Shielding Design of the SPring-8 XFEL Facility

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Abstract

Shielding design of the 8 GeV class X-ray Free Electron Laser facility at SPring-8 (XFEL/SPring-8) has been performed by using the semi-empirical code,SHIELD11, and the Monte Carlo code, FLUKA for the bulk shield. These results were compared with each other. The Beamline hutches of the XFEL/SPring-8 have been also designed and estimated the leakage doses including the incident conditions of the abnormal electron aberrance.

1. Introduction

The 8 GeV class X-ray Free Electron Laser facility at SPring-8 (XFEL/SPring-8) is now under construction to obtain the X-ray laser with the shortest wavelength of less than 0.1 nm based on the practical experience of the SCSS prototype facility (250MeV, 30nC/s) [1]. XFEL/SPring-8 is based on three new technologies. One is the low emittance thermionic gun, one is the C-band accelerators of up to 8GeV and 60 nC/s, the other is the in–vacuum type undulators. The length of this system is about 415m, 235m, and 66m for the accelerator section, the undulator section, and the experimental hall, respectively. Based on the ALARA principles, the design criteria at the SPring-8 site are 8μSv/h, 2.5μSv/h, and 100μSv/y, for the radiation controlled area, the boundary of the controlled area, and the site boundary, respectively. For the shielding design of the facility, we employed the SHIELD11 code [2], analytical methods and the Monte Carlo code FLUKA [3], and the results were compared with each other..

2. XFEL/SPring-8

The XFEL/SPring-8 facility has been constructed at just close to the 1km long beamline of SPring-8. The accelerated 8 GeV electrons passing through the undulator with about 120m length go down into beam dump with the inclined angle of 20 degrees, and then the laser lights go straight into the experimental area through the shield wall in the direction of the SPring-8 storage ring. Fig.1 shows the illustration of the XFEL/SPring-8 comfigurations including the electron beam loss assumptions. The facility will have 5 beamlines by using the switing magnet to swing the accelerated electron beam, and two beamlines are now under construction in the first stage. This machine has three bunch compressors and two chicaines, and these components can remove the dark current. Therefore, the maximum energy of dark current at the each sections can be shown in this figure. Based on the beam dynamics simulations, we dicided the beam loss assumptions as follows,

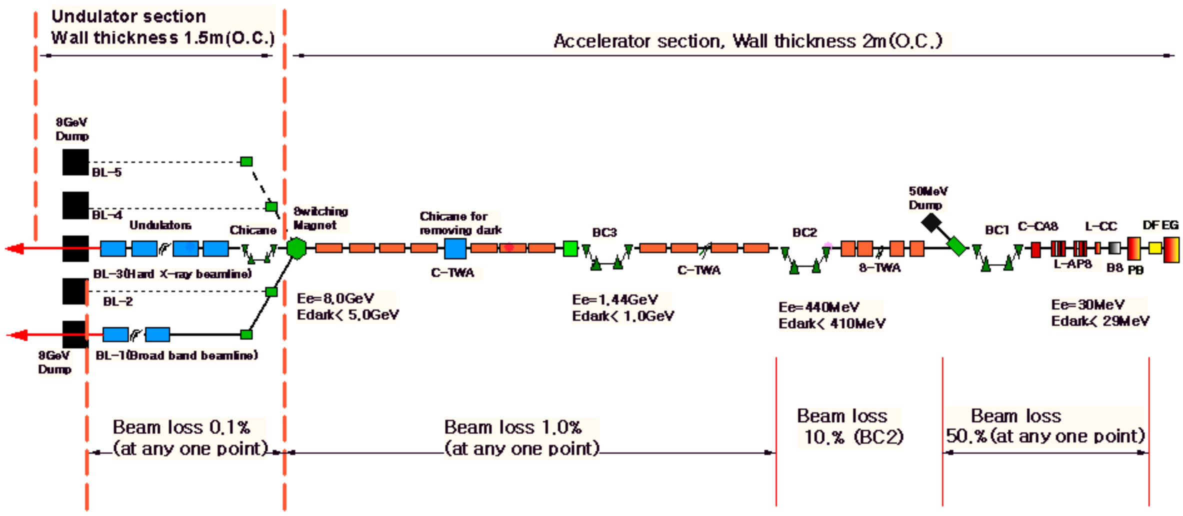

Fig.1 - Illustration of the XFEL/SPring-8 comfigeretions including the electron beam loss assumptions.

50% from the electron beam deflector to 50 MeV dump (electron energy is up to 50 MeV), 10% from 50 MeV dump to the beam compressor No. 2(BC2, electron energy is up to 440 MeV), and 1 % at any points from BC2 to the out of switching magnets in the accelerator section. In the undulator section, 0.1 % beam loss were assumed at any one point except the 8 GeV dump because the beam must be high quality to oscillate the X-ray laser. Besides, the beam loss must be avoided as low as possible to protect the radiation damage of the permanent magnet of the undulators so that the beam halo monitor [4] and the beam loss monitor [5] will be installed in this section.

3. Comparison between Jenkins' formula, SHIELD 11 and FLUKA calculations

For the bulk shielding calculations of SPring-8, we employed the Jenkins' formula [6] and modified Swanson's formula [7]. Recently, SLAC released the convenient code for the bulk shield calculation, SHIELD 11, based on the Jenkins' formula that has some distinct features such as the capability of wide application, especially without restriction of the scattering angle, with considering the self shielding of the target, and local shield, automatically. In order to apply the shielding design of the XFEL/SPring-8, the calculation results between Jenkins' formula, SHIELD11, and FLUKA were compared each other for the calculation models as shown in Fig.2. In this model, we employed the cylindrical target made of iron with 20cm in thickness and 20cm in radius. For the shield wall, we employed the ordinary concrete with the density of 2.2 g/cm^3 and from 1 m to 2.5 m in thickness. In the SHIELD 11 calculations, we performed with

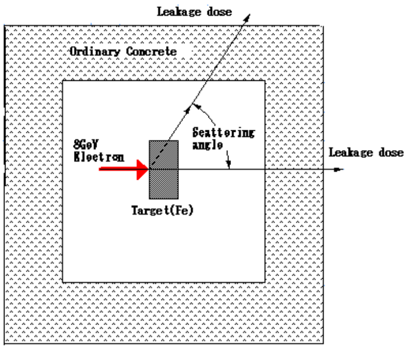

Fig.2 - Calculation models for the intercomparison of the semi-empirical methods and Monte Carlo code.

and without considering the self shield of the target. For the Jenkins' calculations, we considered two cases, one is only considering the shield wall, the other is considering the shield wall and 20 cm iron target as a local shield. In the FLUKA simulations, effective dose with worst geometry and ambient dose were estimated. The attenuation lengths which were employed in SPring-8 shielding design and in SHIELD 11 are summarized in Table 1 for ordinary concrete with the density of 2.2 g/cm^3, iron, and lead. In this table, the upper stands indicate the attenuation lengths which used in the SPring-8, and the lower stands indicate the attenuation lengths of the SHIELD 11 for each radiation source. For photons, the attenuation lengths are almost same. On the other hand, the attenuation lengths of the iron and lead are different for neutrons and the attenuation lengths for high energy and intermediate neutrons are the same in the SHIELD 11 code.

(cm)

Material		Neutron High Energy (λ_1)	Neutron Intermediate (λ_3)	Neutron Giant resonance (λ_2)	Photon (λ)
Ord. Concrete	SPring-8	54.6	25.0	13.7	18.9
	SHIELD11	54.55	25.0	13.64	19.1
Iron	SPring-8	21.3	12.4	6.8	4.3
	SHIELD11	18.6	18.6	6.0	4.3
Lead	SPring-8	22.7	18.3	10.0	2.1
	SHIELD11	17.6	17.6	8.54	2.1

Table 1 - Attenuation lengths which we employed in SPring-8 shielding design and SHIELD11.

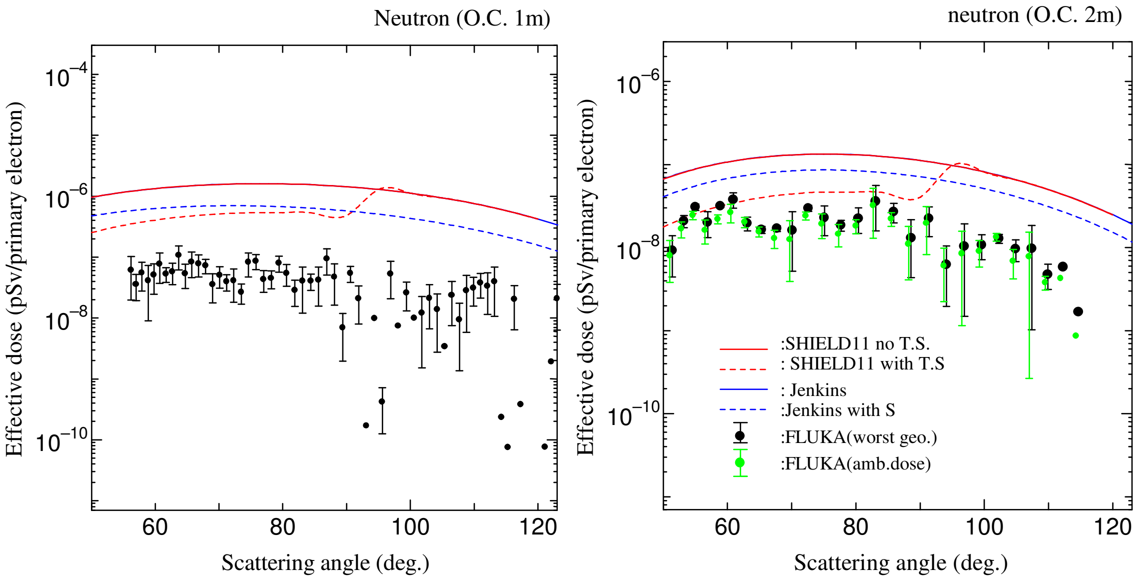

Fig.3 - Neutron leakage dose distributions in the lateral direction for the case of ordinary concrete shield wall with 1m (left side) and 2m(right side) thick. Red dotted and solid lines indicate the calculation results by using SHIELD 11 with and without considering the self shielding of the target, respectively. Blue dotted and solid lines are the results using Jenkins' formula with and without considering the local shield of iron. Black and green dots are the results by using FLUKA for the effective dose (worst geometry) and the ambient dose.

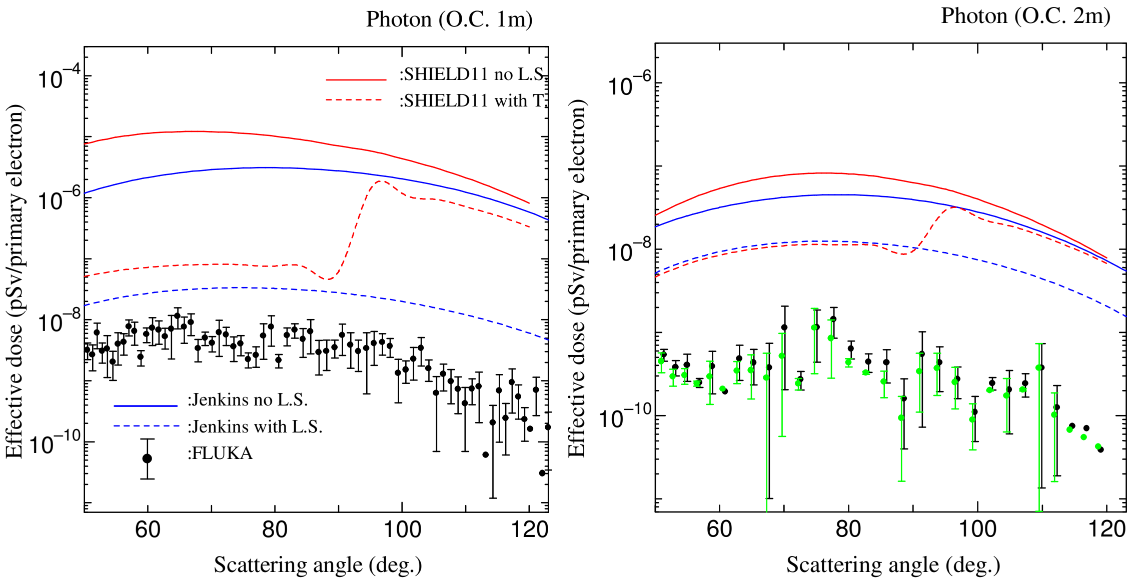

Fig.4 - Photon leakage dose distribution in the lateral direction for the case of 1m and 2 m shield wall of ordinary concrete. Each line and dots indicate the same meaning as Fig.3.

The calculation results of the neutron leakage dose distributions in the lateral direction are shown in Fig.3 for the shield wall of 1 m and 2 m ordinary concrete, and photon dose distributions are in Fig.4.for 1m and 2m shield wall. In these calculations, the SHIELD 11 calculations indicate more conservative leakage dose than that of the FLUKA calculations, and nearly equal of the Jenkins' calculations. The leakage dose calculations in the forward direction are shown in Figs.5 and 6 as functions of scattering angle and the thickness of shield wall. As shown in these figures, the results of the Swanson's are most conservative for photon dose in the case of less than 2 m thickness of the shield wall. On the other hand, the FLUKA simulations show the highest values for neutrons.

4. Shielding calculations around the beam dump and the beamline of XFEL/SPring-8

The beam dump of 8 GeV is installed with inclination angle of 20 degrees and Fig.7 shows the illustration of the beam dump area. The 8 GeV beam dump has a double cylindrical structure, and the core (inner cylinder) is made of graphite, and outer is the iron with 40 cm thick. The iron plate with 65 cm thick is placed at the upper side of the dump for the shield. The thicknesses of the bulk shield in lateral direction and the roof are 1.5 m, and 2.5 m in the forward direction. Two collimators and one sweep magnet are installed for the safety in front-end of the XFEL beamline. The leakage dose distributions outside the roof are shown in Fig.8 by using SHIELD 11during the electron beam injection into the dump. In the calculation, the electron beam intensity is 1nC with the repetition rate of 60 Hz. As shown in the figure, the neutron dose is dominant outside the roof.

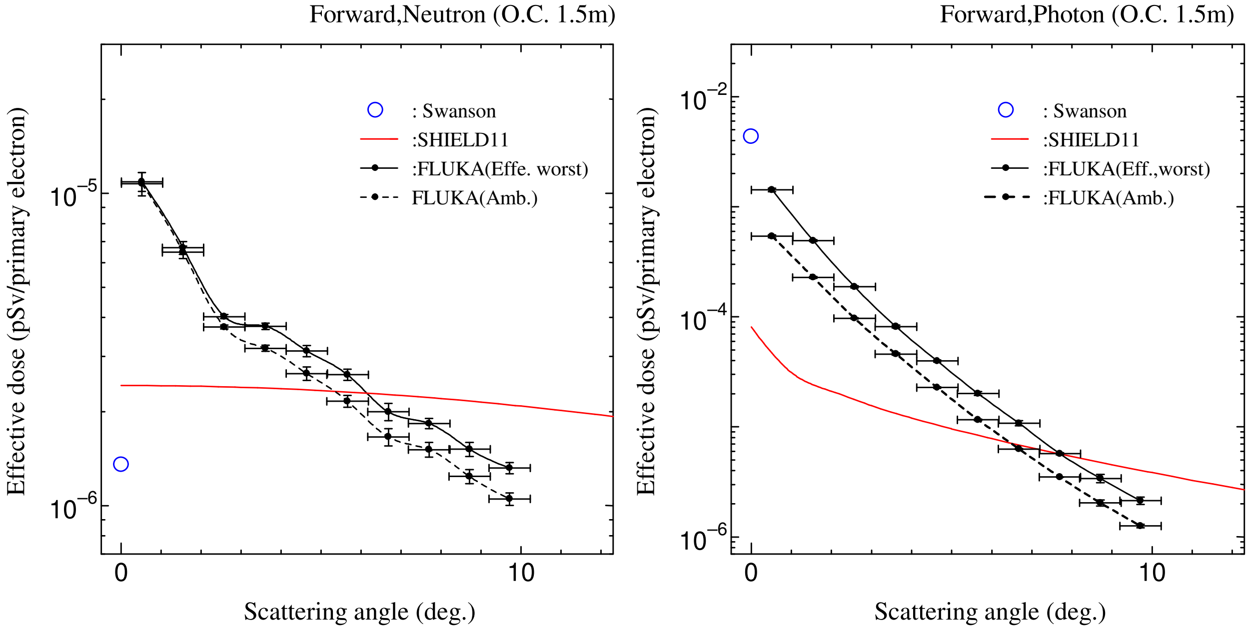

Fig.5 - Leakage dose distribution in the forward direction with the ordinary concrete shield wall of 1.5m thick as a function of the scattering angle as shown in Fig.2. The left side figure is for neutron dose, and right side is for photon dose. Blue circle indicates the calculation results of the modified Swanson's, red line is the SHIELD 11 calculation. Black solid line and dotted line show the FLUKA simulation of effective dose with worst geometry and the ambient dose, respectively.

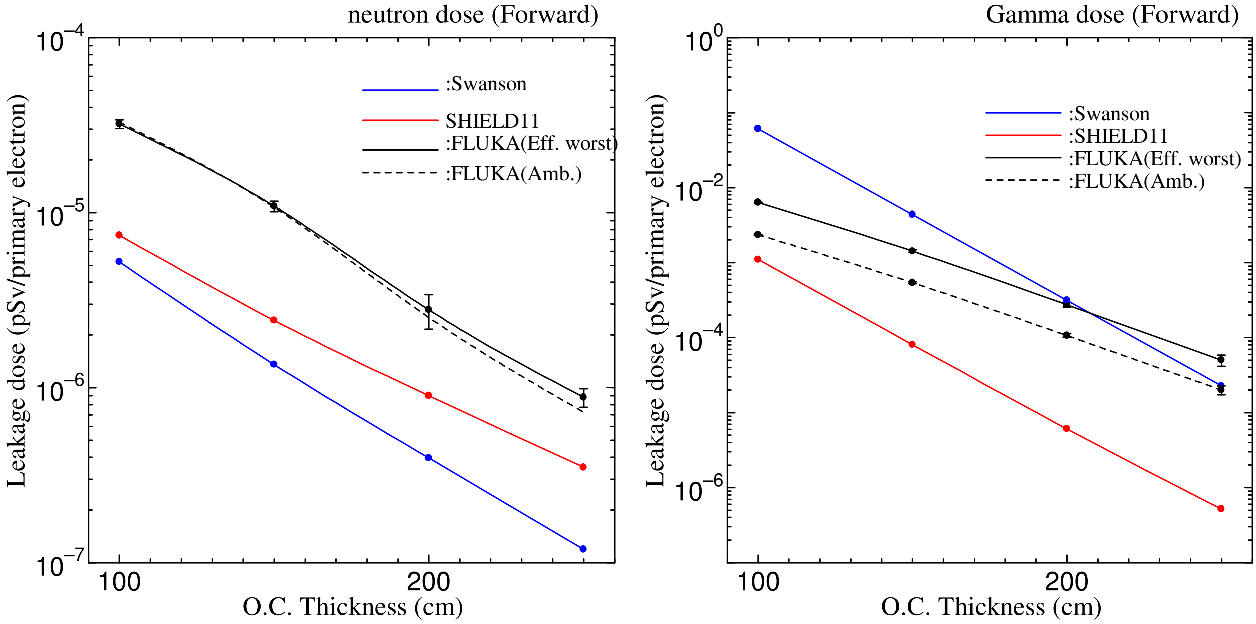

Fig.6 - Leakage dose distribution as a function of the ordinary concrete thickness at the 0 degrees scattering angle. The left side figure is for neutron dose, and right side is for photon dose. Blue line shows the results of the Swanson's, and others are the same as Fig.5.

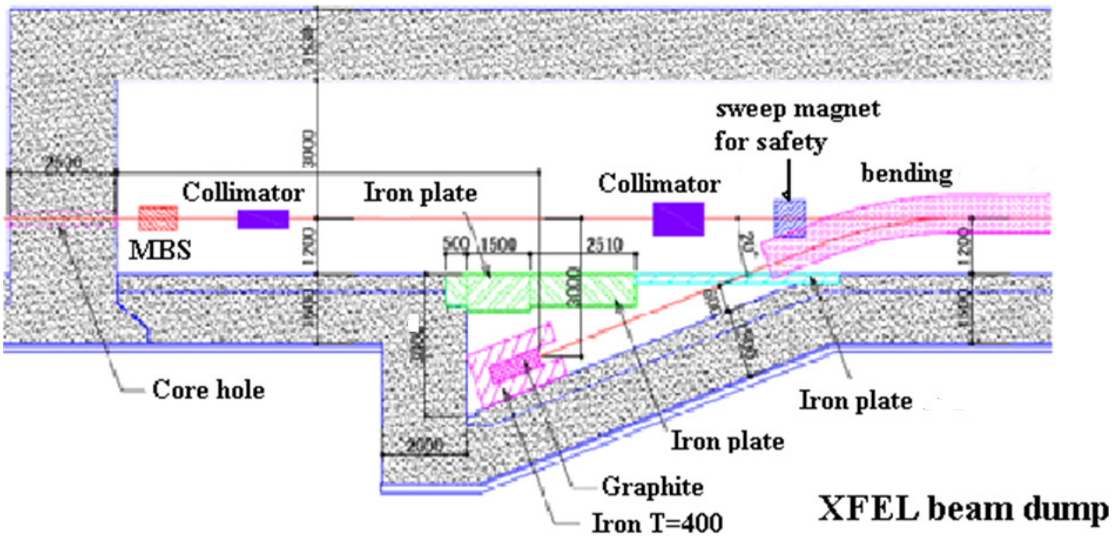

Fig.7 - Cut a way view of beam dump area.

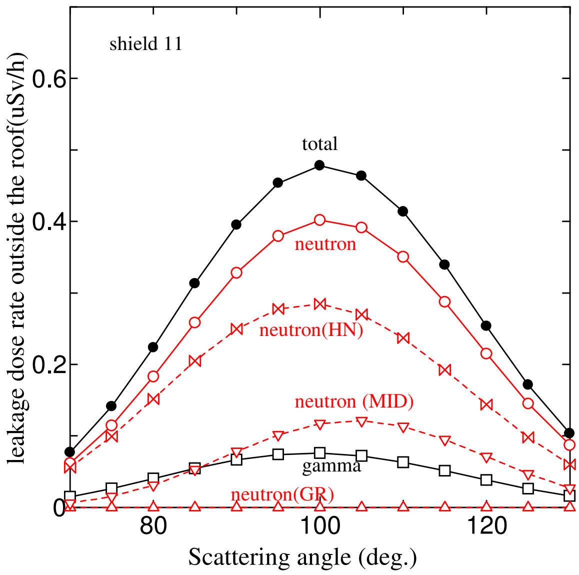

Fig.8 - Leakage dose distribution outside the roof.(neutron(HN) means the dose due to high energy neutrons, neutron (MD) means the dose due to intermediate energy neutrons, and neutron(GR) means the dose due to giant resonance neutrons).

The 8 GeV electrons are always injected into beam dump by the bending magnet. However, we must take care of the accidental conditions such as the power loss of the bending magnet by some blunder. In this case, the 8 GeV electrons can invade into optics hutch even though the safety interlock system is tripped immediately, and this is very dangerous. To avoid this situation, the sweep magnet for the safety must be installed in the downstream of the bending magnet. Fig.9 shows simulation result of the dose distribution by using FLUKA during this dangerous case. In this case, the sweep magnet is designed as 0.9Tesla and 57 cm in length, and the aperture size of the first collimator is 13mm ϕ at 5 m distance from the magnet. This figure shows that the trajectory of the 8GeV electron is inclined by the sweep magnet and the electrons hit the collimator. Some bremsstrahlung photons invade into the optics hutch through the hole of the shield wall to lead XFEL into the experimental area. However, 8GeV electrons never inject into the optics hutch.

In the shielding design of the XFEL/SPring-8, we assumed the beam loss of 0.1% will be occurred within the undulator section. When the electron beam loss is occurred in the undulator section, the power of the bremsstrahlung which invades into the optics hutch depends strongly on the collision angle of the electron beam and the aperture size of the collimator. Figure 10 shows the simulation results of the injection angle dependence of the invaded power into the optics hutch with the same calculation configuration as shown in Fig.9 by using EGS4[8]. In the simulation, we found that the invaded power is saturated when the injection angle is less than about 0.5 mradian so that we set the 0.1mradian for the safety calculation of the XFEL beamline. The simulation results of the photon dose and the neutron dose distribution around the optics hutch are shown in Fig.11by using FLUKA. In the case, 0.1% of the 8GeV electrons is lost at the upstream of the bending magnet of the beam dump. The simulation configuration is the same as shown in Fig.9 and the shield wall of the optics hutch side wall is 80 cm ordinary concrete, and 1m for the back wall. In the simulation, the copper with 5 cm thickness is assumed for the first scatterer and the local shield made of lead with 10cm in thickness. As shown in the figure, the doses due to neutrons caused by photo-nuclear reactions of the bremsstrahlung are notable in the optics hutch.

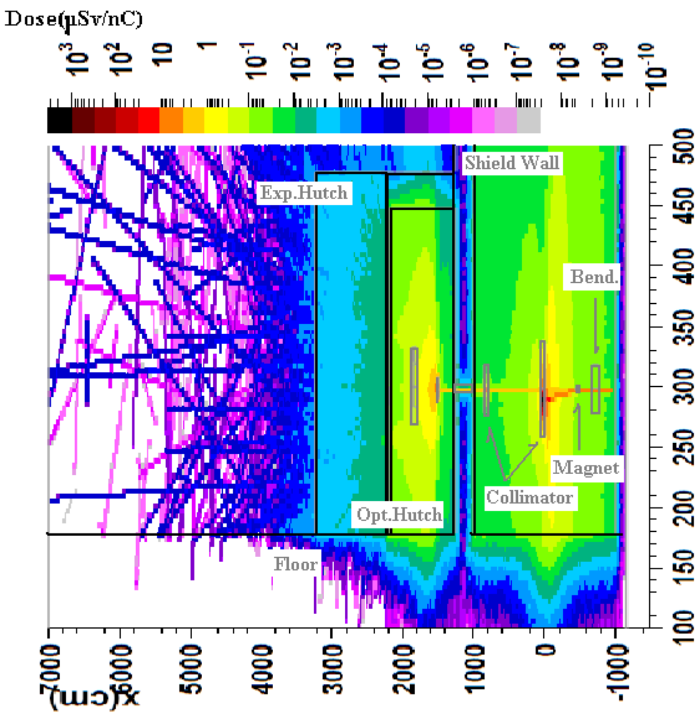

Fig.9 - The dose distribution when the power of bending magnet is lost and the electron beam hits the collimator.

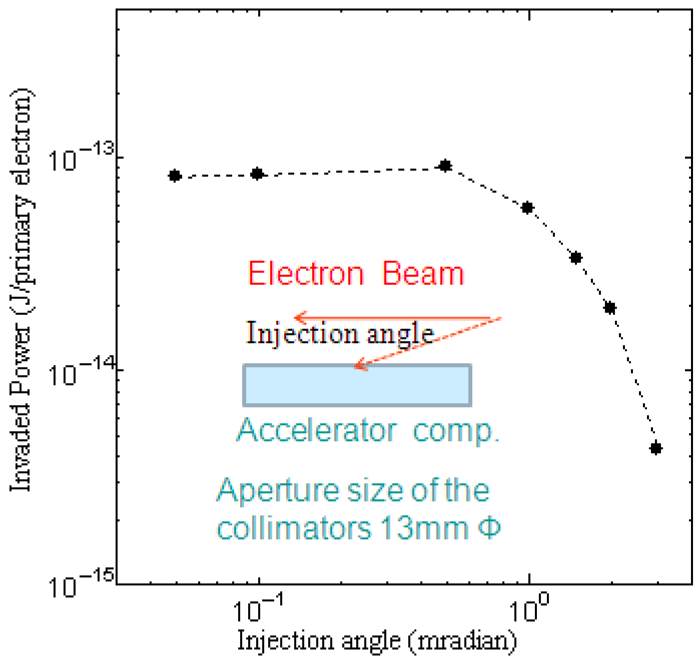

Fig.10 - Injection angle dependence of the invaded bremsstrahlung photon power.

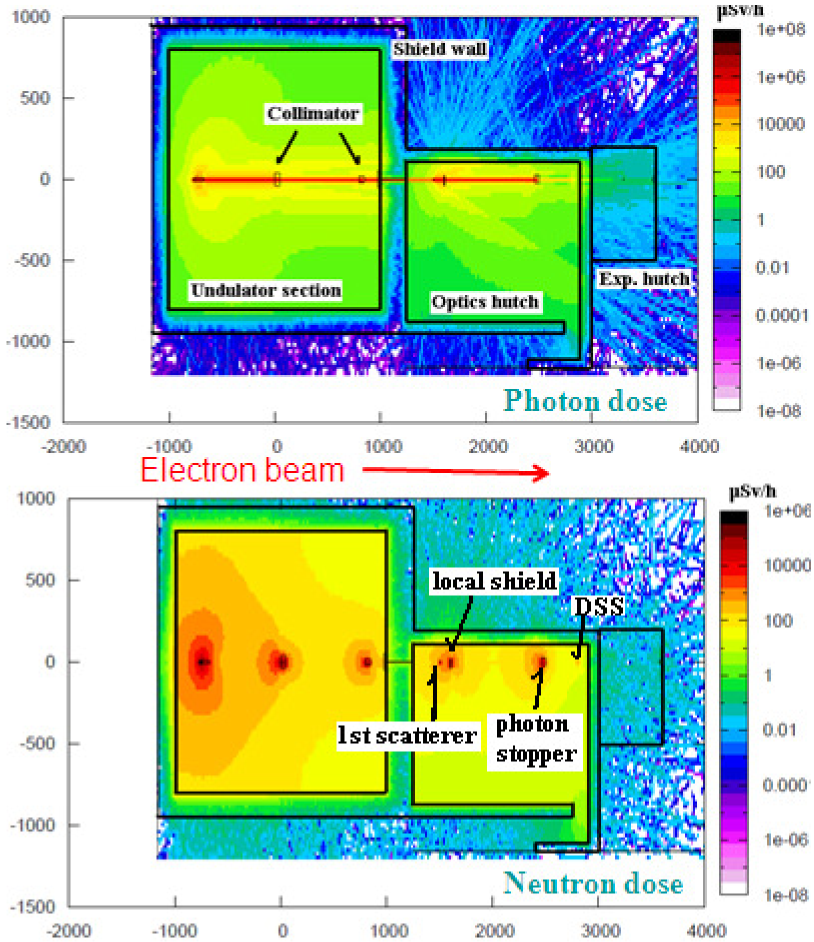

Fig.11 - Photon and neutron dose distributions due to 0.1% electron beam loss at the upstream of the bending magnet. (The upper and lower stands are photon and neutron dose distributions, respectively. The size of the local shield for 1st scatterer is 60cmWx60cmHx10cm lead, photon stopper is 50cmWx50cmHx40cm lead).

5. Summary

For the design of the bulk shield of XFEL/SPring-8, we employed the SHIELD11 code, the Jenkins' formula, the modified Swanson's method, and the Monte Carlo code FLUKA, and compared each other. As the results of the leakage dose at the lateral direction, we found the calculation results by using the Jenkins' underestimate in comparison with the SHIELD 11 for gamma dose, and neutron doses are almost the same. Both gamma and neutron doses calculated by SHIELD11 show the conservative values in comparison with that of FLUKA (effective dose with worst geometry). For the doses at the forward direction, SHIELD 11 underestimates both the gamma and neutron doses in comparison with that of FLUKA so that we must take care of the calculations in the forward direction. For the XFEL beamline shielding, we must consider three radiation sources, one is the synchrotron radiation including XFEL, one is the gas bremsstrahlung, and the other is the high energy radiations due to the accelerated electron beam loss including photoneutrons. In the XFEL/SPring-8 case, however, the two former sources make not so much severe conditions in comparison with that of the electron beam loss. And these conditions strongly depend on the injection angle of the electron beam loss. For the estimation of the radiations due to the electron beam loss, we employed the FLUKA code in the shield design of the XFEL/SPring-8 beamline. The shield tunnel and the building of the XFEL/SPring-8 have been constructed, and the accelerators are now under construction. The commissioning will be started in next year.

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