PARTICLE TRACKING SIMULATIONS FOR EXFEL COMPLEX SHAPE COLLIMATORS

V.G. Khachatryan*, V.H. Petrosyan, T.L. Vardanyan, CANDLE SRI, Yerevan 0040, Armenia

Abstract

The study sets the objective to investigate through numerical simulation the produced secondary radiation properties when the electron beam particles hit collimator walls. Using particle tracking simulation code FLUKA, the European XFEL electron beam as well as beam halo interaction with the collimator were simulated [1,2]. The complex geometrical shape and material composition of the collimator have been taken into account. Absorbed dose spatial distribution in the material of the collimators and particle fluencies from the downstream surface of the collimator were simulated for the total secondary radiation and its main components.

INTRODUCTION

The beam halo consists of particles per bunch with large betatron or energy amplitudes. Evaluation of the number of large-amplitude particles which can be expected due to the scattering processes, wakefields, and magnet nonlinearities is a difficult task. The beam collimation systems are applied to get rid of beam halo. description of collimators with the picture of general view and the photo of "Collimators Block" unit is provided Nina Golubeva [3] The XFEL main collimator CL.COLM (4 collimators) is a sytem consisting of 4 Titanium alloy tubes (diameters are 4, 6, 8 and 20 mm) distributed vertically, internal pure Al block and outer Copper block (length=50cm) with brazed cooling tubes[4]. Collimator with its movers will be located inside the steel housing (length=1m), in vacuum. In numerical calculations with FLUKA only the main characteristics of geometry has been taken into account. Therefore, somewhat simplified geometry was used in calculations which includes only main collimator block, steel housing and beam pipe (with 40.5mm diameters). The thickness of the titanium tubes and beam pipe wall is 2 mm. All tubes (0.5m long) are not tapered. Vertical direction movers enable the usage of any of four aperture of the collimator. The general view does not correspond to the exact final design. EXFEL linear accelerator beam main parameters are specified in Table 1 [2].

Table 1: Beam Parameters at Undulators

Energy	17.5 GeV
Emittance (normalized)	≤ 1.4 mm-mrad
Beta function	≈ 220 m
Spot size	9 x 10^{-5} m

*Khachatryan@asls.candle.am

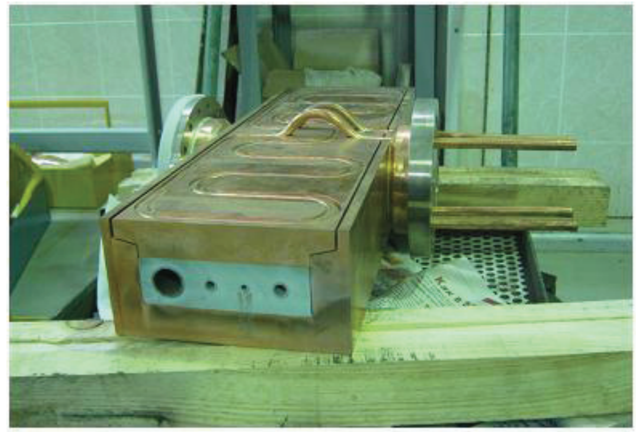

Figure 1: The photo of "Collimators Block" unit (The photo is provided by N. Golubeva) [3].

BEAM IMPACT ON COLLIMATOR WALL

At the undulator the beam size corresponds to the beta function value 220 m [3]. We took 17.5 GeV for the beam energy and 1.4 mm-mrad for the beam normalized emittance.

Bending or corrector magnets supply current values deviations from the stationary ones deflect the beam to the collimator wall. The simulation of the beam impact on the collimator is important from the radiation protection point of view, since high rate of the radiation produced can be harmful for both humans and sensitive equipment. Spatial distribution of the radiation field downstream collimator may indicate where an additional shielding would be useful. We assume that miss-stirred beam hits the front wall of the titanium tube at the coordinates x=0, y=0.4 cm. Electromagnetic cascade has been developed in the body of the titanium tube and then the shower spreads out to the neighbouring volumes (Figure 2). All the plots shown in Figures 2 and 3 are normalized to one of the primary particle. One can see that downstream to collimator outside beam pipe dose rate (Dose-Equivalent) reaches to a few Pico Sievert (≤10 pSv) per primary electron. That corresponds to 0.06 Sieverts per 1nC. Plots in the Figure 2 (right column) depict dose distribution [pSv] along the channel with maximum value. A full scale electromagnetic shower developments starts at the middle of the collimator. Figure 3 shows particle fluencies from the downstream surface of the collimator [GeV^{-1} cm^{-2}]. Note that the Fluence from the surface of the housing flange prevails in the low energy region while at higher energies most radiation passes through the beam pipe cross sectional area.

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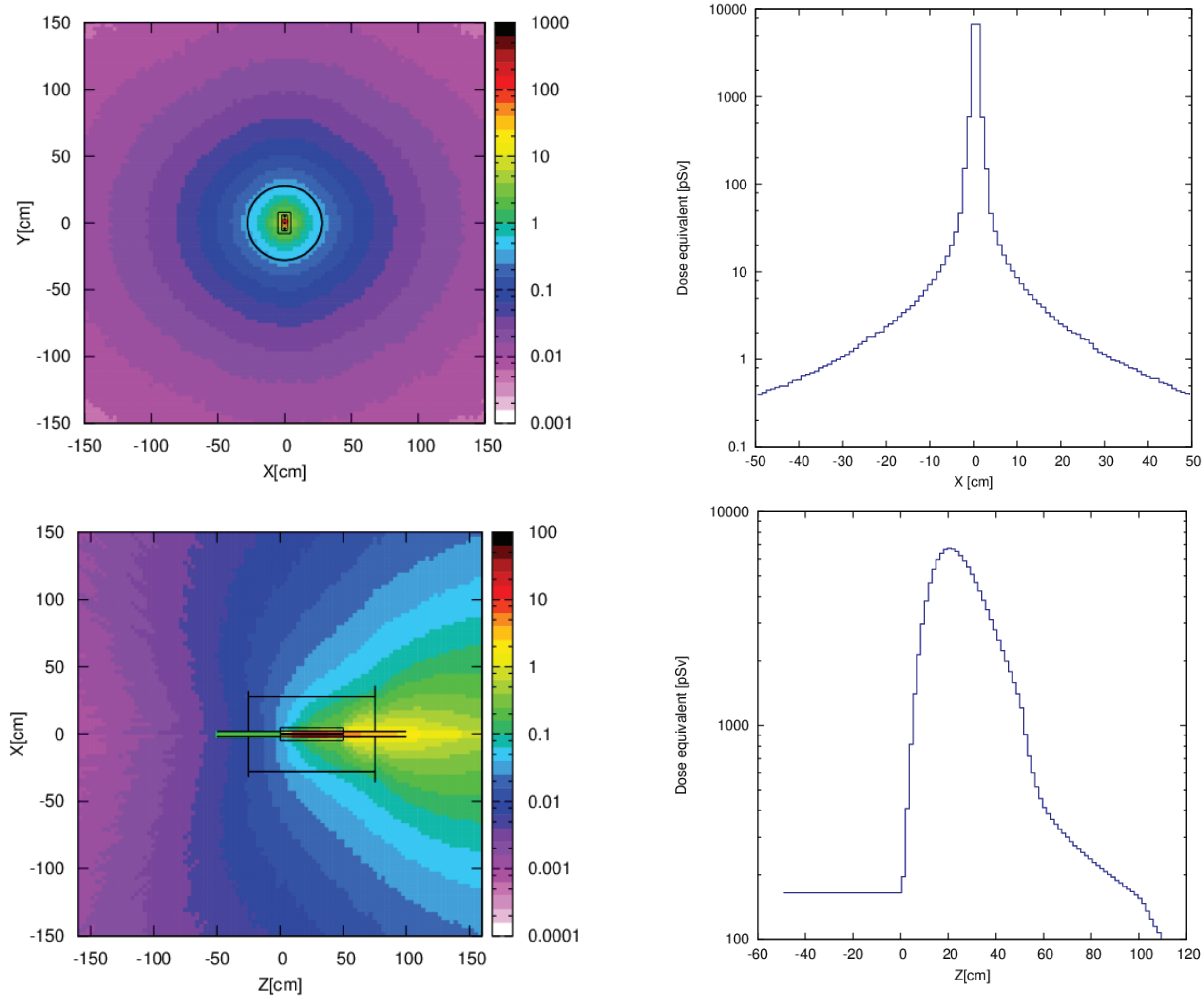

Figure 2: Dose distribution in picoSieverts (left column). Dose distribution in picoSieverts along channel with maximum value (right column).

Beam electrons lose their energy in the volume of the collimator mainly though electromagnetic showers (~75.6%), (Table 2). Hadron and muon energy loss channels compose only 0.1 % of the total energy loss. Unwanted hazardous radiation accounts for 24% of incident beam energy carried by the particles escaping the collimator.

Table 2: The energy available per beam particle in GeV and percentage of total energy loss is divided into several prompt radiation channels

	GeV	Percent
Hadron and muon energy loss	2.5×10^{-2}	0.1
Electro-magnetic showers	1.32	75.6
Nuclear recoils and fragments	1.3×10^{-3}	0.0
Low energy neutrons	4.6×10^{-4}	0.0
Particles escaping the system	4.20	24
Energy per beam particle	16.5	100

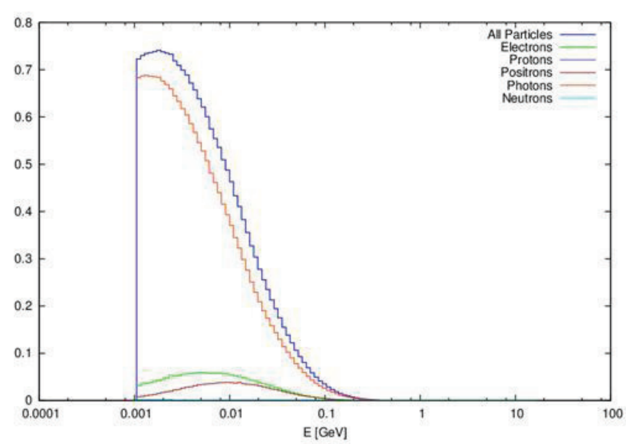

Figure 3: Particle fluencies from the downstream surface of the collimator [GeV^{-1} cm^{-2}].

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BEAM HALO INTERACTION WITH COLLIMATOR

When radiation detectors indicate that the electron beam hits collimator wall, the beam will be steered to the dump quickly enough to avoid significant damage by the radiation. Thus that mechanism cannot be considered as a halo source. Besides, the produced particles are widely spread over energy, spatial and angular ranges and the magnetic lattice will draw them promptly out of the beam orbit.

The peripherals of the beam starts just from the beam gun and part of it passes through the magnetic lattice and reaches undulators. The particles of the beam halo are being lost continuously in interactions with the beam pipe walls. The most efficient way to get rid of the beam halo is collimation. In the result of the halo particles impacts on the collimator walls, a secondary particles coming out of collimator volume are being produced (Photons, electrons, positrons, neutrons, etc.). The dominating component of the secondary radiation is the gamma component. They are insensitive to the magnetic field of lattice and keep their direction of the motion becoming part of the general radiation background. Part of the electrons can contribute to the beam halo.

Since some processes (energy spread, lattice imperfections, interactions with the beam diagnostic equipment, various types of beam instabilities etc.) contribute to the beam halo continuously, further collimation is necessary. Therefore, four collimators of the same type will be installed in EXFEL collimator section.

Input and Output Files Description

To make use of beam transport codes or just lattice transfer matrices it is convenient to rely on the FLUKA capabilities to take beam input and output files as an ASCII table with the particle parameters presented in the separate columns.

In order to do calculations from the custom beam distribution, the user should give the ASCII file. A layout of the data is organized as a table with 9 columns (ID, X,Y, Z, COSX, COSY, COSZ, E), where ID is a type of particle (for example 3 for electrons), X,Y,Z are coordinates in [cm], COSX, COSY, COSZ are the cosines of moving direction with respect to axes and E is the energy in GeV. It is possible to give input file with the mixture of different particles using IDs of particles.

Output files are given in the same format as input files and are written to the different files depending on particle types. For electrons, positrons, protons, photons, neutrons individual output files are created and data of other particles are written in the same file as the mixture of particles. The program is flexible enough to give output files with different formats and any customization is possible if desired. Data organization in that format make possible to use transfer matrices from the magnetic lattice description to transport beam parameters between the individual collimators.

Initial Halo Types

Two options of the beam halo particles spatial distribution inside beam pipe have been considered:

1) Particles are normally distributed along radial direction with the maximum at the beam pipe axis;

2) Particles distances from the beam pipe axis are uniformly distributed.

Divergence angles are chosen to be correlated with the particle distance from the axis, in a way that $xx' \sim \varepsilon$, where $\varepsilon = 0.41\times10^{-10}$ is the beam natural emittance.

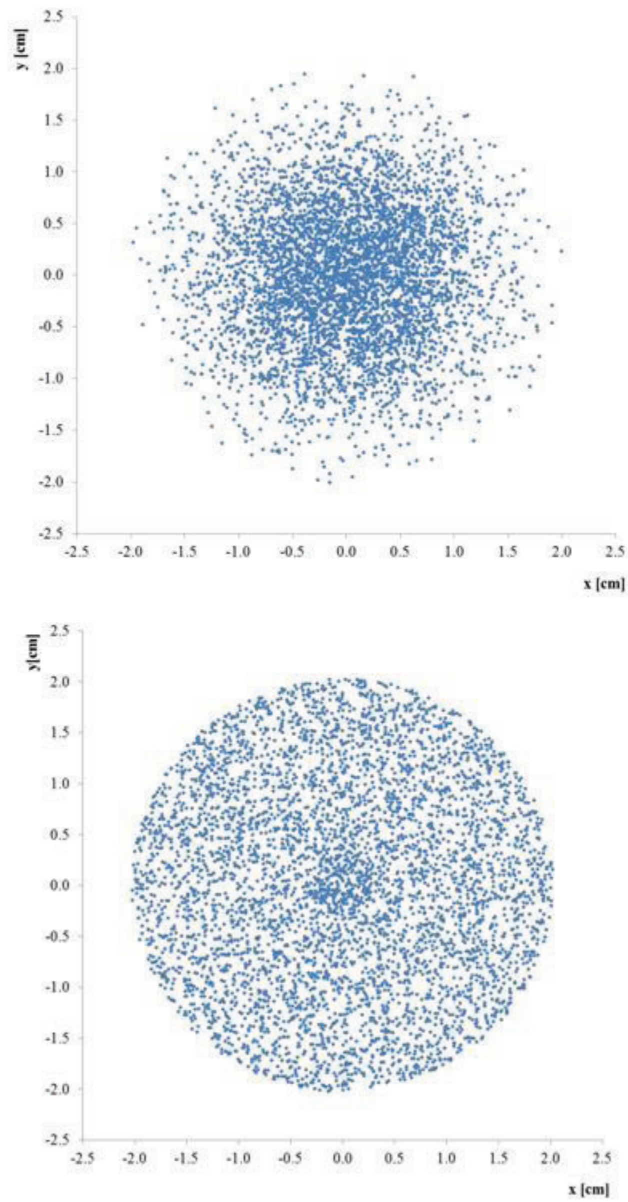

Figure 4: Beam halo particles spatial distribution (5 000 entries) at the entrance (top) and exit (bottom) of the first collimator.

Halo at the First Collimator Exit

Beam halo particles spatial distribution at the entrance and exit of the first collimator is presented in Figure 4.

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When the beam halo consisting of the normally distributed within inner area of the beam pipe interacts with the first collimator, the halo coming out from downstream surface of the collimator in the beam pipe region is dominated by the photons (Figure 5). The majority of the electrons and positrons have the energy close to core value 17.5 GeV are being driven by the magnetic lattice to the 2nd collimator entrance while almost all photons are being lost because of the dogleg shape of the undulator section.

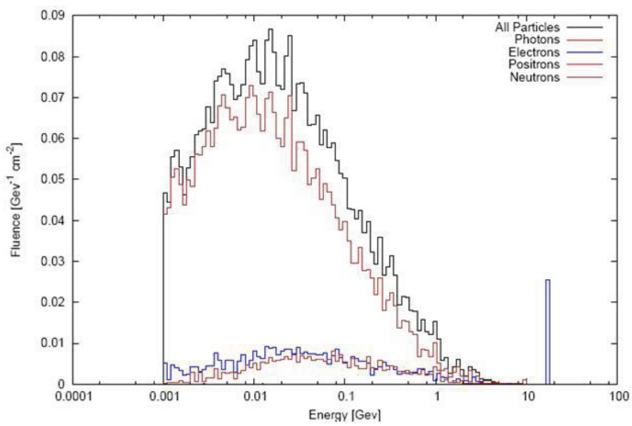

Figure 5: Particle fluencies from the beam pipe region of the 1st collimator surface (Particles per primary electron) produced by the beam halo.

FLUKA simulations show that interaction of the beam halo with the first two collimators significantly reduces halo population (Tables 3, 4). If one assumes that halo particles mean energy is about 17.5 GeV, then 43% of halo energy is absorbed in the first collimator volume, while the mean energy of halo particles incident on the second collimator becomes 1.2 GeV, 24% of which is being lost there.

Table 3: Particle fluencies from the beam pipe region of the collimator surface (Particles per cm^2 per primary electron). Surface area is 12.87 cm^2

Particle Type	Collimator1	Collimator2
All Particles	0.38	0.21
Electrons	$4.06\ 10^{-2}$	$2.31\ 10^{-2}$
Positron	$2.8\ 10^{-2}$	$1.57\ 10^{-2}$
Photons	0.31	0.177
Neutrons	$1.7\ 10^{-5}$	$1.77\ 10^{-7}$

Table 4: Particle fluencies from the collimator-housing surface (Particles per cm^2 per primary electron). Surface area is 50265.48 cm^2

Particle Type	Collimator1	Collimator2
All Particles	11.57	6.59
Electrons	1.21	0.70
Positron	0.81	0.47
Photons	9.54	5.41
Neutrons	$5.63\ 10^{-3}$	$2.26\ 10^{-4}$

SUMMARY AND CONCLUSION

Using particle tracking simulation code FLUKA, the European XFEL electron beam as well as the beam halo interaction with the collimator were simulated. The XFEL main collimator CL.COLM (4 collimators) is a system of four collimators inserted into dogleg shape collimator section. In numerical calculations with FLUKA the characteristics of geometry have been taken into account using SIMPLE GEO package.

We took 17.5 GeV for the beam energy and 1.4 mm-mrad for the beam normalized emittance. Beta function is ≈ 220 m (Spot size (σ_x) is 9 x 10^{-5} m) at the collimator. The beam halo consists of particles per bunch with large betatron or energy amplitudes. Two types of beam halo filling the inner volume of the beam pipe were simulated.

Bending or corrector magnets supply current values deviations from the stationary ones can deflect the beam to the collimator wall. The simulation of the beam impact on the collimator wall is important from the radiation protection point of view, since high rate of the radiation produced can be harmful both for humans and sensitive equipment. The results of the simulations of the beam impact on the collimator wall show that downstream to collimator outside beam pipe dose rate (Dose-Equivalent) reaches to a few Pico Sieverts (≤10 pSv) per primary electron.

To find the effectiveness of the collimator in reducing a beam halo the interaction of the two different types of halo with the collimator were simulated. The parameters of the electrons coming out from the downstream surface of the collimator were transferred to the entrance of the next collimator at the EXFEL collimator section using linear transfer matrices.

The study of the beam halo dynamics is in progress including the evaluation of the number of large-amplitude particles which can be expected due to the scattering processes, wakefields, and magnet nonlinearities [5].

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