Shielding Re-Evaluation for the Linac to Booster Transfer Line at the Canadian Light Source

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Abstract

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 are located just before the injection point into the booster. Due to a technical issue with the new power supplies a decision was made to revert back to the old power supplies. During the old power supply re-installation, the polarity of one of the dipole was inadvertently reversed by crossing the power supply leads. Subsequently during start-up procedures of the accelerators, operators were unable to detect any beam inside the booster ring. 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 dipole magnet between ±5% of nominal field strength. During the attempt to restore beam, an alarm on a radiation monitor in the occupied area within the booster pit was triggered. While attempting to recover the beam, the control room operator miss-steered the electron beam into the beam pipe located just before the injection point into the booster. The beam was terminated and a subsequent investigation of the LTB transfer line by engineers and accelerator physicist revealed the reverse polarity connection on the power supply. This event was considered as a reportable event by Canadian Nuclear Safety Commission and a formal root cause analysis was required and completed in October 2010. The results of the investigation resulted in a series of recommendations including assessing the shielding to ensure it meets the shielding design criteria specified in the CLS Safety Report. The purpose of this talk is to present the radiation measurements that were carried out in June 2010 to reproduce and better characterize the miss-steering event and describe the shielding re-evaluation to determine additional local shielding requirements for the affected area. FLUKA Monte Carlo simulations were carried out for various experimental scenarios including studying the effect on radiation dose in the occupied area for different magnetic field strengths. An additional local shielding was installed and shielding validation was completed in May 2011.

1. 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. During the attempt to restore beam, CLS staff members were twice sent to the booster ring RF pit to reset the booster ring RF. On the second visit to the pit, it was discovered that a radiation warning alarm was sounding. The alarm was triggered due to a 0.05 mSv/h upper dose rate limit being exceeded. No indication of this alarm was sent to the control room. The beam was terminated and HSE was contacted. A 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. 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

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dipole (B1300-02) could produce dose rates as high as 21.6mSv/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 AOD 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 as laid out in the CLS Safety Report [1]. Factoring in a 15 minute time frame, a dose rate of 4mSv/h is required to designate the reverse polarity incident as an "event".

A TapRooT® investigation was performed [2]. In the TapRooT report, eighteen recommendations were put forth to guard against an event of this nature. Among the recommendations, it was proposed that:

- Stricter configuration controls be placed on the installation of the dipole magnets.
- Polarity checks be implemented into the inspection procedures.
- The leads of the dipole power supplies be more clearly labeled and colour coded.
- An alarm should sound in the control room when dose rate limits are exceeded on the AARMs.
- Additional shielding be installed around the LTB transfer area.

These recommendations, now implemented, are intended to minimize the chance of a polarity reversal during future power supply installs or exchanges and to ensure a quick response if such an event occurs.

This report present the measurements taken in response to the reverse polarity event and outline the design, verification and installation of the shielding needed in the linac-to-booster (LTB) transfer area. A shielding design based on CLS shielding design criteria is presented which will provide adequate protection in the case of a beam miss-steering along the LTB transfer line between dipole magnets B1300-02 and B1300-03.

2. Experimental Studies

In June of 2010, the reverse polarity event was reproduced under controlled conditions. The experimental floor was cleared and survey measurements were carried out by Nuclear Energy Workers (NEWs). The electron beam parameters for all experiments are outlined in Table1. These parameters are consistent with normal beam operations.

Table 1: The beam parameters for experimental studies

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

Figure 1 illustrates the LTB transfer area and the various features of interest. In 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.

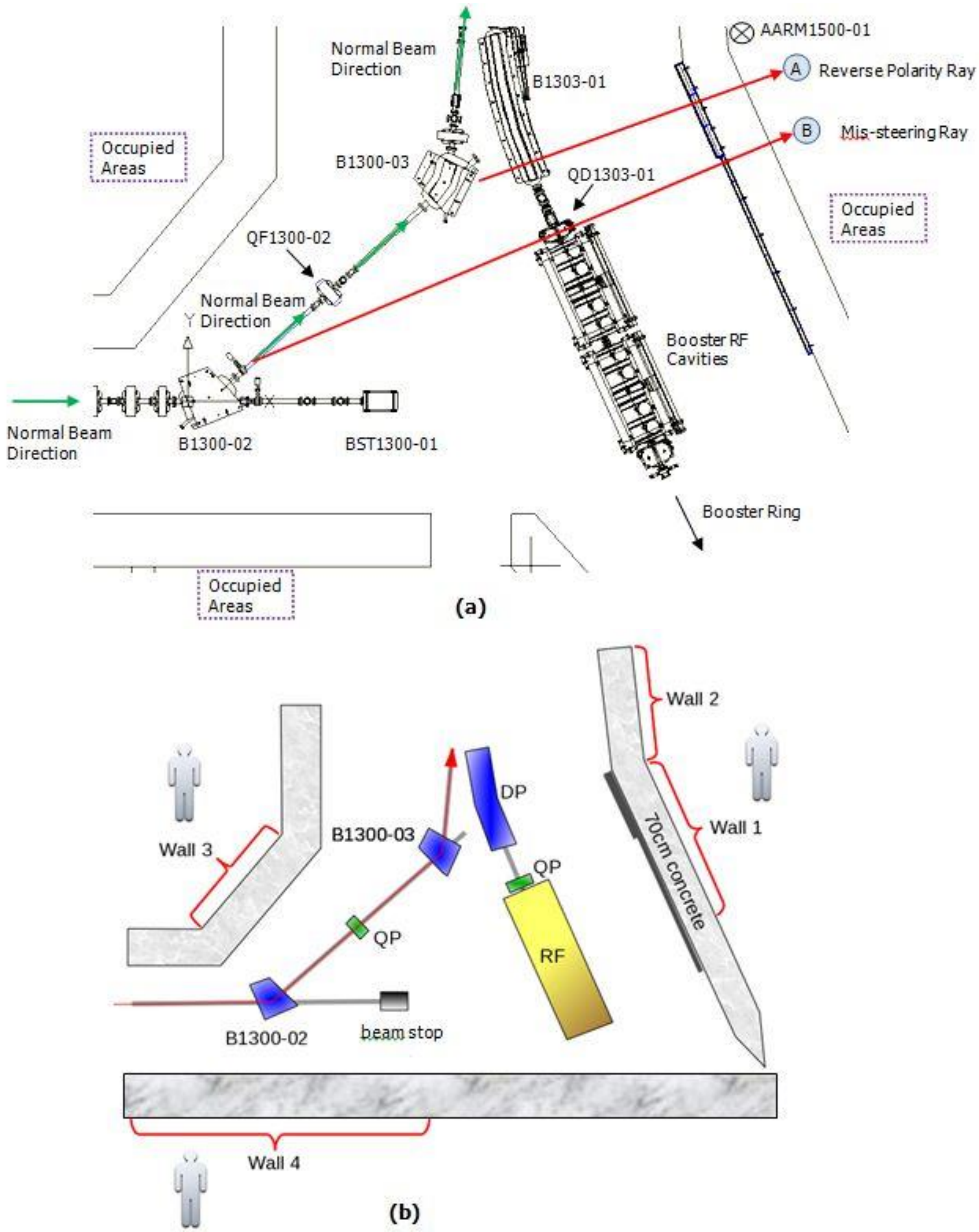

Figure 1: A layout of the Linac-to-Booster (LTB) transfer area. (a) A CAD representation modified from Reference [3]. Arrows represent the normal path of the beam, the reverse polarity and miss-steering events. Occupied areas are also labeled; (b) A simplified representation of the LTB transfer area used in the FLUKA simulation.

Dose data was collected using both optical luminescence detectors (Luxel manufactured by Landauer®) and hand held survey meters (HPI 1030 by Health Physics Instruments, 451P by Inovision Radiation Measurements, and FHT752 by Thermo Electron Corporation). Electronic Personnel Dosimeters (EPD) were worn by staff during the measurements. Table 2 gives the specifications of the detectors used.

Table 2: Summary of detectors used in radiation measurements.

Survey Meter	Particle Type	Energy Range	Dose Rate Range
HPI 1030	photon+neutron	>100keV	1μSv/h-10mSv/h
451P	photon	>25keV	5μSv/h – 50mSv/h
	beta	>1MeV	
FHT 752	neutron (BF3)	0.25eV to 10 MeV	1.8μSv/h-1Sv/h
Optical Luminescence Dosimeter	**Particle Type**	**Energy Range**	**Dose Rate Range**
Landauer Luxel	photon	5keV-40MeV	10μSv/h-10Sv/h
	beta	150keV-40MeV	100μSv/h-10Sv/h
	neutron	0.25eV-40MeV	200μSv/h-250mSv/h

All experiments presented in this report 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. For the experimental scenarios that will be presented here, dose rate measurements were taken outside the accelerator/booster shielding tunnel on contact with the four shielding walls and roof.

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. The first experiment was a reproduction of the reverse polarity event itself. The second experiment involved turning off the second dipole (B1300-03). The third and fourth experiments reproduced the mis-steering of the beam by reducing the field strength of the first dipole (B1300-02). Table 3 outlines the experimental scenarios. The details of each experiment are described in the proceeding sections.

Table 3: A summary of experiments performed on the LTB transfer line.

	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

2.1 Experiment 1

In the first experiment, polarity of the second dipole (B1300-03) was reversed. The result was a mis-direction of the electron beam out of B1300-03 and into the shielding wall. Several Luxel dosimeters were placed outside the 4 concrete shielding walls. Around the projected point of beam impact (refer to the blue circle A symbol in Fig.1a), measurements indicate that the maximum photon deep dose rate at beam height did not exceed <u>0.03 mSv/h</u>. The dose rates were elevated above and below the lead plate. Directly above the projected point of impact (200 cm above the floor), the photon dose rate was highest at <u>0.37 mSv/h</u>. Below the point of impact (80cm above the floor), the maximum photon dose rate was 0.08 mSv/h. The measured dose rates decreased laterally from the projected point of impact. The maximum dose rates outside of walls 3 and 4 were 0.03 mSv/h and 0.02 mSv/h respectively. Neutron doses were below the minimum detectable limit for Luxel dosimeters along the 4 shielding walls. A hand held measurement (FHT752) did register a neutron dose rate of 0.025 mSv/h at a height of 80 cm from the floor behind wall 1. Photon and neutron measurements on the roof yielded maximum dose rates of 0.12 mSv/h (HPI 1030) and 0.04 mSv/h (FHT752) respectively.

2.2 Experiment 2

In Experiment 2, the magnetic field of the second dipole was turned off. The beam proceeded through the dipole and was largely attenuated by various components of the booster ring. The maximum photon dose rate at beam height was measured at 0.380 mSv/h. The photon dose rate above beam height was elevated with a maximum measured dose rate of 0.880 mSv/h at 280 cm above the floor. The photon dose rates below beam height were relatively low with a maximum measured dose rate of 0.050 mSv/h (110 cm above the floor). No neutron dose rates above the lower detectable limit of the FHT 752 detector were registered behind shielding walls 1 and 2. No measurements were taken behind wall 3. Behind wall 4, hand held measurements detected dose rates of 0.002 mSv/h and 0.016 mSv/h for photons and neutrons respectively. Maximum photon and neutron dose rates on the roof were 0.1 mSv/h and 1.3 mSv/h respectively. The high (fast) neutron dose rate was measured with a Luxel dosimeter. The FHT 752 neutron survey meter registered a neutron dose on the roof of 0.027 mSv/h.

2.3 Experiment 3

In Experiment 3, the magnetic field strength of the first dipole (B1300-02) was reduced to 95.5% of nominal strength with the polarity of the second dipole (B1300-03) reversed from normal. The result was a mis-steering of the electron beam out of the first dipole and through the beam pipe that adjoins the first and second dipoles. The mis-steering of the beam produced a particle shower incident on shielding walls 1 and 2. At beam height, there is adequate shielding for walls 1 and 2 from the 70cm concrete wall plus the 10cm lead plate. The photon dose rates at beam height did not exceed 0.1 mSv/h. Above beam height, 200cm from the floor, the photon dose rates were significantly elevated. At the point directly above the projected electron beam impact site (wall 2), the photon dose rate was 21.6 mSv/h. The maximum measured photon dose rate below beam height was 7.24 mSv/h (80cm from the floor). No neutron dose above the lower detectable limit was registered along these shielding walls. Behind walls 3 and 4, the maximum photon dose (hand held) was 0.03 mSv/h. No neutron dose above the lower detectable limit was registered. Hand held measurements on the booster ring roof indicated dose rates of 0.140 mSv/h and 0.015 mSv/h for photons and neutrons respectively. Results for Over-steering of the beam by 104.5% of the nominal field strength were not measured. However, it is reasonable to assume that dose rates would be similar due to the near symmetry of the geometry. This assumption also applied to the conditions of experiment 4.

2.4 Experiment 4

In Experiment 4, the magnetic field strength of the first dipole (B1300-02) was reduced to 95.5% of nominal strength with the polarity of the second dipole (B1300-03) set to normal. Again, the result was a mis-steering of the electron beam out of the first dipole, into the beam pipe and shielding wall. Luxel dose measurements were taken at three heights. For walls 1 and 2, at beam height (140 cm from the floor), the photon dose rates did not exceed 0.16mSv/h. Again, much of the radiation was attenuated by the concrete wall, lead shielding and various components of the LTB transfer line and BR. At a height of 200 cm from the floor a maximum photon dose rate of 14.26 mSv/h was recorded at a point directly above the projected beam impact site. The measurements show the dose rate falling off laterally from this point along the wall. A single measurement below beam height (80cm) also yielded an elevated photon dose rate of 4.08 mSv/h. Neutron dose rate measurements were also taken along the shielding wall. No dose was registered above the lower detectable limit. No dose rates above detectable limits were registered behind walls 3 and 4 or on top of the booster ring roof.

2.5 Experiments Summary

Table 4 presents the maximum dose rates measured by the Luxels 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. A high neutron dose rate (1.3 mSv/h) was captured in experiment 2. However, this measurement could not be reproduced with the handheld survey meters. The next highest neutron dose rate (all four experiments) was 0.04 mSv/h. Nevertheless, a 1.3mSv/h dose rate translates to 0.325 mSv/event for a 15 minute event. This dose rate satisfies the dose rate criteria for an event.

From the experiments, it is evident that the scenario of most concern is the miss-steering of the electron beam by the B1300-02 dipole into the beam pipe. Dose rates were as high as 21.6mSv/h which exceeds the Safety Report criteria for an event (< 4 mSv/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. The major source of concern is the particle shower created in the steel beam pipe between the B1300-02 and B1300-03 dipoles. Therefore, 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. However, those scenarios were examined in simulation in order to identify any hot spots that may have been missed with the surveys.

Table 4: Maximum measured Luxel photon dose rates for walls 1 and 2

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

3. Shielding Analysis

To assess the additional local shielding requirements for the LTB transfer area, Monte Carlo simulations were performed for the four experimental scenarios. Calculations were done using the FLUKA [6,7] particle simulation code (version 2008.d). Due to long simulation run times (approx. 1day per simulation) effective dose rates were estimated from particle fluence.

Simulations indicated that there was little difference between the dose rates for mis-steering the beam when the B1300-03 magnet was in a normal (Experiment 4) or reverse polarity (Experiment 3) configuration. The majority of the radiation was due to the shower created in the beam pipe before the electron beam ever reaches B1300-03. The difference in the experimental results may be due to the uncertainty in the Luxel measurements (±15%) combined with changes in experimental setup between experiments. To reduce simulation time, shielding was only designed for the normal polarity configuration. This shielding will be adequate in the unlikely case that B1300-03 is placed in a reverse polarity configuration.

For neutron production, photonuclear interactions were activated (Δ resonance, quasi-deuteron interactions, and giant resonance). Electron and photon production thresholds were 100 keV and 10 keV respectively. The statistical error in simulated dose rates for photons and neutrons was generally less than 1% with the pre-existing shielding in place. With added shielding, the increased attenuation led to poorer statistics and higher uncertainty (8-12%). The achievable statistical accuracy was limited by the simulation run time (1 day to achieve the quoted uncertainties above).

3.1 FLUKA Geometry of the LTB Transfer Line

Figure 2 illustrates the geometric model of the LTB transfer area. All dimensions in the model were taken directly from a CAD drawing [3] of the LTB transfer area. The major difference in the model in figure 2 from the actual LTB transfer area is the absence of the RF cavity. Ray tracings showed that the RF cavity was not in the direct path of the particle shower. Therefore, it was omitted. Nevertheless, any shielding design will only be enhanced by the attenuation of the RF cavity.

For the geometric model, 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.

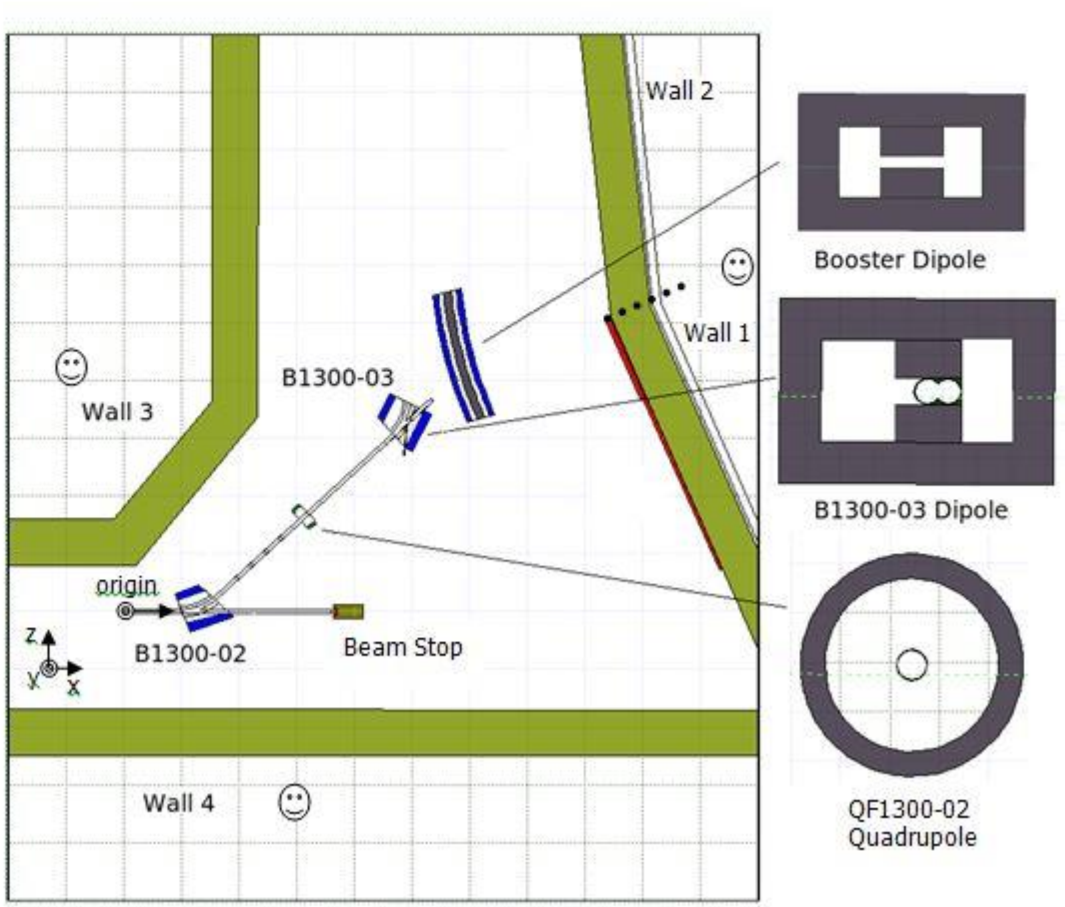

Figure 1: The FLUKA Geometric Model of the LTB transfer area. Walls 1-4 are labeled. The smiling faces represent the viewing perspective for the 4 walls when looking at graphs in this document. The dotted line represents the divider between walls 1 and 2.

3.2 Reproduction of Experimental Data in the FLUKA Simulation

The effective dose rates for walls 1 through 4 and the booster ring roof were scored 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 such as girders 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 [4,5]. In particular, effective dose was calculated for the "worst" irradiation geometry using radiation weighting factors derived by Pelliccioni [4]. The scoring resolution was 7.5cm x 16cm x 5cm. The scoring resolution was somewhat arbitrary and was chosen as a compromise between spatial resolution and statistical uncertainty. The targeted simulation statistical uncertainty was less than 5% which was typically achieved.

Figure 3 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. As stated above, 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.

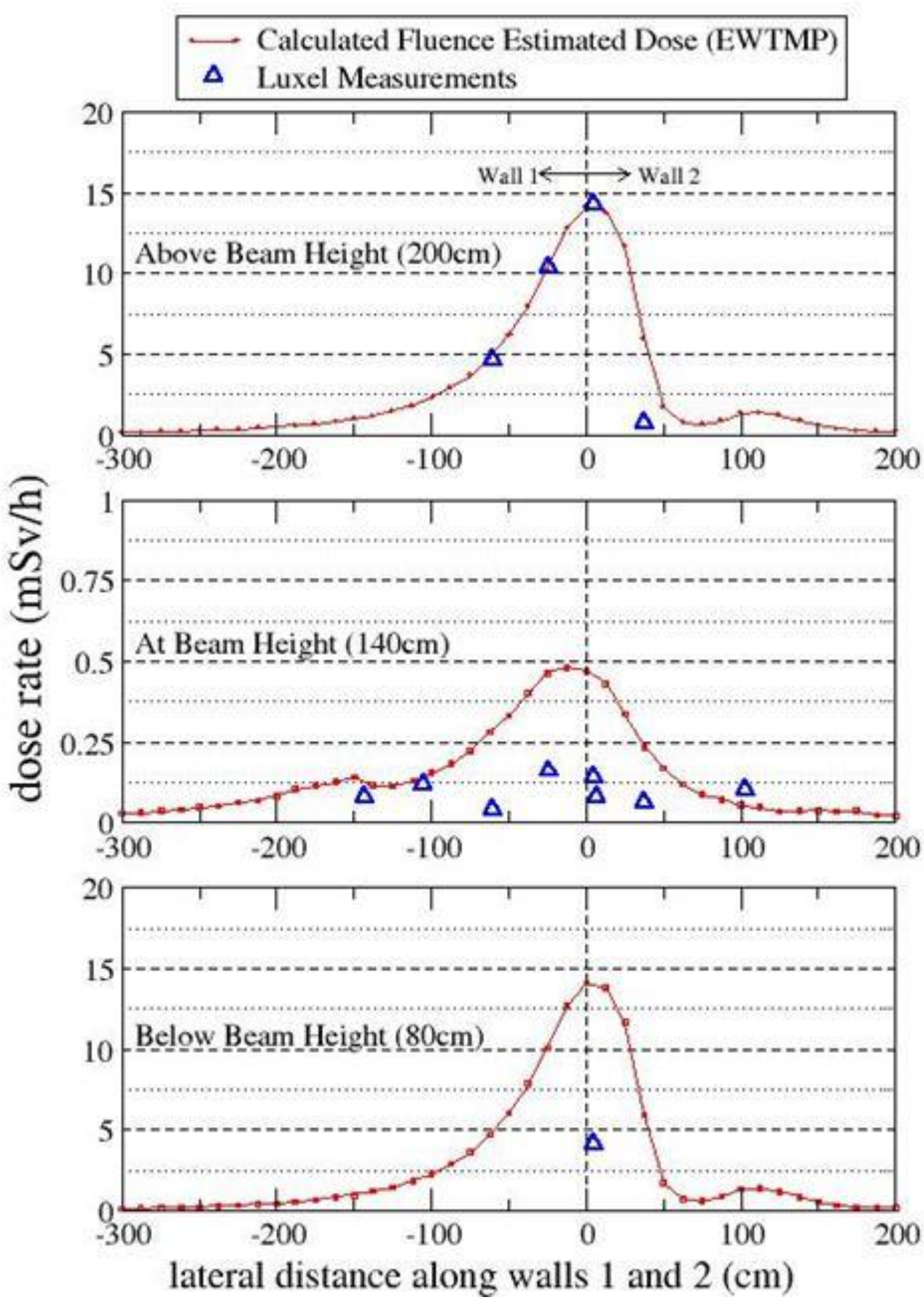

Figure 2: Comparison of measured Luxel gamma dose rate measurements to FLUKA simulation with 95.5% field strength for the B1300-02 dipole. In the figure EWTMP refers to the "worst case" fluence to effective dose conversion factors.

3.3 Maximum Dose Rates for the Walls and the Roof

To identify the location of the dose rate maximum behind walls 1 through 4, a two-dimensional map of dose rate was calculated. Generally, the hotspots for all experimental setups were caught by the array of Luxel detectors. Walls 1 and 2 along with the roof contained significantly elevated dose rates for the four experiments. However, walls 3 and 4 typically yielded acceptably low dose rates (on the order of 0.010mSv/h) without any added shielding. Therefore, much of the focus was directed at walls 1,2 and the roof. For experiments 1, the simulated dose rates were on the order of 0.1 mSv/h. At beam height, the simulated dose rate for experiment 2 did approach 1mSv/h. This dose rate, which is higher than that measured, may be due to the differences in the simplified model to the true LTB transfer line and surrounding accelerator components. Regardless, the dose rate levels are acceptable (< 4 mSv/h) for an event.

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 figures 4 and 5. The highest photon dose rates approached 100mSv/h behind walls 1 and 2 (Figure 4) while the highest neutron dose rate was 0.5 mSv/h also behind walls 1 and 2 (Figure 5). The dose rate distributions clearly indicate the presence of the beam pipe. A circular ring can be seen in the right of figure 4 which is caused by the presence of the beam pipe. To the left of the circular ring is the hotspot caused by the particle shower. This dose rate pattern was studied for a range of B1300-02 field strengths between 30 and 99%. Generally, as the field strength is reduced, the photon profile becomes wider (as the electron beam is steered towards the beam stop) and more intense (approaching 100mSv/h). For neutrons, the hotspot increases in intensity with decreasing field strength. However, the dose rate never exceeded 0.660mSv/h. The dose rate levels for walls 3 and 4 for a B1300-02 field strength of 95% of nominal were below 0.10mSv/h. This was the case for all field strengths studied. For the roof the highest dose rate calculated was for photons at 0.117mSv/h. A summary of the maximum dose rate for each field strength is outlined in Table 5. Generally, the uncertainties in photon and neutron dose rates were on the order of 1% and 5% respectively. It should be noted that when the beam is slightly miss-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.

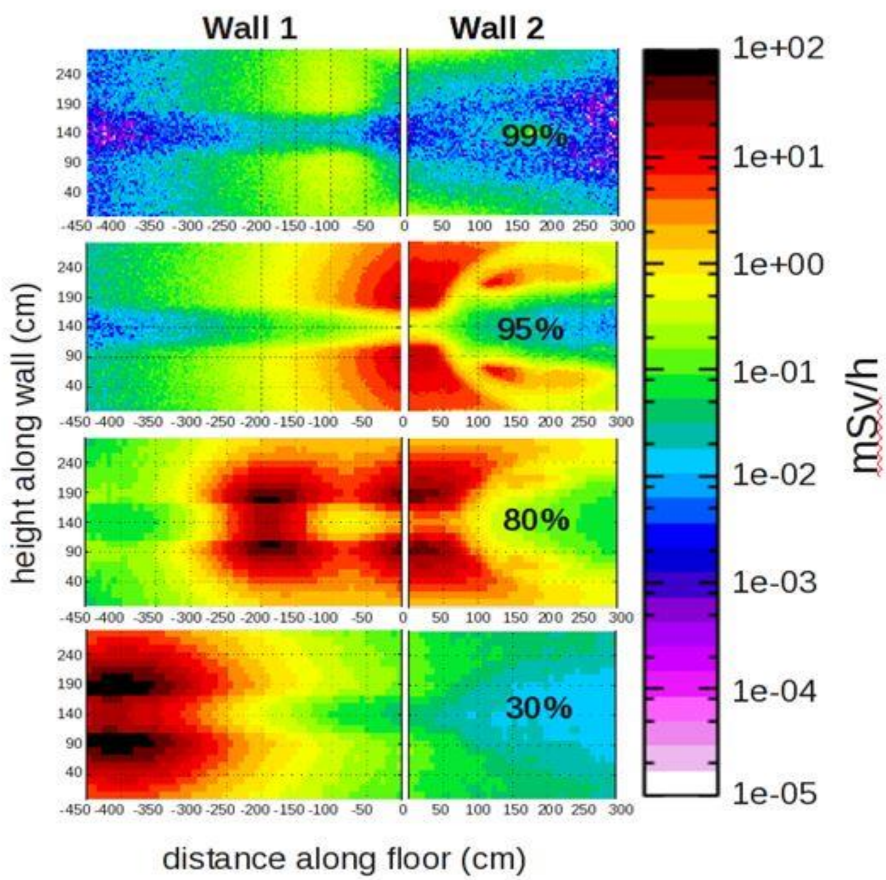

Figure 3: Photon dose rate map for walls 1 and 2 - B1300-02 at 99, 95, 80 and 30% field strength

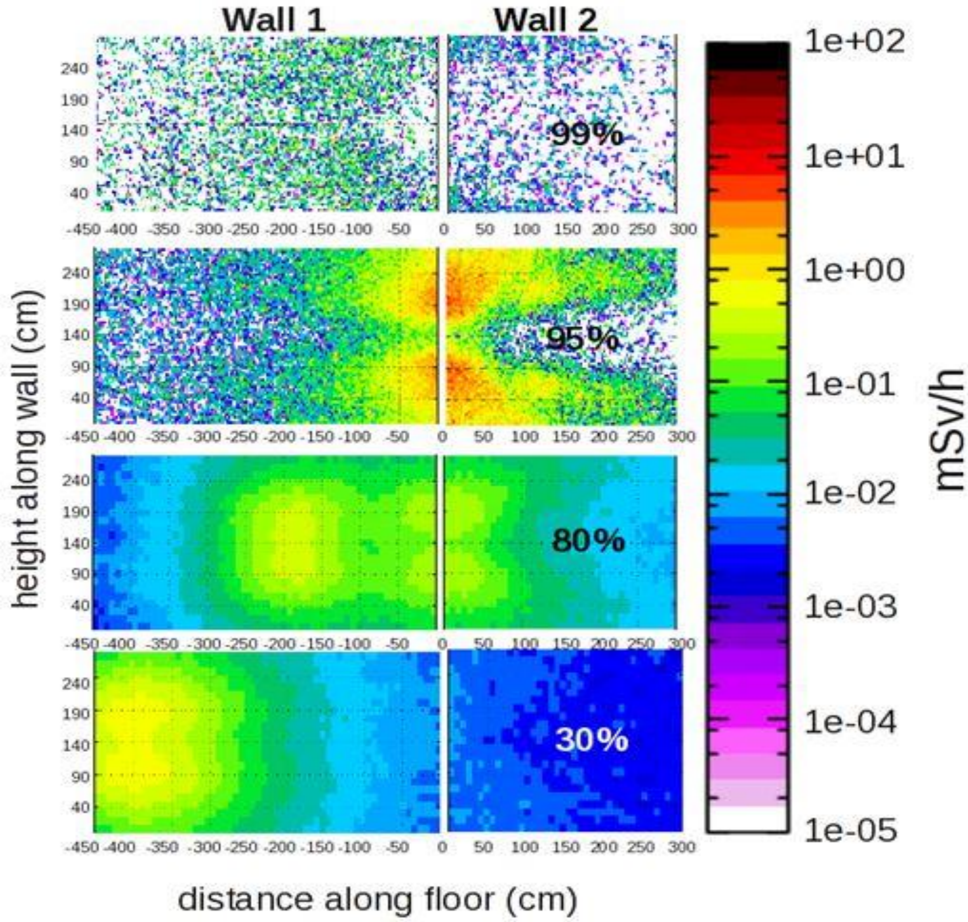

Figure 4: Neutron dose rate map for walls 1 and 2 - B1300-02 at 30, 80 and 95% field strength

Table 5: Summary of maximum calculated dose rates for the miss-steering of B1300-02 without shielding (Uncertainty in photon dose rates were generally <1%. Neutron dose rate uncertainty was <5%.)

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

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3.3 Additional Local Shielding Assessment

The simulated local shielding design is illustrated in Figure 6. 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. This additional local shielding reduces dose rates below 0.100mSv/h. The photon and neutron dose rate maps for walls 1and 2 with B1300-02 at 99, 95, 80 and 30% nominal field strength are given in Figures 7 and 8. The photon and neutron dose rates for the roof are given in Figure 9. When comparing Figures 7 and 8 to Figures 4 and 5, a substantial reduction in dose rate is observed due to the added shielding. For all walls and the roof, the dose rates do not exceed 0.100mSv/h when the simulated shielding was in place. Results for other field strengths were comparable. Table 6 presents a summary of maximum calculated dose rate for each B1300-02 field strength examined.

The additional shielding design, presented here, provides adequate protection against a miss-steering of the first dipole (B1300-02). The shielding reduces dose rates outside the LTB transfer area to values below 0.100mSv/h which well below the CLS safety criteria for an event (< 4mSv/h) lasting 15 minutes or less.

The shielding thickness was chosen with the dimensions of the available lead bricks in mind. The available lead bricks have a dimension of 5cm x 10cm x 20cm. The results show that the shielding thicknesses are greater than that required to meet the safety criteria for an event.

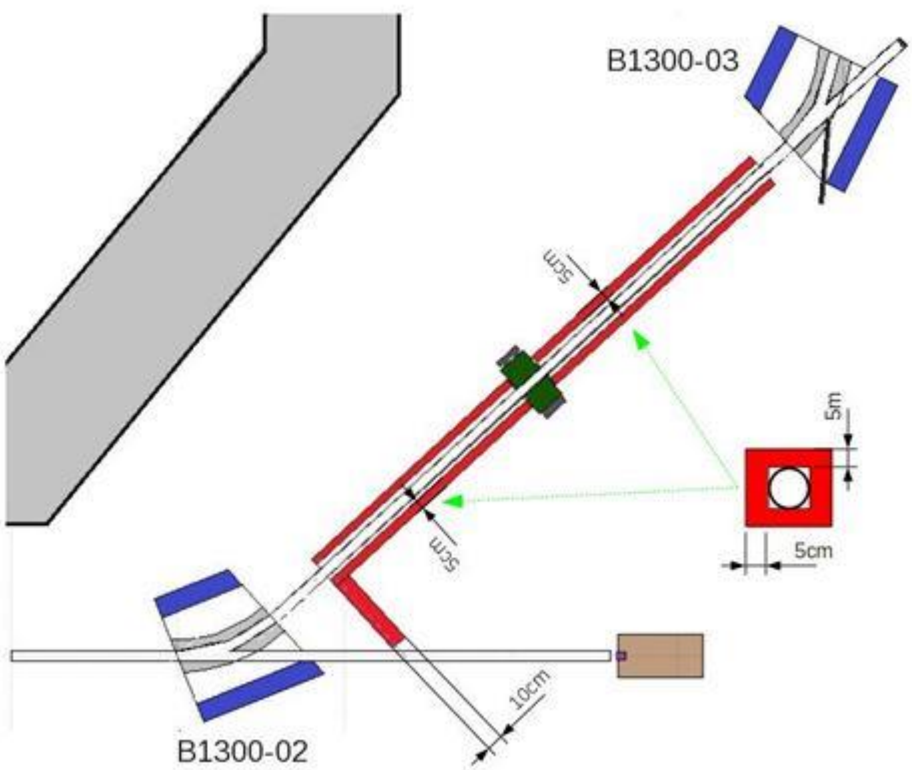

Figure 6: The shielding design. The design consists of a 5cm thick column of lead (red) that runs along the beam pipe. For large angle mis-steering, a right angle wall is placed near the B1300-02 dipole. The wall is 10cm thick and 60cm in height (centered at beam height).

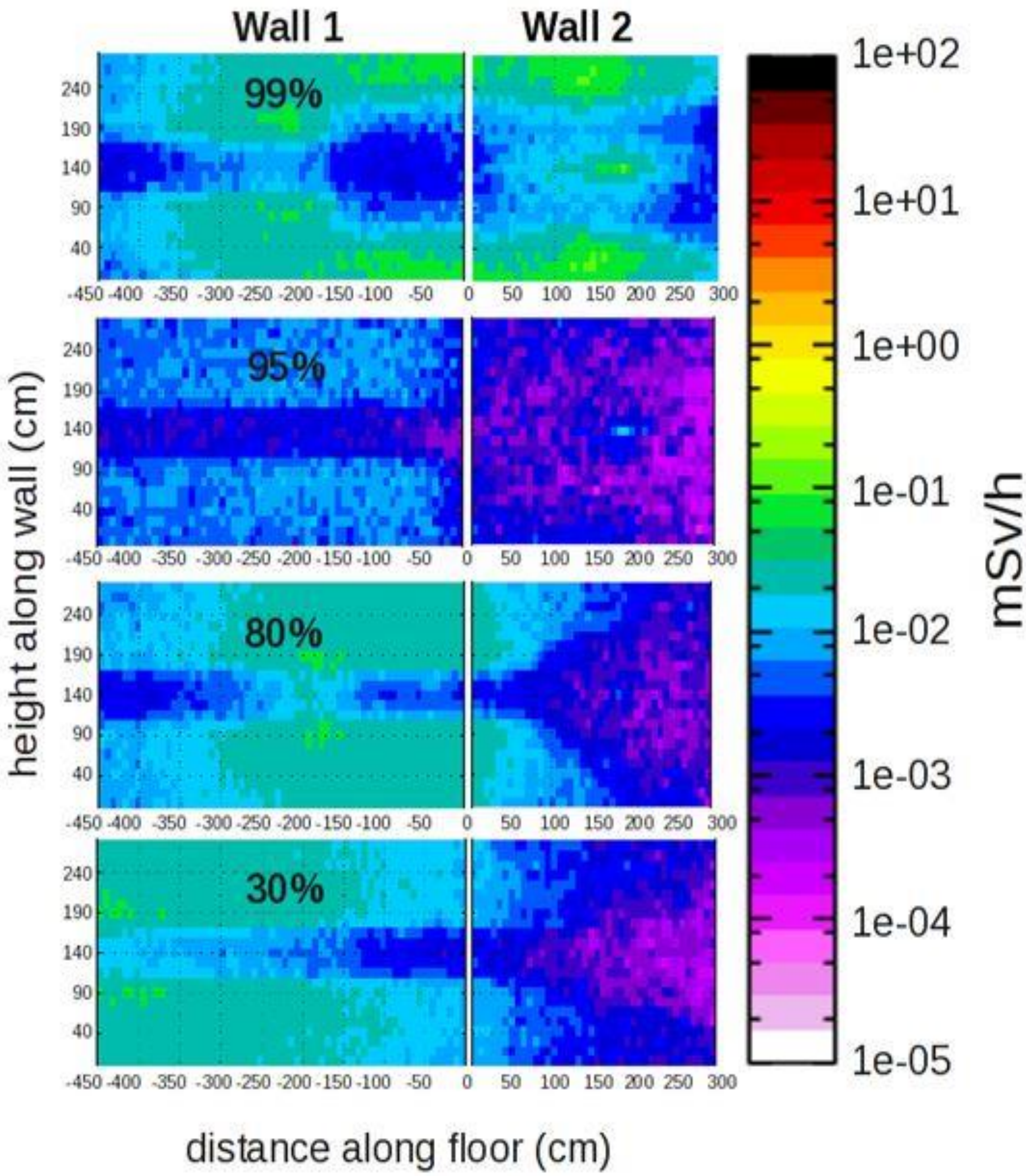

Figure 7: Photon effective dose rate map for walls 1 and 2 with additional shielding

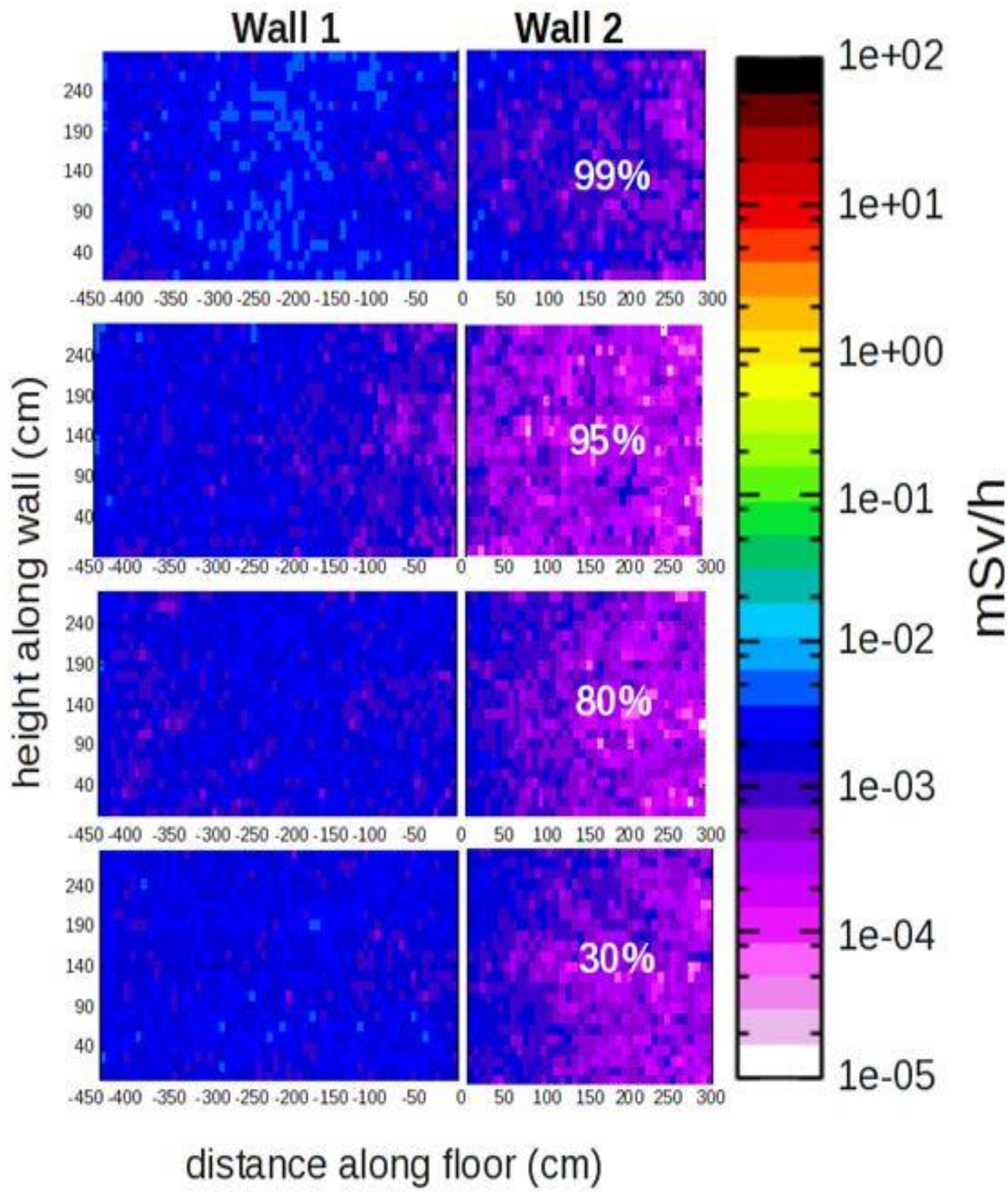

Figure 8: Neutron effective dose rate map for walls 1 and 2 with additional shielding.

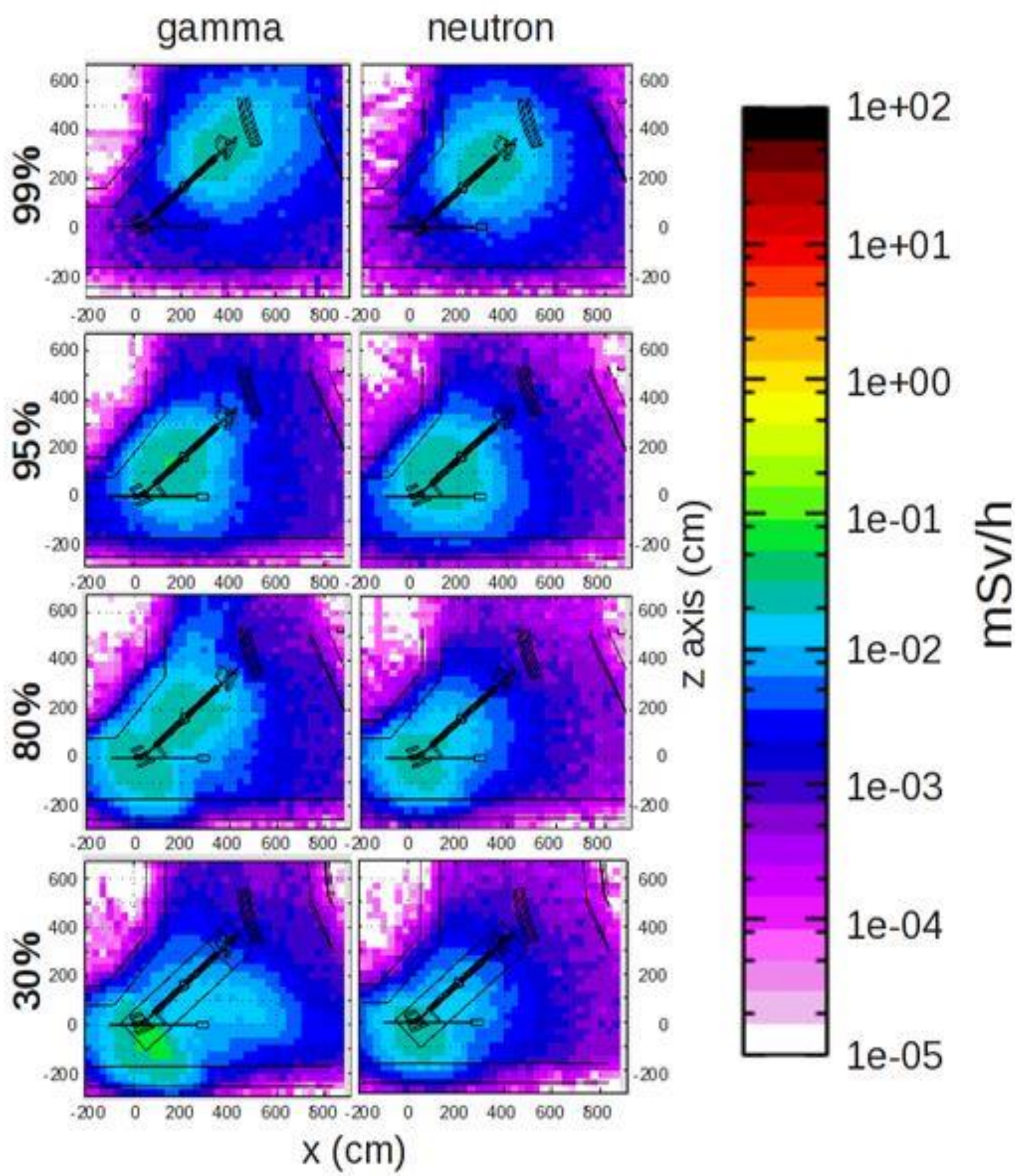

Figure 9: Photon and neutron effective dose rate map for the roof with additional shielding.

Table 6: Summary of the maximum calculated dose rates for the miss-steering of B1300-02 with additional 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

3.4 Local Shielding Validation

On February 14th and 21st of 2011, measurements were performed to validate the shielding design. Prior to measurement, a test version of the shielding was installed. This shielding design is shown in Figure 10. As high dose rates are focused on walls 1 and 2, measurements were concentrated there.

The shielding consists of a column of lead around the beam pipe between the B1300-02 dipole and the QF1300-02 quadrupole. A second column of lead is installed between the QF1300-02 quadrupole and B1300-03 dipole. The columns are constructed of lead bricks which are 20cm x 10cm x 5cm in dimension. The columns are placed as close as possible to the pipe and form a 5cm thick layer of shielding around the pipe. For large angle mis-steering, a wall 60cm tall (centered at beam height), 40cm wide and 10cm thick is installed between the beam pipe and the beam dump.

Figure 10: Initial shielding design for the LTB transfer line (Upstream View).

During the experimental studies, the 250 MeV electron beam was steered over a large range of angles (determined by the power limits of the B1300-02 dipole). Specifically, the beam was steered from 5% to 110% of the nominal setting at discrete values. A handheld radiation survey was performed around the LTB transfer area using the 451P, HPI-1030, FHT752 survey meters described in Table 2. The maximum dose rates observed during the survey are summarized in Table 7 along with the simulation results. Generally, the measured and simulated dose rates are on the same order of magnitude.

From Table 7, it is evident that a gap exists in the shielding for field strengths between 70% and 90%. This gap in shielding, which corresponds to dose rates as high as 2.8mSv/h is due to a space between the shielding wall (between the beam pipe and beam dump) and shielding column (which runs along the beam pipe). This space is labeled in Figure 10. It is also noted that dose rates for B1300-02 field strengths less than 10% are elevated (approaching 2mSv/h as seen in Table 7). This is likely due to a particle shower created in the beam stop pipe. The impact of this elevated dose rate is minimal based on occupancy and duty factor. The elevated dose occurs in an area of the booster pit that would not be normally occupied as it is blocked by RF conduit and equipment. Normal occupied areas would be several meters away from the shielding wall which would yield an inverse squared decrease in the dose rate. Nevertheless, such an event is unlikely to last more than 15 minutes and the 5% field strength dose rate for this duration is reduced to 0.45mSv/event which is below the event level limit.

Table 7: Summary of maximum measured and simulated dose rates along walls 1 and 2 with shielding installed.

B1300-02 FIELD	Maximum Dose Rates along Walls 1 and 2			
(%)	mSv/h			
	Handheld Survey		FLUKA Simulation	
	Gamma	Neutron	Gamma	Neutron
5	1.8	N/a	N/a	N/a
10	0.18	N/a	N/a	N/a
30	0.012	N/a	0.062	0.004
50	0.034	N/a	0.058	0.004
70	2.5	0.030	N/a	N/a
85	2.8	N/a	N/a	N/a
90	2.0	N/a	N/a	N/a
95	0.030	0.003	0.015	0.005
97	0.056	0.006	N/a	N/a
99	0.030	0.010	0.104	0.006
110	0.002	<0.001	N/a	N/a

To improve the shielding between 70% and 90% field strength, the existing shielding installation was modified. The new shielding, shown in Figure 11, consists of a continuous wall of attenuation between the beam pipe and beam dump. Measurements were taken in May of 2011 with the modified shielding design. Dose rates were measured for 95%, 70% and 50%. As outlined in Table 8, the modified design reduced dose rates for the impacted field strengths below event level limits. With the gap in the shielding removed, it is reasonable to assume that the other field strengths (85% and 90%) with higher dose rates are also reduced.

With the validation complete, the shielding has been permanently installed. The shielding has been painted yellow to clearly identify its purpose and all relevant CAD drawings have been updated. The shielding has been labeled and assigned a CLS part number.

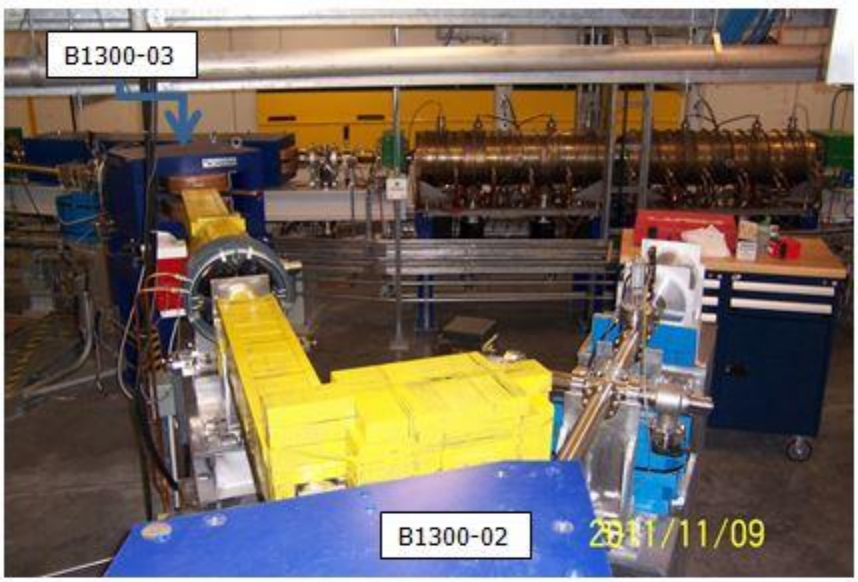

Figure 11: The Modified Shielding Installation (Downstream View). The modified shielding consists of the joining of the shielding column along the beam pipe and the shielding wall between the beam pipe and beam dump.

Table 8: Summary of supplementary maximum measured and simulated dose rates along walls 1 and 2 with modified shielding installed

B1300-02 FIELD	Maximum Dose Rates along Walls 1 and 2			
(%)	mSv/h			
	Handheld Survey		FLUKA Simulation	
	Gamma	Neutron	Gamma	Neutron
50	0.002	0.039	0.058	0.004
70	0.002	0.032	N/a	N/a
95	0.004	0.060	0.015	0.005

4. Conclusion

A shielding design for the LTB transfer line has been presented. Based on simulation results and radiation measurements, the additional shielding was shown to provide adequate radiation protection for a mis-steering of the B1300-02 dipole. The dose rates outside the LTB transfer area are expected to be below 0.1 mSv/h. This is well below the 1 mSv per event (4 mSv/h for a 15 minute event) limit defined in the CLS Safety Report.

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