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PARTICLE TRACKING SIMULATIONS WITH FLUKA FOR DESY FLASH AND EXFEL COLLIMATORS

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Abstract

The objective of the study is the simulation of the produced secondary radiation properties when the electron beam halo particles hit collimator walls. Using particle tracking simulation code FLUKA the European XFEL electron beam interaction with the titanium collimator and copper absorber of the undulator intersections as well as FLASH beam interaction with the tapered collimator were simulated.

Absorbed dose spatial distribution in the material of the collimators was simulated for the total secondary radiation and its important photon and neutron components. Residual dose rate after irritation of the collimator material by the electron beam was calculated.

INTRODUCION

Collimators are used in FLASH and European XFEL to cut off electron beam halo [1,2]. Secondary radiation is emitted when electron beam interacted with collimators, beam diagnostic devices and residual gas. Analytical methods based on the empirical formulae [3] are suited for the calculation of the electron interaction with the vacuum chamber residual gas, fine wires or thin sheets. Particle-tracking codes can be used to simulate the passage of the particles through the matter when particle beam interacts with the collimator, beam chamber walls or large pieces of instrumentation. We will use FLUKA [4] to simulate the interaction of the electron beam with the FLASH and European XFEL collimators made of Titanium and Copper. The main characteristics of the collimator materials are given in Table 1.

Table 1: Collimator Material Properties

Property	Copper	Titanium
Z	29	22
A	63.55	47.88
Density [g/cm^3]	8.96	4.54
Radiation length [cm]	1.43	3.56
Moliere radius [cm]	1.6	2.85
Critical energy [MeV]	20.2	26.2

Radiation study applying particle simulation code is instrumental for validation of the collimators material and geometry choices. It gives also an opportunity to design an appropriate shielding to protect personnel and prevent radiation damage of the sensitive equipment and electronics.

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FLASH TAPERED COLLIMATOR

On FLASH facility four cylindrical symmetric copper made tapered collimators of the same type are installed [5]. The collimators are cylindrical tubes with inner tapered holes. The length of the tapered parts are 200 mm each and non-tapered central part length is 100 mm. Minimal inner radius is 0.2 mm, while maximal inner radius at the ends is equal to 4.5 mm.

It is assumed that FLASH 1.27 GeV beam electrons hit collimator inner wall at grazing angle on the XZ plain (Fig. 1,2). Energy deposition in the collimator volume and its vicinity is calculated using FLUKA, which allows to simulate energy deposition or particle fluence on the given mesh independent of the geometry. Plots are normalized to 1nC primary charge.

Absorbed dose distribution XY projection is shown in Fig. 1. Absorbed dose is expressed in Greys (J/kg). Within the hole of the collimator, where the material does not exist (vacuum), absorbed dose is zero. Maximal dose can be found near the beam impact point. Absorbed dose distribution XZ projection is show in Fig. 2. Absorbed dose is expressed in Greys (J/kg). Distribution maximum is shifted towards positive X direction coinciding with the beam impact point. Radiation dose distribution XY projection is completely symmetric with respect to Y-axis.

The main component of the radiation is photon component. Based on the absorbed dose distribution YZ projection depicted in Figure 1 one can conclude that the most radiation is emitted towards upstream direction. In downstream direction radiation is effectively being absorbed by collimator material and much less amount of the radiation leaves collimator body. Other important component of the radiation is neutron radiation. Though neutrons carry much less energy compared to gamma component, they have high penetrating capacity. Compared to photons larger part of neutrons penetrates collimator body in downstream direction.

Beam particles incident on collimator loses 84% of their energy via electro-magnetic shower while secondary radiation particles leaving collimator material carry 16% of energy (Table 3).

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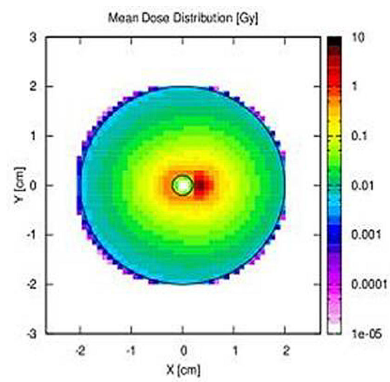

Figure 1: Energy deposition distribution in the collimator material in the XY plain (absorbed dose in Greys).

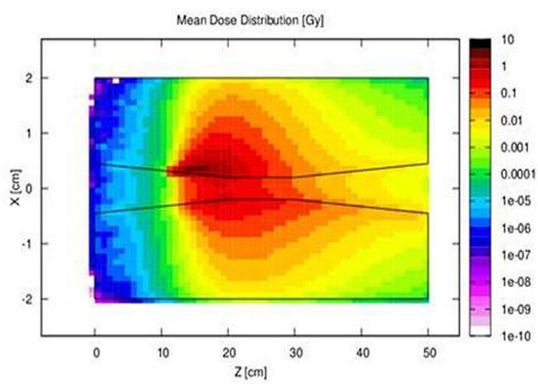

Figure 2: Energy deposition distribution in the collimator material in the XZ plain (absorbed dose in Greys).

XFEL CYLINDRICAL STEP COLLIMATOR

On XFEL facility cylindrical symmetric titanium made collimator is installed [5]. The length is 500mm, the inner radius is 2 mm and the outer radius is 20 mm. The collimator is made of titanium with material parameters presented in Table 1. It is assumed that the European XFEL 16.5 GeV beam electrons hit collimator front wall.

Beam particle incident on collimator losses 70% of its energy via electro-magnetic shower while secondary radiation particles leaving collimator material carry 29% of energy (Table 3). Radionuclides are being produced via photonuclear and electro nuclear interactions thus causing residual radiation when beam operation has stopped (Fig. 3 and Table 2). It should be noticed that a given amount of radionuclides are being produced if beam bombards the collimator body for two weeks. It will take much longer time to get a significant amount of the radionuclides if only beam halo particles hit the collimator.

Table 2: Residual Nuclei with the Yield Greater than 0.1 nuclei/cm^3/Primary

Nuclides	Yield [nuclei/cm3/pr]
^{1}H	0.5331
^{4}Be	0.1569
^{46}Ti	0.3326
^{47}Ti	0.9713
^{48}Ti	0.2848

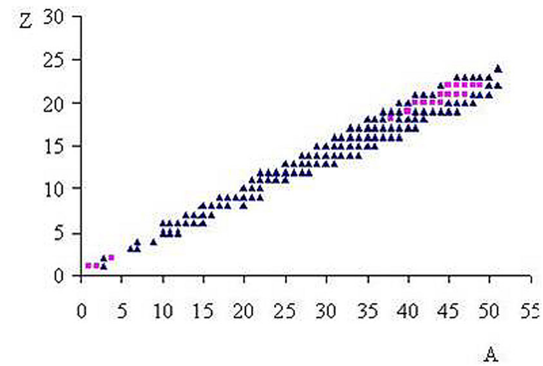

Figure 3: Produced residual nuclei within the titanium collimator body after 2 weeks beam operation. Triangles denote the nuclei with the yield greater than 10^{-6} nuclei/cm^3/pr while squares denote the nuclei with the yield greater than 10^{-2} nuclei/cm3/pr.

XFEL UNDULATOR INTERSECTION TAPERED COLLIMATOR (ABSORBER)

On XFEL facility undulator intersections cylindrical symmetric copper made tapered collimators are installed [5]. The geometry of collimators is similar to that of Figure 1and Figure 2 with the length of the tapered parts L1=9.5 mm each and non-tapered central part length L2=3 mm. Minimal inner radius is $b = 0.4$ mm, while maximal inner radius at the ends is equal to $d = 0.44$ mm. The collimator is made up of copper with a conductivity of. $k = 5.8 \times 10^7$ S/m. It is assumed XFEL 16.5 GeV beam electrons hit collimator inner wall at grazing angle on the XZ plain.

Beam particle incident on collimator losses only 0.2% of its energy via electro-magnetic shower while secondary radiation particles leaving collimator material carry 99.8% of energy (Table 3). Table 4 presents the composition of the radiation from the surface of the copper absorber.

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Table 3: The energy available per beam particle in GeV (% of total energy loss) is divided into prompt radiation channels

Property	**EXFEL titanium collimator**	**EXFEL copper absorber**	**FLASH tapered collimator**
Hadron and muon energy loss	0.012 (0.1%)	1.0 x10^{-04} (0.0%)	9.5 x10^{-04} (0.1%)
Electro-magnetic showers	11.6 (70.4%)	3.8 x10^{-02} (0.2%)	1.1 (84%)
Nuclear recoils and fragments	5.9 x10^{-04} (0.0%)	7.0 x10^{-06} (0.0%)	3.7 x10^{-05} (0.0%)
Low energy neutrons	8.9 x10^{-05} (0.0%)	9.0 x10^{-08} (0.0%)	1.1 x10^{-05} (0.0%)
Particles escaping the system	4.84 (29.3%)	16.46 (99.8%)	0.2 (16%)
Energy per beam particle	16.5 (100.%)	16.5 (100.%)	1.27 (100.%)

Table 4: Composition of the Radiation from the Surface of the Copper Absorber (Particles per primary electron)

	Particles per primary
Electrons	4.64 ±0.08%
Positrons	2.42 ±0.26%
Protons	4.06 ±4.0%
Neutrons	0.026 ±2.6%
γ- Quanta	18.7 ±0.01%
Total	25.8 ±0.07%

CONCLUSION

The European XFEL electron beam interaction with the titanium collimator and copper absorber of the undulator intersections as well as FLASH beam interaction with the tapered collimator were simulated applying particle tracking simulation code FLUKA. Absorbed dose spatial distribution in the material of the collimators was simulated for the total secondary radiation and its most important gamma and neutron components. Energy spectrum of the produced total radiation and its photon and neutron components were calculated. Angular and spectral double differential distributions of the radiation energy emitted by collimator surfaces were obtained. Residual dose rate after irritation of the collimator material by the electron beam was calculated. Particle fluencies from the collimators' surface (Particles per primary electron) are presented in Table 5.

Table 5: Particle Fluencies from the Collimator Surface (Particles per primary electron)

Collimator	**Total**	**Photons**	**Neutrons**
EXFEL titanium collimator	14.0 +/- 0.032 %	12.0 +/- 0.024%	0.03 +/- 0.49 %
EXFEL copper absorber	25.8 +/- 0.069 %	18.7 +/- 0.084 %	0.026 +/- 2.6%
FLASH tapered collimator	0.408 +/- 0.05%	0.375 +/- 0.043 %	0.0015 +/-2.4%

Obtained results can be used to assess the effectiveness of the collimators for eliminating beam halo and make decision on radiation protection measures. Detailed study of the secondary radiation composition, spectrum, dose, angular and spatial distribution by means of particle tracking simulation is on the way.

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