Lead thickness required to shield synchrotron radiation experiments

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RadSynch 2015
4th June 2015

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DESY

Ockham‘s razor

[Numquam ponenda est pluralitas sine necessitate]()

Plurality must never be posited without necessity

We know:
A ‚target‘ is in the beam
The mechanisms of production of secondary radiation (fluorescence, scattering (pp))
Properties of the shielding (lead)
Number of photons as function of energy (source, optics)
The geometry of the enclosure

We don‘t know:
The composition of the target (air, slits, sample)
The geometry of the target (angle of incidence)
The position of the target along the beam

We want to know:
The required lead thickness
Worst cases (conditions for a survey)

1287-1347

Generation of secondary radiation

Secondary photons from a thick target

$$n = n_0\,(Z r_e^2 C_{KN} + \sigma_\alpha + \sigma_\beta)/(Au)/(\mu_S/\rho_S)$$

n_0:incoming photons of energy E_0

$\sigma_\alpha(Z)$, $\sigma_\beta(Z)$: fluorescence cross section $E_\alpha < E_\beta < E_0$

M. O. Krause, C. W. Nestor, C. J. Sparks, E. Ricci. *X-Ray Fluorescence Cross Sections for K and L X Rays of the Elements.* Oak Ridge, Tennessee : Oak Ridge National Laboratory, 1978

C_{KN} Klein-Nishina scattering cross section $C_{KN}(E_0,\theta)<1$, $E_S < E_0$

r_e classical electron radius, A atomic mass number, u atomic mass

μ_S/ρ_S mass attenuation coefficient of the target

Absorbed dose

Attenuation by shielding

$I=I_0(e^{-\mu_H t_{eff}})$

Absorption in the dose object

$D=nE_S\ (1-\exp(-\mu_T L_O))\ (\mu_E/\mu_T)\ /\ \rho_D a L_0$

μ_E,μ_T energy and total absorption coefficient, ρ_D ,aL_0 density and volume

Dose due to secondary radiation (surface)

$$D = \frac{n E_S \mu_E}{\rho_D \pi r^2} = n_0 E_S \frac{Z r_e^2 c_{KN} + \sigma_\alpha + \sigma_\beta}{Au \pi r^2} \frac{\mu_E/\rho_D}{\mu_S/\rho_S}\ e^{-\mu_H t_{eff}}$$

Required shielding thickness

$$\mu_H t_{eff} > \ln\left(\dot{n}_0 E_S \frac{\mu_E/\rho_D}{\mu_S/\rho_S} \frac{Z r_e^2 C_{KN} + \sigma_\alpha + \sigma_\beta}{Au\pi\, r^2 \dot{D}}\right)$$

$\mu_H t_{eff} >$ ln $\dot{N}_0 E_S/(\pi \dot{D} Au)$ + ln$[(\mu_E/\rho_D)/(\mu_S/\rho_S)]$ + ln $(Z r_e^2 C_{KN} + \sigma_\alpha + \sigma_\beta)/r^2$

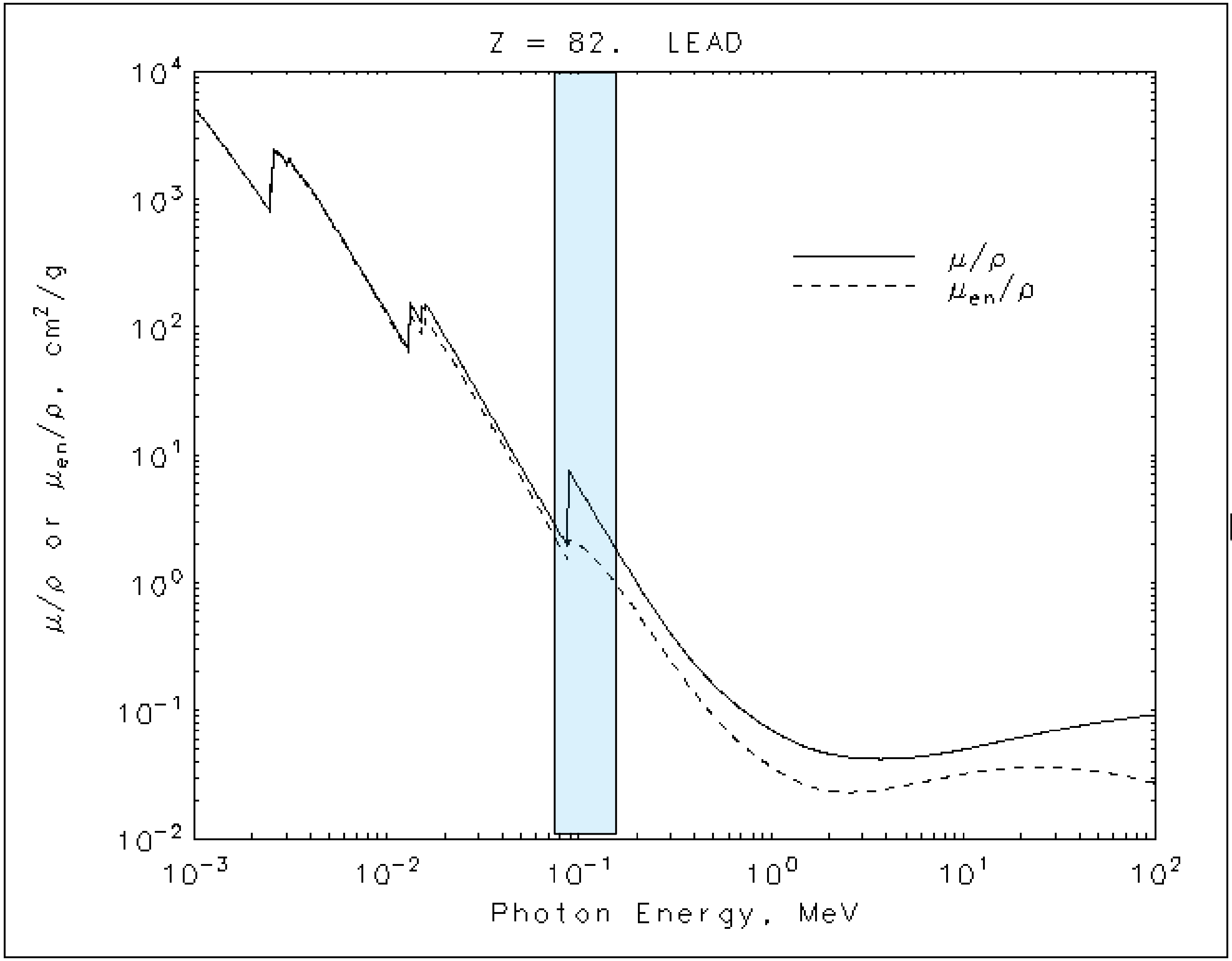
$\dot{D}<0.5\mu Sv/h$ design goal, $(\mu_E/\rho_D)/(\mu_S/\rho_S)<1$

in practical units:
$\mu_H t_{eff} > \ln n_0[s^{-1}] + \ln E_S[keV] + \ln(0.08 Z C_{KN} + \sigma_\alpha[b] + \sigma_\beta[b]) - \ln(A) - 2\ln(r[m]) - 17.63$

At low energies (neglecting scattering, or adding it to σ_β)
$\mu_H t_{eff} > \ln n_0[s^{-1}] + \ln E_S[keV] + \ln(0.08Z + \sigma_\alpha[b] + \sigma_\beta[b]) - \ln(A) - 2\ln(r[m]) - 17.63$

At high energies (neglecting fluorescence, A/Z ≥2)
$\mu_H t_{eff} > \ln n_0[s^{-1}] + \ln E_S[keV] + \ln(Z C_{KN}) - 2\ln(r[m]) - 20.85$

Absorption in lead



E[MeV]	μ/ρ[cm²/g]
2.00000E-02	8.636E+01
3.00000E-02	3.032E+01
4.00000E-02	1.436E+01
5.00000E-02	8.041E+00
6.00000E-02	5.021E+00
8.00000E-02	2.419E+00
8.80045E-02	1.910E+00
K8.80045E-02	7.683E+00
1.00000E-01	5.549E+00
1.50000E-01	2.014E+00
2.00000E-01	9.985E-01
3.00000E-01	4.031E-01
4.00000E-01	2.323E-01
5.00000E-01	1.614E-01
6.00000E-01	1.248E-01
8.00000E-01	8.870E-02
1.00000E+00	7.102E-02

Seltzer, J. H. Hubbel and S. M. *Tables of X-Ray Mass Attenuation Coefficients.* NIST. 1989.
http://www.nist.gov/pml/data/xraycoef/

The standard undulator @ P22

$$\mu_H t_{eff} > \mathit{ln}\, n_0[s^{-1}] + \mathit{ln} E_S[keV] + \mathit{ln}(0.08Z + \sigma_\alpha[b] + \sigma_\beta[b]) – \mathit{ln}(A) – 2\mathit{ln}(r[m]) – 17.63$$

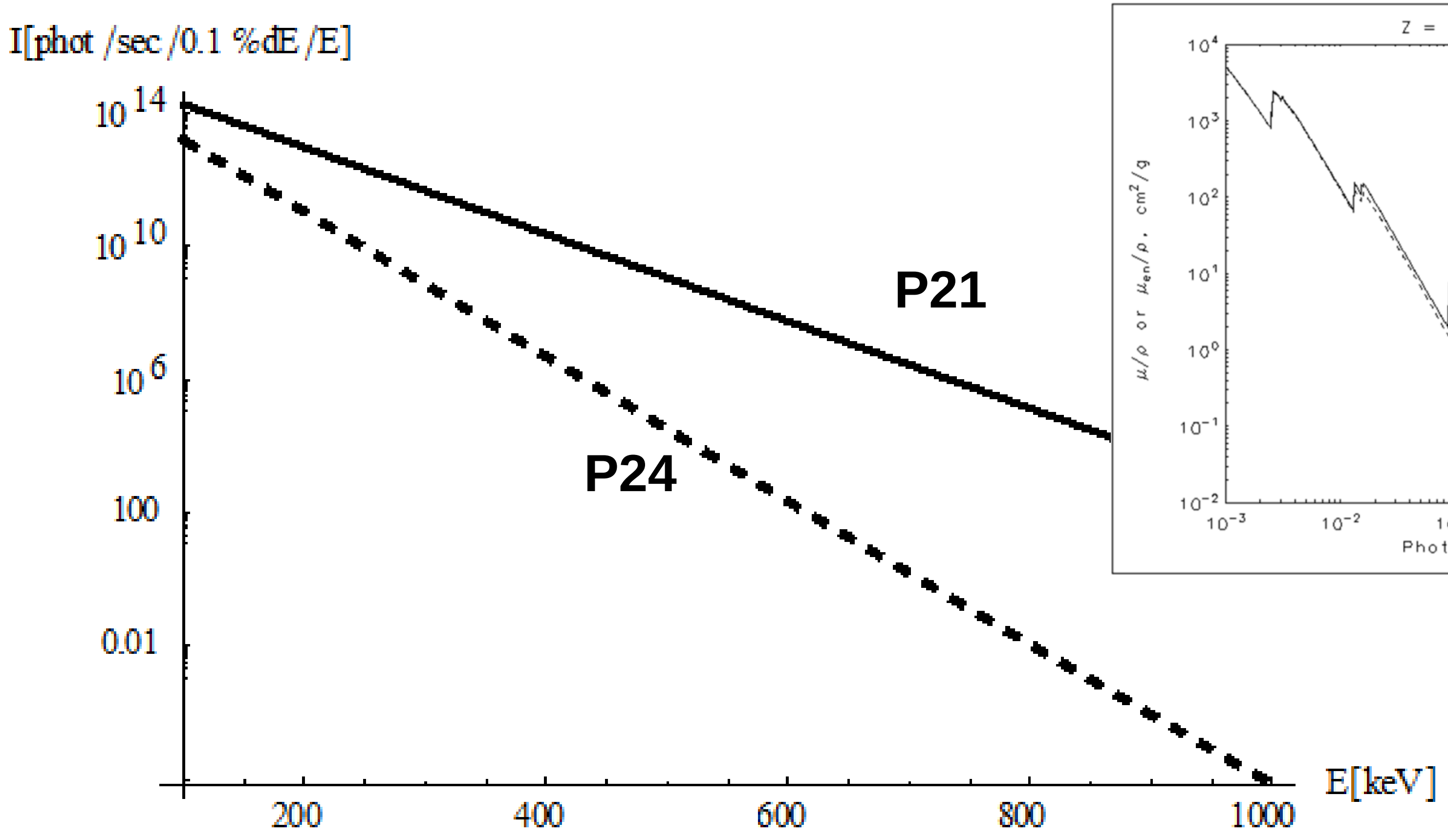
Fluorescence dominates below ~150keV

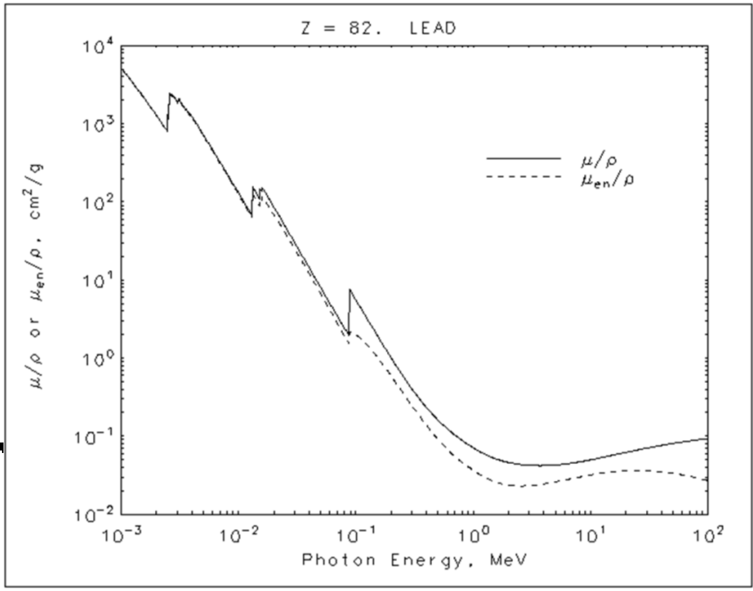
$\dot{N}_0[s^{-1}]$	E[keV]	Element	A	Z	σ_α [b]	σ_β [b]	μ_β [cm²/g]	$1/\rho\mu_\beta$ [mm]	r [m]	N_{att}	t [mm]	hkl
4,22E+13	30	Sb	121,76	51	4710	880	30,32	0,0300	1	19,16	0,574	111
1,58E+12	53	Tb	158,93	65	2719	549	8,1	0,1122	1	15,71	1,763	111
3,30E+12	90	Pb	207,2	82	1460	310	1,91	0,4760	1	16,15	7,686	111
1,44E+12	90	Pb	207,2	82	1460	310	1,91	0,4760	1	15,32	7,291	220
6,93E+11	90	Pb	207,2	82	1460	310	1,91	0,4760	1	14,59	6,943	311
2,23E+11	90	Pb	207,2	82	1460	310	1,91	0,4760	1	13,45	6,404	333

E_S replaced by $E=E_0$

With the thickness required to shield against β fluorescence (and scattering) the contribution of α fluorescence (lower energy and therefore stronger attenuation but higher cross section) is calculated (same spread sheet, but not shown here). Depending on this result the thickness has to be increased.

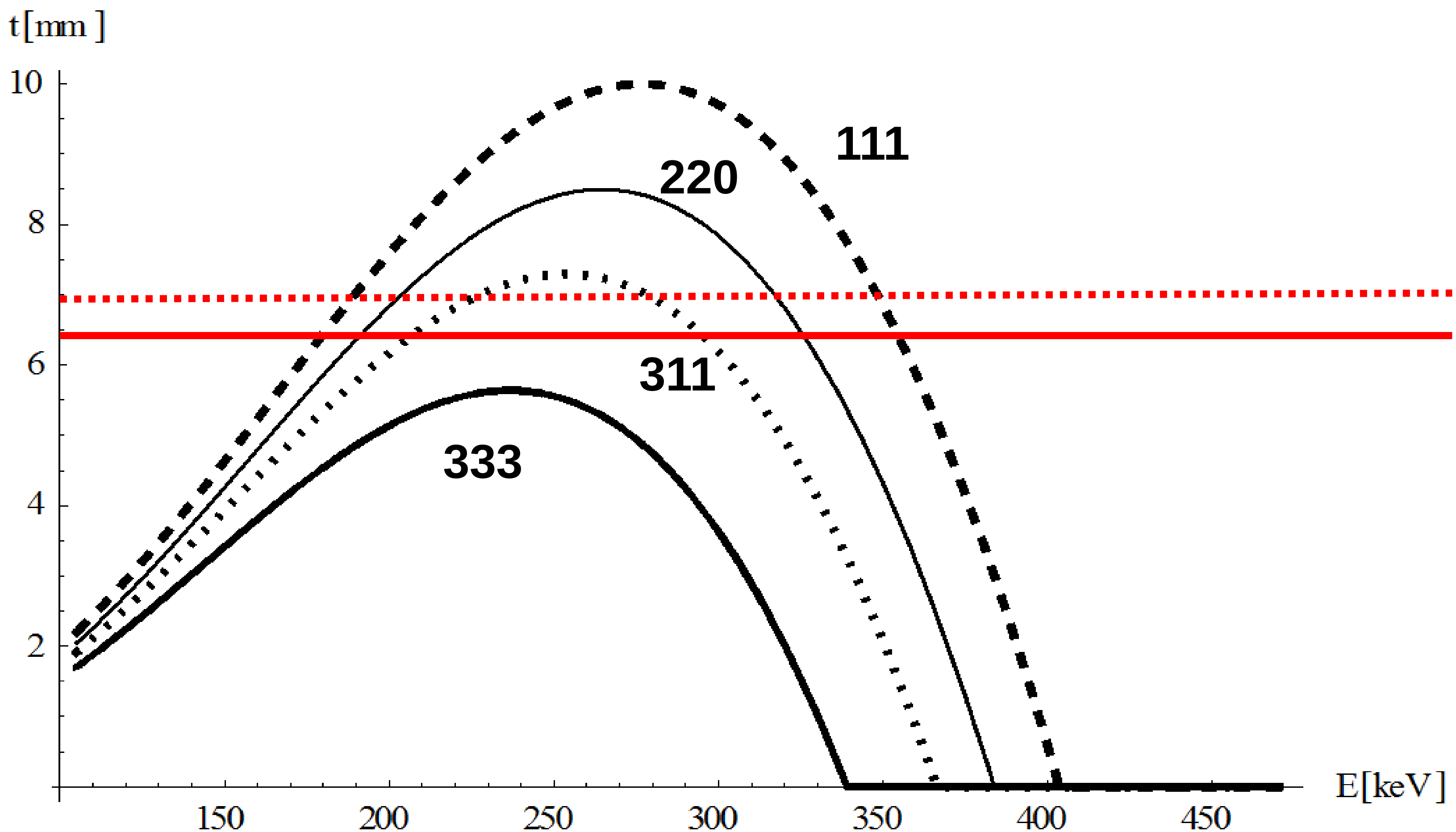
High energies





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

Standard undulator



$C_{KN}(E_0,\theta)=1,\ E_S=E_0$ (forward scattering)

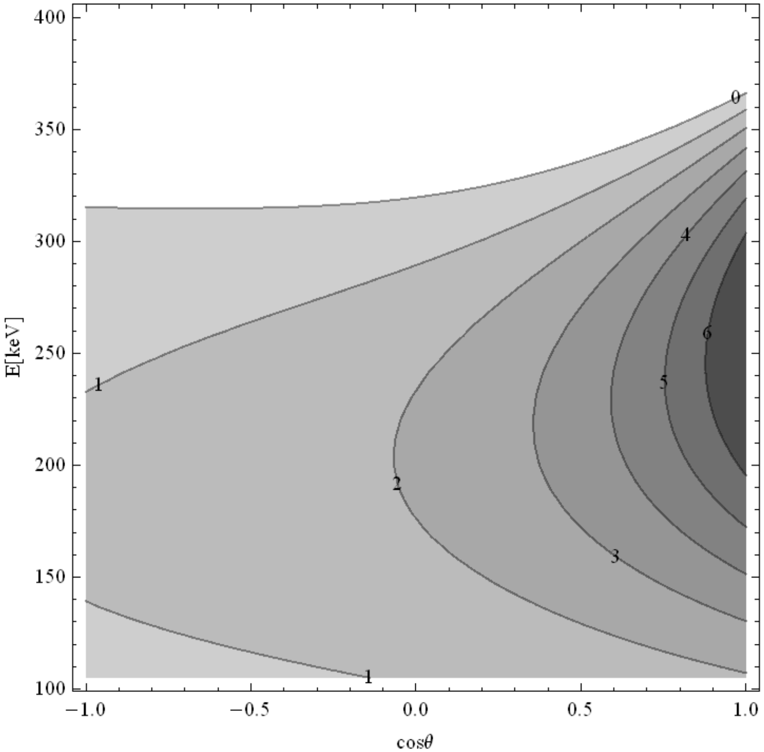
High energy scattering

$$C_{KN} = \frac{(1+\cos^2\theta)\left\{1+\frac{\varepsilon^2(1-\cos(\theta))^2}{(1+\varepsilon(1-\cos\theta))(1+\cos^2\theta)}\right\}}{2(1+\varepsilon[1-\cos\theta])^2}$$

$\varepsilon = E_0/mc^2$

$$E_S = E_0 / (1+\varepsilon(1-\cos\theta))$$

Both, cross section and secondary energy depend only on incoming energy and scattering angle

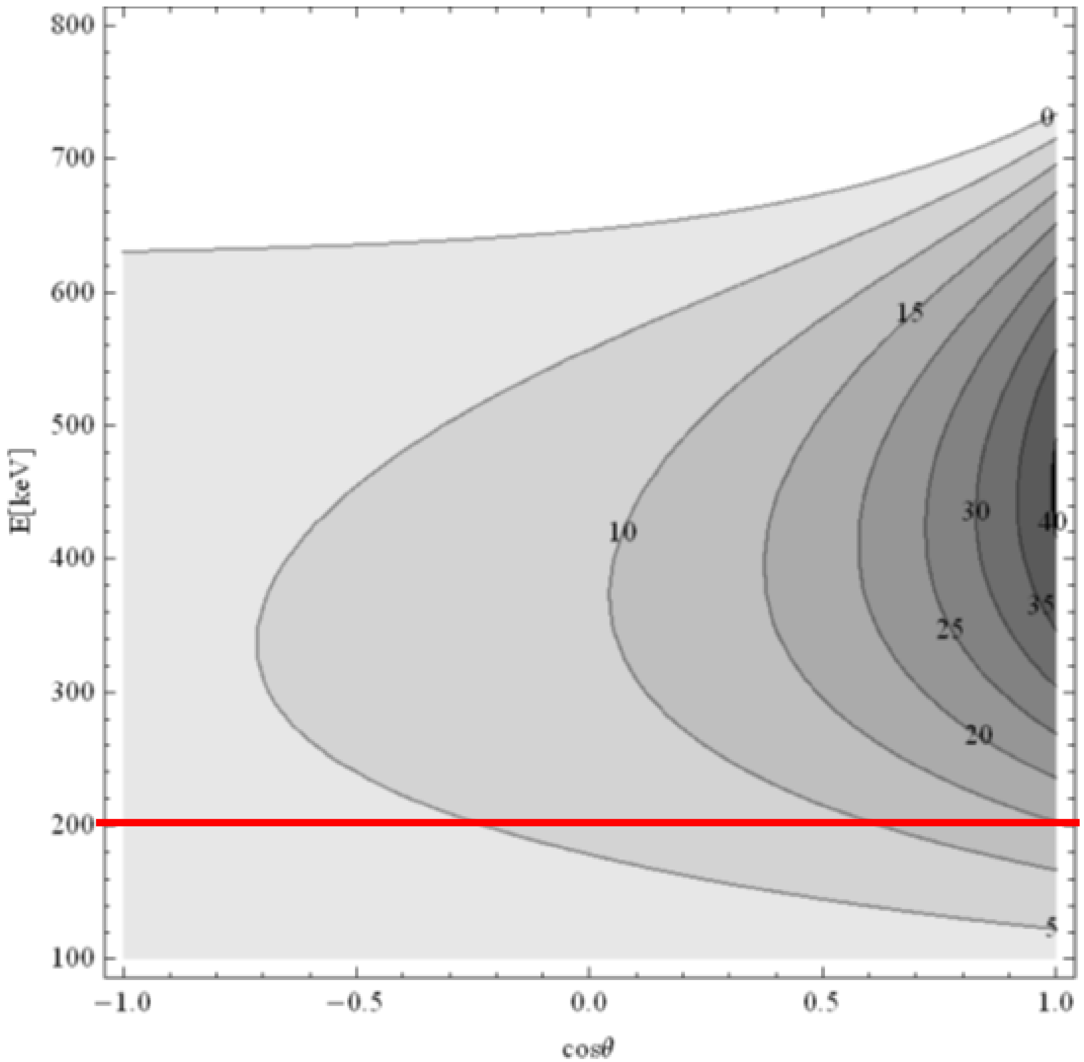


Required lead thickness to shield against scattered radiation (311 reflection @ P24)

High energy wiggler W45 @ P21

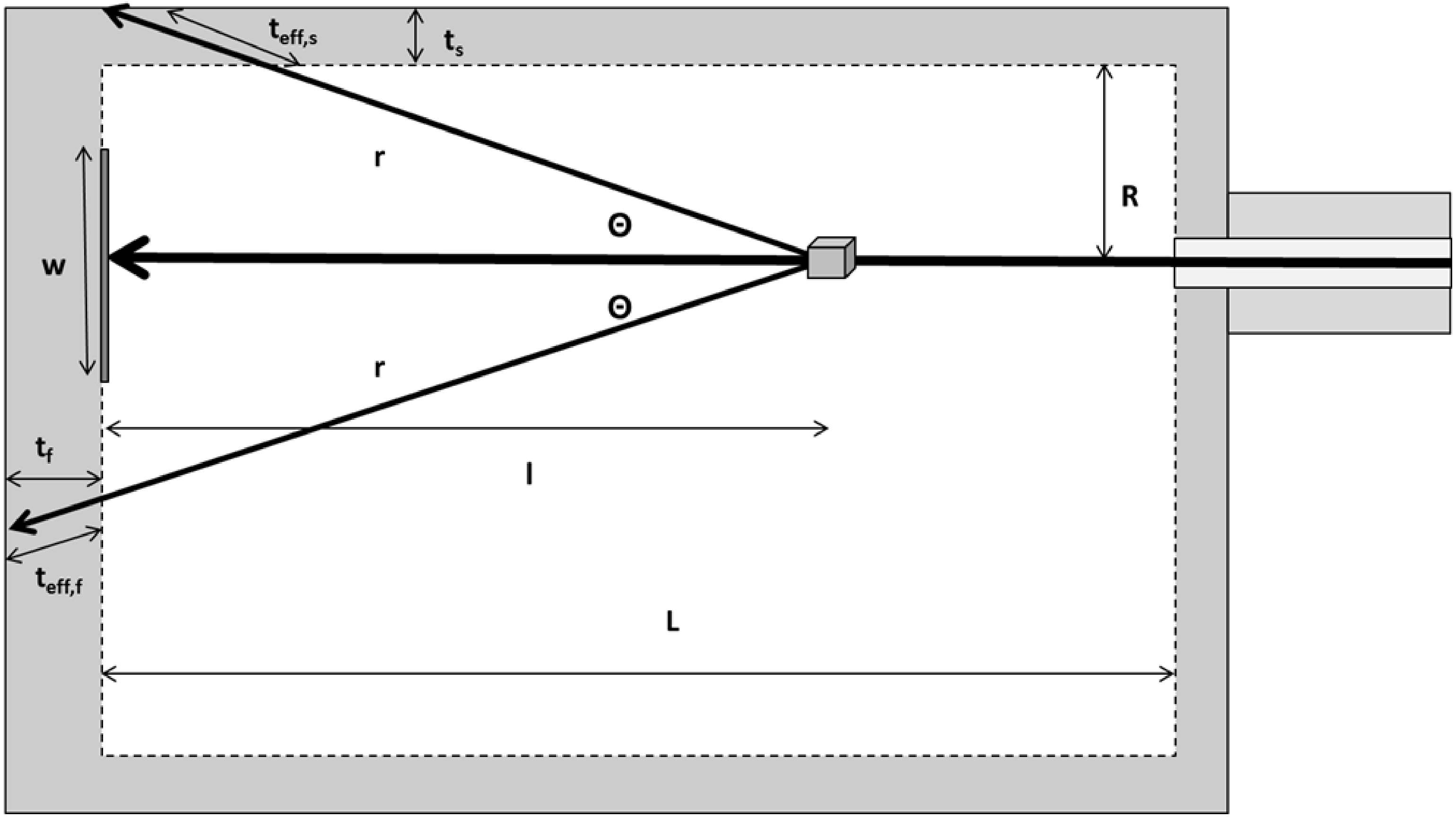
To shield against lead fluorescence a thickness of 11 mm (distance to target 1m) respectively 10 mm (distance 2m) would be required (assuming an ideal 111 mosaic DCM). Shielding against scattering would far exceed these thicknesses.

Therefore it was decided to limit the energy range (travel range of monochromator crystals).
The third harmonic (333 reflection has three times higher energy but about thirty times lower intensity.



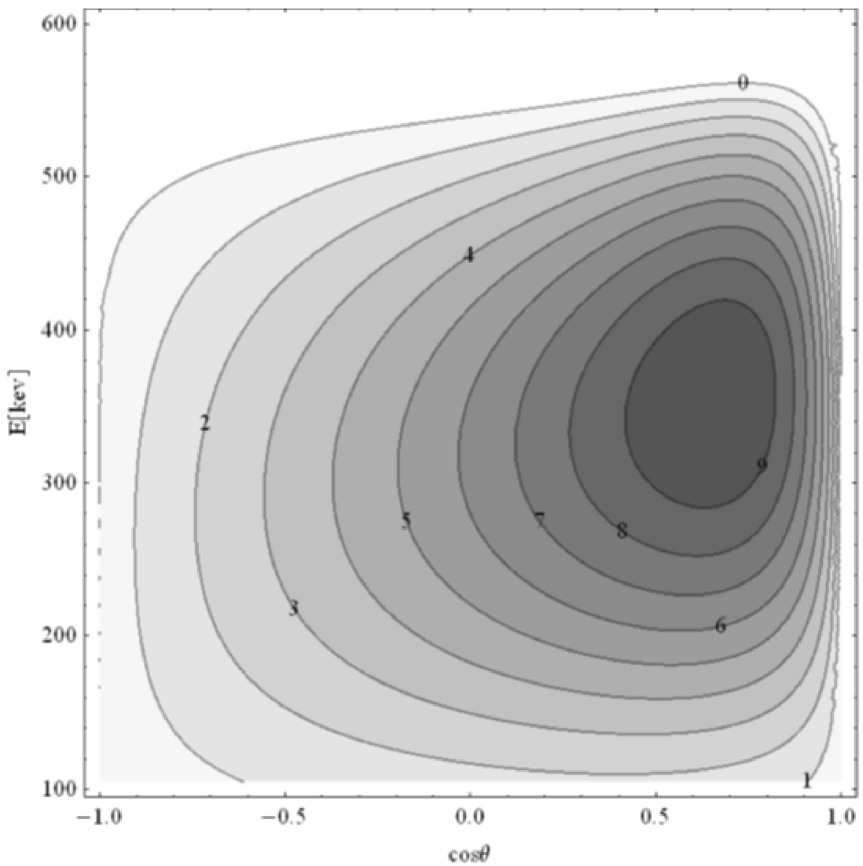
Geometry of the experiment

Up to now no assumptions about the scattering geometry have been required.
Except that the target is in the beam.

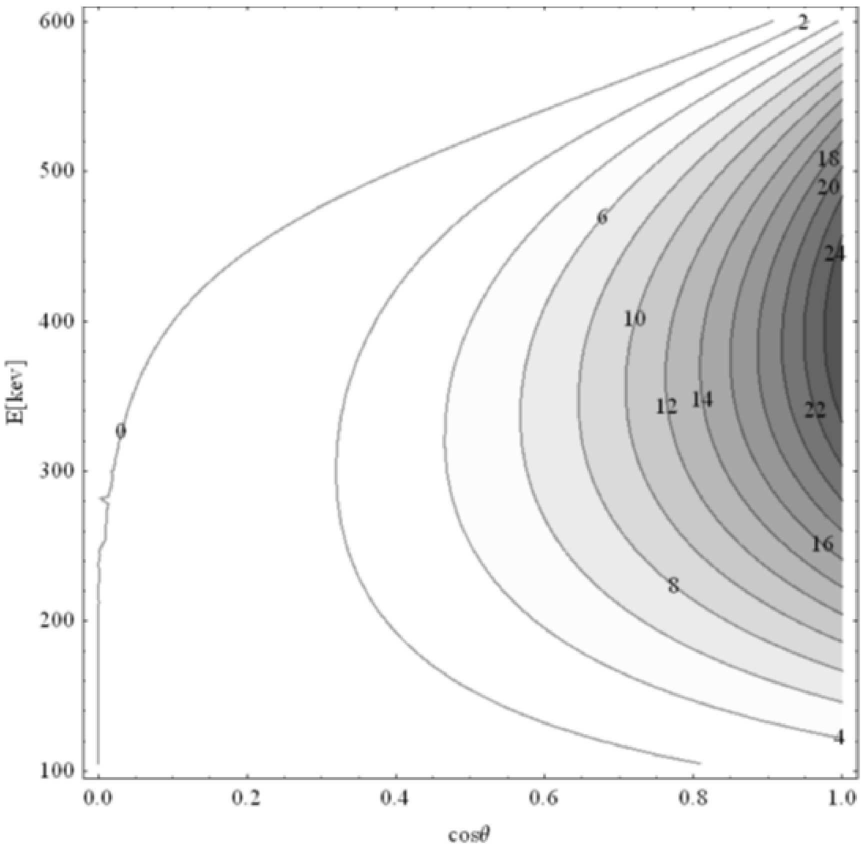


$t_{eff,s}$= t_s/sinθ $t_{eff,f}$= t_f/cosθ r_s= R/sinθ r_f= l/cosθ r_b=(L-l)/cosθ

3rd harmonic (333) @ P21



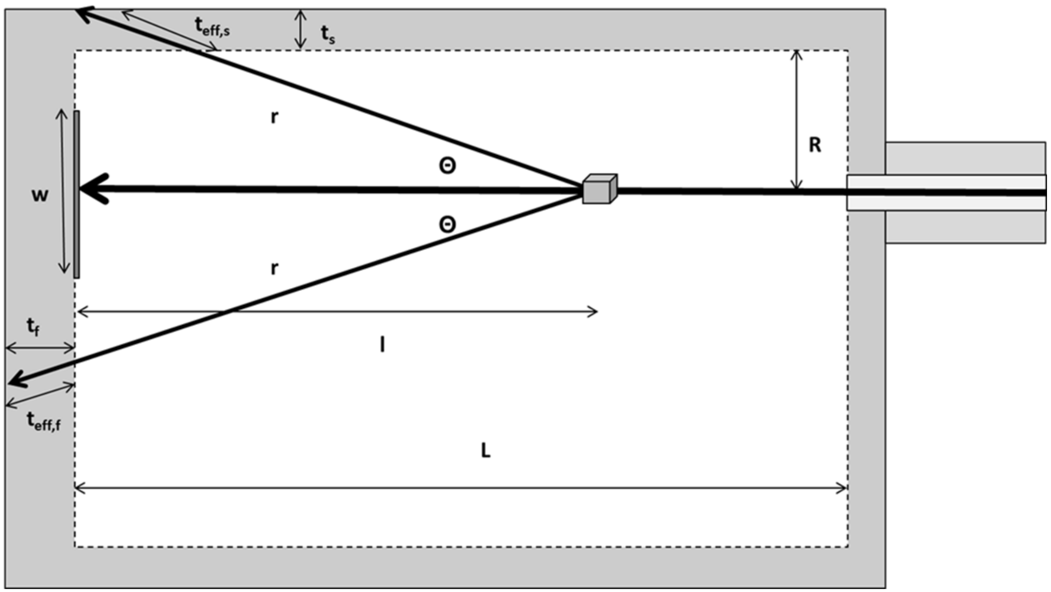
Thickness of sidewall below 10mm (distance 1m)



Thickness of front wall up to 25 mm (forward direction, distance 1m)

Front wall & survey

$$\cos\theta = l/\sqrt{l^2 + (\frac{w}{2})^2} \qquad 2\ln r = \ln(l^2 + \left(\frac{w}{2}\right)^2)$$



P21:

t=25 mm (0.7m<w<1.6m)

t=20 mm (w>1.6m)

$$t \;>\; t_a\, l/\sqrt{l^2 + (\frac{w}{2})^2} * [\ln(\dot{n}_0 E_S) + \ln C_{KN} - \ln(l^2 + \left(\frac{w}{2}\right)^2) + \ln(r_e^2/2\pi u\dot{D})]$$

$$= l/\sqrt{l^2 + \left(\frac{w}{2}\right)^2}\left((t_{eff.max} - t_{a,max}\left(\ln(l^2 + \left(\frac{w}{2}\right)^2\right)\right)$$

$t_a = 1/\mu_H$

Given w, we can calculate t as function of l and determine the worst case yielding the target position for a survey

Summary

- A simple calculus has been developed based on the (known) properties of source, optics, shielding material and the fundamental interaction mechanisms (fluorescence and scattering).
- Below ~150 keV (isotropic) fluorescence dominates and calculations can be performed using a simple spread sheet
- For higher energies scattering has to be taken into account
- If required the anisotropy of scattering is used to optimize the shielding thickness
- From the calculations also the (worst case) conditions for a survey can be determined

Acknowledgement

I want to thank **DESY-FS**

especially Markus Tischer (calculation of spectra using PHOTON) and Ulrich Lienert (calculation of reflectivity of curved (mosaic) crystal monochromators)

for your attention

Round robin

Handbook