus be relaxed thanks also to the reduced dimensions of the new vacuum chamber which, for the moment, is assumed to be a ceramic tube with an external diameter of 36 mm and an internal one of 30 mm (it is still to be verified the possibility to realize an internal coating of titanium as in the present ceramic chambers). The kicker geometry scheme could remain the same as in the actual Elettra, but for the calculations an optimized kicker gap of 46 x 42 mm (hor. and ver. respectively) has been assumed, leaving the length of the magnet at 600 mm and the distances between the magnet centers of the two pairs at 1141 mm. Thus the operating parameters are shown in the following table.

<table>
<thead>
<tr>
<th>Kicker magnets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Hor. and ver. aperture</td>
<td>46 x 42 mm</td>
</tr>
<tr>
<td>Distance between core centers</td>
<td>1141 mm</td>
</tr>
<tr>
<td>Nominal bump (hor.)</td>
<td>8 mm</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>0.078 T</td>
</tr>
<tr>
<td>Peak current</td>
<td>2.6 kA</td>
</tr>
<tr>
<td>Current pulse duration</td>
<td>5 µs</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>4.5 kV</td>
</tr>
</tbody>
</table>

Still there exists the possibility to explore additional optimization of the dimensions and positions of the kickers. To give an example of a simple parametric study, the following picture show the variation of the magnetic field and of the main circuit parameters as function of the core length and of the core separation in each kicker pair. In particular
the cores separation in each kicker pair has been set up in such a way to maximize the magnets separation, which is the best choice in order to keep the magnetic field and consequently the circuit operating parameters at minimum levels.

<table>
<thead>
<tr>
<th>Kicker length [mm]</th>
<th>core dist. [cm]</th>
<th>B [mT]</th>
<th>I_{peak} [kA]</th>
<th>V [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>54.1</td>
<td>78</td>
<td>2.6</td>
<td>4.55</td>
</tr>
<tr>
<td>550</td>
<td>64.1</td>
<td>81</td>
<td>2.7</td>
<td>4.66</td>
</tr>
<tr>
<td>500</td>
<td>74.1</td>
<td>86</td>
<td>2.87</td>
<td>4.82</td>
</tr>
<tr>
<td>450</td>
<td>84.1</td>
<td>92</td>
<td>3.07</td>
<td>5.04</td>
</tr>
<tr>
<td>400</td>
<td>94.1</td>
<td>99</td>
<td>3.3</td>
<td>5.35</td>
</tr>
<tr>
<td>350</td>
<td>104.1</td>
<td>110</td>
<td>3.66</td>
<td>5.76</td>
</tr>
<tr>
<td>300</td>
<td>114.1</td>
<td>123</td>
<td>4.13</td>
<td>6.33</td>
</tr>
</tbody>
</table>
As a final consideration, changing the magnet geometry will result in a new design of the ceramic vacuum chamber (as well as all the relevant mechanics) installed in each magnet gap. The following picture shows a possible cross section scheme for the kicker magnet and the relevant vacuum chamber.

16.2.3 SEPTA GEOMETRY AND OPERATING PARAMETERS

The geometry of septum magnets must be revised. Given the direction of the beam to be injected and the coordinates of the entry and exit points in the septa magnets, as provided for in the Elettra 2.0 overview, it is not possible to find an arch of circumference able to connect the two points and being tangent to the entry and exit directions. This is true even in the present geometry of Elettra and because of this the septum magnets are operating slightly unbalanced; actually the first magnet must deflect the beam more than the second one. The smaller kicker bump (dictated by the beam dynamics) will call for a closer position of the second septum (see previous picture) toward the storage ring axis, thus increasing the transverse separation between the septa entry and exit points. Keeping the present magnets and merely adjusting their positions would result in a strong unbalance between the two magnets which would operate with parameters summarized by the following table.

<table>
<thead>
<tr>
<th>Septum Magnets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>720 mm</td>
</tr>
<tr>
<td>Hor and ver aperture</td>
<td>30 x 15 mm</td>
</tr>
<tr>
<td>Total deflection</td>
<td>8.6 deg</td>
</tr>
<tr>
<td>Peak magnetic field (S1 – S2) (^2)</td>
<td>0.88 – 0.50 T</td>
</tr>
<tr>
<td>Peak current (S1 – S2)</td>
<td>10.6 – 6.0 kA</td>
</tr>
<tr>
<td>Current pulse duration</td>
<td>50 μs</td>
</tr>
<tr>
<td>Charging voltage (S1 – S2)</td>
<td>1.6 – 0.9 kV</td>
</tr>
</tbody>
</table>

\(^2\) S1 is the first magnet seen by the electron beam coming from the BTS transfer line and S2 follows.
If the second septum worked well within safety limits (6 kA and 0.9 kV are easily achievable even by the technologies adopted in Elettra), the first septum would operate with stressing parameters, an unwanted condition especially having, as top priority, the reliability of the system during long term operations in top-up.

A different geometry has been investigated to solve the problem. Given the coordinates of the new exit point, a new entry point is chosen in such a way that

- there exists an arc of circumference connecting the two
- this arc is tangent to both the directions of the BTS transfer line and the Storage Ring axis.

Thus a possible configuration with the relevant operating parameters is reported in the following table.

<table>
<thead>
<tr>
<th>Septum Magnets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>620</td>
</tr>
<tr>
<td>Hor and ver aperture</td>
<td>30 x 15</td>
</tr>
<tr>
<td>Total deflection</td>
<td>8.6</td>
</tr>
<tr>
<td>Peak magnetic field (S1 – S2)</td>
<td>0.8 – 0.8 T</td>
</tr>
<tr>
<td>Peak current (S1 – S2)</td>
<td>9.6 – 9.6</td>
</tr>
<tr>
<td>Current pulse duration</td>
<td>50</td>
</tr>
<tr>
<td>Charging voltage (S1 – S2)</td>
<td>1.4 – 1.4 kV</td>
</tr>
</tbody>
</table>

New, shorter magnets must be realized as well as the relevant vacuum chamber. Also in this case there is space for additional improvements and optimizations. The following picture shows in magenta the present axis geometry and in green the optimized geometry according to the new exit point position. In both cases the input and exit points are highlighted with circles.

16.3 ALTERNATIVE INJECTION SCHEMES

The conventional injection schemes, like the one described above, may not be suitable if the accelerator beam dynamics impose severe constraints on the hardware, due to the high performances required by the electron beam parameters, which ultimately are reflected in the quality of the emitted light. In such cases, the most challenging feature to deal with is the dimension of the beam as well as the aperture of the storage ring and all the relevant and connected hardware dimensions, namely the vacuum chamber diameters, etc.
Alternative injection schemes could be explored in order to optimize the available space dedicated for the injection task as well as the relevant hardware. Among the possible schemes, there is an interesting one reported in [1]. The process is based on the action of a Septum magnet and a single pulsed multipole (a quadrupole, sextupole or even an octupole can be used). The Septum magnet provides the majority of the deflection, as in the conventional case, leaving the last fraction to a multipole magnet instead of four kickers.

The pulsed magnetic field of the multipole is zero along the storage ring axis but increases, according to the multipole order, off axis. An off axis beam will thus experience a dipole component which will bend the beam and finally will put it in the direction of the storage ring axis, ideally with a small offset.

This type of pulsed multipole must be carefully designed (pulsed operations always require high voltages and peak currents) and optimized adopting particle tracking techniques in order to meet the present constraints (injection angle, entry and exit point coordinates, etc.).

In the following the basic behaviors of a typical sextupole and an octupole are briefly compared.

<table>
<thead>
<tr>
<th>Common parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore diameter</td>
<td>30 mm</td>
</tr>
<tr>
<td>Max. current</td>
<td>5 kA</td>
</tr>
<tr>
<td>Core length</td>
<td>500 mm</td>
</tr>
</tbody>
</table>

Figures 16.3.1 and 16.3.2 show the simulated field of a realistic sextupole and octupole core, respectively.
In Figure 16.3.3 and 16.3.4 the graph of the vertical components of the magnetic field generated by the two multipoles are compared.
The following table shows other useful working parameters: the magnetic field at a given radius (8 mm has been chosen since this is the position of the Septum shield proposed above, in a conventional injection scheme) gives an indication of the deflection capability of each magnet; the inductance is a useful figure of merit to briefly estimate the working parameter of the relative power circuit.

<table>
<thead>
<tr>
<th></th>
<th>Sextupole</th>
<th>Octupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical field at 8 mm</td>
<td>0.122 T</td>
<td>0.061 T</td>
</tr>
<tr>
<td>Magnet inductance</td>
<td>5.6 µH</td>
<td>6.56 µH</td>
</tr>
</tbody>
</table>
As expected, at any given radius within the bore radius, the field of the octupole is lower than that of the sextupole\(^3\) (in this particular case the octupole field is nearly half of that of the sextupole when the offset is 8 mm) and this highlights the importance of optimizing the magnet performances by means of particle tracking methods, in order to achieve the required deflection.

In both cases the magnet inductance is rather high needing to drive the magnet with a current pulse; the upper limit of the charging voltage of the power circuit and the pulse duration will fix the maximum performance of the pulsed multipole.

The following table summarizes a typical set of working parameters for both types of pulsed multipoles.

<table>
<thead>
<tr>
<th></th>
<th>Sextupole</th>
<th>Octupole</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>5000</td>
<td>5000</td>
<td>A</td>
</tr>
<tr>
<td>Core legth</td>
<td>50</td>
<td>50</td>
<td>cm</td>
</tr>
<tr>
<td>Calculated stored energy(^4)</td>
<td>1.4</td>
<td>1.64</td>
<td>J/cm</td>
</tr>
<tr>
<td>Inductance</td>
<td>5.60E-06</td>
<td>6.56E-06</td>
<td>H</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2.00E+09</td>
<td>2.00E+09</td>
<td>eV</td>
</tr>
<tr>
<td>Estimated deflection(^5)</td>
<td>13</td>
<td>10</td>
<td>mrad</td>
</tr>
<tr>
<td>Pulse duration(^12)</td>
<td>5.00E-06</td>
<td>5.00E-06</td>
<td>s</td>
</tr>
<tr>
<td>Capacitor</td>
<td>4.52E-07</td>
<td>3.86E-07</td>
<td>F</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>1.76E+04</td>
<td>2.06E+04</td>
<td>V</td>
</tr>
</tbody>
</table>

Section references


17. ALIGNMENT

To build a new state-of-the-art synchrotron light source the magnet components have to be aligned as precisely as possible for both high absolute accuracy and extreme relative accuracy. In particular, we have to control the transverse and vertical position of 192

---

\(^3\) Sextupole fields scale as \(x^2\), whilst octupole fields scale as \(x^3\).

\(^4\) The POISSON code solves static magnetic fields in 2D thus the stored energy of the field is referred to the unit length used by POISSON i.e. cm.

\(^5\) This result is not obtained by means of particle tracking, but by evaluating the transverse average field and assuming that value as a constant field. A better and more reliable result is obtained with particle tracking techniques.

\(^12\) The same pulse duration of the kickers presently working in Elettra has been assumed. Relaxing this parameter will result in a lower charging voltage which, at the moment, is rather high.
quadrupoles, 240 sextupoles and 48 dipoles within a relative accuracy of 0.03 mm and overall circumference within 0.5 mm. The relative tolerances expressed in total errors for magnet alignment are given in the following table:

<table>
<thead>
<tr>
<th>Object</th>
<th>δX</th>
<th>δZ</th>
<th>δY</th>
<th>θs</th>
<th>θz</th>
<th>θy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Steering</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

In order to specify the survey network of the Elettra 2.0 storage ring, several simulations have been performed by Spatial Analyzer Axyz software. For the accuracy of the instrument we have taken the values from the literature which are:

Absolute Angular Performance:
- accuracy (MPe): +/- 15 µm + 6 µm/m
- repeatability (MPe): +/- 7.5 µm + 3 µm/m

Absolute Distance Performance:
- accuracy (MPe): +/- 10 µm
- reproducibility (MPe): +/- 5 µm

The standard deviation of the budget for the Elettra 2.0 quadrupoles and sextupole is:
- magnetic centre to socket \( \delta_1 = 10 \mu m \)
- socket to girder \( \delta_2 = 20 \mu m \)
- socket to SR network reference \( \delta_2 = 50 \mu m \)

\[ \delta_{tot} = 55 \mu m \]

The standard deviation of the budget for the Elettra 2.0 dipole is:
- Fiducialization socket \( \delta_2 = 10 \mu m \)
- socket to SR network reference \( \delta_2 = 50 \mu m \)

\[ \delta_{tot} = 51 \mu m \]

About 350-450 reference points fixed on the wall are chosen for the storage ring network. They are also used to check the long range deformation.

The full network survey of Elettra 2.0 involve measuring 1900 azimuthal and zenithal directions and 1900 distances using the Absolute Tracker AT401. Spatial Analyzer Axyz software will be used for survey data collection, least square adjustment, on-line coordinate measurements and error analysis. The temperature in the tunnel must be keep stable within +/-0.5° range.
There are three sockets as references on top of each component such as bending, quadrupole and sextupole. The positions of the sockets will be measured during field measurement or mechanical characterization.

Quadrupoles and sextupoles on girder will be installed precisely and aligned in the laboratory (temperature 20° ±0.5) using laser tracker LT 600 and Portable Measurement Arm CAM22, 30 µm tolerance is required. Each dipole and girders are supported on three precision movement jacks.

Pre-alignment and precise alignment
All girders will be fixed at their designed location within ±1 mm, precise alignment will start after reaching temperature stability.

Periodic survey and alignment is carried out to maintain the magnets and other components in their required positions.

18. ENERGY EFFICIENCY

The new source will be designed with the objective of increasing significantly the global energy efficiency in order to reduce electricity consumption. In fact, the cost of electricity currently represents a significant fraction of the Elettra running costs. Electricity costs are expected to increase further in the coming decades and consequently improvements in two main domains have been identified:

1) The RF systems will be tailored to the reduced losses per turn (about 22% reduction to those of present Elettra), with an expected reduction of about one third with respect to the present RF power consumption due also to further developments such as solid state amplifiers.

2) An increase in the efficiency of the production of magnetic fields for the lattice: New designs will produce stronger magnetic fields with less power consumption. Our intent to use permanent magnets where possible will further enhance the energy efficiency. Air cooled magnets are considered that will further save electric energy costs compared to the 1 MW power of the magnet water-cooling system of the present Elettra.

The overall power consumption of the storage ring, excluding the injector, is expected to be about 2/3 of the present value. This will counteract the forecasted increase of energy costs over the 10 to 15 years to come.

19. INFRASTRUCTURE

This new machine will be very demanding from the point of view of temperature stability by about one order of magnitude. Therefore the design of the new (or refurbished) plants must take this into account as well as energy savings that now cannot be overlooked.

Since we have to replace the old machine - but not the beamlines - with a completely new one, some preliminary issues must be addressed:

- extraordinary maintenance of lifting facilities;
- temporary lighting and power plants for Service Area and Storage Ring;
- provisional safety cover for existing beamlines;
- a new opening gate driveway in the external Booster area;
- provisional logistics inside the building;
- contracts for disassembly, handling, disposal;
- construction of indoor and outdoor storage areas.

Concerning the plants, following is an overview of how we are planning to proceed:

19.1 MECHANICAL SYSTEMS

19.1.1 PRIMARY COOLING SYSTEM
The architecture of the system will remain the same with replacement of obsolete equipment with other similar systems of greater energy efficiency (cooling towers, pumps, refrigerators, heat exchangers, etc.).

19.1.2 SECONDARY COOLING CIRCUIT
Since Elettra 2.0 will require much lower thermal loads, the architecture of the system will remain the same. An accurate ordinary and extraordinary maintenance is planned and the replacement of obsolete equipment will be carried out with other similar in greater energy efficiency. New achromat distributors to replace the existing ones will be installed in the Service Area. A new flexible piping system with flow switches, thermostats, valves, etc. will be provided for the Elettra facilities.

19.1.3 AIR CONDITIONING SYSTEM FOR EXPERIMENTAL HALL
Extraordinary maintenance of existing plants will be provided for.

19.1.4 AIR CONDITIONING SYSTEM FOR SERVICE AREA
A detailed study of the temperature stability and distribution will be carried out to meet the specified demanding requirements. The Service Area will be served by 12 air treatment units in closed air circuits installed in the Service Area near the external wall or (if necessary) on the roof. The external fresh air and the smoke extraction will be ensured by appropriate fans.

19.1.5 AIR CONDITIONING SYSTEM FOR STORAGE RING
A detailed study of the temperature stability and distribution will be carried out to meet the specified demanding requirements. The Storage Ring will be served by 8 air treatment units in closed air circuits installed on the roof of the Service Area. A new plenum for inlet air will be realized near the internal shield of the Storage Ring. The external fresh air and the smoke extraction will be ensured by appropriate fans.

19.1.6 COMPRESSED AIR PLANT
Extraordinary maintenance of existing plants will be provided for.
19.2 ELECTRICAL INSTALLATIONS

19.2.1 ELECTRICAL CABINET-BUILDING X
Since the total electrical load will be lower in Elettra 2.0, the architecture of the system will remain the same with maintenance and/or replacement of obsolete equipment with other similar equipment of greater energy efficiency. Extraordinary maintenance of existing plants will be provided for and in particular the replacement of obsolete systems such as switchboards, Metal Clad and Power Center, instrumentation and the power factor correction system. A new Power Center for a no-break system will be installed. The electrical power control system will be upgraded in order to reach greater energy efficiencies.

19.2.2 TECHNOLOGICAL BUILDINGS (R,V,S05)
Extraordinary maintenance of existing plants will be provided for with the replacement of all switchboards of the Motor Control Center. The control system will be implemented to increase the efficiency and redundancy (based on S7 Siemens system).

19.2.3 EXPERIMENTAL HALL
Assuming that the existing layout of beam-lines will remain the same, the following electrical engineering actions will be provided for:
• A partial refurbishment of the plant will be carried out to better reach high electrical efficiency (e.g. Led lighting in Experimental Hall).
• The fire detection system will be implemented in the Experimental Hall.

If the beamlines layout is modified, this will require major changes in the electrical distribution Plant.

19.2.4 SERVICE AREA AND STORAGE RING
A new plant, both lighting and power system, will be provided for these areas. This new layout will assure a good distribution and optimization of the voltage drops and the redundancy.
A new high efficiency lighting plant (e.g. based on LED lighting) will be installed.
A new fire detection system and plant grounding will be installed in these areas.

19.3 CIVIL ENGINEERING

19.3.1 EXPERIMENTAL HALL
Extraordinary maintenance of building roof will be provided for.

19.3.2 SERVICE AREA
A new double floor and a new roof will be realized according with new plants requirements.
Extraordinary maintenance of the area will be provided for.

19.3.3 STORAGE RING
A plenum as a double-walled perforated plate for inlet air will be realized near the internal shield of the Storage Ring. Possible removal and/or adjustment of the supports of the
machine in reinforced concrete. Repaving background. Remake the double floor, according to the new plant requirements. Ordinary maintenance of the area will be provided for.

19.3.4 TECHNOLOGICAL BUILDINGS

Extraordinary maintenance of buildings finishing, as waterproof coats, antacid, concrete basements, etc., after mechanical and electrical works (e.g. cooling towers replacement, new installation of air treatment units, etc.).

20. AUXILIARY SPACES

Additional spaces will be needed in order to measure components, decommission and install Elettra 2.0.

A 600 m$^2$ (20 m x 30 m) needed for vacuum systems (oven etc. clean environment)
A 100 m$^2$ (10 m x 10 m) needed for magnetic measurements
A 100 m$^2$ (10 m x 10 m) needed for mechanical components assembly
A 300 m$^2$ (10 m x 30 m) needed for storing the new components to be installed
A 500 m$^2$ (15 m x 30 m) needed for the decommissioning components. This space need not be of high quality, but the old components should be stored for radiation measurements before they can be sold or disposed of (depending on the radiation measurements outcome).

21. INSERTION DEVICES

21.1 PERFORMANCE OF CURRENT IDs IN ELETTRA 2.0

The present set of insertion devices operating at the present Elettra source includes 6 Elliptical Polarization Undulators (EPU), 12 Linearly Polarized Undulators (LPU), and three wigglers. The technology used for their construction is mostly based on permanent magnets, with the only exception of an electromagnetic elliptical wiggler and of a high field superconducting wiggler. Table 21.1.1 below lists the main parameters of the existing sources.
With the transition to the low emittance lattice of Elettra 2.0, the brilliance of these sources will increase by a factor of between 2 and 20 depending on the wavelength as can be seen in Figure 22.1.1 where the performance of some of the above mentioned insertion devices for the old and the new machine are shown.

<table>
<thead>
<tr>
<th>ID</th>
<th>Pos</th>
<th>Period (mm)</th>
<th>Nper</th>
<th>Length (m)</th>
<th>Bo (T)</th>
<th>Kmax</th>
<th>Min. gap (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U4.6</td>
<td>2</td>
<td>46</td>
<td>98</td>
<td>2 x 2.3</td>
<td>0.92</td>
<td>4.0</td>
<td>13.5</td>
</tr>
<tr>
<td>U12.5</td>
<td>3</td>
<td>125</td>
<td>3 x 12</td>
<td>3 x 1.5</td>
<td>0.51</td>
<td>5.9</td>
<td>32</td>
</tr>
<tr>
<td>U12.5</td>
<td>6</td>
<td>125</td>
<td>3 x 12</td>
<td>3 x 1.5</td>
<td>0.57</td>
<td>6.7</td>
<td>29</td>
</tr>
<tr>
<td>APU7.0</td>
<td>7</td>
<td>70</td>
<td>1.5</td>
<td>32 (fixed)</td>
<td>adjustable phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W14.0</td>
<td>5</td>
<td>140</td>
<td>3 x 19 poles</td>
<td>3 x 1.5</td>
<td>1.50</td>
<td>19.6</td>
<td>22</td>
</tr>
<tr>
<td>EEW</td>
<td>4</td>
<td>212</td>
<td>16</td>
<td>3.3</td>
<td>0.50</td>
<td>0.10</td>
<td>Ky=10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>fixed</td>
</tr>
<tr>
<td>EU6.0</td>
<td>9</td>
<td>60</td>
<td>36</td>
<td>2.2</td>
<td>0.78</td>
<td>0.51</td>
<td>Ky=4.4</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>19</td>
</tr>
<tr>
<td>EU12.5</td>
<td>9</td>
<td>125</td>
<td>17</td>
<td>2.1</td>
<td>0.77</td>
<td>0.60</td>
<td>Ky=9.0</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.6</td>
</tr>
<tr>
<td>EU10.0</td>
<td>1</td>
<td>100</td>
<td>2 x 20</td>
<td>2 x 2.0</td>
<td>1.02</td>
<td>0.78</td>
<td>Ky=9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>EU4.8</td>
<td>8</td>
<td>48</td>
<td>44</td>
<td>2.0</td>
<td>0.58</td>
<td>0.34</td>
<td>Ky=2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>EU7.7</td>
<td>8</td>
<td>77</td>
<td>28</td>
<td>2.1</td>
<td>0.92</td>
<td>0.64</td>
<td>Ky=6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>F8</td>
<td>10</td>
<td>140</td>
<td>2 x 16</td>
<td>2 x 2.2</td>
<td>0.75</td>
<td>0.14</td>
<td>Ky=9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kx=3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>SCW</td>
<td>11</td>
<td>64</td>
<td>49 poles</td>
<td>1.5</td>
<td>3.5</td>
<td>19.6</td>
<td>fixed</td>
</tr>
<tr>
<td>Short</td>
<td>56</td>
<td>17</td>
<td>1.0</td>
<td>0.5</td>
<td>2.63</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Figure 21.1.1: Brilliance of selected insertion devices on Elettra (left) and Elettra 2.0 (right)

21.2 PERFORMANCE OF FUTURE IDs

The next generation of IDs will exploit at best the characteristics of the new machine while taking into account the needs of the experiments. In very general terms, the potential performance of future devices is summarized in figure 21.2.1, showing brilliance, total flux and coherent flux for three representative undulators covering the low, middle and high photon energy ranges. The undulators considered here have a length of 4.5 m (the same length available at present) and the electron beam is assumed to be well matched in the straight sections. It can be seen that the coherent fraction will be very high, more than 50% up to 1 KeV and more than 10% up to 3 KeV.
Figure 21.2.1: Brilliance, total flux and coherent flux for undulators with the following characteristics: U100: period = 100 mm, N_{per} = 45, K_{max} = 9; U50: period = 50 mm, N_{per} = 90, K_{max} = 4.5; U25: period = 25 mm, N_{per} = 180, K_{max} = 2.3

21.3 ADJUSTABLE PHASE UNDULATOR

Until 2016, all Elettra permanent magnet devices have been of the Adjustable Gap Undulator type (AGU), in which the desired emission wavelength is selected by changing the distance between the upper and lower magnetic arrays. In contrast, the Adjustable Phase Undulator (APU) is a fixed-gap device whose field strength is varied by shifting longitudinally the upper array relative to the lower one.
A prototype APU was recently designed and built, whose parameters are listed in Table 21.3.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length (cm)</td>
<td>7.0</td>
</tr>
<tr>
<td>Number of periods</td>
<td>21</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>32</td>
</tr>
<tr>
<td>Magnetic Material</td>
<td>NdFeB</td>
</tr>
<tr>
<td>Maximum field (T)</td>
<td>0.45</td>
</tr>
<tr>
<td>Maximum K</td>
<td>2.95</td>
</tr>
<tr>
<td>Magnet width (mm)</td>
<td>50</td>
</tr>
</tbody>
</table>

The mechanical system (see Figures 21.3.2 and 21.3.3) incorporates a number of original solutions helping assembly and allowing easy access to the magnet gap for the measurements and the tuning of the device.
Figure 21.3.2: Model drawing and picture of a magnetic module

Figure 21.3.3: The APU prototype being characterized on the measurement bench in the Insertion Device Laboratory of Elettra – Sincrotrone Trieste.

The peak field agrees well with model calculations, as can be seen in figure 21.3.4.
Trajectory straightness and phase errors were corrected using iron screws placed on the side of the magnets. Multipole errors were also reduced using small permanent magnets attached at both ends of the undulator, the so called “magic fingers”, see figures 21.3.5, 21.3.6 and 21.3.7 below.

Figure 21.3.5: Tuning screw (left) and holder for Magic Fingers (right).

Figure 21.3.6: Trajectory calculated from the magnetic field measured after magnetic shimming.
Figure 21.3.7: Distribution of the field integrals at maximum field (upper plot) and at zero field (lower plot), measured after application of the magic fingers.

Figure 21.3.8: The APU installed in the storage ring
Commissioning of the new device on Elettra has been extremely fast. No effect on the stored beam lifetime or on the injection rate during top-up was observed. A closed orbit distortion was observed only in the horizontal plane, reaching up to a negligible 3 µm rms. As can be seen in figure 21.3.9, the measured perturbation is well correlated with magnetic field integral predicted for an ideal device.

![Field integrals vs array shift](image1)

**Figure 21.3.9:** Measured closed orbit (lower plot) compared with the on-axis field integrals (upper plot) as a function of the array shift.

Based on this successful installation, future upgrades of the other LPUs may adopt the same solution and be converted from AGUs to APUs, with significant benefits in terms of cost and reliability. Given the importance of these aspects, an R&D program is now starting aiming to develop a compact fixed-gap, adjustable-phase EPU, to be tested again for compatibility with the storage ring operation.

### 22. IMPACT ON THE CURRENT PHOTON SOURCES

This section presents some general considerations on the impact that the new Elettra 2.0 electron beam would have on the existing sources. Some preliminary conclusions and important aspects to be considered for the Elettra 2.0 conceptual design and beamlines upgrade are:

According to the Elettra 2.0 magnetic design and the preliminary optical simulations we can assert that the new photon sources would increase the brilliance (photons/s/mm²/mrad²/0.1%bw), from one up to two orders of magnitude, as in the case of the bending magnets.

Elettra 2.0 will operate at 400 mA, thus the flux in terms of photons/s/0.1%bw, integrated through the in-use front end apertures (slits, pinholes, masks etc.), will increase roughly by a factor 4/3 since Elettra, at 2 GeV, operates at 310 mA. The loss of flux in
the high energy region due to the choice of operating at 2 GeV full time, would be partially compensated by the increase in the machine current.

Undulator beamlines would improve their performance due to the new photon source reduced dimensions and the increased storage ring current. The figure below compares the fluxes through the operative entrance slits for several energies and two different harmonics in the case of Elettra 2.0 2 GeV, Elettra 2 GeV and Elettra 2.4 GeV. The source considered is the LPU shared by the ESCAMicroscopy and the SuperESCA beamlines.

The reduced source dimension will also contribute to increase the resolving power at the exit slits. Accurate calculations will be provided in the Conceptual Design. The lower values of emittance also would give the possibility to adopt optics with higher demagnification factor, thanks to the reduced photon source divergence. These improvements could be limited by the possible achievement of the diffraction limit condition.

As mentioned above, this could be an interesting result for all of the bending magnet beamlines that need to extend the investigation field with reasonable fluxes in higher energy regions. MCX or XAFS beamlines, actually working on a BM from the possible introduction of superbend sources. The superbend sources in a 2 GeV machine normally are superconducting dipoles able to produce a very strong magnetic field and consequently an intense flux of high energy photons. They might introduce optical asymmetries that degrade the emittance, unless they are installed in symmetric positions along the ring. Strong superbends are installed in some third generation light sources (see the three superbends at ALS that support eight beam-lines mostly dedicated to protein crystallography or the 7 T wiggler at BESSY II).

The high magnetic field mini-wiggler could be an alternate solution in terms of energy spectrum and photon flux. However, the lateral oscillation of electrons within the device, when combined with the low emittance, give rise to a double source that is unacceptable for most applications. For SYRMEP an additional problem is the photon source dimension that forces one to move the experimental station further away from the source to recover the necessary spatial coherence conditions. The superbend solution seems there-
fore the most appropriate solution for MCX, XAFS as well as the SYRMEP beamline at Elettra 2.0 (see next section).

The increased brilliance requires enhancing the optical properties of the beam transport in general, so one has to pay attention to the following important aspects in order to degrade the photon beam as little as possible:

i. The optical surface quality of mirrors, gratings and crystals will have to be commensurate with the new characteristics of the different sources.

ii. Smaller focal spots in general and in particular those at the exit slits have to be stable in position; so maximum care will have to be employed to suppress the vibrations of optics and mechanical structures.

iii. Thermal stability of the beamlines and of the environment will be crucial.

23. BEAMLINE SIMULATIONS

The first preliminary evaluation of the expected improvements of the beam parameters at the sample or at the secondary source has been performed for some representative upgraded Elettra 2.0 beamlines. The use of beam defining apertures (pinholes or entrance slits) have been considered as well. In the case of the Nanospectroscopy beamline a more detailed evaluation of the beam transport has been performed to foresee the new focus shape and its dimensions at the sample.

The Elettra beamlines operating at the bending magnets in the range of the Hard X-rays, will necessarily have to change the source type because of the magnetic field of the new bending magnets will be reduced to \( \approx 0.8 \) T. SYRMEP, XAFS, MCX and XRF belong to this category. For these beamlines we propose the use of Compact Wigglers or Superbends with different magnetic fields according to the experimental requests and the machine constrains.

Some surprises can be expected for the wigglers operated with Elettra 2.0. The wiggler sources with long period and high magnetic field present a relevant amplitude of the electrons transversal trajectory that appears not compatible with Elettra 2.0. The Elettra 2.0 small electron-beam emittance permits to resolve the photons source in two separate structures leading to unacceptable effects ones reproduced at the sample. This is the case of the W14 wiggler with a magnetic field of 1.6T, a period of 140 mm and a K of 21 actually operating at the Diffraction Beamline XRD1. Depending on the experimental requests, two possible solutions are use of wiggler sources with smaller value of K or superbends.

In vacuum undulators have also been considered, to meet requests for micro beams at the sample in the range 2.5 - 10 KeV. Possible candidates for such type of sources are XRD, XAFS, SAXS and XRF. A preliminary feasibility study for a \( \mu \)XRD beamline is presented in the following.
# RESULTS FROM THE FIRST PRELIMINARY CALCULATIONS FOR 5 REPRESENTATIVE BEAMLINES

## TWINMIC 400 eV on axis, 1st harmonic (compact undulator)

<table>
<thead>
<tr>
<th>Source dimension FWHM</th>
<th>732 µm x 52 µm</th>
<th>105 µm x 15 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse spatial coherence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_\chi$=1%</td>
<td>$C_\chi$=12.8%</td>
<td></td>
</tr>
<tr>
<td>$C_\chi$=26.7%</td>
<td>$C_\chi$=94.4%</td>
<td></td>
</tr>
</tbody>
</table>

| Brilliance (ph/s/mm$^2$/mrad$^2$/0.1%bw) | 2.7e+17 | 1.5e+19 |
| Spectral photon flux (ph/s/0.1%bw) current working beam aperture (1 mm diameter pinhole at 12.6 m) | 1.9e+14 | 4.0e+14 |

| Secondary source profile (source for the microscope) FWHM simulated current optics, simulated 0.5 µrad rms tangential slope error | 81 µm x 7 µm | 33 µm x 3 µm |

| Spectral flux spatial density on axis (ph/s/0.1%bw/µm$^2$) expected gain: | one order of magnitude |

---

## NANOSPECTROSCOPY 400 eV on axis, 3rd harmonic

<table>
<thead>
<tr>
<th>Source dimension FWHM:</th>
<th>479 µm x 50 µm</th>
<th>132 µm x 28 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse spatial coherence:</td>
<td>$C_\chi$=2.7%</td>
<td>$C_\chi$=20.5%</td>
</tr>
<tr>
<td>$C_\chi$=51%</td>
<td>$C_\chi$=89.9%</td>
<td></td>
</tr>
</tbody>
</table>

| Brilliance:(ph/s/mm$^2$/mrad$^2$/0.1%bw) | 2.2e+18 | 3.7e+19 |
| Spectral photon flux: (ph/s/0.1%bw) current working beam aperture (0.65mm x 0.73 mm at 11.517 m) | 1.9e+14 | 4.8e+14 |
Spot profile at the sample:
Measured spot profiles **Elettra 2 GeV**  Simulated spot, **Elettra 2.0** mirrors with 0.5 μrad rms tangential slope error

7.0 μm x 2.0 μm FWHM

1.6 μm x 2.0 μm FWHM

Spectral flux spatial density on axis (ph/s/0.1%bw/μm²):  **expected gain one order of magnitude**

<table>
<thead>
<tr>
<th><strong>MCX beamline</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Magnet-BM BM</td>
</tr>
<tr>
<td><strong>Source dimension FWHM</strong></td>
</tr>
<tr>
<td>310 μm x 60 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectral flux (ph/s/0.1%BW)</th>
<th>15 keV</th>
<th>30 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>current working beam aperture 2.0 mrad x 0.18 mrad</td>
<td>1.9e+11</td>
<td>1.3e+09</td>
</tr>
<tr>
<td>8.9e+12</td>
<td>1.0e+11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.26e+12</td>
<td>3.50e+11</td>
</tr>
</tbody>
</table>

Spot profile at the sample FWHM - Simulated spot, mirrors with 0.5 μrad rms tangential slope error

330 μm x 140 μm

500 μm x 80 μm

21 μm x 72 μm

<table>
<thead>
<tr>
<th><strong>newSYRMEP – Superbend 3.5T</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Magnet-BM BM</td>
</tr>
<tr>
<td><strong>Source dimension FWHM</strong></td>
</tr>
<tr>
<td>320 μm x 60 μm</td>
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</table>

<table>
<thead>
<tr>
<th>Coherence length at 30 m (sample position) and 30 KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>X = 4 μm</td>
</tr>
<tr>
<td>Z = 25 μm</td>
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</tbody>
</table>
Spectral flux (ph/s/0.1%BW) through 7.0 mrad x 0.18 mrad (current acceptance)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Flux (ph/s/0.1%BW) 8 keV</th>
<th>Flux (ph/s/0.1%BW) 20 keV</th>
<th>Flux (ph/s/0.1%BW) 30 keV</th>
<th>Flux (ph/s/0.1%BW) 40 keV</th>
<th>Flux (ph/s/0.1%BW) 50 keV</th>
<th>Flux (ph/s/0.1%BW) 70KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 keV</td>
<td>1.4e+13</td>
<td>7.0e+11</td>
<td>3.5e+10</td>
<td>1.7e+9</td>
<td>8.7e+7</td>
<td>/</td>
</tr>
<tr>
<td>20 keV</td>
<td>7.0e+11</td>
<td>2.2e+13</td>
<td>1.0e+13</td>
<td>4.4e+12</td>
<td>2.0e+12</td>
<td>2.5e+11</td>
</tr>
<tr>
<td>30 keV</td>
<td>3.5e+10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 keV</td>
<td>1.7e+9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 keV</td>
<td>8.7e+7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70KeV</td>
<td>/</td>
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</tr>
</tbody>
</table>

Micro XRD - new in-vacuum undulator beamline

**source**
- Length 1.5 m
- Period 20 mm
- K(max) 1.5

**beamline**
- Sample to source distance ≈ 45000 mm.
- Experiment energy range between 2.5÷4.0 KeV and 10 KeV
- Energy resolution 2•10⁻⁴ with Si (111);

**spot size at the sample:**

\[ \leq 10 \times 10 \, \mu m^2 \]

**Photon flux on the sample:**

from \(10^{13} \, \text{ph/s}\) to \(10^{12} \, \text{ph/s}\) (at the max energy)
24. IMPACT ON SCIENCE

In this section we provide some specific examples of materials research that will benefit from the evolution of Elettra toward the novel DLSR Elettra 2.0 source. Today researchers charged with designing and fabricating new materials have already recognised that in order to obtain novel properties, not present in existing materials, new states of matter should be created. Often novel electronic, chemical, and magnetic properties emerge from phenomena taking place on a scale ranging from few atoms to a few nanometers, so that the properties of complex composite materials may substantially differ from the macroscopic properties of material constituents.

Along with improving classical fabrication technologies for optimising structure and function, more often a variety of external stimuli are used, namely external fields such as electric, magnetic fields, optical or X-ray excitation to induce new states of matter. These stimuli provide a pathway to specific minima in the free energy that can give rise to non-equilibrium, long-lived states with a new electronic and structural order. The relevant physical phenomena are diverse depending on the type of the materials and may include metal-to-insulator transitions, magnetic ordering, electron transport, etc. Questions that have to be considered relate to the inhomogeneous distribution of magnetic, electronic, or structural order parameters, whether the nanoscale properties can be restored after the system is driven out of equilibrium, or if the non-equilibrium state can be stabilized by chemical or structural methods so that the novel properties of interest can be maintained when the stimuli are removed. For understanding the nanoscale physical properties that are responsible for the performance of many smart materials we need probes with capability to visualize morphology – electronic structure and their lateral distribution with sufficient time and lateral resolution.

The great potential of synchrotron-based spectroscopy and microscopy methods in terms of structural, chemical, electronic and magnetic sensitivity has long been recognized, but the imperfection of the X-ray beams have imposed certain spectral, spatial and temporal limits. As briefly discussed above the photon flux parameters of the Elettra 2.0 should overcome the present resolution-sensitivity limits for understanding interactions that control ‘macroscopic’ phenomena in functional materials as chemical reactions, phase transitions, events in biosystems etc. Indeed, Elettra 2.0 cannot reach the femtosecond time resolution of FELs, but will enable its users to follow the evolution of complex functional materials at their natural length scales expanding the time resolution down to sub-nanosecond range.

24.1 CONDENSED MATTER

24.1.1 CORRELATED SYSTEMS AND MAGNETISM

Strongly correlated systems are of great interest both for basic science and potential technological applications, and include superconductors, topological insulators, 2D materials, artificial heterostructures, and magnetic systems, usually in the form of thin films and nanostructures. In these complex systems the electronic correlations should be explored at different energy, momentum, length and time scales, while tuning external stimuli - temperature, pressure, external fields - across their complicated phase diagrams. Many open questions remain open concerning, e.g.: (i) the interplay between magnetism and superconductivity; (ii) competing phases of orbital, spin and charge degrees of freedom; (iii) spatial ordering phenomena.

154
As noted above almost all materials are intrinsically heterogeneous, e.g., nanometer-size electronic inhomogeneities in oxides observed as variations in the superconducting gap, are a well-known phenomenon. Although recognized, the intrinsic electronic heterogeneity in correlated systems is still poorly understood and one of the key questions is how the functional properties of these materials depend on the nanoscale phase separation and chemical or electronic differences at a local scale. Along with heterogeneity, modern nanotechnology trend is fabrication of smaller and smaller devices that require proper micro-probe techniques for controlling their properties for optimization of the technological process.

The only way to respond the stringent request for understanding the role of heterogeneity in these complex functional materials and to explore the properties of nano-devices is pushing the lateral, spectral and temporal resolution of ARPES, RIXS, IR and Raman spectroscopy and coherent X-ray scattering, as exemplified below.

24.1.1.a NANO-ARPES AND SPIN-ARPES

Figure 24.1 shows several examples of nano/micro-ARPES results obtained by SPEM at the Spectromicroscopy beamline of Elettra. The first panel illustrates the micro-domains formed during metal-to-insulator transition of Cr doped vanadium oxide $(V_{1-x}Cr_x)O_3$ by changing the temperature between 320 and 200 K. This transition was monitored by measuring the photoemission yield at the Fermi energy. Pushing the spectral and spatial resolution we can follow in real time all details in the initial formation and evolution of transient states between the PI and PM phases, which a milestone in understanding the exotic properties of these materials.

![Image](image-url)

Figure 24.1 Left: Images of Fermi energy, illustrating inhomogeneous Mott transition (fundamental phenomenon of electronic correlations) between the PI (red) and PM (blue) phases of Cr-doped vanadium oxide, $(V_{1-x}Cr_x)O_3$ by changing the temperature between 320 and 220 K (From S. Lupi et al, Nat. Commun 1, 105, 2010). Middle: Evolution of the electronic structure evolution in 2D dichalogenide layered materials (From H. Yuan et al. Nano Lett. ASAP DOI: 10.1021/acs.nanolett.5b05107). Right: Band parameters and hybridization in 2D semiconductor heterostructures 1 ML MoSe$_2$ on 1 ML WSe$_2$/Gr representing micro to nanoscale devices (From N. Wilson et al, arXiv preprint arXiv:1601.05865, 2016).

The second panel shows ARPES spectra and images that reveal the thickness-dependence of electronic structure by comparing results for mono-, bi-, and multilayer micro-regions of tiny MoS$_2$ flakes. The third panel shows result for a 2D heterostructure obtained by depositing 1 ML of MoSe$_2$ on 1 ML WSe$_2$/graphene, where the band parameters and orbital hybridization are addressed by microprobe ARPES. These are the
first pioneering ARPES measurements with submicrometer resolution and photon flux at least an order of magnitude lower than in conventional ARPES. The great potential of nanometer sized (sub-50 nm) probe is clear: measurements of phase transitions and real devices with nano-ARPES will become routine with Elettra 2.0. Coupled to recent developments and in particular using the new more efficient time-of-flight detectors, realization of a spin-resolved ARPES instrument with nanometer-size beam will become possible as well.

24.1.1.1b XPEEM AND COHERENT SOFT X-RAY SCATTERING – XPCS

XPEEMs at Elettra with imaging, spectromicroscopy and micro-ARPES have also been at the forefront in the characterization of advanced materials to be exploited in new electronic devices, such as memristive oxides, 2D layers and topological insulators. Besides the need for better understanding of the growth, crystal structure and electronic properties, experiments should aim at testing real devices under operation conditions, e.g., probing micron-sized flakes connected to electrodes, acting as transistors or sensors. The potentials of the multi-technique capabilities of the SPELEEM operating at Elettra is illustrated with an example of graphene on Ir(001) in Figure 24.2. Distinct physisorbed and chemisorbed phases with flat and buckled morphology are revealed, which are organized into alternating, stripe-shaped domains. In another study, the morphology and spatial distribution of Ar intercalated under graphene on Ir(100) revealed formation of nanobubbles (NB) upon high-temperature annealing.

Figure 24.2 Left: (a) μ-ARPES pattern (near EF) of a graphene island on Ir(001) (b) Cross section through a graphene Dirac cone along the profile indicated by the red dashed line in (a). (c) Intensity profile as a function of electron energy. (d) Dark-field XPEEM image of a graphene island obtained by imaging photoelectrons at the K point in the diffraction plane. (e) XPEEM image at EF acquired by collecting electrons at normal emission. (From A. Locatelli et al, ACS Nano 7 (2013) 6955-6963); Middle: Ar L3 XAS-PEEM, Ir 4f7/2 and C 1s XPEEM images and X-ray absorption spectra from inside and outside the red circles, indicating Ar bubbles (From G. Zamborlini, et al, Nano Lett. 15(9), (2015) 6162). Right: X-ray magnetic circular dichroism of magnetic skyrmions: reversible change in skyrmion size applying magnetic field \( \mu_0 H_x = 4 \text{ mT} \) (From O. Boulle et al, Nat. Nanotech. 11, (2016).449–454).

The recent interest in the field of two-dimensional layers is directed towards heterostructures consisting of sheets of different materials that can be very successfully tackled with XPEEM along with studies of magnetism in nanostructured and complex materials such as oxides, e.g., manganites and multiferroics. These all require imaging techniques based
on magnetic circular and linear dichroism, microprobe-ARPES and also the implementation of spin filtering is of crucial importance. In this regard, it will be crucial to implement instruments that can operate in a broader temperature range, necessarily reaching cryogenic temperatures, with samples under applied magnetic/electric fields, and with diffraction imaging capability and improved energy resolution.

The higher brilliance of Elettra 2.0 will contribute to decreasing exposure times. Tomographic applications permitting to unravel the 3D magnetic domain configuration in thin nanotubes and rods will further broaden the range of application of magnetic microscopy. The availability of operation modes for the machine to foster the development of stroboscopic imaging techniques with time resolution approaching few picoseconds will be an asset.

In addition to the XPEEM, the planned new XPCS branch at Nanospectroscopy will enable us to simultaneous complementary information by following fluctuations in the coexisting phases in quantum and magnetic materials tuning to the resonance of selected sample constituents.

24.1.1c NANO-RIXS

A new beamline for Nano-RIXS at Elettra 2.0 will help us to characterize the intrinsic inhomogeneities of electronic excitations within all degrees of freedom in oxide materials and investigate their origin. Oxide heterostructures made of layered transition metal oxides have exotic properties that can be used for the design of device components for advanced technologies based on the electronic and magnetic materials properties. In the future, artificially designed electronic systems providing complex or coupled functionalities will be indispensable. Unconventional superconductors within transition metal oxides (TMOs) and related material families are another important class of materials that is of high relevance for future improvement of energy generation, transmission and storage. As already mentioned above, competition of the interactions in all degrees of freedom gives rise to many phase transitions in TMOs and coexistence of nanoscale phases with different chemistry, charge order and spin is very common.

The improved energy resolution of RIXS at future DLSRs will enable the study of the spin excitations in materials with smaller super-exchange interactions between 10 meV and 100 meV, or high-energy spin excitations in cuprate and iron pnictide superconductors and their parent compounds. This will allow exploitation of the spin dynamics in, for example, iron selenides, nickelates, cobaltates and manganites. For unconventional superconductors it will be interesting to increase the energy resolution below the energy scale of the superconducting gaps. It has been suggested by theory that the dynamical structure factors of charge and spin that can be probed with momentum-dependent RIXS can give direct access to the pairing symmetry and the phase of the order parameter. Analyzing the polarization conditions of the scattered beam in RIXS will allow the character of the detected excitations to be assessed. Such analysis will make it possible to discriminate between spectral contributions from charge and spin excitations.

Similar arguments are true for electronic end spin interactions with several fundamental scientific problems relevant for the physics of cuprates made out of connected CuO$_4$ plaquettes. RIXS maps will be able to be acquired in parallel simultaneous detection of incident and detected photon energies with new spectrometer concepts at DLSRs that use a
vertical line focus of the incident beam on the sample combining vertical imaging and horizontal dispersion in the spectrometer optics. For electronic systems with partially occupied d-shell and more complicated electronic ground states than the relatively simple d⁹ valence configurations of insulating cuprates, RIXS maps will be particularly powerful in obtaining a quick overview about existing electronic excitations and their resonating behavior.

The Elettra 2.0 high-brightness source would allow us to achieve in both nano-ARPES and nano-RIXS spectromicroscopy angle and energy resolution comparable to that of current state-of-the-art conventional ARPES and RIXS instruments. Combining nano-RIXS with nano-ARPES and adding the spatio-temporal resolution of XPCS, achievable thanks to the DLSRs coherence, one can obtain full information about the electronic structure - charge excitations, orbitons, phonons, magnons- charge-spin domain dynamics and other coupled excitations in complex and nanostructured materials at the nanometer-nanosecond scales.

24.1.1.d VUV RAMAN and NANO-IR

VUV Raman Spectroscopy is also appealing for exploring correlated systems. For example there are well distinct states of O2p nature in the valence band of Mott-Hubbard metal oxides presenting metal-insulator transitions, and the VUV excitation from these 2p bands to the empty 3d states will present strong resonances. The subsequent Raman shifts make it possible to extract information on crucial parameters for the description of these systems, e.g., the d-d interaction. The applicability of VUV Raman spectroscopy for highly correlated systems is not limited to oxides: for instance, a discrepancy between the conclusions drawn with conventional Raman spectroscopy and with inelastic X-ray scattering on the study of the vibrational excitations in MgB₂ strongly suggests the use of VUV excitation to study these features, in order to reduce the coupling with electronic excitations. Since such the electronic bands probed by VUV Raman are usually at a binding energy of 6-10 eV the intense tuneable light from Elettra 2.0, competing the conventional lasers into the UV, will be an asset.

IR and THz nanospectroscopy will provide new information, complementary to those obtained with the nano-ARPES and RIXS, very important in cases of radiation sensitive materials. Along with probing the presence of surface plasmons in nanostructured materials, nano-IR can be used as a source for surface plasmons injection in conventional and quantum materials. Moreover, the possibility of investigating locally the absorption and dispersion of mid-IR and THz radiation at the local scale around the plasmon hot spot, permits to estimate the enhancing field factor and also investigating the behavior of plasmonic materials in a strong electric field environment.

24.1.2 FUNCTIONAL MATERIALS FOR CATALYSIS, ENERGY CONVERSION AND ENERGY STORAGE

Another highly relevant field is heterogeneous catalysis where the functionality is determined by the surface properties and strongly related to the catalyst nanoparticle size, presence of modifiers for improving selectivity and/or stability, and the role of the support materials. Catalysts have widespread applications in the syntheses of the majority of produced chemicals, in car exhaust gas converters and in energy storage and energy conversion devices. An exploding field today is photocatalysis, relevant to efficient solar energy conversion. It has attracted growing interest with attempts to realize artificial photosyn-
thetic systems that mimic natural photosynthesis, exploring composite materials that combine effective inorganic metal oxide catalysts with efficient charge carrier mobility, and organic light-harvesting material with tunable energy levels.

In the last decade, the ability to characterize the structure and chemical evolution of catalysts interacting with adsorbates has dramatically been improved due to the advances in methodology based on photoelectron and X-ray emission spectroscopy (PES, XAS and XES) with high spectral resolution, implementing microprobes for adding lateral resolution as well. Ideally catalyst studies should be performed in-situ, under realistic reaction conditions - temperature and reactant pressures - correlating in real time the catalyst status and the corresponding changes in fabrication parameters, reactants and products. The gap between these values of the reaction parameters used in industrial catalytic reactions and those achievable in experimental surface science studies has been partially bridged by the use of near ambient pressure methods (reaction cells and pulsed gas jets in differentially pumped systems). These in-operando studies are the only viable route in the attempt to optimize the production process or reveal the active chemical states and all possible undesired processes that lead to catalyst deactivation.

To shed light on the relationship between performance and structural and chemical changes occurring during transient reaction states along with structural and chemical information at meso and nanoscales one needs sufficient temporal resolution. The complexity of catalytic system is that the processes involved occur at very different time scales – from femtoseconds for bond breaking and bond formation to seconds and minutes for many mass transport processes - diffusion, pattern formation, dissolution, etc. - which involve functional meso-nano structures, interphase regions, etc.

For example, in classic catalysis the macrokinetic time scales using reagent pressure/ratio or temperature changes are easily reachable, but in photocatalysis we are still limited at the ultrafast scale by employing pump-probe methodology. Measuring at the micro/macro-kinetic time scale enables spectator species to be distinguished from those that actively participate in a reaction. The ultrafast time domain will unravelling individual and fundamental reaction steps. Despite the large progress in the ability to control structure at the molecular level, mono-dispersion of active site structure and composition has not been achieved for heterogeneous catalysts.

Elettra 2.0 will offer new capabilities with AP-PES and AP-SPEM, XPEEM, nano-RIXS-XES, nano-XAS, ptychography and XPCS for exploring ‘in-operando’ the fabrication and performance of catalytic systems. We believe that combing these methods ultimately hold the promise to disentangle not only the structure of the active site but also the structural changes that the site undergoes during the catalytic cycle and relate this to the micro/macro-kinetic parameters of the catalytic reaction. It should be noted that the methods should be used complementary in selective manner, since whereas for fabrication processes bulk information is essential the characterization of the catalyst structure and chemistry, for studies of catalytic reactions, which occur at the gas or liquid/solid interfaces the catalyst surface state is of main interest.

24.1.2.a AMBIENT PRESSURE NANO-SPEM

The adaptability of the UHV SPEM where focusing optics, sample handling and electron detection are decoupled, has made possible important upgrades and developments for
partially overcoming the pressure gap. The challenges and the solutions for near ambient pressure SPEM experiments, developed or tested at Elettra recently, use different approaches - pulsed jet of gas and environmental cells, running the whole system in the regular operation mode without the necessity of a differentially pumped electron energy analyzer. Figure 7 shows two representative results obtained using an environmental cell and a pulsed gas jet, respectively. The performance of one of the current versions of the near ambient pressure cell, illustrated in the left panel, allows for heating and ambient pressures or liquid environment when using graphene membranes. The promising results makes us confident that using these approaches at Elettra 2.0 we will be able to push the lateral resolution well below the present limits of about 100 nm.

![Diagram](image)

Figure 24.3 Left: Raw SPEM Cu LMM image obtained upon partial reduction of Cu$_2$O surface in 0.2 mbar H$_2$ 723 K. (b) Processed ‘Cu$^0$/Cu$^{+1}$ ratio image’, emphasizing the chemical contrast between the two oxidation states (the reduced Cu domains appear brighter). It is obtained by dividing the ‘grey-dashed bar’ image to the ‘black-dashed bar’ one, corresponding to the Cu$^0$ and Cu$^{+1}$ electron kinetic energy windows respectively. (c) Normalized Cu LMM spectra measured in the indicated locations in the image (a) of the reduced and still oxidized areas. The inset illustrates the NAPC design and working principle. Right: Simultaneous monitoring by spectro-imaging the reduction front and generated current during electrochemical reaction, ignited near the NiO electrode/YSZ electrolyte interface of single Mn-Ni cell. The Ni 2p spectra energy shift is a measure of the over-potential resultant from the current flow generated by the hydrogen oxidation (local H$_2$ pressure 1 mbar using pulsed jet of gas) that starts on the NiO electrode, whereas the growth of Ni metallic component measures the reduction rate. (From B. Bozzini et al, Sci. Rep. DOI: 10.1038/srep02848)

24.1.2.b NANO-SXM AND PTYCHOGRAPHY

The present power of X-ray ptychography combined with keyhole CDI and nano-NEXAFS for in situ spatio-temporal studies of catalyst fabrication in a sealed wet environment is illustrated in Figure 25.4. Pushing the lateral resolution to the sub-100 nm scales allowed for better understanding the factors controlling co-electrodeposition process of Mn-Co/polypyrrole (PPy) nanocomposites, promising oxygen reduction catalyst for replacing Pt in batteries and fuel cells. The local material redistribution as a result of consecutive in situ electrochemical biasing steps is encoded in the absorption images (Figure 8a) measured with photon energy below the Mn L edge (636 eV) for which Mn, Co and C have comparable absorption.

The images encode both the lateral changes and the amount of the deposited material, quantified by the changes in the absorption of the aggregates plotted on the right of each

set of images. Notable are the oscillations with deposition time which indicates occurrence of at least two competitive events: co-deposition and diffusion. NEXAFS across atomic edges provided chemical information preserving the lateral resolution.

Figure 24.4 (a) Absorption images taken below the Mn L edge representing Local material redistribution as a result of consecutive in situ electrochemical biasing steps. The plot to the right shows the variation in absorption in the aggregate (blue line) and the background (red line), highlighting the sizable changes in the aggregate substance compared to the background. (b) Absorption images of a sub-region reconstructed from ptychographic scans acquired at photon energy below (636 eV) and above (641 eV) the Mn L absorption edge, where the contrast differences outline the Mn lateral distribution. (c) Absorption image taken below the Mn L edge, where the distribution of Mn$^{2+}$ and Mn$^{4+}$ states are indicated with red and green the corresponding absorption spectra measured scanning at 18 different energies from 636 to 647 eV are shown on the right panel. (From G. Kourousias et al, Nano Research 9, 2016, 2046).

Comparison of the contrast levels within the darker sub-regions in the two maps in Figure 25.4 (b), taken below (636 eV) and above (641 eV) the Mn L edge, provides detailed insights about the Mn lateral distribution within the ~ 100 nm co-deposit aggregate: the darkest features in the image taken above the Mn edge correspond to locations with the highest Mn content. By performing spectroscopic ptychography at photon energies across the Mn L edge we could also reveal the lateral distribution of Mn$^{2+}$ and Mn$^{4+}$ oxidation states, which was found to depend strongly on the local current densities.

Optimizing the fabrication processes is a key for obtaining catalyst structure with the desired activity, selectivity and stability and other smart nano-structured materials. Today such experiments are very time consuming, and this makes 3D imaging experiments rather difficult. Along with making such experiments much faster, also the lateral and spectral resolution achievable would greatly benefit from the substantial increase in the coherent flux of Elettra 2.0. Although X-ray 3D microscopes would never be able to compete with transmission electron microscopes in terms of ultimate resolution, they would allow non-destructive studies of thicker samples under at a resolution of the order of 5 nm or better.

Many grand challenge problems will be addressed with techniques that provide in-
operando 3D maps of chemical and structural sample heterogeneity with nanometer resolution. A good example is provided by the poorly understood solid-electrolyte interphase (SEI), a phase-heterogeneous, few-nanometer-thick metastable region that develops at electrochemical interfaces. The SEI determines how well a battery functions and how likely it is to fail. Tools that probe important factors such as: i) the chemical inventory of the SEI; ii) interphase transport of the intercalating species; iii) the structure of granular electrode materials commonly used in batteries to assess the impact of repeated intercalation-de-intercalation cycles, are crucial to developing batteries with high storage capacity and lifetime. Similarly, as nanometer resolution of particles in many classes of heterogeneous and functioning mesoscale materials is becoming important, interest in applying a robust suite of X-ray spectroscopic tools with a focused beam has also grown.

24.1.2.c NANO-IR

The chemistry of smart nanomaterials can also be successfully investigated with IR microspectroscopy coupled with IRSR nanoscopy. The wide wavelength range covered by IRSR, coupled with the sensitivity of IR nanoscopy to both the real and imaginary part of the material refractive index, allow for organic, metalorganic and metallic states characterization, complementing the elemental information that could be obtained from X-ray based microspectroscopies. In particular, IR should be the most favorable approach to study composite materials with organic constituents, as block copolymers, protein-carbohydrate mixtures - i.e., models for drug-excipient interaction - etc. New insights can also be expected from IRSR studies of solid-state organic reactions including also high pressure or photon-induced syntheses by mesoscale chemical characterization. The reactions can be imaged in real time, monitoring the sample homogeneity, and using the nanometric resolution it will be possible to zoom in and study the reaction at the interface between the reactants.

24.2 ATOMIC, MOLECULAR, AND NANOPARTICLE SCIENCE

Atomic and molecular targets for investigation have a hierarchy of increasingly fine detail: electronic, vibrational, and rotational, with ever smaller excitation energies, so that this field utilizes fully the highest available spectroscopic resolution. As well, intrinsic line shapes carry more information than in condensed matter studies, as they are not subject to some extrinsic effects such as heterogeneity. Thus atomic and molecular science will benefit from the increased energy resolution available from a DLSR source. Samples are typically dilute, and for free nanoparticles, they may be extremely tenuous. Cluster and nanoparticle research will benefit from the increased performance of Elettra 2.0. Experiments involving more than one photon may be labeled “optical experiments”, and they include photon-in/photon-out techniques (RIXS, fluorescence), pump-probe and excited state spectroscopy. A major boost will come from the much finer focus that will be achieved due to the increased brilliance of the beam: the source size and divergence currently limit the achievable spot size. In the case of dynamical studies with pump-probe methods, for example, the count rate is currently limited by the minimum spot size of the synchrotron light – a larger spot means that many molecules which are not pumped are ionized, and they give rise to background signal.

A similar argument applies to coincidence experiments, where two or more particles (electron + electron, electron + ion(s), electron + photon) are measured from a single
process (see Fig. 24.5 (Left)). These experiments give a more complete picture of the dynamics of the interaction of radiation with matter than simple spectroscopy where one particle is detected. A small, well-defined spot is optimal for producing the best signal to false-coincidence count rate as well as to improve resolution when using imaging techniques (in the sense of Velocity Map Imaging methods). This class of experiments provides dynamical information such as electron correlations in small quantum systems, or hydrogen transfer, isomerization and selective bond breaking in larger molecules.

Figure 24.5 Left: Coincidence measurement of photoabsorption spectra of Ar2 and ArNe dimers (produced as a mixture in a gas jet.) The coincidence measurement allows the separation of signals due to Ar ions, two simultaneous Ar ions, or simultaneous Ar and Ne ions. A recently discovered process, Interatomic Coulombic Decay was investigated for the first time with core excitations. (From P. O’Keefe et al, J. Phys. Chem. Lett. 4 (2013) 1797). Experiments of this kind will be much improved by the use of a DLSR source. Right: Nitrogen core level photoemission spectrum (top curve) of the nucleobase guanine, one of the five fundamental “letters” in the DNA/RNA “alphabet”. The spectra show that free guanine exists in four different forms (tautomers) in the gas phase, see theoretical smooth curves, 1 to 4). Because of the thermal sensitivity of the molecule, low temperatures were used, and the sample density was very low, so that data acquisition times were long. Higher quality data will be acquired at Elettra 2.0 in shorter times. (From O. Plekan et al, J. Phys. Chem. A 113 (2009) 9376).

The combination of flux and focusing can also be exploited to perform studies of nanoaggregates (from molecules to nanoparticles) in reaction cells and under near-ambient conditions to investigate how the environment affects the modification of their chemical physics properties. The Gas Phase beamline at Elettra is well adapted to such studies as the effective differential pumping makes liquid jet sources, wet cells and similar sample environments easily compatible with the UHV requirements of the monochromator optics. Dynamics can be studied on the time scale of 100 picoseconds to microseconds.

A major theme of current research at the Gas Phase and CIPO beamlines is the investigation of molecules and systems of interest for life sciences. Many of these biochemically interesting systems are thermally labile and can only be brought into the gas phase in low concentrations or produced as ionic species, via electrospray ionization for example, and then trapped in proper devices before interacting with synchrotron radiation (see Figure 24.5 (Right)). In both cases the Elettra 2.0 will provide a more suitable light for the inve-
The present Gas Phase beamline was designed to be matched to the brilliance of the current Elettra ring. We calculate that with new optical elements and monochromator matched to the Elettra 2.0 DLSR source, performance will increase by at least an order of magnitude, measured for example, as count rate at a given resolution, or flux in a given spot size.

24.3 LIFE SCIENCES

The correlation of the functionality of biomaterials, natural or synthetic, to the atomic and/or molecular characteristics of its constituents, requires the understanding of meso-scale organization and phenomena. At the mesoscale, from few tens up to hundreds of nanometers, atomic and molecular properties meet macroscopic-functional behavior. Complementary soft and hard X-ray techniques can address biological problems at different lengths scales and the transitions between scales are of crucial importance for understanding very complex systems where individual roles of each player matters.

Crucial aspects include, e.g., the atomic structure and function of constituent protein molecules and distribution of this ‘complex’ in the cell, its role for the cell function, intercellular interactions, etc. For addressing these questions at a more advanced level we should go beyond macromolecular crystallography using the new opportunities offered by DLSR Elettra 2.0. Here the proper combination of X-ray and IR micro and nanoprobe could provide new insights that will have an impact on the solution of many health and environmental issues. In many cases the use of Nano-IR will be advantageous by circumventing radiation damage.

24.3.1 FROM PROTEIN SCIENCE TO CELLULAR BIOLOGY

It is a well-established paradigm that the function of a protein is related to its structure. An in-depth understanding of this relationship is required to rationally clarify the molecular mechanisms related to protein functionality or dysfunctionality, and it is of paramount importance in numerous filed of science, from biophysics to molecular biology and medicine. Severe limitations to protein structural characterization are imposed by proteins that are challenging to crystallize (i.e., membrane proteins), or available in limited quantities (i.e., mutated proteins involved in rare diseases as genetic disorders or cancer).

The increased anomalous scattering signal at the planned 4-8 keV microfocus beamline at Elettra 2.0 will complement the existing harder X-ray beamlines opening new routes for exploiting small protein crystals and solving the phase problem to tackle more specific biological questions. Along with detailed structural information about large biomacromolecules one can develop new methodologies for creating 2D ordered structures of DNA/RNA and proteins to explore not only their structure and also their response to different physiological environment, temperature and radiation. Such experiments will be complementary to the SAXS/WAXS and XCPS, which will address the same problem with much better time resolution.

In fact, even in the case of large bio-molecules for which crystallographic structures are already known, the possibility to determine their conformational details in a physiologi-
cal environment could open new perspectives in the field of proteomic. Surface Enhanced IR Absorption Spectroscopy (SEIRA) supported by plasmonic devices allows for mid-IR signal enhancement up to $10^5$, making SEIRA suitable for protein conformational characterization in monolayers and at very low and biological relevant concentrations, up to femtomolar detection sensitivity.

SR-SEIRA microscopy strengthens further the technique capabilities, simultaneously reducing the data acquisition time thanks to the brightness advantage of IRSR. This advantage will be further emphasized for Elettra 2.0 and translated to spectral regions of interest also for nucleic acids (DNA/RNA) or other molecules of biological relevance thanks to its broadband nature. In this respect, comparable approaches could be extended to the FIR regime, a spectral region almost unexplored for biomolecules. In particular, understanding their behavior as a function of temperature or pressure will greatly improve our knowledge on the mechanisms ruling intermolecular interaction and the interaction of biomolecules with the environment.

Protein functionality/dysfunctionality is mostly driven by protein-protein or protein-membranes interactions. Protein aggregation in fibrillar structures and transmembrane protein functions are clear examples of this paradigm, responsible for many amyloidogenic disorders, such as Alzheimer, Parkinson and prion diseases. IRSR nanospectroscopy and complementary X-ray methods will be key tools for the investigation of relevant mesoscale phenomena in biological systems to understand the biological organization and mimic it. They will have impact on many science fields spanning from biomedicine and biology to biotechnology and bioelectronics. The expected improvement of spatial resolution in X-ray imaging, XAS and XRF at DLSRs will allow access to morphological and elemental details that cannot be achieved nowadays.

For example, at the TwinMic beamline XRF imaging and XAS techniques have been used to characterize ferruginous bodies formed around asbestos fibers in the lung tissue of human patients. The complementation of IR microscopy has allowed us to highlight the presence of associated amyloidogenic deposits. SAXS/WAXS-XCPS offer many approaches for studies in solution adding time resolution as well. The conformational changes of, e.g., membrane proteins have already been under exploitation with SAXS.

24.3.2 FROM A SINGLE ORGANISM TO A COMMUNITY

A favorable mutation in a single cell can spread to an entire population in a matter of hours, within communities of microorganisms, such as bacteria or algae. This can lead either to organisms more resistant to drugs or simply more fitted to survive in a specific environment. The thorough biochemical profiling and lack of radiation damage of micro/nano-IR, complemented with X-ray based microscopy, spectroscopy and scattering providing further in-depth chemical information down to atomic and ps spatial and time resolution, can have strong impact in diverse fields of life science, including:

**Antibiotic resistance** In numbers, only in the European Union, 25000 people die each year due to infections caused by antibiotic-resistant bacteria. This results in economic losses in the estimated order of €1.5 billion due to extra health care costs and productivity losses. The European Commission funds research projects on multi-drug resistant (MDR) pathogens through its Framework Programs (FP) for research and innovation.
The support started with FP5 in 1999 and continued through to FP7 and Horizon 2020 today.

Bacteria are complex entities that heavily rely on collaborative behavior, but detailed chemical information about individual organisms and their interactions is still scarce. To adhere on a surface these microorganisms organize in biofilms (BFs), i.e., tightly packed groups of cells embedded via self-produced Extracellular Polymer Substance (EPS), which also acts as protective barrier. Today it is recognized that ~60% of infections involve biofilm-associated microbes and most alarming is that the BF production seems to increase the resistance to antibiotics. Since the EPS synthesized by microbial cells vary in composition, IRSR-microscopy and IRSR-nanospectroscopy are promising tools for revealing the chemical and physical properties of these matrices and help designing strategies to address the issue. Further insights on the role played by the mutated structure of the enzymes that allow bacteria to become resistant will be provided by micro-XRD, also those that cannot easily be crystallized. SAXS based approaches are fundamental for exploring details in the resistant mechanisms under physiological ambient.

**Biofuels and pollution** Microorganisms can also have a positive impact, as “machineries” for producing fine chemicals (e.g., biofuels from algae and aquatic biomass or capture and convert greenhouse gases (CO₂). The chemical characterization provided by complementary IR and X-ray imaging and micro/nano-spectroscopy at the single cell level can be used to select the best organisms in terms of conversion rate, product quality, as well as to better understand the biochemical processes involved, with relevant impact on the environment and life quality as well.

**Biomineralization** Biomineralization phenomena play important roles in biology, geology, biotechnology and medicine. The production of minerals by living organisms is a very attractive mean for addressing pollution problems using bacteria to metabolize toxic metals and gases or for materials engineering applications. X-ray microprobe spectroscopies, imaging and tomography techniques have already been used on the micro-nano-to-atomic scale to understand the mechanisms of biomineralization. Bacteria can metabolize via biomineralization either toxic metals (for example they have been used to remediate groundwater contaminated with uranium or chromium) or sequester CO₂ from the atmosphere. Biomineralization processes are efficient, clean, take place at mild conditions and give products of higher quality with respect with the synthetic ones. Therefore, the knowledge of the chemistry guiding these processes will be of paramount importance and can greatly benefit by the joint collaboration in DLSRs of X-rays analytical tools, from soft and hard X-ray imaging, including 4D CT to X-ray absorption spectroscopy and X-ray fluorescence and non-disruptive techniques like IRSR spectroscopy, imaging and nanospectroscopy.

24.4 RADIATION DAMAGE

When increasing the source brightness and enhancing the photon flux within the irradiated spot, the issue of radiation damage and sample survival should be seriously considered. Even with the X-ray fluxes available from current SR sources, organic systems are typically destroyed during experiments within seconds or minutes and also changes in the chemical status of inorganic condensed matter systems (loss of atomic constituents in, e.g., oxides) has been evidenced using microprobes with very high flux densities. With the advent of DLSR sources the radiation damage from EUV, soft and hard X-rays will
become an even more serious issue. Radiation damage has been widely studied and recently at Elettra we have investigated the relative resistance of different biomolecular constituents in the cell to X-ray doses by combining transmission X-ray microscopy and IR spectromicroscopy, as illustrated in Figure 10. The results suggest that reducing the acquisition time when using X-rays for spectroscopic purposes (e.g., XAS) may be insufficient to avoid radiation damage effects, so that implementing and complementing nano-IRSR techniques will be a necessity.

In the case of photon-in/electron-out detection, independently from the sample resistance, fundamental limitations at very high photon fluxes are imposed by space-charge effects due to scattering of the emitted electrons. This undesired effect currently hinders effective implementation of both PES and ARPES from solid-state samples at FELs, which produce ultra-short, ultra-intense laser pulses with low repetition rates. Both radiation damage and space-charge broadening effects are strongly dependent on the material and on the photon energy through parameters such as: (i) the photon absorption and penetration depth; (ii) the dielectric susceptibility of the material; (iii) the escape depth, energy and angular distributions of the emitted photoelectrons.

The dependence of space-charge broadening on material parameters has been used as a fingerprint in studies of phase transitions. For example, the metal-to-insulator transitions lead to a substantial reduction in the screening properties. Along with increasing substantially, space-charge broadening, an energy shift due to the space charge can be observed as well. These shifts (typically to higher kinetic energy) are of the same order as the energy broadening, and will strongly impact on the determination of quantitative, such as the energy gap versus temperature at the Fermi level, especially for sharp transitions when material properties are fast fluctuating.

These undesirable effects can be controlled by reducing the photon flux when necessary and developing methodologies to continuously changing samples or the irradiated region. Pushing the detector technology to improve the detectors efficiency and speed would be
an important development to allow us to employ reduced photon fluxes. The implementation of DLSR sources may actually bring some advantages. By reducing the photon spot size one can reach a regime where the space-charge cloud becomes quasi one-dimensional - in the normal direction - so that electron-electron interactions remain dependent only on the pulse length. A way to minimize space-charge effects due to the high photon density will require long pulses of DLSRs to minimize space-charge effects from the high photon density.

When important, radiation damage should be handled by operating beamline and spectrometer optics at lower efficiencies, using non-focused grazing-incidence geometries where the photon flux will be distributed over larger areas, or continuously changing samples or the irradiated region. Liquid jets and other beam-based sample introduction methods are ideally suited for the latter, while for solid samples manipulators capable of rapidly moving the sample with high precision will be needed.

24.6 SCIENCE OPPORTUNITIES COMPLEMENTARY TO FEL

DLSR and XFEL sources naturally complement each other. DLSRs provide high average brightness and very high repeat rate with high coherence, while FELs have the extreme peak brightness and time structure required for ultra-fast time resolution or single-shot experiments, higher coherence and lower repeat rates relative to DLSR.

Just as experiments using FELs allow for unprecedented flexibility in measuring dynamical events, experiments using DLSRs will be more suitable to measure statistical quantities such as spectral functions, dynamical structure factors, space-time correlation functions, etc. The spectroscopic and spatio-temporal sensitivity of soft X-rays will benefit both kinds of study, and indeed will be crucial in drawing connections between them. Connecting the regimes of molecular- and unit cell-scale dynamics to few-nanometer-scale statistical kinetics is a tremendously important goal in diverse contexts that will require both kinds of facilities.

Understanding and controlling the dynamics of photoexcitation, for example, will benefit from FELs in the ultrafast time domain, where a popular goal is to map charge and nuclear motion through a conical intersection. This is intrinsically dynamical. By contrast, kinetic motion on a complex energy landscape, e.g., in a complex oxide, will ultimately need to be coarse-grained, parametrized, and treated statistically to model macroscopic functions on longer time scales.

Measuring statistical quantities such as spectral functions with ARPES, dynamical structure factors with RIXS and XPCS, and space-time correlation functions with transient grating experiments and time-resolved microscopy provide robust, statistical approaches to connect experiment to theory on the relevant spatial and temporal scales.

For atomic, molecular and optical science, there is already a strong interaction between Elettra and FERMI, and this is a two-way street: users at both light sources often have ideas that require the other source, and carry out experiments there. The new properties of Elettra 2.0 bring the facility more closer to those of FERMI, and will increase the number of scientific experiments that can be conducted there, and feed this symbiosis.
Figure 24.6. Ion coincidence map from small Mg clusters. This experiment was inspired by work at FERMI, and discovered a new process (Electron Transfer Mediated Decay) which had been theoretically predicted but not observed previously. (From A. LaForge et al, Phys. Rev. Lett. 116 (2016) 203001).

25. INDUSTRIAL IMPACT

25.1 BACKGROUND

Elettra Sincrotrone Trieste has always been strongly committed to technology transfer and supporting industrial research and development. In 2004 the Industrial Liaison Office (ILO) was established, making Elettra Sincrotrone Trieste an early example of a trend that would soon emerge among universities and research institutions worldwide. ILO enabled the exploitation of the newly developed technologies, competences and skills, as well as the promotion of the industrial use of Elettra and, starting in 2010, FERMI. Recently, to comply with industrial procedures, Elettra obtained the ISO 9001:2008 quality certification and the BS OHSAS 18001:2007 safety certification and presently is the only synchrotron radiation center with such certifications.

Since the beginning ILO activities have focused on making available to industry the experience and competences of the researchers of Elettra Sincrotrone Trieste and in supporting private companies in areas such as quality control, optimization of production processes and the development of subcomponents and materials. The Elettra synchrotron radiation source has 28 different beamlines and experimental stations, equipped with all of the most important X-ray based techniques in the areas of spectroscopy, spectromicroscopy, diffraction, scattering and lithography, available for both academic and proprietary industrial research. Such techniques allow the measurements of many classes of materials, including metals, semiconductors, superconductors, catalysts, ceramics, glasses, polymers, magnetic materials, materials for energy, electronic and bio-medical appliances, biomaterials, etc., providing crucial information to Italian and European companies that operate in fields as diverse as high-tech materials, agri-food, energy, environment, chemistry, catalysis, medicine, diagnostics, pharmacology, electronics, ICT, and many others.
In the last 5 years, industrial use of the Elettra synchrotron radiation source from some 70 different industrial concerns and has generated an average of 800 thousand euros per year of revenues. This value is 75% greater than that obtained in the previous 5 years and brings the total revenues deriving from proprietary research for industry to 5 million euros in the last 10 years. More than 50% of these have been generated by projects financed by large companies, that invested in developing joint long-term projects combining multiple measurements techniques with the professional expertise available thanks to the multidisciplinary character of the infrastructure. Best examples include research activities by multinational companies such as ENI (chemistry), Zambon Chemicals S.p.A. (pharma), Chiesi Farmaceutici S.p.A (pharma), Merck Serono S.p.A. (pharma), ASML Netherlands B.V. (semiconductors), ST Microelectronics (semiconductors), Carvico S.p.A. (textiles), Honeywell (sensors), Wartsila Italia S.p.A. (metallurgy).

Short term projects or feasibility tests involving mainly SMEs, some of them operating in the local area, have focused on the characterization of materials or optimization of industrial products and processes, and are usually performed through projects financed by the OPEN Lab initiative of AREA Science Park. Often, the access to the facilities with feasibility tests raised the awareness of the industry about the potential use of synchrotron light sources and created the conditions for the participation in projects financed with European and National funds, to which they would not have had access without the intervention of Elettra Sincrotrone Trieste.

In addition to the industrial use of the beamlines and experimental stations, engineers and researchers at Elettra Sincrotrone Trieste have designed innovative hardware and software for ultra-high vacuum applications, precision mechanics, optics, electronics and ICT. Initially developed for internal use, such products attracted the interest of industrial and academic institutions and started to generate increasing revenues. Some of the technologies have been successfully licensed to multinationals (such as Hamamatsu), or enabled the innovative startups to penetrate the international markets. The royalties that Elettra receives through these channels amount to tens of thousands of euros a year.

In 2007 Elettra Sincrotrone Trieste transferred its insertion device technology to the spin-off company Kyma S.r.l. Today Kyma is a global leader in the design, production and installation of customized insertion devices, which are the heart of the modern light sources. It has a turnover of 3 million euros. Beside Kyma, there are at least three other companies worth to be mentioned in this context: Cosylab (Slovenia), Instrumentation Technology (Slovenia), Caenels (Italy). They are world leaders in the instrumentation and control systems for accelerators and were founded by people, who previously worked at Elettra. Together they are employing about 200 employees with a global turnover of more than 20 million euros.

Many electronic instruments that the staff of Elettra Sincrotrone Trieste developed to meet the facility needs, were launched on the market and are nowadays in use by the universities and other large scale research infrastructures around the world. Several complex custom products, such as beamlines, refocusing mirror systems or RF devices, also developed internally, are sold commercially worldwide. Such commercial activities in the last 5 years generated more than 5 million euro revenues. This value is 47% greater than that obtained in the previous 5 years.
The proposed Elettra 2.0 upgrade will bring about new and more powerful characteristics of the machine, beamlines and experimental stations and this, on the one hand, will attract new academic as well as new industrial users. On the other hand, new and existing clients will benefit from the development of the new state-of-the-art technologies required to implement Elettra 2.0.

25.2 PERSPECTIVES FOR INDUSTRIAL PROPRIETARY RESEARCH

The implementation of Elettra 2.0, a diffraction-limited storage ring (DLSR), the upgrade of the present beamlines and instrumentation and the construction of a number of new advanced beamlines and experimental stations offering APPES, HAXPES, RIXS and XPCS, will make the Laboratory even more attractive for solving problems in material sciences, condensed matter physics, chemistry and biology, and contribute to meet the challenges in material fabrication, characterization and integration brought about by emerging technologies.

The expected increase in the source brightness and decrease in the source size will lead to: (1) improved spatial resolution, making possible to convert many of the present spectroscopic methods to micro- or nano-spectroscopy; (2) increased signal-to-noise ratio, that will improve the efficiency and spectral resolution of low-yield methods such as RIXS and HAXPES; (3) increased coherence, that will boost lenseless imaging CDI and ptychography for characterization of 1D, 2D and 3D nanostructured material. In general, the combination of increased brightness-coherence will open unprecedented possibilities for materials characterization, with access to dynamic processes that determine their functionality.

These significant improvements in the performance at Elettra 2.0 instruments, accompanied by further developments in detectors efficiency, sample environments and data processing should allow new classes of experiments in many disciplines and will attract more industrial users who are looking for means to overcome the existing technological barriers.

25.2.1 MATERIAL SCIENCE APPLICATIONS

The properties of complex functional materials currently utilized in technology are a direct result of their size, structural, chemical, electronic and magnetic organization at variable length and time scales. Examples include advanced materials currently used in electronic, magnetic and energy devices, sensing and drug delivery and also in the production processes of chemical and pharmaceutical industries. DLSR will enable the characterization of such materials with vastly improved spatial and spectral resolution, offering new opportunities to companies interested in their development.

25.2.1.a CHEMICAL AND BIO SENSORS

The sensor industry is a robust global market, valued at more than $123 billion in 2016 and expected to increase to nearly $240.3 billion in 2022. While Image sensors lead the market, with a value of nearly $16.3 billion in 2016, there is a sensible growth in the use of chemical and bio sensors pushing for new developments leading to increasing number of applications. Honeywell with more than 1,400 patents, is a
big player at this market and in recent years Elettra scientists have been involved in Honeywell research activities as well.

The growing demand for biosensor applications is expected to reach in areas such as point-of-care testing segment up to, home diagnostics, environmental monitoring, research laboratories market worth more than $30 billion in 2022. A similar growth rate is expected for chemical sensors that play a critical role in many manufacturing applications for closed-loop feedback control to achieve product quality, maintain efficiency and reduce environmentally hazardous emissions.

The trend is toward the development of novel materials tailored to specific, or targeted, applications as gas sensors for home or industrial applications. Since all type of recent and under development sensors are based on use of complex nanostructured materials, the potential of various synchrotron-based methods in terms of surface, depth, structural and chemical sensitivity are becoming indispensable characterization tools for improving fabrication processes in order reach the desired performance of bio and chemical sensors. More fundamental focused studies through XRM, HPPES, IR and micro-XAFS techniques via experiments under in operando conditions will provide feedback about durability, reliability and stability of various sensors suggesting possible solutions for improving the technological process.

25.2.1.b CATALYSTS

One of the distinctive fields where Elettra 2.0 is expected to have a strong impact is in the studies of catalytic materials that play crucial functional roles in important industrial chemical processes, batteries, fuel cells, electrochemistry, pollution control and green chemistry. For all these reasons, global demand on catalysts was valued $33.5 billion in 2014 and it is expected that it will witness a robust growth in the next years.

Catalysts are some of the first nano-materials used in the chemical industry, and research continues to implement cheaper, more efficient and durable catalysts with the desired properties. Recently the demand for green chemistry has fostered the development of artificial photosynthetic systems that mimic natural photosynthesis, using composite materials that combine effective inorganic metal oxide catalysts with efficient charge carrier mobility.

Scientists at Elettra-Sincrotrone Trieste have already used spectroscopic, microscopic and scattering method to exploit catalytic materials, nanostructured electrodes, energy device components in static and near-operation conditions. In this respect, exploiting processes occurring at solid surfaces in contact with gaseous and liquid ambients are of extreme importance in heterogeneous catalysis. The developments of environmental reaction cells, the enhanced spatial resolution offered by ptychography and CDI in reflectivity and the new capabilities of the present and planned APPES, RIXS, XPCS using Elettra 2.0 for exploring catalysts in-operando conditions, should attract a number of companies in several industrial fields and in particular their R&D centers.

25.2.1.c NOVEL NANOMATERIALS

The growing industrial interest on low dimensional nano-materials like graphene, nanotubes and nanowires has been witnessed by the increasing market shares in recent
years. The global commercial market for graphene for instance is valued at $76.7 million in 2016 and is forecast to grow to $743.9 million by 2026. For example the exotic properties of graphene make this material a key component for future technologies. Still, controlled fabrication of very high quality graphene and its characterization when its is incorporated in actual devices remains an unresolved issue.

Low dimensional 1D and 2D materials have been in recent years one of the major research topic at Elettra Sincrotrone Trieste and have led to some industrial projects financed by private companies. The industrial sectors in which they could be employed include semiconductors, renewable energy (solar cells, energy storage, etc.), chemical and mechanical industries. The study of their electronic properties, chemical reactions, materials functionalization and compounds will be strongly improved by the availability of Elettra 2.0.

25.2.1.d SEMICONDUCTOR INDUSTRY

Miniaturization in electronics, optoelectronics and other technological sectors (e.g., relevant to life sciences, energy, sensors and precision instrumentation) imposes stringent requirements for fabrication of thin film heterostructures with high control on the their thickness down to a few nanometers. The global market for atomic layer deposition and other ultrathin film deposition equipment increased from $1.1 billion in 2014 to $1.5 billion in 2016, and is estimated to continue growing in the next years. In recent years, following advances in nanotechnology, printing ink-based nanomaterials (e.g., nanopowders, nanofibers, nanowires and nanotubes) have been developed. Thin film processes based on printing of nanomaterials are also becoming increasingly popular in the semiconductor industry, adopting technologies that, until a few years ago, were only used to manufacture thick film devices.

As the trend in miniaturization continues, in particular within the electronics industry, the introduction of technologies that allow for the deposition of nanofilms (films that are equal to or less than 100 nm) and ultrathin films (nanofilms with a thickness below 30 nm) are expected to be the next technological advance. Synchrotron-based techniques can be proper characterization tools for improving the processing of efficient materials, understanding failure, crack formation and stress propagation that occur at the nanometer level. Thanks to the brightness and coherence of the DLSRs, key tools such as coherent imaging in combination with X-ray photoemission microscopy (XPEEM), X-ray scattering and photon correlation spectroscopy will provide all of the desired information about the thin film structure and their electronic and magnetic properties.

In particular, upgraded instrumentation at the nanospectroscopy beamline and the new beamline for Nano-RIXS foreseen at Elettra 2.0, will allow investigations of electronic and magnetic properties of materials (e.g., oxide materials) and can be used to enhance the design of memory device components and by companies such as ST Microelectronics, already and industrial client of Elettra Sincrotrone Trieste, and Micron Technology Inc., that recently studied phase change memory devices (that include a phase-change memory layer on a semiconductor substrate) at the XAFS beamline.
25.2.2 LIFE SCIENCES APPLICATIONS

Determining the structure of proteins and other macromolecules has been one of most important results obtained by the systematic use of synchrotron radiation. In recent years, industrial customers of Elettra Sincrotrone Trieste have used XRD, SAXS and IR techniques in projects for drug characterization and protein production. Elettra 2.0 will offer new opportunities to study molecules, molecular aggregates and microorganisms, providing new insights that will have an impact on the solution of many health and environmental issues at a more advanced level.

In particular, the expected improvement in spatial resolution for X-ray imaging, XAS, XRF and IR, together with the new NanoIR experimental station, will provide access to morphological, chemical and elemental details that cannot be obtained otherwise. In-depth chemical information will have an impact on several fields of life sciences including, antibiotic resistance, biofuels and pollution, biomineralization and many more. All such sectors are growing rapidly.

25.2.2.a ANTIBIOTIC RESISTANCE

The global antibiotics market was valued at nearly $41.0 billion in 2015 and is expected to reach $44.7 billion by 2020 with annual growth rate of 2.0%. The market is highly fragmented with many big players in the pharma field including Merck and Co. and Zambon Chemicals that have already been involved in research activities at Elettra Sincrotrone Trieste. Since in the antibiotics market the regulatory requirements that oversee the efficacy and safety data of new molecular entities have led to greater uncertainty and risk, many pharmaceutical companies invest in methods involving combinational chemistry and target-based genomic approaches instead of simply screening to identify antibiotics from natural sources, a process that tends to be inefficient and time-consuming. All of these laboratory techniques may benefit from an in-depth morphological, elemental and chemical analysis performed with the use of the new DSRL source.

25.2.2.b BIOFUELS

The global biofuels industry production is expected to grow to 67.2 billion gallons per year by 2022 at a 2.2% annual growth rate from the 58.6 billion gallons per year today. 2015 has been a year of capacity expansion for several technology areas, including biomass-to-sugars, catalytic conversion, gasification, and anaerobic digestion. Reports predict that in the next six years in this sector there will be a shift in technologies away from bioconversion processes and towards thermochemical and catalytic technologies. The chemical characterization provided by complementary IR and X-ray imaging and micro/nano-spectroscopy at the single cell level at Elettra 2.0 will be an important tool to select the best organisms in terms of conversion rate and product quality.

25.2.2.c MICROBIAL

Regarding bio-mineralization, microorganisms (bacteria, fungi or algae) or their by-products (e.g., enzymes) are also used to remove or degrade the hazardous components of waste materials (bioremediation). Studies in this field already have been per-
formed at Elettra Sincrotrone Trieste using XAF or XRF techniques and the improvement in their performances afforded by the Elettra 2.0 upgrade will enhance the potential of such studies. The market for microbes and microbial products used in various environmental applications was worth around $441 million in 2014 and is expected to exceed $643.3 million by 2020.

25.3 TECHNOLOGY PLATFORM

Engineers and researchers at Elettra Sincrotrone Trieste are meeting the technical challenge of implementing the Elettra 2.0 upgrade by designing a wide range of new high-performance components. Thanks to their invaluable expertise in ultra-high vacuum, precision mechanics, radiofrequency, diagnostics and optics, these teams have been designing new state-of-the-art magnets, RF devices, diagnostic instrumentation, high-end beamline detectors, power supplies and control system hardware and software.

As described in the background section, the products designed in the past at Elettra Sincrotrone Trieste to meet the internal needs of the facility, often demonstrated an important market potential. That this is likely to happen also in case of Elettra 2.0 is already confirmed by the external interest in the instrumentation designed for Elettra 2.0. The innovative Electron Beam Position Monitor, A2720 power supply, and the corrector magnets seem to be a good match for the needs of the European Spallation Source, the Extreme Light Infrastructure, Solaris, SESAME, and many other large scale infrastructure under development worldwide.

25.3.1 MAGNETIC DEVICES AND POWER SUPPLIES

Elettra 2.0 magnets will be in general stronger than those of the present Elettra storage ring, and will be designed with air-cooled coils. It is estimated that they will consume only 10% of the current energy consumption, which will make this "greener" technology attractive also to other large scale facilities. For the needs of Elettra 2.0, a new and improved laboratory for magnet characterization and alignment will be established, making available services that could be offered to industry and other research facilities.

The design of the magnets has a direct and strong influence on the design of the power supplies. Elettra Sincrotrone Trieste has a long tradition in power supply development and more than 300 units of different power supply models have directly been sold in the past ten years to different laboratories and facilities around the globe. This number does not include the power supplies was sold by licensing the products to CAEN. One of the major strengths of the new models developed for Elettra 2.0 is high-performance interface with the control and protection systems.

25.3.2 RF SYSTEMS

The RF cavities developed for the current Elettra storage ring are highly reliable and have been sold to other facilities around the world, including ALBA, CAT, and SESAME. The model under development for the new DSRL source is based on the existing technology upgraded with a new mode-suppression function ensuring higher efficiency and high performance. A new digital Low Lever RF system is also being developed that could be offered to similar facilities around the world.
25.3.3 DIAGNOSTICS

Among the different diagnostics tools the beam position monitors (BPM) are the most important diagnostic system in the machine. Thus Elettra decided to develop a new BPM system to be used for Elettra 2.0 and for the potential upgrade of the existing FERMI BPM system. With the innovative approach which successfully overcomes the limitations of existing commercial systems, the Elettra BPM could be deployed on the future DSLR light sources as well as for the BPM upgrade of the current machines.

25.3.4 CONTROL SYSTEM

The Elettra 2.0 control system will be based on the ultimate technologies in the field of electronics and information and communication technology (ICT). The system architecture and the hardware/software solutions adopted will assure a complete control of all the devices connected to the control system. Concepts of Smart Production and Smart Services typical of Industry 4.0 development program will be the base of the implementation.

The Internet-of-Things (IOT) ideas will also be adopted. The same philosophy will be utilized for the plants in charge of the production and distribution of energy in the laboratory, where several sources and consumers of energy will be connected in a Smart Grid with the goal to improve the efficiency and reduce the costs and the carbon footprint.

Collaborations and synergies could be established with other European research institutes and with industries interested in developing innovative technologies. On the other hand, companies, which do not have the necessary resources for the R&D programs in this field, could benefit from the developed technologies to improve their production processes according to Industry 4.0 strategies.

25.3.5 BIG DATA

Possible industrial/commercial outcomes of the scientific data acquisition, analysis and management may span from new methodologies for scientific data and big data storage, compression and transport to the development of brand new algorithms for scientific data processing in fields such as computerized tomography, coherent diffractive imaging and, in general, new tools for scientific computing and data analysis based on artificial intelligence and machine learning.

25.3.6 DETECTORS

Elettra Sincrotrone Trieste has always excelled in detector development, and has sold several of its detectors to different European facilities. The 3D Cross-Delay Line Detectors as well as the cutting-edge Diamond Detectors and Silicon Drift Detectors, which are currently under development for the needs of Elettra 2.0 upgrade, have an important market potential.
26. IMPLEMENTATION
   (OMITTED)
27. DISMANTLING AND INSTALLATIONS
   (OMITTED)
28. COMMISSIONING
   (OMITTED)
29. PRELIMINARY COST AND MANPOWER ESTIMATES
   (OMITTED)