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Estimation of the lead thickness required to shield scattered radiation from synchrotron radiation experiments

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HIGHLIGHTS

- A thickness estimates to shield scattered radiation at photon beam lines is given.
- No specific assumption on composition and geometry of the target are required.
- Energy and distribution of scattered radiation only depend on primary energy and angle.
- The approach not only yields the required thickness but also conditions for a survey.

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ABSTRACT

In the enclosure of synchrotron radiation experiments using a monochromatic beam, secondary radiation arises from two effects, namely fluorescence and scattering. While fluorescence can be regarded as isotropic, the angular dependence of Compton scattering has to be taken into account if the shielding shall not become unreasonably thick. The scope of this paper is to clarify how the different factors starting from the spectral properties of the source and the attenuation coefficient of the shielding, over the spectral and angular distribution of the scattered radiation and the geometry of the experiment influence the thickness of lead required to keep the dose rate outside the enclosure below the desired threshold.

1. Introduction

In a recent publication (Wroblewski, 2014) a simple scheme was derived to estimate the shielding thickness for monochromatic synchrotron beam lines in the energy range below about 150 keV. In this regime fluorescence is the dominant source of secondary radiation and the arising field of secondary radiation may be regarded as isotropic. This allowed for a simple factorization of the influence of energy, intensity, distance from the primary beam and the cross sections for fluorescence and scattering on the intensity of the secondary radiation. The required lead thickness could thus be estimated by a simple spread sheet calculation.

For higher energies of the primary beam, however, Compton scattering becomes the dominant effect. The Klein–Nishina cross section is a function of the energy of the incident radiation and the scattering angle. Furthermore, the energy distribution becomes angle dependent with energies decreasing from forward to back scattering (Leroy and Rancoita, 2004). An approach using the maximum cross section and the highest energy would thus yield good values for the forward direction but overestimate the thickness of the side and front walls. A more realistic but still conservative approach must, therefore, consider the angular and energy distribution of the scattered radiation. For this purpose Monte-Carlo codes like EGS4 (Nelson et al., 1978), EGSnrc (National Research Council Canada) or FLUKA (Fassò et al., 2001) but also analytical codes like PHOTON (Chapman, 1988) or STAC8 (Asano and Sasamoto, 1994) have been developed. Both approaches, however, require rather specific assumptions about the target (composition, geometry, angle of incidence, etc.) and also the enclosure. Such assumptions may lead to differing results for identical beam lines. This was the case for PETRA III where for otherwise identical parameters (2 m device length, period 29 mm, peak field 0.81 T, $dE/E = 1\%$) STAC8 gave for beam line P05 extending to higher energies (50 keV, 3rd harmonic 150 keV) a lower lead thickness than for P13/P14 using only lower energies (35 keV, 3rd harmonic 105 keV) (Leuschner and Asano, 2008). As in most cases the energy is tunable at both beam lines so that the

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spectrum P05 includes that at P13/P14. A typical synchrotron radiation experiment is, furthermore, distinguished by its high variability both in composition (samples, optics, slits, etc.) and geometry. Therefore, a more fundamental approach is required.

The dose rate outside the enclosure depends on the number and energy of the primary photons, the scattering properties of the target, its distance to the dose object and the effective thickness and attenuation of the shielding. It will be shown that each factor (and thus the entire calculus) can be expressed as a function of the spectral properties of the incident radiation and the scattering angle at the target. After deriving the general expression for the dose arising due to scattering (fluorescence has already been treated in Wroblewski (2014)) each factor will be discussed separately to highlight its influence leading finally to an estimate for the required shielding thicknesses.

2. The basic equation

The number of scattered photons is given by the number of incoming photons n_0 times the Klein–Nishina scattering cross section of the electron $r_e^2C_{KN}$ (where $r_e=2.82\times10^{-15}$ m is the classical electron radius and C_{KN} describes the distribution in energy and angle of the scattered photon for an incoming photon of energy E_0) times the number of scattering electrons along a length L_S.

$$n = n_0 r_e^2 C_{KN}\rho_S(Z/(Au))(1-exp(-\mu_S L_S))/\mu_S \tag{1}$$

with Z the atomic number, A the atomic mass number, u the nucleon mass, μ_s the linear attenuation coefficient and ρ_S the density of the object. In the case of a thick scatterer (L_S->∞) this number is

$$n = n_0 r_e^2 C_{KN}(Z/(Au))/(\mu_S/\rho_S) \tag{2}$$

with the mass attenuation coefficient μ_S/ρ_S (Seltzer and Hubbel, 1989). The radiation is attenuated exponentially by the wall of the enclosure of effective thickness t_{eff} composed of a material with (energy dependent) attenuation coefficient μ_H. The (energy dependent) number of photons leaving the enclosure is thus

$$n = \frac{n_0 Z r_e^2 C_{KN}}{Au(\mu_S/\rho_S)}e^{-\mu_H t_{eff}} \tag{3}$$

The dose defined as absorbed energy per mass in an object outside the enclosure is given by

$$D = nE_S\big(1-exp(-\mu_T L_O)\big)(\mu_E/\mu_T)/\rho_D a L_0 \tag{4}$$

where μ_E/μ_T is the ratio of the energy-absorption coefficient and the total attenuation coefficient (at the energy of the scattered radiation E_S) of the object of density ρ_D and volume aL_0 (with its area a given by the solid angle in a distance r from the scatterer). The dose at the surface of the object (small L_0) is then

$$D = \frac{nE_S\mu_E}{\rho_D\pi r^2} = n_0 E_S\frac{Zr_e^2C_{KN}}{Au\pi r^2}\frac{\mu_E/\rho_D}{\mu_S/\rho_S}e^{-\mu_H t_{eff}} \tag{5}$$

To stay below a desired dose rate $\dot{D}$ the condition

$$\mu_H t_{eff} > \ln\left(\dot{n}_0 E_S\frac{\mu_E/\rho_D}{\mu_S/\rho_S}\frac{Zr_e^2C_{KN}}{Au\pi r^2\dot{D}}\right) \tag{6}$$

(with $\dot{n}_0$ the number of incoming photons per time) must be fulfilled. This expression can be simplified by assuming that the factor $(\mu_E/\rho_D)/(\mu_S/\rho_S)$ is smaller than unity. This is justified because for a given energy the mass attenuation coefficient even of light materials like air exceeds the mass energy absorption coefficient of tissue and the variation in the mass energy absorption

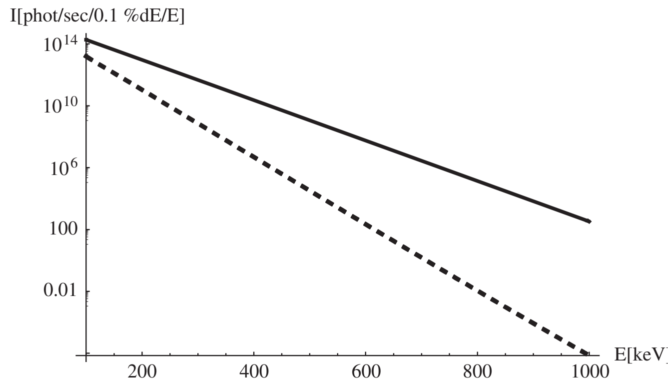

Fig. 1. Photon flux as function of energy for the standard undulator (dashed) and the W45 wiggler at the P21 beam line showing exponential decay.

coefficient (of tissue at high photon energies) is negligible. Assuming further $A/Z\le 2$ we obtain

$$\mu_H t_{eff} > \ln\left(\dot{n}_0 E_S\frac{r_e^2C_{KN}}{2\pi u r^2\dot{D}}\right) \tag{7}$$

The energy E_S of the secondary radiation is given by

$$E_S = E_0/(1+\varepsilon(1-\cos\theta)) \tag{8}$$

where $\varepsilon=E_0/mc^2$ is the so called reduced energy and θ the angle between the incident and the scattered photon.

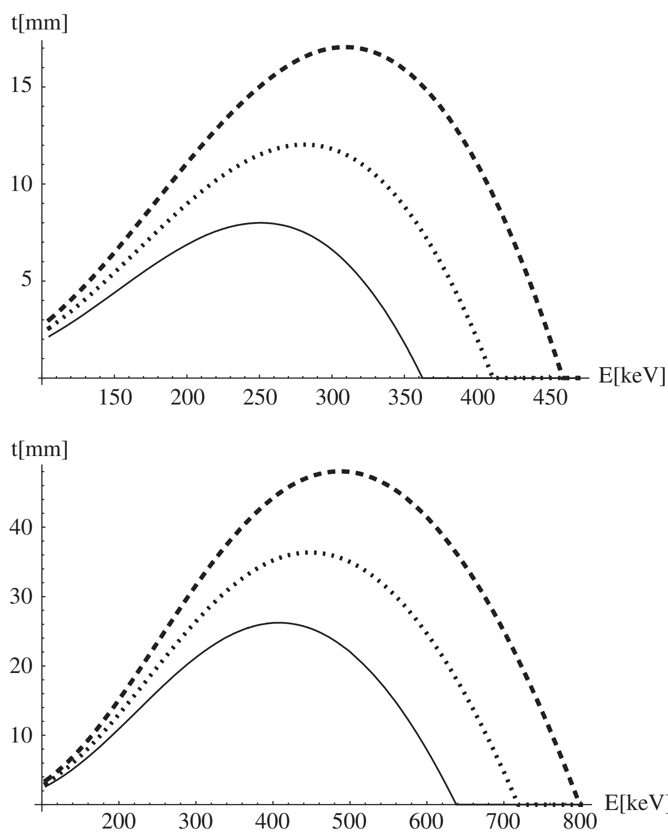

Fig. 2. Thickness required to shield against secondary radiation in the forward direction for the standard undulator (top) and the wiggler for the P21 beamline (bottom) for bandwidths of $dE/E=1\%$ (dashed), 10^{-3} (dotted) and 10^{-4}. Zero thickness indicates that at these energies the intensity is so low that even without shielding the dose rate from scattered photons in one meter from the target stays below the desired threshold. As expected the curves show a maximum at a certain energy. The shift of this maximum to higher energies with increasing bandwidth is due to the increase of the attenuation length with energy.