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Preliminary Shielding Estimates for NSLS-II Beamlines and Front Ends

P. K. Job,

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P.K. Job and W.R. Casey
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1. Shielding Objectives at NSLS II Beamlines

The National Synchrotron Light Source II (NSLS II), a Department of Energy (DOE) Facility, is subject to the DOE radiation protection rules established in 10 CFR 835. It is planned to operate with an administrative control level of 100 mrem per year, well within the legal limits established in Part 835. Shielding for the NSLS II beamlines will be designed to maintain levels through the shielding to < 0.05 mrem/hr. A worker could work immediately adjacent to the shielded enclosure along the beam line for 2000 hours per year and not exceed >100 mrem/year, such that the individual beamline scientist dose will be (ALARA).

2. Sources of radiation

The radiation present on the experimental floor can be separated into sources that come through the ratchet wall penetration and those that come through the ratchet wall itself.

2.1 Radiation through the Ratchet Wall

In the process of operating the storage ring, as well as producing the desired synchrotron radiation, there is considerable generation of other radiation behind the storage ring wall. The shielding for this parasitic radiation is achieved by the concrete shield wall and the local shielding at various locations inside the storage ring. During the commissioning of the storage ring, surveys will be made to determine if any "hot spots" exist, and, if so, additional local shielding will be employed to reduce the dose rates on the experimental floor to acceptable levels. The dose to a user on the Experiment Hall floor by radiation through the ratchet wall is intended to be small. The design of the shielding for the storage ring and other accelerator systems is covered in other shielding notes (NSLS-RP-TN 2).

2 .2 Radiation through the Ratchet Wall Penetration

It is intended that synchrotron radiation be transported to the beamlines through the accelerator ratchet wall. This penetration also permits other types of radiation to escape from the shielded enclosure, including;

- Radiation from electron beam hitting storage ring components
- Gas bremsstrahlung created from electron interaction with the residual gas molecules in the vacuum chamber
- Synchrotron radiation created by the bending magnets and the insertion devices

These radiation sources are analyzed in this note and shielding is specified in accordance with the criteria described above. It should be noted that neutrons are not a significant source of radiation exposure along the beam lines as had been predicted by the PICA[1] neutron shield program and confirmed by the measurements[2] in other synchrotron radiation facilities. Therefore neutron shielding on the experiment floor for the beamlines has not been evaluated.

2.2.1 Interaction of Stored Beam with Storage Ring Components

If the stored electron beam collides with any storage ring component, a bremsstrahlung shower will be produced[3]. Only a small portion of this radiation makes it through the synchrotron radiation apertures. In addition bremsstrahlung collimators in the front end will severely limit the line of sight through the ratchet wall penetration. These collimators allow only radiation scattered in small angles to the beam path to exit onto the experimental floor. The beamline shielding present to account for other radiation sources normally will be more than sufficient to stop the radiation from beam losses inside the storage ring components.

Since it is planned to operate NSLS II in a top-off mode, additional consideration is needed to inject at full storage ring energy into the ring with shutters open. These detailed analyses will be conducted at a later time. As a matter of good practice, it is expected that initial commissioning of NSLS II will be performed with the beamline safety shutters (located inside the ratchet wall) closed during injection. The closed shutters will keep any radiation that might come through the ratchet wall penetration. When NSLS II begins operating in a "Topoff" mode with the safety shutters open, the additional radiation due to this mode of operation will need to be fully evaluated. Analysis and experience at the other facilities indicates that it is not expected to be a problem[4].

2.2.2 Gas Bremsstrahlung from the Vacuum Chamber

Gas bremsstrahlung is produced by the interaction of the storage ring electron beam with residual gas molecules in the ring vacuum chamber. Such interactions are one of the sources of stored beam loss, result in beam decay, and occur continuously during the storage ring operation. Gas bremsstrahlung interactions take place all around the storage ring, but are a particular problem in the straight sections for the insertion devices. Bremsstrahlung is produced in a very narrow beam in the straight path and sums up for the entire straight path in the line of sight of the beamlines. The NSLS2 straight beam paths are 16 m in length. (The straight beam path length is not the same as the insertion device straight section length).

The total beam integrated bremsstrahlung dose rate D (rem/h) from the straight particle trajectory in the vacuum chamber of the storage ring at a distance L from the center of the straight path is usually approximated by semi-empirical equations. There are three common empirical relations have been in use historically. The semi-empirical equation proposed by Frank[5] had been successfully utilized at the Advanced Photon Source and other similar facilities. Using the equation developed by Frank, the dose rate due to primary bremsstrahlung at a distance L from the end of the straight path is described as;

$$\text{Dose Rate (rem/h)} = \frac{3.0\times 10^{-4}}{\Pi\times X_0}\ \frac{E^2}{0.511^2}\ \frac{l\times I}{L(L+l)}$$

Where X_0 = Radiation Length of air at 10^{-9} Torr = 2.34×10^{16} cm

l = Effective length of the straight path (16 meters)

I = Beam Current in e/s (3.1×10^{18} electrons/s for 500 mA)

E = Electron Beam Energy in MeV

L is nominally taken as 20 meters. This equation yields a primary bremsstrahlung dose rate of 240 rem/hour.

Another analysis developed by Ferrari[6] et.al. gives the following expression for dose rate produced by the primary bremsstrahlung in the insertion device beamlines at a distance of L from the straight path.

$$\text{Dose Rate (rem/hour)} = 2.5\times 10^{-25}\ \frac{E^{2.67}}{0.511^{2.67}}\ \frac{l\times I}{L(L+l)}\ \frac{P}{P_0}$$

Where *l* = Effective length of the straight path (16 meters)

I = Beam Current in e/s (3.1×10^{18} electrons/s for 500 mA)

E = Electron Beam Energy in MeV

P = Operating pressure in the vacuum chamber in ntorr

P_0 = 1 ntorr

L is nominally taken as 20 meters. This equation yields a primary bremsstrahlung dose rate of 280 rem/hour.

Chronologically the first expression developed in this regard is by Rindi and Tromba[7]. This simple expression provides the dose rate at 10 meters from the straight path as;

$$\text{Dose Rate (rem/hour at 10 m)} = 1.7\times 10^{-14}\ E^{2.43}\ \frac{P}{P_{atm}}\ Il$$

Where *l* = Effective length of the straight path (16 meters)

I = Beam Current in e/s (3.1×10^{18} electrons/s for 500 mA)

E = Electron Beam Energy in MeV

P = Operating pressure in the vacuum chamber

P_{atm} = Atmospheric pressure

This expression yields a primary bremsstrahlung dose rate of 450 rem/h at 10 meters and 112 rem/h at 20 meters.

Table 1 gives the estimated primary bremsstrahlung dose rates in the NSLS II beamlines calculated by the three semi-empirical expressions at 20 meters from the center of the straight path for a straight path length of 16 meters and vacuum chamber pressure of 1 ntorr. Methods 1 and 2 give similar results compared to method 3. Being conservative, methods 1 and 2 are used to estimate the primary bremsstrahlung dose rates for the NSLS2 insertion device beamlines.

Table 1 Primary Bremsstrahlung Dose Rates at the NSLS II Beamlines

	Bremsstrahlung Dose Rates (rem/h)
Method 1 (Lure-APS)	240 rem/h
Method 2 (Ferrari)	280 rem/h
Method 23(Rindi-Tromba)	112 rem/h

Beam Energy = 3.5 GeV
Beam Current = 500 mA
Straight section Path Length = 16 meters
Distance to the dose point = 20 meters
Straight section vacuum = 10^{-9} torr

The transverse dimensions of the shutters and collimators can be determined by the ray trace diagrams.

3. Shielding Simulations

3.1 Simulation Tools

Bremsstrahlung Scattering Calculations for NSLS II ID Beamlines were carried out using the EGS4 electron-gamma shower simulation program[8]. This implementation is part of the CALOR program package distributed by the Radiation Shielding Information Center (RSIC) of the OakRidge National Laboratory. EGS4 simulates the coupled interactions of photons and electrons with materials over an energy range from a few keV to several TeV. It also includes a stand alone program PEGS4, which creates cross sections to be used by EGS4. Physical processes simulated by this program include bremsstrahlung production, positron annihilation at rest and in flight, Moliere multiple scattering, Moller and Bhabha scattering, Compton scattering, pair production, photoelectric effect and continuous energy loss by Bethe-Bloch formalism. The photoneutron production and transport is not simulated by EGS4. But measurements at the other third generation light source facilities have confirmed that the photoneutrons are not a radiation hazard at the synchrotron radiation beamlines[2].

The Synchrotron radiation scattering calculations for NSLS II beamlines have been performed using the STAC8 program[9]. 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.

3.2 Geometry for Computation and Results for Shutter/Stop Thickness

The primary bremsstrahlung dose rates at the insertion device beamlines determine the thickness of bremsstrahlung shutters, stops and collimators in the beamlines and front ends. Figure 1 shows the geometry used in the EGS4 simulations to calculate the thickness of lead and tungsten required to attenuate the dose rate < 0.25 mrem/h at the downstream side of the stop/shutter on contact. These shutters will be located inside the shielded enclosures. The primary bremsstrahlung source term was estimated using the empirical formulae from Table 1 to scale the dose rate results. In the geometry used in this calculation of shutter thickness, the bremsstrahlung beam from the NSLS2 straight section is incident on a lead or tungsten block with transverse dimensions of 20 x 20 cm^2. The actual transverse dimensions of the shutter remain to be determined. The stop is followed by the ICRU tissue[10] of 30 cm thick to score the dose at the downstream side of the shutter/stop. The ICRU tissue is binned into 1 cm^3 bins for scoring the dose and the maximum dose is taken as the dose index.

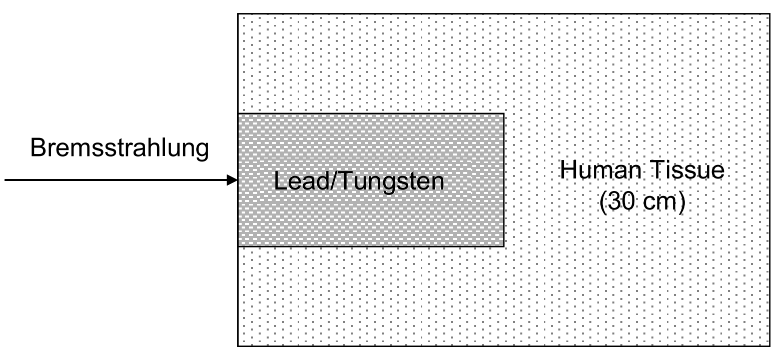

Figure 1. Simulated EGS4 Geometry of the NSLSII safety shutters.

Table 2 shows the primary bremsstrahlung dose rates predicted by the two methods and the thickness of lead or tungsten required to reduce the radiation dose rate at the back of the shutter/collimator < 0.25 mrem/h (< 2.5 μSv/h). The dose rates at the downstream surface in the ICRU tissue was calculated as a function of lead or tungsten thickness at three dimensions. The calculated dose rates are also fitted using an effective exponential attenuation factor and doses at greater depths are extrapolated. The results are also plotted in Figure 2 for source calculated by method 1. It can be seen that a lead thickness of > 30 cm and a tungsten thickness of >20 cm is required as stops/shutters at NSLS II beamlines to reduce the dose rate to < 0.25 mrem/h (<2.5 μSv/h) taking into account the conservative primary bremsstrahlung source term. (0.25 mrem/hr was used as the shield requirement, since these devices will be within other shielded enclosures)

Table 2 Shutter/ Collimator Thickness for NSLS II Insertion Device Beamlines

	LURE-APS	Ferrari-CERN
Bremsstrahlung Dose Rate (rem/h)	240 rem/h	280 rem/h
Lead Thickness required (cm)	28.9 cm	29.2 cm
Tungsten Thickness required (cm)	19.6 cm	19.8 cm
Dose Rate behind the stop/shutter (mrem/h)	0.25 mrem/h (2.5 μSv/h)	0.25 mrem/h (2.5 μSv/h)

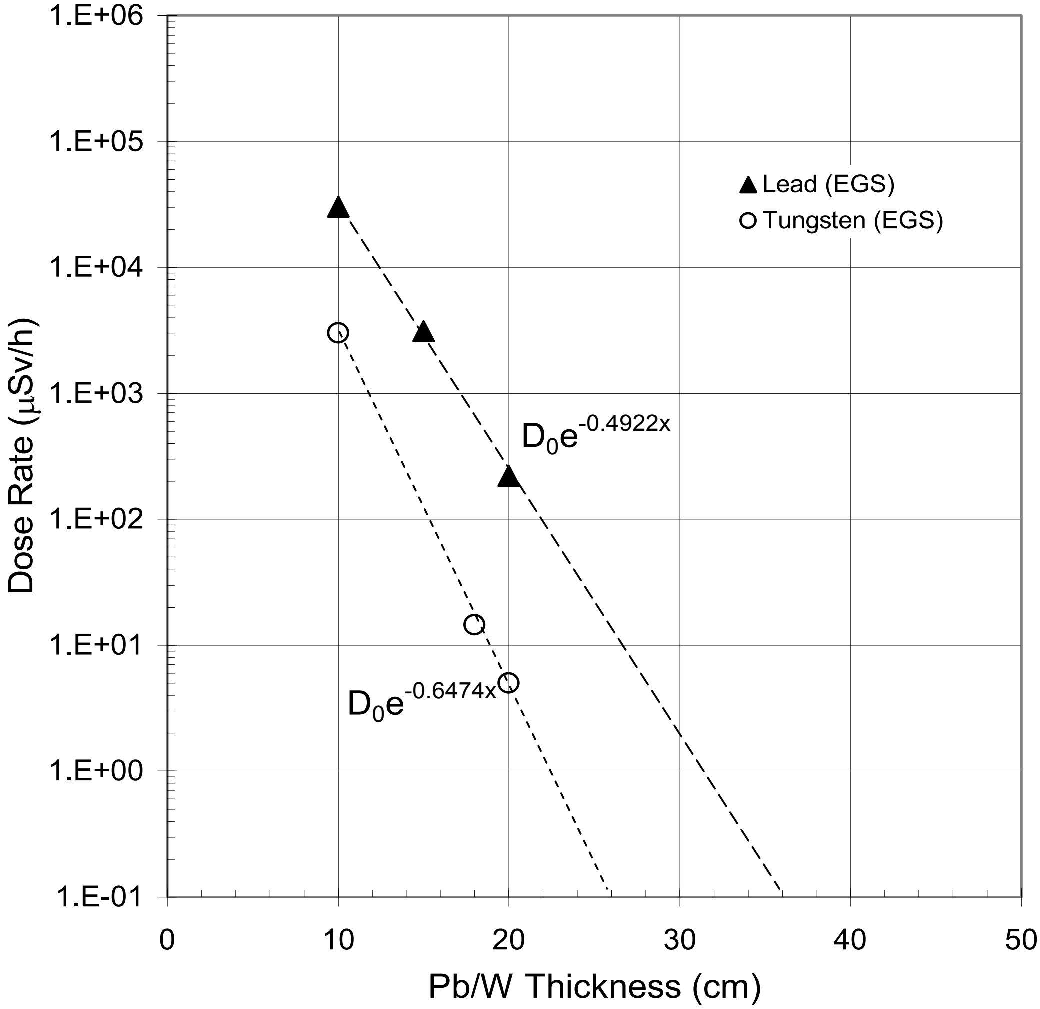

Figure 2 Contact Dose Rates at the Downstream Surface of the Shutters/Stops (Bremsstrahlung Source Calculated by Method 1)

3.3 Geometry of Computation for Bremsstrahlung and Synchrotron Radiation Scattering

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 and mirrors etc. These components vary from beamline to beamline. Therefore calculations were performed with a worst case potential scatterer, upstream of the First Optics Enclosure (FOE), of typical dimensions of 2.0 m width, 3 m height and 10 m length. Figure 3 shows the geometry of computation for bremsstrahlung and synchrotron radiation scattering to estimate the shielding requirements for the NSLS II FOEs. The worst case potential scatterer for bremsstrahlung is taken as 3 cm thick copper and for synchrotron radiation as 0.1 cm aluminum with small transverse dimensions. In addition, a 10 meter path in air in the FOE is also taken as the potential scatterer for the synchrotron radiation. The EGS4 calculations were performed for bremsstrahlung and STAC8 calculations were performed for synchrotron radiation.

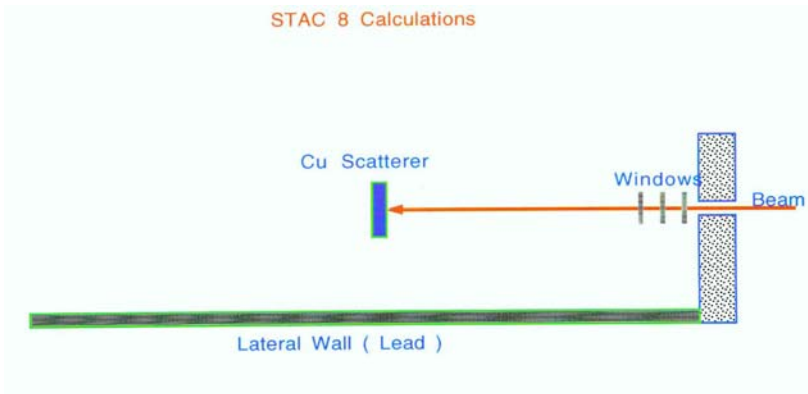

Figure 3 EGS4 and STAC8 Geometry for Bremsstrahlung and Synchrotron Radiation Scattering Calculations

4. Shielding Estimates for the NSLS II Beam Line Enclosures

4.1 First Optics Enclosures

Preliminary shielding estimates for the NSLSII First Optics Enclosures (FOE) are calculated using the available beamline and Insertion Device parameters. For each shielding situation the synchrotron and bremsstrahlung shielding have been calculated for the representative station geometry. The shielding requirements for both bremsstrahlung and synchrotron radiation are calculated. The shielding simulations for bremsstrahlung were done using the EGS4 program and for synchrotron radiation using the STAC8 program. In most cases, one of the sources (bremsstrahlung/ synchrotron radiation) dominates for the shielding requirement and the contribution of the other becomes negligible, thus the calculated shielding for the dominant source can be implemented. The insertion device source spectra are calculated using the SPECTRUM[11] program. All bremsstrahlung and synchrotron radiation calculations were done at 500 mA of beam current at 3.5 GeV electron beam energy. Also all the doses are scored in the ICRU tissue on contact unless otherwise mentioned, instead of at a distance of 30 cm from the dose point. Occupational exposure of personnel is most likely to occur in the vicinity of experimental stations along the beamlines. Shielding of these areas is designed to maintain individual exposures when in contact with the hutch wall as < 100 mrem/year for 2000 hours of exposure per year. Thus the experimental station shielding is designed to meet or exceed the criterion to ensure that occupational radiation doses are ALARA.

4.1.1 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 3 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.

Figure 4 gives the scattered bremsstrahlung dose rates 1 meter away from a 3 cm thick copper scatterer in terms of μSv/h (0.1mrem/h). The bremsstrahlung forward beam direction in this figure is 90 degrees. The transverse directions are 0 degrees and 180 degrees. Calculations are for 240 rem/h primary bremsstrahlung dose rate. It can be observed that the scattered bremsstrahlung beam is highly forward peaked.

For calculating the shielding requirements for the downstream wall of the First Optics Enclosure (FOE), the calculated dose rates (DR) from Figure 4 has been used. The minimum distance from the copper scattering target to the down stream wall 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 required lead thickness for the downstream wall of the FOE as a function of the scattering angle to achieve the design dose limit of < 0.05 mrem/h is calculated using the expression;

$$\text{Lead Thickness (cm)} = [\ \ln (0.01 \times DR) - \ln 0.05\ ] / 0.473$$

The minimum attenuation coefficient of 0.473 cm^{-1} for lead has been used in these calculations for bremsstrahlung attenuation.

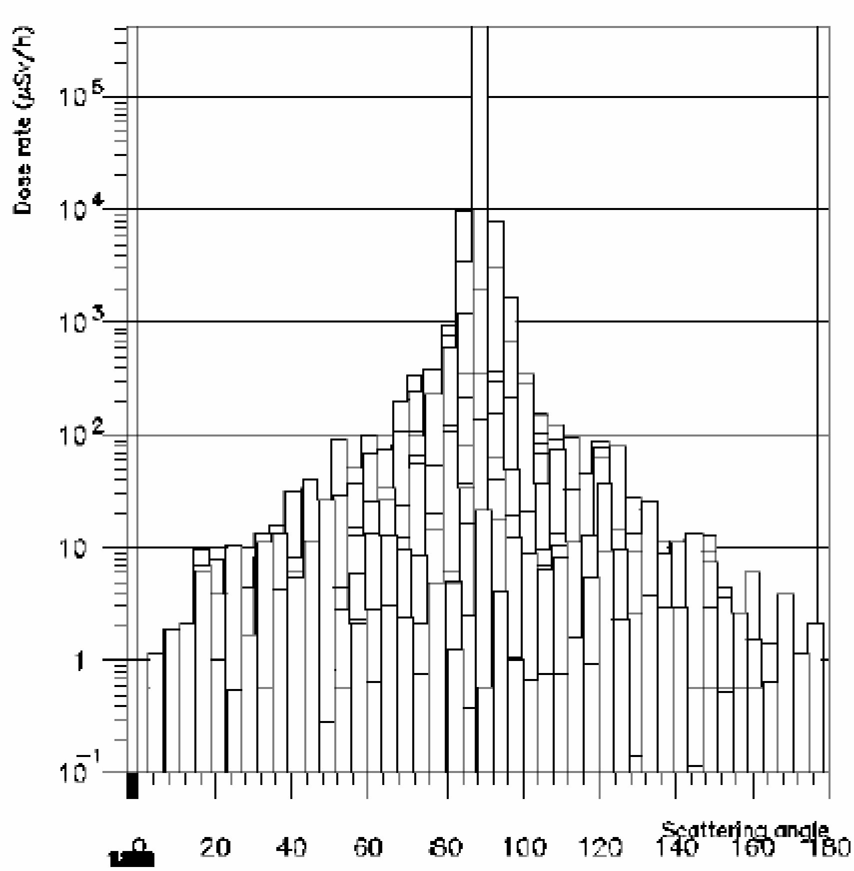

Figure 4 Scattered Bremsstrahlung Dose rates at 1 meter for the NSLSII Beamlines (Primary bremsstrahlung scattered from a Cu Target of 3 cm thickness with small transverse dimensions)

Table 3 provides the calculated lead thickness for the downstream wall of the FOE as a function of the scattering angle to achieve the design dose limit of < 0.05 mrem/h. 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 collimators or bremsstrahlung stops approximately from 0 to 2 degrees. Considering a uniform downstream wall thickness of 5 cm, additional shielding will be required for scattering angles < 4 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. Presently a uniform downstream wall thickness of 50 mm is recommended.

Table 3 Shielding Estimates for the First Optics Enclosure (Bremsstrahlung scattering only)[a]

Angle (deg.)	Dose Rate mrem/m^2·h	Lead thickness Downstrem Panel (cm)[b]	Lead thickness Side Panel (cm)	Lead thickness Roof (cm)	Half width of local Shielding Required (cm)
1	5.0×10^3	14.6	2.3	0.4	17
2	1.5×10^3	8.65	2.3	0.4	34
3	7.0×10^2	7.04	2.3	0.4	52
4	4.0×10^2	5.86	2.3	0.4	69
5	2.2×10^2	4.59	2.3	0.4	87
6	1.5×10^2	3.78	2.3	0.4	100
8	1.0×10^2	2.93	2.3	0.4	140
10	7.0×10^1	2.17	2.3	0.4	170

(a) Lead thickness required to reduce the dose rate to < 0.05 mrem/h for bremsstrahlung scattering from a 5x5x3 cm^3 Cu scatterer at the upstream of the FOE, Beam Current 500 mA, Beam Energy 3.5 GeV. FOE has a length of 10 meters.
(b) A uniform thickness of 5.0 cm is recommended. Additional shielding in the forward direction can be achieved by the stop/collimator and local shielding.

The lateral wall (side wall) shielding for the FOE can be calculated using the same equation;

$$\text{Lead Thickness (cm)} = [\ln DR - \ln 0.05] / 0.473$$

Because of the relatively large statistical fluctuation of calculated DR at 180 degrees and 0 degrees in figure 4, an average DR of 0.15 mrem/h (1.5 μSv/h) has been used to calculate the required lead thickness for the side wall to achieve the design dose limit of < 0.05 mrem/h. This gives a lead thickness of

$$\text{Lead Thickness (cm)} = [\ln 0.15 - \ln 0.05] / 0.473 = 2.3 \text{ cm}$$

A side wall thickness of 23 mm is recommended for the insertion device beamlines. The roof of the experimental stations is assumed to be at distance of 1.5 m from the beam. The distance adjustment factor for DR in this case is $1/1.5^2$. The shielding thickness for the roof can be calculated by the expression

Lead Thickness for Roof (cm) =[ln (DR×0.4) – ln 0.05] / 0.473

Taking an average transverse DR of < 0.15 mrem/h, the expression yields a roof thickness of 4 mm for the insertion device experiment stations. This thickness is smaller than the lead thickness required for synchrotron radiation shielding in most cases.
It must also be emphasized that the bremsstrahlung production is linear with respect to the pressure in the vacuum chamber. In the present calculations for the primary bremsstrahlung source term, a vacuum chamber pressure of 1 ntorr is assumed. It is imperative to maintain a vacuum of <1ntorr in the storage ring to minimize bremsstrahlung production during the storage ring operation.

4.1.2 Synchrotron Radiation Scattering Calculations with STAC8

Synchrotron radiation scattering calculations to estimate the shielding requirements for the NSLSII First Optics Enclosure was performed by the STAC8 shield program. The worst case scatterer of 0.1 cm aluminum is used as a potential scatterer located at the upstream part of the FOE. In addition, a 10 meter air path along the length of the station has also been considered as an additional potential scatterer of the synchrotron radiation in the station.

The source spectrum for the NSLSII insertion devices for this calculation was generated by STAC8 program. Four kinds of insertion devices were considered for the NSLSII beamline station shielding design. The salient parameters of these insertion devices, calculated by STAC8 program is given in Table 4.

Table 4 NSLS II Insertion Device Parameters used for Beamline Shielding Calculations

Device Type	No. of Poles	B_{eff} (Tesla)	Period (mm)	Power at 500 mA (kW)	Critical Energy (keV)	Aperture in First Optics Enclosure
DW	120	1.8	100	75.25	14.66	4 x 10 mm
U19	316	1.0	19	11.64	6.26	4 x 4 mm
U14	286	1.4	14	15.46	8.75	4 x 4 mm
SCW	10	3.5	150	35.57	28.47	4 x 8 mm

a. Station dimensions of 2 x 3 x 10 meters are assumed
b. All Calculations for 3.5 GeV beam energy at 500 mA
c. Straight path in the line of sight of the insertion device beamlines is assumed to be 16 m.

The lateral walls of the First Optics Enclosures are assumed to be at a distance of 1 meter and the roof at 1.5 meter from the beam. Shielding for these areas is calculated to maintain individual exposures when in contact with the experimental station wall as

< 100 mrem/year for 2000 hours of exposure per year. This converts to an effective dose rate of < 0.05 mrem/h at the occupiable areas.

Table 5 gives the preliminary shielding estimates for the First Optics Enclosure at NSLS2 for four insertion device beamlines. Required shielding estimates for the side panel, roof and the upstream panel are given for synchrotron scattering only calculations.

Table 5 Preliminary Shielding Estimates for NSLS II First Optics Enclosures (Synchrotron Radiation only)

Lead Thickness (mm)

Insertion Device	Side Panel (mm)	Roof (mm)	Upstream Panel(mm)
U19	8	7	8
U14	10	9	10
SCW	16	14	16
DW	14	12	14

a. All calculations are done for Beam Energy of 3.5 GeV at 500 mA
b. Insertion Device parameters are used from Table 4
c. Station dimensions are assumed to be 2.0 x 3.0 x 10.0 m^3
d. Side panels are at a distance of 1 m and roof at 1.5 m away from the beam

5. Shielding Recommendations for NSLS2 First Optics Enclosures

Table 3 and Table 5 summarize the shielding estimates for the First Optics Enclosures and white beam stations of the NSLS II beamlines. Table 3 provides the shielding estimates from bremsstrahlung scattering calculations only, while Table 5 provides the shielding estimates from the synchrotron radiation scattering only calculations. In each case the shielding requirement for the dominant source must be implemented.

To summarize, the bremsstrahlung shielding dominates for the downstream panel and the side panel, and the synchrotron radiation dominates for the roof and the upstream panel. Table 6 compiles the shielding requirements for the NSLS2 First Optics Enclosures. Shielding requirements for the four kinds of insertion device beamlines are given. Lead shielding of 50 mm is needed for the entire downstream wall of all insertion device beamlines to shield the forward peaking bremsstrahlung scattering source. An additional 50 mm of lead (100 mm total) is needed for the central portion around the beam penetration. This lead shielding can be achieved by the appropriate design of the local shielding around the beam pipe. It is also desirable to design bremsstrahlung collimators at appropriate locations upstream of the First Optics Enclosures close to the potential bremsstrahlung scattering components.

Table 6. Summary Shielding Requirements for NSLSII First Optics Enclosures

Insertion Device	Side Panel (mm)	Roof (mm)	Upstream Panel (mm)	Downstream Panel[a] (mm)
U19	23	7	8	50
U14	23	9	10	50
SCW	23	14	16	50
DW	23	12	14	50

(a) An additional 50 mm of lead locally around the beam pipe penetration.

6. Maximum Credible Radiological Incident Analysis for Beamlines

In the shielding estimates of NSLS II injection losses, an average injection frequency of one every minute into the storage ring from the booster synchrotron is assumed. A highly unlikely scenario of 20 nC/s the capacity of the Linac, is injected into the storage ring continuously and 100% lost at the septum, is considered for the radiological consequences of injection loss at the booster septum (NSLS-RP-TN 2).

A maximum credible incident for the beamlines is defined as, in addition to the above, a dipole magnet at the downstream of the injection septum is shorted, and the 100 % injected beam proceeds along the direction of one of the beamlines. However the missteered electron beam will generally be unable to proceed farther than a collimator or a front end shutter. It will most likely be intercepted and create an electromagnetic shower on one of the front end shutters or collimators. This would result in higher dose rates in the first optics enclosure of the beam lines, if this accidental scenario persists. The shielding wall of the storage ring is designed for a beam loss charge of 77.5 nC/h, 10% of the stored beam loss at any given location. The shielding for the storage ring is designed for a dose rate of < 0.25 mrem/h at the occupiable regions. Dose rates during this accidental scenario will be a factor of 929 greater than the limiting dose rates. The dose rates will be < $(7.2 \times 10^4/77.5)\ 0.25 = 232$ mrem/h at the exterior of the shield wall of the storage ring on contact adjacent to the first optics enclosure regions.

Loss of vacuum in the insertion devise straight path is another credible incident that can cause higher dose rates around the first optics enclosures of the beamlines. In the bremsstrahlung source calculations in section 2.2.2, a straight section pressure of 10^{-9} torr is assumed. A sudden loss of vacuum to 1 torr in the straight section will have an increased bremsstrahlung production by a factor of 10^9. We further assume that this scenario will last only for < 1 millisecond (approximately 1000 turns of the beam) before the beam gets completely absorbed. No credit is given to the engineering controls that trip the beam at vacuum loss. The FOEs are designed for a dose rate of < 0.05 mrem/h on contact at the exterior of the shield panel. The dose rate during this accidental scenario will be higher by a factor of 10^9, but will last only for a millisecond. The total dose commitment to an individual beamline scientist due to one such incident will be < $(0.05\times10^9)/(3.6\times10^6)$ = 14 mrem.

The probability of these failure scenarios to occur simultaneously is extremely small and the radiological consequences of these incidents are insignificant. In addition, sufficient conservative factors are included in the shielding estimates for the beamlines to provide additional margin of safety. Dose rates in the present estimates are calculated on contact at the exterior of the bulk shielding, which is conservative. It is also prudent to assume a time duration for an incident, such that the total dose commitment to the personnel during such an unlikely scenario can be estimated. Continuous injection for prolonged periods can also be limited by the engineering controls.

7. References

1. Gabriel, T. A., PICA, Intra-nuclear Cascade Calculations, ORNL 4687 (1971).

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

3, Perkins, D.H., Introduction to High Energy Physics, Addison Wesley Publishing, (1984).

4. Moe, H., et. Al., Radiological Considerations for TopUp at APS, APS-LS 276 (1998)

5. Frank, J.C., LURE EP 88-01 (1988).

6. Ferrari, et.al., Estimation of Gas Bremsstrahlung, Health Physics, 68 (1995)

7. Tromba, G. and A.Rindi, Gas Bremsstrahlung from Electron Storage Ring, Nucl.Instr. Meth., A292 (1990).

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

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

10. ICRU 46, Radiation Interaction Data with Body Tissue (1992).

11. Shaftan, T., Private Communication (2006).