SHIELDING CALCULATIONS AND ACTIVATION STUDIES FOR THE PSI POSITRON PRODUCTION EXPERIMENT

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Abstract

The Future Circular Electron-Positron Collider (FCC-ee) is a proposed next-generation particle accelerator, planned as the first stage of the larger Future Circular Collider project at CERN. It is an electron-positron collider designed to be a precision instrument for studying fundamental physics.

The PSI Positron Production (P^3) is the planned proof-of-principle experiment for the FCC-ee positron source. The main goal of this experiment is to test new technology and validate the envisioned positron production scheme. To this end, a prototype of the FCC-ee positron source will be hosted at the SwissFEL facility at the Paul Scherrer Institute in Switzerland.

A dedicated bunker has been built inside the SwissFEL tunnel, and the experimental components are installed. Simulations have been performed with the FLUKA.CERN Monte Carlo code to dimension the P^3 bunker and local shielding elements. Calculations have been repeated for various target models since different target options will be tested.

This contribution briefly describes the ingredients of the P^3 experiment and details the dedicated bunker and the local shielding. It shows the expected dose rate distribution outside the P^3 bunker. The foreseen activation is also discussed.

GEOMETRY MODEL

The P^3 experiment is installed in the SwissFEL linac at the Paul Scherrer Institute (PSI) inside a dedicated bunker. A brief description of the different components is reported in the following. Additional details can be found in Refs. [1, 2].

The geometry implemented in the FLUKA.CERN Monte Carlo code [3–6] is shown in Fig. 1.

During operation, the SwissFEL 6 GeV electron beam will be deflected towards a target. A charge of 200 pC will be delivered at a frequency of 1 Hz. The goal is to estimate the rate of positron production for different targets. Three target models were considered in the calculations. Two targets are made of tungsten. The first has a cylindrical shape, while the second is conical [7]. The third is a tantalum cylinder.

The target is surrounded by a high-temperature superconducting (HTS) solenoid [8]. Its magnetic field is taken into account in the simulations.

The produced electrons and positrons are subsequently accelerated using two radio-frequency (RF) cavities, each of which is surrounded by eight solenoids.

The electron and positron beams are then separated by a bending magnet and directed toward two Faraday cups,

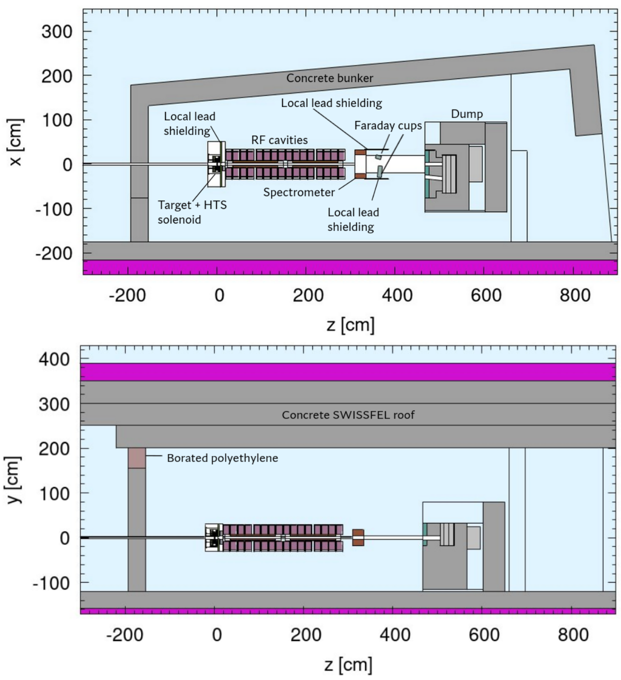

Figure 1: P^3 experiment geometry implemented in the FLUKA.CERN code: top view at beam height (top) and side view at beam position (bottom). The beam is moving along the z-axis. The x-axis is the horizontal axis, oriented towards the SwissFEL tunnel. The y-axis is opposite to gravity. The main components are indicated in the picture. Iron is shown in brown, the representative mixture of copper and water in orchid, tungsten in turquoise, steel in light grey, polyethylene in green, normal concrete in grey, borated polyethylene in light-red and soil in violet. The figure is obtained using the Flair graphical interface [9].

which are used to measure the generated charge. The magnetic field is assumed to be constant inside the magnet opening and multiple values have been studied.

Lastly, a beam dump is incorporated at the end of the beamline. This is made up of various blocks of different materials: steel, concrete, and polyethylene. An existing beam dump will be used, but it has been reinforced to comply with the P^3 experiment and the radioprotection requirements.

Two local shielding components have been designed to reduce the prompt dose. A 6 cm long lead plate is placed at the exit of the HTS magnet to absorb the radiation generated at the target.

Two identical lead plates are located at the side of each Faraday cup to intercept low energy charged particles, which have a high deflection angle and are deviated by the dipole

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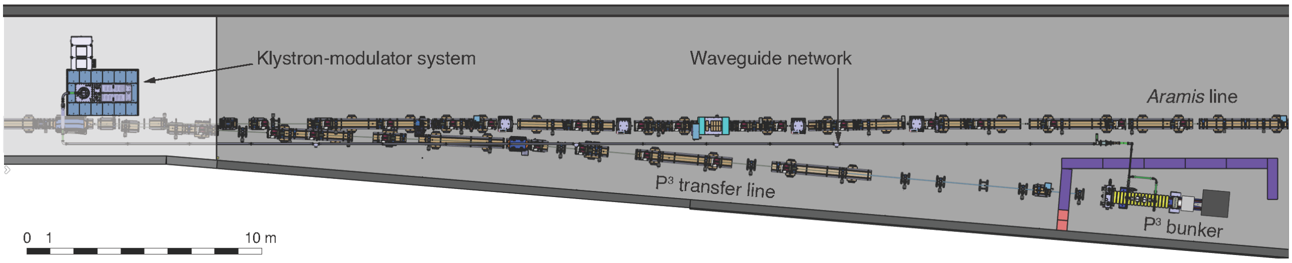

Figure 2: P^3 installation at SwissFEL.

magnetic field towards the bunker and tunnel walls. Their thickness along the x-axis is 1.5 cm. Their height is 20 cm and their length along the beam direction is 54 cm.

The walls of the P^3 bunker are made of normal concrete and have a thickness of about 50 cm. They extend for 2.75 m from the SwissFEL floor. The space between the wall and the SwissFEL roof is filled with borated polyethylene, as shown in Fig. 1. The wall behind the dump is tilted and is not closed to facilitate the transport of the different components.

The P^3 bunker does not have a roof. The radiation moving upwards is absorbed by the SwissFEL roof, which is made of normal concrete and has a thickness of 150 cm (Fig. 1).

Figure 2 shows the P^3 experiment as it is integrated into the SwissFEL bunker.

SOURCE TERMS

Three different source terms are considered. The first source term is used to assess the expected dose values in the initial phase of the experiment. The sum of the second and third source terms is used to evaluate the expected dose during normal operations. The contribution of charged particles is counted twice, as explained in the following. The results obtained are therefore conservative.

6 GeV Electron Beam on Dump

At the beginning of operations, the target may not be present. A charge of 200 pC will be delivered to the dump at a frequency of 1 Hz.

When calculations were performed, the P^3 bunker was not yet built and it was not sure if it could be completed before commissioning. Therefore, simulations have been carried out, replacing the P^3 bunker walls with air in the FLUKA.CERN geometry.

6 GeV Electron Beam on Target

During normal operations, a charge of 200 pC will be delivered to the target at a frequency of 1 Hz.

The effect of the RF cavities on the secondary electrons and positrons produced at the target cannot be easily simulated in the FLUKA.CERN Monte Carlo code. This is therefore not considered in this calculation. The dipole field is also not included. Charged particles are therefore not accelerated or bent. Nevertheless, they are not neglected and contribute to the dose values.

The effects of the RF cavities and of the dipole magnetic field are taken into account with the third source term, as described below.

Accelerated Charged Particles

Tracking simulations have been used to take into account the effect of RF cavities [2]. Electrons and positrons were transported through the RF cavities with the ASTRA code [10]. Their distributions at the exit were saved into a file which was then used as an input for Monte Carlo simulations.

Different dipole magnetic fields have been studied. The highest dose outside the P^3 bunker has been obtained when the dipole field is set to the maximum possible value of 0.4 T. These results are presented in the following.

DOSE RATE VALUES OUTSIDE THE P^3 BUNKER

The dose rate distributions in the different regions of interest for the three targets are very similar. In the following, the distributions for the cylindrical target made of tungsten will be presented.

Dose Rate Values in the SwissFEL Tunnel

Figure 3 illustrates the expected dose rate distribution in the SwissFEL tunnel during normal operations. The values are obtained as the sum of the contributions of photons and neutrons of the second and third source terms.

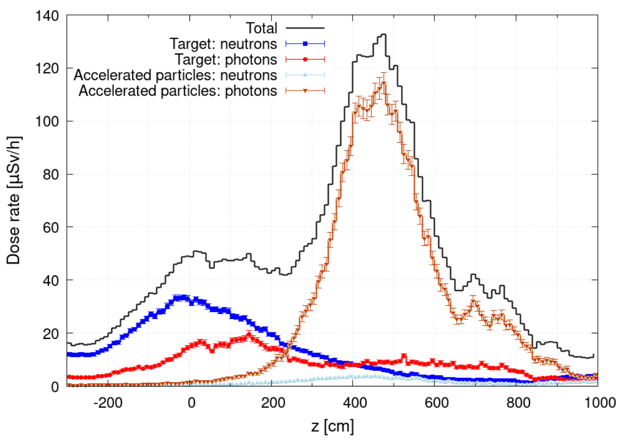

Figure 3: Maximum dose rate in the SwissFEL tunnel as a function of z during normal operations (second and third source terms).

The maximum total dose rate is approximately 130 µSv/h. The largest contribution is due to the photons generated by the accelerated electrons and positrons.

The maximum dose rate obtained for the first source term is significantly higher (almost 200 µSv/h) since the P^3 bunker is omitted in the simulations.

Dose Rate Maps in the Forest, above the Roof

Figure 4 shows the expected neutron dose rate maps in the forest above the roof when the beam hits the dump (top) and when the beam hits the target (bottom). The contribution of the third source term (the accelerated charged particles) is not displayed because it is negligible. The contribution of photons is also not shown, as it is significantly lower.

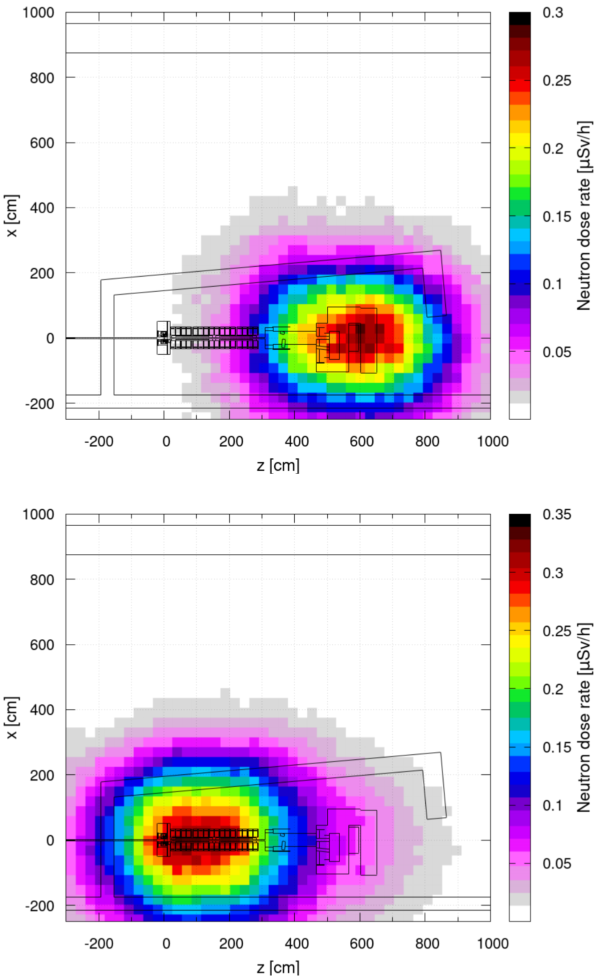

Figure 4: Neutron dose rate map in the forest above the roof of the SwissFEL tunnel due to the first (top) and second (bottom) source terms.

In both cases, the maximum dose rate is below 0.35 µSv/h. The dose rate values are reduced by a factor of two at a transverse distance of 2 m.

Fences have been built in the forest above the experiment to prevent the access of people and large animals in the area, where dose values higher than 0.05 µSv/h are expected.

ACTIVATION

Following irradiation, experiment components can be activated and, during maintenance, workers may be exposed to residual radiation. Dedicated simulations have been performed to assess the expected activation.

Two irradiation scenarios have been considered. In the first case, the target is irradiated during a single machine shift. The target is exposed to beam particles for 30 hours and the assumed charge rate is 200 pC per second.

In the second case, the same target is used for an entire year, undergoing irradiation during six machine shifts spaced 60 days apart, with no beam in between. During each shift, the target is exposed for 30 hours and the assumed charge rate is 200 pC per second. The first target geometry is considered as it is the default one.

The residual dose is then calculated immediately after the last irradiation period and after different cooling times: 1 hour, 1 day, 10 days, 30 days, and 2 years.

As expected, the most activated component is the target. The highest residual dose is predicted at its location, as shown in Fig. 5.

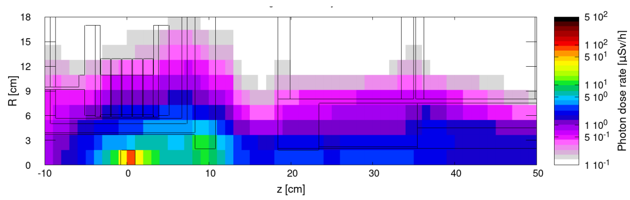

Figure 5: Photon dose rate maps in the z-R plane after 1 year of irradiation after a cooling time of 30 days. The first target is considered.

The maximum dose rate values for the different cases are summarized in Table 1 for a cooling time of 30 days and 2 years.

Table 1: Maximum Residual Dose Rate Values after Different Cooling Times

Target	Irradiation time	Max. residual dose rate 30 days	Max. residual dose rate 2 years
Target 1	6 × 30 hours	35 µSv/h	2.5 µSv/h
Target 1	30 hours	16 µSv/h	0.5 µSv/h
Target 2	30 hours	31 µSv/h	1 µSv/h
Target 3	30 hours	33 µSv/h	1 µSv/h

CONCLUSIONS

Monte Carlo simulations have been performed to estimate the prompt dose in different regions of interest outside the P^3 bunker and to evaluate the expected residual dose for maintenance work and for future disposal. The results obtained have been presented to Swiss authorities, and the permissions to start commissioning were granted. The first beam on the dump is expected to arrive by the end of May 2026.

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