SLAC–PUB–6410
January 1994
(M)

IMPACT OF GAS BREMSSTRAHLUNG ON SYNCHROTRON RADIATION BEAMLINE SHIELDING AT THE ADVANCED PHOTON SOURCE+

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ABSTRACT

The Advanced Photon Source (APS) currently under construction at Argonne National Laboratory will be one of the world's brightest synchrotron radiation facilities. The storage ring, capable of storing currents up to 300 mA at 7.0 GeV and 200 mA at 7.5 GeV, will produce very intense and energetic synchrotron radiation (E_c = 24 keV for bending magnets and E_c = 37.4 keV for wigglers, where E_c is the critical energy). The synchrotron radiation (SR) beam lines consisting of experimental enclosures and transport lines will have to be shielded against synchrotron radiation and gas bremsstrahlung scattered from beam line components. For insertion devices placed in the straight sections (length = 15 m), the gas bremsstrahlung produced by the interaction of the primary stored beam with residual gas molecules or ions in the storage ring vacuum chamber dominates the SR beam line shielding. The impact of gas bremsstrahlung on the SR beam line shielding is discussed in this paper.

I. INTRODUCTION

The Advanced Photon Source (APS) currently under construction at Argonne National Laboratory, Illinois will be one of the world's brightest synchrotron radiation facilities. The machine is composed of an electron linear accelerator (linac), a positron linac, a positron accumulator ring (PAR), a booster synchrotron injector, and a storage ring (Fig 1). Electrons produced by an electron gun will be accelerated to 200 MeV in the linac and allowed to strike a target, producing electron-positron pairs. The positrons will be captured, focussed and accelerated to 450 MeV, and then accumulated in the PAR, from which they will be transported to the booster synchrotron which will raise their energy to 7 (or 7.5) GeV. The positrons (7.2 x 10^{10} e^+/s), will then be injected into the storage ring (circumference = 1104 m), which is capable of storing circulating currents up to 300 mA at 7.0 GeV and 200 mA at 7.5 GeV.

Special bending magnets and focussing magnets will guide the beam as the positrons move at nearly the speed of light around the circular storage ring maintained at a vacuum of 0.133 to 0.0133 μP_a (10^{-9} to 10^{-10} torr). The positrons radiate energy (synchrotron radiation) as they are being deflected in the fields of storage ring bending magnets (BMs) or special magnets called insertion devices (IDs) which are placed in the straight sections (length = 15 m) of the storage ring. The synchrotron radiation (SR) is polarized, highly collimated, and very intense.

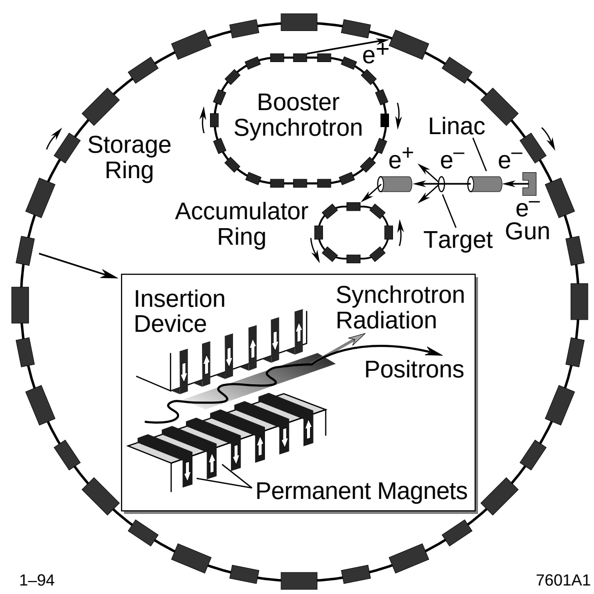

Figure 1: The Advanced Photon Source.

+Work supported by Department of Energy contract DE–AC03–76SF00515.

*Initial work performed at the APS while on contract from SLAC.

**Work performed at SLAC, while on leave from CERN.

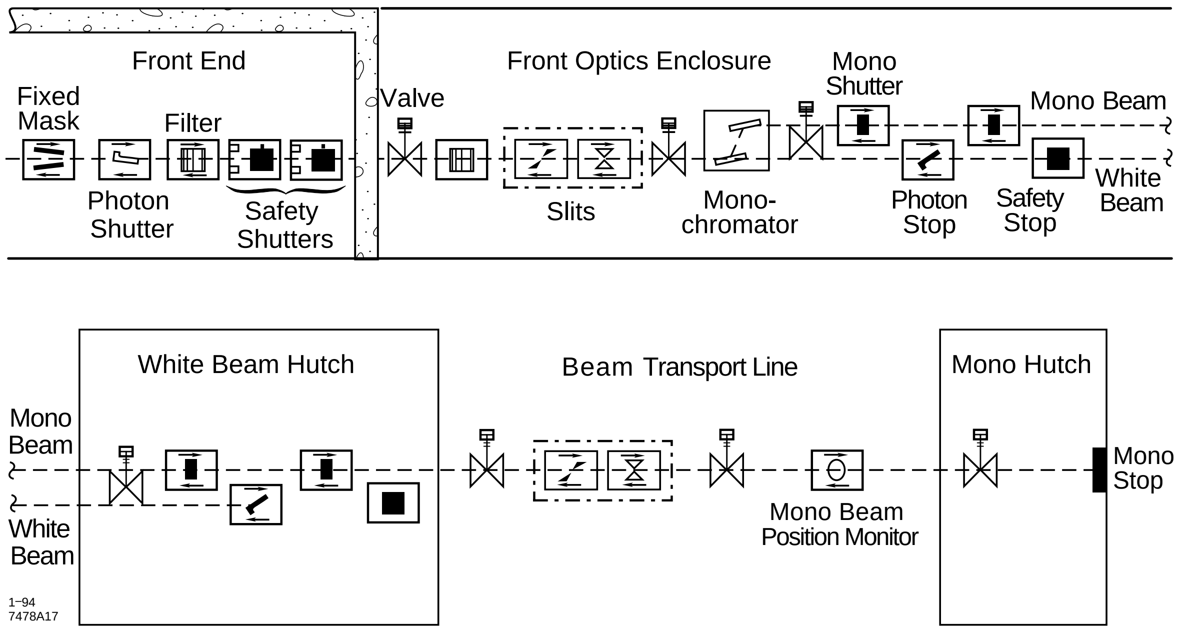

Figure 2: Schematic of a Model APS SR Beamline.

An ID consists of a series of short magnets with alternating magnetic fields (Fig 1), which cause the particles to either wiggle or undulate as they pass through the device. Since the positrons are forced to change direction many times in a short distance, the brightness (number of photons per second per unit solid angle per unit source area) is greatly enhanced. Wigglers produce very intense, energetic radiation over a wide range of x-ray energies while undulators yield radiation of selected energy with high brightness. Sixty-eight SR beam lines, half originating at BMs and the other half at IDs will be transported to the Experimental Floor through penetrations in the ratchet-shaped storage ring shielding walls. The portion of the SR beam line within the storage ring is referred to as the front end (Fig. 2).

A typical APS SR beam line will consist of a first-optics enclosure (FOE), a white beam hutch (WBH), a beam transport line (BTL) and a monochromatic beam hutch (MBH) (Fig. 2). The entire SR spectrum, known as the white beam, can be transported to the WBH, or if desired a monochromator can be used in the FOE, and a monochromatic (mono) beam can be transported to the MBH, for experimental purposes. Mirrors may sometimes be used in the FOE to obtain “pink beam” (reflected white light).

Photons and neutrons produced by the interaction of the primary injected or stored positron beam with the storage ring components may be of the concern on the Experimental Floor during normal or abnormal beam operating conditions. Protection is achieved through adequate design of the storage ring shielding wall and the use of local shielding. In addition, the front-end photon shutter and two safety shutters (Fig. 2) are closed during injection and during entry into the FOE under stored beam conditions. The photon shutter absorbs most of the synchrotron radiation traveling down the synchrotron beam line, while the safety shutters (30 cm of tungsten) provide protection in the forward direction from gas bremsstrahlung and photons from beam losses in the storage ring.

Gas bremsstrahlung is produced by the interaction of the primary stored beam with residual gas molecules (H_2, CO, CO_2, CH_4, etc) or ions in the storage ring vacuum chamber. It is produced in a narrow cone, the characteristic emission angle being given by $1/\gamma$, where $\gamma = E_0/m_0c^2$ (E_0 = primary beam energy, m_0c^2 = rest mass energy of electron/positron). Gas bremsstrahlung becomes very important for straight sections in the storage ring, since the contribution from each interaction adds up to produce a narrow monodirectional beam which travels down the SR beam line along with the synchrotron radiation. Both gas bremsstrahlung and synchrotron radiation can scatter off any beam line component that they strike (mirrors, slits, masks, shutters, monochromators, etc). If energetic enough, the gas bremsstrahlung can develop an electromagnetic shower in any target that it strikes. In addition, gas bremsstrahlung can produce neutrons in any target, if the photon energy is greater than the threshold for photo-neutron production. Scattered gas bremsstrahlung requires far greater shielding thicknesses than scattered synchrotron radiation.

According to Ferrari et al.,[1] the maximum gas bremsstrahlung dose rate D (Gy/h) in the forward direction

Table I: Ratio of Gas Bremsstrahlung Dose Rates.

	APS	ESRF	SSRL
E_0(GeV)	7.0	6.0	3.0
I (mA)	300	100	100
L (m)	15	15	5
d (m)	20	20	20
Dose Rate Ratio	61	14	1

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(for energies ranging from 100 MeV to 1 GeV and straight section lengths of 1 to 50 m) is given by:

$$D = 2.5 \times 10^{-27} \left(\frac{E_0}{m_0 c^2} \right)^{2.67} \frac{L}{d(L+d)} I \frac{P}{P_0},$$

where E_0 is the primary beam energy (MeV); m_0c^2 is the rest-mass energy of the electron/positron (MeV); L is the length of the straight section (m); d is the distance from the end of the straight section(m); I is the stored beam current (e^-/sec); P is the pressure in the straight section (Pa); and Po = 1.33 x 10^{-7} Pa (10^{-9} torr). Since the gas bremsstrahlung gets more forward peaked as the primary beam energy increases, this expression was derived using different scoring areas at different energies. For E_0 > 500 MeV a scoring area of 0.0059 cm^2 was used.

Using the above expression (assuming that it is still valid at 7.0 GeV), the gas bremsstrahlung dose rates at a given pressure for d = 20 m are shown in Table I for the APS, the ESRF (European Synchrotron Radiation Facility), and SSRL (Stanford Synchrotron Radiation Facility). Thus we see that the gas bremsstrahlung dose rate in the forward direction for the APS will be 61 times higher than that for SSRL. This implies that scattered gas bremsstrahlung dose rates will also be much higher for the APS than for SSRL.

At most of the existing synchrotron radiation facilties, such as SSRL, gas bremsstrahlung in the forward direction is shielded by safety stops placed in the median plane of the primary stored beam and at the back of the experimental enclosure/hutch. The safety stops in the APS FOE and WBH (Fig. 2) are made of tungsten 30 cm thick. However, the lateral and back walls of most of these facilities have been shielded for scattered synchrotron radiation. Since gas bremsstrahlung dose rates will be much higher at the APS, it is clear that the impact of scattered gas bremsstrahlung, and neutrons produced by gas bremsstrahlung, on synchrotron beam line shielding must be considered carefully. The gas bremsstrahlung dose rates in the forward direction will be discussed in an separate paper.

II. SHIELD DESIGN CRITERION

The shielding for the synchrotron beam lines is designed to keep the annual integrated dose equivalent, at the shield surface, in occupied areas to less than 5 mSv. This design criterion is based on DOE recommendations.[2] For a 2000-h operating year this corresponds to 2.5 μSv/h.

III. SHIELDING METHODOLGY

The shielding design and methodology for the APS SR beam lines is described in detail in an APS internal document.[3] Since the publication of this document, additional Monte Carlo studies on scattered gas bremsstrahlung have been performed. The results of these calculations will be presented in this paper. Only the shielding for the FOE and WBH of the IDs is discussed in this paper, since the gas bremsstrahlung for a bending magnet (bending radius = 39 m, acceptance = 6 mrad) is reduced significantly because of the much shorter effective straight section seen by the beam line (6 mrad x 39 m = 0.234 m). The gas bremsstrahlung beam will be spread over a larger area in the case of the bending magnet. The shielding thicknesses for the lateral walls of the BM FOE and WBH are dominated by scattered synchrotron radiation.[3]

In order to meet the shield design criterion of 2.5 μSv/h at the shield surface, three radiation components need to be considered for the lateral and back walls of the ID FOE and WBH (higher levels are allowed for the roof, which is unoccupied): a) scattered synchrotron radiation; b) scattered gas bremsstrahlung; and c) neutrons produced by gas bremsstrahlung.

For synchrotron radiation, since the critical energy for the ID increases with the square of the primary beam energy, the beam parameters of 7.5 GeV and 200 mA will be used. For gas bremsstrahlung the beam parameters 7 GeV and 300 mA will result in the highest dose rates.

IV. SCATTERED SYNCHROTRON RADIATION

The synchrotron radiation traveling down the beam line will scatter off every component it strikes. In the forward direction the beam can be stopped with shutters and stops; in the lateral and backward directions the walls of the FOE and WBH have to be thick enough to stop the scattered synchrotron radiation. The shielding was determined using the PHOTON computer program.[4] PHOTON calculates dose in the following sequence: 1) calculation of photon flux as a function of energy and vertical opening angle of the synchrotron beam; 2) attenuation by filters; 3) a scattering processs; and 4) conversion from photon flux to dose.

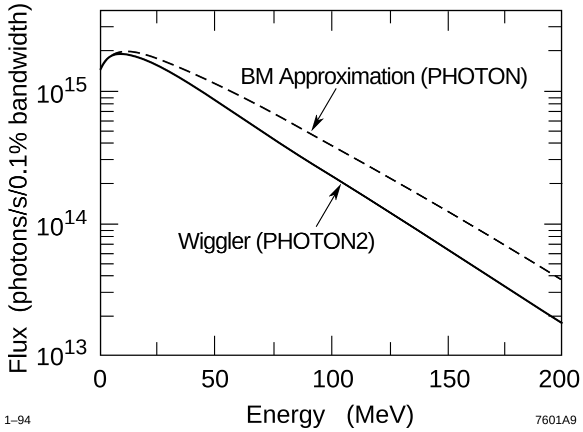

Figure 3: Comparison of the Wiggler Spectrum using PHOTON and PHOTON2.

Compton scattering is the primary mechanism for scattering at the large angle necessary to strike a shielding wall at or near normal incidence (where the effective shielding thickness is a minimum). Low-energy photons, which are more efficiently elastically scattered through large angles, will not penetrate the shielding walls and therefore will not contribute to the dose outside the shielding. The details of the shielding methodology can be found in Ref. 3. PHOTON was originally written to calculate the flux for bending magnets, but can be extended to wigglers, because the wiggler flux is N times the bending magnet flux (N = number of magnetic poles). However this overestimates the horizontally off-axis flux. PHOTON2 is a modified version of PHOTON which calculates the wiggler spectrum using the proper wiggler horizontal beam distribution.[5] Figure 3 shows a comparison of the wiggler spectrum, between PHOTON and PHOTON2. Based on calculations performed with PHOTON, the lateral and back walls of the Insertion Device FOE and WBH require 1.6 and 1.9 cm of lead, respectively, for shielding against scattered synchrotron radiation. Because the roof will not be occupied, it is shielded for 25 μSv/h, and therefore requires only 1.2 cm of lead.

V. SCATTERED GAS BREMSSTRAHLUNG

As in the case of scattered synchrotron radiation, it is difficult to define the worst case scattering target. Therefore two copper targets were chosen, one inclined at 1.25° to the horizontal plane (4.0 x 3.0 x 90 cm) representing the backing on a horizontal mirror and the other at normal incidence to the beam (radius = 2.54 cm, length = 5.0 cm).

The FLUKA program was used to determine the production and scattering of gas bremsstrahlung. The most recent version of the code[6,7] includes a complete treatment of electron/positron and photon interactions at all energies above 1 keV, and in particular an accurate description of bremsstrahlung angular distributions. In the simulation, the straight section (length= 15m) was represented by an air target at atmospheric pressure. The interaction probability per positron would be extremely low at the actual pressure of the residual gas. As long as the positron interaction probability is kept smaller than a few percent, self-absorption can be neglected. As discussed by Ferrari et al.,[1] the calculated results can be scaled to the actual pressure value, provided that all interactions except bremsstrahlung are suppressed or at least minimized. Therefore, no positron multiple scattering was allowed in the air target. Positrons bending in the fields of the storage ring magnets were accounted for by removing them at the downstream end of the air target (since they will not travel down the SR beam line). For the inclined target the gas bremsstrahlung beam was incident at the mid-point of the target, whereas for the normal-incidence target, the beam was incident on the front surface.

The bremsstrahlung beam was transported through vacuum (representing the vacuum in the beampipe) until it struck the target (enclosed in vacuum) located 31.6 m from the start of the straight section. A 1-cm-thick hemispherical shell of ICRU tissue was placed 1 m from the point of incidence, with air as the intervening medium.The energy deposited in the tissue at different angles from the point of incidence, and the fluence crossing each volume element of tissue at these angles was scored. The calculations were also performed with the addition of a 1.905-cm-thick hemispherical shell of lead in front of the tissue. The positron (C_e) and photon (C_p) cut-offs for the different media were as follows: Air (target) C_e = 10 MeV, C_p = 1.0 keV; Air (killing region) C_e = 7.0 GeV, C_p = 1.0 keV; Air (intervening) C_e = 10 keV, C_p = 1.0 keV; Copper (target) C_e = 50 keV, C_p = 10 kev.

The hemispherical lead shield was divided into three regions of equal thicknesses, and importance sampling (Russian Roulette/splitting) was applied at boundary crossings on a region by region basis. In each case the average and standard deviations of the mean for 5 runs were determined. The number of particles for each run was as follows: normal target ~41000; normal target with lead ~7000; inclined target ~10,500; and inclined target with lead ~2700.

Ferrari et al.[3] have recommended that for long straight sections (> 10 m), the simulation should be carried out at 1/10 of the atmospheric pressure (instead of at atmospheric pressure), because the distribution of interactions in the long straight section will differ at the two pressures. This approach should lead to a slight difference in dose rates when the final results are obtained by scaling from the dose rates at 1 atmosphere. This deviation in linearity was

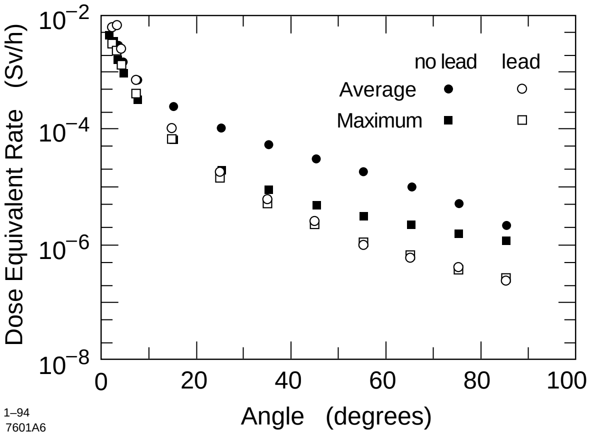

Figure 4: Dose Equivalent Rates vs Angle for Normal-Incidence Target with and without Lead Shielding.

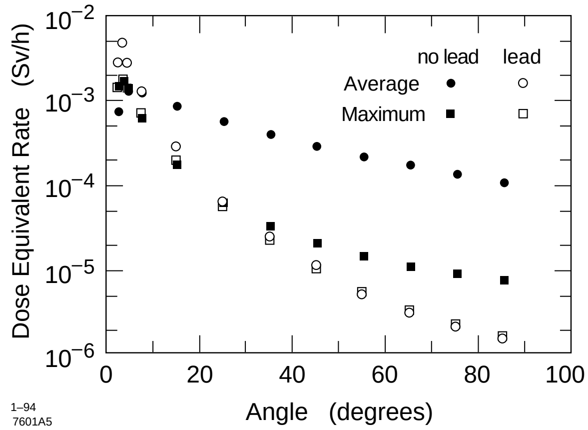

Figure 5: Dose Equivalent Rates vs Angle for Inclined Target with and without Lead Shielding.

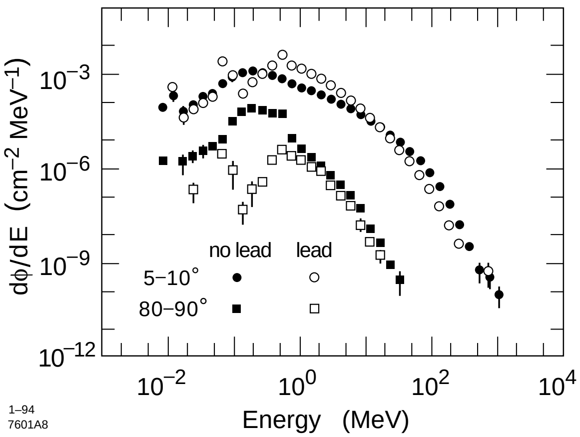

Figure 6: Photon Spectra for Normal-Incidence Target with and without Lead Shielding.

investigated and found to be insignificant for scattered gas bremsstrahlung

The average (obtained by scoring energy deposition) and maximim scattered gas bremsstrahlung dose equivalent rates, with and without lead shielding, are shown as a function of angle at 1 m from the point of incidence (for I = 300 mA and P = 0.133 μPa) in Figs. 4 and 5 for the normal-incidence and inclined targets, respectively. The maximum dose equivalent rates are obtained by multiplying the photon fluence rates by the maximum fluence to dose equivalent conversion factors published by Rogers.[8] These factors are the maximum dose equivalent per unit fluence for broad parallel beams of monoenergetic photons incident on a 30-cm-thick slab of ICRU tissue. The scattered gas bremsstrahlung beam is a diverging beam consisting of a spectrum of photons. Further, these conversion factors do not account for contributions to the dose by charged particles produced in the target or the air. Therefore the applicability of Rogers' conversion factors in this situation is in question. The error bars are less than 5% and are therefore not visible on the figures.

Figures 4 and 5 show that, in general, the average dose equivalent rates are higher than the corresponding maximum dose equivalent rates, when there is no lead. As discussed above, this difference could probably be attributed to the dose deposited by charged particles emanating from the target. The addition of lead results in better agreement between the two methods except in the forward direction (angles < 15°) where the particles are energetic enough to propogate the shower in the lead shield. When these calculations were repeated by replacing the air between the target and the tissue with vacuum, no significant differences in the results were obtained. This finding indicates that charged particle contribution to dose from interactions in air is negligible. The maximum dose equivalent is not necessarily obtained in the first 1-cm-thick layer of tissue at the small angles (< 15°). Hence, the dose equivalent rates shown in Figs. 4 and 5 for small angles are not conservative.

Figures 6 and 7 show the photon spectra at angles of 5–10° and 80–90° for both the normal-incidence and inclined targets, with and without lead shielding ($d\phi/dE$ = differential photon flux per energy interval dE per positron). The spectra at large angles are much softer than the spectra in the forward direction. The 0.511 MeV annihilation photon peak is clearly visible.

In order to apply these results to the shielding design of the Insertion Device FOE and WBH, a model hutch of length 7.7 m and distances from beampipe to lateral wall and roof of 1.2 m and 1.5 m, respectively, is considered. The distances of the target and the bremsstrahlung safety stop from the front of the hutch are 0.2 and 7.1 m respectively. Using the results from Figs. 4 and 5, the dose equivalent rates outside the hutch at different angles are obtained (Table II). The total dose equivalent rate outside the hutch should be less than 2.5 μSv/h. Since there will be some contribution from neutrons, the hutch will be shielded for 1.2 μSv/h from scattered gas bremsstrahlung. In order to keep the dose equivalent rates below 1.2 μSv/h outside the FOE/WBH lateral walls, at least 2.5 cm and 1.9 cm of lead are required for the inclined target and normal-incidence target, respectively. In addition, at angles smaller than 45°, extra shielding is required. In the forward direction the bremsstrahlung safety stop provides protection up to 1°. From 1 to about 8°, the scattered gas bremsstrahlung will strike the back wall. Hence the back wall will be made of lead, of thickness 5 cm with additional local shielding (5 cm of lead) in the forward direction. The inclined target in this case represents a horizontal mirror reflecting synchrotron radiation away from the storage ring towards the lateral walls of the hutch. For mirrors reflecting synchrotron radiation towards the storage ring, the angular distribution of scattered gas bremsstrahlung is different. It must be noted that any increase in pressure in the straight section will cause a corresponding increase in the scattered gas bremsstrahlung dose equivalent rates.

Table II: Dose Equivalent Rates at Different Angles for Normal Incidence and Inclined Targets.

	DOSE EQUIVALENT RATE (μSv/h)			
	LEAD THICKNESS 1.905 cm		LEAD THICKNESS 2.54 cm	
Angle (degrees)	Normal Incidence Target	Inclined Target	Normal Incidence Target	Inclined Target
7.5	12.7	21.8	–	–
15.0	4.6	13.1	3.4	9.0
25.0	2.2	7.9	1.2	3.8
35.0	1.3	5.5	0.62	2.1
45.0	0.80	3.8	0.56	1.3
55.0	0.47	2.4	0.18	0.69
65.0	0.32	1.6	0.13	0.42
75.0	0.20	1.3	0.09	0.31
85.0	0.15	1.0	0.07	0.24

VI. NEUTRONS FROM GAS BREMSSTRAHLUNG

Neutrons may be produced in any target with which the gas bremsstrahlung interacts, if the photons have energies above the threshold for photo-neutron production. These neutrons will have average energies of a few MeV. The neutron production depends on target material and dimensions, increasing with target thickness until it reaches a maximum, and then saturates. The neutron yields from infinitely thick targets are given as a function of energy in Ref. 9.

Among the various elements for which neutron yields are given, tungsten has the second highest yield. Since both the FOE and WBH have tungsten gas bremsstrahlung safety stops FLUKA was used to score the photon energy crossing the tungsten surface in the energy range of 6 MeV (~threshold for photo-neutron production) to 7 GeV. The maximum neutron yield from Swanson,[9] was then used to determine the neutron dose equivalent rates outside the FOE/WBH. The dose equivalent rates outside the lateral wall (d = 1.2 m) and outside the back wall (d = 0.6 m) from the tungsten stop, without accounting for transport/attenuation in the stop or the walls, are 4 and 15 μSv/h, respectively. For a thick copper target, the dose equivalent rate will be reduced by about a factor of 2. Thus the tungsten stop will have to be shielded with about 15 cm of polethylene (Tenth Value Layer = 13.0 cm for average energy = 2.0 MeV)[10] in the backward direction and 8 cm in the lateral direction in order to reduce the dose equivalent rates to less than 1.2 μSv/h.

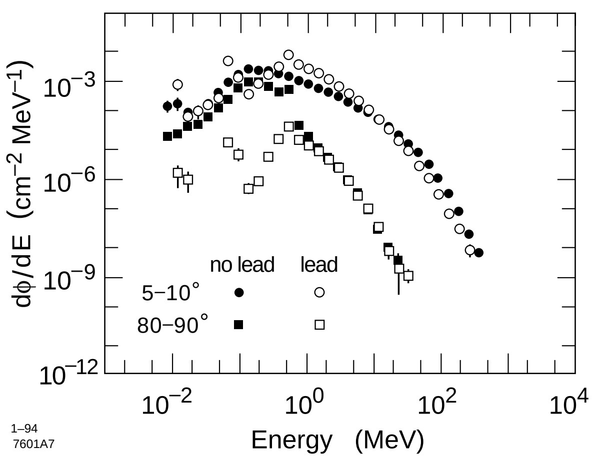

Figure 7: Photon Spectra for Inclined Target with and without Lead Shielding.

CONCLUSIONS

Monte Carlo calculations indicate that scattered gas bremsstrahlung and neutrons produced by gas bremsstrahlung determine the shielding thickness for the APS Insertion Device First Optics Enclosure and White Beam Hutch. Calculations are currently underway to determine the impact of other kinds of targets (different material, dimensions, and angle of inclination).

.CKNOWLEDGEMENTS

The authors would like to thank the various staff ıembers of the APS Experimental Facilities, Alfredo errari of INFN, Italy and Ken Kase of SLAC for useful iscussions and information. Gratitude is also expressed to .osemary Wedding and the SLAC Publications ›epartment for their help with this document. Work ıpported by Department of Energy contract DE–AC03– 6SF00515.

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