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Revised Shielding Estimates for the NSLS-II Beamlines at 3.0 GeV Beam Energy

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1. Introduction

The shielding calculations for the NSLS2 beamlines are repeated with 3 GeV beam energy and the revised source parameters. Shielding requirements for the first optics enclosures, monochromatic experimental stations and the monochromatic beam transports are calculated. Calculations are carried out for a contact dose rate of < 0.05 mrem/h which correspond to100 mrem/year for 2000 work hours per year.

2. Simulation Tools

Bremsstrahlung Scattering Calculations for NSLS II ID Beamlines were carried out using the EGS4 electron-gamma shower simulation program[1]. This implementation is part of the CALOR program package distributed by the Radiation Shielding Information Center (RSIC) of the Oak Ridge National Laboratory. EGS4 simulates the coupled interactions of photons and electrons with materials over an energy range from a few KeV to several TeV. The photoneutron production and transport is not simulated by EGS4. Scaling measurements from other third generation light sources[2] have given a neutron dose rate limit of ~10 µrem/h at NSLS-II beamlines, which is only 20% of the design dose rate limit of 0.05 mrem/h. It is concluded that the photoneutrons are not a significant radiation hazard at the synchrotron radiation beamlines at NSLS-II.

The Synchrotron radiation scattering calculations for NSLS II beamlines have been performed using the STAC8 program[3]. STAC8 has been developed at Spring8 facility and has been used extensively at other third generation synchrotron radiation facilities. STAC8 generates insertion device radiation spectrum and monochromatic beams with a fixed band width. The program simulates photon transport by Compton scattering (with anisotropy), Rayleigh scattering and photo-absorption. It calculates scattered photon flux as a function of energy and angle and converts photon flux to dose rates. Build up factors in the shielding materials are taken into account while the effect of polarization has not been considered.

3. Geometry and Sources used for Bremsstrahlung and Synchrotron Radiation Scattering calculations

The synchrotron radiation and bremsstrahlung can be scattered from any potential component in the beamlines and front ends. Such components include windows, slits, mono-chromators, mirrors etc. These components differ from beamline to beamline. Therefore calculations are performed with a worst case potential scatterer, located at the upstream end of the First Optics Enclosure (FOE), of typical dimensions of 2.0 m width, 3 m height and 10 m length. Figure 1 shows the geometry of computation for bremsstrahlung and synchrotron radiation scattering to estimate the shielding requirements for the NSLSII FOEs. The worst case potential scatterer for bremsstrahlung is taken as 3 cm thick copper. For synchrotron radiation the thickness of aluminum scatterer was optimized to maximize scattering of the synchrotron radiation. Typically 10 mm aluminum scatterer with small transverse dimensions maximizes the scattering of the synchrotron radiation in the first optics enclosures and experimental stations.

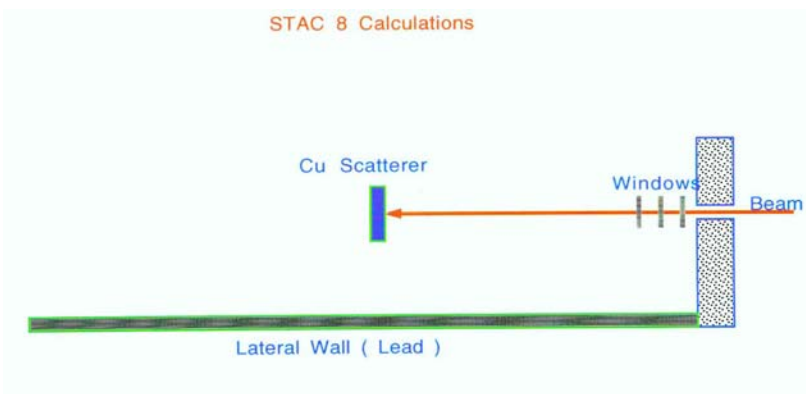

Figure 1 EGS4 and STAC8 Geometry for Bremsstrahlung and Synchrotron Radiation Scattering Calculations

Bremsstrahlung source for the EGS4 simulations was calculated from the straight particle trajectory and the pressure in the vacuum chamber using the semi-empirical relations[4]. The particle energy is assumed to be 3.0 GeV at 500 mA of beam current and the storage ring vacuum is assumed to be 1 ntorr. The straight path particle trajectory for the insertion devices (ID) is taken as 15.5 meters and for the bending magnet (BM) and three pole wigglers (3PW) is taken as 6.62 meters. Therefore the corresponding bremsstrahlung source term for BM and 3PW beamlines is smaller by a factor of 2.4. The bremsstrahlung shielding requirements for the BM and 3PW beamlines are lesser than that of the ID beamlines.

Table 1 gives the source parameters used for synchrotron radiation in the STAC8 calculations. All synchrotron radiation source calculations are done at 3.0 GeV of beam energy and 500 mA of beam current.

The horizontal opening angle for the ID or BM source fans and the minimum horizontal and vertical fixed mask apertures in the first optics enclosures are given in column 2 of Table 1. These are the minimum apertures necessary to pass through the full synchrotron radiation fan into the first optics enclosures in order to make shielding calculations with STAC8. The critical energy (E_c) and the total power correspond to 3.0 GeV of beam energy and 500 mA of beam current as calculated by STAC8.

Table 1 Source Parameters for the NSLS II Beamlines

Source	Source opening angle (mrad-Hori.) FOE Aperture	No.of Periods	B_{eff} (T)	Period (mm)	Length (meters)	E_c (KeV)	Total Power (KW)
DW	3.0 mrad-H (60×5 mm^2)	75	1.8	90	7 m	10.8	62.2
EPU45 L.Mode	1.0 mrad-H (14×4 mm^2)	89	1.03	45	4 m	6.52	13.8
U20	1.0 mrad-H (4×4 mm^2)	148	1.03	20	3 m	6.65	9.4
BM	10.0 mrad-H (200×5mm^2)	1	0.4		2.6 m	2.4	0.172
3PW	4.0 mrad-H (80×5 mm^2)	1	1.12		0.25 m	6.7	0.370

4. Shielding Estimates of First Optics Enclosures

4.1 Bremsstrahlung Scattering Calculations with EGS4

Bremsstrahlung scattering calculations for the representative geometry of NSLSII experiment stations are performed using EGS4. The computational geometry given in Figure 1 is used. EGS4 calculates integral energy deposition per particle at various regions of the geometry. The radiation dose (energy deposited per unit mass) at any given location per particle is calculated from the 3-dimensional energy deposition profile in the standard ICRU tissue placed at the location, taking the maximum energy deposition per unit mass**.** Once energy deposition per particle at each region is available, the absolute dose rate at any region can be scaled using the primary bremsstrahlung dose rate provided by the empirical formulae[4]. The scattered bremsstrahlung dose rates are calculated as a function of scattering angle from 3 cm copper scatterer located at the upstream end of the FOE.

For calculating the shielding requirements for the lateral and downstream wall of the First Optics Enclosure (FOE), these calculated dose rates (DR) have been used. The minimum distance from the copper scattering target to the down stream wall of the FOE is taken as 10 meters. For small angles, a constant distance of 10 m to the wall is assumed and the distance adjusted dose factor is taken as 10^{-2}. The distance of the lateral wall from the copper scatterer has been taken as 1 m. The required lead thickness for the downstream wall of the FOE as a function of the scattering angle to achieve the design dose limit (DDL) of < 0.05 mrem/h is calculated using the expression;

$$\text{Lead Thickness (cm)} = [\ln(0.01 \times DR) - \ln(DDL)] / 0.492$$

The minimum integral attenuation coefficient of 0.492 cm^{-1} calculated by EGS4 program for lead has been used in these calculations for bremsstrahlung attenuation.

Table 2 A and B provide the calculated lead thickness for the downstream panel and the lateral panel of insertion device FOE as a function of the scattering angle to achieve the design dose limit of < 0.05 mrem/h. Similarly Table 3 A and B provide the calculated lead thickness for the downstream panel and the lateral panel of BM and 3PW FOE as a function of the scattering angle to achieve the design dose limit of < 0.05 mrem/h.

Table 2A Bremsstrahlung Shielding for the Downstream Panel of the First Optics Enclosures of the Insertion Device Beamlines

Angle (deg.)	Dose Rate ($mrem/m^2 \cdot h$)	Pb to shield < 0.05 mrem/h (mm)
1	3.7×10^3	134
2	1.1×10^3	110
3	5.1×10^2	94
4	2.9×10^2	82
5	1.6×10^2	70
6	1.1×10^2	63
8	7.3×10^1	54
10	5.1×10^1	47

The lateral panel shielding for the FOE can be calculated using the same equation taking the scattered dose rate (DR) at 90 degrees from the scatterer;

Lead Thickness (cm) = [ln DR – ln (DDL)] / 0.492

Because of the relatively large statistical fluctuation[4] of calculated DR at 90 degrees in the scattering profile, an average dose rate (DR) of 0.15 mrem/h for insertion device beamlines, and 0.062 mrem/h for the BM and 3PW beamlines has been used to calculate the required lead thickness for the side panel to achieve the design dose limit (DDL) of < 0.05 mrem/h. The lateral panel is assumed to be at a distance of 1 meter from the Cu scatterer. The roof is assumed to be at a distance of 1.5 meters from the beamline.

Table 2B Bremsstrahlung Shielding for the Lateral Panel of the First Optics Enclosures of the Insertion Device Beamlines

Angle (deg.)	Dose Rate ($mrem/m^2 \cdot h$)	Pb to shield < 0.05 mrem/h
90	0.12	18

Table 3A Bremsstrahlung Shielding for the Downstream Panel of the First Optics Enclosures of the BM and 3PW Beamlines

Angle (deg.)	Dose Rate ($mrem/m^2 \cdot h$)	Pb to shield < 0.05 mrem/h (mm)
1	1.5×10^3	116
2	4.6×10^2	91
3	2.1×10^2	76
4	1.2×10^2	65
5	7.1×10^1	54
6	4.6×10^1	45
8	3.0×10^1	36
10	2.1×10^1	29

Because of the forward peaking nature of the high energy bremsstrahlung scattering, the lead shielding thickness required at small angles along the beam direction is large.

In practice this will be satisfied by the presence of bremsstrahlung collimators and stops approximately to cover 0 to 6 degrees scattering. Considering a uniform downstream wall thickness of 50 mm, additional shielding will be required for scattering angles < 6 degrees. This can be satisfied by the appropriate local lead shielding additionally around the beam transport pipes. The exact transverse dimensions of this local shielding can be calculated once the FOE station dimensions are available. A uniform downstream panel thickness of 50 mm is recommended for the insertion device and 30 mm for the BM and 3PW beamline first optics enclosures. Additional local shielding will be required around the beam pipe penetration.

Table 3B Bremsstrahlung Shielding for the Lateral Panel of the First Optics Enclosures of the BM and 3PW Beamlines

Angle (deg.)	Dose Rate ($mrem/m^2 \cdot h$)	Pb to shield < 0.05 mrem/h
90	0.05	none

4.2 Synchrotron Radiation Scattering Calculations with STAC8

Synchrotron radiation scattering calculations to estimate the shielding requirements for the NSLSII First Optics Enclosures (FOE) are performed by the STAC8 shield program. Typically a scatterer of 10 mm aluminum, normal to the beam, is used as a potential scatterer located at the upstream part of the FOE. For each source spectrum the scatterer thickness is optimized to maximize the synchrotron radiation scattering. The shielding requirements for the synchrotron radiation of the lateral panels and the roof are calculated using STAC8 for the five sources given in Table 1. These results are compared with the bremsstrahlung shielding requirements and the dominant requirement is given as the recommendation in the next section.

4.3 Shielding Recommendations for the First Optics Enclosures

Table 4 gives the combined results of the STAC8 and EGS4 calculations for the shielding requirements of the lateral panel and the roof for the five sources. The shielding requirements for the downstream panels of the first optics enclosures are dominated by bremsstrahlung and therefore the recommendation in section 4.1 applies.

The station dimensions are taken as 2 m wide, 3 m high and 10 m long. The lateral panel is at a distance of 1 m and the roof is at distance of 1.5 m from the beamline. If the stations are narrower the shielding estimates need to be re-evaluated.

Table 4. Shielding Recommendations for NSLS2 First Optics Enclosures (Pb thickness for the lateral panel and the roof)

Beamline Source	Lateral Panel Pb to shield <0.05 mrem/h (mm)	Roof Pb to shield < 0.05 mrem/h (mm)	Downstream Pb to shield < 0.05 mrem/h (mm)
DW	18	10	50
EPU45	18	5	50
U20	18	6	50
BM	3 (Fe)	3 (Fe)	30
3PW	5	4	30

5. Shielding Estimates for the Monochromatic Experimental Enclosures

The shielding calculations for the monochromatic experimental stations are carried out by the STAC8 program. Since bremsstrahlung is stopped in the first optics enclosures, no EGS4 simulations are necessary to estimate the shielding thickness of the side, roof and downstream panels. Five reflections (111, 333, 444, 555, 777) with corresponding bandwidths are considered for these calculations. One of the energies (88 KeV) corresponds to the K-edge energy of lead. The five energies and their corresponding bandwidths used for the monochromatic experimental station shielding calculations are given in Table 5.

Table 5 Monochromatic Beam Energies and Bandwidths used for STAC8 Calculations

Energy (KeV)	Band Width (KeV)
22	2.2×10^{-3}
66	5.3×10^{-4}
88	5.3×10^{-4}
110	1.3×10^{-4}
154	4.0×10^{-5}

All calculations for the shielding of the monochromatic experimental stations are done for the Beam Energy of 3.0 GeV at 500 mA. Experimental station dimensions are assumed to be 2 m Width x 3 m Height. Side panels are at a distance of 1.0 m and the roof at 1.5 m away from the beamline.

5.1 Shielding Recommendations for the Monochromatic Experimental Enclosures

The results of these calculations are provided in Table 6. The recommended shielding thickness for the side panels, roof and upstream/downstream panels are given. An appropriate monochromatic stop shall be provided in the line of sight of the beam in the monochromatic experimental station.

Table 6 Shielding Recommendations for NSLS2 Monochromatic Experimental Stations

Beamline Source	Lateral Panels to shield <0.05 mrem/h (mm)	Roof to shield < 0.05 mrem/h (mm)	US & DS Panels to shield < 0.05 mrem/h (mm)
DW	4 Pb	3 Pb	4 Pb
EPU45	6 Fe	3 Fe	6 Fe
U20	6 Fe	3 Fe	6 Fe
BM	2 Fe	2 Fe	2 Fe
3PW	3 Fe	2 Fe	3 Fe

a. All calculations are done for Beam Energy of 3.0 GeV at 500 mA
b. Station dimensions are assumed to be 2 m Width x 3 m Height
c. Side panels are at a distance of 1.0 m and roof at 1.5 m away from the beamline

5.2 Shielding Recommendations for the Pink Beam Experimental Enclosures

In most cases the pink beam experimental stations (assuming 30 -50 KeV cut-off) have the same shielding requirements as the monochromatic experimental stations because of the absence of higher energy synchrotron radiation component in the pink beam. However bremsstrahlung needs to be completely stopped in the upstream station.

The thermal load handling needs separate analysis. Pink beam from bending magnets typically do not require cooling, whereas an undulator pink beam normally requires cooling.

6. Shielding Estimates for the Monochromatic Beam Transports

Most beamlines at the NSLSII will have a monochromatic beam transport between the first optics enclosure and the monochromatic experimental station. These transport pipes may require shielding depending on the synchrotron radiation source of the beamline. In every case careful ray tracing of the synchrotron radiation need to be carried out to ensure that no part of the beam hits the transport pipe.

Stac8 simulations are carried out using 10 meters of air at 1 atmosphere as the potential scatterer inside the beam transports. Shielding thickness for the monochromatic beam transports was calculated for a conservative dose rate of < 5 mrem/h on contact, on the surface of the transport pipe, in the event of a complete loss of vacuum in the transport. The energies with corresponding bandwidths as in the monochromatic station shielding calculations are also used for the transport shielding calculations. Calculations are also carried out for the presence of potential solid scatterers like flags/screens etc. inside the transports as this may require additional local shielding.

6.1 Shielding Recommendations for the Monochromatic Beam Transports

Table 7 provides the results of the transport shielding calculations using STAC8. Shielding requirements for loss of vacuum and for the presence of potential solid scatterer in the transport are given for the five NSLSII beam line sources. All calculations are at 3.0 GeV beam energy and 500 mA of beam current. Shielding is calculated for a surface dose rate of < 5 mrem/h on contact due to a complete vacuum loss in the beam transport line. The vacuum pipes for beam transport are assumed to be 6" of diameter.

Table 7 Shielding Recommendations for Monochromatic Beam Transports

Beamline Source	Shieldng required for < 5 mrem/h due to complete vacuum loss in the beam transport (mm)	Shielding required locally on beam transport for < 0.05 mrem/h for a solid scatterer (mm)
DW	3 Pb	7 Pb
EPU45	1.5 Pb	3.0 Pb
U20	1.5 Pb	3.0 Pb
BM	2 Fe	3.0 Pb
3PW	3.0 Fe	3.0 Pb

7. Recommendations for Material and Thickness for Monochromatic Beam Shutters in the First Optics Enclosures

Table 8 gives the minimum thickness of the material required for the monochromatic beam shutters in the first optics enclosures as calculated from STAC8 program. It is assumed that the residual white beam and bremsstrahlung are stopped by appropriate stops, upstream of these monochromatic shutters. These shutters facilitate access to the experimental stations when necessary while beam is stopped in the first optics enclosure. They stop or pass the monochromatic beam reflected by the monochromators to the experiment stations. The energy and corresponding bandwidths considered in the STAC8 calculations are also provided in Table 8.

Table 8 Summary Monochromatic Beam Shutter Calculations

Beamline Source	Monochromatic beam energies considered (KeV)	Monochromatic beam bandwidths Considered (5)	Shutter Material	Minimum thickness required
DW	22 66 88 110 154	5×10^{-4} 4×10^{-5} 3×10^{-5} 6×10^{-6} 1.5×10^{-6}	Tungsten	7 mm
EPU45	22 66 88 110 154	5×10^{-4} 4×10^{-5} 3×10^{-5} 6×10^{-6} 1.5×10^{-6}	Tungsten Copper	4 mm 55 mm
U19	22 66 88 110 154	5×10^{-4} 4×10^{-5} 3×10^{-5} 6×10^{-6} 1.5×10^{-6}	Tungsten Copper	5 mm 70 mm
BM	22 66 88 110 154	5×10^{-4} 4×10^{-5} 3×10^{-5} 6×10^{-6} 1.5×10^{-6}	Iron Copper	5 mm 3 mm
3PW	22 66 88 110 154	5×10^{-4} 4×10^{-5} 3×10^{-5} 6×10^{-6} 1.5×10^{-6}	Copper	35 mm

d. All calculations are done for Beam Energy of 3.0 GeV at 500 mA

It can be seen that for the insertion device beamlines a tungsten monochromatic photon shutter is preferable and for the BM and 3PW beamlines, a copper or iron shutter is adequate.

8. Summary

Shielding calculations for the NSLSII first optics enclosures, monochromatic beam enclosures and monochromatic beam transports are carried out using EGS4 and STAC8 computer programs. The results are summarized in this note. Calculations for the monochromatic beam shutters in the first optic enclosures are also done and the results are provided. These results can be used as guidelines for the beamline designs of the five listed sources at the NSLSII.

Reference

1. EGS4 Code System, User's Manual, SLAC265 (1985).

2. Pisharody, M.,et.al. Dose Measurements of Bremsstrahlung Produced Neutrons, Nucl.Instr.and Meth. A230 (1999) page 542.

3. STAC8 Program Manual, Y.Asano, Spring8 Publication (1998).

4. P.K. Job and W.R. Casey, Preliminary Shielding Estimates for NSLSII Beamlines and Front ends, NSLSII Technical Note 14, July 25, 2006.