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Memo

date: *April 19, 2013*

to: *RSC*

from: *D. Beavis*

subject: *MCI Evaluations at 2, 4, 6, 8, 10, and 12 O'clock IRs*

Preamble:
This is an incomplete draft that is being released and archived to provide a partial basis for making a decision to allow RHIC beam per ring to be increased to $3*10^{13}$ protons per ring at 255 GeV. The memo that discusses the entire facility will refer to this draft.

Introduction

The Maximum Credible Incident (MCI) for beam faults has been examined at each of the Intersection Regions (IR) at RHIC. The upgrade to increase the beam intensity to $5*10^{13}$ protons per ring is in progress. A similar but smaller intensity increase will also occur for ions, so that the maximum exposure in an MCI will be from a proton beam fault. There is also a desire to increase the energy from 250 GeV to 300 GeV. This will be examined at the six O'clock IR and demonstrate how the higher energy impacts the potential dose. The main issue for an increase in proton beam energy is the substantial increase in the muon leakage out the side shields known as the muon lobes. The muons generated at several locations have the potential to reach the site boundary. The muon calculations are on-going and will not be presented in this report. **The increase in beam energy for routine operations to 300 GeV will need to wait till the completion of the analysis. It will be concluded that the intensity increase to $5*10^{13}$ protons per ring can be recommended for approval.** There were sufficient margins in the RHIC Project calculations that the increased intensity less exposure than presented in the initial project reports for the IR locations. In addition, better tools are being used that reduce some of the systematic overestimates of dose in the forward direction. However, it should be pointed out that there is much less conservatism in the numbers presented in this report when compared to the RHIC Project reports.

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

[1] M. Harrison and A.J. Stevens, AD/RHIC/RD-52, Jan. 1993; RHIC SAD Appendix 8; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app08.pdf

shield wall the beam loss in an MCI determines the shielding thickness when coupled to the exposure criteria. The maximum beam loss assumption was that the entire beam in a ring could be lost 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 160 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 and all shielding was designed by the RHIC Project based on these criteria.

An RSC subcommittee met to establish[3] 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 limit the exposure from an MCI to 100 mrem. Areas where the dose is higher but the occupancy is low, such as the RHIC berm, will have the work planning to examine if the workers will be near a weak location. Any area in which the dose can exceed 1000 mrem in an MCI will be modified to prevent access.

It is important to note that all areas inside the perimeter of the RHIC facility are controlled areas. Based on the terminology used by the RHIC Project all personnel inside are classed as "Radiation Workers". For several years building 1005 and the road over the berm have been upgraded to being Controlled Areas in anticipation of the intensity upgrade.

New Estimate of Potential Dose from an MCI at RHIC IRs

The calculations for the IRs have been conducted by D. Beavis and K. Yip using MCNPX[4]. Neutron weighting factors have been incorporated into the calculations using the values in MCNPX or provided by Cossairt and Kamran[5]. The produced particles have been tracked through the materials and geometry. The equivalent dose can be estimated by tracking all particles at all energies through the shielding and then calculating the equivalent dose. Outside the thick shields used at the IRs the dose is dominated by neutrons. It requires substantial computer time to calculate thick shields with the tracking of all the low energy particles. However, the high energy particles become in equilibrium with the low energy portion of the spectrum since the high-energy cross sections are smaller. The high-energy particles are continuing to repopulate the low energy portion of the spectrum as it is absorbed. Therefore, one only needs to calculate the high energy component and then deduce the total dose using fluence-to-dose conversion factors. It will be shown in several calculations that the results obtained in this fashion are accurate[6].

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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] RSC Minutes of August 25, 2009; http://www.c-ad.bnl.gov/esfd/RSC/Minutes/8_25_09Minutes.pdf

[4] MCNPX version 2.7C for some of the analysis. D. PELOWITZ (ed.), "MCNPX User's Manual", Version 2.7.0, Los Alamos National Laboratory, LA-CP-11-00438 (2011).

[5] J. Donald Cossairt and Kamran, FERMILAB-PUB-08-244-ESH.

[6] It is important that this technique is not used where the inherent assumptions are not satisfied.

The estimation of equivalent dose outside the shields will depend on details of how the proton beam is lost, the geometry and composition of the targeted materials and shielding, and the overall geometric layout. The proton beam will be assumed to be scrapped inside the various magnets and beam pipes along the transport near or inside the IR. The location which produces the highest dose outside the shielding is identified using the loss assumptions of the RHIC Project. At most IRs the DX magnet produces the highest radiation levels outside the shielding. However, it is possible the high beta quads which are assume to have twice the beam loss as DX magnets can create the largest losses at **which IRs if any**.

The beam is scrapped inside the machine components with a small angle into the beam pipe of typically a few milli-radians. The equivalent dose outside the shielding is not sensitive to this angle. The MCNPX version used does not account for effects of the magnetic field. The potential impact the magnetic field has on the strength of the source created by scrapping a proton beam in a DX magnet was examined by calculating the dose with and without a magnetic field using the MARS[7] code and then comparing the results to MCNPX. The comparison was conducted by K. Kip[8]. It was concluded that there was essentially no difference with and without the magnetic field for the peak of the distribution. The dose distribution almost unchanged in this azimuthally integrated distribution.

The geometry in most cases will be approximated with the dimensions at the mid-plane and then made azimuthally symmetric about the beam axis. In many cases this is a conservative approximation and the use of symmetry makes reduces the calculation time substantially. As in any approximation one must ensure that the assumptions are appropriate.

Some problems cannot use the various approximation techniques discussed above. In that case the analysis must use the full three dimensional representation and full energy spectrum to arrive at an accurate result. On the other hand there are often appropriate means to get an initial evaluation of the problem before beginning detailed simulations.

6 O'clock IR—STAR

The STAR IR will be the first IR to be discussed. The shield wall has already been examined and documented in a previous report[9]. The report used the techniques discussed above for the dose estimation external to the STAR shield wall. That report identified several factors which account for MCNPX calculation predicting lower dose per proton outside the shield wall. Some of the reduction was conjectured to be caused by the issue that CASIM[10] Monte Carlo code had too much radiation in the forward direction. The RHIC Project calculations for outside the wall

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[7] MARS code, N. Mokhov, "MARS Code Developments, Benchmarking, and Applications", FERMILAB-Con_00/066, March 2000; http://lss.fnal.gov/archive/2000/conf/Conf-00-066.pdf

[8] K. Yip EP&S Division Note 161; http://www.c-ad.bnl.gov/esfd/ES&F%20Tech%20Notes/169.pdf

[9] D. Beavis Memorandum, " Shielding Wall Requirements at STAR", April 20, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Memos/STAR_wall.pdf

[10] Casim code reference, A Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets", FNAL, 1975.

estimated[11] a dose of 280 mrem from an MCI on DX. The present calculations predict 45 mrem for the same beam intensity. For a beam of $5*10^{13}$ protons ate 250 GeV the present analysis predicts 130 mrem for an MCI on the IR end of the DX magnet.

The dose outside the STAR shield wall was estimated to be 130 mrem in an MCI for 250 GeV protons with a half the $5*10^{13}$ protons striking the DX magnet at the downstream end. The 130 mrem has a factor of 1.3 that the RHIC Project used for the maximum asymmetry for enhanced radiation caused by the DX magnetic field. A factor of 1.5 was also incorporated. This factor was the ratio of the dose from MARS verses MCNPX in a simple target/tunnel geometry[12]. It is not known which code is more accurate so at the time of that report the factor of 1.5 was incorporated to be more conservative.

The RSC reviewed[13] the calculation on May 9, 2012 and accepted the techniques and the results. Additional issues at the IR were noted and RSC requested that they be examined. These include the dose out the end walls and the potential dose at the fence lines around the IR.

Two of the figures from the report on the STAR IR will be reproduced in this report to add clarity to the discussion. The approximated geometry is shown in Figure 1. The width of the hall

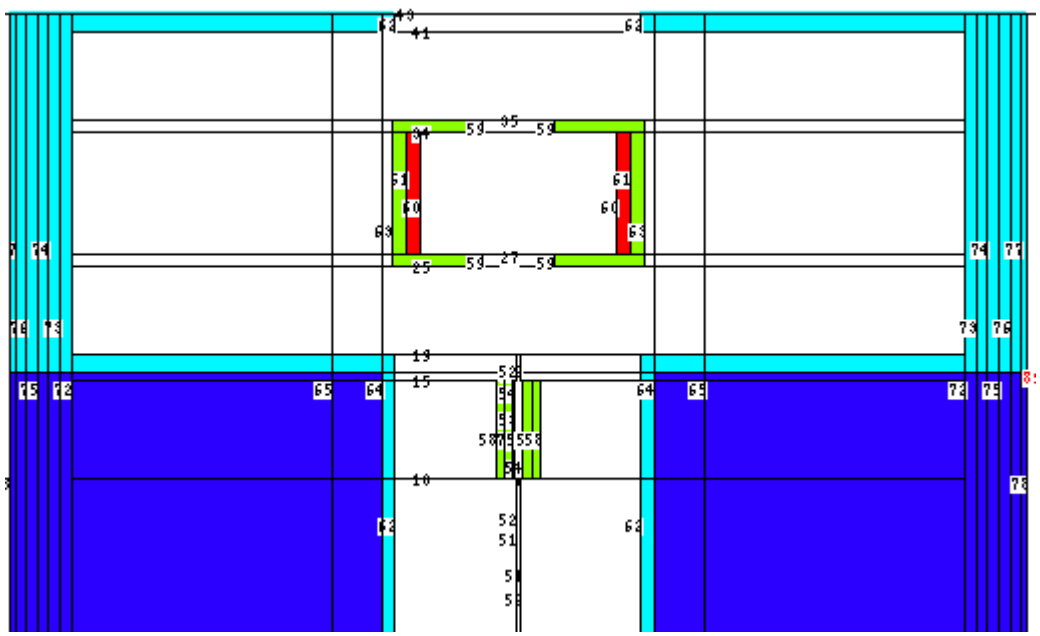

Figure 1: Layout of DX, STAR, and shielding used in MCNPX simulation.

[11] A. Stevens, "Verification of the Sufficiency of the Backwall Thickness at 6 O'clock", May 2, 1996; http://www.c-ad.bnl.gov/esfd/RSC/Memos/Blackwall_5_2_95.pdf

[12] K. Yip, "Comparison between MCNPX and MARS in equivalent dose outside a tunnel geometry", May 23, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Memos/kin_MCNPX_5_23_12.pdf

[13] RSC Minutes of May 9, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Minutes/05_09_12Minutes.pdf

was chosen to match the distance from the beam line to the wall on the outside. The neutron fluence was then tallied at different depths along the wall for several above sources. The neutron fluence for neutrons with energy greater than 20 MeV is shown in Figure 2 for 1 meter z-bins on the outside surface of the shield wall.

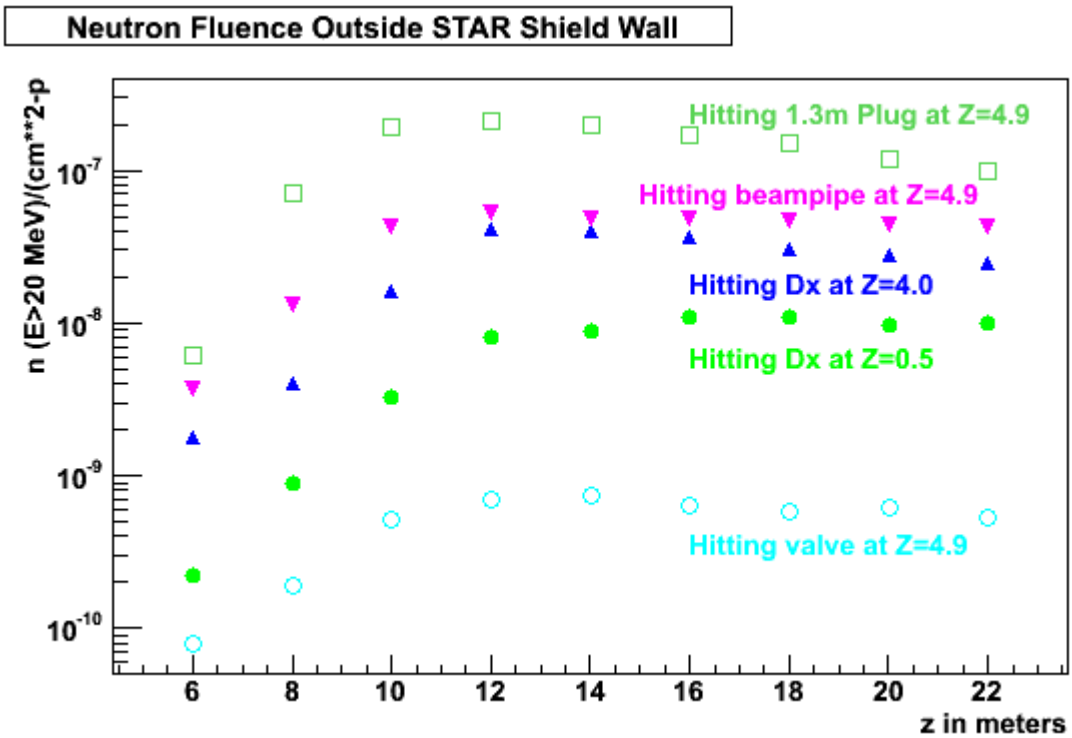

Figure 2: Neutron fluence with energy greater than 20 MeV penetrating the 5.5 feet light concrete shield wall at STAR. Several beam scrapping locations are assumed. The IR retaining walls are at z=6.2 meters and Z= 22.4 meters.

The distribution can be compared to the Figure 2 in the RHIC Report[11]. The distribution is similar but the original report took into account the change in the walls at the two ends of the IR. It was noted that the shield wall at the ends is only three feet thick from floor to ceiling. However, the lower portion of the wall is shadowed by labyrinth shielding and the main shield wall also shadows the wall. This thin shield was not a concern and the dose should be less than 100 mrem[14]. The same conclusion applies to the new calculation but has not been repeated. In addition there is a strip of three foot shielding across the top of the main shield wall. This does not have any material shadow it. The potential dose outside this area near the ceiling can be estimated by increasing the dose by 4.7 [exp(2.5*.62)] to account for the 2.5 feet less concrete. Thus the peak dose could be 611 mrem.

[14] A.J. Stevens memorandum of May 2, 1995; " Verification of Sufficiency of Backwall Thickness at 6 O'clock"; http://www.cad.bnl.gov/esfd/RSC/Memos/Blackwall_5_2_95.pdf

There are a series of cable penetrations[15] high on the west side of the STAR shield wall. The estimate for the worst case is 860 mrem in an MCI considered by the project at that time. These penetrations are high. The dose rate for an MCI at the upgraded intensity should be lower due to the factors discussed in the footnote 9 on the STAR shield wall. The labyrinths were evaluated[16] to have an attenuation of better than 10^{-3}. The roof section of the labyrinths was shown[17] to be sufficient so that the labyrinth formula was appropriate. The calculations have not been repeated but all these locations should have lower dose with the upgraded intensity due to the conservative nature of the original estimates.

Elevated work near the STAR shield wall is not allowed with beam operations to avoid having personnel get too close to the weak locations.

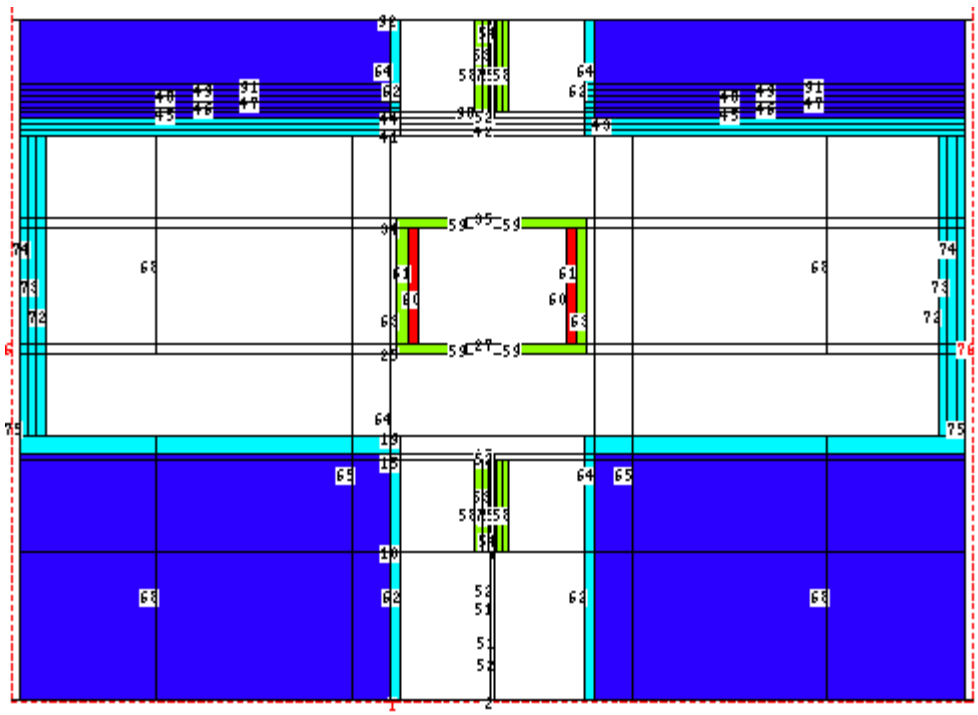

Figure 3: The MCNPX Model used to calculate the dose outside the south IR wall and the end wall.

A model similar to that used for the assembly area wall was used to determine the dose outside the south side wall and the end wall of the STAR IR. The distance[18] to the inside of the south side wall is 16 meters. The neutron fluence outside the three feet of light concrete as a function of Z is shown in Figure 4. The figure can be seen to be very similar to figure 2. For the 5.5 thick

[15] http://www.c-ad.bnl.gov/esfd/RSC/Memos/MemoAttachments/CablePenetrations_JUNE95.pdf

[16] A.J. Stevens memorandum of April 17, 1995; "Labyrinths in Proposed STAR Shield Enclosure"; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app38.pdf

[17] A.J. Stevens memorandum of April 19, 1995, "Roof Thickness in the STAR Enclosure"; http://www.c-ad.bnl.gov/esfd/RSC/Memos/MemoAttachments/RoofThicknessesSTAR_APRIL95.pdf

[18] Based on drawing A300150004. The side wall is three feet thick and the roof is 3.75 feet thick. The end wall is three feet thick.

concrete wall for the north side of STAR. The highest neutron fluence out the side wall concrete is $1.34*10^7$ n/cm^2 with energy greater than 20 MeV. For a fault of $2.5*10^{13}$ protons at 250 GeV on the end of DX the dose would[19] be 75 mrem. This is inside the STAR IR fence. In addition there is at least six feet of soil that need to be penetrated and the fence line is at a transverse distance of 29.3 meters. Adjusting for these factors provided for an estimated dose at the fence line of 7 mrem. This is at an elevation of 28 feet above the ground. A direct ray from DX to the top of the fence would have 29 feet of soil in the path. The area outside the IR fence is a Controlled Area. It is concluded that the dose to personnel outside the fence is sufficiently low.

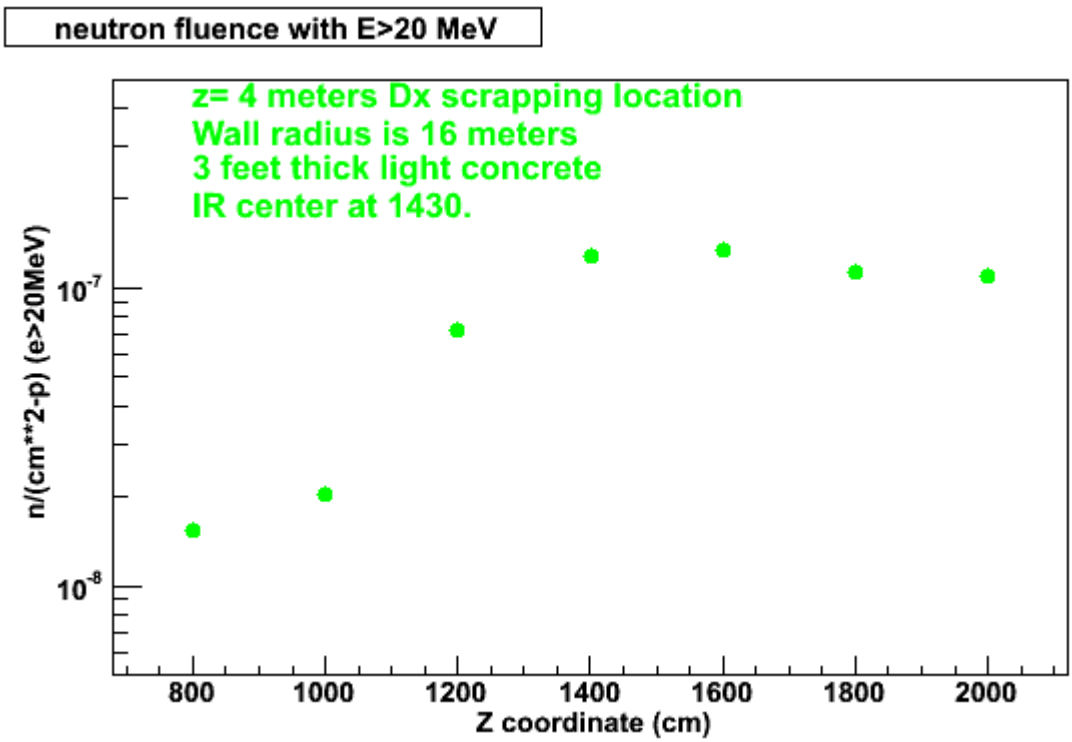

Figure 4: The neutron fluence with energy greater than 20 MeVoutside of the concrete side wall.

The end wall will have higher fluence outside the concrete than the side wall. The neutron fluence with energy greater than 20 MeV is shown in Figure 5 as a function of radius. The green circles show the calculation with the magnet in place and the blue squares with the magnet removed. There is a factor of 20 or more increase at intermediate radii if the magnet is removed. The increase in small radii with the magnet in place is due to the holes in each endcap. The STAR EMC is not in the model. The overall distribution agrees with the conclusions[20] of the RHIC Project. However, the absolute magnitude has a large disagreement. Both the Footnote 20 and this report agree that the magnet/no magnet fluence are the same at essentially 11-12 meters of transverse distance. The present calculation predicts $2.6*10^{-14}$ rem/p while the RHIC Project had $4*10^{-13}$ rem/p at 11 meters transverse distance.

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[19] The fluence to dose conversion factor of $6.5*10^{-5}$ mrem/(n/cm^2) for E> 20 MeV has been used.

[20] A.J. Stevens, "End Wall Dose Estimates at 6 O'clock", June 1995; http://www.c-ad.bnl.gov/esfd/RSC/Memos/MemoAttachments/Endwalldose_JUN95.pdf

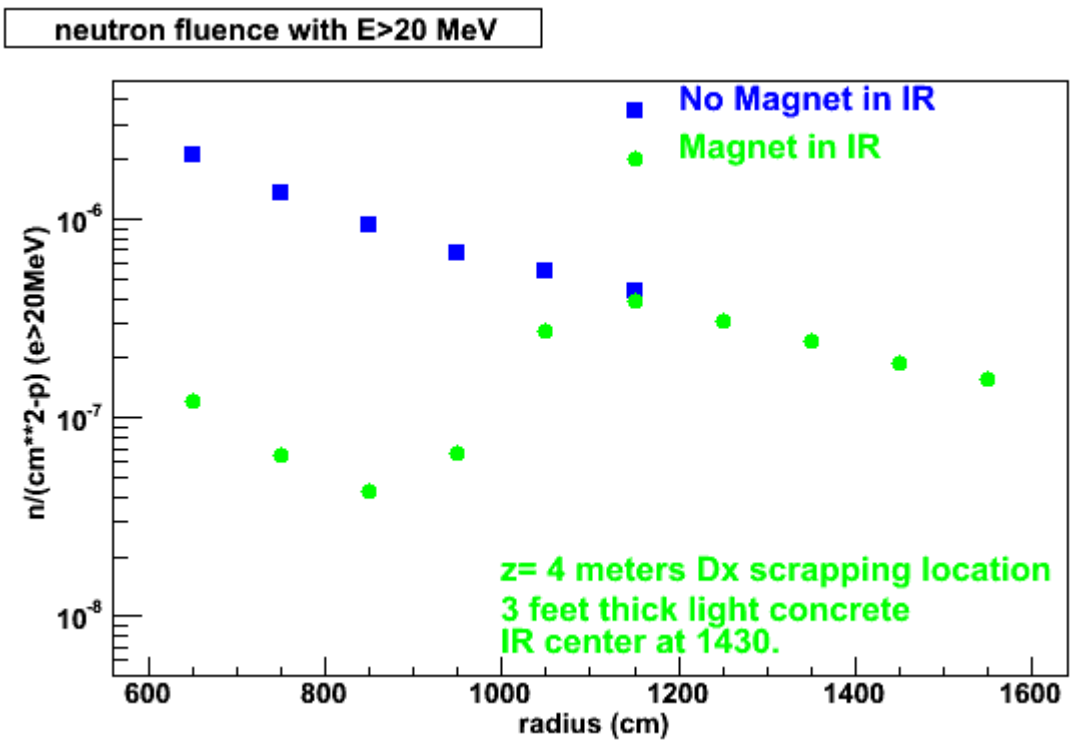

Figure 5: The neutron fluence after the 3 feet of light concrete end wall as a function of radius. The data points show with the STAR magnet in place (green circles) and with the magnet removed (blue squares).

The dose in an MCI at a transverse distance of 7.5 meters is estimated to be 100 mrem based on the MCNPX calculations out the end wall. This is directly over the beam and has no soil[21] shielding. With the magnet removed the dose would be 2200 mrem. This area is enclosed in a fenced area with access not allowed during beam operations.

The soil outside the end walls slopes down to lower elevation on the inside of the ring than the outside. The soil elevation decreases to 79 feet before the side wall shielding. This allows beam to go out the end wall without hitting soil behind the end wall and clear the side concrete shield. The transverse distance is approximately 12 meters. Using the calculations above an MCI could produce 650 mrem just outside the end wall. The locations that can be irradiated without soil are the top of the DAQ/control rooms, the second floor of the mechanical equipment room, and the cooling tower area. The equipment room has twice the distance as the end wall so that a reduction of a factor of four is expected. With the magnet removed the dose rate could increase a factor of two to 375 mrem. The top of the DAQ/control rooms could see doses of between 300-450 mrem depending on the location. With the magnet removed an increase of less than a factor of two would occur. Finally, the area around the cooling tower is farther than the equipment room from the source. The ground elevation at the cooling tower is approximately 64 feet. The rays from the end of DX to the cooling tower must cross through berm contours that are at least

[21] See Figure 1 of footnote 20.

at an elevation of 86 feet. This would place rays without soil shielding well above the top of the cooling tower.

The dose from an MCI has been examined for building 1006B. The highest dose occurs near the north-west corner if the magnet is not in the IR. The dose is estimated to be 250 mrem. With the magnet in place the highest dose occurs along the east wall and is approximately 60 mrem at the highest. Rough estimates of the soil shielding were obtained from a topo map of the area.

4 O'clock IR—RF

The intersection region at 4 O'clock is utilized by the RHIC RF systems. The external shielding is design to protect personnel from the potential x-rays that can be generated by the RF cavities and from potential beam losses. The protection of personnel from MCI beam losses established the shielding design and the fenced perimeter. The overall site layout for the 4 O'clock IR is provided by drawing 904-06-01-site, and shown Figure 6 below. An enlargement of the shielded tunnel is shown in Figure 8. The techniques used for the STAR area will be used to examine the 4 O'clock shielding. The main features of the shield and barriers are:

1. A nearly uniformly thick five foot light concrete wall on the outside of the ring.
2. A nearly uniform four-foot thick roof.
3. A wall with two large perpendicular shield wall on the inside of the ring which serve as port to install large items in this section of the RHIC ring.
4. The fence on the outside of the ring is at 60 feet and 120 feet from the shield wall. The fence on the inner ring is at distances of 100, 68, and 26 feet from the line defined by the outside shielding on the north side of the IP.

The MCNPX model for the outside shield wall is shown in Figure 9. Only the two DX magnets and a beam pipe are included inside the shielding. The dose distribution of high energy neutrons are plotted in Figure 10 as a function of z for the outside surface of the shield wall when the beam strikes the DX magnet at z=90 cm and 400 cm. The distribution of striking the DX magnet at 90 cm has a higher peak and falls off faster in the forward direction then the distribution for beam striking the magnet at 400cm. This is similar to the discussion[22] of the sparse and thin lattice given by the RHIC Project for losses in AtR for two different mass distributions along the beam transport. The second DX magnet can be seen to affect the distribution due to the scattering of the forward radiation. The peak for the z=90 distribution is $8.5*10^{-7}$ n/cm^2 which would correspond to a dose of 1400 mrem at contact with the wall. At a transverse distance of 60 feet from the shielding this would correspond[23] to 55 mrem. The IR fence is a barrier that keeps personnel at least 60 feet from the shielding on the outside and for the non berm region the fence is 120 feet away.

[22] Ref ATR note

[23] The result for the shield wall has been scaled by $1/r^2$ to 22.8 meters. The fence has no location on the dose peak for either DX magnet with either beam direction. The dose where a person could stand at a fence is lower than this number.

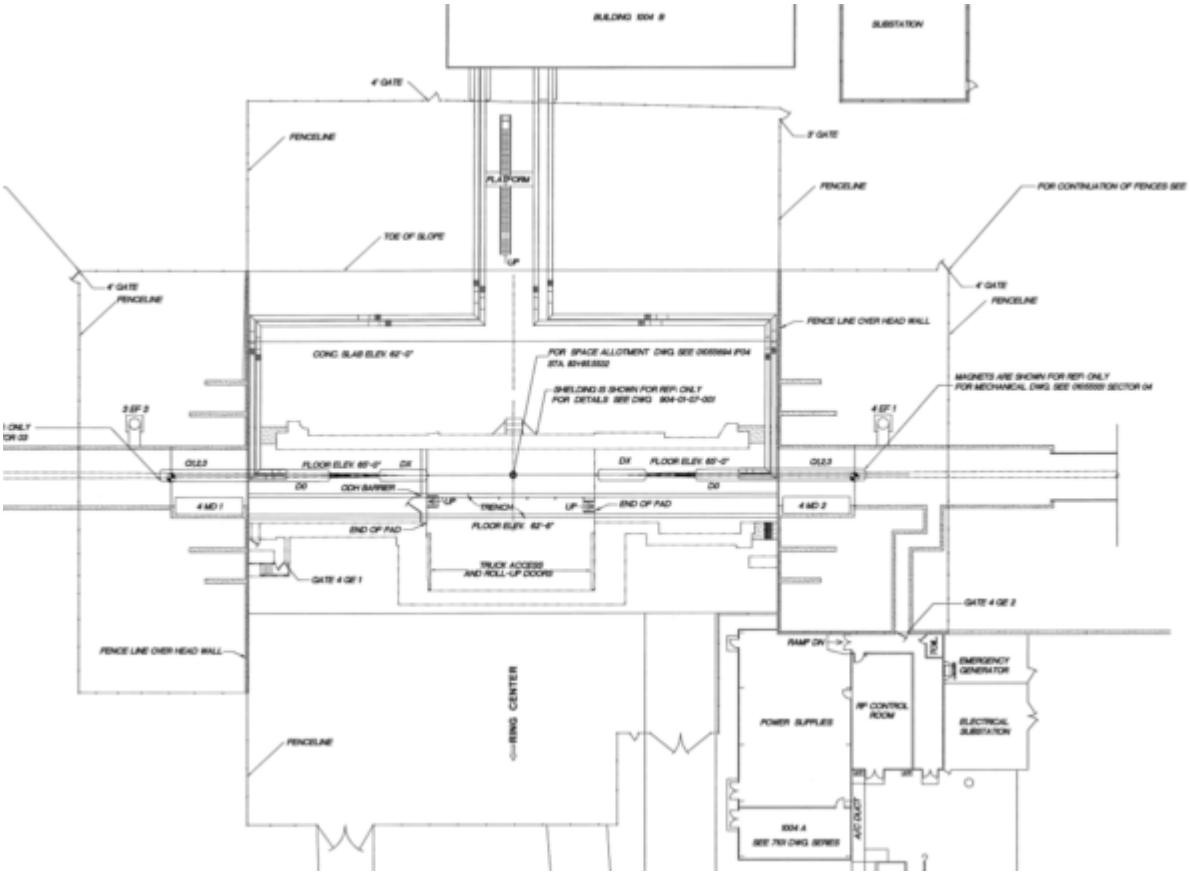

Figure 6: Site layout at 4 O'clock. The fences, shielding and support building are shown.

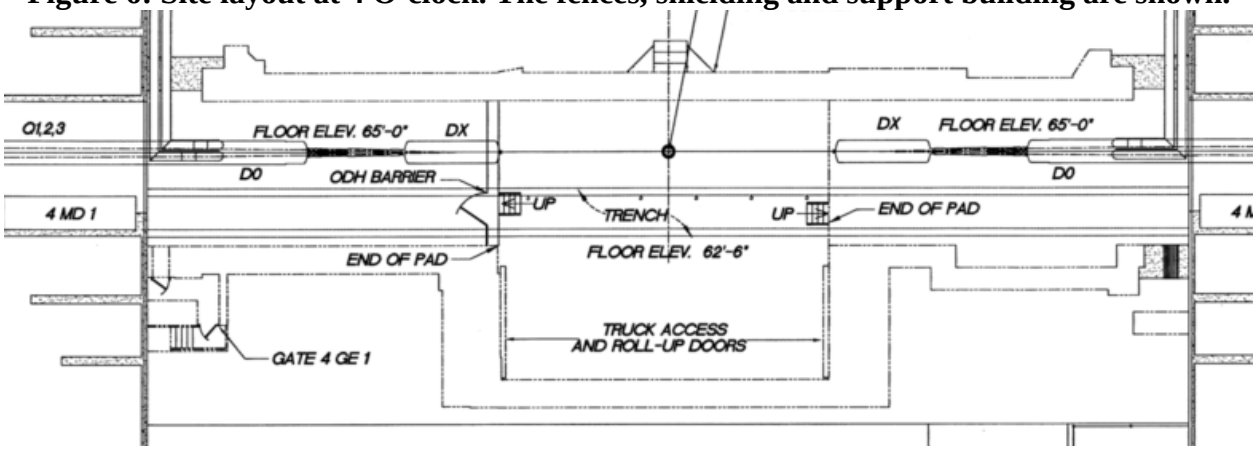

Figure 7: Enlargement of the shielding walls of IR4.

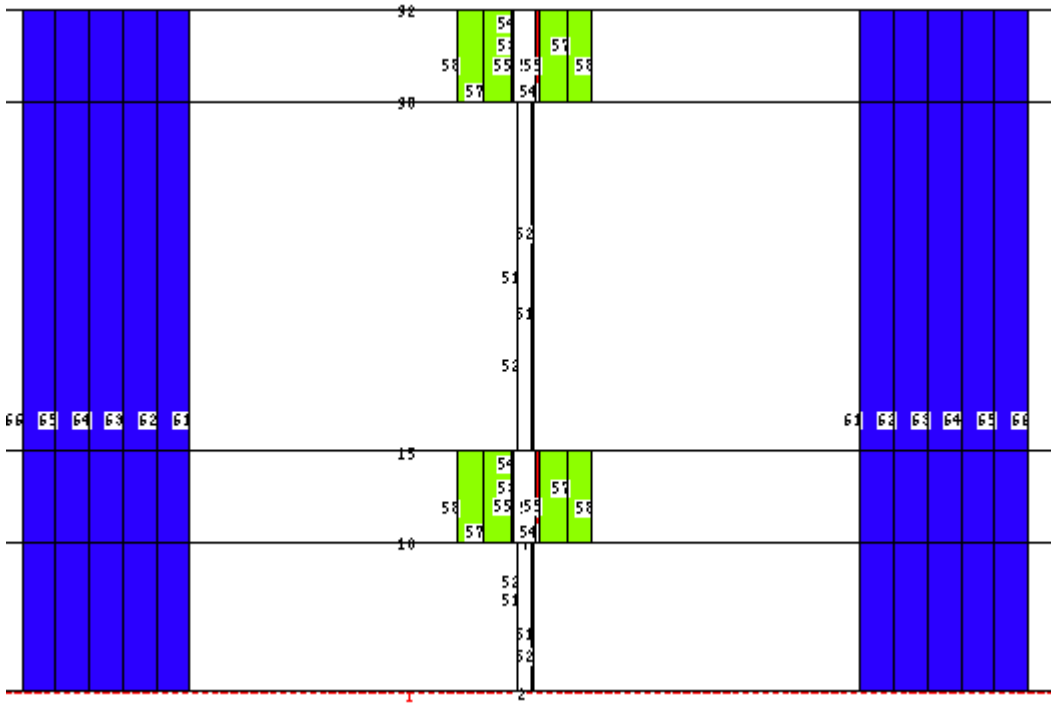

Figure 8: The azimuthal approximation of the outside wall at 4 O'clock. The shield wall is five foot thick and constructed of light concrete. The DX magnets are modeled the same as used for the STAR IR.

The neutron fluence as a function of z is shown in Figure 10 for beam striking the DX magnet at z=400cm. The dose in contact with the shield wall (r=450cm), 500 cm away from the shield wall (r=950cm) and 1000cm from the shield wall (r=1450cm) are shown. The details of the neutron fluence are smeared by the dispersion of the emission angles as the radius increases. The dose at the corner of the fence can be estimated from each DX. A maximum dose of 50 mrem occurs at the fence corner where the fence starts to change transverse distance from the beam. The dose from hitting the closer DX magnet is nearly the same, independent of which end is hit. The DX magnet that is farther away would produce 35 mrem from the facing the IP. If twice the beam were to strike Q2 the level at the fence corner would be smaller. This area near the fence is uncontrolled. The dose in an MCI exceeds the normal limits[24] applied for uncontrolled area by the C-AD RSC. That limit is normally 20 mrem. The dose does not exceed the limits of 160 mrem used by the RHIC Project.

The dose in the uncontrolled areas near the fence can be reduced to less than 20 mrem in an MCI. Three means to reduce dose are:

- Add shadow blocks
- Define a new sections of Controlled Area to keep personnel away from the fence (both side of the berm) till they are shadowed by the retaining wall at the end of the IR
- Conduct a more complete evaluation that may provide a lower estimate.

Small Controlled areas seem to be the most expedient.

[24] See the C-AD Shielding Policy.

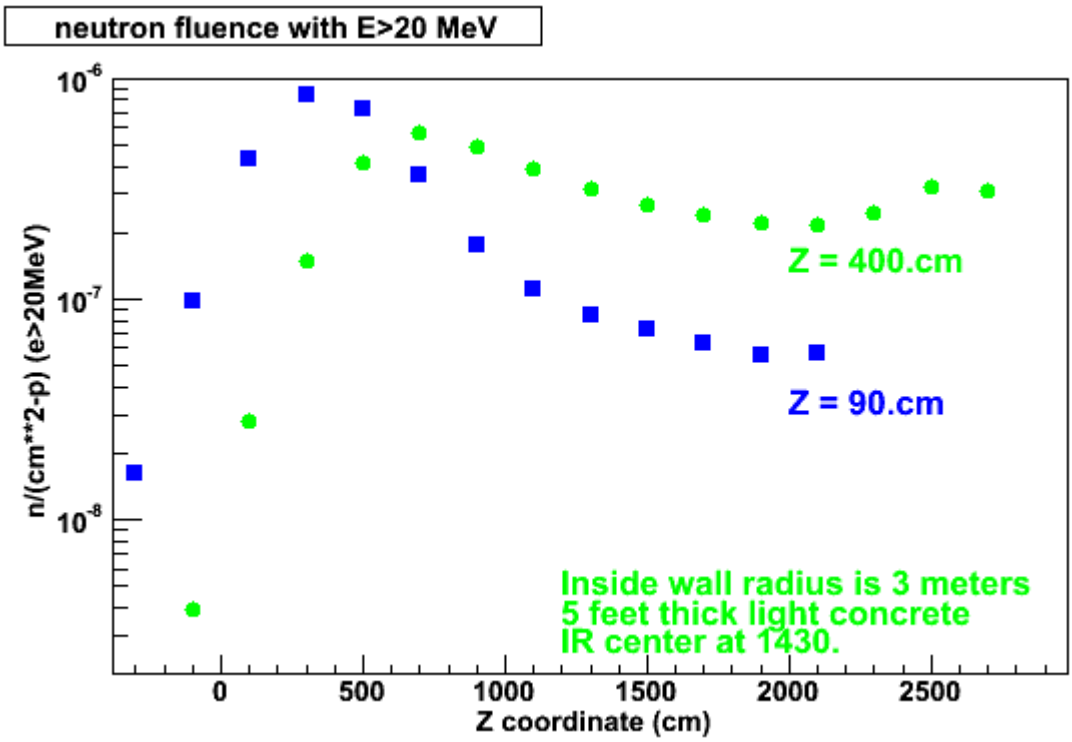

Figure 9: The fluence of neutrons with energy greater than 20 MeV as a function of z for beam striking the DX magnet. The magnet was hit at 90 cm and 400 cm.

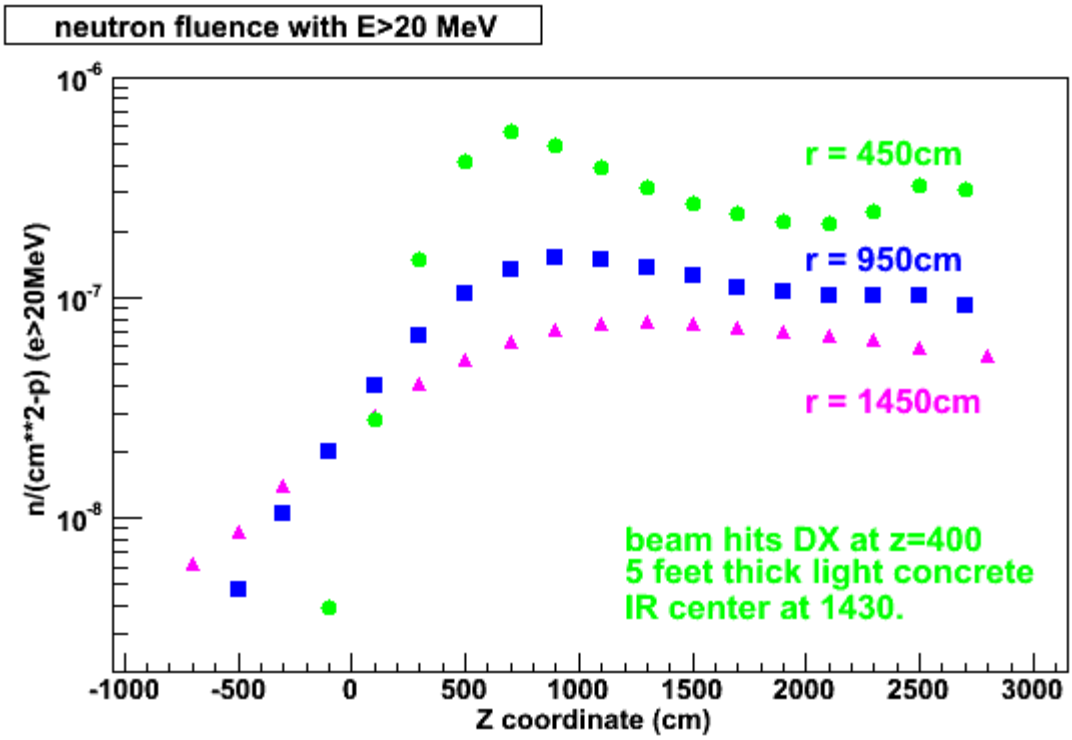

Figure 10: The neutron fluence (E>20 MeV) at three radii for beam striking DX at 400cm. The results at 450 cm are in contact with the shield wall on the outside of the ring. The other radii are still inside the IR fence on the outside of the ring.

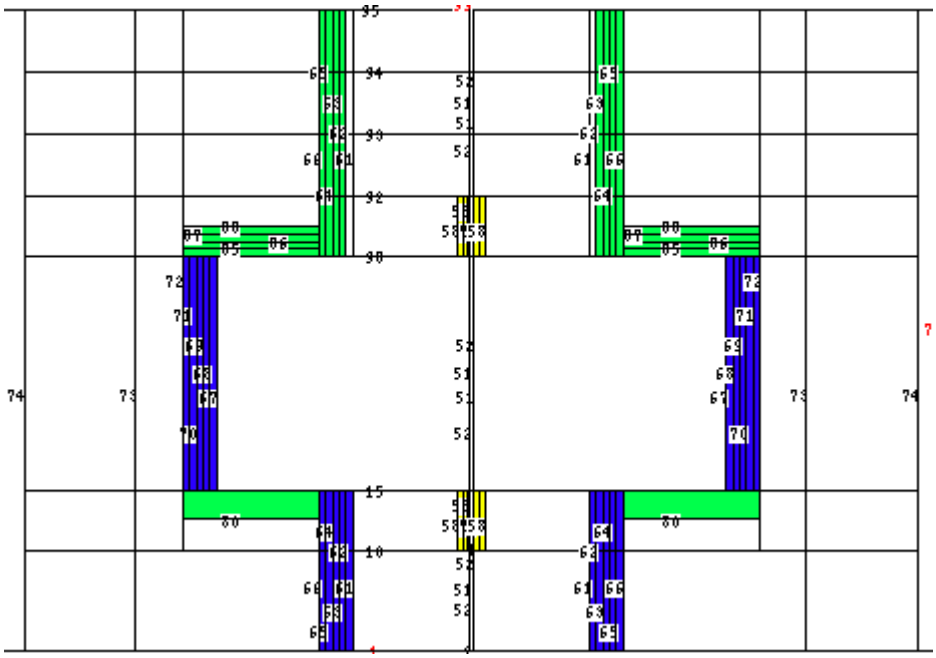

Figure 11: Model of the inside shielding of IR4. The green sections are heavy concrete and the blue sections are light concrete.

The MCNPX model for estimating the dose the inside of the ring is shown in Figure 11. The magnet portals in the wall are heavy concrete. The side wall on the 3 O'Clock side of the IR is heavy concrete. Some minor details that should not impact the conclusions have not been put into the model. The side wall between the portals is light concrete. The 250 GeV proton beam was made to hit the DX magnet at z=90cm. Figure 12 displays the neutron fluence as a function of z for surfaces 73 (r=15 m) and surface 74 (r=20m). Surface 73 is the closest that a person can approach the beam line on the outside of building 1004A, as can be seen in Figure 6 & 7. The dose for an MCI is 10 mrem at the fence near building 1004A. The neutron fluence from surface 74 can be used to estimate an MCI dose of 13 at the fence which is 37 meters from the beam line. It is possible that the peak of the dose is blocked by the portal wall on the 2 O'clock side. The results for the shield wall on the ring outside can be used to estimate the dose at the fence at 37 meters to be 20 mrem if the wall a uniform 5 feet of light concrete. The area outside the fence is a Controlled Area.

2 O'clock IR—CeCpop

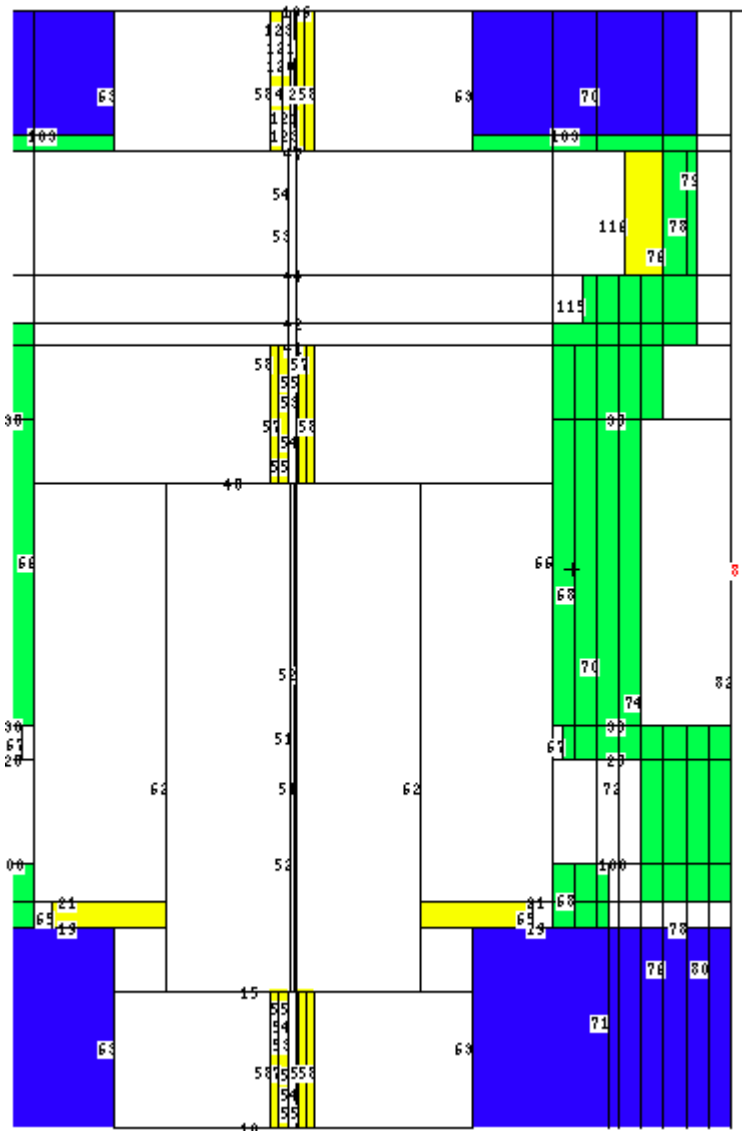

Figure: 2 O'clock IR model for MCNPX. The two DX magnets and the D0 on the 3 O'clock side are present. The model has rotation symmetry but has been shifted to show the IR wall the faces inside the ring.

PHENIX IR—8 O'clock

E-lens IR—10 O'clock

12 O'clock IR

Conclusions

References

1. D. Beavis memorandum, June 9, 2010; http://www.c-ad.bnl.gov/esfd/RSC/Memos/STAR_wall_upgrade.pdf
2. 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
3. RSC minutes of Jan. 31, 2002, http://www.c-ad.bnl.gov/esfd/RSC/Minutes/01_31_02%20minutes.pdf