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Reevaluating linear accelerator shielding for 320 μA of proton beam

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Abstract

The collider-accelerator facilities at Brookhaven National Laboratory (BNL) have been developing since the completion of the experiments they were originally built for, and their uses for research have evolved over the years with a variety of users. With these changes, we must be careful to avoid potential radiation hazards of worst-case scenarios, although these faults are unlikely. One of these changes in the Collider-Accelerator Department (C-AD) is the replacement of power supplies and upgrading the linear accelerator (Linac) radiofrequency system to allow the Brookhaven Linac Isotope Producer (BLIP) to use a 320 μA average current. This current of 320 μA is greater than any current that the Linac shielding has withstood before, and thus this project in reevaluating the Linac shielding is necessary to ensure all future Linac research is conducted safely. Particularly, this project aims to estimate the radiation doses in the Alternating Gradient Synchrotron (AGS) tunnel near the Linac tunnel and in the equipment bay room near the gate valve of the last tank (tank 9) of Linac. To do this, we used the particle transport code, Monte Carlo N-Particle 6.2 (MCNP6.2), to perform the simulation and model the facilities of Linac and AGS at BNL. This simulation allowed us to investigate the extent of radiation dose rates in various areas of the facilities by placing detectors in specific locations. We could therefore determine whether the dose rates due to these faults is acceptable for limits set by the Department of Energy (DOE) and BNL, and if the shielding is sufficient. As a result of completing this project, I have added coding physics simulations and parallel processing with Unix to my repertoire of skills.

I. Introduction

In the C-AD facilities at BNL there is shielding in place to limit all radiation exposure. The original design for the Linac shielding used estimates made in 1966 of the doses and dose rates outside the shielding. The Linac operating current has gradually increased over the years, so this project aims to reevaluate the shielding, focusing on two main areas, both shown in Figure 1**.**

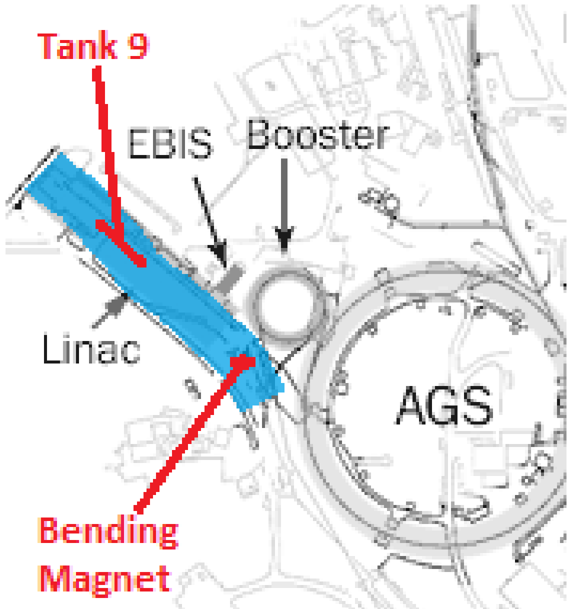

Figure 1: Map showing locations of faults this project investigates

The first area is in the High Energy Beam Transport (HEBT) line, where there is a bending magnet that has not been in use for several years. Today, high current proton beams from Linac are normally diverted to BLIP or Booster. For routine operation, some small current of proton beams would enter the HEBT line only when we want to measure the proton polarization during polarized-proton runs. During this mode of operation, the proton beam is dumped at a beam stop, NZ225, in front of this magnet. A high current of proton beams, such as 320 μA, may reach the bending magnet only during a very unlikely fault in which the beams were not diverted to BLIP or Booster and the beam stop is somehow not in its normal position to stop the beam. This would then give rise to radiation in the AGS tunnel. Since the bending magnet has not been used for several years, the beam stop NZ225 has been set in its proper position to stop any proton beams and therefore the above scenario of having two unlikely faults is not a credible event. The fault that a high current would enter the HEBT line during our 24-hour/7-days-a-week operation and hit the beam stop is a slightly more credible event, though still unlikely. The second area is at the last tank (tank 9) of the Linac tunnel. Here, a trench and several drain pipes serve as a path for radiation from the beam to the equipment bay room if the tank vacuum valve is accidentally closed with the beam running. This work is theoretical in that the faults are unlikely situations and we could not perform the experiments and measure data in actuality; we had to use a simulation to make estimates of the radiation doses and rates with the current shielding of the Linac tunnel.

II. Methods

Since this project is concerned with the worst-case faults in the Linac tunnels, a simulation was necessary to create them and determine if the shielding that is currently in place is sufficient in keeping the radiation doses and rates at an acceptable level. To create this simulation, we used MCNP6.2, which is a 3-D, general purpose, continuous energy, generalized geometry, time-dependent Monte Carlo radiation-transport code capable of tracking many particle types over broad ranges of energies.[1] With this software, we could model the structures of the areas of Linac we were interested in and use a 320 µA current in the simulation.

This software package comes with a variety of tally designators, or detectors, which we used to attain the results from the simulations. We used a tally designator that estimated the flux of a designated particle at a given point. We had the detector estimate the flux of neutrons at our selected points, which made our results be given in rem/proton. From there, we could convert our resulting estimates to rem/second, rem/hour, etc.

We placed detectors in various areas around the location of the faults where high dose rates could have an effect on people. In the fault with the beam stop and bending magnet, this area would be in the AGS tunnel, specifically around the AGS/HEBT gate. The exact locations of the detectors here are shown in Figure 2, where, in each pair, the first is 10 cm (3.9 in) from the wall and the second is 30.5 cm (1 ft) from the wall. To create the structures needed for the simulation, I used drawings from the C-AD Windchill system as models to replicate the geometry in the code. For the geometry in this area, I used the preliminary drawing D25-M-1656, as well as drawings D25-M-1657 and D25-M-1658 from the Windchill system. Collectively, these drawings are of the HEBT lines of Linac, starting at the bending magnet and ending where HEBT meets the AGS tunnel.

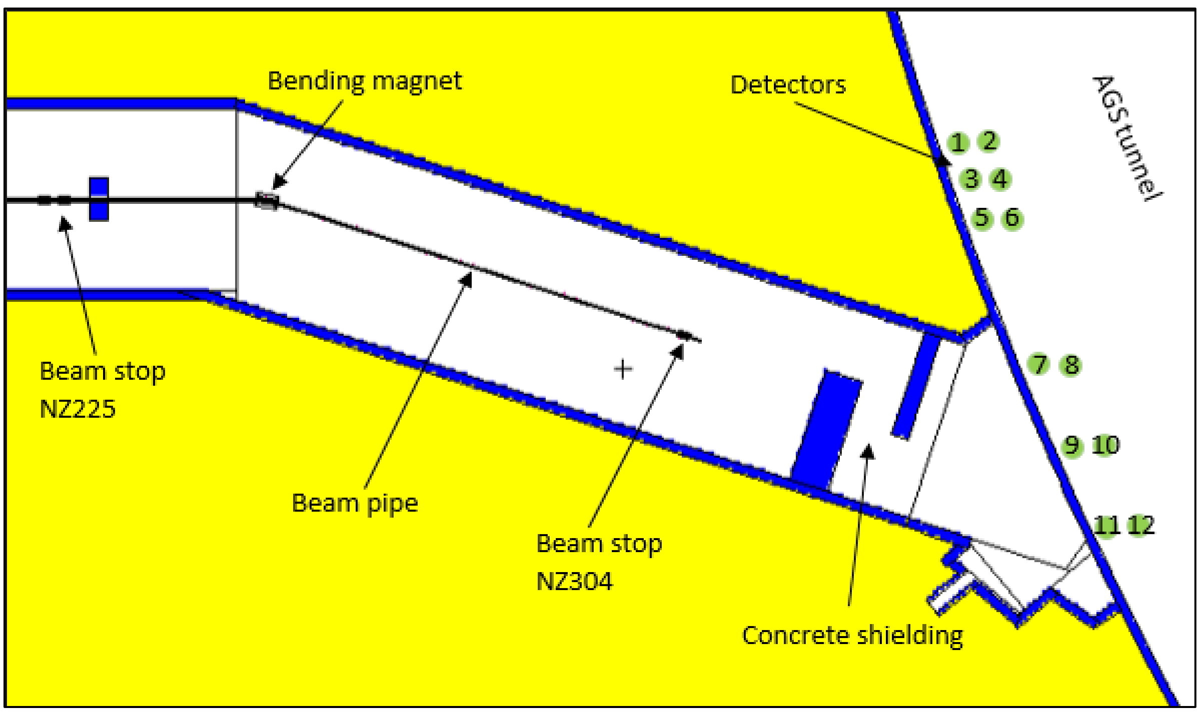

Figure 2. Picture of HEBT line to AGS tunnel from MCNP6.2, top view (XZ)

In the fault with the tank valve of tank 9 in Linac, the area we were interested in was the equipment bay room, which lies parallel to the Linac tunnel and is connected to it through drain pipes and a trench. The locations of the detectors here are shown in Figures 3, 4, and 5. Each detector was placed 10 cm behind the end of the pipes in the equipment bay room, with one set placed at chest height and the other set at the height of the center of the pipes. For modelling the geometry of this area, I used drawings 2484-403-S34 and D25-M-1651 from the CA-D Windchill system. It should be noted that this method of recreation causes a degree of systematic uncertainty, which we have yet to account for in our results.

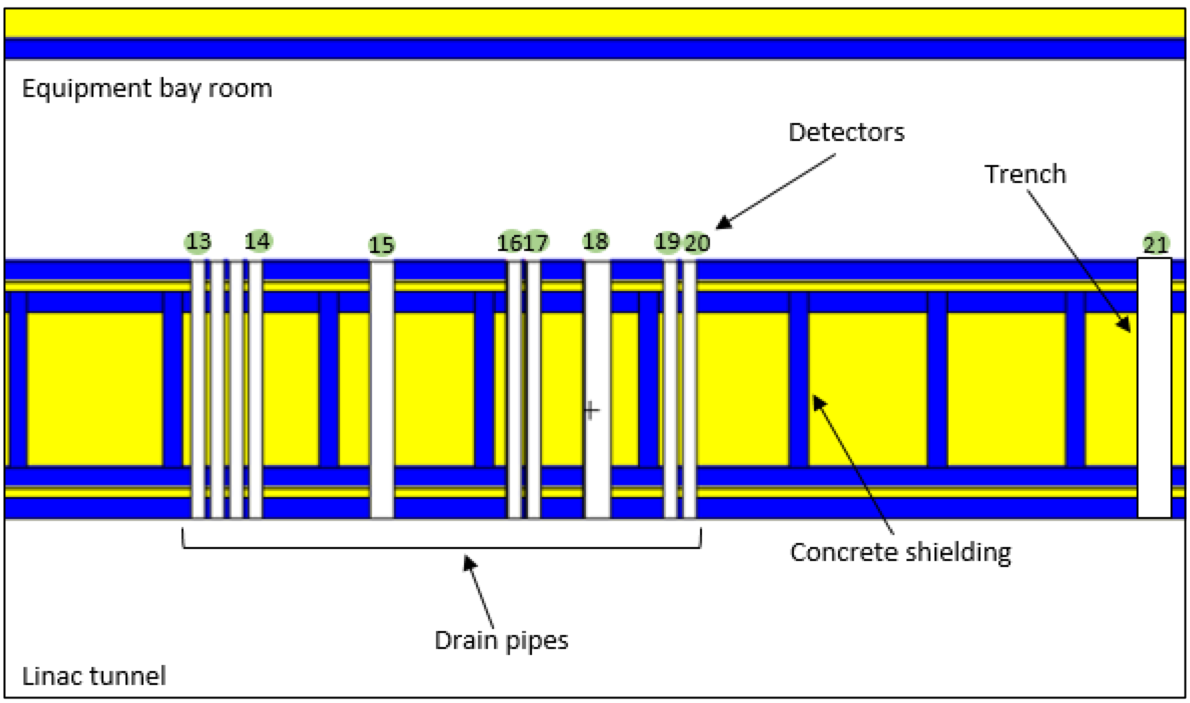

Figure 3 Picture of Linac and Equipment Bay Room from MCNP6.2, top view (XZ), floor height

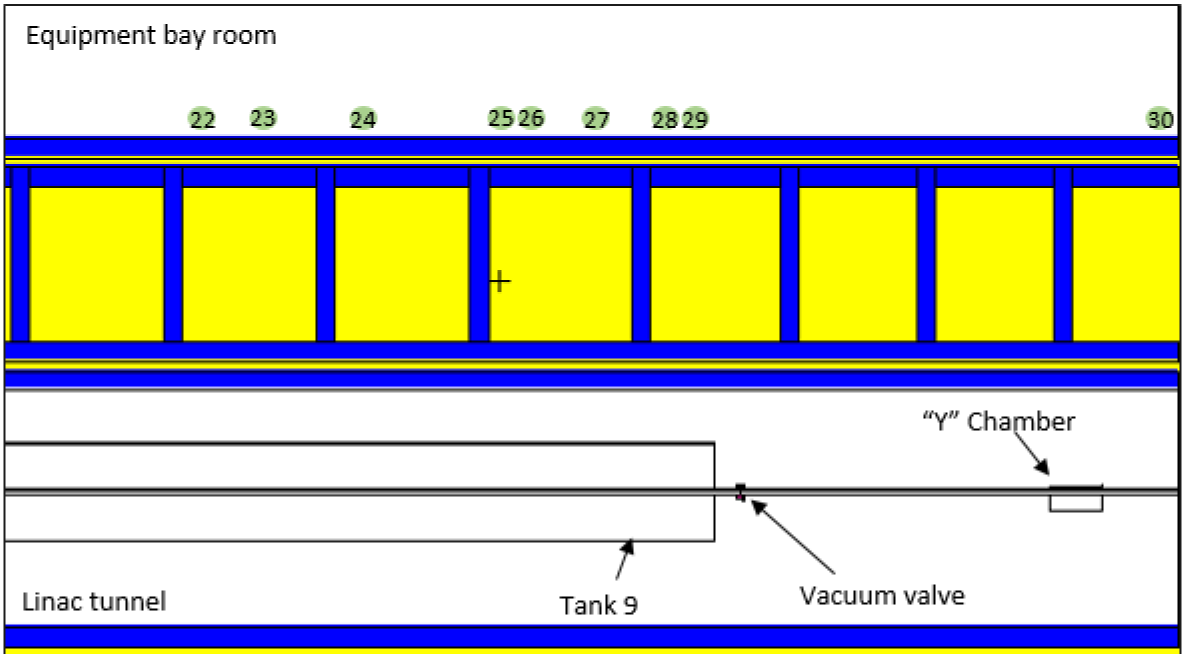

Figure 4. Picture of Linac and Equipment Bay Room from MCNP6.2, top view (XZ), beam pipe or chest height

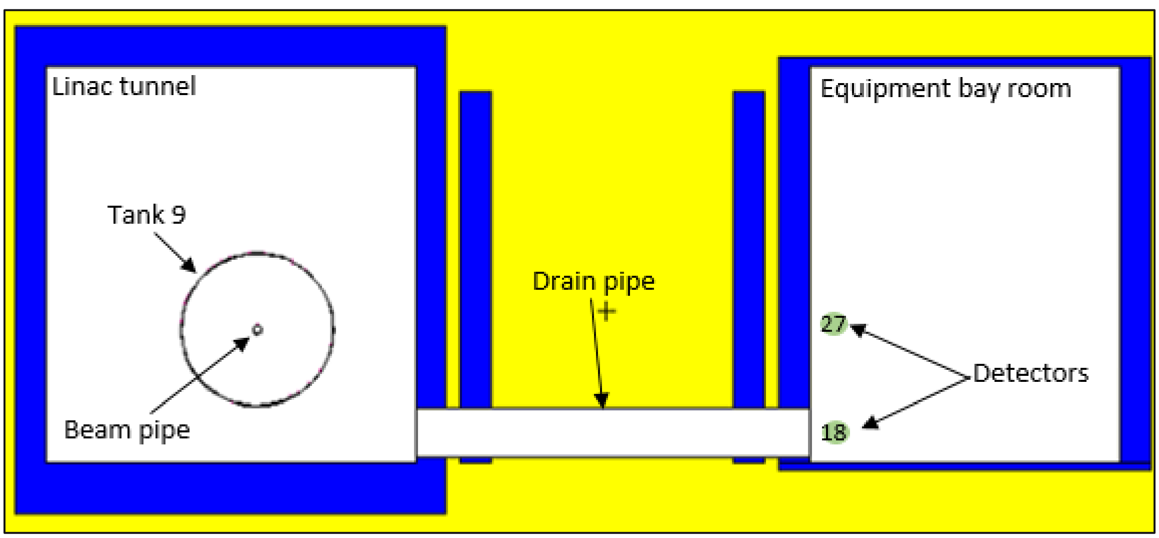

Figure 5. Picture of Linac and equipment bay room from MCNP6.2, front view (XY)

III. Results

In making our estimates, we took into consideration that the area radiation monitors, or chipmunks, interlock the Linac off in approximately 0.75 seconds[2] and thus report the dose rates due to a fault in mrem/0.75 seconds.

One of the situations we found estimates for was where the proton beam of 320 µA average current is dumped at the NZ225 beam stop. All of our dose rate estimates from the detectors in this situation are provided in Table 1. We found that the highest rate estimate came from detector 8. With this highest estimate of 2.18×10^{-18} rem/proton (± 3.7%) and a 320 µA current we calculated the highest dose of radiation in the AGS tunnel adjacent to HEBT to be 3.3 mrem (± 3.7%) in a fault.

Detector	rem/proton	Uncertainty
1	3.08×10^{-20}	±7.3%
2	3.31×10^{-20}	±3.4%
3	3.03×10^{-20}	±4.4%
4	3.41×10^{-20}	±3.2%
5	3.20×10^{-20}	±5.4%
6	3.51×10^{-20}	±3.0%
7	1.76×10^{-18}	±13%
8	2.18×10^{-18}	±3.7%
9	1.49×10^{-18}	±7.1%
10	1.38×10^{-18}	±2.2%
11	9.25×10^{-19}	±8.0%
12	9.10×10^{-19}	±3.5%

Table 1. Radiation dose rates estimated by detectors when beam hits beam stop NZ225

We also estimated the dose that would arise if the beam line was on, the beam stop was not in a position to stop the beam, and the magnet remained off. This event is not credible, but we ran the simulation for the situation and recorded the resulting estimates for educational purposes. These estimates are shown in Table 2. The highest rate of 3.10×10^{-17} rem/proton (± 1.6%) came from detector 7. With this estimated rate and assuming a 320 µA current we calculated the dose in this case was 46.4 mrem (± 1.6%) in a fault. The area of these highest dose estimates is shown in Figure 6, where the detector was placed 10 cm behind the AGS tunnel wall. These results are both lower than the DOE established limit of 100 mrem/year for an untrained person, and are very low compared to the average yearly radiation dose to a someone in the general population of the United States, from natural background and artificial sources, of 620 mrem/year.[3] Therefore, even with an unlikely fault, someone exposed to these radiation doses is unlikely to go over the set limits, as the chipmunks will detect the fault and shut off the beam in approximately 0.75 seconds.

Detector	**rem/proton**	**Uncertainty**
1	4.52×10^{-19}	±4.3%
2	4.94×10^{-19}	±2.3%
3	4.59×10^{-19}	±3.7%
4	5.13×10^{-19}	±2.6%
5	4.90×10^{-19}	±5.9%
6	5.33×10^{-19}	±2.9%
7	3.10×10^{-17}	±1.6%
8	2.86×10^{-17}	±2.1%
9	2.65×10^{-17}	±3.7%
10	2.58×10^{-17}	±1.7%
11	1.40×10^{-17}	±4.8%
12	1.34×10^{-17}	±3.0%

Table 2. Radiation dose rates estimated by detectors when beam stop NZ225 is not in position to stop the beam

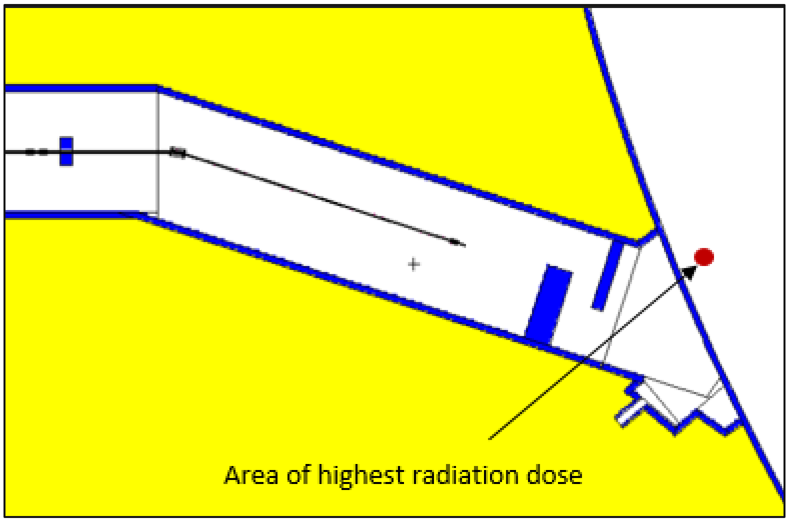

Figure 6. Picture of HEBT lines to AGS showing area of high radiation dose rates in faults

Routine loss can occur in the AGS tunnel area due to proton-polarization measurements during polarized-proton runs, in which polarized-proton beams starting in Linac are injected into the Relativistic Heavy Ion Collider (RHIC) through the Booster and AGS. There is a polarimeter just upstream of the NZ225 beam stop that measures the proton polarization, and the polarized-proton beam is dumped at NZ225. With a 0.09 µA current [4] —which is specifically configured for polarization and other measurements, and is intentionally small— hitting this beam stop and using the dose rate from detector 8 of Table 1, we estimated the dose rate in the AGS tunnel to be approximately 4.4 mrem/hour (± 3.7%), which is below the available chipmunk interlock levels.

If the bending magnet is ever used again, a potential risk could be from one of the beam stops closer to the AGS tunnel having been removed recently to be used somewhere else. The only known reason that the bending magnet could still be used would be for an energy measurement, although this energy measurement is now routinely done with a laser profile monitor. We assume the proton beam current for the energy measurement is similar to that for the polarization measurement, i.e. 0.09 µA. In this situation, the beam would be dumped at the beam stop NZ304.

Our estimates from each detector in this event are shown in Table 3. The highest estimate of 9.26×10^{-17} rem/proton is from detector 7. Using this highest estimate and assuming a current of 0.09 μA, we estimated the dose rate with this current to be 187 mrem/hour (± 9.5%). The location of this highest rate is the same as that shown in Figure 6. This is above any chipmunk interlock level, with the highest being 50 mrem/hour. Since the rate of routine loss is this high, if an energy measurement is to be taken with the bending magnet, the second beam stop should be replaced or additional shielding should be added. Also, the dose rates should be reexamined before running.

Detector	**rem/proton**	**Uncertainty**
1	9.94×10^{-19}	±2.6%
2	1.12×10^{-18}	±1.9%
3	1.09×10^{-18}	±5.6%
4	1.16×10^{-18}	±1.9%
5	1.09×10^{-18}	±3.5%
6	1.19×10^{-18}	±1.7%
7	9.26×10^{-17}	±9.5%
8	8.71×10^{-17}	±1.4%
9	4.21×10^{-17}	±3.0%
10	3.79×10^{-17}	±1.3%
11	1.42×10^{-17}	±4.4%
12	1.39×10^{-17}	±2.7%

Table 3. Radiation dose rates estimated by detectors when beam hits beam stop NZ304

In the other fault situation, at the last tank (tank 9) in Linac, the beam collides with the vacuum valve of tank 9 accidentally. The estimates of dose rates from each detector at chest height are shown in Table 4. The highest rate of 1.64×10^{-19} rem/proton is from detector 27. Assuming a current of 320 µA, we used this rate to estimate the highest whole-body dose in a fault to be 0.25 mrem (± 5.2%). The area of this dose is indicated in Figure 7. Since the drain pipes and trench are located near the floor, we also placed detectors on the floor to get estimates for the extremity rates in a fault. The estimates from all the detectors on the floor in this situation are shown in Table 5. The highest rate of 1.75×10^{-17} rem/proton came from detector 18. With this estimate and assuming a current of 320 µA, we estimated the highest dose in this area to be 26.3 mrem (± 0.4%) in a fault. Both of these results are lower than the DOE established limit of 100 mrem/year for an untrained person, making it unlikely that someone in this area at the time of a fault will approach the set yearly limits.

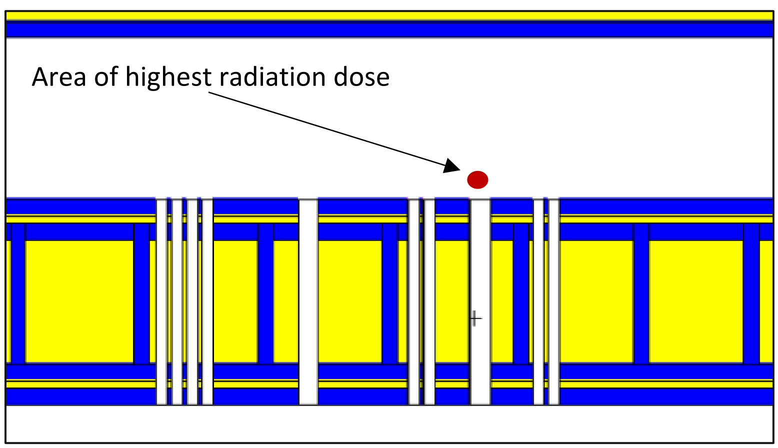

Figure 7. Picture of Linac and Equipment Bay showing area of high radiation dose in faults

Detector	rem/proton	Uncertainty
22	3.23×10^{-20}	±3.0%
23	2.83×10^{-20}	±4.2%
24	5.67×10^{-20}	±7.3%
25	1.17×10^{-19}	±5.7%
26	1.31×10^{-19}	±6.9%
27	1.64×10^{-19}	±5.2%
28	1.28×10^{-19}	±7.6%
29	1.07×10^{-19}	±4.8%
30	1.43×10^{-19}	±2.4%

Table 4. Radiation dose rates estimated by each detector at chest height when hitting vacuum valve of Tank 9 in Linac

Detector	rem/proton	Uncertainty
13	1.55×10^{-19}	±2.8%
14	2.05×10^{-19}	±4.1%
15	1.84×10^{-18}	±1.1%
16	9.75×10^{-19}	±1.8%
17	1.14×10^{-18}	±1.8%
18	1.75×10^{-17}	±0.4%
19	3.28×10^{-18}	±1.1%
20	3.91×10^{-18}	±1.0%
21	5.10 in $\times10^{-18}$	±12%

Table 5. Radiation dose rates estimated by each detector on floor when hitting vacuum valve of Tank 9 in Linac

For an additional test, we tried placing 1 inch of sand to fill the end of the drain pipes and trench to emulate sand bags in our Monte Carlo code and ran the same simulation again. We found there was no significant difference in doses at chest-height with the sand compared to those without the sand.

IV. Conclusion

The estimates of radiation dose rates from our simulations indicate that the current Linac shielding is sufficient for keeping dose rates in certain faults below the established limits at the highest average beam intensity of the 320 μA, with the area radiation monitors, known as chipmunks, interlocking Linac off in approximately 0.75 seconds. Our estimates for dose rates in the bending magnet and AGS area for proton polarization measurements also indicate sufficient shielding. In the situation where one needs to use the bending magnet again, such as in an energy measurement, the dose is above chipmunk interlock levels. Because of this, we recommend the second beam stop, NZ307, that has been moved should be placed back to its original location near NZ304 and doses in the AGS tunnel with this second beam stop should be reevaluated.

This project expands the dose and dose rate estimates done in previous years, incorporating the greater beam current as well as structural and usage changes in the Linac tunnels. One could further this project by estimating any systematic uncertainties that exist, running the simulations longer to lower statistical uncertainty, and placing more detectors to gather data for more areas.

V. References

[1] Werner, Christopher, *MCNP User's Manual Code Version 6.2* (Monte Carlo Methods, Codes, and Applications, Los Alamos National Laboratory. October 27, 2017).

[2] Geller, Joe, *Time to Chipmunk Interlock for Large Radiation Faults* (Collider-Accelerator Department, Brookhaven National Laboratory. January 27, 1999).

[3] *Radiological Worker 1 Training Study Guide* (Training & Qualifications Program Office, Brookhaven National Laboratory. October 6, 2016).

[4] Vincent LoDestro and Deepak Raparia, Linac group of C-AD at BNL, private communication.

VI. Acknowledgements

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