Radiological safety studies for the TeraFERMI beamline at FERMI (Elettra)

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Abstract

The TeraFERMI beamline, currently under construction at the FERMI seeded free electron laser (FEL) facility in Trieste, Italy, will provide terahertz (THz) pulses during normal FEL operation.
The THz radiation will be produced in the beam dump section of FERMI Undulator Hall by the interaction of the electron beam with a thin metallic target. It will then be transported to the Experimental Hall inside a large diameter (about 22 cm) vacuum chamber, crossing two shielding walls.
The radiological safety implications related to the beamline construction, which was not foreseen in the original accelerator layout, have been investigated using FLUKA Monte Carlo code. Radiation measurements have been carried out to validate simulation results.

1. Introduction

FERMI is a seeded free-electron laser driven by a 1.5 GeV electron linac, producing highly brilliant photon pulses in the ultraviolet and soft X-ray wavelength region [1,2].
As illustrated in Figure 1, the facility consists of three main parts: the Linac tunnel, the Undulator Hall and the Experimental Hall.

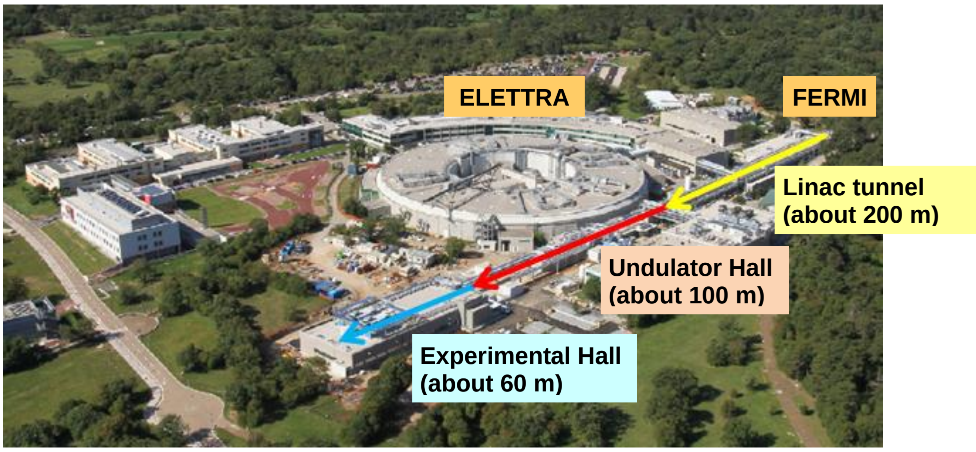

Fig.1 - Overview of FERMI facility.

A schematic layout of the accelerator is shown in Figure 2.
Electron bunches, with up to 800 pC charge and emitted at repetition rates up to 50 Hz, are extracted from a photocatode radiofrequency gun (RF Gun) [3] and, after being accelerated to the maximum energy, opportunely compressed and manipulated to the desired spatial properties [4,5], are then transferred to the Undulator Hall.
A system of dipole magnets (spreader), installed at the beginning of the Undulator Hall, permits transporting the electron beam through one of the two separate and complementary undulator sections, FEL-1 or FEL-2. FEL-1 is a single stage harmonic upshift FEL, delivering light in the 100-20 nm wavelength range [6] while FEL-2 is a double stage harmonic upshift FEL, covering the spectral range from 20 to about 4 nm [7].
After passing through the undulator chain, the electrons are deflected to the right towards the Main Beam Dump (MBD) along a common transfer line, while the FEL photon beam propagates straight ahead into the Experimental Hall.
The transfer line towards the MBD includes one dipole magnet for each FEL line (B1 for FEL-1 and B2 for FEL-2), deflecting the electron beam by a horizontal angle of 15.7°, and two additional dipole magnets (B3 and B4), each deflecting the beam of 31.4°. More details about the transfer line design and optics are available in [8].

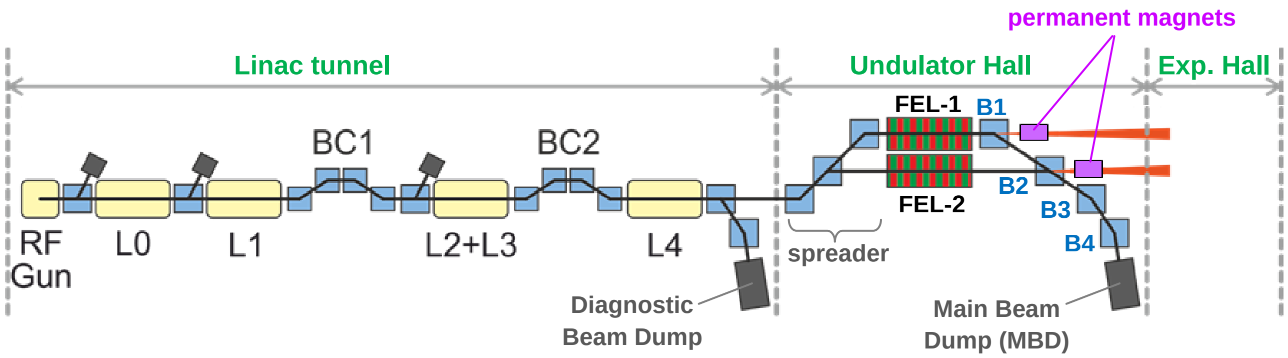

Fig.2 - Schematic layout of the FERMI free electron laser: the accelerating structures (L0, L1, L2+L3 and L4) are shown in yellow, the main dipole magnets in blue, the undulator sections (FEL-1 and FEL-2) in red/green and the beam dumps in grey. BC1 and BC2 are the two bunch compression stages.

The Experimental Hall begins just beyond the end of the Undulator Hall, as illustrated in Figure 3. The concrete shielding wall separating the two halls is 300 cm thick on the accelerator axis and 370 cm thick in the part that develops laterally to the MBD.

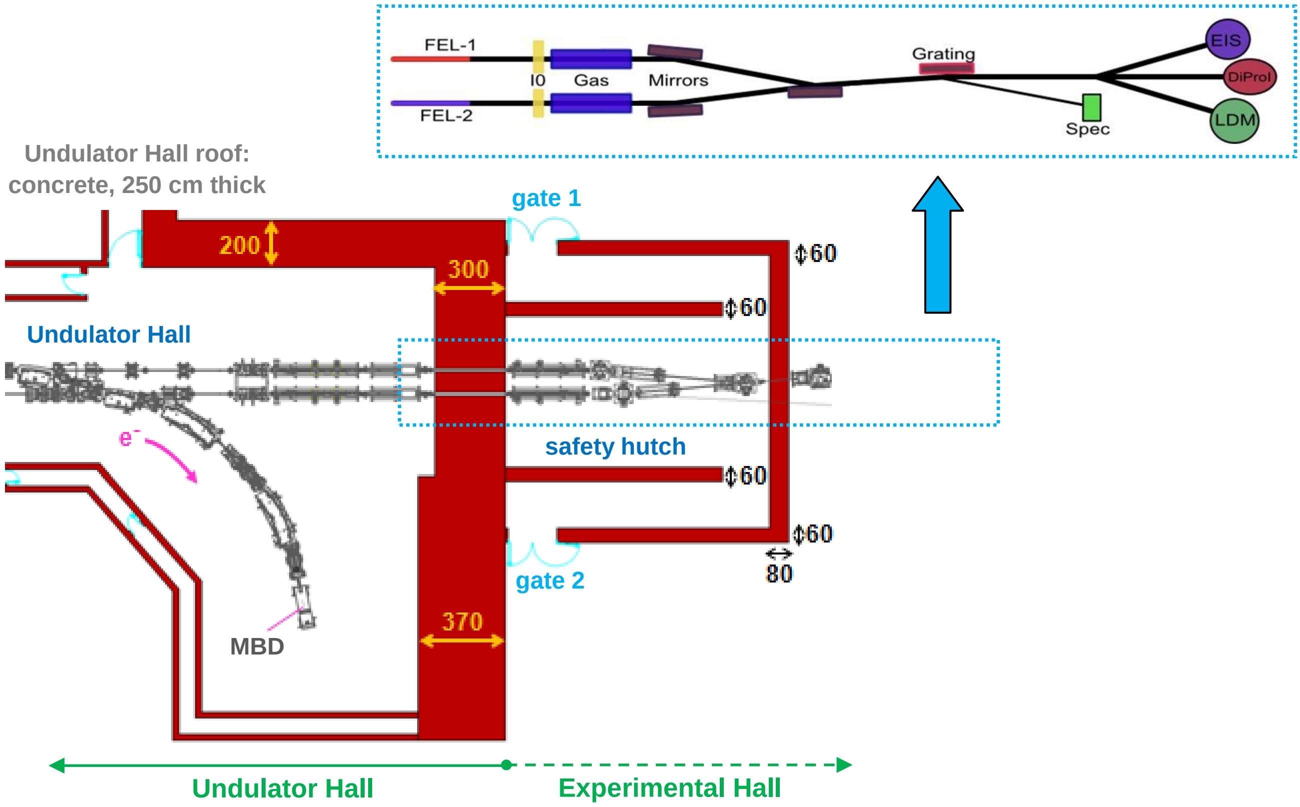

Fig.3 - Schematic layout of the last part of the Undulator Hall and of the first part of the Experimental Hall (all measures are in centimetre). In the top frame, a sketch of the FERMI beamlines is shown.

At present the Experimental Hall houses three beamlines [9-12], EIS (Elastic Inelastic Scattering), DiProi (Diffraction Projection Imaging) and LDM (Low Density Matter), all open to external users.

The first part of the beamline optics is enclosed inside concrete shielding walls (safety hutch). The lateral walls of the safety hutch are 60 cm thick, whereas the shielding wall located in the forward direction has a thickness of 80 cm. The concrete roof is 60 cm thick. Two metallic gates (gate 1 and gate 2 in Figure 3) allow access to the hutch when the electron beam is not being transported in the Undulator Hall.

From the radiation protection point of view, the safety hutch is an exclusion area during FEL operation, whereas the rest of the Experimental Hall is classified as a “non-designated area”.

2. The TeraFERMI Project

The idea of the TeraFERMI project is to exploit the FERMI electron beam to produce coherent THz pulses in the range from 0.3 to 15 THz [13], without affecting FEL operation.
The beamline will make use of electron bunches with a bunch length between 50 fs and 1 ps; the production mechanism of the THz radiation will be based on the emission of coherent transition radiation (CTR) which occurs when relativistic electrons cross a thin metallic target screen.
The source chamber will be installed in the transfer line to the MBD (Figure 4) and will extract THz radiation from the same electrons that have previously participated to the FEL process, therefore working in a parasitic way with respect to the FEL beamlines.
Two different CTR screens, a 350 µm thick silicon screen coated with 1 µm of aluminum, and a 1 µm thick free standing circular aluminum foil, will be installed inside the chamber. The two silicon screens will be separated by an adjustable gap (1-5 mm), thus allowing the chamber to be used as a Coherent Diffraction Radiation (CDR) source. All the screens will be oriented with a fine tunable 45° angle with respect to the electron beam.

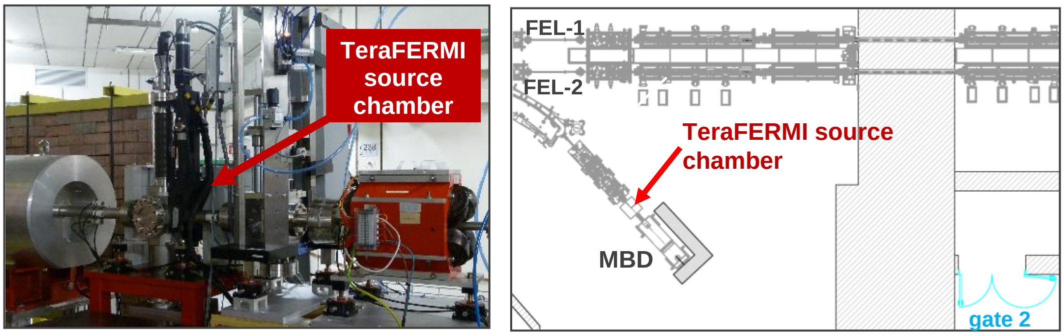

Fig.4 - Position of the TeraFERMI source chamber inside the Undulator Hall.

The THz light will then be transported to the experimental end station located about 20 m downstream. In order to control divergence effects and to ensure a regular refocusing of the beam, the THz light transport line will be divided into segments oriented at 90° with respect to each other, each one starting with a focusing or a plane mirror (Figure 5).

3. Radiological Issues related to the TeraFERMI Project

From the radiation protection point of view, the most critical issue in the TeraFERMI project is related to the need of large diameter (about 22 cm) vacuum chambers for the THz radiation transport to the Experimental Hall. These require drilling large holes in the accelerator shielding walls, through which unwanted secondary radiation produced by beam losses occurring in the Undulator Hall might easily propagate.
The need of dividing the THz radiation transport line into several segments to permit the refocusing of the THz beam suggested the idea to position the new holes in the shielding walls at the pavement level, far away from the electron beam axis.
Figure 5 shows the lateral view of the TeraFERMI transport line.

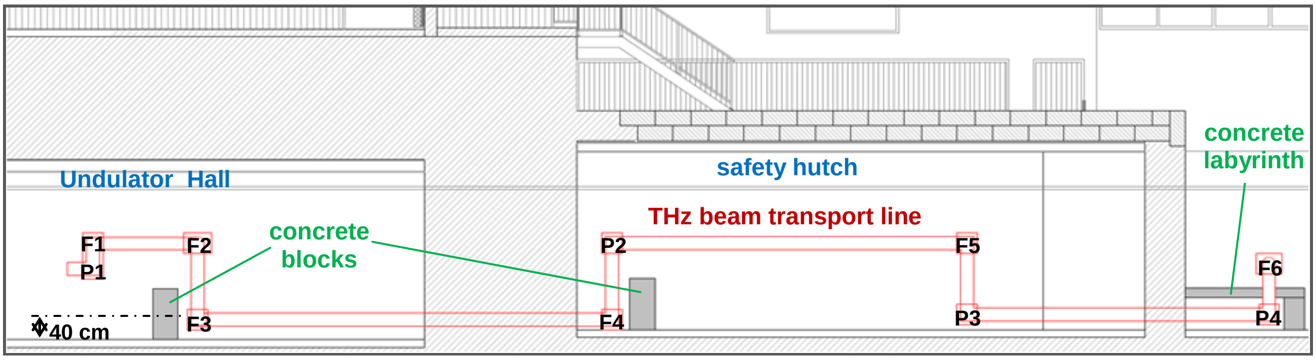

Fig.5 - Lateral view of the THz radiation transport line, with the position of the focusing (F1, F2, F3, F4, F5, F6) and of the plane (P1, P2, P3, P4) mirrors.

The holes in the Undulator Hall and in the safety hutch shielding walls will have a diameter of about 25 cm. Two local shielding elements (base 100x50 cm^2, height 100 cm), consisting of concrete blocks utilized in the past for the commissioning of Elettra storage ring, will be positioned in the Undulator Hall and in the safety hutch, to intercept the secondary radiation propagating towards the Experimental Hall.
The last segment of the THz transport line will be extracted from the safety hutch in a labyrinth shielded duct; it will be made of concrete with a lateral and top thickness of 20 cm and a forward thickness of 40 cm.
To improve the control of the electron beam transport along the MBD transfer line and, consequently, to reduce the probability of beam losses in the MBD area, a re-arrangement of the MBD zone layout was planned (Figure 6), in conjunction with the installation of the THz source chamber inside the Undulator Hall. This re-arrangement will mainly consist of the removal of the dipole magnet B4, and consequently the shortening of the transfer line and the re-positioning of the nearby optics and diagnostics. The MBD itself will be moved backwards and its orientation will be changed with respect to the original design. A 40 cm thick concrete shielding will be positioned around the dump to further attenuate the intensity of the secondary radiation propagating towards the Experimental Hall.

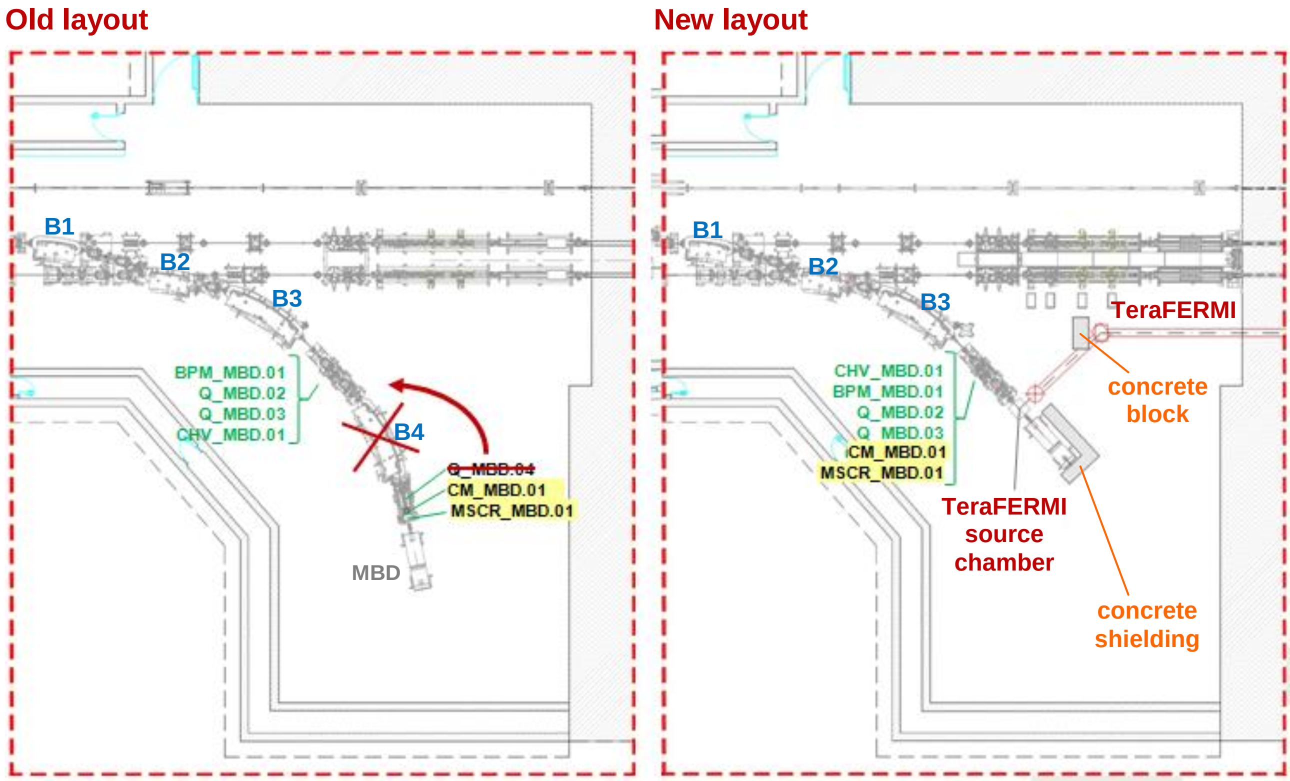

Fig.6 - Overview of the accelerator layout before and after the rearrangement of the MBD area.

4. FLUKA Simulation

4.1. Simulation Set-Up

The radiation field distribution in the MBD zone and around the safety hutch was investigated through a Monte Carlo simulation based on the FLUKA code [14,15] version FLUKA2011.2c.0.
The elements modeled in the simulation geometry were the concrete shielding walls in the MBD zone and around the safety hutch, the openings in the shielding walls utilized for the transport of FEL and THz radiation towards the experimental stations, the FEL-1 and FEL-2 vacuum pipes, the transfer line towards the MBD, the dipole magnets B1, B2 and B3 with their vacuum chambers, the MBD structure and finally the local shielding walls/blocks installed in the FEL-1/FEL-2 front-end, in the MBD area and in the safety hutch.
The optics located inside the safety hutch were not modeled, taking into account the fact that this effort would only have contributed to a slight decrease of the predicted radiation dose rate, while considerably increasing the simulation complexity.
The propagation towards the Experimental Hall of the radiation produced during beam losses occurring in the Undulator Hall was studied taken into account two particular planes of interest:

- The first one, parallel to the floor and positioned on the electron beam axis, was used to investigate the radiation transmission through FEL-1 and FEL-2 pipes crossing the 300 cm thick shielding wall (this plane will be referred to as “electron beam axis plane” in the remaining part of the document).
- The second one, parallel to the previous plane and positioned on axis with the TeraFERMI pipe through the 300 cm thick shielding wall, was utilized to investigate the radiation transmission through the 25 cm diameter openings foreseen for the TeraFERMI beamline (this plane will be referred to as “TeraFERMI hole axis plane” in the remaining part of the document).

Figure 7a and Figure 7b show a top view of the FLUKA simulation geometry on the two planes, whereas the structure of the B1, B2 and B3 magnets vacuum chambers and the cross section of the MBD model are illustrated, respectively, in Figure 8 and Figure 9.

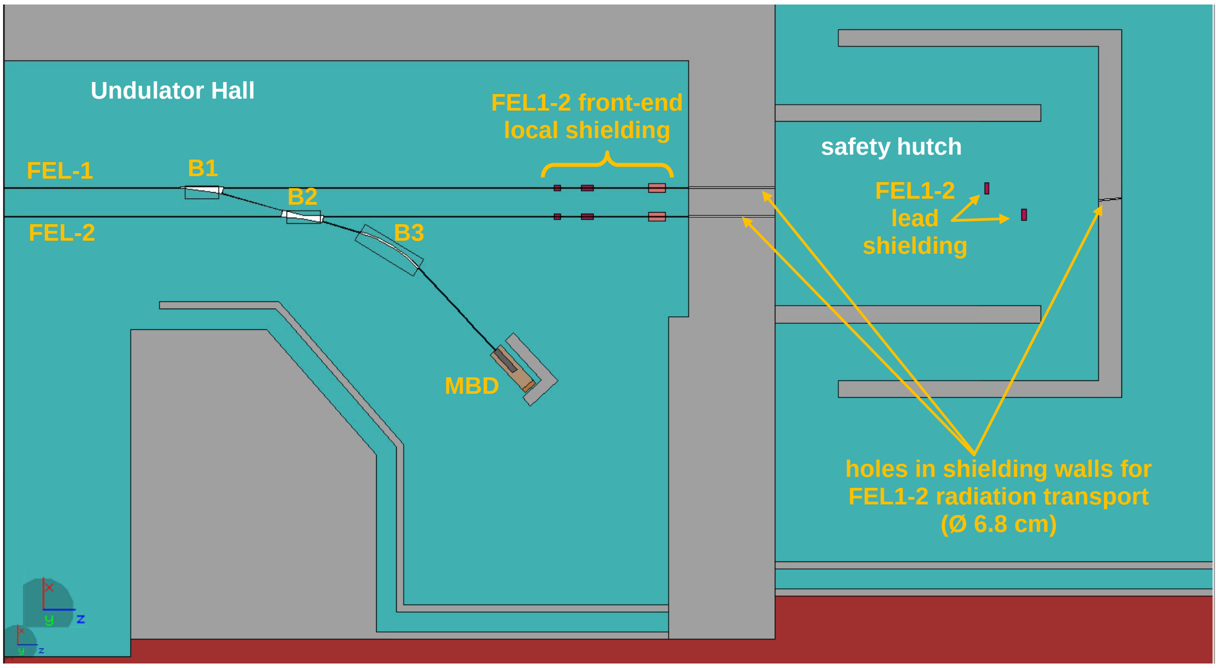

Fig.7a - Top view of the FLUKA simulation geometry on the electron beam axis plane.

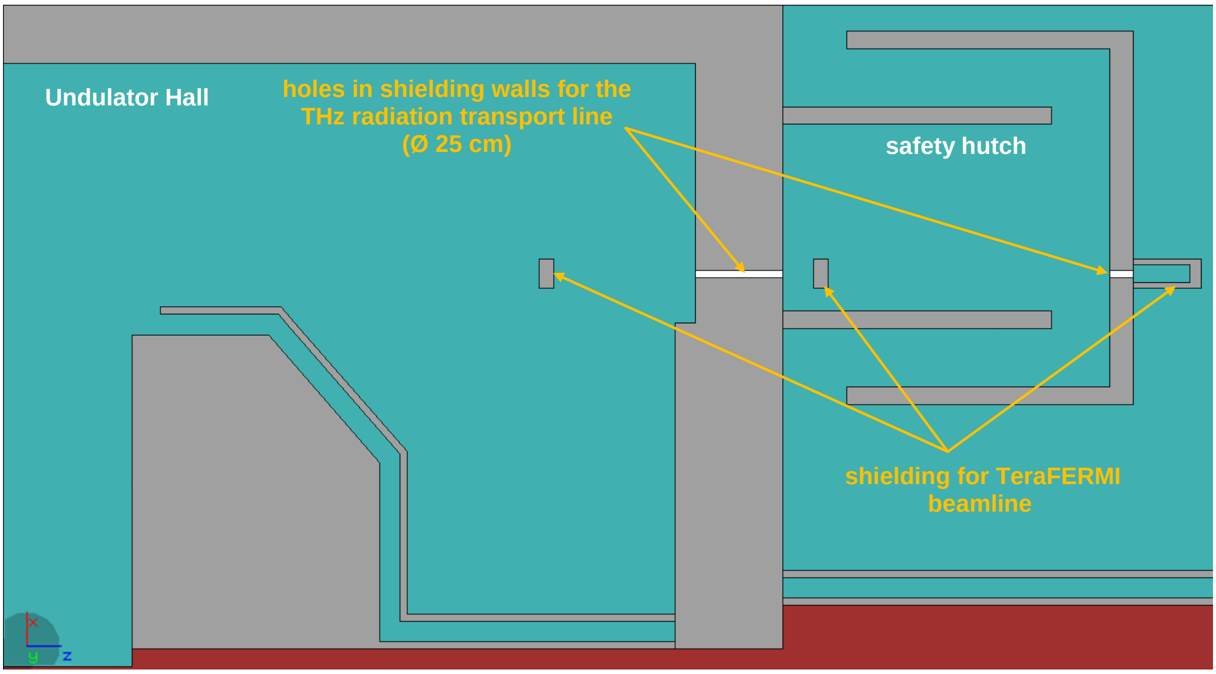

Fig.7b - Top view of the FLUKA simulation geometry on the TeraFERMI hole axis plane.

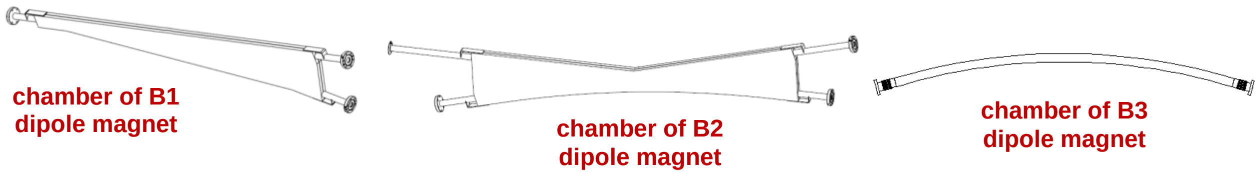

Fig.8 - Layout of B1, B2 and B3 magnets vacuum chambers.

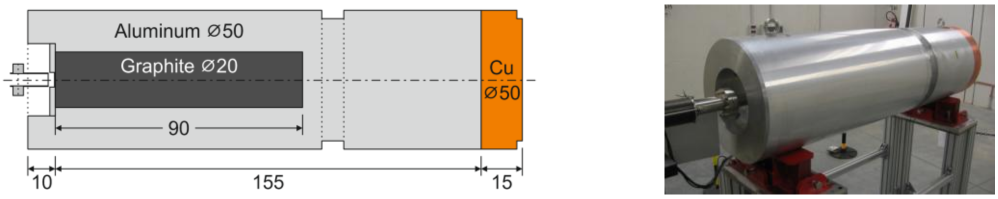

Fig.9 - Cross section of the MBD structure modeled in the simulation (on the left) and photo of the installed MBD (on the right). The FERMI dump mainly consists of an aluminum cylinder measuring 50 cm in diameter, surrounding a graphite core and ending with a copper endcap. All measures are in centimetre.

For all the simulation studies presented here the electron energy was set at 2.0 GeV, which is the maximum energy authorized for FERMI. The kinetic energy cut-off was fixed at 100 keV for electrons and at 10 keV for photons. Photo-neutron production was activated and neutrons were transported down to thermal energies. To improve simulation statistics outside the accelerator shielding, biasing techniques were adopted.

5. Results

5.1. Normal Operation

Figure 10 shows the total ambient dose equivalent rate distribution when a 2.0 GeV, 1000 pC, 50 Hz electron beam is transported without losses along the transfer line, up to the MBD.

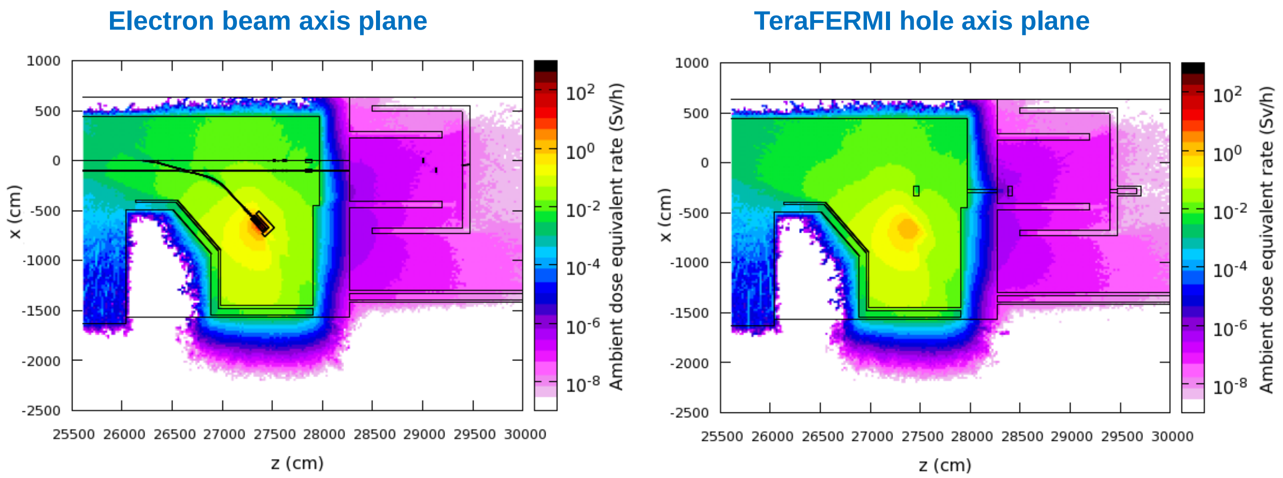

Fig.10 - Total ambient dose equivalent rate distribution on the electron beam axis plane and on the TeraFERMI hole axis plane, averaged over 20 cm in x, 20 cm in y and 20 cm in z.

As expected, the most critical area in the Experimental Hall is located just beyond the Undulator Hall shielding wall, on the right side of the safety hutch.
Figure 11 shows the dose equivalent rate distribution along the exterior of the Undulator Hall shielding wall. The yellow part of the graphs represents the area enclosed inside the safety hutch, which is not accessible to personnel when the electron beam is being transported inside the Undulator Hall.
Outside the hutch, the maximum dose rate expected on both planes of interest is about 0.5 µSv/h, which is compatible with the designation of the zone as “not-classified area”. Inside the hutch, the maximum radiation dose rate is predicted at the exit mouth of TeraFERMI hole (about 2.7 µSv/h due to neutrons and 0.3 µSv/h due to photons).

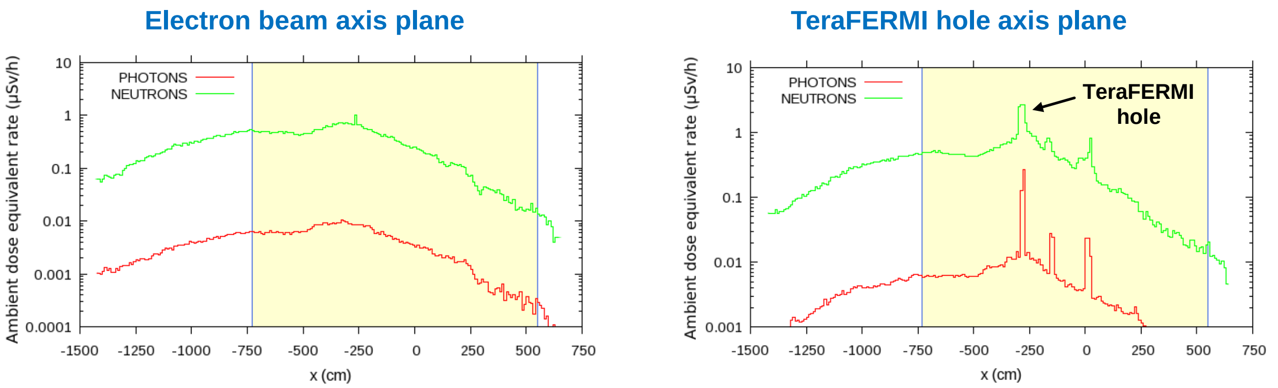

Fig.11 - Normal operation: ambient dose equivalent rate distribution along the exterior of the Undulator Hall shielding wall, averaged over 10 cm in x, 20 cm in y and 20 cm in z.

Figures 12 and 13 show the photon and neutron contribution to the total ambient dose equivalent rate, and clearly confirm that outside the accelerator shielding most of the radiation dose rate is due to neutrons both on the electron beam axis plane and on the TeraFERMI hole axis plane.

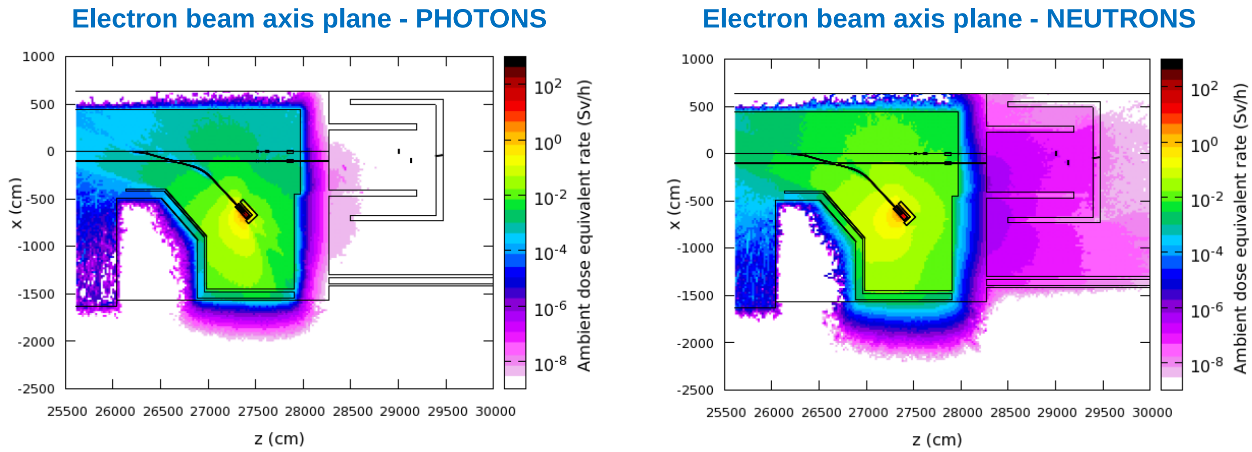

Fig.12 - Photon and neutron ambient dose equivalent rate, plotted on the electron beam axis plane, averaged over 20 cm in x, 20 cm in y and 20 cm in z.

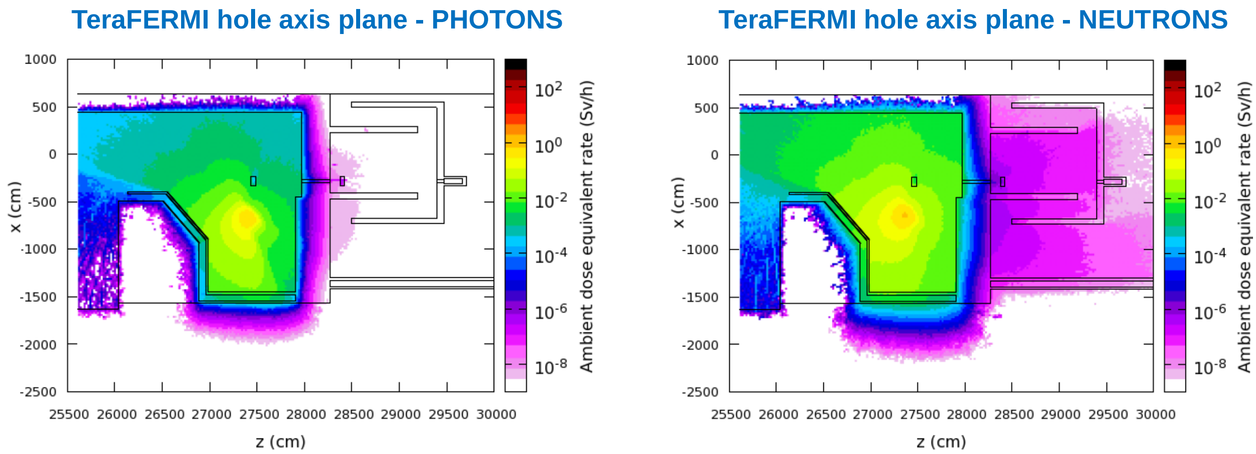

Fig.13 - Photon and neutron ambient dose equivalent rate, plotted on the TeraFERMI hole axis plane, averaged over 20 cm in x, 20 cm in y and 20 cm in z.

5.2. Beam Loss Scenarios

In principle, the number of beam loss scenarios that could be investigated by FLUKA simulations is infinite. Nevertheless, for this specific study, the most interesting scenarios are the ones producing significant electron beam losses in the area just upstream of the first 25 cm diameter TeraFERMI hole, due to the possible propagation of unwanted radiation through the opening in the shielding.

The following paragraphs present and discuss in detail two extreme cases, both involving full electron beam loss in the first part of the transfer line towards the MBD, and analyze the radiological impact outside the accelerator shielding in the areas accessible to personnel.

5.2.1. Beam Loss Scenario n°1

The first beam loss scenario takes into consideration a 2.0 GeV, 1000 pC, 50 Hz electron beam that, moving on FEL-1 transport line, is not correctly bent by dipole magnet B1 and therefore impinges on the magnet vacuum chamber.
To produce this scenario, the intensity of the B1 dipole magnetic field was changed from 1.530 T (nominal value for a 2.0 GeV electron beam) to 1.492 T (nominal value for a 1.95 GeV electron beam), which is the lower limit accepted by the Personnel Safety System before stopping the operation with the beam.
Figure 14 shows the total ambient dose equivalent rate distribution on the two planes of interest: as expected, the beam loss is strongly peaked forward and, as far as the TeraFERMI beamline is concerned, a significant portion of the scattered radiation is channeled through the first 25 cm diameter hole. The scattered radiation is then strongly attenuated by the concrete block positioned in the safety hutch.

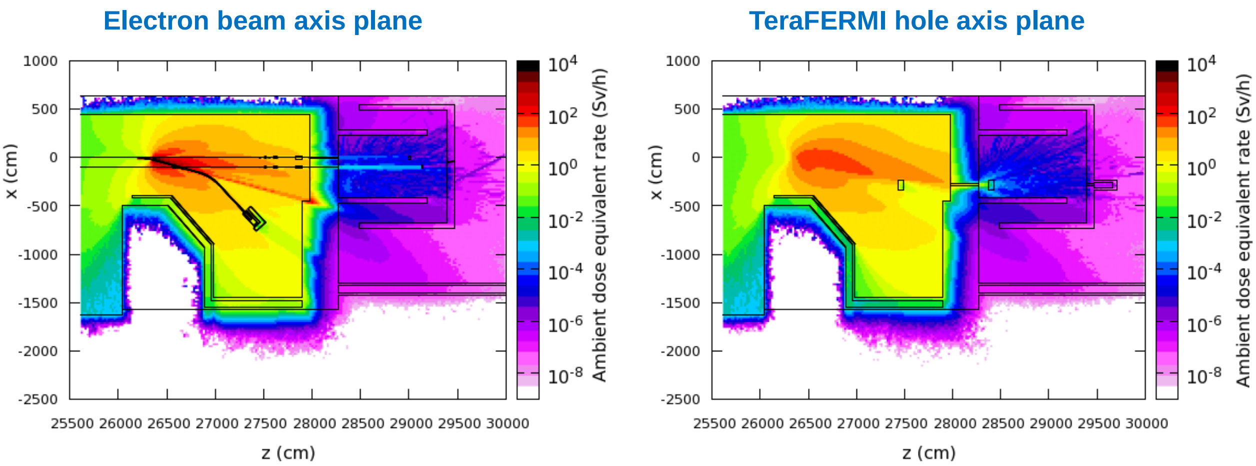

Fig.14 - Beam loss scenario n°1: total ambient dose equivalent rate distribution on the two planes of interest, averaged over 20 cm in x, 20 cm in y and 20 cm in z.

Figure 15 shows the photon and neutron ambient dose equivalent rate distribution averaged over the first 20 cm on the z-axis, just outside the Undulator Hall shielding wall.

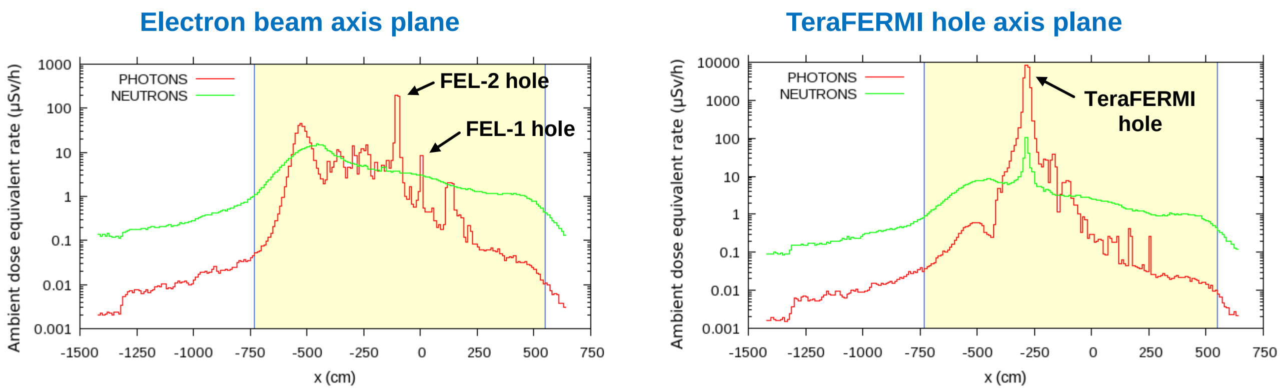

Fig.15 - Beam loss scenario n°1: ambient dose equivalent rate distribution along the exterior of the Undulator Hall shielding wall, averaged over 10 cm in x, 20 cm in y and 20 cm in z.

Outside the hutch, the maximum radiation dose rate expected along the Undulator Hall shielding wall on both planes of interest is about 1 μSv/h, and is mainly due to neutrons. Inside the hutch, the maximum dose rate is expected at the exit of the TeraFERMI hole (about 10 mSv/h) and is due to photons.
A similar analysis, performed to study the ambient dose equivalent distribution along the exterior of the right wall of the safety hutch, where gate 2 is installed, returned as result a maximum dose rate of about 1.4 μS/h for neutrons and of 0.4 μS/h for photons on both planes of interest.

5.2.2. Beam Loss Scenario n°2

The second beam loss scenario takes into consideration a 2.0 GeV, 1000 pC, 50 Hz electron beam moving on FEL-2 transport line: as in the previous case, a significant electron beam loss is produced by decreasing the intensity of the magnetic field generated by the dipole magnet B2 from 1.530 T (nominal value for a 2.0 GeV electron beam) to 1.492 T (nominal value for a 1.95 GeV electron beam).
Figure 16 shows the total ambient dose equivalent rate distribution on the electron beam axis and on the TeraFERMI hole axis plane. The distribution of the photon and neutron ambient dose equivalent rate along the exterior of the Undulator Hall shielding wall is plotted in Figure 17.
Also in this scenario a significant part of the scattered radiation is channeled through the first 25 cm diameter opening and is effectively attenuated by the concrete block positioned in the safety hutch.
As shown in Figure 17, the radiation dose rate expected outside the safety hutch along the Undulator Hall shielding wall remains lower than 1.0 µSv/h on both planes of interest, and is mainly due to neutrons.

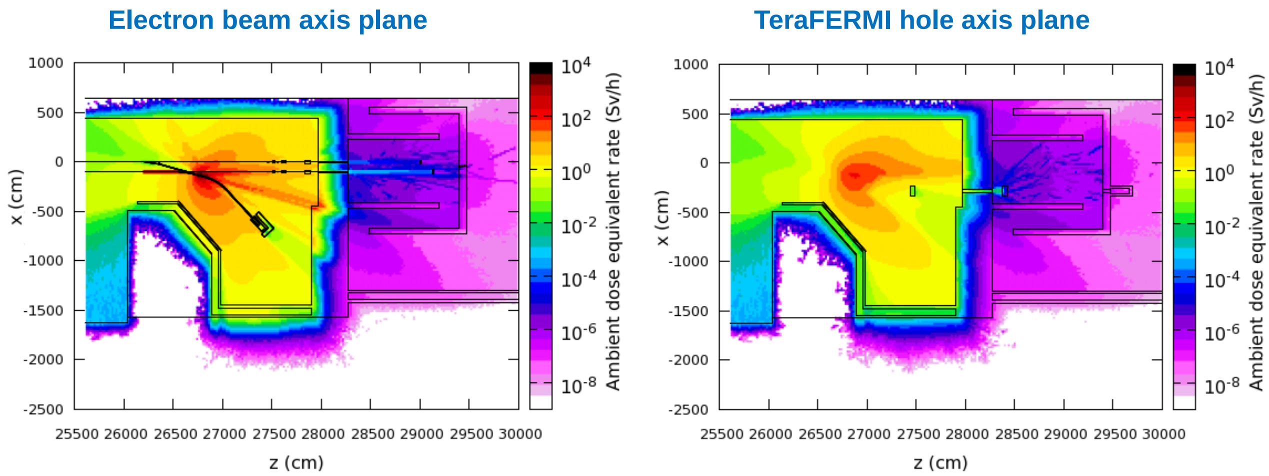

Fig.16 - Beam loss scenario n°2: total ambient dose equivalent rate distribution on the two planes of interest, averaged over 20 cm in x, 20 cm in y and 20 cm in z.

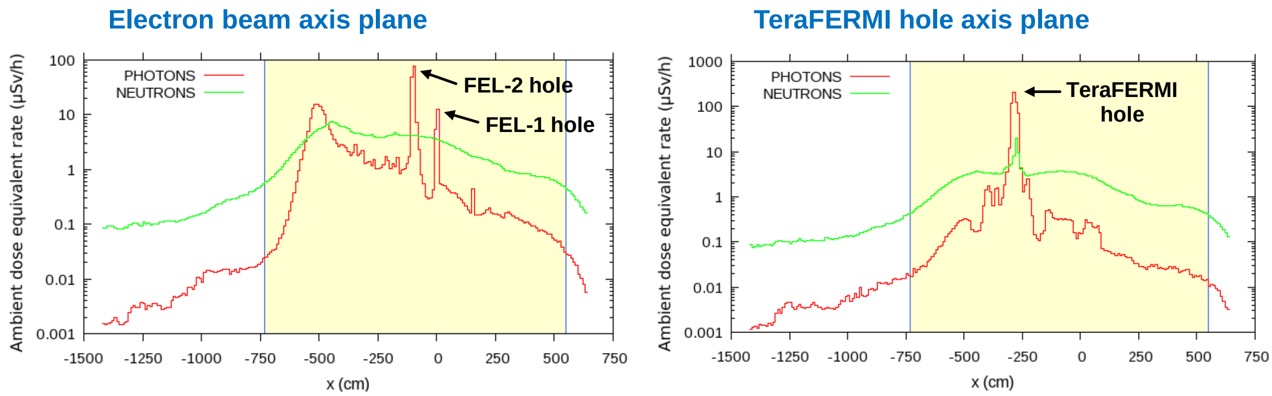

Fig.17 - Beam loss scenario n°2: ambient dose equivalent rate distribution along the exterior of the Undulator Hall shielding wall, averaged over 10 cm in x, 20 cm in y and 20 cm in z.

The maximum ambient dose equivalent rate expected along the exterior of the hutch right wall, where gate 2 is installed, is about 0.6 µS/h for neutrons and 0.14 µS/h for photons on both planes of interest.

5.2.3. Considerations about Beam Loss Scenarios

In the study of beam loss scenarios, after investigating which radiation dose rate is produced in the "worst case accident", one of the most interesting questions is how long a loss would go on before some (Personnel or Machine) Protection System intervenes.
In the FERMI accelerator, to ensure a rough control of electron beam transport inside the Undulator Hall when the beamlines stoppers are open, the Personnel Safety System continuously monitors the energy

matching between the dipole magnets of the spreader and the dipole magnets of the MBD transfer line (B1, B2 and B3), and stops the operation with the beam if a discrepancy exceeding 50 MeV is measured.
A further check is performed through five current monitors located at the beginning and at the end of each undulator section and just upstream of the MBD, as shown in Figure 18: if, for the FEL line that is in operation, the discrepancy between the first and the second current monitors exceeds 10%, the Personnel Safety System automatically stops the operations with the beam after few seconds. The same action is taken if the discrepancy between the second and the third current monitors exceeds 20%.
This means that, taking into account the two beam loss scenarios described above, even if they might occur because the considered decrease in the magnetic field is within the range accepted by the Personnel Safety System, they would last only few seconds thanks to the interlock based on the current monitor readings.

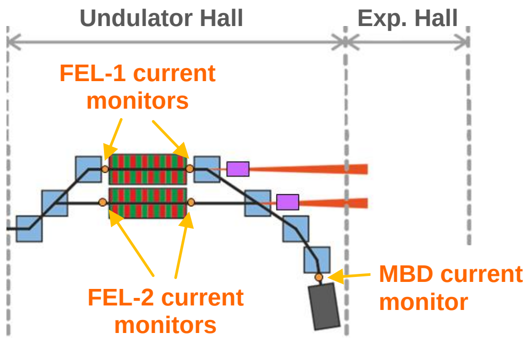

Fig.18 - Position of the Undulator Hall current monitors connected to the Personnel Safety System.

6. Experimental Benchmark

To validate the simulation results, an experimental benchmark was carried out positioning a PTW32002 ionization chamber and a Framework Scientific ABC1260 bubble detector in different locations around the MBD and comparing the detector measurements with the dose rate calculated through the FLUKA code. All the details about the simulation and the experimental set-up are presented and discussed in [16].
The agreement between predicted and measured values was within 9% for neutrons (up to 200 pC/bunch); a maximum deviation of 25% was found for the electromagnetic component in a single location, whereas in all the others it was less than 20%.
Taking into account the complexity both of the simulation and of the experimental set-up, the benchmark was considered satisfactory and the simulation model validated.

7. Conclusions

The radiological issues related to the TeraFERMI project have been evaluated using the FLUKA Monte Carlo code. Different beam loss scenarios have been simulated and analyzed: no significant increase in radiological hazard is expected from the beamline installation.
Regarding the TeraFERMI project schedule, during the shutdown between December 2014 and January 2015 the THz radiation source chamber was installed in the Undulator Hall and the MBD zone layout was modified as discussed in Section 3. The beamline installation is planned for Summer 2015 and commissioning will start in Autumn 2015. The first THz photons are expected by the end of 2015.

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