Dose calculation in the user area under beam-loss scenario at Canadian Light Source

Asm Sabbir Ahmed[1] and Mohammed Benmerrouche[2]

[1]*Canadian Light Source Inc., 44 Inovation Boulevard, Saskatoon, SK S7N 2V3, CANADA*
[2]*Brookhaven National Laboratory, Photon Sciences Division, Upton, NY 11973, USA*

ABSTRACT

This paper describes the dose distribution near and surrounding a beamline (Hard X-Ray Micro Analysis - HXMA), at events of unwanted beam loss scenarios during Top-up mode of operation at Canadian Light Source.

The radiation doses were calculated using particle transport code: FLUKA. The information including physical size, location, and material of the different beamline components were extracted from the original CAD drawings and were incorporated in the Fluka model. Three beam loss scenarios were considered: (i) Beam is miss-steered in the storage ring (ii) Beam hits metal components inside the ring and (iii) Beam enters Primary Optical Enclosure (POE) and hits optical components. The results are presented.

1. INTRODUCTION

Canadian Light Source Inc. (CLSI) is adopting 'Top-up' mode of operation, instead of the existing 'Decay mode' operation in order to provide uninterrupted synchrotron radiation in the experimental floor. This new mode of operation requires keeping the beamline front end safety shutter open during injection. From the radiation protection and radiation safety perspective, it is important to maintain that the beamline users and users' area are safe, secured for all operational condition. This paper describes the methodology and results of a study that describes the dose distribution near and surrounding a beamline (Hard X-Ray Micro Analysis - HXMA) at CLS, at events of unwanted beam loss scenarios during Top-up mode of operation. This study is conducted to establish a 'proof of concept' of measuring the worst radiaiton hazard. It is proposed that, if the methodology and results as described in this document meet the CLSI safety requirement of validating the shielding wall, the same concept can be used for other beam lines in the facility and may not need to repeat the same study.

1.1. CLSI Safety Dose limit

The safety dose limits used in this document followed the dose levels as mentioned in the CLSI Safety Report [1] are:

(i) Normal operation: Dose rate < 5 μSv. h^{-1} for the Controlled Access Zone

(ii) Total dose < 1.0 mSv for any single beam-loss incident.

CLSI Safety Report defines four (04) different zones [1]:

- Public Access zone (PAZ)
- Free Access Zone (FAZ)

- Controlled Access Zone (CAZ) and
- Restricted Access Zone (RAZ).

All POE, SOE and experimental floor belong to CAZ. The dose rate for this zone is expected to be less than 5 $\mu Sv.h^{-1}$. In addition to this, a second dose constraint was used: dose < 1.0 mSv for a single event.

The purposes of this document are: (1) build a Monte Carlo model for particle transport calculation for the HXMA beamline (2) use the model to calculate the radiation dose in the user area under 3 beam loss scenarios with the beamline front end safety shutter open (3) provide a rationale regarding the efficacy of the existing shielding wall.

2. MATERIALS AND METHODS

2.1. Monte Carlo Model

The radiation doses that are presented in this document were calculated using the advanced particle transport code, called FLUKA [2]. The basic geometry of the POE hutches for all the beamlines was drawn using FLAIR [3]. The information including physical size, location, and material of the different beamline components were extracted from the original CAD drawings and were incorporated in the Fluka model. In order to reduce the time and simplify the FLUKA geometry, each component was included without changing the basic physical size and compositions. The shielding-principles and design parameters for primary optical enclosure (POE) were taken from CLS documents [4, 5]. Figure 1 shows the horizontal and vertical views for the problem-geometry.

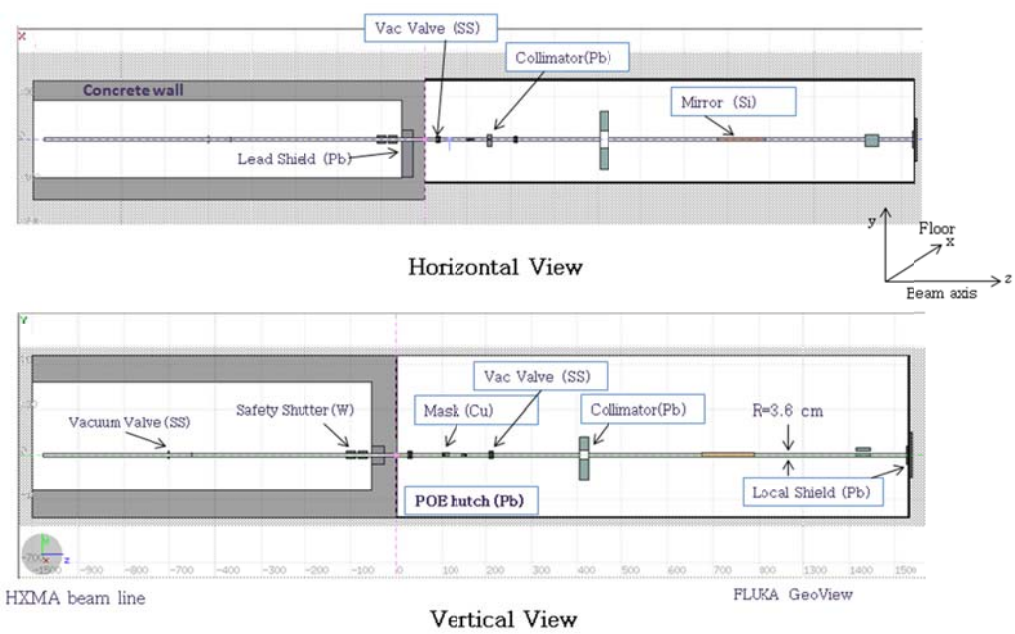


Figure 1: The horizontal and vertical view of the straight section of a storage ring along with the Front end and POE hutch. The geometry is drawn with the FLUKA visual editor

2.2. Shielding Materials and Thickness

The shielding thicknesses of side walls and ceiling of POE and secondary optical enclosures (SOE) hutches are summarized in Table 1. These shielding parameters were adopted for the Phase–I beam lines at CLSI. For example, HXMA beamline. The design of the radiation shielding follows the ALARA (As Low as reasonably achievable) principle. Figure 2 shows the shielding walls for POE hutch.

Table 1: Shielding parameters used in the Monte Carlo model as described in this document. The shielding parameters for HXMA beamline was used in this model.

Enclosure type	Beamline #	Lead thickness (mm)	Lead thickness (mm)	Lead thickness (mm)
		Roof	Sidewall	Back wall
POE	HXMA-06ID	10	10(30 locally)	30(130 locally)
SOE		3.0	4.0	5.0

POE side wall has 1 cm lead wall, floor to ceiling; with 2 cm local shield at +/- 50 cm of the beam line. POE back wall has 3 cm lead wall, floor to ceiling; Guillotine 3 cm, local shielding at the back 5 cm at +/- 50 cm of the beam line.

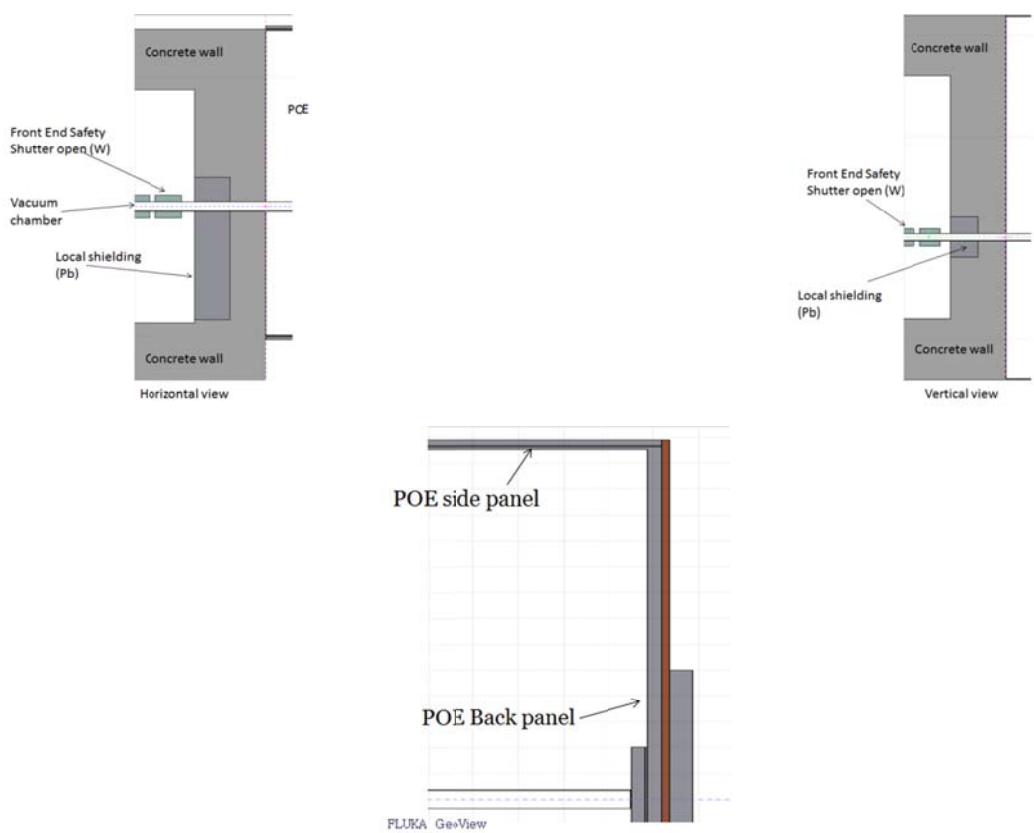


Figure 2: The geometry of the HXMA POE, drawn with the FLAIR

2.3. Radiation Sources

The source was defined as 2.9 GeV electrons propagating along the beam line axis (z-axis). The source was approximated as a pencil beam, forward peaked.

In the case of a beam loss scenario inside the storage ring, the types of radiation likely to be involved are described in the CLSI documents [1]. According to the CLSI Safety Report, the hazards associated with ionizing radiation inside CLSI may be raised at different operational stages: loss of electrons from the beam at various stages of acceleration; loss of electrons from the beam circulating in the storage ring; and synchrotron radiation emanating from bending magnets and insertion devices located around the storage ring.

The types of radiation considered in this study:

- Photon and Bremsstrahlung radiation
- Neutrons [Giant resonance neutron, medium energy and high energy]

The maximum charge of electrons in one fill of the booster ring is 3.4 nC [6]. However, typically, 1 nC charge is delivered at 1 shot/sec, injected from the booster to the storage ring. If there is 100% loss of the injected beam, it is assumed that the rate at which the beam will be lost is 1 nC per sec. The dose levels inside and outside of POE hutches were estimated based on the assumption that, 1 nC of injected beam is completely lost at one point during each beam loss scenario.

The HXMA beam line is a multipurpose hard X-ray beam line. This beam line has an 'Insertion Device' that consists of 63 poles superconducting wiggler. The energy range that is used in this beamline is 5 to 40 kev.

2.4. Beam-loss Scenarios

Three beam loss scenarios were considered: (i) Beam is miss-steered in the storage ring (ii) Beam hits metal components inside the ring and (iii) Beam enters Primary Optical Enclosure (POE) and hits optical components.

Table 2: The beam-loss scenarios studied

Loss scenario	Description	Consequence	POE scenario
CASE 1 Beam is miss-steered vertically [see Appendix:1]			
	miss-steered> 4 mrad	Hit upper wall of vacuum chamber	Vertically lost beams hit SR shielding wall
CASE 2 INJECTED beam is obstructed	Hit misaligned component in the Storage ring	Create shower in the SR	Elevated dose level outside of the POE walls with FE SSH open

CASE 3 INJECTED beam lost to the beam line	Hit components INSIDE the POE	*) May hit thick target like mask made of Cu *) May directly hit the optical components (Focussing mirror made of Si)	Elevated dose level at outside of POE walls

2.5. Scoring and Dose Calculation

In FLUKA, the estimated dose is scored for a given detector, generally called 'Estimator'. Two 'Scoring cards' were used together in this study. The first card was 'Usrbin,' the second was 'Auxsrore.'

'Usrbin' alone, can score 'Fluence', for a single or multiple particles over a uniform spatial mesh independent of geometry, called a 'Binning'. 'Cartesian Binning' was used to define the geometry along 'XYZ' directions.

'Auxscore' command converts the 'Fluence' to 'dose equivalent' with dose equivalent conversion factors.

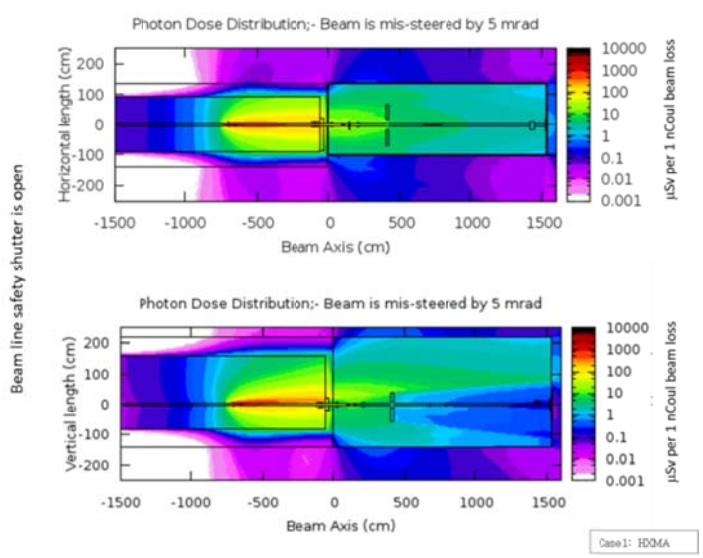
The 'Fluence' is expressed in 'Particles/cm^2 per unit primary weight.' The particle fluence was converted to 'Dose-Eq.' The unit for the estimated parameter was 'Pico Sievert/Particle.' The results are displayed as '2D color plot,' where each color corresponds to a pre-defined range of values. A normalization factor was used to convert the dose per particle to an equivalent of dose per event. To estimate the normalization factor, the maximum number of electrons that might loss during an injection from booster to storage ring, was used. The number of electrons per lost event was 1.0 nc or 6.25×10^{9} electrons.

According to the source assumption, the amount of beam loss per event is 1 nCoul/s of injected beam. The unit of the dose presented in this document is μSv/nCoul.

3. RESULTS & DISCUSSION

3.1. Case 1: Beam is Miss-Steered in the Straight Section: HXMA Beamline

Case 1: Photon dose distribution



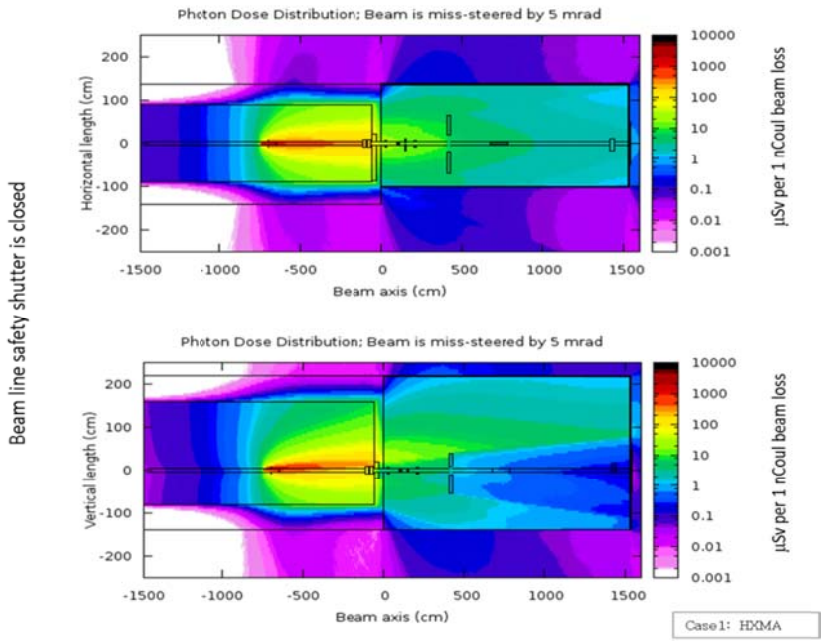
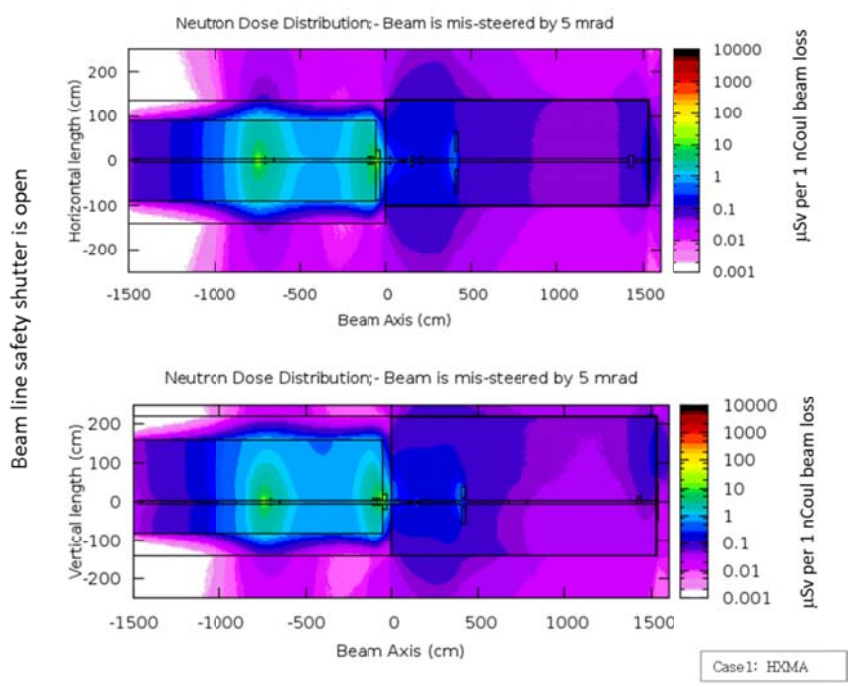


Figure 3: Dose distribution for photon inside and outside of the POE hutches, when beam is miss-steered in the straight section of the storage ring [section 2.4].

Case 1: Neutron dose distribution



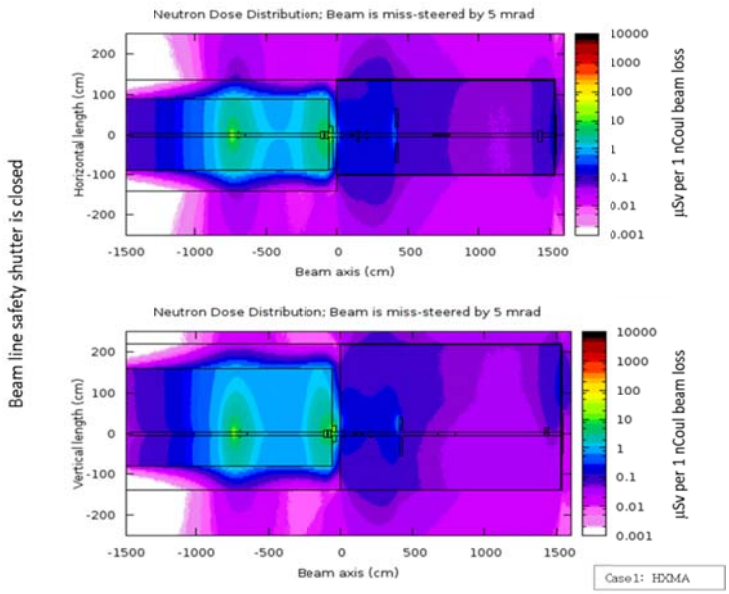


Figure 4: Dose distribution for neutron inside and outside of the POE hutches, when beam is miss-steered in the straight section of the storage ring [section 2.4].

For Case 1 beam loss scenario, the total dose at outside of the POE hutches contribured by all types of particles, are plotted in Figures 5 and 6. The beam line safety shutter was open. In Figure 5a & 5b, 3 different key locations are marked in each view (horizontal and vertical) and the corresponding doses are plotted separately for each location, presented in Figure 6.

Case 1: Total dose for all particles

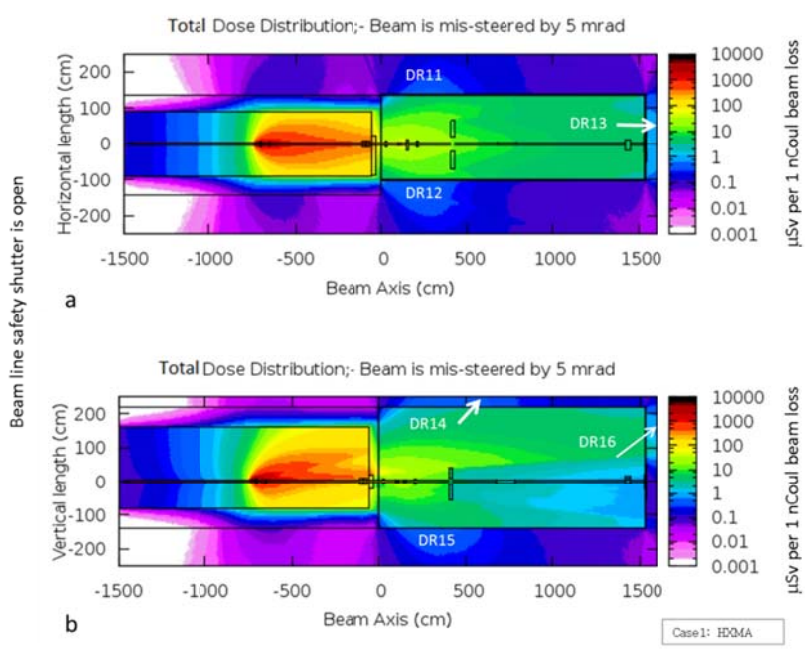


Figure 5: Total dose distribution for all particles inside and outside of POE hutch, when beam is miss-steered in the straight section of the storage ring: (a) Horizontal view (b) Vertical view. Locations `DR11` to `DR16` indicate dose locations.

Case 1: Total dose for all particles

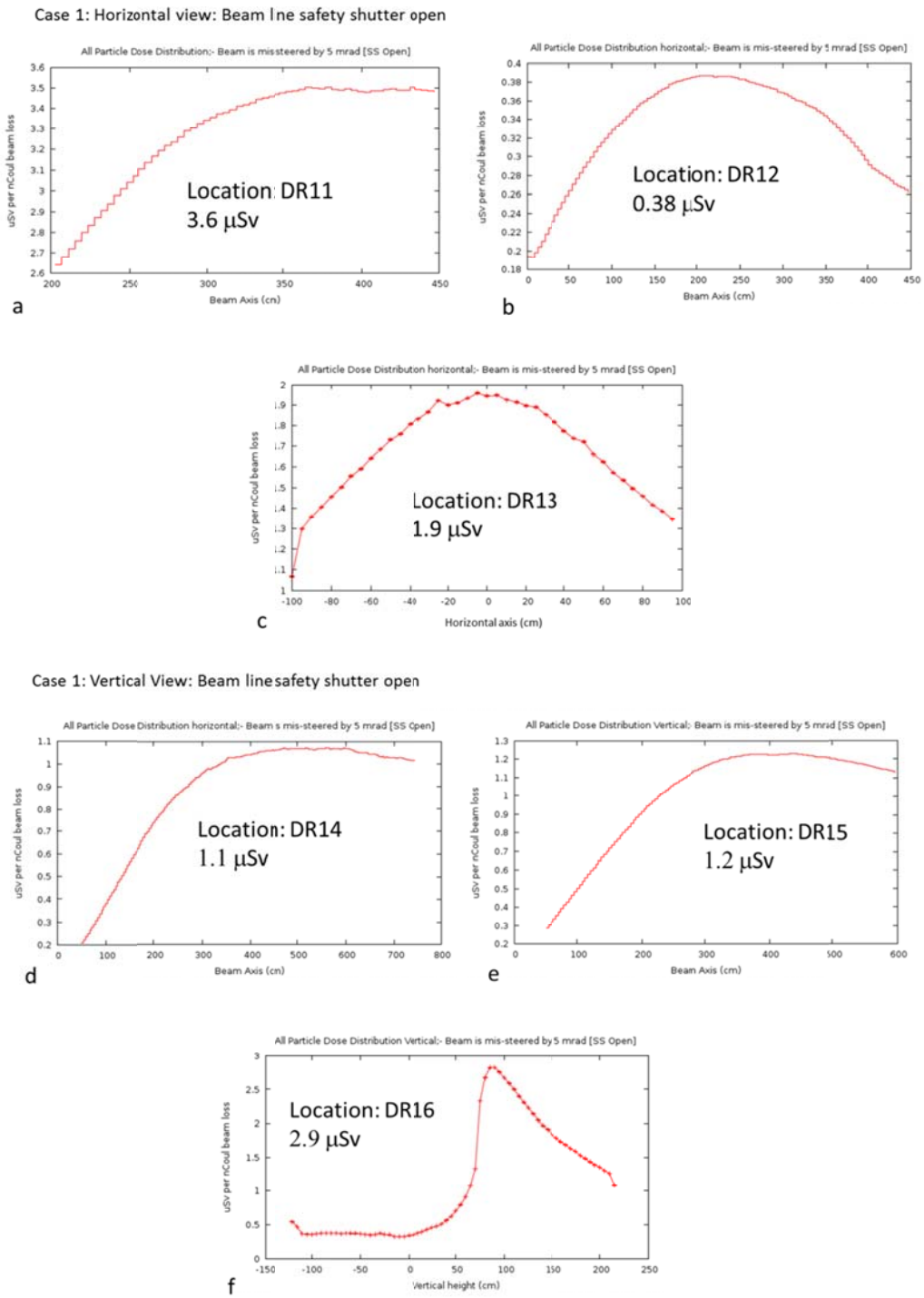


Figure 6: Total dose at key locations, indicated in Figure 6. Plots `a to f` show the doses for corresponding locations of DR11 to DR16. Error bars in Figs. c and f indicate low relative error.

3.2. Case 2: Beam hits the misaligned components in the straight section of storage ring

Case 2: Photon dose distribution

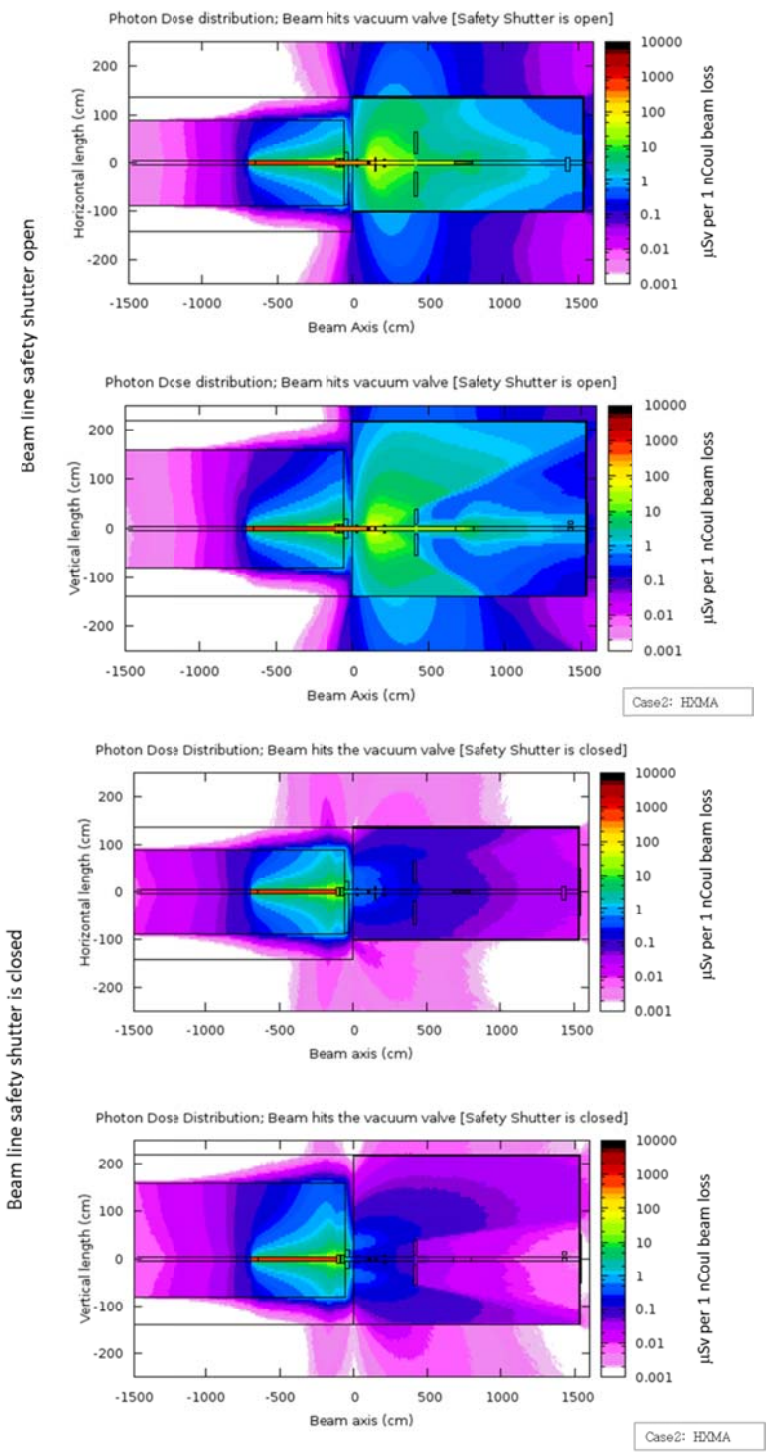


Figure 7: Dose distribution for photon inside and outside of the POE hutch, when beam hits misaligned component (vacuum valve) in the straight section of the storage ring [section 2.4].

Case 2: Neutron Dose Distribution

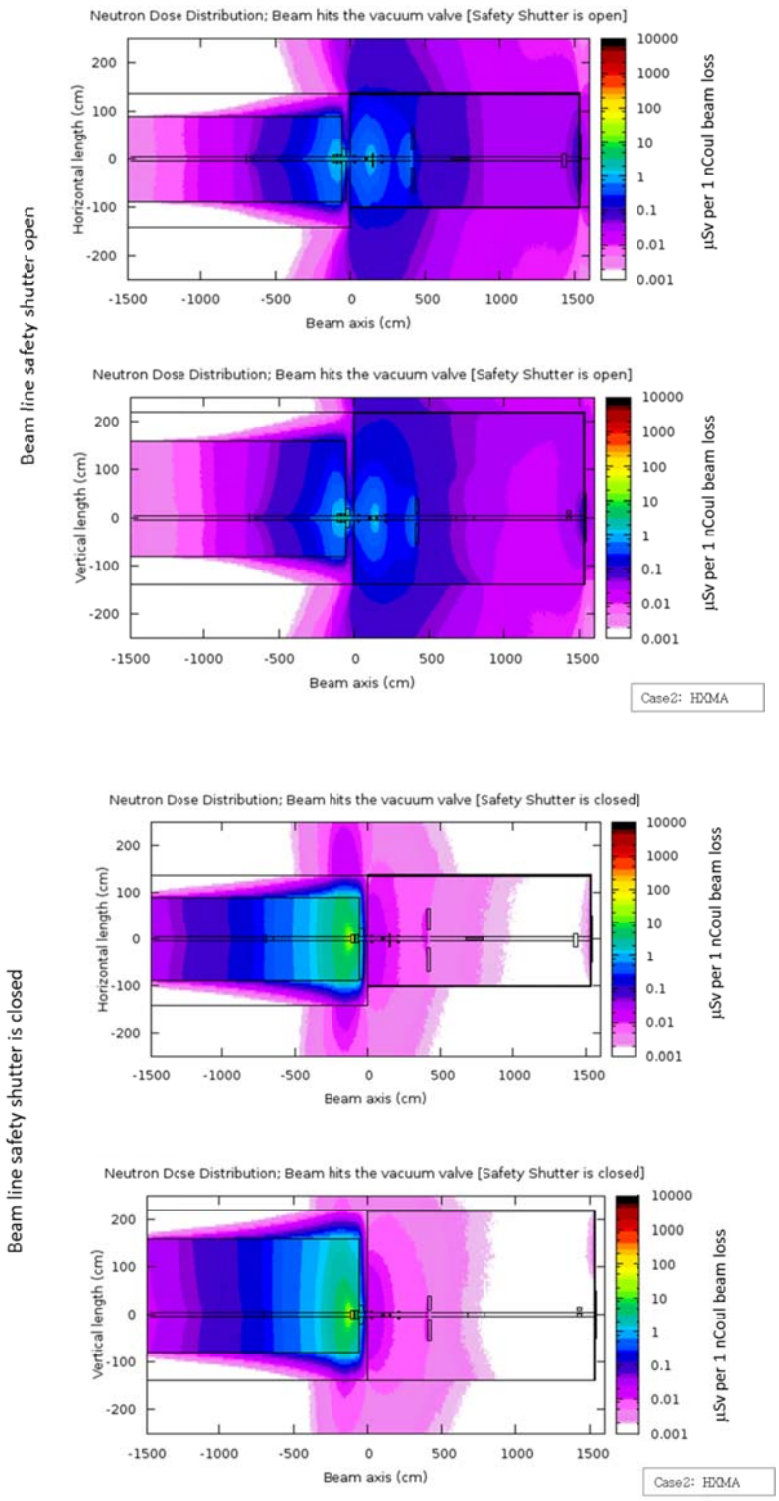


Figure 8: Dose distribution for neutron inside and outside of the POE hutch, when beam hits misaligned component (vacuum valve) in the straight section of the storage ring [section 2.4].

Case 2: Total dose distribution

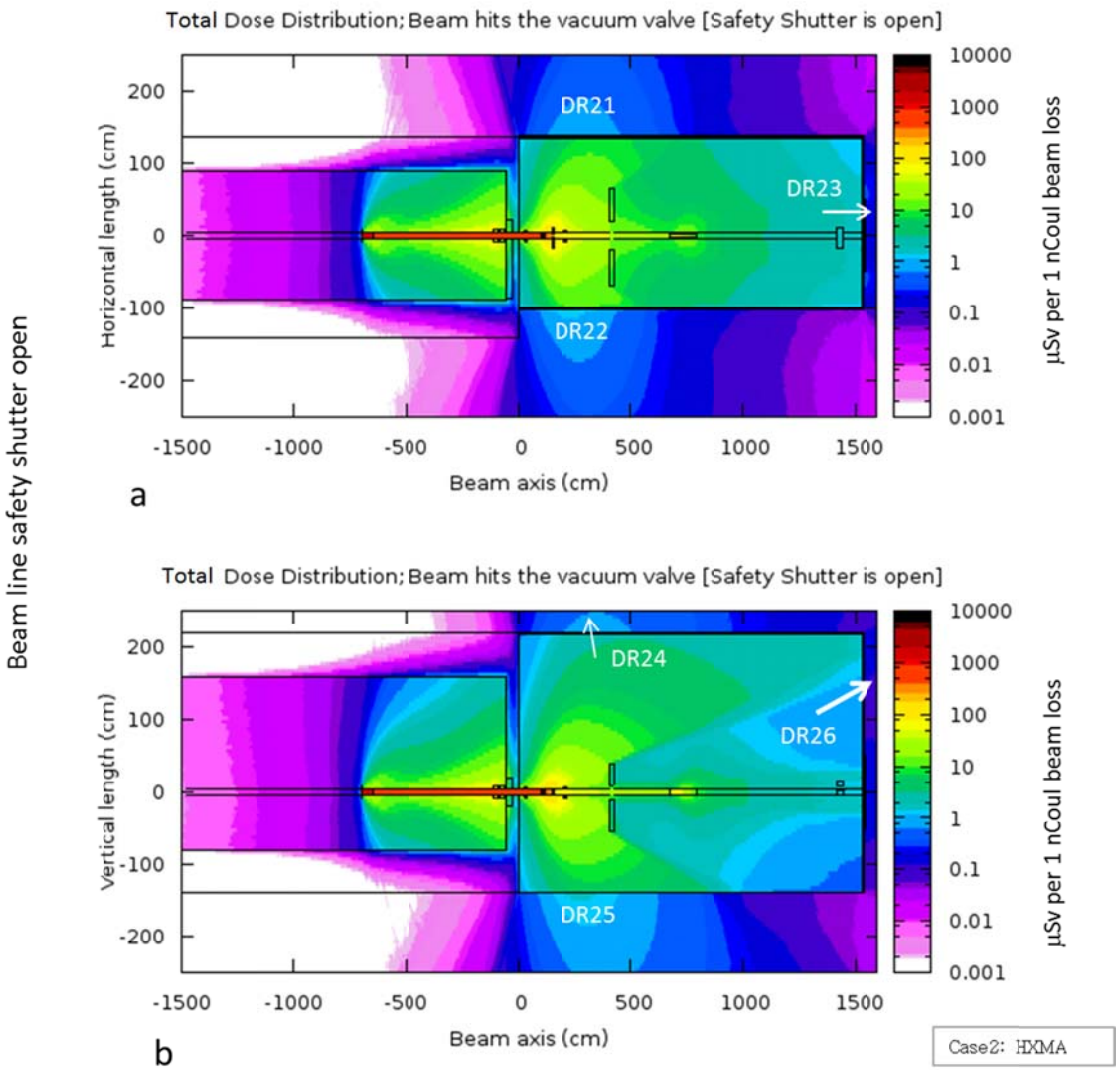


Figure 9: Total dose distribution inside and outside of POE hutch, when beam hits a misaligned component (vacuum valve) inside the ring (section 2.4): (a) Horizontal view (b) Vertical view. The beamline front end safety shutter was open. The doses for regions DR21 to DR26 are further illustrated in Figure 10.

Case 2: Total Dose for all particles

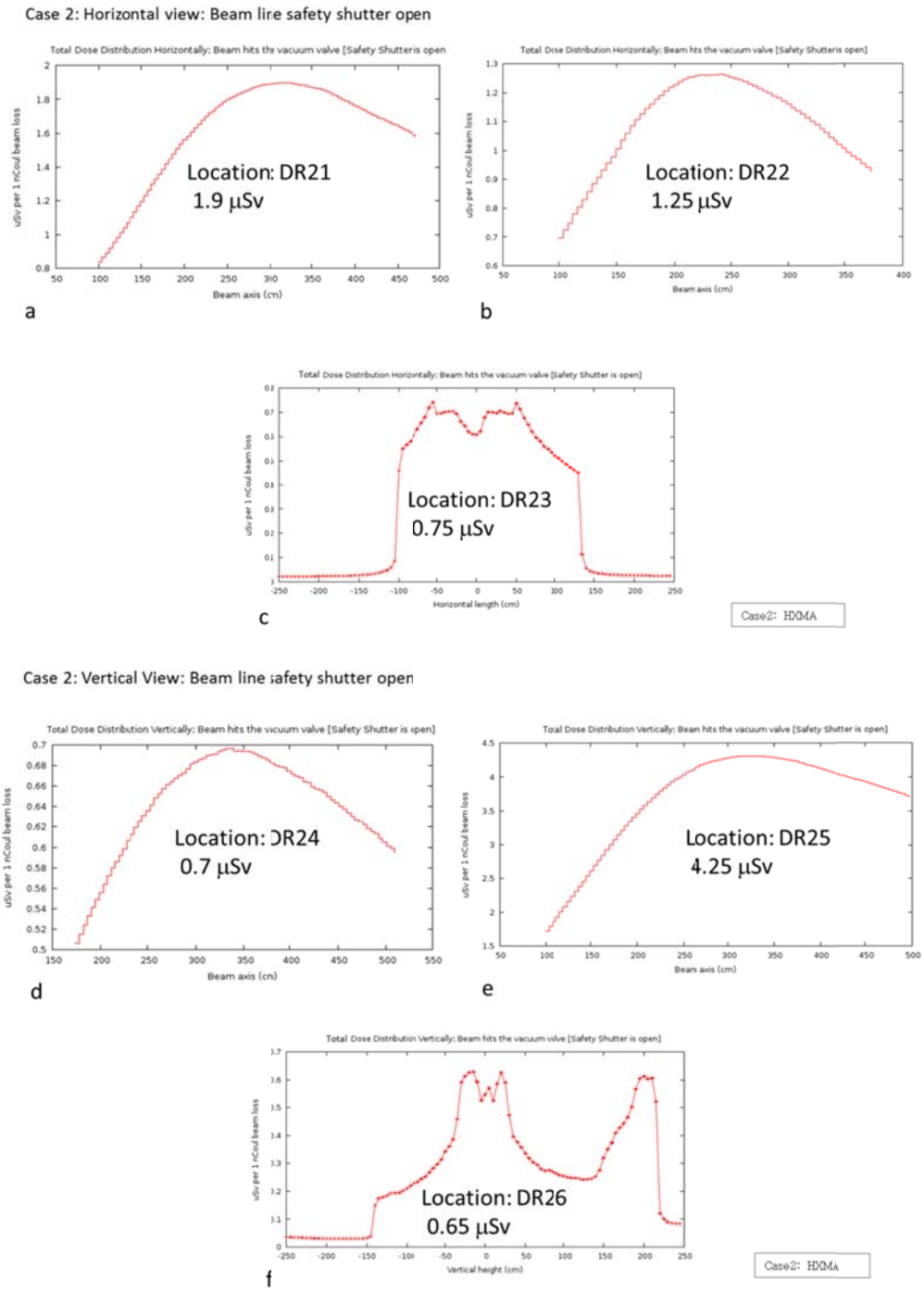


Figure 10: Total doses at key locations (DR21 to DR26) as indicated in Figure 10. Plots `a to f` show the doses for corresponding locations of DR21 to DR26.. The error bars in Figures c and f indicate the relative error and it was less than 2%.

3.3. Case 3: Beam is lost to the beamline and hits the optical components inside the POE hutch

Case 3: Photon dose distribution

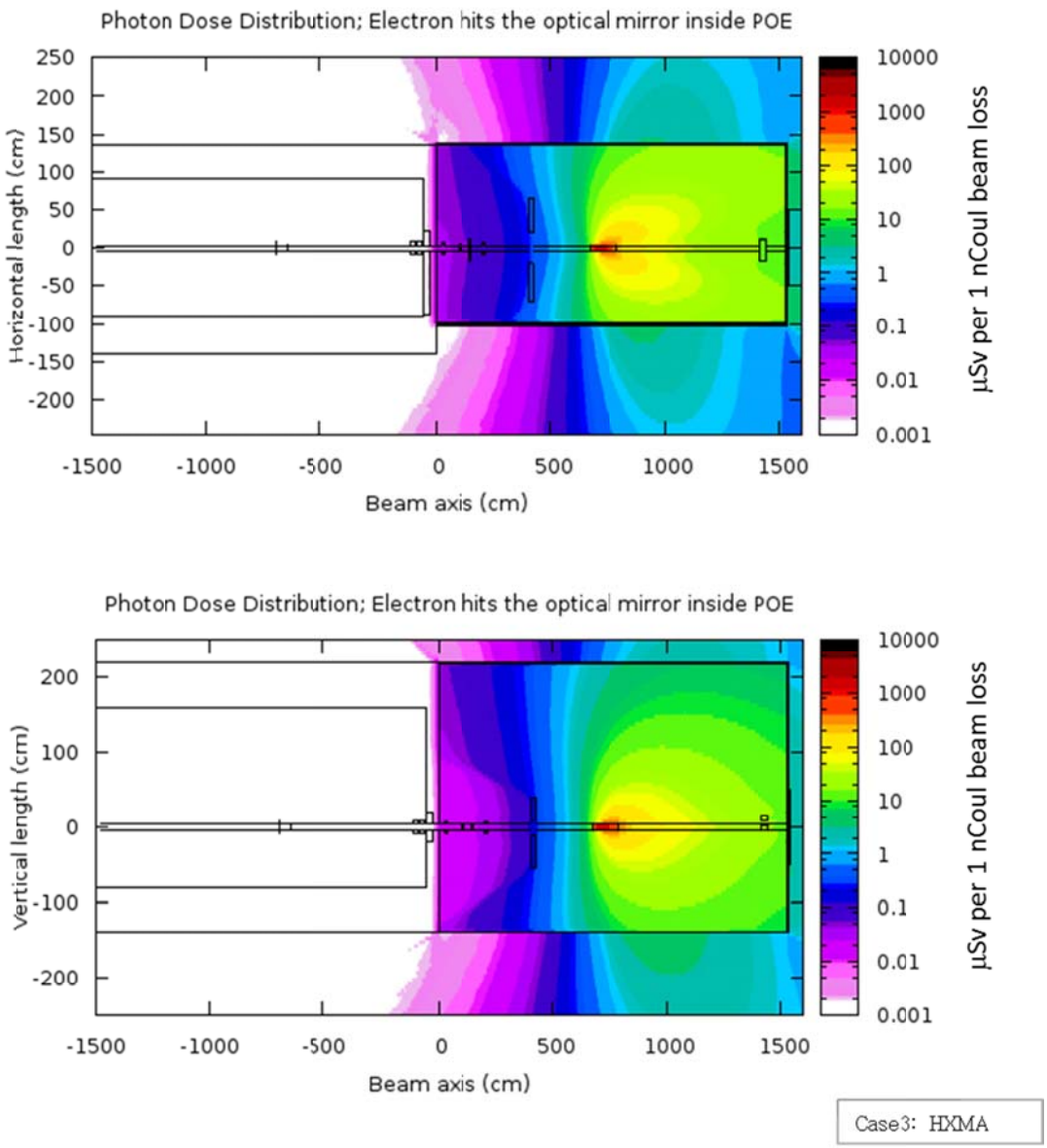


Figure 11: Dose distribution for photon inside and outside of the POE hutch, when beam hits component inside the hutch [section 2.4].

Case 3: Neutron dose distribution

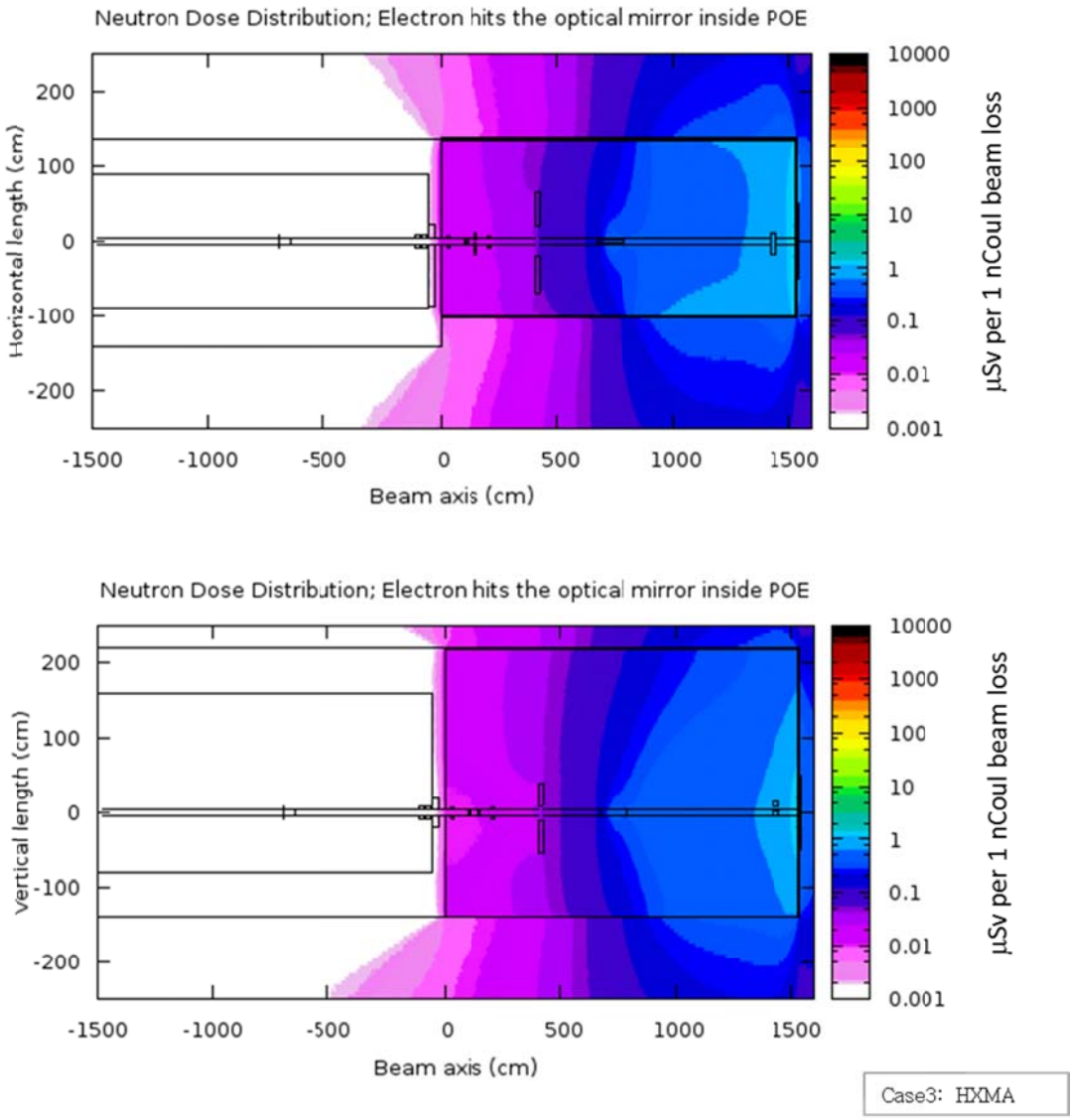


Figure 12: Dose distribution for neutron inside and outside of the POE hutch, when beam hits component inside the hutch [section 2.4].

Case 3: Total dose distribution

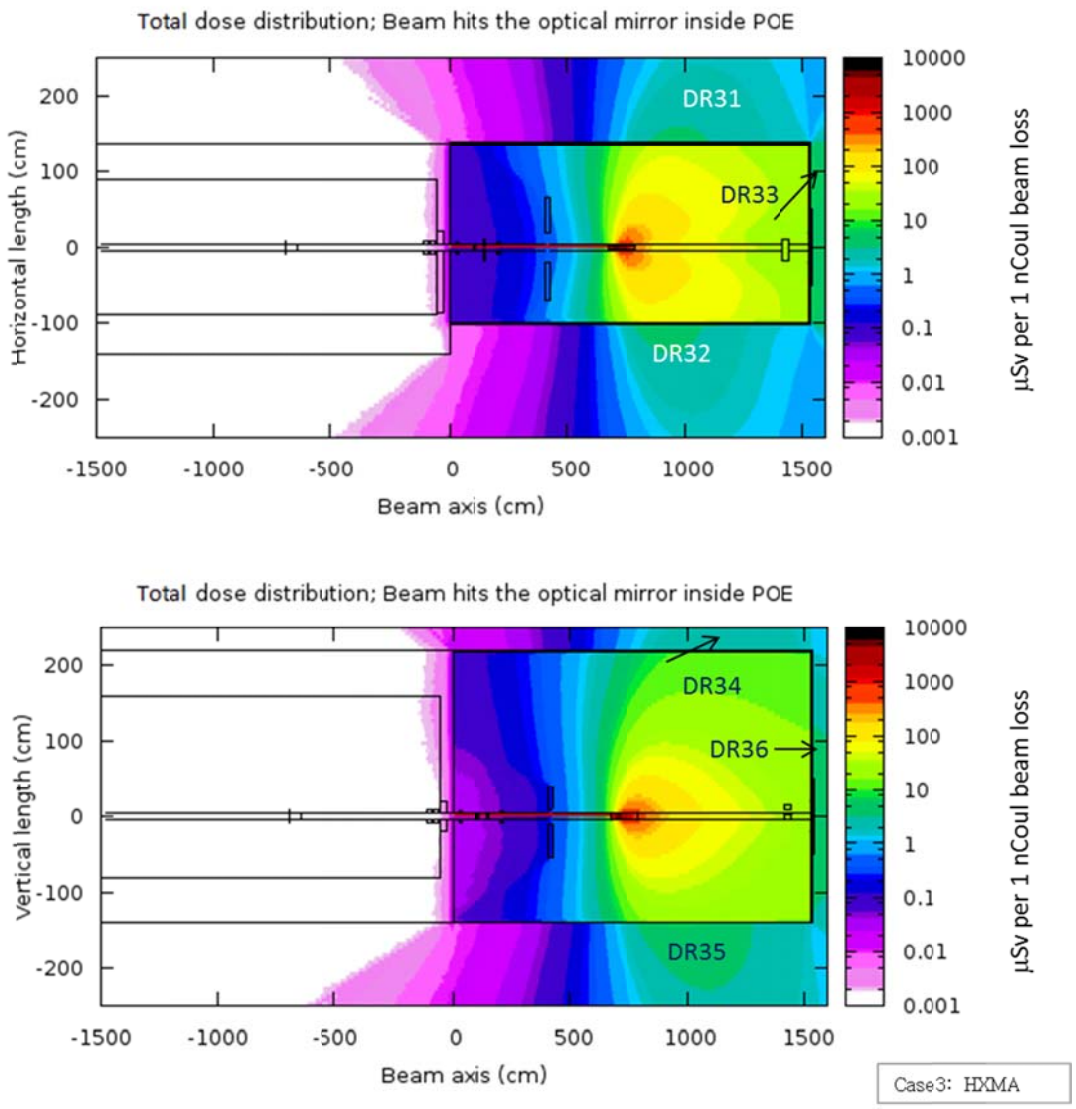


Figure 13: Total dose distribution inside and outside of POE hutch, when beam hits a component inside the POE (section 2.4): (a) Horizontal view (b) Vertical view. The doses for regions DR31 to DR36 are further illustrated in Figure 14.

Case 3: Total dose distribution at outside of POE

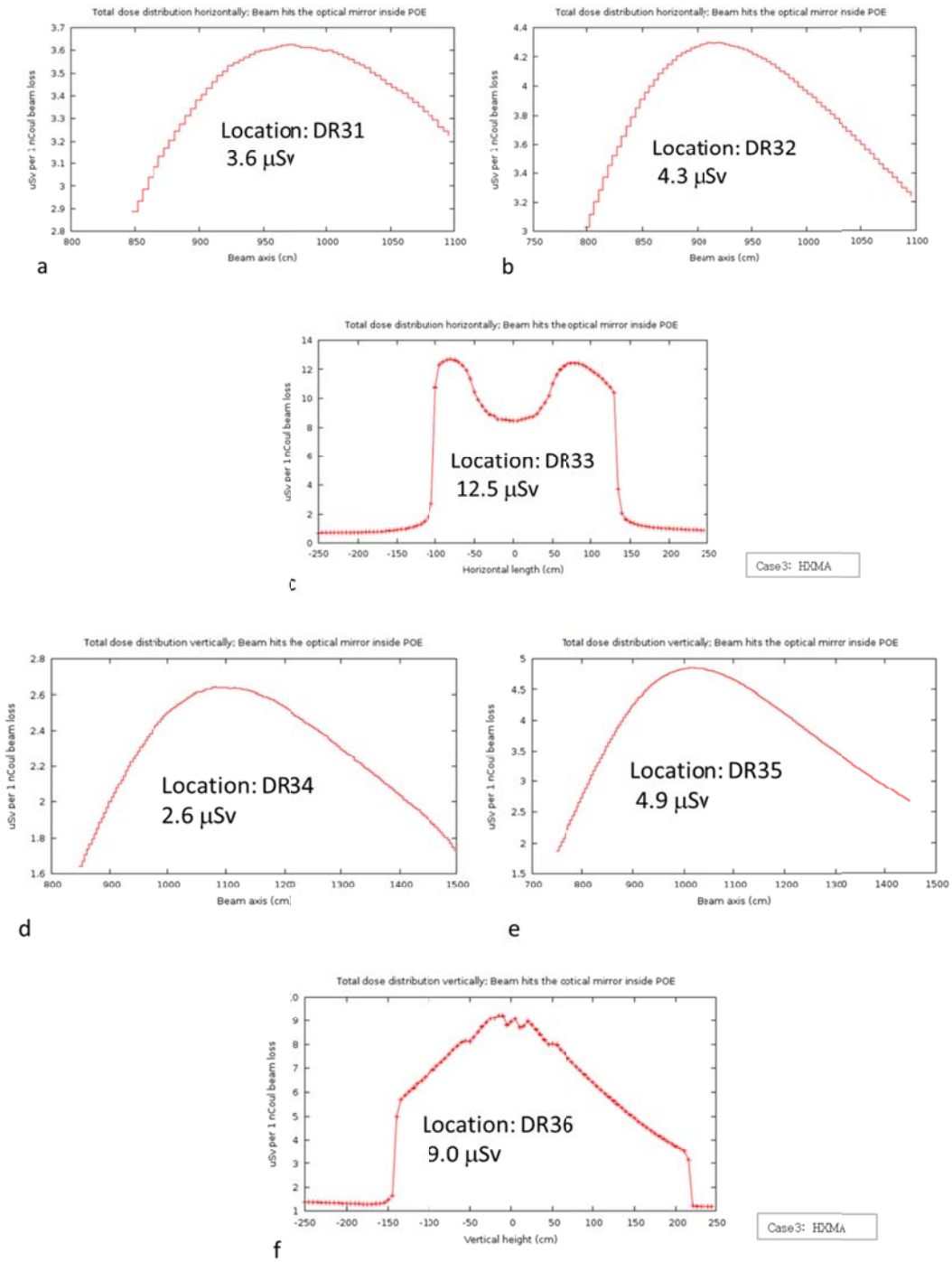


Figure 14: Total doses at key locations (DR31 to DR36) as indicated in Figure 13. Plots `a to f` show the doses for corresponding locations of DR31 to DR36. The error bars in Figures c and f indicate the relative error and it was less than 2%.

Case 3: Total dose inside the POE hutch

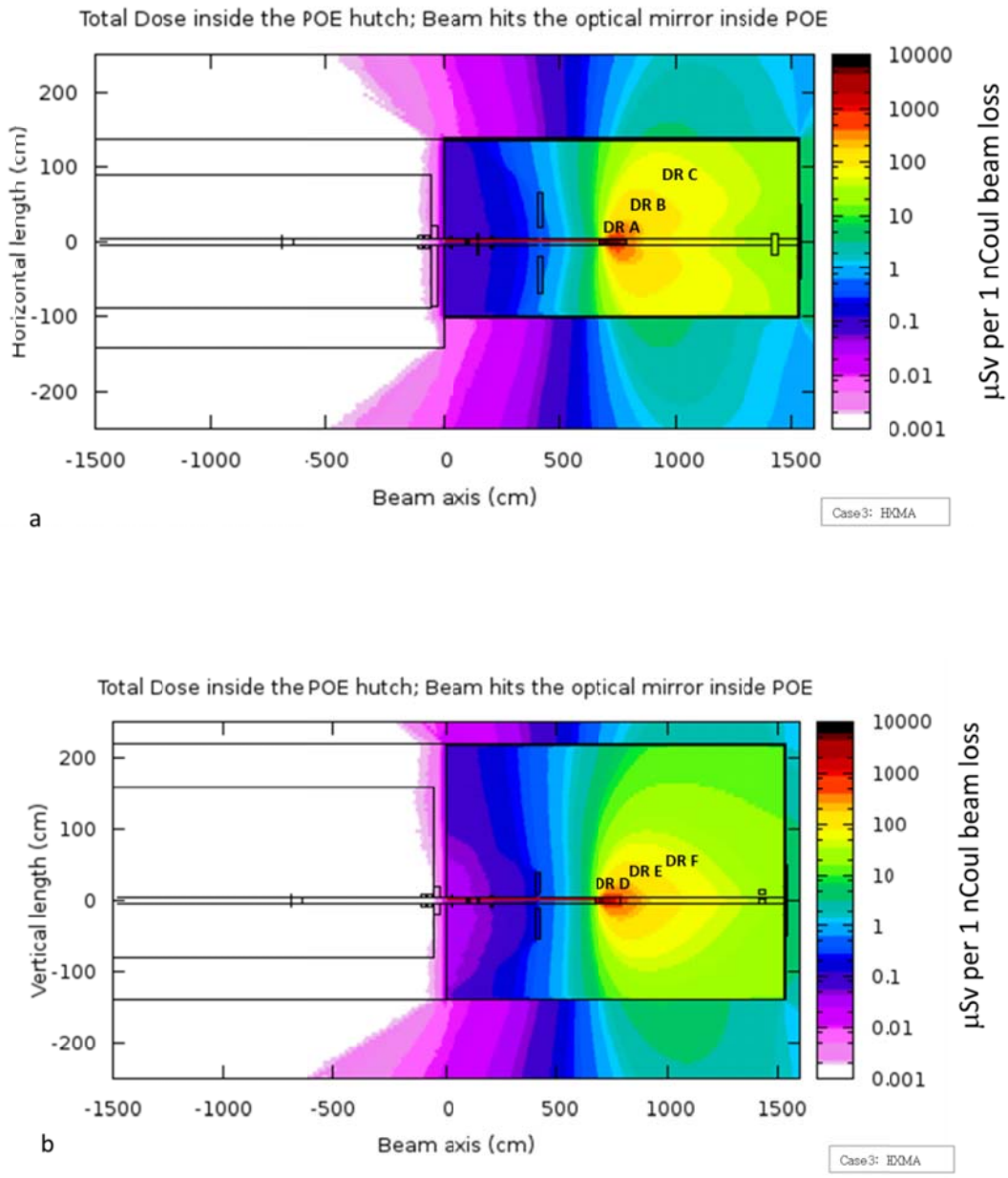


Figure 15: Total dose distribution when beam hits optical component inside the POE: (a) Horizontal view (b) Vertical view. The doses for regions DR-A to DR-F are further illustrated in Figure 16.

Total dose inside the POE hutch

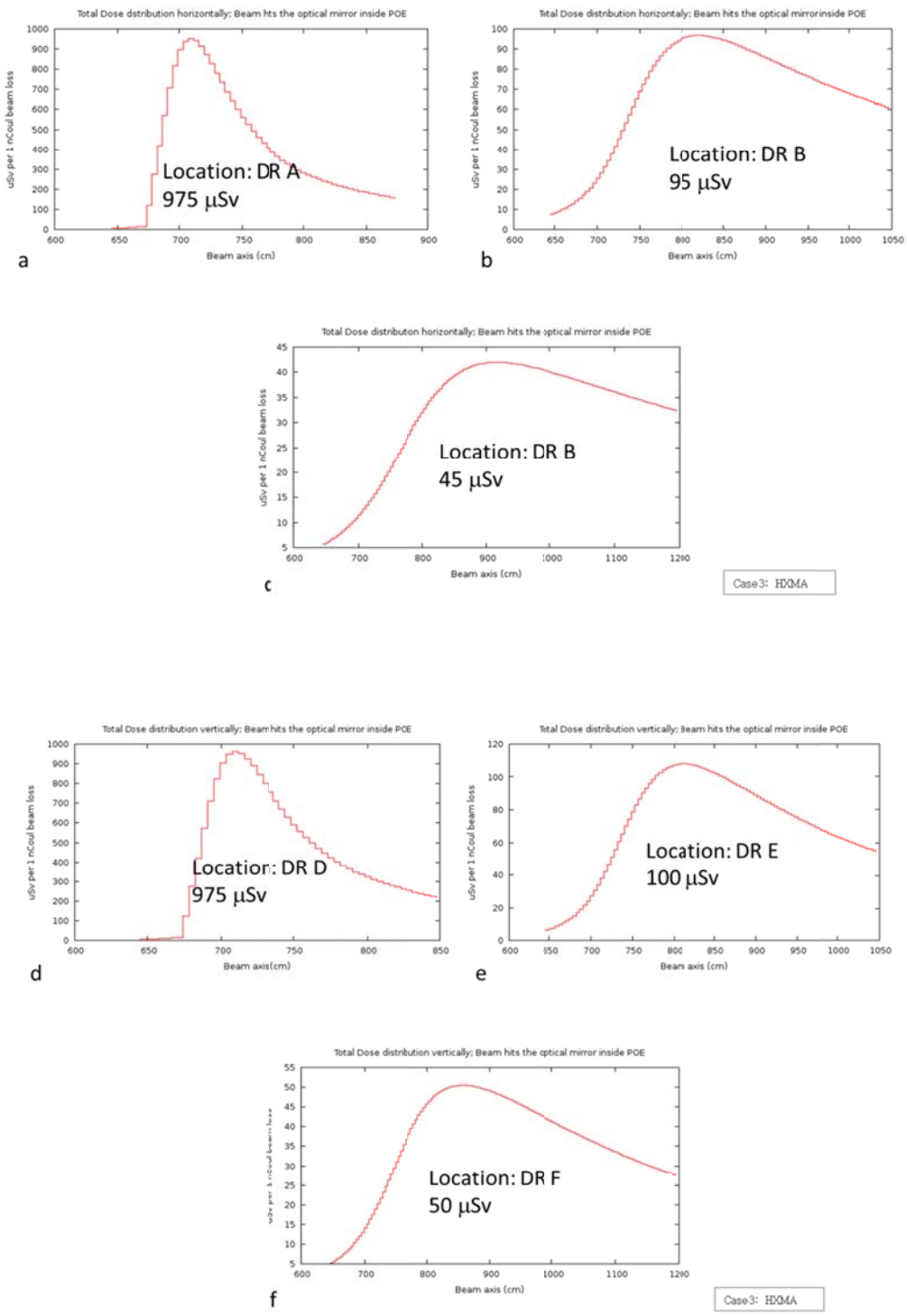


Figure 16: Total doses at key locations (DR A to DR F) as indicated in Figure 16. Plots `a to f` show the doses for corresponding locations of DR A to DR F.

With the BL FE SSH open, there are some risks, even at minimal level, that the injected beam may be miss-steered in the SR or may cause a shower inside the storage ring due to the misaligned components [7]. Some studies also studied the cases where the beam was lost inside the POE. Considering the worst beam lost scenarios and the worst dose hazard within the user area, three different beam loss cases were modeled and the dose levels were studied.

When the beam line safety shutter is open, the beam line ACIS doesn't allow any occupancy inside the POE when the safety shutter is open. That means, no user or personnel will be inside the POE when the safety shutter is open. However, the users are allowed to work outside of the POE hutch during this operation.

The dose at a given location depends on the amount of beam that is likely to be lost during the beam loss event. Typically, the amount of charge that is injected from BR to SR per single shot is 1 nCoul.

For case 1: when beam is miss-steered in the straight section of the storage ring, the dose level in the user area outside of POE is reportedly lower in comparison to other cases. It is also reported that, the dose levels are same for both the SSH open and SSH closed. The reason is the beam was miss-steered vertically upward to hit the wall of the vacuum chamber and then the upper part of the SR shielding wall (far above the level of SSH). This beam loss scenario may happen both in the normal mode and in the top-up mode and there is no difference to the case whether the SSH is open or close.

For case 2: when beam hits miss-aligned components inside the SR and creates a shower, a significant change in the dose level is observed in Figures 7 & 8 with FE SSH open and closed.

For case 3: when beam hits the optical component inside the POE, the maximum dose at outside of POE was found as 12.5 μSv outside the wall (wall between POE and SOE) along the beam axis. However, for this beam loss scenario, the maximum dose inside the POE was found as high as 975 μSv within 200 cm of radial distance from the target component. This high dose is not a concern from safety perspective as there won't be any occupancy inside the POE.

The results produced in this document are reasonable and justified in comparison to other published results. One study was conducted in the Brookhaven National Laboratory USA (NSLS) [8]. In that study, PK Job et al estimated the total dose equivalent rate at the exterior of the downstream wall of the first POE at beam height, was about 3.0E+05 milli-rem per hour (mrem/h). The beam loss scenario for the above study is close to the Case 3 beam loss and the result is shown in Fig. 14c. For Case 3 beam loss scenario, the maximum dose rate at outside of POE wall was 12.5 μSv, calculated for 1 nCoul/s beam loss. With proper conversion, this dose equals to 6.75E+04 mrem/h. The difference in the estimated dose is normal for the following reasons:

- NSLS beam energy 3.0 Gev, CLS beam energy 2.9 Gev
- The POE at NSLS has a lateral wall of 1.8 cm and a downstream wall of 5.0 cm thick lead; CLS has lateral wall thickness of 1 cm (total 3 cm locally) and 3 cm downstream wall thickness (11 cm locally)
- The target used in NSLS study was a Safety mask, made of copper (Cu); target in CLS study was Optical mirror, made of silicon (Si).

According to the CLSI Safety Report, the maximum permissible dose per event that an occupant may receive is 1 mSv. Considering a beam loss as a 'single event,' it is expected that no occupant (either user or worker) will to receive a dose higher than 1 mSv integrated over the total beam loss period. The estimated dose that is described in this document can be considered as the 'extreme case.' In reality, the dose rate to the occupant would be much less than this.

4. CONCLUSION

It can be concluded that, the user can work in the user area with the BL FE SSH open. The POE shielding wall is adequate to protect the user if the beam loss time is minimized by proper mitigation. In order to achieve the proper mitigation, the following recommendations are provided:

- Installing additional AARMS at each beam line at strategic beam loss locations
- Setting the 'Cumulative dose rate alarm' in a minimum level (yet to determine and require experimental measurements) to ensure minimum tolerance of beam loss
- Ensure redundancy between the hardware and software to shut off the gun when the dose limit is reached

5. REFERENCES

[1] CLSI Safety Report, Document: 11.18.40.2

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[3] Vlachoudis V, "FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA" Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009

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[5] CLSI Beamline Enclosure Shielding, Presentation: Health, Safety & Environment, CLSI, 2005

[6] *CLS Source parameters needed for shielding calculations.* CLSI 0.2.35.1

[7] CLSI Top up hazard and risk analysis, 5.18.52.1

[8] Job PK, Casey WR, Radiological Implications of Top-off operation at National Synchrotron Light Source-II, Nucl Inst Methods in Physics Research A, 2011, 638, 15-21

APPENDIX: 1

Miss-steered beam in the front end

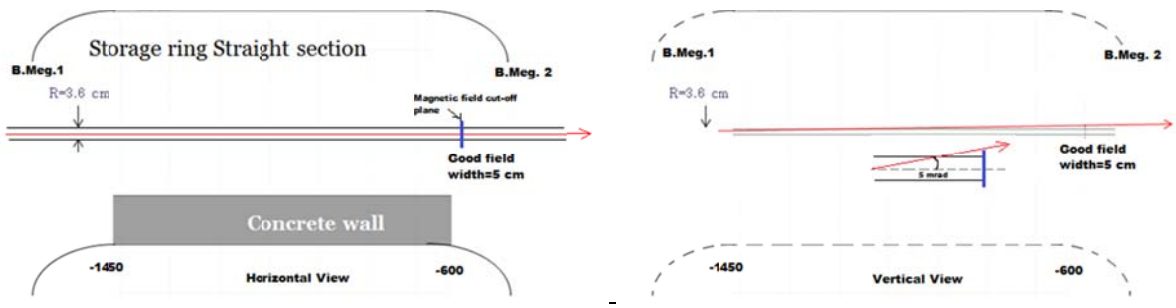

Figure: Schematic diagram of calculating the beam miss-steering. The assumption for the 'miss-steered source term' was made based on the physical length of the straight section, good field width of the bend magnet.

The following information and facts were used:

(*) The radius of the vacuum chamber was = 3.6 cm
(*) The good magnetic field width = 5 cm; [CLSI document: 5.8.31.1.Rev.0]. This indicates that the magnetic field extends beyond the vacuum chamber.
(*) The straight section was measured from center to center of two bend magnets (≅850 cm)

Assumption for simulation study:

(*) The beam was assumed as a pencil beam, sharply forward peaked. NOT as a 'Gaussian beam'.
In the Monte Carlo model, the study was performed to simulate the 'worst beam loss case'. Therefore, a 'pencil beam' was used to maximize the 'impact' of the collision to the target. The idea was to measure the worst dose out-side the shielding wall.
(*) Several angles were tried to simulate the 'Worst miss-steered beam.' However, the angle for the 'worst case' was calculated under the following condition:
θ = arc tan (5/850) = tan-1 (0.0059) = 0.005 rad = 5 mrad;

At this angle, the beam hit the wall of the vacuum chamber and barely cross the magnetic field barrier [see the figure above].

The physical information of the beam:

According to the physical specification, the beam has the following properties:

(*) During the worst case, the beam can be off the orbit by 1.8 cm; the divergence angle can be as high as 1.8 mrad with respect to the beam axis.

(*) Typically, a beam is 'Gaussian shaped' with FWHM (0.3, 0.3). This means that the beam is 'spatially' extended and not sharply forward peaked. The errant injected beam may be spatially extended higher. This feature of the beam was not considered during the 'shielding analysis.'