The FERMI project @ Elettra: radiation protection and safety issues

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Abstract

FERMI is a fourth generation light source under construction at the Sincrotrone Trieste laboratory, close to the Elettra synchrotron light source. It will be a single-pass seeded FEL, based upon the conversion of the 1.2 GeV linac used in the past as injector of the Elettra storage ring and recently replaced with a full energy booster synchrotron.

The FEL will operate in the wavelength ranges 120 nm ÷ 40 nm in the first phase, 25 nm ÷ 5 nm in the second one.

The original layout of the linac has been deeply modified with the addition of seven new accelerating sections received from CERN, the substitution of the conventional termoionic gun with a new photoinjector and the installation of two bunch compressors systems. In order to fulfill the stringent requirements of the project, the machine will be equipped with an energy feedback system and a high accuracy low level RF system, capable of reaching very accurate stabilities in terms of RF phase and amplitude. The machine will operate in a single bunch at 50 Hz.

The linac is housed in an underground tunnel 180 m long. The earth provides for the lateral shielding. The undulator and experimental halls under development downstream of the accelerator tunnel are at the same underground level. At the end of the undulator hall, 100 m long, a set of bending and focusing magnets transport the beam to the beamdump, while the produced FEL light continues in the forward direction and is extracted through the front-end. In the experimental hall, the first part of the beamlines, including the first two optics components, are enclosed inside a shielded hutch.

The yearly dose limits we enforced for *free*, *supervised* and *controlled* areas are 0.5 mSv, 2 mSv and 5 mSv respectively, compared to the corresponding limits of 1 mSv, 6 mSv and 20 mSv established by Italian regulations in compliance with the European/Euratom directives. The classification of different areas around the accelerator will be presented.

Similarly to the Elettra facility, the personnel safety system will be based on low level computers, Programmable Logic Controllers (PLCs), chosen with high safety level programmed with *fail safe* logic and redundancy in controls using, where possible, diverse criteria in the choice of the actuators. The logic of the safety system will be discussed.

Environmental monitoring outside the tunnels will be based on a network of gamma and neutron detectors located at some reference points in the experimental hall and in the undulator Service Area. In addition, some gamma monitors located in the vicinities of the beamlines exits will be interlocked with the personnel safety system to prevent unwanted exposures to personnel.

1. Introduction

The original layout of Elettra was based on a 1.2 GeV, 10 Hz, electron Linac operating as an injector for the Elettra storage ring. Injection operation was carried out with all the beamlines beam stoppers closed and all the front-end hutches searched: the energy of the injected beam was then ramped inside the storage ring up to 2.0 GeV (with a stored current of 320 mA) or up to 2.4 GeV (with a stored current of 140 mA), according to the users'shifts calendar.

To permit full energy injection and top-up operation the project of a new injector, consisting of a 100 MeV 3Hz linac pre-injector and a 2.5 GeV booster, started in March 2005 [1].

The design and construction of the new injector lasted about 3 years: the "old" linac was shut off in October 2007 and from March 3rd 2008, after the connection of the booster with the storage ring, Elettra storage ring was again operating for the users with the new injector. From The October 2007 a phase of revision and upgrading of the "old" linac started, to permit its re-utilization for the FERMI project.

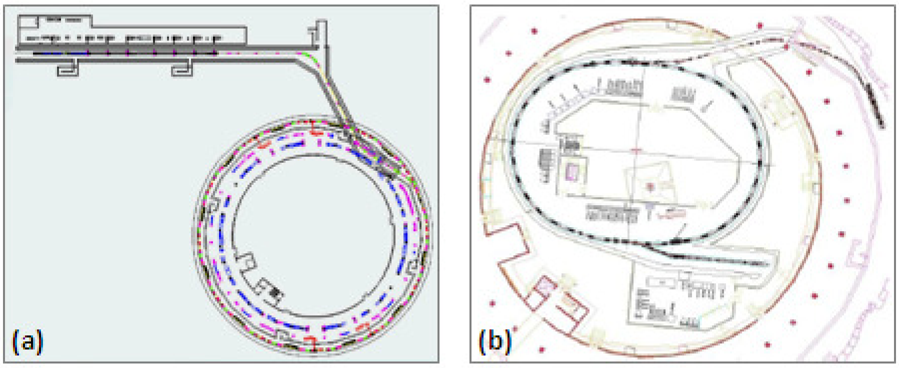


Fig.1 - The original Elettra layout with the old linac (a) and the new booster injector layout (b).

2. The main features of the FERMI project

The FERMI@Elettra light source is a high brilliance 4th generation, single-pass seeded FEL, based upon the re-utilization of the "old" 1.2 GeV Elettra linac. It has been designed to accelerate electrons up to 2.0 GeV at 0.1 μA maximum average current and optimized to produce FEL beams in two fundamental wavelength ranges: 100÷20 nm (FEL1) and 20÷3 nm (FEL2). The whole accelerator is housed in an underground tunnel.

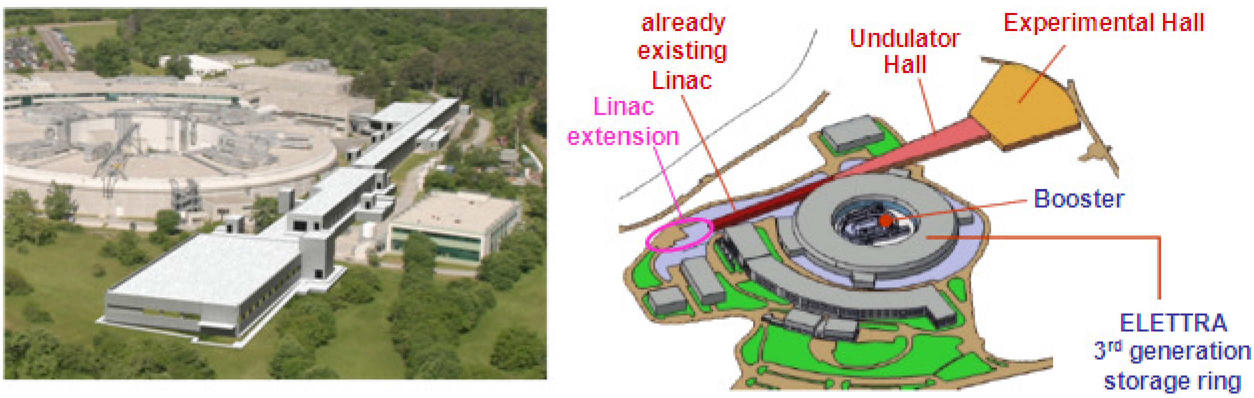


Fig.2 - The FERMI building project.

As far as the logic of the safety system is concerned, the FERMI accelerator will be divided into three main areas: the *Linac*, where the electron beam is produced and accelerated up to the maximum energy, the *Undulator Hall* where the electrons interact with the magnetic field of the undulators producing the FEL beams, and the *Experimental Hall* where the FEL beams are extracted and utilized by researchers.
A Personnel Safety System will assure safety conditions for personnel entering the accelerator tunnels and for the Experimental Hall users. It will be based on a Siemens SIMATIC S7 Programmable Logic Controller (PLC) of high safety level (Category 4). The main safety criteria that will be applied are redundancy (e.g. double door switches), diversification of actuators/controls (e.g. double and different technology switches for all the beam stoppers), and fail-safe logic.

2.1. The Linac

With the development of the FERMI project, the layout of the pre-existing linac will be deeply modified: the original gallery will be extended (upstream the already existing tunnel, as shown in Fig.2), to permit the installation of seven new accelerating sections donated by CERN and of all the new machine components. The termoionic gun will be substituted with a high brightness photoinjector developed in collaboration with MAX-lab and the Particle Beam Physics Laboratory at UCLA [2].
To operate the new accelerator at 50 Hz, instead of the original 10 Hz, eight new TH2132 klystron modulators will add to the previous seven and new RF plants will be installed. Two diagnostic lines at 100 MeV and at 300 MeV will be constructed in the first part of the tunnel to characterize the beam.

At the end of the linac sections, the beam, accelerated up to the maximum energy, will be transported to the the Undulator Hall or will be bended along a further diagnostic line (i.e. the original linac-to-ring transfer line) ending with a beam dump (see Fig.3).
A beam stopper (BST_{Linac}) placed at the end of the linac sections will permit to stop the electrons within the linac area and will be utilized in the definition of the personnel safety condition for entering inside the Experimental Hal front-end hutch (see Paragraph 2.3).
The linac gallery will have an entrance door, which will work also as emergency exit, and four emergency exits, all controlled by the Personnel Safety System. A door that can be opened only from the tunnel inside, positioned at the beginning of the tunnel, will permit to move inside the gallery the most bulky machine components.
Access inside the tunnel will be inhibited by the Personnel Safety System if radiofrequency is applied to the photo-injector RF cavity or to the accelerating sections. Once the radiofrequency is shut off, the person who wants to enter the accelerator gallery will have to pass an authorized badge in the badge reader next to the door, extract the safety key unlocked by the Personnel Safety System, wait for the final assent given by the control room operator who unlocks the door after recognizing the person through a camera, open the door, enter, close the door and deposit the key in the internal key panel.
As long as a safety key is present in the internal key panel or extracted from the external one and as long as a name results in the PLC presence list, the Personnel Safety System will prevent the control room operator from applying radiofrequency to the photo-injector RF cavity or to the accelerating sections.
A search procedure will guarantee that nobody remains inside the machine tunnel after the shutdown periods.

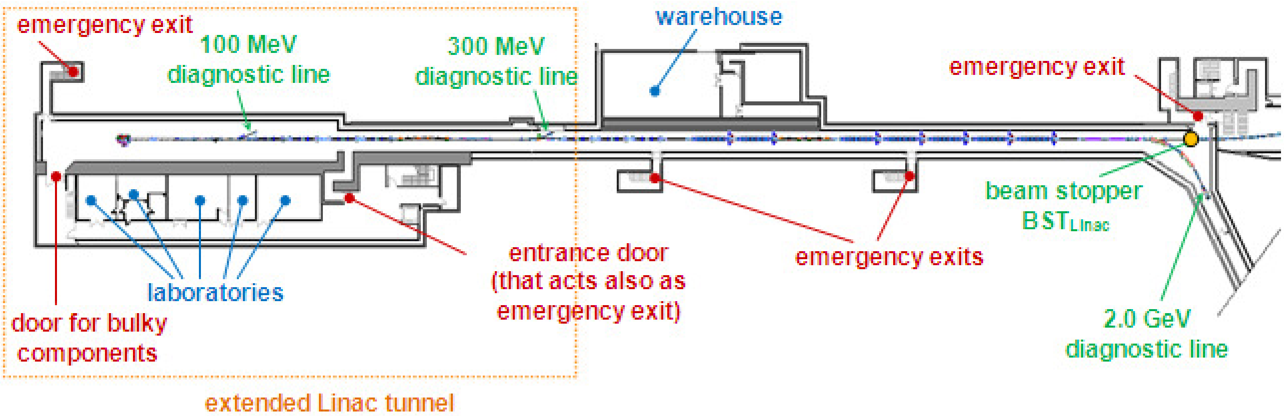


Fig.3 - The FERMI Linac project.

The part of the machine tunnel already constructed is shielded laterally by earth and on the roof with 2 m ordinary concrete (ρ = 2.3g/cm^3) in the first part (where electron energy reaches 0 ÷ 600MeV) and with 0.65 m ordinary concrete plus 1.35 heavy concrete (ρ = 3.6 g/cm^3) in the second part (where the beam can be accelerated up to 2.0 GeV). As far as shielding calculation is concerned, the parameters taken in consideration for the original linac design (1992) are listed in the following table.

maximum acceleration energy	2 GeV
maximum average current:	0.1 µA
acceleration efficiency along the sections	20%
beam loss scenario	continuous total beam loss at the end of the linac if the beam was not correctly bended along the linac-to-ring transfer-line
occupancy factor for the free areas outside the tunnel	1
dose limit for the free areas	0.1 mSv/year

Table 1 - FERMI parameters for shielding calculation.

On the right side of the linac extended tunnel, beyond the shielding wall, some laboratories (photo-injector laser beam, timing, vacuum, etc.) will be located, to be classified as free areas with full occupancy factor (see Fig.2). On the roof an extension of the already built klystron gallery will be constructed, to be classified as free area (exception done for the fenced areas next to the klystron modulators when switched on).

As a result, the extended tunnel shielding design provides for a 2 m ordinary concrete wall on the right side and 2 m ordinary concrete roof.

2.2. The Undulator Hall

As far as the Undulator Hall is concerned, the parameters taken in account for the shielding calculation are the same as for the Linac in terms of maximum energy and current. The laboratories to be constructed over the first part of the Undulator Hall roof (Laser laboratory and Service Area) will be free areas with full occupancy factor. The roof will be shielded with 2.55 m ordinary concrete, the tunnel will be laterally shielded by earth, and a wall of 3 m will separate the Undulator Hall from the Experimental Hall (see Fig.4).

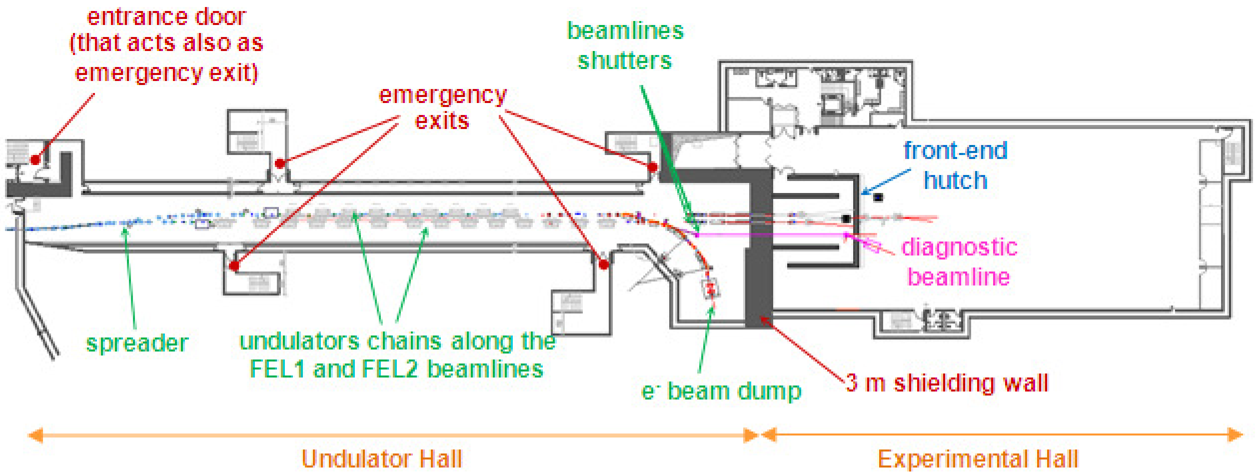


Fig.4 - The Undulator Hall and the Experimental Hall.

The electron beam, channelled alternatively along the FEL1 or FEL2 beamline through a set of bending and focusing magnets (*spreader*), will interact with the magnetic field of the undulator chains to produce the FEL radiation. At the exit of the undulators, the electrons will be transported towards the beam dump whereas the FEL beams will be extracted through the front-end wall.
The Personnel Safety System will check the correct bending of the electron beam towards the beam dump, by continuously monitoring the current of the bending magnets (to stop the beam in case of failure) and by continuously comparing the current measured by a toroid placed at the end of each undulator chain with the current detected by a toroid placed at the end of the final beam dump transfer-line. Two permanent magnets, positioned along the FEL1 and the FEL2 beamline, after the bending of the electron beam towards the beam dump, will prevent accidental electrons channeling into the beamlines.
Each beamline will have two tungsten shutters placed upstream the 3 m shielding wall.
A specific diagnostic beamline, named "High energy streak camera optical transport line" and indicated in pink in Fig.4, will utilize the visible radiation produced by the electrons bended towards the beam dump at the exit of the undulator chains, to monitor the longitudinal stability of the electron beam and, as a consequence, the FEL photon pulse stability.

The Undulator Hall tunnel will have one entrance door and five emergency exits. The enter the tunnel the same safety conditions provided for the Linac access will have to be fulfilled. A search procedure will guarantee that nobody remains inside the machine gallery after the shutdown periods.

2.3. The Experimental Hall

Besides the diagnostic beamline described before, the Experimental Hall will host 3 beamlines: DIPROI (DIffraction and PROjection Imaging), EIS (Elastic and Inelastic Scattering) and LDM (Low Density Matter).

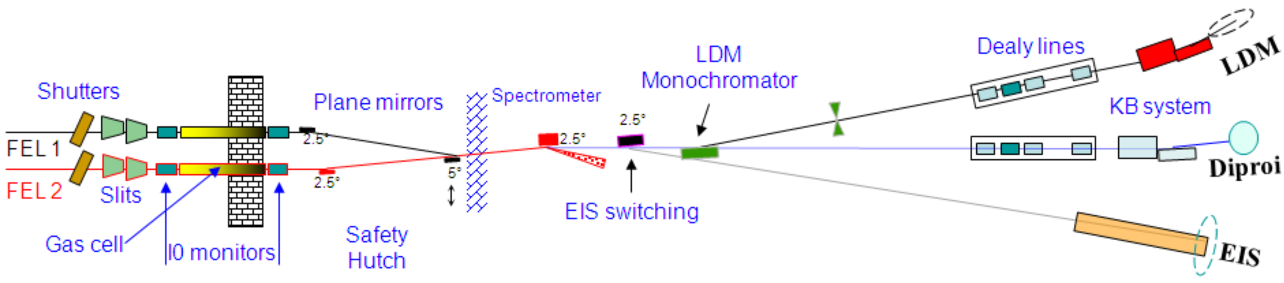


Fig.5 - FERMI beamlines.

The first part of the beamlines, including the first two optics components, will be enclosed inside a front-end hutch shielded laterally with 0.60 m ordinary concrete and in the forward direction with 0.80 m ordinary concrete.
Access inside the hutch will be inhibited by the Personnel Safety System if the linac beam stopper BST_{Linac} is open or if one of the the beamline radiation monitors, placed just outside the front-end hutch, will detect a level of radiation exceeding a fixed threshold. To enter the hutch, the operator will have to insert a safety key in a panel to unlock a second key to open the door. A search procedure is provided to be sure that nobody remains inside the hutch before starting operations with the beam.
The Personnel Safety System will permit to extract FEL radiation inside the front-end hutch only if a set of satety conditions will be fulfilled: the hutch must be searched, the beamline monitors must work correctly and detect no alarm radiation dose rate, the electron beam must be correctly bended towards the beam dump at the end of the Undulator Hall.

3. Radiation protection criteria and dose limits

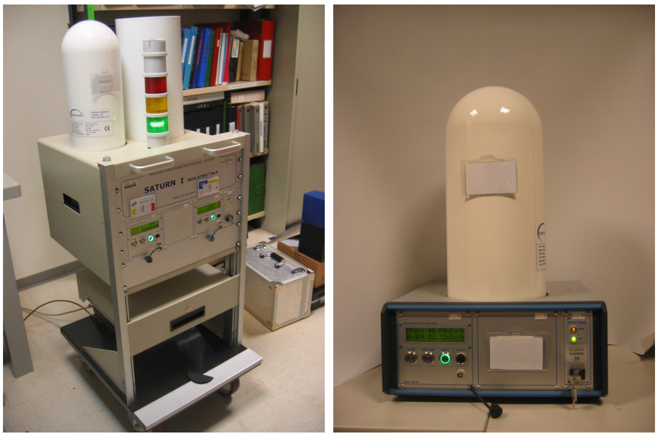
The areas classification and the provided dose limits are listed in the following table.

Area classification	Areas description	Target limit	Dose limit provided by Italian law
Controlled areas	Machine tunnel with linac in stand-by (access controlled by safety system), delimited areas close to activated components and beam dumps, delimited zones around klystron modulators	5 mSv	20 mSv
Free (not classified)	Experimental hall - low permanence areas	0.5 mSv	1 mSv
Free (not classified)	Experimental hall - user stations Laser hall and Service area during normal operation	0.1 mSv	1 mSv

Table 2 - Areas classification and dose limits.

4. Radiation monitoring

Environmental radiation monitoring will be based on El.Se. S.r.l. gamma/neutron monitors (16 atm pressurized argon-nitrogen ionization chambers plus BF3 rem counters) and on passive thermoluminescence dosimeters (GR200A TLDs).
A gamma monitor will be placed outside the Experimental Hall front-end hutch along each beamline and will be connected to the Personnel Safety System. If a pre-fixed threshold limit dose will be exceeded, the Personnel Safety System will close the BST_{Linac}, the beamlines beamstoppers and will inhibit the photo-injector cavity radiofrequency.
The response of these ionization chambers to pulsed gamma radiation field has been tested inside the “old” Elettra linac tunnel before its shutting off [3].



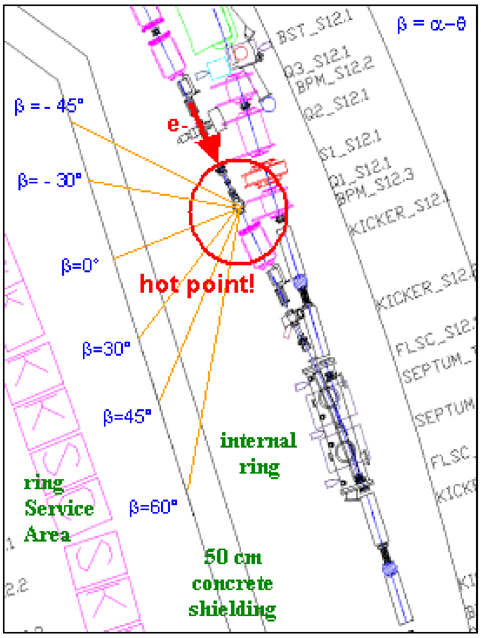
Characteristics of the gamma ionization chambers
- model: Centronic Mod. IG5
- response as a function of energy:
  - 80keV÷120keV: ±20%
  - 120keV÷2MeV: ±5%
- equivalent doserate range: 0.01µSv/h÷0.1Sv/h
- environmental conditions: 0÷50°C
- precision on environmental doserate measurements: ±5%
- automatic change of scale based on microprocessor

Characteristics of the neutron rem counters
- model: FAG Biorem

Fig.6 - The gamma/neutron monitors that will be utilized for FERMI environmental dosimetry.

5. First benchmark of Geant 4 simulation code

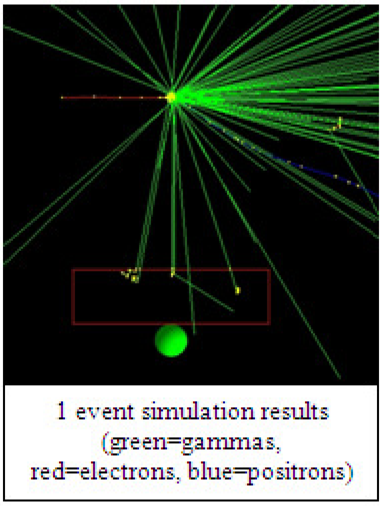
To face some of the future tasks (e.g. the calculation of the shielding around the first mirror in the Experimental Hall front-end hutch), a Monte Carlo code based on Geant 4 will be developped.
To calculate the shielding thickness needed for the FERMI accelerator, semi-empirical formulas were utilized [4-6], validated in the past by experimental measurements carried out inside the Elettra storage ring service area. The details of the experiments are described in reference [7].
The gamma radiation field produced by the 900 MeV electron beam impinging on a ring beamstopper was measured at different angles through a PTW Freiburg (model 32003 - volume 10000 cm^3) ionization chamber placed beyond the Service Area shielding wall (see Fig.7).



target material (beam stopper)	copper
target shape	cylinder
target radius r	4 cm
target thickness t	8 cm
target attenuation coefficient μ_1	0.271 cm^{-1}
radiation length in target X_0	1.45 cm
shielding material	ordinary concrete (ρ = 2.35 g/cm^3)
α	98°
distance target-shielding a at 90°	183.6 cm
shielding attenuation coefficient μ_2	0.053 cm^{-1}
shielding thickness d at 90°	50 cm

Fig.7 - Layout of the experimental measurements described in reference [7].

The same geometry was simulated with Geant 4 toolkit to construct a benchmark with semi-empirical formulas and experimental measurements.
An appropriate Geant 4 physics list including electromagnetic, low energy neutron and hadronic processes was selected. The detector was simulated as a water sphere of 30 cm diameter. The dose was calculated from the energy deposited by secondary charged particles produced by primary gammas and neutrons. Results at β=0° (Fig.7) are shown in the following figures.



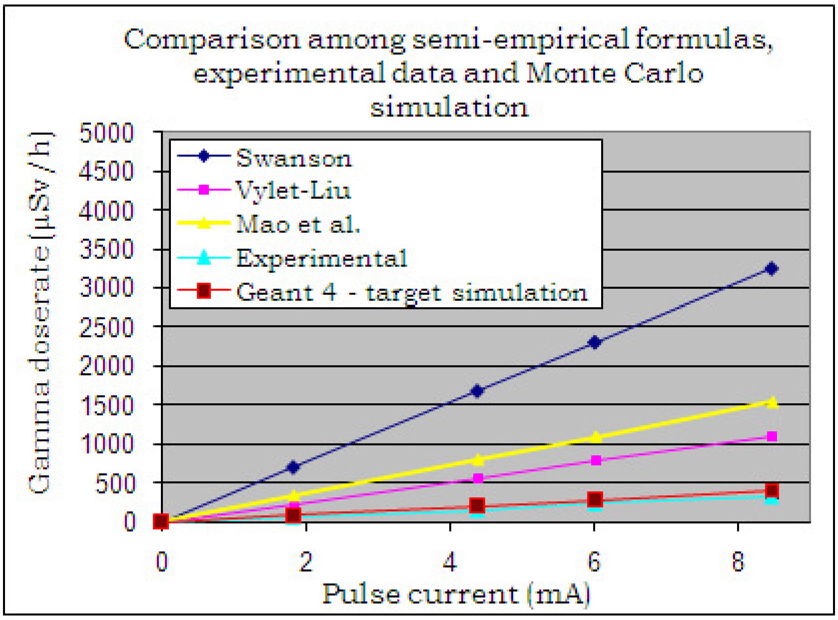


Fig.8 - Preliminary benchmark of semi-empirical formulas and experimental measurements with Geant 4 simulation.

6. Summary and perspectives

The FERMI@Elettra light source is now under construction at Elettra and will accelerate an electron beam up to 2.0 GeV at a maximum current of 0.1 μA to produce high brilliance FEL beams: main shielding design, Personnel Safety System interlocks and gamma radiation monitors for environmental radiation dosimetry have been described and discussed. To face the future tasks (e.g. the calculation of the shielding around the first mirror in the Experimental Hall front-end hutch) we have started to develop a Monte Carlo code able to simulate complex geometries. Preliminary results obtained with Geant 4 toolkit have been described and the study is now in progress.

References

[1] M. Svandrlik, "Overview of the status of the Elettra booster project", Proceedings of EPAC08, Genoa, Italy, 2201-2203.
[2] M.Trovò *et al.*, "Status of the FERMI@Elettra photoinjector", Proceedings of EPAC08, Genoa, Italy, 247-249.
[3] A. Vascotto *et al.*, "Development and Experimental Performance Evaluation of a Dose-Rate meter for Pulsed Beam", these proceedings
[4] W. P. Swanson, "Radiological safety aspects of the operation of electron linear accelerators", Technical Reports Series n.188, IAEA, 1979
[5] X. S. Mao *et al.*, "90 degrees Bremsstrahlung Source Term Produced in Thick Targets by 50 MeV to 10 GeV Electrons", SLAC-PUB-7722, 2000
[6] V. Vylet and J. C. Liu, "Radiation Protection at high energy electron accelerators", Rad. Prot. Dos., Vol.96, n.4, 2001
[7] K. Casarin *et al.*, "The new full-energy injector for the Elettra light source", 2nd RADSYNCH International Workshop, Grenoble, 2002.