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## I. Introduction

This note describes estimates of the dose equivalent through penetrations the PHENIX shield wall due to hypothesized faults on the beam pipe near the 8 o'clock interaction region. Estimates were made using the Lahet Code System (LCS),[1] which has been previously described.[2] Previous estimates were made on a preliminary design of the shield wall and presented to the AGS/RHIC Radiation Safety Committee (RSC).[3] A brief summary of both those estimates and the results of the RSC meeting is given here since they form the motivation for the calculations reported in this note.

The shield wall consists of "permanent" sections on either side of a large movable shield wall door. Both the permanent sections and the door are constructed from light concrete blocks, the former being 5.5 ft. thick and the latter 5.0 ft. thick. The dose immediately behind these structures, estimated by CASIM runs where penetrations represented by cracks, etc. are ignored, for a Design Basis Accident fault is 250 mrem (5.5 ft. section) and 339 mrem (5.0 ft. door). To this is added dose estimates through penetrations obtained from LCS estimates. The LCS results presented to the RSC[3] were primarily focused on cracks (3/8" vertical and 1/4" horizontal) in the permanent section. The worst case found was 180 mrem.[4] Although this result remains valid, significant changes to the design compared to what had been estimated were noted at the RSC meeting, and additional calculations were requested. Specifically, the following areas were requested to be re-examined:

- The design of the emergency personnel exit labyrinth had changed compared to that estimated. The dose exterior to the labyrinth should be re-estimated [CK-PHENIX-02].

- The boundary between the movable shield door and the permanent section was observed to be different than what was estimated. A new estimate should be made [CK-PHENIX-03].

- A six foot thick base foundation (poured concrete) at floor level exists which had not been considered previously. Estimates are required for cable penetrations which exist in this foundation [CK-PHENIX-05] and for the penetration at the movable wall track [CK-PHENIX-06].

- The movable wall is designed to be crack-less vertically but not horizontally. Dose estimates through horizontal cracks in the movable wall must be made [CK-PHENIX-09].

Each of these are examined below. Two general aspects of the calculations are described here, the first of which is those parts of the PHENIX detector which were simulated. In all simulations the following components were present: beam pipe, muon ID steel, the muon magnet's piston, lamp-shade, and back plate, the central magnet pole piece, and the copper nose cone. In the simulations of dose through the penetrations in the base foundation (Sections V and VI below), the support rails were added to the geometry, since these are "viewed" through these penetrations. Neglected were the central magnet return yoke, tracking detectors, and support structures other than the rail system. In these simulations, the (1.3mm thick) steel warm beam pipe of the DX magnet was extended a somewhat arbitrary distance into the collision hall after which a 2.4 mm thick aluminum beam pipe beginning at a radius of 3.62 cm. was assumed. In the beam (Z) direction the geometry begins at the beginning of the DX magnet, and the collision hall begins at Z = 4.2m and is 18.59m long.

The second general aspect of the calculations that must be mentioned is the problem with statistical precision, which was also described earlier.[3] In the results below, individual computer "runs" of typically 1000 primary particles (100 GeV/c neutrons) each are made in a specific configuration, where a "configuration" means specific locations of both the primary interaction and the point (or points) where dose is being evaluated. These runs can take up to several days of execution time. Typically the results quoted below are some average value ± the rms. of several runs. However, in some cases the rms. can exceed the average. This is believed to be due to "rare" events in which a high energy hadron (most likely a neutron > 20 MeV) interacts in the shield wall very near the penetration.[5] Given available computer resources, this class of events is *undersampled*. An example from the cracks calculations of Ref. [3] is a particular configuration which gave a value of $3.7 \pm 7.5 \times 10^{-15}$ rem/primary based on 3 runs of 350 primaries per run. When the statistics were quadrupled the result "settled down" to $1.59 \pm 1.23 \times 10^{-15}$ rem/primary. There are simply not enough computer resources available to pursue each fluctuation in a similar manner. When these situations arise in the calculations reported here, the average value plus 1 rms. is quoted as an upper limit.

As mentioned above, a configuration consists of the interaction of a 100 GeV/c neutron at a specific location on the beam pipe together with point detectors at specific locations. The general procedure in the calculations, whose results are described below, was to move the location of the interaction point (in approximately 2.5m steps) until the maximum dose for each point detector in a given configuration is found. The output of the code is an estimate of rem per primary neutron. This is normalized to total dose equivalent by multiplying by $2.24 \times 10^{13}$ neutrons and then by 2. The first normalization factor corresponds to half the total beam at four times design intensity where an Au nucleus is simply treated as 197 neutrons. The factor of 2 is present because of the usual RHIC Project procedure of doubling the neutron quality factor.

## II. Labyrinth

As mentioned above, the design of the labyrinth had changed following calculations that had been done based on a preliminary design. In addition to having the current design in the simulation, the calculations here have greater statistical precision than the preliminary estimates. The first step in this sequence of calculations was to move the interaction point with the point detector position at the exit of the labyrinth **without the polyethylene door previously recommended.**[3] The configuration was then changed to include a 4 cm. thick polyethylene door with point detectors on either side. The final result for the detector on the outside of the door was $5.3 \pm 1.3 \times 10^{-16}$ rem/neutron. With the normalization described in the last section, the dose per DBA fault is:

**$24 \pm 6$ mrem/fault**

This is about a factor of 12 lower than the value obtained without the presence of the door. The actual best estimate should be increased slightly since the recommended door thickness[3] was 1.5" (3.8 cm.) rather than the 4 cm. in the simulation, but this is of no consequence.

## III. Horizontal Cracks in Movable Wall

Previous calculations have shown that the dose through horizontal cracks is very sensitive to the position of the crack relative to the accelerator mid-plane. Inspection of the design drawing shows one crack (interface between two blocks) to be about 52 cm. from the mid-plane and the next-nearest crack 104 cm. from the mid-plane. The simulation for this series of calculations assumed a 1/4" crack (which is significantly larger than expected) in the movable wall at these distances from the mid-plane. Point detectors were placed 15 cm. behind this crack at two locations along the crack in the Z direction.

The dose per primary neutron as a function of the source position is shown in Fig. 1. For the crack nearest the midplane,[6] the maximum is $1.16 \pm .06 \times 10^{-14}$ rem/neutron. With the canonical normalization this converts to 520 mrem per DBA fault. **Discounting this relative to whole body dose by a factor of 3 gives 173 mrem which, when added to the solid wall dose of 339 mrem, slightly exceeds the 500 mrem criteria.**

**However, as mentioned above, 1/4" is in all likelihood significantly larger than the crack that will exist in reality**. Previous calculations have shown the low energy dose to be proportional to the crack width. Clearly it will be important (in any event) for the as-built movable door to be carefully inspected. It should also be noted that the mid-plane is more than 17 ft. above the assembly room floor.

## IV. Movable Wall Interface

The interface between the movable wall and permanent wall sections is shown (in a highly schematic manner) in Fig. 2. In the previous estimate,[3] the gap at the back of the permanent section had been 0.5", the overlap 12", and the face of the permanent section had been concrete. In the estimate reported here, the steel face on the permanent section was added, the back gap was increased to 1.0", and the overlap decreased to 10".

An attempt was made to place two point detectors in this geometry. Both were placed 30 cm. from the end of the overlap in Z and 15 cm. in back of the permanent section (see Fig.2). One was on the mid-plane (in the vertical Y coordinate) and the second about 9 ft. below the mid-plane at the same X and Z coordinates. However, the statistics were so difficult here that the values for both positions were averaged.[7] Even with this averaging, the rms. was typically greater than the average as discussed in Section I above. Table I therefore shows the upper limits as defined in Section I vs. source position.

**Table 1. Upper Limit Estimate at Interface**

| Source Position (cm.) | Dose in rem/n (mean + 1σ) |
|---|---|
| 185 | $5.7 \times 10^{-16}$ |
| 600 | $2.1 \times 10^{-16}$ |
| 900 | $2.4 \times 10^{-16}$ |
| 1200 | $5.1 \times 10^{-16}$ |
| 1500 | $.62 \times 10^{-16}$ |

The highest value corresponds to the source on the beam pipe within (at the center of) DX. The estimate for this point must be increased by 1.3, which is a "typical" enhancement on the mid-plane due to effects of magnetic field.[8] With this additional increase to the normalization the dose per DBA fault becomes:

**< 33 mrem**

Although this must be considered whole body dose, it is not a problem.

## V. Cable Penetrations

As mentioned in the Introduction, the base of the PHENIX wall is a 6 ft. thick section of poured concrete. Through this base run two sets of cable penetrations which are empty holes in the simulation. One set is an array of 12 4 inch diameter holes rotated 12.5° from the normal (X direction in the LCS coordinate system) and the other an array of 18 4 inch holes rotated 16.5° from the normal. The individual holes are nominally 6 inches from their neighbors in arrays of 3 × 4 and 3 × 6 for the two sets respectively. As also mentioned in the Introduction, both the calculations in this Section and the next included simulation of the PHENIX rail system, which was modeled as 6.7 cm. thick steel bars with the height and pattern of the actual rail system.

For most of the runs, the dose was estimated at the positions of an array of 5 point detectors forming a line with 1m spacing in the X direction going away from the wall, with the closest detector centered on one of the holes in the 12 hole array. This was done in order to observe the fall off, which might be much slower for many holes than for a single one. Runs were made with the beam going in both directions to see if the effect of the angle of the holes could be observed.

The results from the point detector nearest the wall is shown in Fig. 3. In this system, the holes are at $Z \cong 1300$ cm. The effect of the source point passing from upstream to downstream of the holes can clearly be observed, but with the limited statistical precision achieved, the angular orientation of the holes is not apparent.[9]

With the normalization of Section I, the worst case of about $5.8 \times 10^{-16}$ rem/n corresponds to **26 mrem.**

The attempt to observe the fall off in X was also limited by statistics. The geometric mean (averaging over the different source positions) of the ratio of the nearest detector to the one farthest (4m) away was 2.4

## VI. Track Penetration

In the last series of calculations reported here, one of the penetrations representing the track for the movable shield wall door, was added to the geometry. The approximation for the track was a steel rail 24 cm. in the Z direction by 7.5 cm. in the Y direction centered in an aperture 48 cm. in the Z direction by 7.5 cm. in the Y direction, leaving two 12 cm. by 7.5 cm holes. The penetration is located about 2m from the cable penetrations, which were also present in the runs made here. **The worst case in these runs was 38 ± 7 mrem.**

## VII. Summary

A series of calculations were performed using the LAHET Code System to estimate dose through penetrations associated with the current PHENIX shield wall design. With a single exception, the estimates for "excess" dose through the planned penetrations are small, about 30 mrem for a Design Basis Accident fault (assuming × 2neutron QF), which is an order of magnitude below the "solid wall" dose estimate.

The exception is the horizontal crack closest to the mid-plane in the movable shield wall. This would also be well within the criteria if it is less than 1/8 inches wide. Inspection of the actual wall will, in any event, be important to ensure that the assumptions made concerning the sizes of penetrations are consistent with the as-built wall.

References/Footnotes

1. R.E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System," Los Alamos National Laboratory Report LA-UR-89-3014, September, 1989.

2. A.J. Stevens, "Comparison of CASIM with the LAHET Code System," AD/RHIC/RD-115, August, 1997.

3. Minutes of Meeting: Radiation Safety Committee, sub-committee, Subj.: "PHENIX Shield Wall Design," September 10, 1996 and October 20, 1997. (An attachment to these minutes is entitled "LAHET Calculations on PHENIX Shield Wall (Preliminary Design)").

4. Dose through narrow widely spaced cracks has a very limited transverse extent. The RSC has approved discounting such dose by a factor of 3 relative to whole body dose. The LCS result for cracks in the 5.5 ft. is therefore considered to be 60 mrem "effective dose equivalent."

5. This is precisely the "component" that had been previously estimated, within the confines of a very restricted geometry, by the DOSEEXIT program. See J.R. Preisig and A.J. Stevens, "Estimation of Neutron Punch-Through in Circular Shielding Penetrations," AD/RHIC/RD-81, November, 1994.

6. The two sets of point detectors were placed at 1/3 and 2/3 of the total length of the wall in the beam (Z) direction. However, to first order at least, only the relative Z value between the source and detector location matters, and since the source is moved to find the worst case dose, sampling at different Z values of the detectors is not very important. The difference between the sets was less than 15%. The numbers in Fig. 1 refer to the highest values found which happens to be the detector closest to the source location.

7. There was no obvious difference between dose estimates for the two point detectors.

8. LCS does not support effects due to magnetic fields. The first point in Fig. 1 also corresponds to a DX source and should be multiplied by 1.3, but this is less than the maximum value quoted.

9. The hole alignment was such that a slight increase from the beam going in the negative Z direction was expected.

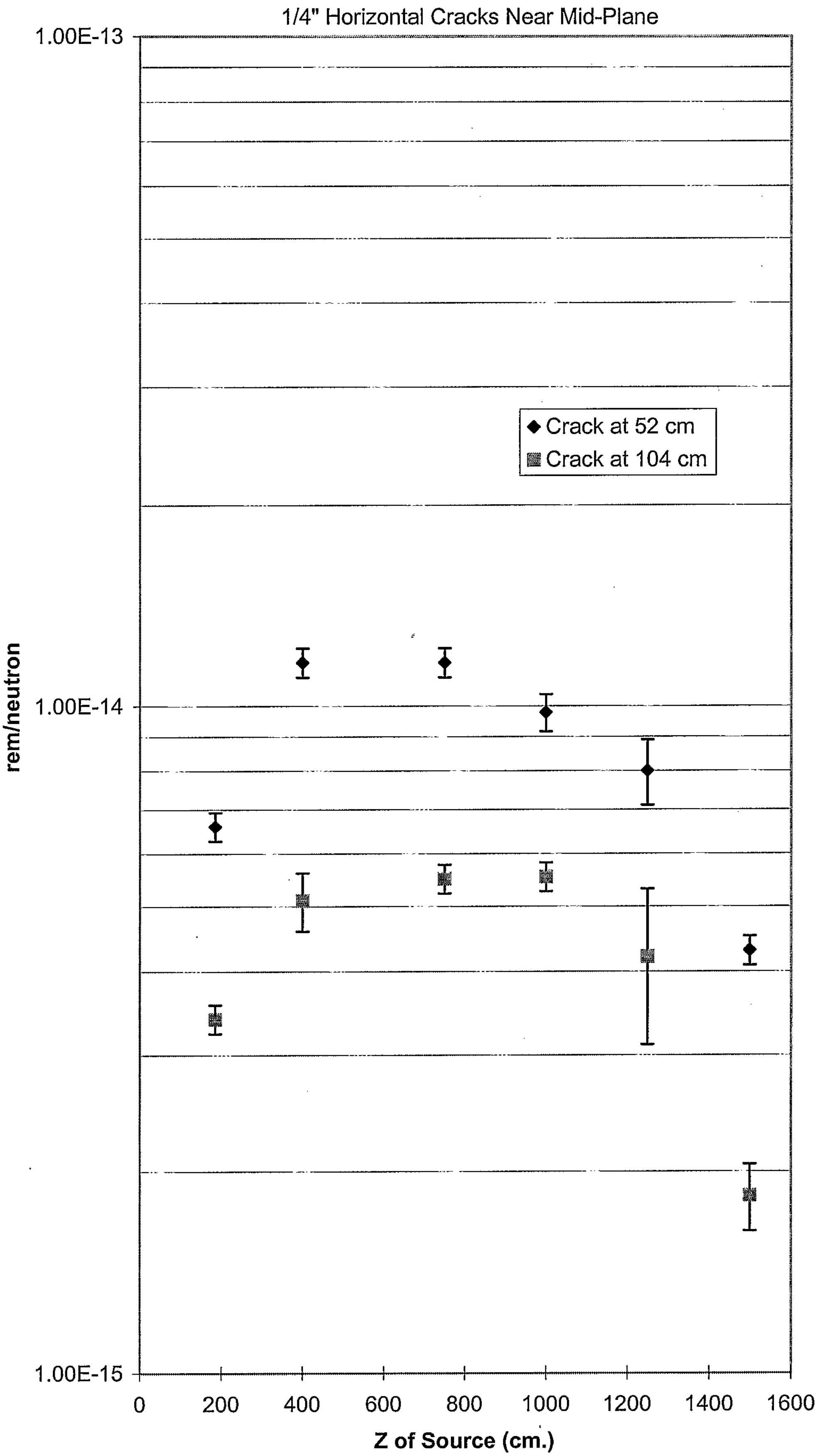
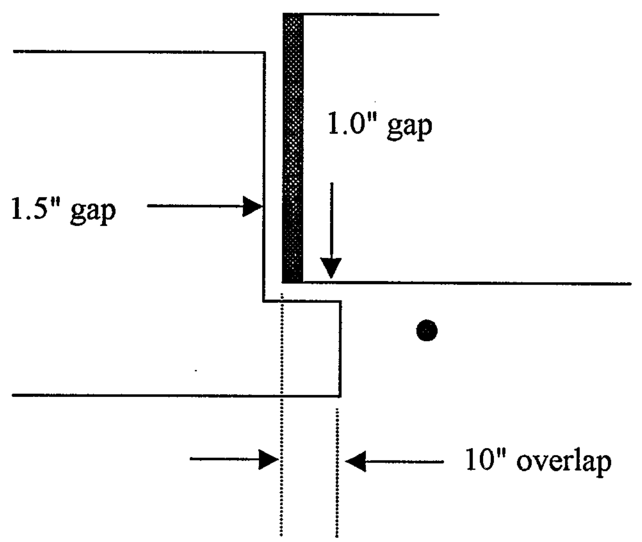

1/4" Horizontal Cracks Near Mid-Plane
1.00E-13
1.00E-14
1.00E-15
rem/neutron
Crack at 52 cm
Crack at 104 cm
0
200
400
600
800
1000
1200
1400
1600
Z of Source (cm.)

Fig. 1




Interface between the movable wall and permanent section (not to scale). The dark section on the edge of the permanent section indicates a steel facing. The circle indicates a point detector.

Fig. 2

Cable Pipes

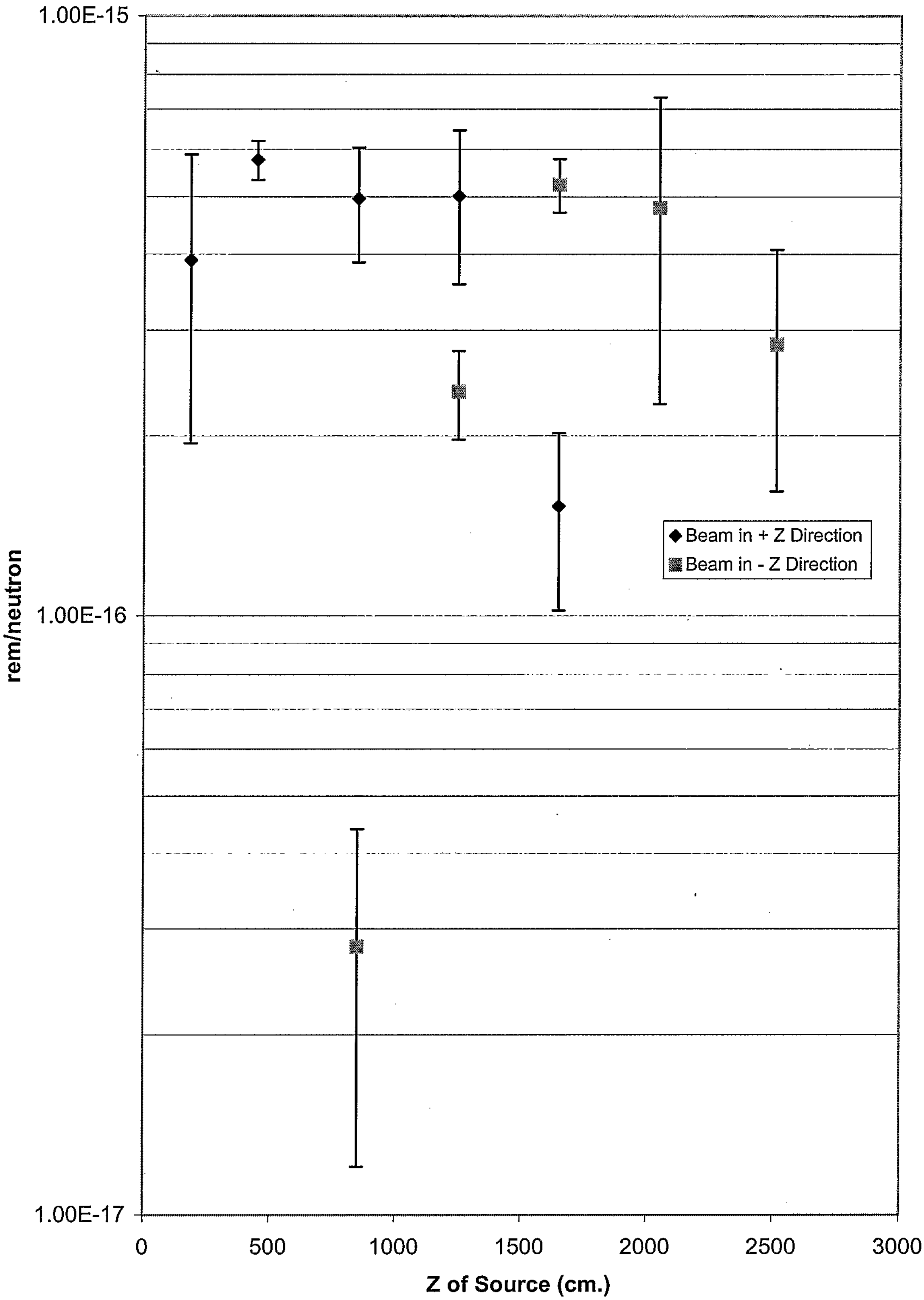



Fig. 3