Design Calculations for the Advanced Photon Source Safety Shutters

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Introduction

A safety shutter at the Advanced Photon Source (APS) is a remotely actuated device that prevents a photon beam from traveling down a beamline into an experimental enclosure. All APS safety shutters are designed to be redundant. When the shutter is closed, two shielding blocks are positioned to stop bremsstrahlung and the synchrotron beam, although either block by itself is designed to provide adequate shielding. Also, the personnel safety interlock system (PSS) detects any shutter failure through redundant switches and takes appropriate measures to shut off the beam during a fault condition. All shutters are designed in the 'fail safe' mode such that, in the event of a power, communication, or mechanical system failure, the shutter will come to a closed state and will remain in the closed state.

The APS shutters/stops are designed for a dose rate of 2.5 µSv/h (0.25 mrem/h) at 30 cm from the downstream side of the stop/shutter. However, for an incident beam of bremsstrahlung photons, it is assumed that half of the dose may be due to photoneutrons. Therefore, the design criteria adopted for the shutters was a photon dose rate of 1.25 µSv/h (0.125 mrem/h) at 30 cm from the downstream surface of the stop/shutter.

A series of calculations was performed using version 2.4 of the Monte Carlo computer program MCNPX [1] to verify the guidelines set forth previously for the APS safety shutters [2]. The original shutter design calculations were carried out using the EGS4 Monte Carlo package [3]. The primary results from these earlier calculations are also included in this report.

Design Simulations

The thickness of white beam stops and shutters at the APS had earlier been calculated [2] using the EGS4 electron-gamma shower simulation program [3], which simulates the coupled interactions of photons and electrons with materials over an energy range from a few keV to several TeV. It also includes a standalone program PEGS4, which creates cross sections to be used by EGS4. Physical processes simulated by this program include bremsstrahlung production, positron annihilation at rest and in flight, Moliere multiple scattering, Moller and Bhabha scattering, Compton scattering, pair production, photoelectric effect, and continuous energy loss by Bethe-Bloch formalism. The geometry, input, and output are to be specified through user-written subroutines. The radiation dose at a given location in a configuration is calculated by EGS4 from the energy deposited in the standard ICRU tissue [4] placed at that location.

The Monte Carlo radiation transport code MCNPX was utilized to simulate a more detailed design geometry of the APS safety shutters. MCNPX is a generalized Monte Carlo program that transports all particles over an energy range of fractions of an MeV to several GeV. The physics, models, and data used in MCNPX are undergoing continual improvement. At present, neutron, proton, and photonuclear libraries are provided for energies up to 150 MeV, with model-based physics used for higher energies. Photon cross sections exist up to a maximum energy of 100 GeV, and electron cross sections exist to a maximum energy of 1 GeV. However, MCNPX extrapolates electron radiative energy loss above 1 GeV. Since the conversion of electron energy into photons is an important physical process for neutron production, it is necessary that the electron radiative losses be handled correctly. As long as the electron radiative energy loss is done correctly, we can have confidence in the photon and neutron doses calculated by the program. Several simulations, performed with both photons and electrons of 7 GeV incident on a copper block, gave results for photon energy spectra consistent with expectations [5].

Geometry for Computations

Figure 1 shows the geometry used in the EGS4 simulations to calculate the thickness of lead and tungsten required to attenuate the dose rate to 1.25 µSv/h (0.125 mrem/h) at the downstream side of the stop/shutter on contact and at 30 cm from the downstream surface. The primary bremsstrahlung source term was estimated using a well-tested empirical formula from existing synchrotron radiation sources [6,7] to scale the dose rate results. The bremsstrahlung beam from the APS straight section is incident on a lead or tungsten target with transverse dimensions of 20 x 20 cm^2. The dose rate at the downstream surface in the ICRU tissue was calculated as a function of lead or tungsten thickness. The calculated dose rates are also fitted using an effective exponential attenuation factor.

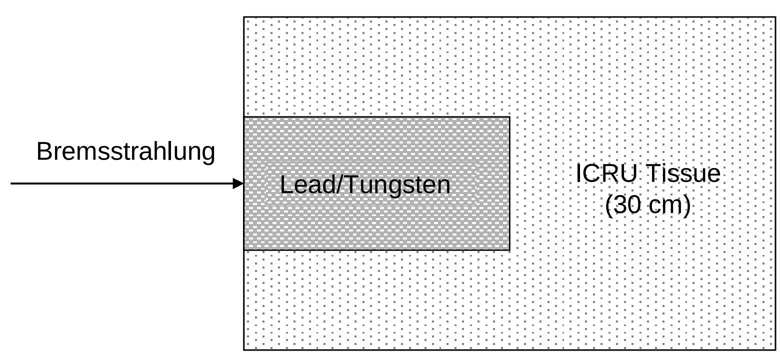

Figure 1. EGS4 simulation geometry of the APS safety shutters.

Figure 2 shows a more detailed geometry simulated in the MCNPX simulations for the safety shutters. Here we have modeled a stepped shutter with a gap between the movable and fixed pieces. This geometry must completely block the possible line of sight of radiation, including the bremsstrahlung shower, from upstream as seen from downstream. In the figure, the slit width shown between the shutter pieces is 2 mm and the step width is 15 mm. The step thickness is 6.67 cm, which represents approximately 20 radiation lengths in tungsten at nominal density. For these calculations we considered slit widths of 0.5, 1, 2, and 4 mm, and step widths of 0, 5, 15, 25, and 35 cm. In addition, we considered three different incident bremsstrahlung beam scenarios. In the first, the beam is normally incident and centered on the slit. In the second, the beam is incident obliquely (only slightly off from normal) and centered on the slit such that it strikes on the side of the first leg of the slit near the beginning of the next leg. In the third case, the beam is again normally incident on the face of the shutter but displaced to one side so that it “just misses” the slit. For all three beam incident scenarios, the bremsstrahlung energy spectrum is uniform across a circular area with a diameter of 1 cm.

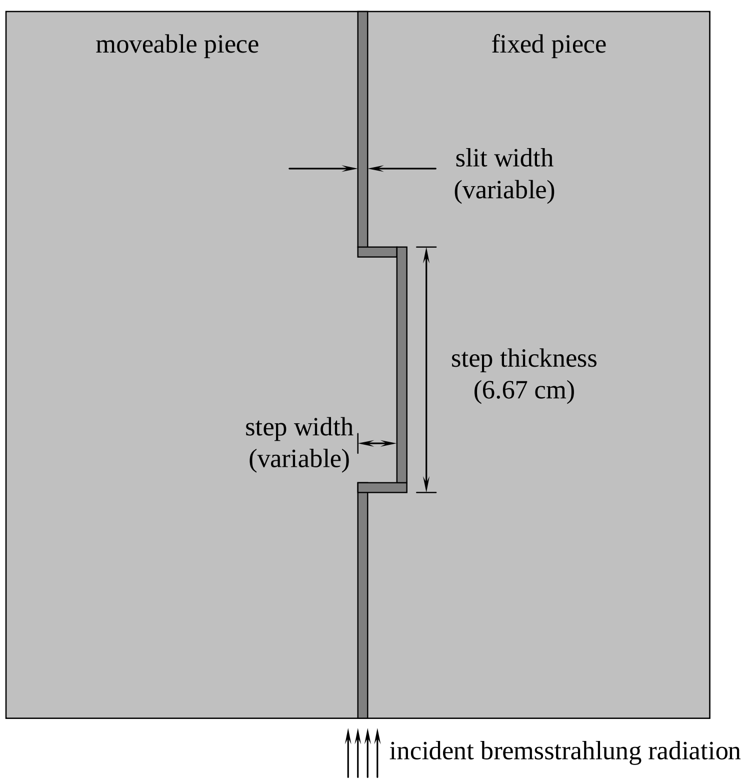

Figure 2. Plan view of MCNPX geometry for APS safety shutters.

The quantity tallied is the fraction of incident beam energy that is transmitted through the slit. To improve the efficiency of the calculations, we used the bremsstrahlung energy spectrum from 80 MeV to 7 GeV and cut off photon and electron energy transport at 2 MeV. To gauge the effect of these approximations, we performed some calculations for which the incident photon spectrum extended down to 1 MeV. Extending the source energy spectrum in this manner did not change the fraction of incident photon energy appearing at the back of the slit, but did result in longer computation times. We also performed calculations in which the transport of photons and electrons was followed down to 100 keV. In these cases the calculated energy transmission was only about 6% higher than when using the 2-MeV cutoff, but again at the expense of computation times that were much longer.

Results of EGS4 Simulations

Figures 3 and 4 give the results of EGS4 calculations as a function of the shutter/stop thickness. Figure 3 gives the contact dose rates at the downstream surface of the shutter block as a function of the block thickness for both lead and tungsten. The results are fitted to an exponential attenuation relation, with the effective attenuation coefficients for both lead and tungsten given in the figures. Figure 4 gives the dose rates at 30 cm away from the downstream surface of the shutter block. Because the size of the photon source is relatively large compared to the distance to the source point, the dose rates at 30 cm are only a factor of three less than those at the rear of the shutter. The results show that the required thickness of the stop/shutter to satisfy the criteria of a photon dose rate of 1.25 μSv/h (0.125 mrem/h) at 30 cm from the downstream surface is approximately 18 cm for tungsten and 28.5 cm for lead.

The EGS4 results are the average of 10000 events with a statistical accuracy of better than 1%. The dose rate for 1 cm^3 of the ICRU tissue has been calculated at the maximum dose point, making the dose estimates conservative. The simulations have taken into account all possible photon interactions with matter at a given energy, with the exception of photoneutron production. The systematic error due to this assumption has been compensated by assigning 50% of the dose allowance to photoneutrons.

Table 1 summarizes the recommendations for the thickness of shutters/stops at the APS beamlines and the front ends that resulted from the EGS4 simulations. The recommended thickness of white beam stops and shutters for the APS front ends and beamlines is 300 mm of lead or 180 mm of tungsten.

Table 1. Recommendations for shutter/stop thickness

Beam Type	Tungsten Thickness	Lead Thickness
ID White Beam	180 mm	300 mm
BM White Beam	180 mm	300 mm

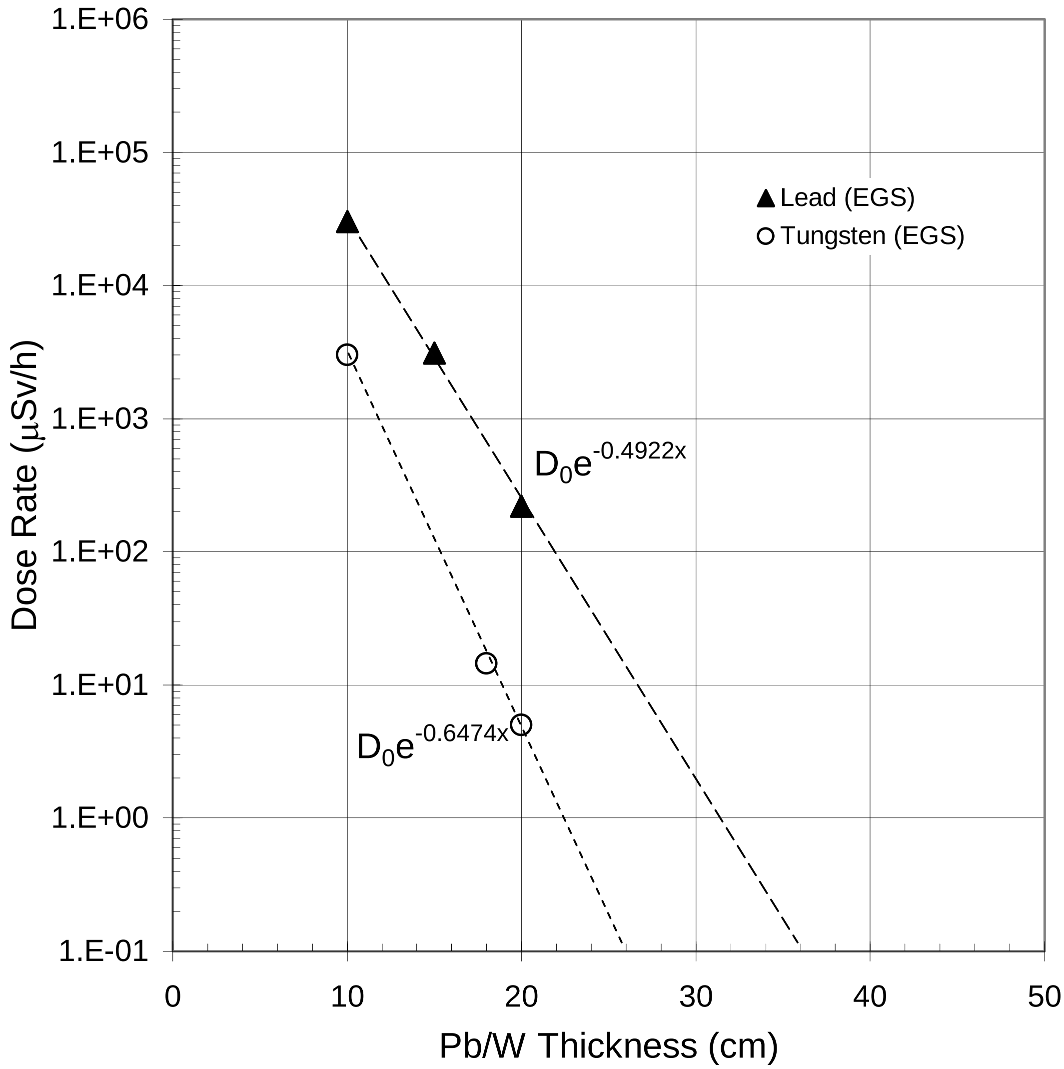

Figure 3. Contact dose rates at the downstream surface of the APS safety shutters (EGS4 simulation).

Results of MCNPX Simulations

Deep penetration problems such as radiation transport through thick shields are among the most difficult to execute using Monte Carlo codes because most of the source particles do not make it through the shield (and thus do not contribute to the result) unless the problem uses variance reduction techniques to optimize the calculation. Considerable effort was expended in generating variance reduction parameters (energy-dependent weight windows and exponential transforms) to improve the efficiency and quality of the results of these calculations. An explanation of these techniques can be found in Ref. [1].

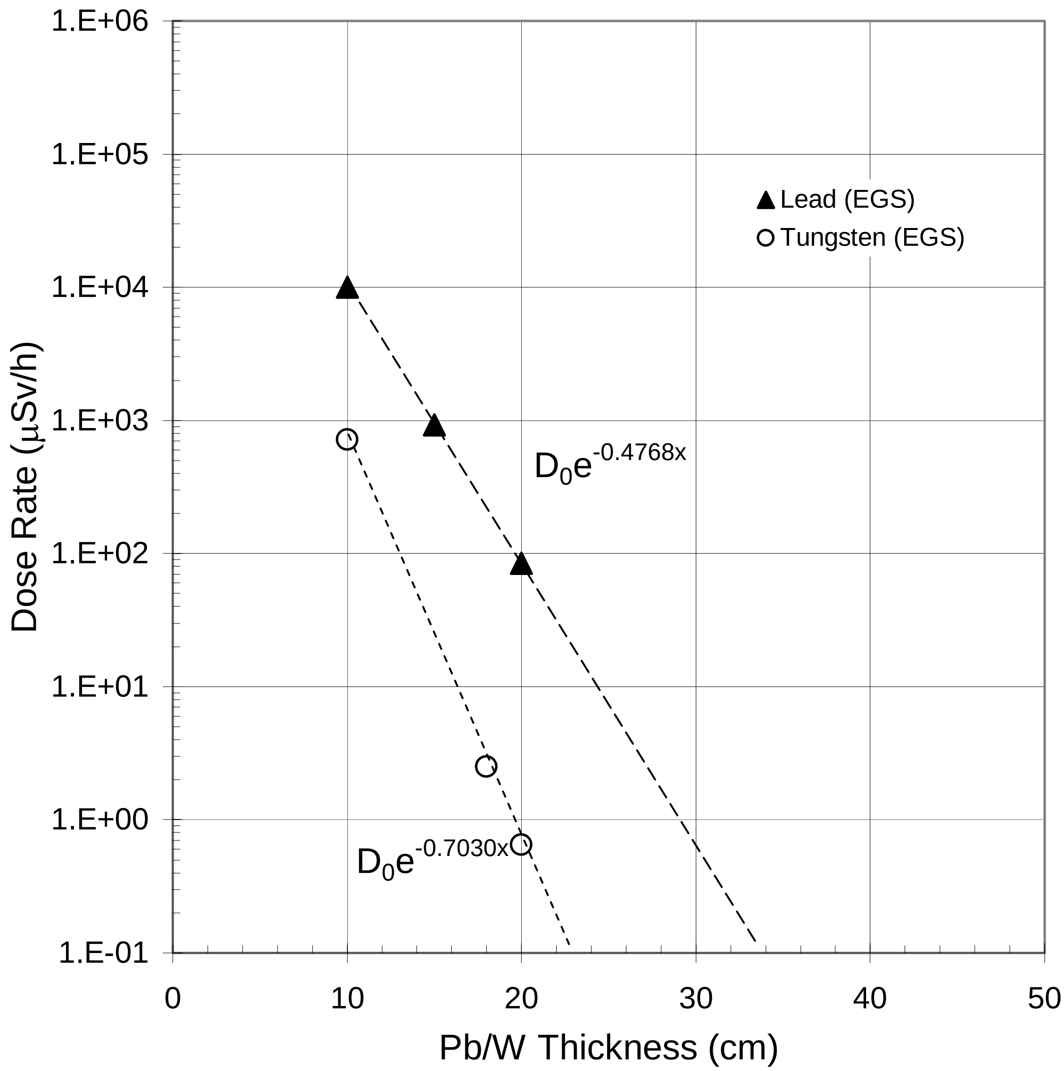

Figure 4. Dose rates 30 cm downstream of the APS safety shutters (EGS4 calculation).

The results for the three beam conditions are shown in Figures 5 through 7. Figure 5 shows the results for the beam normally incident and centered on the slit, Figure 6 shows the results for the beam incident obliquely and centered on the slit, and Figure 7 shows the results for the beam normally incident on the face of the shutter but displaced to one side of the slit. In each case we have plotted the fraction of incident photon energy that is transmitted out the back end of the slit. The results show that, as the slit width increases, the transmitted energy fraction increases approximately as the third power of the width. For all three incident beam scenarios, there is a large difference in the transmitted energy fraction between step widths of 0 mm and 5 mm, with the exact difference a function of the beam conditions. There is a smaller difference between the 5-mm and 15-mm step widths. For step widths larger than 15 mm, the differences in transmitted energy between step widths are smaller still.

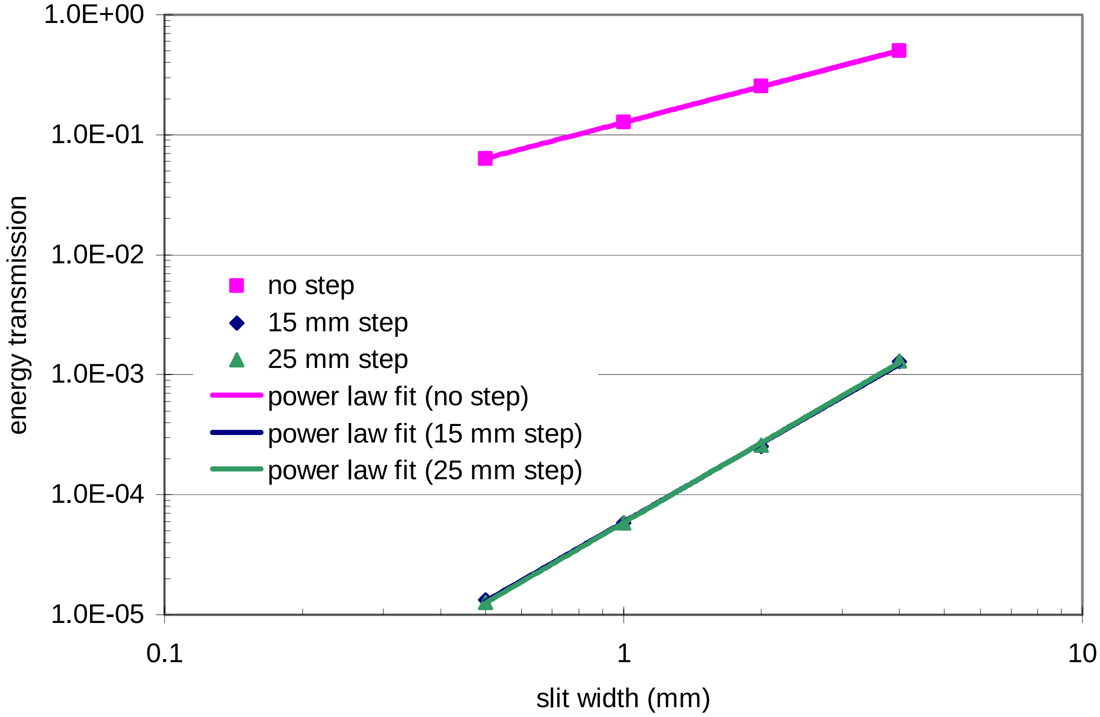

Figure 5. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident on opening in shutter).

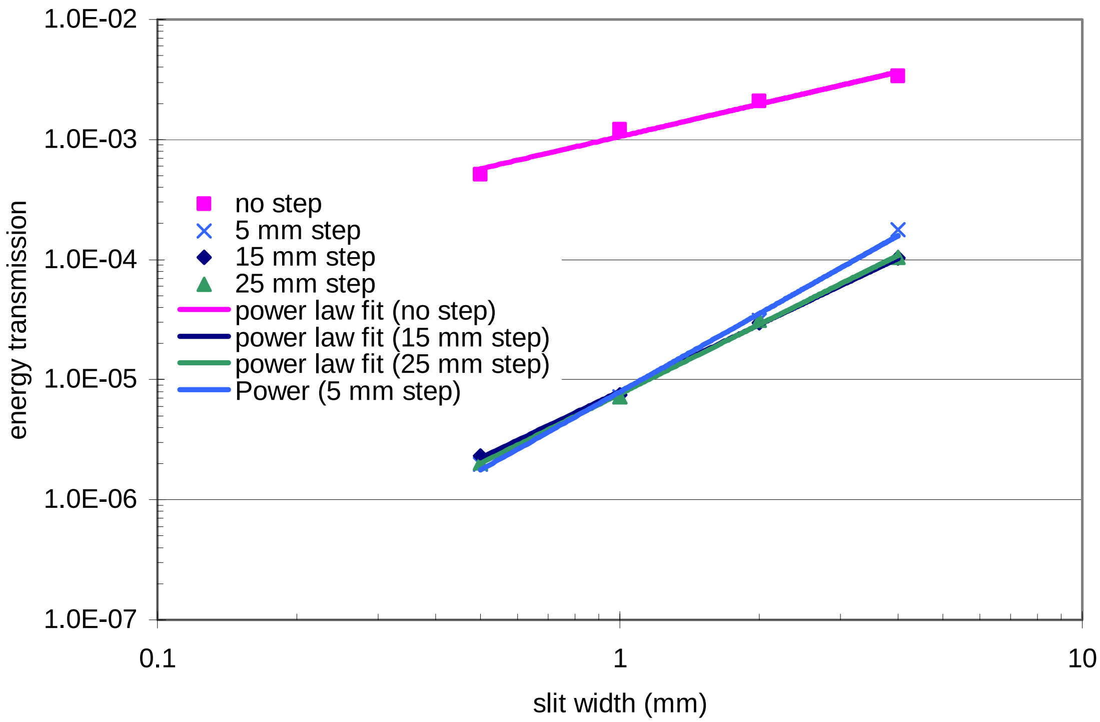

Figure 6. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam obliquely incident on opening in shutter).

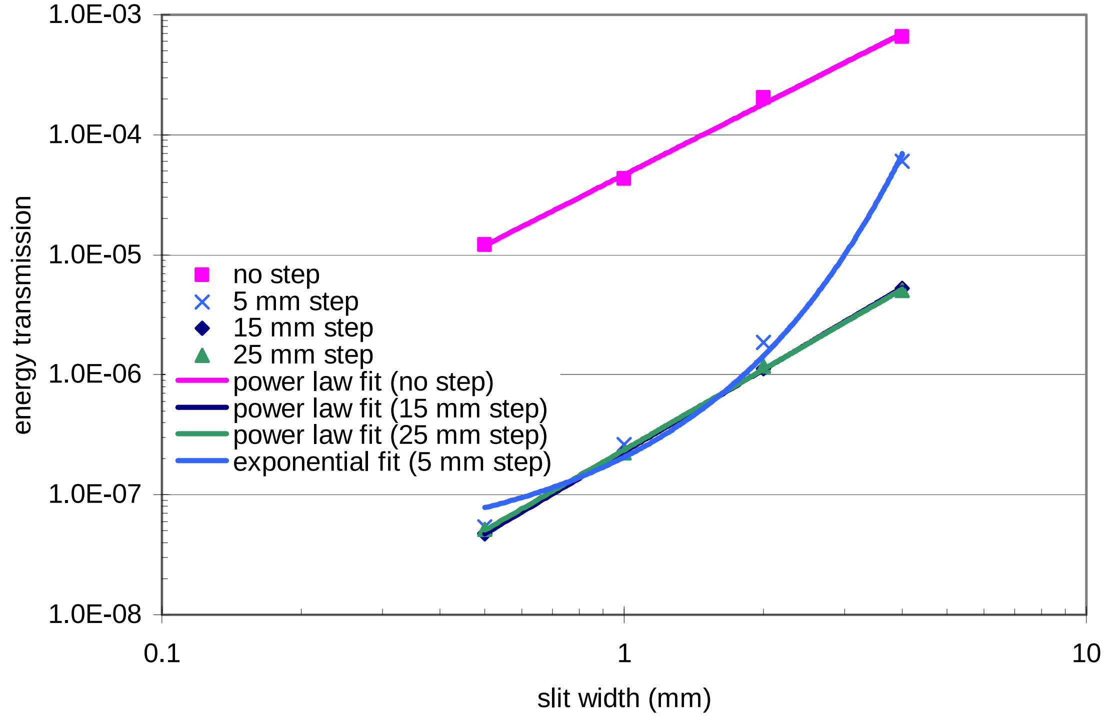

Figure 7. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident at the edge of the opening in shutter).

Based on these results, a step width of 15 mm may be adequate to contain the shower for the step thickness (20 radiation lengths) considered here. However, consistent with shower theory [8] and previous shielding measurements [9], we conclude that the 25-mm step width (three Moliere radii) will provide a margin of safety over the 15-mm step width.

Figures 8 through 11 show the data contained in Figure 7, but use linear scales for the axes to better show the variation of transmitted energy fraction for smaller values of energy transmission. These figures show that the transmitted energy fraction (and thus the transmitted dose) is much larger when the step width is 5 mm than when it is 15 mm, for all values of the slit width. For example, when the slit width is 4 mm, the transmitted energy fraction is about 10 times higher for a 5-mm step width than for a 15-mm step width. Similarly, when the slit width is 2 mm, the transmitted energy fraction is about 50% higher for a 5-mm step width than for a 15-mm step width. Even for a 1-mm slit width we found that the transmitted energy fraction was 20% higher for the 5-mm step width than for the 15-mm step width. Within the statistics of the calculations, the transmitted energy fractions are the same for 15- and 25-mm step widths, but shower theory tells us that the energy transmitted using a 25-mm step width will be less than for the 15-mm step width. The energy transmitted through a shutter with a slit width of 2 mm and step width of 25 mm is sufficiently low to provide an adequate safety margin.

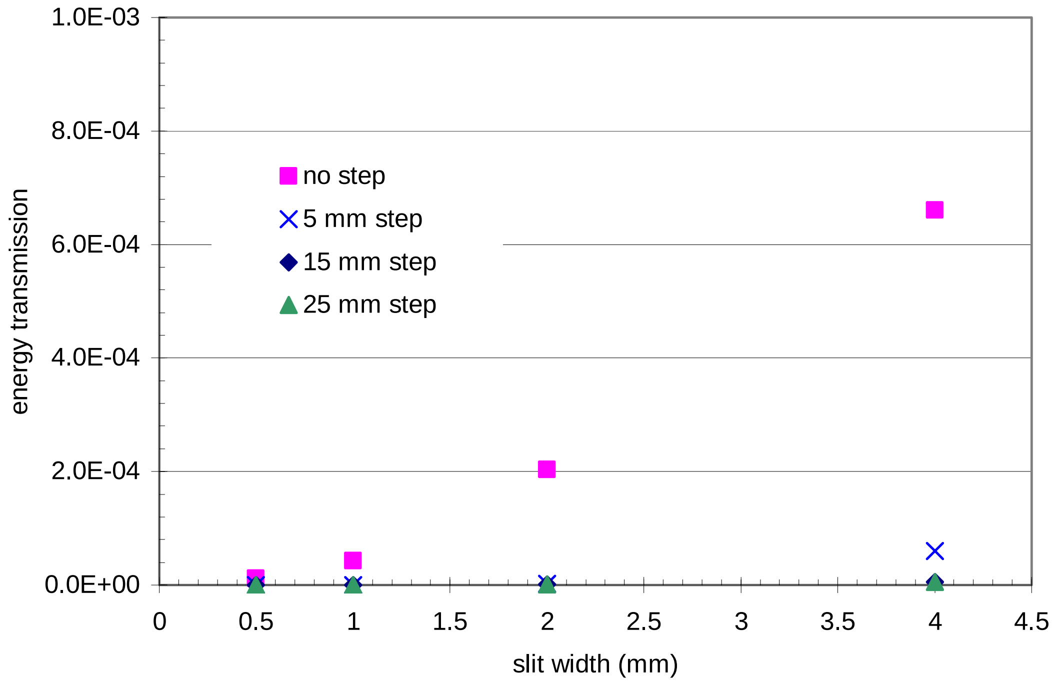

Figure 8. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident at edge of opening in shutter). The same data are shown as in Figure 7, but with linear scales along each axis.

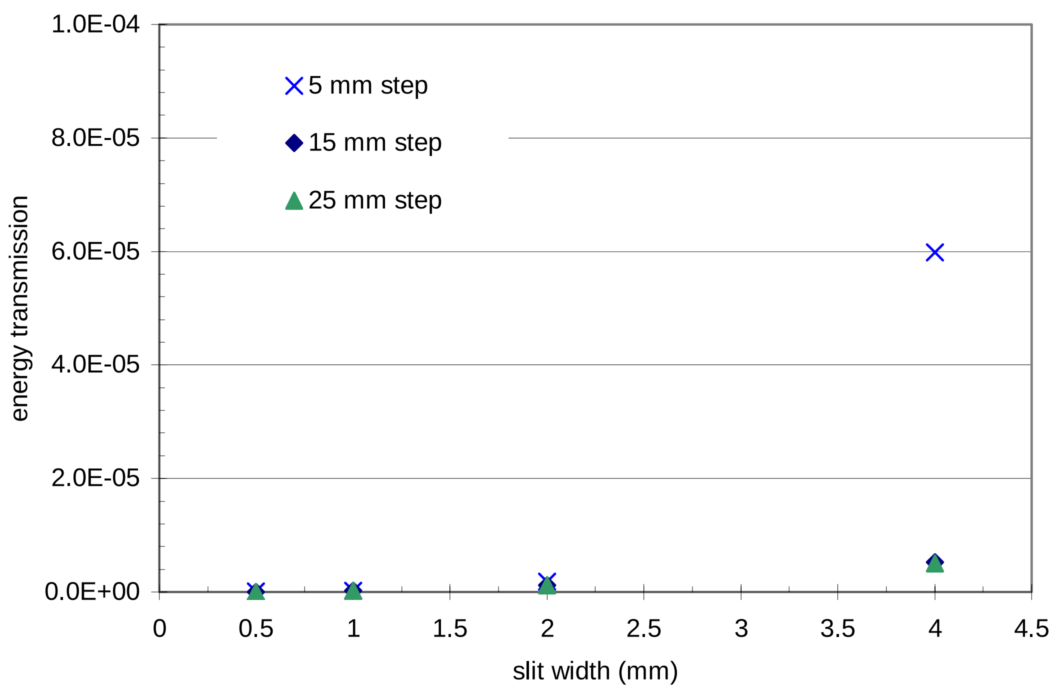

Figure 9. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident at edge of opening in shutter). The same data are shown as in Figure 8 for energy transmissions in the range 0 to 10^{-4}.

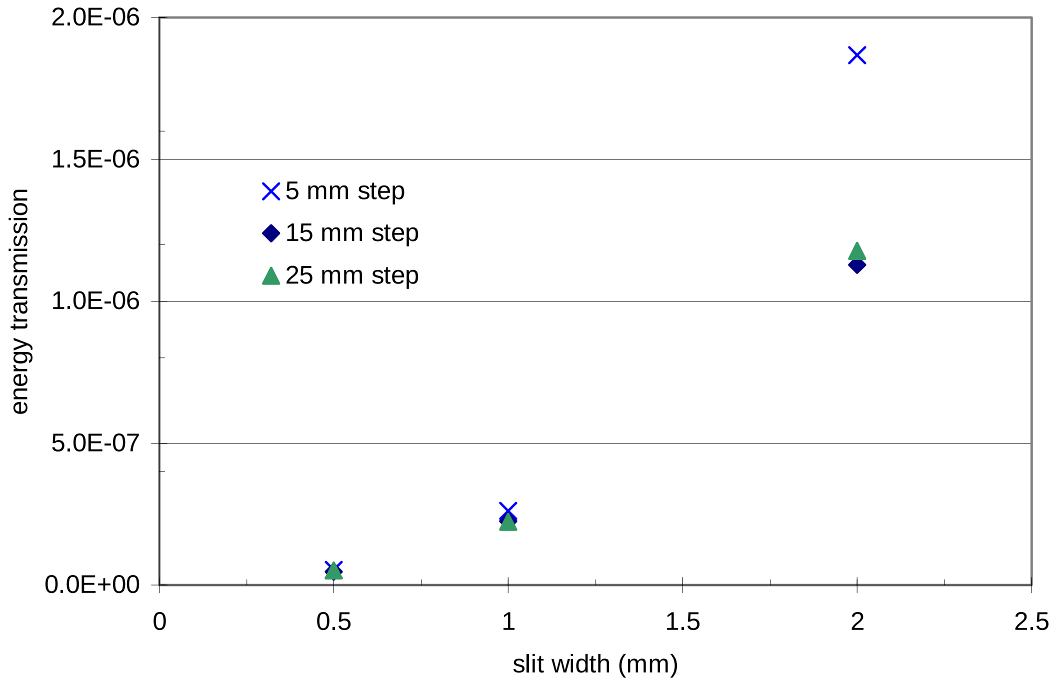

Figure 10. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident at edge of opening in shutter). The same data are shown as in Figure 8 for energy transmissions in the range 0 to 2·10^{-6}.

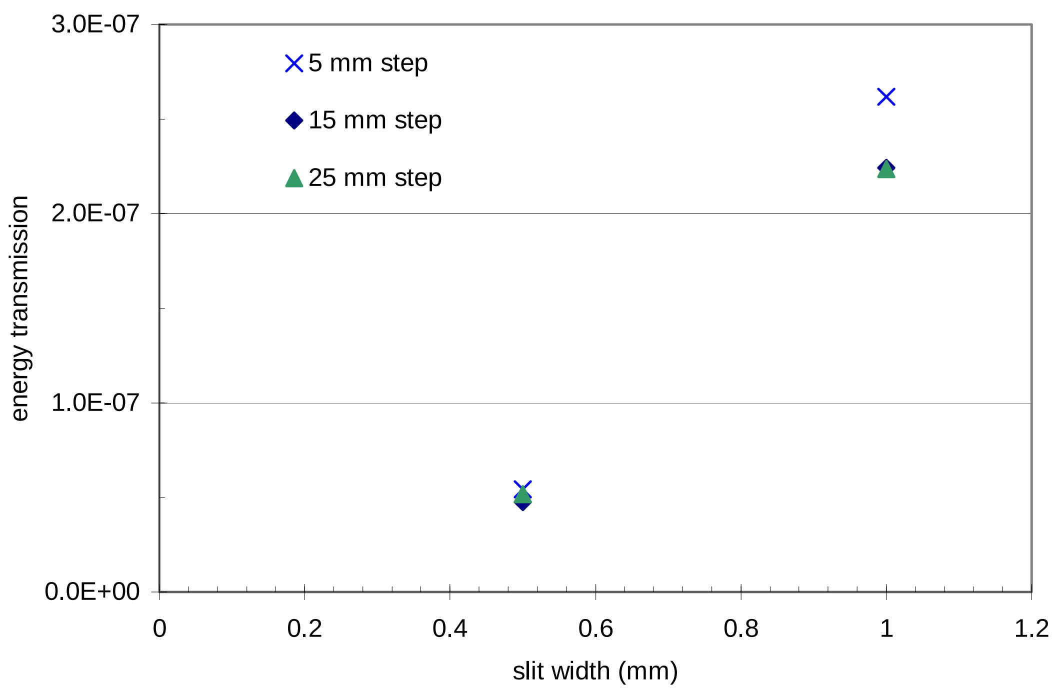

Figure 11. Energy transmission vs. slit width for the APS tungsten bremsstrahlung shutters (photon beam normally incident at edge of opening in shutter). The same data are shown as in Figure 8 for energy transmissions in the range 0 to 3·10^{-7}.

Conclusions

The MCNPX calculations we performed for the APS safety shutters have confirmed the results of the original safety shutter thickness calculations carried out using EGS4. The thickness of white beam stops and shutters at the APS had been calculated using the EGS4 code. The thickness of the stops/shutters is calculated for a dose rate of 1.25 μSv/h (0.125 mrem/h) at 30 cm from the downstream side of the stop/shutter. The recommended thickness of white beam stops and shutters is 300 mm of lead or 180 mm of tungsten. The transverse dimensions of the shutters/stops are determined from the primary bremsstrahlung ray tracing. The extremal ray in the case of primary bremsstrahlung ray tracing should not be closer than 45 mm from the lateral edge of the lead or 35 mm from that of the tungsten shield block.

A detailed analysis of the APS shutter geometry has also been performed using the MCNPX Monte Carlo program. Results show that a labyrinth step width of 15 mm may be adequate to contain the shower for the step thickness (20 radiation lengths) considered here**.** However, both analytical bremsstrahlung shower theory and measurements of 6.3 GeV electromagnetic showers in lead and concrete [9] show that a longitudinal depth of 20 radiation lengths and a transverse dimension of three Moliere Radii is required to contain 99% of the shower within the materials in which it is generated. Therefore, for the design of the labyrinths in the hard metal of a bremsstrahlung/white beam shutter, a labyrinth step width of approximately three Moliere Radii of transverse dimensions with a longitudinal depth of approximately 20 radiation lengths is recommended in order to contain the bremsstrahlung shower within the shutter. The Moliere radii for lead and tungsten are about 15 mm and 8 mm, respectively, while the radiation lengths for lead and tungsten are about 5.6 mm and 3.5 mm [10].

References

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