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Memo

date: *March 10, 2014*

to: *RSC*

from: *D. Beavis*

subject: *Muons Created in Abort Pre-fires with an Orbit Bump in the RHIC 11 O'clock Arc*

Motivation

The abort kickers spontaneously fire several times in a year in each ring. These events are often referred to as pre-fires. These pre-fires occur without a trigger. The trigger is designed so that the "abort gap" is inside the kickers while their field is not sufficient to deflect the beam into the beam dump. During a pre-fire a portion of the beam (10% to 20%) will be scrapped at various locations around RHIC. The remaining beam is deflected into the beam dump. STAR has stated that the pre-fire losses near STAR are causing issues with electronics and would like the impact on their detectors to be reduced as much as possible.

C. Montag has requested that the radiation issues be examined for 100 GeV gold beam with an orbit bump[1] in the IR10 to IR12 arc, which will cause pre-fires losses to be concentrated in this location. All issues radiological have been examined[2] except for the potential for muons to exit the berm and result in either on-site or off-site exposure. **This report will demonstrate that the loss of 100 GeV protons and Au ions in the middle of the IR10 to IR12 arc (also IR10 to IR8) will not exceed off-site or on-site exposure limits.**

Method

A simple method will be utilized to provide a conservative limit to the amount of 100 GeV beam that can be lost in the middle of the arc between IR10 and IR12 and be well below BNL and DOE requirements for potential radiation exposure. The RHIC soil shield is designed on the outside with six muon lobes. The lobes are intended to provide extra soil shielding to reduce the dose from muons created in the straight sections. High-energy muons are almost exclusively created in the straight sections. The outline of the muon shield is shown in Figure 1. The high energy muons have trajectories that are tangent to the RHIC ring at the locations where the beam

[1] A similar orbit bump for the yellow beam is planned for the arc between IR10 and IR8, counter-clockwise rotation.
[2] http://www.c-ad.bnl.gov/esfd/RSC/Memos/PrefireDump_3_10_14.pdf

scrapes. It is clear from Figure 1 that the muons scrapped at 11B will transverse through less soil shielding then those created in the straight sections.

An outline of how the dose is estimated in this report is:

1. Estimate the energy loss of the muons in the berm. This establishes the minimum energy of particles to be tracked to the inside of the tunnel wall.
2. Assume a target thickness and then scale to 100% beam loss, if appropriate.
3. Estimate the muon fluence to the outside of the berm.
4. Convert the muon fluence to dose using conversion factors.
5. Scale the result to the site boundary using $1/r^2$.

There are three distances that are important for estimating the potential muon dose off-site. These distances are the effective decay distance in the RHIC tunnel, the thickness of soil the muon trajectory passes through, and the distance to the site boundary. Figure 1 is not detailed enough to obtain these numbers.

The site topographical map was examined to determine the distance from 11B to the tunnel wall and the distance from the tunnel wall to where the muons would exit the berm, see Figure 2. The distance for straight trajectories from the scrapping location to the tunnel wall is 155 feet and the thickness of soil is 450 feet[3]. A site map was used to establish that the distance from the location the muons exit the berm to the site boundary is 7000 feet. For comparison the numbers for the blue beam dump given in the RHIC SAD[4] are: decay distance 78 meters, exit of berm 321 meters from dump, thickness of the berm is 263 meters (860 ft) and 584 meters for dump to site boundary. For muons created by interactions in the beam dump there is substantially more soil for the muons to penetrate but much less distance to the site boundary. In the RHIC SAD analysis the decay distance was assumed to be from the creation point of the pion or kaon in the beam dump to the beginning of the arc where the pions and kaons would interact if they had not already decayed. For 250 GeV protons the muon fluence that escapes the berm is dominated by particles created[4] in the first proton interaction.

[3] This soil thickness of 465 feet has been rounded down to 450 feet to cover other possible nearby areas.
[4] See Appendix 18 of the RHIC SAD; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app18.pdf

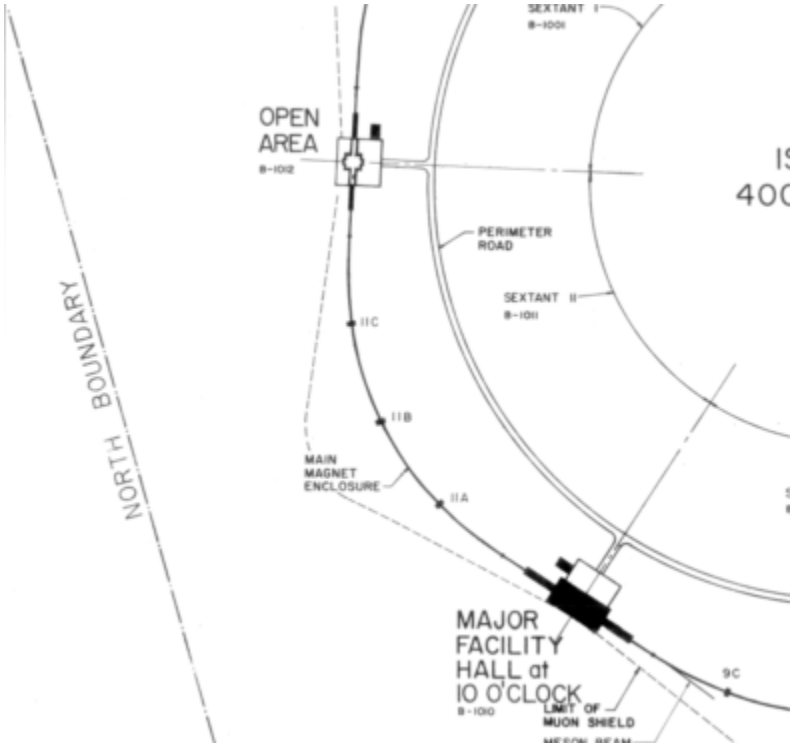

Figure 1: The orbit bump for the blue beam is planned to cause pre-fired beam to scrape at 11B. The outline of the muon shield is shown as a dotted line and the site boundary as a dotted-dashed line. The blue beam circulates clockwise.

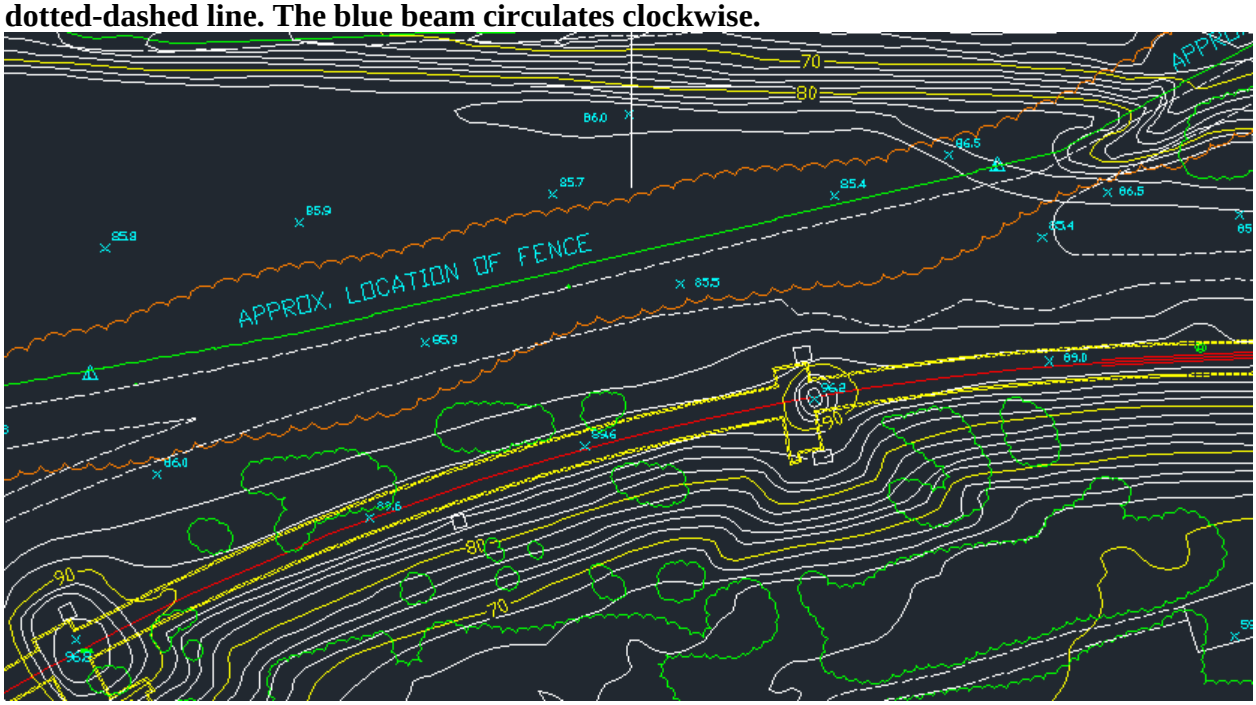

Figure 2: Topo map of the terrain relevant for the losses in the 11 O'clock arc. The 11B alcove is in the lower left hand corner of the figure. The muons would exit the berm above the gully in the upper right hand corner.

Published tables for the muon range and energy loss in soil and other materials were used to establish the minimum energy for muons to escape through the 450 feet of soil. The calculated range and energy loss for muons in FNAL soil has been published[5]. The soil density has been adjusted from the 2.0 g/cc to 1.8 g/cc which is used at RHIC. The resultant minimum muon energy was found to be 50 GeV. A more recent report[6] provides a table for light concrete which was scaled to BNL soil density. The minimum energy was a few GeV higher than the soil result scaled for Reference 5. The 50 GeV minimum energy should be conservative since the muon energy loss in materials which exist inside the tunnel were ignored.

The muon fluence to the inside of the tunnel wall is estimated by using the Monte Carlo code MCNPX 2.7c[7]. The geometry has been simplified in this analysis to provide an upper limit to the dose exterior to the soil shield and at the site boundary. Several steel targets of varying thickness were used to estimate the generation of particles and the resultant decays of some particles to muons before they hit the tunnel wall. The tunnel is simulated as two meters in radius and with no materials inside. Material in the tunnel would typically cause the hadrons to interact and thus result in particles of lower energy that could not generate muons with energy greater than 50 GeV. Protons were propagated except for the cell immediately after the target. This prevents un-interacted protons in thin targets from striking the tunnel wall and generating high energy particles at the tunnel wall, which would not occur in a more realistic simulation. Neutrons were found not to contribute to the high-energy muon fluence and were not transported in the analysis.

The muon fluence was tallied on surfaces from the tunnel wall to the exterior of the soil shield. Hadrons interacting in the soil did not generate more high-energy muons and their transport was usually terminated at the tunnel wall. The muons were tallied on surfaces at several distances from the target and extending beyond the distance to the exterior berm surface. The change with distance enabled an estimate of the divergence of the muons. As the soil was removed from most of the analysis the results do not include the multiple scattering of the muons in the soil. The muon divergence is approximately 5 milli-radians.

The dose to the site boundary is obtained by multiplying the muon fluence by $8.2*10^{-4}$, $(200\ m/7000\ m)^2$. This provides a large reduction factor compared to the blue beam dump and collimator.

The fluence to dose conversion factors for muons and other particles are given[8] in ICRP publication 116 for energies up to 10 GeV. Values for the conversion coefficients up to 100

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[5] G. Koizumi," Muon dE/dx and Range Tables for Tevatron Energies: Results for Some Shielding Materials", May 9, 1978, TM-786.

[6] D.E. Groom, N.V. Mokhov, and S.I. Striganov, "Muon Stopping and Range Tables 10 MeV-100TeV", Atomic Data and Nuclear Data Tables **78**, 183-356 (2001).

[7] MCNPX version 2.7C was used for the calculations in this report. D. B. Pelowitz et al., "MCNPX 2.7.C Extensions", LA-UR-10_00481, March 5, 2010.

[8] ICRP,2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 166, Ann. ICRP 40(2-5).

GeV are provided in another paper[9]. A fluence-to-dose conversion factor of $5*10^{-8}$ rad-cm^2 will provide a conservative conversion factor for the muon fluence that is less than 100 GeV emerging from the berm. For 100 GeV protons striking the steel target the muons emerging from the berm are dominated by muons with energies less that 10 GeV, i.e. initial energies of 50 to 60 GeV.

The RHIC design manual[10] was used to obtain information on the RHIC magnets. The arc dipole magnets are 9.73 meters long (cold mass) and have integrated field strength (for 250 GeV protons) of 32.677 T-m. The cold mass has a radial thickness of 7.4 cm. The beam will interact in the beam pipe inside the cold mass. The beam interaction is simulated with a pencil proton beam striking a steel disc with an 8cm radius and a fixed length. The quadrupoles and other magnets in the assemblies within the arc have a similar diameter cold mass as the dipoles.

The results for the muon fluence at the tunnel wall for several target thicknesses spanning 2cm to 120 cm are shown in Table I. The results demonstrate that as the target becomes thicker the number of primary proton interaction increase resulting in increased muon fluence until the target become thick enough that the pion and kaons interact before they have a chance to escape the target and decay. The 2 cm thick target creates more muons that can penetrate the berm than an 80 cm thick target even though nine times fewer proton interactions occur in the thinner target. This completion between particle creation and decay is well known. A discussion and simple model has been discussed by A.H. Sullivan[11].

Table I: Muon fluence for 100 GeV protons striking a steel target within 50 cm of a straight trajectory.

Target	**Muon fluence at tunnel wall Muons/(cm^2-incident p)**	**% of initial protons that interact in target**
2 cm steel	$1.5*10^{-9}$	11%
20 cm steel	$6.3*10^{-9}$	69%
80 cm steel	$1.0*10^{-9}$	99%
120 cm steel	$2.9*10^{-10}$	100%

The magnetic field was ignored in the simulation. As noted in reference 4 the field in the cold mass can be treated as a simple ratio to the central field. At full field (250 GeV protons and corresponding to 100 GeV Au) the cold mass is approximated with a constant field of 1.4 T. The particles that generate muons outside the berm are produced at angles less than 5 mr. Therefore, they cross the magnet yoke essentially on the horizontal plane. For a 50 GeV particle crossing the cold mass of a dipole requires more than 4 meters before the trajectory[12] exits the iron.
The dipole and quadruple assemblies have an inter-connect space that is less than 1.5 meters long. This is the largest gap in cold mass along which a particle could cross. A particle would need to cross a minimum of 2.5 meters of cold mass. The use of the 80 cm target number given

[9] T. Sato, A. Endo, and K. Niita, "Fluence-to-Dose Conversion Coefficients Based on ICRP Publication 103 Using the PHITS Code", Progress in Nuclear Science and Technology, vol. 2, pp. 432-326 (2011)
[10] RHIC Design Manual, Revised Oct. 1994; http://www.bnl.gov/cad/accelerator/docs/pdf/RHICConfManual.pdf The 1994 design manual was used for this report. The link is for an updated version.
[11] A.H. Sullivan, NIM A239 197 (1985).
[12] This assumes that the trajectory is produced with an outward angle of 5 mr.

above should be conservative for beam loss in any location in the arc. The insertion regions were not considered[13] in this analysis since the orbit bump is intended to be placed in the middle of the arc near alcove 11b.

Au beam will be considered as 197 protons interacting in the magnet assembly at a fixed spot. A full store will be assumed to be equivalent to $5*10^{13}$ 100 GeV protons. The main difference between protons and Au is that for 100 GeV protons the central field of the magnets and the field in the cold mass are 2.5 times lower. Thus the particles are deflected more slowly out of the cold mass creating an effectively longer target. The dose from muons exiting the berm is 0.3 mrads for the loss of a complete fill. The muon dose limits on the berm do not place stringent requirements for the orbit bumps. The muon dose at the site boundary would be 0.23 micro-rads for the same loss. This is many orders of magnitude below the BNL and DOE limits. It is expected that the losses due to the orbit bumps with pre-fires will be equivalent the loss of one full machine fill in a year of operations.

The yellow orbit bumps has muons aimed at a natural hill in the site topography. To exit the soil the muons for yellow losses must travel through substantially more soil than those generated by the blue beam losses. The resultant doses are much smaller than from the blue orbit bumps.

The physics model for high energy particle production in MCNPX was changed to test the sensitivity to the physics model. The model LAQGSM was used for protons striking the 2 cm long target. LAQGSM produced[14] 1/3 of the muons above 50 GeV when compared to the default physics model.

Preliminary results for 250 GeV protons suggest that the muon fluence above 50 GeV would be 10-50 times higher. The dose would still be acceptable both on the berm and site boundary if these preliminary results are correct.

CC:

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[13] The insertion regions do not have the same assembly structure as the arcs. The insertion regions are considered as part of the straight sections.
[14] The computation time for the identical calculation was almost ten times longer.