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

P. Chowdhury and G. Cubbon
Health, Safety & Environment Department
Canadian Light Source Inc.
Saskatoon, Canada

8th International Workshop on Radiation Safety at Synchrotron Radiation Sources

DESY Hamburg, Germany

Scope of Presentation

- Overview of CLS Storage Ring & Beam-lines
- Top up – Objective & Safety
- Analytical Model and Data Inputs
- Computed dose at the Vulnerable Points
- Some Experimental Results

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Top up – Objective & Safety

- In 'Top-Up' mode, the stored beam current will be kept maximum by injecting typically one pulse in a minute.
- Beam-lines are available 24/7 & beam-line optics remain steady at thermal equilibrium – by avoiding turbulence due to front end shutters open/close.
- During the top-up mode injection, however, the Beam-line Safety shutters remain open.
- Inviting remote possibility that a pulse of injected electrons might travel down the front end of a beam line into the primary optical enclosure (POE).
- The consequences of an injected pulse of electrons entering a POE are evaluated and covered in this talk.

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Top up – Thermal Stability of Optics

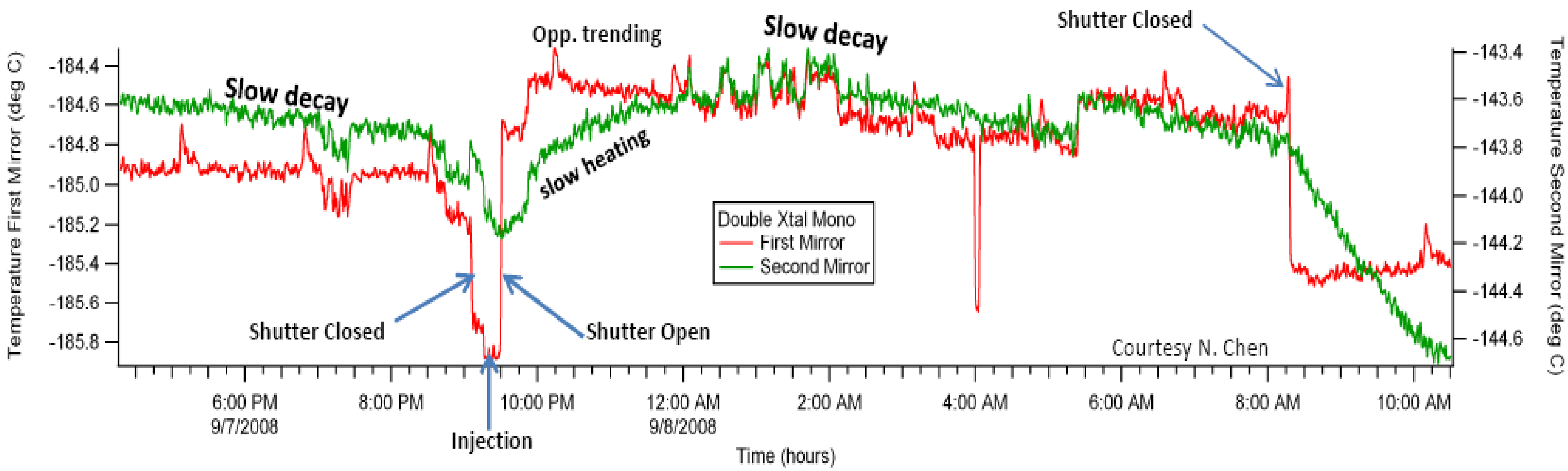

Fig: Temperature behavior of HXMA double crystal monochromator over 24 hrs

- A change in e-beam current will cause a proportional change of heat load on beamline optics affecting their thermal mechanical stability.
- The above Figure shows the effect of shutter open/close on the stability on the CLS HXMA liquid nitrogen cooled double crystal monochromator.
- A stable beam current will minimize the effects of changing heat load.
- This can ultimately improve photon position and energy stability for a beamline.

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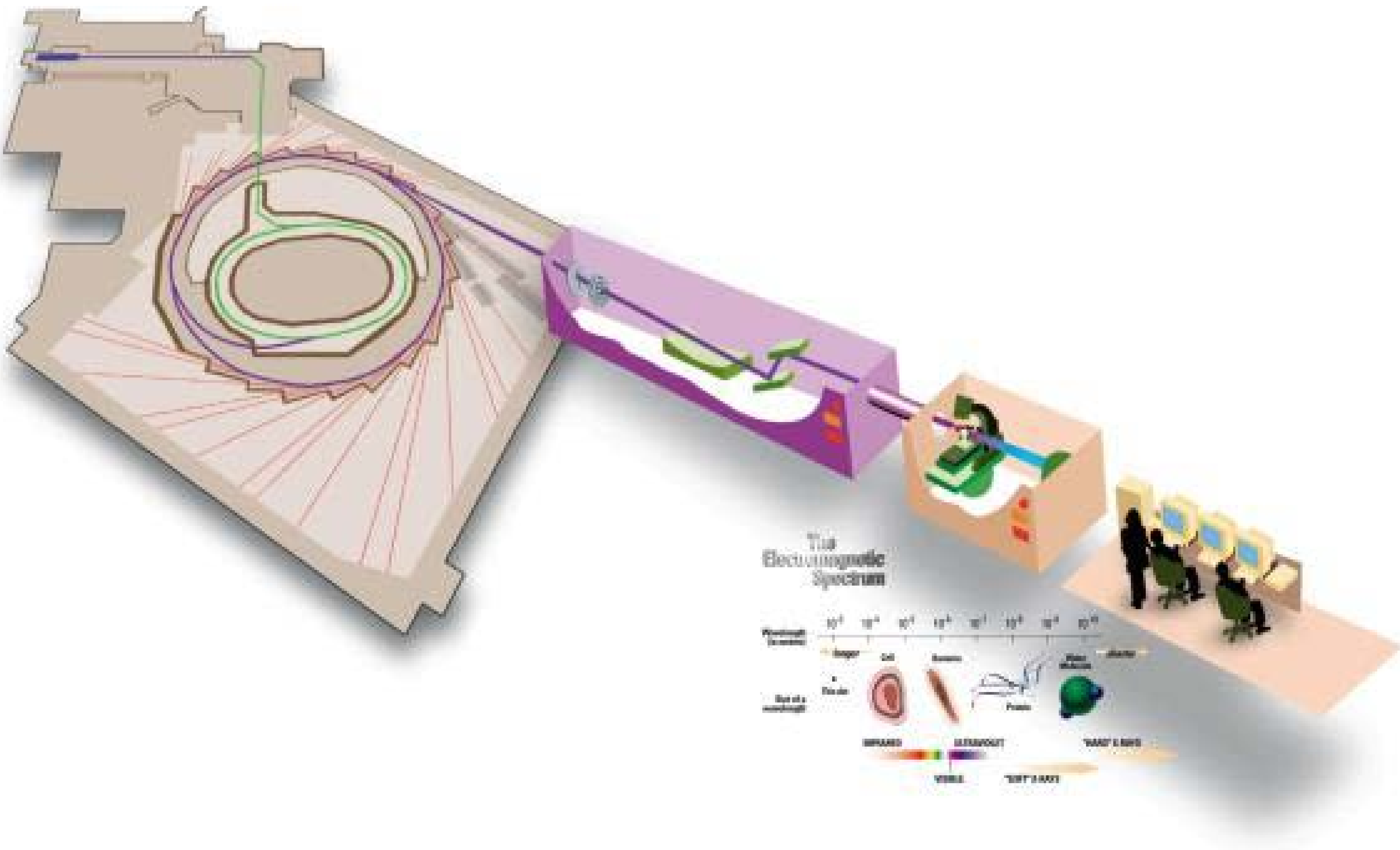
CLS Storage Ring Beam Lines



How the Facility Looks?

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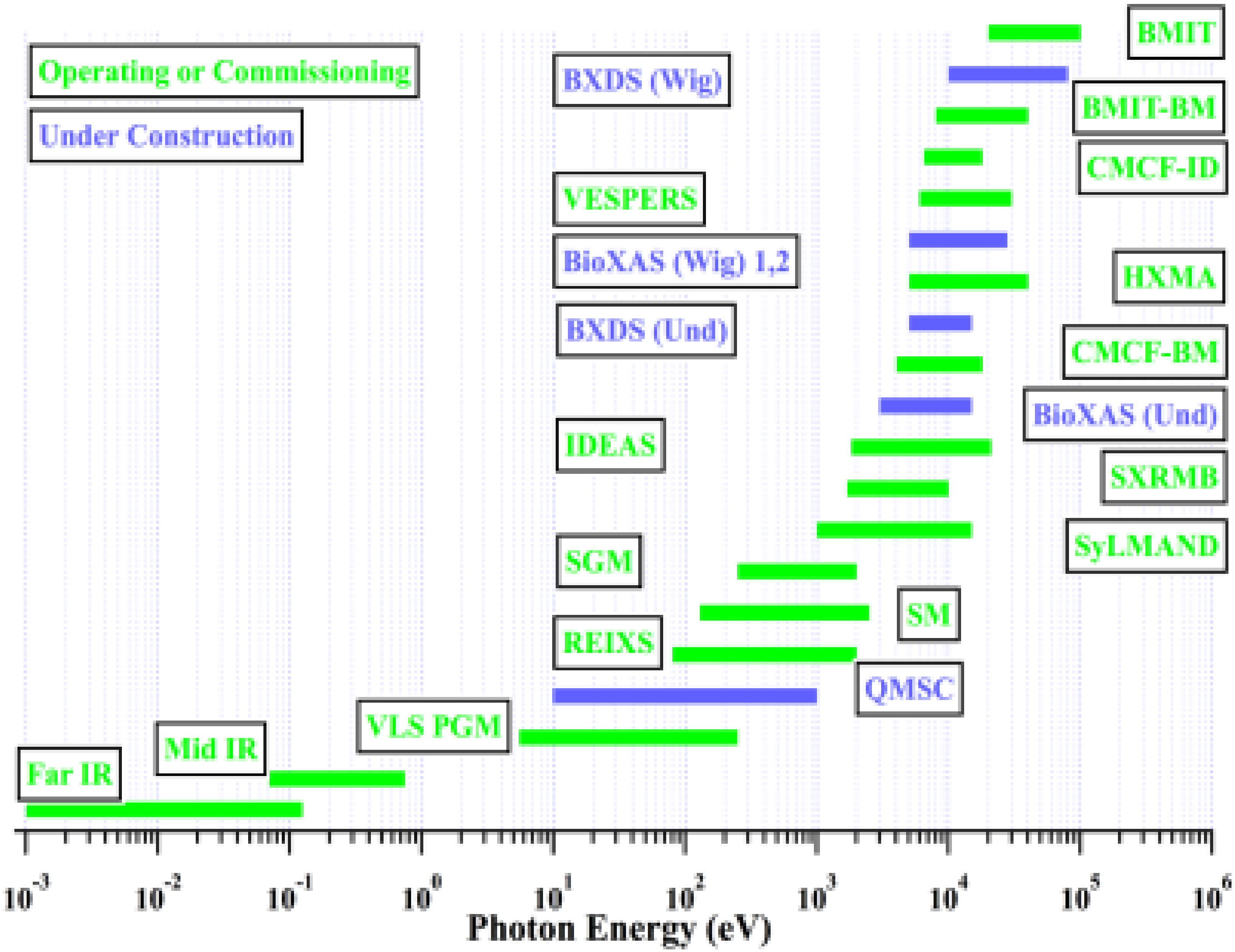
Beam Lines Energy Range



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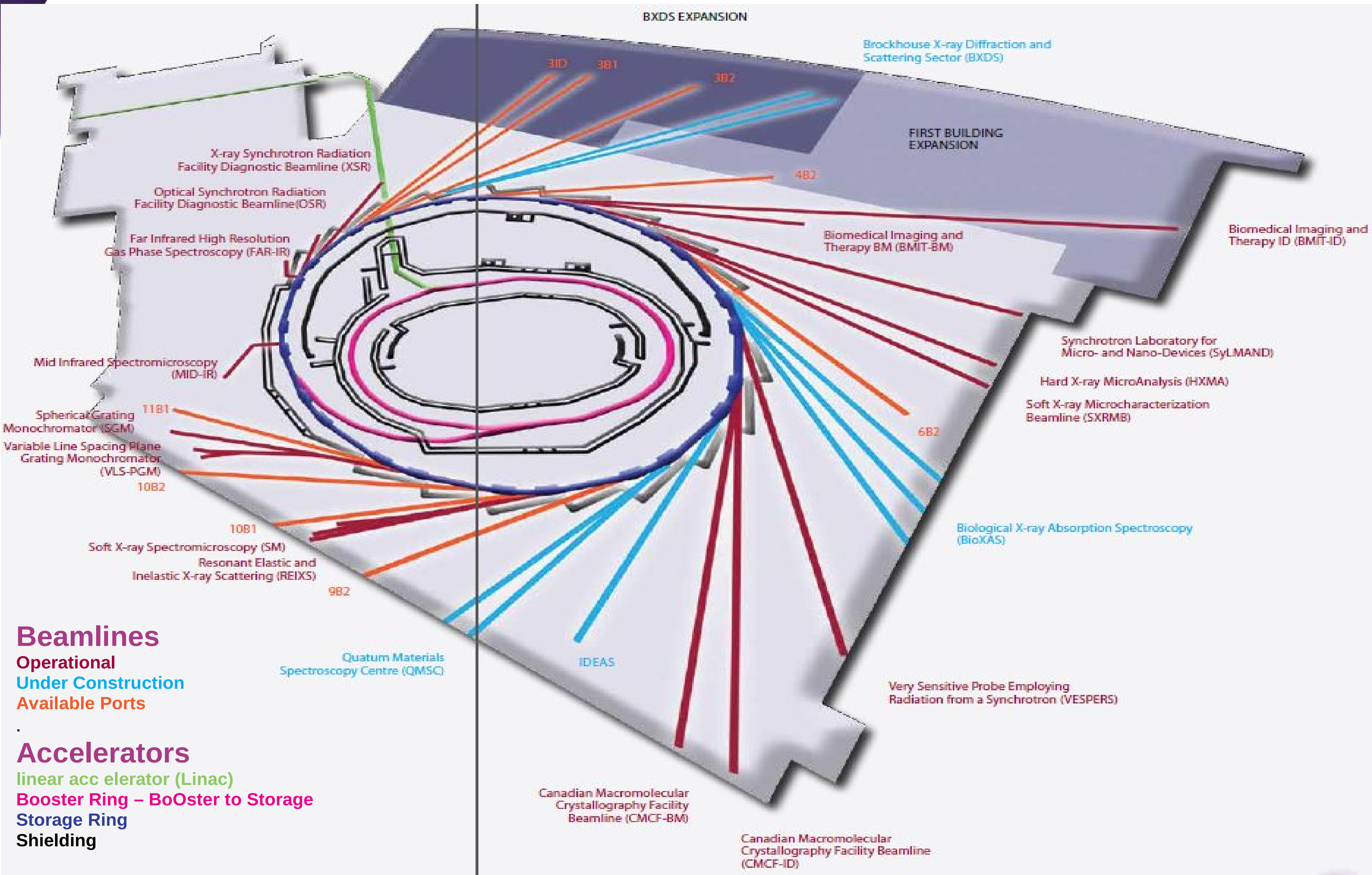
Layout of the Beam Lines



Beamlines

Operational
Under Construction
Available Ports

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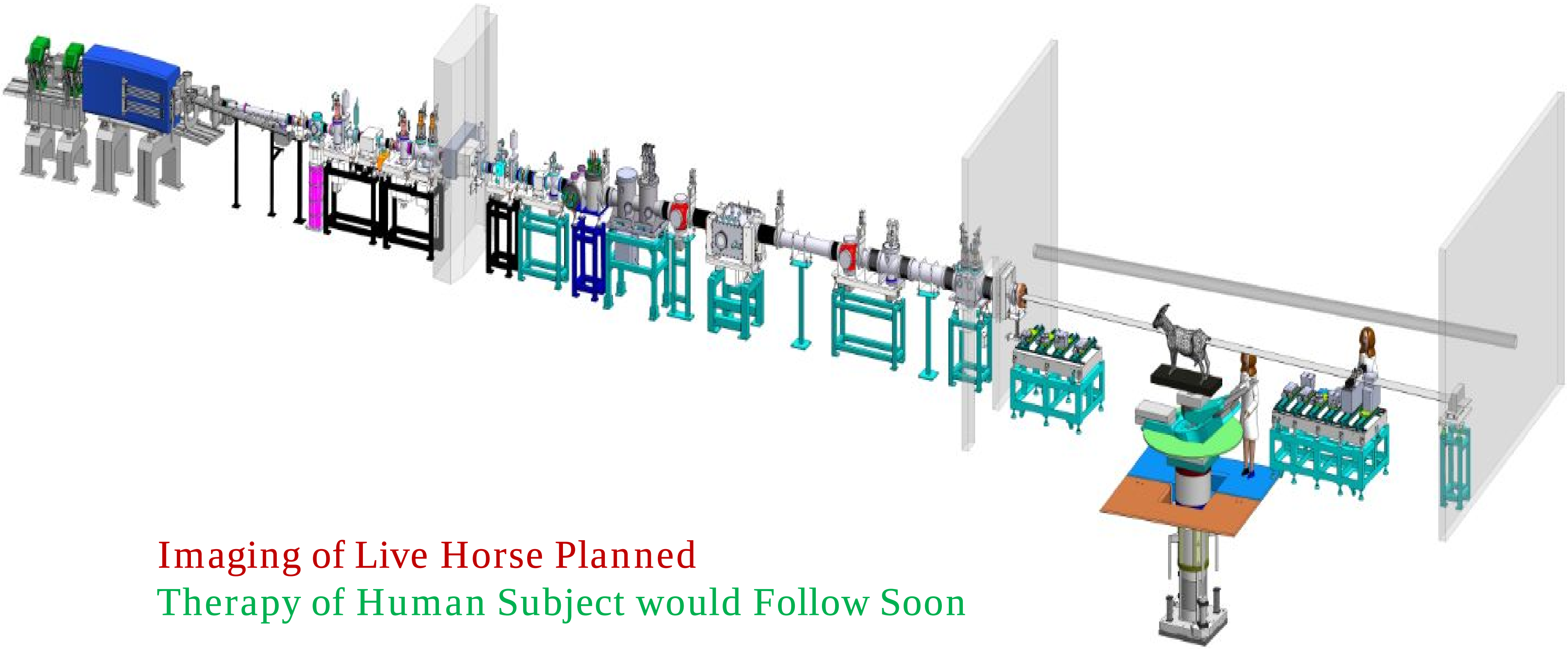
Accelerators

linear acc elerator (Linac)
Booster Ring – BoOster to Storage
Storage Ring
Shielding

BMIT Beam Lines



Imaging of Live Horse Planned

Therapy of Human Subject would Follow Soon

Radiological Implications of Top-up Operation: Dose Computations at the Vulnerable Points

The consequences of an injected pulse of electrons entering a POE are evaluated 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.

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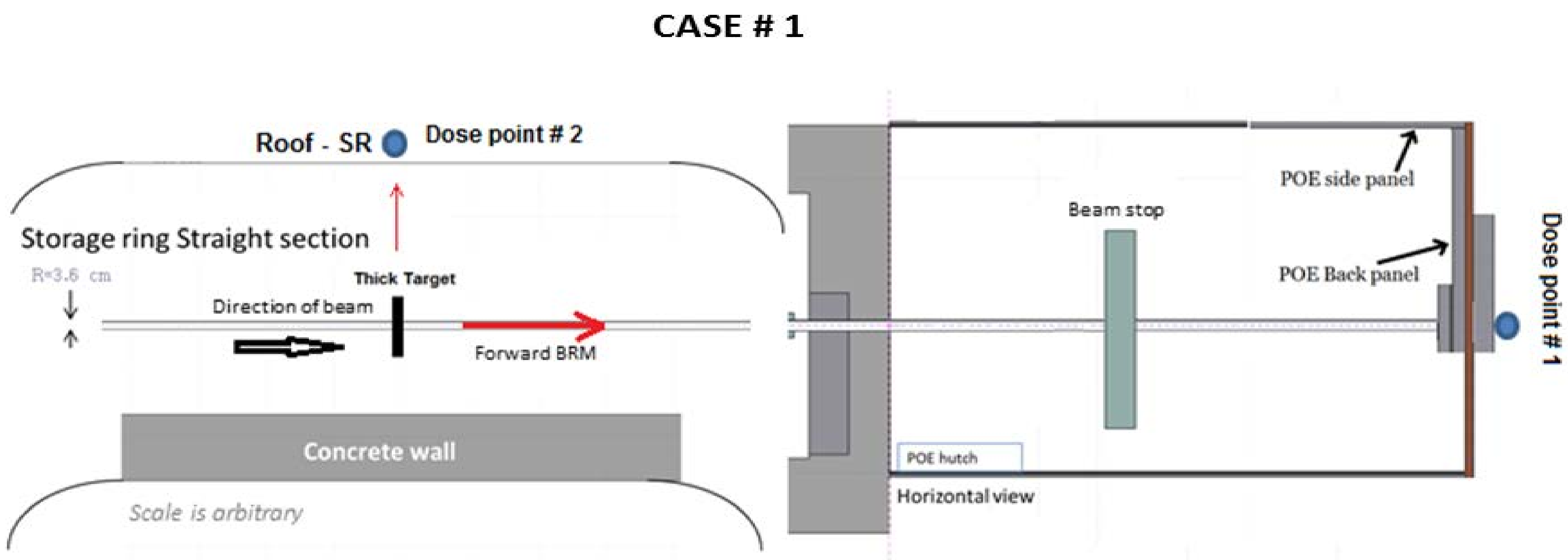
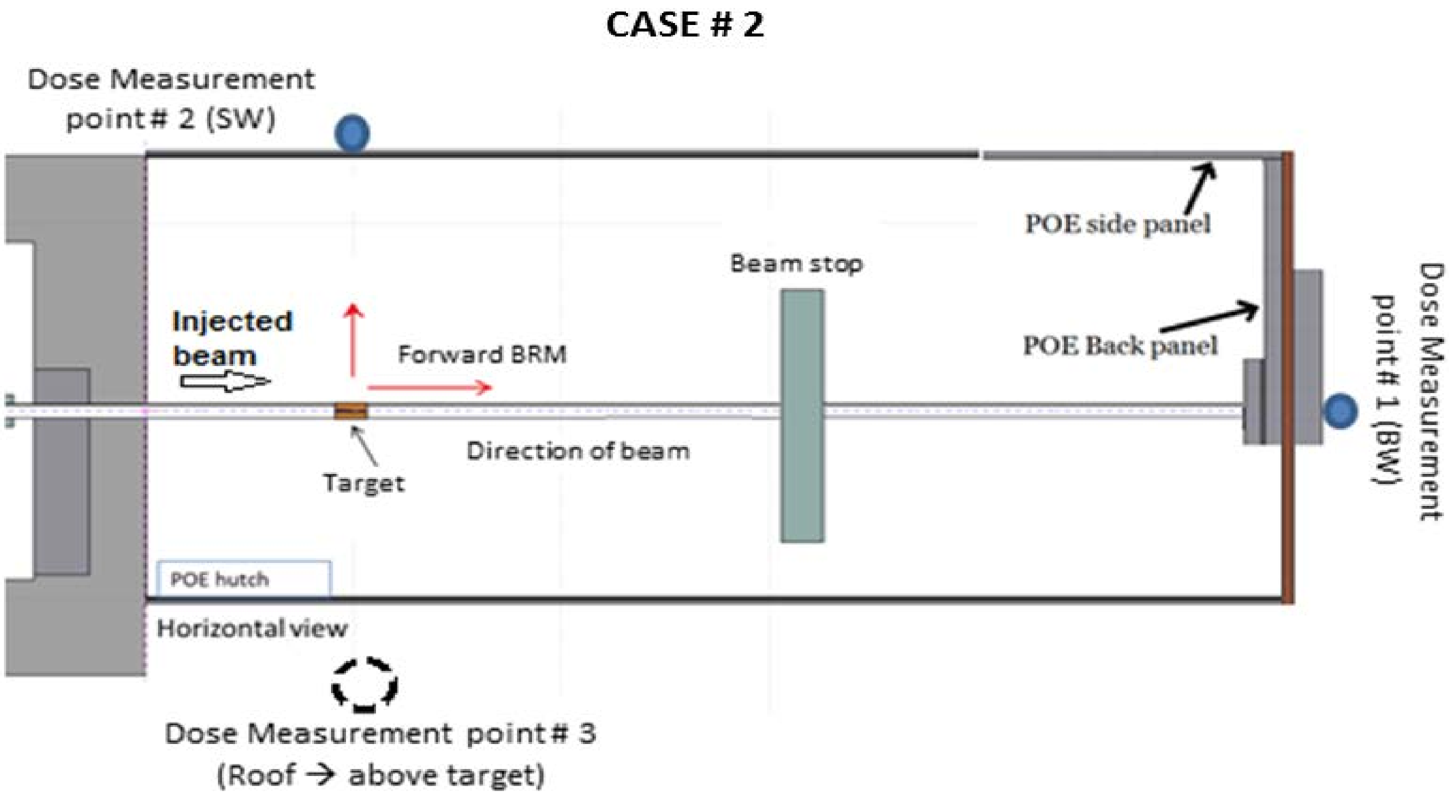
Case 1: 500 mA beam in the storage ring hit a vacuum valve (thick target) at the middle of a straight section and lost at one point releasing 827 J energy



Radiation dose resulting from Bremsstrahlung (BRM) and neutrons estimated :

- (a) 90 Deg: The perpendicular component of the BRM and neutrons hit the ceiling of SR and dose estimated outside of SR roof - 60 cm concrete.
- (b) 0 Deg: Highly forward peaked BRM and neutrons enter the nearest POE with the openFE SSH and hit the ‘brem-stop’ inside the POE, the resulting doses were calculated at a point outside of the POE back wall (BW).

Case 2: 1 nC Electron Pulse from the booster to the storage ring Enters POE via the open BL FE SSH



Radiation dose resulting from Bremsstrahlung (BRM) and neutrons estimated :

- (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.

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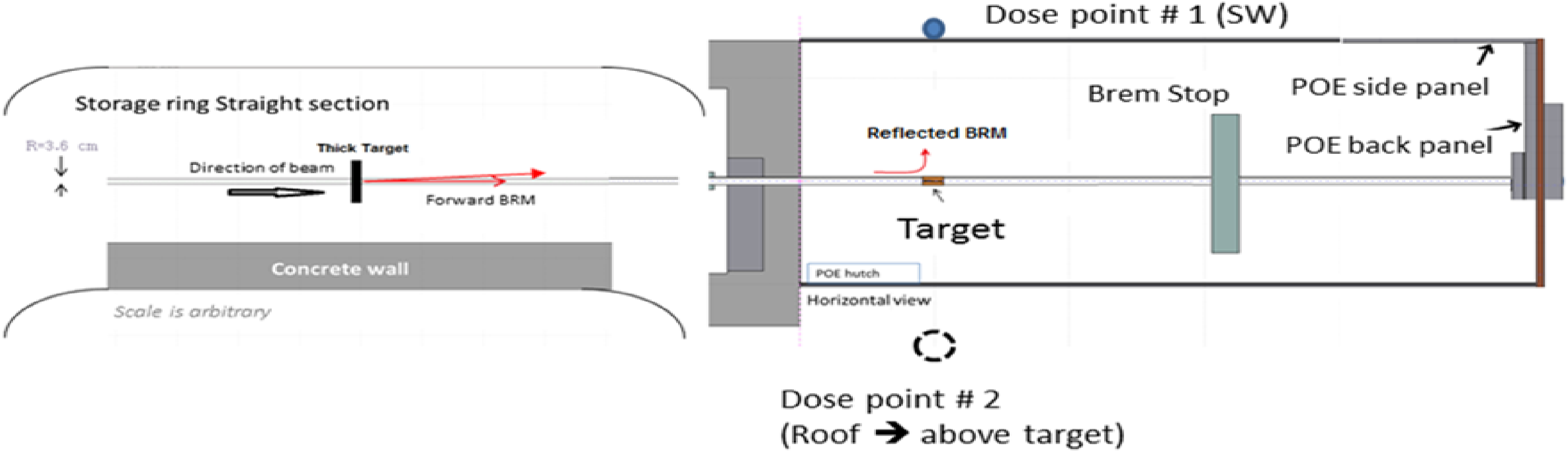
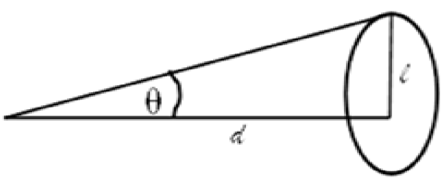
Case 3: Stored beam hitting thick-target creates BRM over a wide angle, the forward peaked BRM ≤ 1mrad enters the POE and reflected at 90 deg by a target

CASE # 3





$l = d * \tan\theta$

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.

Radiation dose resulting from only Bremsstrahlung (BRM) estimated :

- (e) Outside of the POE SW
- (f) Outside of the POE Roof

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The methodology used for estimating the dose rates

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

- ❖ Distance between the source point and the measurement-location
- ❖ Shielding thicknesses
- ❖ Energy Deposited (Joules)

- ➢ The parameters required for the dose calculation are summarized in the following Tables 1 and 2 for all of the 14 existing beamlines at the Canadian Light Source.

Table 1- Shielding Material and Thicknesses for Beamloss Calculations

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

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

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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

EQUATIONS USED FOR DOSE CALCULATIONS

The unshielded bremsstrahlung dose profile is estimated by:

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

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

- 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

References

[1] Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Swanson et. al., 1979, IAEA Technical Report Series: 188

[2] Advanced Photon Source: Radiological Design Considerations, Moe HJ, 1991, APS-LS-141 Revised.

The unshielded neutron dose Computation

The unshielded neutron dose profile for 90º in iron is given in the following Table.

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 Computation Considering Shielding

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

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

- D = Dose rate in μSv/h
- P = Beam Power (in Watts)
- Hi = Unshielded dose from a given source material (μSv·m^2/Joules)
- r = Distance to the source point (meters)
- ρ = density of shielding material (g/cm^3)
- λi = attenuation length of the ith 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.

Results - Case 1a: 500 mA Stored Beam Lost Inside

The table below shows the total dose resulting from the bremsstrahlung and neutrons at a vertical point of the storage ring:

- With 600 mm thick concrete roof at a distance of 2.2 meters and at 90 degrees from the location of the complete loss of 500 mA stored 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

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RESULTS - CASE 1B & CASE 2: 1 NC INJECTED ELECTRONS IN POE

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

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

RESULTS - CASE 1B AND CASE 2: CONTINUED

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**

RESULTS - CASE 1B AND CASE 2: CONTINUED

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

RESULTS - CASE 3: 500 MA STORED BEAM LOST, BREMSSTRAHLUNG SCATTERED IN POE

Beamline	Dose (µSv)	Beamline	Dose (µSv)	Beamline	Dose (µSv)
XSR	**BRM**	**HXMA**	**BRM**	**IDEAS**	**BRM**
Case 3 - POE Sidewall	1.886	Case 3 - POE Sidewall	0.264	Case 3 - POE Sidewall	0.603
Case 3 - Roof	1.996	Case 3 - Roof	0.359	Case 3 - Roof	0.455
BMIT ID	**BRM**	**VESPERS**	**BRM**	**QMSC**	**BRM**
Case 3 - POE Sidewall	2.630	Case 3 - POE Sidewall	6.112	Case 3 - POE Sidewall	0.206
Case 3 - Roof	0.283	Case 3 - Roof	0.359	Case 3 - Roof	0.359
BMIT BM	**BRM**	**BioXAS**	**BRM**	**SM**	**BRM**
Case 3 - POE Sidewall	0 .003	Case 3 - POE Sidewall	0.208	Case 3 - POE Sidewall	2.928
Case 3 - Roof	0.283	Case 3 - Roof	0.359	Case 3 - Roof	0.359
SYLMAND	**BRM**	**CMCF ID**	**BRM**	**SGM/PGM**	**BRM**
Case 3 - POE Sidewall	0.425	Case 3 - POE Sidewall	0.344	Case 3 - POE Sidewall	3.054
Case 3 - Roof	0.455	Case 3 - Roof	0.359	Case 3 - Roof	0.359
SXRMF	**BRM**	**CMCF BM**	**BRM**		
Case 3 - POE Sidewall	1.301	Case 3 - POE Sidewall	8.604		
Case 3 - Roof	0.456	Case 3 - Roof	0.455		

Results to Note

- Case 1: 500 mA beam 'lost' inside the storage ring at a thick target, resulted in a combined dose of 392.93 µSv from the Bremsstrahlung & Giant Resonance, Medium, and High Energy Neutrons. The max dose found in POE back wall was 122.85 µSv.

- This represents an extreme case scenario, where the entire stored beam is lost at a single point. The dose is still below 1 mSv, the CLS design limit for a worst case beam loss event.

- Case 2: An injection pulse of 1 nC was lost inside a POE. The maximum dose of 401.05 µSv was found at the CMCF BM sidewall.

- Case 3: Our calculations showed that the dose outside a POE sidewall or roof from a POE target scattered bremsstrahlung originally generated from the loss of a 500 mA beam inside SR1 is very low. The maximum dose value found was 8.6 µSv.

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Top-Up Experimental Measurements

Measurement Goals:

1. POE measurements during continuous injection with SSH open
2. POE stored beam measurements with 300 mA
3. Energy mismatch between SR1 and BR1 during injection
4. Closed SR1 valve struck at theoretical injection angle to maximize potential of Bremsstrahlung radiation entering an insertion device beam line POE

Measurement Protocol # 4:

- Radiation measurements was completed with the Front End Safety Shutters (SSH) open for an insertion device (11 ID SGM-PGM) beam line during continuous injection under the conditions shown below.
- Inject into SR1 valve at proper angle

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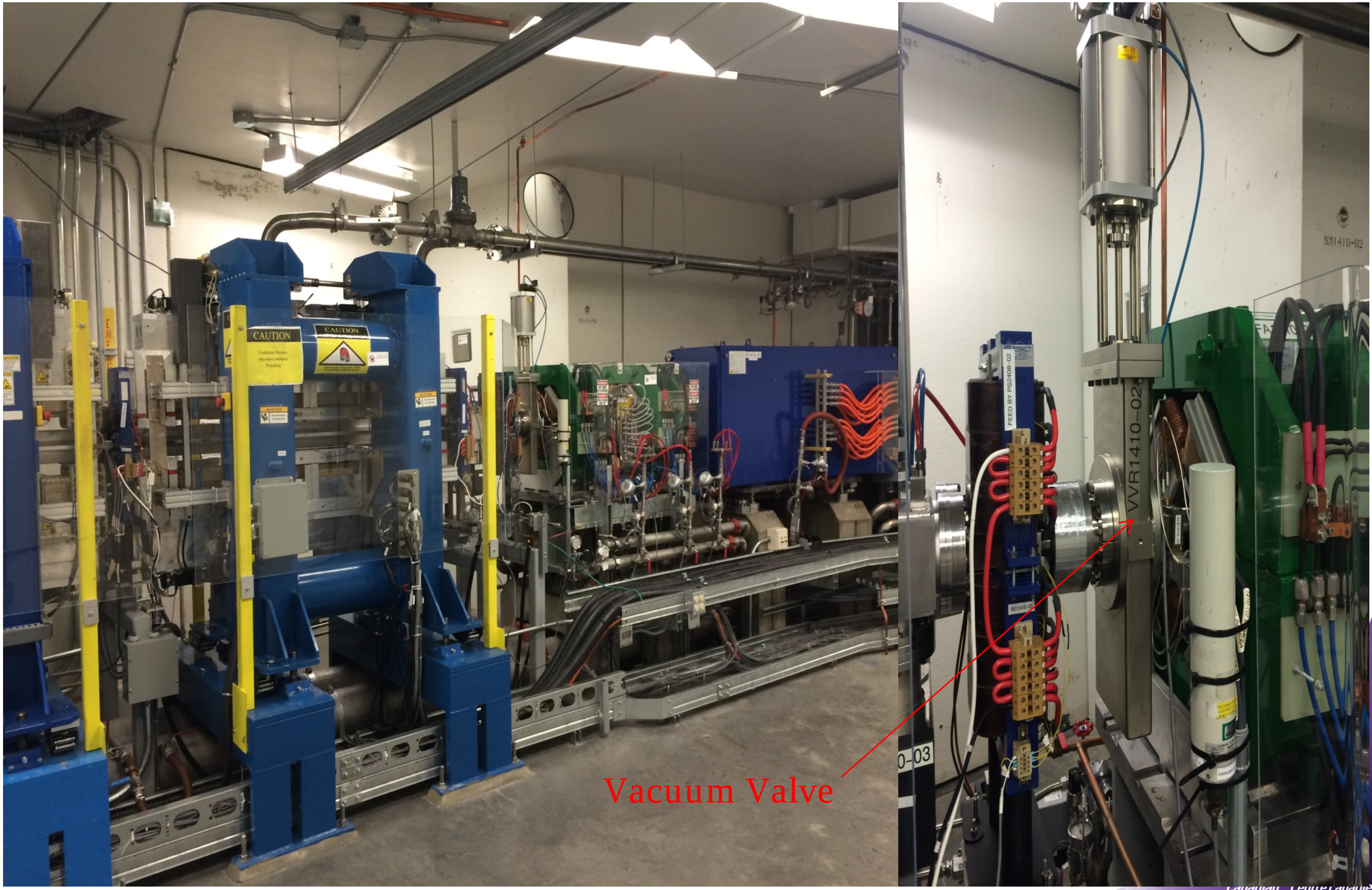
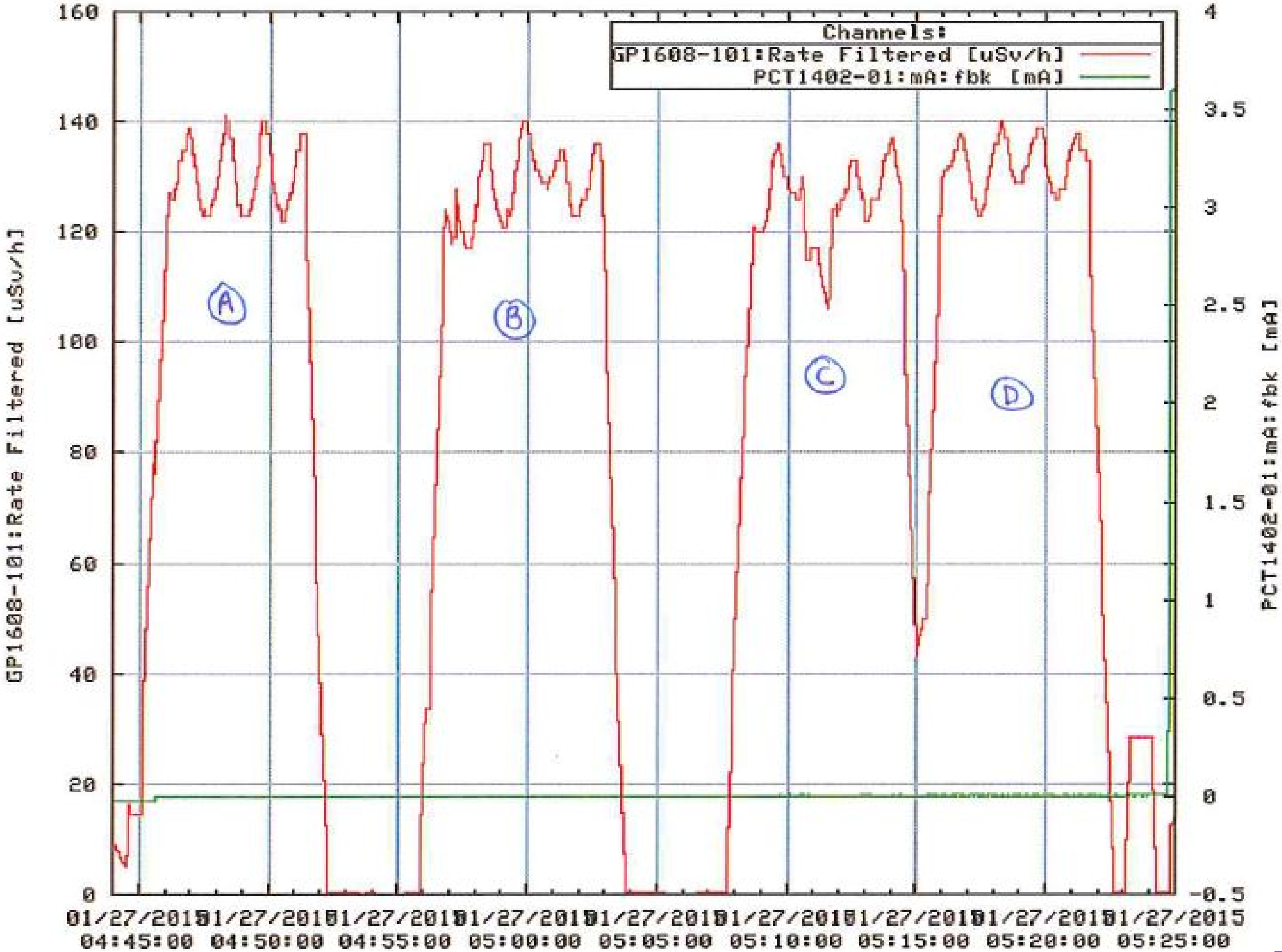
Top-Up Experimental Set-up



The vacuum valve was closed and e-beam was hitting the valve during continuous injection into the storage ring



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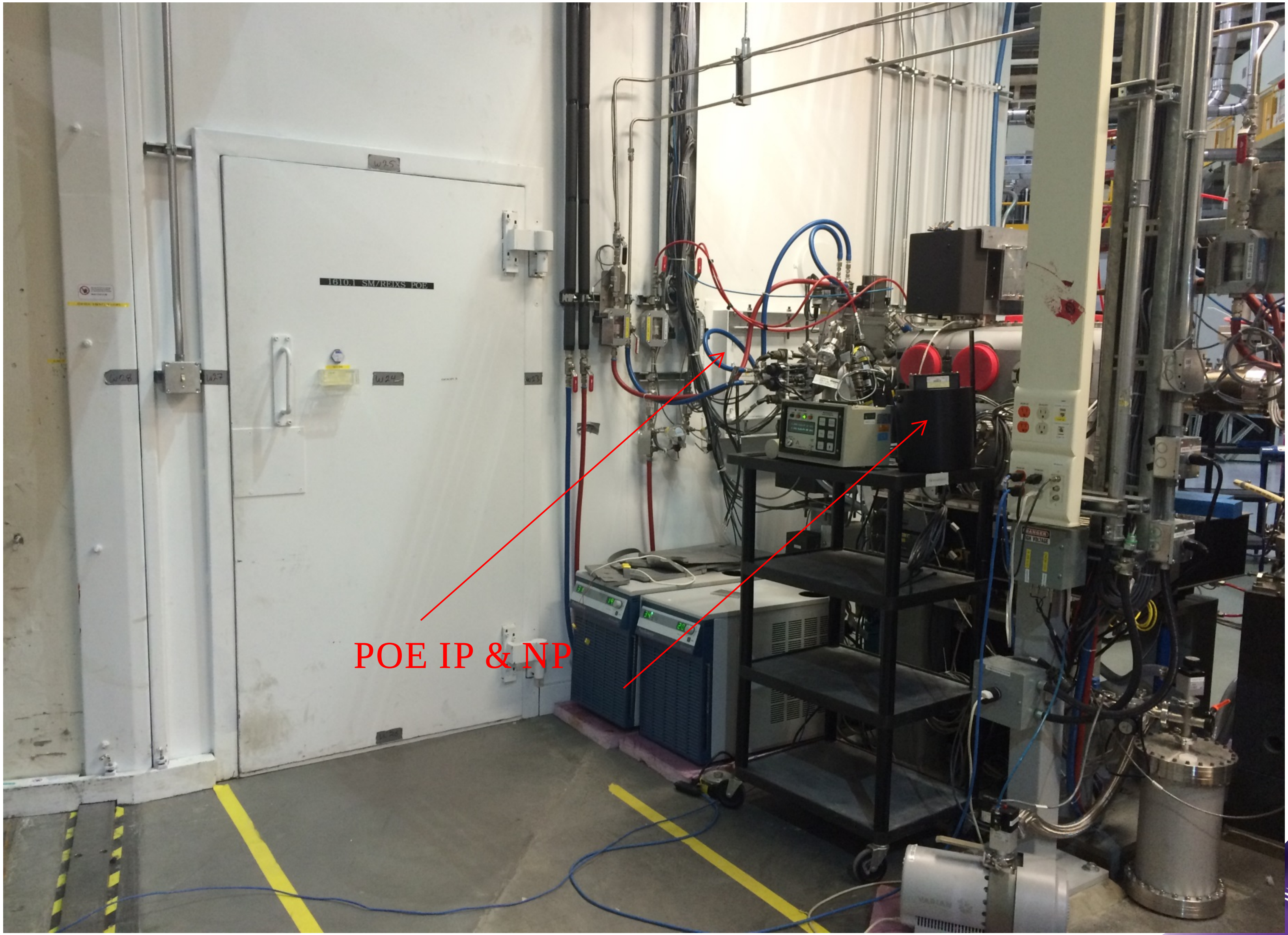
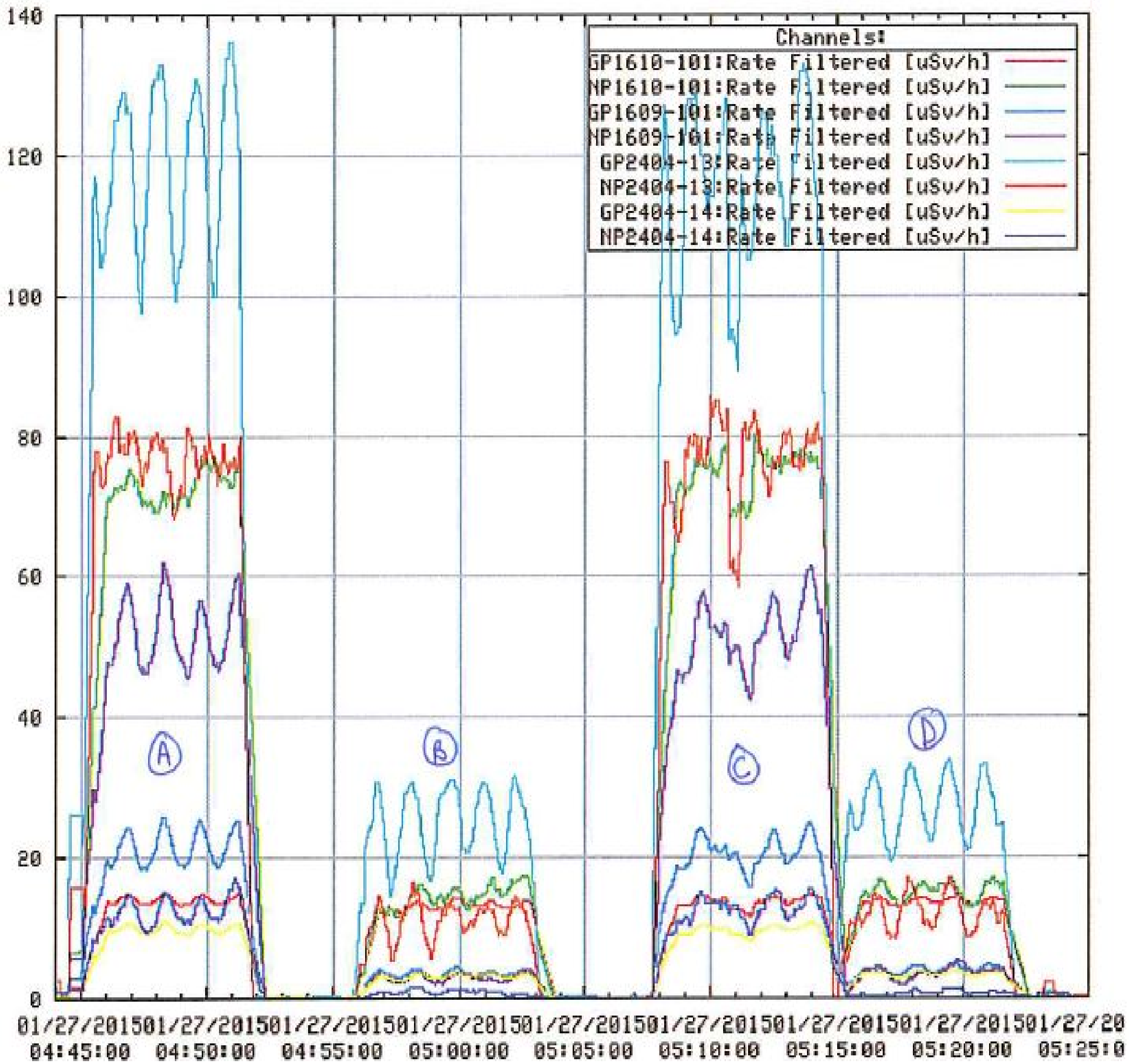
Top-Up Experimental Set-up



The vacuum valve was closed and e-beam was hitting the valve during continuous injection into the storage ring



- Test A-SSH Open, normal injection;
- Test B-SSH Closed, normal injection;
- Test C-SSH Open, modified kicker setting;
- Test D-SSH Closed, modified kicker setting.

Test A and C created quite high dose rates:

- Near the front POE door next to the ratchet wall at 10ID
- At the back wall of the POE

Showed no difference with the kicker settings changed

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The vacuum valve was closed and e-beam was hitting the valve: Results

- Only a few handheld meter readings were taken due to the high neutron dose rates around the POE.
- With the SSH at 10ID open the AARMS data revealed that the combined dose rate of gamma plus neutrons was in the order of 90 uSv/h at the 10ID front wall door, 75 uSv/h on the 10ID roof and 20 uSv/h at the backwall of 10ID.
- Inside the POE we found a combined dose rate of 200 uSv/h.
- Tests B and D with the 10ID SSH closed position had produced far less neutrons (~80% less radiation than Tests A and C).

Conclusions

- 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 beam-line POEs if an injected pulse of electrons could travel down through the beam-line front end.

- The probability of such occurrence has been found to be very low.
- Reference: Failure Mode Analysis in Preparation for "Shutters Open" Injection at the Canadian Light Source, CLSI Document 5.18.91.1

- 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.

- This would ensure that the radiation exposures to personnel ALARA during Top-up Operation or Injection with the Safety Shutters Open.

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Acknowledgements

- Dr. Mark de Jong and Dr. Les Dallin for their inputs on the Top-up Project.
- Darin Street and Andrea Albert for their help with the Top-up validation Experiments.
- We thank also the CLS Operations Staff that helped during the Development mode shifts.