A MULTISTAGE HGHG-SCHEME FOR THE BESSY SOFT X-RAY FEL MULTIUSER FACILITY*

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Abstract

2nd generation FEL facilities in the VUV to soft X-ray range delivering reproducible ultra short photon pulses at an energy level of mJ/pulse will open up new physical frontiers. Tuneability of photon-wavelength and variable beam polarization as well as synchronization to external lasers will be essential for the future ultra-fast time-resolved pump-probe experiments utilizing these novel FEL base synchrotron light sources. Furthermore, using a RF photoinjector in combination with a CW superconducting (s.c.) linac, free selectable pulse repetition rates and pulse pattern can be realized. Distributing the electron bunches to different FEL-lines allows effective multi-user operation.

Following this approach BESSY proposes a soft X-ray HGHG-FEL multi-user facility for the VUV to soft X-ray range.

INTRODUCTION

Ultra-short pulses from free electron lasers will be *the* tool in future time-resolved fs-physics experiments. However there is an on-going debate on the best FEL scheme how to derive intrinsic stable photon beam as is mandatory for any future multi-user FEL facility. The cascaded High-Gain-Harmonic-Generation (HGHG)-FEL scheme as pioneered by BNL [1], is the most promising scheme in achieving high performance reproducible and stable fs-photon pulses in the soft X-ray wavelength range $\lambda \leq 1.2$ nm, i.e. photon energies up to 1 keV.

In the HGHG approach a seed from an external high power fs-laser co-propagates with the electron bunch through an undulator (modulator), modulating the electron energy if the resonance condition

$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left(1 + K^2\right)$$

is met, where λ_L denotes the laser wavelength, λ_U is the undulators period, γ is the electron Lorentz factor and K the undulator field parameter. The imprinted energy modulation has a period length equal to the laser wavelength λ_L and an envelope corresponding to the seed pulse, increased by the slippage of electrons relative to the laser field over the N_U undulator periods.

In a following dispersive section the energy modulation is transferred into a spatial density modulation. The bunching structure reflects the laser fundamental wavelength and its harmonics $h \cdot \lambda_L$. In a second undulator (radiator), tuned to be in resonance to a specific harmonic $n \cdot \lambda_L$, the micro-bunches will emit coherently when the modulation depth $\Delta\gamma$ fulfills the condition $\Delta\gamma \geq n\sigma_\gamma$, where σ_γ is the electron beam energy spread. The resulting photon output is used as the seed field of a next HGHG stage.

Thus the stages consist of a sequence of modulator - dispersive section - radiator, the last stage followed by a final amplifier. In this long undulator, the FEL amplification process is brought to saturation at the desired wavelength.

Generation of stable ultra-short photon pulses thus is the result of the high-quality characteristics of the external optical fs-seed pulse in the first HGHG-stage dominating the statistical noise features from self amplified spontaneous emission.

Two to four HGHG stages are needed to down-convert the seed laser wavelength from the tunable frequency multiplied high power fs-Ti:Sa laser ($\lambda \approx 230$ - 460 nm) to the desired range in the FEL-lines.

To avoid degradation of the FEL process in the various HGHG stages of the cascade, the "fresh bunch technique" [2] is applied, i.e. the photon field and the interacting electrons are delayed with respect to each other. Thus there is always a new, "unused" part of the

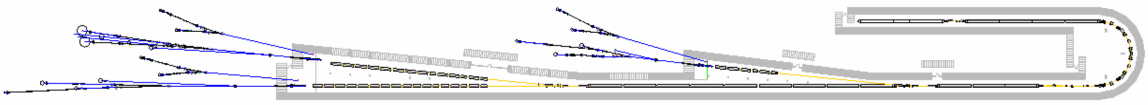

Fig. 1: Foot print of the BESSY soft X-ray user facility with three independent FEL-lines serving three beam lines each. The total length of the facility is approximately 400 m.

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electron bunch interacting with the electromagnetic field from the preceding HGHG-stage.

THE BESSY SOFT X-RAY USER FACILITY

The Technical Design Report for the BESSY Soft X-ray FEL based on the multi-staged HGHG scheme was published recently [3]. This FEL-user facility will operate three FEL-lines in parallel, spanning the photon energies 24 eV – 120 eV, 100 eV – 600 eV and 500 eV– 1000 eV, delivering pulses of ≤ 20 fs (fwhm) duration at variable beam polarization. Fig. 1 gives a foot print of the machine layout.

A superconducting 2.3 GeV CW-linac is used as driver in the FEL process. In combination with an injector (1 kHz repetition rate, to be replaced by a superconducting photoinjector at a later stage of the project) high flexibility is achieved with respect to pulse repetition rate and pulse pattern, providing the opportunity to adjust to the experimenters specific needs.

FEL Output Simulations

To derive detailed information on the photon beam properties, time-dependent simulations have been performed in a start-to-end approach [4,5], using a modified version of GENESIS 1.3 [6]. Typical results of time resolved power distribution and spectral power distribution as calculated for the low-energy and medium-energy FEL-lines are depicted in figure 2.

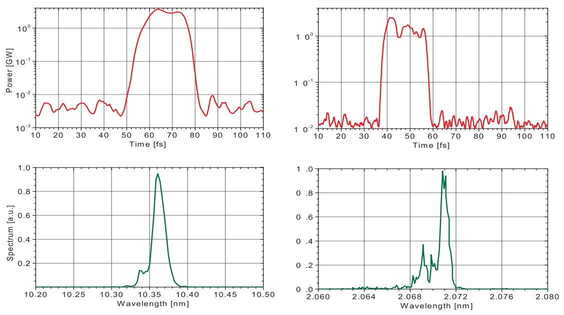

Figure 2: Time-resolved power distribution (top) and spectral power distribution (bottom) calculated for the low-energy and medium energy FEL at wavelength of 10 and 2 nm .

The calculations correspond to the high energy end of the two and three fold staged FEL-lines, corresponding to a wavelength of 10.3, and 2.0 nm. In all cases a 17 fs (rms) Gaussian seed pulse of 500 MW peak power was assumed.

The simulation results show a constant power level and a reasonable clean spectrum for the FEL photon beam. However, as the interacting electrons experience a non-constant seed due to the seed pulse shape and the slippage effect, the energy modulation imprinted in the modulators differs along the interacting part of the electron beam. Optimizing for maximum photon beam brilliance, those electrons corresponding to the seed pulse center typically will be overbunched when having passed the dispersive section and thus perform synchrotron oscillations in the ponderomotive bucket. As a result sidebands are generated in the spectral distribution. These sidebands which are pronounced only at the low energy part of the spectrum due to the slippage effect. This effect repeats in the following HGHG-stages. Thus the higher the number of stages the sideband structure becomes more and more complex and pronounced. Means to suppress the effect are described elsewhere [7].

Based on the simulation results the main performance parameters of the BESSY-FEL are listed in table 1. Comparing the FEL parameters to a 3rd generation light source as BESSY II, the gain in peak brilliance is more than 10 orders in magnitude.

Table 1: Main performance parameters of the BESSY X-FEL. Values in brackets refer to an s.c. injector as planned at a later phase of the project.

Parameter	**Value**	**Unit**
No. of FEL lines	3	
No of beamlines	9 (15)	
Electron energy	2.3	GeV
Emittance	1.5	π mm mrad
Bunch length	290	µm
Peak current	1.75	kA
Beam power	18 (150)	kW
Wavelength range	51 – 1.24	nm
Photon peak power	1.5 – 14	GW
Ave. Power	0.26 – 0.02	W
Beam size	14 – 160	µm
Divergence	27 – 140	µrad
Pulse duration	< 20	fs
No. of pulses in train	3 (1)	
Repetition rate	1 (25)	kHz
No of photons/pulse	$2{\cdot}10^{11} – 7 \cdot 10^{13}$	
Peak brilliance	$6{\cdot}10^{29} – 1.3 \cdot 10^{31}$	(s mrad^2 mm^2 0.1% bw)$^{-1}$

The RF-Photoinjector

Operation of the BESSY-FEL is planned at a 1 kHz repetition frequency at the three FEL-lines. Thus the injector has to deliver bunch trains containing three single bunches. The spacing of bunches will be 3 µs, a compromise between an acceptable duty cycle of the room-temperature gun cavity and the demands on the linac RF-system with respect to beam loading.

To generate the electron bunches at a charge of 2.5 nC a RF photoinjector based on the PITZ design [8] is intended to be used. Calculations show that with a short rise and decay time of about 3 ps and a 40 ps “flat-top” intensity profile photocathode laser-pulse a normalized slice emittance of less than 1.5 π mm mrad can be achieved [9]. Thus the PITZ-type photogun modified to higher repetition rates will be the technical starting point for the BESSY-FEL.

However, a superconducting RF-gun, as is presently under construction by a FZR-BESSY-MBI-DESY consortium, will replace the injector later on.

The CW-Linac

The superconducting acceleration structures are based on the TESLA linear collider modules that have demonstrated reliable operation at TTF [10]. The TESLA modules consist of eight niobium 9-cell cavities, each module being 12 m long. 18 modules are needed for the 220 m long 2.3 GeV linac. The operation field of ~16 MV/m CW is the economical optimum with respect to investments and long-term operation costs. Minor modifications are required to adapt the (pulsed) TESLA technology for CW. The changes are due to the increased He-flux from the cavities (20.5 W/cavity) requiring a modest enlargement of the two-phase He supply line.

To confirm the basis for a reliable CW operation an detailed qualification program started at BESSY. Test of couplers and tuners, optimization of cryogenic parameters such as bath temperature are performed. For this purpose a Horizontal Bi-Cavity Test facility (HoBiCaT) has been set up [11].

Tests of new concepts for damping microphonics - most important in our CW operation - are under preparation. The test bench also will allow optimization at realistic conditions during RF source development, allowing for a cost-optimized specification for the 144 units of 1.3 GHz-power sources. Commissioning of the bench is in progress. 1.8 K LHe is provided from an existing Linde TCF50 cryogenic plant connected to a pumping station.

Two 9-cell cavities completely manufactured and processed by industry have been delivered and are available now for testing.

The Beam Delivery System

A kicker system will be used to extract single bunches from the main linac into the low and medium energy FEL-lines at beam energies of 1.0 and 2.3 GeV respectively. Extreme tight tolerances in the order of $\Delta\theta/\theta \approx 5\cdot10^{-5}$ are required on the relative stability and reproducibility of the extraction angle θ.

As the kicker stability is determined primarily by the power converter, a pulser design was developed based on IGBT power semiconductors.

After careful design of the pulser geometry to minimize intrinsic inductivities and optimization of grounding, the measurements revealed a peak to peak stability of $\Delta\theta/\theta \leq 5\cdot10^{-5}$ of the system over a time scale of hours[12]. Figure 3 depicts a single kicker pulse as generated by the new pulser. The pulser repetition rate is 1 kHz, the pulse width less than 3 µs, compatible with the bunch spacing.

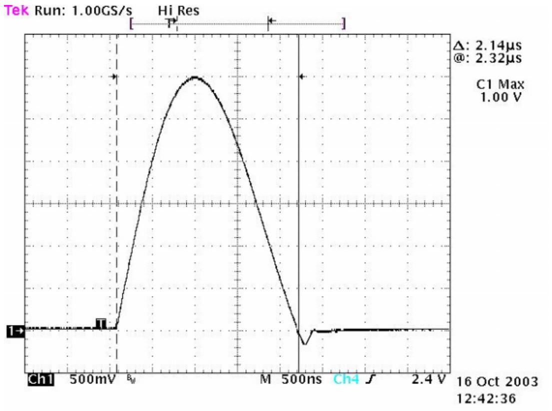

Figure 3: Single pulse as achieved with the new high stability pulser.

The Beam Collimation

Beam collimation to protect the undulators modules from electron losses and dark-current will be achieved by a compact 43 m long dedicated beamline between linac and undulators sections. The collimator acts as transverse and longitudinal phase space filter avoiding degradation of the radiation sensitive NdFeB undulator structures. For transverse collimation round apertures in absorber blocks are used. Particles outside the tolerable transverse acceptance intercept the absorbers.

Energy collimation is achieved with apertures located in a closed dispersion bump in a dogleg structure. The present system[13] is optimized for an acceptance bandwidth of 5% in energy spread.

The Undulator Sections

For the three FEL-lines in total 120 m of undulators of different period lengths is needed to ensure a proper matching between modulator and radiator of the various stages, ranging from λ_u = 122 mm to 28.5 mm. A minimum gap of 10 mm is sufficient to cover the full wavelength range. In each case the undulators are variable gap devices, the radiators of the last HGHG-stage and the final amplifier undulators will follow the elliptical permanent magnet design now known as APPLE III design.

The modulators are very short undulators (< 3 m each). The radiators and final amplifiers however will be built up from segments of typically 3.5 m in length. These segments are spaced by 0.95 m long intersections equipped with phase shifters, focusing quadrupole magnets, steering elements, vacuum pumps and a variety of diagnostic elements as OTR, wire scanner and beam position monitors for beam characterization and manipulation, see figure 4.

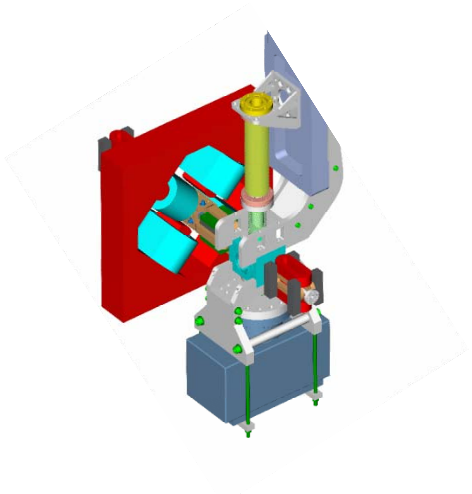

Figure 4: 3-D model of the compact intersection region with components for beam focusing, steering, diagnostics and vacuum pumps.

Special attention has been paid to the undulator vacuum chamber to avoid beam degradation arising from wakefields. An all Cu-vacuum chamber with a beam duct of surface roughness < 100 nm (rms) is favored for the design.

Beamlines

The three FELs will be equipped with three beamlines each: optimized for high resolution experiments, a "white light" beamline without any monochromatization and a high intensity station conserving the short pulse structure of the FEL beam. Table 1 gives the main parameters for the high-energy (HE) FEL beamlines as an example. Data were calculated from detailed ray-tracing.

Dedicated undulators using the spent beam from the FEL are planned at a later phase of the project.

Table 1: Main parameters for the HE-FEL beamlines.

Beamline	Bandwidth (meV)	Pulse length (fs)	Pulse energy (nJ)	Energy density (mJ/cm^2)
High resolution	20 - 33	650 – 120	2.4 – 10	0.23 – 1.4
White light	2000	10	11000	120000
Short pulse	800	11	600	250
FEL output	2000	10	15000	1000

CONCLUSIONS AND OUTLOOK

The proposed seeded soft X-ray FEL facility ideally will complement the 3rd generation synchrotron light source BESSY II. The machine is based on existing technology making use of hardware developments for high energy physics colliders and/or hard X-ray FELs.

Future options such as seeding with future intense short-wavelength High Harmonic Generation (HHG) lasers (λ ~ 30 nm) as well as options to expand the number of FEL-lines from three to five have been incorporated into the design of the soft X-ray FEL.

The flexibility of the CW-accelerator together with features as continuous wavelength tuning, variable beam polarization, will efficiently open-up the field of ultra-fast time resolved spectroscopy allowing to take advantage of the specific characteristic of seeded FELs, i.e. transverse and longitudinal coherence of ultra-short pulses at highest peak brilliance.

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