

Radiation Shielding of Insertion Device Beamlines Using a Mirror as the First Optical Element

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Abstract

The radiation shielding for an Advanced Photon Source (APS) insertion device beamline using a mirror as the first optical component is discussed. The beamline layout for a specific Synchrotron Radiation Instrumentation Collaborative Access Team beamline (sector 2 of SRI CAT) is described, and the methodology used to determine the radiation shielding is presented. Results indicate that, by using a x-ray mirror with a critical energy of 32 keV for total reflection, an undulator beam containing nearly all x-rays in the 0 - 32 keV spectral range can be delivered to experiment stations while the radiation shielding requirement outside the first optical enclosure is similar to that for an APS monochromatic beamline.

I. Introduction

Radiation shielding is one of the most important aspects in the design of an synchrotron beamline for high-energy storage rings, such as the APS. In this design of the SRI-CAT sector 2 insertion device beamlines, the radiation shielding was considered an important aspect in the selection of the optical design and the layout of beamline components. Our objective was to provide the full functionality required by the scientific programs planned for the beamlines while reducing construction cost and easing maintenance with proper integration of the beamline shielding with the optical design. We describe in this note the optical design used in our beamline and the methodologies used to determine the shielding requirements.

II. Design Criteria

For Department of Energy Facilities, the primary document on radiation safety is the *Radiation Control Manual (RadCon Manual)* [1]. The RadCon Manual requires that new facilities be designed so that the annual integrated dose equivalent received by an individual be no more than 500 mrem [1]. With the assumption of a 2000-hour working year, this becomes a dose equivalent rate (DER) of 0.25 mrem/h. The value of 0.25 mrem/h will be used as the criterion to be met throughout this document unless otherwise noted. This DER design limit is identical to that used in the "Guide to Beamline Radiation Shielding Design at the Advanced Photon Source" (ANL/APS/TB-7) [2].

Nonroutine situations may exist for a limited duration that would result in higher radiation dose equivalent rates. Under those conditions, the beamline cannot be used for conducting routine operations. Depending on the duration, a higher DER may be permitted, and shielding requirements for such situations will be discussed below.

The expected operating conditions of the APS storage ring are 7.0-GeV ring energy and 100-mA positron current. Higher storage ring energy and positron current, however, is possible at a future time. Because it is undesirable to retrofit shielding for structures such as hutches, the following storage ring operation parameters are used to make shielding calculations for the worst case. For synchrotron radiation, the storage ring energy is 7.5 GeV, and the stored positron current is 200 mA. For gas bremsstrahlung radiation, 7 GeV and 300 mA are assumed for the storage ring energy and current, respectively.

III. Description of Radiation Shielding Conditions of the Insertion Device Beamlines of SRI-CAT Sector 2 Using a Mirror as the First Optical Element

III.1 Beamline Layout

The layout of the SRI-CAT sector 2 insertion device (ID) beamline is shown in Figure 1. The ID beamline consists of three branch lines sharing the same straight section of the storage ring, the same front end, and the same first optical enclosure (FOE, labeled as 2-ID-A in Fig. 1). The schematic layout of the major optical and shielding components in the FOE is shown in Fig. 2. The branching is achieved using several mirrors. The most critical optical element in this beamline design is the horizontally deflecting mirror (M1 in Fig. 2). The advantages of using this mirror have been described elsewhere, and only a summary is provided here [3, 4]. The primary functions of this mirror are: (1) thermal management of beamline optical components, (2) suppression of unwanted high-order harmonics of undulator radiation when it is used with a monochromator, (3) separation of bremsstrahlung radiation from synchrotron radiation in conjunction with beam stops and collimators, and (4) suppression of high-energy x-rays, which reduces the amount of shielding required for downstream beamline transport. The last two functions are important aspects of our beamline design, and the radiation shielding in the presence of a mirror is the subject of this technical note.

III.2 Description of Shielding Considerations

The radiation to be shielded in our beamlines can be grouped into four categories: (1) primary high-energy bremsstrahlung radiation (BR) produced from either scattering of the stored positrons by the residual gas molecules in the storage ring or by collision of the positrons with the vacuum chamber, (2) secondary bremsstrahlung radiation (SBR) resulting from scattering of BR by optical components in the beamlines, (3) neutrons produced by either BR or SBR, and (4) synchrotron x-ray beams produced by the insertion device and bending magnet and scattering of the beam by components in the beamlines.

In general, the first three categories of radiation should be shielded as close to their source points as possible because (1) they do not contain useful radiation for synchrotron x-ray experiments, and (2) the complications for radiation shielding associated with the design, operation, and maintenance of downstream optical and vacuum components can be substantially reduced.

The synchrotron radiation can be separated from BR by using either a reflecting optic (e.g., x-ray mirror) or a diffracting optic (e.g., crystal monochromator) to offset the undulator beam from

BR. The BR is then subsequently stopped by using a heavy-metal beam stop. For our beamline design, a mirror/beam-stop combination is used to separate the BR from the synchrotron beams. In the following sections, the shielding requirements for BR, SBR, neutrons, and synchrotron radiation are discussed.

IV. Shielding Requirements for BR, SBR, and Neutrons

IV.1 Shielding Requirements of the FOE for BR, SBR, and Neutrons

IV.1.1 BR Collimation by the APS Front End

The standard APS ID front-end design includes several lead apertures (see Figs. 3a and 3b), which reduce the solid angle of BR entering the FOE. The effective BR collimation angles for the horizontal and vertical planes are also shown in Figs. 3a and 3b, respectively. Note that the BR collimation angles for the inboard and outboard directions are different, with the inboard angle smaller than the outboard angle.

IV.1.2 Mirror Incidence Angle Selection

The separation of the synchrotron beam from the BR using a x-ray mirror requires that the incidence angle on the mirror be larger than one half of the effective BR collimation angle at the mirror location. In practice, a larger incidence angle is required to ensure that the BR can be effectively separated from the synchrotron radiation by a beam stop. While the minimum incidence angle is set by the separation of the synchrotron beam and the BR, its maximum value is set by the largest x-ray energy required by the scientific programs planned for the beamline because, for a x-ray mirror, high x-ray reflectivity can only be obtained when the incidence angle is less than the critical angle for total reflection.

In our beamline design, a grazing-incidence angle of 0.15° (2.6 mrad) deflecting horizontally in the inboard direction is selected for the first mirror M1 (Fig. 2). The rationale for this selection has been described elsewhere and only the part relevant to the radiation shielding is discussed here [4]. The reason for deflecting the x-ray beam toward the storage ring is that the effective collimation of the BR in the inboard direction is much smaller than that in the outboard direction. At 0.15° grazing-incidence angle, the offset from the center of the reflected synchrotron beam to the center of the BR at the beam stop (K3 in Fig. 4a) is about 32.4 mm. Because the offset is proportional to the distance between the mirror and K3, it is useful to increase this distance if possible. Note that both K2 and K3 in Fig. 4a are required to obtain a minimum distance of 8 mm between the point where BR strikes on K3 and the aperture of K3. In Fig. 4b, a ray tracing for BR in the vertical direction is also given. From Figs. 4a and 4b, we conclude that the BR is completely stopped with the FOE.

IV.1.3 Scattering Source in the FOE for BR

In order to calculate or estimate the shielding requirement for the walls and roof of the FOE and the beamline transport downstream from the FOE, it is necessary to know the angular distribution of SBR from various scattering targets in the FOE. It is also necessary to know the worst case scattering target in the FOE. In normal operations, the primary scattering target will be the mirror M1, shown in Fig. 2. Because the thickness of the coating materials for the M1 mirror will be less than 1000 Å thick, the substrate material of the mirror will be the main scattering source for SBR. Although Si has been chosen as the substrate material for the M1 mirror at the present time, we also considered the possibility of using copper as a substrate material at a later date. For a substrate with linear dimensions of 10 x 10 x 120 cm and an incidence angle of 0.15° (Fig. 5), we found that the Si substrate requires more stringent shielding requirements than does the Cu substrate. This is because the mirror size in both cases allows for a bremsstrahlung shower to be fully developed but the absorption of the bremsstrahlung is less for Si than it is for Cu. Therefore, the SBR scattered by the Si mirror substrate will be used to determine the shielding for the FOE and the downstream beamline transport. As we will show below, the shielding requirement of the FOE for the SBR scattered by the Si mirror substrate is more stringent than those recommended in ref. 2.

The angular distributions of SBR dose equivalent rate (DER) for the Si scattering target were calculated, and the results are shown in Fig. 6. In order to obtain the maximum dose rate as a function of angle between BR and SBR in the horizontal plane, the three-dimensional plot in Fig. 6 is projected onto the plane defined by the horizontal angle axis and dose rate axis, and the results are shown in Fig. 7a. Figure 7b shows the results with better angular resolution over a smaller angular range. Figure 8 shows a similar projection on the plane defined by the vertical angle axis and dose rate axis.

Because the neutron production rate for Si is much smaller than that for W and even for Cu, the neutron shielding requirements of the FOE may be much less than that calculated for a similar FOE at the APS [2]. During commissioning of the beamlines, the neutron dose rate will be measured and appropriate shielding added if necessary.

IV.1.4 Shielding of the FOE Back Wall

For calculating the shielding requirements for the FOE back wall, the calculated DER in Fig. 7b is adjusted by the distance from the mirror to the back wall. The minimum distance from mirror to back wall is 6.5 m. For simplicity, a constant distance of 6.5 m is used to calculate the factor needed for the distance-adjusted DER and the result is $1/(6.5)^2 = 0.024$. Table 1 lists the lead thickness of the FOE back wall that is required to achieve the DER design limit of 0.25 mrem/h as a function of scattering angle. The required thickness is calculated using the expression $t = [\ln(0.024 \times 0.1 \times \text{DER}) - \ln 0.25] / 0.473$ (cm), where 0.024 is the adjustment factor due to distance, the DER is obtained from Fig. 7 for a given scattering angle of interest, the factor 0.1 is the conversion factor from μSv to mrem, and the denominator 0.473/cm is the minimum of the linear absorption coefficient of lead at about 3 MeV bremsstrahlung radiation.

Table 1 Lead Shielding vs Scattering Angle for FOE Back Wall

Scattering angle (degrees)	0	1	2	3	4	5	6	7	8
Pb thickness (cm)	15.4	13.7	11.1	9.6	8.2	7.7	7.4	6.2	4.8

Table 1 indicates that the lead shielding required to reduce the DER in the forward direction varies rapidly as a function of scattering angle. For compatibility with the standard APS FOE design, which has 5.08 cm of lead shielding on the back wall and an additional 5.08 cm of lead 1 m around the beam, additional local shielding will be needed.

The local shielding consists of a W piece placed in front of the M2 mirror (W1 in Fig. 2) and a bremsstrahlung beam stop located near the back wall of the FOE. The W piece has a circular hole in its center. The size of this hole and overall dimensions of the W piece are chosen to provide SBR shielding that covers the scattering angles between 1 and 7 degrees around the BR. Because the minimum of the linear absorption coefficient for W is 0.71/cm, which is about a factor of 1.5 that of Pb, the extra W thickness required near the FOE back wall is $(13.7 - 5.08)/1.5 = 5.75$ cm. The bremsstrahlung beam stop near the back wall of the FOE should be centered with the BR and have a radius greater than 23 cm to cover the scattering angles between 0-1 degrees around the BR. The minimum thickness of the bremsstrahlung beam stop is 15.4 cm for Pb or 10.3 for W.

IV.1.5 Shielding of the FOE Side Wall

Because of the relatively large statistical fluctuation in the calculated DER in Fig. 7a in the large angle region, a smooth curve of the maximum DER value is drawn and used for calculating the radiation shielding. The lateral distance between the center of the beamline and the FOE side wall is approximately 1.33 m. The angle between the BR and the line connecting the mirror and the corner of the FOE side wall and back wall (see Fig. 2) is 11.6 degrees. From Fig. 7a, we see that the calculated DER for 11.6 degrees is about $250 \mu\text{Sv/h} = 25 \text{ mrem/h}$. Adjusting the DER by the distance between the mirror and the corner, the DER at the corner is approximately equal to 0.56 mrem/h. To reduce the DER below 0.25 mrem/h, a Pb shielding 1.7 cm thick is required. This thickness is less than that of the 1.9 cm lead shielding for a standard APS FOE hutch. Table 2 lists the Pb thickness required to obtain the DER design limit as a function of angle for the side wall using the same procedure described above.

Table 2 Lead Shielding for the FOE Side Wall

Scattering angle (degree)	11.6	20	30	40	50	60
DER from Fig. 7 (mrem/h)	25	10	5	2.8	1.7	1
Distance adjusted DER (mrem/h)	0.56	0.66	0.7	0.68	0.56	0.42
Pb thickness (cm)	1.7	2.1	2.2	2.1	1.7	1.1

The results in Table 2 indicate that the standard FOE side-wall shielding may not be enough for some scattering angles, and additional local shielding may be necessary. The local shielding, however, is very modest and will be added if necessary.

IV.1.6 Shielding of the FOE Roof

The distance between the beamline and the roof of the FOE is 1.95 meters. The scattering angle in the vertical direction for the roof is larger than 17.5° , which is the angle between the beamline and the line connecting the mirror and the corner formed by the back wall and the roof. Because of low occupancy of the FOE roof, a DER design limit of 2.5 mrem/h will be used for calculating the shielding requirement. Following the procedure described for calculating the shielding requirements for the side wall, we concluded there is no lead shielding required for the FOE roof for bremsstrahlung radiation, but shielding is required for synchrotron beam, and the calculation is presented in Section V.

IV.1.7 Additional Considerations

It is interesting to note that the FWHM of the BR natural divergence angle is approximately $\theta = 1.134/\sqrt{E(\text{GeV})} = 1.134/\sqrt{1957E(\text{GeV})}$, where $E(\text{GeV})$ is the storage-ring energy expressed in units of GeV. For $E(\text{GeV}) = 7$, $\theta = 83 \mu\text{rad}$ is approximately 4 and 1.5 times larger than the FWHMs of the vertical and horizontal divergences, respectively, of the undulator A first harmonic radiation. Thus it may be possible to design a beamline with an aperture that has high transmission of the undulator beam but low transmission of BR. This conclusion holds even though the effective BR source size is extended. Since the reduction in DER of BR or SBR by a 1-cm Pb shielding is only about 1.6, the use of a small BR aperture may be worthwhile to consider in some beamline designs.

IV.2 Shielding Requirements of Branch Line 2-ID-E for SBR

IV.2.1 Shielding Source Considerations

SBR shielding for the branch line is needed at the downstream end of the FOE. Shielding is required only for the portion of SBR that transmits through the aperture of the lead collimator K3-E located at the FOE back wall (Fig. 2). The aperture of K3-E is assumed to be 12 mm in the horizontal direction and 20 mm in the vertical direction. The K3-E is made of W and is 10 cm thick.

The shielding of SBR in the beamline outside of the FOE can be grouped into the following two types: (1) shielding of the SBR directly scattered from the mirror, and (2) the scattering of the SBR by other vacuum or optical components in the beamline. In our beamline design, the first shielding type is provided by a photon shutter located inside the FOE and the second shielding type by the beamline transport.

IV.2.2 Photon Shutter Shielding Requirement

For the first shielding type against SBR, there are no clear guidelines from the DOE or other relevant agencies on how to estimate dose rates for small beams in designing facilities. A DOE implementation guide on external dosimetry [5] gives criteria for dosimetry of skin exposures, but it does not directly apply here. We have followed the general philosophy in this guideline in developing our methodology. The problem is to determine the dose when the beam is not giving

a whole-body dose but deposits its energy into a much smaller volume. In such cases, likely movement of the human body should be considered if many hours are required for a significant dose to be deposited in a particular volume.

In this study, we have decided to take the following approach when dealing with beams smaller than 100 cm^2 . For shielding a beam with cross section A less than 100 cm^2 , the effective DER that needs to be shielded is $\text{DER}_{\text{effect}} = g \text{ DER}$, where $g = A/100$ (A in units of cm^2), DER is the maximum dose rate within the beam, and the minimum value of g is 0.1.

The cross-sectional area A of the SBR at the downstream end of the K3 collimator increases with the distance L from the mirror M1 and is smaller than 100 cm^2 for $L < 42$ meters. For $L = 13.28$ m, $A = 10 \text{ cm}^2$. Thus, $g = 0.1$ will be assumed for $L < 13.28$ m.

From Fig. 7b, we obtained $\text{DER} = 1.5 \times 10^5 \text{ Sv/h} = 1.5 \times 10^4 \text{ mrem/h}$ for forward scattering (0 degree of scattering angle). Therefore, for $L < 13.28$ m, $\text{DER}_{\text{effect}} = 1.5 \times 10^3 \text{ mrem/h}$. The thickness T of solid tungsten (W) or lead (Pb) required to attenuate the $\text{DER}_{\text{effect}}$ to 0.25 mrem/h can be calculated using the following expressions.

$$T_{\text{W}} = [\ln(1.5 \times 10^3/L^2) - \ln 0.25]/0.71 \text{ (cm) for W} \quad (1)$$

and

$$T_{\text{Pb}} = [\ln(1.5 \times 10^3/L^2) - \ln 0.25]/0.48 \text{ (cm) for Pb,} \quad (2)$$

where L is the distance expressed in meters between the mirror and the point of interest for calculation.

For $42 \text{ m} > L > 13.28 \text{ m}$, $A = 5.67 \times 10^{-6} L^2$, and $\text{DER}_{\text{effect}} = g 1.5 \times 10^4/L^2 = 8.5 \text{ mrem/h}$. Expressions (1) and (2) become

$$T_{\text{W}} = [\ln 8.5 - \ln 0.25]/0.71 = 5 \text{ cm} \quad (1a)$$

and

$$T_{\text{Pb}} = [\ln 8.5 - \ln 0.25]/0.48 = 7.5 \text{ cm.} \quad (2a)$$

Note that the thickness of the shielding material calculated in this segment of the beamline is independent of L . For $L > 42$ m, the DER decreases with L increasing, and thus the shielding requirement is less stringent than for $L < 42$ m.

Using the expressions above, the required shielding thicknesses against the direct SBR from the mirror as a function of L are calculated for Pb and W, and the results are tabulated in Table 3.

Table 3 Photon Shutter Shielding vs Distance from the Mirror

L (m)	6.5	13.3 - 42
T_{Pb} (cm)	10.3	7.5
T_{W} (cm)	7.0	5

The results in Table 3 indicate that if the photon shutter has a W block with thickness of 7 cm or more, the DER outside the FOE would be less than the DER design limit. Our shutters are designed to have two W blocks of 7 cm total thickness. Under normal operation conditions, the DER in our experimental station, which is located more than 30 meters from the M1 mirror, is substantially smaller than 0.25 mrem/h.

IV.2.3 Beamline Transport Shielding Requirement

For the second category of shielding, the spectrum and the integrated DER of the SBR portion passing through the lead collimator K3-E (see Fig. 2) are two important parameters. The integrated DER (DER_{int}) can be calculated by converting the $DER = 1.5 \times 10^5 \mu\text{Sv/h}$ into DER per solid angle and then multiplying by the solid angle subtended by the K3-E collimator. The solid angle covered for calculating a $DER = 1.5 \times 10^5 \mu\text{Sv/h}$ in Fig. 7b is $1/57.3 \times 1/57.3 \text{ radian}^2$, and the solid angle subtended by the K3 collimator is $2 \times 1.2/(650)^2 \text{ radian}^2$. From these values, we obtained the $DER_{int} = 2798 \mu\text{Sv/h} = 279.8 \text{ mrem/h}$, which is about three orders of magnitude smaller than the integrated DER of BR incident on the Si mirror substrate in the FOE [6].

The angular distribution of the second category of SBR scattered by a W target with a cross section of 4 cm \times 4 cm and a thickness of 3 cm was calculated, and the result is shown in Fig. 9. The W target is assumed to represent a possible strong scatterer in the beamline. For this calculation, all the SBR was assumed to strike in a 2 cm \times 1.2 cm area on the W target. Note that the maximum equivalent dose rate is less than $2.3 \mu\text{Sv/h} = 0.23 \text{ mrem/h}$ at a distance of 1 meter from the scatterer and does not vary significantly over all the scattering angles calculated.

The results in Fig. 9 indicate that, if an optical component may act as a scattering source of SBR in performing its designed function during normal beamline operation, such as the pink-beam slit in our beamline, it should be housed in an enclosure. The walls of this enclosure may not need any shielding material, such as Pb, if their distance from the scattering source is 1 meter or more. For a smaller all-source distance, additional shielding should be used.

For a hypothetical case in which a piece of metal is left in the beam transport tube, the DER received by an individual may be larger than 0.25 mrem/h because the diameter of the transport tube is only about 10 cm. If the metal piece scatters SBR as efficiently as the W target, the distance-adjusted DER at 22 cm from the scattering source is 5 mrem/h without the presence of shielding. However, because the hypothetical case considered here is a nonroutine situation of limited duration and the metal piece may scatter SBR much less than the W scattering target used for modeling, a higher DER may be permitted. With the assumption that the total annual duration of an individual working in the vicinity at this high-radiation area is less than 100 hours and that the scatterer is less efficient than the W target, we believe there is no need for additional shielding for this special case for SBR. In addition, lead shielding 9 mm thick will be used as the standard beam transport tube for this beamline, and it will reduce the DER by a factor of about 1.5.

The SBR spectrum calculated for the Si substrate is shown in Fig. 10. The results indicate that the majority of the SBR photons are in the 1-6 MeV energy range. The photons in this energy range have a much smaller neutron yield than do high-energy electrons or photons [7]. The

combination of the small neutron yield and the fact that the integrated DER_{int} is much smaller than the integrated DER of BR entering the FOE lead us to believe that neutron shielding of the beamline transport is significantly less than that calculated for the shutters/stops (see Ref. 2) and thus is not required. The assumption will be tested during commissioning of the beamline.

IV.3 Shielding Requirements of Branch Line 2-ID-C for SBR

Similar to the case for branch line 2-ID-E discussed above, SBR to be shielded for the 2-ID-C beamline downstream of the FOE is that portion of the SBR that originates from the scattering of BR by the mirror or other components and transmits through the lead collimator K3-C located at the FOE back wall (Fig. 2). The use of the M2 mirror for deflecting the x-ray beam to this branch line has very little effect on the beamline shielding against bremsstrahlung radiation. The aperture of K3-C is assumed to be 20 mm in the horizontal direction and 20 mm in the vertical direction. The K3 is fabricated using W and is 10 cm thick.

Similar to the case for the 2-ID-E branch line, during the normal beamline operating conditions, the most stringent shielding requirement is the case in which the M1 mirror substrate is Si. However, because the angle between the branch line and the BR is much larger than that for the 2-ID-E branch line, the shielding requirement for this branch line is relatively modest.

For the first shielding type of SBR during normal beamline operating conditions, the same approach for small beam shielding (as in Section IV.2.2) is followed. The cross section A of the SBR at the downstream end of the K3-C collimator increases with the distance from the mirror L and is smaller than 100 cm^2 for $L < 25$ meters. Following the same procedure used for the 2-ID-E branch lines, we concluded that a shutter with 4.2-cm-thick W will be adequate for reducing the DER below the design limit of 0.25 mrem/h downstream of the FOE.

For the second shielding type, the integrated $DER_{int} = 47$ mrem/h of the SBR portion passing through the lead collimator K3-C (see Fig. 2) is obtained using the same procedure used in the previous section. Angular distribution of the SBR scattered by an optical component can be estimated by scaling down the results shown in Fig. 10 by a factor of 6 because the $DER_{int} = 47$ mrem/h is about a factor of 6 smaller than that for the 2-ID-E branch line. Therefore, there is no need to shield the SBR scattered by a beamline component.

IV.4 Shielding Requirements of Branch Line 2-ID-B for SBR

Because of the relatively large scattering angle of K3-B collimator, the DER passing through it is less than that passing through K3-C collimator. Therefore, a shutter with 4.2 cm of W shielding would be adequate for shielding SBR during normal operating conditions for the 2-ID-B branch line. The K3-B collimator is the same size as the K3-C collimator, and, therefore, there is no need to shield SBR scattered by a vacuum or beamline component.

V. Shielding of Beam Transport for Synchrotron Radiation

As discussed in Section IV.2, the SBR does not create any special shielding requirement for the beam transport. Hence, the shielding of pink-beam transport will be determined by scattered synchrotron x-rays. Calculations were performed with a modified version of the PHOTON program, taking into account the reflectivity of the Pt mirror, which has the highest critical energy for total reflection and thus is the worst case for shielding consideration. The APS wiggler A was used as the source, although undulator A and a 5.5-cm undulator are actually planned for sector 2, because (i) the 5.5-cm undulator can have a critical energy similar to that of wiggler A, (ii) wiggler A is of more general interest, and (iii) to facilitate comparison with the white-beam case that had been studied in Ref. 2. Parameters are listed in Table 4. Two types of scatterers similar to those described in Ref. 2 were modeled inside a 6-inch-diameter beam pipe: 30 cm of copper and 30 cm of air at 1 atm. Copper was selected as an efficient scatterer, and it may represent any slit or aperture material present between the beam transports. Conversely, the 30 cm of air represents a vacuum failure inside the beam transport. In either case, the scattered radiation was shielded by Pb of various thicknesses surrounding the beam pipe. The absorbed dose by human tissues located behind the Pb shielding was then calculated. The Pb thickness and the corresponding dose rate are listed in Table 5.

Table 4 Parameters Used to Calculate Shielding of Beam Transport against Scattered Synchrotron X-rays.

Source	Wiggler A
Positron Energy	7.5 GeV
Positron Current	200 mA
Critical Energy	37.4 keV
Number of Poles	56
Vertical Acceptance	4/
Horizontal Acceptance	1.08 mrad
Energy Range (white beam)	1 – 300 keV
Bandpass* (mono. Beam)	0.1% (E/E)
Scatterer	30 cm Cu or air (at 29.45 m from the source)
Beam Pipe	6" dia.

The photon energy E of the monochromatic beam is chosen to provide the maximum dose rate behind the PB, whose thicknesses are listed in Table 5 for the individual monochromatic-beam case. This peak energy may vary with the Pb thickness and the beamline configuration.

Table 5 shows that 7 mm of Pb are needed on a pink-beam transport to shield against Cu scatterers for the wiggler A source, while 21 mm of Pb are required if the mirror is removed. This result is plausible after examining the reflected spectrum of Pt in Fig. 11. Directly below the Pb K edge at 88 keV, the reflectivity is about 1×10^{-3} , and from 150 to 250 keV, the reflectivity is between 1×10^{-4} and 1×10^{-5} . These two spectral regions are the “weak spots” of the Pb shielding, as can be seen from Fig. 12. The penetration depth in Pb for 88 keV x-rays is about 0.5 mm and for 250 keV x-rays is about 1.5 mm. Therefore, the 250 keV x-rays are harder to shield against than the 88 keV x-rays. In the case without a mirror, the Pb thickness has to be increased from 7 mm to 21 mm in order to reduce the spectral dose in the 150–250 keV region by 4-5 orders of magnitude. In the pink-beam case, this reduction is provided by the mirror, and the resulting spectrum actually peaked at 88 keV.

Several safety factors are already built into this calculation. First, the wiggler is modeled as a bending magnet of fixed critical energy. This ignores the fact that, for a wiggler, the critical energy decreases with the horizontal opening angle, and thus this assumption tends to overestimate the flux of high-energy x-rays. Second, PHOTON assumes scattering occurs at a point instead of over an extended length, which is probably conservative for scattering from air. Third, the scattering is assumed to be isotropic, which tends to overestimate the amount of materials needed to shield against the scattering positioned at 90° from the direct beam. Also, the calculations did not take into account the presence of stainless steel around the beam pipe. The vacuum pipe consists of two layers of 1/8-inch-thick stainless steel. The dependence of the scattering cross section on the polarization of the incident beam, however, was not considered.

Table 5 Pb Thicknesses Required for Shielding a Pink-Beam Transport against Scattered X-rays and the Resulting Dose Rate. (The white-beam cases, which were discussed in Ref. 2, are listed here for comparison.)

(i) 30 cm Cu Scatterer:			
		<u>With Mirror</u>	<u>No Mirror*</u>
	White Beam	7 mm Pb (0.2 mrem/h)	21 mm Pb
	Mono. Beam	5 mm Pb (0.2 mrem/h)	15 mm Pb
(ii) 30 cm Air Scatterer:			
		<u>With Mirror</u>	<u>No Mirror*</u>
	White Beam	5 mm Pb (0.2 mrem/h)	11 mm Pb
	Mono. Beam	3 mm Pb (0.3 mrem/h)	8 mm Pb

* Data from Ref. 2

So far, we have considered the presence of a solid object that creates a lot of scattering inside the beam transport. Another potential hazard is the x-ray beam directly hitting the beam transport. This could be minimized by placing adequate apertures and masks along the beam. But it is conceivable that this would happen by accident or during alignment. Then, the major concern is not the direct x-ray transmission through the Pb shielding, because the x-ray beam will be incident on the beam pipe at a grazing angle (10° or less), and it will see a very thick layer of Pb. However, X-rays scattered from the Pb and the Pb fluorescence can see a much shorter path through the Pb if they go through the Pb almost normal to the surface. It can be assumed that most of the scattering and fluorescence occurs near the surface of the Pb because of the grazing incidence. This allows the scattering and shielding to be counted as two individual events in PHOTON, even though physically both occur within the same material. As a study case, we chose the pink-beam case of the wiggler A source, where 7 mm of Pb was recommended in Table 5 to shield against a Cu scatterer. A thick Pb target was used as an efficient scatterer, and it was surrounded by 7 mm of Pb. The dose rate immediately after the 7 mm of Pb was found to be 4 mrem/h. In addition to previously mentioned safety factors already built into PHOTON, the actual dose rate will be considerably lower in this case for two more reasons. First, the footprint of the pink beam on the beam transport will be elongated due to the grazing incidence, so scattering takes place over an extended area instead of localized at a point. Second, there are other physical restrictions on how close a person can get to the shielding. For instance, the two layers of stainless steel around the beam pipes will increase the minimal distance to 13 mm, which will bring the dose rate to less than 1.2 mrem/h. Thus, we feel that, for a wiggler source, 7 mm of Pb is also sufficient for shielding against the pink beam hitting the transport itself.

Acknowledgment

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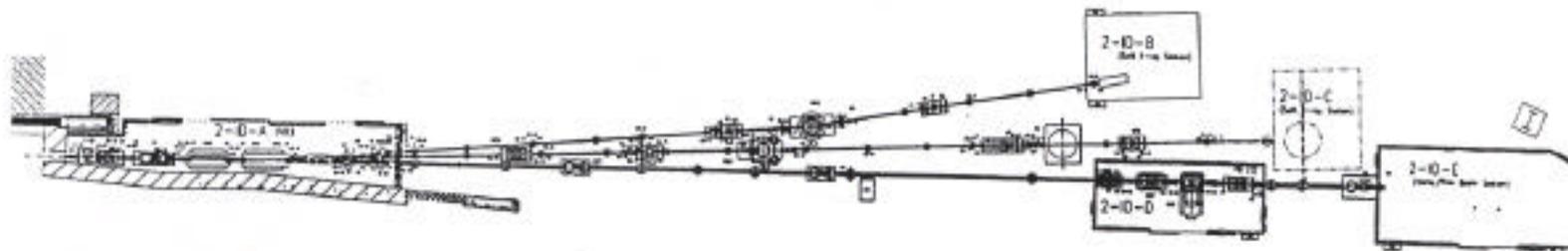


Fig. 1. Beamline layout of the SRI-CAT Sector 2.

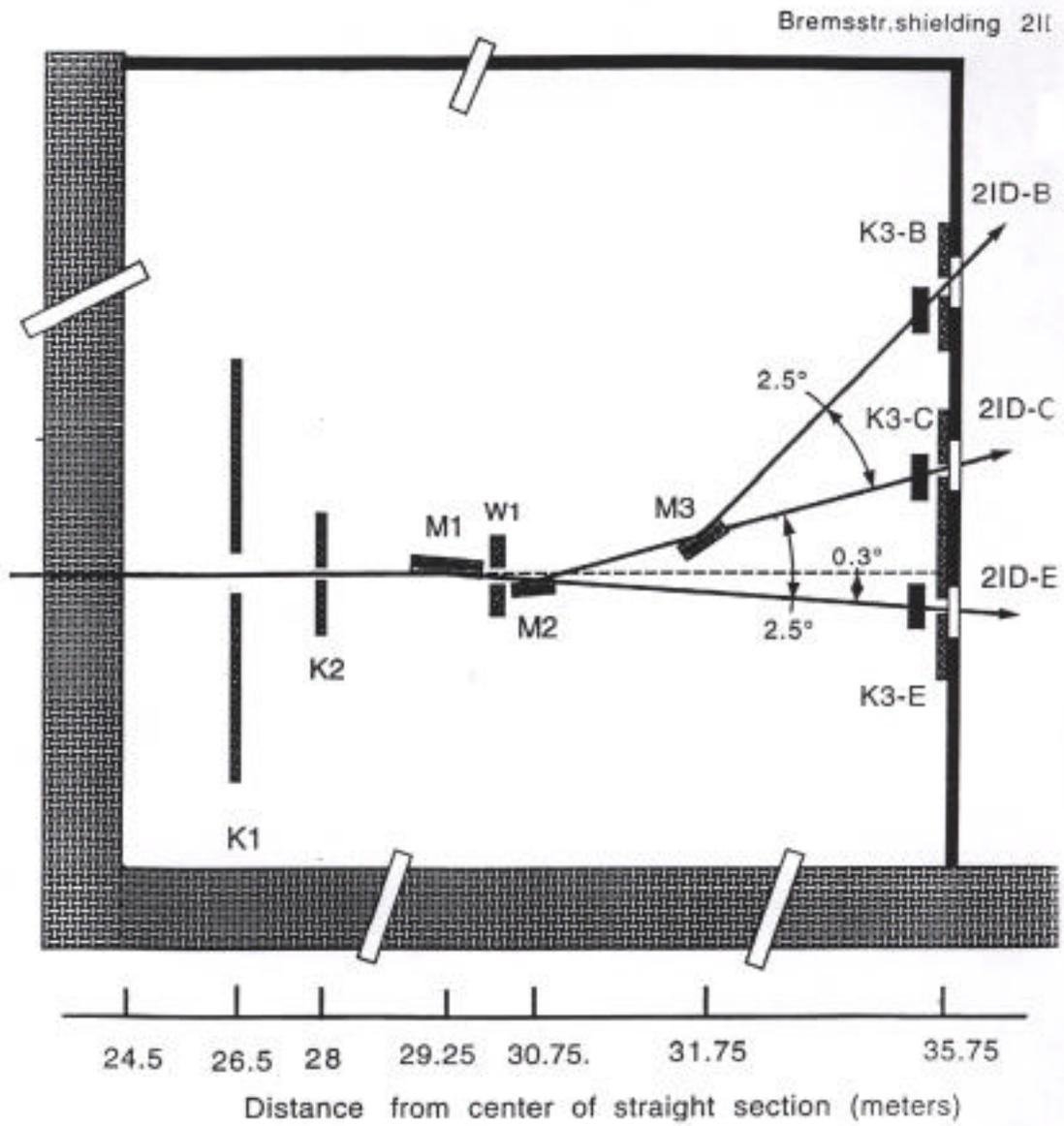


Fig. 2. Schematic layout of major optical and shielding components in the first optical enclosure.

ADVANCED PHOTON SOURCE

ID FRONT END
BREMSSTRAHLUNG RAY TRACING
(HORIZONTAL)
 $X : Z = 40 : 1$

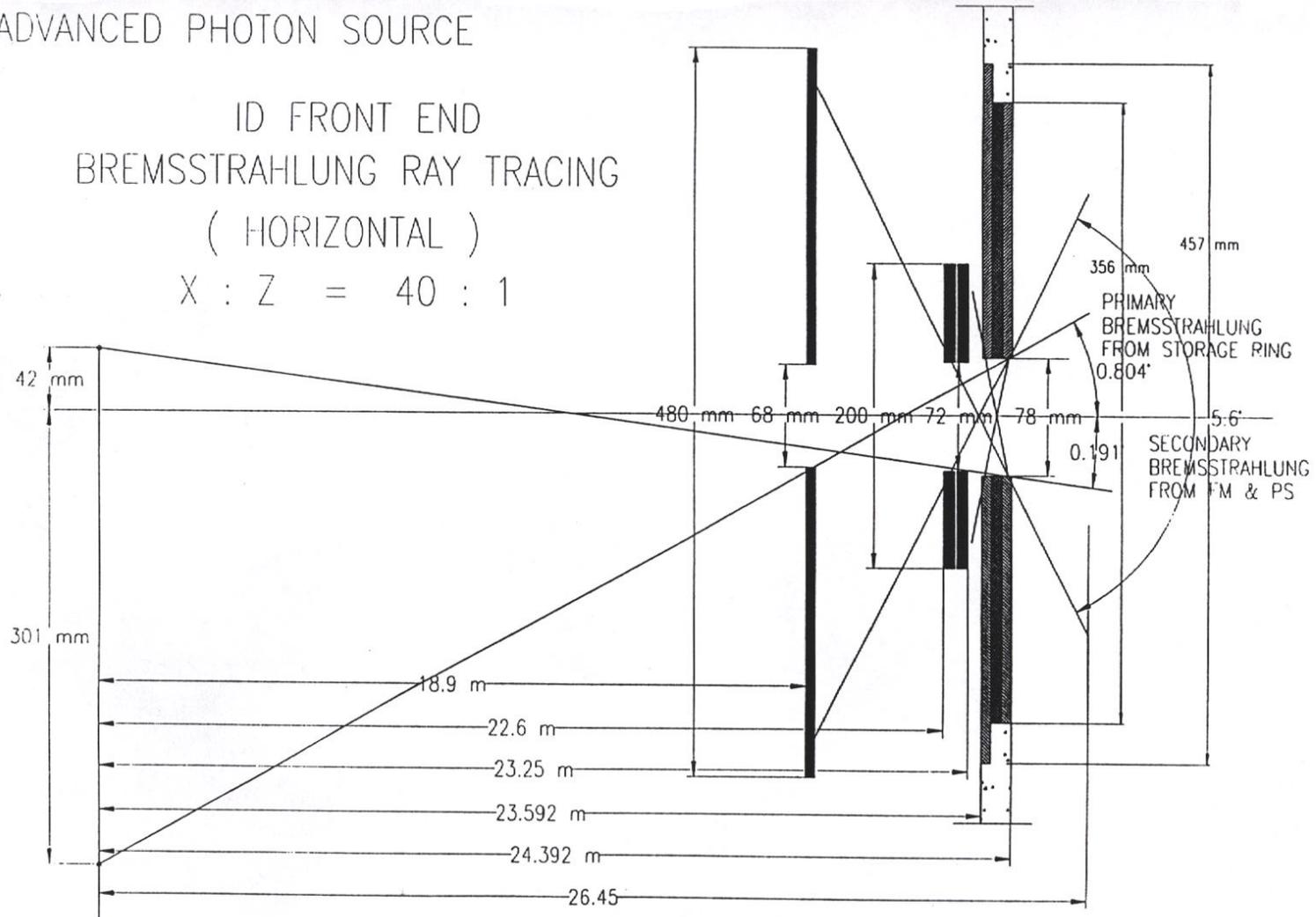


Fig. 3a. Bremsstrahlung ray tracing of the APS undulator front end in the horizontal plane.

ADVANCED PHOTON SOURCE

ID FRONT END
BREMSSTRAHLUNG RAY TRACING
(VERTICAL)
 $Y : Z = 40 : 1$

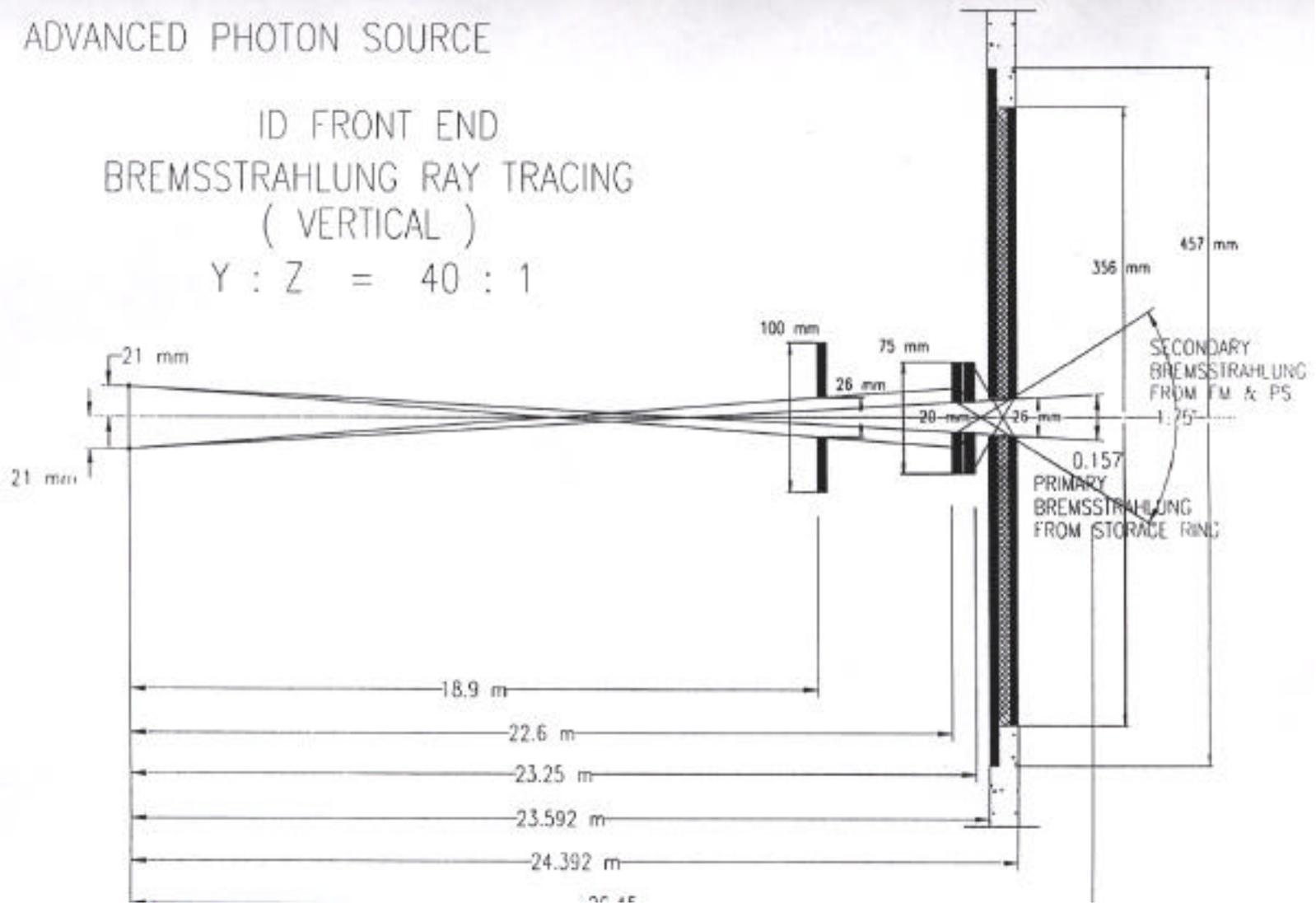


Fig. 3b. Bremsstrahlung ray tracing of the APS undulator front end in the vertical plane.

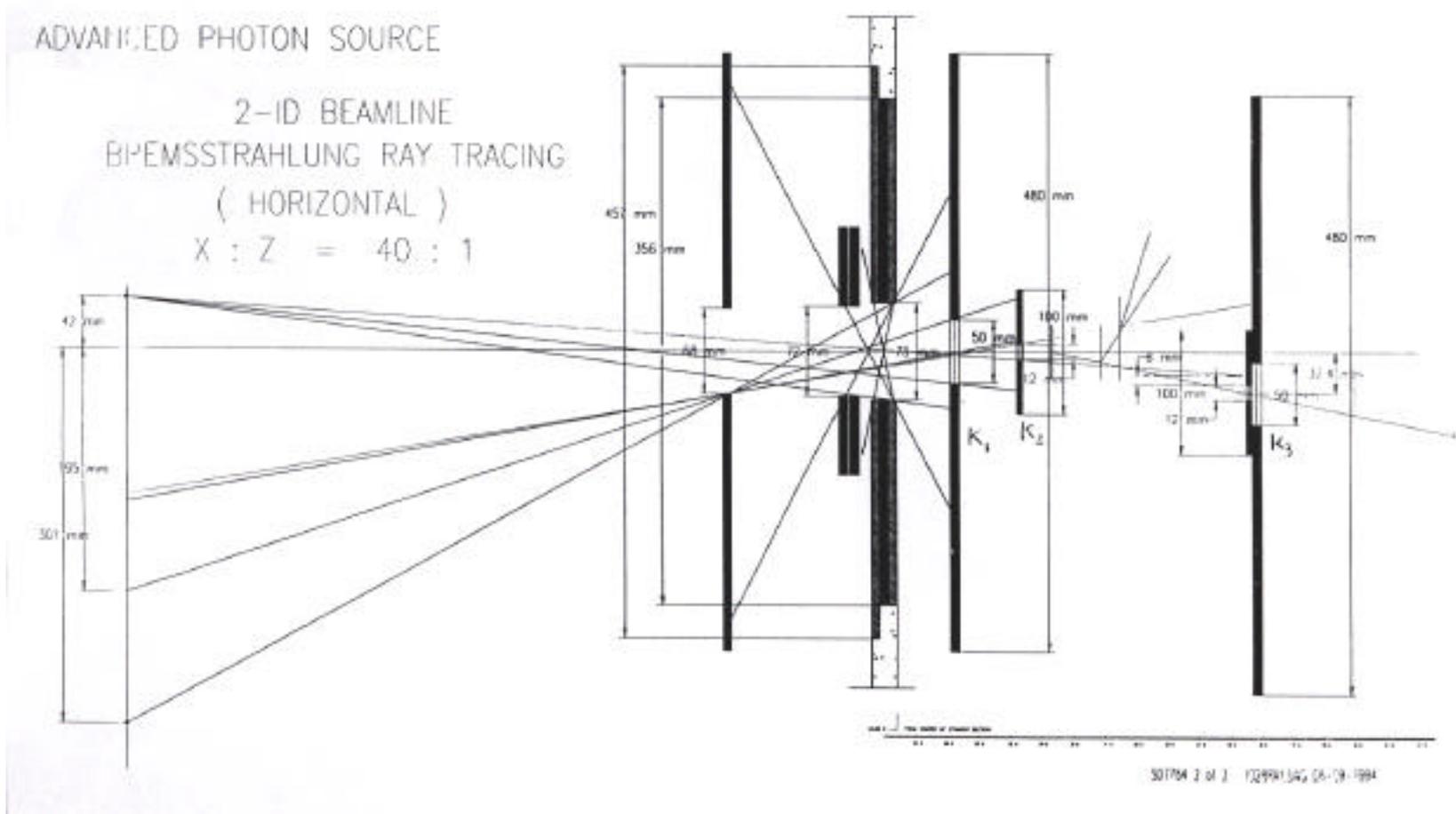


Fig. 4a. Bremsstrahlung ray tracing of the SRI-CAT Sector 2 insertion device beamline in the horizontal plane.

ADVANCED PHOTON SOURCE

2-ID BEAMLINE
BREMSSTRAHLUNG RAY TRACING
(VERTICAL)

$$Y : Z = 40 : 1$$

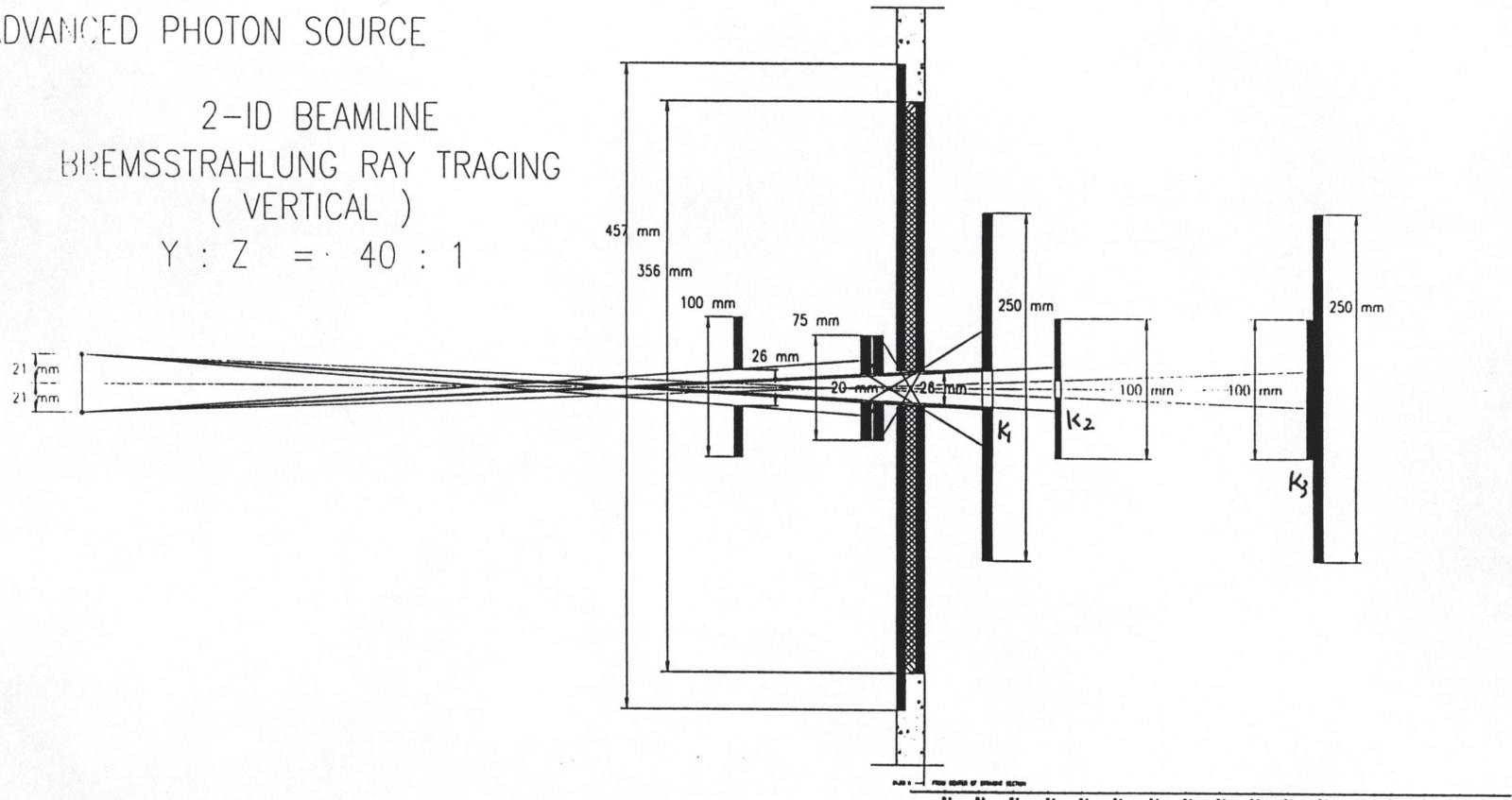


Fig. 4b. Bremsstrahlung ray tracing of the SRI-CAT Sector 2 insertion device beamline in the vertical plane.

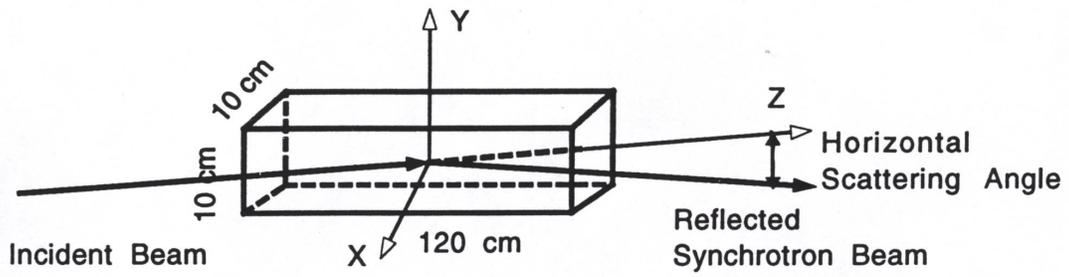


Fig. 5. Schematic of the geometric parameters of the Si mirror considered for beamline shielding and the coordinates used in this report. The Z axis is along the direction of the primary BR.

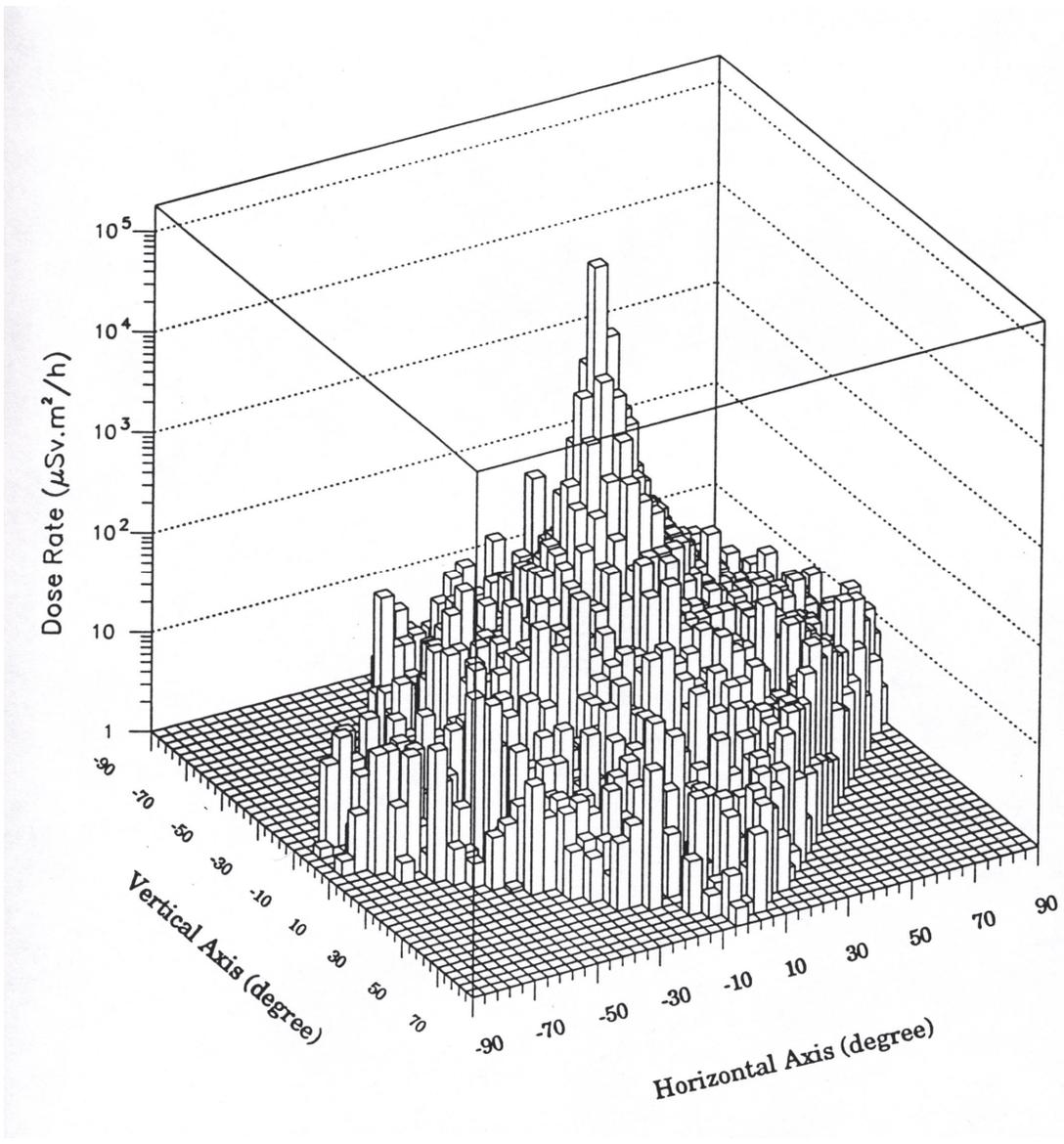


Fig. 6. Angular distribution of the SBR originated from the scattering of BR by the Si mirror.

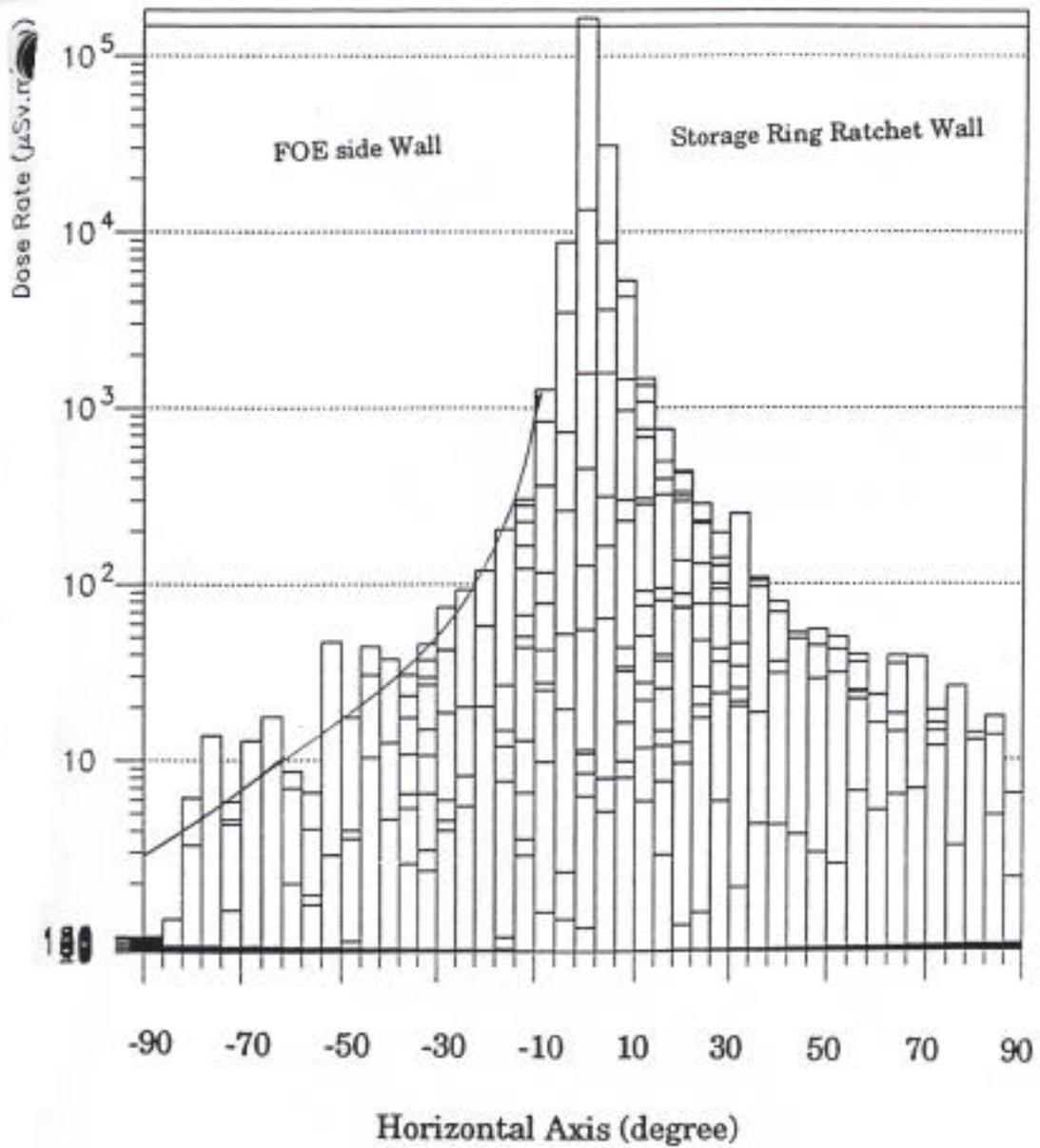


Fig. 7a. Angular distribution of the SBR DER in the horizontal plane obtained by projecting the three-dimensional plot in Fig. 6 to the planes defined by the horizontal axis and the dose rate axis. The DER value is integrated over a 1 degree solid angle.

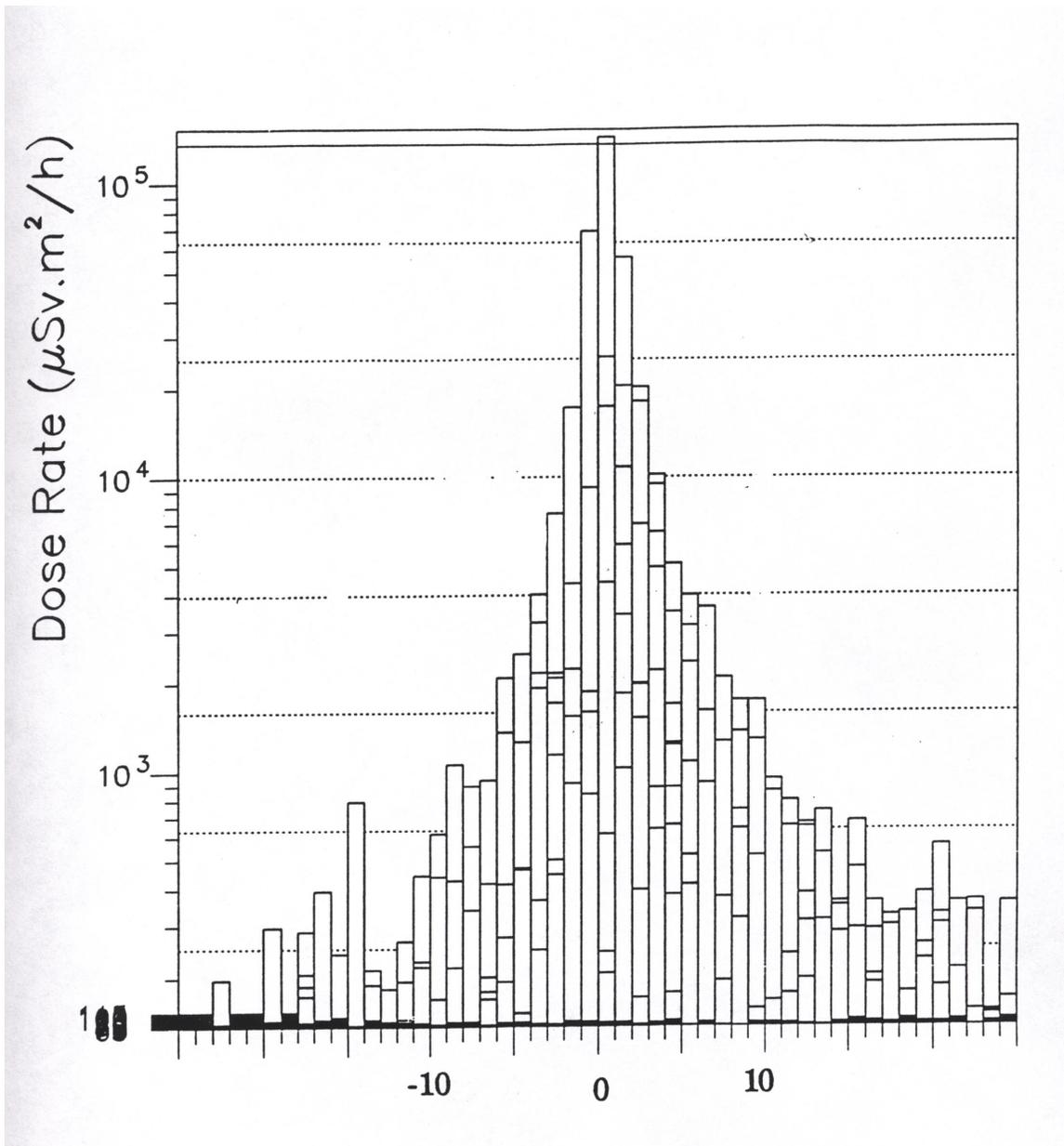


Fig. 7b. Similar to Fig. 7a but with better angular resolution and over a smaller angular range. The DER value is integrated over a 1 degree by 1 degree solid angle.

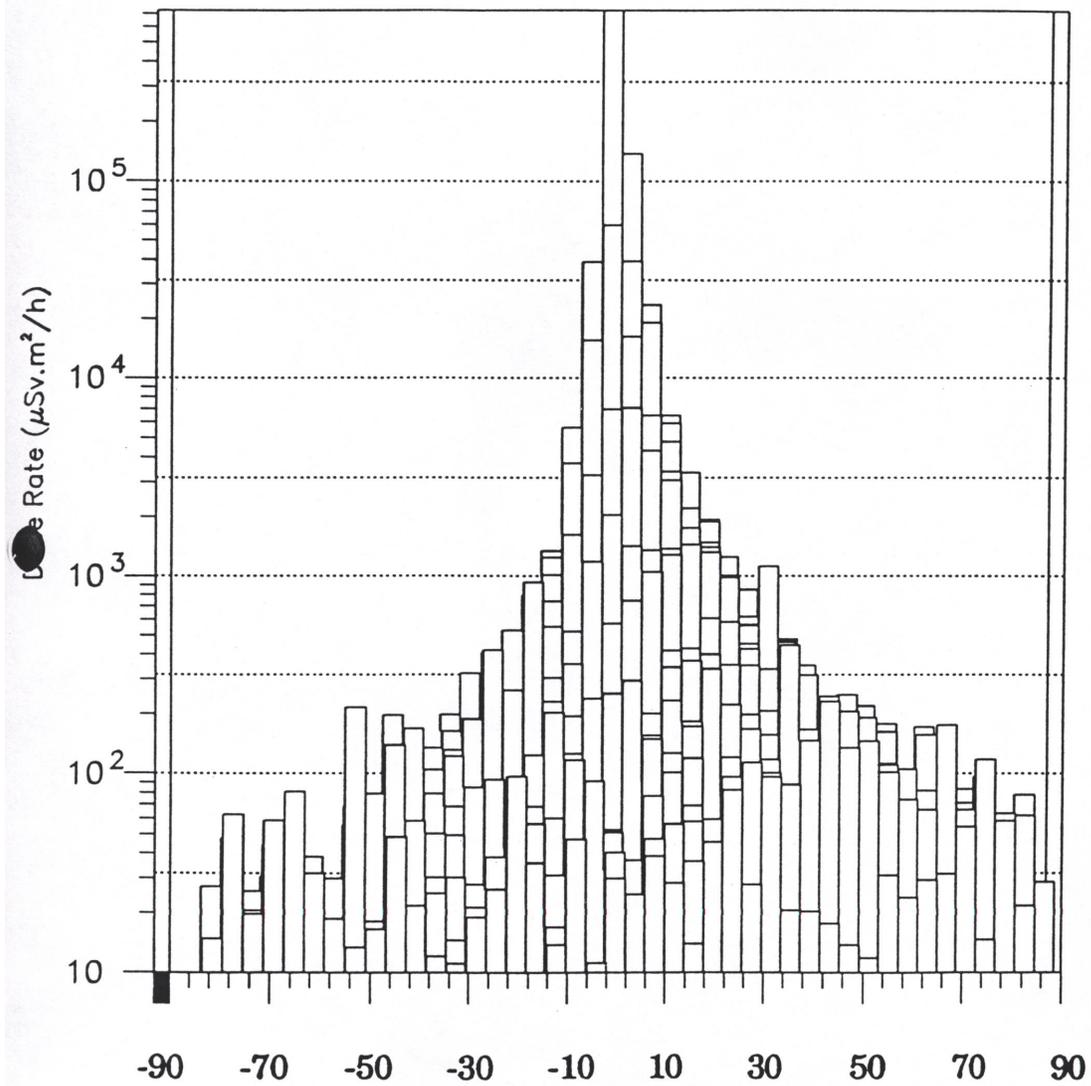


Fig. 8. Angular distribution of the SBR DER in the vertical plane obtained by projecting the three-dimensional plot in Fig. 6 to the planes defined by the vertical axis and the dose rate axis. The DER value is integrated over a 1 degree by 1 degree solid angle.

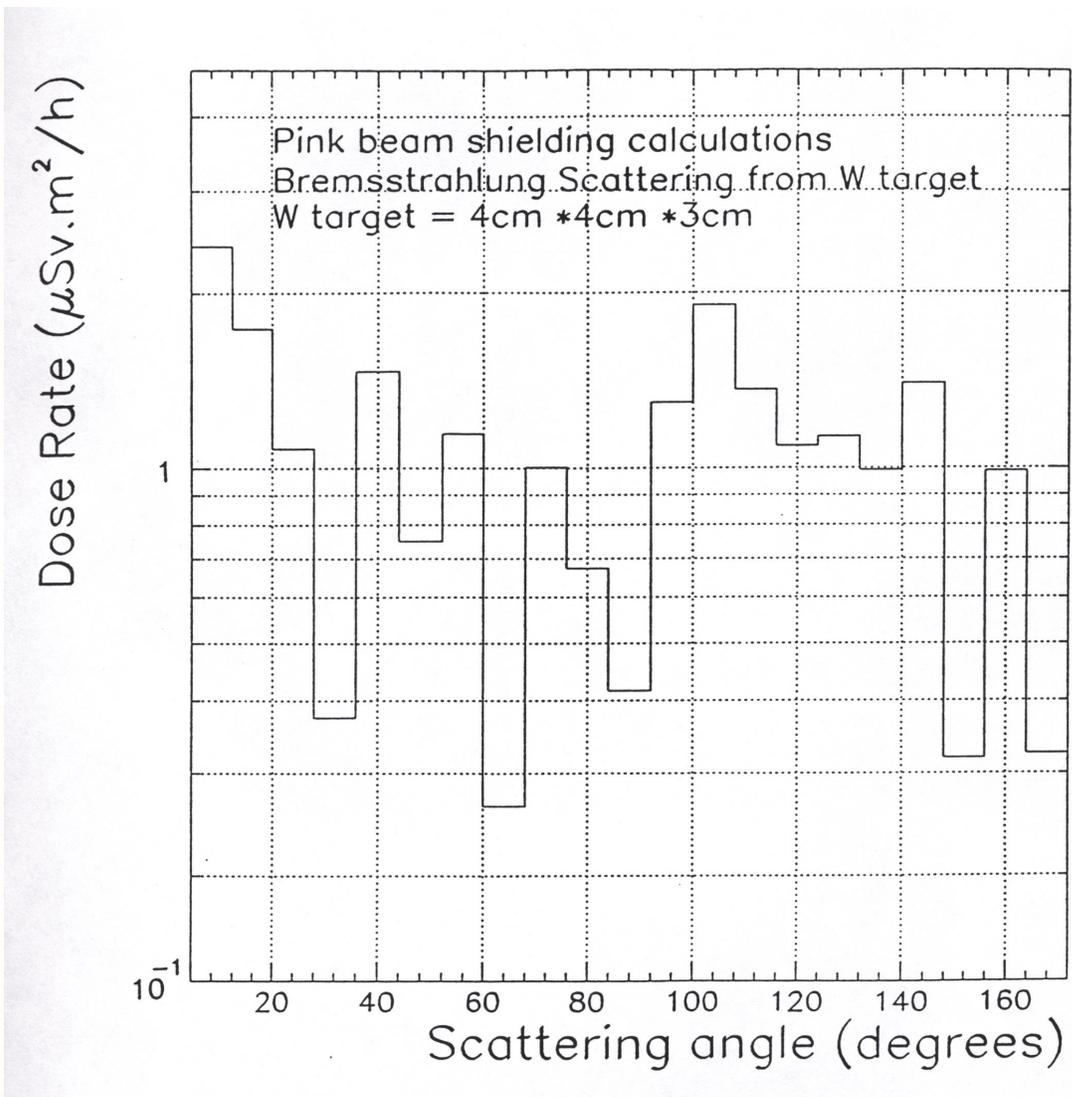


Fig. 9. Angular distribution of the SBR scattered by a W target with a cross section of 4 cm x 4 cm and a thickness of 3 cm. The SBR considered here is the portion of the SBR from the Si mirror that transmits through the K3-E collimator.

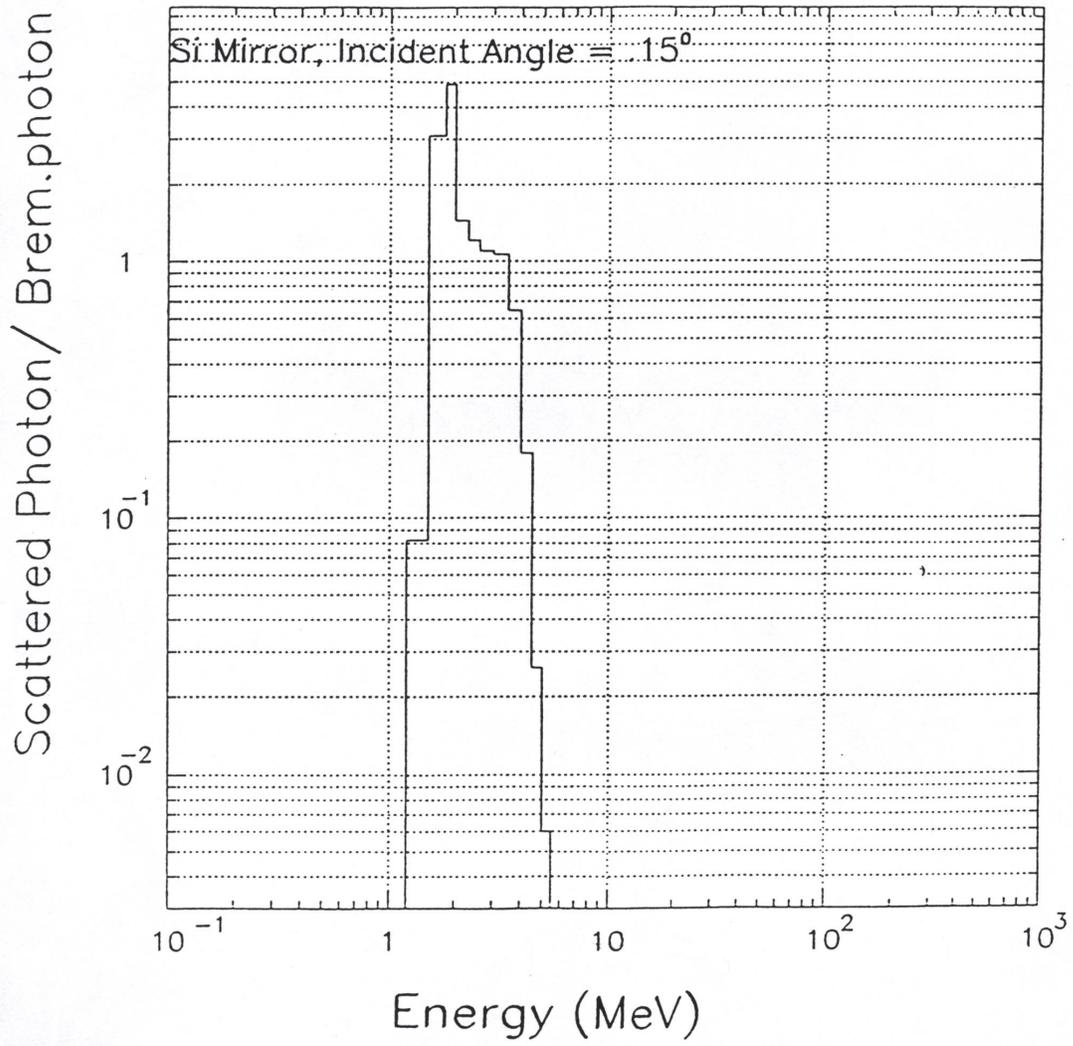


Fig. 10. Spectrum of SBR from the Si mirror scattering of BR.

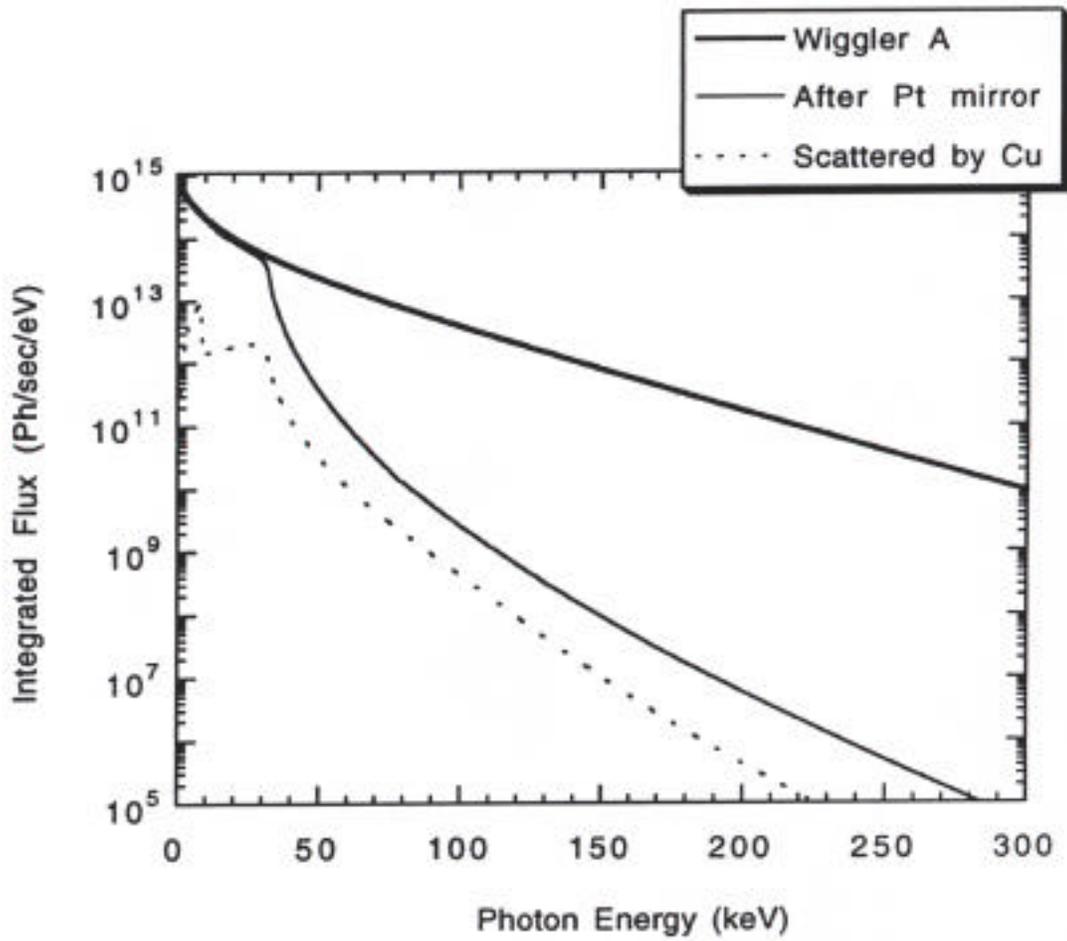


Fig. 11. Angle-integrated spectral flux from the APS Wiggler A and after reflecting off a Pt mirror at $\theta = 0.15^\circ$. The total scattered flux from a 30-cm-thick Cu block is also shown.

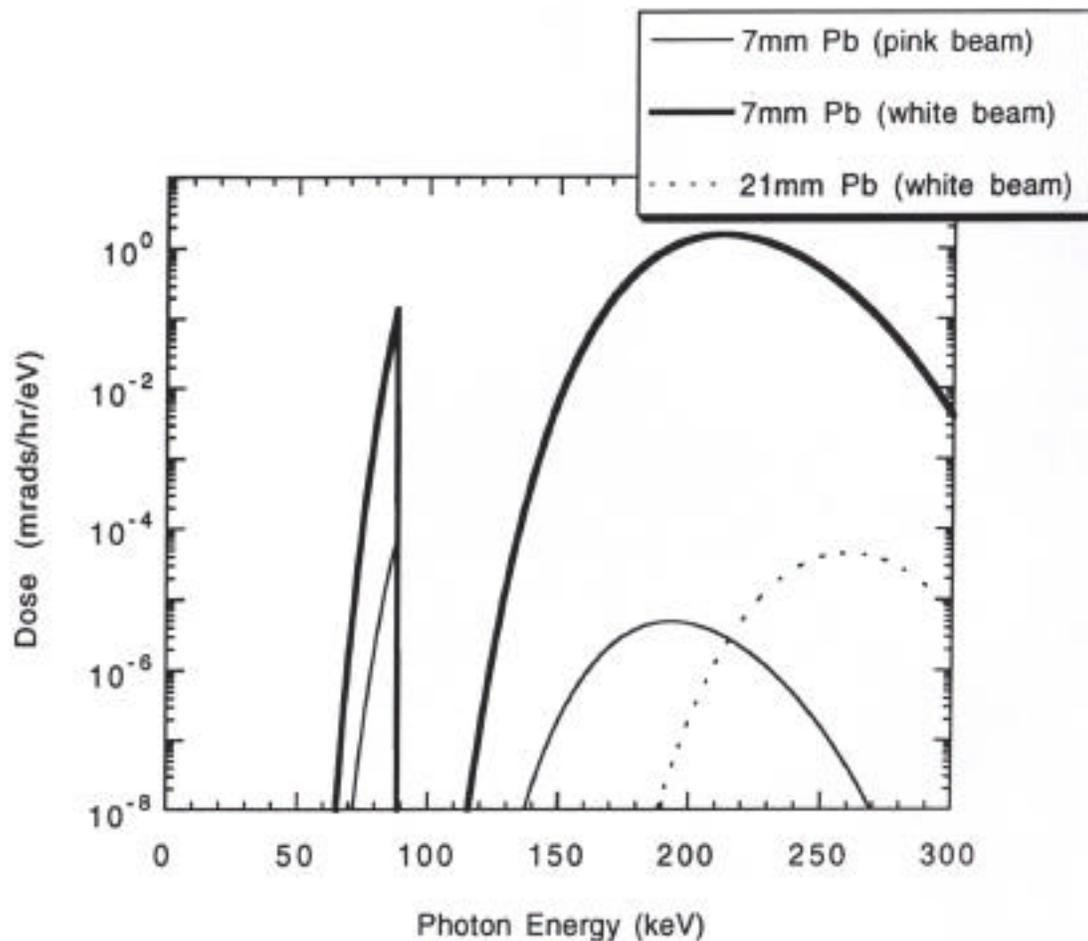


Fig. 12. Spectral dose received on human tissues for different thicknesses of Pb on the beam transport. A 30-cm-thick Cu scatterer was assumed. The incident x-ray beam may come directly from a Wiggler A source (white beam) or after reflected from a Pt mirror at $\approx 0.15^\circ$ (pink beam).