Lead thickness required to shield synchrotron radiation experiments

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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 spectral properties of the source, the reflectivity of the monochromator and the attenuation coefficient of the shielding influence the thickness of lead required to keep the dose rate outside the enclosure below the desired threshold. Due to the high variability of synchrotron radiation experiments no specific assumptions are made about the composition and geometry of the target but worst case scenarios are developed. This approach not only yields the required thicknesses but also shows possibilities for optimization for example by limiting the energy range or by increasing the shielding thickness only in certain directions. Finally it also yields the worst case conditions (energy, composition and position of the target) for a survey. Examples for two beam lines at the PETRA III extension namely a standard experiment (fluorescence dominates) and a high energy station (scattering dominates) will be given.

1. Introduction

In recent publications [1,2] an expression for the dose (rate) outside the enclosure of a synchrotron radiation experiment using a monochromatic beam has been derived:

$$D = N_0 E_S \frac{Z r_e^2 C_{KN} + \sigma_\alpha + \sigma_\beta}{A u \pi r^2} \frac{\mu_E / \rho_D}{\mu_S / \rho_S} \, e^{-\mu_H t_{eff}} \tag{1}$$

Where N_0 is the number of incident photons (per time), E_S the energy of the secondary radiation, A the atomic mass, u the atomic mass number and r the distance between target and dose object. The exponential term describes the attenuation by the shielding wall having an attenuation coefficient μ_H and an effective thickness t_{eff} . The ratio of the energy absorption coefficient of the dose object μ_E / ρ_D to the mass attenuation coefficient of the target μ_S / ρ_S can be regarded as smaller unity and will in the following be set to one. The cross sections for the generation of α and β fluorescence are σ_α and σ_β [3] while that for scattering is given by the Klein-Nishina factor C_{KN} times the square of the classical electron radius r_e multiplied by the number of electrons [4]. With the above made assumption we get for the effective thickness of the shielding

$$t_{eff} > \ln\left(N_0 E_S \frac{Z r_e^2 C_{KN} + \sigma_\alpha + \sigma_\beta}{A u \pi r^2 \mathrm{D}}\right) / \mu_H \tag{2}$$

Most of the values in the bracket show only variation within few orders of magnitude and due to the logarithmic dependence only slightly influence the required thickness. Only the number of photons decreases exponentially with energy well above the critical energy of the source.

The required thickness is thus dominated by the attenuation coefficient of the shielding. The contribution of photo absorption to this coefficient decreases with about the third power of energy but shows also discontinuities at the electron binding energies of the inner shells. Therefore for lead as shielding material three ranges need to be considered. The region below the K-edge (88keV) where the attenuation decreases with energy; that slightly above the edge, where the cross sections of heavy targets (like lead) may be high but the energy of the secondary radiation may fall into the minimum of the attenuation just below the edge and the range above about 150 keV where the attenuation is lower than at the above mentioned minimum.

2. Low energy beam lines (P24)

Although the energy of the primary beam is tunable in most cases its energy range may be limited by the optics. This is for example the case for the P24 beam line at the PETRA III extension. Here the highest energy achievable with the planned Si111 double crystal monochromator is limited to below 53keV. In this regime the contribution of fluorescence to the secondary radiation is orders of magnitudes higher than that from scattering (Table 1, $r_e^2 = 0.08b$)). The worst case (smallest attenuation) is given for the characteristic radiation of an element just below the highest possible energy (in this case Terbium). Therefore only the lead thickness for this case must be calculated which for convenience may be done using a simple spread sheet. About 2mm lead would be sufficient to stay below the desired dose rate of 0.5µSv/h (corresponding to 1mSv per working year of 2000 hours) in 1m distance from the beam. It should, however, be kept in mind that the beam also may contain higher harmonics (333 reflection) that may excite heavier elements like lead. If the fundamental is tuned to about 30keV the 3rd harmonic is just above the lead edge and the β fluorescence of lead falls into the minimum before the lead edge. Even though the reflectivity and thus the number of photons is an order of magnitude lower than for the 111 reflection about 6.5mm of lead are needed.

$\dot{N}_0[s^{-1}]$	E[keV]	Element	A	Z	σ_α [b]	σ_β [b]	μ_β [cm²/g]	$1/\rho\mu_\beta$ [mm]	r [m]	N_{att}	t [mm]	hkl
4,22E+13	30	Sb	121,76	51	4710	880	30,32	0,0300	1	19,16	0,574	111
1,58E+13	53	Tb	158,93	65	2719	549	8,1	0,1122	1	18,01	2,021	111
3,30E+12	90	Pb	207,2	82	1460	310	1,91	0,4760	1	16,15	7,686	111
2,23E+11	90	Pb	207,2	82	1460	310	1,91	0,4760	1	13,45	6,404	333

Table 1 – Part of a spread sheet for the calculation of lead thicknesses to shield against fluorescence N_{att} is the number of attenuation lengths ($\boldsymbol{t_a = 1/\rho\mu_\beta}$). The (small) contribution of scattering is added to the β fluorescence assuming the same energy. The contribution of α fluorescence may also be determined with this spread sheet (not shown) but is usually only few percent

Although the energy of the 3rd harmonic is also limited (below 160keV) and the intensity from higher harmonics is lower a final check was made by calculating the contribution of scattering for the entire energy range (assuming the reflectivity of the 333 reflection and setting A/Z=2). As already mentioned the number of photons from a synchrotron radiation source decreases exponentially with energy for energies well above the critical energy (also undulators show a wiggler like behavior at these energies). For very high energies the intensity of the primary beam is than so low that even without shielding the number of secondary photons at a certain distance would fall below the desired threshold. For the P24 undulator the worst case requiring the highest effective thickness occurs (for forward elastic scattering) at about 240keV where it is still below 6 mm. Calculations taking the angular and energy dependence of the scattered radiation into account are not needed in this case because the scattered radiation has lower energies (and thus higher attenuation) than the primary beam and C_{KN} is smaller than unity. Therefore, a thickness of 6.5mm (or 6mm in 2m distance) is sufficient to shield against fluorescence and scattering.

3. High energy beam lines (P21)

The insertion device (W45) at P21 has a higher field and thus a higher critical energy than the U32 undulator at P24. Furthermore curved (mosaic) crystals are used for increased intensity at high energies. For an optimized DCM of 10 mm thickness the reflectivity for the 111 reflection goes with 1.13/E[keV] and that of the 3rd harmonic with 0.037/E[keV][5]. While 11mm of lead would be sufficient to shield against fluorescence about 40mm would be required to shield against (forward) scattering. It was, therefore, decided to limit the energy of the fundamental to below 200keV. In this case at least for the side wall no additional shielding would be required. Again the contribution of the 3rd harmonic has to be calculated but in this case the anisotropic character of scattering needs to be considered not to overestimate the thicknesses.

Both, the energy of the scattered radiation and the factor C_{KN} only depend on the energy of the primary beam and the (cosine of the) scattering angle[4]. Having a more detailed view on the geometry of the experiment shown in Fig.1 we see that also the effective thickness for the walls as well as the distances from the target are given by simple trigonometric relations and can also be expressed as functions of the cosine of the scattering angle (for the isotropic case t_{eff} was the wall thickness and r was equal R or l respectively).

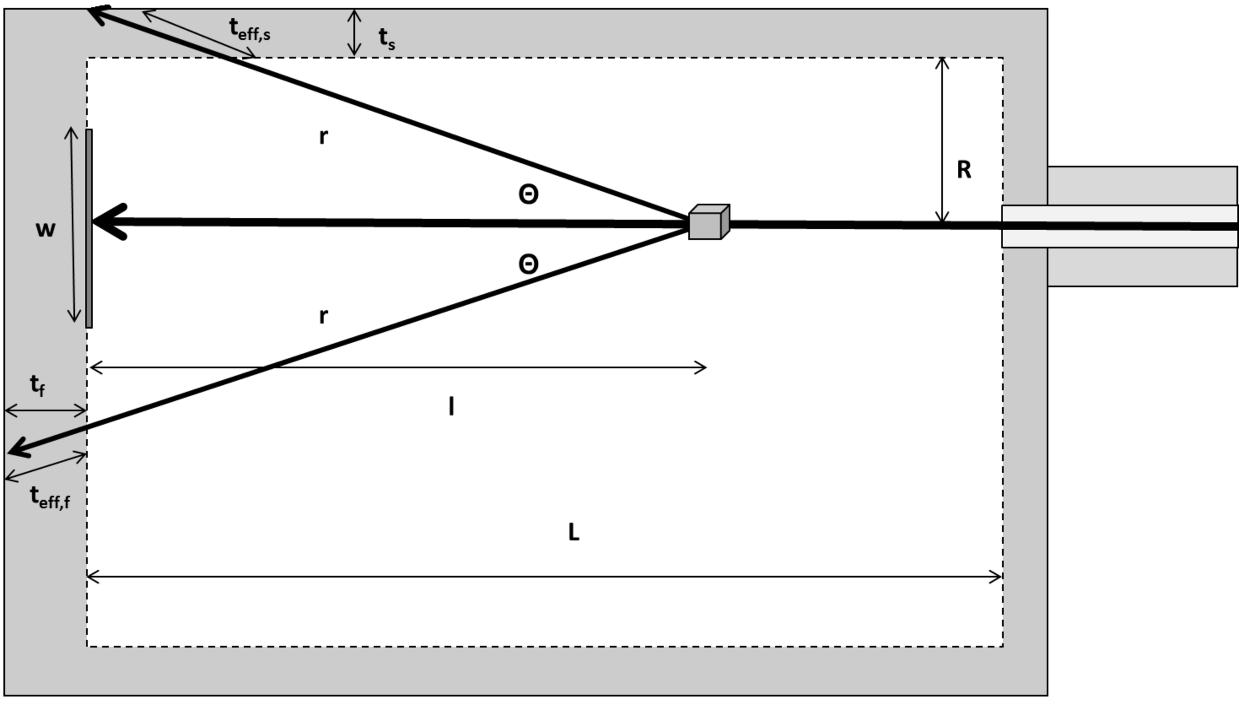

Fig.1 – Geometry of an experiment

Due to the dependence on only two parameters the results of the calculations can be represented by contour plots. Fig.2 shows the thicknesses for the side and the back (downstream) wall (values for the front wall are below 5mm). It is clear that for front, side and roof the thickness that is required to shield against fluorescence is already sufficient. The back wall however must have a higher thickness at least around the primary beam especially because there the distance to the target can fall below 1m.

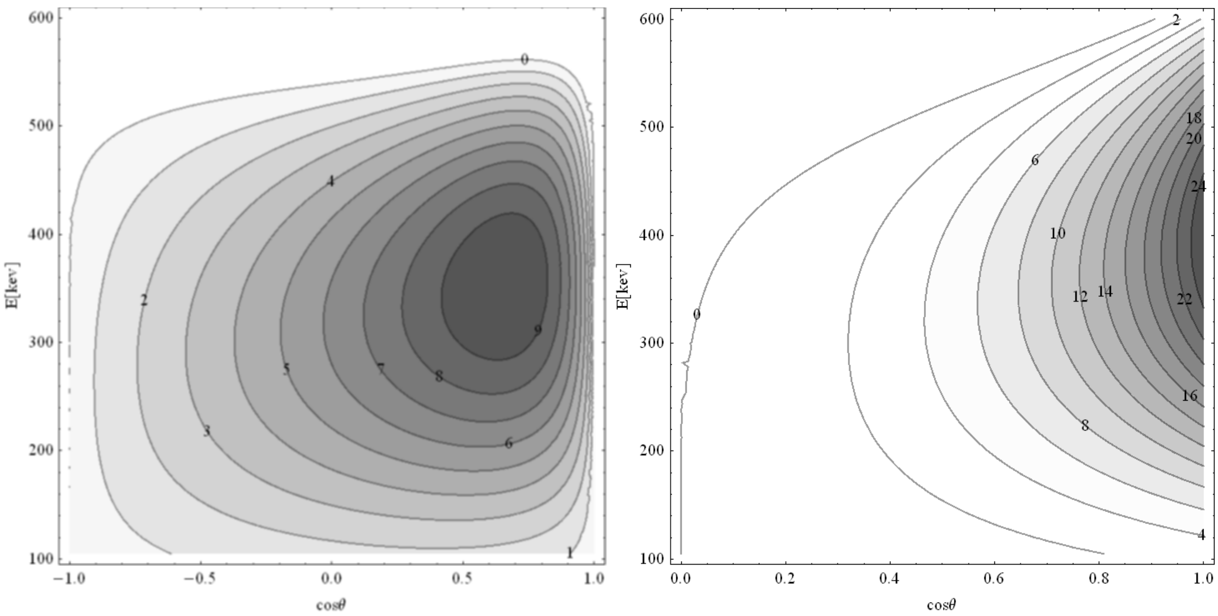

Fig.2 – Shielding thickness in mm as function of energy and scattering angle for the side (left) and back wall (right)

4. Front and back wall, beam tubes and conditions for a survey

The distance of the primary beam (and thus the target) to the side wall is well known. For a beam tube it may be assumed that the primary beam hits the inner wall of the tube. The spread sheet shown as Table 1 can be used to determine the shielding thickness of the tube in an iterative process. Inserting the hutch wall thickness of 0.007m as a first approach for the distance r into the last row will yield a value of slightly more than 11mm for the thickness. With this value of 0.011m inserted for r the resulting thickness will be slightly below 11mm. Therefore, 11mm is the value for which the shielding thickness equals the distance between target (inner wall) and dose object (at outer wall).
At the front and back wall the lateral distance to the primary beam is limited by the diameter of the beam tube or the width of the beam stop respectively. In the latter case the thickness as function of the distance of the target from the beam stop (along the beam) can be derived from Fig.2 as

$$t > t_a\, l/\sqrt{l^2+(\tfrac{w}{2})^2} * [\ln(N_0 E_S) + \ln\left(\frac{Z r_e^2 C_{KN}+\sigma_\alpha+\sigma_\beta}{Au\pi D}\right) - \ln(l^2+\left(\tfrac{w}{2}\right)^2)] \quad (3)$$

The maximum of this function not only defines the required thickness but also yields the position where a target should be positioned (worst case) for a survey. The material of the target should be chosen depending on whether fluorescence (heaviest element that can be excited) or scattering (water) lead to the worst case. In case of the front wall usually fluorescence dominates (low energies in backscattering). Instead of l the distance between target and front wall (L-l) has to be used in eq.3.
Equation 3 may also be used to define areas of the back wall where its thickness may be reduced. For P21 having a beam stop of w=0.7m the required thickness would be 25mm but could be reduced to 20mm above a radius of 0.8m around the primary beam.

5. Summary

Based on the known properties of source and optics, the mechanisms of the production of the secondary radiation and the properties of the shielding material the worst cases and thus the highest required thickness of the shielding were derived. For energies below about 150keV few calculations at discrete energies are sufficient. At higher energies scattering becomes dominant. Here energy and intensity depend on only two parameters namely the energy of the primary beam and the scattering angle. For such simple relations no dedicated code needs to be written but calculations can be done using a computer algebra system [6]. The calculations for the source and the optics are not subject of this paper. In this case it is useful to rely on experts in these fields [5,7].

References

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