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# Comparison of FLUKA and STAC8 for shielding calculations of the hard X-ray line of the LCLS

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## Abstract

This Note describes calculations of the shielding necessary to reduce the dose rate to less than 0.05 mrem/h when synchrotron radiations emitted by the LCLS electrons beam hit a worst type scattering target located in the hard X-ray line. The calculations were performed using the FLUKA Monte-Carlo code and as well as the STAC8 analytical code. The photon spectrum used as a source term corresponds to the spectrum of spontaneous and FEL photons emitted when an electron beam of 13.7 GeV (a 17 GeV electron beam was also considered for some cases) goes through the LCLS undulator system. The calculations have shown that after very thin layer of shielding the shielding requirements are **dominated by spontaneous photons** with an energy greater than 50 keV. The spectrum used is relevant for shielding calculations downstream of the Front End Enclosure (FEE) since the effect of the **C1 collimator** and of **the two hard X-ray mirrors of the Offset Mirror System (OMS)** which significantly reduces the spectrum intensity were taken into account in the spectrum determination. The geometrical configurations considered addressed two different issues: the aim of the first one is to determine the minimum pipe thickness necessary to reduce the dose to 0.05 mrem/h when the beam hits a target enclosed in the pipe considering that personnel may be located at proximity of the beam line. Calculations performed with FLUKA and STAC8 indicate that a standard **4" diameter steel pipe** would need to be **6.2 mm thick**. The same shielding could be reached by wrapping a standard steep pipe (4" diameter) **0.83" thick with 0.6 mm of lead**. The second generic calculations were performed with the same target surrounded by a lateral and downstream slab of shielding material in order to determine the minimum thickness of the lateral and downstream walls when an experiment is being carried out inside a hutch. A very good agreement was found between FLUKA and STAC8 for **the lateral wall shielding requirement, namely 0.191 mm of lead, 1.03 mm of steel or 20.5 mm of concrete**. For the downstram wall, the results obtained with STAC8 were found to be more conservative and were therefore used. To reduce the dose rate to less than 0.05 mrem/h on contact to **the downstream wall it is found that either 0.90 mm of lead or 6.2 mm of steel or 88 mm of concrete** are necessary. Those requirements were provided to LCLS during the design phase of the Far Experimental Hall hutches.

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## 1 Source terms

### 1.1 Previous calculations

Requirements of the hutch wall thickness for the hutches of the Near Experimental Hall (NEH) and of the Far Experimental Hall were already specified in an earlier study by H. Vincke and A. Fassò in 2005 [1, 2]. The calculation was based on the spontaneous radiation (SR) produced in the LCLS undulator system. The power of the spontaneous photons was found equal to 2.19 W for 14 GeV electron beam. In order to take into account the effect of the Offset Mirror System (OMS) located inside the Front End Enclosure (FEE), the SR spectrum was folded twice with the reflectivity coefficients of a $0.9°$ tilted silicon mirror coated with a layer of platinum. The reflectivity coefficients of this mirror have a cut-off energy at 60 keV. The raw spontaneous photon spectrum is plotted in black in Figure 1 and the spectrum used for the calculations after applying the reflectivity coefficients of the two mirrors is shown in red.

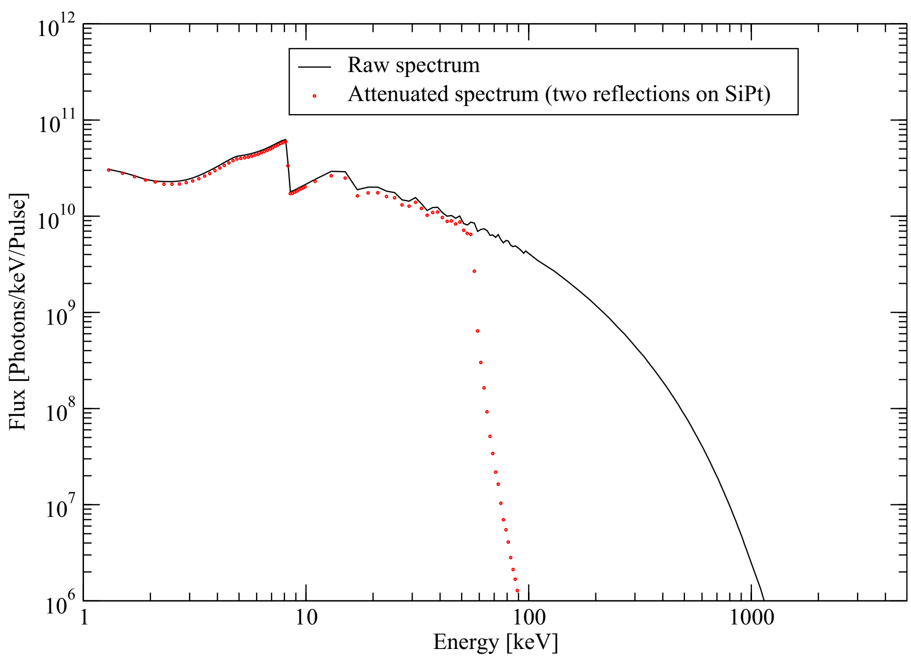



Figure 1: Spontaneous photons spectra used for the determination of the hutch wall thickness specified in Ref. [1, 2].

Based on the spectrum shown in Figure 1 (red curve), the shielding requirements were found equal to **0.12 cm** and **0.16 cm** of **lead** for the side wall and the roof respectively. For the downbeam wall, 0.2 cm of lead were recommended with a local reiforcement using a 100 cm×100 cm×0.2 cm lead plate in the forward direction. In addition, similar requirements using lead based shielding as well as the equivalent amount of steel or concrete can be found in Ref. [2]. Based on the FLUKA calculations the following shielding was recommended for the hutch construction :

• On the sides 0.6 cm iron or 0.12 cm lead or 8.2 cm concrete
• Down beam wall: 0.2 cm of lead with a 1 m×1 m×7 cm iron or 0.9 cm lead plate.
• Roof: 0.4 cm of iron or 0.16 cm of lead or 6 cm concrete.

### 1.2 Spontaneous radiations

The SR spectrum which was used for the calculations presented in this Note differs strongly from the one mentioned above. A detailed description of the parameters relevant for the determination of the spectrum as well as the calculation scheme can be found in Ref. [3, 4]. The spontaneous spectrum was calculated for 3729 undulator periods of length equal to 30 mm and a peak magnetic field of 1.25 Tesla. With an electron beam energy of 13.64 GeV, the power of spontaneous photons is equal to 2.47 W which is similar to the power reported in Ref. [1, 2].

In order to determine the spectrum used as a source term, the spatial and spectral characteristics of the photons were generated with the program GENESIS for a plane perpendicular to the beam axis at a given distance from the downstream end of the undulator system. The fraction of photons which goes through the C1 collimator aperture (5 mm diameter) was determined by selecting photons contained in a square aperture of 6.6 mm x 6.6 mm. It should be noted that smaller apertures (3 mm collimators) and small mirror acceptances downstream of the C1 collimator were not considered in the estimate of the spontaneous spectrum. Mirror reflectivity data were extracted from two different sources as indicated in Ref. [3] in order to cover the entire energy range for which the spontaneous spectrum was calculated. Parameters relevant for the determination of the reflectivity coefficient of the two mirrors are indicated in Table 1. As it can be seen in the last two rows of Table 1, it is assumed that the mirror surface and interfaces have no imperfection.

Table 1: Parameters used in the mirror reflectivity calculations Ref. [3].

| Parameter | | Hard X ray line |
|---|---|---|
| Number of mirrors | | 2 |
| Mirror incidence angle | | 1.35 mrad |
| Coating | Material | SiC |
| | Thickness | 50 nm |
| | Density | 2.89 $g/cm^3$ |
| Substrate material | | Single chrystal silicon |
| High-spatial-frequency roughness | Top surface | 0.00 nm |
| | Coating substrate / Interface | 0.00 nm |
| Polarization geometry | | P |

The reflectivity coefficients obtained for the hard X-ray mirror are shown in black in Figure 2. The difference with the reflectivity coefficients used in Ref. [1, 2] which are plotted in red can be observed above the cut-off energy of 24 keV.

The apertured (C1 collimator) and filtered (mirrors) spontaneous spectrum used for the calculations presented in this Note is plotted in red in Figure 3 for the nominal electron energy of 13.7 GeV. The characteristics of the spontaneous spectrum appears in Figure 3, they consist of the undulator fundamental at 8.27 keV and a series of higher harmonic peaks, both even and odd superimposed to a continuous spectrum. The spectrum shown in red in Figure 1 is also plotted in Figure 3 in order to illustrate the difference between the two calculations. In the 1 keV to 24 keV energy range for which the mirror reflectivity coefficients are close to 1 in both cases (see Figure 2), the effect of the C1 collimator which significantly reduce the SR spectrum intensity can be observed.

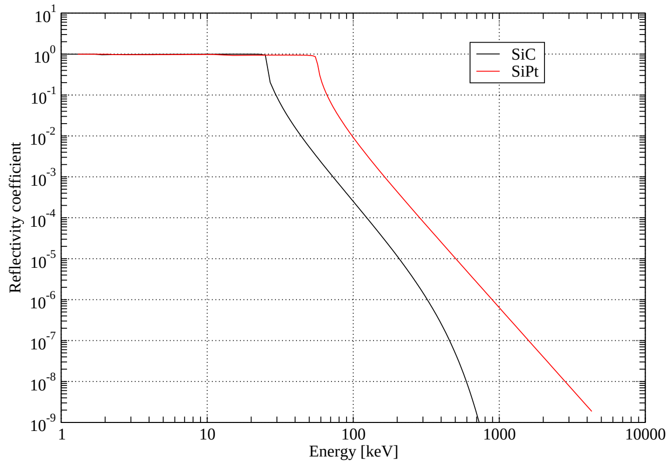



Figure 2: Reflectivity coefficients for a SiC mirror used for the determination of the source spectrum used in this Note (black) compared to the one of SiPt (red) used for the determination of the spectrum used in Ref. [1].

In addition, a spontaneous photon spectrum for a 17 GeV electron beam going through the undulators was evaluated using the same procedure described above [5]. This spectrum is plotted in blue in Figure 3. Despite the fact that the critical energy ($E_c(keV) = 0.6650 E_e^2(GeV)B(T)$) is higher by a factor 1.5, the mirror attenuation is the dominant effect and the total transmitted power equal to 97 $\mu J$ per pulse (equivalent to an average power of 0.012 W @ 120 Hz) is only increased to 112 $\mu J$ per pulse (equivalent to an average power of 0.013 W @ 120 Hz) for the 17 GeV electron beam [5].

### 1.3 FEL photons

The spatial extension of the FEL photons source is very limited compared to the one of the spontaneous spectrum, it therefore passes unobstructed through the different apertures of the OMS. The spectral distribution of the FEL peaks for odd harmonics through the $13^{th}$ is indicated in Table 2 based on 2 mJ of saturated power for a fundamental peak energy of 8.27 keV.

Table 2: FEL spectrum characteristics for the $13^{th}$ first harmonics.

| Photon Energy (keV) | Incident Flux (photons/pulse) | Pulse Energy | Filtered Flux (photons/pulse) | Filtered Pulse Energy (photons/pulse) |
|---|---|---|---|---|
| 8.27 | $1.51 \times 10^{12}$ | 2.00 mJ | $1.48 \times 10^{12}$ | 1.96 mJ |
| 24.8 | $1.01 \times 10^{10}$ | 40.0 μJ | $9.39 \times 10^{9}$ | 37.3 μJ |
| 41.3 | $6.04 \times 10^{8}$ | 4.00 μJ | $1.29 \times 10^{5}$ | 8.52 x 10-1 nJ |
| 57.9 | $1.73 \times 10^{8}$ | 1.60 μ | $1.53 \times 10^{3}$ | 1.42 x 10-2 nJ |
| 74.4 | $1.68 \times 10^{7}$ | 200 nJ | 16.6 | 1.98 x 10-4 nJ |
| 90.9 | $2.20 \times 10^{6}$ | 32 nJ | $4.02 \times 10^{-1}$ | 5.85 x 10-6 nJ |
| 107 | $2.32 \times 10^{5}$ | 4 nJ | $1.06 \times 10^{-2}$ | 1.83 x 10-7 nJ |

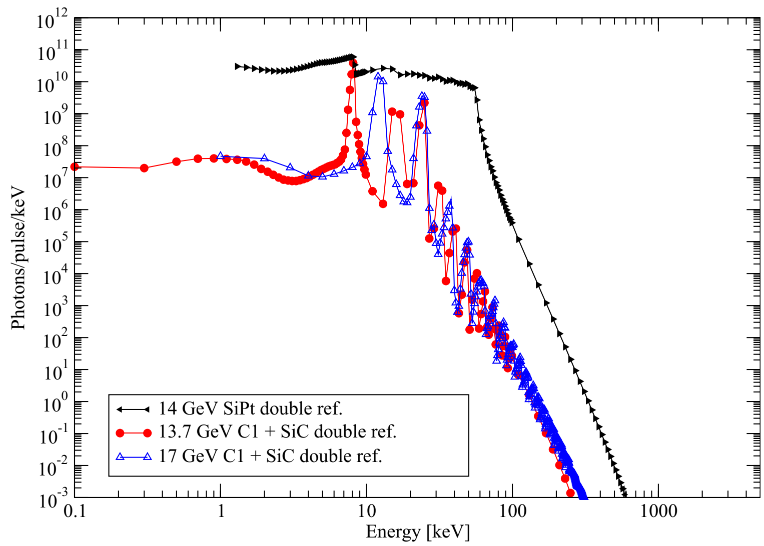



Figure 3: Spontaneous photons spectra used for calculations reported in this Note (plotted in red and blue) compared to the one used for calculations reported in Ref [1] (plotted in black).

## 2 The FLUKA calculations [6, 7]

### 2.1 Source

A user source routine was written in order to sample primary photons from the spontaneous radiation spectrum shown in red in Figure 3. The particles were sampled uniformly from the distribution (between 1 keV and 990 keV), the weight of the particles was then adjusted to account for the difference in emission probability.

### 2.2 Transport settings

A purely analog calculation was performed. Transport and production cutoffs were set at the minimum energy of 1 keV for photons, electrons and positrons.

### 2.3 Scoring and normalization

The dose rate was calculated using the fluence determined with a track length estimator inside a three dimensional mesh superimposed to the FLUKA geometry and fluence to dose energy dependent conversion factors. The effective dose conversion coefficients for the WORST irradiation geometry using Pelliccioni radiation weighting factors [10] were invoked through the fluscw user routine distributed with the code [9]. It should be noted that below 50 keV, conversion coefficients for air kerma per unit fluence are used to estimate the dose induced by photons. Figure 4 illustrate the difference between the coefficients used for the determination of the ambient dose equivalent ($H^{*}(10)$) and the coefficients used for the effective dose calculations using the air kerma below 50 keV.

Dose rate calculated by FLUKA are expressed in pSv per primary particles. A normalization factor equal to 3.106E12 x 3600 x 1E-9 x 100 was used to convert the results to mrem/h (the integral of the spectrum shown in red in Figure 3 is equal to 3.106E12 photons per second considering a repetition rate of 120 Hz).

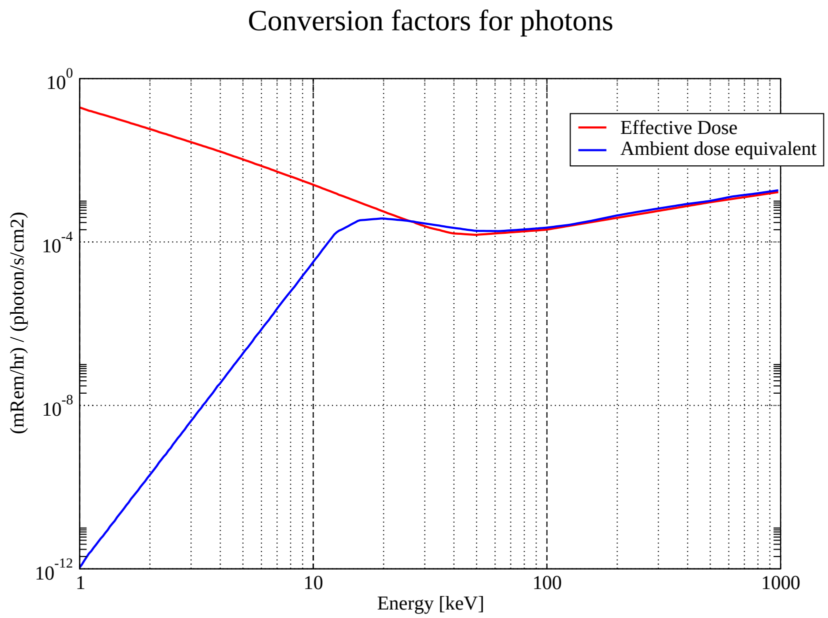



Figure 4: Comparison of the conversion coefficient between the effective dose and ambient dose between 1 keV and 1 MeV.

In addition to the dose rate, the particle fluence was scored using a boundary crossing estimator between different regions defined in the FLUKA geometry. Such energy dependent fluence spectra are very useful to see how the source spectrum is being attenuated going through the shielding.

### 2.4 Slanted mirror enclosed inside the beam pipe

The aim of this calculation is to determine if the pipe thickness (2 mm of steel) is sufficient to limit the dose on contact to the outter surface of the pipe to 0.05 mrem/h when a target is inserted into the beam path. A worst case scattering target (2-cm thick slab of silicon with incidence angle $0.155°$) is introduced into the beam path in the upstream portion of the vacuum pipe in the first hutch. The dose rate is shown for a two dimensions plot centered on the target in order to determine the maximum dose. The foreseen pipe thickness in the three hutches of the NEH is equal to 2 mm [4]. A configuration with a 1 mm thick lead pipe was tested in order to compare shielding properties of lead and steel. Figure 5 shows the dose rate calculated for the target enclosed in the steel pipe (2 mm thick), in this case the dose rate on contact with the beam pipe has a maximum of 0.3 mrem/h and is greater than the design value of 0.05 mrem/h. The minimum pipe thickness or the additionnal shielding which has to be implemented around the pipe if 2 mm thick steel pipe are used were determined using the STAC8 code and can be found in Table 4.

Using a 1 mm thick lead pipe leads to a much lower dose rate outside the pipe as it can be seen in Figure 6. The maximum dose rate on contact with the pipe is 0.01 mrem/h in this case.

In order to investigate how the 1 mm of lead stops photons as compared to the 2 mm of steel, the photon spectrum entering the inner surface of the pipe was compared to the spectrum exiting the pipes in the two cases as shown in Figure 7. As expected photons are more attenuated going through 1 mm of lead than 2 mm of steel.

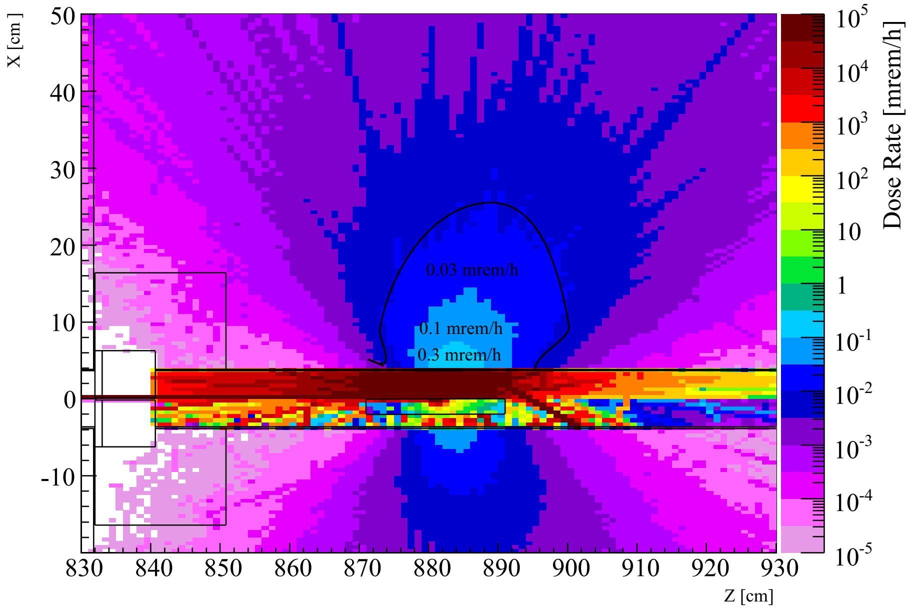



Figure 5: Dose rate when a slanted carbon mirror enclosed in a 2 mm thick steel beam pipe is hit by the spontaneous photons.

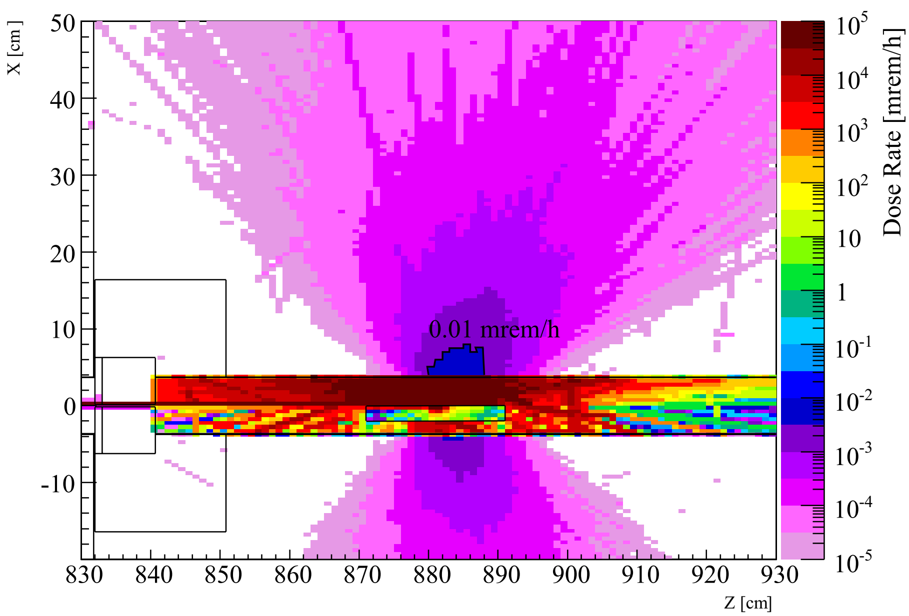



Figure 6: Dose rate when a slanted carbon mirror enclosed in a 1 mm thick lead beam pipe is hit by the spontaneous photons.

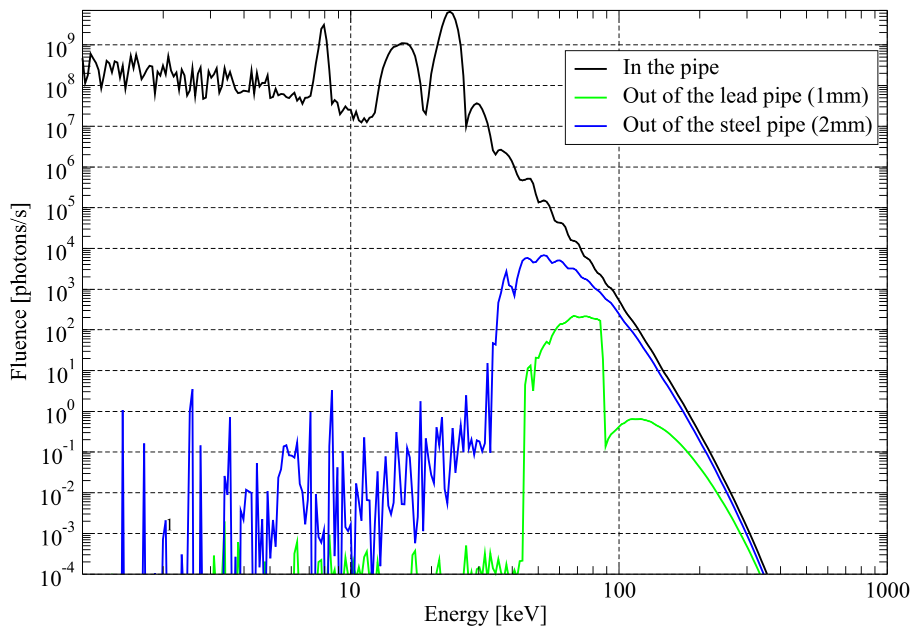



Figure 7: Photon spectrum scattered out of a worst type target (black curve) and attenuated by a 2 mm thick steel pipe (blue curve) or 1 mm thick lead pipe (green curve).

### 2.5 Hutch wall thickness requirement

#### 2.5.1 Geometry

For the determination of the wall thickness, a generic FLUKA geometry with a slanted carbon mirror surrounded by one lateral wall and one downstream wall both located at 100 cm as shown in Figure 8 was used. Both walls have a thickness of 2 mm and were divided in ten 0.2 mm thick slabs for scoring purpose. In one calculation the two walls are made of steel while in the other one they are made of lead.

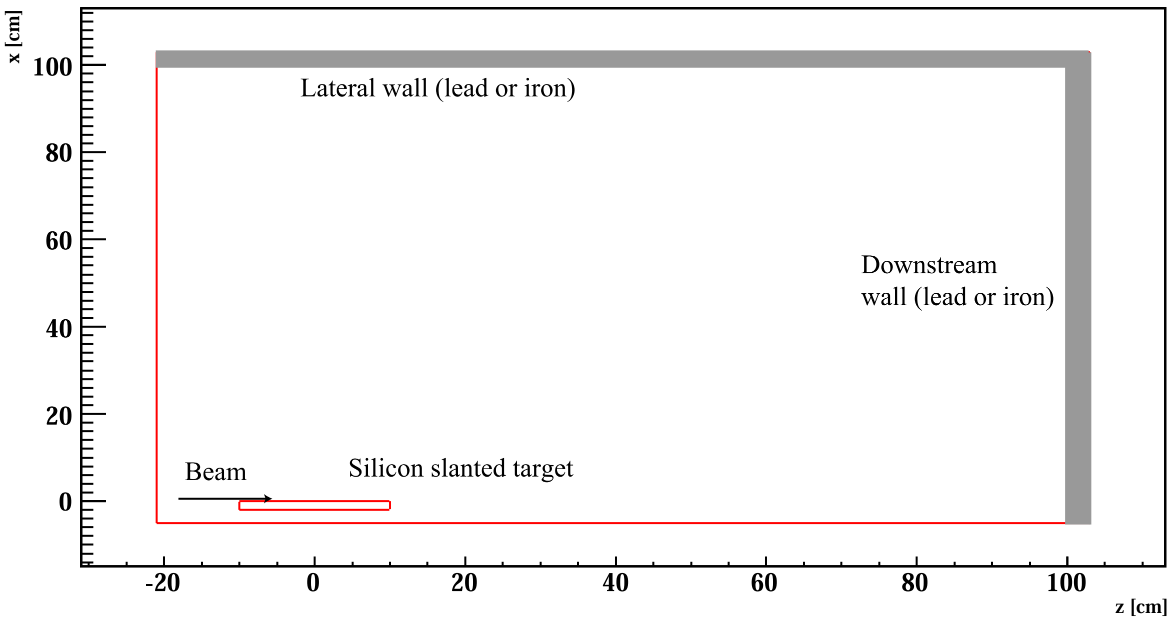



Figure 8: Sketch of the geometry used for the study of the lateral and downstream hutches wall thickness.

#### 2.5.2 Spontaneous radiations

In the first set of calculations, spontaneous photons from the 13.7 GeV spectrum were simulated (red curve in Figure 3). Two meshes one overlapping exactly the lateral wall and the other one the downstream wall were used to score the dose rate. The dose rate inside 0.2 cm thick slabs parallel to the beam axis for the lateral wall are shown in Figure 9, the top figure shows results obtained for the steel case while results for the lead wall are shown on the bottom figure. The design limit of 0.05 mrem/h for the dose rate is indicated in the figure to indicate the minimum shielding thickness which is required. In the case of lead shown in the bottom figure, after 0.2 mm of shielding the dose rate appears to be inferior to 0.05 mrem/h along the lateral shielding. This result is in good agreement with requirement reported in Ref. [8] using a similar photon spectrum for the study of the possible mono-chromator shielding inside the third hutch.

For the steel lateral wall, 1.2 mm of stainless steel is required to reduce the dose rate to less than 0.05 mrem/h (in this case the maximum dose rate is equal to 0.005 mrem/h, 10 times lower than the design value). Significant statistical fluctuations can be observed for wall thicknesses comprise between 0.4 mm and 1.0 mm. Those fluctuations are due to the fact that some low energy photons in the energy range of the fundamental peak are not stopped in the first 0.2 mm. Those photons have a significant contribution to the dose rate compared to higher energy photons due to the fact that conversion coefficients were calculated based on the air kerma approximation and increase exponentially as the energy decreases. For lead, due to the much higher absorption cross section in this energy range this effect is not observed since low energy photons are absorbed within the first 0.2 mm of shielding.

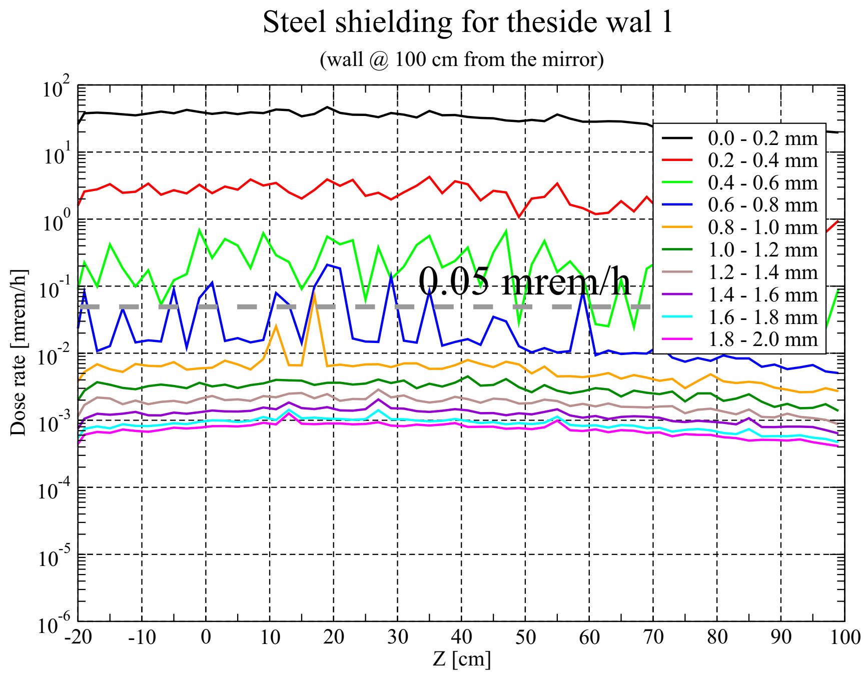
The same approach was performed for the downstream wall. For this case, results shown in Figure 10 are rather similar to the ones obtained for the lateral wall. The main difference is the presence of a small peak due to photons going straight through the mirror. However, the same requirements as for the lateral wall, namely 0.2 mm of lead or 1.2 mm of steel apply for the downstream wall.

In order to see if a higher threshold for photon transport could be used (in STAC8 photons with an energy less than 10 keV are not considered), the energy dependent photon fluence entering the different shielding slab was scored for the steel lateral wall. The different spectra are shown in Figure 11. The spectrum in black corresponds to the photon fluence hitting the target, this spectrum is very useful to verify that the source spectrum shown in Figure 3 was properly sampled over the entire energy range of interest with the user source routine and that the normalization factor is correct. It should be noted that the spectrum in Figure 3 is determined for one photon pulse while the spectrum in black in Figure 11 corresponds to the fluence averaged over one second considering a repetition rate of 120 Hz for the accelerator. The spectrum in red shows the photons which are scattered out of the target in all directions. Compared to the source spectrum in red, it can be seen that a significant fraction of the photons are absorbed by photoelectric effect inside the mirror especially at lower energies. The spectrum of photons reaching the lateral shielding wall are shown in green, it should be noted that photons travel 100 cm or more through air which despite its very low density reduces the spectrum in the low energy part. The photon spectra after 0.6 mm, 1.4 mm and 1.8 mm are shown in blue, purple and orange respectively. As it can be seen in Figure 11, after such a thickness of steel, no photon with an energy less than 10 keV contributes to the dose rate. In addition, after 1.2 mm of steel, photons with an energy below 50 keV which are significantly reduced, consequently there are no ambiguity on the use of the air kerma approximation below 50 keV for the estimation of the fluence to dose convertion factors.

### 2.5.3 FEL photons

The contribution of FEL photons to the dose rate were calculated in different FLUKA runs using the same geometry as shown in 8 and a mono-energetic photons beam for the different harmonic energy. The normalization which is used for the dose rate calculations take into account the FEL intensity indicated in the fourth column of Table 2 (after the mirrors attenuation) considering a repetition rate of 120 Hz.

The dose rate for different shielding of steel for the lateral wall is shown in Figure 12. Considering a thickness of 1.2 mm of steel, the maximum contribution (of the order of $2 \times 10^{-4}$ mrem/h compared to $5 \times 10^{-3}$ mrem/h for the contribution of spontaneous photons is the same conditions) is found for FEL photon of 41.3 keV (the number of photons from higher energy being drastically reduced by the mirrors). The contribution of photons from the fundamental harmonic is negligible after 0.2 mm of steel.



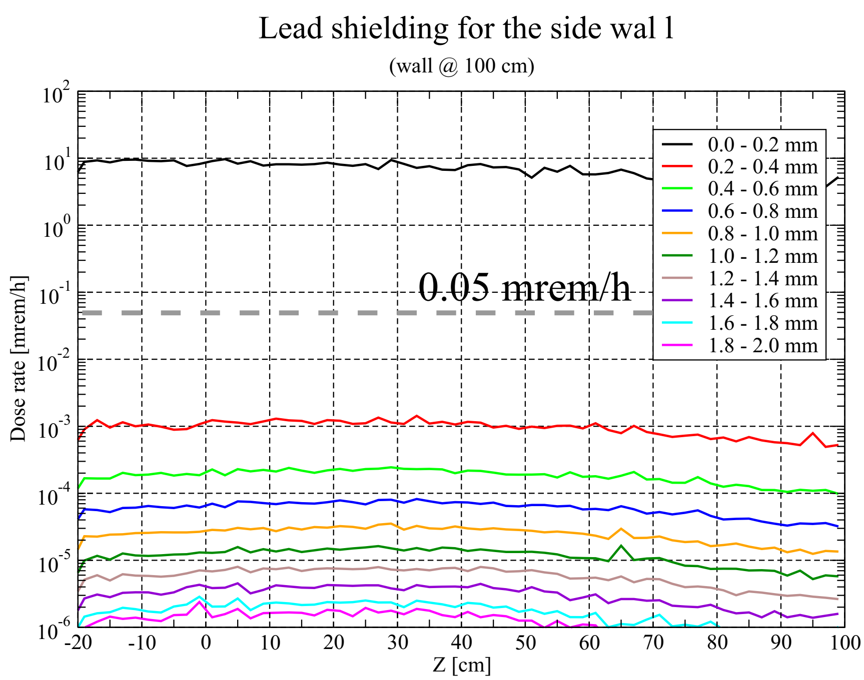
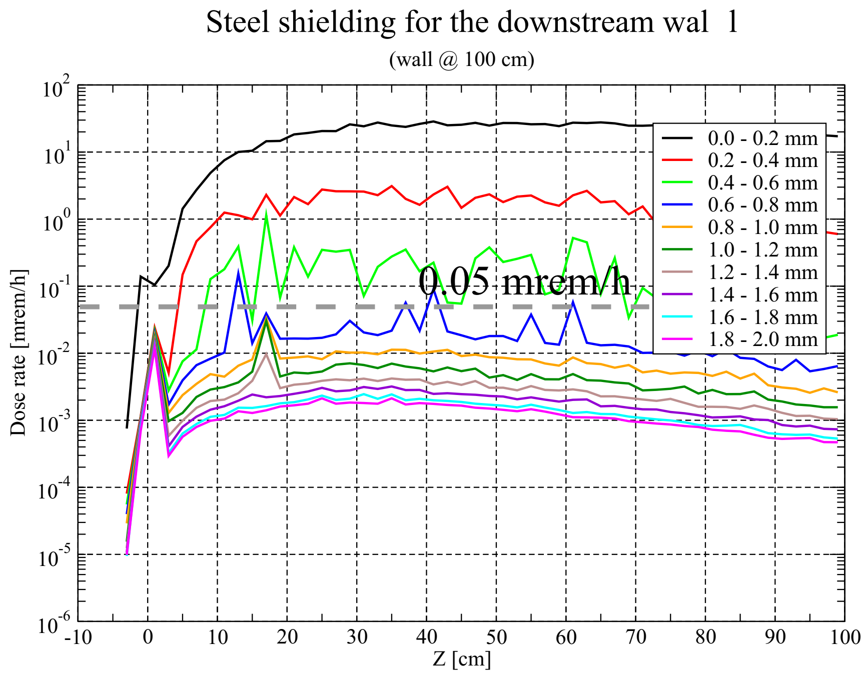




Figure 9: Dose rate inside the different slabs of the lateral wall for a steel wall (top figure) and a lead wall (bottom figure). The dose rate for different shielding thicknesses can be compared to the design value of 0.05 mrem/h (dashed curve).



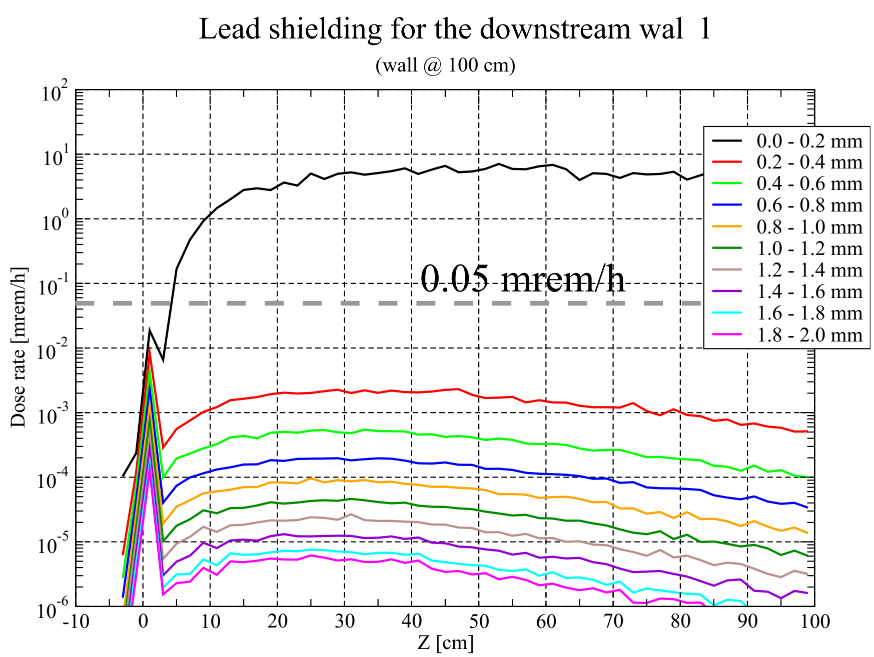




Figure 10: Dose rate inside the different slabs of the downstream wall for a steel wall (top figure) and a lead wall (bottom figure). The dose rate for different shielding thicknesses can be compared to the design value of 0.05 mrem/h (dashed curve).

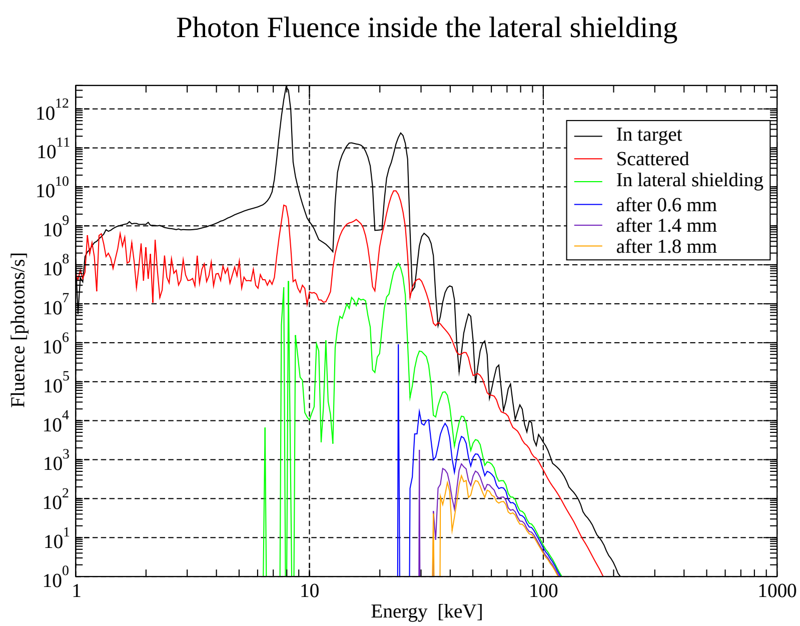



Figure 11: Energy dependent photon fluence calculated with a boundary crossing estimator. The spectrum in black shows the photon hitting the target, the spectrum in red correspond to the photons scattered out of the target and the spectrum in green to the photons entering the shielding. The photon spectra after going through 0.6 mm, 1.4 mm and 1.8 mm of steel are shown in blue, purple and orange respectively.

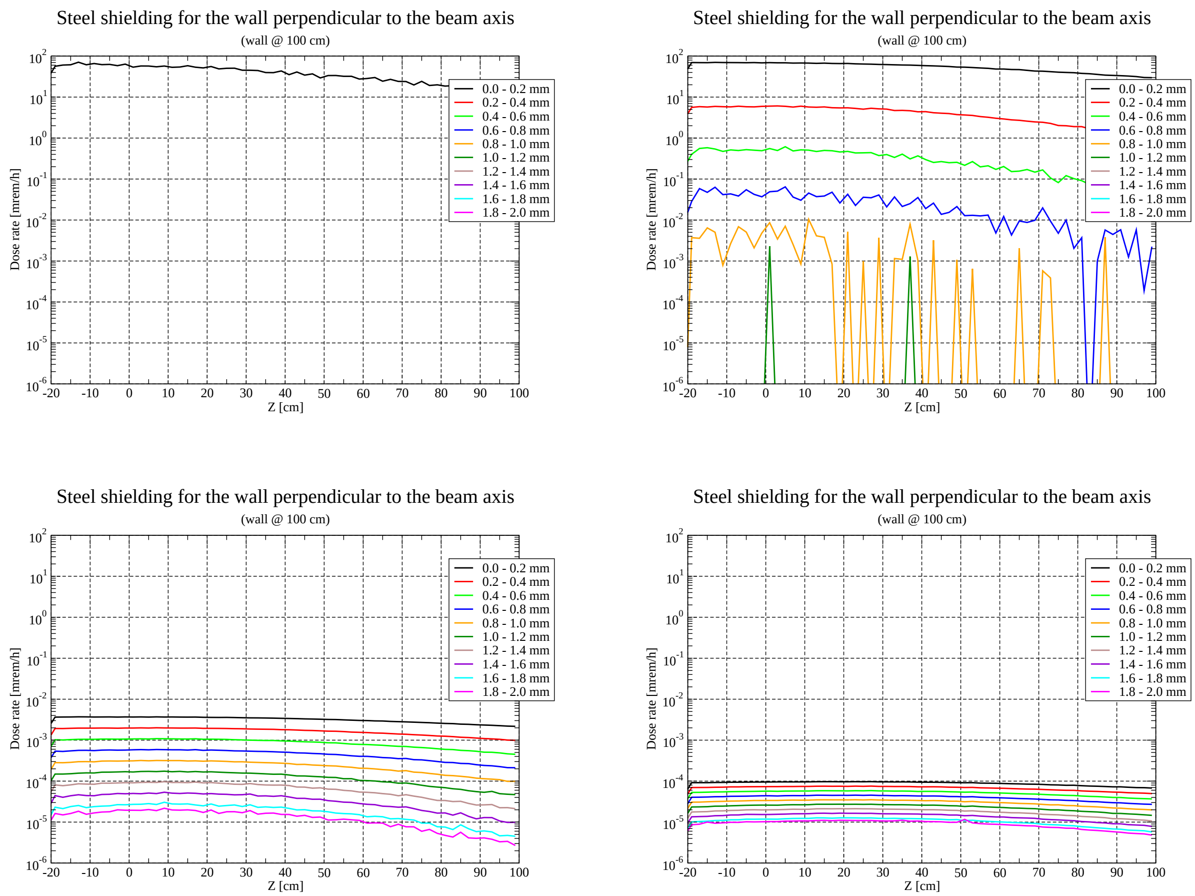



Figure 12: Contribution to the dose rate of FEL photons from the fundamental harmonic (8.27 keV top plot on the left), the first odd harmonic (24.8 KeV, top plot on the right), the second odd harmonic (41.3 keV, bottom plot on the left) and the third odd harmonic (57.9 keV bottom figure on the right).

# 3 STAC8 calculations

STAC8 Version 2 for Windows [11] was used to estimate the shielding necessary to reduce the dose to 0.05 mrem/h for different geometrical configurations. The dose rate due to photons from the FEL peaks in Table 2 (except for the fundamental peak which is below STAC8 treshold) was calculated, along with the rate from the spontaneous photons corresponding eihter to the 13.7 GeV electron beam (red curve in Figure 3) or 17 GeV electron beam (blue curve in Figure 3). The maximum of the effective, ambient and 70 micron dose equivalent was considered in each case. The input spectrum was normalized to photons/eV/s for a 120-Hz pulse rate. A generic worst-case scattering target (a 2-cm thick slab of silicon with incidence angle 0.155°) was considered, and dose rate was calculated at multiple angles on the downstream wall (100 cm from the target) and on a cylindrical (coaxial with the incident beam) side wall at various distances from the target. Buildup in the shielding material was taken into account, but polarization was not considered. The fluence-to-dose conversion factors in STAC8 have a lower energy cutoff of 10 keV, so the results do not include the FEL fundamental peak (8.3 keV) or the part of the spontaneous spectrum below 10 keV. FLUKA results discussed in Section 2.5.3 show that the contribution of FEL photons from the fundamental peak to the dose rate is negligible after a very thin layer of shielding.

The contribution of spontaneous and FEL photons have been scored separately for a lateral steel wall 1.6 mm thick at 30 cm from the target as well as for a 4.6 mm thick steel wall 100 cm downstream. Table 3 shows the contribution of the the spontaneous and FEL photons for the two cases mentioned above with their relative contribution to the total dose rate. Results in 3 show that the contribution of FEL photons account only for a few percents of the total dose rate.

Table 3: Contribution of spontaneous photons and FEL to the dose rate for the lateral steel wall located 30 cm from the target and for the downstream steel wall located 1 m after the target.

| | Lateral wall (30 cm, 1.6 mm Fe) | | Downstream wall (100 cm, 4.6 mm Fe) | |
|---|---|---|---|---|
| | Dose rate mrem/h | % of total | Dose rate mrem/h | % of total |
| SR | 0.0480 | 94 | 0.0480 | 99 |
| 8.27 keV FEL | | | | |
| 24.8 keV FEL | $2.29 \times 10^{-4}$ | 1 < | $1.49 \times 10 - 17$ | 1 < |
| 41.3 keV FEL | $2.21 \times 10^{-3}$ | 4 | $1.57 \times 10 - 5$ | 1 < |
| 57.9 keV FEL | $4.65 \times 10^{-4}$ | 1 | $3.64 \times 10 - 4$ | 1 < |
| 74.4 keV FEL | $1.38 \times 10^{-5}$ | 1 < | $5.14 \times 10 - 5$ | 1 < |
| Total | 0.0509 | 100 | 0.0484 | 100 |

Several other configurations were considered, the thickness of material which is necessary to reduce the dose rate to 0.05 mrem/h for those different cases is indicated in Table 4. For some cases, the thickness of the shielding was determined for 13.7 GeV and 17 GeV spontaneous photons spectrum, but as it can be seen in the table that the thickness of material required in the two cases does not change significantly. FEL photons were considered only for the two cases shown in Table 3 since it was shown that FEL photons account only for a few percents of the total dose rate. Considering the lattest available spontaneous photon spectra the shielding requirement as indicated in Table 4 differs strongly than those derived using the non-apertured spectra and the mirrors with the 60 keV cutoff which are indicated in Ref. [1, 2].

Table 4: Thickness necessary to reduce the dose rate to 0.05 mrem/h determined with the analytical code STAC8 for different geometrical configurations considering 13.7 GeV and 17 GeV electron beam energies. The indicated distance corresponds to the distance between the scatt.

| | Distance | Energy | Lead (mm) | Steel (mm) | Concrete (mm) |
|---|---|---|---|---|---|
| Side wall | 30 cm | 13.7 GeV | 0.3 | 1.6 | |
| | 30 cm | 17 GeV | 0.35 | 2.1 | 39 |
| Side wall | 5.44 m | 13.7 GeV | 0.108 | 0.56 | |
| | 5.44 m | 17 GeV | 0.122 | 0.6 | |
| Side wall | 100 cm | 13.7 GeV | 0.18 | 0.94 | 19 |
| | 100 cm | 17 GeV | 0.191 | 1.03 | 20.5 |
| Downstream wall | 100 cm | 13.7 GeV | 0.68 | 4.6 | |
| | 100 cm | 17 GeV | 0.90 | 6.2 | 88 |
| Pipe | 5cm | 17GeV | 2 Fe (pipe) + 0.6 lead | 6.2 | |

# 4 Comparison of the STAC8 and FLUKA calculations

The approach used in STAC8 and FLUKA are significantly different. Not all configurations considered with STAC8 where run with FLUKA as they require more computing time. However for the case of the lateral and downstream walls located 100 cm away from the scattering target were run with both codes. For the lateral wall, the minimum steel thickness necessary to reduce the dose rate to less than 0.05 mrem/h determined with FLUKA is found to be comprised between 1.0 and 1.2 mm which can be compared to the 0.98 mm derived from the STAC8 analysis. The results are in rather good agreement when it is considered that the FLUKA approach is very conservative, indeed a thickness comprises between 1.0 and 1.2 mm leads to a dose which is less than 0.005 mrem/h (a factor of 10 below the design criteria). The thickness comprises between 0.8 and 1.0 mm (orange curve on the top Figure 9) shows one statistical fluctuation slightly above the design value of 0.05 mrem/h but it leads to a dose rate of the order of 0.01 mrem/h besides this fluctuation.

The lateral wall calculations done at 30 cm and 5.44 m using STAC8 can be compared to the FLUKA analysis done for the wall located at 1 m and differs from the ones used in the FLUKA calculations since the dose rate was calculated for several thickness of materials in the FLUKA calculations (from 0.2 mm to 2 mm in steps of 0.2 mm). Taking the the thickness deduced from the STAC8 calculation, it is possible to rescale the dose rate obtained with FLUKA (at 100 cm) to the same distance as in STAC8 (30 cm of 5.44 m) using the $1/r^2$ rule as it is shown in Table 5. For the lateral wall, when results are rescaled to the same distance the dose rate calculated with FLUKA and STAC8 are rather similar.

Table 5: Comparison of the STAC8 and FLUKA calculations. For the lateral walls results were rescaled to the distance used in the STAC8 calculations.

| STAC8 | | | FLUKA | | | | |
|---|---|---|---|---|---|---|---|
| distance | thickness | dose rate (mrem/h) | distance | Thickness | dose rate (mrem/h) | $r^2_{FLUKA}/r^2_{STAC8}$ | corrected dose rate (mrem/h) |
| 30 cm | 1.6 mm Fe | 0.05 | 100 cm | 1.4-1.6 mm | 0.003 | 11 | 0.03 |
| 544 cm | 0.56 mm Fe | 0.05 | 100 cm | 0.4-0.6 mm | 0.8 | 0.034 | 0.03 |

For the estimation of the thickness of the downstream wall the STAC8 and FLUKA calculations can be compared directly since both have been performed at a 100 cm distance. Considering the

14 GeV spontaneous spectrum, it is found with FLUKA that 1.0 mm of steel is necessary in order to reduce the dose rate to less than 0.05 mrem/h. Using STAC8, it appears that more than 4 times this thickness is necessary. consequently for shielding recommendations, the results obtained with STAC8 are used.

## Conclusions

The spontaneous photon spectrum used for the calculations presented in this Note was compared to the one used for previous shielding estimates. The new spectrum now take into account the effect of the C1 collimator and the cutoff energy of two SiC mirrors at 24 keV which significantly reduce the spontaneous photons intensity. Due to the difference in source term used for the calculations, it is found that less shielding is now necessary to reduce the dose rate to 0.05 mrem/h.

The contribution of photons (FEL and spontaneous including the fundamental peak at 8.27 keV) below 10 keV which is the cutoff used in the STAC8 calculations was determined using FLUKA, it was found negligible after thin thickness of shielding material. FEL photons were taken into account for both calculations scheme, it appears that they only contribute to a few percents of the total dose rate while spontaneous photons dominate the shielding requirements. STAC8 and FLUKA lead to similar results when it comes to determine the lateral wall thickness, however the downstream wall thickness estimated with STAC8 is four time bigger than the one deduced from the FLUKA calculation.

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