Radiological Considerations of Top-off Operation at NSLS-II

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1. Introduction

High current (500 mA) and low emittance (~1 nm) have been specified for NSLS-II to achieve ultra high brightness in a medium energy (3 GeV) storage ring[1]. This leads to the expectation that the lifetime in NSLS-II will be limited by touschek scattering, and after commissioning will settle in at ~3 hours. It may well be less in the early days of operation. At the same time, the intensity stability specified by the user community is 1% or better. Given the anticipated lifetime of the storage ring, incremental filling called Top-off injection at intervals the order of ~1 minute will be required to maintain this beam stability. The ability to perform top-off injection is a key capability for NSLS-II, providing relatively small but frequent charge injections to the storage ring to keep the stored beam current nearly constant. Top-off operations are in place at other advanced third generation light sources like Advanced Photon Source[2][3] at Argonne National Laboratory, Stanford Synchrotron Radiation Source[4][5] and at the Advanced Light Source at Berkeley[6]. It is judged to be impractical to make these incremental fills by cycling safety shutters at each injection to provide radiation protection. Additionally, closing the front end safety shutters during each injection will also adversely affect the stability of beamline optics due to thermal cycling. Hence the radiological consequences of injection with front end safety shutters open for top-off operation is a major concern to be addressed. This Technical note summarizes results of radiological analysis carried out for NSLS-II Top-off operation with the front end safety shutters open.

2. Radiological Concerns of Top-Off operation

The primary radiological safety concern for the top-off injection with the safety shutters open is the scenario where electrons could be conveyed down to the user beamline through the front end to the First Optics Enclosure (FOE) due to the erroneous combination of lattice magnetic field settings[7]. It is of paramount importance to ensure that such events are of remote possibility. Several layers of redundant engineering controls are to be employed for this purpose. Nevertheless, it is prudent to carryout simulations to evaluate the dose consequences of such an incident.

Particle tracking simulations[8] by the NSLS-II accelerator physicists have shown that by a set of interlocking requirements of the lattice magnetic fields and by the implementation of some physical apertures, the errant electron beam can be confined to the front end components within the storage ring. During abnormal situations, where the magnetic lattice settings are deviated to the extreme of the interlocked values, the full injected beam may incident on a beamline front end[9] component. The resulting bremsstrahlung can penetrate though the concrete shield wall of the storage ring or through the ratchet wall aperture to the experiment floor. The radiological consequences of such an event can still be undesirable but less devastating than the beam entering the first optics enclosures of the beamlines. Particle trajectory simulations[8] are carried out to ensure that the errant beam will not pass beyond the front end fixed mask or the photon shutter apertures in the event of maximum deviation of lattice magnetic field values within the interlocked window. Radiological consequences of such events on the experimental floor have also been evaluated.

3. Simulation Methodology for Dose Calculations

FLUKA Monte Carlo simulation program[10] is used to calculate the radiation levels at the occupied regions of the experiment floor due to errant electron beam incident on front end or beamline components. FLUKA is a coupled electron, photon, neutron transport program simulating particle transport through different shielding materials like concrete, lead, copper etc. FLUKA program can calculate ambient dose equivalent rates[11] or effective dose rates[11] from the particle flux using ICRP74[12] radiation weighting factors and tissue equivalent factors.

Three sets of FLUKA simulations are carried out to evaluate the radiological consequences at the experimental floor due to errant electron beam coming down through the front end. Based on tracking simulation results[8], dose rate calculations are carried out with the 15 nC/s full injected beam incident on the front end photon shutter or fixed mask. In each case total ambient dose equivalent rates and neutron ambient dose equivalent rates at the experiment floor along the storage ring concrete wall are calculated using the ICRP 74 radiation weighting factors. In the worst case scenario of beam entering the optics enclosure, due to redundant interlock failures, dose equivalent rates are calculated along the lead shield wall outside of the First Optics Enclosure (FOE) at the experiment floor.

4. Frontend Configuration for Radiation Simulation

Figure1 gives the typical NSLS-II beamline frontend configuration[9] for insertion device beamlines. The relevant radiation safety components are the copper fixed aperture mask, lead collimators, copper photon shutter and two lead safety shutters. The ratchet wall collimator is 25 cm thick lead, in addition to 115 cm of concrete. The lead collimator spans the entire width of the ratchet wall with 50 cm vertical dimension symmetric to the beam plane. Beyond the ratchet wall the First Optics Enclosure (FOE) has lead lateral walls of thickness 1.8 cm and downstream lead wall of 5.0 cm.

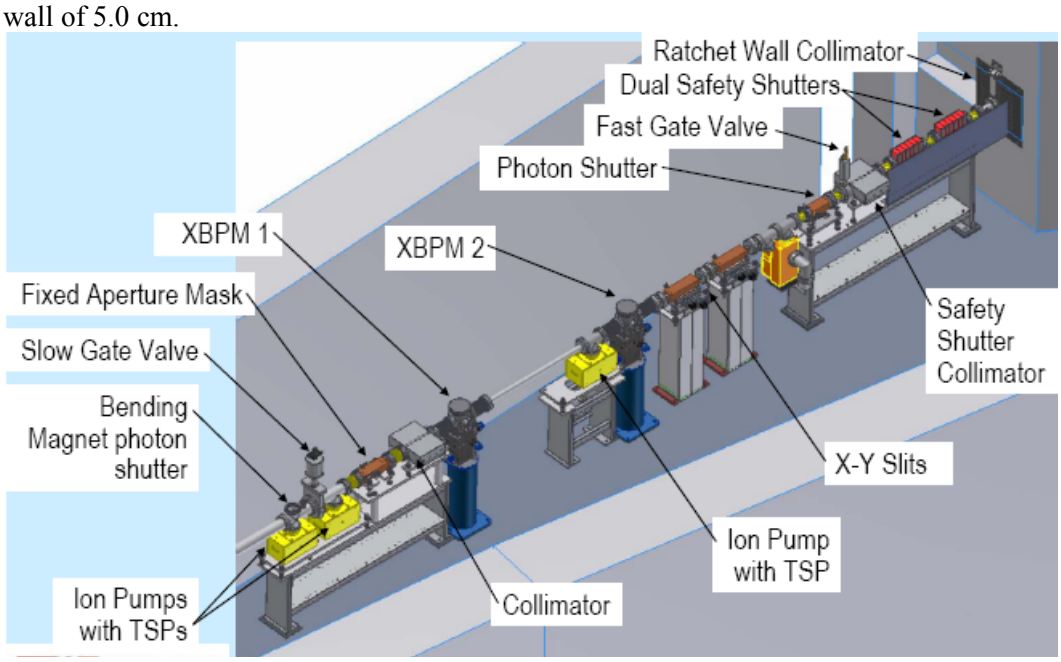

Figure1 NSLS-II Frontend Configuration for IXS Insertion Device Beamline

Figure2 gives the schematic diagram of front end and FOE configuration simulated by the FLUKA program. The concrete walls are normal density concrete. Being anamorphic, the drawing is not to scale. The lateral concrete wall is 80 cm thick and the ratchet wall is 140 cm of concrete with 25 cm thick lead collimator (not visible in the figure) embedded in the beam plane. Fixed masks and photon shutters are made of Glidcop. Collimators, bremsstrahlung stops and the First Optics Enclosure (FOE) walls are of lead. Simulated components in the first optics enclosure are one copper mask and one lead bremsstrahlung stop. The ratchet wall collimator has aperture of 1.6 cm horizontal and 1.08 cm vertical dimensions. Other front end components are simulated in the FLUKA program with actual dimensions and material compositions.

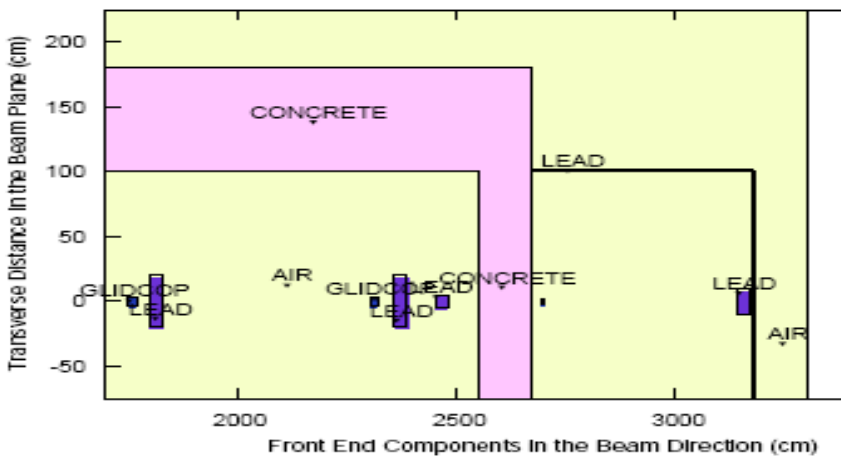

Figure.2 Front End and Beamline Configuration used for FLUKA Simulation.

5. FLUKA Simulation Results

5.1 Injected Electron Beam on Fixed Aperture Mask

Figure 3 gives the schematic dimensions of the first fixed aperture mask at the NSLS-II inelastic x-ray scattering beamline. This beamline has an insertion device as source. The mask is located inside the storage ring at 17.48 meters and the ratchet wall upstream boundary is at 25.3 meters from the middle of the straight section. Two sets of calculations are carried out for this configuration. One set with the injected beam incident at the upstream edge and a second set with the beam incident at the downstream edge of the fixed mask aperture.

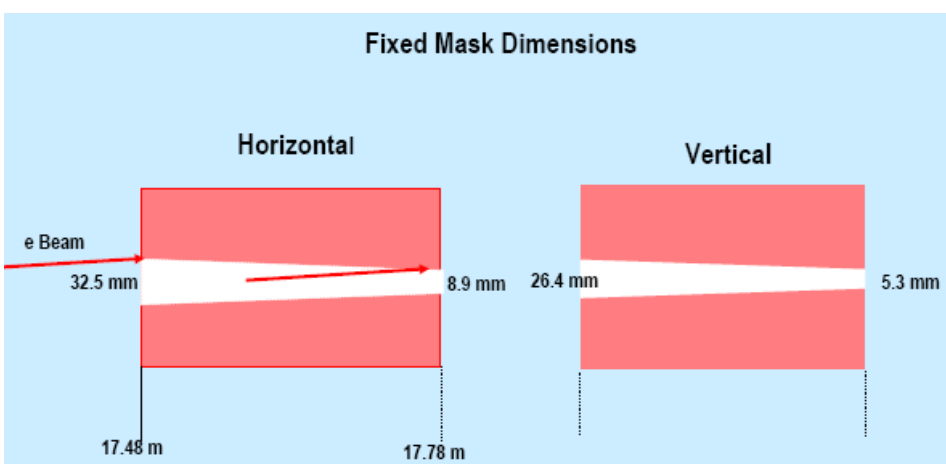

Figure 3 Fixed Aperture Mask Design for the IXS-ID Beamline (Glidcop)

The standard beam-target configuration in FLUKA[13] has been used for the beam loss scenarios to calculate the resultant ambient dose equivalent rates at the occupied regions. For both configurations the total ambient dose equivalent rates and neutron ambient dose equivalent rates have been scored at the exterior concrete wall of the storage ring at the beam height. The radiation weighting factors from ICRP 74 have been used to calculate the ambient dose equivalent rates for 15 nC/s injected beam loss. The safety shutters are open in both the simulations.

5.1.1 Beam at the Upstream Edge of Fixed Mask Aperture

Figure 4 shows the total ambient dose equivalent rate distribution in the horizontal plane when the injected beam is incident at the upstream edge of the fixed mask aperture. The dose rate distribution is at the beam height in the horizontal plane corresponding to a full injection beam loss of 3 GeV electrons at a rate of 15 nC/s. Figure 5 provide the same data plotted along the exterior of the storage ring concrete wall at the beam height. The maximum ambient dose equivalent rate 500 mrem/h occurs along the exterior of the storage ring concrete wall at the transverse region from the fixed mask. This corresponds to ~0.14 mrem per injection pulse of 15 nC.

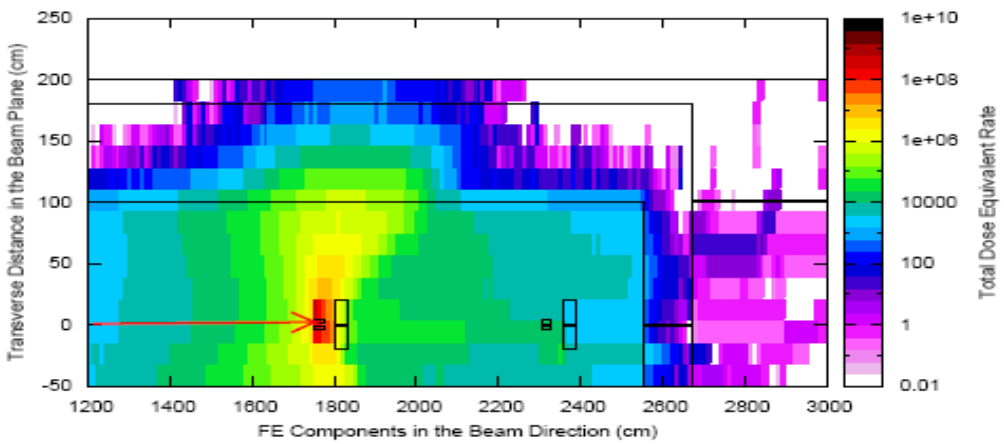

Figure 4. Total Ambient Dose Equivalent Rate Distribution in the Horizontal Beam Plane (15 nC/s Injected Beam incident at the upstream edge of the fixed mask aperture)

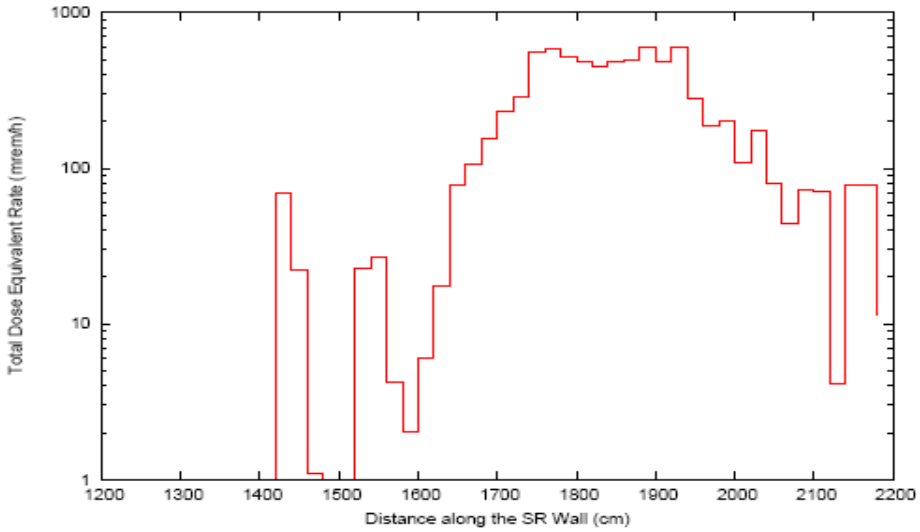

Figure 5. Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Storage Ring Wall at the Beam Height (15 nC/s Injected Beam incident at the upstream edge of the fixed mask aperture)

Figure 6 gives the neutron ambient dose equivalent rate distribution for the same beam loss scenario calculated using ICRP74 neutron weighting factors along the exterior of the storage ring concrete wall at the beam height. Maximum injected electron beam of 15 nC/s is incident at the upstream edge of the fixed mask aperture. The maximum neutron dose rate is < 200 mrem/h for the 15 nC/s beam loss at the upstream edge of the fixed mask aperture. This corresponds to < 55 µrem per pulse of 15 nC. Figure 4 also indicate that the dose rates outside the 18 mm lead walls of the first optics enclosure for this beam loss scenario are close to background.

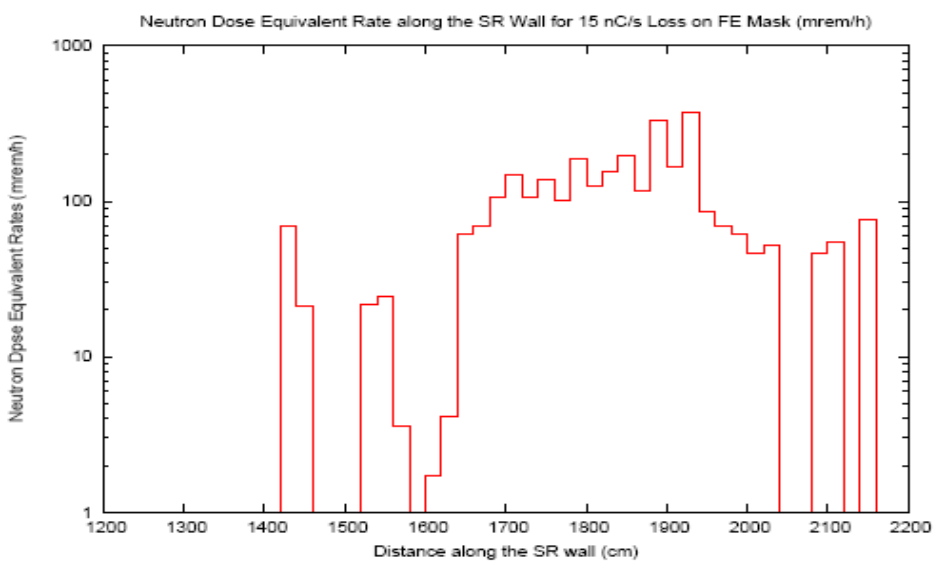

Figure 6. Neutron Ambient Dose Equivalent Rate Distribution along the Exterior of the Storage Ring Wall at the Beam Height (15 nC/s Injected Beam incident at the upstream edge of the fixed mask aperture).

The radiation hazard from this top-off injection beam loss incident is low. The anticipated location of the interlocked area radiation monitors is close to the maximum dose location for this loss scenario and is expected to trip the beam within a few pulses of the injected beam loss. Area radiation monitors at the experimental floor provide sufficient protection from this incident.

5.1.2 Beam at the Downstream Edge of Fixed Mask Aperture

Figure.7 shows the total ambient dose equivalent rate distribution in the horizontal beam plane when the injected beam is incident on the downstream edge of the fixed mask aperture. This total dose rate distribution is at the beam height in the horizontal plane corresponding to a full injection beam loss of 3 GeV electrons at a rate of 15 nC/s. Figure 8 provide the same data plotted along the exterior of the storage ring concrete wall at the beam height. The maximum ambient dose equivalent rate of ~100 mrem/h occurs along the exterior of the storage ring concrete wall close to the transverse location from the fixed mask. This corresponds to ~0.03 mrem per injection pulse of 15 nC. The lower dose rates than the scenario1 of case 5.1.1 at the exterior of the concrete wall is due to the difference in beam loss profile. Beam loss being at the downstream edge of the fixed mask aperture, the shower development on the fixed mask is incomplete and is distributed on the downstream components of the frontend. This causes the dose being distributed along the storage ring wall with reduced maximum dose rate at any given location.

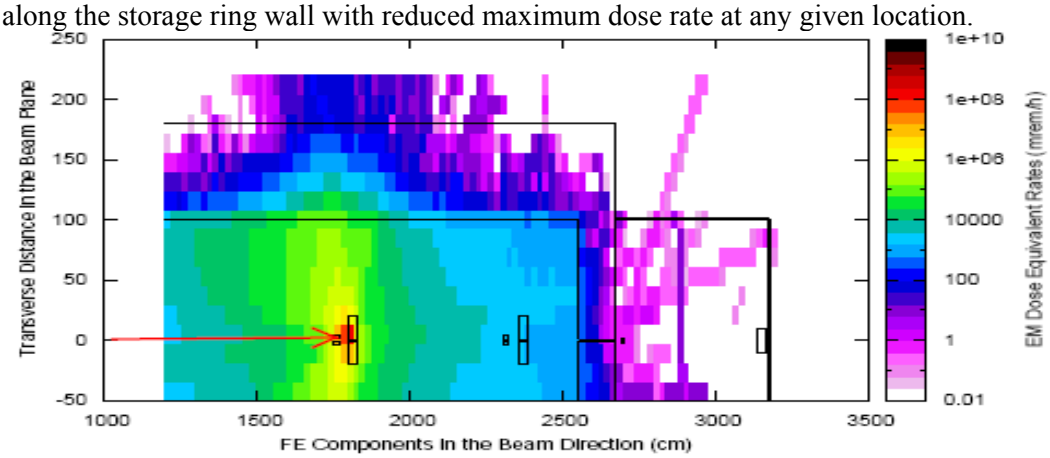

Figure 7. Total Ambient Dose Equivalent Rate Distribution in the Horizontal Beam Plane (15 nC/s Injected Beam incident at the downstream edge of the fixed mask aperture)

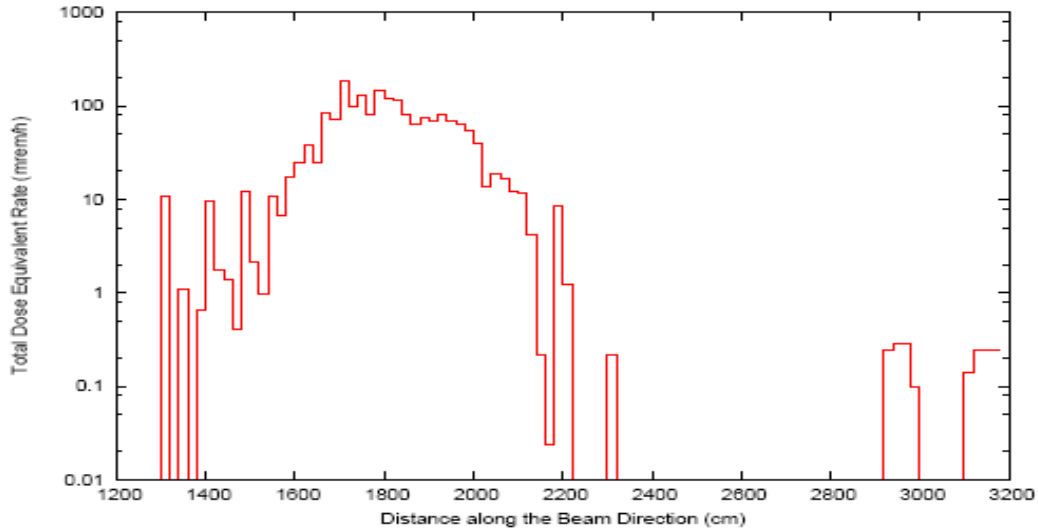

Figure 8 Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Storage Ring Wall at the Beam Height (15 nC/s Injected Beam incident at the downstream edge of the fixed mask aperture)

Figure 9 gives the neutron ambient dose equivalent rate distribution calculated using ICRP74 neutron weighting factors along the exterior of the storage ring concrete wall at the beam height for the same beam loss scenario. Maximum injected electron beam of 15 nC/s is incident at the downstream edge of the fixed mask aperture. The maximum neutron dose rate is < 100 mrem/h for the 15 nC/s beam loss at the downstream edge of the fixed mask aperture. This corresponds to < 30 µrem per pulse of 15 nC. The neutron dose rates are not lower by the same ratio as the total dose rates between cases1&2 because of additional neutron production in the front end collimators and shutters. Figure 7 also indicate that the dose rates outside the 18 mm lead walls of the first optics enclosure for this beam loss scenario are close to the background.
The anticipated location of the interlocked area radiation monitors is close to the maximum dose location for this loss scenario and is expected to trip the beam within a few pulses of beam loss. The radiation hazard from this top-off incident is low and the interlocked area monitors will provide sufficient protection.

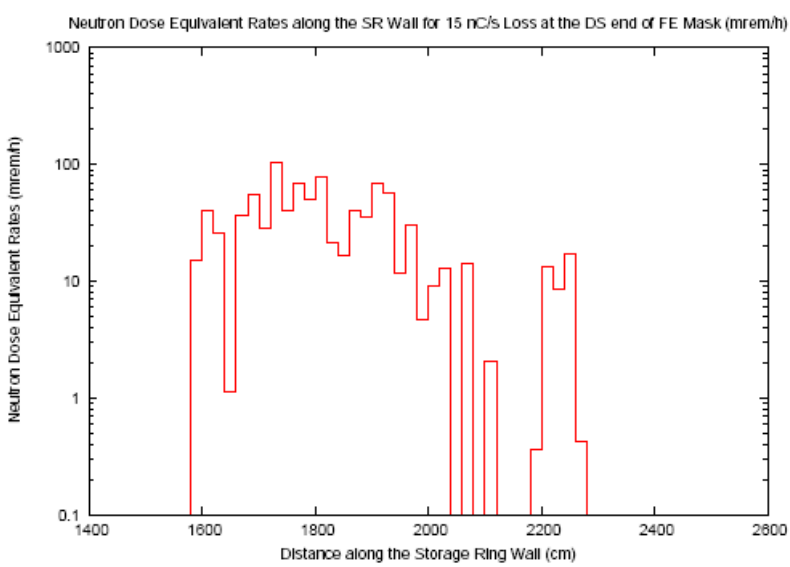

Figure 9 Neutron Ambient Dose Equivalent Rate Distribution along the Exterior of the Storage Ring Wall at the Beam Height (15 nC/s Injected Beam incident at the downstream edge of the fixed mask aperture)

5.2 Injected Electron Beam on the Front End Photon Shutter

5.2.1 Beam on Photon Shutter with Safety Shutters Open

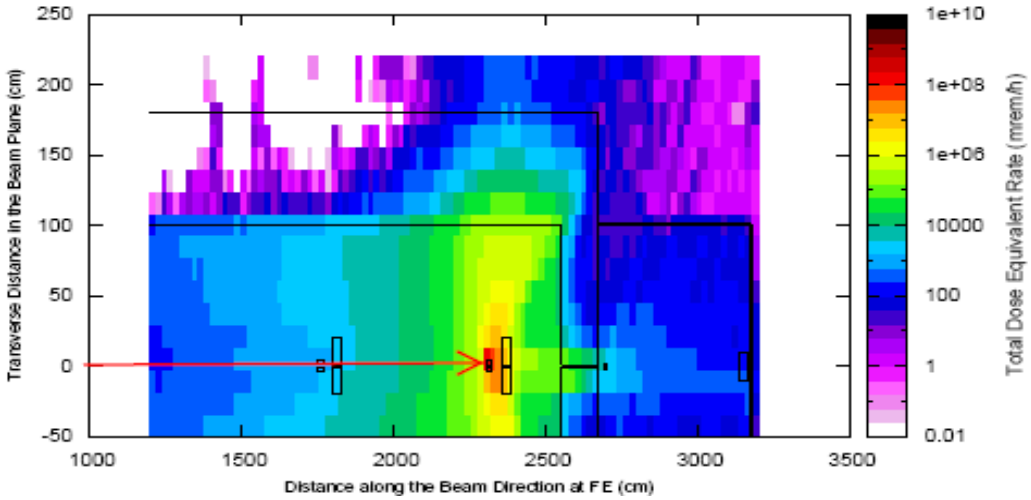

Figure 10 Total Ambient Dose Equivalent Rate Distribution in the Horizontal Beam Plane (15 nC/s Injected Beam incident on the photon shutter)

Figure 10 gives the total ambient dose equivalent rate distribution in the horizontal beam plane for 15 nC/s injected beam incident on the front end photon shutter inside the storage ring. The safety shutters are in open position and the first optics enclosure is secured. Figure 11 provide the same data plotted along the exterior of the storage ring concrete wall at the beam height. The maximum dose rate of 500 mrem/h occurs along the exterior of the storage ring ratchet wall close to the transverse location from the photon shutter at the experimental floor. This corresponds to ~0.14 mrem per injection pulse of 15 nC. A lead collimator immediately downstream of the photon shutter shadows the beam loss location from the ratchet wall, but for the aperture.

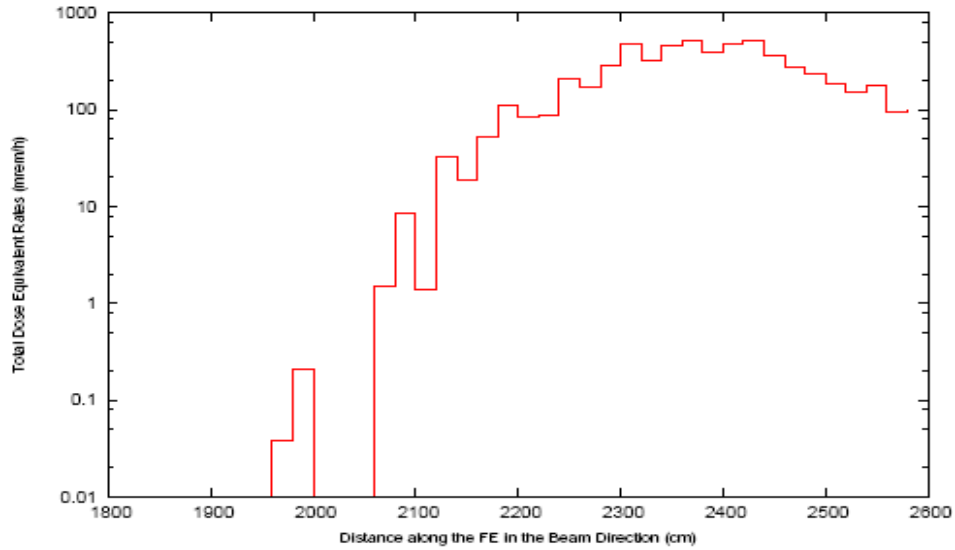

Figure 11 Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Storage Ring Wall at the Beam Height (15 nC/s Injected Beam incident on the photon shutter)

Figure 12 Show the total ambient dose equivalent rate distribution for the same beam loss scenario in the horizontal beam plane along the exterior of the ratchet wall inside the first optics enclosure. 15 nC/s Injected electron beam is incident on the photon shutter. The safety shutters are open and the optics enclosure is secured. The maximum ambient dose equivalent rate is < 300 mrem/h at the ratchet wall collimator aperture. The dose rate has a maximum at the ratchet wall collimator aperture and decreases towards the lead lateral wall of the optics enclosure from the beam position. Figure 10 also indicate that the dose rates at the exterior of the lateral walls of the optics enclosure is < 10 mrem/h compared to the dose rates at the exterior of the storage ring concrete wall for the same injection beam loss scenario when the safety shutters are open.

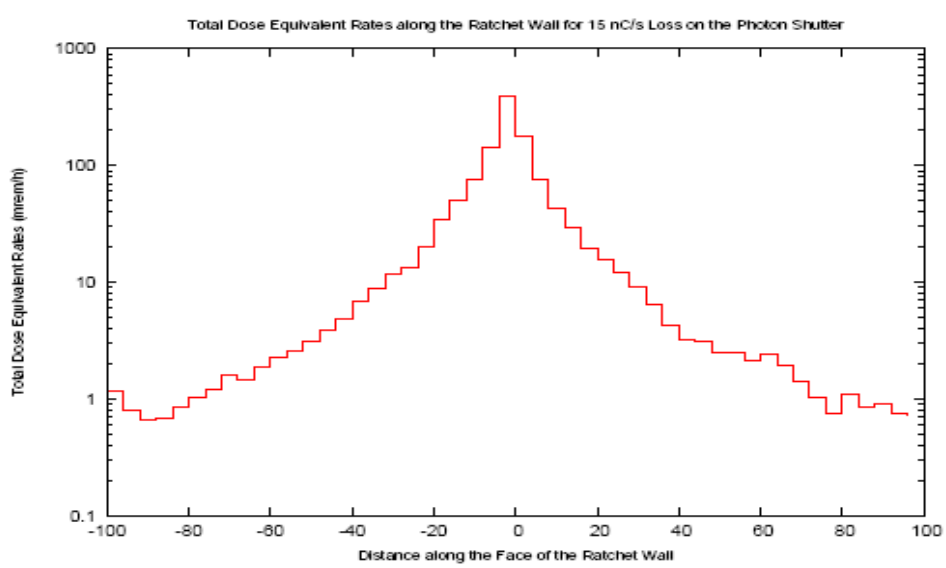

Figure 12 Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Ratchet Wall in the Horizontal Beam Plane inside the First Optics Enclosure (15 nC/s Injected Beam incident on the photon shutter, The safety shutters are open and the optics enclosure is secured)

5.2.2 Beam on Photon Shutter with Safety Shutters Closed

Figure 13 gives the total ambient dose equivalent rate distribution in the horizontal beam plane for 15 nC/s injected beam incident on the front end photon shutter as in 5.2.1 when the safety shutters are closed and the first optics enclosure is unsecured. The maximum dose rate 500 mrem/h at the exterior of the storage ring concrete wall is unchanged and occurs at the transverse location from the photon shutter on the experimental floor. This corresponds to ~0.14 mrem per injection pulse of 15 nC.

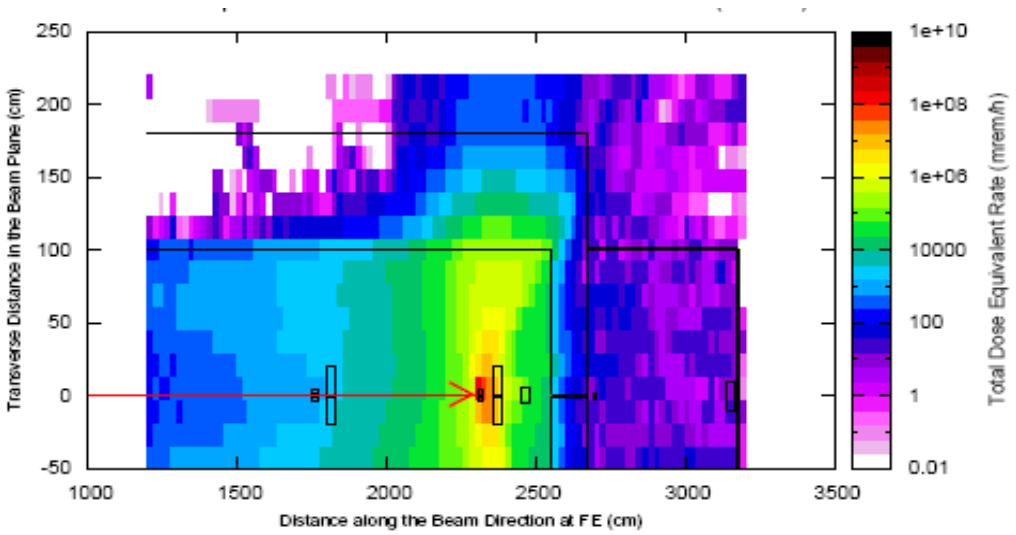

Figure 13. Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Ratchet Wall at the Beam Height (15 nC/s Injected Beam incident on the photon shutter and the safety shutter is closed)

Figure 14 gives the total ambient dose equivalent rate distribution along the exterior of the ratchet wall inside the first optics enclosure in the beam plane when the safety shutters are closed and the first optics enclosure is unsecured. For this scenario the users can be in the first optics enclosure. 15 nC/s Injected electron beam is incident on the photon shutter. The maximum dose rate inside the first optics enclosure is < 1.0 mrem/h showing that the safety shutters are providing adequate protection to the users inside the first optics enclosure during this beam loss incident.

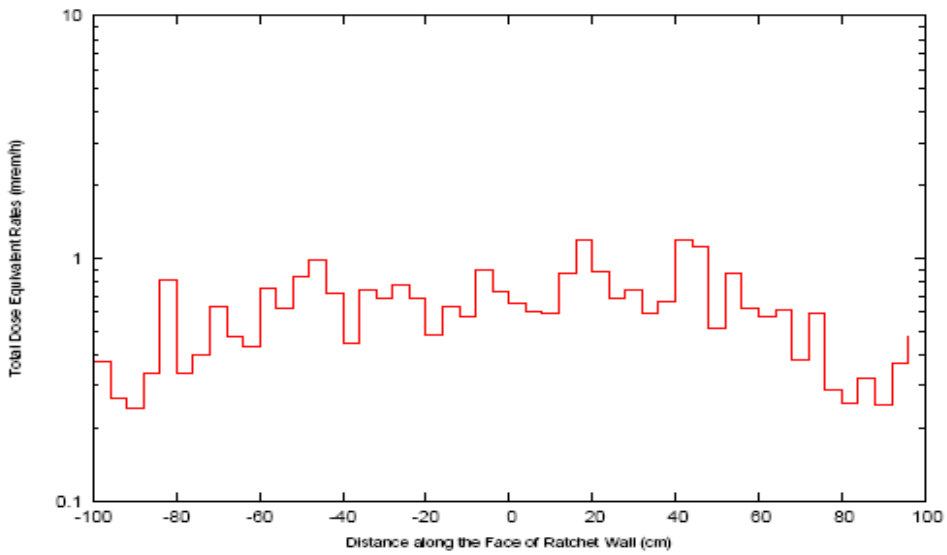

Figure 14 Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Ratchet Wall in the Beam Plane inside the First Optics Enclosure (15 nC/s Injected Beam incident on the photon shutter. The safety shutters are closed and the optics enclosure is unsecured)

The anticipated location of the interlocked area radiation monitors is close to the maximum dose location along the storage ring wall for this loss scenario and is expected to trip the beam within a few pulses of the injected beam loss. It can also be noted that the dose rates corresponds to an injection beam loss of 15 nC/s for one hour. The continuous injection capability without beam being stored will be limited at all situations by the engineered/administered controls; by the Loss Monitoring Control (LCM) system. The dose commitment to a person for any radiological incident will be limited to 10 mrem per incident.

5.3 Injected Electron Beam on a Mask in the First Optics Enclosure

The most serious radiological safety concern for the top-off injection with the safety shutters open is the scenario where electron beam could be conveyed down to the First Optics Enclosure (FOE) of the user beamline through the front end due to the erroneous combination of lattice magnetic field settings. It is important to ensure by redundant protection systems that such an event is an extremely remote possibility. At NSLS-II several layers of redundant engineering controls will be employed to mitigate this serious concern. Some of the engineered controls employed at other light sources are the presence of a stable stored beam in the storage ring during the top-off injection and interlocking critical lattice magnetic filed values within safe limits as determined by the particle tracking simulations. Interlocked sweeper magnets at the front ends, deflecting the errant beam away from the occupied regions, are also an attractive option. Radiological safety simulations to evaluate the dose consequences of such an incident have been carried out by FLUKA and the results are reported here.

Figure 15 Show the results of this simulation. The total ambient dose equivalent rate distribution in the horizontal beam plane is given when 15 nC/s injected electron beam enters the first optics enclosure (FOE) of the beamline. The FOE has a lateral wall of 1.8 cm and downstream wall of 5.0 cm of lead. There are two beamline components simulated inside the first optics enclosure, a copper mask at the exit port of the ratchet wall and a bremsstrahlung stop close to the downstream wall of the FOE. The errant beam of 15 nC/s is first intercepted by the copper mask

with a limiting beam aperture. The safety shutters are open and the FOE is secured. Nevertheless, the experimental floor around the FOE is a high occupancy region.

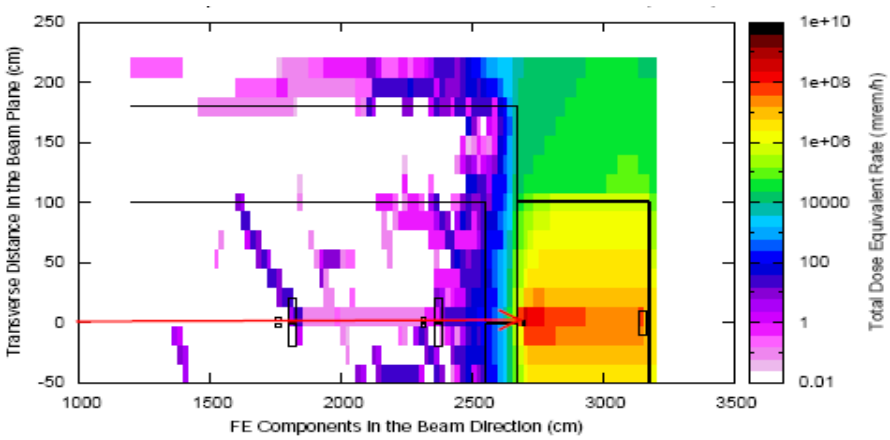

Figure 15 Total Ambient Dose Equivalent Rate Distribution in the Horizontal Beam Plane (15 nC/s Injected Beam incident on a copper mask in the first optics enclosure)

Figure 16 shows the same results plotted along the exterior of lateral wall of the first optics enclosure in the horizontal beam plane. The maximum total ambient dose equivalent rate at this region is > 100 rem/h due to the top-off injection beam loss in the first optics enclosure. This corresponds to ~30 mrem per pulse of the injected beam.

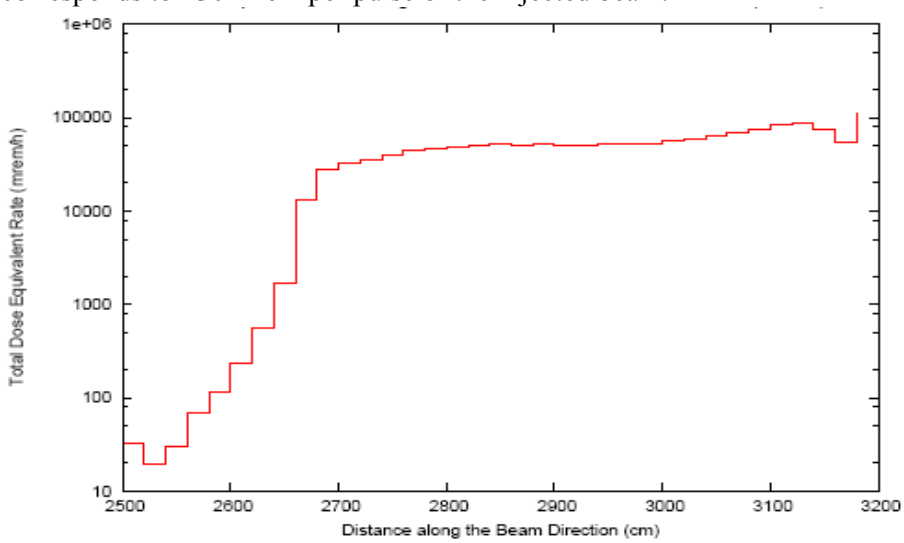

Figure 16 Total Ambient Dose Equivalent Rate Distribution along the Exterior of the Lateral wall of the First Optics Enclosure in the Horizontal Beam Plane (15 nC/s Injected Beam incident on a mask in the optics enclosure)

Figure 17 gives the neutron ambient dose equivalent rate distribution along the exterior of the lateral wall of the first optics enclosure (FOE) for the same scenario as in figure 16. The neutron rates are roughly 20% of the total dose rates at the upstream and as much as 50% at the downstream end of the FOE lateral wall.

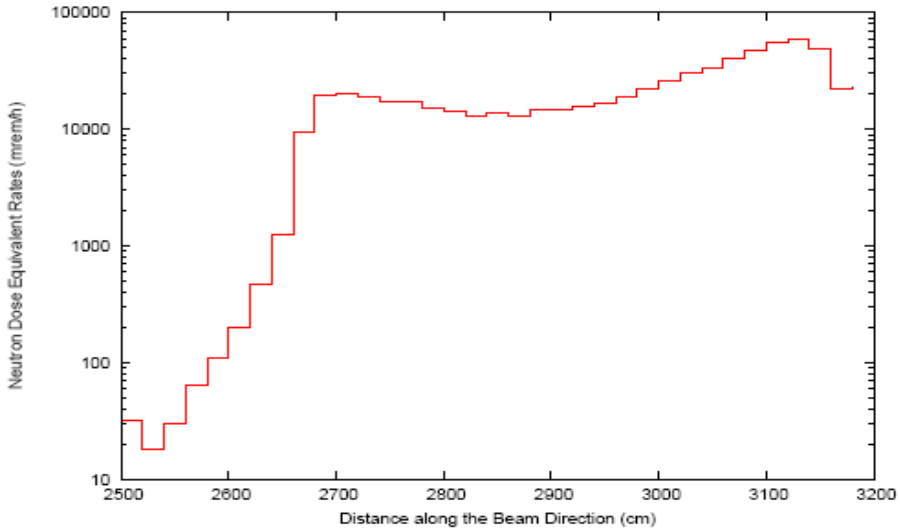

Figure 17 Neutron Ambient Dose Equivalent Rate Distribution along the Exterior of the Lateral wall of the First Optics Enclosure at the Beam Height (15 nC/s Injected Beam incident on a mask in the optics enclosure)

This accident scenario is made highly improbable by several engineered safety controls. The stored beam is expected to trip for the first errant pulse and the subsequent injections will be disabled. In addition to the stored beam condition and the magnetic field interlocks for the top-off injection, every operating first optics enclosure will have an interlocked area radiation monitor mounted on the exterior shield wall. An unaccepted dose scenario at the exterior of the first optics enclosure will also trip the safety shutters of the beamline.

6. Discussion of Results and Conclusions

Particle tracking simulations have shown that by a set of interlocking requirements of the storage ring lattice magnetic fields, an errant electron beam can be confined to the front end components during top-off injection. In the extreme situation, the full injected beam will be stopped by a mask or collimator at the front end within the storage ring. FLUKA Monte Carlo simulations have been carried out to calculate the radiation levels at the occupied regions of the experiment floor due to the injected electron beam incident on front end components like a fixed mask aperture or a photon shutter. Ambient dose equivalent rates at the experimental floor for 15 nC/s injected beam incident on these components have been evaluated. Radiological consequences of the unlikely scenario of injected electron beam entering the first optics enclosure, due to redundant interlock failures have also been evaluated.

In the event of a full injected beam loss of 15 nC/s at the front end fixed mask, the maximum ambient dose equivalent rate is < 500 mrem/h at the transverse direction from the mask along the exterior of the storage ring concrete wall. This corresponds to a dose commitment of ~0.14 mrem per injection pulse of 15 nC. The same is true for the scenario of the errant injected beam incident on the photon shutter. For this case the maximum dose rate occurs along the exterior of the storage ring wall at the transverse direction close to the photon shutter. The neutron dose rates are ~30-50% of the total dose rates for either case. The maximum dose rate for this beam loss scenario inside the first optics enclosure with safety shutters closed is < 1.0 mrem/h, showing that the safety shutters are providing adequate protection to the users inside the first optics enclosure even during an extreme beam loss incident inside the storage ring.

The anticipated location of the interlocked area radiation monitors is close to the maximum dose location for these loss scenarios and is expected to trip the beam within a few injected pulses. Interlocked radiation monitors provide adequate protection at these locations of the experiment floor. It can also be noted that the calculated dose rates are for an injected beam loss of 15 nC/s for one hour. The continuous injection capability without beam being stored will be limited at all situations by the engineered controls and the dose commitment to a person at the experimental floor for any beam loss scenario will be limited to 10 mrem per incident.

In the highly unlikely event of the full injected beam conveyed to the first optics enclosure (FOE) due to redundant interlock failures, the maximum total ambient dose equivalent rate along the lead wall of the first optics enclosure calculated by FLUKA is >100 rem/h. For this scenario the safety shutters are open and the FOE is secured. This corresponds to a maximum dose commitment of ~30 mrem per pulse of the injected beam loss. The neutron dose equivalent rates are roughly 20% of the total dose at the upstream and as much as 50% at the downstream end of the lateral wall of the FOE. This variation is due to additional photoneutron production from the downstream bremsstrahlung stop at the end of the enclosure. This accident scenario is made highly improbable by several engineered safety controls and the beam is expected to trip even for the first errant pulse. In addition, there will also be interlocked-radiation area monitors on the exterior of the lateral walls of the first optics enclosures which will trip the beamline safety shutters.

7. References

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