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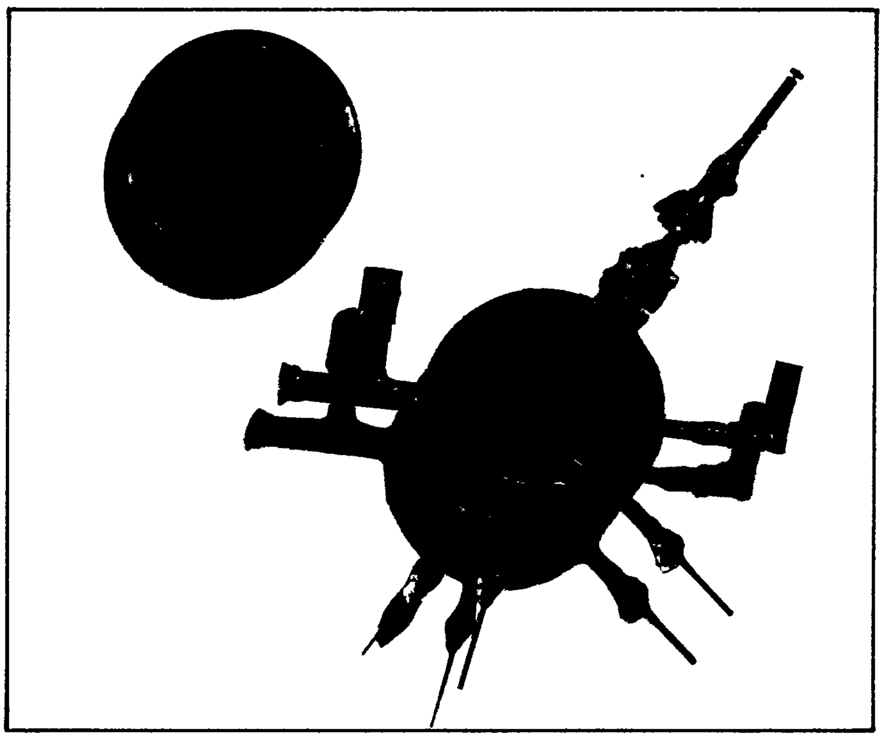
# ENVIRONMENT, HEALTH AND SAFETY DIVISION

## ALS Synchrotron Radiation Shielding

R.J. Donahue

October 1995



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# ALS Synchrotron Radiation Shielding

**R. J. Donahue**

ABSTRACT

This note discusses the assumptions and results of synchrotron radiation shielding estimates for ALS bend magnet and wiggler beamlines. Estimates of gas bremsstrahlung production are not included and are dealt with elsewhere[1].

## Introduction

The ALS currently has provisions for approximately 10 insertion devices and 36 bend magnet beamlines. The purpose of this note is to document the assumptions, tools and techniques for synchrotron radiation shielding of existing and planned ALS beamlines. A partial summary of parameters is given below. Some of these beamlines, particularly the bend magnet beamlines, will be terminated in personnel accessible hutches or end stations. Wiggler and undulator beamlines are more likely to be terminated in inaccessible experimental vacuum chambers. Since the characteristic spectrums and intensities of each of these types of beamlines are quite different, each will be discussed separately. In order to be consistent with radiation design criteria used for the shielding of the linac, booster and storage ring, the following criteria are used in this note:

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- Storage ring current: 800 mA
- Energy: 1.9 GeV
- Dose rate criteria - normal: 0.1 mrem/hr (200 mrem/2000 hrs)
- Dose rate criteria - accident: 100 mrem per event

All calculations were performed using the PHOTON[2] program written for synchrotron radiation dose and energy deposition calculations at the National Synchrotron Light Source (NSLS) at Brookhaven National Lab and used at various other synchrotron facilities[3] around the world. A Vax FORTRAN version of this program has been converted for use on Unix workstations. This program is being distributed via anonymous ftp at fubar.lbl.gov with permission of the authors. The program uses a single electron dipole magnet approximation for calculating the incident synchrotron spectrum. Wigglers are treated as n-pole dipole magnets, *i.e.*, n times the dipole magnet spectrum where n is the number of poles or periods of the wiggler. The decrease in critical energy with horizontal opening angle is conservatively ignored. PHOTON calculates both the direct beam spectrum and the indirect scattered spectrum. The Compton-scattered angular distribution is assumed to be isotropic. This is probably reasonable within about a factor of two for photon energies of importance to shielding[4]. Undulators were not discussed in the original PHOTON program, however, justification will be provided indicating that the program is still applicable to the shielding calculations of undulator beamlines.

## Bend Magnet Shielding

The only hutch currently operating at the ALS is for the $\mu$Probe beamline, BL10.3. The hutch is located approximately 32 meters from the source point *i.e.*, the tangent to the stored electron beam. The hutch is conservatively assumed to be able to accept 5 mradH. Beamsize is estimated to be 10 mm high by 3.5 mm wide. The critical energy, used by PHOTON for calculation of the synchrotron spectrum, is 3.25 KeV for this bend magnet beamline.

PHOTON calculates two sources of radiation dose rates: direct and indirect. The direct dose rate is determined by using the direct transmitted synchrotron flux spectrum through a set of filters. This is done by specifying a filter, like a thin lead shield, followed by the NICK command for calculating the absorbed dose rate. The indirect dose rate is determined by calculating the rate of total inelastically (Compton) scattered radiation from a filter. This is done in the program by specifying a filter, like a steel sidewall, followed by the WALL and WHOM commands for calculating the absorbed dose rate. Two assumptions are made in the program regarding scatter: first that the scattering is isotropic, and second that the source of scattering acts as a point source and therefore geometrically attenuates as $\frac{1}{r^2}$ where $r$ is the distance from the source.

Figure 1 shows the calculated direct beam shielding requirements for the $\mu$Probe hutch. Curves are shown for steel, lead and 3 mm ($\frac{1}{8}$") of steel followed by lead. To meet the limit of 0.1 mrem/hr a minimum of 3 mm inch of steel followed by 3 mm inch of lead is required. In the case of the $\mu$Probe hutch there is direct line of sight to the straight section requiring a 10 inch lead backstop for gas bremsstrahlung. This is more than sufficient to shield the direct synchrotron radiation. However, future hutches may be designed which do not have direct line of sight with the source point and therefore do not have a bremsstrahlung backstop. Calculations here suggest that the back wall (direct) should be thicker than a 3 mm steel side wall (scatter) by the addition of 3 mm of lead. The approach taken at the NSLS[5] is to use the indirect dose rate to determine all wall thicknesses and any hot spot directly downstream of the beam is handled by conservative shield

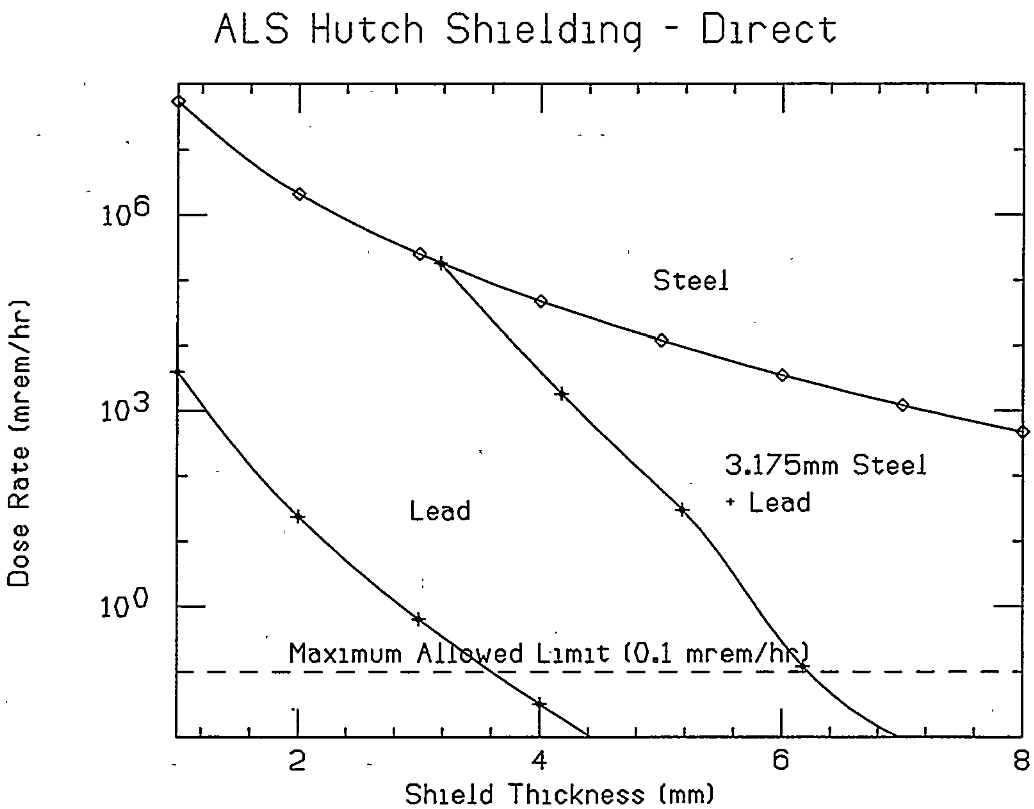


**Figure 1:** ALS $\mu$Probe hutch direct beam shielding requirements.

calculations (*i.e.*, horizontal acceptance, final thickness, etc.) and any local shielding as required by measurements. This approach should also be acceptable at the ALS, provided that the direct beam cannot be directed over a large area of the hutch back wall. In these cases, the addition of 3 mm of lead shielding for bend magnet hutches will mitigate the possibility of unacceptably high dose rates.

Figure 2 shows the direct transmitted flux spectrums for the various shield thicknesses. One should note the importance of higher energy photons with increasing shield thickness. A simple rule of thumb indicated in these dose spectra is that synchrotron radiation shielding seems to be controlled by photons with energies approximately equal to ten times the critical energy of the beamline.

The lead curves end at about 88 keV. This corresponds to the k-edge of lead at 88.004 keV (see Fig. 3. At this point the Photoelectric absorption cross section $\mu_a$, jumps from 1.53 g/cm$^2$ to 7.21 g/cm$^2$. Since exponential attenuation is assumed

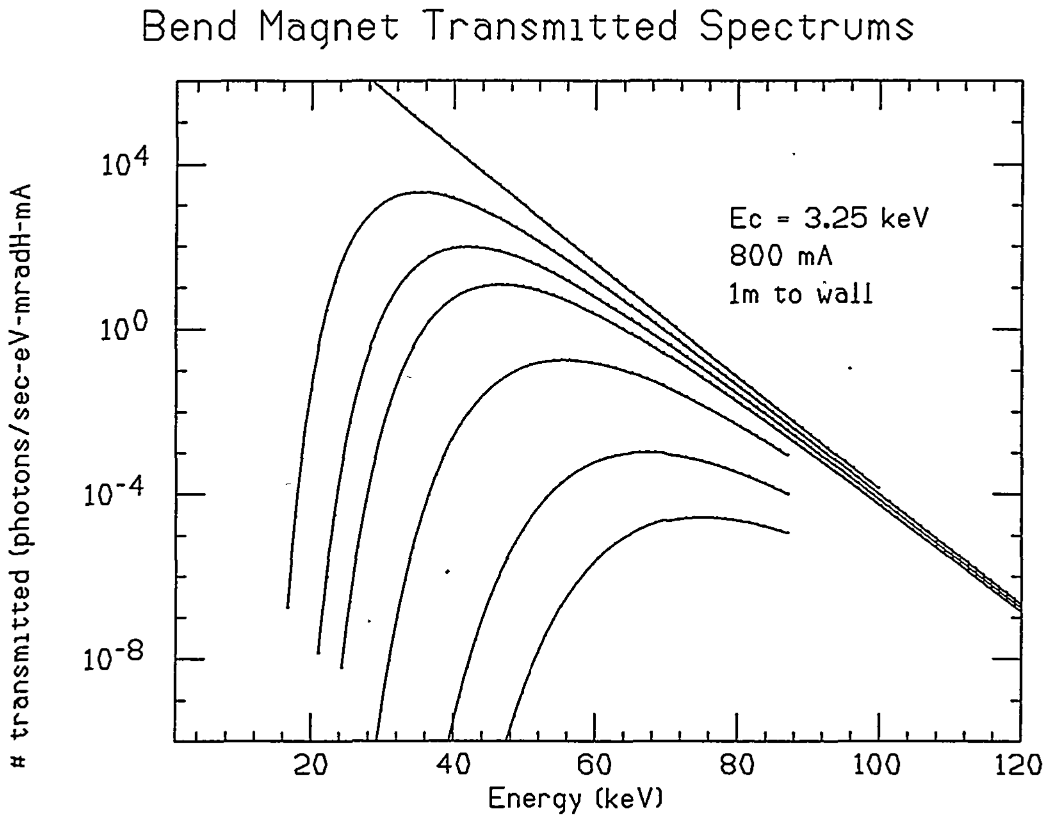


**Figure 2:** ALS $\mu$Probe hutch direct transmitted flux spectrums. The straight line represents the unshielded synchrotron spectrum. The top three curves are for steel shield thicknesses of 1, 2 and 3 mm, respectively. The bottom three curves are for 1, 2 and 3 mm of lead, respectively.

($e^{-\mu_a x}$) photons of energy greater than 88.004 keV wil not contribute substantially to the transmitted flux spectrum. For photon shutters and where space is very limited a tungsten-lead composite (tungsten powder mixed with lead?) may be considered, although no application has yet been justified. This is an effective shielding combination because the tungsten and lead K-edges occur at 69.525 KeV and 88.005 KeV, respectively - the energy region which dominates the dose spectrum.

Figure 3 shows the results of calculations for the indirect (scattered) synchrotron through a stainless steel side wall.

The results show that a minimum of 2 mm of steel is required to maintain dose rates less than 0.1 mrem/hr. Lead is not shown on this plot since 1mm

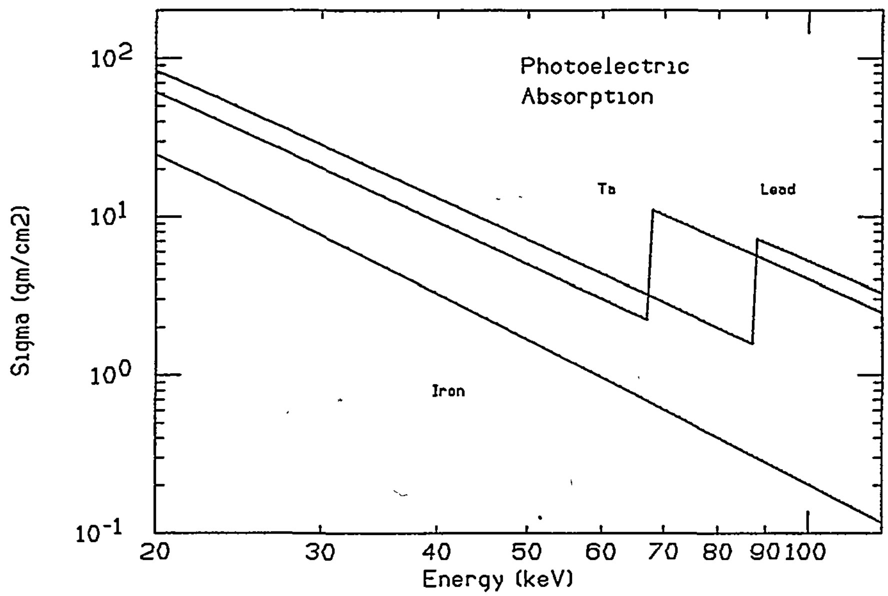


**Figure 3:** Photoelectric absorption cross section for lead and iron.

of lead reduced the scatter dose to less than 0.2 $\mu$rem/hr. Figure 4 shows the transmitted flux spectrum for the scattered synchrotron radiation for the three steel thicknesses.

In general, 3 mm of steel is sufficient shielding for ALS bend magnet beam line components which provide a large amound of scatter (mirrors, monochrometers, etc.) and for bend magnet hutches. For scaling purposes the dose is proportional to the horizontal acceptence and inversely proportional to the square of the distance along the beamline. Beam spot size has no affect on the scatter dose rate.

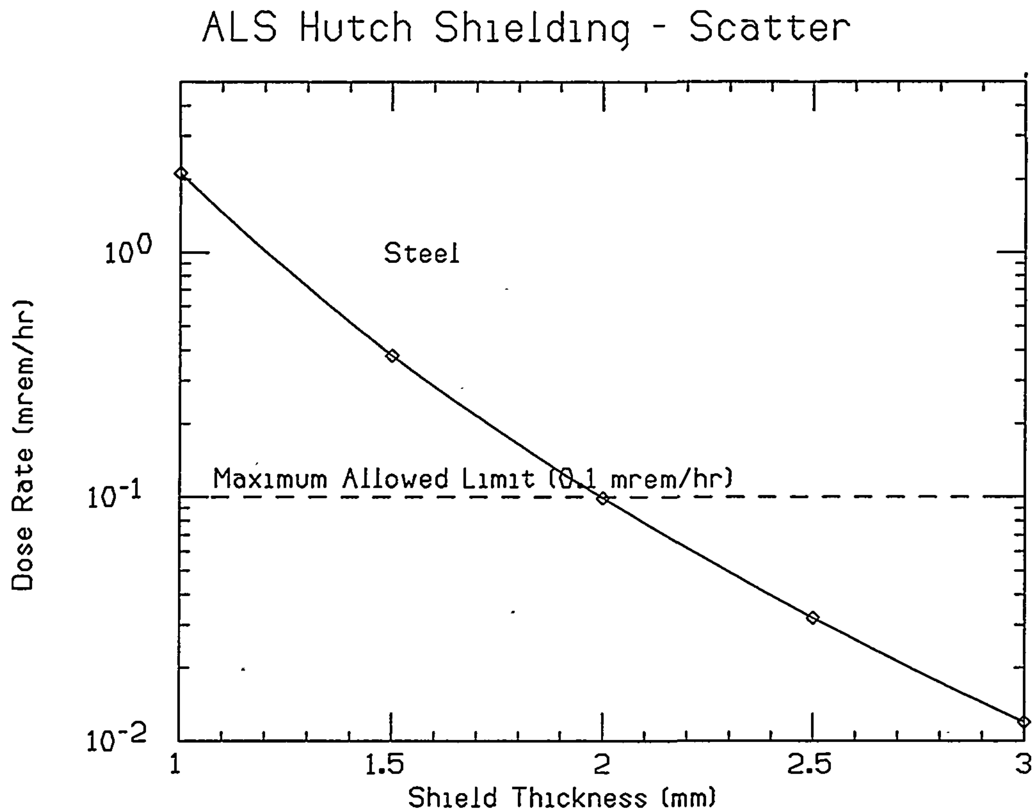


**Figure 4:** ALS $\mu$Probe hutch indirect (scattered) shield requirements.

## Wigglers/Undulators

The PHOTON program assumes that a wiggler spectrum can be approximated as an n-pole bend magnet spectrum, where n is the number of poles or periods. This is reasonable since they are both smooth varying functions. Further, it was used to determine dose rates from the X-17 Superconducting Wiggler Beamline at the NSLS. Calculated dose rates were generally high (conservative) by a factor of 2 to 8 compared to measurements.

Undulator spectrums are different than wiggler spectrums and therefore the use of PHOTON's n-pole dipole magnet spectrum should be discussed. Undulator spectrums are characterized by sharp peaks at certain harmonic energies for on-axis radiation and softer peaks for off-axis radiation. A paper by Dejus, et. al.[6] suggests that this assumption is still valid for purposes of radiation protection.

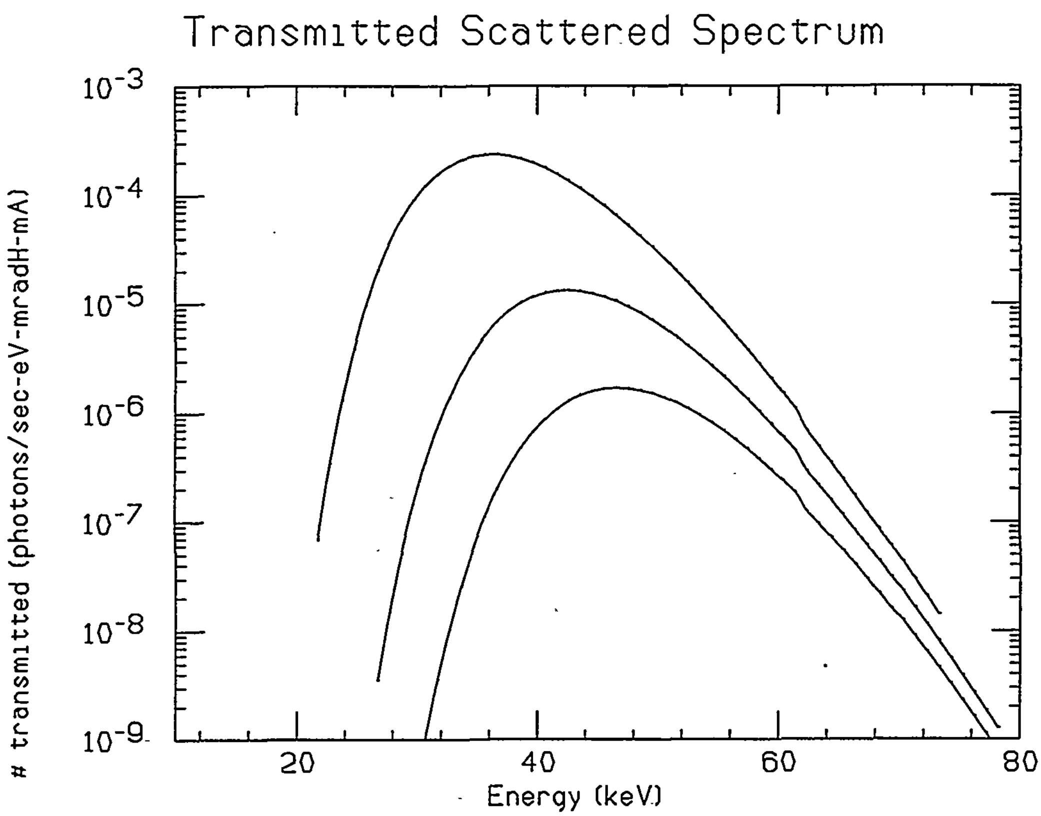


**Figure 5:** ALS $\mu$Probe hutch indirect (scattered) transmitted flux spectrum.

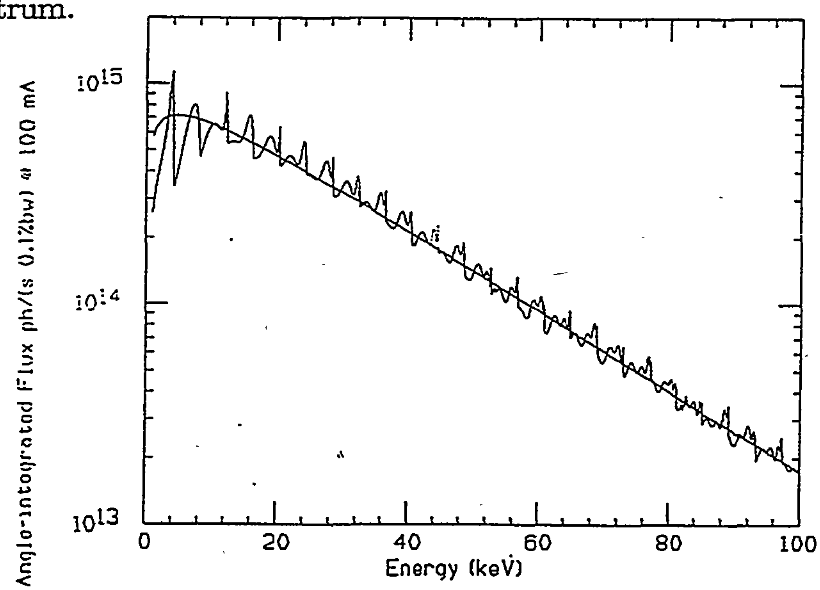


**Figure 6:** Comparison of angle-integrated flux for APS Undulator A using a modified Bessel function approximation and the wiggler approximation†.

Figure 5 shows the angle-integrated photon flux for the 6 GeV Advanced Photon Source Undulator A. Two models are used: a modified Bessel function which shows the undulator peaks, and a wiggler approximation (essentially the n-pole dipole magnet spectrum) which shows a smooth function. The conclusion that can be made from this plot is that above about 30 keV the two models produce spectrums which are very similar - certainly close enough for radiation protection purposes. The transmitted flux spectra shown earlier (Figures 2 and 4) demonstrate that this is the dominant photon energy after only 1 to 2mm of stainless steel. Theory[7] predicts that agreement increases as the deflection parameter K increases ($K > 1$) and the energy is large ($E > E_c$). Therefore the current version of PHOTON, using the n-pole dipole approximation can be used for estimating scatter radiation from ALS undulators. Similar assumptions have been justified at the 2.5 GeV NSLS[8] where synchrotron spectrums more closely match those of the ALS.

A 2 Tesla, 37 pole wiggler magnet is being designed for beamline 5.0. This is the first high-powered insertion device beamline to bring beam into a user-accessible end station[9]. It is also the first ALS wiggler beamline. All other straight sections are either unused at this time or contain undulators. The undulator harmonics are too low in energy at the ALS for use as crystallography devices.

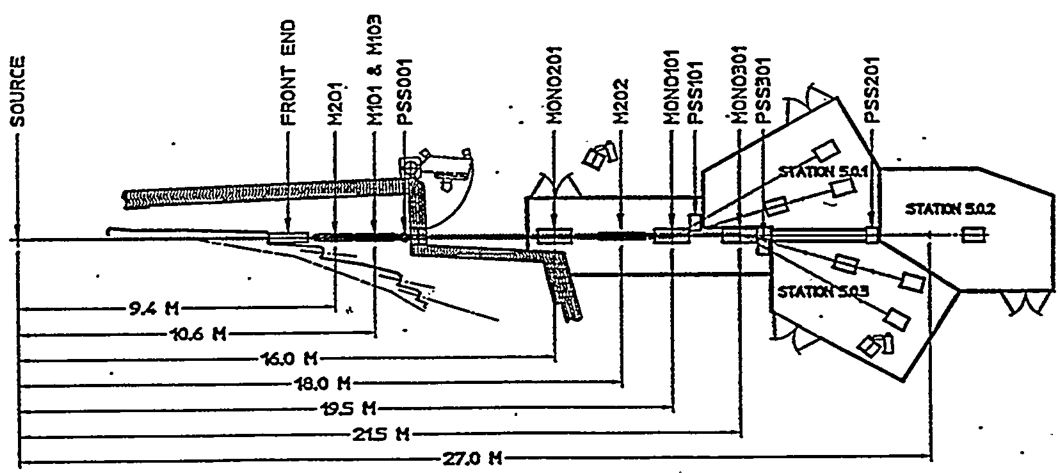


**Figure 7:** Schematic layout of ALS Beamline 5.0 branchlines.

This beamline will have one central beamline and two branchlines. All three beamlines will terminate in user-accessible experimental hutches. A plan view of the beamline layout is shown below. Radiation shielding calculations for these beamlines will now be made.

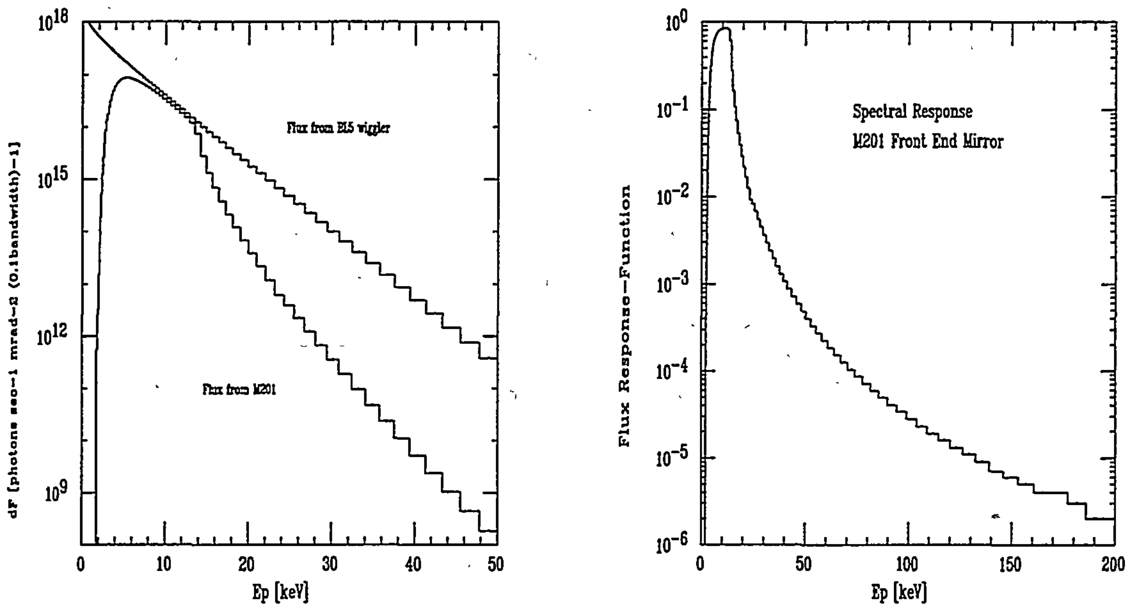


**Figure 8:** Spectral flux density before and after BL5.0 M201 mirror on the left and the corresponding M201 response function to be folded into spectral dose calculations of PHOTON.

Fig. 8, on the left, shows the spectral flux density before and after the M201 mirror[10] inside the storage ring shield wall. In addition, the low-energy portion of the bottom curve has been filtered by a 125 $\mu$m graphite filter and a 125 $\mu$m beryllium x-ray window just upstream of the M201 vertical collimating mirror. The plot on the right represents the spectral efficiency of the M201 mirror, determined by ratioing the two spectral flux density curves on the left. This efficiency will be folded into the white beam calculations estimated using PHOTON in order to avoid grossly overestimating the dose rate downstream of the M201 mirror. This can be justified since the M201 device is a vertical collimating mirror which offsets the beamline vertically downstream of the mirror. The majority of the white beam is intercepted by mirrors inside the storage ring shield wall. A small fraction (0.5 mrad) on the outboard sides is transported to a set of beam position monitors outside the shield wall and is then terminated immediately downstream in the thick copper bremsstrahlung collimating spool. Radiation protection credit should be taken for such components as permanent mirrors inside the storage ring shield wall if they can be shown to provide passive protection and fail in a radiation-safe mode.

The central beamline, 5.02, can accept 1.5 mradH while the outside beamlines, 5.01 and 5.03, can accept 3 mradH. For radiation protection purposes all three beamlines are assumed to accept 3 mradH radiation from the wiggler. The critical energy for the 2 Tesla wiggler is assumed to be 4.9 KeV. Beam spot size varies with location along the beamline, from about 4 mm vertically and 24 mm horizontally ($\sim$1 cm$^2$) at a monochrometer to 0.3 mm x 0.3 mm ($\sim$10$^{-3}$ cm$^2$) at the target location in the hutch.

For each beamline there are at least three radiation shielding concerns: the experimental end station (hutch) wall thicknesses since this is where the synchrotron beam is terminated, the monochrometer tank wall thickness since a large fraction of the incident higher-energy (unwanted) photon flux can be scattered off the mirror, and any local safety shutter or beam stop used for access into a hutch without having to use the Personnel Safety Shutter (PSS) inside the shield wall. The 5.0 PSS is shared by all three beamlines. Hence using it shuts off all three. It is therefore desirable to provide local controls for access into an individual hutch without effecting the operation of the other two hutches.

One additional source of radiation not quantified here is scatter radiation from gas bremsstrahlung. This is particularly important for mirrors or monochrometers which may absorb a large fraction of the on-axis white beam. For beamline 5.0 this will be partially mitigated by using an in-vacuum, well-shielded copper mask. This mask will be placed upstream of the first monochrometer and is used to shadow the central gas bremsstrahlung core between the three seperate usable

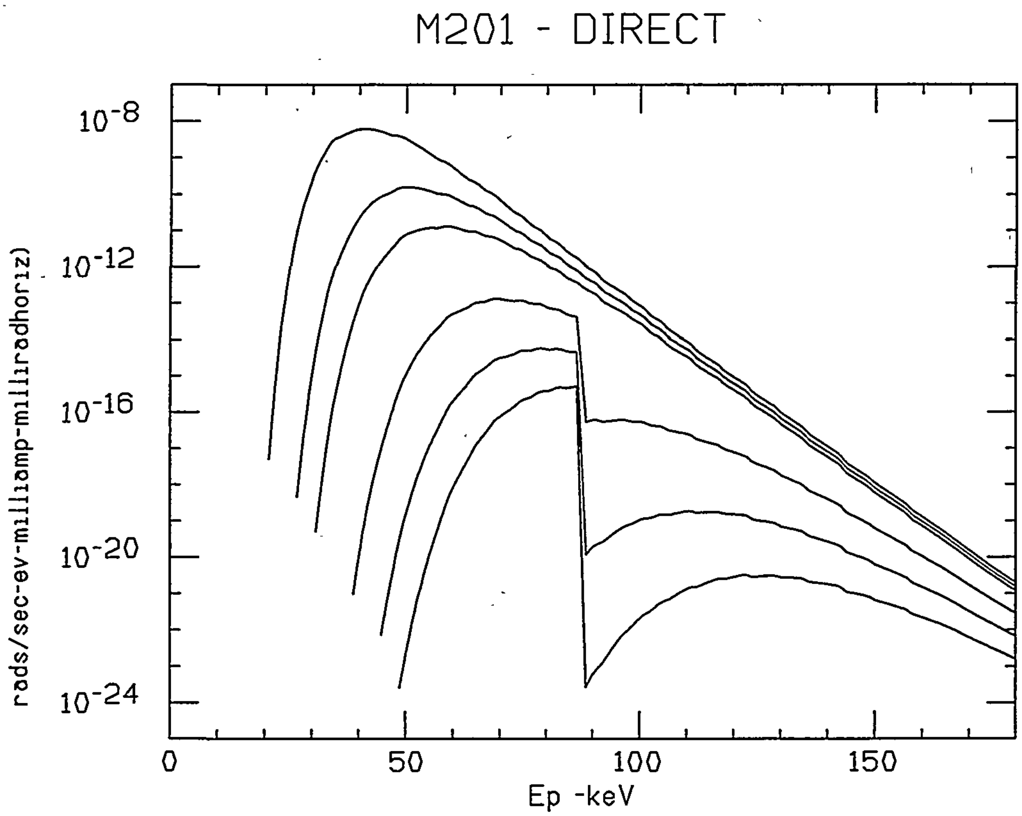


**Figure 9:** Direct beam dose spectra at beamline 5.02 MONO201 monochrometer tank. The top three curves are for 2, 4 and 6 mm of steel, respectively. The bottom three curves are for a composite of 6 mm steel followed by 1, 2 and 3 mm of lead.

synchrotron beams. This will be verified with radiation surveys of the beamline during commissioning.

The dose rates from scattering the entire synchrotron beam inside MONO201 tank are shown in Fig. 10 for various shield materials and thicknesses. It can be seen that if the monochrometer tank were constructed out of 6 mm stainless steel no additional shielding would be required. If the tank were constructed out of 25.4 mm aluminum then an additional 1 mm of lead wrapping around the tank would be required. These shielding requirements apply to any source of synchrotron scatter radiation on beamline 5.0, including the experimental hutches.

The dose rate from the direct synchrotron beam at the location of the Personnel Safety Shutter 201 (PSS201) is shown in Fig. 11 as a function of shield thickness

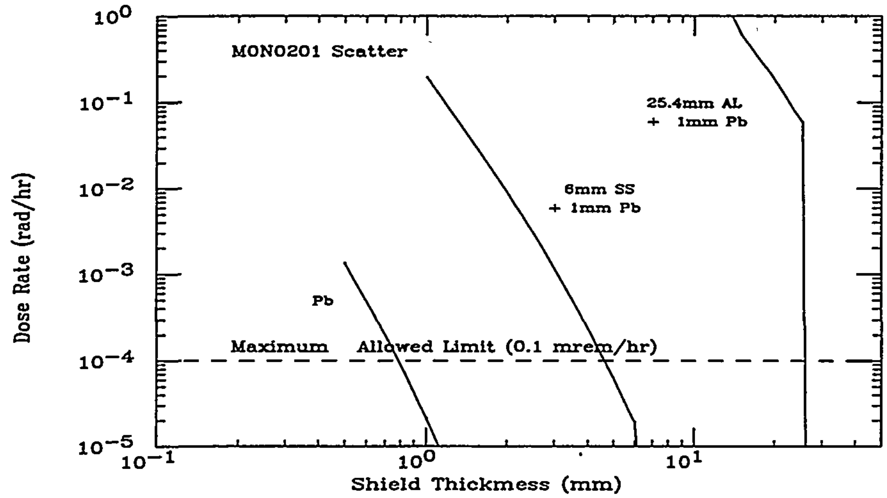


**Figure 10:** Beamline 5.0 Monochrometer 201 scatter radiation dose rates for various shield materials and thicknesses.

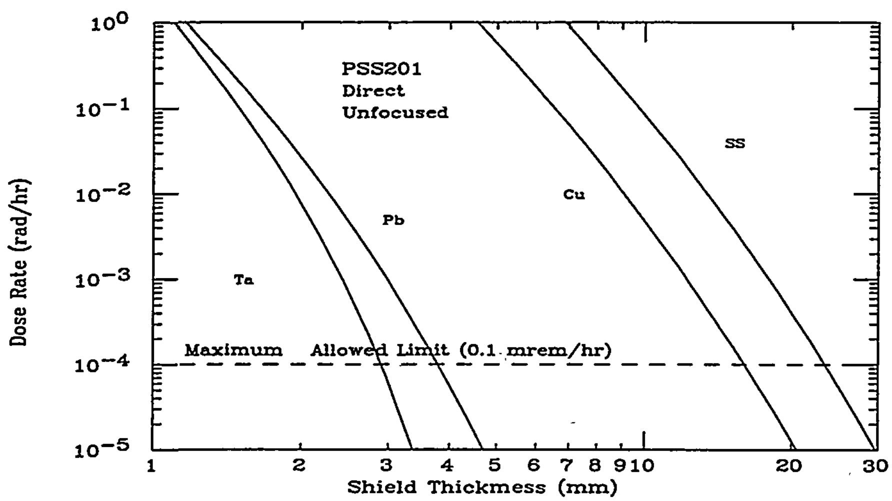


**Figure 11:** Beamline 5.0 Personnel Safety Shutter 201 (PSS201) direct, unfocused radiation dose rates for various shield materials and thicknesses.

for a shutter/shield constructed out of Ta, Pb, Cu or SS. It is currently envisioned that PSS201 will be constructed out of a water-cooled Cu plate. The required thickness to maintain the downstream dose rate to less than 0.1 mrem/hr from synchrotron radiation is about 18 mm. It is not yet clear if these personnel safety shutters will also act as bremsstrahlung shields to allow downstream hutch access.

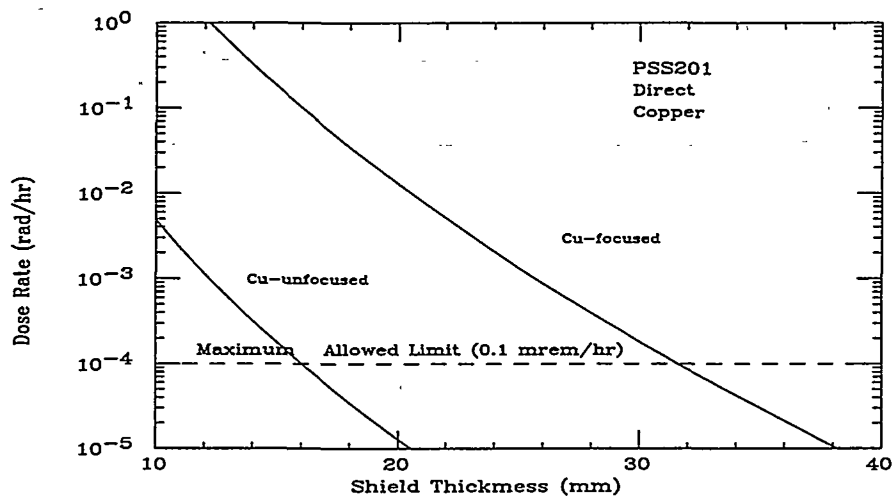


**Figure 12:** Beamline 5.0 Personnel Safety Shutter 201 (PSS201) direct radiation dose rates for a Cu shutter, considering both focused and unfocused beams.

It should be noted that the beams incident on PSS 201, 202 or 203 are not focused beams. Beam cross-sectional area is about 1 cm$^2$. Downstream of the second mirror the beam is focused to about 1 mm$^2$, hence the dose rate over a very small area has increased by three orders of magnitude. This is shown in Fig. 12 for a Cu shutter. the required thickness of Cu for the focused beam is 32 mm.

As an additional note of interest Fig. 13 is a plot of the radiation dose spectra from 3 mm Ta, 4 mm Pb, 16 mm Cu and 22 mm SS. These are the thicknesses of a shield/shutter which reduce the direct beam dose rate to approximately 0.1

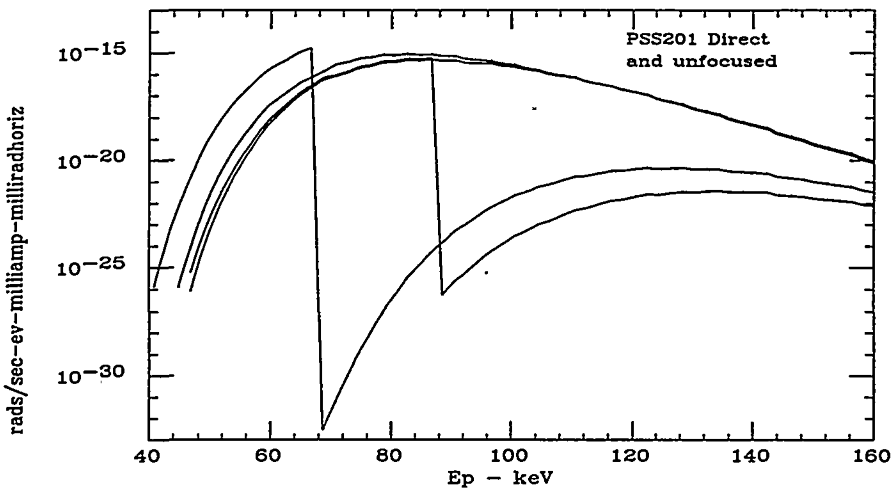


**Figure 13:** Radiation dose rate spectra from thicknesses (see text) of Ta, Pb, Cu and Pb which give downstream dose rates of approximately 0.1 mrem/hr for PSS201 unfocused beam.

mrem/hr. The Cu and SS curves cannot be distinguished. The Ta and Pb curves are evident from their K-edges at 69.525 KeV and 88.005 KeV, respectively. This is shown only to demonstrate that part of the synchrotron spectrum which dominates the dose rate attenuation in various shields.

## Discussion

It has been shown that the PHOTON program is applicable for use in synchrotron radiation shielding calculations for ALS bend magnet, wiggler and undulator beamlines. Bend magnet beamlines are relatively uniform in their beam specifications and therefore the estimates of shield thickness made here should cover the majority of planned bend magnet hutches. This is not the case for wiggler and undulator beamlines, where there can be relatively large variations in peak magnetic fields, number of poles, acceptance, optical devices, etc, and therefore these beamlines should be handled on a case-by-case basis.

## Acknowledgements

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