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Investigating radiation at RHIC access road using Monte Carlo simulation

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Abstract

The implementation of beam energy and intensity upgrades on the RHIC berm may lead to concerning radiation doses above the berm east of building 1005, part of the entrance road to the RHIC ring. This location is currently a controlled area which restricts access to the RHIC ring including building 1005. Simulations were used to determine radiation levels above the road and where necessary shielding will be implemented for the entrance road to RHIC to be classified as an uncontrolled area. Transport code MCNP6.2 was used to model geographical and construction specifications of the RHIC berm located underneath Renaissance Road, as well as accelerator details including the magnets and beam pipes. Particles at beam energy 275 GeV were simulated in a Linux cluster system located at Brookhaven National Laboratory and a radiation dose of 11.48($\pm$8.1%) mrem above the RHIC entrance was determined.

1 Introduction

Beam operations at RHIC may give rise to radiation with varying doses along the RHIC berm. The consideration of beam line upgrades have led the entrance to the RHIC ring (Renaissance Road) just above the berm to be classified as a controlled area. This is partly due to the fact that, from a previous estimate [1], the estimated radiation dose during a Maximum Credible Incident (MCI) with increased beam energy and intensity above Renaissance Road seems to be above 100 mrem. Since the accelerator underneath the junction of the Renaissance Road and the ring is not a location of limiting aperture, an MCI around this area is a beam fault in which 0.5 of the total beam intensity is lost at the beam pipes underneath the entrance road [1].

The Collider-Accelerator Department at Brookhaven National Laboratory (BNL) is seeking solutions to allow for Renaissance Road to be classified as an uncontrolled area. Using Monte Carlo N-Particle (MCNP6.2) transport code, the RHIC berm, accelerator, and magnetic details will be modeled. Simulations at beam energy 275 GeV will be run in a Linux Cluster at the Scientific Data and Computing Center (SDCC) at BNL, mainly used for running the export-controlled software MCNPX and MCNP6, to determine accurate radiation doses during an MCI for the area. The results will be used to determine if/where necessary radiation shielding must be implemented to ensure the entrance becomes an uncontrolled area, thus allowing unrestricted access to building 1005.

2 Methods

2.1 Empirical Dose Estimation

Existing radiation dose estimations were calculated by Dana Beavis using the following empirical equation:

$$D = \frac{(38,800\, rem) * e^{(-\frac{d}{att})}}{(r_t * r_t)} \tag{1}$$

assuming a full beam intensity of 2.28×10^{13} protons at beam energy 250 GeV, where D is the dose in rem, d is the berm thickness in feet, att is the attenuation length of shielding in feet, and r_t is the transverse distance in feet. r_t for this part of the berm was found by subtracting the elevation of the beam pipe $69\frac{1}{6}$ ft from the elevation of the tunnel height 76 ft, plus the elevation of the road 13 ft above the tunnel ceiling and the additional 3 ft above the surface of the road. The value 55.94 mrem, or 56 mrem, was obtained using Eq.1 with values d = 13 ft, att = 2 ft, $r_t = 22\frac{5}{6}$ ft and a factor of 0.5 for half of the full beam intensity.

Doubling beam intensities and increasing beam energy by 30% (i.e. 325 GeV) correspond to a scaling factor of $2 \cdot (1.3)^{0.8} \approx 2.5$ [1]. Multiplying this scaling factor to the aforementioned 56 mrem, one obtains a dose of 140 mrem in an MCI. More than 10 years after [1] was written, the highest attainable beam energy at RHIC is now believed to be about 275 GeV [1]. For this report all simulations were performed at beam energy 275 GeV, and the full beam intensity was assumed to be 5×10^{13} protons. With these slightly revised conditions, the estimated dose due to an MCI at Renaissance Road is about 132.4 mrem [2].

For its use, Eq.1 is very generic. The actual doses may vary greatly due to the differences in specific accelerator and magnet configurations. In this report the authors describe a set of simulations with a detailed model of the entrance via Renaissance Road and its surroundings in MCNP6.2, and will compare results with the dose 132.4 mrem obtained from Eq.1.

2.2 Berm Simulation

A detailed model spanning 10 m of the RHIC berm, tunnel, beam pipes, and magnets east of building 1005 at approximately 5 o'clock was constructed with MCNP6 transport code using several sources. Orientations of the model in the XY, YZ, and XZ planes are shown in Fig. 1. The coordinate system of the model is described for clarity. The x-axis follows the North-South (N-S) direction of the tunnel, the y-axis follows the vertical height of the model, and the z-axis follows the counterclockwise West-East (W-E) length of the tunnel. Important details pertaining to construction of the model are described below. The model was then simulated extensively in a Linux cluster system at BNL. Attention was focused at 3 ft above Renaissance Road where radiation doses on human traffic are being questioned.

2.2.1 Berm

A survey of the RHIC berm performed by Matt Ilardo and Charles Folz provided information on the slope and elevation of Renaissance Road. Three images measured the vertical distance from the top of the tunnel to the the road surface at the west gutter (WG), center line (CL), and east gutter (EG) of Renaissance Road [3]. A center elevation of approximately 13.2 ft taken from CL was used to define the height of soil shielding above the RHIC tunnel. To calculate the West-East slope of the road, the center elevations from WG and CL were compared over a distance of 5 m. Similarly, to calculate the N-S slope of Renaissance Road

[1] The energy scaling, $\left(\frac{325}{275}\right)^{0.8}$, would only result in a factor of 1.14 on doses.

[2] 55.94 mrem multiplied by $\left(\frac{275}{250}\right)^{0.8}$ and $\frac{5}{2.28}$ is 132.4 mrem.

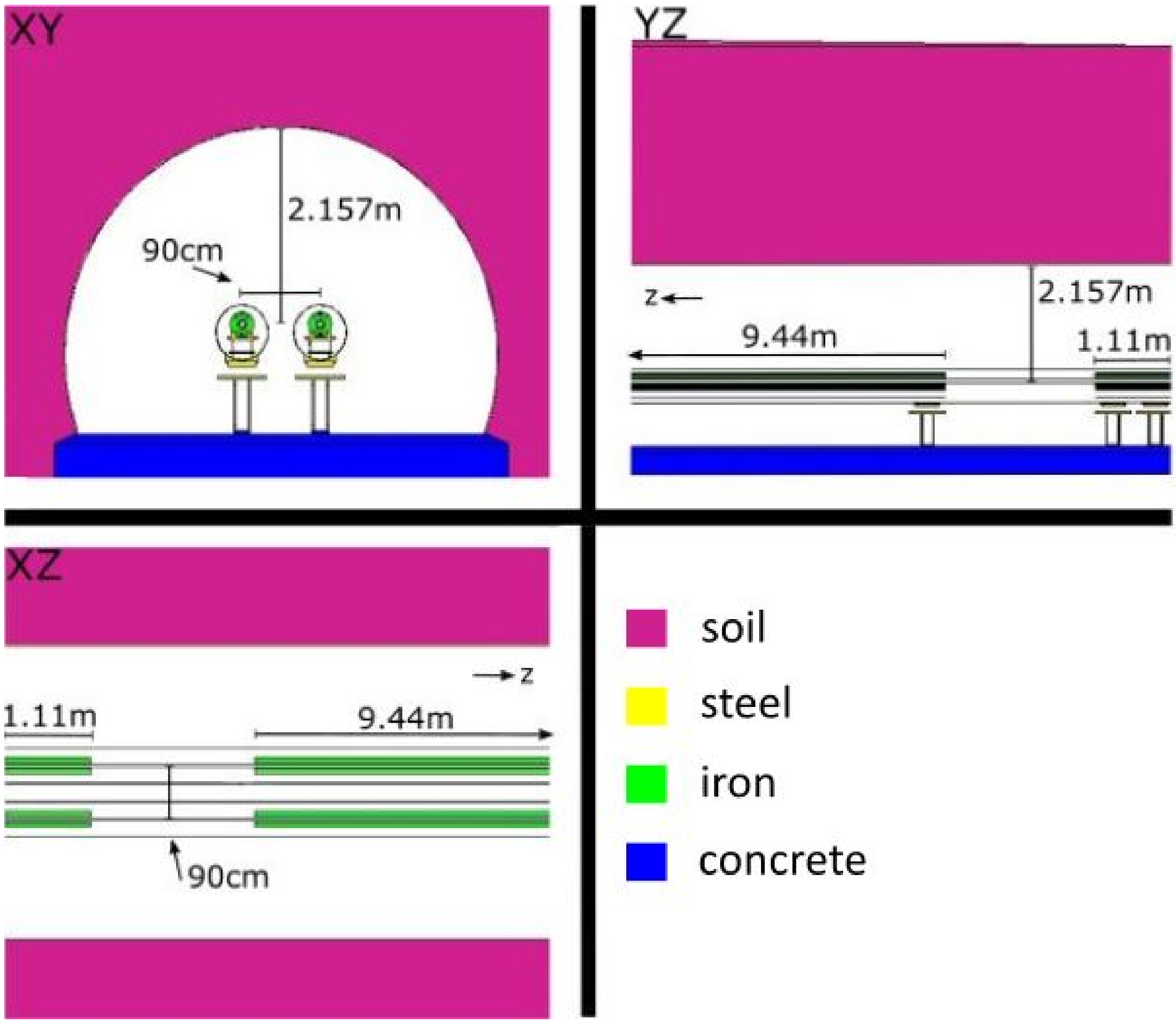

Figure 1: XY [2],YZ, and XZ plane of RHIC berm, where pink represents soil, white represents vacuum, dark blue represents concrete, green represents iron, and yellow represents steel. Fig. 2 shows what the magnets look like inside of the beam pipes. A 10×10 m area in the XZ plane was assumed for the model.

the north and south elevations of CL were used. The distance between the two elevations was 70 in., stated by the surveyors.

The resulting N-S slope of -0.003 and W-E slope of 0.0004 shown in Table 2 were extended to 10 m lengths for model simplicity. Although the slopes of the road are quite small, as much detail as possible was used for this part of the model. More detail improved the accuracy of simulated radiation doses a person would receive if they were standing at the entrance to RHIC.

Elev.1(ft.)	Elev.2(ft.)	direction	slope
12.9658	13.1959	W-E	0.0004
13.7632	13.7447	N-S	-0.003

Table 2: Road slope elevations

2.2.2 Tunnel

The RHIC tunnel is 13.2 ft below the surface elevation $89-90$ ft of Renaissance Road with an inner diameter of $16-4\frac{3}{8}$ ft. The concrete floor is marked at an elevation of 65 ft., and the ceiling of the tunnel is 11 ft above at elevation 76 ft [2].

Inside of the RHIC tunnel are the beam pipes, 90 cm [4] apart. Midway between their centers, at x = 0 in the model, is exactly 2.157 m [3] to the roof of the tunnel. From Fig. 1 in the XY plane the reader can see the beam pipe on the right is referred to as blue, while the beam pipe on the left is referred to as yellow. The blue beam pipe has clockwise particle direction, vice versa for the yellow beam pipe. At the 5 o'clock location underneath Renaissance Road, the blue beam pipe is closer to the center of the RHIC ring.

2.2.3 Magnets

Surrounding each beam pipe at specific intervals are iron yokes surrounding copper coil arrangements to produce dipole/quadrupole magnetic fields. The Q12 magnet, 1.11 m in length, and the D11 magnet, 9.44 m in length [5], were incorporated in the model, shown in Fig. 2. They differ only in the configuration of their copper coils and total length in the z-direction.

Helium tubes and electrical buses [6] were included in each iron yoke to make the model more realistic. The base supports for the iron yokes and beam pipes were modeled from existing engineering drawings [6] and images from a tunnel visit [7]. Beam pipe supports were

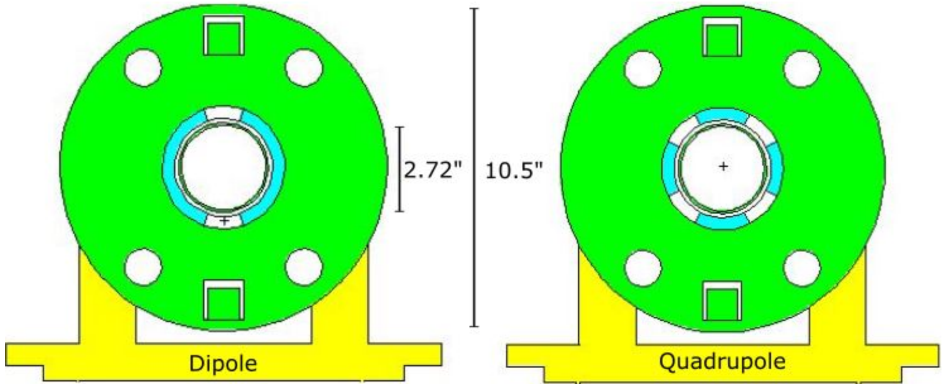

Figure 2: dipole and quadrupole magnets, where green represents iron, yellow represents steel, light blue represents copper, and white represents vacuum.

placed at each end of the magnets, although there are more supports at the real RHIC beam. The base dimensions are approximate and were minimized to prevent excessive shielding in the model.

3 Analysis

Simulations were run with different parameters in an effort to find the highest radiation dose a person may experience 3 ft above Renaissance Road. Nine detector point tallies were used to survey doses per incident proton along the length of the road above the RHIC tunnel. A detector tally (F5) in MCNP6.2 makes use of a variance reduction method ("next event estimator") that allows for more efficient simulations[8]. Unless otherwise specified, F5 tallies were used for simulations in this report. The Cartesian coordinate system for the model was set up such that the positive x-axis pointed towards the center of the RHIC ring, positive y-axis pointed to the sky, and the positive z-axis pointed in the direction of proton flow in the yellow ring.

Two runs were performed with the same geographic parameters to observe the effects of magnetic fields on doses. The magnetic field produced by D11 with a maximum stepsize of 1 cm was tested, and the results are shown in Fig. 3. Differences between the two runs were negligible, and magnetic fields produced by Q12 and D11 were excluded from further runs for efficiency.

Shown in Fig. 4 is a comparison of radiation doses from hitting the sides of the yellow and

[3]Protons in the blue beam pipe move in the negative z-direction with an angle about -3.67 mrad (suggested by accelerator experts) in the x-direction for particles hitting the side of the beam pipe closest to the center of the road above. Protons in the yellow beam pipe move in the opposite direction with the same angle for particles to hit the side of the beam pipe closest to the center of the road above.

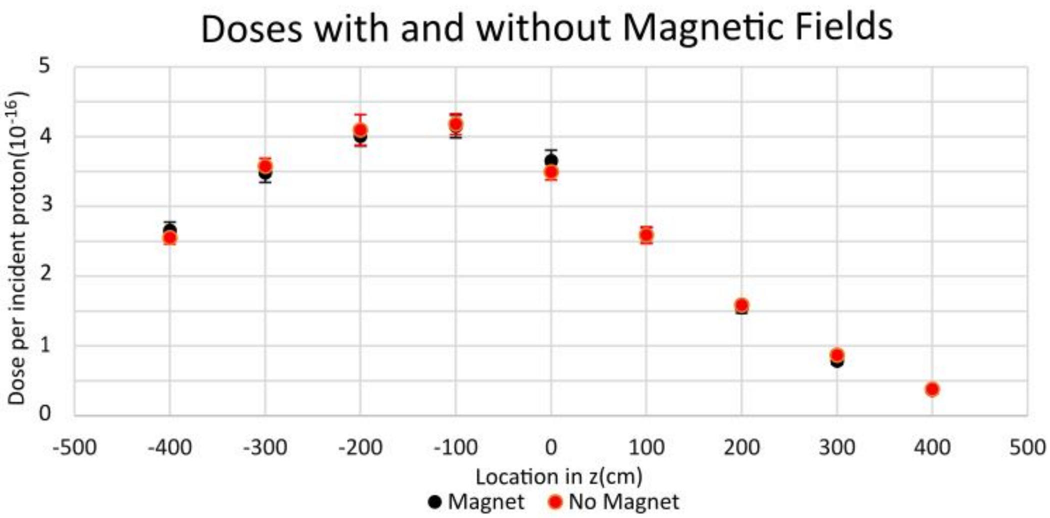

Figure 3: Dose per incident proton comparisons when blue beam pipe is hit from side at z = 200 cm.

blue beam pipe. Particles in the yellow and blue beam pipes circulate in opposite directions[3] and during simulations the beams were hit in different directions as well.

As there would be more radiation in the forward beam directions, the doses were expected to be higher in the negative z-direction for the blue beam pipe and higher in the positive z-direction for the yellow beam pipe. The distribution of data in Fig.4 is consistent with expectations and there is little fluctuation in dose depending on where particles were designated to collide with the beam pipes.

For these four runs, the maximum radiation dose was $4.18 \times 10^{-16}(\pm 3.6\%)$ rem per incident proton at z = -100 cm in the blue beam pipe, designated by red in Fig. 4. The maximum dose observed in the yellow beam pipe was $4.16 \times 10^{-16}(\pm 3.9\%)$ rem per incident proton at z = 100 cm. This dose resulted from hitting the beam pipe at z = -200 cm, which is an area of the beam pipe that is not surrounded by any magnet. One might expect the iron yoke of the magnet to provide extra shielding, but the presence of the magnet also acts a scattering target to help bring neutrons to the surface of Renaissance Road. It is likely that these two effects largely cancelled each other out.

Runs at different z and y coordinates along the blue beam were examined to see how doses varied. Shown in Fig. 5 are three runs and their respective dose spectrums. The black data points correlate to a run hitting the side of the blue beam pipe at z = 200 cm, and the green data points correlate to a run hitting the side of the blue beam pipe at z = 150 cm. The third data set correlates to hitting the ceiling of the blue beam pipe at z = 200 cm.

The highest doses 3 ft above Renaissance Road were around z= -100 cm or z = -200 cm. The maximum dose $4.37 \times 10^{-16}(\pm 3.1\%)$ mrem per incident proton found using 9 point

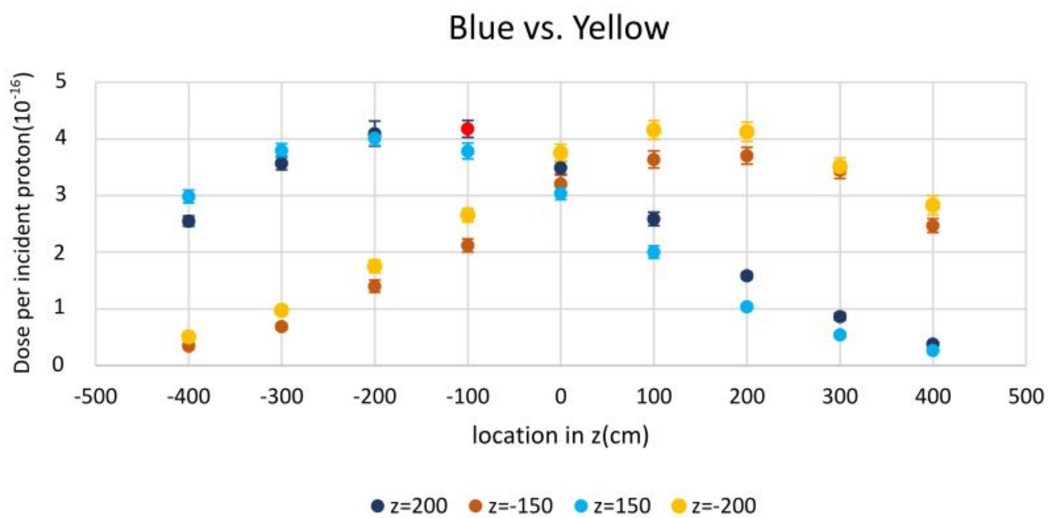

Figure 4: Dose per incident proton with two simulations each from the yellow and blue beam pipe. The yellow beam pipe was hit from the side at z = -150 cm and z = -200 cm, and the blue beam pipe was hit from the side at z = 150 cm and z = 200 cm. All runs except at z = -200 cm were surrounded by magnets.

detectors placed along the length of the z-axis was observed by hitting the top of the blue beam pipe at z = 200 cm. The maximum doses for each run are about the same as the highest doses in Fig. 4 if one takes statistical uncertainties into account.

In the blue ring an exploration of the cross section at z = -100 cm of the RHIC berm was conducted. 8 point detectors were used along the cross section of the RHIC berm 3 ft above the road to record doses from a collision into the side of the blue beam pipe at z = 200 cm, shown in Fig. 6. Doses were highest in the center strip of the road x = -100 cm to x = 100 cm and decreased with distance from the RHIC tunnel center. No outlying doses were discovered, nor any doses higher than those at x = 0 cm for other runs along the blue beam pipe.

To compare and cross-check the doses found from previous F5 tallies, the track-length F4 tally [8] in MCNP6.2 was used. F4 tallies need prolonged time and more statistics to produce dose results with comparable accuracy as those of F5 tallies. The colliding point where the previous maximum dose was found, hitting the top of the blue beam pipe at z = 200 cm, was selected to check the resulting dose above the road at z = -100 cm.

By chance, two different directions to hit the top of the blue beam pipe were used in simulations, one in the positive y-direction and another in the negative x-direction. Results from the F4 tallies were consistent with previous simulations using point detectors (F5 tallies). The highest dose found from both F4 and F5 tally simulations was 4.59×10^{-16} ($\pm 8.1\%$) rem per incident proton.

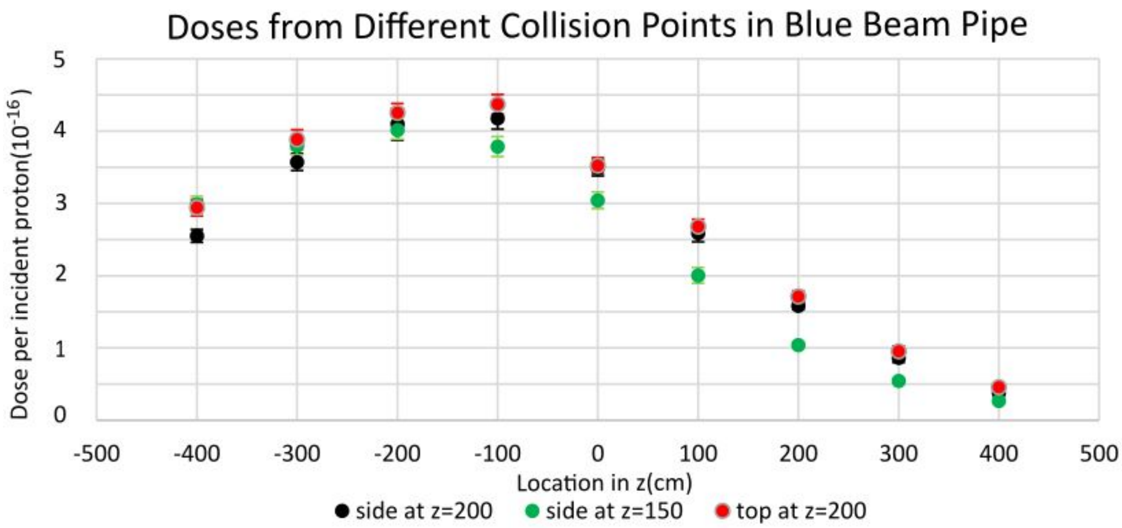

Figure 5: Dose per incident proton comparisons with three simulations on the blue beam pipe, two hitting the side of the pipe at z = 150 cm and z = 200 cm, and one hitting the top of the beam pipe at z = 200 cm.

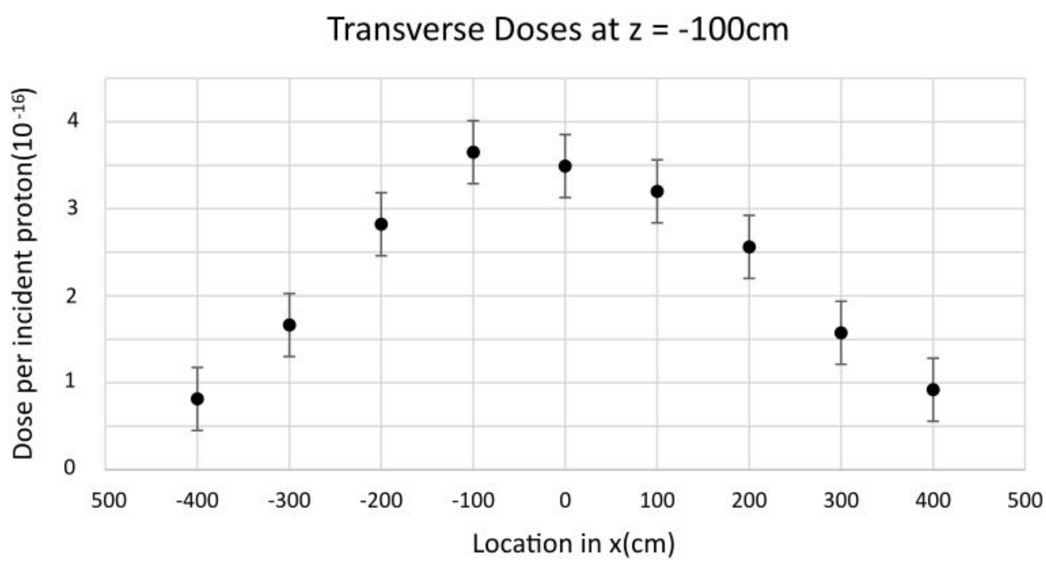

Figure 6: Dose per incident proton along the x-axis at z = -100 cm from a collision into the side of the blue beam pipe at z = 200 cm.

Previous simulations adhered to the common practice that only protons and neutrons are transported. As another cross-check, a simulation with a collision point into the side of the blue beam pipe at z = 200 cm was performed in which photons are added to the transport. The dose results including both neutrons and photons are shown in Fig. 7.

The total doses for a simulation with both neutrons and photons transported in MCNP6.2 agree with doses from previous runs. Over the course of dose exploration stated in this report,

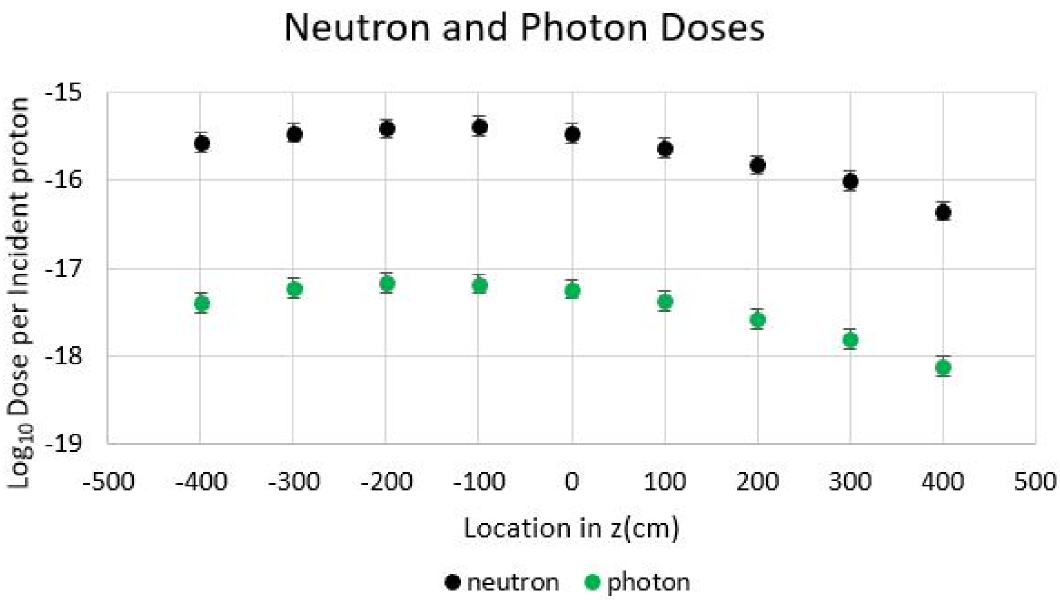

Figure 7: Dose per incident proton along the z-axis for a collision in the side of the blue beam pipe at z = 200 cm. Logarithmic doses per incident proton for neutron (black) and photon (green) activity in simulation.

no outlying or inconsistent doses were found.

4 Conclusions

Various simulations were performed on a section of the RHIC berm to examine radiation doses at the entrance to RHIC during a beam fault (MCI). Maximum doses in both the blue and yellow beam pipes at different collision angles and locations were consistent with little variation. The highest dose from all performed simulations was 4.59×10^{-16} rem per incident proton. At half of the full beam intensity, 2.5×10^{13} protons [9], this corresponds to about 11.48 mrem with an 8.1% statistical uncertainty.

At 3 ft above Renaissance Road, the previous dose approximation 132.4 mrem from Eq.1 is more than 10 times larger than the highest dose found from this set of simulations. With simulated values well below a cautionary cap of 100 mrem, the entrance to RHIC via Renaissance Road can be reclassified as an uncontrolled area without adding additional shielding to the berm.

5 Acknowledgements

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References

[1] D. Beavis, "Potential Dose on the RHIC Berm", December 30, 2009: `https://www.c-ad.bnl.gov/esfd/RSC/Memos/RHIC_berm.pdf`.

[2] Drawing number : A3001B0111 by R. Tulipano, "RHIC Construction Major Facilities @ 12:00", April 21, 1997.

[3] C. Folz, M. Ilardo, "CL ROAD", "WEST GUTTER", "EAST GUTTER", "beam to tunnel", June 2020: `https://brookhavenlab.sharepoint.com/:f:/r/sites/MyOwnTestingArea/Shared%20Documents/RHIC%20Entrance%20Road%20Radiation/survey?csf=1&web=1&e=z8vrD6`.

[4] Accelerator Division, "RHIC Configuration Manual"(Collider Accelerator Department, Brookhaven National Laboratory, September, 2006): `https://www.bnl.gov/cad/accelerator/docs/pdf/RHICConfManual.pdf`.

[5] Steven Tepikian has provided the current RHIC MAD-X lattice files for both blue and yellow rings in RHIC.

[6] Drawing number : 12120191 by J. Massim, S. Mulhall, "CQT4 Magnet Assembly Area 16, Station 6, CQT4 Cryostat and Magnet Assembly without Flanges", August 9, 1996.

[7] Thanks to Don Bruno's team for taking all the pictures inside the RHIC tunnel on July 8, 2020.

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

[9] K. Yip, "Potential radiation doses outside the IR8 West Wall penetration during a fault" March 15, 2019: `https://www.c-ad.bnl.gov/esfd/RSC/Memos/2019-3-15%20sPHENIX%20West%20Wall%20Penetration.pdf`.