Radiological Implications of Top-up Operation at Canadian Light Source: Dose Computations and Measurements at the Vulnerable Points

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Abstract

The Canadian Light Source (CLS) is a third generation synchrotron light source operating with a 2.9 GeV electron beam. The facility includes a linac that generates a 250 MeV electron beam at 1 Hz frequency. A transfer line transports the electron pulses to a booster ring where the electron energy is increased to 2.9 GeV. A second transfer line transports the electrons to the storage ring where a beam current of up to 250 mA is accumulated at present. However, the design of the facility suggests that it can be operated at 500 mA. The circulating electron beam while passing by a bending magnet or through an insertion device creates synchrotron light that is currently used at 14 beam lines with different photon flux and energy outputs.

The CLS facility operates in 'Decay Mode', where the storage ring is filled every 8 to 12 hours to a maximum operating current that decays through random loss of electrons as the stored beam circulates. The injection cycle requires about 10 minutes. While by keeping the beam-line front end safety shutters closed during the injection cycle, it provides radiation protection with minimum heat load to the beam-line optics, however, the beam-lines are not only available during the injection cycle, but they also require as much as an hour to reach thermal equilibrium after the front end shutters re-opened. We are evaluating the consequences of switching to the 'Top-up' injection mode where the safety shutters remain always open thus providing an opportunity to continuous use of the beam-lines. In the 'Top-up' mode, the stored beam current will be kept at the maximum operating current by 'topping up' the storage ring, typically once in a minute with one or two injection pulses.

The radiological risk due to the open shutters during injection could be enhanced as there is possibility that the pulse of injected electrons might travel down through the front end of a beam line into a primary optical enclosure (POE). The POEs at CLS have been designed to ensure that they are adequate to contain synchrotron and gas Bremsstrahlung [BRM] radiation generated from a 500 mA stored beam, and also for a single event of a loss of the 500 mA beam. The consequences of an injected pulse of electrons entering a POE are being evaluated now considering the following three beam loss cases.

Case 1: 500 mA Stored Electron Beam Terminated at Storage Ring (SR) Vacuum Valve
Case 2: 1 nanoCoulomb (nC) Injected Electron Pulse Enters a POE
Case 3: Single Point SR Beam Loss – forward peaked BRM enters POE and Scattered by a thick target.

The dose computations were made using analytical equations [1, 2] for the vulnerable locations outside the POEs for all the 14 beam-lines for the above three beam loss scenarios. The computation includes doses resulting from BRM, giant resonance, medium energy, and high energy neutrons for the chosen dose points, such as POE back-wall for both case 1 and case 2, and POE roof & side-wall for case 2. For case 3, the same equations were used and the dose was determined only from the Bremsstrahlung and for the POE roof & side-wall dose points.

During the development mode shifts of first quarter 2015, Top-up radiation measurements were conducted at half a dozen beam lines, where Active Area Radiation Monitors (AARM) set-up at

each beam line recorded the radiation dose during the test, supplemented by handheld dosimeter measurements that were made at several locations around the enclosures.

The above-mentioned preliminary results that were presented at the RadSynch15 Workshop at DESY-Hamburg indicated that performing Top-up operation at the CLS may impact the radiation levels in the occupied areas outside the beam-line POEs if an injected electron pulse travels down the beam-line front end. Although the probability of such an occurrence is very low, enabling a hardwired shutdown of the injection process by the existing AARMs will ensure that CLS will maintain radiation exposure levels below the designated 1 mSv dose limit for the worst case accident scenario, and continue to maintain radiation exposures to personnel ALARA.

1. INTRODUCTION

The Canadian Light Source Inc (CLSI) is desirous of operating the synchrotron radiation beam lines on a continuous basis, which requires the electron beam injection from the linac to the storage ring via the booster ring, by keeping the front end safety shutters open [3]. The CLSI Safety Report [4] has been compiled with all the safety aspects of CLS normal operation, which clearly established that the existing bulk shielding placed throughout the facility was effective at mitigating the radiation hazard to personnel. However, in normal modes of operation, the safety shutters remained closed during the injection periods. The CLS shielding design goals include a maximum radiation dose of 1 mSv to any person as a result of any worst case accident scenario, and 5 μSv cumulative hourly radiation dose to any worker, user, or contractor in a controlled access zone during normal operation. The safety analysis also determined that the natural losses resulting from an operating storage ring current of 500 mA would not produce radiation levels exceeding the design goals in the occupied areas of the facility during normal operation.

In the document Hazard Analysis of injection with the Safety Shutters Open [5], it was determined that the risk of radiation exposure to personnel during injection with the safety shutters open required a theoretical evaluation to ensure that the radiation levels still remain within the original shielding design objectives. The theoretical evaluation has been completed in the following two parts.

A particle tracking review of the probability of electrons being injected into a CLS front end has been completed using the computer code DIMAD. The report [6] concluded that the probability of electrons being transferred down a front end into a beam line enclosure was impossible during normal operation, and highly improbable during an accident scenario.

This document investigates the radiological consequences of ‘worst case’ scenarios for the electron beam injection with the synchrotron radiation beam line safety shutters open. The theoretical evaluation method that was used earlier in the Safety Report [4] is extended in this report. The radiological hazards are evaluated using analytical equations originally derived from Swanson et. al. [1] and developed further by Moe [2].

2. BACKGROUND

The Canadian Light Source (CLS) is a third generation synchrotron light source operating with a 2.9 GeV electron beam. The facility includes a linac that generates a 250 MeV electron beam at 1 Hz frequency. A transfer line transports the electron pulses to a booster ring where the electron energy is increased to 2.9 GeV. A second transfer line transports the electrons to the storage ring where a beam current of up to 250 mA is accumulated at present. However, the facility is designed to allow operation of upto 500 mA stored beam. The circulating electron beam while passing by a bending magnet or through an insertion device creates synchrotron light that is currently used at 16 beam lines with different photon energy outputs.

The normal mode that the CLS facility is currently in operation is typically a 'Decay Mode'. In Decay Mode, after the storage ring is filled to a maximum operating current, the electron beam is allowed to 'decay' through random loss of electrons as the stored beam circulates. Every 8 – 12 hours, when the stored beam level has fallen by about 40%, an injection cycle is initiated to refill the stored beam to the maximum operating current. The injection cycle lasts about 10 minutes. The beam-line front end safety shutters are closed during the decay mode injection cycle. By closing the safety shutters, the heat load on beam-line optics due to radiative particle bombardment is minimized. The following Figure 4 shows the effect of current decay and injection on the stability on the liquid nitrogen cooled double crystal monochromator at the HXMA beam line [7]. A change in e-beam current will cause a proportional change of heat load on beamline optics affecting their thermal mechanical stability. A stable beam current will minimize the effects of changing heat load. This can ultimately improve photon position and energy stability for a beamline. As a result, the beam-lines are not only unavailable during the injection cycle, but they also require as much as an hour to reach thermal equilibrium after the front end shutters are re-opened. The possibility of switching to an injection mode where the safety shutters remain open would increase the effective operational beam time with all the beam-lines significantly.

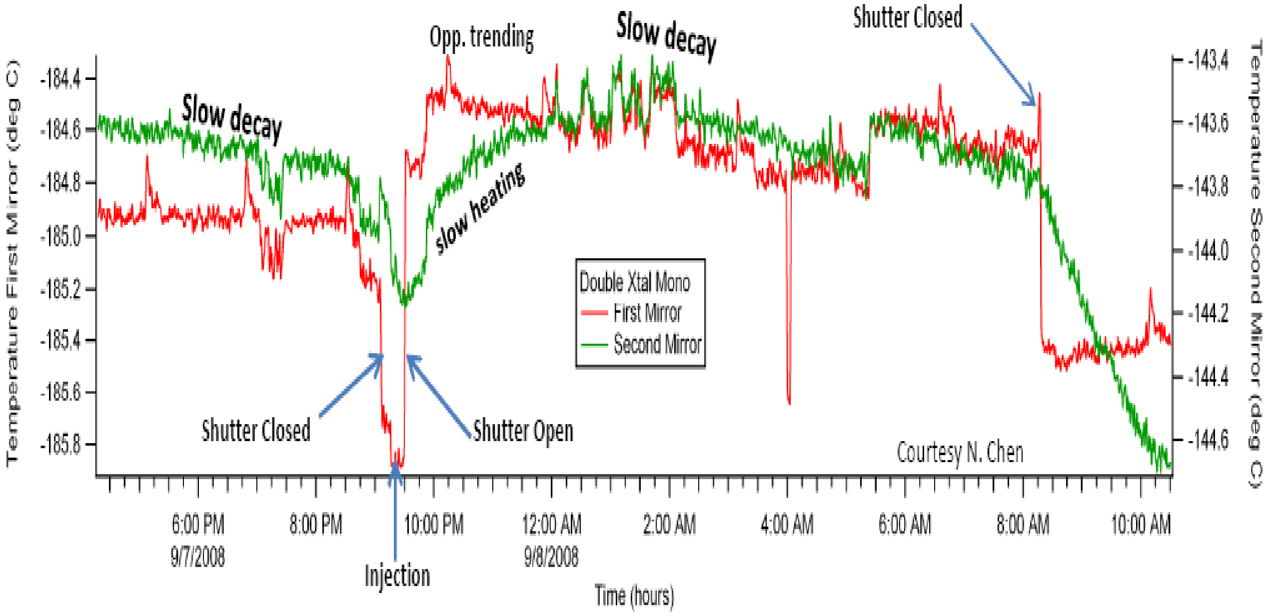


Figure 4: Temperature behavior of HXMA double crystal monochromator over 24 hrs

Injection with the safety shutters open is expected to be performed in one of two operational modes. In one mode, the injection will be performed every 8 – 12 hours as is the current practice, but the safety shutters will remain open. In the other so called 'Top-Up' mode, the stored beam current will be kept close to the maximum operating current by 'topping up' the storage ring, typically once in a minute with one or two injection pulses.

For both the injection modes with the shutters open, the radiological risk is different than the decay mode due to the possibility that a pulse of injected electrons might, in a highly improbable case, travel down to the front end of a beam line into a primary optical enclosure (POE). The POEs at CLS have been designed and tested to ensure that they are adequate to contain synchrotron and gas bremsstrahlung radiation generated from a 500 mA stored beam, and also for a single event of a loss of the 500 mA beam [4]. The consequences of an injected pulse of electrons entering a POE are evaluated in this report.

3. RADIATION SHIELDING ANALYSIS

Three beam loss conditions were considered for the dose calculations. Beam loss conditions were chosen that can occur now, as well as the additional conditions during top-up, to provide a comparison of decay and top-up modes.

3.1 BEAMLOSS CONDITIONS

Case 1: 500 mA Stored Electron Beam Terminated at SR1 Vacuum Valve

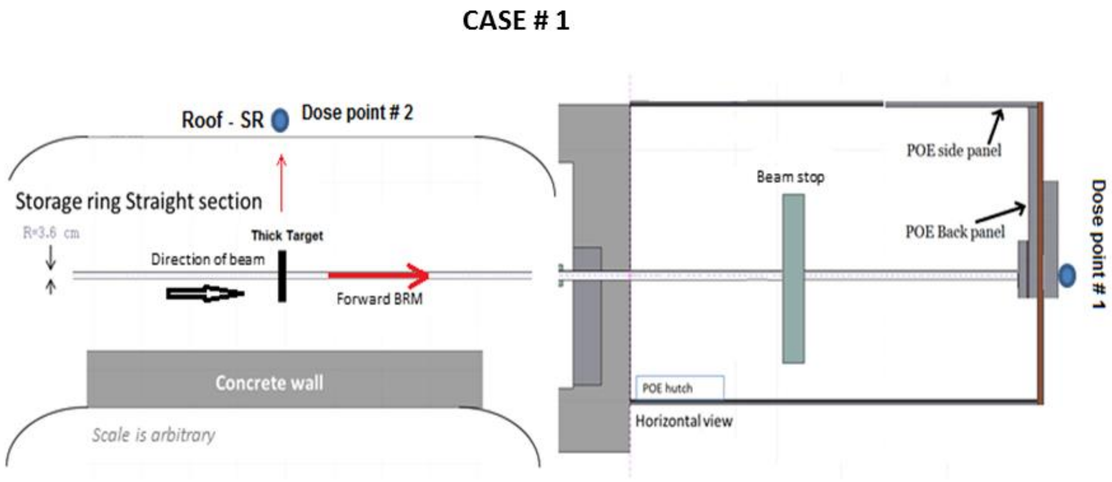


Figure 1 - Beamloss Case #1

This case may occur in either Top-Up or Decay modes. In this analysis, 500 mA of stored beam in the storage ring is allowed to hit a vacuum valve at the middle of a straight section and is completely lost at one point. The vacuum valve is assumed to be equivalent to a 'thick target' that is made of iron. The total amount of energy released is 827 Joules. The radiation dose from the resulting Bremsstrahlung (BRM) radiation and neutrons was estimated at two different angles:

(a) 90 Deg: The perpendicular component of the BRM and neutrons hits the ceiling of the SR and the dose is estimated outside of SR roof. SR roof is made of concrete with a thickness of 60 cm that is uniform at all locations. Therefore, the dose for SR roof was calculated only at one location.

(b) 0 Deg: Highly forward peaked BRM radiation and neutrons enter the nearest POE with the FE SSH open and hit the 'brem-stop' inside the POE. The resulting doses were calculated at a point outside of the POE back wall (BW).

<u>Case 2</u>: 1 nanoCoulomb (nC) Injected Electron Pulse Enters a POE

This beam-loss may happen during Top-up injection with the BL FE SSH open. In this analysis, the average charge that is extracted from the booster to the storage ring (BTS) line per injection equals to 1 nC or 6.25×10^9 electrons. The radiation dose is calculated based on 100% loss of the injected beam at a thick target within the POE.

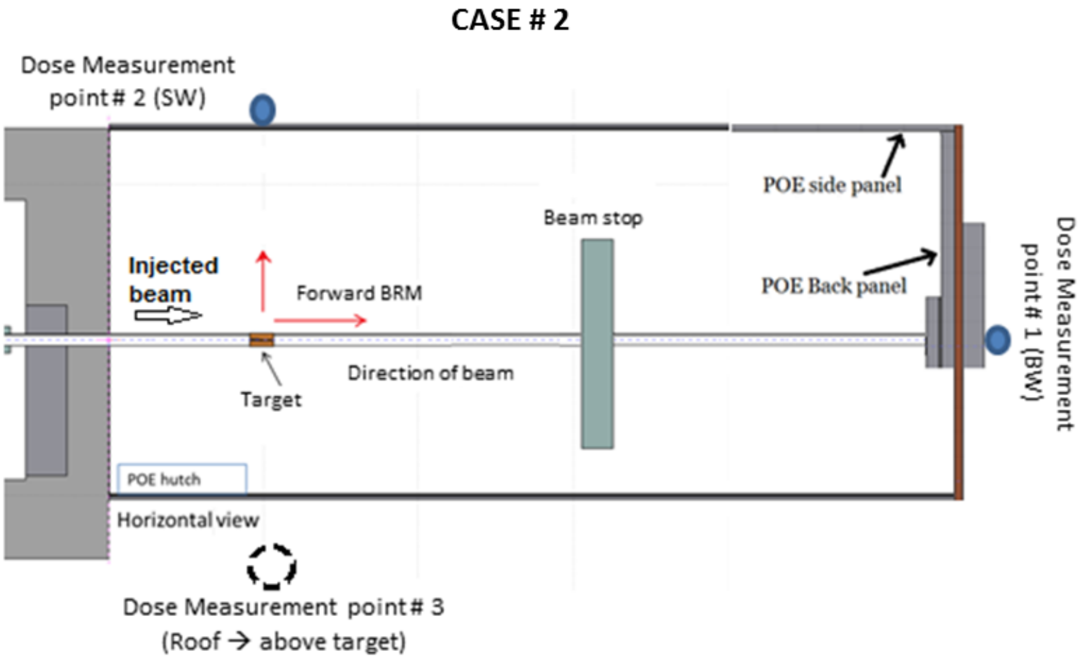


Figure 2 - Beamloss Case #2

The radiation doses generated due to the BRM radiation and neutrons was estimated at two different angles:

(c) 0 deg: Dose was calculated outside of POE BW.

(d) 90 deg: The dose resulting from the perpendicular component of the BRM and neutrons hitting the side wall (SW) and ceiling of the POE was calculated.

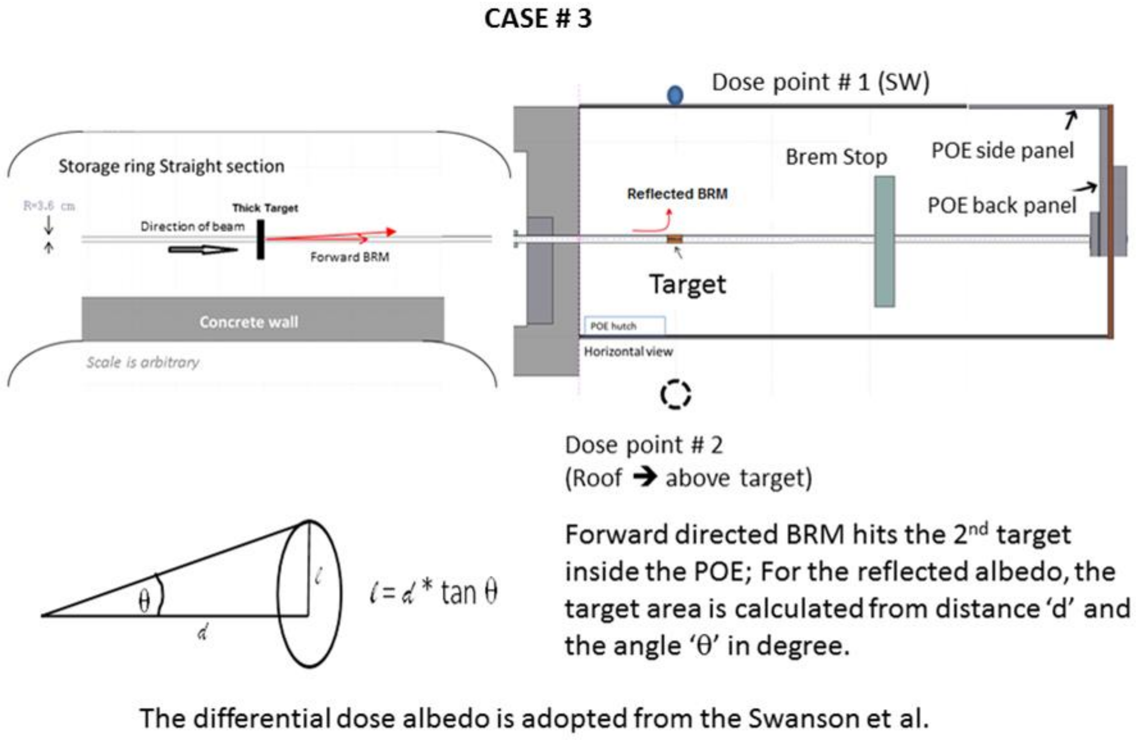
<u>Case 3</u>: Single Point SR1 Beam Loss inside SR – forward peaked BRM enters POE and Scattered by a thick target.

Stored beam is lost at a vacuum valve (thick-target) location inside the SR. The beam loss creates BRM radiation over a wide energy range and distribution angle. The forward peaked BRM (opening angle$\leq$1mrad) enters the POE and is reflected at 90 deg at a target location inside the POE. Assuming a differential dose albedo of 0.01 (see Fig: 49; Swanson et al 1979) [1], the radiation dose was calculated at two locations:

(e) Outside of the POE SW

(f) Outside of the POE Roof

The source energy and the analytical equations used for calculating the neutrons BRM radiation at 0 deg and 90 deg are given in the following section 4.



Forward directed BRM hits the 2nd target inside the POE; For the reflected albedo, the target area is calculated from distance 'd' and the angle 'θ' in degree.

The differential dose albedo is adopted from the Swanson et al.

Figure 3 - Beamloss Case #3

3.2 SHIELDING MATERIAL, THICKNESSES AND SOURCE DISTANCES

The dose at a given location depends on the following parameters:

(i) Distance between the source point and the measurement-location

(ii) Shielding thicknesses

(iii) Energy Deposited (Joules)

In addition to the shielding added specifically for radiation protection purposes, each beamline front end contains a number of masks and collimators with narrow apertures that limit the actual synchrotron beam size reaching the POE. The apertures therefore also limit the BRM that may reach a POE.

The acceptance angle for CLS beamlines is 1 milliRadian (mR), which is slightly larger than the cone created by the forward peaked BRM radiation. Therefore if electrons or scattered BRM travel on axis down a beamline, they could theoretically reach the first element in the POE. Shielding thicknesses and source to shielding distances were determined using the technical drawings available for each beamline. The parameters required for the dose calculation are summarized in Tables 1 and 2 for all of the 14 existing beamlines at the Canadian Light Source. A similar analysis will be performed for any new beamline created in the future.

Table 1- Shielding Material and Thicknesses for Beamloss Calculations

***All shielding calculations include 6 mm steel for enclosure walls and roof**

Beamline	**BRM Stop Material**	**BRM Stop (cm)**	**BW*Lead Shielding (cm)**	**SW* Lead Shielding (cm)**	**Roof * Lead Shielding (cm)**
XSR (02B2)	Lead	15	4.5	0.5	0.5
BMIT (05ID-2)	Tungsten	18	27	3.5	1.5
BMIT (05B1-1)	Lead	18	5	3.5	1.5
SyLMAND (05B2-1)	Lead	16	3	4	0.5
SXRMB (06B1-1)	Lead	28.2	3	3	0.5
HXMA (06ID-1)	Tungsten	30	11	3	1
VESPERS (07B2-1)	Tungsten	20	4	0.5	1
BIOXAS (07-ID)	Lead	18	2.5	3	1
CMCF1 (08ID-1)	Lead	30.6	16	3	1
CMCF2 (08B1-1)	Lead	30	3	3	0.5
IDEAS (08-B2)	Lead	18	3	0.5	0.5
QMSC (09-ID)	Lead	18	13	3	1
SM/REIXS (10ID)	Lead	22	9	3	1
SGM/PGM (11ID)	Lead	28	16	3	1

Table 2 - Source Distances (cm) Used for Beamloss Calculations

Case	**1b**	**2**			**3**		
SHD Wall	BW	BW	SW	Roof	POE Target	SW	Roof
XSR	21.5	14.5	1.08	1.05	7	1.08	1.05
BMITID	52	38.5	0.45	2.2	13.5	0.45	2.2
BMITBM	28.1	19.5	12.5	2.2	8.6	12.5	2.2
SyLMAND	19.2	9.5	0.995	2.2	9.7	0.995	2.2
SXRMB	19.7	11.2	0.72	2.2	8.5	0.72	2.2
HXMA	26	15	1.6	2.2	11	1.6	2.2
VESPERS	22.9	13.4	0.6	2.2	9.5	0.6	2.2
BioXAS	27.74	14.41	1.80	2.2	13.33	1.8	2.2
CMCF1	47	34.5	1.4	2.2	12.5	1.4	2.2
CMCF2	20.9	12.4	0.28	2.2	8.5	0.28	2.2
IDEAS	17.15	5.97	1.91	2.2	11.17	1.91	2.2
QMSC	17.55	2.0	1.81	2.2	15.56	1.81	2.2
SM/REIXS	18.5	6	0.48	2.2	12.5	0.48	2.2
SGM/PGM	22.7	13.4	0.47	2.2	9.3	0.47	2.2

4. SHIELDING CALCULATIONS

Case 1 and Case 2

The beamloss conditions described above involve loss of the entire 500 mA of stored beam (827 J) or loss of one nanoCoulomb of injected beam (2.9 J). Both situations are extreme worst case scenarios that have a very low probability of occurrence.

The CLS Safety Report describes the methodology for estimating the theoretical dose rates outside the CLS bulk shielding, and the equations used are derived from (use numbers for refs).

The unshielded bremsstrahlung dose profile is estimated by:

$$H_B(\theta_B) = 0.167\, E_o\,(2^{-\theta_B/\theta_{1/2}}) + 8.33\,(10^{-\theta_B/21}) + 0.25\,(10^{-\theta_B/110})$$

Where:

$H_B(\theta_B)$ is the bremsstrahlung dose relative to an angle θ from the electron beam direction in units of mSv.m^2/Joules,

E_o is the electron beam energy in MeV

$\theta_{1/2} * E_o = 100$ MeV deg, and θ_B is the angle between the forward beam direction at the point it strikes the component and the line segment from that point to the dose point.

The unshielded neutron dose profile for 90° in iron is Table-3 that is adapted from reference [4].

Table 3 - Source Values for Iron

Material	Z	Dose (10^{-6} Sv·m^2.J^{-1} at 90° to Beam)		
		GRN	MEN	HEN
Iron	26	3.28	.286	.0268

GRN is considered to be isotropic, while the angular dependent dose profile for MEN and HEN is obtained by the following equations:

$$D(\theta)MEN = F(90^o)MEN/(1 - 0.75\cos\theta)$$

$$D(\theta)HEN = F(90^o)HEN/(1 - 0.72\cos\theta)^2$$

Where:

$F(90^o)MEN = 0.286$ mSv·m^2/Joule

$F(90^o)HEN = 0.0268$ mSv·m^2/Joule

The dose at any point D through a known amount of shielding can then be calculated by:

$$D = 3600 \times P \times \sum_i \left(\frac{H_i}{r^2} \times e^{\left(-\rho d / \lambda_i\right)} \right)$$

Where:

D = Dose rate in μSv/h

P = Beam Power (in Watts)

Hi = Unshielded dose from a given source material ($\mu Sv \cdot m^2$/Joules)

r = Distance to the source point (meters)

ρ = density of shielding material (g/cm^3)

λi = attenuation length of the *i*th shielding material (cm^2/g)

d = shielding thickness (cm)

All point source losses are calculated assuming iron as the target for neutrons, and the angular dependence of the medium and high energy neutrons are considered.

5. RESULTS

CASE 1: 500 MA STORED BEAM LOST IN SR1

The table below shows the total dose resulting from the bremsstrahlung and neutrons at a vertical point of the storage ring with a 600 mm thick concrete roof that is at a distance of 2.2 meters and at 90 degrees from the location of the complete loss of 500 mA store electron beam. The dose is created from the 827 J of electron energy being absorbed by a thick iron target inside the storage ring. This dose is well below the 1 mSv dose limit for a worst case radiation event.

Dose Point	Source	Shielding Material & Thickness (mm)	BRM (μSv)	GRN (μSv)	MEN (μSv)	HEN (μSv)	Total (μSv)
SR1 Roof (2.2 m)	500 mA e-beam (827 J)	Concrete 600	369.50	16.51	5.58	1.34	392.93

Table 4 - Beamloss Case #1a Results

CASE 1B AND CASE 2: 1 NC INJECTED ELECTRONS IN POE

Since the case 1b and case 2 both involve the POEs and doses due to BRM, GRN, MEN and HEN they are clubbed together in the following Table 5.

Beamline	Dose (μSv)				
XSR	BRM	GRN	MEN	HEN	Total
Case 1 - POE back wall	75.87	1.42	0.21	0.19	77.67
Case 2 - POE Roof	69.21	7.92	0.70	0.07	77.90
Case 2 - POE Sidewall	65.42	7.48	0.66	0.06	73.63
Case 2 - POE backwall	0.58	0.01	0.00	0.00	0.60

BMIT ID	BRM	GRN	MEN	HEN	Total
Case 1 - POE back wall	0.00	0.02	0.00	0.00	0.03
Case 2 - POE Roof	9.82	1.68	0.15	0.01	11.67
Case 2 - POE Sidewall	91.19	34.89	3.20	0.30	129.59
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
BMIT BM	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	8.49	0.65	0.10	0.09	9.32
Case 2 - POE Roof	9.82	1.68	0.15	0.01	11.67
Case 2 - POE Sidewall	0.12	0.05	0.00	0.00	0.17
Case 2 - POE backwall	0.06	0.00	0.00	0.00	0.07
SYLMAND	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	120.51	1.84	0.27	0.24	122.85
Case 2 - POE Roof	15.77	1.80	0.16	0.02	17.74
Case 2 - POE Sidewall	14.73	6.89	0.64	0.06	22.31
Case 2 - POE backwall	0.42	0.01	0.00	0.00	0.43
SXRMB	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.36	0.74	0.12	0.11	1.33
Case 2 - POE Roof	15.77	1.80	0.16	0.02	17.74
Case 2 - POE Sidewall	45.13	14.12	1.29	0.12	60.65
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
HXMA	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.00	0.06	0.01	0.01	0.09
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	9.14	2.86	0.26	0.02	12.28
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
VESPERS	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.12	0.40	0.06	0.06	0.64
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	211.96	24.25	2.15	0.20	238.56
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
BioXAS	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	**0.63**	**0.38**	**0.06**	**0.05**	**1.12**
Case 2 - POE Roof	**12.45**	**1.74**	**0.16**	**0.01**	**14.36**
Case 2 - POE Sidewall	**7.22**	**2.26**	**0.21**	**0.02**	**9.70**
Case 2 - POE backwall	**0.01**	**0.00**	**0.00**	**0.00**	**0.01**
CMCF ID	**BRM**	**GRN**	**MEN**	**HEN**	**Total**

Case 1 - POE back wall	0.00	0.04	0.01	0.01	0.06
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	11.94	3.73	0.34	0.03	16.04
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
CMCF BM	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.14	0.58	0.10	0.09	0.90
Case 2 - POE Roof	15.77	1.80	0.16	0.01	17.74
Case 2 - POE Sidewall	298.38	93.35	8.52	0.80	401.05
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
IDEAS	BRM	GRN	MEN	HEN	Total
Case 1 - POE back wall	0.49	0.94	0.16	0.14	1.73
Case 2 - POE Roof	15.77	1.80	0.16	0.02	17.74
Case 2 - POE Sidewall	20.92	2.26	0.21	0.02	23.40
Case 2 - POE backwall	1.69	0.06	0.01	0.01	1.77
QMSC	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.49	0.94	0.16	0.14	1.73
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	7.22	2.26	0.21	0.02	9.70
Case 2 - POE backwall	0.13	0.25	0.04	0.04	0.47
SM	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.45	0.85	0.14	0.13	1.56
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	101.53	31.76	2.90	0.27	136.47
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
SGM/PGM	**BRM**	**GRN**	**MEN**	**HEN**	**Total**
Case 1 - POE back wall	0.00	0.23	0.04	0.04	0.31
Case 2 - POE Roof	12.45	1.74	0.16	0.01	14.36
Case 2 - POE Sidewall	105.90	33.13	3.03	0.28	142.34
Case 2 - POE backwall	0.00	0.00	0.00	0.00	0.00
				Max:	401.05

Table 5 - Beamloss Case #1b & #2 Results

Case 3: 500 mA Stored Beam Lost in SR1, Bremsstrahlung Scattered in POE

Beamline	Dose (µSv)	
XSR	**BRM**	**Total**
Case 3 - POE Sidewall	1.886	1.886
Case 3 - Roof	1.996	1.996
BMIT ID	**BRM**	**Total**
Case 3 - POE Sidewall	2.630	2.630
Case 3 - Roof	0.283	0.283
BMIT BM	**BRM**	**Total**
Case 3 - POE Sidewall	0 .003	0 .003
Case 3 - Roof	0.283	0.283
SYLMAND	**BRM**	**Total**
Case 3 - POE Sidewall	0.425	0.425
Case 3 - Roof	0.455	0.455
SXRMF	**BRM**	**Total**
Case 3 - POE Sidewall	1.301	1.301
Case 3 - Roof	0.456	0.456
HXMA	**BRM**	**Total**
Case 3 - POE Sidewall	0.264	0.264
Case 3 - Roof	0.359	0.359
VESPERS	**BRM**	**Total**
Case 3 - POE Sidewall	6.112	6.112
Case 3 - Roof	0.359	0.359
BioXAS	**BRM**	**Total**
Case 3 - POE Sidewall	0.208	0.208
Case 3 - Roof	0.359	0.359
CMCF ID	**BRM**	**Total**
Case 3 - POE Sidewall	0.344	0.344
Case 3 - Roof	0.359	0.359
CMCF BM	**BRM**	**Total**
Case 3 - POE Sidewall	8.604	8.604
Case 3 - Roof	0.455	0.455

IDEAS	**BRM**	**Total**
Case 3 - POE Sidewall	0.603	0.603
Case 3 - Roof	0.455	0.455
QMSC	**BRM**	**Total**
Case 3 - POE Sidewall	0.206	0.206
Case 3 - Roof	0.359	0.359
SM	**BRM**	**Total**
Case 3 - POE Sidewall	2.928	2.928
Case 3 - Roof	0.359	0.359
SGM/PGM	**BRM**	**Total**
Case 3 - POE Sidewall	3.054	3.054
Case 3 - Roof	0.359	0.359

Table 6 - Beamloss Case #3 Results

6. Discussion

Dose calculations were completed for three different beam loss scenarios using analytical equations. The calculations provided dose results for Bremsstrahlung, Giant Resonance Neutrons, Medium Energy Neutrons, and High Energy Neutrons for the chosen dose points for case 1 and case 2. For case 3, the same equation was used, however, to determine the bremsstrahlung dose only.

Case 1, where the full 500 mA stored beam would be ‘lost’ inside the storage ring at a thick target, resulted in a combined dose of 392.93 µSv as depicted in Table-4. This is representative of an extreme case scenario, where the entire stored beam is lost at a single point. The dose is still below the 1 mSv, CLS design limit for a worst case beam loss event.

The radiation dose was found to be largest in case 2, where an injection pulse of 1 nCi was lost inside a POE. The forward directed BRM (0 deg) sees the greatest shielding thickness. In most cases, the dose is negligible at the zero degree calculated dose points due to the POE backwall lead shielding and the significantly thick beamstop, which is used to attenuate the bremsstrahlung travelling down the beam lines. The 90 deg BRM component passes through less shielding thickness before reaching the calculated dose point and in some cases would quickly exceed the 1 mSv limit for an accidental scenario. The maximum dose of 401.05 µSv was found at the CMCF2 BM sidewall. The generated dose calculation results, for all the locations outside the POEs performed for all the 14 beam-lines, are shown in Table-5.

This worst case scenario implies that the injection process must be inhibited before a third consecutive pulse is allowed to reach the POE in order to meet CLS radiation safety design objectives. CLSI will, as part of the implementation of injection with the shutters open, deploy radiation monitors outside each beamline POE that will inhibit the injection process when the cumulative dose limit of any monitor reach 2.5 µSv.

For Top-up operation, beam injection is expected to proceed with one or two injected pulse once on a minute. The Active Area Radiation Monitoring System (AARMS) is currently set to inhibit the electron gun if the dose exceeds 2.5 µSv/h [8]. Therefore the injection process would be easily shut down within two injection cycles prior to the 1 mSv dose limit being reached if an injected pulse were lost inside a POE.

During normal injection of one pulse per second with the safety shutters open, the injection system would need to be inhibited in a very short period of time. Therefore a more robust AARMS system is being implemented where a hardwired relay connection from each AARMS station to the injection system will quickly disable the injection system if the cumulative dose limit is reached.

In case 3, the theoretical dose calculation show that the expected dose outside a POE sidewall or roof from a POE taeget scattered bremsstrahlung originally generated from the loss of a 500 mA beam inside SR1 is very low. The maximum dose value calculated was 8.6 µSv.

The above results indicate that performing injection with the safety shutters open as a mode of operation at the CLS may impact radiation levels in occupied areas outside the beamline POEs if an injected pulse is able to travel down a beamline front end. Although the probability of this occurrence has been shown to be very low [6], enabling a hardwired shutdown of the injection process by the existing AARMS will ensure that even in an extreme case CLS will maintain radiation exposures below the 1 mSv dose for a worst case accident scenario, and also continue to maintain radiation exposures to personnel ALARA during Top-up Operation or Injection with the Safety Shutters Open.

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