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ALARA Review of NSLS-II Shielding Design

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DISCLAIMER

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Introduction

Radiation exposure to staff and users as the result of National Synchrotron Light Source II (NSLS-II) operations must comply with Brookhaven National Laboratory (BNL) and Department of Energy (DOE) radiation requirements and must be maintained as low as reasonably achievable (ALARA). The purpose of this document is to review the basis for the design choices used to limit radiation exposure at NSLS-II and demonstrate that the shielding and other radiological design features have been effectively and optimally integrated into the design of NSLS-II facilities.

In particular, this analysis is intended to demonstrate that the following requirements from 10 CFR Part 835 have been adequately addressed:

Part 835 Sec. 835.1002 - Facility design and modifications.

During the design of new facilities or modification of existing facilities, the following objectives shall be adopted:

(a) Optimization methods shall be used to assure that occupational exposure is maintained ALARA in developing and justifying facility design and physical controls.

(b) The design objective for controlling personnel exposure from external sources of radiation in areas of continuous occupational occupancy (2000 hours per year) shall be to maintain exposure levels below an average of 0.5 mrem (5 microsieverts) per hour and as far below this average as is reasonably achievable. The design objectives for exposure rates for potential exposure to a radiological worker where occupancy differs from the above shall be ALARA and shall not exceed 20 percent of the applicable standards in Sec. 835.202.

(c) Regarding the control of airborne radioactive material, the design objective shall be, under normal conditions, to avoid releases to the workplace atmosphere and in any situation, to control the inhalation of such material by workers to levels that are ALARA; confinement and ventilation shall normally be used.

(d) The design or modification of a facility and the selection of materials shall include features that facilitate operations, maintenance, decontamination, and decommissioning.

Sources of Radiation Exposure at NSLS-II

Background - NSLS-II will be a synchrotron light source operating at 3 GeV with a maximum stored beam of 500 mA. The storage ring will be supplied with electrons from a 200 MeV linac and a 3 GeV booster synchrotron. The injection system can deliver 15 nC/s when initially filling the ring, but will normally provide ~ 15 nC/pulse when topping off the storage ring about once/minute.

Electron storage rings are in wide use throughout the world for this purpose and sources of occupational radiation exposure to workers at these facilities are well known. Radiation exposure to workers or the public is almost entirely from external exposure occurring during operation. Because the overall power associated with the NSLS-II accelerators and storage ring is very small compared to that associated with a high intensity accelerator, activation hazards are in general low. As an example, the highest levels observed from induced activity at the existing NSLS (operating since 1983) are typically in the few tens of μrem/hr at contact with a few locations at a few mrem/hour, many of these latter locations decreasing rapidly over time after the electron beam has been turned off.

Although low, activation hazards have been evaluated and documented in detail in reference 1, including:

- Exposure to residual radiation induced in machine components and beam dumps
- Inadvertent release of activated cooling water to the environment
- Inadvertent release of radioactive contamination to groundwater by allowing rainwater to leach through activated soil
- Exposure to activated air.

The remainder of this review will focus on the potential for exposure from direct radiation penetrating the shielding and the design criteria used in determining the shield thickness for the accelerator and photon beam lines.

Sources of external radiation which must be shielded are generated at electron loss points within the accelerator and at photon scatter points in beam lines. In preparing the design, the locations of loss points were identified and estimates of electron losses were developed in conjunction with the accelerator physicists responsible for the design (see reference 2).

Dose Assessment and Optimization Analysis

Part 835.1002 requires that the shield design objective for controlling personnel exposure from external sources of radiation in areas of continuous occupational occupancy (2000 hours per year) shall be to maintain exposure levels below an average of 0.5 mrem (5 microsieverts) per hour and as far below this average as is reasonably achievable. The design objectives for exposure rates for potential exposure to a radiological worker where occupancy differs from the above shall be ALARA and shall not exceed 20 percent of the applicable standards in Sec. 835.202.

NSLS-II operation will produce external radiation levels above background in the following locations: (a.) Ring Building, (b.) RF Building, (c.) Injection Building, (d.) Bermed areas above linac and booster. Only the Ring Building will have a continuous occupancy throughout the year and is the focus of this analysis (see attachment A for occupancy assumptions). The other locations will have intermittent occupancy. The bermed areas will have minimal occupancy during operations and will be restricted as necessary to limit the potential for exposure.

The design objective used to shield all of these loss locations is 0.5 mrem/h during normal operations in contact with the exterior surface of the closest shield wall, thereby satisfying the first part of the section 835.1002 requirement for continuously occupied locations. It is worth noting that the calculations determining the required shield thicknesses were performed using a conservative set of assumptions for the following factors:

- Beam losses are assumed to occur at a single point (rather than scattered and distributed over a more lengthy surface)
- The most conservative attenuation lengths in shield material are used
- Doses are calculated using thick target dose equivalent factors
- Electron loss estimates are conservatively picked and are based on a 2 hour life time (rather than the expected 3 hour life time)
- No credit is taken for self-shielding associated with internal accelerator components.

Measurements made at the European Synchrotron Radiation Facility comparing actual radiation levels to calculated levels based on a similar set of assumptions determined that predicted levels were conservative by a factor of 10 – 20 for their facility.

Ring Building

It should be noted again that only the Ring Building has a continuous occupancy. In order to satisfy the ALARA criterion, we need to evaluate the total dose that would be saved if a lower design criterion was used and compare that to the additional costs that are incurred in increasing the shield thickness. If the value of the dose saved is less than the cost of increased shielding, then the additional costs can be viewed as not warranted and the shield considered to be optimized. The dose savings for 5000 hours of user program and 800 hours of accelerator physics studies are included. The details of the ALARA optimization calculation are given in attachments A and B.

Accelerator Enclosures

Using the occupancy and operating assumptions described in attachment A, the 30 year integrated dose equivalent resulting from NSLS-II normal operations and machine studies is estimated in attachment B to be ~ 175 rem for a shield designed to 0.5 mrem/h. The saved dose for designing to 0.25 mrem/h is ~89 rem. The value of the saved dose is $946,000 and the cost of increasing the shield thickness to reduce radiation levels to 0.25 mrem/h is ~$1,800,000[1]. It is concluded that the dose saved by shielding to 0.25 mrem/h does not warrant the additional costs; and the shield design can be considered optimized.

There is one small portion of the Ring Building affected by the higher losses in the injection region. A separate analysis is performed in attachment B which indicates that supplemental shields are cost effective for the injection region and should be provided to reduce radiation levels to 0.5 mrem/h in this area during 1 hz injection periods.

Hutch Shields

Using the occupancy and operating assumptions described in attachment A, the 30 year collective dose equivalent for 58 beam lines resulting from a 5000 hours per year operating schedule is ~ 10750 person-rem for experimental end stations (typically called mono stations) and the First Optical Enclosure (FOE) hutches designed to 0.5 mrem/h. The 30 year collective dose for hutches designed to 0.05 mrem/h is ~ 1075 person-rem. The saved dose for designing to 0.05 mrem/h is ~9675 person-rem. The value of the saved dose is $106,000,000 and the cost of increasing the shield thickness in both FOE and the mono-hutch to reduce radiation levels to 0.05 mrem/h is ~$1,450,000. It is concluded that the dose saved by shielding the hutches to 0.05 mrem/h is quite substantial and worth the increased costs. The hutches will be shielded to 0.05 mrem/h.

Conclusion

Based on the analysis summarized above, we conclude:

I. The concrete bulk shield for the storage ring designed to 0.5 mrem/h complies with the requirements defined in Part 835.1002 and is ALARA.

II. Supplemental lead shields provided in the injection region which reduce radiation levels to 0.5 mrem/h complies with requirements defined in Part 835.1002 and is ALARA.

III. The lead shielding in the beam line hutches designed to 0.05 mrem/h complies with the requirements defined in Part 835.1002 and is ALARA.

[1] Total cost of concrete based on increasing the thickness of concrete shielding in walls and roof by 15 cm. This cost is based on estimates provided by the NSLS-II Conventional Facilities Division.

IV. The estimated total annual dose for the facility designed to these criteria is ~39.3 person-rem with an average dose per worker/user assuming 3500 workers of ~ 11 mrem.

It is worth noting that there have been two design reviews of the proposed NSLS-II shields by a knowledgeable group from other synchrotron radiation sources to assure that the shielding methodology and assumptions are reasonable and consistent with international practices. The Review Committee concluded that the proposed shields are reasonable and consistent with designs at other facilities.

Administrative Controls to Maintain Exposure ALARA During Operations

There are a number of programs that will be in place when NSLS-II operates to ensure the effectiveness of shielding and control of radiation exposure.

Accelerators and beamlines will be subject to an initial commissioning period under highly controlled conditions to confirm that adequate shielding consistent with the shielding policy is provided. Set-points for interlocked radiation monitors and beam loss monitors will also be established during commissioning to ensure that fault conditions are detected and interlocked in a manner consistent with the shielding policy.

The on-going effectiveness of shielding will be actively monitored by radiation instruments located on the experimental floor and other locations, and by frequent area-surveys performed by the health physics personnel. Additional local shielding will be provided to reduce the radiation field as needed. Passive area monitors will also be used to integrate doses in various areas. The results will be analyzed for trends, and shielding will be improved in the form of supplementary shielding as appropriate.

The work areas adjacent to the accelerator enclosures (Linac, Booster, Storage Ring) and beam lines, including the Service Buildings, will be posted as radiologically Controlled Areas. The tunnel providing access to the inner area of the site and the berms adjacent to the Linac and Booster may also be posted. Posting requirements will be determined during machine commissioning. Proper radiation and facility specific training will be required for access to all posted areas. During the initial years of commissioning and operation, a radiation dosimetry badge will be issued for all personnel working in the Controlled Areas. It is expected that following verification of shielding effectiveness that short-term users and visitors will not be required to wear a dosimeter while on the experimental floor. This verification process is expected to take 2 – 3 years. Access into the Controlled Areas will be controlled through the use of card readers (or other similar controlling device) at access points to the building. Areas within the Controlled Areas may have additional postings such a Radioactive Material Areas and Radiation Areas, as required. Direct access to either the electron or synchrotron beams will be prevented by the use of radiation safety interlocks described in the Preliminary Safety Assessment Document (PSAD). Although not frequently needed at the NSLS, Radiological Work Permits (RWP) will be issued by Radiological Control Division personnel as required in accordance with the criteria in the BNL Radiological Control Manual.

A radiation monitoring program will be established in the Controlled Areas to protect workers and to assure that their doses are kept ALARA. Radiation surveys will be performed to assure that proper shielding is in place, to monitor machine operations and to assure the containment of sealed sources or experiment samples. Different types of radiation monitoring will occur at NSLS-II, e.g. personal dosimetry (e.g. Thermoluminescent Devices or TLDs), passive area dosimetry (e.g. TLDs), active area monitors with local and remote read-out to the Control Room, and hand-held survey instruments used by trained personnel.

References

1. Preliminary Activation Analysis of Soil, Air and Water near the NSLS-II Accelerator Enclosures; P.K. Job and W.R. Casey, NSLS-II Technical Note 50, August 15, 2008

2. Shielding Requirements for NSLS-II, P.K. Job and W.R. Casey, BNL-79774-2008-CP, January 2008

Attachment A

Operating and Occupancy Assumptions for ALARA Design Review

I. Operating conditions

Energy – 3 GeV

Stored Current – 500 mA

Life-time – 2 hours

5000 hours per year for user program

- Top-off every 72 secs to keep current at or near 500 mA
- 200 complete fills per year

Accelerator Physics – 1000 hours per year

- 200 hours per year at 1 hz injection rate and maximum injection current (15 nC/s)
- 800 hours per year for other studies at conditions similar to normal operation (i.e. 500 mA stored beam, top-off operation 1 pulse per minute top off

II. Anticipated Occupancies around Storage Ring

A. During User program

The highest occupancies on the floor will occur during the operating periods in which the user program is on-going. In order to estimate the potential radiation exposure that will take place during the user program, estimates of occupancies must be assumed as described below. For analysis purposes we assume the occupancies described below. These estimates are conservative and maximize the potential occupancies and radiation exposure. It should be noted that the occupancies for the users and NSLS-II beam line staff is much higher than that of the NSLS-II operating staff. NSLS-II operating staff (e.g. members of the RF Group, power supply group, interlock group) are not routinely on the floor, but rather enter the building to adjust or trouble shoot components during studies or normal operations to seek to improve performance. Higher occupancies are assumed for members of the ESH Group and floor coordinators who have a greater routine presence on the floor.

Group 1- beam line staff & users at mono-chromatic end-station

Assumptions: We assume 3 personnel per beamline located at an average distance of 30 cm from an end station wall. We assume 58 beamlines in operation located at an average distance of 10 meters from the storage ring wall. We assume 5000 hrs/y occupancy with storage ring operating.

Hutch wall is 1 m from beam line scatter point
0.05 x (100/130 cm)^2 = 0.03 mrem/h dose rate from the beamlines
0.5 mrem/h x (2/12)^2 = 0.014 mrem/h dose rate from the storage ring

Group 2 – beam line personnel performing maintenance in FOE while storage ring operating

Assumptions: Periodically beam line personnel must enter the FOE to perform install, adjust or maintain equipment within the enclosure. Such entry requires that the beam line be secured by shutting the safety shutter. Therefore such work will normally be done during scheduled accelerator maintenance periods in order to maximize beam line productivity, therefore we assume only a 10% occupancy during the standard 5000 hour operating year. We assume 2 personnel at each of 58 beamlines working 30 cm from the storage ring wall for 500 hrs/y with accelerator operating and beam line off

0.5 x (2/2.3)^2 = 0.38 mrem/h dose rate from the storage ring

Group 3 – infrared beam lines

Assumptions: We assume 3 Infra-Red scientists per beamline, 6 beamlines with occupancy at 1 m from wall and 4 beamlines at 10 meters from the storage ring wall. We assume 5000 hrs/y occupancy with storage ring operating

0.5 x (2/3)^2= 0.22 mrem/h dose rate for 6 beamlines
0.5 mrem/h x (2/12)^2 = 0.014 mrem/h dose rate for 4 beamlines

Group 4 – Beam line personnel working on top of FOE while beam line is in operations

Assumptions: Provisions are made for use of the top of the FOE for storage. We assume that there will be need intermittently during beam line operations for personnel to place or retrieve equipment from the hutch top. We assume a total of 5% of the operating cycle as the occupancy on the top and that the person is kneeling down rather than standing. We also assume that the person accesses the hutch by walking on the mezzanine. Therefore, we have 1 person per beamline, 58 beamlines, 30 cm from the hutch top. 250 hours per year on hutch-top; 25 hours per year on mezzanine traveling to hutch top – 1 m from mezzanine floor

0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine for 25 hrs/y
0.05 x (1.5/1.8)^2 = 0.035 mrem/h dose rate at 30 cm from the hutch top for 250 hrs/y.

Group 5 – Members of the Power Supply Group

Assumptions: We assume a maximum of 2000 person hours per 5000 hour operating year on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 6 – Members of the Vacuum Group

Assumptions: We assume a maximum of 2000 person hours per 5000 hour operating year on the mezzanine working at an average distance of 1 meter from the floor.

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 7 – Members of the Insertion Device Group

Assumptions: We assume a maximum of 100 person hours per 5000 hour operating year on the mezzanine working at an average distance of 1 meter from the floor.

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 8 – Members of the Interlock Group

Assumptions: We assume a maximum of 100 person hours per 5000 hour operating year on the mezzanine working at an average distance of 1 meter from the floor.

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 9 –Floor Coordinators, health physics staff and ESH personnel

Assumptions: We assume a maximum of 2500 person hours (5 people at 500 hours each) per 5000 hour operating year working at a distance of 1 m from the SR wall and mezzanine floor. We also assume a maximum of 500 person hours per 5000 hour operating year (5 people at 100 hours each) working at a distance of 30 cm from endstation and also from FOE.

Dose rate on mezzanine at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter

Dose rate at 30 cm from hutch at 0.05 mrem/h criteria = 0.05 x (100/130 cm)^2 = 0.03 mrem/h dose rate

B. During Accelerator Physics studies

Occupancies on the experimental floor during accelerator studies will be much lower than occupancies during the normal user program since beam lines are not available for use in the research program. However, it is assumed that some personnel will be present to set up for future work and to make adjustments to beam line and research equipment. These estimates are based on current experience at NSLS and other light sources and are judged to be conservative estimates.

i. High current, fast injection studies assumed for 200 hours/per year

Group 1- beam line staff & users at mono-chromatic end-station

Assumptions: We assume 1 person for every other beamline working at a distance of 10 meters from the storage ring wall for a total of 29 people working during the 200 hours.

30 mrem/h x $(2/12)^2$ = 0.83 mrem/h dose rate from the storage ring

Group 2 – beam line personnel performing maintenance in FOE while storage ring operating

Assumptions: We assume 1 beam person per every other beam line for a total of 29 people working in FOEs at a distance of 30 cm from the storage ring wall. We assume FOEs are occupied for 100 hours during accelerator studies.

30 x $(2/2.3)^2$ = 22.7 mrem/h dose rate from the storage ring

Group 3 – infrared beam lines

Assumptions: We assume 1 infrared beamline scientist for every other beamline, a total of 3 people working at 1 meter from the storage ring wall and 2 people working at 10 meters from the storage ring wall. We assume 200 hrs/y occupancy.

30 x $(2/3)^2$= 13.3 mrem/h dose rate for 6 beamlines
30 mrem/h x $(2/12)^2$ = 0.83 mrem/h dose rate for 4 beamlines

Group 4 – Beam line personnel working on top of hutch during studies

Assumptions: We assume 1 person for every other beamline, a total of 29 people exposed for 10 hours on the hutch top during high injection studies. We also assume 1 hour on mezzanine traveling to hutch top at 1 m from mezzanine floor

30 x $(3/4)^2$ = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine for 25 hrs/y

Group 5 – Members of the Power Supply Group

Assumptions: We assume a maximum of 80 person hours on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 30 x (3/4)^2 = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 6 – Members of the Vacuum Group

Assumptions: We assume a maximum of 80 person hours on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 30 x (3/4)^2 = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 7 – Members of the Insertion Device personnel

Assumptions: We assume a maximum of 4 person hours on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 30 x (3/4)^2 = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 8 – Members of the Interlock Group

Assumptions: We assume a maximum of 4 person hours on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 30 x (3/4)^2 = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 9 – Members of the Floor Coordinators, health physics staff and ESH personnel

Assumptions: We assume a maximum of 100 person hours working at a distance of 1 m from the SR wall and mezzanine floor.

Dose rate at 0.5 mrem/h criteria = 30 x (3/4)^2 = 16.9 mrem/h dose rate from the storage ring at 1 meter on mezzanine

ii. 1 pulse/min injection assumed for 800 hours/per year

Group 1- beam line staff & users at mono-chromatic end-station

Assumptions: 1 person for every other beamline working located at a distance of 10 meters from the storage ring wall. A total of 29 people working for 800 hours during accelerator studies

0.5 mrem/h x (2/12)^2 = 0.014 mrem/h dose rate from the storage ring

Group 2 – beam line personnel performing maintenance in FOE while storage ring operating

Assumptions: 1 beam person per every other beam line. A total of 29 people working in FOEs at a distance of 30 cm from the storage ring wall. FOEs are occupied for 400 hours during accelerator studies.

0.5 x (2/2.3)^2 = 0.38 mrem/h dose rate from the storage ring

Group 3 – infrared beam lines

Assumptions: 1 Infrared beamline scientist for every other beamline, a total of 3 people working at 1 meter from the storage ring wall and 2 people working at 10 meters from the storage ring wall. 800 hrs/y occupancy during accelerator physics studies.

0.5 x (2/3)^2= 0.38 mrem/h dose rate for 6 beamlines
0.5 mrem/h x (2/12)^2 = 0.014 mrem/h dose rate for 4 beamlines

Group 4 – Beam line personnel working on top of hutch during studies

Assumptions: 1 person at every other beamline, a total of 29 people exposed for 50 hours per year on the hutch top. 5 hours per year on mezzanine traveling to hutch top – 1 m from mezzanine floor

0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine for 25 hrs/y

Group 5 – Members of the Power Supply Group

Assumptions: a maximum of 320 person hours on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 6 – Members of the Vacuum Group

Assumptions: a maximum of 320 person hours per year on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 7 – Members of the Insertion Device personnel

Assumptions: a maximum of 16 person hours per year on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 8 – Members of the Interlock Group

Assumptions: a maximum of 16 person hours per year on the mezzanine working at an average distance of 1 meter from the floor

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

Group 9 – Members of the Floor Coordinators, health physics staff and ESH personnel

Assumptions: A maximum of 400 person hours working at a distance of 1 m from the SR wall and mezzanine floor.

Dose rate at 0.5 mrem/h criteria = 0.5 x (3/4)^2 = 0.28 mrem/h dose rate from the storage ring at 1 meter on mezzanine

III. Comparison of Accelerator Physics Studies on Shielding Requirements

Based on these assumptions identified in I. above, we can calculate the total number of electrons/year accelerated and lost in ring. This parameter is a key factor in determining the adequacy of the shield.

Electrons lost during User Program

200 fills per year = 200 x 1.3 μC / fill = 2.6 x 10^2 μC/y → 2.6 x 10^2 x 6.24 x 10^{12} e/μC = 1.62 x 10^{15} electrons per year injected and lost per year

With 2 hour life and 500 mA beam we will lose ~ 11 nC/min

If injection efficiency is 80%, we must inject 13.2 nC/min

Total number of electrons injected and lost over 5000 hours of stored beam is:

5000 hours/y x 60 min/h x 13.2 nC/min = 3.96×10^6 nC/year lost during stored beam =

3.96×10^6 nC/year x 6.24×10^9 e/nC = 2.47×10^{16} electrons per year lost

Total number of electrons lost during user program are $1.62 \times 10^{15} + 2.47 \times 10^{16} =$

2.63×10^{16} per year

Accelerator Physics Studies

Assume 200 hours of 1 hz injection studies

200 hours/y x 3.6×10^3 s/h x 15 nC/s injected x 6.24×10^9 e/nC = 6.74×10^{16} electrons per year lost

Assume that the other 800 hours are at 1 injection /min rate

800 hours/y x 60min/h x 15 nC/min injected x 6.24×10^9 e/nC = 4.49×10^{15} electrons per year lost

Total electron/yr lost during accelerator physics studies = $6.74 \times 10^{16} + 4.49 \times 10^{15} = 7.19 \times 10^{16}$

Conclusion: Over the course of the year, electrons lost during accelerator physics studies have the potential to be higher than the total losses that occur during the user program. The potential for radiation exposure during accelerator studies will depend on the nature of the studies and the occupancies on the experimental floor during the accelerator studies. Accelerator studies are normally scheduled well in advance and many participants in the normal user program will not be present since beam lines are not available during studies. Occupancy assumptions used in our calculations during accelerator study periods are therefore much lower than normal operating periods.

However, as indicated in the analysis above for electrons accelerated per year, it is clear that high intensity injection studies have the potential to produce higher radiation levels in occupied areas. During the early years of commissioning and operations, 1 hz injection periods will likely be needed to establish operating parameters that permit achievement of design goals for accelerator performance. Because of the potential for higher radiation levels during prolonged 1 hz injection studies, all accelerator studies will require work planning and administrative control of occupancy, particularly in areas located near the storage ring wall (including work conducted inside the FOE) and on the mezzanine floor. Such restrictions will be most probable when initial commissioning of the ring is conducted, and periodically, but not frequently during the remainder of the operating life-time of the facility (such as recovery of vacuum after bleed-up periods). Because of the special controls that will be applied and the unpredictable forecasting of prolonged 1 hz injection over the 30 year history of the facility, the potential radiation exposure of 1 hz operation is not included in the estimates of total integrated dose for the facility. The total integrated dose does include the estimates of dose received during 800 hours of accelerator studies conducted at normal operating parameters.