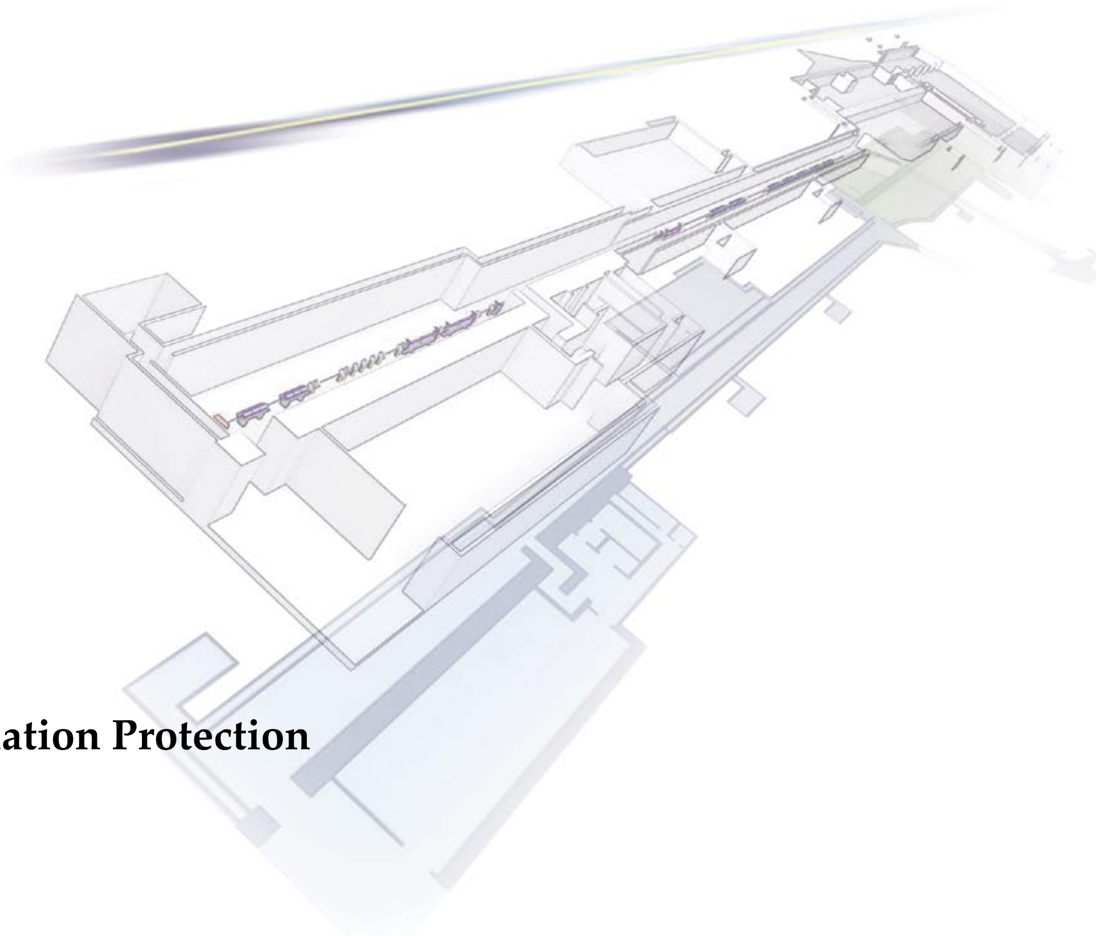

15 Radiation Protection

Synopsis

The main goals of Radiation Protection are to evaluate the ionizing radiation sources produced in the linac and undulator tunnel and in the beamline hutches, to estimate the needed biological shielding barriers and to adopt appropriate safety systems for personnel protection.

In the design of the shielding for FERMI, the different sources of ionizing radiation produced inside the accelerator tunnel have been considered. The radiation intensity depends strongly on the electron beam energy and current and is related to the beam loss frequency and distribution inside the machine.

The evaluation of the shielding thickness has been performed on the basis of semi-empirical expressions available from the literature and that have been validated by experimental measurements performed at ELETTRA during radiation protection surveys.

The goals of dose limits for the various areas around the facility (*free*, *supervised*, and *controlled* areas) are lower than those established by Italian regulations in compliance with the European/Euratom directives.

According to our project goals, only the linac and undulator tunnel will be classified as *controlled area*. The undulator Service Area and seeding laser room will be considered *supervised areas* while the experimental hall outside the beamline hutch will be a *free access area*. Only personnel involved in machine operation will be classified as *radiation workers* and will be monitored using personal dosimeters. The experimental users will be *not classified* from the radiation protection point of view.

Radiation monitoring outside the tunnels will be based on passive dosimeters and on a network of active gamma and neutron detectors located at various points of the experimental hall and of the undulator Service Area. Similarly to the ELETTRA storage ring, radiation monitors will be connected to the radiation safety system and beamlines operation will be prevented if predetermined gamma dose-rate thresholds is exceeded.

15.1 Ionising Radiation Sources

During normal operation of the accelerator, gamma and neutron radiation fields are produced where all or a fraction of the beam is lost, i.e. around beam-stoppers, beam dumps or collimators. In case of malfunctions, beam losses can also be distributed elsewhere, such as along the accelerating sections, around the spreader, or inside magnets.

In addition, high energy gamma rays (the so-called "gas bremsstrahlung") are generated in the interaction of the electron beam with the residual gas inside the vacuum chamber: its intensity is proportional to the vacuum pressure but it is much lower than the radiation intensity produced by beam losses, therefore it does not determine the accelerator shielding thickness.

Gas Bremsstrahlung is produced mainly in the forward direction and is transported through the beam pipe outside the shielding, together with FEL radiation. Since this radiation is very penetrating, it must be taken into account in the shielding evaluation of the beamlines hutch, together with high energy scattered radiation produced by beam losses inside the accelerator tunnel.

Synchrotron radiation generated in the bending magnets along the transfer line towards the beam dump can be partially extracted from the accelerator tunnel through the beampipe but it is peaked at lower energies (X-rays) and it does not determine the shielding requirements for the beamline hutches.

The interaction of high energy electrons with matter gives rise to large amounts of secondary particles (gamma rays, electrons, positrons, neutrons) which represent, from the health physics point of view, the effective radiation sources to consider in the shielding calculation.

The products of the electromagnetic cascade generated by the electron beam can be divided into four components:

i) High energy gamma rays (up to the energy of the primary electrons) generated in the electromagnetic cascade initiated by the electrons. The cascade at high energy is peaked mainly in the forward direction; however, lateral and backward components must also be considered.

ii) Medium energy neutrons (up to a few MeV) generated by giant resonance reactions of gamma rays with matter. These neutrons are emitted isotropically from the interaction region.

iii) High energy neutrons (up to a few hundred MeV) produced by gamma ray interactions with nucleus components (quasi-deuteron interactions, photo-pion production). They have a low forward preference; their intensity is much lower than the intensity of medium energy neutrons, but they may determine the shielding thickness in the forward direction as they are far more penetrating.

iv) Muon pairs (μ+/μ-) are produced by gamma rays whose energy is higher than 212 MeV, with a cross section much lower than the e+/e- production. Compared with the gamma component, in the

FERMI energy range the muon intensity is absolutely negligible once the shielding thickness in the forward direction is higher than 1.5 m of ordinary concrete [1].

The interaction of the primary electron beam and of the cascade products with machine components produces radioactive isotopes. The induced radioactivity at FERMI will affect mainly the beam dumps and, in much lower measure, beam-stoppers, collimators, vacuum chamber and IDs. Particular attention will be devoted to the design and fabrication of the beam dumps. They will be limited in number, positioned in areas remote from the machine and shielded locally, in order to reduce as much as possible exposure to personnel accessing the machine tunnel during maintenance periods. The composition and layout of the beam dump targets will be optimized to reduce long-lived radioisotope production and to contain as much as possible the secondary cascade.

15.2 Radiation Shielding

15.2.1 Methods for Shielding Evaluation

The most commonly used method for the evaluation of shielding thickness for an accelerator facility is based on semi-empirical expressions obtained from experimental data of shower production and development. These formulas correlate the beam energy and power with equivalent radiation sources of given intensities produced during the beam losses. Monte Carlo simulation techniques can also be used to simulate beam losses in very simple geometrical configurations and to calculate the consequent dose distribution and propagation.

The shielding for the FERMI facility has been evaluated using some semi-empirical expressions proposed by several authors [1, 7]. Furthermore, radiation measurements performed at ELETTRA during radiation protection surveys have been used as benchmarks.

15.2.2 Accelerator Parameters, Working Factors and Dose Limits

The intensities of radiation sources produced during beam losses depend on the following factors:

- beam characteristics (energy, current, repetition rates),
- beam loss scenarios (acceleration efficiency, faults and malfunctions frequencies, expected duration of beam losses),
- machine use factors and operation modes.

The dose limits for personnel and population established by Italian regulations in compliance with the European/ Euratom instructions, foresee the definition of three areas: **free access areas** (“aree non classificate” or “zone libere”), **supervised areas** ("zone sorvegliate") and **controlled areas** ("zone controllate"). In Table 1.3.1 the dose limits foreseen according to the above regulations, together with our goals for the commissioning and normal operation of the facility, are reported.

Table 1.3.1: Dose limits foreseen fo,r different areas of the FERMI facility.

	Free access areas	Supervised areas	Controlled areas
Italian/European Regulation Dose limits (mSv/year)	1	6	20
Our goals during commissioning (mSv/year)	0.5	4	10
Our goals during normal operations (mSv/year)	0.5	2	5

15.2.3 Shielding Requirements for the Accelerator

The shielding for the roof of the linac was originally designed for a 2 GeV machine with maximum average current of 0.1 μA. With these parameters, assuming operation of the machine as injector of the storage ring, i.e. about 1 hour/day, and producing beam losses at full power into one of the beam-stoppers located along the linac-to-storage ring transfer line, the shielding thickness adopted for the roof was 1.5 m of heavy concrete plus 0.5 m of ordinary concrete. During operation of the FERMI FELs, the beam energy will not exceed 1.2 GeV; however, the machine is foreseen to run continuously with beam losses into the beam dumps. Calculations show that the present shielding thickness for the roof can be maintained provided local shielding is installed around beam dumps, beam-stoppers, collimators and close to other points where part or fraction of beam can be preferably lost. The shielding of the wall at the end of the undulators hall will be fabricated from ordinary concrete with a thickness of 3 m.

15.2.4 Shielding Requirements for the Beamlines

The main source to consider in designing the shielding for the beamline hutches is gas bremsstrahlung. A further contribution could be due to the channeling through the beamline vacuum chamber of the secondary particles (i.e. gammas, electrons and neutrons) produced in unwanted partial beam losses occurring in the undulator hall.

These two radiation components will interact with the first optics elements of the beamlines and further develop downstream. Therefore, the first mirror must produce a deviation of the FEL beam of not less than three degrees so as to intercept most of the high energy radiation. The shielding of the beamline hutches will be realized in ordinary concrete, the thickness of which will be finalized on the basis of Monte Carlo simulations once the technical designs of the beamlines is finalized. Additional lead shielding will be positioned around those elements more affected by the high energy products of the gamma component.

15.3 Areas and Personnel Classification

15.3.1 Areas and Personnel Classification

In accordance with the above considerations, the following areas classification is foreseen:

Controlled areas ("zone controllate") including:

- the entire linac tunnel and undulator hall with machine in stand-by status,
- the delimited areas adjacent to each klystron in the klystron hall,
- the delimited areas around beam-stoppers and beam dumps with machine in *shutdown status*.

Supervised areas ("zone sorvegliate") concerning:

- the undulator Service Area and seeding laser room during the commissioning of the facility.

Free access areas (“zone libere”) include:

- the laser room, adjacent to the linac front-end,
- the undulator Service Area and seeding laser room at the end of the facility commissioning,
- the experimental hall and all the areas outside the linac and undulator tunnels.

Personnel involved in machine operation will be classified as radiation workers (Cat. B).

15.4 Radiation Safety System

The access control system for FERMI must guarantee that access to the machine tunnel and to the beamline hutches is allowed when safe conditions for personnel are fulfilled. The system is based on low level computers, the Programmable Logic Controllers (PLCs). The access to accelerator tunnel is also supervised by PCs located in the control room. The system fulfills three basic requirements: fail safe logic, redundancy and less than complete automation. The fail safe logic guarantees that if a fault condition occurs in one of the safety components, the machine or the beamline is stopped in a safe status. The redundancy assures that the permission to enter the accelerator tunnel or the hutch is given only if at least two independent conditions are fulfilled at the same time.

Direct operator intervention is requested to give the final assent during the access procedure (to unlock the entrance door) to enter the machine tunnel or to guarantee that nobody remains inside the accelerator after a period of shutdown (*patrol* inspection). For the beamline hutch, an inspection (search procedure) is required to have assent to open the beamline’s beam stoppers.

15.4.1 Elements Controlled by Radiation Safety System

The Radiation Safety System will relay the access conditions to the machine tunnel and to beamlines hutch based on a certain number of signals coming from different devices. These signals are mainly:

- the photoinjector HV power supply and klystron modulator (HV_photoin, RF_ photoin),
- the klystron modulator feeding the different accelerating sections and X-band section (RF_ linac, RF_ Xband),
- the beam-stopper positioned at the end of the linac tunnel (BST_linac),
- the beam-stopper located at the end of the undulator hall (BST_linac).

Other elements are controlled by the safety system to guarantee a correct transport of the beam towards the beam dump. These are:

- the HV power supply of the bending magnets, at the end of the undulator hall, that allow the beam transport into the beam dump;
- the toroids for measuring the beam current along the transfer line to the beam dump.

15.4.2 Access Procedures

15.4.2.1 Access to Accelerator Tunnel and *Patrol* Inspection

Similar to the present safety philosophy for the ELETTRA storage ring, the procedure to enter the injector tunnel during a *stand-by* period of machine is based on the following operations:

- the person presents his/her personal card at the automatic badge reader. If the accelerator is switched off and the person is authorized to enter, the system gives the first assent to open the door;
- in the panel positioned near the badge reader, one of the keys is automatically unlocked by the system; the person takes the key out of the panel;
- the control room operator, after recognizing the person through a TV camera, gives the third and final assent for the entrance and unlocks the door;
- the person enters, closes the door and deposits his key in the inner panel.

The exit procedure consists of the same steps in the reverse sequence, excluding the operator consent: one must take the key out of the internal panel, open the door, deposit the key in the external panel and have the card read.

During the machine shutdown, free access is given to the tunnel and all the doors remain unlocked. At the end of a shutdown period the operator is required by the system to perform a *patrol* inspection in order to verify that nobody remains inside the machine enclosure. This procedure requires that the operator enters the accelerator tunnel using a special badge and executes a complete inspection pushing patrol buttons during the search.

15.4.2.2 Conditions for Entrance Inside the Accelerator Tunnel

Access to the accelerator tunnel is allowed if the following conditions are together fulfilled:

- the photoinjector is OFF;
- no radiofrequency is applied to the linac accelerating sections;
- a delay time has passed from the photoinjector switching off. This will permit to minimize radiation exposure risk due to the induced radioactivity.

Special rules and procedures will be established to access the area around the beam dump.

15.4.2.3 Access to the Beamline Hutches and "Search Inspection"

The first part of the beamlines, called "front-end hutch", will be enclosed inside shielding walls It will be accessible through two doors.

Similarly to the ELETTRA beamlines, the access to the hutch is performed using two keys, called the "B" and "C" keys that must be inserted into the apposite locks on the key panel positioned near the door.

The procedure foresees the following operations:

- the user inserts the "B" key in the key panel and rotates it (this operation will unlock the "C" key);
- the user extracts the "C" key and uses it to open the hutch door (the extraction of the "C" key will lock the "B" key in the panel).

Once finished the work inside the hutch, an inspection ("search") must be performed to verify that no one is still inside before starting the operation with the FEL beam. The search inspection corresponds to the exit procedure from the hutch.

The inspection will be performed as follows:

- after asking everybody to exit the hutch, the user enters the hutch keeping the "C" key with him,
- he/she closes all the hutch doors,
- he/she inserts the "C" key in the search panel and rotates it, pushing at the same time the search button,
- he/she exits the hutch, closes the door and insert the "C" key in the key panel within 30 seconds from pushing the button,
- he/she rotates the "C" key and extracts the "B" key within 10 seconds.

If the inspection is not correctly executed, the safety system will generate an emergency status. Two additional safety devices (optical barriers) will help the search execution and permit to detect the presence of other persons inside the hutch during the inspection.

15.4.2.4 Conditions for Entrance Inside the Beamline Hutches

Access to a beamline hutch is allowed if the following conditions are fulfilled simultaneously:

- the beam-stopper placed at the end of the linac tunnel is closed,
- all the beam-stoppers placed at the end of the Undulator Hall after the electron beam extraction towards the beam dump are closed,
- the radiation levels measured by the radiation monitors placed around the Experimental Hall beamlines do not exceed a pre-established threshold.

15.4.2.5 Alarms and Emergencies

An emergency status will be generated in one of the following conditions:

- one of the hutch or machine doors is forced open;
- one of the emergency button placed inside the machine or the hutch is pushed;
- one of the two optical barriers detects the presence of somebody inside the hutch
- a search inspection is not correctly executed;
- the radiation monitors do not work properly or one of the alarm thresholds has been exceeded.

For any alarm status the machine or the beamline is stopped in a safe status.

The machine is stopped by switching off, at the same time, the HV and RF systems of the photoinjector and the HV and RF systems of all the accelerating sections.

The FEL beam in the beamlines hutch is switched off closing the beam-stopper placed at the end of the linac tunnel and all the beamstoppers placed at the end of the Undulator Hall after the electron beam extraction towards the beam dump.

15.5 Laser Radiation

All main laser systems, described in Chapter 10, emit light with parameters corresponding to Class IV, as defined by the international laser safety standard IEC 825-1. Both eye and skin exposure to emission by these lasers is potentially hazardous and therefore all safety precautions, prescribed by the above safety standard, will be adopted. In particular, all laser rooms and laser entrance ports (e.g. at photoinjector) will be signed and equipped according to the above standard. It has to be noted that very high attention has to be given to the safety aspects of the user lasers, because the nature of the experiments may require frequent changes of geometry, wavelength, etc, and access to them is granted to higher number of people and also during FEL operation (contrary to machine lasers).

15.6 Radiation Monitoring System

15.6.1 Internal Beam Loss Monitors

A network of gamma detectors is installed inside the linac tunnel to localize the dose distribution due to beam losses occurring along the different accelerating sections. The existing system will be integrated with new modules to cover the entire tunnel and upgraded with higher dynamic range electronics in case a higher sensitivity is required.

15.6.2 Radiation Monitoring Outside the Shielding

Radiation monitoring system must be designed to be able to detect radiation pulses of very short duration. Environmental monitoring outside the tunnels will be based on passive dosimeters such as TLD, films, imaging plate and bubble detectors. In addition, a network of active gamma and neutron detectors will be located at various points of the experimental hall and in the undulator Service Area. Similarly to the monitoring system in the ELETTRA experimental hall, these detectors will be connected to a PC and will provide measurements of instantaneous doserates and integrated doses over pre-determined periods.

Each unit consists of an environmental ionisation chamber for measuring the gamma dose, a BF3 counter for the neutron component and a micro-processor for communications with the PC. Measurements of instantaneous dose-rates and integrated doses over pre- determined periods are communicated to the PC every minute.

As explained in the previous section, in addition to the environmental stations, some gamma monitors located in the vicinities of the beamlines exits will be connected with the beamline personnel safety system.

Each monitor provides three signals whose meanings are:

1) no failure status

2) pre-alarm status

3) alarm status.

The beamlines PLC acquires these signals generating the following actions:

1. **no failure status OFF** (malfunction) causes: no entry allowed in the beamlines hutch, the closure of all the beamstoppers of the beamlines front-end, closure of the linac beamstopper,

2. **pre-alarm status ON** (pre-alarm) causes: no entry allowed in the beamlines hutch, the closure of all the beamstoppers of the beamlines front-end,

3. **alarm status ON** (alarm) causes the same actions produced for the malfunction.

15.7 Radiation Safety Rules and Procedures

Personnel entering radiation areas are required to record their entrance in a register. Access to radiation areas is allowed to radiation workers holding personal dosimeters. Occasional access to radiation areas is allowed to authorised personnel (not classified as radiation worker) that have been assigned a guest dosimeter with real time reading.

15.8 Radiation Safety Training

The personnel involved in machine and beamlines operations will be trained in radiation safety issues. Three main training levels are foreseen, according to the different personnel tasks. These will be oriented to: radiation workers, machine operators and beamlines users. Procedures, manuals and training materials are available at the web site of ELETTRA ([10]-[12]).

Radiation workers will be trained on the risks of exposure to ionizing radiation, in the Radiation Protection rules to access classified areas and in the procedures to access the accelerator and undulator tunnel. In addition, operators will also be trained in the logic and philosophy of the machine and beamlines safety systems.

Beamlines users will be trained in the procedures to access the beamlines hutch and in the logic and philosophy of the beamlines safety systems.

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[11] "Radiation Protection at the beamlines": collection of internal reports available at http://www.elettra.trieste.it/organisation/genserv/health/index.html. (It includes: Radiation Protection Handbooks for the beamline users, Radiation emergency procedures for beamlines, etc.).

[12] Videotape "Radiation and General Safety" for users, ELETTRA staff and suppliers. It can be watched at: http://www.elettra.trieste.it/organisation/genserv/health/video/index.html.

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