EUROPEAN
SPALLATION
SOURCE

Neutron and X-Ray shielding

Günter Muhrer

www.europeanspallationsource.se

Outline

- Why do we need shielding?
- Definitions
- Natural and every day radiation
- Physics: Gamma and Neutron
- Tools:
    - Handbook
    - Monte Carlo Particle Transport Codes
- Deep penetration challenge
- Instruments background
    - Homemade problem
    - crosstalk

Why do we need to shield against radiation?

- Damage to the human body (Sievert or Rem)
- Damage to the equipment (Gy or Rad)
- Damage to experimental data (noise level of the data)

Units (protection of equipment)

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- Gray [Gy] and Radiation Absorbed Dose (Rad) are the two most commonly used units that quantifies the dose received by equipment.
- 1 Gy = 1 J/kg
- 1 Gy = 100 rad

Units (protection of humans)

- Sievert [Sv] and Röntgen Equivalent Man (Rem) are the two most commonly used units that quantifies the dose received by human body.
- 1 Sv = 100 rem
- Like Gy, Sv has the SI unit of J/kg, however Sv is the absorbed dose convoluted with the respective biological damage factors, which are usually published by the International Commission on Radiological Protection (ICRP)

Units (protection of data)

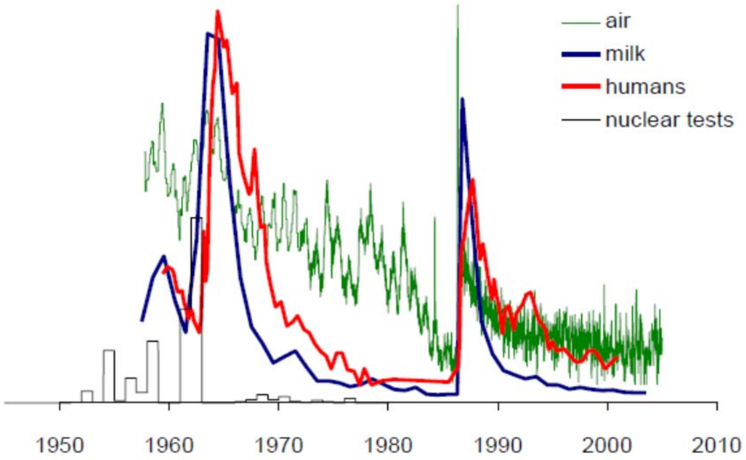
- The definition of the noise of an experiment will depend on the experiment.

Sources of natural radiation

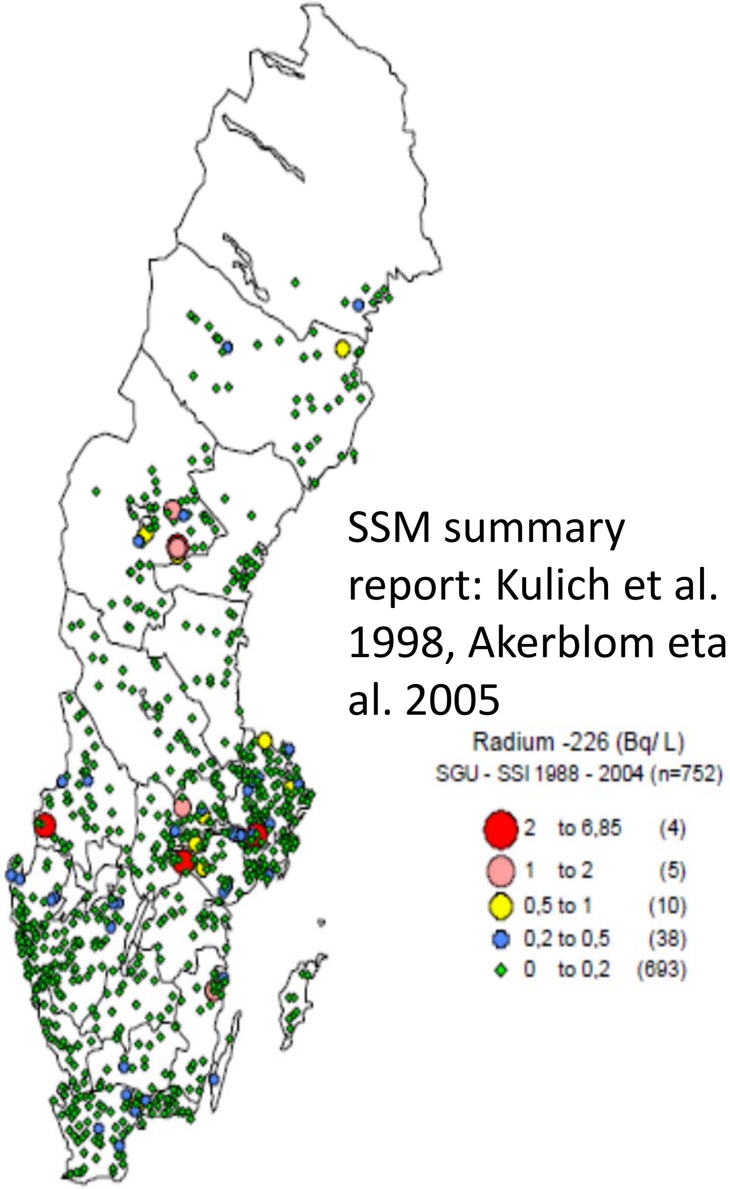
Los Alamos, NM, USA

Source	mSv/year
Radon	2
Cosmic	0.28
Terrestrial	0.28
Internal	0.4
Medical X-rays	0.39
Nuclear Medical	0.14
Consumer Products	0.1
Other	0.03
Total	3.62

Sources of natural radiation

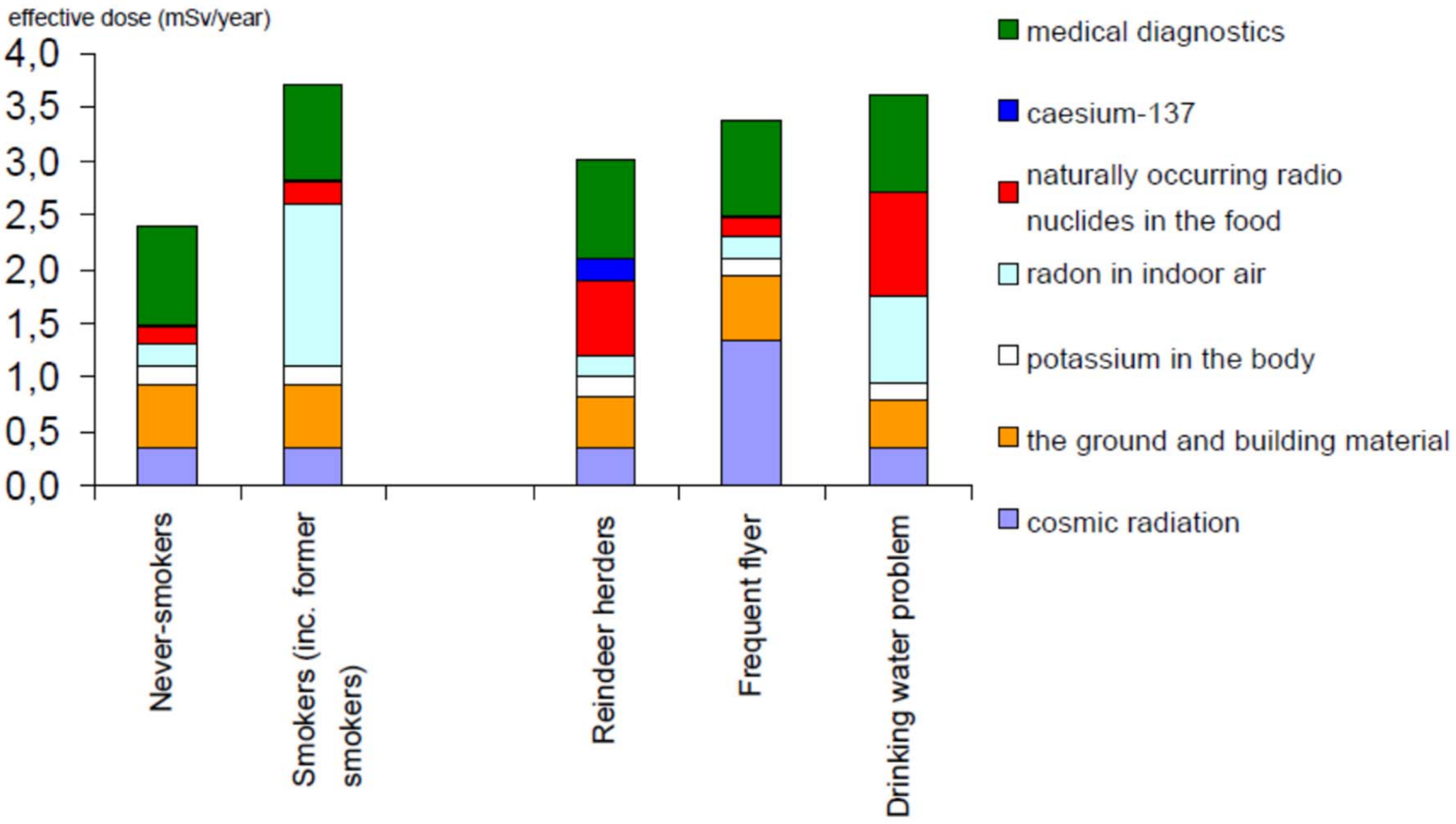


SSM summary report: Concentration of ^{137}Cs (arb. Units) in milk and populations (control group Stockholm)



SSM summary report: Kulich et al. 1998, Akerblom eta al. 2005

Dose as a function of human behavior



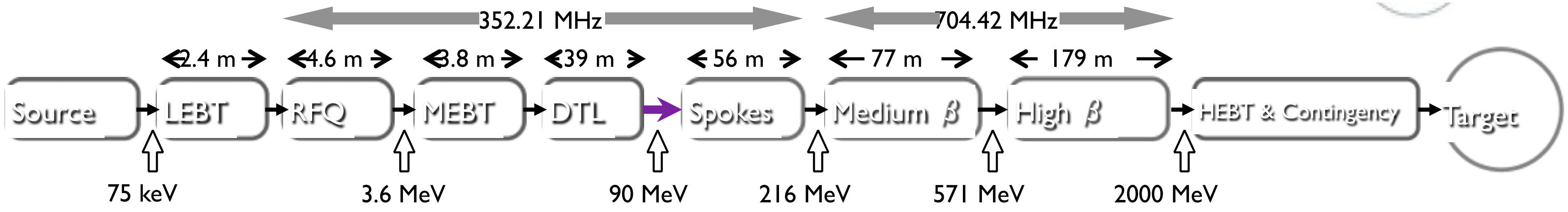
Dose as a function of occupation

Occupation	cause	mSv/year
DOE employees and site worker	radiaolgical work activities	0.44
medical personal	patient diagnosis/treatment	0.7
Grand Central Station workers	building materials	1.2
nuclear power plant workers	radiological work activities	7
Sweden Rad worker B	radiological work activities	6
Sweden Rad worker A	radiological work activities	20
airline flight crew members	cosmic	10
international space station	cosmic	150
flight to Mars	cosmic	500 - 1000

Dose as a function of medical investigation

Procedure	mSv
Dental X-ray per image	0.01
conventional lung investigation	0.08
mammography	0.1
conventional lower back investigation	1.5
computer tomography brain	2.2
computer tomography thorax	6.5
computer tomography abdomen	10

ESS proton accelerator



352.21 MHz
704.42 MHz

2.4 m | 4.6 m | 3.8 m | 39 m | 56 m | 77 m | 179 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

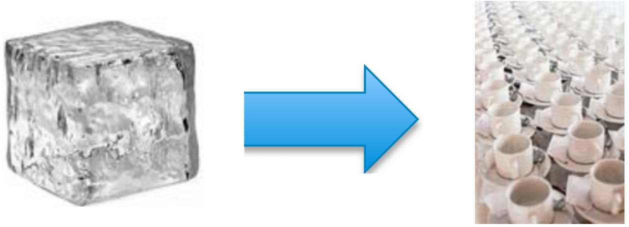
75 keV | 3.6 MeV | 90 MeV | 216 MeV | 571 MeV | 2000 MeV

Accelerating protons to almost the speed of light
in pulses hitting the target 14 times per second.

Energy per pulse equals to

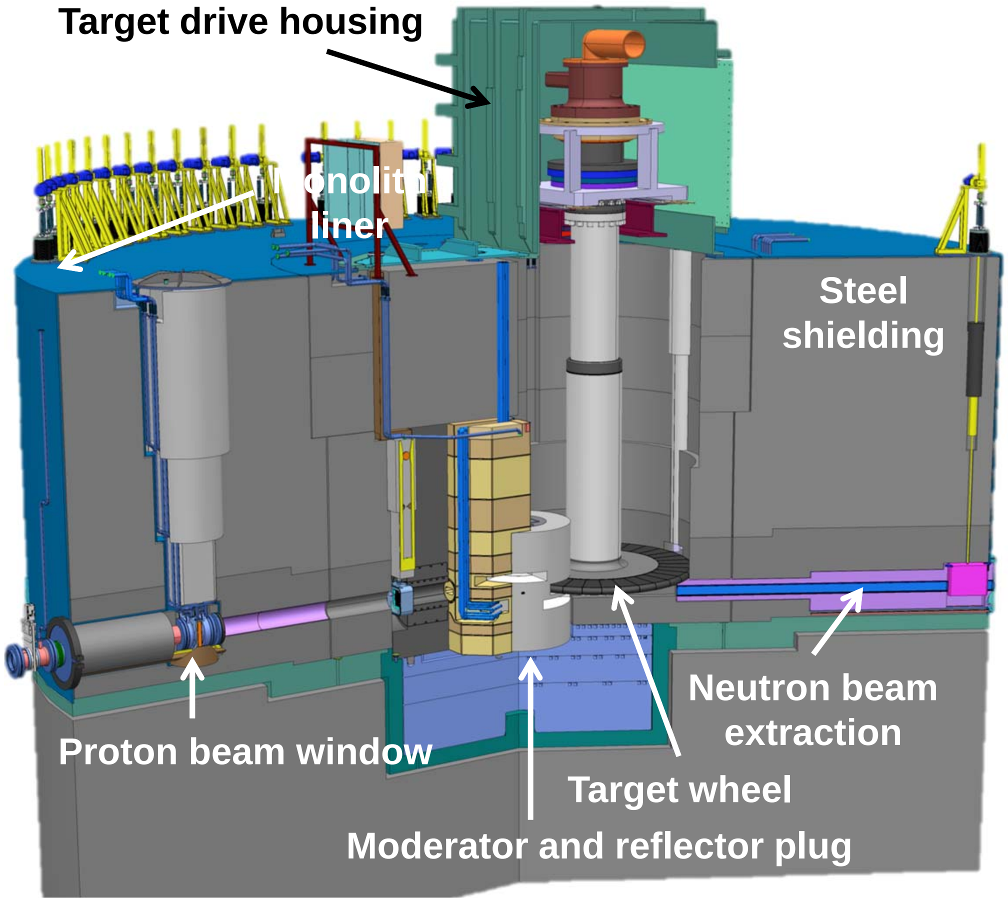
- 16lb (7,2kg) shot travelling with 1100 km/h.
- melting approx. 1 kg (1 liter) of ice …

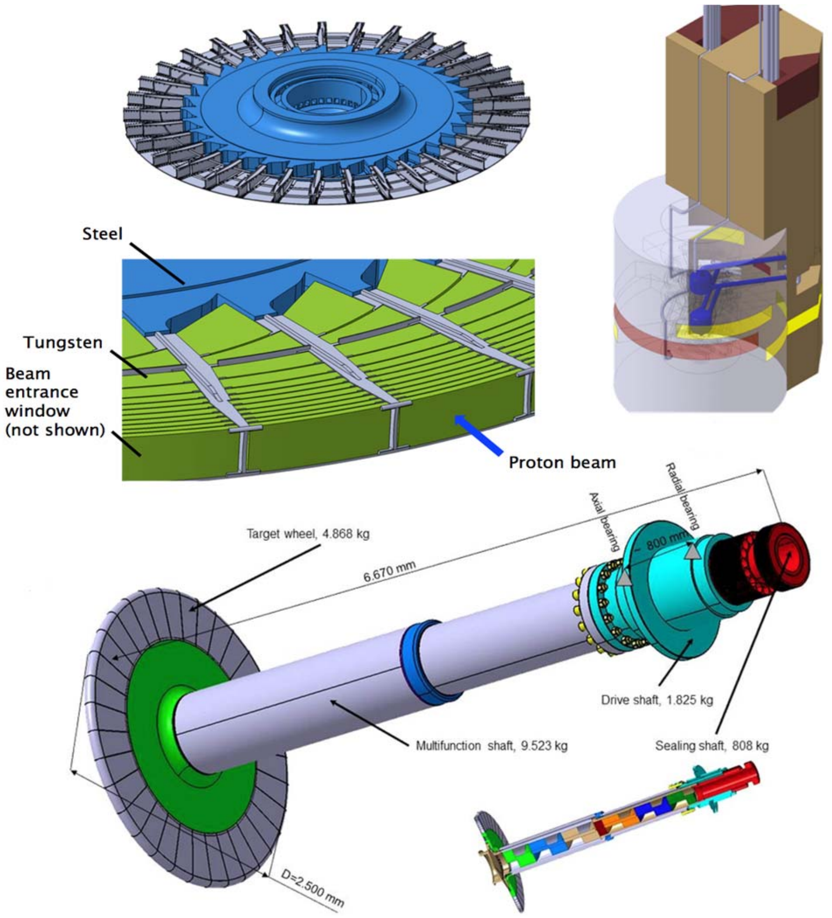
…. *and next pulse boils it.*



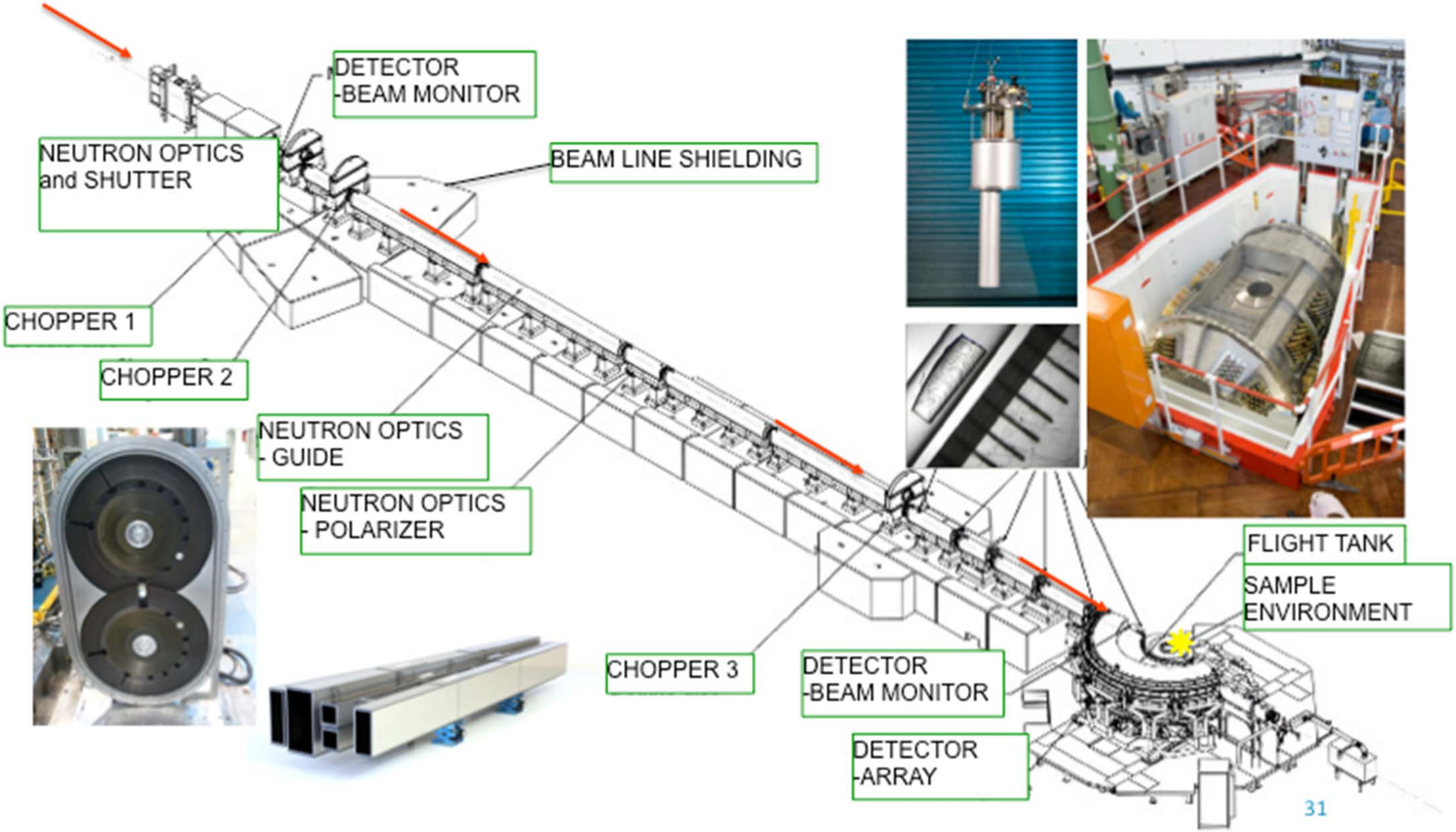
ESS Target Moderator Assembly with Monolith

Converting protons into neutrons and slowing them down.





Generic Instrument



DETECTOR
-BEAM MONITOR

BEAM LINE SHIELDING

NEUTRON OPTICS
and SHUTTER

CHOPPER 1

CHOPPER 2

NEUTRON OPTICS
- GUIDE

NEUTRON OPTICS
- POLARIZER

CHOPPER 3

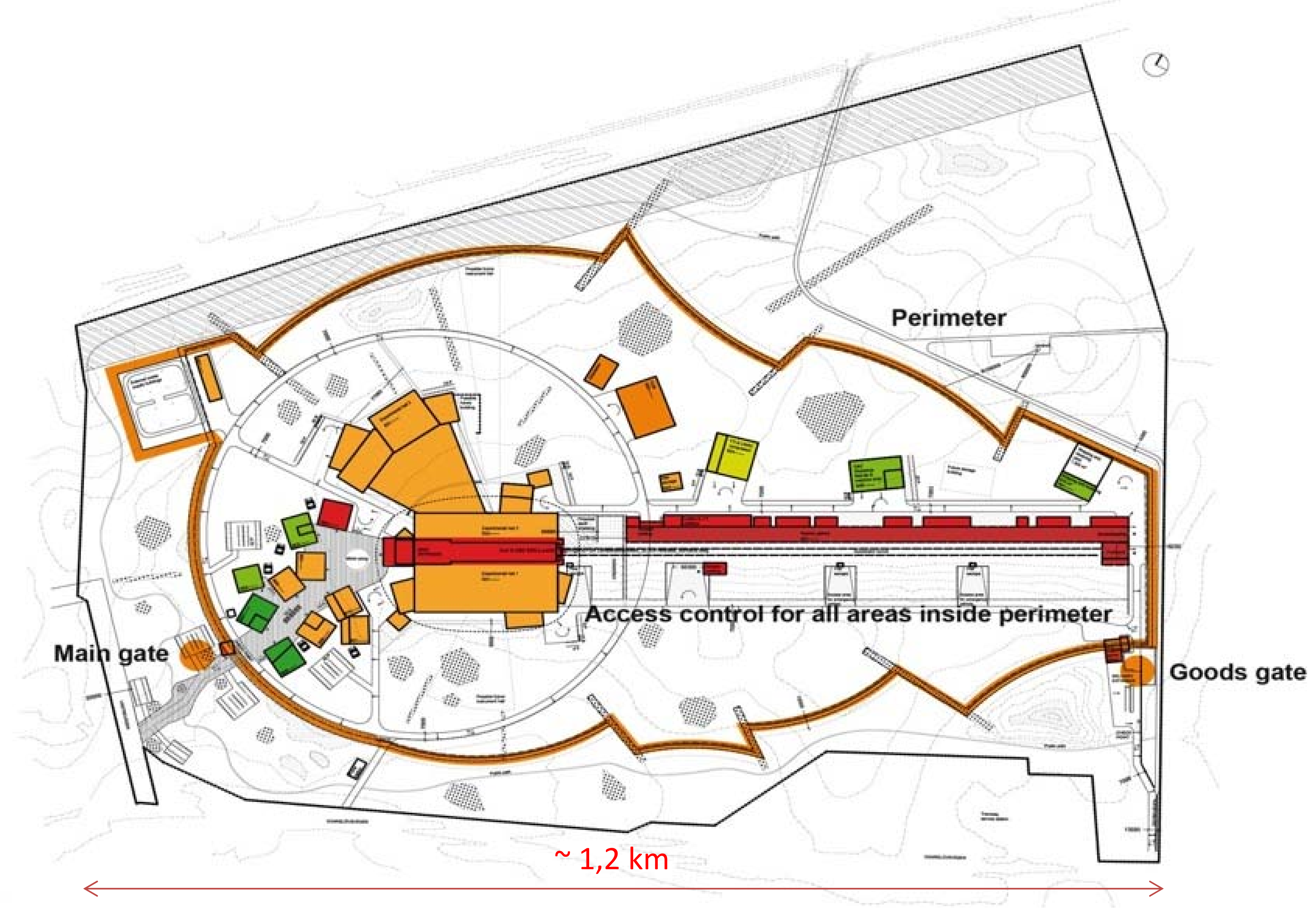
DETECTOR
-BEAM MONITOR

DETECTOR
-ARRAY

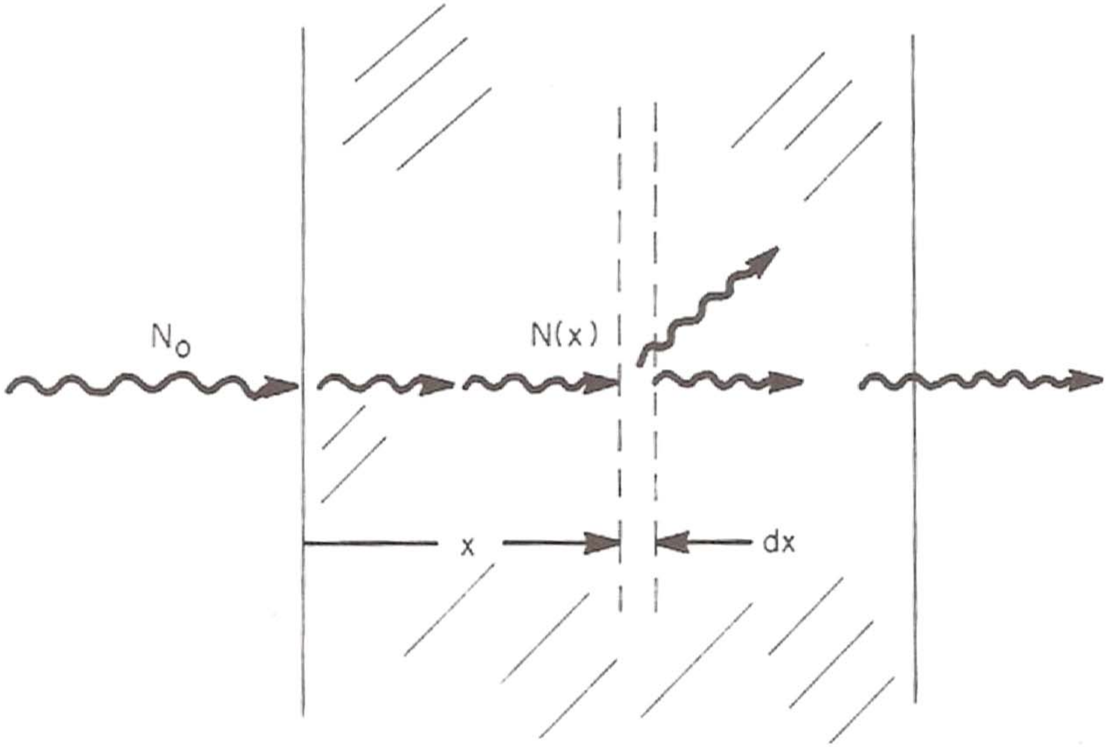
FLIGHT TANK

SAMPLE
ENVIRONMENT

The ESS Site Covers 75 Hectares



Physics: Attenuation

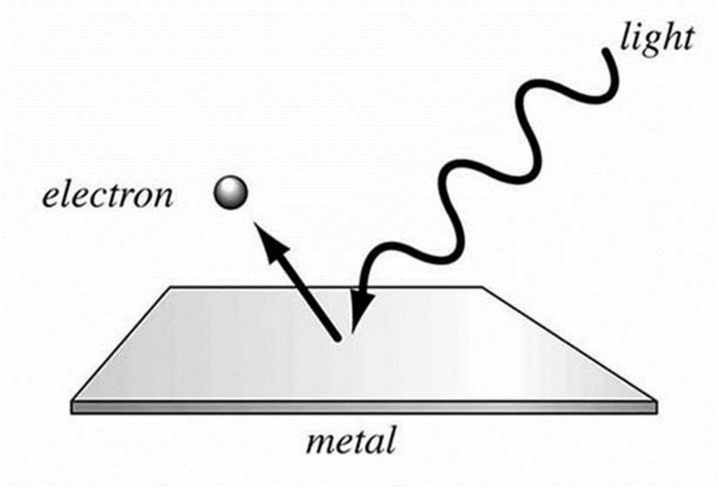


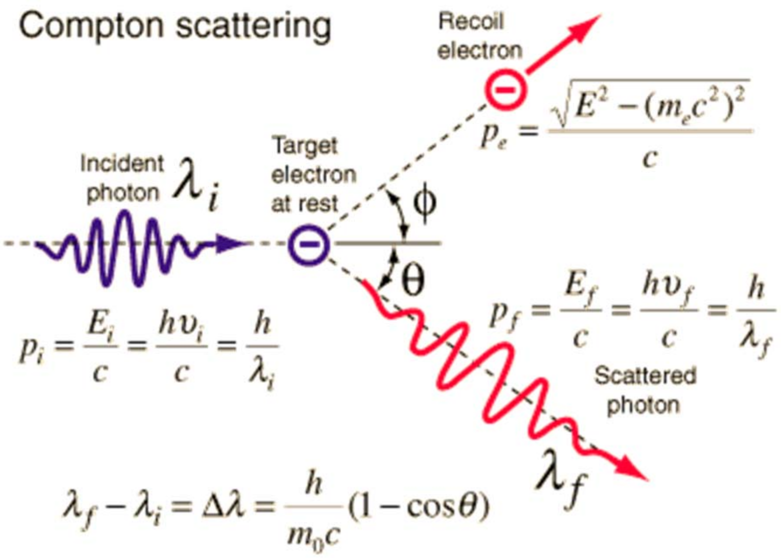
$$dN = -\mu N dx \Rightarrow N(x)=N_0 e^{-\mu x}$$

Physics: Photons

- Photoelectric effect

  During the photoelectric effect the photon will be absorbed by the matter and an electron will be emitted.





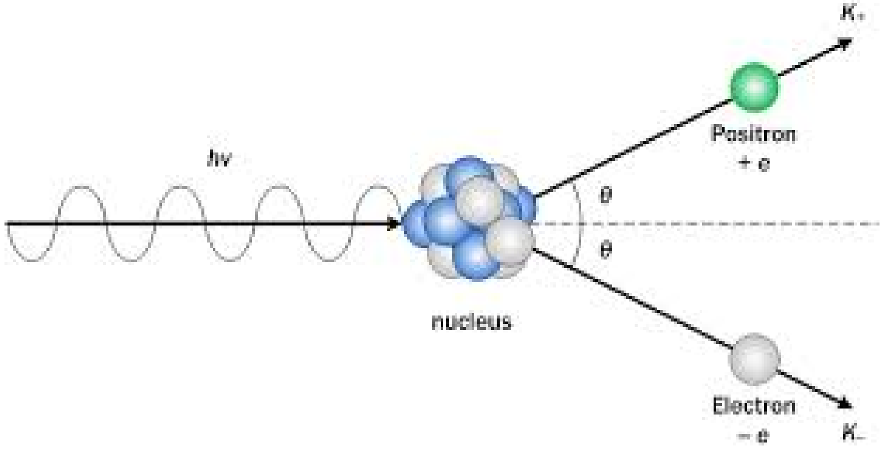
- Compton effect

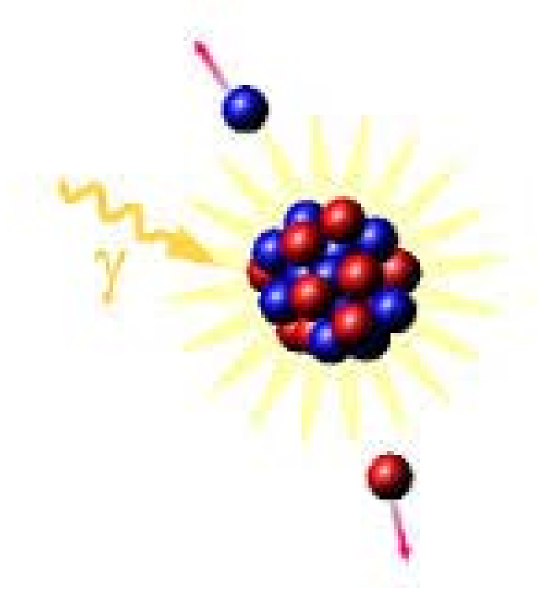
  Compton effect is the inelastic scattering of a photon on a charged particle, unusually electron. It results in a reduction of the photon energy and a momentum change of the photon (Compton scattering.) or the photon gets absorbed and a different photon with a lower energy will be emitted (Compton absorption).

Physics: Photons

- Pair production

  A photon with an energy of at least twice the electron rest mass, can be converted into a electron-positron pair.

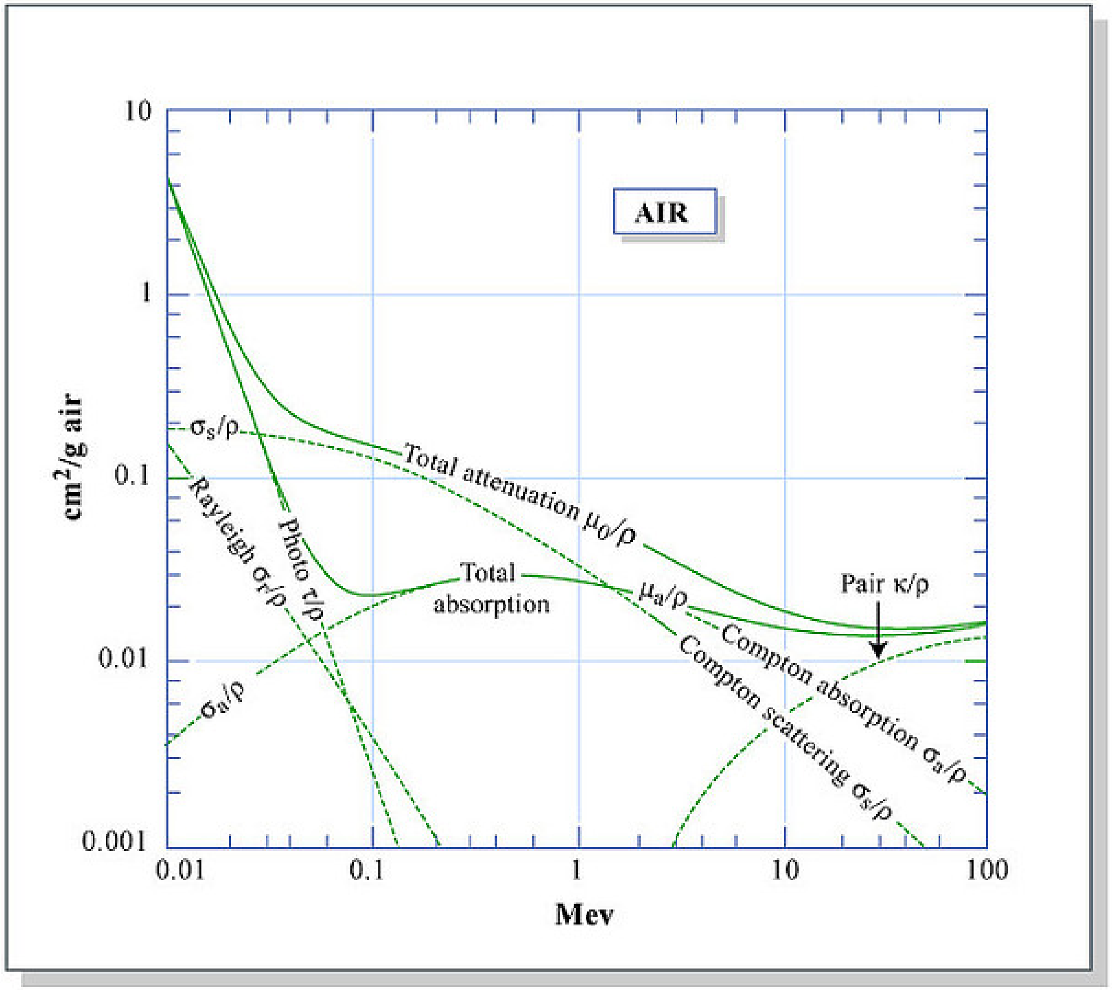




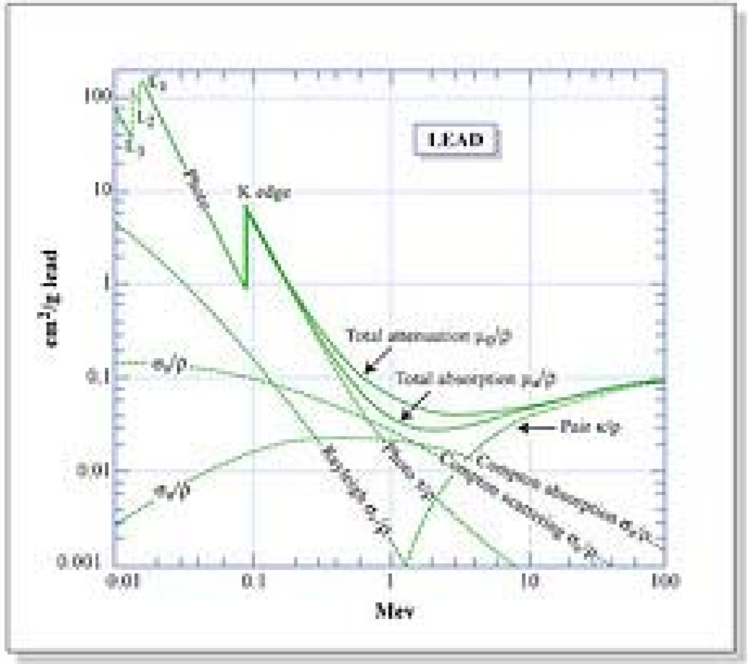
- Photonuclear reactions

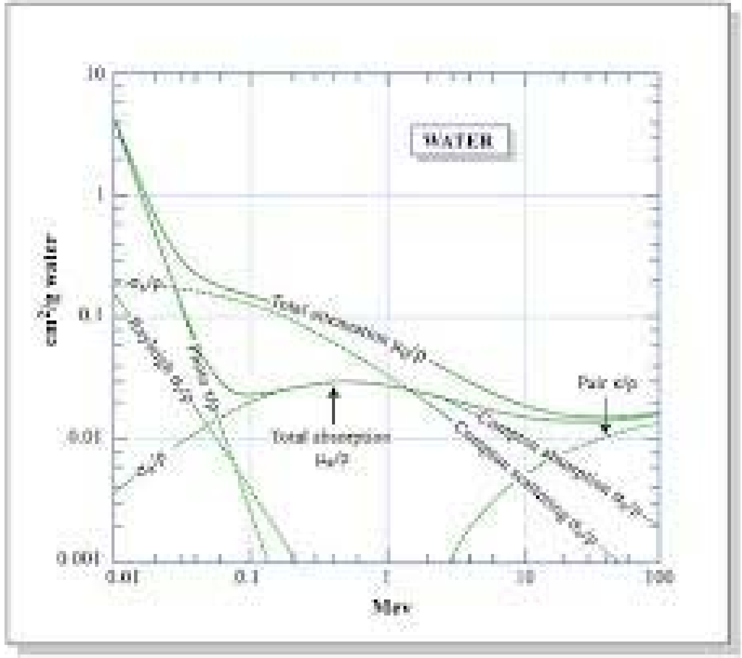
  Photons can be absorbed by an atomic nucleus and a nucleon will be emitted (e.g. (γ,n) reaction).

Photon mass attenuation factor in air



Photon mass attenuation factor in lead and water





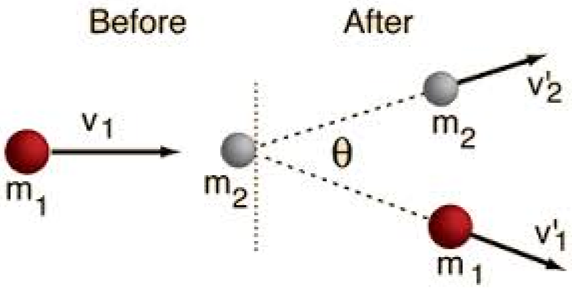
Physics: Neutrons

- Slowing down process:

  The slowing down process of neutrons in matter can be described by the two body problem from classical mechanics.

  Nuclear physicist define this as an elastic process, because the neutron-nucleus system does not loose energy.

  Neutron scattering define this as an inelastic process, because the neutron looses energy.



Physics: Neutrons absorption

- Capture:

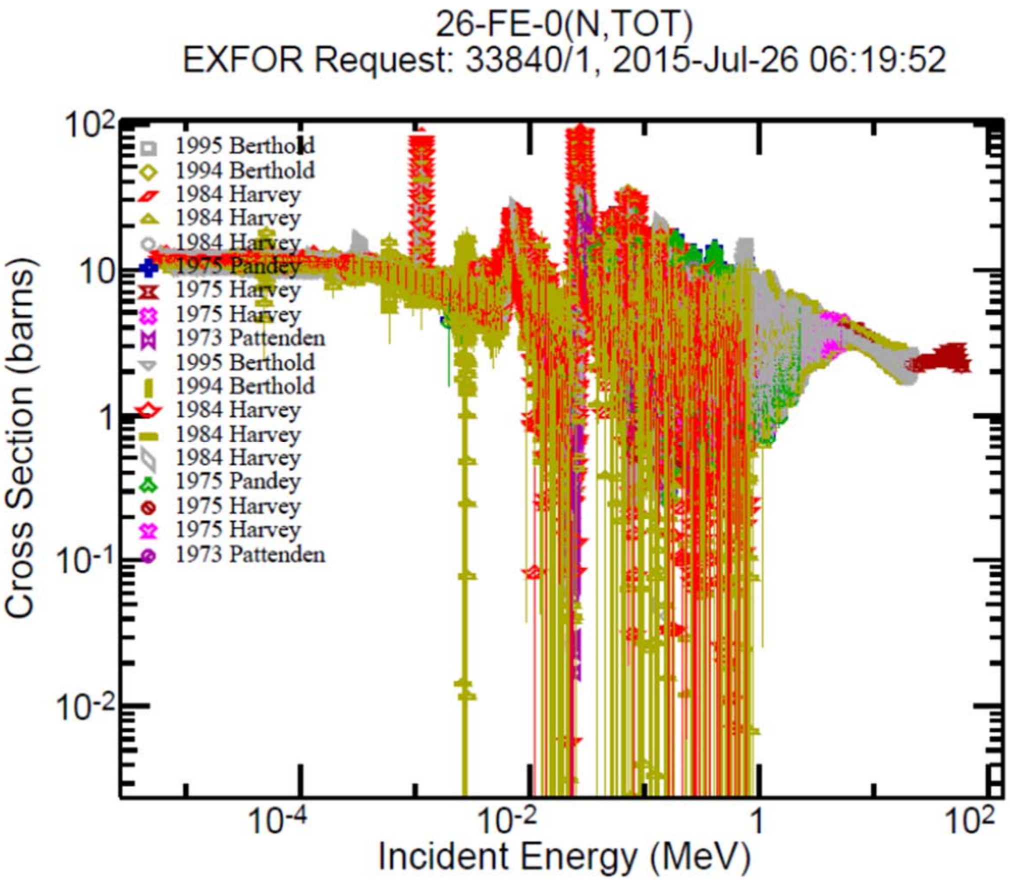
  This process a low energy neutron gets by a nucleus and a different particle will be emitted.

  e.g.:

  - $^{3}He(n,p)^{3}H$
  - $^{6}Li(n,t)^{4}He$
  - $^{10}B(n,\alpha)^{7}Li$
  - $^{14}N(n,p)^{14}C$
  - $^{113}Cd(n,g)^{114}Cd$
  - $^{1}H(n,g)^{2}H$

- Resonances:

  In this process neutron with energies of the excitation level of the nucleus get absorbed and the nucleus will be put into am excited state.



Tools

- Handbook calculations

  e.g: A.H. Sullivan: “A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators.” Nuclear Technology Publishing Ashford, Kent, TN23 1JW, England

- Monte Carlo Particle transport codes
  - MCNP(X)
  - FLUKA
  - PHITS
  - MARS

- Activation Codes
  - CINDER
  - FISPACT
  - Activation Script
  - Gamma Script

Handbook: accelerator losses

$$H = \frac{H_0 e^{-\frac{d}{\lambda}}}{R^2}$$

$$H_0(90^0) = 1.7 * 10^{-14} E_0^{0.8} \quad \mathrm{Sv*m}^2 / p$$

Handbook: target shielding (Moyer Model)

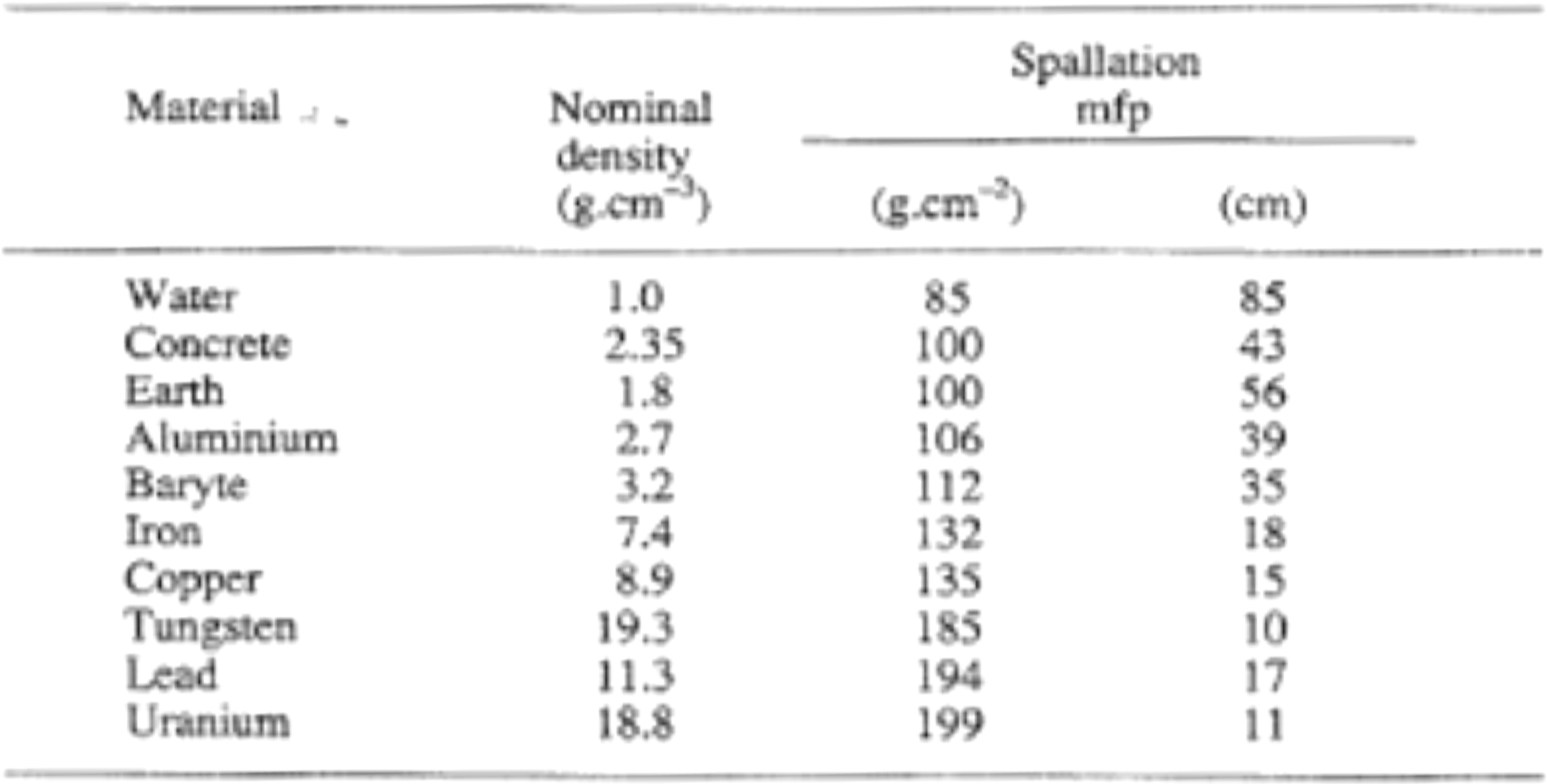
Moyer Model:

$$H=I_*H_0(E_p)/r^2{}_*e^{-\beta\theta}{}_*e^{-d/\lambda}$$

- $H_0(E_p)=4*10^{-7}\ E_p^{0.8}$ Sv h^{-1} m^2 nA^{-1} = source term*
- r = distance from the spill point to the detector
- β = 2.3/radian*
- d = shielding thickness
- λ = dose attenuation length in the shielding material
- θ = angle between the proton beam and the direction from the spill to the detector
- I = proton current

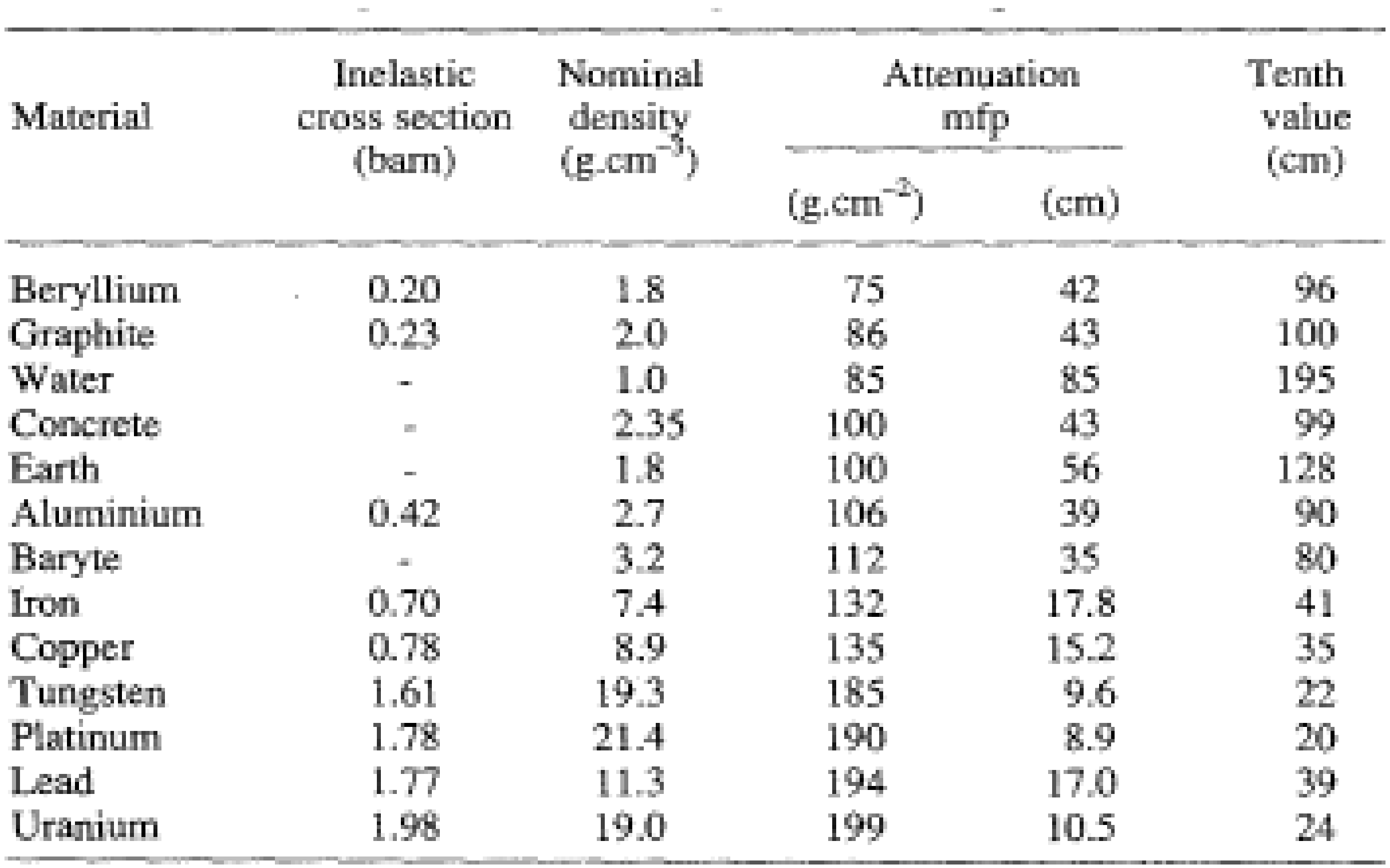
*Thomas and Thomas, Health Physics **46**, 954 (1984)

Handbook: Neutron dose attenuation lengths



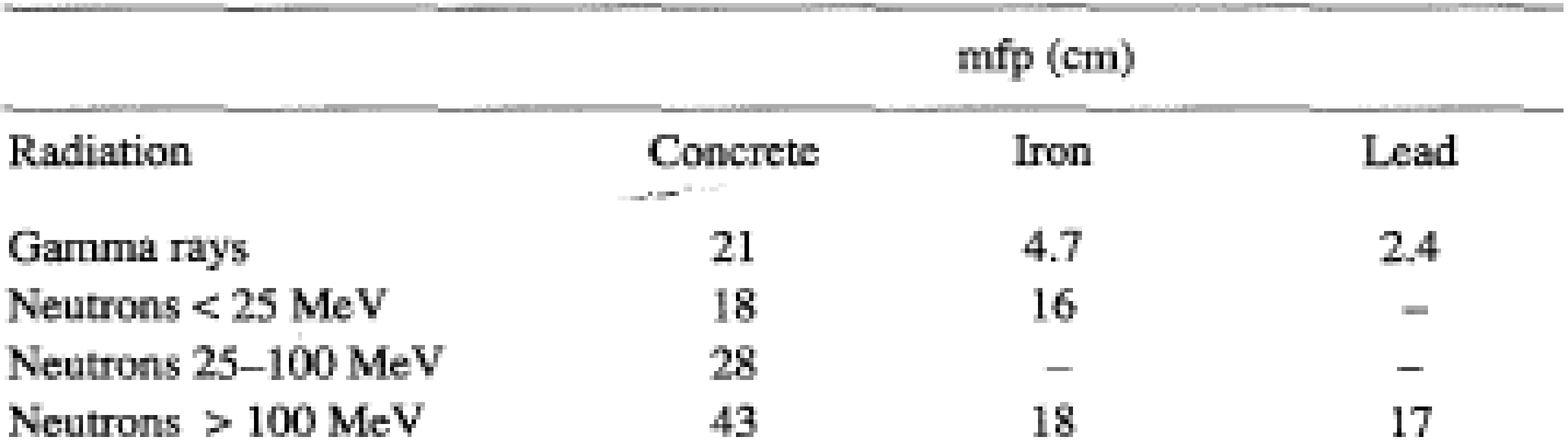
Material	Nominal density (g.cm^{-3})	Spallation mfp	
		(g.cm^{-2})	(cm)
Water	1.0	85	85
Concrete	2.35	100	43
Earth	1.8	100	56
Aluminium	2.7	106	39
Baryte	3.2	112	35
Iron	7.4	132	18
Copper	8.9	135	15
Tungsten	19.3	185	10
Lead	11.3	194	17
Uranium	18.8	199	11

Handbook: Neutron dose attenuation lengths and tenth layers



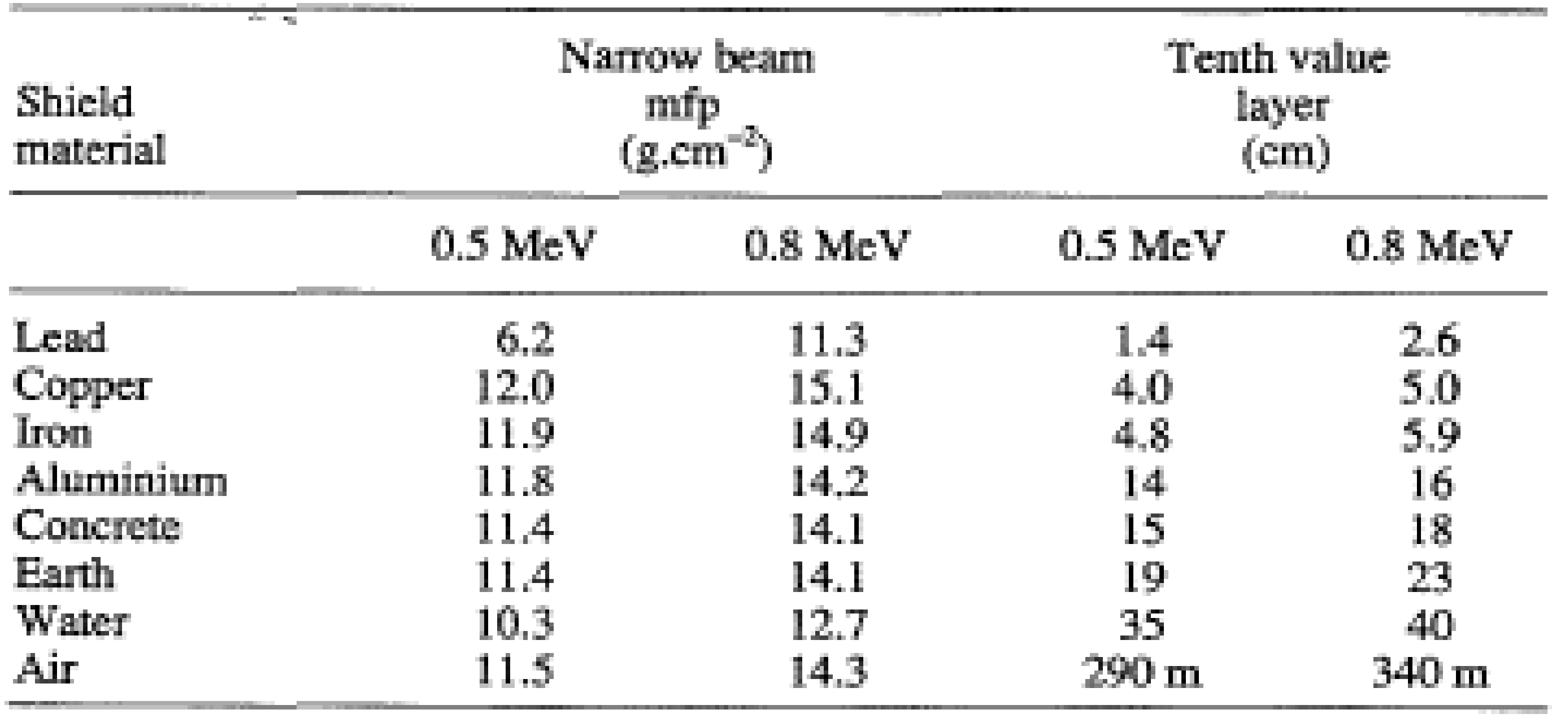
Material	Inelastic cross section (barn)	Nominal density ($g.cm^{-3}$)	Attenuation mfp		Tenth value (cm)
			($g.cm^{-2}$)	(cm)	
Beryllium	0.20	1.8	75	42	96
Graphite	0.23	2.0	86	43	100
Water	-	1.0	85	85	195
Concrete	-	2.35	100	43	99
Earth	-	1.8	100	56	128
Aluminium	0.42	2.7	106	39	90
Baryte	-	3.2	112	35	80
Iron	0.70	7.4	132	17.8	41
Copper	0.78	8.9	135	15.2	35
Tungsten	1.61	19.3	185	9.6	22
Platinum	1.78	21.4	190	8.9	20
Lead	1.77	11.3	194	17.0	39
Uranium	1.98	19.0	199	10.5	24

Handbook: Gamma and Neutron dose attenuation length



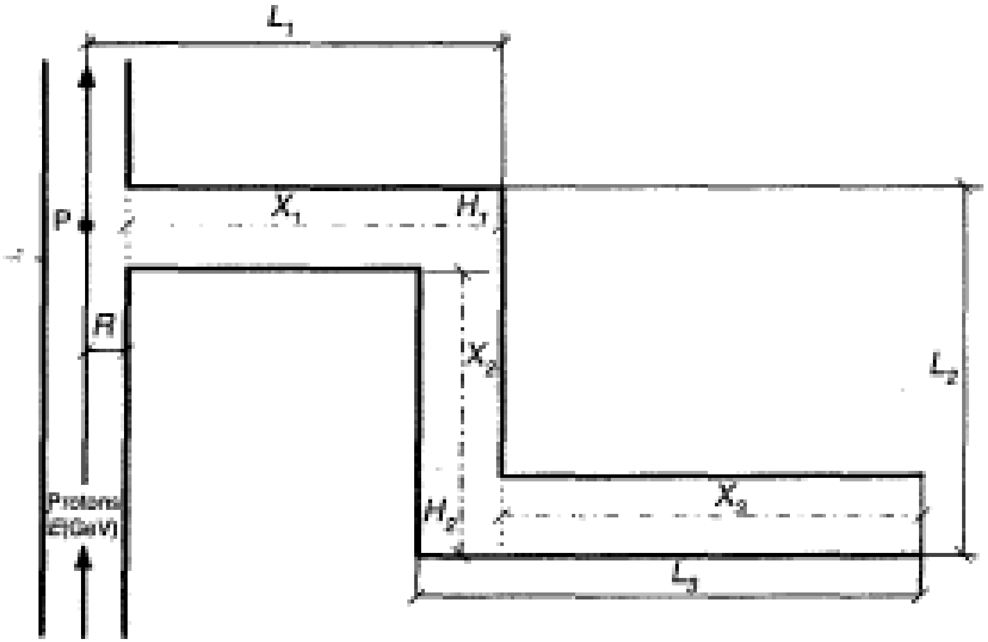
	mfp (cm)		
Radiation	Concrete	Iron	Lead
Gamma rays	21	4.7	2.4
Neutrons < 25 MeV	18	16	–
Neutrons 25–100 MeV	28	–	–
Neutrons > 100 MeV	43	18	17

Handbook: Gamma dose attenuation lengths



Shield material	Narrow beam mfp (g.cm^{-2})		Tenth value layer (cm)	
	0.5 MeV	0.8 MeV	0.5 MeV	0.8 MeV
Lead	6.2	11.3	1.4	2.6
Copper	12.0	15.1	4.0	5.0
Iron	11.9	14.9	4.8	5.9
Aluminium	11.8	14.2	14	16
Concrete	11.4	14.1	15	18
Earth	11.4	14.1	19	23
Water	10.3	12.7	35	40
Air	11.5	14.3	290 m	340 m

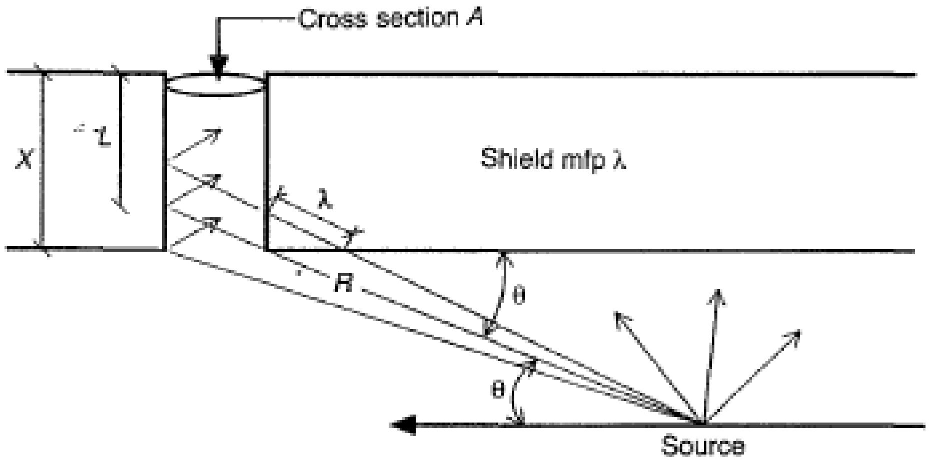
Handbook: Chicane 1(3)



$$H_1 = H_0 / L_1^2$$

$$H_n = H_{(n-1)} \cdot \frac{K.A_{(n-1)}.\sqrt{A_n}}{L_n^3}$$

Handbook: Chicane 2(3)



$$A_{\mathrm{eff}} = A \tan(\theta) + \lambda\sqrt{A} \sin(\theta)$$

$$H = H_m \cdot \frac{K.A_{\mathrm{eff}}.\sqrt{A_n}}{L^3}$$

(a) the amount of radiation entering the hole,~ $A_{\mathrm{eff}} \times H_m$;
(b) ratio of the effective hole cross section to wall area ~ $\sqrt{A}/L$;
and
(c) inverse square of distance the scattered radiation travels into the hole = $(1/L)^2$.

Handbook: Chicane 3(3)

$$H_n = H_1 \times K^{n-1} \frac{A_1}{A_n} \cdot \left(\frac{\sqrt{A_2}}{L_2} \cdot \frac{\sqrt{A_3}}{L_3} \cdots \frac{\sqrt{A_n}}{L_n} \right)^3$$

$$\frac{H_n}{H_0} = \frac{T(n,A)}{L_1^{\,2}(L_2 L_3 \ldots L_n)^3}$$

$$T(n,A) = (K \times A^{3/2})^{n-1}$$

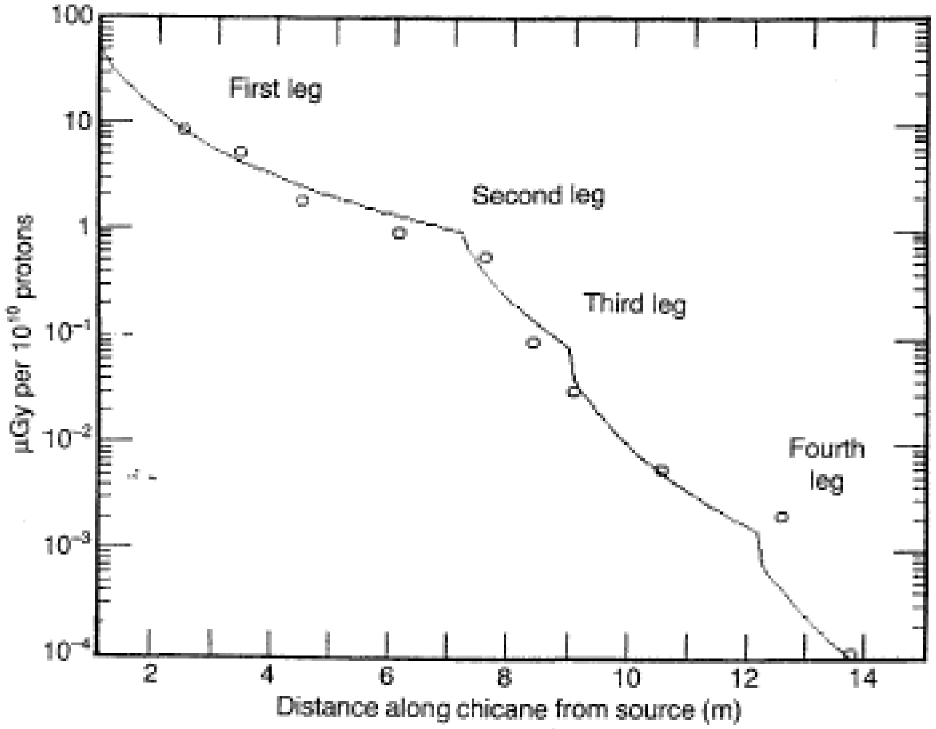
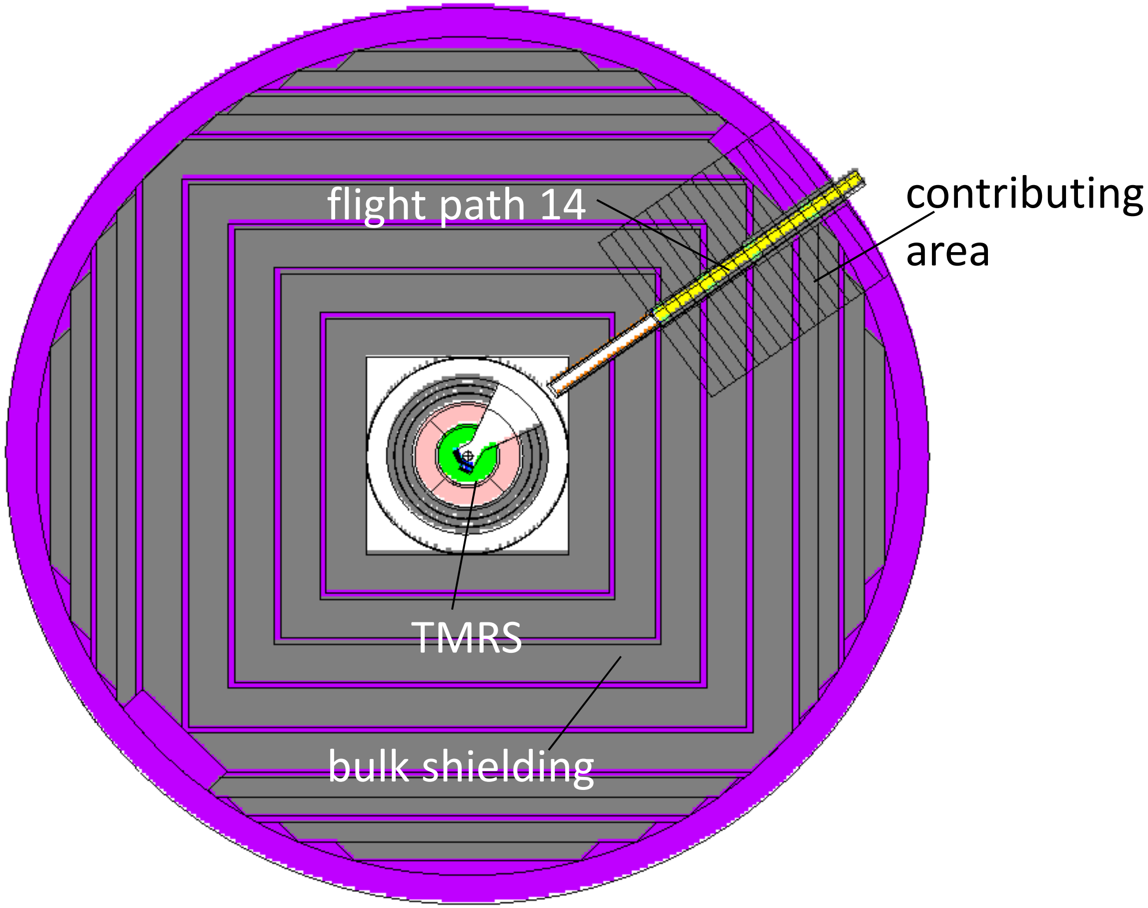


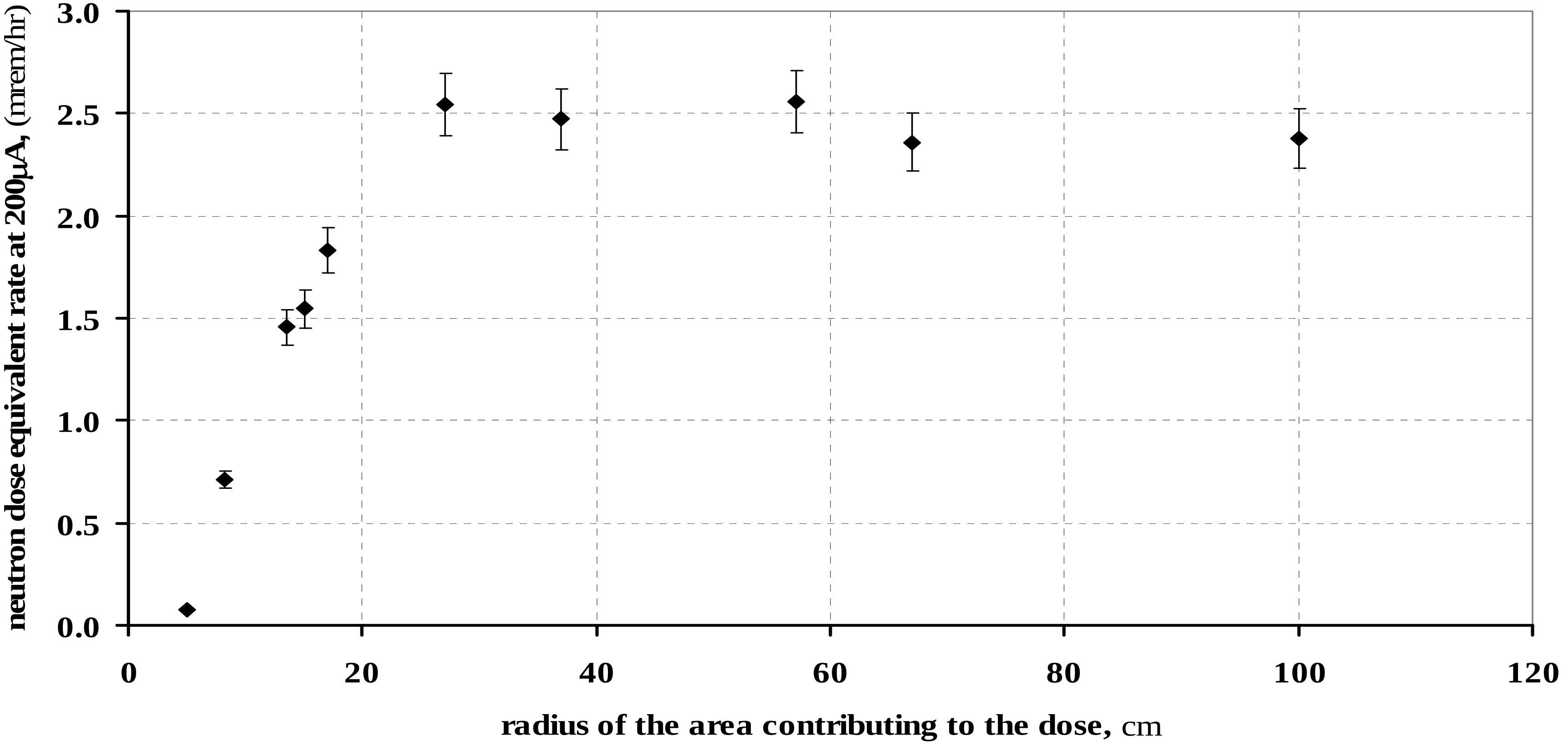
Figure 2.30. The calculated radiation level along the four legs of a chicane compared to measured data[15] using a 400 GeV proton beam on a 1 interaction length target opposite the entrance to the chicane. Dose equivalent given in Figure 2.21 was converted to absorbed dose assuming a constant quality factor of 3.

Monte Carlo Deep Penetration: Balancing act between need for speed and biasing the result 1(3).

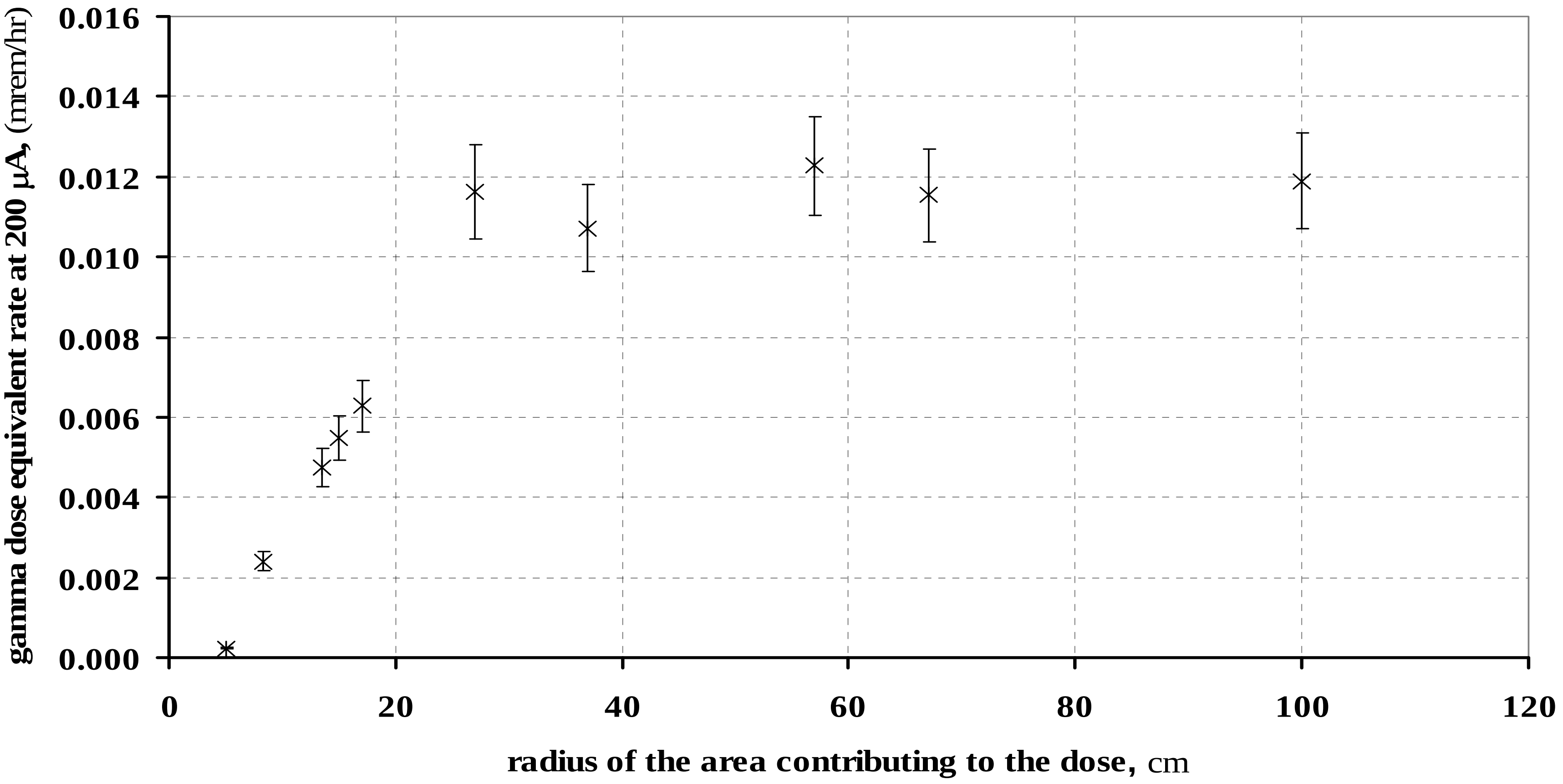
Monte Carlo Model for Neutron Beamline Mercury Shutter Calculations



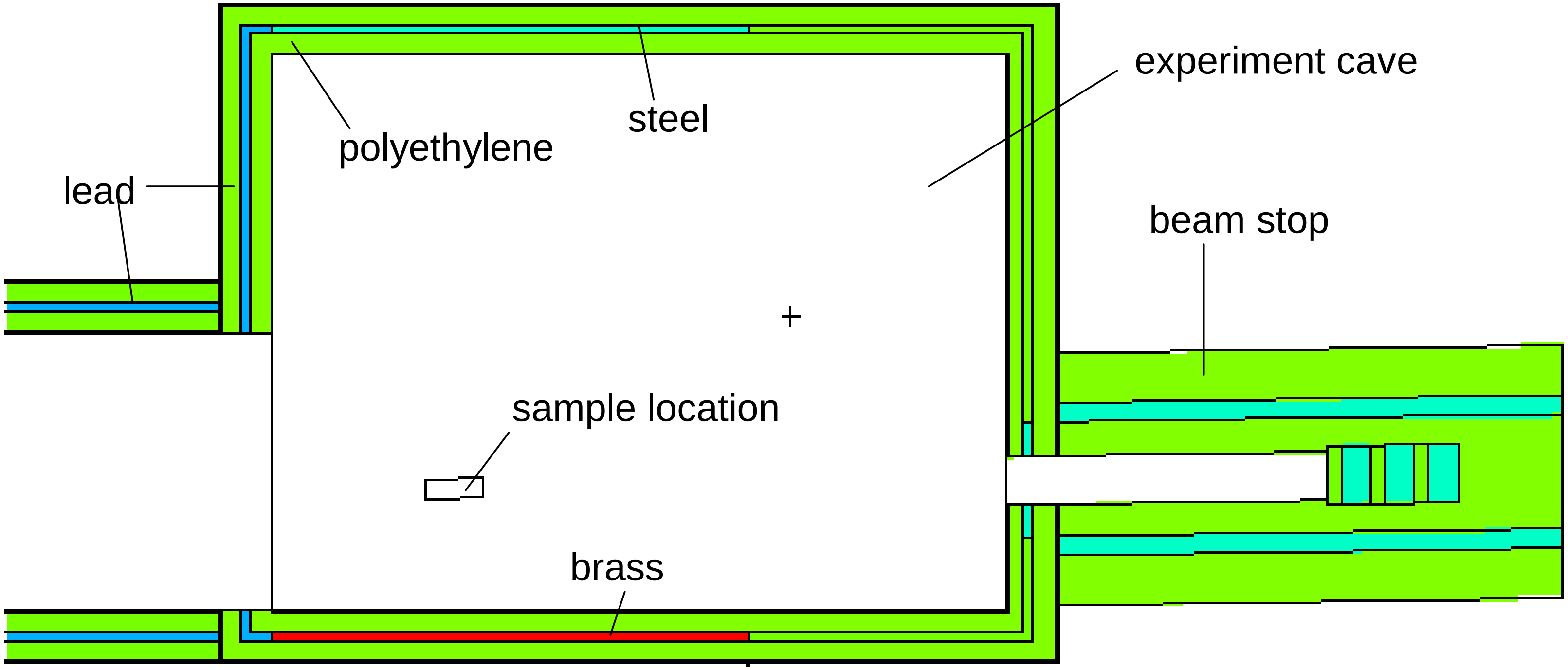
Monte Carlo Deep Penetration: Balancing act between need for speed and biasing the result 2(3).



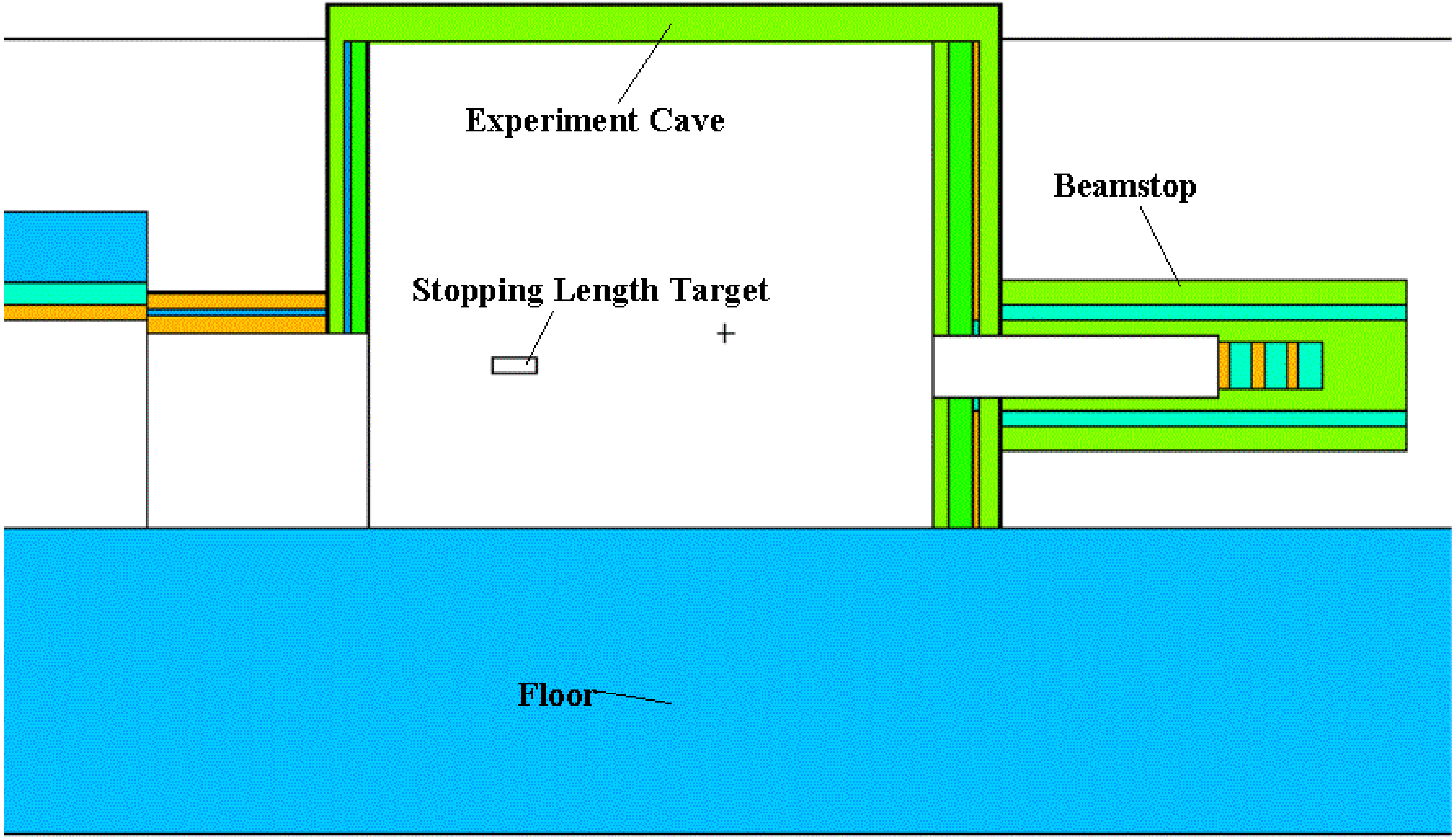
Monte Carlo Deep Penetration: Balancing act between need for speed and biasing the result 3(3).



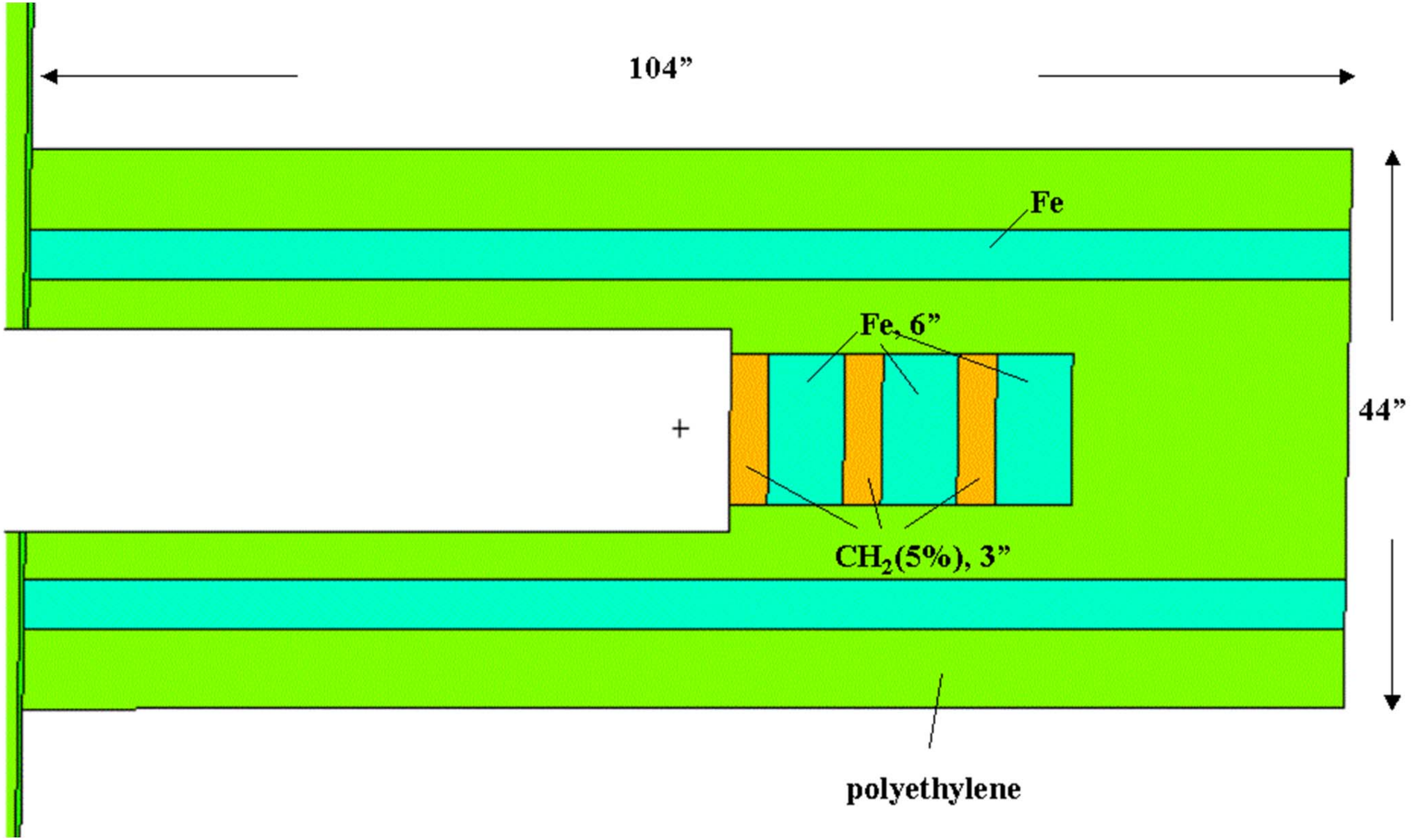
Background: Asterix 1(5)



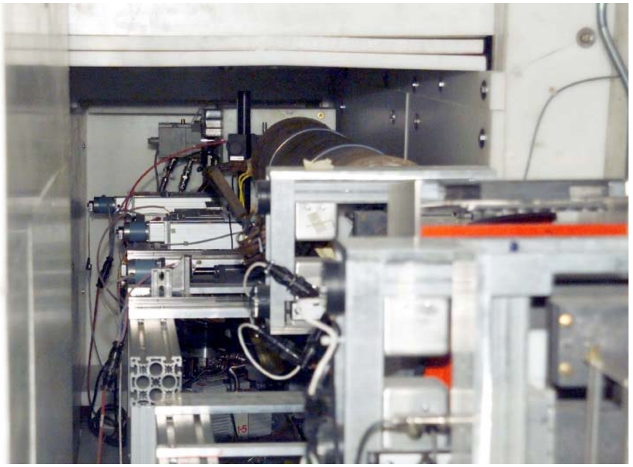
Background: Asterix 2(5)

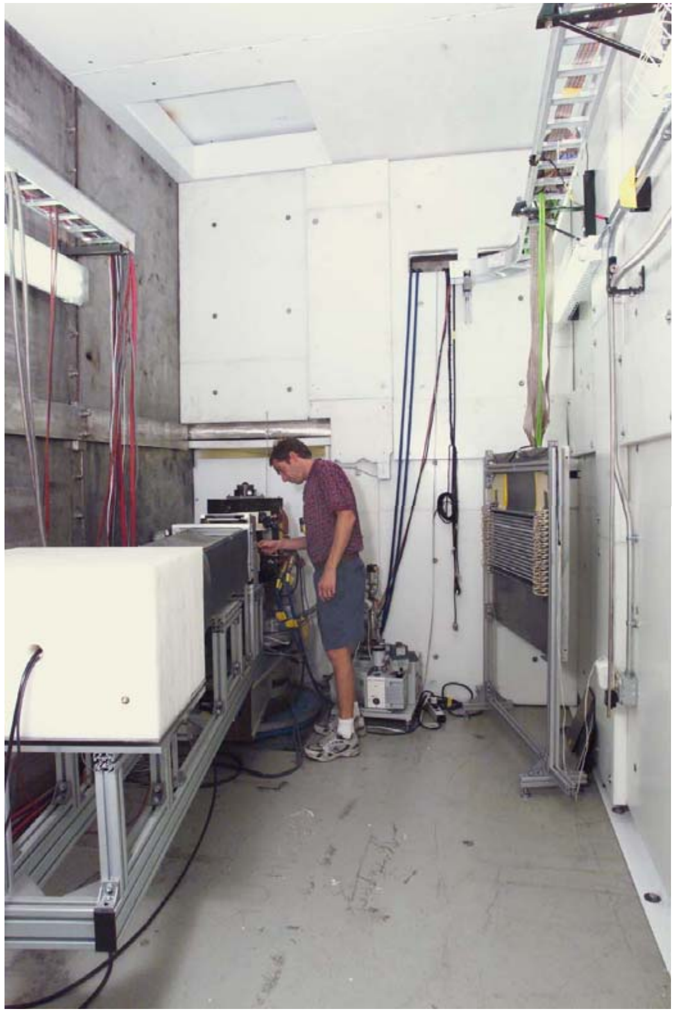


Background: Asterix 3(5)



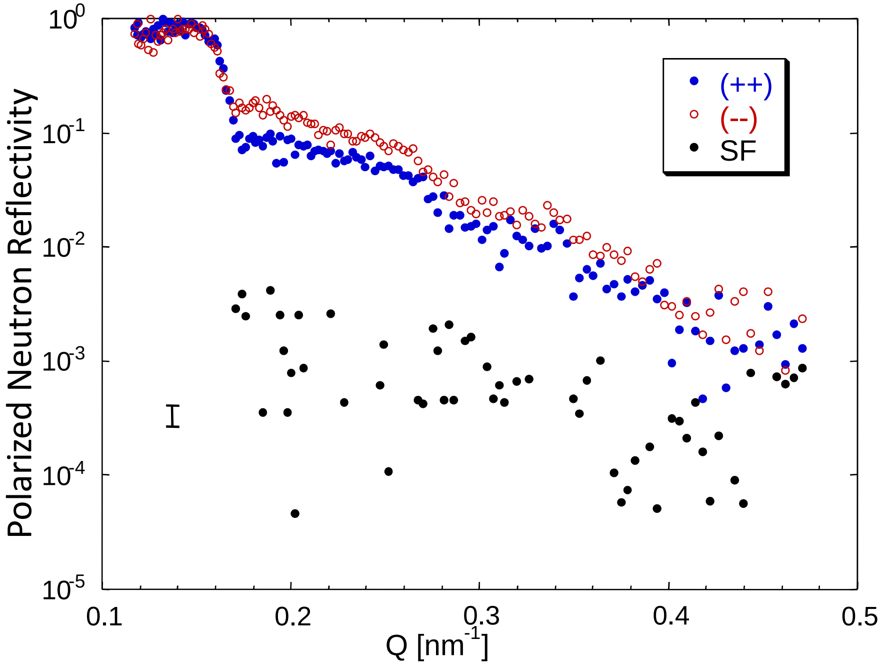
Background: Asterix 4(5)



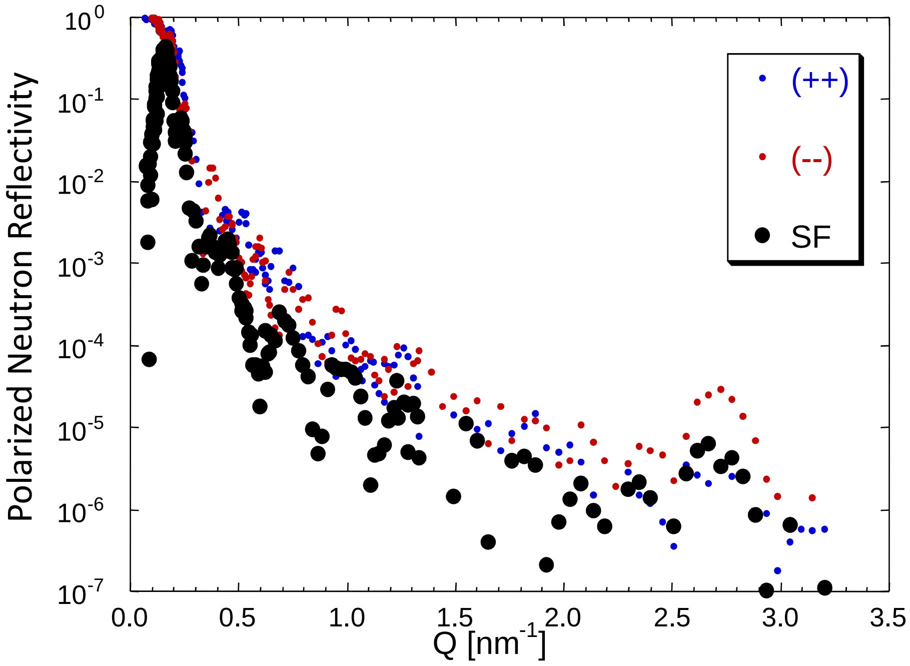


Background: Asterix 5(5)

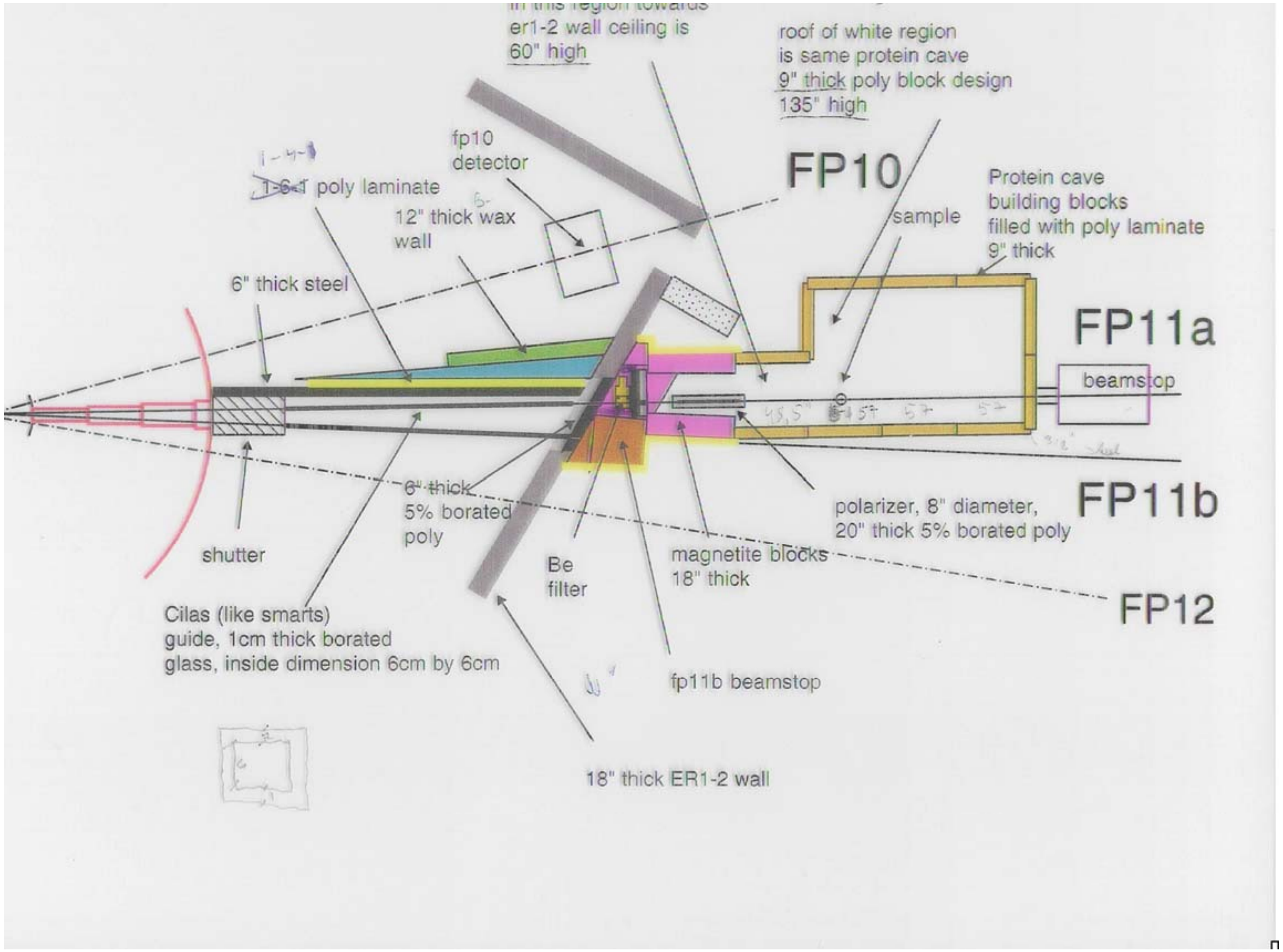
P-SPEAR ('98)
24+h measurement



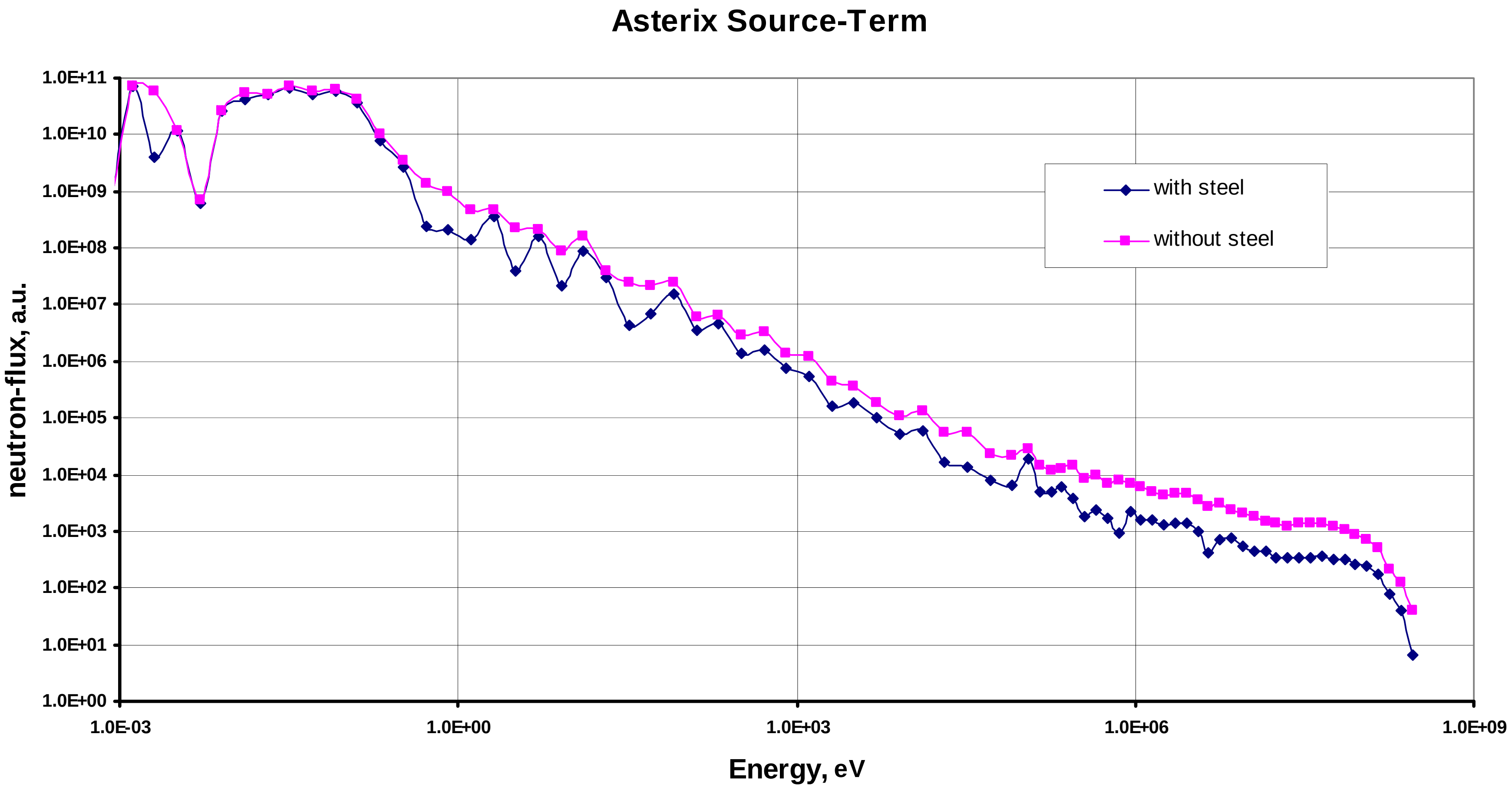
Asterix ('02)
19h measurement



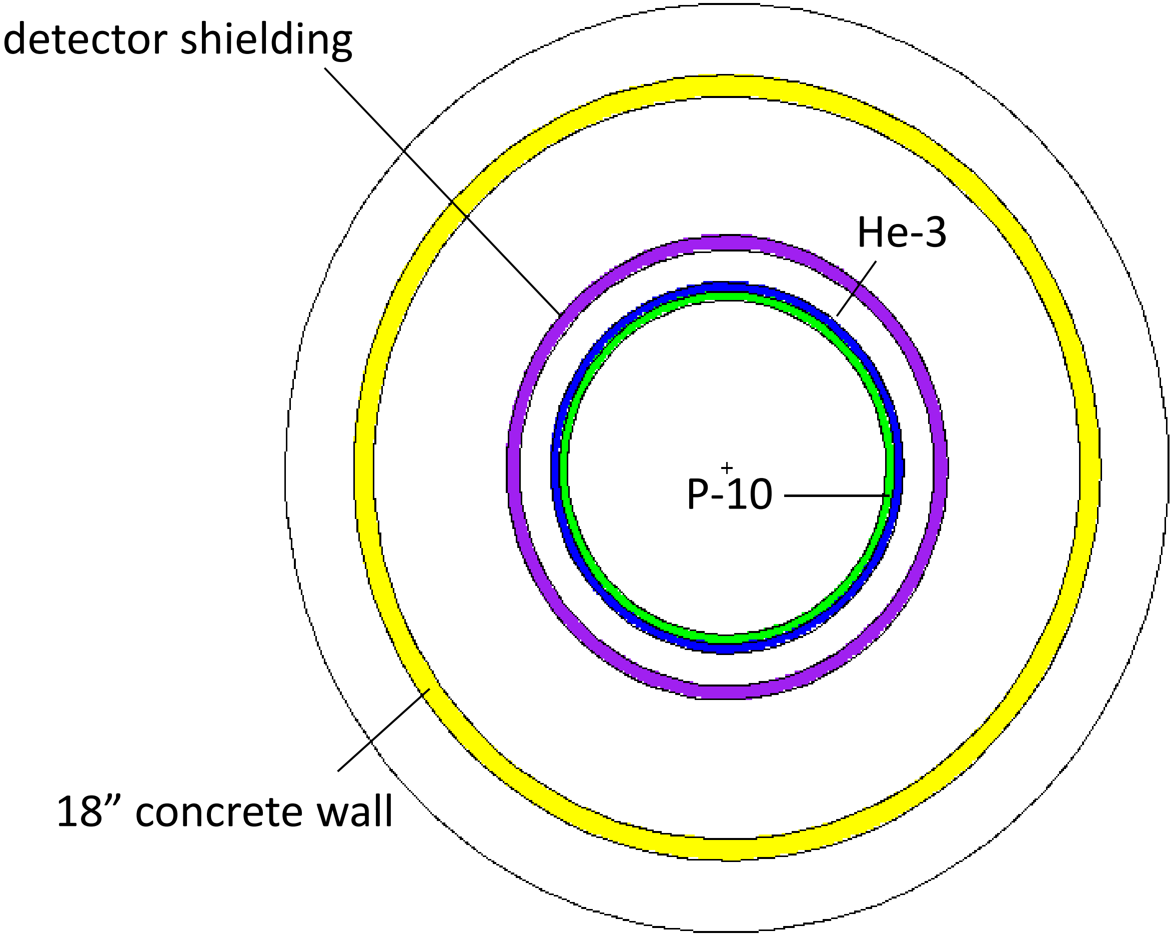
Instrument crosstalk: LQD-Asterix 1(4) Layout



Instrument crosstalk: LQD-Asterix 2(4) Source Term



Instrument crosstalk: LQD-Asterix 3(4) Detector



Instrument crosstalk: LQD-Asterix 4(4) Metric

	CH_2 (12”) (no Fe)	**CH_2 (12”)** (with Fe)	**B_4C (6”)** (with Fe)	**B_4C (6”)** (no Fe)	**B_4C (1”)** (with Fe)	**B_4C (1”)** (no Fe)	**CH_2/B_4C (3”/3”)** (with Fe)	**CH_2/B_4C (3”/3”)** (no Fe)
(n,p) in He-3	100%	35%	6%	19%	7%	35%	3%	35%
γ in He-3	100%	36%	38%	121%	26%	67%	39%	117%
γ in P-10	100%	36%	38%	122%	27%	67%	39%	116%

What I hope you have heard?!

- We live in a radiation environment.
- There are very powerful Monte Carlo Particle Transport tools, but do not use them as a back box.
- Laminated shields
- Instruments background can vary by orders of magnitude depending on the instruments cave design.
- An instrument background metric is of great help
- One does not need a modern super-computer to do instrument background calculations.