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I. Description of Studies

Fault studies were performed on June 28 and 29, 2000 with the primary purpose of validating the shielding configurations at the 2 o'clock (BRAHMS), 6 o'clock (STAR) and 8 o'clock (PHENIX) regions. In addition, measurements were made at a "typical spot on the RHIC berm" (where the soil shield thickness is 13 ft.) and at one of the "worst case" vents which protrude from the berm.

In the most common study performed, the current in the D0 magnet upstream of the Interaction Region (IR) was lowered, so that an incoming Au bunch (or a few bunches) would strike the beam pipe at the position of DX. An initial "set up" study, performed at the 12 o'clock IR, displayed both the BPMs (Beam Position Monitors) and BLMs (Beam Loss Monitors) in this region as the fault was created. When the BLM indicated near total loss on the upstream DX, the BPM near the downstream showed no signal, confirming the fault. In the actual fault studies, the BPMs were sometimes displayed, but in general, reliance was placed on the BLM signal for verification that the fault was created at the position intended.[1]

In addition to the upstream DX faults, additional faults were created at 3 specific locations using dipole trim supplies. One of these locations was the blue ring Q3-Q2 region upstream of 8 o'clock. This location was chosen to "illuminate" the PHENIX South Side shield, where the PHENIX gas mixing house is located, because the DX magnet is actually downstream of the labyrinth leading to PASS gate 7GE1. The other two locations were chosen to create faults at positions, as mentioned above, corresponding to a typical berm configuration and one of the worst case vents. The vent case is interesting because it is believed to be the worst case location on the berm which is not fenced.

Calibrated HPI-1010 instruments were used to measure the dose at specific locations, primarily in and around the IRs, at the times the faults were being created. Particular attention was paid to *possible* or *suspected* weak spots in the shielding configurations. For example, at the 8 o'clock IR, measurements were made near the exit of the emergency escape labyrinth, near cracks between the permanent shield wall and the shield doors, and near cable penetrations in the shield wall base block. Since the shielding configurations (and most detectors) are asymmetric, measurements were needed in both the blue and yellow rings.

The 1010s were more sensitive than had been assumed in planning the fault studies. The instruments could clearly respond to dose levels (on the face of the meter) below 0.5 μrad, although variations on this most sensitive scale at this level become "sizable."[2] Readings below 0.5 μrad are reported below as *upper limits* of 0.5 μrad.

II. Shielding Design

The shielding was designed to a criteria of less than 250 mrem *dose equivalent* for a Design Basis Accident (DBA) fault of 1.14×10^{11} interacting Au ions at 100 GeV/u. In general, when some calculation indicated that this criteria might be approached, some change to the configuration was made to provide some modest safety factor, so that typically, the nominal DBA estimate was 60% of this or about 150 mrem for this assumed fault.

Several important points must be discussed. First, the shield design is for dose equivalent, not dose, the quantity measured. In comparing expectations from the design to the measurements, a quality factor of 5 is assumed.[3] Second, the measurements are performed at 8.62 GeV/u (kinetic energy), not 100 GeV/u. Here, the expectations assume $E^{0.8}$ scaling. Finally, it should be noted that in doing the shielding design, a careful search (in software!) is made for worst case conditions. In fault studies, one does what is possible – certainly 'throwing the beam' on DX is not exactly what was simulated.

Below the expectations will be scaled to dose per 10^8 ions. The scaling factor is:

$$\frac{10^8}{1.14\times10^{11}}\left(\frac{8.62}{100}\right)^{0.8}\left(\frac{1}{5}\right) = 2.47\times10^{-5}$$

III. Results from IR Studies

The nominal 150 mrem per DBA fault scales to 3.7 μrad per 10^8 ions, and the 250 mrem criteria to 6.2 μrad per 10^8 ions. The highest values of dose measured during the fault studies is shown in Table 1 below.[4]

Table 1 Maximum Measured Dose in μrad per 10^8 ions

Location	Blue Ring	Yellow Ring
PHENIX So. Side	< .15	—
PHENIX IR	< .47	< .04
BRAHMS IR	.08	.05
STAR IR	.45	.09

Table 2 shows the results of Table 1 scaled to the DBA fault discussed above.

Table 2 Max. Measured Dose Scaled to Dose Equivalent in mrem per DBA Fault

Location	Blue Ring	Yellow Ring
PHENIX So. Side	< 6.1	—
PHENIX IR	< 19	< 1.6
BRAHMS IR	3.2	2.0
STAR IR	18.2	3.6

The upper limits on the PHENIX So. Side measurement and the Yellow Ring PHENIX IR measurement correspond to the limit mentioned above, individual fault readings less than 0.5 μrad. The upper limit on the Blue Ring PHENIX IR fault is somewhat different. Every fault measurement was repeated at least 3 times. In one of the Blue Ring PHENIX IR faults, a non-repeatable measurement of 1 μrad was obtained. This single measurement is treated here as an upper limit. All other non-zero measurements were very consistent.

The maximum PHENIX IR measurement (i.e., the limit just explained) was obtained at a position immediately behind the shield wall that views cracks between the permanent shield wall and both of the plug doors. The maximum dose at the BRAHMS IR, in both the Blue and Yellow ring faults, was at a corner of the fast electronics hut that views one of the cable-ways that penetrate the shield wall. The maximum dose at the STAR IR, again in both the Blue and Yellow ring faults, was at the West Labyrinth entrance gate. For additional details concerning the positions measured, the reader is referred to the Fault Study Log in the MCR.

All the entries in Table 1 have a 10% systematic error which is the assumed calibration accuracy of the current transformers used in the beam intensity measurements.[5] The measurements are a factor of 8 or more below the design expectations, which indicates the shield was designed with an adequate margin of safety.

IV. Results from Berm Studies

(A) *Typical Location*

Prior to the fault study, a location on the berm had been selected which was in a 'regular tunnel' section and had very close to the nominal 13 ft. of earth shield. Here, the complexity of the shielding configuration at the IRs is not present, so that the geometry is simple, and the simulation straight-forward. Although the geometry is simple, the shielding medium (soil) is variable – as the water content of the soil increases, soil becomes more effective as a shield, due to both the density increase and the increased presence of hydrogen which is an effective neutron moderator. The porosity in the (sandy) soil is such that 2 cu. ft. of water will fill voids in about 6 cu. ft. of BNL soil.[6]

The value quoted in the RHIC project for a DBA fault 3 ft. above the height of the typical location on the berm was 57 mrem, which was the result of a CASIM estimate. Also shown in the comparison to the measurement is what is referred to as the "Tesch" result which is based primarily on measurements, and is intended to apply to "concrete or sand shields."[7]

Table 3 shows the results, scaled as before with a small correction to the berm height.

Table 3 Dose at Berm Height at 8.62 GeV/u

Source	μrad per 10^8 Au ions
CASIM (dry soil)	1.57 ± .28
Tesch (dry soil)	1.07 ± .19
Fault Study msmt.	0.36 ± .04

The errors shown are purely systematic. The errors on the estimates correspond to an assumed thickness uncertainty of 4 inches, whereas the error on the measurement is the systematic error on the beam intensity mentioned above. As indicated in the table, the soil density in the CASIM and Tesch estimates is assumed to be the dry soil value of 1.8 g/cc. As discussed above, the water content impacts the soil density. If the average amount of water were present,[6] the estimates would be lower by a factor of about 1.5

(B) *Vent*

Also prior to the fault study, a "worst case" RHIC vent had been selected wherein it was deemed possible to create a fault immediately in front of the vent entrance. The estimate of dose equivalent at the exit of the vent[8] had been made using a combination of LAHET/MCNP and CASIM.[9] Again, the same assumptions have been made in scaling the dose equivalent to measured dose, with the result shown in Table 4.[10]

Table 4 Dose Near Vent at 8.62 GeV/u

Source	μrad per 10^8 Au ions
LAHET/MCNP	$1.04 \pm .15$
Fault Study msmt.	$0.72 \pm .24$

Again, the errors shown are systematic.[11]

V. Conclusions and Acknowledgements

The primary purpose of fault studies is to make sure that no unpleasant surprises are encountered when comparing *measured faults* to *hypothetical faults* generated in a computer simulation. A considerable margin of safety exists between the results of the Intersection Region measurements reported here and the computer design which was, of course, intended to be conservative.

The "typical" berm measurement, in the simplest possible geometry, was also lower than had been estimated, although by a more modest amount. Although a part of this overestimate may well be due the particular conditions of the soil at the time of the measurement, a significant margin of safety would appear to exist as compensation for the possibility of extended periods of little rainfall.

The author would like to acknowledge the efforts of several people who were instrumental in the successful completion of these studies. Special thanks are due to Waldo MacKay who first ran simulations for the desired fault conditions and then set up the machine parameters and the fault verification process. Chuck Schaefer provided calibrated 1010 instruments, and made special tests prior to the fault studies indicating that they would provide the sensitivity required. The aid of the accelerator physics group, especially Dejan Trbojevic, in performing the measurements is also gratefully acknowledged, as is the aid of Mike Robles, Ken Boland, and Shelby Bowers who helped this author "in the field."

Footnotes/References

1. In one study (in the blue ring at the 6 o'clock IR) a scan of the D0-DX current was performed as radiation measurements were made near the STAR shield wall. The maximum radiation was found at the value obtained in the 12 o'clock set-up study, but the radiation at about ¾ of the nominal current was only slightly less.

2. The variations referred to are both meter-to-meter variations and variations on the dose measurement reported by various people. The difference between 'a flicker' on the meter and a 0.2 or 0.3 µrad reading is not significant.

3. This is a 'traditional' neutron quality factor assumption. It is the same assumption made for the chipmunks, and is based on measurements made at the AGS for protons at 24 GeV.

4. A 15% correction has been applied to all the data to allow for loss on the injection septum magnet.

5. L. Ahrens, private communication.

6. E Lessard, private communication. On average, soil at BNL has 10% water by volume, but this varies seasonally.

7. K. Tesch and H. Dinter, "Estimation of Radiation Fields at High Energy Proton Accelerators." Radiation Protection Dosimetry Vol. 15, No. 2, pp 89-107 (1986). The results from concrete are often applied to soil

8. The actual point of measurement was 1 ft. to the side of the vent protrusion, at an elevation 3 ft. above the local berm.

9. A.J. Stevens, "Improved Estimation of Dose Near Vent Exits in the RHIC Collider Tunnel," AD/RHIC/RD-122 (1998). At the position of the source relative to the vent entrance, CASIM contributes almost nothing. The estimate is therefore referred to in the text as a LAHET/MCNP estimate.

10. The vent was actually better (i.e., protruding at a point where the berm is higher) than the one analyzed in Ref. [8] above by an estimated factor of 1.6. The estimate scaled is the first point in Fig. 2 of Ref. [8] scaled down by 1.6. The systematic error on the LAHET/MCNP estimate in Table 3 is simply an assumed error in this scaling.

11. The large systematic error on this measurement relates to an uncertainty on beam remaining in the machine after creation of the faults. The only problem in this fault study of which this author is aware was imperfect communication between the control room and the field in this study. The systematic error on the measurement in Table 3 is assigned to encompass the *possibility* that 50% of the beam did not interact near the vent.