Shielding Re-Evaluation for the Linac to Booster Transfer Line at the CLS

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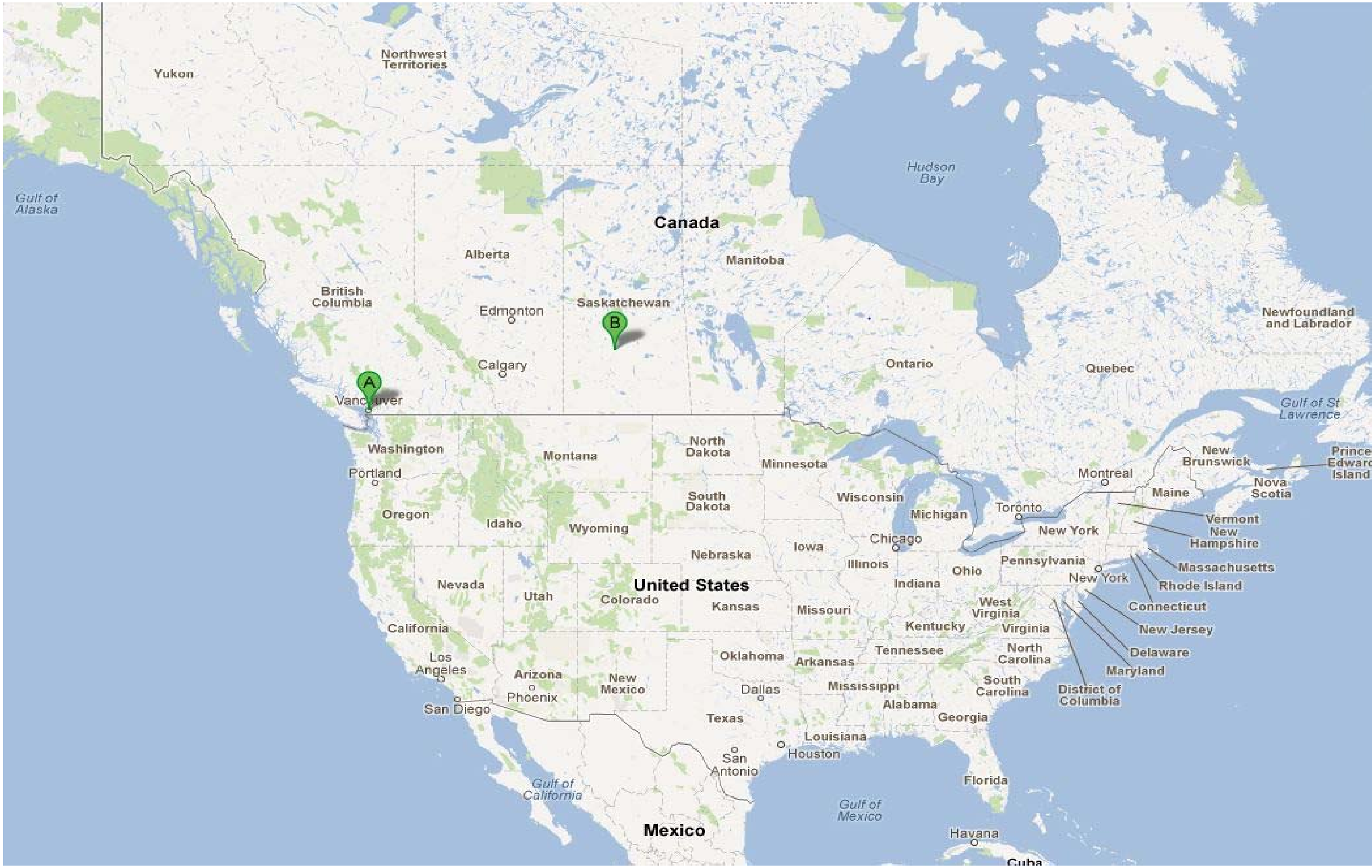
Where is CLS located?
Saskatoon, Saskatchewan, Canada

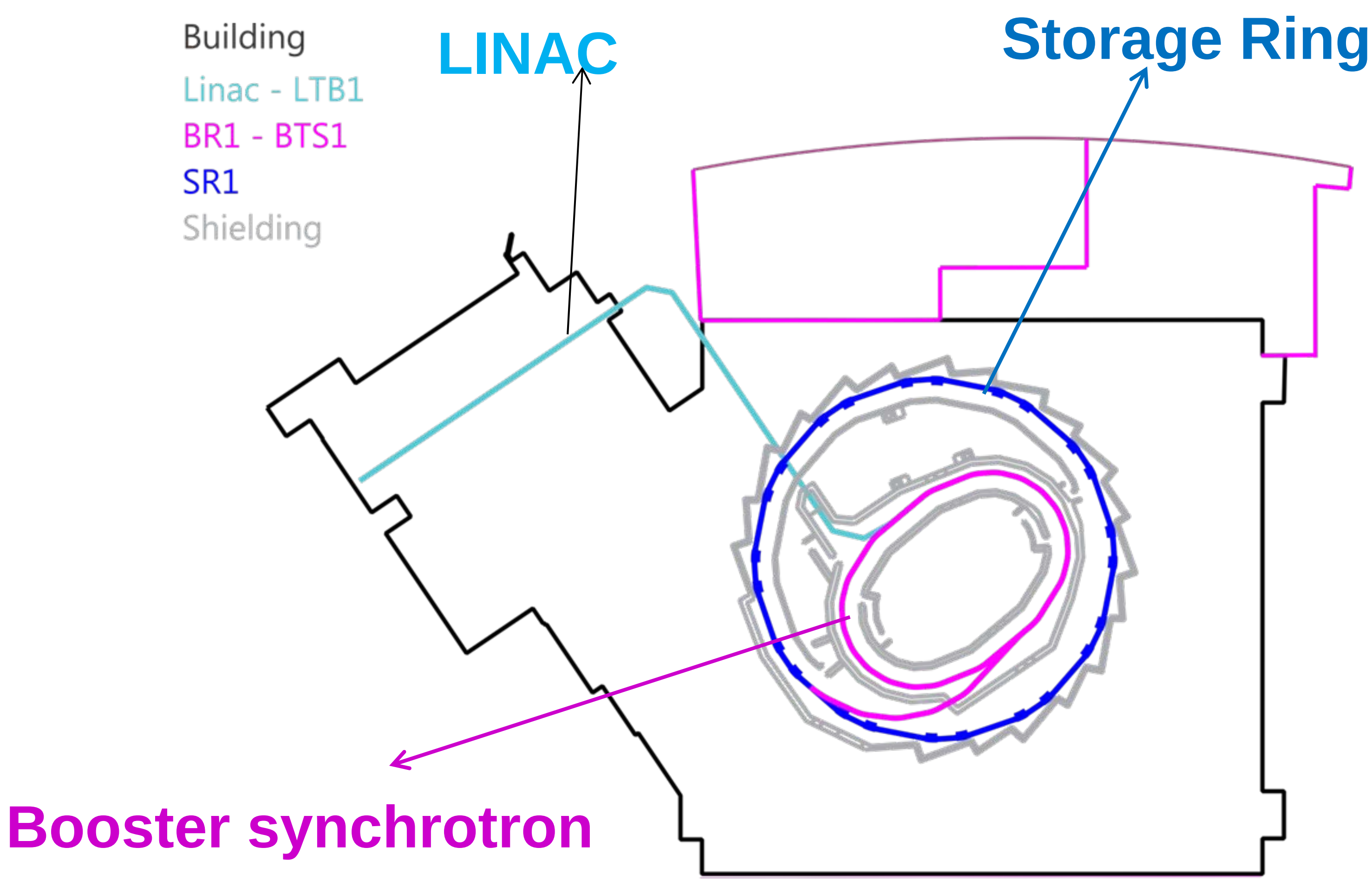


CLS facility on the University of Saskatchewan Campus

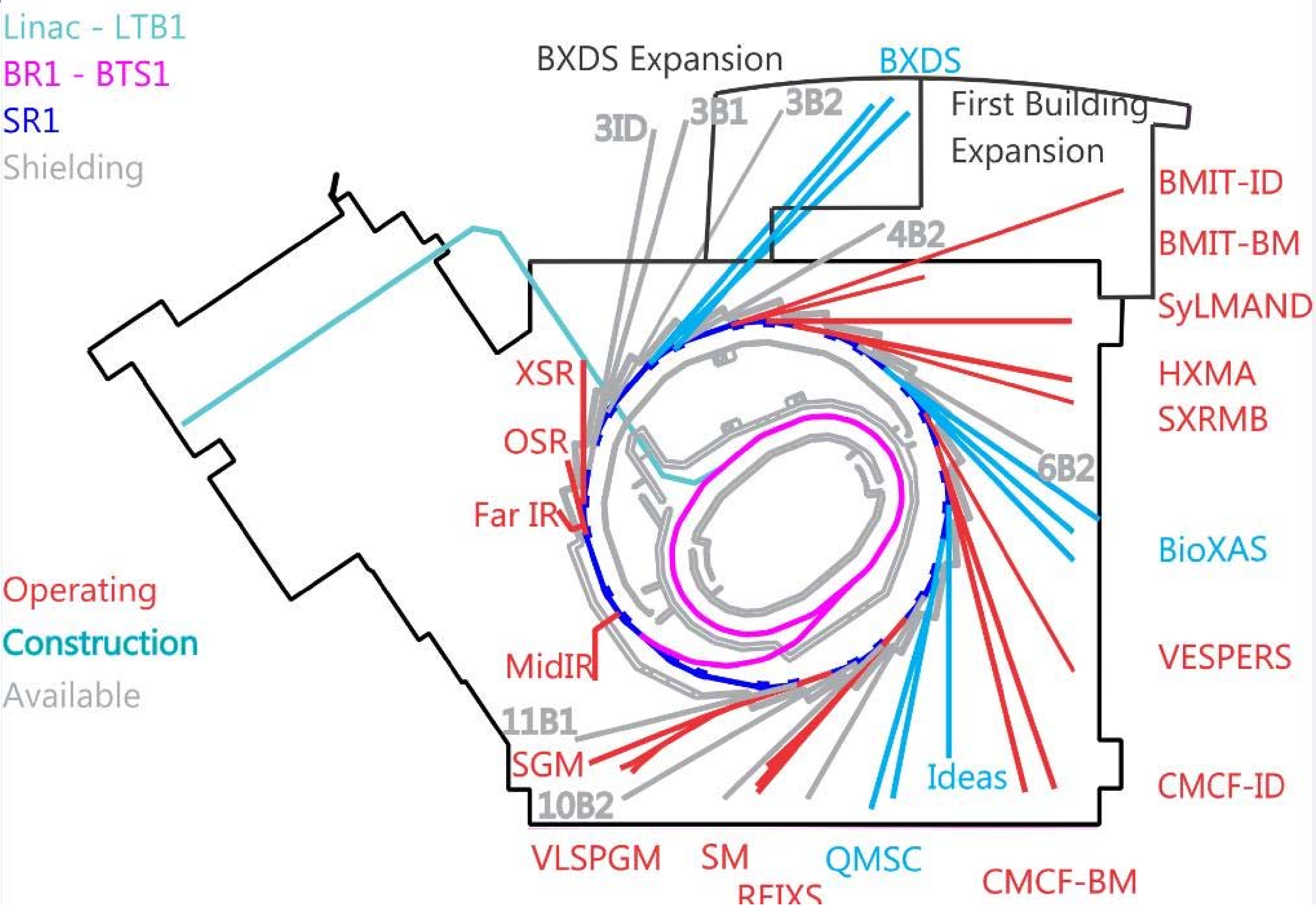
Canadian Light Source History

- **1964** – The Saskatchewan Accelerator Laboratory (SAL) opens, led by U of S physics professor Leon Katz
- **1974** – Michael Bancroft & Bill McGowan (UWO) propose that Canada builds a synchrotron
- **March 31, 1999** – CFI announces a contribution of $56.4M (Total costs for phase 1 ~$173M)
- **2000: CNSC Licence to construct**
- **2001: CNSC Licence to Operate/Commission**
- **July 2004 - CNSC approval of routine operation**
- **October 22, 2004** – Official opening
- **June 30, 2005** – Official completion of the CFI project
- **2006 – Obtain Licence Class 1B for 6 years**
- **April 17, 2006** – First publications based on CLS data
- **May 31, 2012 – Licence to operate expires**

The CLS Accelerator Facility

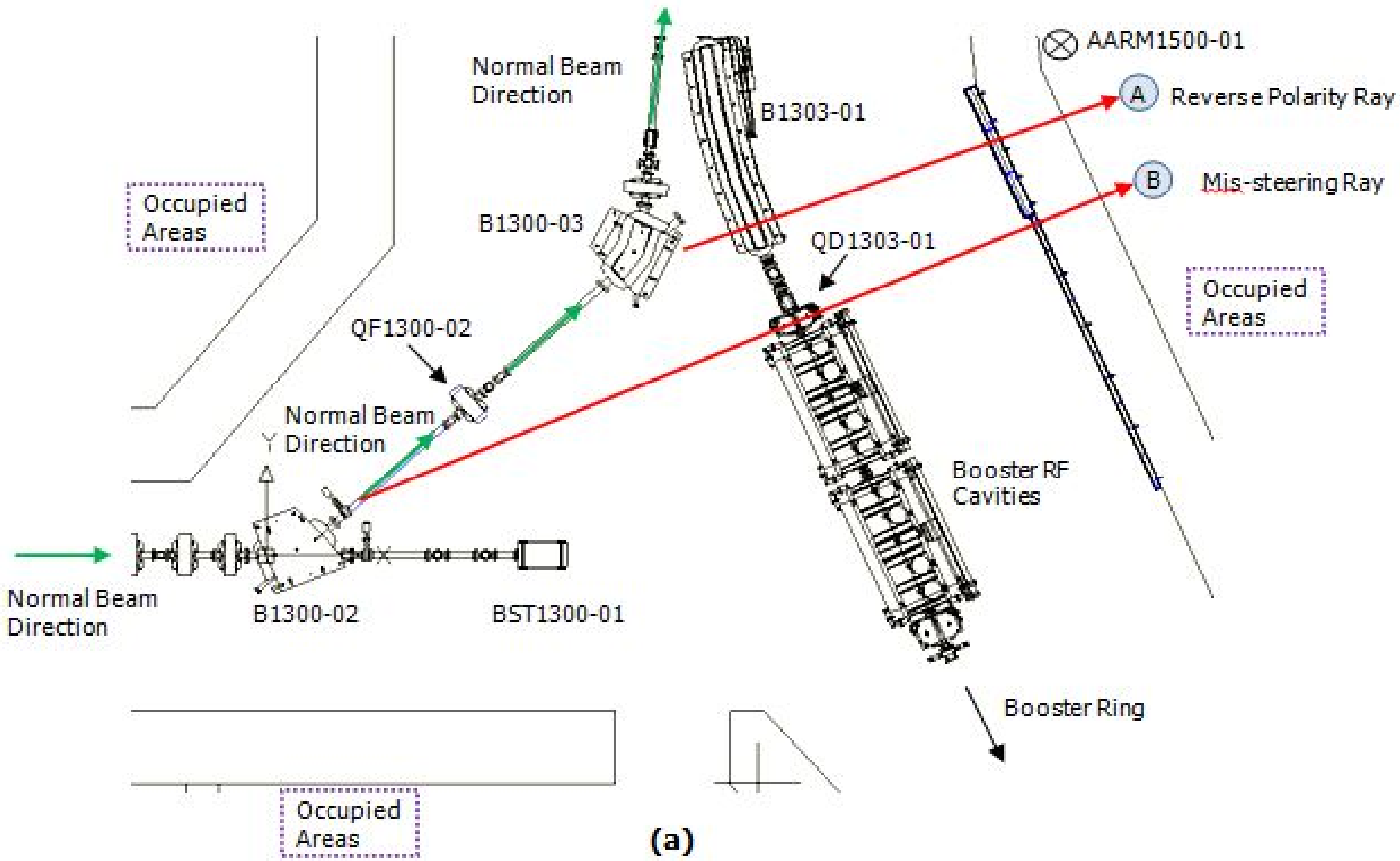


Accelerators and Beamlines



CLSI operates: 15 beamlines in 2012 – 21 beamlines in 2014

Linac to Booster Transfer Line between Dipoles B1300-02 and B1300-03



A layout of the Linac-to-Booster (LTB) transfer area extracted from CAD drawing. Arrows represent the normal path of the beam, the reverse polarity and mis-steering events. Occupied areas are also labeled.

Introduction

- In October of 2009 as part of regular maintenance, four power supplies corresponding to six dipole magnets were replaced along the linac-to-booster (LTB) transfer line.
- Two of these dipole magnets, referred to as B1300-02 and B1300-03 create a field which bends the electron beam from the straight line of the linac and into the booster ring oval.
- Due to a failure to pass testing, a decision was made to revert back to the old power supplies.
- During the old power supply re-installation, the polarity of the B1300-03 was inadvertently reversed by crossing the power supply leads.
- Subsequently during startup procedures, the accelerator operations division (AOD) was unable to detect any beam inside the booster ring (BR). An attempt was made to restore beam to the booster ring by steering the beam.
- The steering was accomplished by varying the field strength of the B1300-02 magnet between 5% of nominal field strength.
- On the second visit to the pit, it was discovered that a radiation warning alarm was sounding. The alarm was triggered due to a 0.050mSv/h upper dose rate limit being exceeded.
- An subsequent investigation of the LTB transfer line by AOD revealed the reverse polarity connection on the B1300-03 power supply.
- There was no beam capture in the booster ring as B1300-03 steered the electron beam away from the booster and towards a nearby shielding wall. While attempting to recover the beam, the control room operator mis-steered the electron beam into the beam pipe between the B1300-02 and B1300-03 dipoles.
- In June of 2010, the reverse polarity incident was recreated and dose rate surveys taken around the LTB transfer area.

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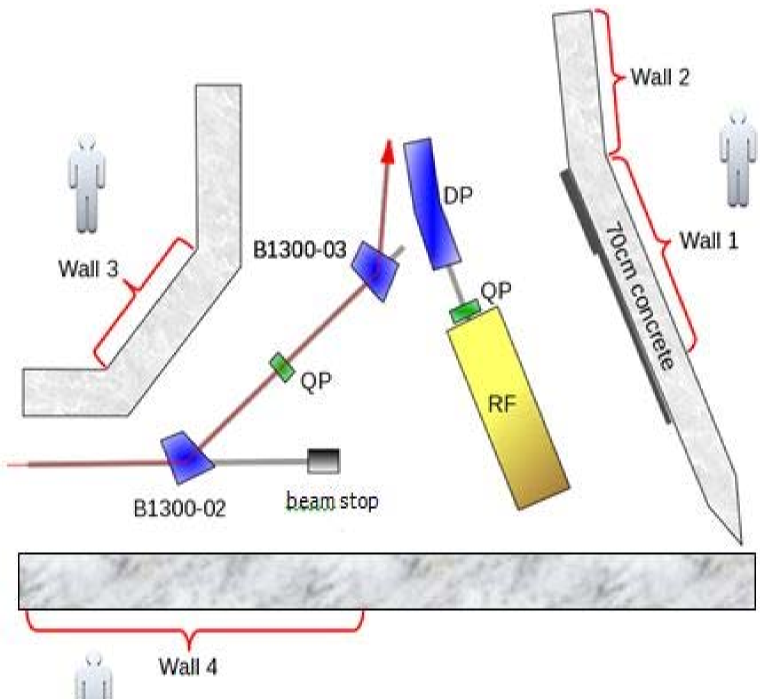
Introduction

- The dose rates when the polarity of the second dipole (B1300-03) was reversed with no mis-steering were well within the safety criteria for an event. However, it was found that a mis-steering of the beam into the beam pipe by the first dipole (B1300-02) could produce dose rates as high as 21.6 mSv/h outside the LTB transfer area shielding walls.
- This dose rate exceeds the criteria for an event. This event was not fully captured by the nearest active area radiation monitor (AARM). The nearest AARM to the dose rate maximum is positioned at beam height.
- Inside the LTB transfer area, there is additional shielding at beam height. This added shielding greatly reduces the dose rate to the AARM. The elevated dose rates due to the mis-steering event were highest above beam height.
- During the original incident, it is estimated that the beam was mis-steered into the beam pipe for 5 to 15 minutes. The LTB transfer line is active every 8 hours for roughly 15 minute. This is the time required to fill the storage ring. It is reasonable to assume that accelerator operator would become aware of a beam loss and terminate the electron beam within this 15 minute window.
- The criteria for a CLS “event” is 1mSv/event. Factoring in a 15 minute time frame, a dose rate of 4mSv/h is required to designate the reverse polarity incident as an “event”.
- Following formal investigation the recommendations included the assessment of beam losses and addition of LTB local shielding.

Simplified LTB Geometry

- Along the LTB transfer line, there are two dipole bending magnets that steer the 250 MeV electron beam into the booster ring.
- These dipoles are designated B1300-02 and B1300-03 respectively. Between the two magnets is a quadrupole (QF1300-02). Between the two dipoles is a steel pipe which is 3.175cm in radius and 1.6mm in thickness.
- Also in the figure are components of the booster ring, namely a booster dipole (B1303-01), quadrupole (QD1303-01), and RF cavities.
- The LTB transfer area is enclosed by several shielding walls labeled 1 through 4 in figure 1(b). Wall 1 consists of 70cm of concrete with a strip section of lead shielding with two discrete thicknesses (5 and 10cm). The strip section of lead is centered at beam height (140cm off the ground) and is 60cm tall. Wall 2 is 70cm of concrete while walls 3 and 4 are 80cm concrete. The roof is 60cm concrete. The concrete shielding has a density of 2.35g/cm^3.



(b)

Experimental studies

- In June of 2010, the reverse polarity event was reproduced under controlled conditions. The beam parameters are:

Parameter	Setting
Current	60 mA
Pulse Width	140 ns
Pulse Frequency	1 Hz
Beam Energy	250 MeV
Beam Power	2.1 W

- Dose data was collected using both optical luminescence dosimeters (OSLD) (Luxel manufactured by Landauer®) and hand held survey meters.
- Electronic Personnel Dosimeters (EPD) were worn by staff during the measurements.
- All experiments involved the manipulation of the field strength and/or polarity of the first and second dipoles (B1300-02 and B1300-03) of the LTB transfer line.
- dose rate measurements were taken in the occupied areas outside the LTB and Booster ring shielding tunnel on contact with the four shielding walls and roof.

Experimental setup

- Four experiments were carried out. The purpose of these experiments was to reproduce the reverse polarity/mis-steering event and measure the photon and neutron dose rates in occupied areas.
- Experiment #1 was a reproduction of the reverse polarity event itself
- Experiment #2 involved turning off the second dipole (B1300-03).
- Experiment #3 and #4 reproduced the mis-steering of the beam by reducing the field strength of the first dipole (B1300-02).

	B1300-02(DAC)		B1300-03(DAC)	
Experiment	**Polarity**	**Field Strength (%)**	**Polarity**	**Field Strength (%)**
1	**Normal**	**100**	**Reverse**	**100**
2	**Normal**	**100**	**OFF**	**0**
3	**Normal**	**95.5**	**Reverse**	**100**
4	**Normal**	**95.5**	**Normal**	**100**

Summary of Experimental Results

- Table below shows the maximum dose rates measured by the OSLD for walls 1 and 2.
- For the four experiments, the measured photon dose rates on walls 3, 4 and the roof did not exceed 0.12 mSv/h.
- The highest neutron dose rate (all four experiments) was 0.04 mSv/h.
- From the experiments, it is evident that the scenario of most concern is the mis-steering of the electron beam by the B1300-02 dipole into the beam pipe.
- Dose rates were as high as 21.6 mSv/h which exceeds the shielding design criteria for an event (<4mSv/h for a 15 minute event) when the first dipole (B1300-02) field strength was reduced by 4.5% (Experiments 3 and 4).
- The dose rates were somewhat lower below beam height and significantly lower at beam height suggesting that some shielding is provided by the BR components and the lead shield attached to the concrete wall.

Position Relative to Beam Height (BH)	Exp 1	Exp 2	Exp 3	Exp 4
	(mSv/h)			
Above BH	0.37	1.3	21.6	14.26
At BH	0.03	0.38	0.10	0.16
Below BH	0.08	0.05	7.24	4.08

Concluding Remarks on experiments

- The major source of concern is the particle shower created in the steel beam pipe between the B1300-02 and B1300-03 dipoles.
  - Additional shielding is needed around the steel pipe as a safeguard against such an event.
- The measured dose rates for experiments 1 and 2 were elevated but below the acceptable dose for a radiation event.
  - Those scenarios were examined in simulation in order to identify any hot spots that may have been missed with the surveys.

Fluka Simulation: Geometry

- The beam pipe, dipoles and quadrupole, were comprised of iron.
- The beam stop was comprised of an aluminum cylinder with a tungsten cylindrical insert.
- The walls were assigned 2.35g/cm^3 density concrete while the strip of shielding on Wall 2 was assigned lead.
- Subsequent shielding added to the model was also comprised of lead.
- The RF cavity was omitted because it was not in the direct path of the particle shower. Nevertheless, any shielding design will only be enhanced by the attenuation of the RF cavity

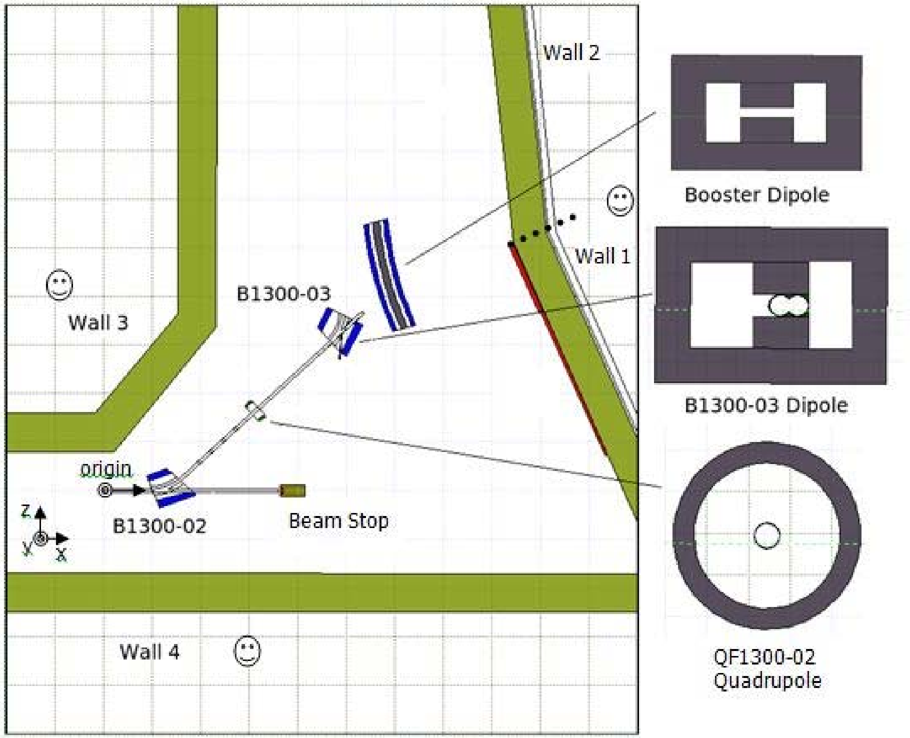


Figure 2: The Geometric Model of the LTB transfer area. Walls 1-4 are labeled. The smiling faces represent the viewing perspective for the 4 walls when looking at graphs in this document. The dotted line represents the divider between walls 1 and 2.

REPRODUCTION OF EXPERIMENTAL RESULTS IN SIMULATION

- The effective dose rates for walls 1 through 4 and the booster ring roof were calculated in simulation for all four experimental setups.
  - Generally, there was good agreement in both the dose rate magnitude and location.
  - When dose rate differences between measurement and simulation did occur, it was due to the incomplete geometry of the simulation.
  - Many of the beamline supports at and below beam height were not included in the simulation model.
  - As a result, simulated dose rates were higher than measured.
- Effective dose rates were estimated from the photon and neutron particle fluence. In particular, effective dose was calculated for the “worst” irradiation geometry using radiation weighting factors derived by Pelliccioni
- The targeted simulation statistical uncertainty was less than 5% which was typically achieved.

Exp Data Vs. Fluka Sim

- Figure presents the calculated and measured dose rates on walls 1 and 2 for the conditions of Experiment 4.
- For measurements taken at or below beam height, the simulation tended to over-estimate dose. This was expected as the model did not include all attenuating structures such as the RF cavity, or the structures that support the beam line components.
- Above beam height, the agreement between measurement and simulation was satisfactory.
- A similar comparison between simulation and measurement was carried out for neutron dose rates. In both measurement and simulation, the neutron dose contribution was found to be negligible for all experimental setups.

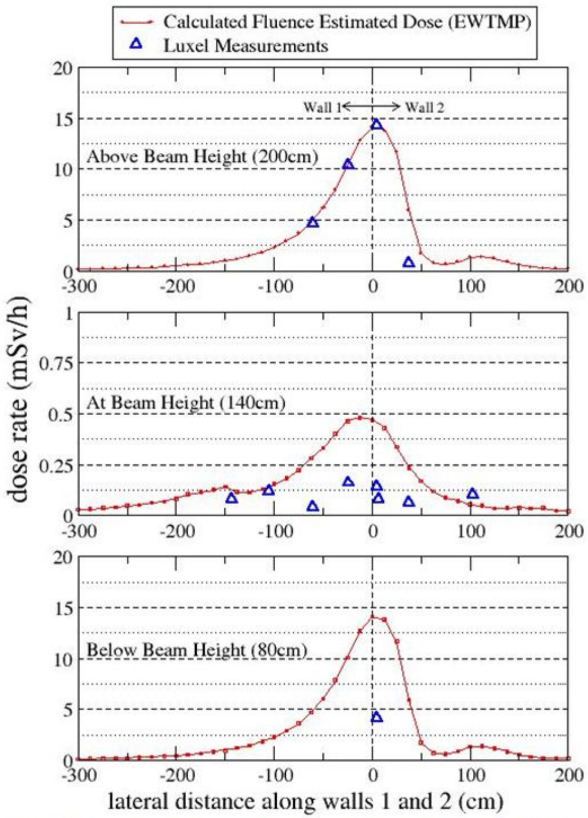


Figure 3: Comparison of measured Luxel gamma dose rate measurements to FLUKA simulation with 95.5% field strength for the B1300-02 dipole. In the figure EWTMP refers to the "worst case" effective dose rate calculated from the particle (photon) fluence.

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MAXIMUM DOSE RATES FOR THE FOUR WALLS AND ROOF

- Walls 1 and 2 along with the roof contained significantly elevated dose rates for the four experiments.
- Walls 3 and 4 typically yielded acceptably low dose rates (on the order of 0.01 mSv/h) without any added shielding.
- The most pertinent results were for that of experiments 3 and 4. The simulated effective photon and neutron dose rate maps for the setup of experiment 4 are presented in next figures.
- The highest photon dose rates approached 100 mSv/h behind walls 1 and 2 while the highest neutron dose rate was 0.50 mSv/h also behind walls 1 and 2.

Dose Profile (Experiment 4)

Photon Dose Rates

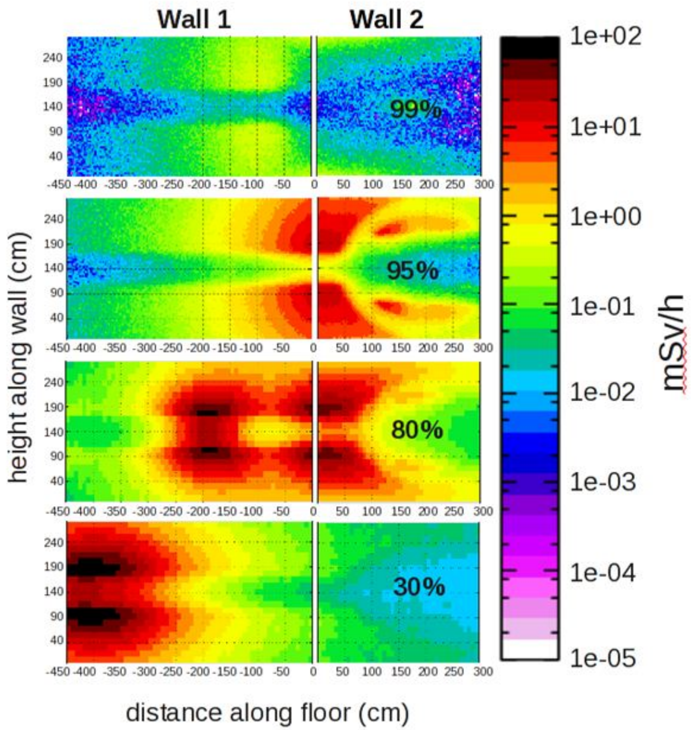


Figure 4: Photon dose rate map for walls 1 and 2 - B1300-02 at 99, 95, 80 and 30% field strength.

Neutron Dose Rates

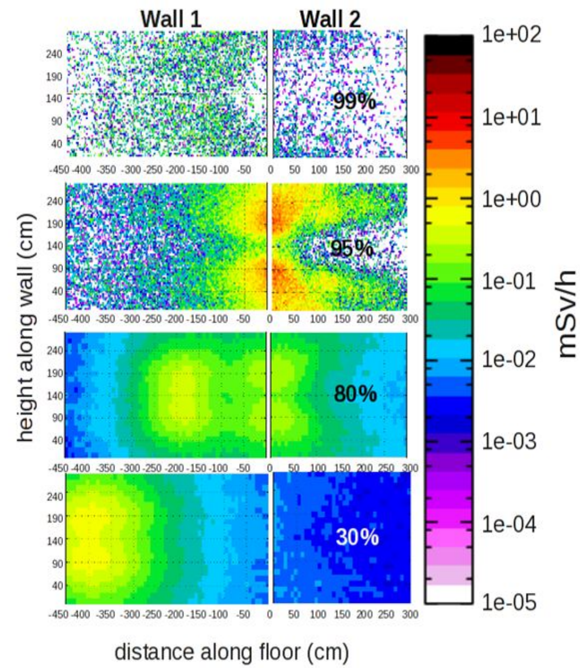


Figure 5: Neutron dose rate map for walls 1 and 2 - B1300-02 at 30, 80 and 95% field strength

Summary of Simulated Maximum Dose rates

B1300-02 FIELD (%)	Wall 1		Wall 2		Wall 3		Wall 4		Roof	
	Dose Rate (mSv/h)									
	g	n	g	n	g	n	g	n	g	n
30	91	0.66	0.16	0.009	0.008	0.002	0.015	0.011	0.036	0.022
50	61	0.36	6.5	0.061	0.040	0.002	0.009	0.009	0.030	0.017
80	66	0.36	42	0.26	0.100	0.005	0.011	0.006	0.033	0.016
90	32	0.26	36	0.27	0.028	0.010	0.008	0.015	0.088	0.023
95	15	0.14	17	0.14	0.023	0.016	0.008	0.017	0.117	0.032
99	0.42	0.01	0.28	0.01	0.012	0.011	0.007	0.011	0.099	0.029

- Table gives a summary of the maximum dose rate for each field strength.
- Generally, the uncertainties in photon and neutron dose rates were on the order of 1% and 5% respectively.
- When the beam is slightly mis-steered (99% of nominal field strength) the dose rates on the four walls and roof are well within acceptable levels for an event even with no additional shielding installed.

Addition of Local Shielding

- To contain the shower at any point along the beam pipe connecting B1300-02 and B1300-03, a lead box, 5cm thick on all four sides, was simulated around the pipe.
- For smaller mis-steering angles (corresponding to a B1300-02 field strength > 90% of nominal value) the local shielding is sufficient to reduce the dose rates below 0.100mSv/h.
- For larger mis-steering angles (corresponding B1300-02 <90% of nominal value) an additional shielding wall (10cm thick, 60cm in height) is required between the beam pipe and beam stop.

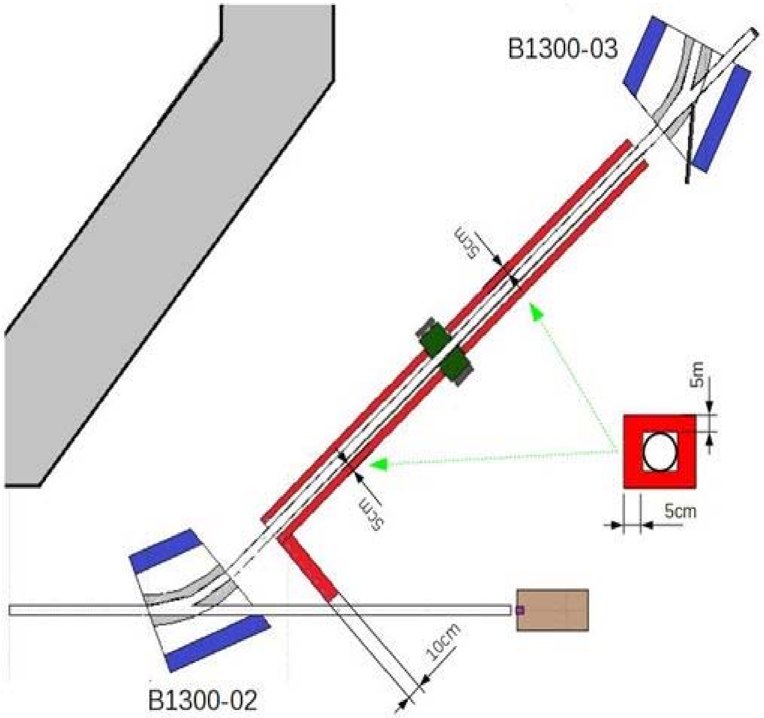


Figure 6: The shielding design. The design consists of a 5cm thick column of lead (red) that runs along the beam pipe. For large angle mis-steering, a right angle wall is placed near the B1300-02 dipole. The wall is 10cm thick and 60cm in height (centered at beam height).

Dose rates with additional Local Shielding

Photon Dose Rates

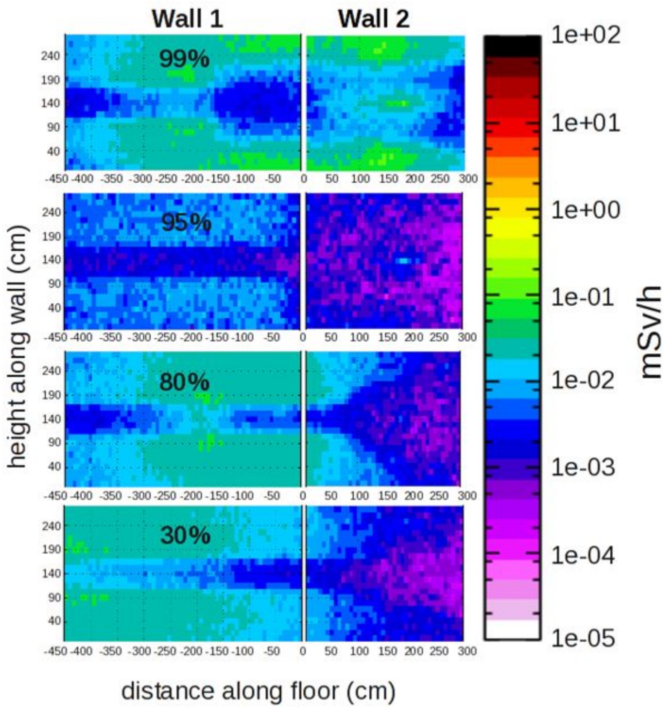


Figure 7: Photon effective dose rate map for walls 1 and 2 with additional shielding

Neutron Dose Rates

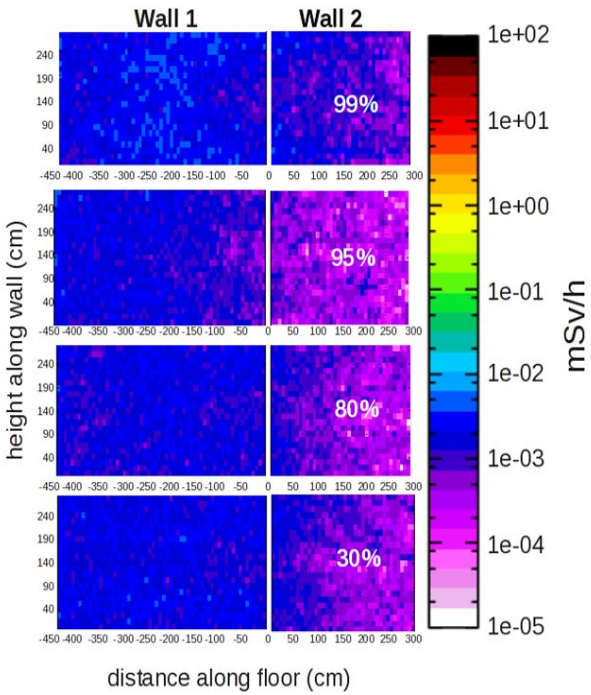


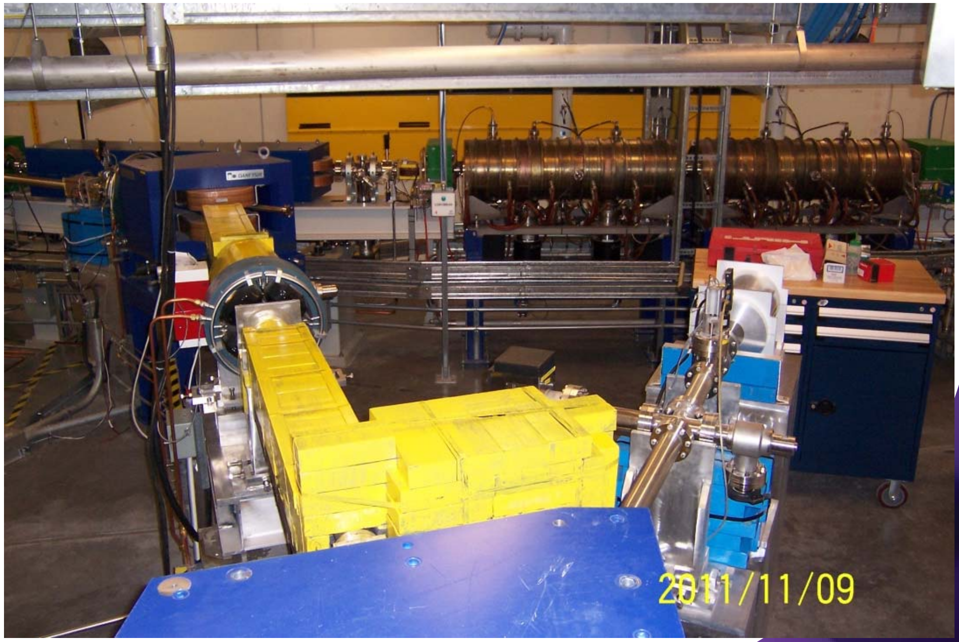
Figure 8: Neutron effective dose rate map for walls 1 and 2 with additional shielding

For all walls and the roof, the dose rates do not exceed 0.100 mSv/h when the simulated shielding was in place !

Summary of the maximum calculated dose rates for the mis-steering of B1300-02 with shielding

B1300-02 FIELD	Wall 1		Wall 2		Wall 3		Wall 4		Roof	
(%)	Dose Rate (mSv/h)									
	g	n	g	n	g	n	g	n	g	n
30	0.062	0.004	0.013	0.003	0.014	0.009	0.021	0.011	0.082	0.038
50	0.058	0.004	0.029	0.003	0.041	0.012	0.014	0.009	0.066	0.038
80	0.068	0.004	0.042	0.003	0.104	0.014	0.009	0.007	0.053	0.036
90	0.016	0.004	0.007	0.002	0.039	0.018	0.006	0.006	0.084	0.043
95	0.015	0.005	0.012	0.002	0.014	0.016	0.003	0.005	0.056	0.049
99	0.087	0.006	0.104	0.005	0.010	0.009	0.003	0.004	0.039	0.036

- In February and May of 2011 measurements were taken to validate the adequacy of local shielding.
- Generally, the measured and simulated dose rates are comparable.



Conclusion

- A shielding design for the LTB transfer line has been presented.
- Based on simulation results and measurements, this shielding design will provide adequate radiation protection for a mis-steering of the B1300-02 dipole.
- The dose rates outside the LTB transfer area will be kept below 0.100mSv/h.This is well below the 1mSv/event (4mSv/h for a 15 minute event) shielding design criteria.

Future Use of Fluka

- Phase III Beamlines (CLS)
  - Continue with beamline shielding design and compare with analytic models and measurements.
- Top-up mode of Operation Radiation Analysis (CLS)
  - Radiation analysis of Front-ends and beamlines, compare with MCNP.
- Accelerator specific radiation analyses (CLS)
  - Local shielding around narrow aperture at ID11 in the Storage ring
- Medical Isotope Project (CLS)
  - Low Energy High Power electron Linac (35 MeV, 40 kW)
  - Comparison between analytic calculations and Fluka estimates for the shielding and activation of accelerator components.

Thank you:

- To Fluka organization for providing the Fluka code and flair.
- To Chris Theis and collaborators for providing SimpleGeo.
- To Anne Trudel and Michael Trinczek (TRIUMF) for providing detailed comments on the shielding analysis report.

Questions?