BNL-101896-2014-TECH

AD/RHIC/RD/113;BNL-101896-2013-IR

# Radiation Safety Considerations Near Collimators

A. J. Stevens

April 1997

Collider Accelerator Department

**Brookhaven National Laboratory**

**U.S. Department of Energy**

USDOE Office of Science (SC)

# DISCLAIMER

AD/RHIC/RD-113

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[1] (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:

$1.1 \times 10^{14}$ Au ions per year
and
$2.85 \times 10^{10}$ 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[2], 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 $2.4 \times 10^{-5}$ rem/star/cc.[3] 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.[4] 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:

Max dose in an hour = 11 mrem
Max dose in a year = **41.6** rem

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 practicable. 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.[5]

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.[6] This expression is:

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

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:

$$R_O \times \frac{\pi}{2} \int_Z SDdz$$

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 ($R_O \times \pi/2$) 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.[8] 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[9] 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**

| Location | Bare Collimators (mrem/yr.) | with Local Shield (mrem/yr.) |
|---|---|---|
| Wm. Floyd Parkway | 0.9 | 0.95 |
| Bldg. 1101 | 1.0 | 1.1 |

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.[10] The production of these isotopes has been measured both at FNAL[11] and BNL[10] 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.[10]

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[12], 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[13] 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 ± 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[14] 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.[15] 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,[16] 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 × $10^{-8}$/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 × $10^{-8}$/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.[17] 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[18], 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 × $10^{-7}$ stars/cc-nucleon which is 3.0 × $10^{5}$ rem/year. The Goebel reduction factor for this labyrinth in Ref. 15 is 1.7 × $10^{-5}$ 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 × $10^{-10}$. 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 × $10^{-9}$, gives 9 mrem per year.

## VI. Elastic Scattering Experiment

The pp Elastic Scattering Experiment[19] must be mentioned since it represents the only possibility for scraping large amount of protons. This experiment must run with 5π mm-mrd emittance instead of the normal 20π. 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,[20] 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 ~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

1. M. Harrison and A.J. Stevens, "Beam Loss Scenario in RHIC," AD/RHIC/RD-52, January, 1993.

2. The collimator (based on a preliminary design) is assumed to exist in the center of a tunnel with 2.54m radius and the star 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 10$\sigma$ 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.

7. Aerial survey of April 3, 1991 prepared by Chas. H. Sells, Inc. The aerial survey map shows 2 ft. elevation contours.

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.

10. P.J. Gollon, et. al., "Production of Radioactivity in Local Soil at AGS Fast Neutrino Beam," BNL-43558, October, 1989.

11. J.D. Cossairt, "Review of the Abort Dump Shonw in the SSC Conceptual Design Report," FNAL TM-1460, April, 1987.

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.]

13. Memorandum from D. Paquette and D. Schroeder to A.J. Stevens dated 6/4/96, Subject: "Radioisotope Production Near RHIC Beam Dumps and Potential Groundwater Impact."

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 ~ 120 mrem/hr after 1 hour of cooling and ~ 50 mrem/hr after 1 day of cooling.

18. P.J. Gollon, "Shielding of Multi-Leg Penetrations into the RHIC Collider," AD/RHIC/RD-76 (1994).

19. W. Guryn, et. al., "Experiments to Measure Total and Elastic pp Cross Sections at RHIC," Proposal dated September, 1995.

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 $6.3 \times 10^{28}$ /cm$^2$-sec, which is likely higher than required.

Star Density per 100 GeV Neutron @13 ft. Depth vs Distance from Collimator

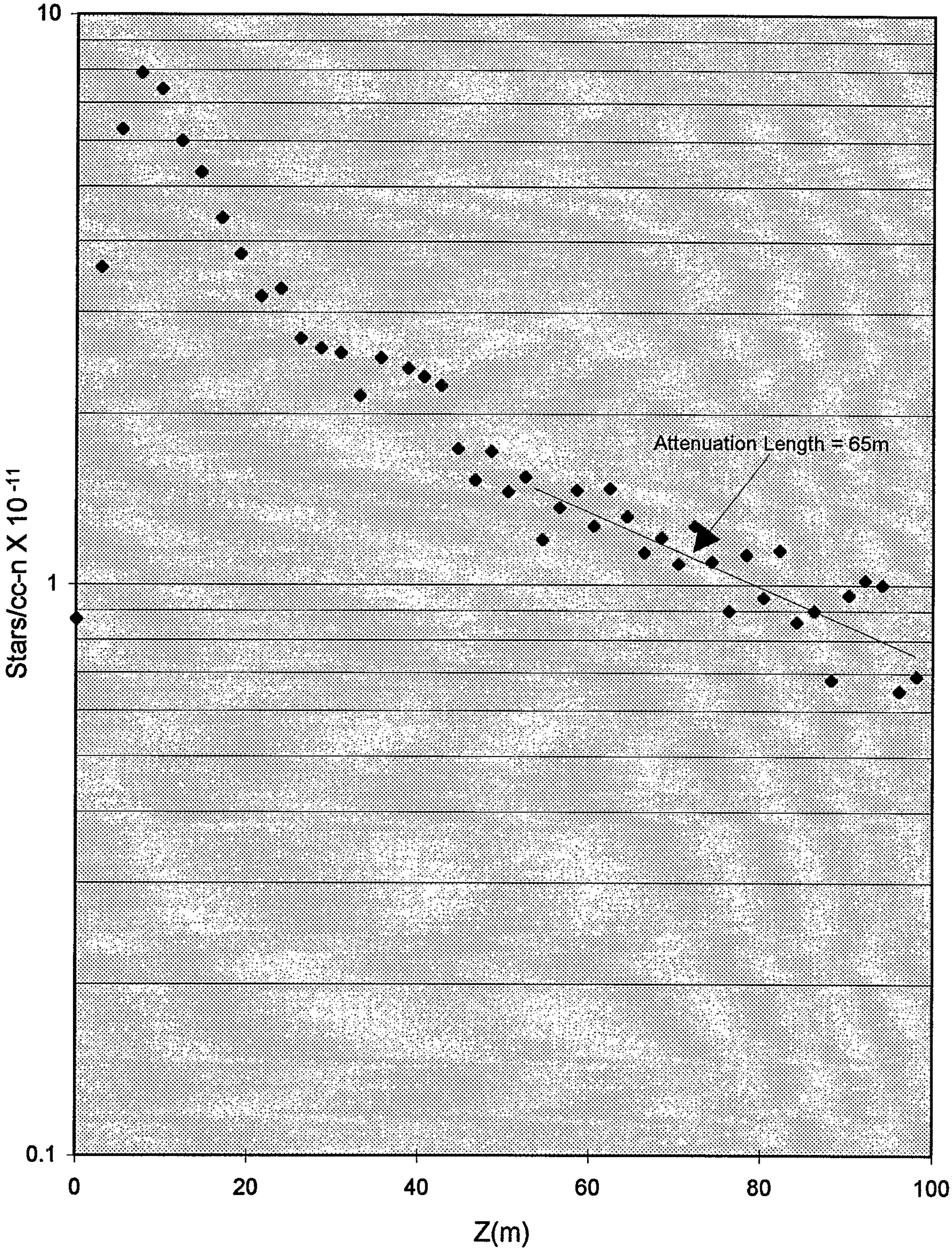


Fig. 1

Star Density as Fig. 1 But With Local Shield

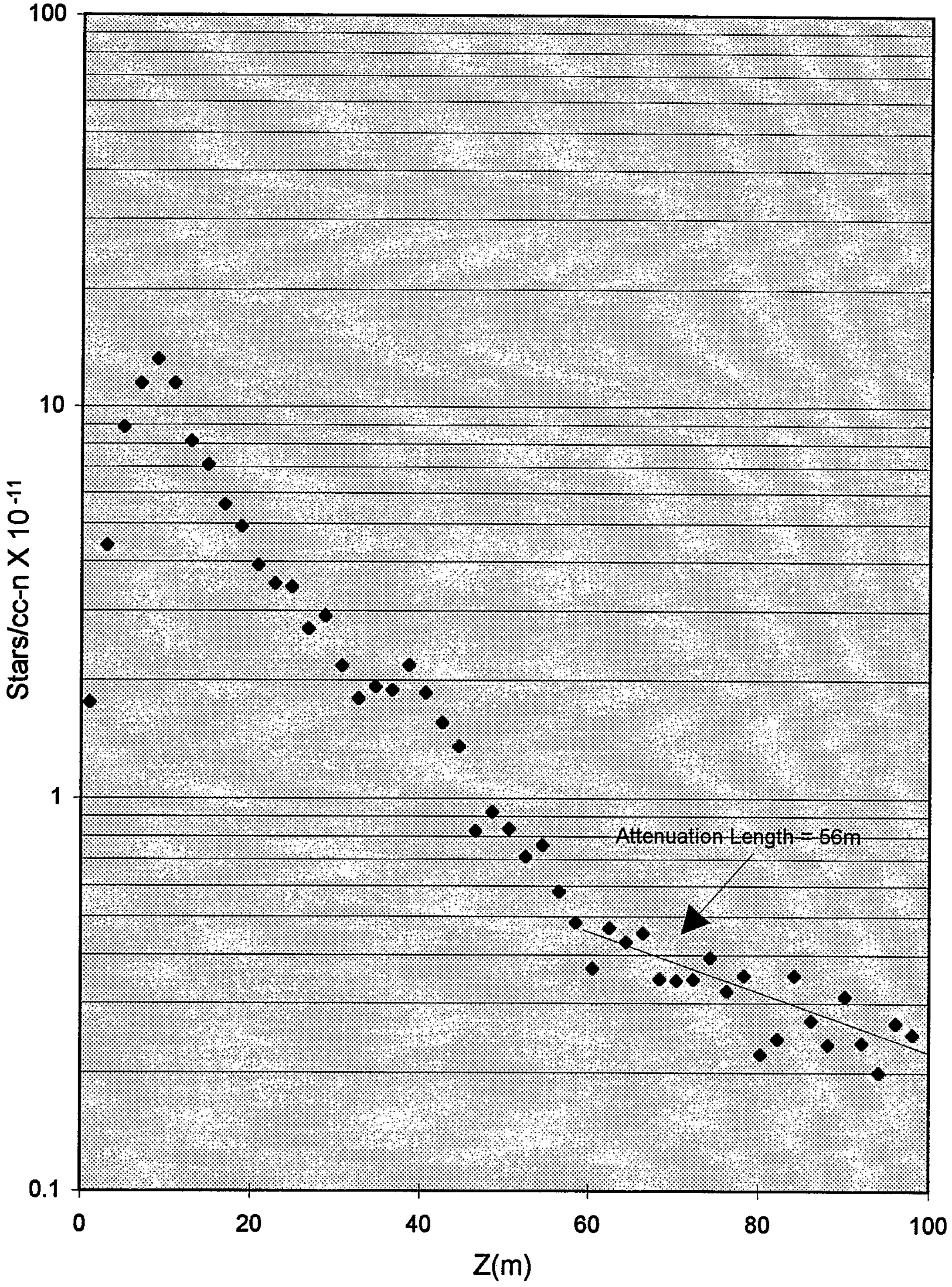
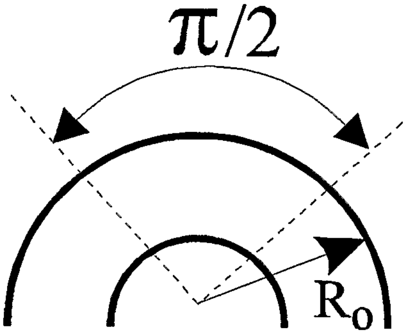
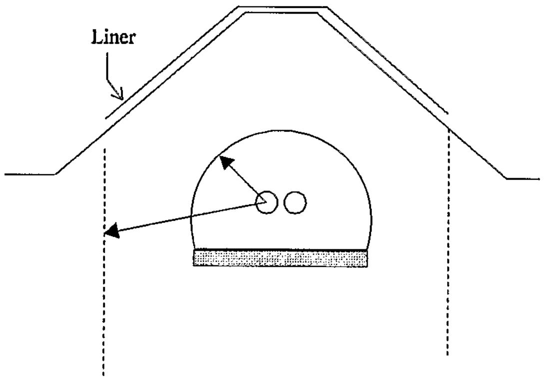


Fig. 2



(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.

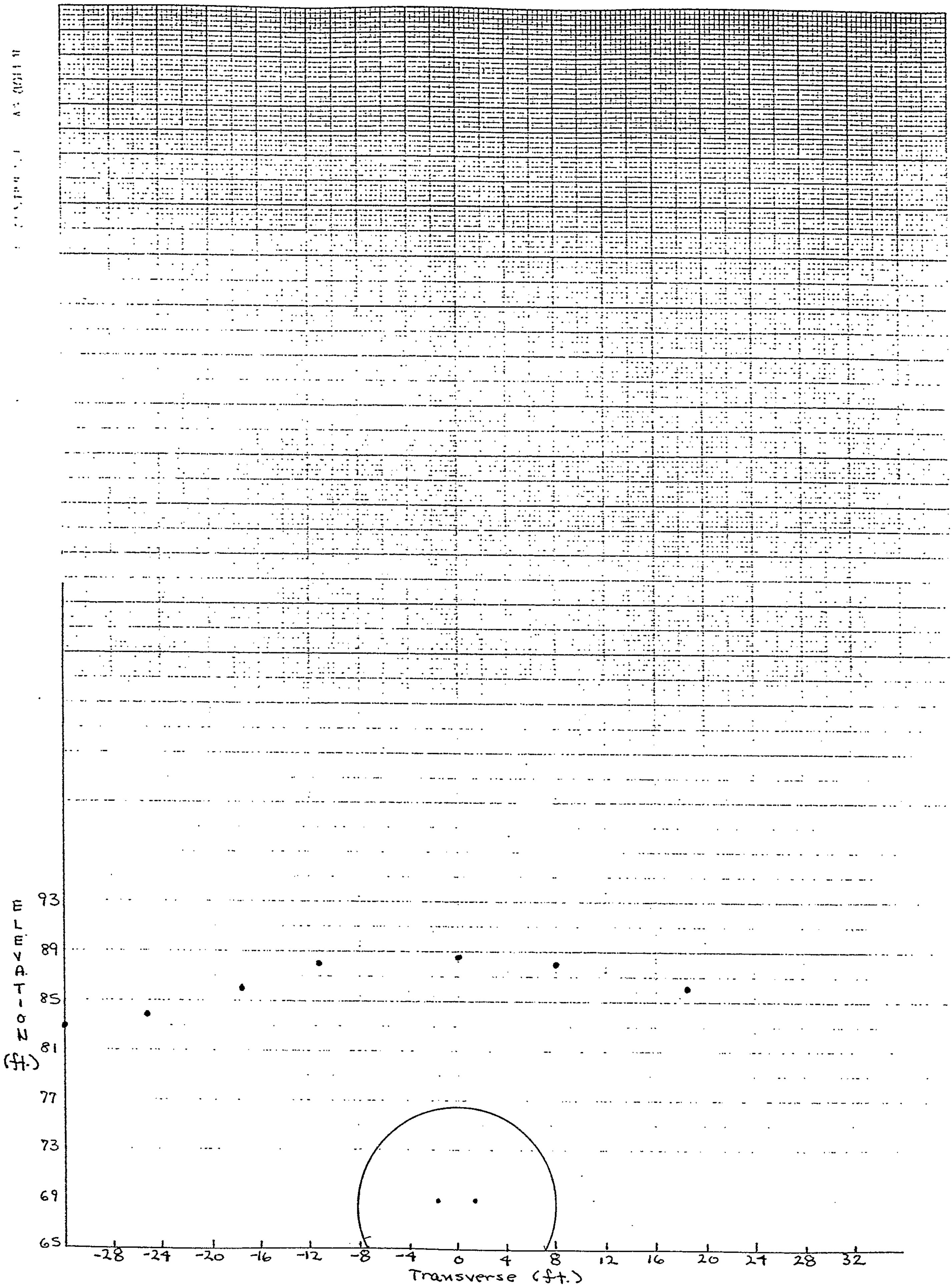


Fig. 4 Typical Cross Section South of the Collimator at 8 o'clock (Counter-clockwise Beam)

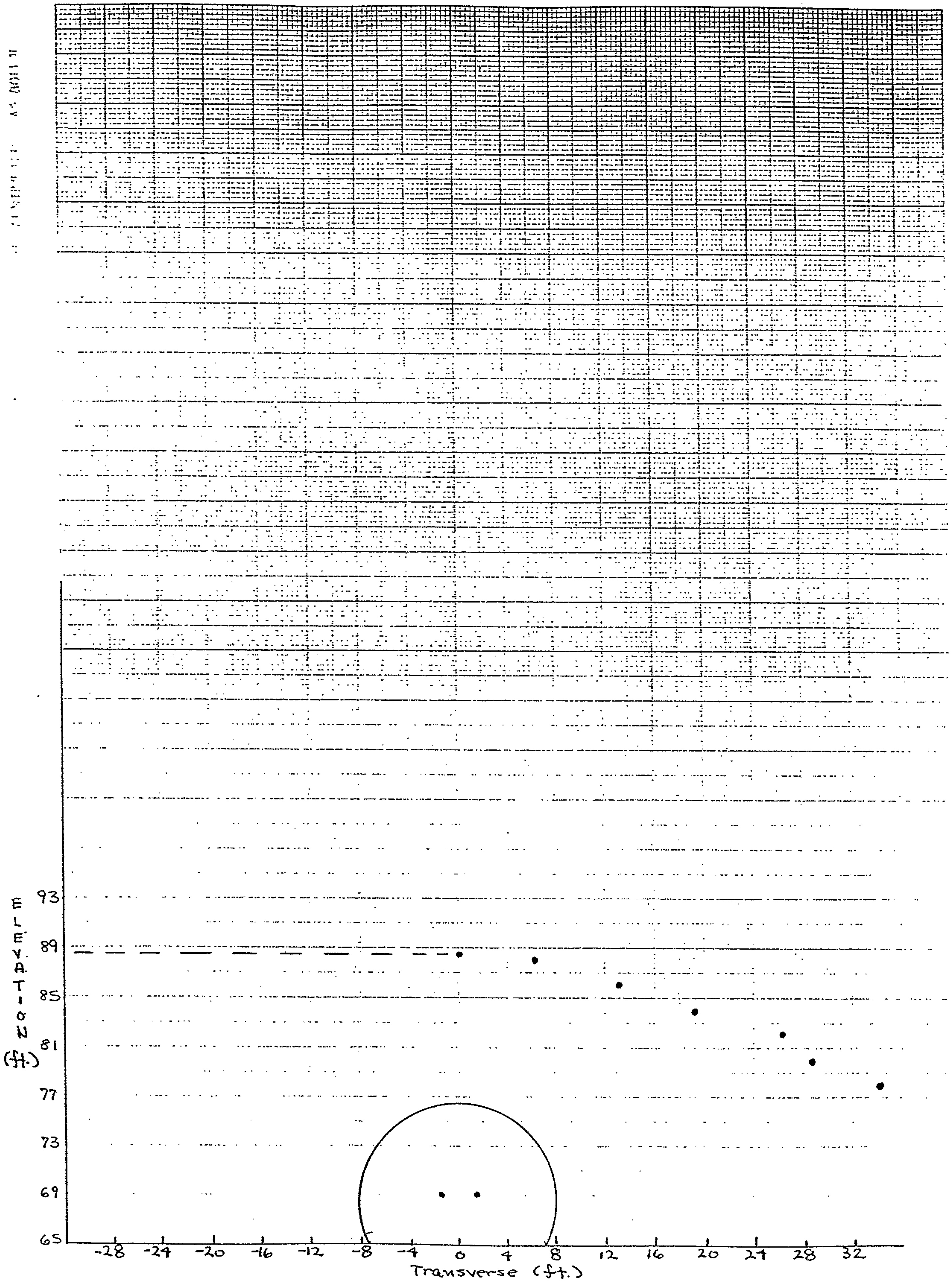


Fig. 5 Typical Cross Section North of the Collimator at 8 o'clock (Clockwise Beam)

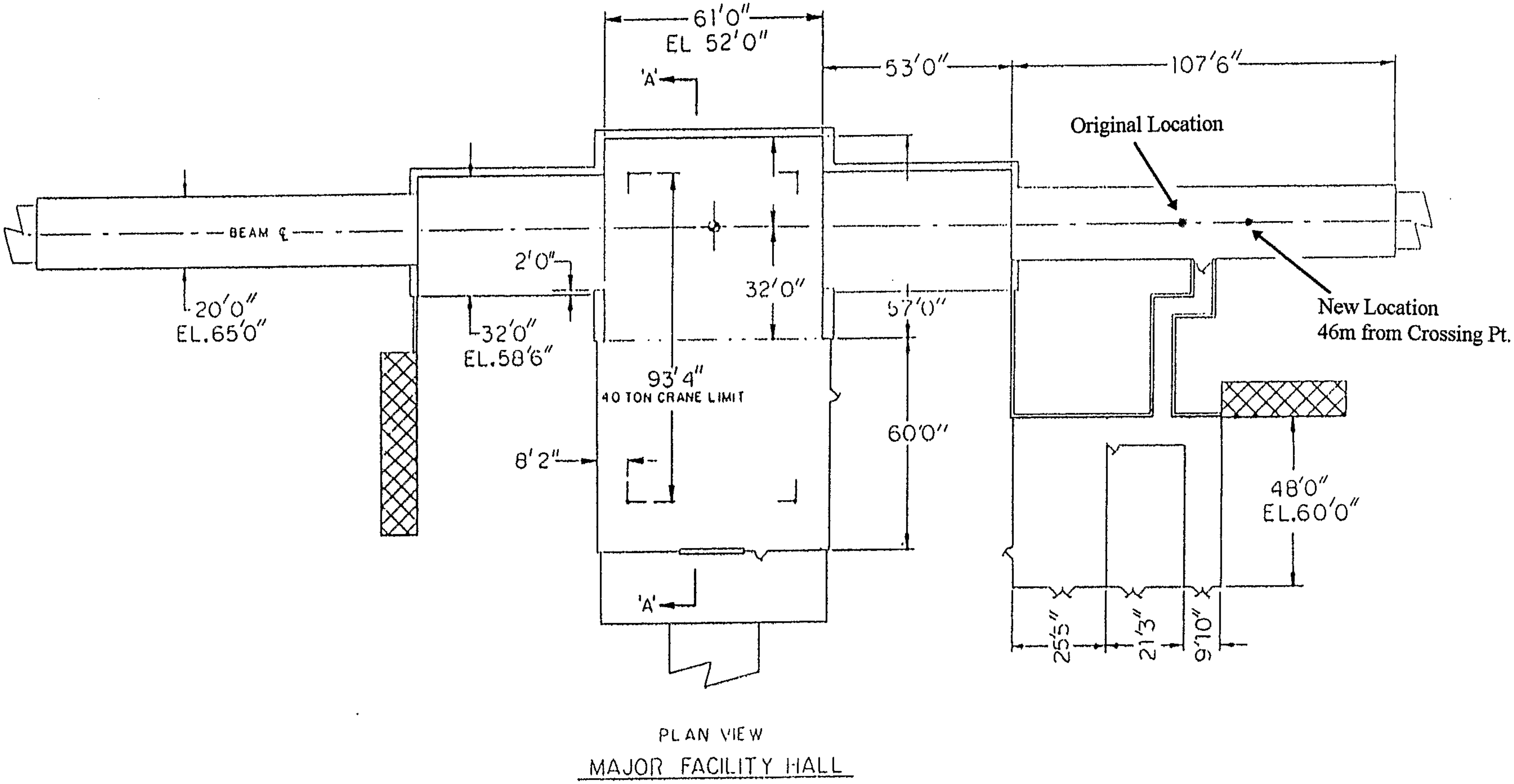


Fig. 6. The 8 o'clock Hall Region, Showing the Collimator Moved Downstream of the Egress Labyrinth. (The Transvserse Direction of the Collimator Positions is Not Shown Accurately)