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Memo

date: *April 20, 2012*

to: *RSC*

from: *D. Beavis*

subject: *Shielding Wall Requirements at STAR*

Upgrades are in progress to increase the proton (and ion) beam intensities. The upgrades will increase the proton beam to an intensity of $5*10^{13}$ protons per ring and beam energy to 300 GeV. The upgrades will result in potential higher exposure in a maximum credible incident (MCI) from a beam fault. Nearly all shielding requirements at RHIC were determined to mitigate the external dose exposure in an MCI rather than chronic exposure. In this report, the requirements for the shielding wall between the STAR IR and the STAR assembly hall at Intersection Region 6 (IR6) will be examined for the intensity upgrades.

RHIC Project Criteria and Estimates

The RHIC Project developed a scenario for the potential beam loss in an MCI as well as chronic losses[1]. The RHIC Project also developed exposure criteria for the RHIC areas[2]. For the STAR shield wall the beam loss in an MCI determines the shielding thickness when coupled to the exposure criteria. The assumption was that the entire beam in a ring could fault on a few limiting apertures and half at an arbitrary location. The potential exposure from an MCI in low-occupancy areas was allowed to be 1000 mrem for "radiation workers" and 100 mrem to "non-radiation workers". For high-occupancy areas the potential exposure from an MCI was allowed to be 500 mrem for "radiation workers" and 160 mrem for "non-radiation workers". The STAR shield wall was designed based on these criteria.

The STAR shield wall design was documented in a series of notes and memorandum. The initial design was discussed[3] by A.J. Stevens in a 1992 note. The design evolved over a series of years and the final design was discussed[4] in a note in 1997. The main shield wall is 5.5 feet thick and composed of light concrete. With half the beam interacting in DX the dose through the shield wall was estimated to be 267 mrem. This does not include any contributions from cracks or the labyrinth. This was well within the RHIC Project criteria.

An RSC subcommittee met to establish[5] exposure criteria for the beam upgrades at RHIC. The exposure limits were more restrictive than the RHIC Project. It recommended that in areas with substantial users that the design should like the exposure from an MCI to 100 mrem. The RHIC Project design for the STAR shield wall does not meet the established criteria for the present intensity. The increased intensity and energy caused it to exceed the criteria more. The STAR wall was examined[6] for the upgraded beam conditions by scaling the RHIC Project numbers

appropriately. The scaled dose is 690 mrem for an MCI with half the beam on DX. It would take an estimated 3 feet of light concrete to reduce the dose to 100 mrem in an MCI. The additional shielding at STAR would create additional efforts to allow the experiment to roll out of the IR. A recalculation of the dose in an MCI was conducted to determine if there was margin to reduce the dose estimates related to factors and assumptions used in the analysis.

New Estimate of Potential Dose from an MCI

The RHIC Project assumptions for calculating the dose through the STAR shield wall were examined. Several factors were identified that suggest that there was margin to reduce the dose estimate. The most immediate is the neutron fluence to dose conversion factor used by the RHIC Project. The RHIC Project used a neutron quality factor twice the value required by 10CFR835 in anticipation of the quality factor being increased. Recently, 10CFR835 was updated and the new weighting factors for neutrons provided. The increases are typically less than a factor of two. A FNAL[7] study demonstrated that for most shielding situations the dose using the new weighting factor was 1.3-1.5 times[8] the dose using the old quality factor. A factor of 0.75 could be conversatively applied to any of the RHIC doses calculations to account for the actual neutron weighting factor. However, this only changes the 690 mrem to 520 mrem for an MCI.

The RHIC Project used the Monte Carlo program CASIM[9] to calculate the shielding effectiveness. This program calculated the transport of particles to a low energy cut-off, typically 47 MeV. The hadron fluence above the energy cut-off was converted to dose using conversion factors. This scheme enables the calculation of the dose through thick shielding, which is CPU intensive if all energies are transported. The technique relies on the fact that after the radiation travels through several interaction lengths of the shield the particle species and energy spectrum is in equilibrium with the high energy hadron component. Therefore one only needs to calculate the high energy component and then deduce the total dose. The code would calculate the density of inelastic collisions (star density) in the shield and then this could be converted into a dose.

The original report for CASIM recommended using a conversion factor of $9*10^{-6}$ rem/(star/cm^3) . The RHIC Project used this conversion factor[10]. The work of G.R. Stevenson[11] suggested that this factor was too large by almost a factor of two. For light concrete Stevenson suggested using a factor of $4.9*10^{-6}$ rem/(star/cm^3). The RHIC Project decided[10] that it was more appropriate to use the original conversion factor and this would at least be a conservative approach. However, this offers the potential to reduce the estimated MCI doses up to a factor of two.

The CASIM code is also know to produce higher estimated doses[10] in the forward direction and underestimate them in the backward direction. A comparison of FLUKA and CASIM can be found in reference 12 and illustrates this point. Depending on the location outside of the shield, CASIM may overestimate the dose or underestimate it. As an example, the liners over the RHIC beam dumps and collimators were designed using CASIM. Later it was recognized[13] that the liners needed to be extended in the backward direction to take into account this underestimation by CASIM. The CASIM code is no longer used at FNAL or elsewhere. Based on the discrepancies it may be worthwhile to recalculate the STAR shielding using a different Monte Carlo code to check the potential dose that could occur in an MCI.

The Monte Carlo program MCNPX[14] was used to calculate the dose penetrating the STAR shield wall. The new neutron weighting factors can be used in the calculation. MCNPX uses an old version of FLUKA to initiate the high energy portion of the hadronic cascade. The STAR detector, DX magnets and shielding were approximated in cylindrical geometry. The symmetry and geometry approximations are used to reduce the amount of CPU necessary to provide adequate statistics. A.J. Stevens discusses 2D verses 3D geometry in reference 3. One factor extracted out of the full 3-D geometry with magnetic field in DX is an asymmetry factor due to the deflection of charged particles. A maximum asymmetry of 1.3 in the horizontal plane was determined by A.J. Stevens and applied to the numbers for faults on DX and D0. MCNPX does not handle magnetic fields and therefore cannot check this factor[15]. The simple geometry used for the calculation in MCNPX is shown in Fig. 1. The shielding wall is a cylinder of 5.5 feet of light concrete at a radial distance of 12 meters. The DX and STAR magnets are approximated. Some detector mass such as the electromagnetic calorimeters are not part of this representation. Some additional details are in the appendix.

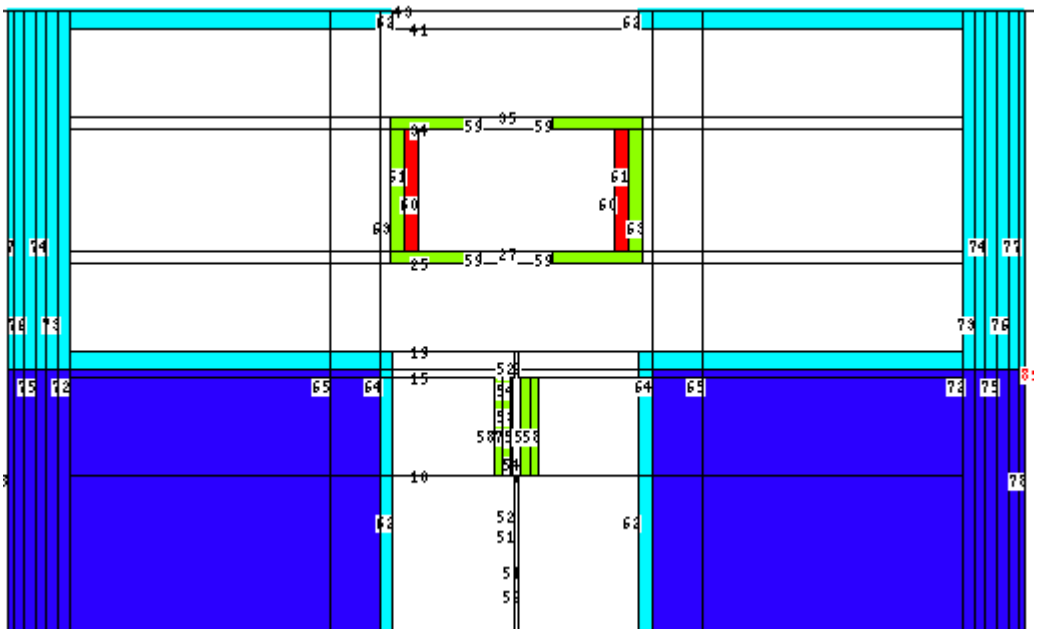

Figure 1: Layout of DX, STAR, and shielding used in MCNPX simulation.

The beginning of the DX magnet defines the z=0 location. The magnet is 4.9 meters long and approximated as layers of steel. It is followed by a section of stainless steel beam pipe. The retaining walls of the tunnel and IR are light concrete. The STAR magnet is approximated as steel and Aluminum. These approximations are crude but expected to provide a reasonable representation of the layout for the shielding calculation.

A pencil beam of 250 GeV protons were directed to strike sections of the interior of DX and the beam pipe. The calculations were conducted with the beam starting 1mm into the surface and with an angle of 1 milli-radian to the surface. Several Z locations were chose for where the beam scraps. These are z=0.5m (near the beginning of DX), z=4.m (90cm before the end of DX), and at z=4.9 (the beam pipe). The low mass hadrons such as neutrons, protons, pions,

kaons etc were transported through the geometry with an energy cut-off of 20 MeV. The neutron fluence above 20 MeV was tabulated along the shielding wall in two-meter z-bins. The results are shown in Figure 2.

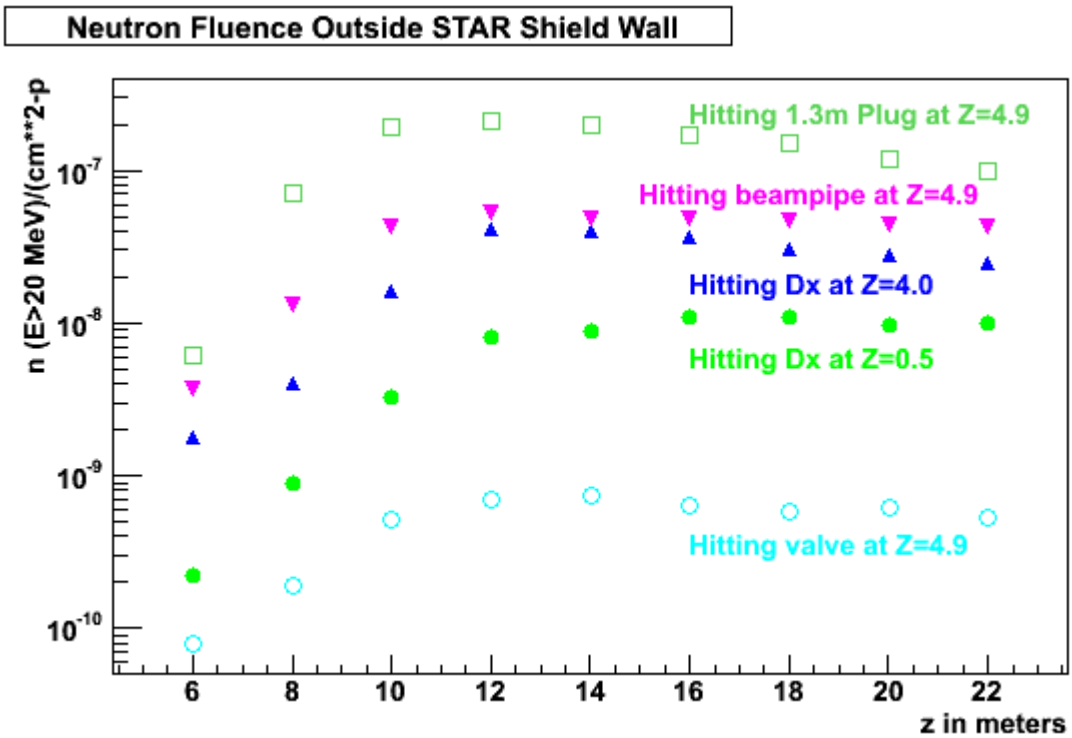

Figure 2: Neutron fluence with energy greater than 20 MeV penetrating the 5.5 feet light concrete shield wall at STAR. Several beam scrapping locations are assumed. The IR retaining walls are at z=6.2 meters and Z= 22.4 meters.

The scrapping examples calculated represent both realistic and unrealistic targets. The largest values are from the 250 GeV proton beam striking a steel plug that has a radius of 7cm and a length of 130 cm. The plug was placed at the end of DX, starting at z=4.9m. It is unlikely that such a target can be hit with the beam. At the same location a 1cm iron value was approximated by filling 40cm of the beam pipe with a density of 0.2 gm/cc. This represents the vacuum value near the pump station. Only 6% of the beam would interact in the valve on the first pass. However, some portion of the beam would continue around the machine to strike the valve again. These multiple passes would need to be accounted for to get a more accurate determination of the valve as a target, although the result is expected to be less than hitting the beam pipe. The other points represent scrapping the DX magnet at 50 cm, scrapping DX at 400 cm, and scrapping the stainless steel beam pipe at 490cm. The outside radius of the DX cold mass is 38cm and although this can provide a good target it can also provide self shielding to reduce the radiation that can reach the shield wall. The iron in the cold mass was decreased to half the thickness for the simulation with the beam scrapping at Z=4.0. The neutrons penetrating the shield wall were increased by 75%. The simulations demonstrate that the IR end of DX is a stronger source than the end in the tunnel.

The results provided in this report can be compared to the CASIM results provided in the initial RHIC documentation. The star density outside a 5 foot thick light concrete wall at STAR was provided in Figure 2 of reference 16. Ignoring the jogs in the shield wall the distributions in Figure 2 above and Figure 2 of reference 16 are similar. The neutron fluence above can be scaled to 5 feet of light concrete (factor of 1.5) and can be decreased to account for the 47 MeV threshold in CASIM (factor of 0.81) . The mean free path of the light concrete in the MCNPX calculation is 43.8 cm. The MCNPX numbers can be converted to star density and a value of $1.1*10^{-9}$ star/(cc-p) is obtained for the peak when the factors are taken into account. This should be compared to the $1.85*10^{-9}$ star/(cc-p) quoted in reference 16. The high-energy hadron fluence is a factor[17] of 1.6 higher in CASIM. The RHIC calculations had the protons uniformly strike the inside of the magnet. If the MCNPX numbers were averaged over the DX magnet the MCNPX result would decrease. To compare dose between the two calculations a number is need to convert high-energy hadron fluence into total dose. This was done in a simple model of having the proton beam strike a steel rod in a light concrete tunnel. The conversion factor obtained in this fashion was $6.5*10^{-5}$ mrem/(hadron>20 MeV) and $8.0*10^{-5}$ mrem per hadron with energy greater than 50 MeV.

A.J. Stevens estimated[16] the total dose outside five foot thick concrete for an MCI as
Dose = $4*(1/2*57*10^{11})(1.3)(1.85*10^{-9}$star/cc)$*(1.8*10^{-2}$ mrem/star/cc)= 328 mrem.
The factor of 1.3 is an upper limit for the asymmetry in the mid-plane that was calculated in full 3-dimensional geometry with magnetic fields. Using the same beam assumptions the MCNPX calculation gives 45 mrem. The MCNPX result is more than a factor of seven less than the RHIC Project estimate. The MCNPX result has used the neutron fluence to dose conversions factors discussed in reference 7. It is important to check the MCNPX number against another modern Monte Carlo code.

K. Yip has repeated the calculation[18] for the total dose outside a light concrete tunnel in MCNPX and in MARS. The MCNPX dose averaged over the concrete surface is $8*10^{-14}$ rem/p. The dose estimated using MARS was 50% higher. MARS has been compared[19] to FLUKA and the two programs have been found to be in reasonable agreement. The factor of 1.5 will be used with MCNPX dose calculation until more details are understood.

The dose outside the STAR 5.5 feet thick concrete shield wall is estimated for the upgraded proton beam energy and intensity. An energy increase from 250 GeV to 300GeV will increase the transverse radiation by factor of 1.16. The maximum number of protons in a ring will be increased to 5*10**13. The factor of 1.3 to account for mid-plane asymmetry due to the magnetic field will also be used. We will assume that half the beam can be lost on the end of DX[20]. The dose[21] is

$.5*5*10^{13}*(4.1*10^{-8}$ n/cm^2 E>20 MeV)$*1.3*1.5*6.5*10^{-5}$mrem/(n/cm^2 with E>20) = 130 mrem.

The reduction is a result of lower penetrating neutron fluence and a smaller high energy fluence to dose conversion. This exceeds the recommendation suggested[5] by an RSC sub-committee., but is a factor of five below the simple scaling[6] of the RHIC estimate.

Conclusions

The results have substantial impact on the planning for the RHIC ring where CASIM results were used to estimate the dose outside a thick for an MCI. The dose outside the STAR shield wall is substantially lower when calculated with MCNPX. Only a small portion of this reduction can be attributed to the use of a conservative quality factor for neutrons by the RHIC Project. The potential dose outside the STAR shield wall from an MCI is five times lower[22] per proton lost than calculated with CASIM. The results for transverse radiation are expected to be lower by a similar factor for other shield walls and the berm. This would imply that no shielding upgrades are needed to accommodate the energy and intensity upgrades, at least where these conclusions can be applied.

Penetrations typically were not calculated in this manner but the initial dose on the labyrinth may have been computed using CASIM. Forward shield walls should be examined and for a fluence to dose conversion factor calculated. Typically, CASIM should be expected to overestimate the dose in the forward radiation an MCI as discussed in the literature.

It is recommended that the STAR shield wall between the STAR IR and assembly area not be upgraded. The calculations provided here should be reviewed. It is unlikely an MCI would occur during any delay in shielding upgrades should the review disagree with the conclusions of this report. The STAR area is monitored by a chipmunk and TLDs are either in place or can be placed to reconstruct exposure if such an event occurs.

References

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2. A. J. Stevens, S. Musolino, and M. Harrison, RHIC SAD Appendix 1; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app01.pdf
3. A.J. Stevens, RHIC/DET Note 5, June 1992: RHIC SAD Appendix 37; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app37.pdf
4. A.J. Stevens, RHIC/DET 23, August 1997; RHIC SAD Appendix 39; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app39.pdf
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7. J. Donald Cossairt and Kamran, FERMILAB-PUB-08-244-ESH.
8. See Table 6 of Reference 7.
9. A Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets", FNAL, 1975.
10. See for example A.J. Stevens, AD/RHIC/RD-83, Dec. 1994, RHIC SAD Appendix 17; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app17.pdf

11. G.R. Stevenson, “Dose Equivalent per Star in Hadron Cascade Calculations”, CERN Report TIS-RP/173 (1988).
12. K. Tesch and H. Dinter, “Estimation of Radiation Fields at High Energy Proton Accelerators”, Radiation Protection Dosimetry” Vol 15 no.2 pp87-107 (1986).
13. RSC minutes of Jan. 31, 2002, http://www.c-ad.bnl.gov/esfd/RSC/Minutes/01_31_02%20minutes.pdf
14. MCNPX version 2.7C was used for the calculations in this report. D. PELOWITZ (ed.), “MCNPX User’s Manual”, Version 2.7.0, Los Alamos National Laboratory, LA-CP-11-00438 (2011).
15. The Monte Carlo Program MARS does transport of charged particles through magnetic fields and could be used to check this factor.
16. A.J. Stevens memorandum of May 2, 1995, “ Verification of Sufficiency of Backwall Thickness at 6 O’clock”. http://www.c-ad.bnl.gov/esfd/RSC/Memos/Blackwall_5_2_95.pdf
17. There is a small mis-match in definition related to other hadrons besides neutrons, this is approximately 5%.
18. Kin Yip private communication.
19. See for example, C. HOa, N.V. Mokhov,, F Cerutti, and A Ferrari, LHC Project Note 411, Feb. 26, 2008; M. Huhtinen and N.V. Mokhov, FERMILAB-FN-697, Aug. 2000.
20. The dose is higher using DX since the factor of 1.3 would not apply for scrapping on the beam pipe, although the resultant numbers are close.
21. The conversion factor uses neutron energy greater than 20 MeV. This is convenient since this is the energy used to calculate the potential soil activation.
22. The MCNPX result is multiplied by 1.5 based on the MARS simulation. This “fudge” factor should be understood better, but is used here in a conservative manner.

Appendix

The simple geometry used in the MCNPX calculations:

DX Magnet

Rmin (cm)	Rmax	Density (g/cc)	Material
0	9.8	0	Vacuum
9.8	10.	7.8	Steel
10.	13.2	1.75	phenolic
13.2	38.	7.8	Steel (cold mass)
38.	60.	0.156	steel

Stainless Steel Beam Pipe (130 cm long)

Rmin	Rmax	Density (g/cc)	Material
0	6.35	0	vacuum
6.35	6.62	7.8	steel

Tunnel

R min	Rmax	Density (g/cc)	Material
0	330.	0	vacuum
330	365	2.35	concrete
365	1200	1.8	soil

STAR Magnet Poles (65cm long)

Rmin	Rmax	Density (g/cc)	Material
0	95.	0.	vacuum
95	340.	7.8	Steel

STAR Magnet (620 cm long)

Rmin	Rmax	Density (g/cc)	Material
0	264	0	Vacuum
264	300	1.35	Aluminum
300	340	6.0	steel

STAR Shield Wall

Rmin	Rmax	Density (g/cc)	Material
0	1200.	0	vacuum
1200.	1365.	2.35	Light concrete