Minutes of meeting: Radiation Safety Committee, sub-committee

Date: Friday, March 5, 1999

Present: A. Etkin, W. Mackay, S. Musolino, A. Stevens

Subjs: Review of Collimators and Other Topics Related to RHIC Turn-On

Several topics were discussed in this meeting, among which were collimators which will be installed downstream of the 8 o'clock IR.

The analysis of radiological topics associated with collimators now planned for RHIC was performed some time ago by A. Stevens. The technical note describing this analysis is included here as Attachment 1. A follow-up memorandum, which describes a more accurate calculation of dose from the collimator at the exit of a nearby personnel labyrinth in the clockwise ring, is included as Attachment 2.

The berm exterior to the position of the collimators will be fenced. Long liners will also cover the berm, and soil added over the first ~100 ft. With these berm modifications, skyshine from the collimators is expected to be below 0.5 mrem per year at the closest point to the site boundary, groundwater is protected from leachable radioisotopes to well below the values at the beam dumps, and the annual dose at the fence boundary is expected to be well below the 240 mrem per year limit. All these numbers refer to 4 times design intensity. Within the support building labyrinth (Bldg. 1008A) a door with some polyethylene will be installed to reduce the dose at the labyrinth exit, which is within a controlled area – TLD required. A chipmunk will also be deployed at this location. This is regarded as an ALARA concern, rather than a prompt radiation issue.

No issues relative to the plans regarding collimators were identified by the sub-committee. Plant engineering intends to have all work completed – the re-grading as well as liner and fence installation – by the May/June commissioning run. If delays develop, the fence alone may be installed. It is not clear at the present time whether the collimators will be installed prior to the commissioning run.

Following up an issue identified in the minutes of the meeting of 01/19/1999, it was agreed that the berm over both Lambertson injection septum magnets should be located, and snow fence erected here if practicable for the commissioning run. Stevens reported that Ed Lessard has informed him that he (Lessard) intends to deploy a few hundred TLD's around the berm in this run, and will reserve several to place at these locations which might be troublesome apertures.

Stevens reported the “discovery” by Chou Lac of two additional holes in the berm within the 8 o'clock fence perimeter. These have the appearance of 21 inch diameter survey holes, but Frank Karl, who was aware of these holes, does not use them. The dose at the exit of these holes would be about 4 rem for the full beam loss at 4 times design intensity. This would not normally be a concern,
given the fenced location, but the pipes emerge about 15 ft. from the downstream edge of the fence. Skyshine from these holes, added to the “no-hole” dose, might well put the dose at the edge of the fence beyond the 160 mrem criteria. It was decided that a patio block barrier should be erected around them, but this is clearly not a concern for the near future. If possible, a radiation barrier should be constructed prior to the physics run now scheduled to begin on Nov. 1, 99.

In a follow-up to the meeting of 02/19/1999, the subcommittee rescinds RSC CK-12 o’clock-5. This was a recommendation to install light sensors across the shield walls at 12 o’clock if practical. The RSC minutes of 07/29/98 state that “This is NOT regarded as a personnel protection device, but as perimeter protection information.” This area is well inside the perimeter fence. The estimated maximum fault dose levels at human height (full 4 times design intensity lost and \( \times 2 \) QF applied) is 10 rem at human height on the ring center inside location and about 20 rem on the opposite side. Other locations exist within fenced areas with comparable fault dose estimates.

In another follow-up to the meeting of 02/19/1999, it was reported that W. MacKay, R. Marascia, and A. Stevens, accompanied by Mike Gaffney, visited several of the radiation barriers at the exits of the cryogenic penetrations. Gaffney recommended lowering the stacked patio blocks to a stacked height not to exceed 4 ft., and, in instances where the line of blocks is longer than about 6 ft., taking additional stabilizing measures, an example of which was an inverted “U” shaped plywood structure hung over the blocks. Marasica will pursue this further with input from Gaffney.

Attachments

Distribution:
  D. Beavis (w/o Attachments)
  A. Etkin (w/o Attachments)
  W. Mackay (w/o Attachments)
  S. Musolino (w/o Attachments)
  A. Stevens (w/o Attachments)

cc: RSC file (w Attachments)
    RSC (w Attachments)
RHIC PROJECT
Brookhaven National Laboratory

Radiation Safety Considerations Near Collimators

A. J. Stevens

April 1997
Radiation Safety Considerations Near Collimators

I. General Remarks/Assumptions

The primary collimators are clearly a concern as regards radiation safety since they are intended to be the place where "lost" beam particles interact. These collimators and the beam dumps, therefore, are expected to be the "hot spots" in the machine.

Unfortunately, the amount of beam which will end up on the collimators is not really known. For the purposes of this note, the assumption will be made that, averaged over a year, 20% of the beam in each ring will interact in the limiting aperture collimator for that ring, and at most 10% of stored beam in a single hour. Faults will also be considered, but the annual assumed beam loss will be shown to be the limiting factor. The annual beam per ring from the Beam Loss Scenario (BLS) is the equivalent of $5.5 \times 10^{14}$ Au ions at 100 GeV/u. It should be noted that this number assumes operation at 4 times the design intensity for 38 weeks a year at 100% efficiency. The 20% loss assumption is somewhat higher than given by Ref. [1] because the internal dump aperture is larger than was assumed when the BLS was written and will therefore "catch" less lost particles than assumed at that time. For the purposes of the estimates made here, therefore, the loss assumptions per primary collimator in normal operation are assumed to be:

\[ 1.1 \times 10^{14} \text{ Au ions per year} \]
\[ \text{and} \]
\[ 2.85 \times 10^{10} \text{ Au ions per hour}. \]

The last number is 10% of the maximum beam per ring per hour in the BLS which corresponds to 1.25 fills per hour. The assumption will also be made that both primary collimators are located downstream of the crossing point at 8 o’clock.

In the subsequent sections of this note the following potential problems are considered: (1) prompt radiation in occupied regions nearest to the collimators, (2) skyshine, and (3) soil activation. Section VII recommends actions to address these problems.

II. Levels Exterior to the Berm

(A) CASIM Calculation for a "Bare" Collimator

One of the first concerns is the level on top of the berm at the nominal 13 ft. depth. Fig 1 shows the results of a CASIM calculation at this depth for 100 GeV/c neutrons interacting in the edge of a "bare" collimator, i.e., a collimator without local shielding. The quantity plotted is the
star density in BNL soil which is related to prompt radiation via the constant $2.4 \times 10^3$ rem/star/cc. The simplifying assumption is made that an Au ion is equivalent to 197 neutrons.

The fall-off with distance in Fig. 1 is extremely slow, a well-known feature of “target in a cave” geometries. The slow fall-off does not go on “forever”. When the tunnel curves the secondaries enter the tunnel wall and soil behind this wall, and the star density drops very rapidly to a negligible value. The distance along the beam line in an intersection region (IR) from the crossing point to the point where the tunnel wall intersects the beam line is 185m. The maximum star density of $8 \times 10^{11}$ in Fig. 1, combined with the loss assumptions given above, gives the following maximum dose equivalent at the nominal shielding thickness:

\[
\begin{align*}
\text{Max dose in an hour} &= 11 \text{ mrem} \\
\text{Max dose in a year} &= 41.6 \text{ rem}
\end{align*}
\]

The annual dose greatly exceeds to the RHIC Project criteria of 240 mrem per year for unrestricted access in a low occupancy region. Some combination of additional shielding and access restrictions will therefore be required. Anticipating the recommendation in the last section of this note, a fence will be required (for a considerable distance) to exclude occupancy near the collimators.

A full beam fault ($2.28 \times 10^{13}$ 250 GeV/c protons) on one of the collimators produces a maximum dose of 80 mrem. Although this is, by design, the most likely location for a fault, the annual “normal operation” dose is clearly the dominant problem.

(B) The Effect of Local Shielding

The fact that the radiation field falls off very slowly in the beam direction adds greatly to the total area of the berm to which earth must be added or access restricted. In principle, the problem of slow fall-off can be reduced by adding local shielding, i.e., shielding within the tunnel as close to the collimator as practical. Unfortunately, the practicality of local shielding within the tunnel is severely constrained, especially in the 8 o’clock IR. In any IR, the distance for material objects outside of the beam pipe is constrained by the requirement to allow room for passage of a magnet transporter or people. Since 8 o’clock is designed to have a $\beta^* = 1$m crossing point, the beta function, and hence the beam pipe diameter, in the collimator region is necessarily large, which means that shielding cannot be placed as close to the beam line as one might like. If view of these considerations, as well as the fact that the collimator does not yet have a final design, a very modest amount of local shielding was assumed, specifically a 1m long steel collar extending from the beam pipe to a radius of 30 cm.

The CASIM calculation for this geometry is shown in Fig. 2. The rate of fall-off is somewhat faster at the expense of a worse maximum. For this geometry, the maximum is 69
rem a year. However, the geometry with local shielding is better for distances in excess of about 40m from the collimator. Comparisons of the two geometries will be made below.

III.- Skyshine

Although fence can solve the "local" problem exterior to the berm, it does nothing to address skyshine. The estimate here, as in the case of the beam dumps, uses the parameterization of Distenfeld and Colvett. This expression is:

\[ R^2 \times \text{Dose in rem per n > 20 Mev} = 8.33 \times 10^{-13} \times \exp(-R / 600) \times (1 - \exp(-R / 47)) \times (R \text{ in m}) \]

where R is the lateral distance from where a neutron > 20 Mev leaves the berm to the point under consideration. Now the flux of neutrons > 20 MeV exiting the berm at any point is given by the star density multiplied by the interaction length in BNL soil (53.28 cm) multiplied by 1.43 where the latter factor corrects from the CASIM threshold of 47 MeV to 20 MeV.

In past estimates of skyshine, integration over the berm surface was approximated by the expression:

\[ R_O \times \frac{\pi}{2} \int_{Z} SD dz \]

where SD is the star density on the top of the berm a distance \( R_O \) from the beam line. The first part of this expression \((R_O \times \frac{\pi}{2})\) approximates the transverse integration as illustrated in the sketch shown in Fig. 3(a). The integration over Z (the beam direction) assumes that the variation in star density in Z is small in comparison to variations in R, the distance to the point of evaluation, so that all the neutrons can summed and placed "at a point." Both aspects of this approximation break down in the collimator situation, at least for the bare collimator geometry. The transverse fall-off of emerging neutrons is faster than given by the approximation because the transverse fall-off of the existing berm is slower than typical, in part because the ring-outside part of the berm is on the muon shielding plateau. Figs. 4 and 5 show existing typical cross sections. If one compares the actual star density at the berm surface shown in Fig. 4 integrated to infinity (75° from the vertical is essentially infinity), it is lower than the approximation by a factor of 0.6. This reduction factor is conservative when applied to the entire berm. The approximation made previously wherein the star density alone was integrated over Z was simply discarded; the skyshine was calculated by numerically integrating the expression of Distenfeld and Colvett rather than integrating the star density and then inserting the results into this expression. The value of R thus changes as the integration along the top of the berm is performed. The results of this integration multiplied by the annual loss is shown in the table below:

The skyshine estimates are comparable with the contributions from the beam dumps taking into account the plan to add berm over the beam dumps. For comparison to the values
## Annual Skyshine to Closest Point Offsite and Unrestricted Onsite Locations with Existing Berm

<table>
<thead>
<tr>
<th>Location</th>
<th>Bare Collimators (mrem/yr.)</th>
<th>with Local Shield (mrem/yr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wm. Floyd Parkway</td>
<td>0.9</td>
<td>0.95</td>
</tr>
<tr>
<td>Bldg. 1101</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

obtained with the existing berm, the calculations were repeated with 3 ft. of soil is added over a 90 ft. length. A reduction of the estimated skyshine at both the site boundary and Bldg. 1101 to about 0.4 mrem/yr. is obtained.

## IV. Soil Activation

Radioisotopes are produced by spallation reactions in the soil. The only two isotopes of practical concern are $^{22}$Na and $^{3}$H, as others are either too short lived to travel any appreciable distance or are not produced in significant quantities. The production of these isotopes has been measured both at FNAL and BNL as 0.075 $^{3}$H atoms per CASIM star and 0.02 $^{22}$Na atoms per CASIM star. Tritium is 100% leachable and $^{22}$Na 7.5% leachable.

The topic of soil activation has previously been consideration in relation to the RHIC internal beam dumps. Each internal dump (with a considerable amount of local shielding) was estimated to produce about a factor of 2 less star concentration per year than the AGS criteria, and the advice of the S&EP division was sought on the adequacy of this situation. A part of the S&EP Division's recommendations was that the RHIC Project consider placing liners over the dumps, in order to minimize leaching of radioisotopes into the groundwater, and subsequently RHIC Project management decided to do so.

In the context of the discussion here, it is important to understand the “theory” of a liner. Fig. 3(b) shows a cartoon liner in cross section. The closest point in soil is indicated by the shortest arrow. However, the liner prevents rainwater from leaching the radionuclides produced at this point into the groundwater. Ideally, a practically sized liner (say $\pm$ 20 ft. in the transverse direction from the tunnel center line) would reduce the leachable star density concentration by the equivalent of about 8 ft. of soil which is indicated in the sketch by the dashed vertical lines and the second arrow. This is a nominal reduction of leachable activity of about two orders of magnitude. One must keep in mind that Fig 3(b) shows only the transverse direction. In the case of the dump, the star density drops so rapidly in the beam direction that two orders of magnitude is readily achieved.

After the lengthy digression above, we return to the case of the collimators being considered in this note. In the bare collimator geometry, the maximum star density at the nearest point in soil, 2m from the beamline, is $6.5 \times 10^{-7}$ stars/cc-nucleon. With the assumed loss in Section I, the maximum star density in soil becomes $1.4 \times 10^{10}$ stars/cc-year. The leachable activity would be 50.6 pCi per cc per year for $^{3}$H and 4.8 pCi per cc per year for $^{22}$Na, which is about 1 order of magnitude higher than the dumps (with liners) are designed to achieve. In the
case of the collimators, the slow fall-off in the beam direction limits the effectiveness of liners. In order to match the reduction of this problem to the level committed to for the dump, a star density of about $7 \times 10^8$/cc-nucleon is required at 2m transverse distance from the beam line. In the case of the bare collimator, this is not achieved short of the position where the tunnel wall intersects the IR region beam centerline. [Shortly after this length, the two orders of magnitude reduction in the transverse dimension again obtains.] In the case of the geometry with the local shield, although the maximum star density at 2m from the beam line is about 40% higher than the bare collimator geometry, the $7 \times 10^8$/cc-nucleon level is achieved 99m (325 ft.) downstream of the beginning of the collimator.

V. Levels in the Tunnel Interior

Levels in the interior of the tunnel are not usually of great interest except for questions related to induced activity on machine components, which have not yet been addressed for the collimators. However, for the collimator in the clockwise ring at 8 o'clock, the collimator's position which has been assumed to this point (upstream edge of collimator 40m downstream of the crossing point) is unfortunately close to the entrance of an access labyrinth as shown in Fig. 6. Following Gollon, the entrance dose for the labyrinth is taken as 85% of the maximum CASIM dose which gives, in the bare collimator geometry, 85% of the dose corresponding to $6.5 \times 10^7$ stars/cc-nucleon which is $3.0 \times 10^5$ rem/year. The Goebel reduction factor for this labyrinth in Ref. 15 is $1.7 \times 10^5$ which gives 5.1 rem per year at the exit of the labyrinth, an obviously unsatisfactory situation. Moving the collimator downstream by 6m puts the entrance 2.4m upstream of the collimator. A CASIM calculation gives an entrance star density in this geometry of $1.1 \times 10^{10}$. However, this author knows of no verification of CASIM calculations in the backwards direction, so that a sizable safety margin should be allowed. Allowing one order of magnitude, $1.1 \times 10^9$, gives 9 mrem per year.

VI. Elastic Scattering Experiment

The pp Elastic Scattering Experiment must be mentioned since it represents the only possibility for scraping large amount of protons. This experiment must run with $5\pi$ mm-mrd emittance instead of the normal $20\pi$. This can be achieved by scraping 0.67 of the beam. However, this experiment can run at low intensity. If one scrapes 0.67 of the design intensity, loss on the collimators is less than 20% of 4 times the design intensity, which has been assumed. This experiment is therefore within the envelope assumed here. It should also be noted that it may well be possible to shave the beam at a lower energy which would greatly reduce the radiation field.

Although not the subject of this note, the impact of this experiment on the radiation levels exterior to the berm in non-fenced regions must be carefully considered before this experiment approaches reality. This cautionary aside is motivated by the fact that the efficiency for scraping protons is only $\sim 50\%$ which means that outscattered protons will interact elsewhere in the lattice. This is a potential problem given the 240 mrem/yr. criteria.
VII. Summary/Recommendations

The magnitude of radiation problems due to beam loss on the primary collimators in RHIC have been considered. The collimators will be located at 8 o’clock, 46m downstream of the crossing point (see Section V above).

The radiation pattern from loss on a collimator, in contrast to a beam dump, has a very slow fall-off in the beam direction. For this reason, calculations were made for two geometries, a “bare” collimator and a geometry which assumed a modest amount of local shielding in the immediate vicinity of the collimator. Although the radiation pattern in the locally shielded geometry has a slightly faster fall-off in the beam direction, the effect is not dramatic.

Anticipated annual radiation levels exterior to the berm (assuming the 4 times design intensity Safety Envelope of the Beam Loss Scenario) greatly exceed the RHIC criteria of 240 mrem/yr. for normal beam loss in a low occupancy regions. A fence is required (in either geometry considered) which extends from 15 ft. upstream of the leading edge of each collimator to 505 ft downstream, a total length of 520 ft. The lateral extent of the fence boundary needs more detailed study, but inspection of typical cross sections of the existing berm indicate that ±40 ft. from the tunnel center line will suffice.

The remainder of the recommendations for addressing potential problems associated with beam loss on collimators are driven by consideration of soil activation. To reduce the concentration of leachable radioisotopes produced near the collimators to that near the internal dumps, liners on top of the berm will be required. Unfortunately, the slow fall-off of the radiation pattern in the beam direction means that long liners are required. In this case, the estimates for the geometry with the local shield indicate that a liner extending 325 ft. from beginning of each collimator would suffice to match the leachable concentration near the dumps. However, the difference in cost between a liner which extends 500 ft. downstream of the collimators and one which extends 325 ft. is not likely to be decisive, and at this distance the leachable concentration decreases significantly below that near the dump. The recommendation is therefore made that local shielding not be attempted, and that the liner length be 5 ft. within the fence length described above on both ends, i.e., that the liner extend from 10 ft. upstream of the leading edge of each collimator to 500 ft. downstream. The lateral extent of the liner should be ±22 ft. near the beginning (in the expanded tunnel section - see Fig. 6) and ±20 ft. thereafter.

Putting liners on the berm top necessitates adding earth cover over the liners. The recommendation is made that 3 ft. of earth be added for a 90 ft. distance beginning at the front edge of each collimator and 1 ft. (or the minimum considered to be sufficient) over the remainder of the liner. 90 ft. (~ 27m, see Fig. 1) is the distance over which the variation of the radiation pattern in the beam direction is relatively rapid.

If the recommendations proposed here are adopted as stated, the estimates made herein at the safety envelope limit become the following: (1) maximum dose exterior to the berm which is inaccessible, ~ 9 rem/yr., (2) maximum dose to accessible regions near the collimators below 240
mrem/yr., (3) maximum leachable radioisotope concentration in soil ~ 10 times below internal dump region, and (4) skyshine to nearest off site and uncontrolled on site locations ~ 0.4 mrem/yr.

References/Footnotes


2. The collimator (based on a preliminary design) is assumed to exist in the center of a tunnel with 2.54m radius and the start density is calculated at a 6.5m radius. The beam direction (Z) position of the upstream edge is downstream of the vacuum flange following the Q3 magnet. The presence of 8 additional magnets (the first of which is Q4) is crudely taken into account, but only one ring is simulated. Spin rotators magnets are also present in principle (assuming the collimators will be placed at 8 o’clock) but are also ignored. The transverse dimensions of the actual tunnel changes with distance, and star densities are sometimes needed at a distance smaller than (say) the assumed tunnel interior, but the scaling of star density with radius and depth in such a simple geometry is very well known.

3. This is double the normal conversion constant in accordance with RHIC Project practice of assuming that the neutron quality factor will someday be doubled and that the dose exterior to thick shielding berms is dominated by low energy neutrons.

4. A conservative estimate was made by assuming a tunnel “filled” with 30 GeV neutrons entering a solid soil wall. The star density at vertical berm height falls over 2 orders of magnitude in 15 meters.

5. The simple geometry assumed for the beam pipe is that the collimator is surrounded by a beam pipe of inner radius 16 cm. from the beginning of the collimator for a distance of 2m. The radius then “necks down” to an inner radius of 6.1 cm. over a 1m length. This radius is (unfortunately) much larger than the “normal” beam pipe radius of 3.645 cm., but must be this large to allow 10σ for an Au beam at 40 emittance. The collimator collar goes from the outer radius of the beam pipe to a radius of 30 cm. between 3.5 and 4.5m from the beginning of the collimator.

6. C. Distenfeld and R. Colvett, "Skyshine Considerations for Accelerator Shielding Design," Nucl. Sci. End. Vol. 26, p. 117 (1966). The expression given in this reference has been multiplied by 2 because skyshine is dominated by low energy neutrons and we are assuming double the current quality factor.


8. Fig. 5, which is typical of the North side of the 8 o’clock IR, would give a smaller reduction factor. The North side is closer to both the site boundary and the closest on-site location.
9. The beam dumps contribute approximately 0.7 and mrem at Wm Floyd (a different place than the collimators) and 1.3 mrem at Bldg. 1001. However, in making these estimates the simplified transverse model was used which is likely an overestimate in the beam dump location also.


12. D. Beavis, et. al., Eds., "AGS Final Safety Analysis Report," August 11, 1993. The criteria is $1.5 \times 10^{11}$ stars per cc per year to the closest point in soil exposed to leaching by rainwater. [The production of $^{22}$Na and $^{3}$H per CASIM star is very well known, having been measured both at FNAL and BNL.]


14. The theory ignores transverse dispersion of rainwater into the “hotter” region which would presumably lessen the effectiveness of the liner. This author is unaware of any methodology for analyzing this effect.

15. The CASIM star density at the closest point is soil for the two geometries considered has the same general character, although much higher in value of course, as the star densities after 13 ft. of soil shielding shown in Figs 1 and 2.

16. The activity quoted is per cc of soil. The activity concentration in water depends on assumptions about leaching. Ref. [12] assumes that a 10% fraction of water leaches all the tritium which would give a water activity concentration 10 times higher than the soil numbers.

17. A crude scaling from estimates of induced activity near the dump gives numbers at 1 ft. distance of $\sim 120$ mrem/hr after 1 hour of cooling and $\sim 50$ mrem/hr after 1 day of cooling.


20. The luminosity for 57 bunches each containing $3.3 \times 10^{10}$ 250 GeV/c protons (the bunch intensity after scraping .67 of $10^{11}$ per bunch) at $5\pi$ emittance and 200m $\beta^*$ is $6.3 \times 10^{28} /\text{cm}^2\text{-sec}$, which is likely higher than required.
Star Density per 100 GeV Neutron @ 13 ft. Depth vs Distance from Collimator

Fig. 1
Star Density as Fig. 1 But With Local Shield

Fig. 2
(a) Illustration of the usual transverse approximation for Skyshine. The quantity approximated is the transverse length integral of the star density at the surface.

(b) Illustration of a Liner for reducing groundwater activation

Fig. 3. Transverse Sketches as Described in the Text.
Fig. 4 Typical Cross Section South of the Collimator at 8 o'clock (Counter-clockwise Beam)
Fig. 5 Typical Cross Section North of the Collimator at 8 o'clock (Clockwise Beam)
Fig. 6. The 8 o'clock Hall Region, Showing the Collimator Moved Downstream of the Egress Labyrinth. (The Transverse Direction of the Collimator Positions is Not Shown Accurately)
Brookhaven National Laboratory

MEMORANDUM

Date: 10/23/97

To: S. Musolino, T. Robinson

From: A.J. Stevens

Subj.: 8 O'clock Labyrinth Simulation

This memorandum is intended to document a LAHET calculation I performed to estimate the dose equivalent at the exit of the 8 o'clock labyrinth. This labyrinth is "exposed" to the clockwise ring collimator, which is expected to be a large source of beam loss in normal operation.

The calculation was based on the current design of John Brodowski. A plan view of the labyrinth area is shown in Fig. 1. The origin of the beam line coordinate system (all dimensions in the figures are in cm.) in Fig. 1 is arbitrary, but the point labeled 792 cm. is the upstream end of the collimator, some details of which are shown in Figs. 2 and 3.

As usual with LAHET, the "beam" was taken to be 100 GeV neutrons with the approximation that an Au ion is equivalent to 197 neutrons. Four runs were made with 12,000 primary neutrons per run. The result was $9.65 \pm 1.90 \times 10^{17}$ rem/neutron.

Now we have to date made the conservative assumption that 20% of each beam will interact on the primary collimator. From the Beam Loss Scenario this is $1.1 \times 10^{14}$ Au ions per year. With the usual $\times 2$ QF assumption, multiplying the numbers above gives:

$$4.2 \pm 1.9 \text{ rem/year}.$$ 

Now this estimate may be very conservative for many reasons, not the least of which is that the BLS assumes 100% efficient operation for 38 weeks a year at 4 times design intensity. However, this is the only personnel labyrinth of which I am aware that has a nearby source and therefore deserves some attention.

Attachments
Vacuum pipe 0.2 cm. thick. Box edges 0.5 cm. thick

Top View

Geometry is cylindrical before and after box.

Fig. 2
Objects 1, 2, 3 (and one identical to 3) exist in very restricted Z intervals

Objects 4, 6, and 7 are 3 cm thick steel plates extending over the "outer box" region

Object 5 is circular centered on outer box

Fig. 3