Monte Carlo Simulations and radiation protection calculations for the X-FEL

Summer Students Programme 2006
DESY-Zeuthen

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Contents

Abstract

This report contains the description of the radiation protection calculations which I did for the planned X-FEL (X-ray Free Electron Laser) during the summer students programme in DESY-Zeuthen in 2006. These Monte Carlo simulations have been done with the FLUKA (see [FLU05]) software.
The report describes how the geometry of the X-FEL facility was modeled to calculate the equivalent dose caused by electro-magnetic radiation for specific regions in the accelerator. Finally I will discuss the results given in form of 2D and 3D graphics obtained from paw and SimpleGeo2.0 (see [SiG06]).

Acknowledgments

First of all I want to thank my supervisor Dr. M. Sachwitz for all the help and support during this summer students programme. Then I want to thank Dr. A. Leuschner for helping me to overcome many problems I had with FLUKA. Finally I also want to thank Dr. Hiller for organizing the whole summer students programme and Mrs. Baer for all her administrative work.

1 Introduction

During the summer students programme 2006 in Zeuthen I worked in the FLASH (Free electron LAser Hamburg) group which also deals with developments for the planned X-FEL accelerator for which the construction starts in 2007 at DESY.
The X-FEL will be a laser light source in the x-ray range with a never before achieved brilliance as one can see in figure 1. It will provide new possibilities for many applications like the analysis of chemical reactions.

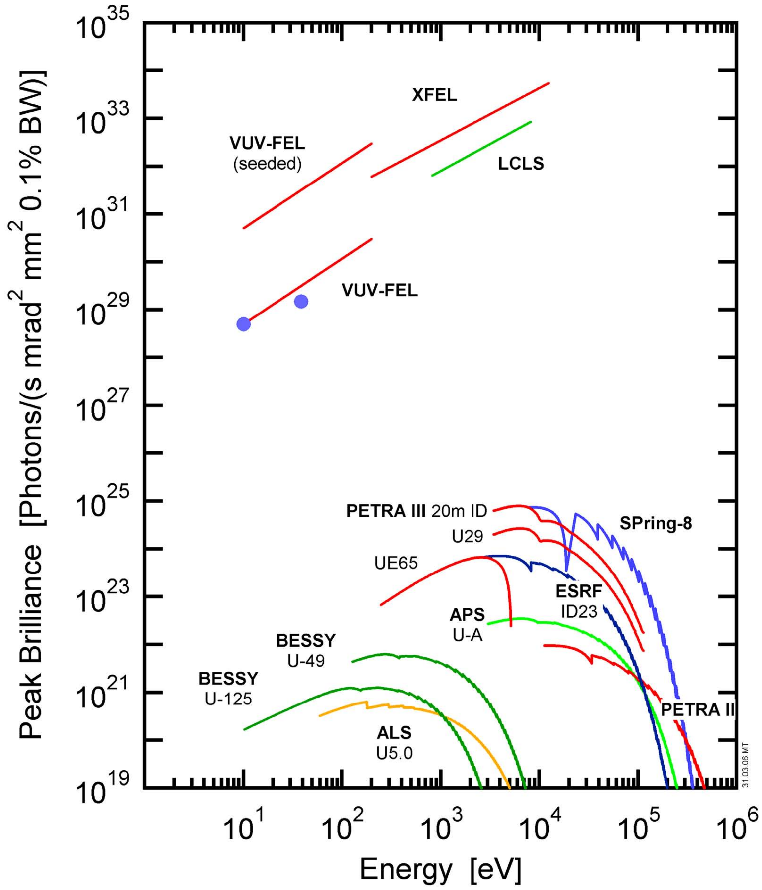

Figure 1: the brilliance of the X-FEL

In the first term the X-FEL facility will consist of a linear acceleration part where the electrons are accelerated up to 20GeV followed by a section of five tunnels with undulators to produce the synchrotron laser light leading to the experimental hall. The overall distance is about 3300m as shown in figure 2.

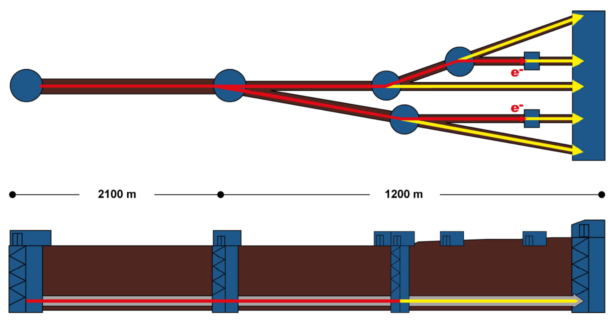

Figure 2: schematic view of the X-FEL facility

2 Parameters of the X-FEL

To use the FLUKA computing environment one has to produce an input file example.inp. As this file is quite hard to produce due to fixed format editing and a complicated reference system for region numbers, it is common to use the ALIFE software (see [ALI05]).
By the help of ALIFE one has to produce a geometry file called example.alife and a file containing the beam and scoring parameters called example.spinp. The advantage is that there is a strict division between geometrical data and physics. Furthermore ALIFE offers an editor which simplifies the input of the geometry.
Finally these two files are combined into an example.inp file which can be used for Monte Carlo simulations in FLUKA.

2.1 Modeling of the geometry

As FLUKA only can handle some simple geometries like cuboids, cylinders or ellipses one really has to simplify the geometrical structure to implement it in FLUKA. Nevertheless the structure has to reflect the real geometry as good as possible to make the calculations reliable.
When I got the plans of the X-FEL facility I started to describe the basic alignment of the tubes containing the main shielding parts in the splitting areas of the tunnels and the dipole regions in front of these buildings like it is shown in figure 3

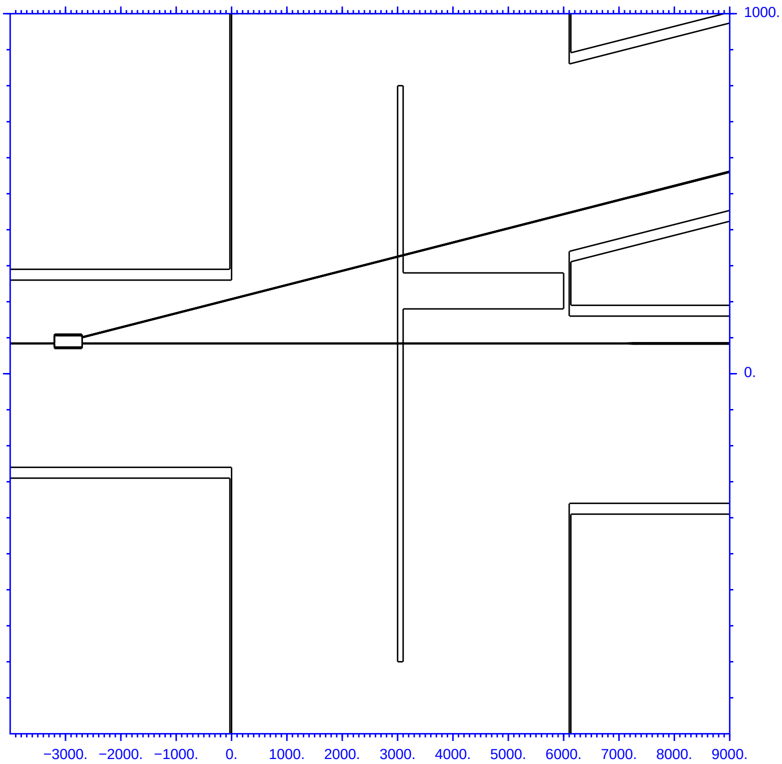

Figure 3: first deflection after the linear acceleration part

For more details I decided to create new files for each region like the undulators or the area where the beamline enters into the experimental hall. Using an additional software called SimpleGeo2.0 it is possible to get 3D plots from the geometry and even to suppress some materials or parts of the geometry. An example is given in figure 4

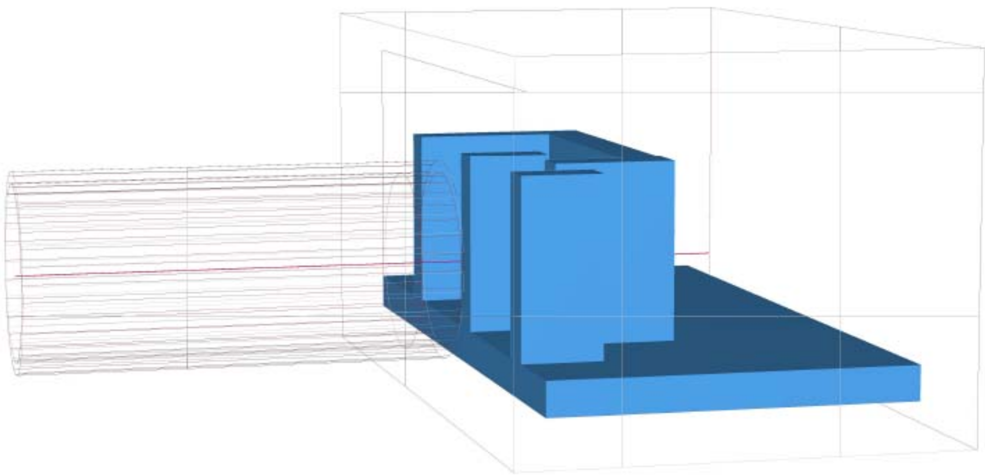

Figure 4: 3D view of the experimental hall

Basically the example.alife file consists of three parts. First there is the material definition where you can define your own materials by giving the density, the atom weight and the atom number. It is also possible to define mixtures as a combination of already defined materials.
The second part is the geometry part where you define your geometrical objects by allocating typical parameters of that object (like the radius, the center and the vector for a cylinder).
In the last part you define which region is filled with which material. There is also the possibility to set a magnetic field in that region or to define biasing and cutoff options which help FLUKA to calculate more effective.

The following example in figure 5 defines a cylinder CYL1 filled with nickel in the region where it subtends another cylinder called CYL2. CYL1 starts at $(x, y, z) = (0m, -10m, 60m)$ has the vector $v = (0m, 0m, 10m)$ and a radius of 0.20m. NF means that there is no magnetic field allocated for that region.

```
MATERIALS
>NICKEL
    Z    = 28
    AWGT = 58.6934
    DENS = 8.902
END
GEOBEGIN
CYL1   RCC    0.0    -1000.0    6000.0   0.0    0.0    1000.0
             20.0
CYL2   ...
END
REGIONS
>NICKEL:NF
+CYL1+CYL2
```

Figure 5: very simple example of an ALIFE input file

2.2 Beam parameters of the X-FEL

The electron beam produced in the X-FEL has an energy of 20GeV. The electrons are transported in trains of 3000 bunches with a frequency of 10Hz. The charge per bunch is 1nC which is 6.24×10^9e. After the undulator section this gives photon pulses of 100fs in the x-ray range as it is explained in figure 6

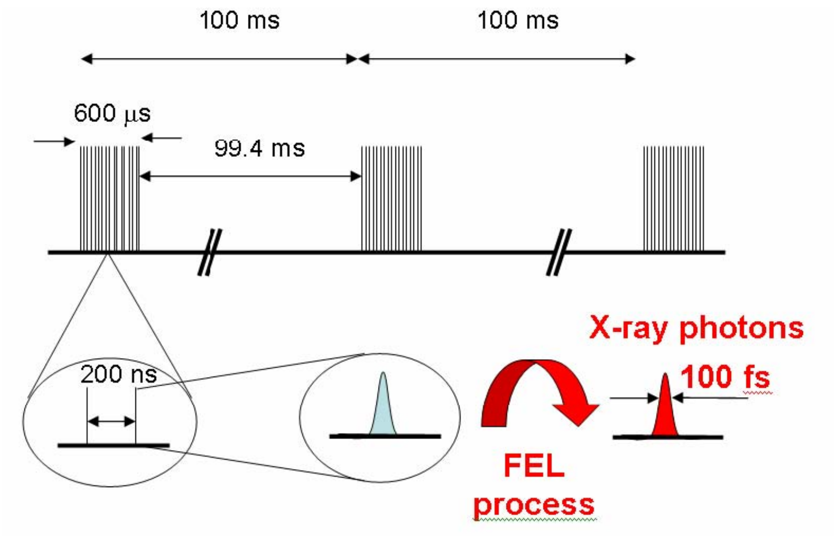

Figure 6: parameters of the X-FEL beam

Thus we can calculate the charge, alternatively the number of electrons per time t in seconds produced by the X-FEL:

$$Q(t) \;=\; 6.24 \times 10^9 e \;\cdot\; 3000 \;\cdot\; 10 \;\cdot t \;=\; 1.827 \times 10^{14} e \cdot t \tag{1}$$

Now we can calculate the number of particles involved in the two main actions we want to consider for our calculations. First for the annual radiation dose we assume that the total working hours per year are 7200h and that we have a general loss of 0.3% of the beam. This leads to the charge of

$$Q_{year} \;=\; Q(7200 \cdot 60 \cdot 60 \cdot 0.003) \;=\; 1.46 \times 10^{19} e$$

For the second case we consider that the duration of a worst case scenario where the beam hits the beamline under a very small angle is about $360s$ [1]. From that we get

$$Q_{worst\ case} \;=\; Q(360) \;=\; 6.74 \times 10^{16} e$$

As the FLUKA results are given in Joule per volume and normalized per primary these results have to be converted into Joule per Kg and must be extrapolated to an appropriated number of primaries involved in the process to get the equivalent dose of the radiation in sievert.

2.3 A first estimation of radiation doses

For the first estimation we will have a look on the radiation outside the tunnel and then we will have a closer look into the undulators.

[1]Longer times would cause a destruction of the beamline due to the high energetic electrons of 20GeV

For high energetic electrons interacting with matter three main categories of secondaries are produced which contribute to the dose: there are the electromagnetical interacting particles like electrons, positrons and photons, then the neutrons produced in the nuclear photoeffect and finally the neutrons produced in cascade processes. These neutrons from cascade processes actually dominate for the dose contribution. Therefore the formula for the dose caused by high energy neutrons behind thick lateral shielding gives a good first estimation for the radiation outside the tunnel.

$$H_n = n_e \cdot h_0 \cdot \frac{E}{E_0} \cdot f_T \cdot \frac{1}{r^2} \cdot \prod_{i=1}^{k} e^{-x_i \rho_i / \lambda_i} \tag{2}$$

In our case we can assume a 30cm concrete shielding plus about 600cm sand because the tunnel system is at least six meters under the earth. The meaning of the variables in this formula and the values for our purpose are the following:

$n_e = \frac{Q}{e}$	$=$	1.46×10^{19}	numbers of electrons involved for annual dose
	$=$	6.74×10^{16}	numbers of electrons involved for worst case
h_0	$=$	$4.00 \times 10^{-13} Sv \cdot cm^2$	dose constant
E	$=$	$20GeV$	electron energy
E_0	$=$	$1GeV$	reference energy
f_T	$=$	1.0	target efficiency for absorbers
	$=$	0.1	target efficiency for linear sources
r	$=$	$500cm$	distance from source to target
x_1	$=$	$30cm$	thickness of concrete
x_2	$=$	$600cm$	thickness of sand
ρ_1	$=$	$2.4g/cm^3$	density of concrete
ρ_2	$=$	$1.8g/cm^3$	density of sand
λ_1	$=$	$100g/cm^2$	weakening factor of concrete
λ_2	$=$	$100g/cm^2$	weakening factor of sand

In our case this leads to

$$\begin{aligned} H_n &= 1.46 \times 10^{19} \cdot 4.00 \times 10^{-13} Sv \cdot cm^2 \cdot \frac{20GeV}{1GeV} \cdot 0.1 \cdot \frac{e^{-30 \cdot 2.4/100} \cdot e^{600 \cdot 1.8/100}}{(500cm)^2} \\ &= 0.463mSv \end{aligned}$$

for the annual dose and

$$\begin{aligned} H_n &= 6.74 \times 10^{16} \cdot 4.00 \times 10^{-13} Sv \cdot cm^2 \cdot \frac{20GeV}{1GeV} \cdot 0.1 \cdot \frac{e^{-30 \cdot 2.4/100} \cdot e^{600 \cdot 1.8/100}}{(500cm)^2} \\ &= 0.002mSv \end{aligned}$$

for the worst case dose. So one can see that no critical values are reached.

For the undulator section one can estimate the dose per year by calculating the bremsstrahlung radiation with the help of the following formula

$$\dot{H} = \dot{h_\gamma}(E) \cdot I \cdot L \cdot p \tag{3}$$

In our case we deal with electrons of $20GeV$ and for the longest undulator with $L = 256m$, an average current of $I = 30\mu A$ (that value is derived from (1)) and the pressure of about $p = 10\mu Pa$ we obtain:

$$\dot{H} \;=\; \dot{h_\gamma}(20GeV) \cdot 30\mu A \cdot 256m \cdot 10\mu Pa \;=\; 82mSv/h$$

which gives an annual dose of about $600Sv$. This value seams to be quite high but one has to take into consideration that nobody can stay in front of the undulators while the machine is running which is verified by security systems.

For detailed information about the doses we will now evaluate the FLUKA results.

3 The FLUKA calculations and their interpretation

To give a graphical output of the FLUKA results one can use different software. The SimpleGeo2.0 software is nice for three dimensional pictures of the geometry and using version 2.0 it is even possible to overlay the geometry and the the results of the FLUKA calculations.
Unfortunately the FLUKA output is not given in Joule per kilogram and moreover it is normalized per primary. Therefore the three dimensional plot as shown in figure 7 can just be used as a first estimation. The section planes shown in blue in this figure can be moved through the geometry and one can even extract the data from one plane into a separate text file.
In the following I will present the results in the form of two dimensional plots created by paw. In these cases the equivalent dose from electro-magnetic radiation is given in sievert. The number of particles involved is either the number of primaries per year or the number of particles involved in the worst case.

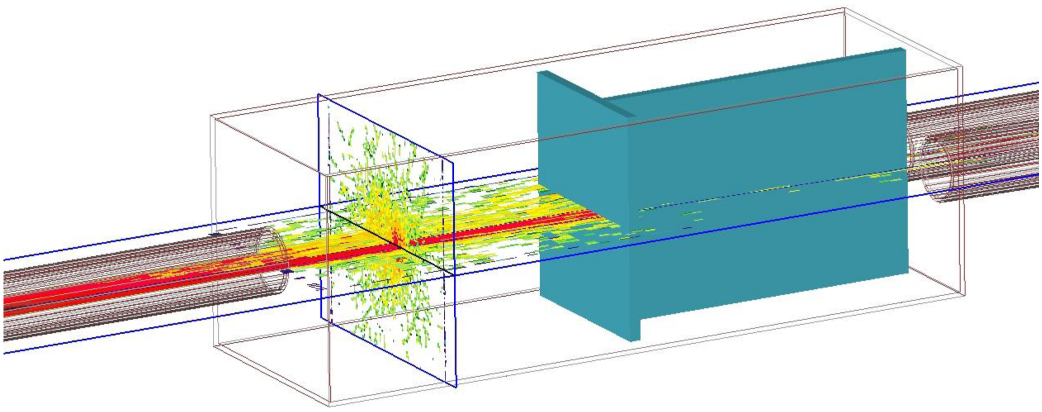

Figure 7: A 3D view of the energy density inside the XS1 building

3.1 The deflection parts

I will exemplify the results for the fifth beamline. After the linear acceleration part it consists of the XS1 building where the beam is separated for the first time followed by an undulator section with the SASE1 undulator. Then another deflection is done in the XS3 building and the beam passes through the second undulator called SASE3 to reach finally the experimental hall.

The following images 8 and 9 show the equivalent dose of electro-magnetic radiation in the deflection parts due to a not correctly arranged magnetic field. Obviously this situation is a worst case situation and does not remain like that for a whole year. Therefore the number of particles used in this simulation equals the number of particles involved in the worst case.

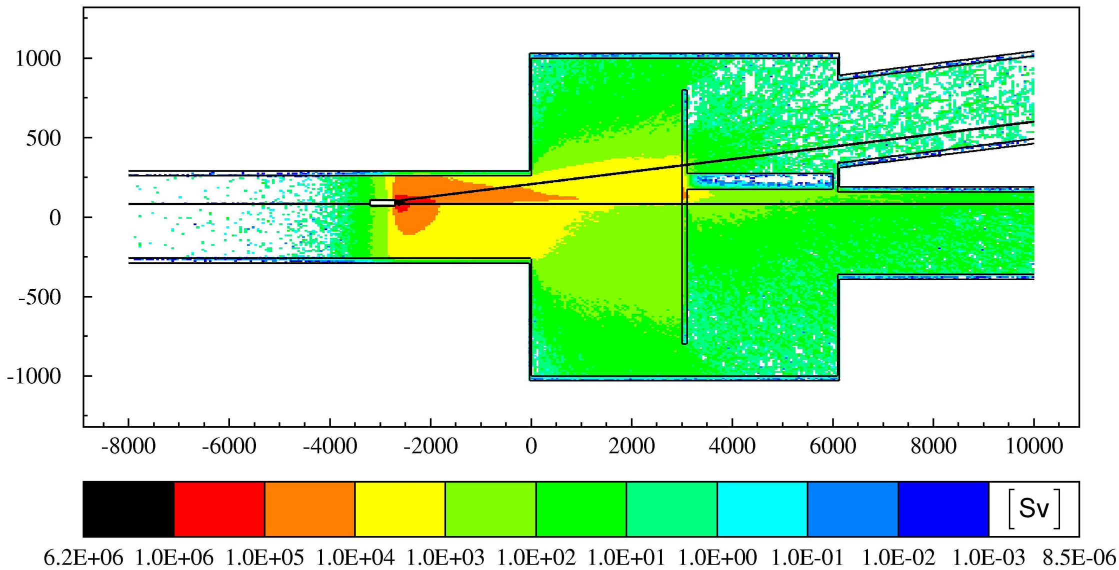

Figure 8: electro-magnetic equivalent dose in the first deflection part

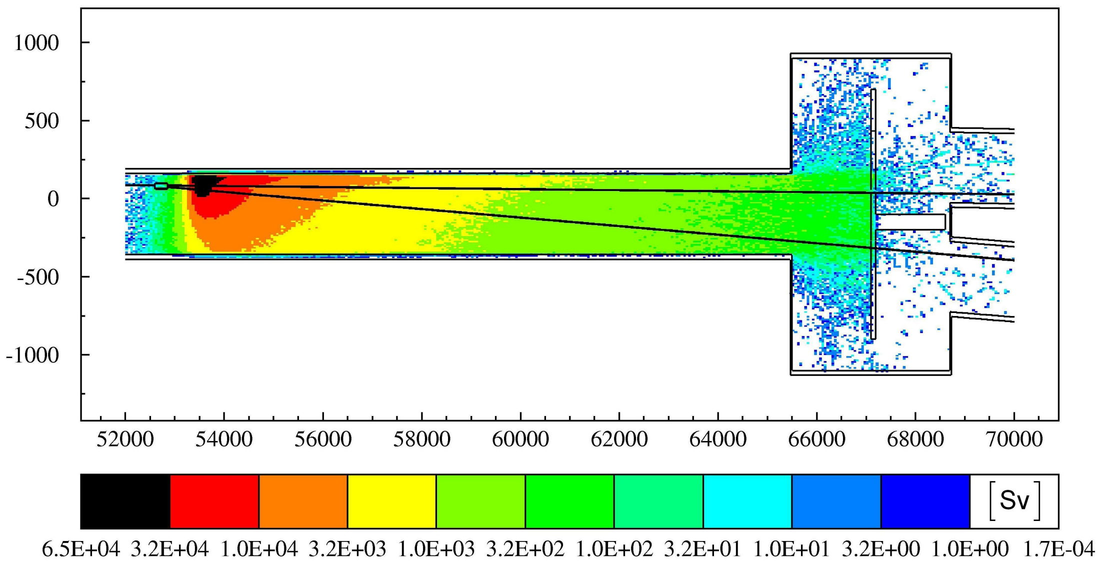

Figure 9: electro-magnetic equivalent dose in the second deflection part

3.2 The undulator parts

In the figures 10 and 11 the equivalent dose of electro-magnetic radiation in the undulators SASE1 and SASE3 is shown. I simulated a worst case where the beam hits the beamline inside the undulator under a very small angle.

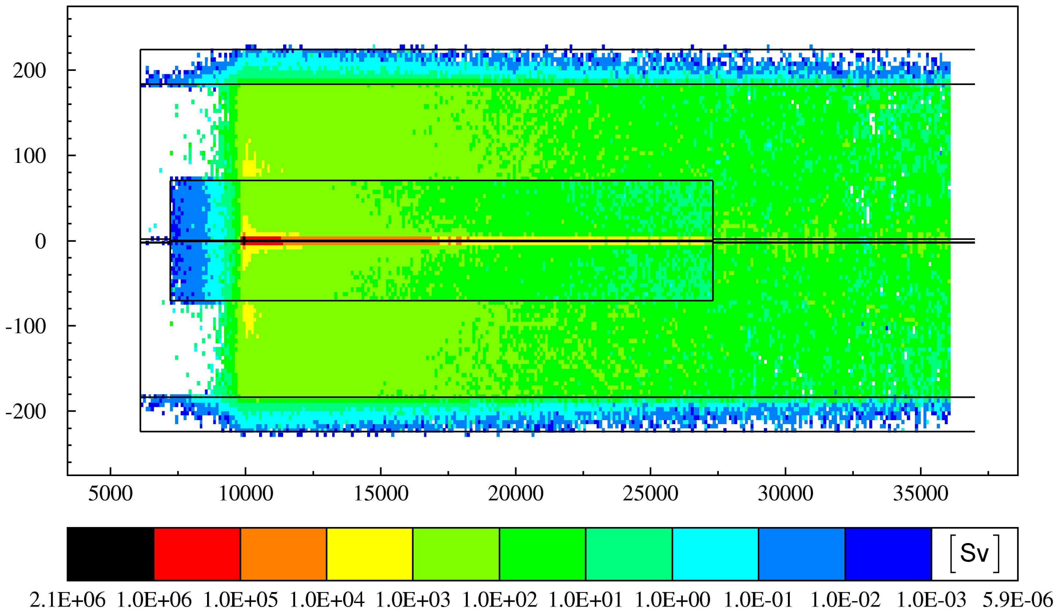

Figure 10: electro-magnetic equivalent dose in SASE1

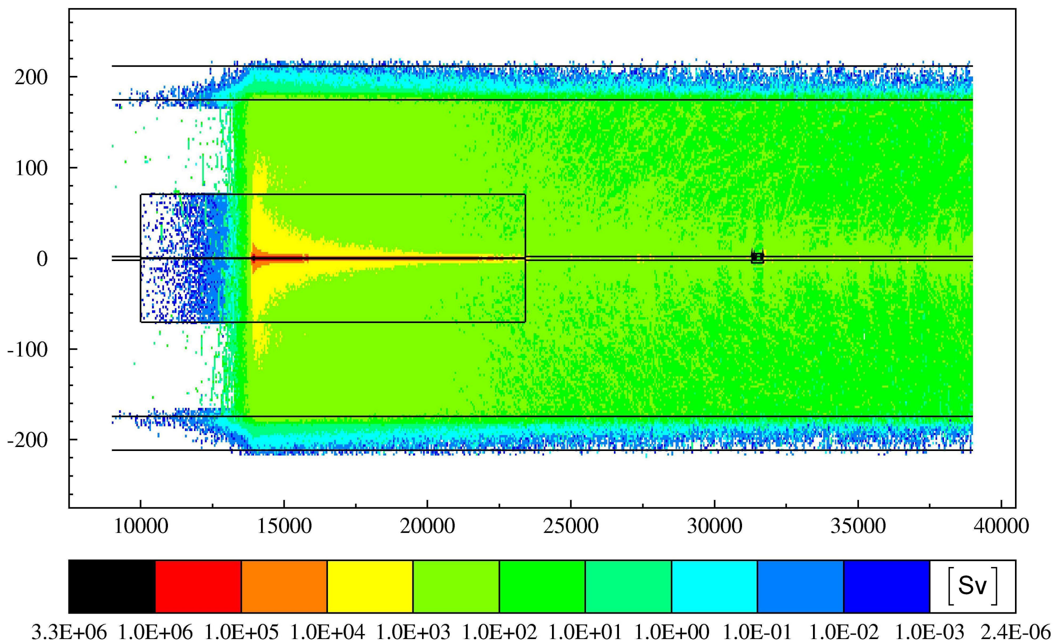

Figure 11: electro-magnetic equivalent dose in SASE3

3.3 The experimental hall

For the experimental hall the situation is different. The beam leading into the experimental hall is not an electron beam but a laser beam. So it consists of photos which have an average energy of about 12.4keV. That is why the plot in figure 12 differs from the ones we saw before.

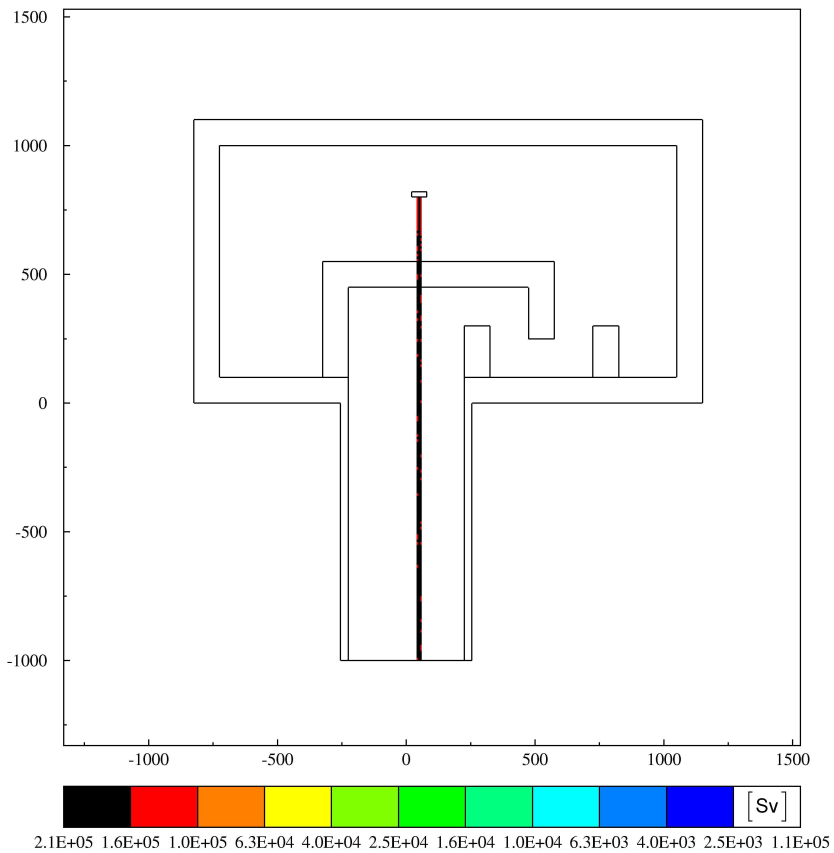

Figure 12: equivalent dose of electro-magnetic radiation in the experimental hall

4 Summary and future prospects

During the summer students programme I tried to get as realistic simulation results as possible. Nevertheless eight weeks is a quite short time to get used to all the needed software (FLUKA, ALIFE, SimpleGeo, paw, ...), to model the geometry and finally to obtain useful results.
To model the geometry can be a very time consuming part of the work. As the geometry is just a model of the real accelerator facility which is quite complicated it is obvious that there are always more details which can be taken into consideration. So one has to find a compromise between too much details and details which are important for the simulations. Another factor is, that FLUKA offers lots of additional options like energy cutoffs, biasing options [2] or a huge amount of scoring options. These options can make calculations more efficient. Anyway in my case I tried not to use too much different parameter because it also needs a lot of time to get a feeling how to tune them correctly.
As the accelerator is still in its planning phase and some of the used values and materials will change during this process therefore these calculations do not lay claim to be completed. Based on the geometry and scoring files I wrote improvements can be applied so that more detailed descriptions of the geometry and scoring options can be made.
For now the calculations give a good overview about the radiation doses which can be expected from electro-magnetic radiation and so this work can be used as a basis for future calculations.

[2]biasing options allow to define the importance of different regions of the geometry

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