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Bremsstrahlung Scattering Calculations for the Beam Stops and Collimators in the APS Insertion-Device Beamlines

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1. Introduction

Bremsstrahlung is produced in the APS storage ring by the interaction of positrons with the residual gas molecules in the vacuum chamber of the storage ring. The bremsstrahlung production causes a serious challenge in shielding the insertion-device beamlines because the entire straight section (15 meters) is in the line of sight of the beamline. The radiation emerges in a narrow cone tangential to the beam path with the characteristic emission angle $1/\gamma$, where γ is E/mc^2, which is the ratio of the kinetic energy to the rest mass for the positrons. This high-energy gamma radiation has an approximate 1/E spectrum with the maximum energy extending up to the particle energy (7 GeV for the APS)[1][2].

Bremsstrahlung, being high-energy photons, produces an electromagnetic shower [3] when it encounters the beamline elements. A beamline element not thick enough to fully contain an electromagnetic shower can cause considerable scatter of the high-energy bremsstrahlung radiation. The low-energy component of the bremsstrahlung can also be scattered and create high dose rates in the first-optical and white-beam enclosures. The fully developed electromagnetic shower will have a photon spectrum almost independent of the material (peaking typically at a few MeVs). The electromagnetic showers in the high-Z materials can also produce photoneutrons [4].

This note reports the summary of EGS4 calculations performed on bremsstrahlung scattering from different beamline components in a typical APS insertion-device beamline. The related recommendations for shielding are also given. The shielding criterion adopted is a total dose rate of 2.5μSv/h (0.25 mrem/h) at 30 cm from the shield [1][5]. This corresponds to an annual cumulative dose of 500 mrem for 2000 hours of occupancy. However in the case of primary bremsstrahlung scatter, half the dose allowance is being left for photoneutrons [1][6]. Therefore the design criterion adopted in such cases is a photon dose rate of 1.25 μSv/h at 30 cm from a source of radiation.

2. Calculation Method

The total beam integrated gas bremsstrahlung dose rate from the insertion-device vacuum chamber was calculated by the equation suggested by Frank [7].

$D = fNl/\pi\alpha^2 X_0 L(L+l)$

where:

D = total beam integrated dose rate for the gas bremsstrahlung in Sv/h,

f = an effective flux-to-dose conversion factor for bremsstrahlung photons ($3.\times10^{-6}$ Gy/hϕ),

$\alpha = 1/\gamma$, ratio of positron rest mass to its kinetic energy,

N = number of positrons/s for the beam current of 300 mA [1],

X_0 = radiation length of air in cm at 10^{-9} torr,

l = effective length of the straight section in cm and

L = distance from the end of straight section in cm to the observation point.

This equation yields a dose rate of 2.2 Sv/h for the APS beam current of 300 mA at 7.0 GeV. There are other semiempirical formulae available to calculate this quantity [8][9]. The calculated value has also been compared with the measurements, although an accurate direct comparison is difficult. The measurements so far show that the semiempirical predictions are somewhat conservative [9].

Bremsstrahlung interactions with materials are simulated by the electron gamma shower (EGS4) code [10], which is a Monte Carlo computer code that simulates the coupled transport of photons and electrons with energies from a few keV to several TeV. It also consists of a stand-alone program PEGS4, which creates cross sections to be used by EGS4, using cross-section tables for elements 1 through 100. Bremsstrahlung production, positron annihilation at rest and in flight, Moliere multiple scattering, Moller and Bhabha scattering, Compton scattering, pair production, photoelectric effect and the continuous energy loss by Bethe-Bloch formalism are the physical processes simulated in this program. The geometry, input and output are to be specified by the user-written subroutines. The bremsstrahlung dose at a given location in a configuration is calculated by EGS4 from the energy deposited in the standard ICRU tissue [11] placed at that location. Since the EGS4 result is expressed as the dose per photon, the dose rate from the bremsstrahlung is obtained by multiplying the dose per photon by the total number of photons produced per unit time in the insertion-device vacuum chamber.

The configurations analysed by EGS4 in this document are:

a. thick lead and tungsten targets,

b. the monochromatic aperture and bremsstrahlung stop,

c. the collimators for the white-beam transport, and

d. a potential scatterer in the white-beam path.

3. Results and Discussion

a. Thick Lead and Tungsten Targets

The scattering of the primary bremsstrahlung from a thick solid target of lead and tungsten is analysed by the EGS4. The primary bremsstrahlung is incident on a lead or tungsten target with transverse dimensions of 20×20 cm^2 and of varying thickness. One of the problems in analysing the thick targets is that the dose rates outside a very thick target (30 cm) will be small, and the error on the dose rates will be large. In order to improve the accuracy, more statistics need to be collected, which strains the available computer resources. To solve this problem, the dose rates near a target of smaller thickness are calculated using EGS4. The thickness chosen was 10 cm, which is nearly 20 times the radiation length of both lead and tungsten. This thickness is sufficient for the high-energy bremsstrahlung to complete showering, and any additional material will cause only pure attenuation. Therefore the dose can easily be extrapolated for any given thickness by the equation

$$D = D_{10cm} e^{-\mu.(t-10)}$$

where t is the total thickness of the stop in cm , and μ the minimum attenuation coefficient [12] of the material of the target in cm^{-1}.

The ICRU tissue of thickness 30 cm, is placed behind the 10-cm block of material, and the maximum dose rate is calculated. The dose rates for the greater thicknesses of the target material are extrapolated from these numbers by the above equation, with the appropriate thicknesses and attenuation coefficients for lead and tungsten, respectively. In order to check our hypothesis, the EGS4 calculations are also done for target thicknesses of 15 and 20 cm. These results are compared with the extrapolated values. The calculations are repeated for the ICRU tissue at 30 cm and 1 m away from the target.

The results of these calculations are shown in Figures 1 and 2. Fig. 1 gives the contact dose rates at the back of the target, and Fig. 2 the dose rates at 30 cm away from the target. The results of the EGS4 calculations are plotted along with the extrapolation. Because of the relatively large source size, compared to the distance to the dose point, the dose rates at 30 cm falls off only by a factor of three. It can be seen that the EGS4 results agree with the extrapolation. The results also show that the required thickness of the target to contain the bremsstrahlung shower such that the dose rate criterion will be satisfied, is 19 cm for tungsten and 28.5 cm for lead. Therefore it is recommended that a minimum thickness of 20 cm of tungsten or 30 cm of lead be used for the primary bremsstrahlung stops and collimators.

Figure 3 shows the back-scatter radiation from a thick Pb target. We found that the back scatter angular distribution is nearly independent of the material of the target. The direction of propagation of the beam in the figure is 0^0. The back scatter is maximum at about 140^0 in the backward direction, which is at a distance of about 8 cm on a 15-cm-diameter beam pipe from the upstream edge of the target. A collar of lead 4.5 cm thick and 10 cm long will be sufficient to contain the backscatter.

The EGS4 results are the average of 10000 events. The dose rate for 1 cm^3 of the ICRU tissue at the maximum dose point has been calculated by EGS4, making our dose estimates conservative. There are no serious systematic errors in the EGS4 simulation. These simulations have taken into account all possible photon interactions with matter at a given energy.

b. Monochromatic Aperture and Bremsstrahlung Stop

The monochromatic aperture and bremsstrahlung stop is a standard APS beamline component made of tungsten. Figure 4 is the schematic diagram of this component, which is a tungsten block 18 cm thick, 15 cm high and 20 cm wide. The aperture is 4 cm in the horizontal direction and 1 cm in the vertical direction and is at 9 cm from the lower edge of the block. This acts as a mono-beam pass and bremsstrahlung stop in the beamlines and is always situated in the first optical enclosure or in a white-beam station. The cases studied are those in which the extreme rays of the bremsstrahlung beam are incident at 1 cm, 0.8 cm and 0.5 cm below the center of the aperture. The bremsstrahlung photons will develop into an electron-gamma shower. Because the Moliere radius of tungsten is approximately 1.0 cm, and the shower can extend roughly three Moliere radii in the transverse dimension, part of the shower enters into the aperture, and some of the shower energy will come out through the aperture in the forward direction. The angular distribution of dose due to this source was calculated by EGS4 by placing the ICRU tissue of 30-cm thickness at the back of the stop, covering the aperture.

The results of these calculations are shown in Figs. 5, 6,and 7. The energy deposited in the ICRU tissue per unit mass in a given angular bin is plotted. The zero direction is the direction of propagation of the the incident beam. The results are given for three points of incidences, 0.5 cm, 0.8 cm, and 1.0 cm from the center of the aperture. From these plots, the dose rates in first optical enclosure (FOE) and in the white-beam station can be calculated.

Table I gives the dose rates in the white-beam station at three different locations from the aperture. Figure 8 shows these locations on a beamline drawing. Location 1 is on the white-beam-station side of the back wall of the FOE, near the unshielded beam pipe. Assuming a 10% occupancy in the white-beam stations, a dose rate of 25 μSv/h is allowed at this location. The results show that an offset of 0.8 cm or larger satisfies this criterion. Location 2 is directly in the beam in the white-beam station. The beam offset of 0.8 cm or more is sufficient to satisfy dose rate criteria assuming a 10% occupancy. Location 3 is outside the white-beam station in the experiment hall, near the 8-mm lead-shielded beam pipe. This is a 100% occupancy area for the three cases studied. The beam is incident on the beam pipe at a very shallow angle. As per our earlier study, dose rates are adjusted for the shallow angles of incidence [13]. It should also be mentioned that approximately 4 cm of copper in the photon stops will also attenuate the bremsstrahlung beam by at least a factor of two.

c. Collimators for the White-Beam Transport

The white-beam transport may require collimators at definite intervals in the beamline to contain the bremsstrahlung depending upon the bremsstrahlung ray tracing. These collimators must be 30-cm-thick lead or 20-cm-thick tungsten. The transverse dimensions must be 20 cm$\times$ 20 cm in the case of lead and 15 cm$\times$ 15 cm in the case of tungsten.

The situation considered in this calculation is the missteering of the beam such that it strikes the downstream edge of the collimator and a shower develops. If the beam happens to strike at a distance far enough from the downstream edge of the collimator to develop a full shower, most of the shower energy will leak into the beam pipe producing high dose rates on the beam pipe. This is the worst-case scenario for the white-beam transport. For a missteered beam that strikes the upstream side of the collimator, the shower will be contained inside the collimator.

The EGS4 code is used to calculate the dose rates for this configuration. The geometry used for this calculation is shown in Fig. 9. The beam is incident at an angle of 4.5 degrees and strikes the collimator 3 cm from the downstream edge and an electromagnetic shower develops.

The results of this calculation are shown in Fig. 10. The angular distribution of the dose in the ICRU tissue is given. This is the surface dose rate at the back of the collimator. From these values, the dose rates on the surface of the 10-cm-diameter beam pipe as a function of distance from the collimator are calculated. Being a fully developed shower, the dose is adjusted for the incident angles [13]. These calculations are repeated for a 15-cm beam pipe with similar conclusions.

Table II gives the thickness of the collar required to contain the shower on the downstream side as a function of the distance from the collimator. The thickness of lead collar is calculated such that the photon dose rate on the beam pipe of 10-cm diameter is 1.25 μSv/h at 30 cm. The results show that a collar of lead 5 cm thick (inclusive of beampipe shielding) and 20 cm long can contain the shower in the case of 2-cm lead-shielded beam pipe. The distance between these collimators depends on the initial size assumed for the bremsstrahlung source and the other collimators used. This analysis should be done in conjunction with the bremsstrahlung ray tracing.

d. Scatterer in the White-Beam Path

The synchrotron radiation and the bremsstrahlung can be scattered from any potential scatterer in the beam path. They can also be scattered from air in the loss-of-vacuum condition, although the bremsstrahlung scattering from air will be very small. The synchrotron radiation scattering from air has been calculated [1], and the shielding requirements for the beam pipe were given. In this report, we present the results from EGS4 calculations for the scattering of bremsstrahlung from air, a thick copper scatterer, and a thin copper scatterer.

Figure 11 gives the results of the EGS4 calculations for the scattering of the bremsstrahlung beam from air in the beam pipe at atmospheric pressure. The bremsstrahlung beam is transported though a 1m-long air column in the beam pipe. After studying 10000 events, the results show that most of the dose is along the beam direction with very little scattering outside the $4^0 \times 4^0$ bin size, which corresponds to a 14-cm-diameter beampipe.

Figure 12 gives the results of bremsstrahlung scattering from a thick copper scatterer of 30 cm length inside the beam pipe. The estimated dose on the surface of the beam pipe will be the worst case. In the figure, the 90^0 angle is the direction of beam propagation. The results show that the contact dose on the beam pipe of 10-cm diameter will be approximately 30 μSv/h. The lead shielding required at this location in order to reduce this to 1.25 μSv/h of photon dose rate at 30 cm from the beam pipe is calculated as 4.4 cm. Therefore we recommend a lead thickness of

4.5 cm (inclusive of beam pipe shielding) at the location of any potential scatterer in the beamline. It can also be inferred from this result that the greatest extent of the bremsstrahlung ray on the lead collimator should not be closer than 4.5 cm from the lateral edge of the collimator. These recommendations can be scaled for appropriate dose rates and distances for a given situation.

Thin scatterers are more complicated than thick scatterers. Figures 13 and 14 give the results of the EGS4 calculations for the bremsstrahlung scattering from a 3-cm-thick copper scatterer. The transverse dimensions of the hypothetical Cu scatterer are 4 cm$\times$4 cm. In this case, the scattering peaks more in the forward direction because the shower is only partly developed. Therefore the dose in the direction perpendicular to the beam path may not be the most conservative case. The shielding required in this particular case in the forward direction of the scatterer as a function of distance from the scatterer is given in Table III. The results show that Pb shielding at least 3 cm thick (inclusive of the beampipe shielding) and 20 cm long in the forward direction is necessary to shield any potential thin targets in a 2-cm shielded beam pipe. In the case of thin scatterers inside the enclosures, local shielding can be provided. Potential scatterers in the white beamline should be avoided as much as possible.

4. Shielding Recommendations

The following is recommended based on this study.

- In the case of primary bremsstrahlung stops and collimators, 30-cm-thick lead or 20-cm-thick tungsten is sufficient to satisfy the dose criteria.
- The extremal ray in the case of bremsstrahlung ray tracing should not be closer than 4.5 cm from the lateral edge of the collimator.
- For the monochromatic aperture and bremsstrahlung stop in the integral shutter, an offset of 0.8 cm or more is safe for the extremal bremsstrahlung ray from the center of the mono-aperture.
- A 2-cm lead-shielded, 15-cm-diameter beampipe is recommended for the white-beam transport, especially when it is outside enclosures (first optical and

white-beam stations) for the ID beamlines. This requirement can be relaxed by the judicious use of collimators and collars. The periodicity of the collimators is to be decided from the bremsstrahlung ray tracing.

• A collar 5 cm thick and 20 cm long (inclusive of the beam pipe shielding) is recommended for the beam missteering and hitting the downstream edge of the collimator. For the backscatter dose from a missteered beam hitting the upstream edge of the collimator, a collar 4.5 cm thick and 10 cm long is recommended.

• Lead 4.5 cm thick (inclusive of beamline shielding) and 20 cm long in the downstream direction is recommended at the location of a potential scatterer in the white beamline outside the enclosures. This is the most conservative case in which the entire bremsstrahlung ray is scattered from a thick target. The scattering of bremsstrahlung from atmospheric air is negligible. Therefore shielding recommendations for 'synchrotron radiation only' [1] criteria are valid in these cases.

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Table I. Summary Results for the Mono-aperture

Beam offset (cm)	Dose Rates (μSv/h)			
	at the aperture	at the back[(a)] wall of FOE	in the[(b)] beamline	outside WBS[(c)] on the pipe
0.5	300.0	37.5	27.2	0.64
0.8	200.0	25.0	18.2	0.43
1.0	100.0	12.5	9.1	0.21

(a) At the back wall of the FOE, in the white-beam enclosure, close to the beam pipe. The beam pipe is unshielded in this case.

(b) In the white-beam enclosure, right in the beamline.

(c) Outside the white-beam enclosure, on the beampipe. The beampipe is shielded by 8-mm lead.

Table II. Thickness of the Collar for the Collimators

Distance from[(a)] the collimator	Thickness of[(b)] lead collar
0.0 cm	4.9 cm
10.0 cm	3.4 cm
15.0 cm	2.6 cm
20.0 cm	1.8 cm
25.0 cm	1.8 cm
47.0 cm	1.3 cm

(a) The missteered beam hits close to the downstream edge of the collimator. The distance is from the downstream edge of the collimator.

(b) In calculating the thickness 'the angle of incidence effect' [13] has been taken into consideration.

Table III. Bremsstrahlung Scattering from a Thin Target

(Copper Target 4 cm×4 cm×3 cm)

Forward distance from the scatterer	Pb thickness on the beampipe
0.0 cm	3.0 cm
10.0 cm	3.0 cm
15.0 cm	2.5 cm
20.0 cm	1.8 cm
25.0 cm	1.5 cm

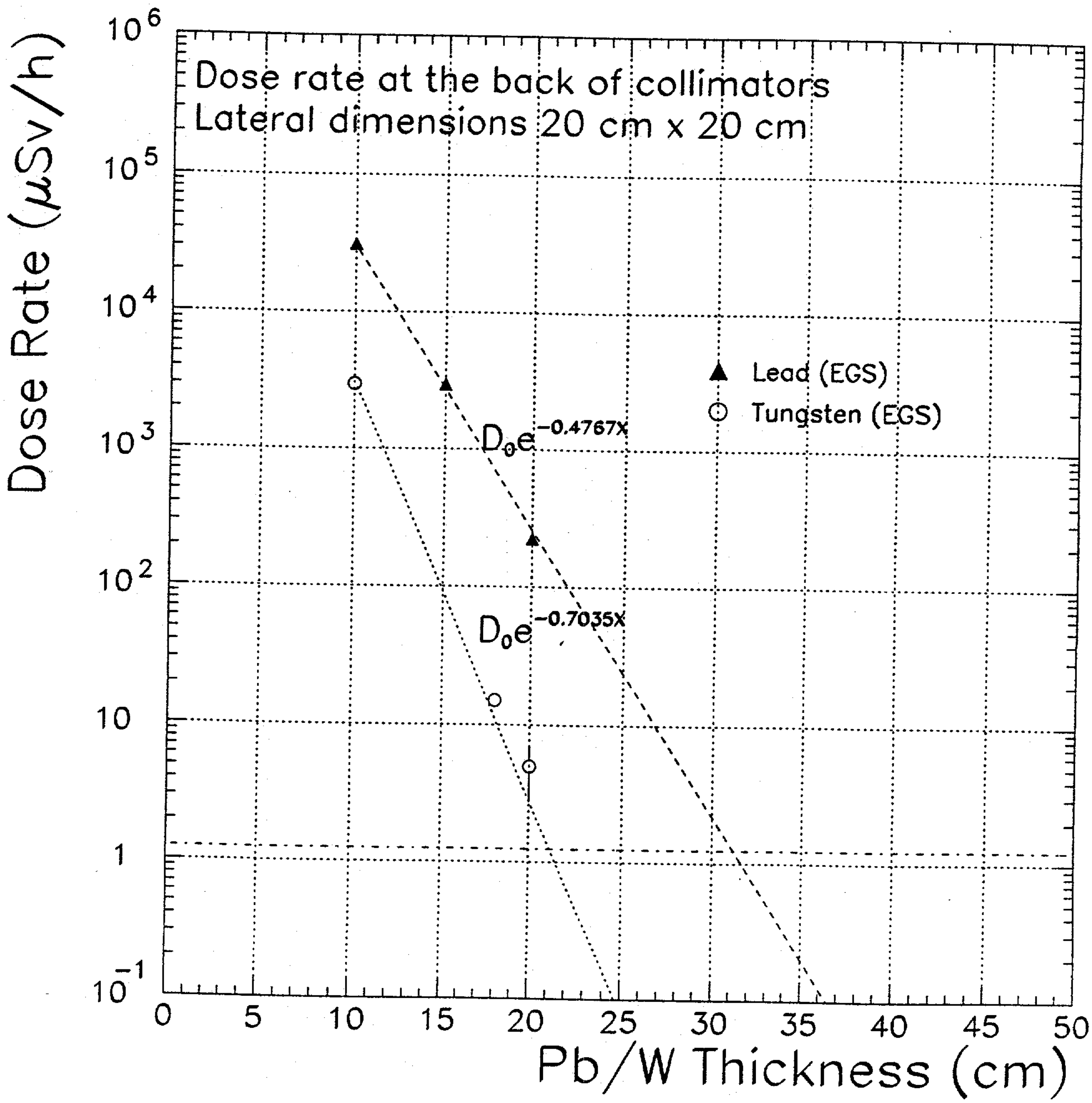

Figure 1. Dose rates at the back of the thick lead and tungsten targets due to the incident bremsstrahlung. The transverse dimensions of the solid block of metal are 20×20 cm^2. The 30-cm -thick tissue is in contact with the target.

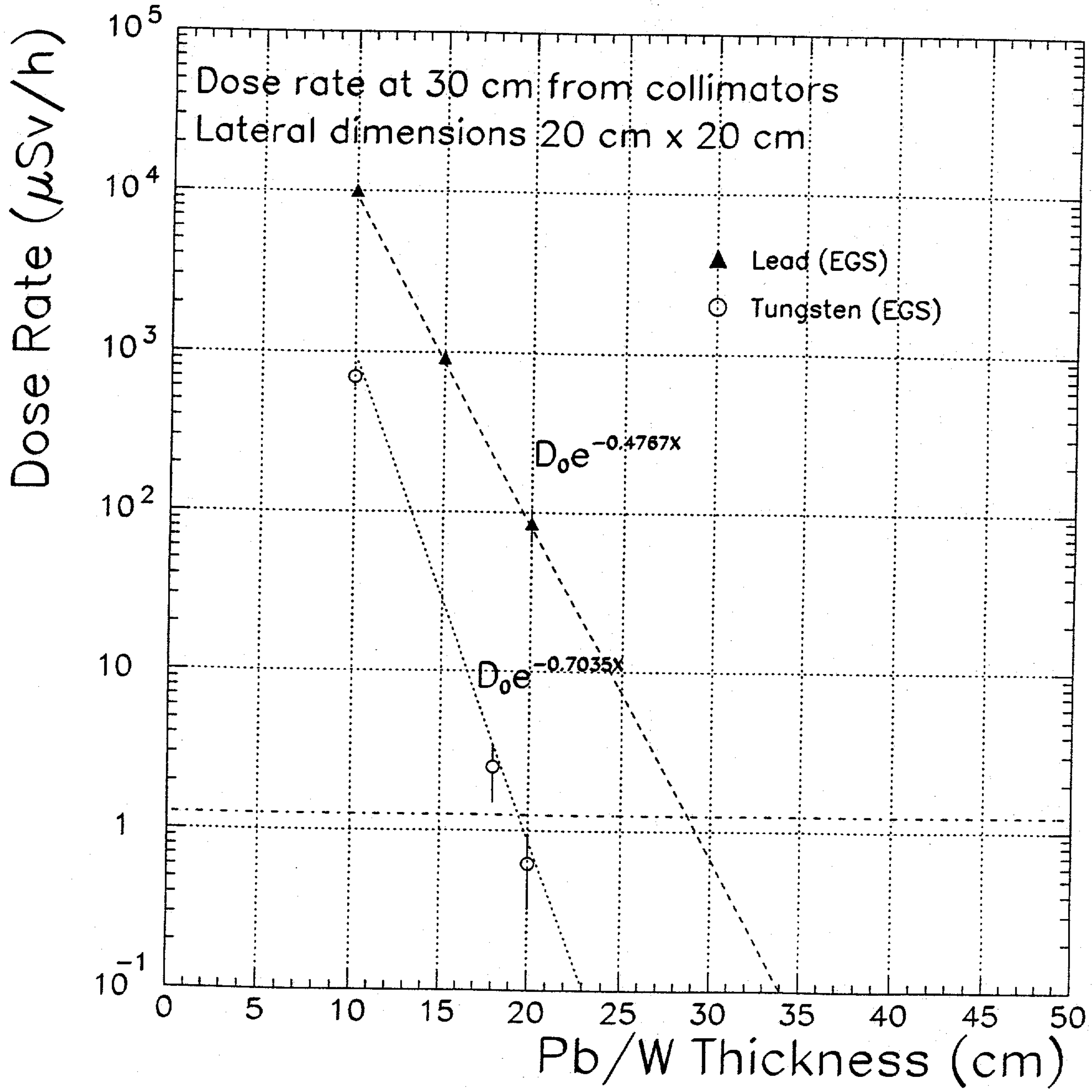

Figure 2. Dose rates at the back of the thick lead and tungsten targets due to the incident bremsstrahlung. The transverse dimensions of the solid block of metal are 20×20 cm^2. The 30-cm -thick tissue is at 30 cm from the downstream side of the target.

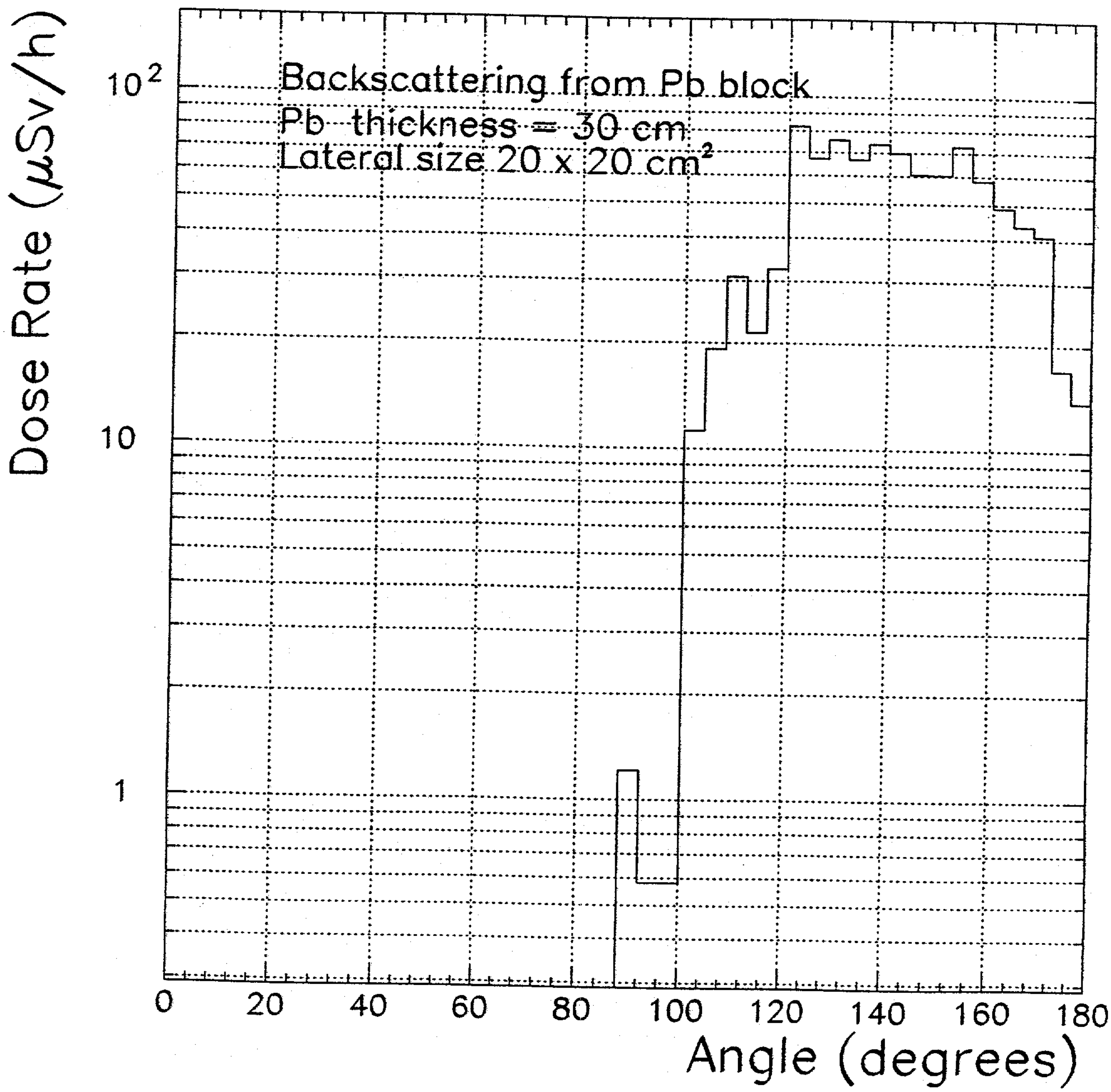

Figure 3. Dose rates due to the back scattering of the bremsstrahlung from a thick lead target. The integrated dose over the azimathal angle is given.

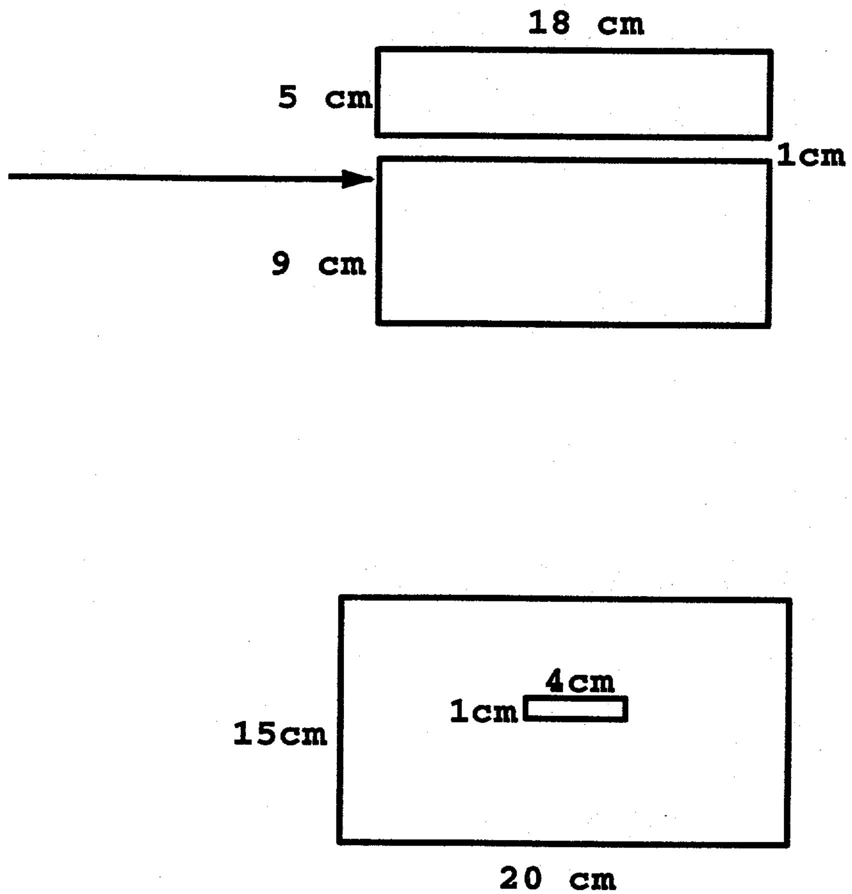

Figure 4. Diagram (side view and front view) of the mono-beam aperture and bremsstrahlung stop. This is made of tungsten and is a part of the integral shutter.

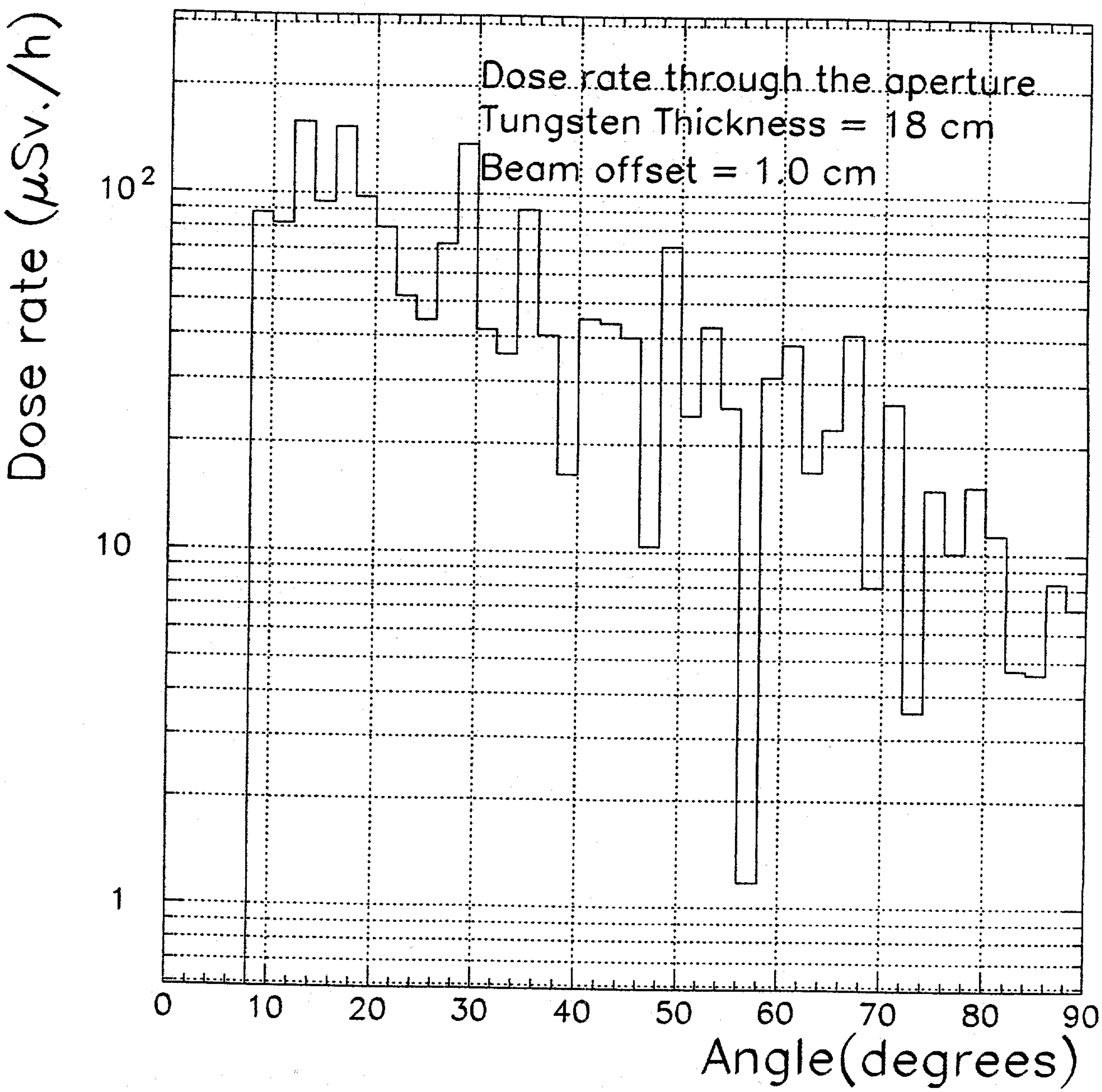

Figure 5. Scattered bremsstrahlung dose through the mono-beam aperture when the mono-beam is shut off. The greatest extent of the bremsstrahlung ray is incident at 1.0 cm from the aperture. Dose rates are estimated by placing the ICRU tissue in contact with the downstream side of stop.

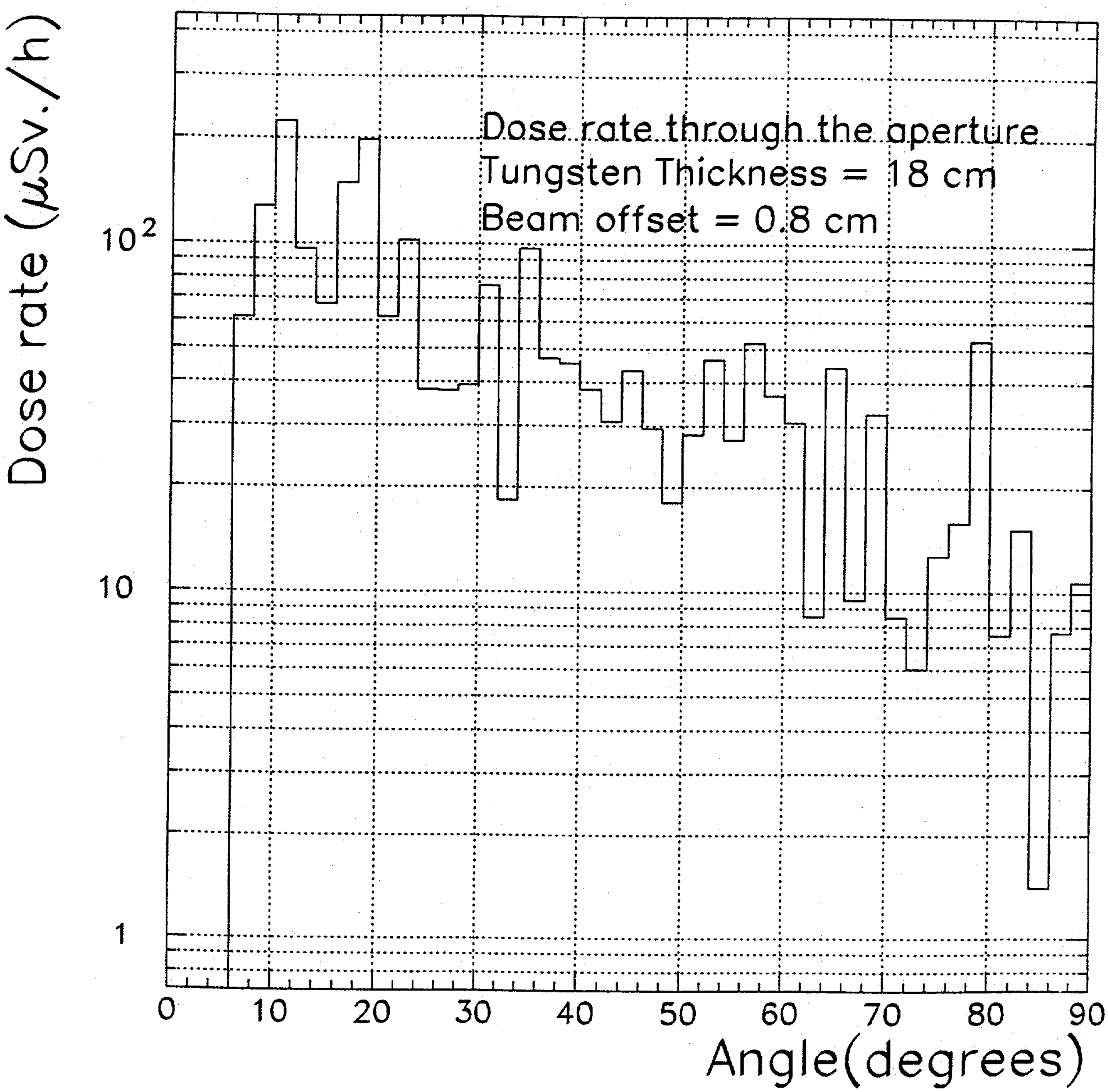

Figure 6. Scattered bremsstrahlung dose through the mono-beam aperture when the mono-beam is shut off. The greatest extent of the bremsstrahlung ray is incident at 0.8 cm from the aperture. Dose rates are estimated by placing the ICRU tissue in contact with the downstream side of stop.

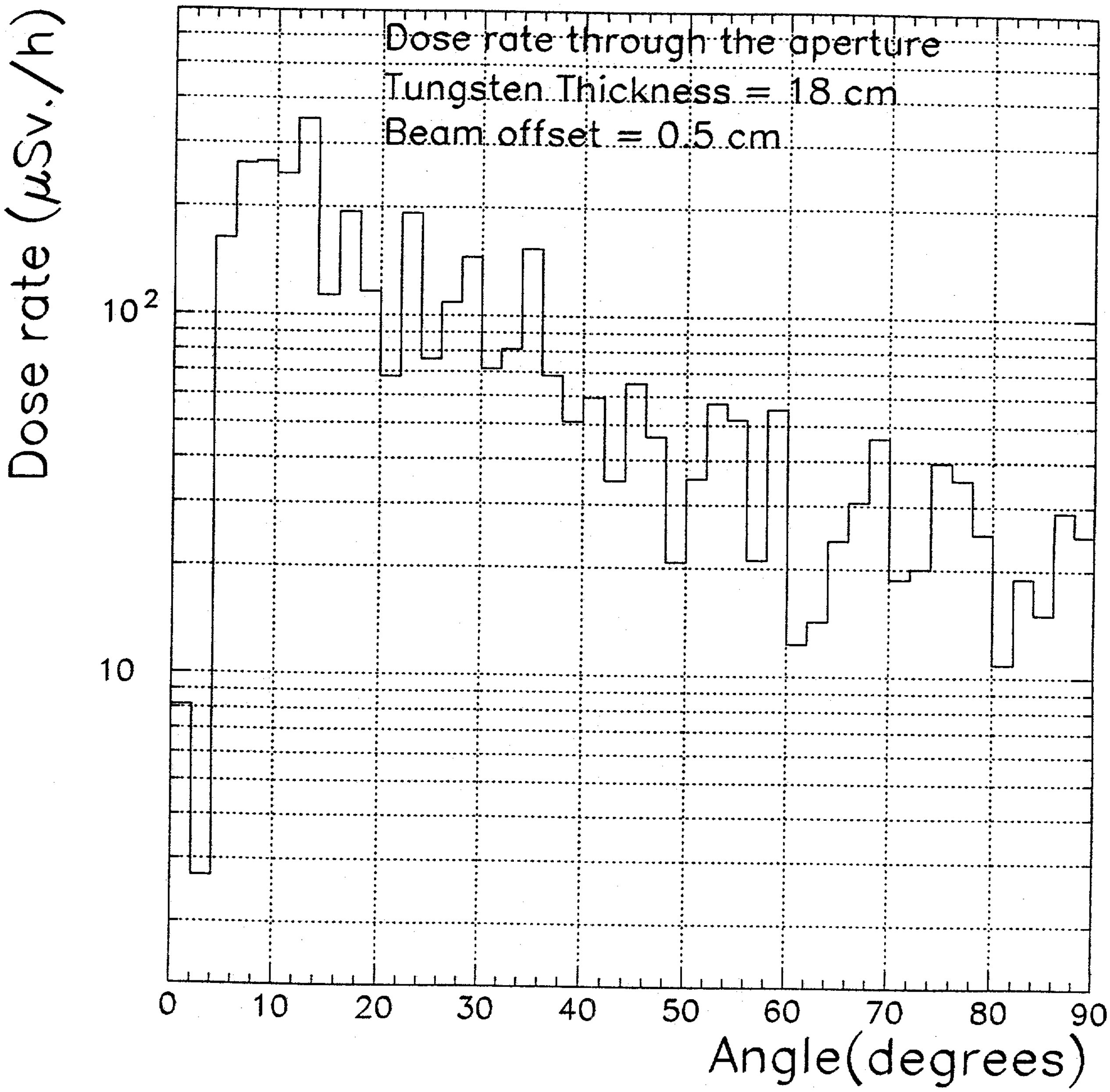

Figure 7. Scattered bremsstrahlung dose through the mono-beam aperture when the mono-beam is shut off. The greatest extent of the bremsstrahlung ray is incident at 0.5 cm from the aperture. Dose rates are estimated by placing the ICRU tissue in contact with the downstream side of stop.

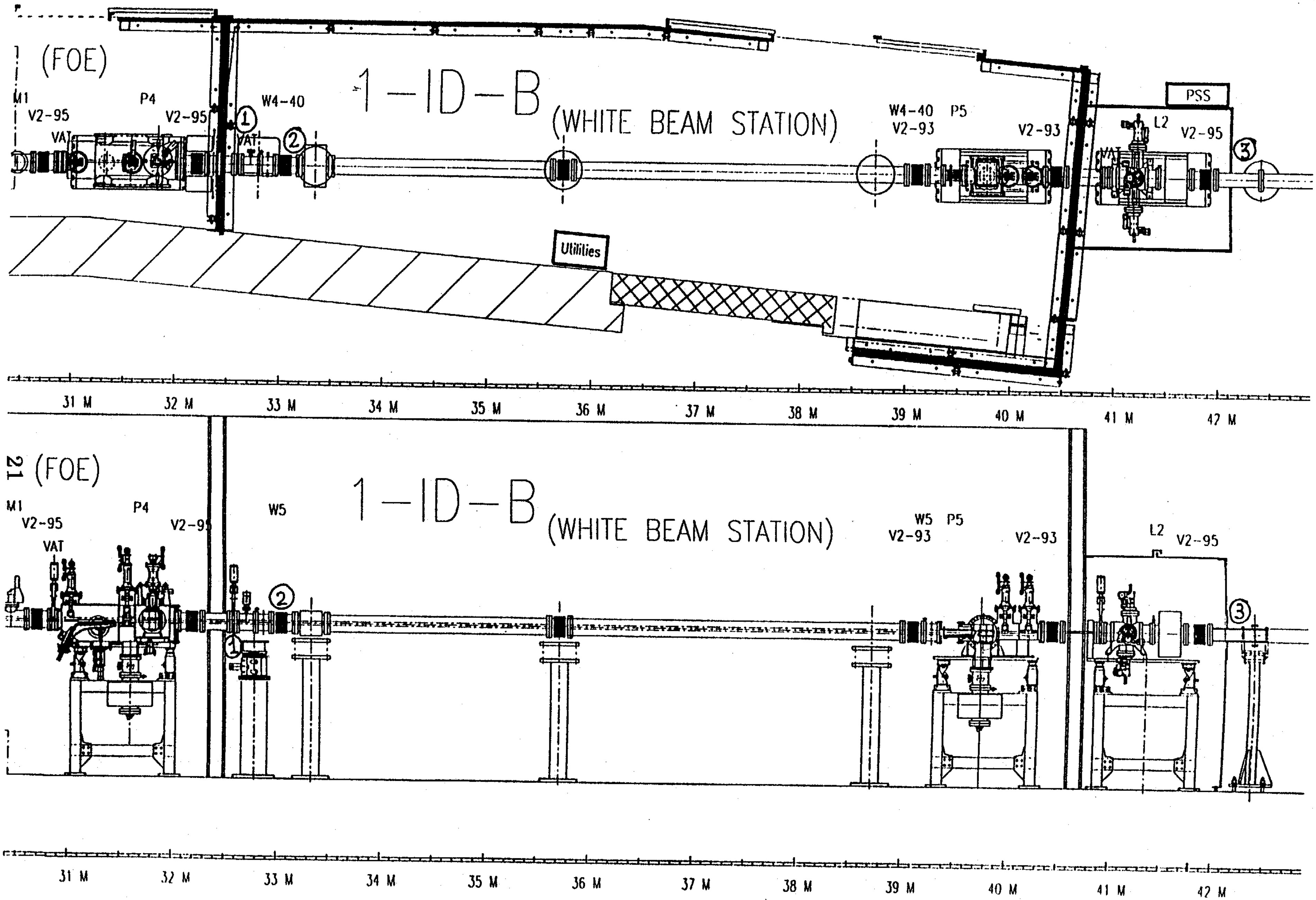

Figure 8. Diagram of white-beam station of 1-ID-B beamline

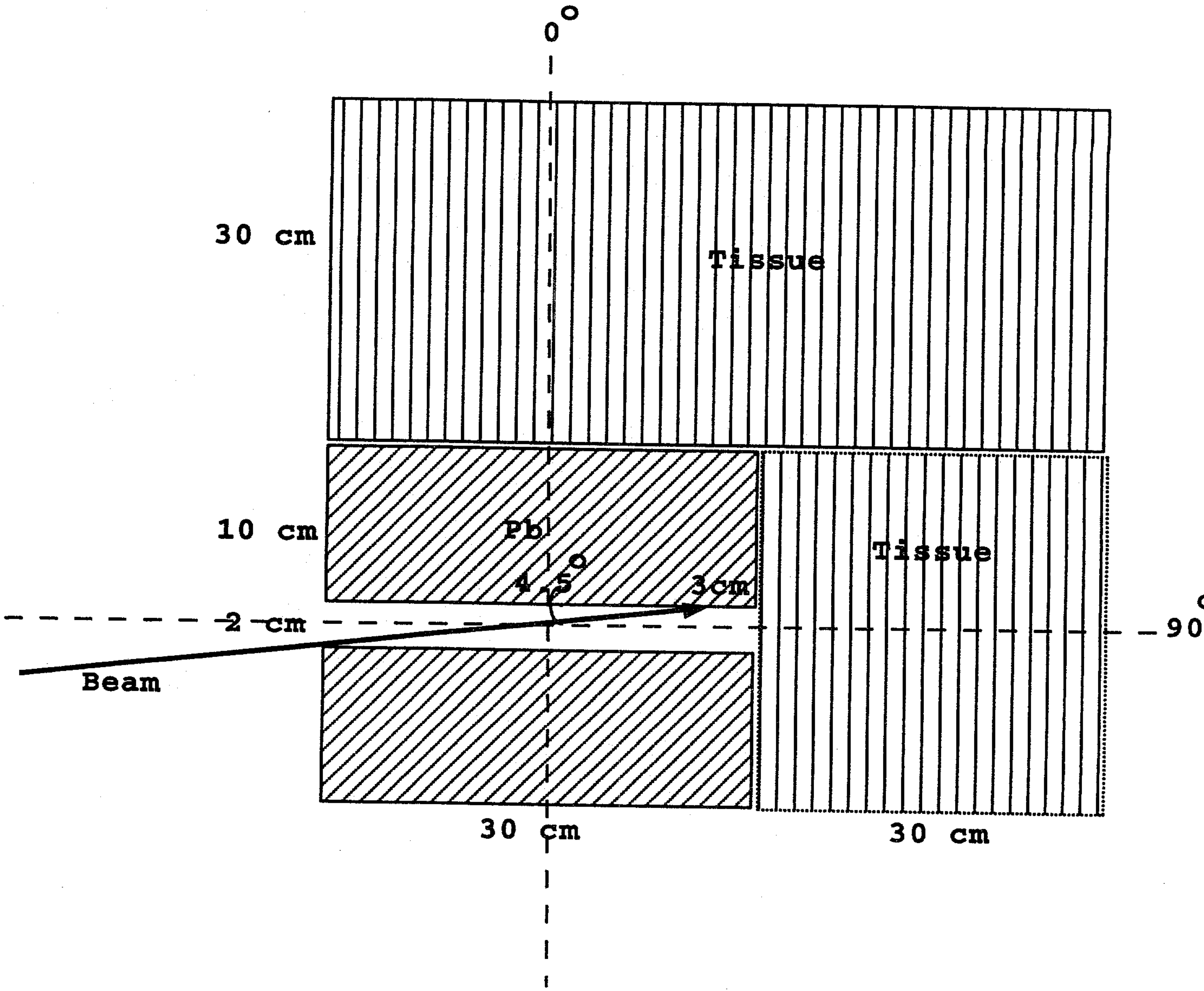

Figure 9. Diagram of the configuration used for the EGS4 calculation to estimate the dose rates on the beam pipe due to the missteered beam hitting the downstream edge of the collimator. The beam is incident at an angle of 4.5^0 and is 3 cm away from the edge. This allows the electromagnetic shower to fully develop.

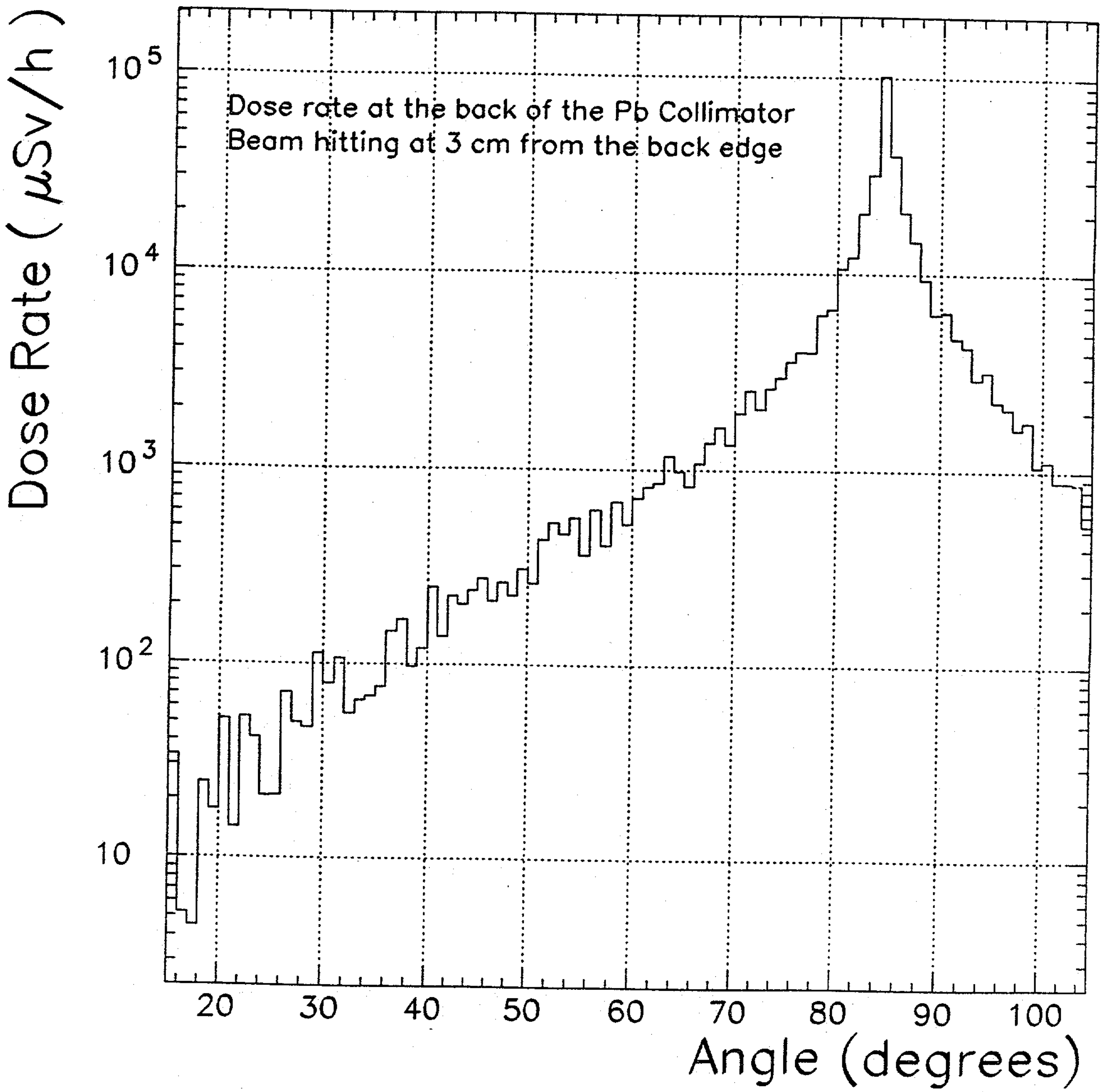

Figure 10. The EGS4 results for the dose rates in the tissue due to the beam hitting at the downstrem edge of the collimator. The tissue is in contact with the collimator. In this plot the 90^0 angle is the beam direction.

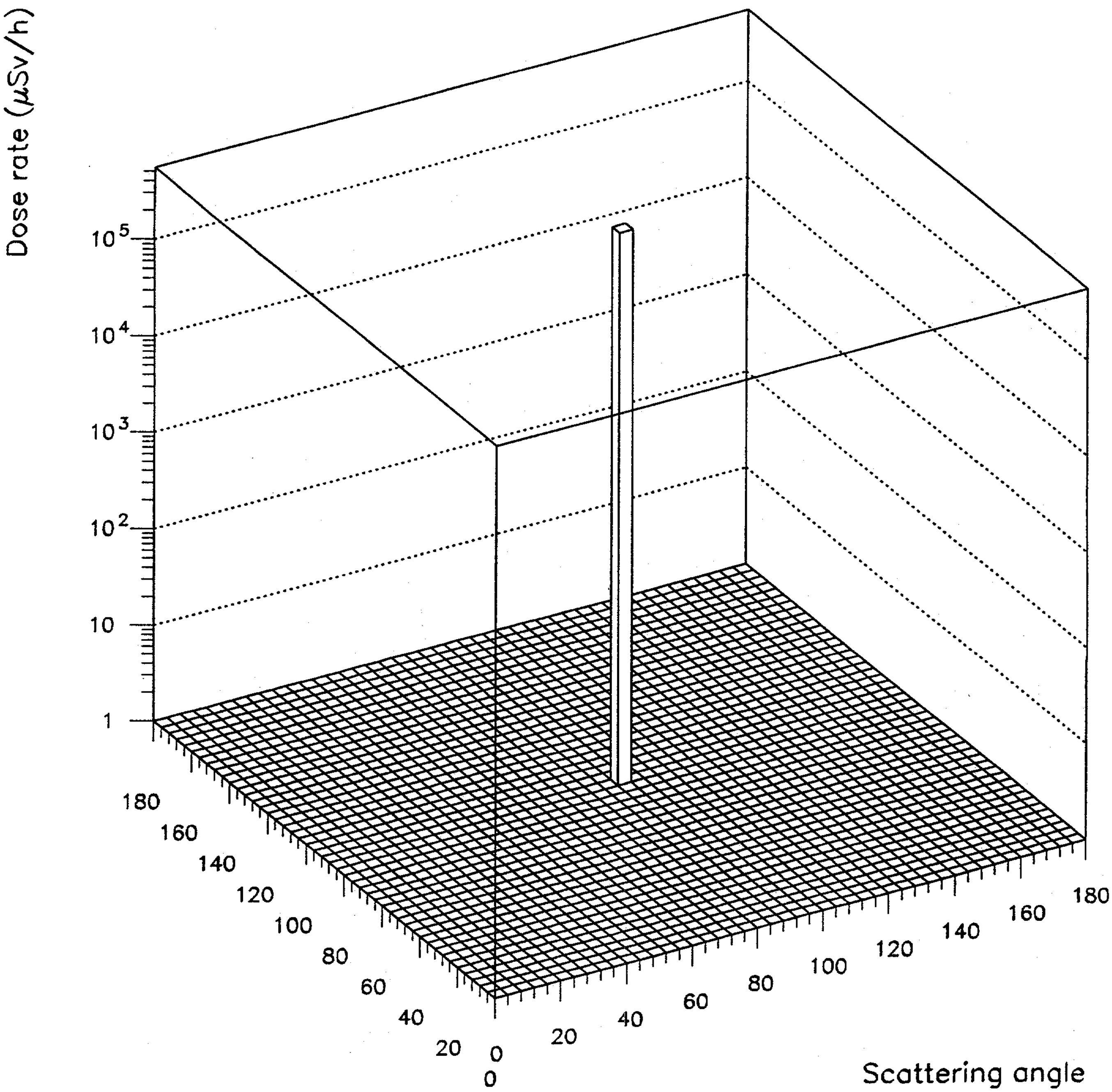

Figure 11. The EGS4 results for the scattering of the bremsstrahlung by a 100cm column of air in a 15-cm-diameter beam pipe (10000 events are simulated).

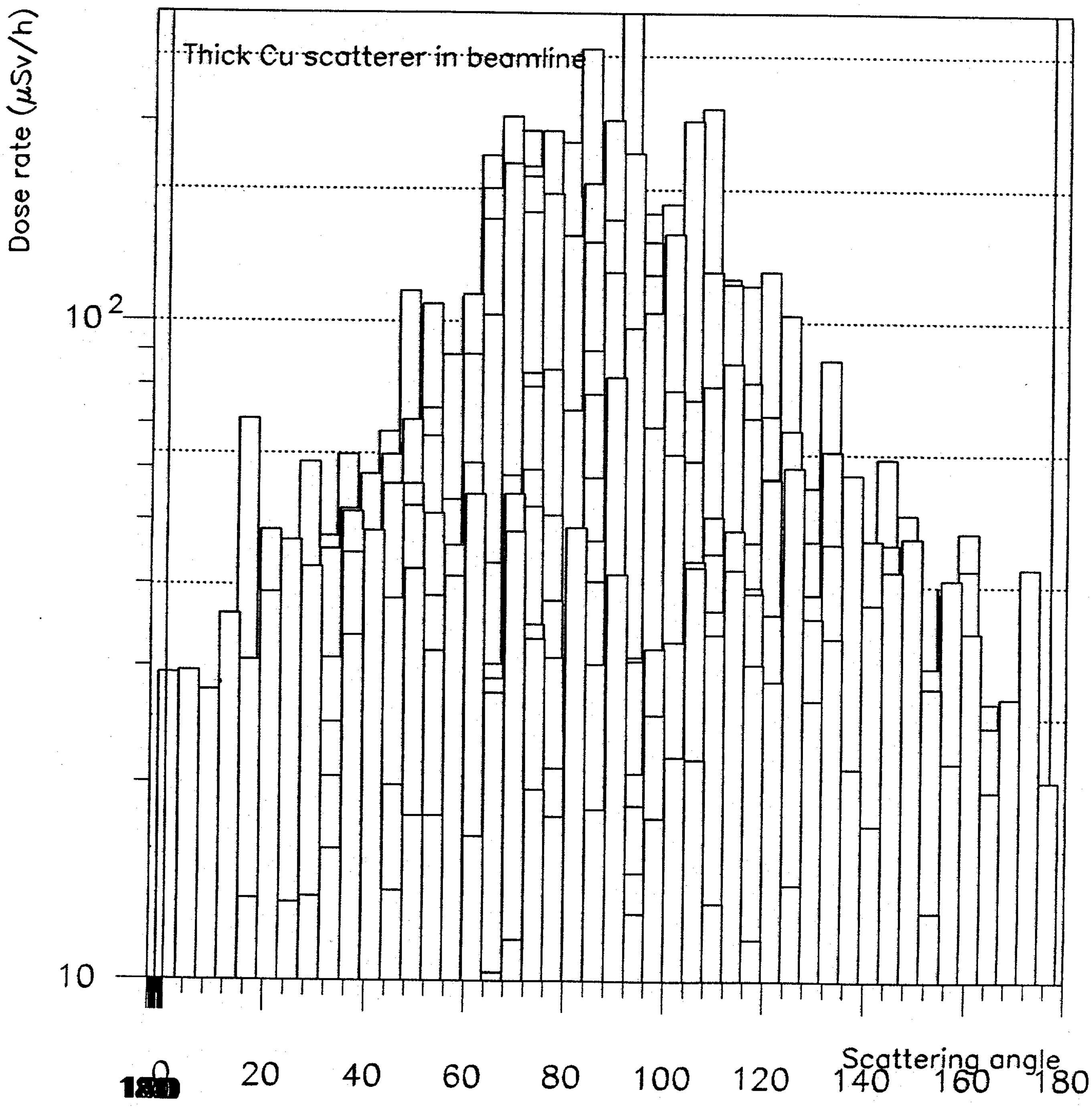

Figure 12. The EGS4 results for the dose rates for the scattering of bremsstrahlung in the beamline by a thick copper target. The tissue is in contact with the target.

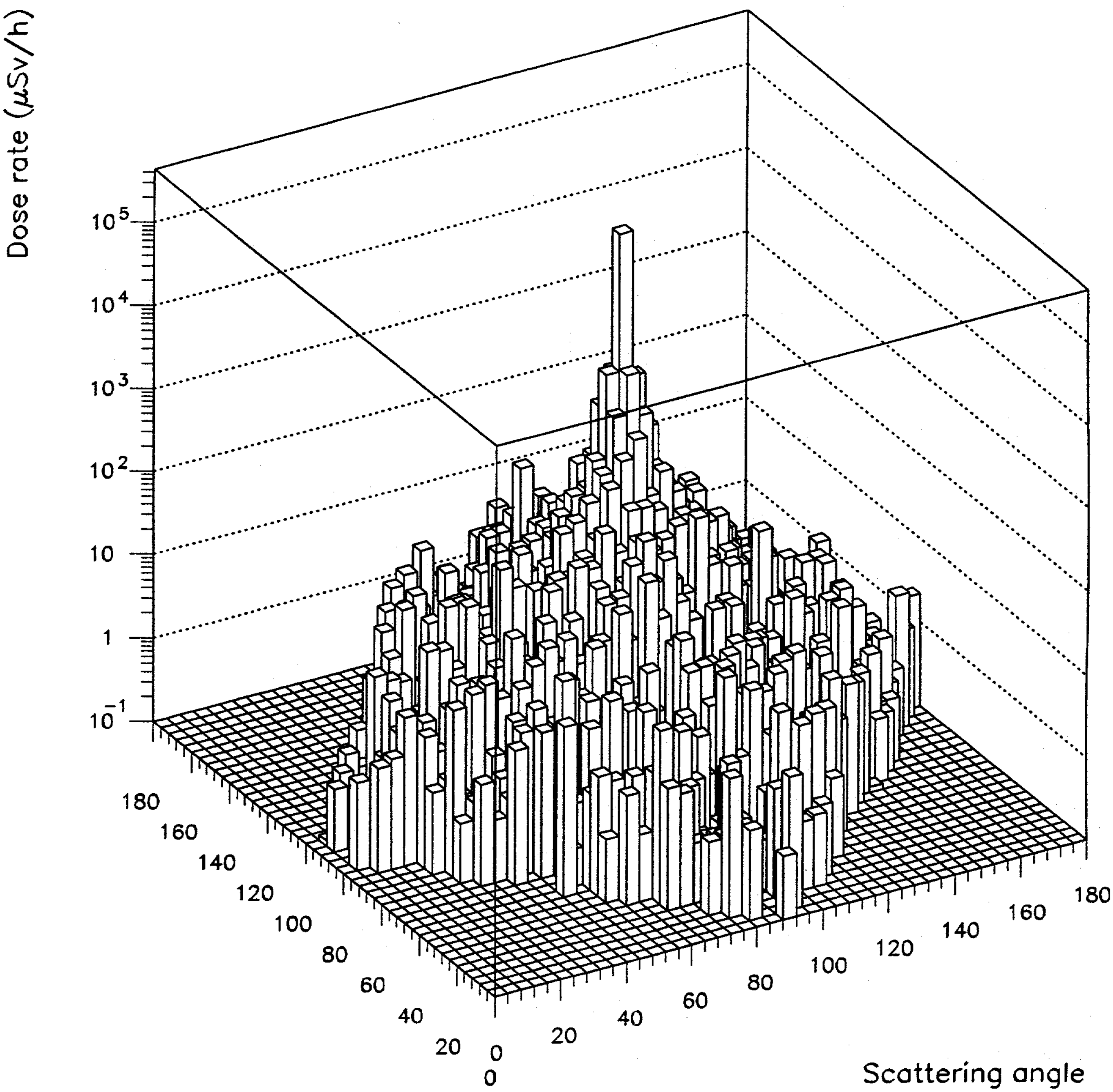

Figure 13. The EGS4 results for dose rates for the scattering of the bremsstrahlung in the beamline by a thin copper target (3 cm) with small transverse dimensions (4 cm×4 cm). (three-dimensional view). The tissue is in contact with the target.

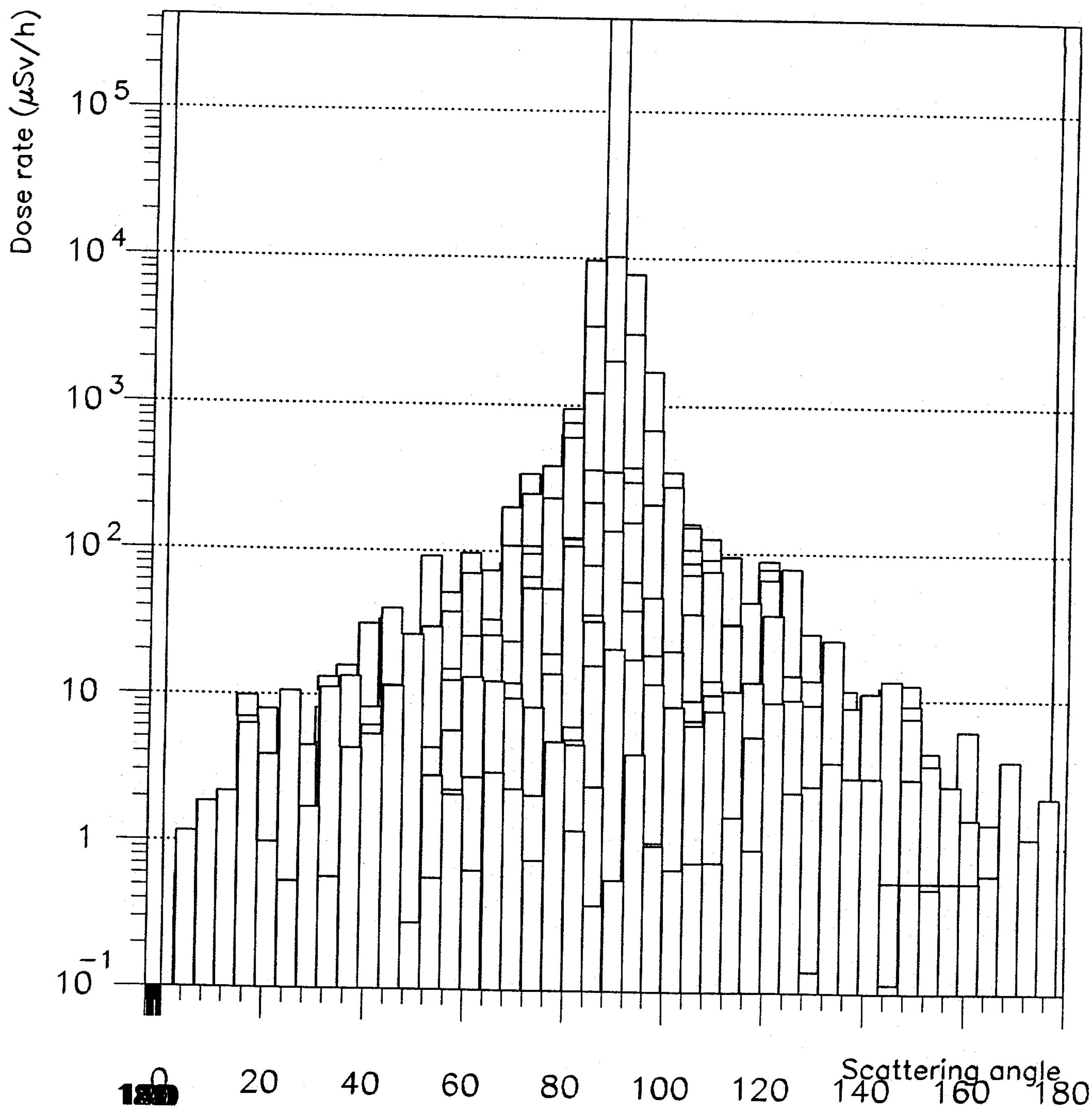

Figure 14. The EGS4 results for dose rates for the scattering of the bremsstrahlung in the beamline by a thin copper target (3 cm) with small transverse dimensions. The tissue is in contact with the target.