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FLUKA Calculations for the Shielding Design of the SPPS Project at SLAC*

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Abstract

The SPPS project (Sub Picosecond Photon Source) at the Stanford Linear Accelerator Center (SLAC) will generate very bright sub-picosecond pulses of x-ray radiation. The peak brightness of SPPS will exceed that of any existing hard x-ray source by several orders of magnitude. The Monte Carlo particle transport code FLUKA code was used for the calculation of radiation levels at the SPPS facility at SLAC. Several beam loss scenarios were considered and the required shielding was determined.

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I. INTRODUCTION

The Sub Picosecond Photon Source (SPPS) [1] is designed to generate very bright sub-picosecond pulses of spontaneous x-ray radiation utilizing the electron beam from the Stanford Linear Accelerator and an undulator installed in the Final Focus Test Beam (FFTB) [2]. Instead of using a ring shaped synchrotron, the electron bunch is compressed in 3 stages in the 2 miles long linear accelerator where the final compression in the FFTB line compresses the 28.4 GeV, 3.2 nC electrons per pulse (10 Hz) to 80 femtoseconds – the world's shortest bunches of electrons.

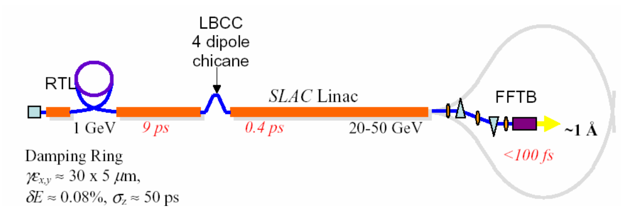

Fig. 1: The e-bunch compression for the SPPS.

A 2.5 m long undulator, that houses an array of permanent magnets with alternating polarity, will turn these tightly compressed electron bunches into x-rays.

Various beam loss scenarios for radiation sources inside the FFTB are discussed in this paper. They include: Losses from e^--beam hitting beamline components and also x-rays from the undulator scattered at the x-ray mirror producing secondary radiation.

II. LAYOUT

The layout of the SPPS facility is depicted in Fig. 2. The generated x-rays from the undulator will be deflected on a x-ray mirror (multilayer monochromator) by 8.5 degrees and will then pass through a penetration of the FFTB and a 30 m long beam pipe outside the FFTB before reaching an experimental hutch in the research yard at the Stanford Linear Accelerator Center (SLAC).

A series of lead collimator will be used to insure the containment of the radiation, two inside the FFTB, (collimator 1 and collimator 2, both have dimensions of 8×8 inch^2 transverse to the beam and 12 inch in beam direction) and one outside the FFTB (collimator 3 - 8×8×8 inch^3). The openings of all collimators are 1×1 inch^2. Two tungsten stoppers (5.2×2.3×12.0 inch^3, w×h×l) which are part of the Personal Protection System (PPS) will provide radiation protection in the experimental hutch as part of the Access Control System.

III. DETAILS OF THE CALCULATIONS

The FLUKA Monte-Carlo particle transport code [3, 4] was used for the determination of the radiation levels inside and outside the FFTB tunnel. Furthermore, the radiation levels around the x-ray beam transport line from the FFTB to the experimental hutch and around the hutch itself were calculated and the required shielding was determined.

The design of the shielding should ensure that the effective dose rate outside the FFTB is below the FFTB design limit of 0.5 mrem/h and outside the experimental hutch below 0.05 mrem/h.

The FLUKA code has been extensively bench-marked against experimental data over a wide energy range for both hadronic and electromagnetic showers.

III.A. Co-ordinate System

The geometry of the FFTB and SSPS used in FLUKA was described in a right-handed orthogonal system with the vertical x-axis perpendicular to the surface. The z-axis was horizontal and parallel to the

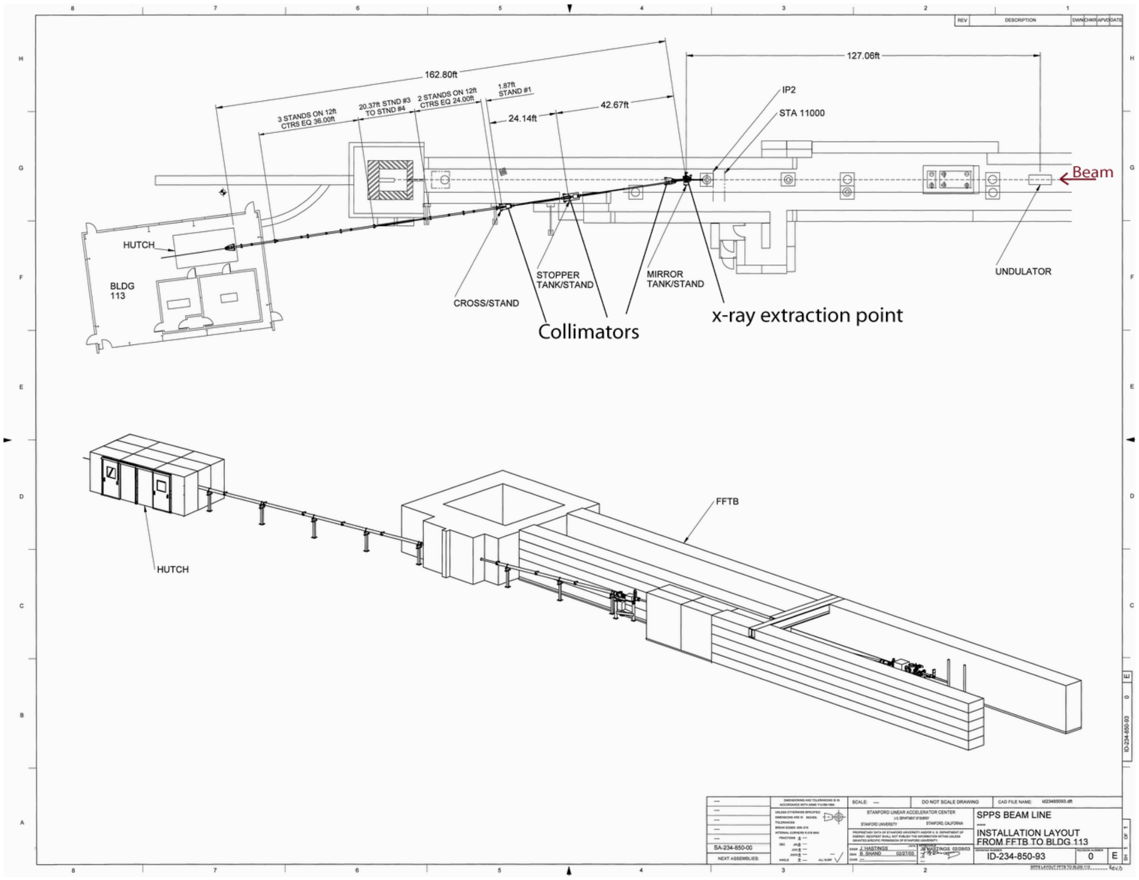

Fig. 2: Layout of the Final Focus Test Beam (FFTB) at SLAC for the SPPS project

FFTB photon beam axis. The y-axis was also horizontal and was pointing towards the right - looking along the beam direction. The origin of the co-ordinate system was chosen to be in the middle of the front face of the x-ray mirror inside the FFTB tunnel.

III.B. FLUKA Geometry

The FLUKA geometry of the FFTB area is shown in a vertical and horizontal sectional cut in Fig. 3 and Fig. 4 respectively. A three inch diameter steel pipe with a wall thickness of 0.083 inch is installed inside the six inch diameter drilling through the FFTB concrete shielding wall. Two lead collimators inside the FFTB will reduce the radiation through the pipe towards the hutch. The first collimator consists of a 1 inch diameter drilling through the Pb-shielding around PC 7.5 and the second collimator is installed in the notch cut of the concrete shielding wall. Collimator 2 has an inner diameter of one inch, an outer diameter of eight inch and a length of 12 inches. The x-ray mirror (20 cm long, 2 cm in height and 1 cm thick) is inclined by 4.25 degrees w.r.t. the beam line in order to reflect the x-rays by 8.5 degrees towards the hutch into Building 113. The quadrupole magnets QSP2 and QSP3 down beam of PC 7.5 around the electron pipe are also implemented into the geometry.

All concrete shielding components were assumed to have a density of 2.35 g/cm^3 and the following chemical composition (the values in brackets give the corresponding mass fractions): hydrogen (0.6%), carbon (0.3%), oxygen (50.0%), sodium (1.0%), magnesium (0.5%), aluminum (3.0%), silicon (20.0%), potassium (1.0%), calcium (19.5%) and iron (1.2%).

III.C. Split FLUKA Runs

In order to limit the amount of CPU time for the calculations of the radiation levels around the x-ray beam pipe and the experimental hutch, the calculations were split into two runs. In a first set of runs (called RUN 1) information of particles reaching a virtual plane outside the FFTB north wall was stored on a file (see Fig. 5).

This information included:

- number of total primaries
- total weight of the primary particles

and information of the dumped particles, like,

- energy
- particle type
- weight
- co-ordinates
- direction cosines

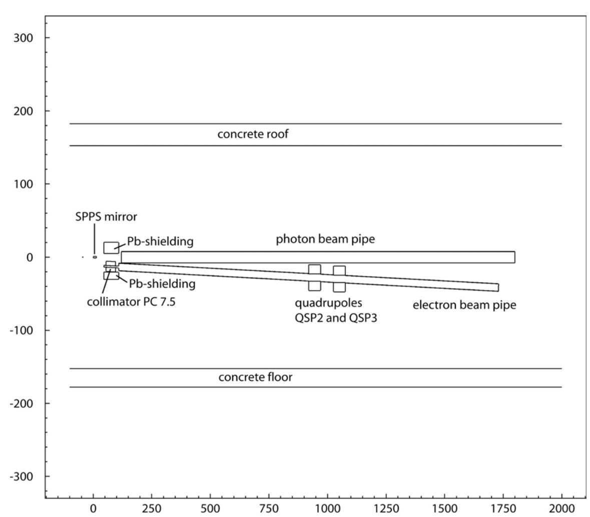

Fig. 3: FLUKA geometry of the FFTB – Vertical sectional cut.

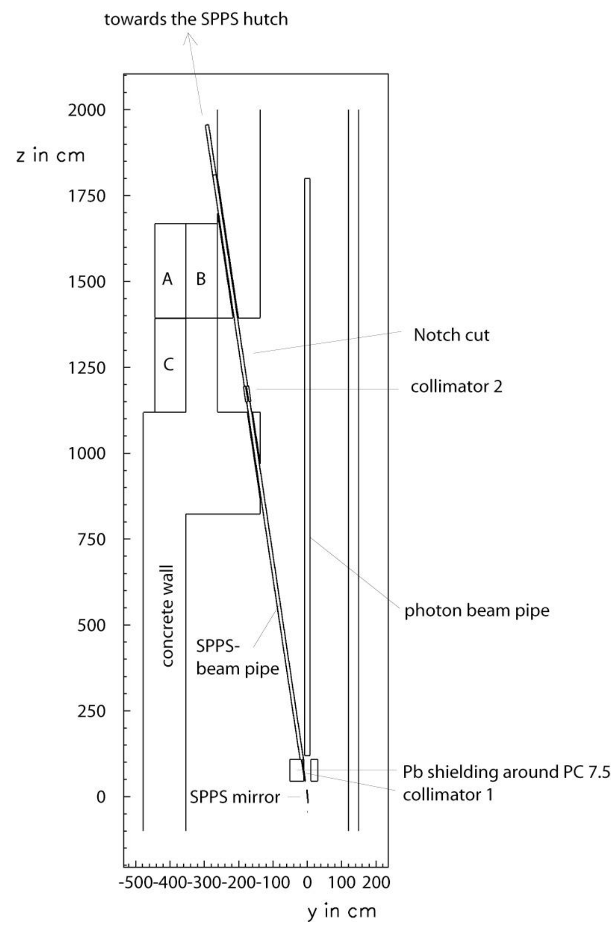

Fig. 4: FLUKA geometry of the FFTB – Horizontal sectional cut at beam height.

In a set of second runs (called RUN 2) these particle information were read into FLUKA as a source file. This 'splitting' avoids time consuming transport of particles until they reach a region of interest. Therefore, different shielding configurations for the experimental hutch were simulated within reasonable time.

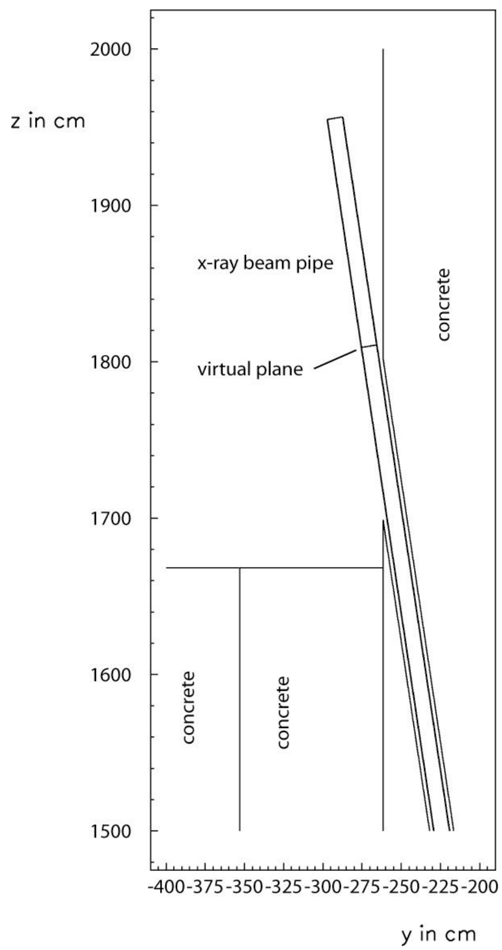

Fig. 5: Details of the FLUKA geometry at the location where the beam pipe exits the FFTB. The virtual plane is also shown where information of particles crossing the plane was written to a file for further processing.

III.D. Beam Losses

Three normal beam loss scenarios inside the FFTB were considered. All three cases were assumed to be additive.

Case 1: Bremsstrahlung photons which are produced by a 28.4 GeV electron beam hitting a 1 cm thick and 1 cm long Cu-cylinder. This case simulates the interaction of an e^--beam halo of 0.5% of the normal beam power of 1kW – *i.e.* 5 W - with apertures up beam of the permanent beam line magnets in the FFTB dump line. The electrons are bent by permanent magnets towards the dump. The produced photons pass through the permanent e^--beam magnets along the existing photon beam line, hit the x-ray mirror inside the FFTB and generate an electromagnetic shower in the mirror and the downstream beamline components. The e^--beam power (beam loss) in this case is assumed to be 5 Watt.

C**ase 2:** Low-energy electrons (21 - 26 GeV[1]) produced by interaction with foils and windows in the e^--beam are separated by the permanent e^--beam magnets in FFTB dump line and are lost in collimator PC 7.5. Total power of the low-energy electrons lost in collimator PC 7.5 is estimated to be 5 Watt, based on the previous FFTB measurements.

Case 3: The continuous x-ray spectrum, which is generated by an undulator, located approximately 34 m upstream of the x-ray extraction point in the FFTB. These x-rays are scattered at the x-ray mirror in the FFTB and are transported to the SPPS hutch. Although the peak power emitted by the undulator is 8.85 GW the average power is only 0.025 W with a critical energy of 200 keV.

III.E. Energy Thresholds

The following thresholds for particles transport were used for the simulations.

RUN 1:

Case 1 and case 2:

1 MeV for all hadrons, electrons and positrons (except for anti-n and K-Long, both 50 MeV, and neutrons which were transported down to 4.14×10^{-10} GeV). For photons an energy threshold of 100 keV was used.

Case 3:

10 keV for photons and electrons/positrons.

[1] FFTB 30.0 GeV Ray Trace, beam stay clear, STA 300M to 375 M, GP-234-328-13 E0

RUN 2:

Case 1 and case 2:

100 keV for all hadrons (except for anti-n and K-Long, both 50 MeV, and neutrons which were transported down to 4.14×10^{-10} GeV). Photons and electrons were transported down to 30 keV.

Case 3:

1 keV for photons and electrons/positrons.

III.F. Biasing

The inelastic interaction length of photons was reduced by a factor of 0.02 in case 1, 2 and 3 in order to enhance the statistical significance of photonuclear reactions. Further, use was made of region-importance biasing in the concrete regions.

III.G. Scoring

For the calculation of the effective dose, the particle fluence was weighted during the scoring procedure by energy- and particle type-dependent conversion factors using the EWMP option in FLUKA as implemented by Roesler [5]. This option uses the Pelliccioni data and the concept of the WORST value of effective dose for any body orientation as described in [6].

IV. RESULTS

IV.A. Particles passing through the x-ray Transport Pipe

The type and the energy of particles passing through the collimators of the beam pipe towards the SPPS hutch was calculated with FLUKA a) before reaching Collimator 3 (8 inch long, 8 inch diameter with a one inch diameter hole) outside of the FFTB tunnel, see Fig. 6 - position 1 and b) just after reaching the hutch in Building 113, see Fig. 6 - position 2. The corresponding power of these particles for all three cases is given in Table 1. The beam power in case 1 (*i.e.* Bremsstrahlung photons produced upstream of the e-beam magnets) is about 50 times higher than in the two other cases but is still very small – only 0.57 μW. From the results, it can be further seen that case 2 (*i.e.* electrons hitting collimator PC7.5 downstream of the e-beam magnets in the FFTB) causes negligible radiation leakage at the hutch. Consequently, dose rate calculations were not performed for case 2. In addition to the radiation leakage the energy deposition in collimator 3 was calculated for case 1 and case 3. It was found that 0.34 μW (case 1) and 0.006 μW (case 3) will be deposited in the collimator. Resulting, that around 60 % of the total power of the particles will be absorbed in this collimator in case 1 and about 50 % in case 3.

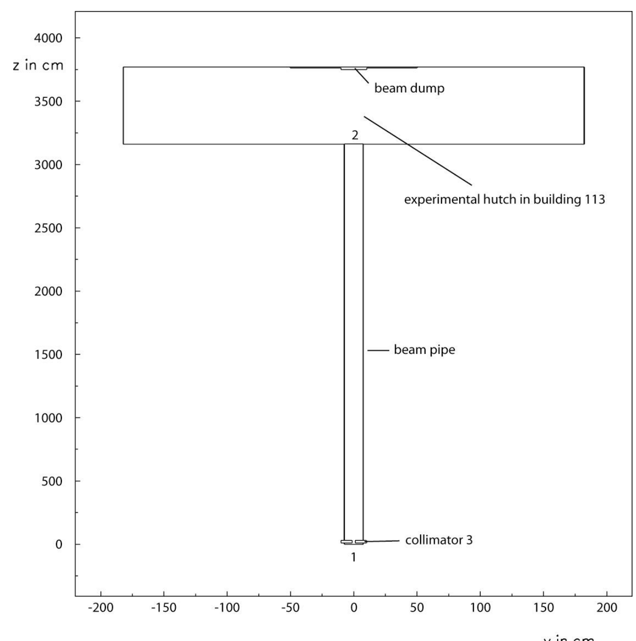

Fig. 6: FLUKA geometry of the beam pipe outside the FFTB and the experimental hutch.

Table 1: Radiation leakage towards the SPPS hutch

Scenario	Calculation bases	Radiation leakage towards the hutch calculated outside the FFTB, see Fig. 6 – Position 1		Radiation leakage towards the hutch calculated at the hutch, see Fig. 6 – Position 2	
Case 1	5 Watt	Photons e^+/e^- Total	0.32 μW 0.25 μW 0.57 μW	Photons e^+/e^- Total	0.12 μW 0.09 μW 0.21 μW
Case 2	5 Watt	Photons e^+/e^- Total	0.01 μW negligible 0.01 μW	Photons e^+/e^- Total	negligible negligible negligible
Case 3	1.67×10^{12} Photons/s*	Photons	0.012 μW	Photons	0.004 μW

* Number of photon/s with energies > 1 keV, photons below 1 keV cannot be transported with FLUKA.

IV.B. Radiation Levels

IV.B.1. Dose Rate at the FFTB

The calculations showed that the maximum effective dose rate outside the fenced off FFTB area (minimum distance from the penetration at the FFTB wall to the fence is ~4.8 m) is well below the FFTB limit of 0.5 mrem/h, see Fig. 7. Outside the fence <0.15 mrem/h can be expected. Close to the penetration a local dose rate of <0.5 mrem/h was calculated.

Further, it was found that the originally foreseen gap between the 3 inch diameter beam transfer pipe and the 6 inch diameter penetration through the FFTB has to be filled from the inside with 2 feet long steel rods and with 8 feet from the outside in order to avoid streaming of radiation (5-10 mrem/h) through the penetration.

The x-rays produced by the undulator and which are not deflected towards the SPPS hutch will end up at a photon stopper in the FFTB. Due to the low power of these x-rays (< 0.025W), the radiation level outside the FFTB will not change.

IV.B.2 Dose Rate inside the x-ray Transport Line

The effective dose rate in the center of the beam pipe (averaged over 1 cm diameter) was calculated to be around 400 mrem/h upstream collimator 3 and drops to 50 mrem/h insight the experimental hutch. It is dominated by photons and electrons/positrons which are generated by a 28.4 GeV electron beam loss in beamline components upstream the x-ray extraction point in the FFTB (case 1), see Fig. 8. The contribution to the total dose insight the pipe caused by x-rays from the undulator (case 3), is only a few percent, see Fig. 9. Radiation inside the beam pipe from beam loss at PC-7.5 was found to be negligible.

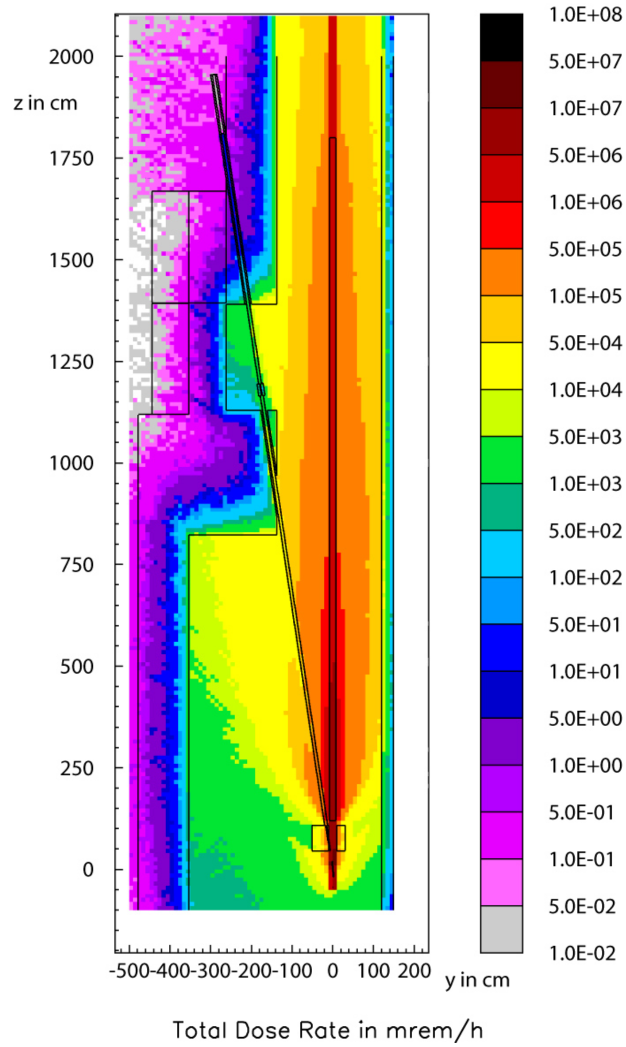

Fig. 7: Total dose rate at the FFTB tunnel

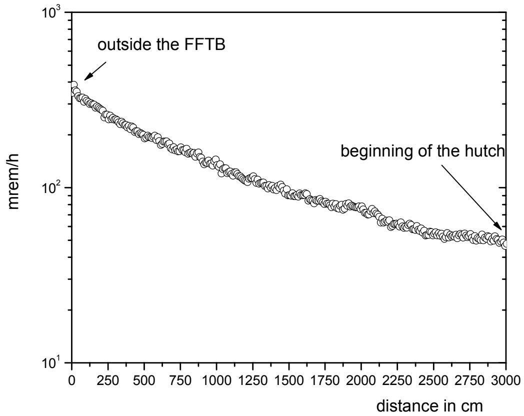

Fig. 8: Case 1 - Total dose rate in the center (1 cm diameter) of the beam pipe

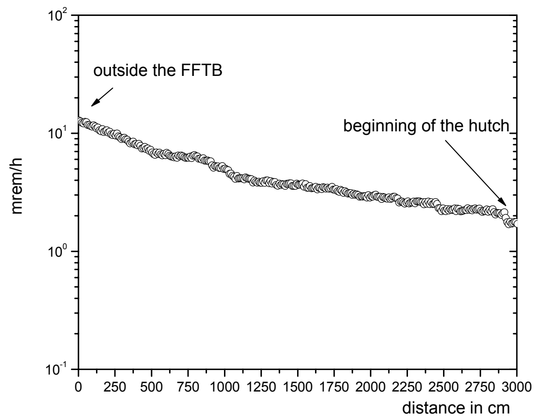

Fig. 9: Case 3 – Total dose rate in the center (1 cm diameter) of the beam pipe

Of further interest was the determination of the dose rate outside the beam pipe which is caused by the radiation leakage through the pipe towards the SPPS hutch. The dose is very well contained in the center of the pipe due to the three collimators around the beam transfer pipe towards the experimental hutch. Moreover, except close to collimator 3, where the dose rate can be 0.5 mrem/h, the radiation level is always below 5×10^{-4} mrem/h.

IV.B.3. Dose Rate at the SPPS Hutch

In order to reduce the dose rates outside the experimental hutch in Building 113 to 0.05 mrem/h (equivalent to 100 mrem/y – assuming 2000 working hour a year) an 8×8×8 inch^3 lead block with a 2 inch thick 40×40 inch^2 steel or lead extension around this dump has to be installed, see Fig. 10. This shield is able to keep the radiation level outside the hutch below 0.05 mrem/h. A hutch wall thickness of 0.3 cm of steel is sufficient.

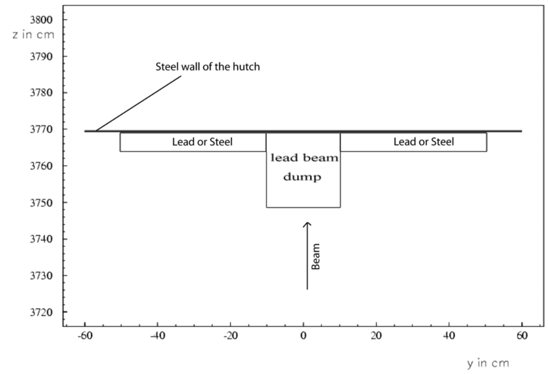

Fig. 10: Horizontal sectional cut through the layout of the beam dump in the experimental hutch in Building 113.

Several calculations have been performed for case 1 (bremsstrahlung photons) and for case 3 (x-rays) in order to compute the dose rate inside and outside the hutch. Fig. 11 shows the dose rate when the beam is impinging on the dump at the end of the hutch for case 1. The spread of the dose is mostly caused by multiple scattering of electrons and positrons in the air of the hutch.

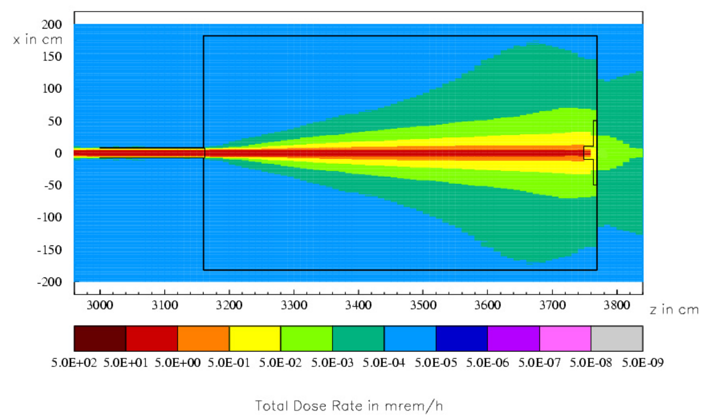

Fig. 11: Case 1 – Total dose rate at the experimental hutch. The beam is impinging on the beam dump downstream the hutch.

Next, a Si-target - 100 cm long, 20 cm wide, 10 cm height - was placed inside the hutch on the beam axis. The contribution to the dose caused by photons, electrons/positrons and neutrons for case 1 is given in Fig. 12 - 15, separately. It can be emphasized that the dose rate outside the hutch is below the limit of 0.05 mrem/h. Furthermore, the dose rate behind the stopper is dominated by photon induced neutrons from the dump.

The total dose rate at the hutch for the x-ray beam striking the target (case 3) is shown in Fig. 16.

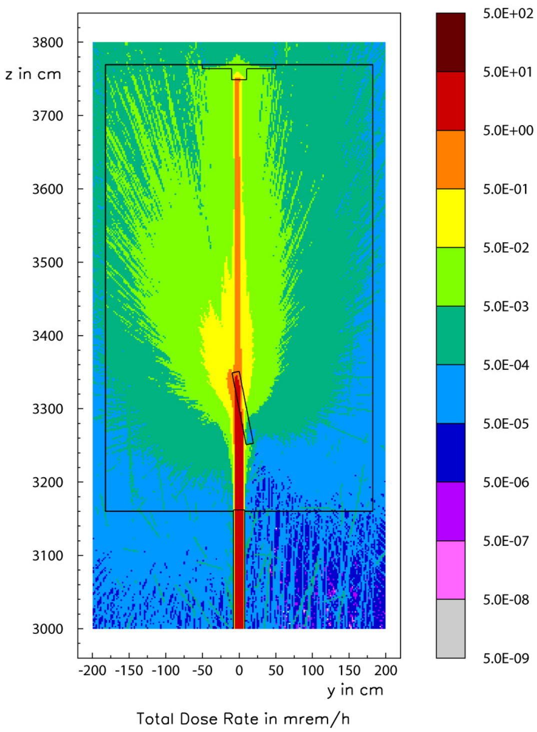

Fig. 12: Case 1 – Total dose rate at the experimental hutch. The beam is impinging on a Si-target.

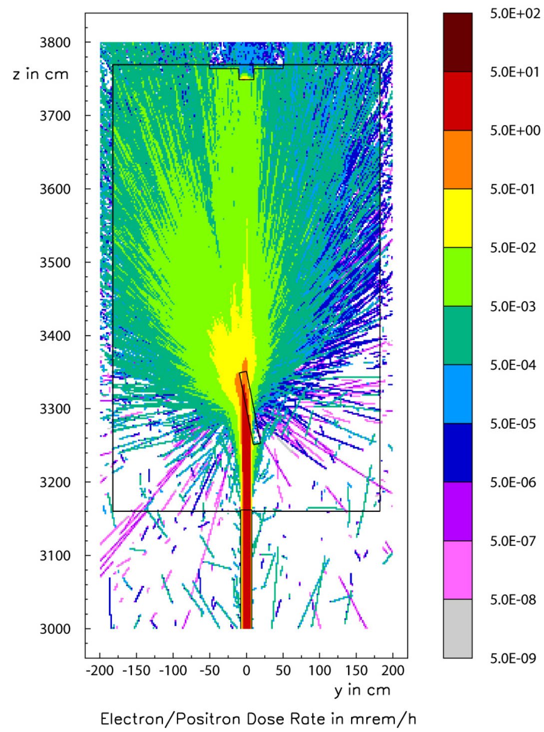

Fig. 14: Case 1 – Electron/positron dose rate at the experimental hutch. The beam is impinging on a Si-target.

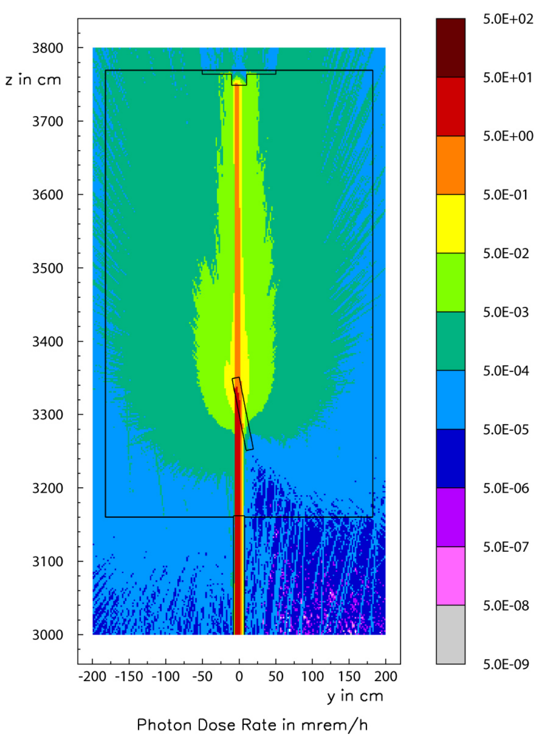

Fig. 13: Case 1 – Photon dose rate at the experimental hutch. The beam is impinging on a Si-target.

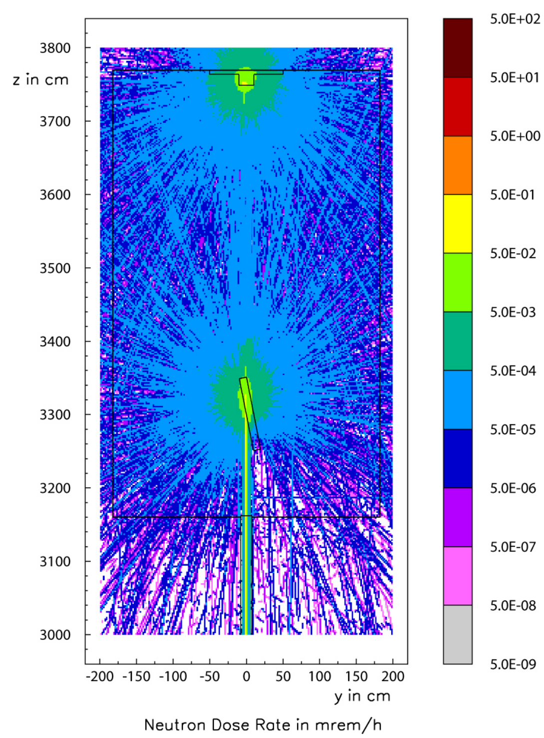

Fig. 15: Case 1 – Neutron dose rate at the experimental hutch. The beam is impinging on a Si-target.

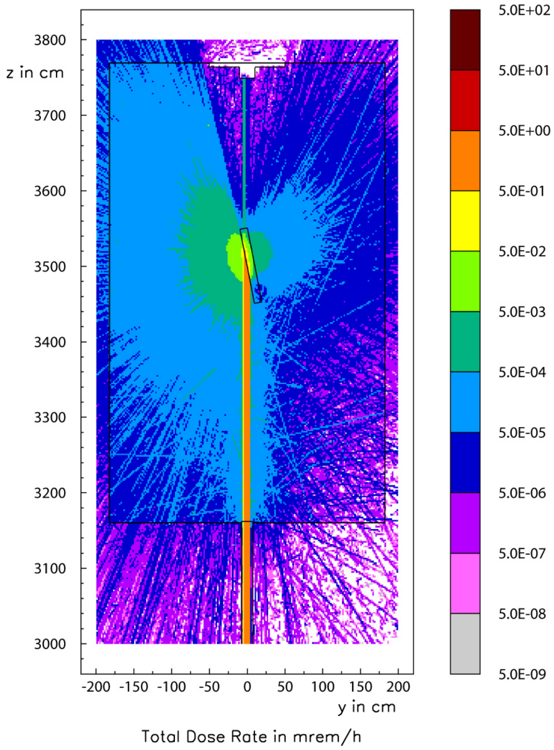

Fig. 16: Case 3 - Total dose rate at the experimental hutch. The x-ray beam is impinging on a Si-target.

IV.C. Particle Spectra

FLUKA was further used to calculate the energy dependent particle spectra for case 1. The spectra were scored a) in front of Collimator 3 and b) inside and c) outside the experimental hutch after scattered on a Si-target (scored within an angle between 60 and 120 degrees w.r.t. the beam).

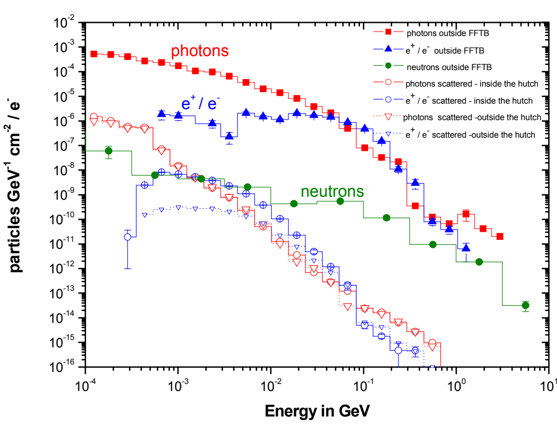

Fig. 17: Spectra of photons, electrons/ positrons and neutrons in case 1 as a function of energy.

V. SUMMARY

The FLUKA code was used for the calculation of radiation levels at the SPPS facility at SLAC. Three beam loss scenarios were considered and the shielding modifications of the FFTB tunnel simulated. Additionally, the required shielding for the experimental hutch was determined by using the methodology of split FLUKA runs.

VI. REFERENCES

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