

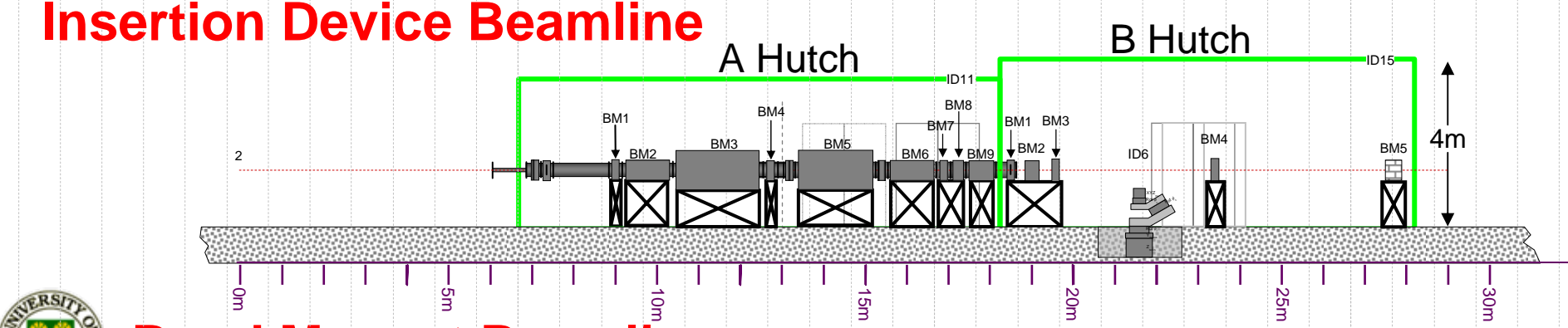
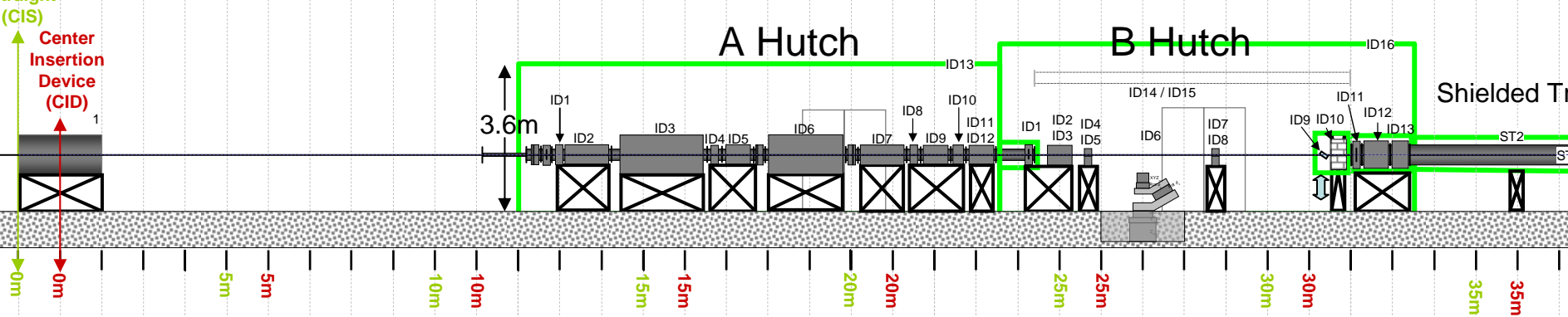
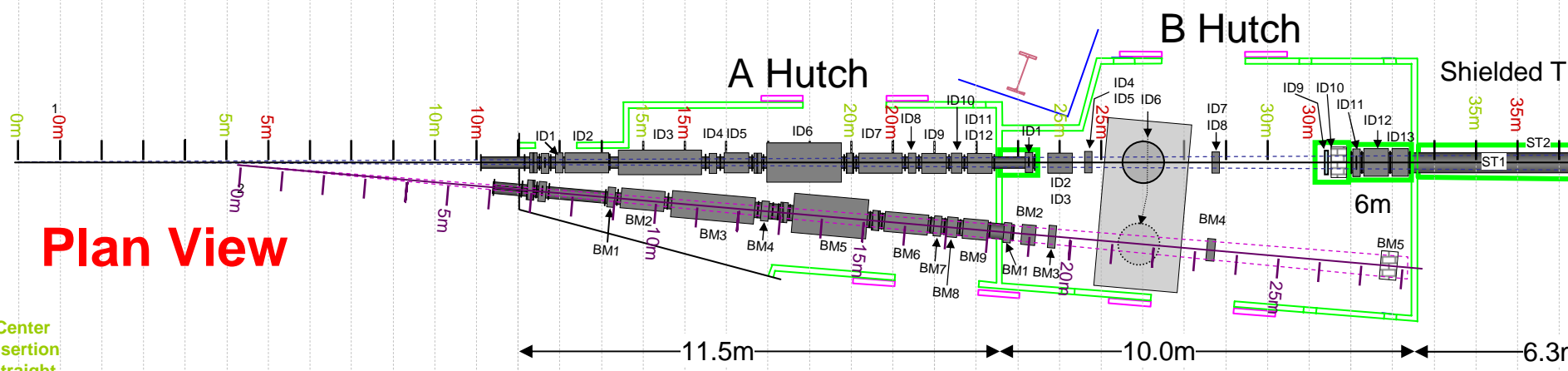
Wiggler Shielding Calculations

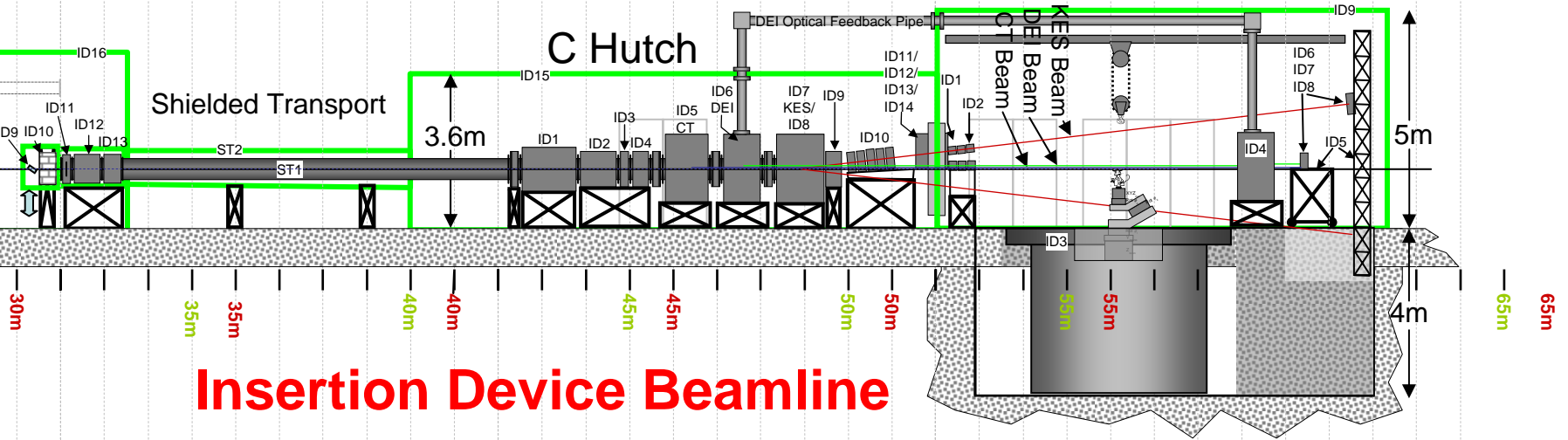
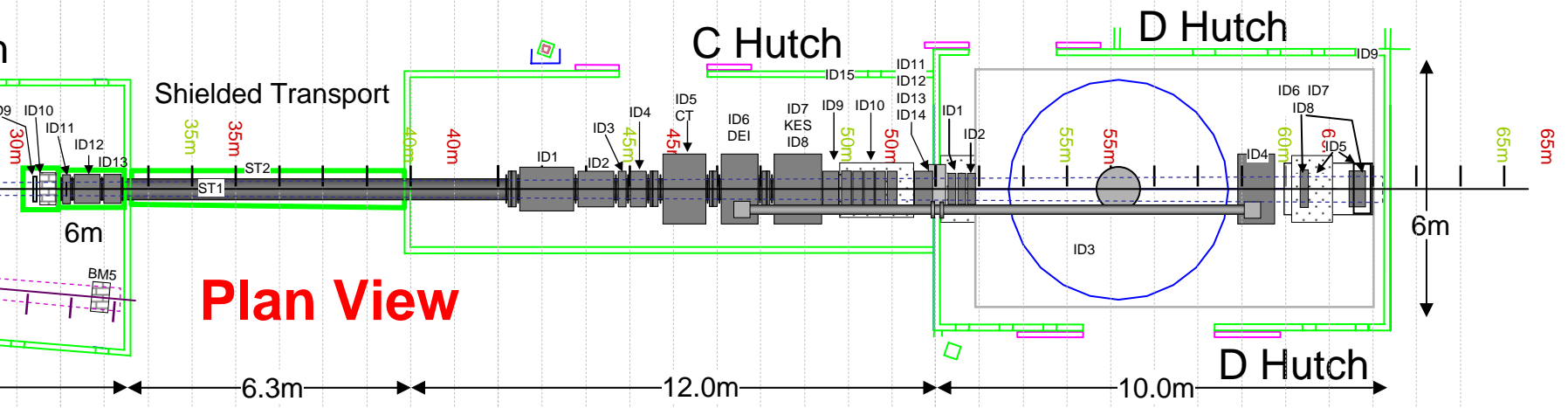
RADSYNCH '07
4th International Workshop on Radiation Safety at
Synchrotron Radiation Sources
University of Saskatchewan
Dean Chapman
Anatomy & Cell Biology
Canada Research Chair in X-ray Imaging

Shielding for BMIT – Biomedical Imaging and Therapy Beamline

- Bremsstrahlung Radiation
 - Not covered here – Juhachi Asai
- Synchrotron Radiation BOTH white and monochromatic
 - Source
 - Scattering
 - Shielding
 - Dose







How Can SR Escape?

- SR Photons are scattered
 - ~~– Elastic Scattering?~~
 - Compton Scattering?
- Only single scattering is considered
 - Estimates found that double scattering <5%
 - From Compton and Fluorescence

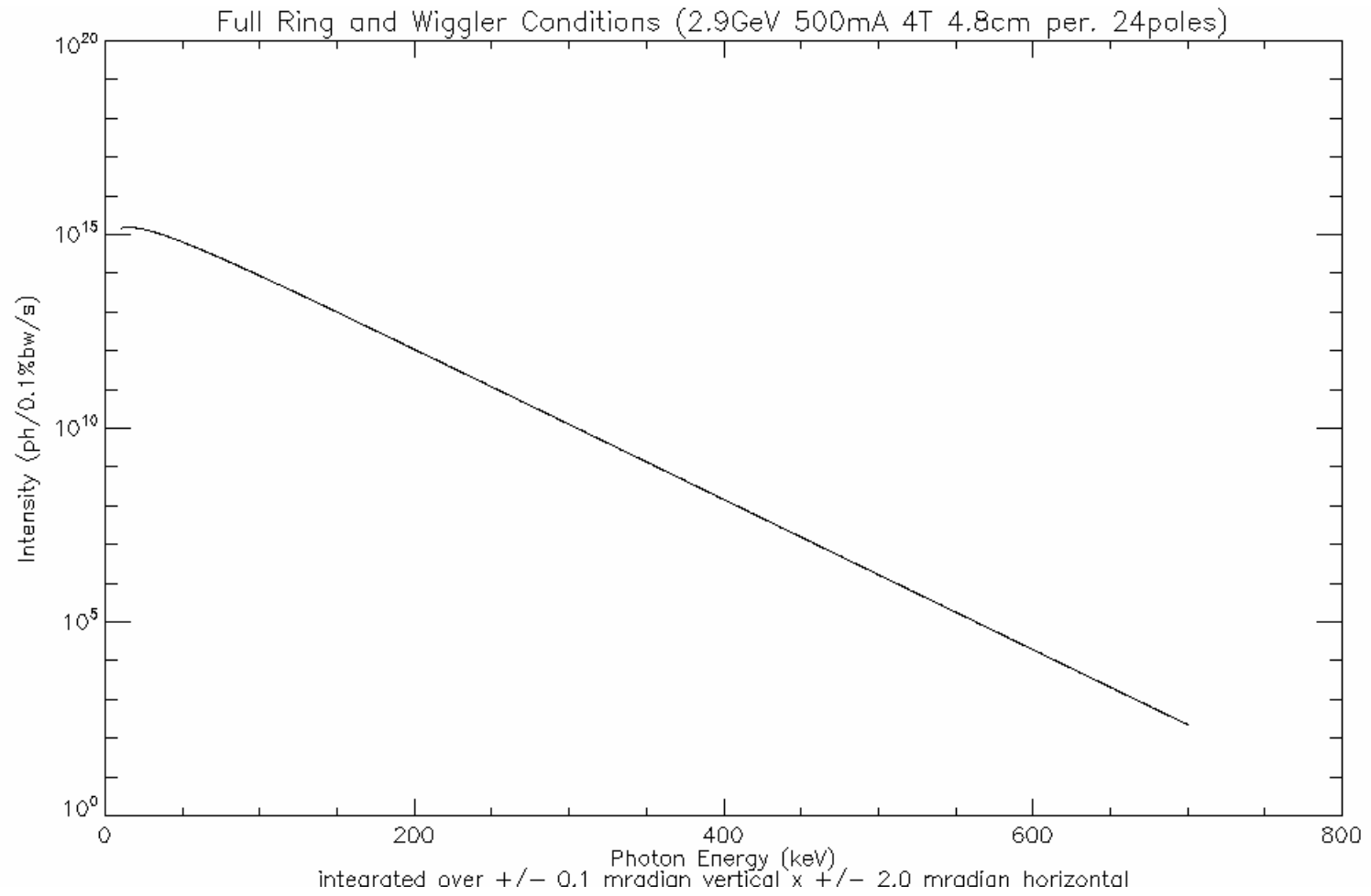


The Source

- Ring Parameters
 - 2.9GeV 500mA
- Wiggler Parameters
 - 4.3T 4.8cm period 12.5 full field periods
 - + 1 half field period
 - Integrated in angle over
 - ± 0.1 milliradian vertical
 - ± 2.0 milliradian horizontal



The Source



Compton Cross-Section

- Relativistic scattering from a free electron – Klein-Nishina (KN)

Unpolarized :

$$\frac{d\sigma_{KN}}{d\Omega} = r_e^2 \left\{ \frac{1 + \cos^2 \theta + \frac{x^2(1 - \cos \theta)^2}{1 + x(1 - \cos \theta)}}{2[1 + x(1 - \cos \theta)]^2} \right\} = r_e^2 \left[\frac{1 + \cos^2 \theta}{2} \right] \left\{ \frac{1 + \frac{x^2(1 - \cos \theta)^2}{[1 + \cos^2 \theta][1 + x(1 - \cos \theta)]}}{[1 + x(1 - \cos \theta)]^2} \right\}$$

Polarized :

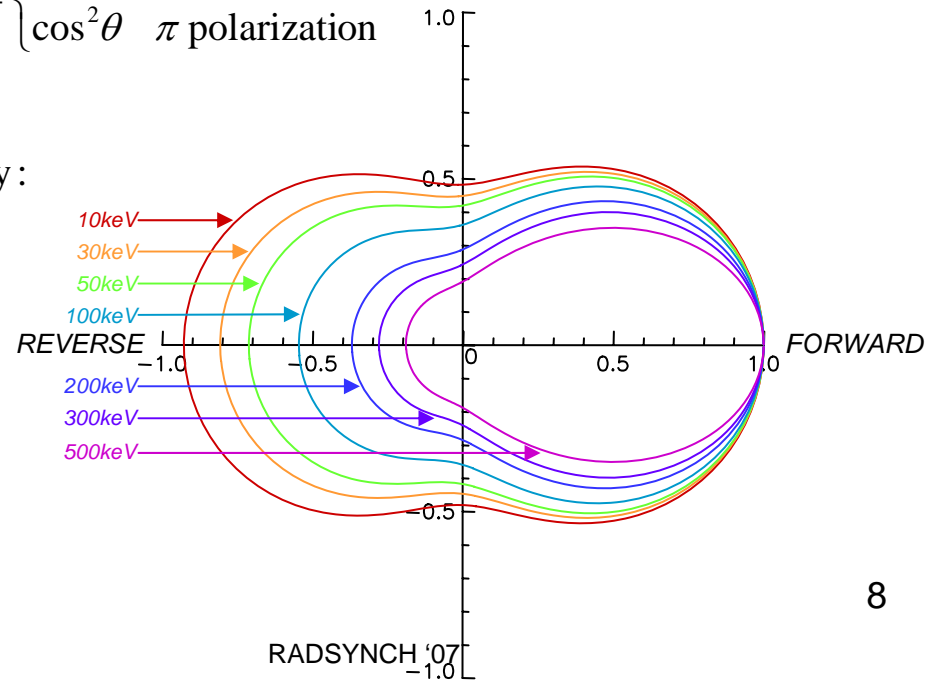
$$\frac{d\sigma_{KN}}{d\Omega} = r_e^2 \kappa^2 \left\{ \frac{1 + \frac{x^2(1 - \cos \theta)^2}{[1 + \cos^2 \theta][1 + x(1 - \cos \theta)]}}{[1 + x(1 - \cos \theta)]^2} \right\} \quad \text{where } \kappa = \begin{cases} 1 & \sigma \text{ polarization} \\ \cos^2 \theta & \pi \text{ polarization} \end{cases}$$

where $x = \frac{E_0}{m_e c^2}$ and the Compton shifted photon energy :

$$E_c = E_0 \left[\frac{m_e c^2}{m_e c^2 + E_0(1 - \cos \theta)} \right] = \frac{x m_e c^2}{1 + x(1 - \cos \theta)}$$

or energy shift ratio :

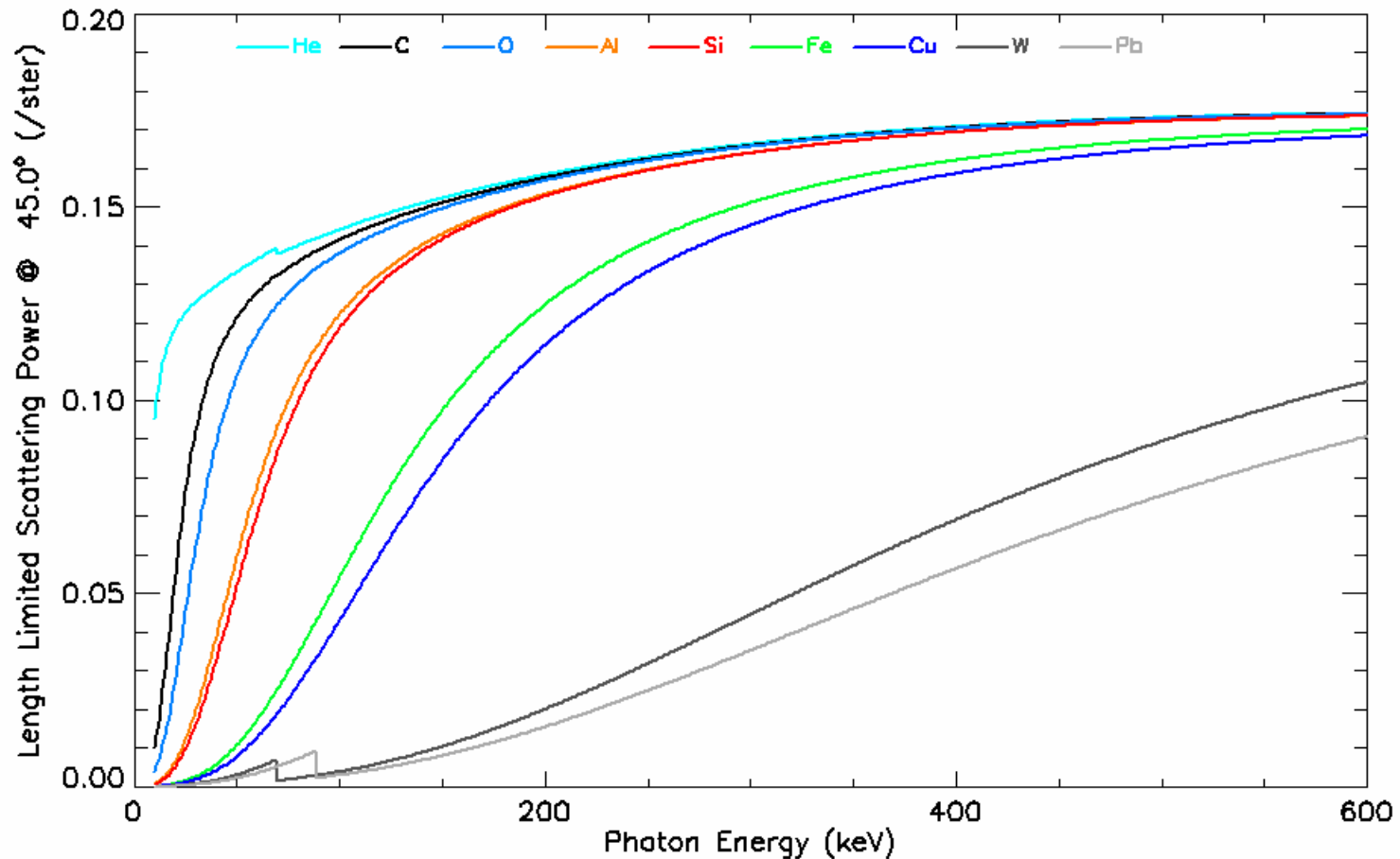
$$\varepsilon = \frac{E_c}{E_0} = \frac{m_e c^2}{m_e c^2 + E_0(1 - \cos \theta)} = \frac{1}{1 + x(1 - \cos \theta)}$$



Scattering Power of Various Elements @

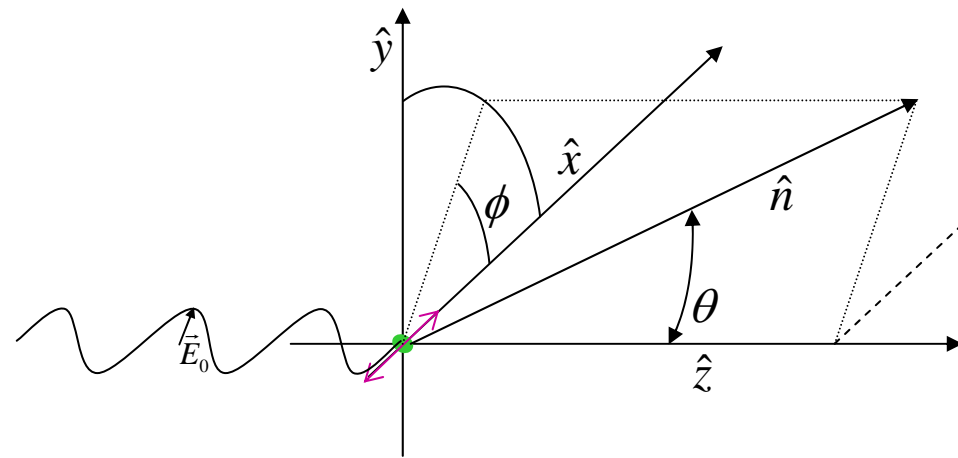
$\theta=45^\circ, \phi=90^\circ$

$$\Sigma_{CS}(E_0, \theta, \phi) = \frac{1}{\frac{\mu}{\rho_{TS}}} \frac{Z r_e^2 (\cos^2 \theta + \sin^2 \theta \sin^2 \phi)}{A u} \left\{ \frac{1 + \frac{x^2 (1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + x(1 - \cos \theta)]}}{[1 + x(1 - \cos \theta)]^2} \right\}$$



Hutch Wall Thickness

- With the definition of a coordinate system for the observer:



$$\hat{n} = \hat{x} \sin \theta \cos \phi + \hat{y} \sin \theta \sin \phi + \hat{z} \cos \theta$$

$$p_{roof} \hat{n} \cdot \hat{y} = t_H = p_{roof} \sin \theta \sin \phi$$

$$p_{roof} = \frac{t_H}{\sin \theta \sin \phi}; \text{ similarly}$$

$$p_{wall} = \frac{t_H}{\hat{n} \cdot \hat{x}} = \frac{t_H}{\sin \theta \cos \phi}$$

$$p_{end} = \frac{t_H}{\hat{n} \cdot \hat{z}} = \frac{t_H}{\cos \theta}$$

in general

$$\hat{h} = \hat{x} \sin \theta_H \cos \phi_H + \hat{y} \sin \theta_H \sin \phi_H + \hat{z} \cos \theta_H ; \text{ hutch wall normal}$$

$$p_H \hat{n} \cdot \hat{h} = t_H$$

$$p_H = \frac{t_H}{\hat{n} \cdot \hat{h}} = \frac{t_H}{\sin \theta \sin \theta_H (\sin \phi \sin \phi_H + \cos \phi \cos \phi_H) + \cos \theta \cos \theta_H}$$



The Source, The Scatter Object, The Shielding & The Dose

$$\begin{aligned}
 \dot{D}_S &= \frac{d\dot{N}_S}{d\Omega} \frac{E_C (\hat{n} \cdot \hat{h})^2}{d_{\perp}^2} \frac{\mu}{\rho_{ED}} (E_C) e^{-\frac{\mu}{\rho_{TH}}(E_C) \frac{\rho_{H^tH}}{\hat{n} \cdot \hat{h}}} \\
 &= \dot{N}_0 \frac{1}{\frac{\mu}{\rho_{TS}}} \frac{Z r_e^2 (\cos^2 \theta + \sin^2 \theta \sin^2 \phi)}{A u} \left\{ \frac{1 + \frac{x^2 (1 - \cos \theta)^2}{(1 + \cos^2 \theta) [1 + x(1 - \cos \theta)]}}{[1 + x(1 - \cos \theta)]^2} \right\} \frac{E_C (\hat{n} \cdot \hat{h})^2}{d_{\perp}^2} \frac{\mu}{\rho_{ED}} (E_C) e^{-\frac{\mu}{\rho_{TH}}(E_C) \frac{\rho_{H^tH}}{\hat{n} \cdot \hat{h}}} \\
 &= \dot{N}_0 (E_0) \frac{E_C (\hat{n} \cdot \hat{h})^2}{d_{\perp}^2} \frac{\mu}{\rho_{ED}} (E_C) \frac{Z r_e^2 (\cos^2 \theta + \sin^2 \theta \sin^2 \phi)}{\frac{\mu}{\rho_{TS}} (E_0) A u} \left\{ \frac{1 + \frac{x^2 (1 - \cos \theta)^2}{(1 + \cos^2 \theta) [1 + x(1 - \cos \theta)]}}{[1 + x(1 - \cos \theta)]^2} \right\} e^{-\frac{\mu}{\rho_{TH}}(E_C) \frac{\rho_{H^tH}}{\hat{n} \cdot \hat{h}}}
 \end{aligned}$$



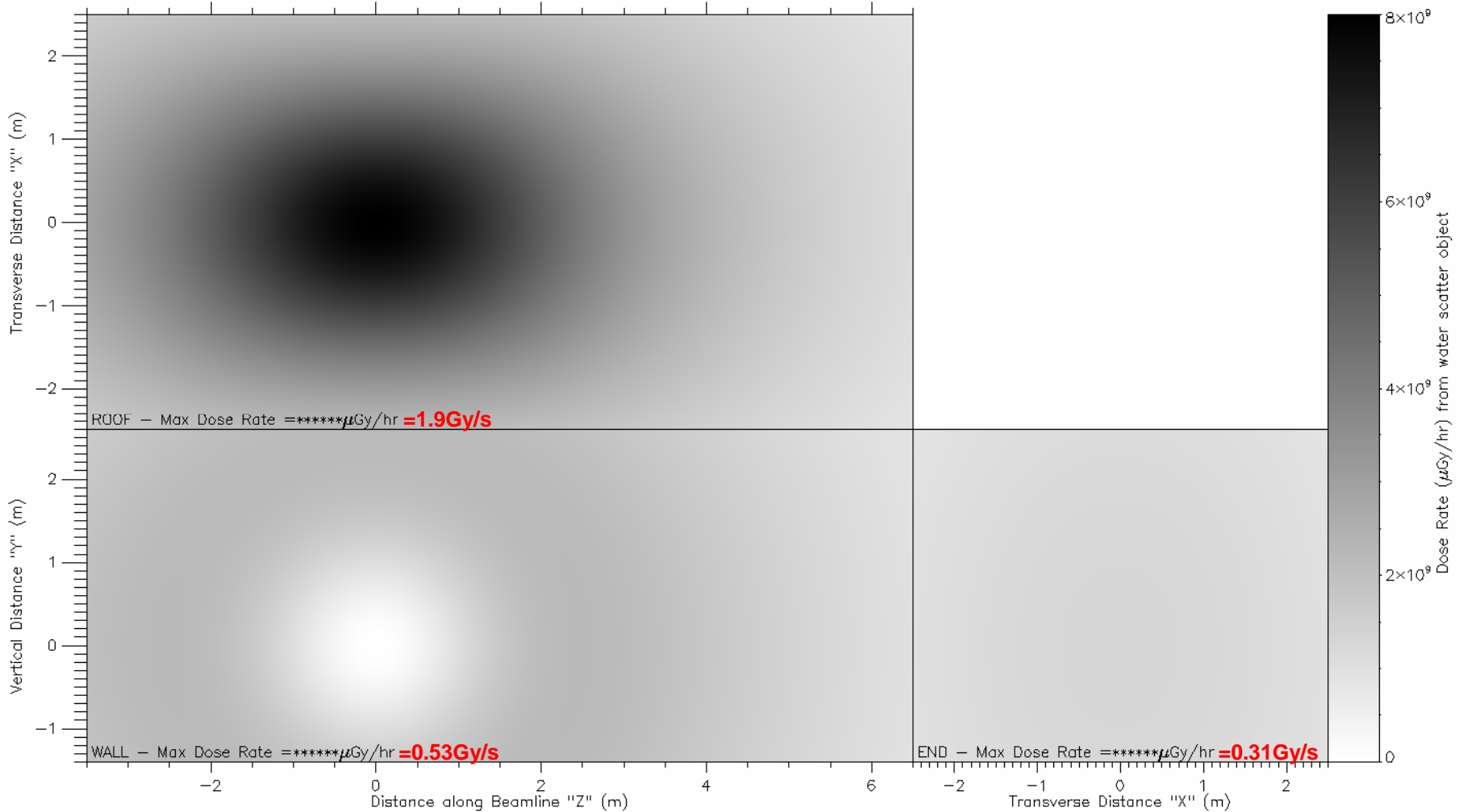
Applications to BMIT

- Scattered White Beam
 - POE1, POE2, POE3
 - White Beam Transport
- Scattered Monochromatic Beam
- Direct Monochromatic Beam



No Shielding – water scatter object

0.00mm Fe Wall + 0.00mm Pb Wall



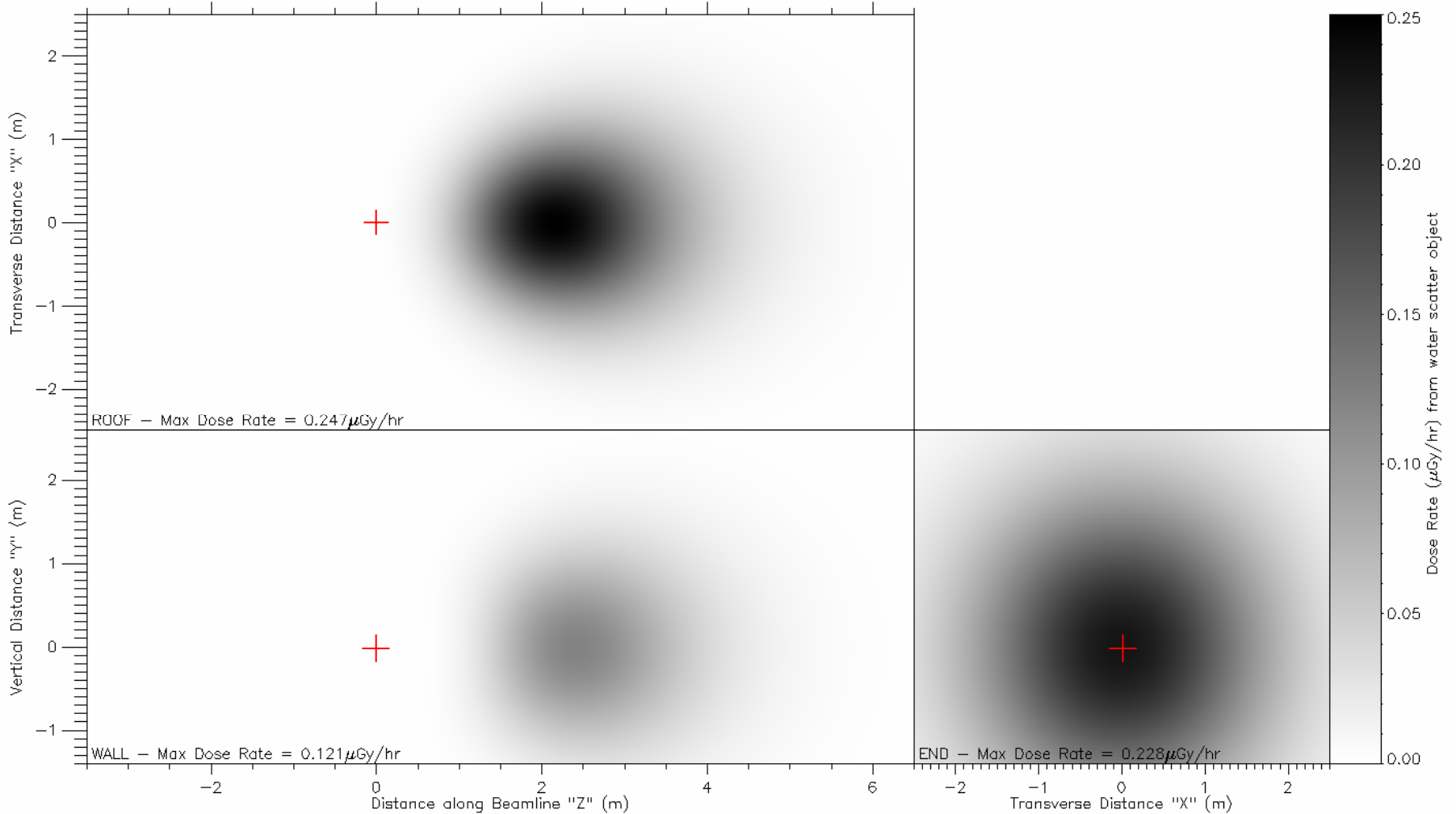
0.00mm Fe Wall + 0.00mm Pb Wall + 0.00mm Pb Wall @ +/- 0.00m above/below beam height

0.00mm Fe Wall + 0.00mm Pb Wall



Dose on POE Walls

6.35mm Fe Wall + 15.00mm Pb Wall

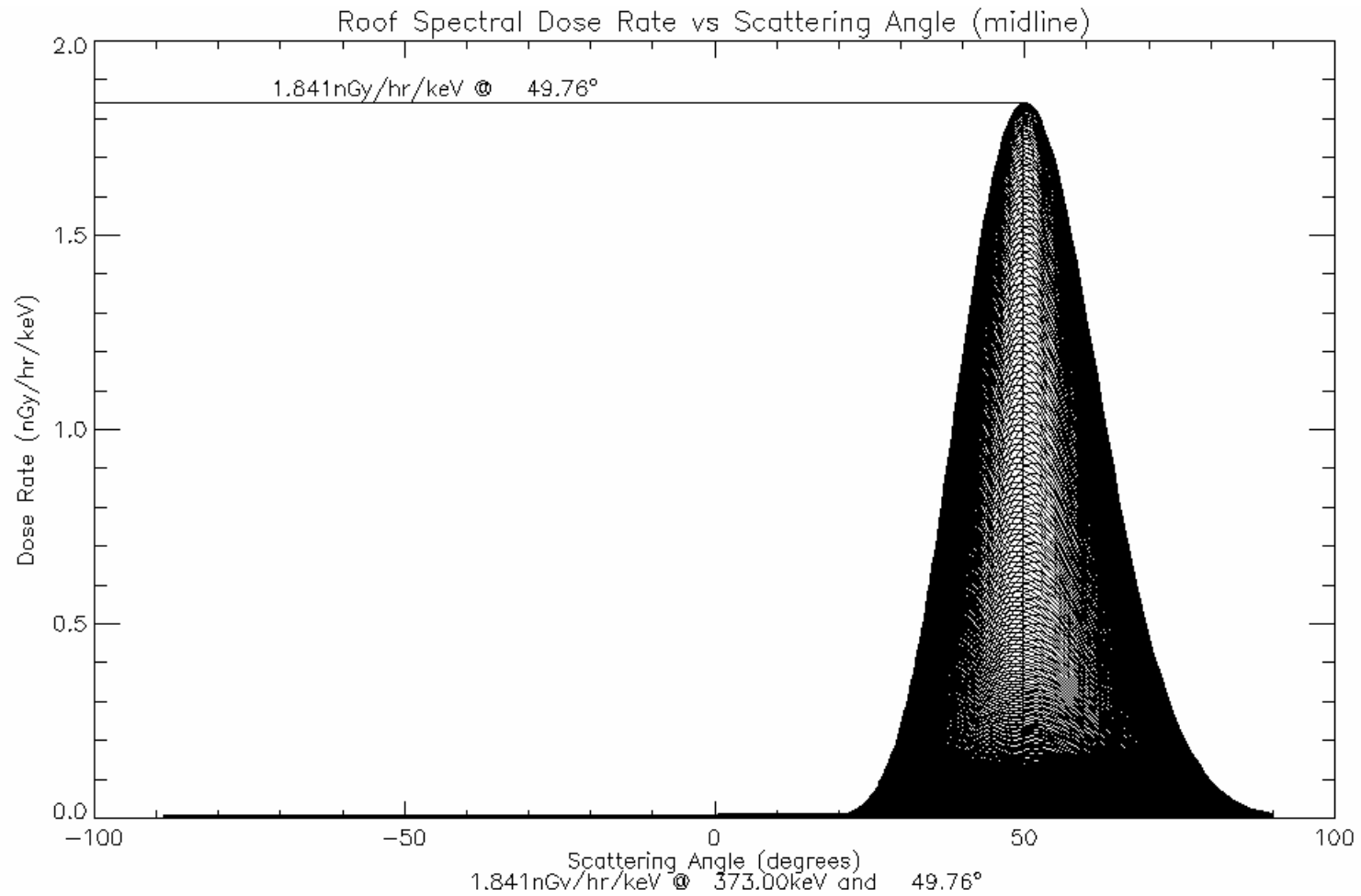


6.35mm Fe Wall + 15.00mm Pb Wall + 30.00mm Pb Wall @ +/- 0.00m above/below beam height

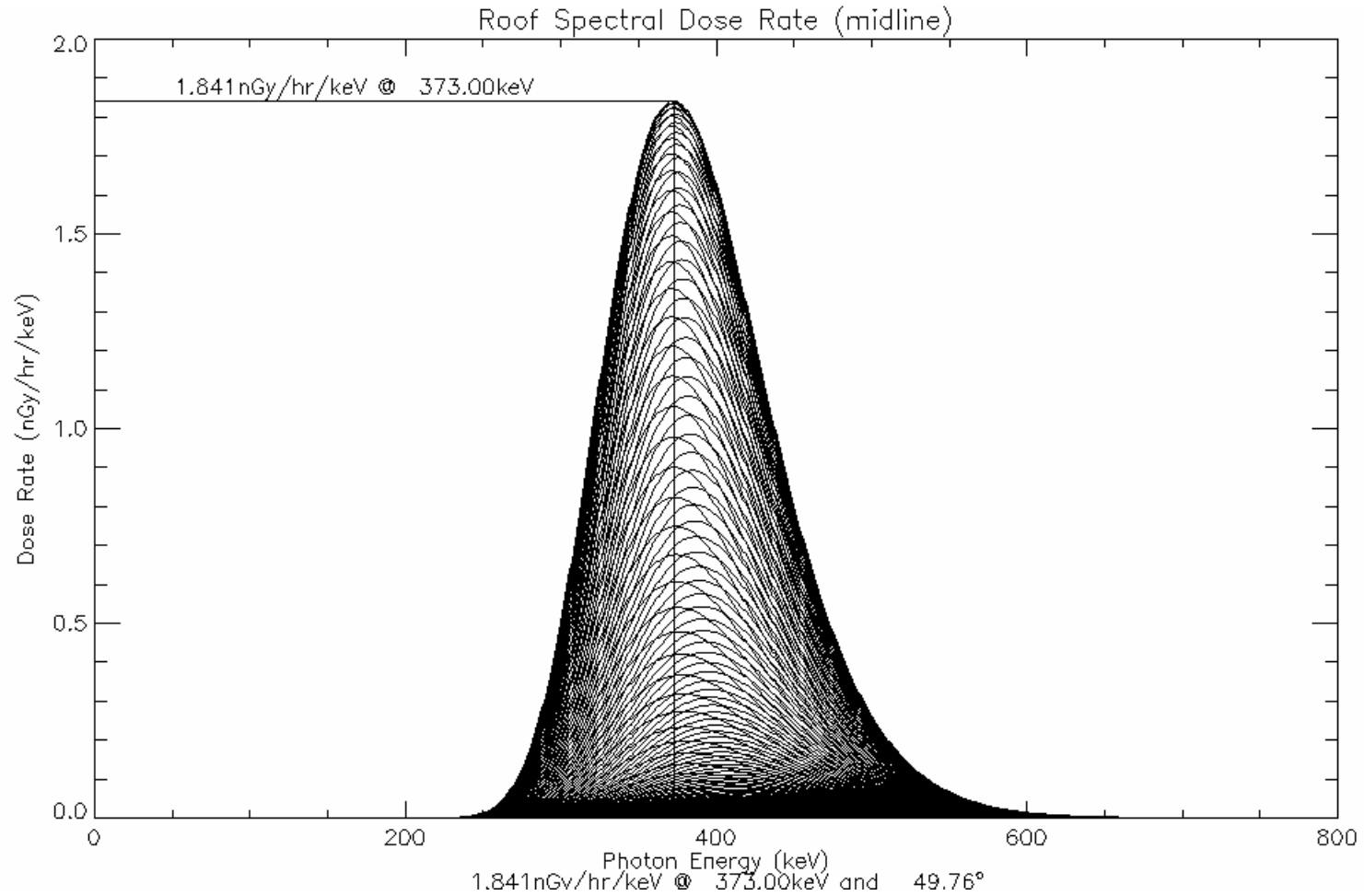
6.35mm Fe Wall + 30.00mm Pb Wall



Spectral Dose Rate vs Scattering Angle; $\phi=90^\circ$



Spectral Dose Rate vs Photon Energy; $\phi=90^\circ$

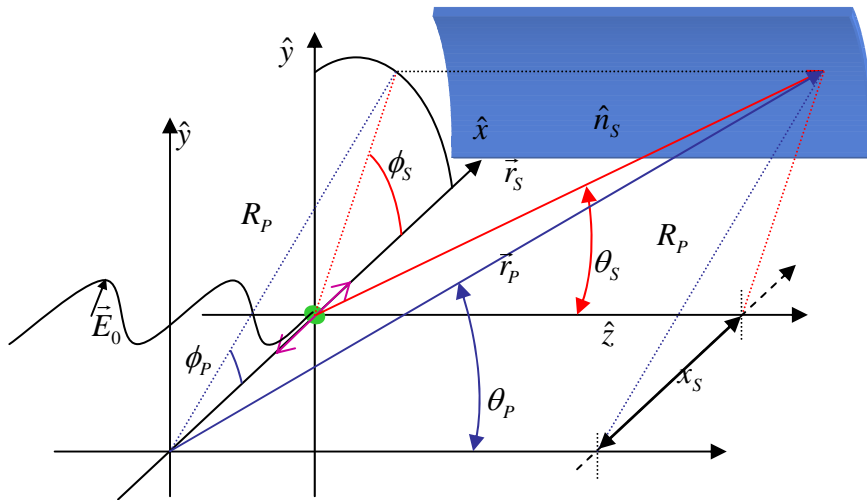


Transport Pipe

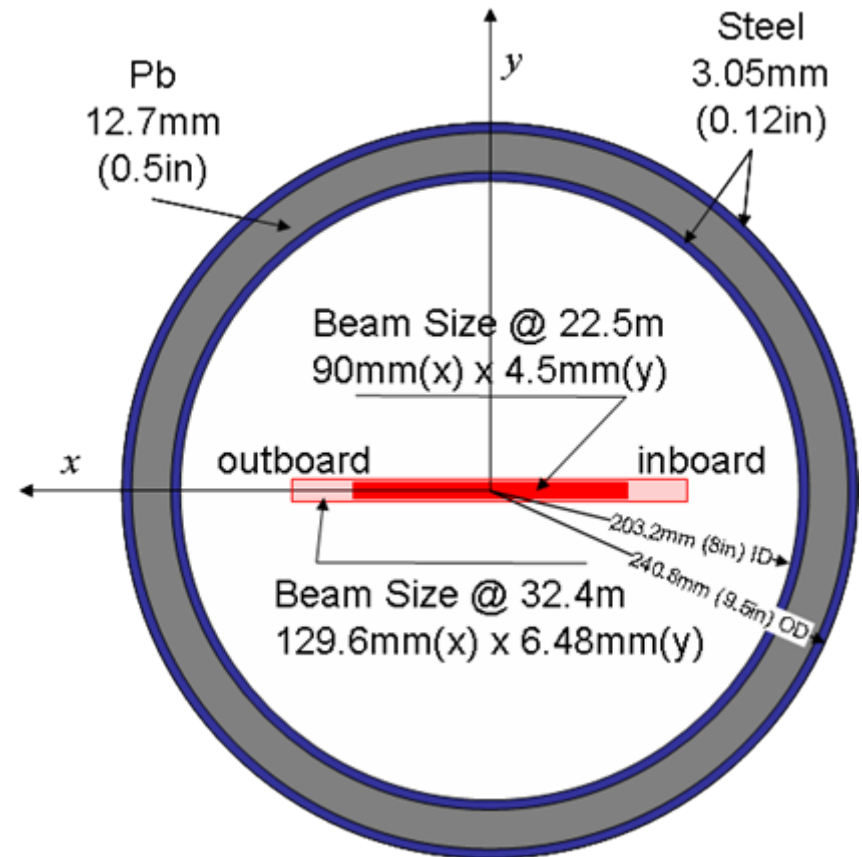
- Scatter Only
- Assumed
 - Air filled pipe plus
 - Be window scatter
- Broke beam in the pieces horizontally and summed contributions from each horizontal piece



Transport Pipe Geometry



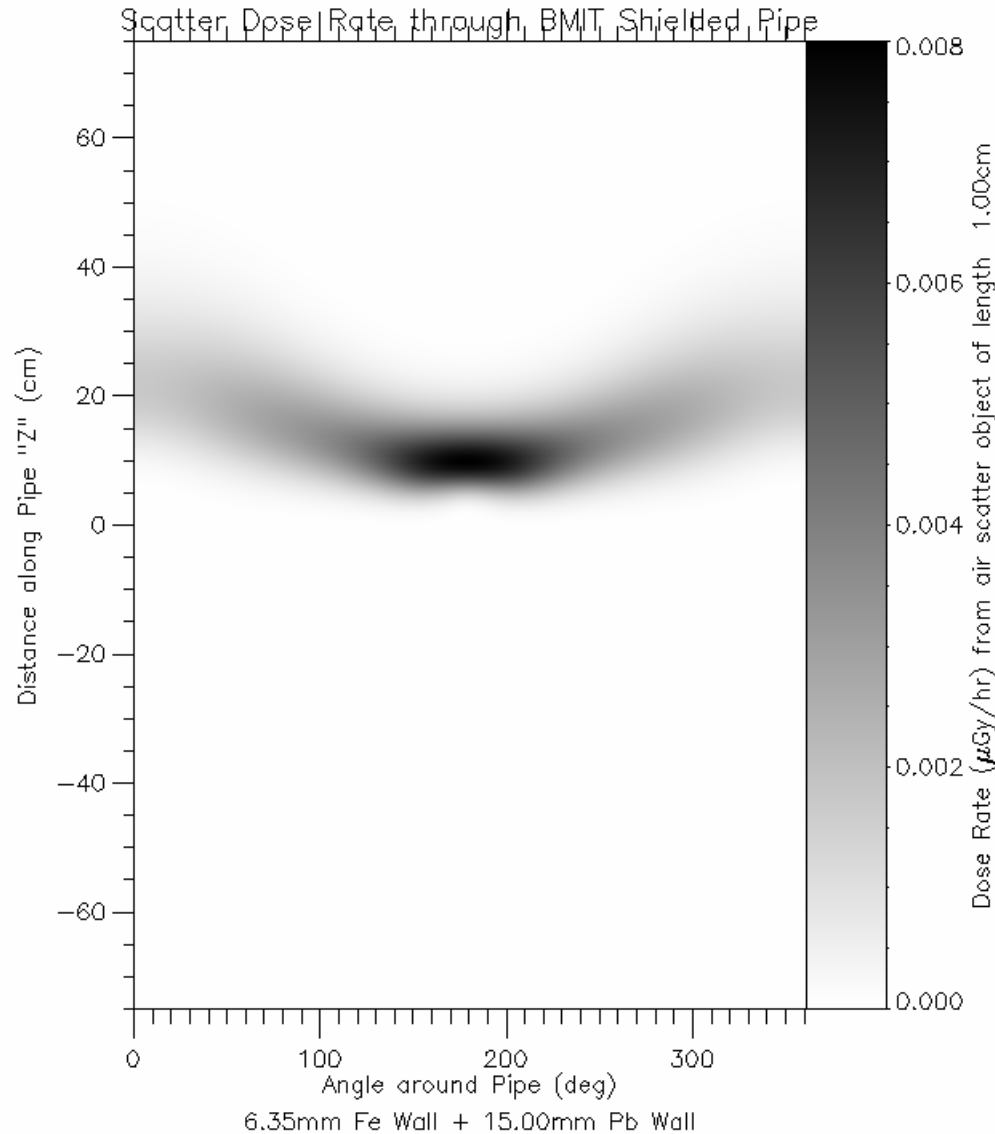
Scattering Geometry



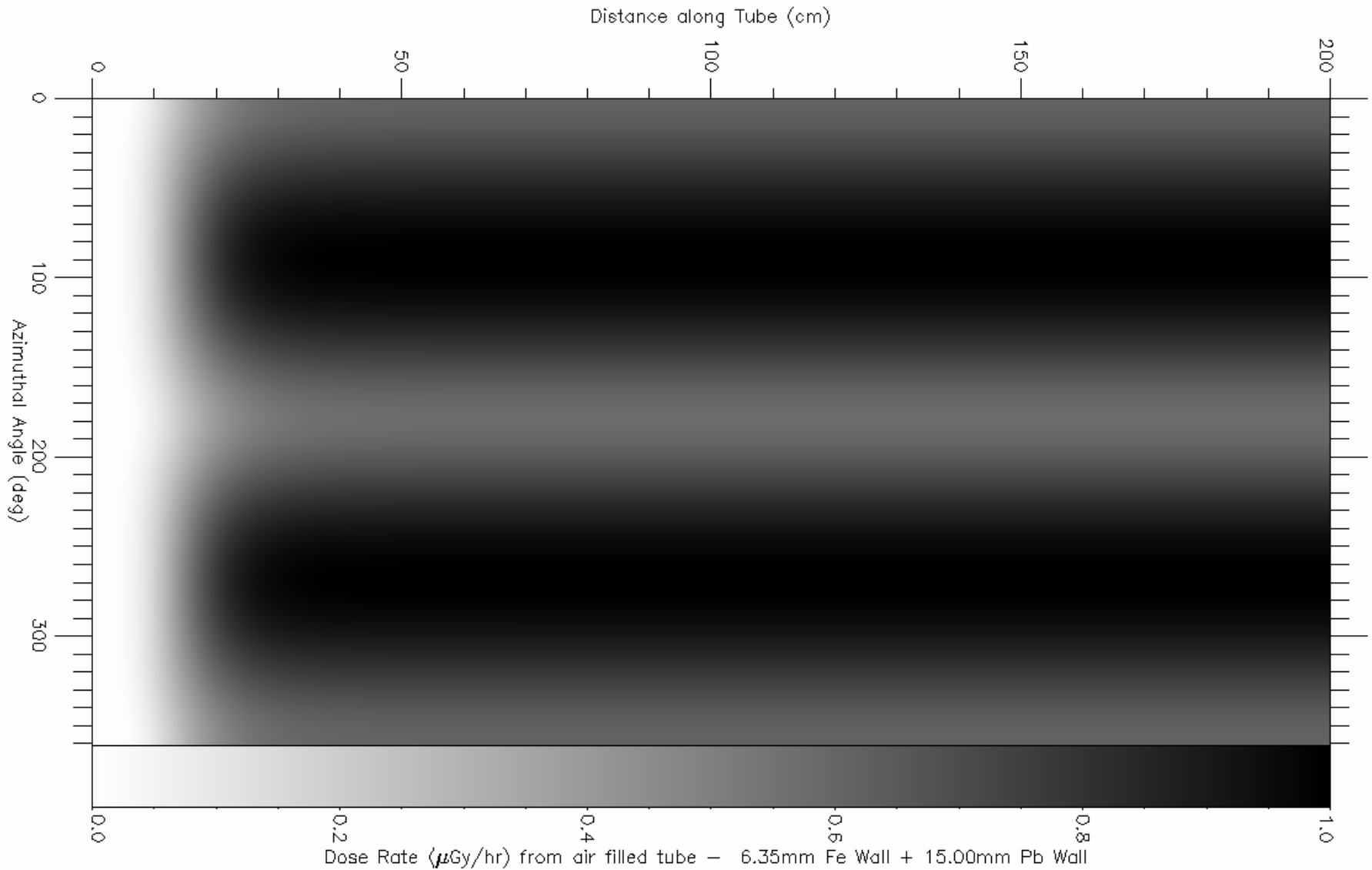
Typical Pipe Dimensions with Beam



Scatter from 1cm width beam at edge of pipe from 1cm thick air slab



Scatter from air filled pipe + Be window



Scattered Monochromatic Beam

- Flux from mono's
 - We use both flat Bragg and bent Laue type monochromators
 - Assume the “worst”
 - Bent Laue and
 - Crystal thickness which maximizes flux
 - Crystal behaves “kinematically”
 - Include harmonics



Maximum Monochromator Performance

Kinematic Integrated Reflectivity

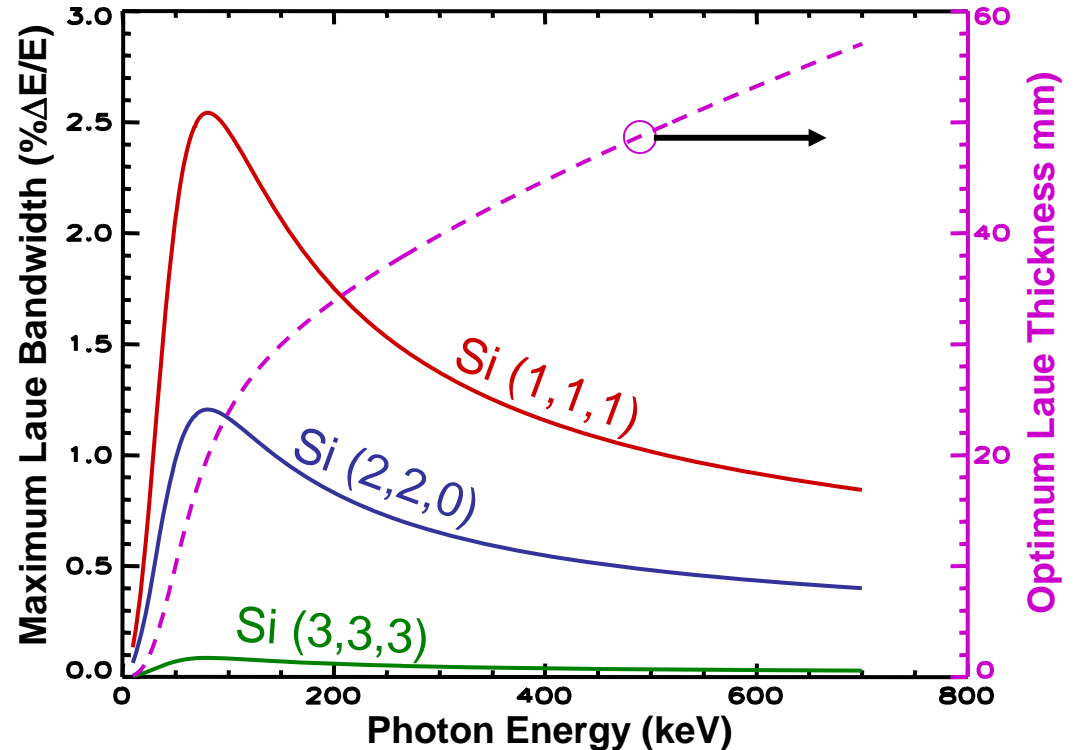
$$R_{HL\text{aue}}^\theta = \frac{QT_0}{\gamma_0} e^{-\frac{\mu_0 T_0}{\gamma_0}} \quad Q = \left(\frac{r_e F_H}{V_C} \right)^2 \frac{\lambda^3}{\sin 2\theta_B}$$

Maximum Possible Integrated Reflectivity

$$R_{HL\text{aue}}^\theta \Big|_{\text{max}} = \frac{Q}{\mu_0} e^{-1} = \left(\frac{r_e F_H}{V_C} \right)^2 \frac{\lambda^3}{e^1 \mu_0 \sin 2\theta_B}$$

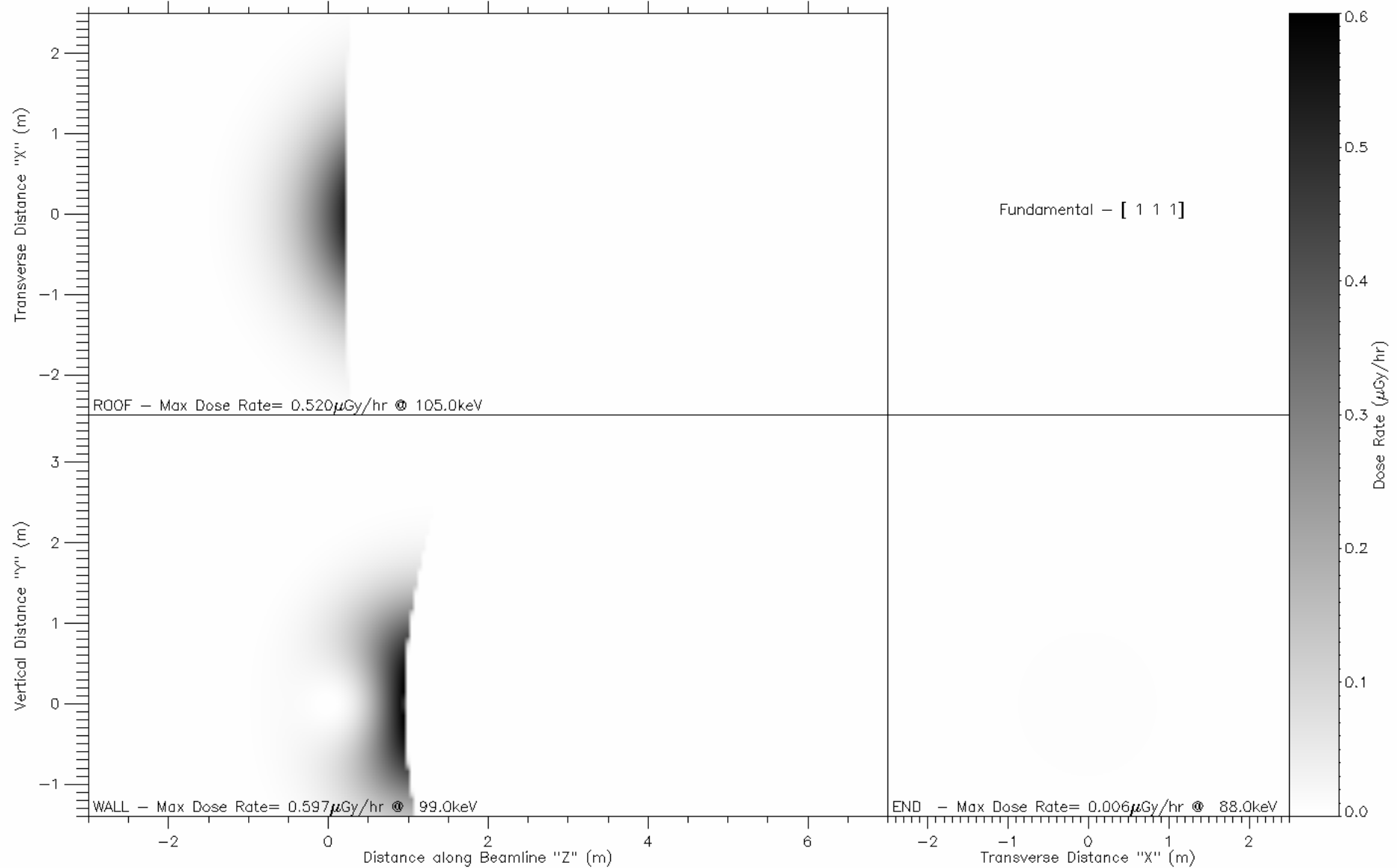
Maximum Energy Bandwidth

$$\frac{\Delta E}{E} \Big|_{\text{max}}^{\text{Laue}}(H, E) = \left(\frac{r_e F_H}{V_C} \right)^2 \frac{2hcd_H^2}{e^1 \mu_0(E)E}$$



Fundamental

6.35mm Fe Wall + 6.00mm Pb Wall

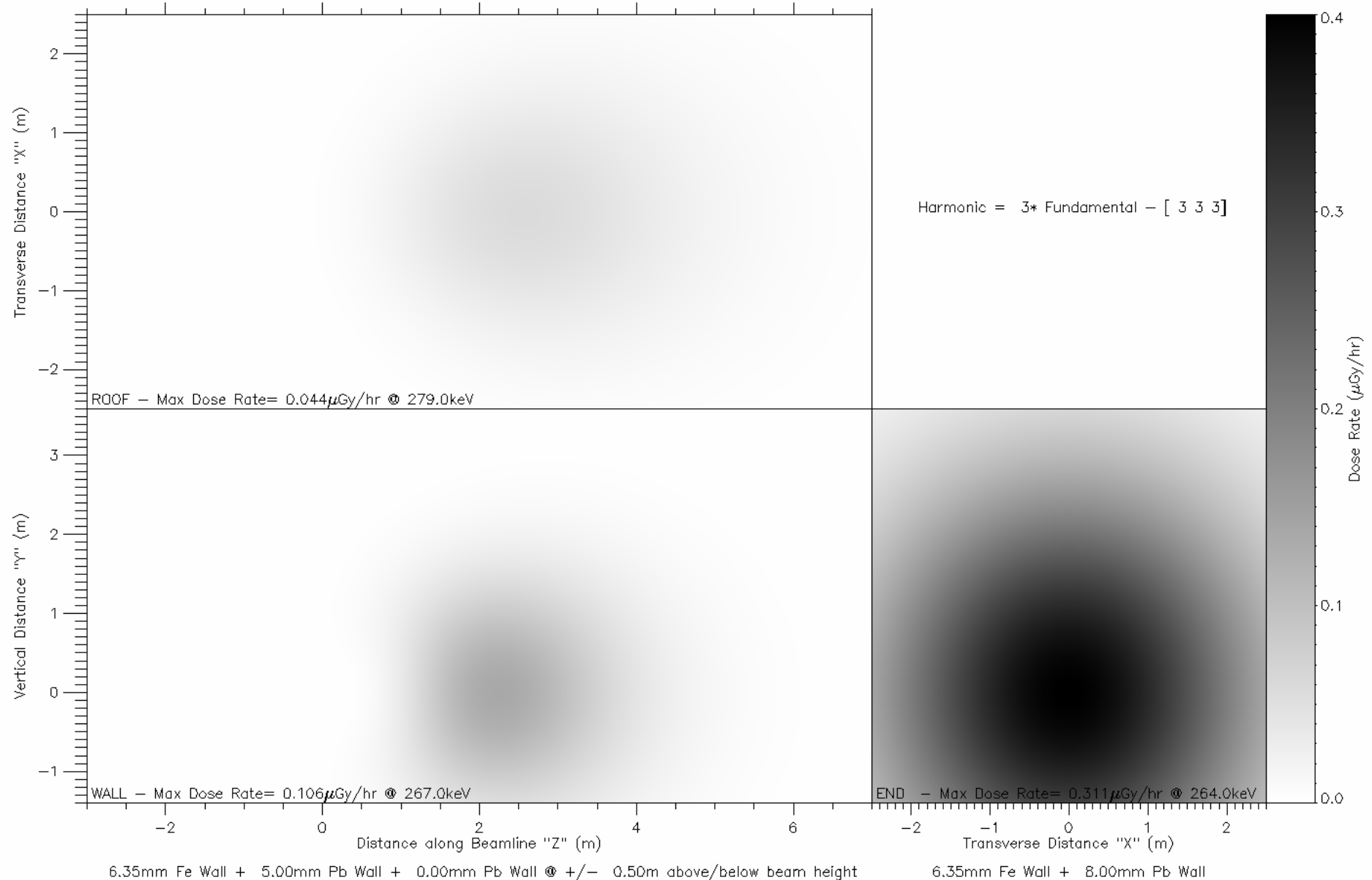


6.35mm Fe Wall + 5.00mm Pb Wall + 0.00mm Pb Wall @ +/- 0.50m above/below beam height

6.35mm Fe Wall + 8.00mm Pb Wall

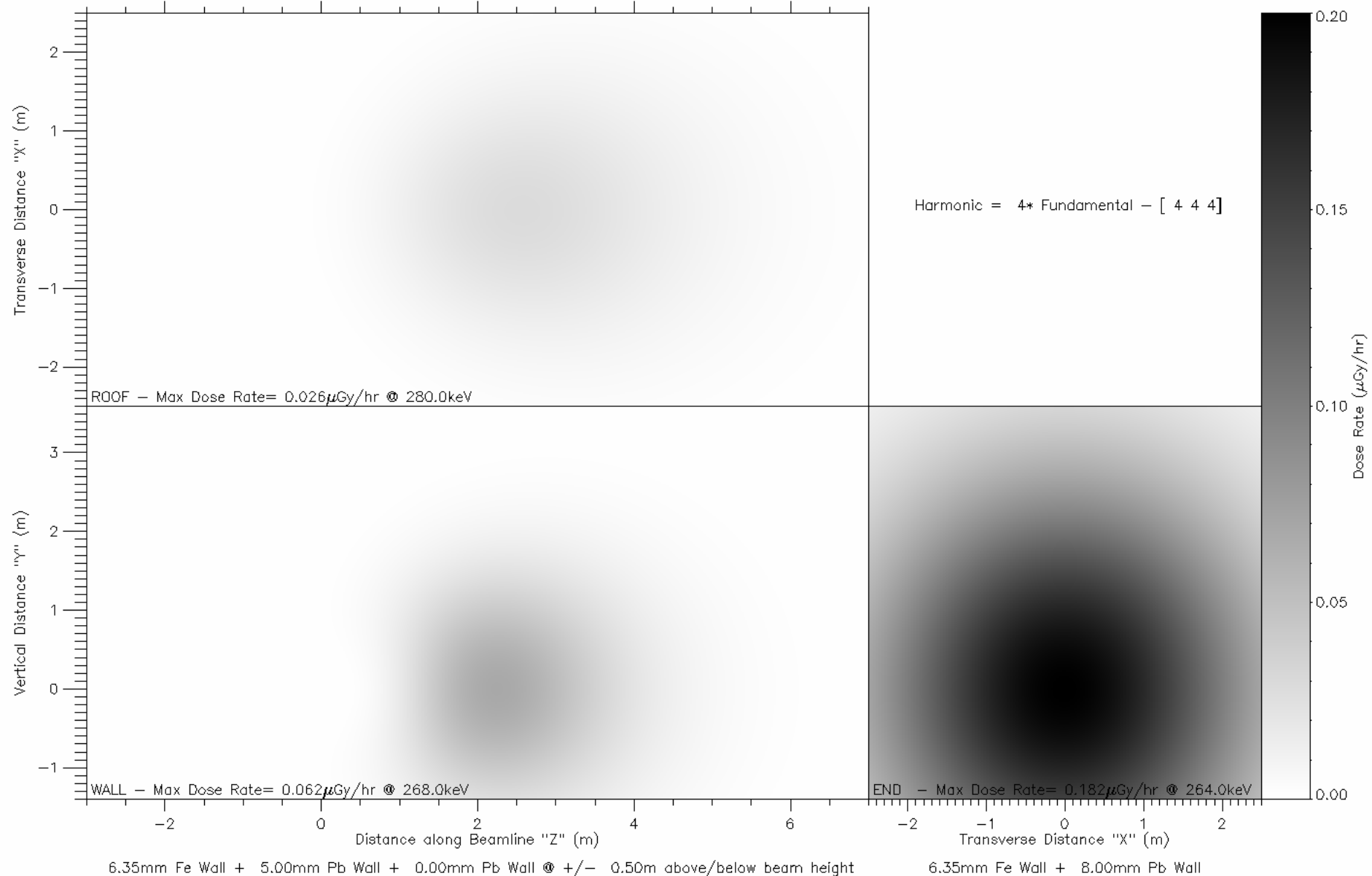
2nd Harmonic (3 x Fundamental)

6.35mm Fe Wall + 6.00mm Pb Wall



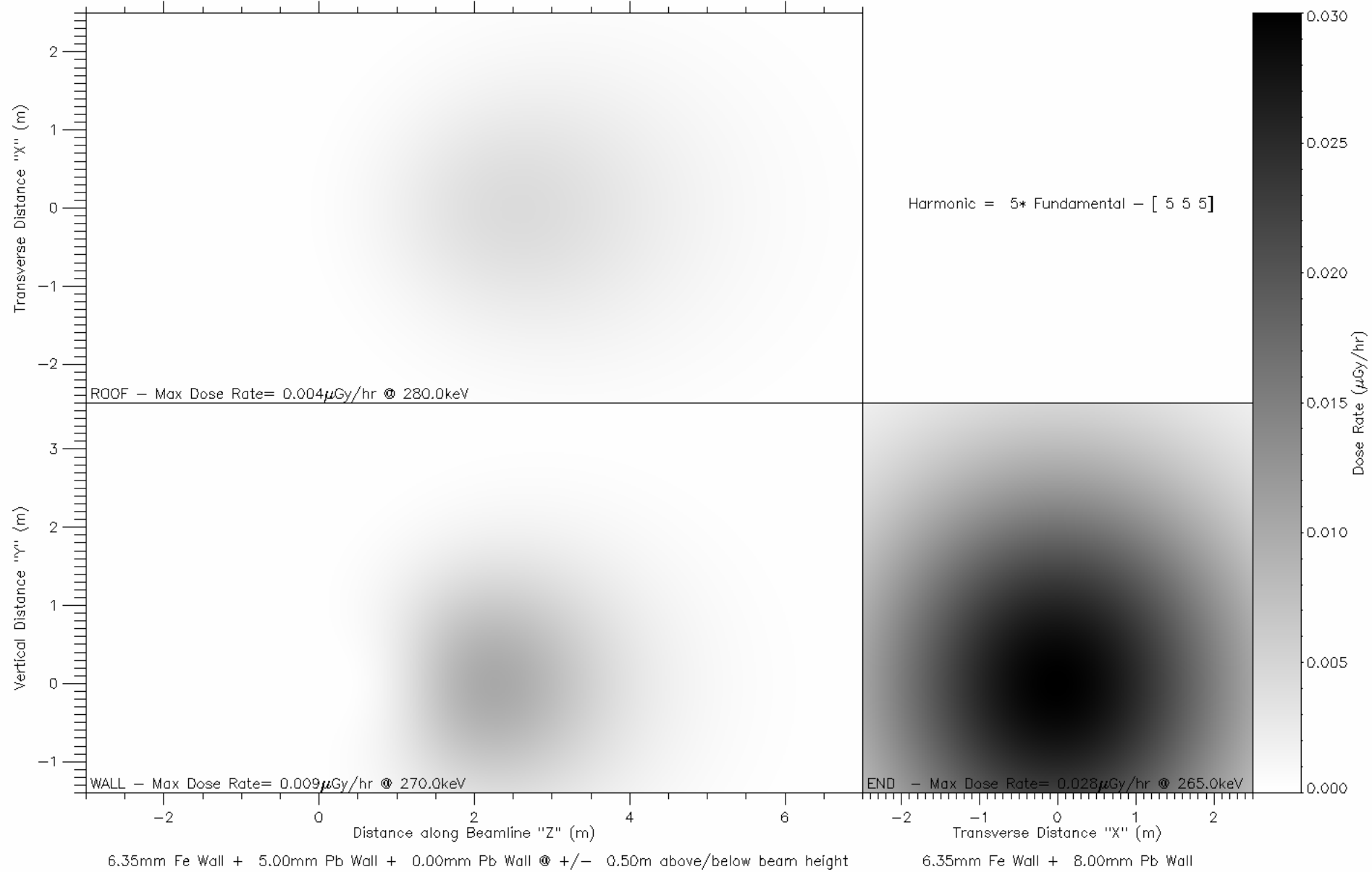
3rd Harmonic (4 x Fundamental)

6.35mm Fe Wall + 6.00mm Pb Wall



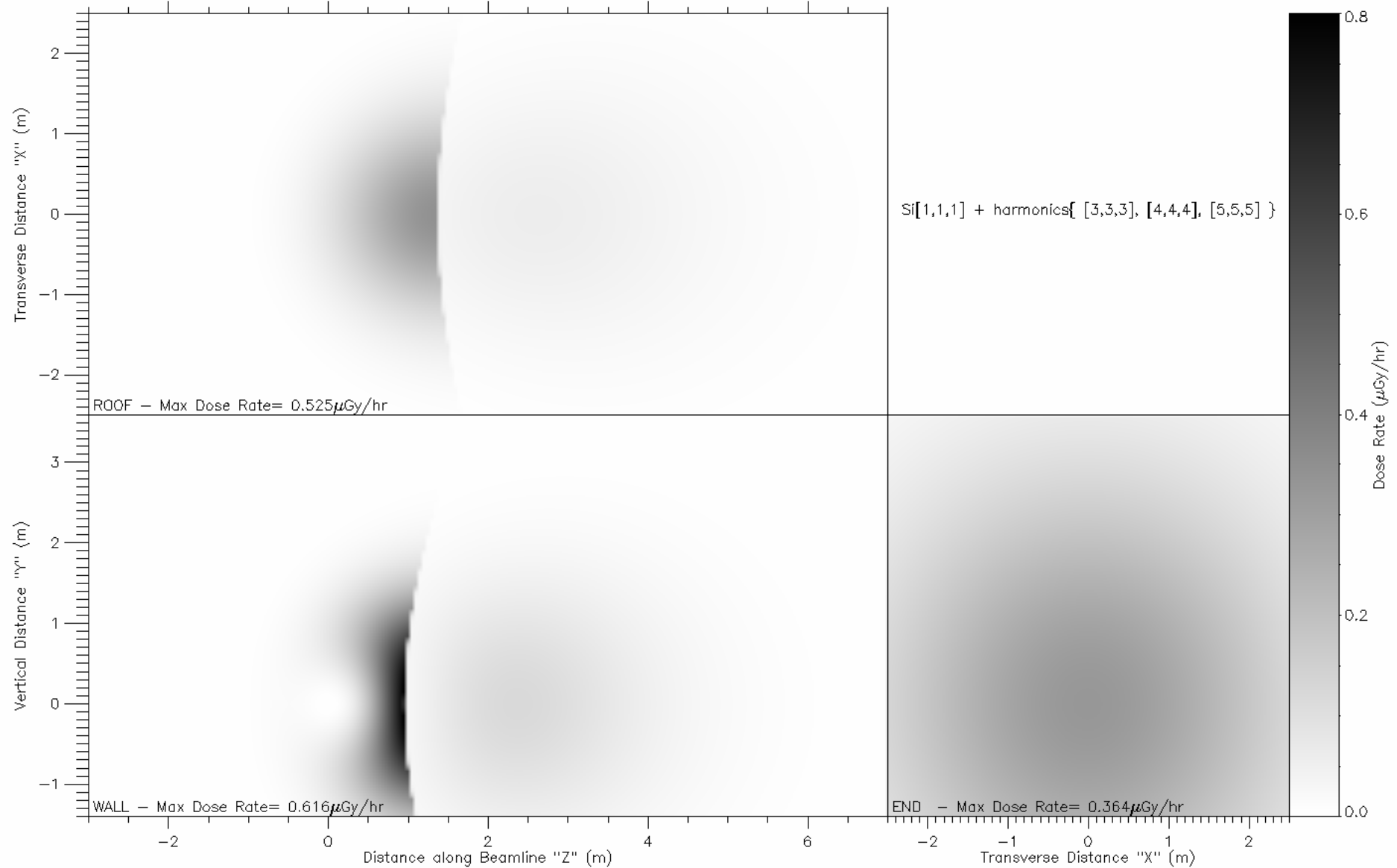
4th Harmonic (5 x Fundamental)

6.35mm Fe Wall + 6.00mm Pb Wall



Fundamental + Harmonics

6.35mm Fe Wall + 6.00mm Pb Wall



6.35mm Fe Wall + 5.00mm Pb Wall + 0.00mm Pb Wall @ +/- 0.50m above/below beam height

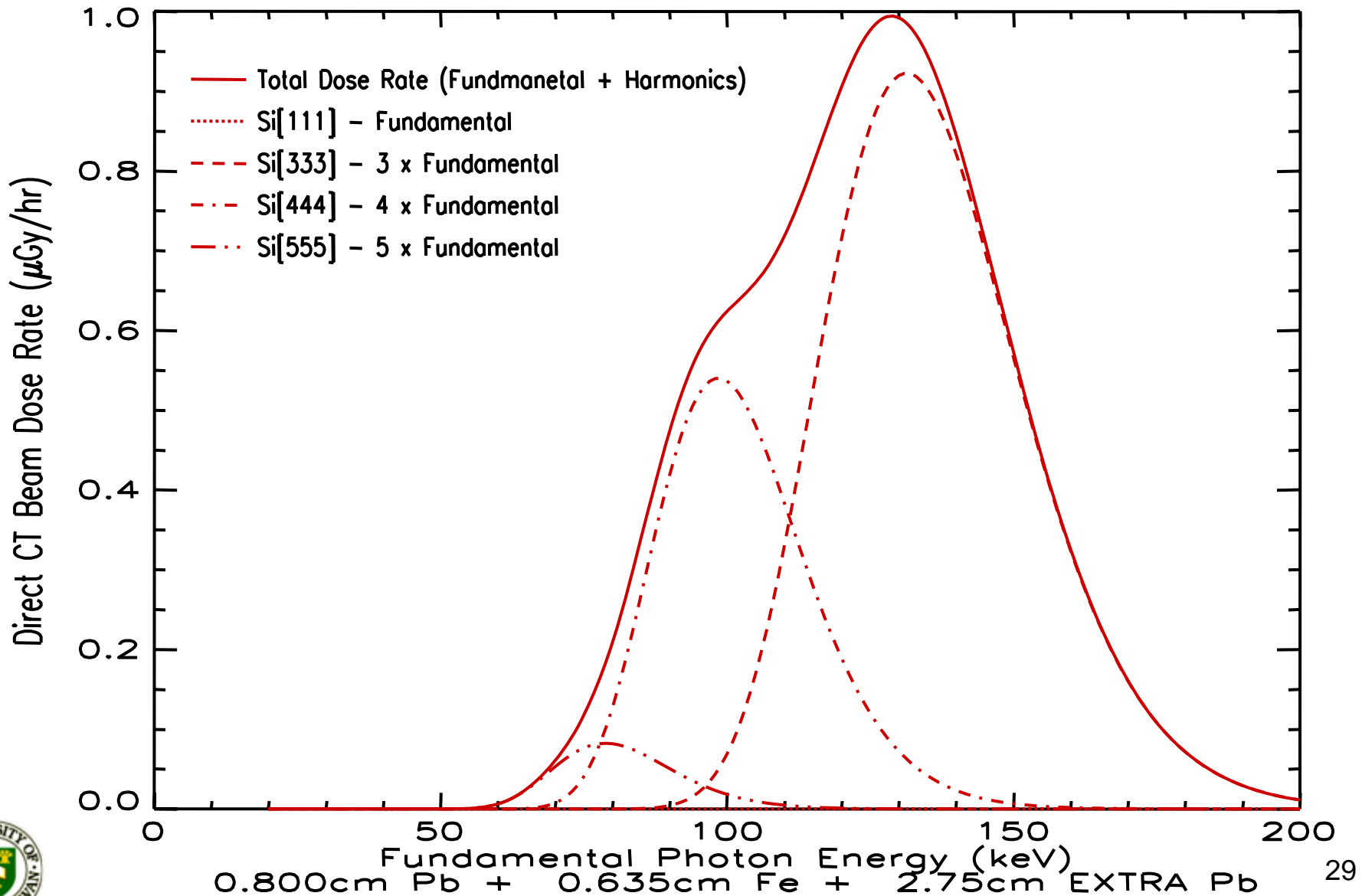
6.35mm Fe Wall + 8.00mm Pb Wall

SOE Shielding – Direct Monochromatic Beams

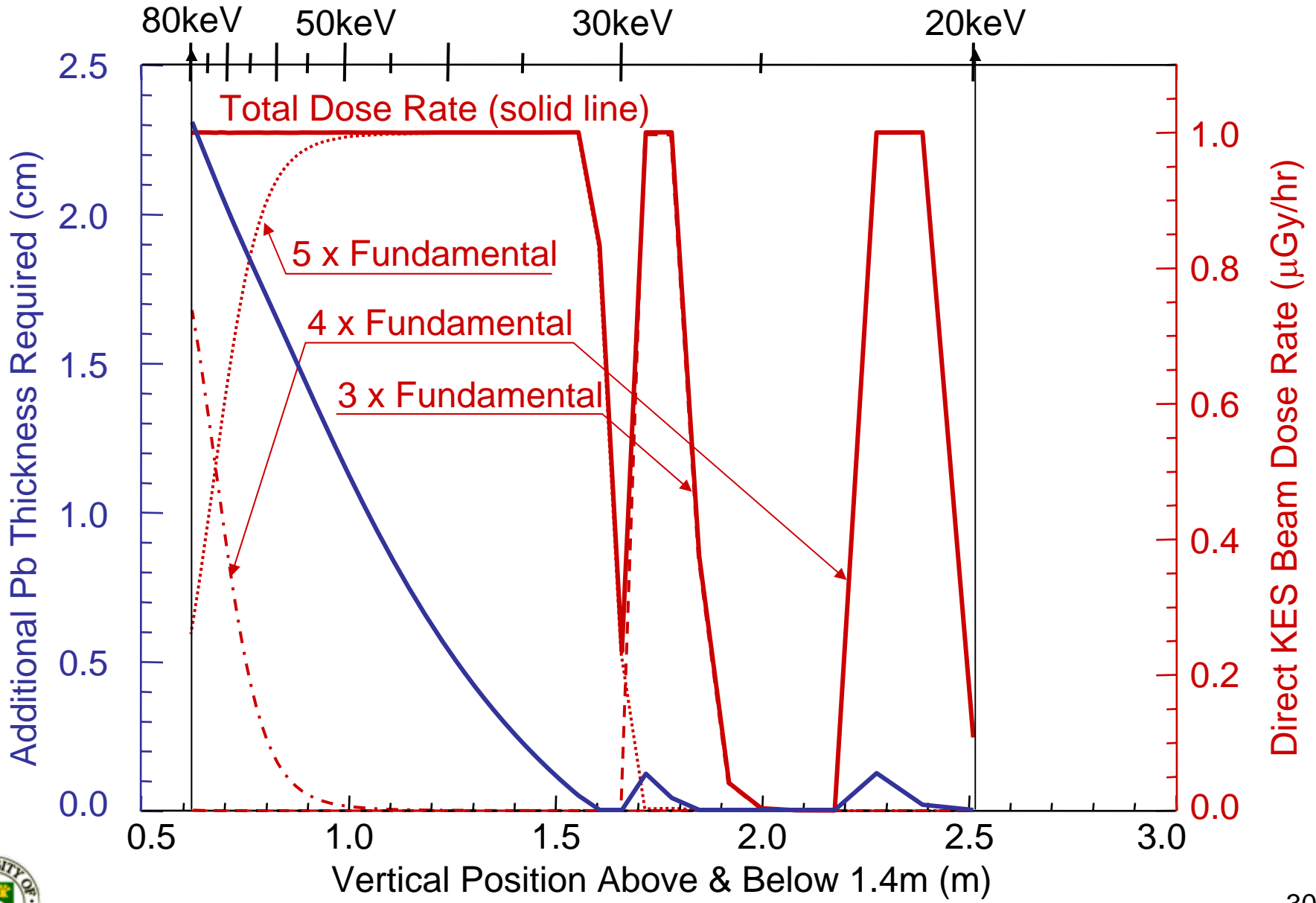
- Double crystal monochromator beams are fixed on the rear wall of the SOE
- KES monochromator (single crystal mono) beams sweep vertically along the wall as the energy is changed



Direct Mono Beam Stop

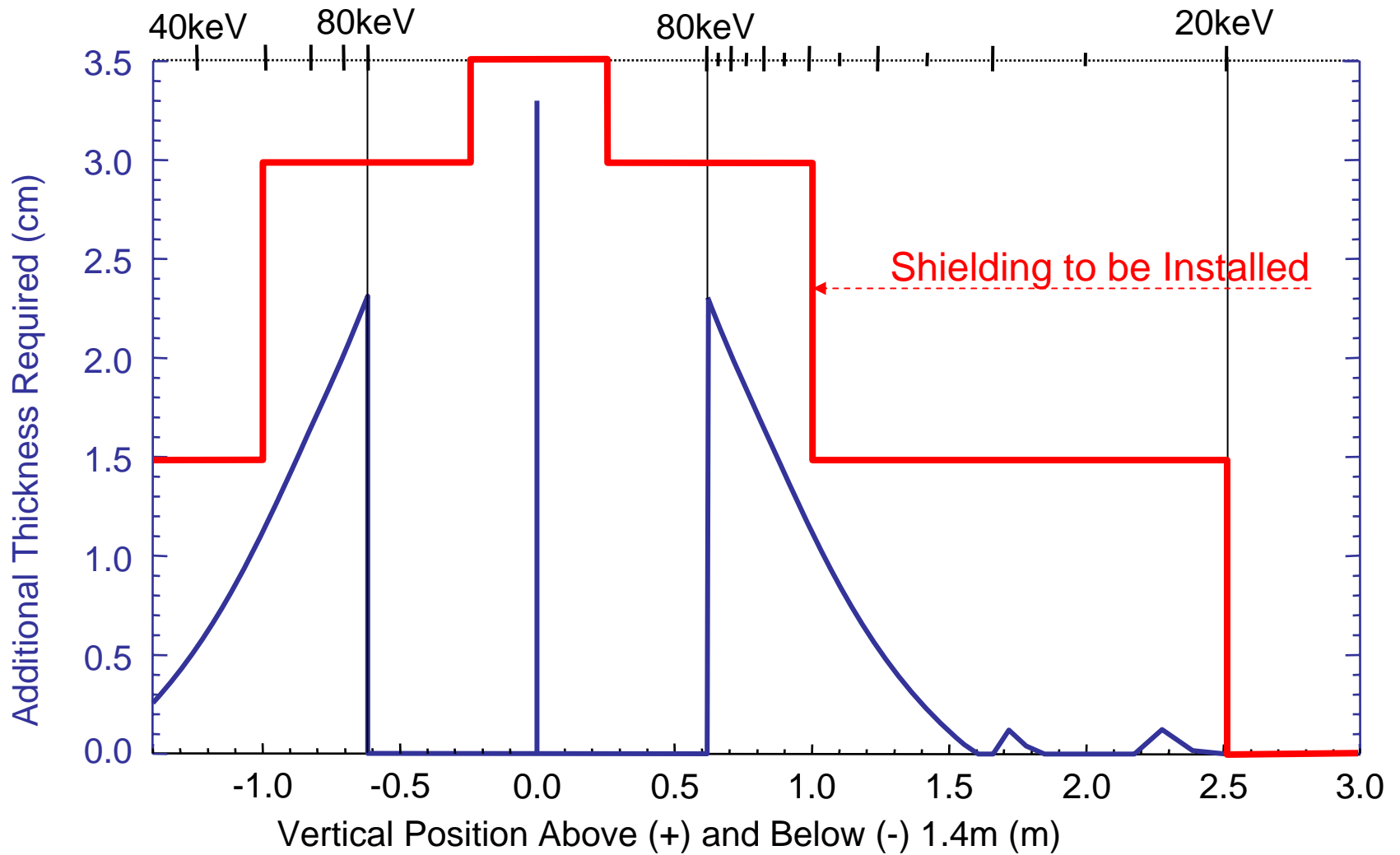


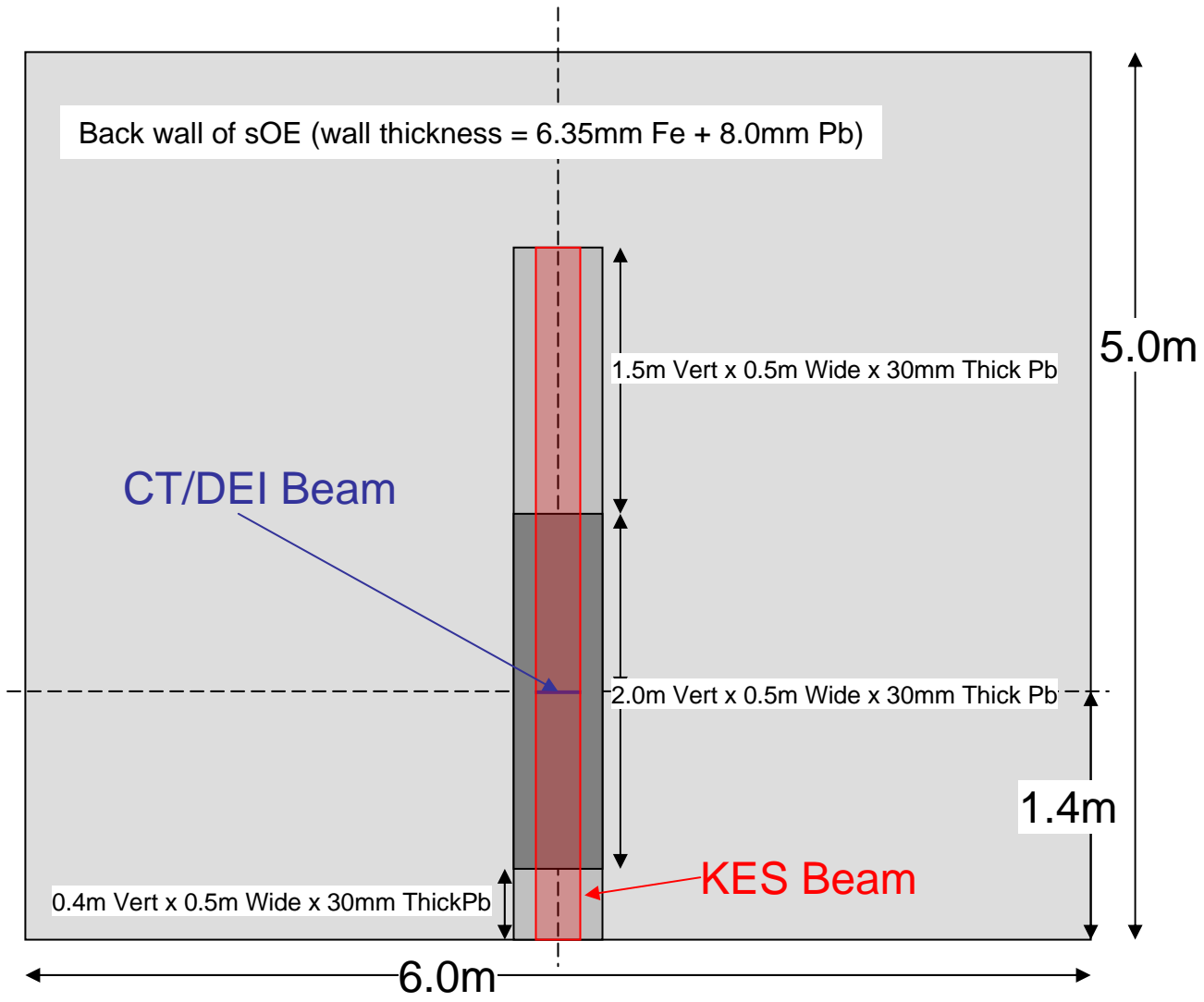
KES Beam on Back Wall



0.80cm Pb + 0.635cm Fe + Additional Pb







Summary

- Calculations done to estimate shielding required for BMIT include
 - POE's
 - This could have been done using other programs such as STACK-8
 - Visual image of dose rate on surfaces of structures
 - Transport pipes (air filled + Be window)
 - A more realistic approach was used to calculate air scatter within pipe including Be window scatter
 - Visual image of dose rate on surface of tube
 - SOE's
 - Maximum possible monochromatic efficiency was used
 - Scattered radiation shielding
 - Direct beam shielding
 - Fixed beam on back wall (“CT Mono” beam)
 - Variable energy single crystal direct beam (KES beam)
- All programs in written in IDL (Interactive Data Language, ITT Visual Information Solutions)

