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Revised Guidelines for the NSLS-II Beamline Shielding Design

P. K. Job,

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1. NSLS-II Beamline Shielding Policy

The annual dose to NSLS-II[1] beamline scientists will be kept well below federal limits and within BNL administrative levels through shielding, operational procedures, and administrative controls. Shielding guidelines to the beamline design have been provided to reduce radiation levels external to the beamline enclosures during normal operation to <0.05 mrem/h and as low as reasonably achievable. Assuming occupancy of 2000 hours per year, this will reduce annual dose limit to the beamline scientists to 100 mrem or less.

2. Shielding Design Calculations

Shielding guidelines for the beam lines have been developed through extensive simulations using EGS4[1], FLUKA[2] and STAC8[3] shielding computer programs. All simulations have been updated for 500 mA of beam current at 3.0 GeV of stored beam energy. The contact dose rates have been calculated at the external surface of the beamline enclosure shield walls. The detailed methodology and results of these calculations have been published as a series of reports as NSLS-II beamline design evolved. These results have been provided in NSLS-II Technical Notes TN 14[4], TN 20[5], TN 32[6], TN 36[7] and TN 40[8]. The results for 3.0 GeV of stored beam energy have also been summarized in a controlled document 'Guidelines to NSLS-II Beamline and Front end Radiation Shielding Design' (LT-ESHDES-08-003-rev001)[9]. The details of the Calculational methodology and results are also available at the NSLS-II share point site (https://ps.bnl.gov/esh/Lists/Radiological%20Analysis/RADetails.aspx). A functional nomenclature standard for shielding components is available in the document library[10].

The present report is a revision of the previous guideline document[9], incorporating results of additional calculations, as detailed information on the six project beamline configurations became available. However, the guidelines presented in this document are by no means complete. Specific calculations may be necessary for special cases of beamline and experiment beam shutter designs.

3. Design Guidelines for Primary Bremsstrahlung Shutters/Stops/Collimators

A bremsstrahlung shutter (commonly called the safety shutter) is provided in the beam line front end to permit safe entry into the First Optical Enclosure (FOE). These devices are adequately sized to stop a primary bremsstrahlung beam generated within the upstream straight section by electron interaction with residual gas molecules or from electrons striking the undulator or the walls of the vacuum pipe. A bremsstrahlung stop in the beam line prevents the high intensity bremsstrahlung beam from passing through a hutch wall and exposing occupants on the experimental floor.

The thickness of the bremsstrahlung stops/shutters is calculated for a dose rate limit of <0.25 mrem/h at the downstream side of the stop/shutter. These shutters or stops will be situated inside the shielded enclosures. A straight beam path of 15.5 meters is taken for insertion device and 6.6 meters is taken for 3PW/BM beamlines. The storage ring vacuum is assumed as 1 ntorr.

Table 1 summarizes the results of the EGS4 calculations for the thickness of bremsstrahlung shutters/stops at the NSLS-II insertion device and bending magnet/3PW beamlines and front ends.

Table1. Results of the Bremsstrahlung Shutter / Stop Calculations

	Insertion Device Beamlines	3PW and BM Beamlines
Bremsstrahlung Dose Rate at 1 nT (rem/h)	176 rem/h	74 rem/h
Lead Thickness required (cm)	27.4 cm	25.6
Tungsten Thickness required (cm)	20 cm	19.5
Dose Rate behind the stop/shutter (mrem/h)	0.25 mrem/h	0.25 mrem/h

The synchrotron radiation will place a significant thermal load on bremsstrahlung shutters and stops. Adequate thermal protection need to be provided to these stops in order that the shielding cannot be compromised. This protection is usually achieved in the beamlines and front ends by appropriately designed copper photon masks/shutters located upstream of the lead / tungsten safety shutters.

An adequate off-set is necessary for bremsstrahlung stop-monochromatic beam pass shutters or collimators, to prevent portions of the bremsstrahlung shower generated in the stop from entering the beam line. This offset will depend on the dimensions of the monochromatic beam aperture. For a 10mm horizontal–4 mm vertical mono-beam tungsten aperture, an offset of 10 mm or more is safe for the extremal bremsstrahlung ray from the edge of the aperture. For the lead apertures, this offset is 15 mm. This guideline need to be evaluated for specific aperture dimensions.

Primary bremsstrahlung collimators need the same thickness as bremsstrahlung stops/shutters. The transverse dimensions of the shutters/stops can be determined from the primary bremsstrahlung ray tracing adding three Moliere radii of the shutter/stop material beyond the extreamal bremsstrahlung ray. Aperture dimensions of the bremsstrahlung collimators are determined based on synchrotron radiation ray tracing. If the collimators are built from straight edged bricks, care is taken to avoid straight seams in the direction of the beam as a safe practice. An overlap of 3 Moliere radii or more is recommended between the seams. Moliere radius for lead is 12.5 mm and that for tungsten is 8 mm[11].

4. Source Parameters Used for Shielding Calculations

Table 2 gives the source parameters used for synchrotron radiation in the STAC8 calculations unless otherwise stated. The horizontal opening angle for the ID or BM source fans in the first optics enclosures are given in column 2 of Table 3. These are the minimum horizontal apertures necessary to pass through the full synchrotron radiation fan into the first optics enclosures (FOE), used for shielding calculations for the FOE.

Table 2 Source Parameters for the NSLS II Beamlines Used for Calculations

Source	Source opening angle mrad-Hori. (FOE Aperture)	No.of Periods	B_{eff} (T)	Period (mm)	Length (meters)	E_c (KeV)	Total Power (KW)
DW100	3.0 mrad-H	75	1.8	90	7 m	10.8	62.2
EPU45 L.Mode	1.0 mrad-H	89	1.03	45	4 m	6.52	13.8
IVU20	1.0 mrad-H	148	1.03	20	3 m	6.65	9.4
BM	10.0 mrad-H	1	0.4		2.6 m	2.4	0.172
3PW	4.0 mrad-H	1	1.12		0.25 m	6.7	0.370

5. Design Guidelines for Monochromatic/ Pink Beam Shutters

One or more beam shutters downstream of the optics in the First Optics Enclosure provides access into the subsequent experimental enclosures. It is assumed that the residual white beam and bremsstrahlung has been stopped by appropriate stops, upstream of these shutters. These are called either monochromatic or pink beam shutters depending on the energy spectrum and the thermal load imparted on the shutter. Guidelines for these monochromatic or pink beam shutters have been developed based on the experimental beam specifications of each beam line taking into account the beam energy, bandwidth, flux, higher harmonics transmitted by the optics and the beam aperture dimensions. The thermal load handling on the pink beam shutters needs separate analysis.

In the present report, calculations for three beamline monochromatic shutters and two pink beam shutters have been presented.

5.1 Monochromatic Beam Shutter Calculations for XPD Beamline

Monochromatic beam shutter calculations for the XPD project beamline has been performed by STAC8 program with the following parameters;

Source:	Damping wiggler (DW100)
Period:	100 mm
Device Length:	7.2 meters
No of Periods:	72
Critical Energy:	10.7 KeV
B Field:	1.8 T
Beam Energy:	3.0 GeV
Beam Current:	500 mA
Beam Aperture in FOE:	37.6 mm Horizontal x 14.3 mm Vertical
FOE Aperture Location:	27.4 meters from the source center

Five higher harmonic reflections (111,333,444,555 and 777) of the fundamental modes of 70 and 75 keV have been considered with a conservative bandwidth of 10^{-3} (0.1%) for all reflections.

The calculated power by STAC8 entering to the FOE is 43.3 KW. The shutter material considered is tungsten (18 g/cm^3) and the shutter location is at 42.3 meters from the source center. Table 3 gives the results of these calculations.

Table 3 Results of the XPD Monochromatic Beam Shutter Calculations

Fundamental Mode (keV)	Tungsten Thickness (mm)	Fundamental Mono-Flux (p/cm^2.s)	Dose rate at DS end of the shutter (mrem/h)
75.0	25	5.16×10^{13}	2.4×10^{-5}
75.0	20	5.16×10^{13}	3.8×10^{-4}

75.0	15	5.16×10^{13}	8.0×10^{-3}
75.0	12	5.16×10^{13}	7.9×10^{-2}
70.0	15	7.87×10^{13}	9.6×10^{-3}

The shutter thickness under consideration is calculated for a contact dose of <0.05 mrem/h at the downstream end of the shutter. To satisfy this specified dose criterion a minimum tungsten thickness of 15 mm is necessary. Transverse dimensions of the shutter can be determined based on the location of the shutter and synchrotron ray tracing.

5.2 Monochromatic Beam Shutter Calculations for HXN Beamline

Monochromatic beam shutter calculations for the HXN project beamline has been performed by STAC8 program with the following parameters;

Source:	IVU20 Undulator
Period:	20 mm
Device Length:	3 meters
No of Periods:	148
Critical Energy:	6.7 KeV
B Field:	1.03 T
Beam Energy:	3.0 GeV
Beam Current:	500 mA
Shutter Aperture:	30.0 mm Horizontal x 25 mm Vertical
Aperture Location:	28.0 meters from the source center (nominal)

Five higher harmonic reflections (111,333,444,555 and 777) of the fundamental mode of 22 keV have been considered with a conservative bandwidth of 10^{-3} (0.1%) for all reflections.

The calculated power by STAC8 entering to the FOE is 9.4 KW. The shutter materials considered are tungsten (18 g/cm^3) and steel (7.8 g/cm^3). Table 4 gives the results of these calculations.

Table 4 Results of the HXN Monochromatic Beam Shutter Calculations

Fundamental Mode (keV)	Material Thickness (mm)	Fundamental Mono-Flux (p/cm^2.s)	Dose rate at DS end of the shutter (mrem/h)
22.0	5 Tungsten	3.6×10^{14}	8.03×10^{-2}
22.0	6 Tungsten	3.6×10^{14}	1.61×10^{-2}

22.0	50 Steel	3.6×10^{14}	2.65×10^{-1}
22.0	55 Steel	3.6×10^{14}	9.72×10^{-2}
22.0	60 Steel	3.6×10^{14}	3.57×10^{-2}

The shutter thickness under consideration is calculated for a contact dose of <0.05 mrem/h at the downstream end of the shutter. To satisfy this specified dose criterion a minimum tungsten thickness of 6 mm or Steel thickness of 60 mm is necessary. Transverse dimensions of the shutter can be determined based on the location of the shutter and synchrotron ray tracing.

5.3 Monochromatic Beam Shutter Calculations for IXS Beamline

Monochromatic beam shutter calculations for the IXS project beamline has been performed by STAC8 program with the following parameters;

Source: IVU22 Undulator
Period: 22 mm
Device Length: 6 meters
No of Periods: 270
Critical Energy: 4.5 KeV
B Field: 0.74 T
Beam Energy: 3.0 GeV
Beam Current: 500 mA
Shutter Aperture: 25.0 mm Horizontal x 15 mm Vertical
Aperture Location: 28.0 meters from the source center (nominal)

Five higher harmonic reflections (111,333,444,555 and 777) of the fundamental mode of 18 keV have been considered with a conservative bandwidth of 10^{-3} (0.1%) for all reflections.

The calculated power by STAC8 entering to the FOE is 9.6 KW. The shutter materials considered are tungsten (18 g/cm^3) and steel (7.8 g/cm^3). Table 5 gives the results of these calculations.

Table 5 Results of the IXS Monochromatic Beam Shutter Calculations

Fundamental Mode (keV)	Material Thickness (mm)	Fundamental Mono-Flux (p/cm^2.s)	Dose rate at DS end of the shutter (mrem/h)
18.0	3 Tungsten	3.24×10^{14}	1.27×10^{-1}
18.0	4 Tungsten	3.24×10^{14}	2.54×10^{-2}

18.0	30 Steel	3.24×10^{14}	1.24×10^{-1}
18.0	35 Steel	3.24×10^{14}	4.58×10^{-2}

The shutter thickness under consideration is calculated for a contact dose of <0.05 mrem/h at the downstream end of the shutter. To satisfy this specified dose criterion a minimum tungsten thickness of 4 mm or Steel thickness of 55 mm is necessary. Transverse dimensions of the shutter can be determined based on the location of the shutter and synchrotron ray tracing.

5.4 Pink Beam Shutter Calculations for the CHX Beamline

Pink beam shutter calculations for the CHX project beamline has been performed by STAC8 program with the following parameters;

Source: IVU20 Undulator
Period: 20 mm
Device Length: 3 meters
No of Periods: 148
Critical Energy: 6.7 KeV
B Field: 1.03 T
Beam Energy: 3.0 GeV
Beam Current: 500 mA
Aperture Dimensions: 0.4 mR Vertical x 0.62 mR mm Horizontal
Aperture Location: 19.3 meters from the source center
First Mirror: 27 meters from the source center (Silicon Substrate)
Mirror Dimensions: 30 cm Length, 5 cm thickness and 5 cm width

The calculated power by STAC8 entering to the FOE is 9.4 KW. The angle of incidence of the synchrotron beam on the mirror in the calculation is 0.18 degrees. Scattered bremsstrahlung from the mirror has not been considered. Mirror coating material and cut-off energy has no effect on these beam scattering calculations.

The pink beam shutter is at a distance of 36.3 meters from the source center. The shutter material considered is tungsten (18 g/cm^3). Table 6 summarizes the results of these calculations.

Table 6 Results of the CHX Pink Beam Shutter Calculations

Tungsten Thickness (mm)	Dose rate at DS end of the shutter (mrem/h)
8	2.03×10^{-1}
9	4.70×10^{-2}

10	1.70 x 10^{-2}

The shutter thickness under consideration is calculated for a contact dose of <0.05 mrem/h at the downstream end of the shutter. To satisfy this specified dose criterion a minimum tungsten thickness of 9 mm is necessary. Transverse dimensions of the shutter can be determined based on the location of the shutter and synchrotron ray tracing.

5.5 Pink Beam Shutter Calculations for CSX Beamline

Pink beam shutter calculations for the CSX project beamline has been performed by STAC8 program with the following parameters;

Source: EPU49 Undulator (Linear Mode)
Period: 49 mm
Device Length: 4 meters
No of Periods: 76
Critical Energy: 3.7 KeV
B Field: 0.62 T
Beam Energy: 3.0 GeV
Beam Current: 500 mA
FOE Aperture: 14.5 mm Vertical x 14.5 mm Horizontal
Aperture Location: 26 meters from the source center
First Mirror: 29 meters from the source center (Silicon Substrate)
Mirror Dimensions: 40 cm Length, 2 cm thickness and 5 cm width

The calculated power by STAC8 entering to the FOE is 4.75 KW. The angle of incidence of the synchrotron beam on the mirror in the calculation is 1.25 degrees. Scattered bremsstrahlung from the mirror has not been considered. Mirror coating material and cut-off energy has no effect on these beam scattering calculations.

The pink beam shutter is at a distance of 34.45 meters from the source center. The shutter materials considered are tungsten (18 g/cm^3) and copper (8.9 g/cm^3). Table 7 summarizes the results of these calculations.

Table 7 Results of the CSX Pink Beam Shutter Calculations

Material Thickness (mm)	Dose rate at DS end of the shutter (mrem/h)
5 Tungsten	5.70 x 10^{-2}
6 Tungsten	1.10 x 10^{-2}
55 Copper	1.55 x 10^{-1}

60 Copper	7.50×10^{-2}
63 Copper	4.80×10^{-2}
65 Copper	3.63×10^{-2}

The shutter thickness under consideration is calculated for a contact dose of <0.05 mrem/h at the downstream end of the shutter. To satisfy this specified dose criterion a minimum tungsten thickness of 6 mm or copper thickness of 63 mm is necessary. Transverse dimensions of the shutter can be determined based on the location of the shutter and ray tracing.

6. Shielding Guidelines for the First Optics Enclosures (FOE)

Table 8 gives the combined results of the STAC8 and EGS4 calculations for the shielding guidelines of the First Optics Enclosures (FOE) for the proposed NSLS-II beamline sources. Shielding thickness for each panel has been calculated for bremsstrahlung and synchrotron radiation and the thickness for the dominant source has been given. Enclosure dimensions are nominally 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 in these calculations. If the stations are narrower the shielding estimates need to be re-evaluated. The shielding thickness for the downstream panels of the first optics enclosures are dominated by forward scattered bremsstrahlung. Therefore a thickness of 50 mm has been recommended for the insertion device and 30 mm for the BM and 3PW beamlines for the FOE downstream panels. Additional collimators and local shielding may be required around the beam pipe and wall penetration depending on the beamline configuration.

Table 8 Shielding Guidelines for NSLS2 First Optics Enclosures

Beamline Source	Lateral Panel (Pb) (mm)	Roof Panel (Pb) (mm)	Downstream Panel (Pb) (mm)
DW100	18	10	50
EPU45	18	5	50
IVU20	18	6	50
3PW/BM	5	4	30

7. Shielding Guidelines for the Experimental Enclosures

The shielding calculations for the experimental enclosures have been carried out by the STAC8 computer program. It is assumed that bremsstrahlung has been completely stopped in the first optics enclosures. Therefore EGS4 simulations are not necessary to estimate the shielding thickness for the experimental enclosures. Five reflections (111, 333, 444, 555, 777) with corresponding bandwidths[12] have been considered for these calculations with the lowest energy as 22 KeV. Table 9 gives the energies and bandwidths considered for these calculations. Enclosure dimensions are assumed to be 2 m Wide x 3 m High. Side panel are at a distance of 1.0 m and the roof at 1.5 m away from the beam centerline.

Table 9 Energies and Bandwidths used for Experimental Enclosure Shielding Calculations

Monochromatic beam energies considered (KeV)	Monochromatic bandwidths Considered (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}

The results of these calculations for five NSLS-II sources are provided in Table 10. The calculated shielding thickness in Pb or Fe for the side panels, roof and upstream/downstream panels have been given for the contact dose rate of <0.05 mrem/h.

Table 10 Shielding Guidelines for Experimental Enclosures

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)
DW100	4 Pb	3 Pb	4 Pb
EPU45	6 Fe	3 Fe	6 Fe
IVU20	6 Fe	3 Fe	6 Fe
BM	2 Fe	2 Fe	2 Fe
3PW	3 Fe	2 Fe	3 Fe

In most cases the pink beam experimental enclosures (assuming 30 -50 keV mirror cut-off energy) need the same shielding thickness as the monochromatic enclosures because of the absence of higher energy harmonics in the pink beam.

8. Shielding Guidelines for the Experimental Beam Transports

The beam transport pipes between the FOE and the experimental enclosures may require shielding depending on the source and experimental-beam characteristics of the beamline. In every case careful ray tracing of the synchrotron radiation must be carried out to ensure that no part of the beam hits the transport pipe.

STAC8 simulations have been carried out using 10 meters of air at one atmosphere as the potential scatterer inside the beam transports simulating a vacuum loss accident. For transport shielding calculations, the same conservative beam harmonic energies and bandwidths have been used as in the experimental enclosure shielding calculations. Being loss of vacuum is an accidental condition, the dose rate criteria adopted for these calculations were <5 mrem/h on contact of the transport pipe. Calculations have also been carried out for the presence of potential solid scatterers like flags/screens etc. inside the beam transports as this may require additional local shielding. The dose rate criteria applied for this operating condition is <0.05 mrem/h on the surface of the transport pipe. Table 11 summarizes these results.

In most cases the pink beam transports (assuming 30 -50 keV mirror energy cut-off) have the same shielding thickness as the monochromatic beam transports because of the absence of higher energy harmonics in the pink beam. Thermal load handling of the pink beam needs separate analysis. However, bremsstrahlung component is assumed to be completely absent in the experimental beam.

Table 11 Shielding Guidelines for the Experimental 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)
DW100	3 Pb	7 Pb
EPU45	1.5 Pb	3.0 Pb
IVU20	1.5 Pb	3.0 Pb
BM	2 Fe	3.0 Pb
3PW	3.0 Fe	3.0 Pb

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