Radiation and Safety

P. Berkvens

1. radiation physics
   - interaction of electrons with matter
   - interaction of photons with matter
   - interaction of neutrons with matter
   - interaction of protons with matter

2. radiation protection
   - definitions
   - rules

3. radiation fields around accelerators
   - electron accelerators
   - proton accelerators
   - synchrotron radiation facilities

4. induced activity

5. radiation monitors

Ionising radiation

→ directly ionising: charged particles (electrons, protons, ...)
→ indirectly ionising: photons, neutrons

of the order of 10 eV required to ionise an atom

electromagnetic radiation:

$$E = \frac{hc}{\lambda} \Rightarrow \lambda \approx 100\,nm$$

(hard ultraviolet)

	ionisation potential (eV)
carbon	11.260
oxygen	13.618
potassium	4.341
iron	7.870
lead	7.416

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Interaction of electrons with matter

The physical processes

1. Ionisation losses
   inelastic collisions with orbital electrons

2. Bremsstrahlung losses
   inelastic collisions with atomic nuclei

3. Rutherford scattering
   elastic collisions with atomic nuclei

Positrons

at nearly rest energy: annihilation
emission of two 511 keV photons

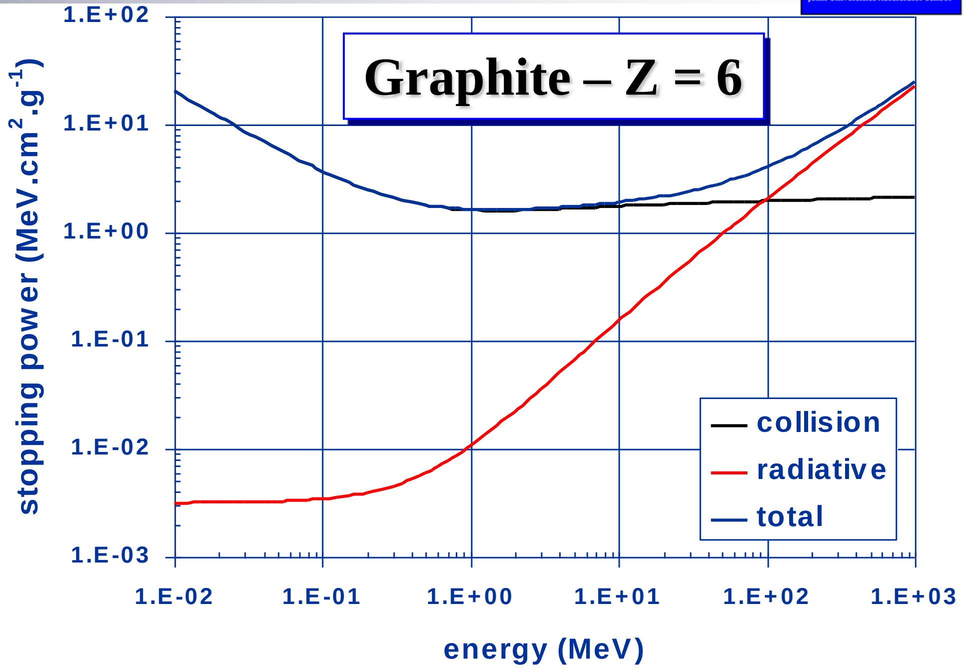
Electrons - stopping power

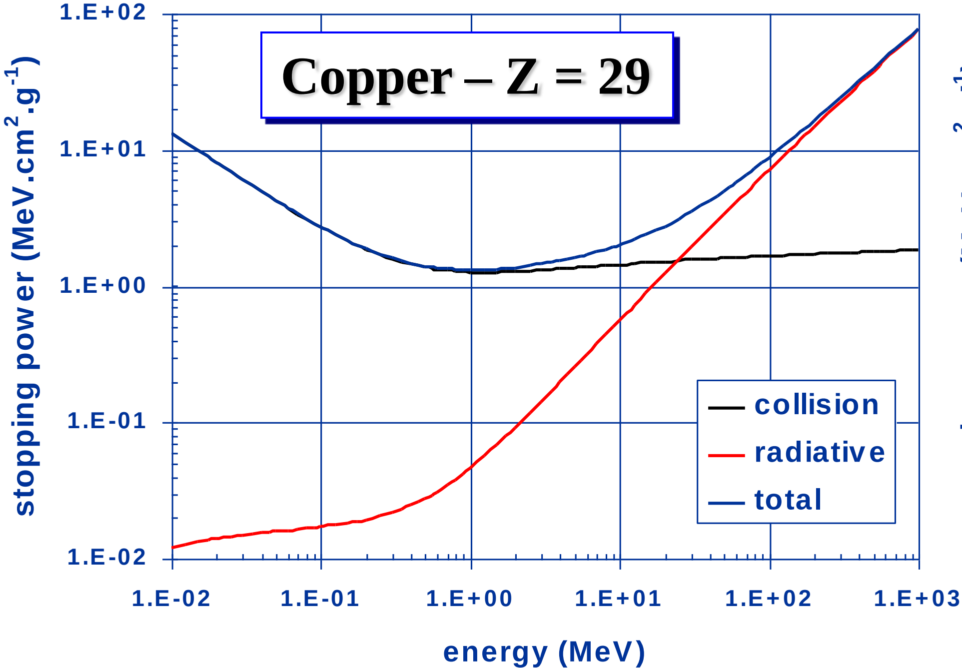
$$\frac{S}{\rho} = \frac{1}{\rho}\frac{dE}{dl}$$

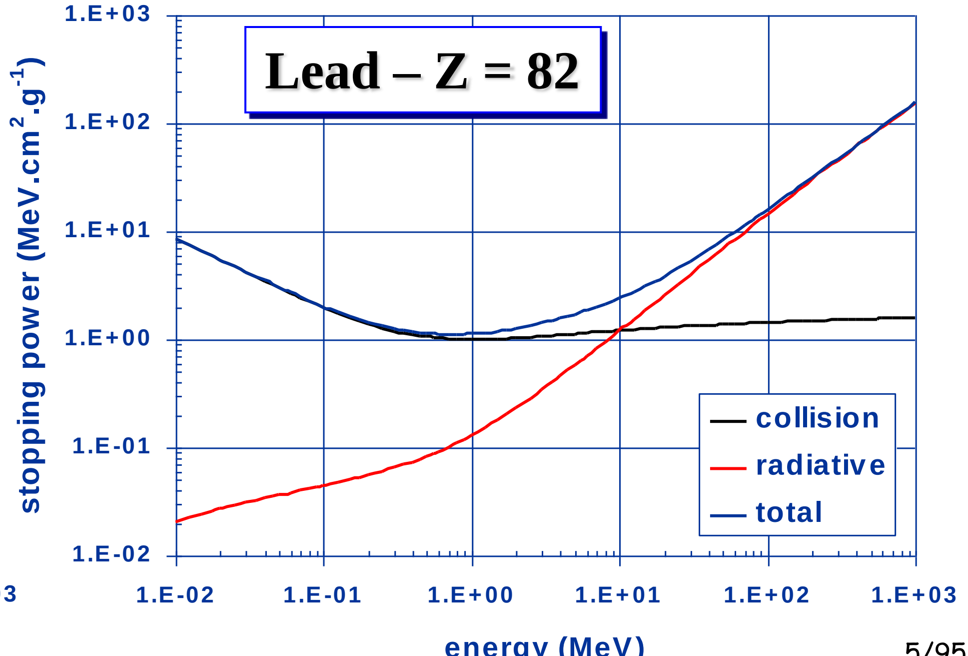
$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{coll} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{rad}$$

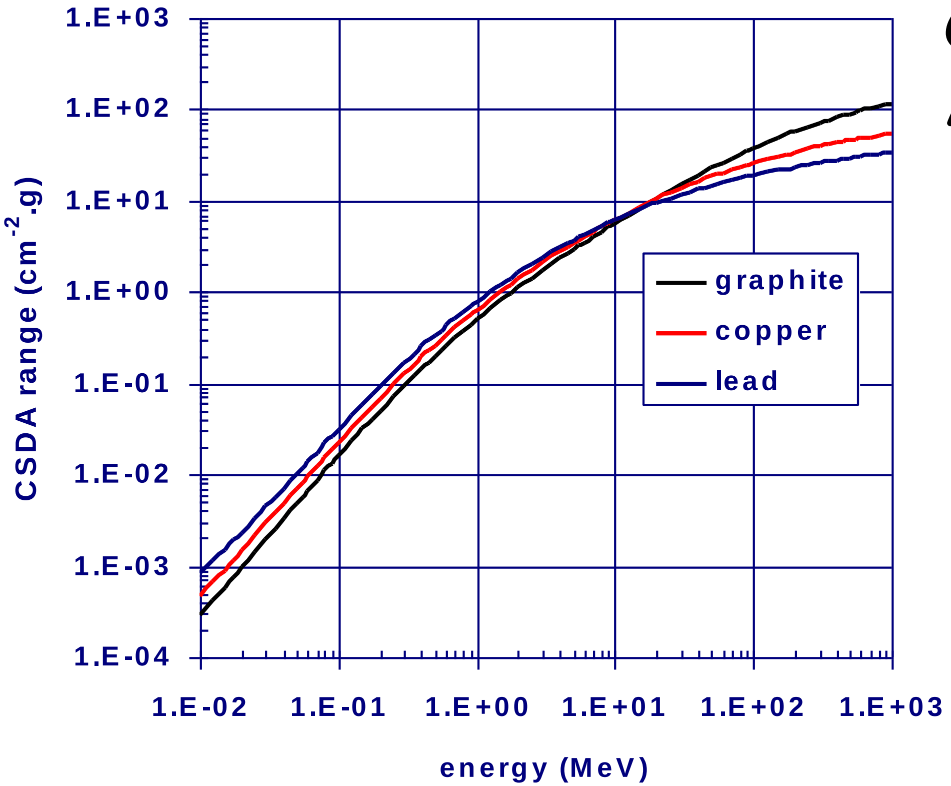
$$\frac{1}{\rho}\frac{dE}{dl} : \text{mass stopping power } (\text{MeV.cm}^2.\text{g}^{-1})$$

$$\frac{dE}{dl} : \text{ linear stopping power } (\text{MeV.cm}^{-1})$$



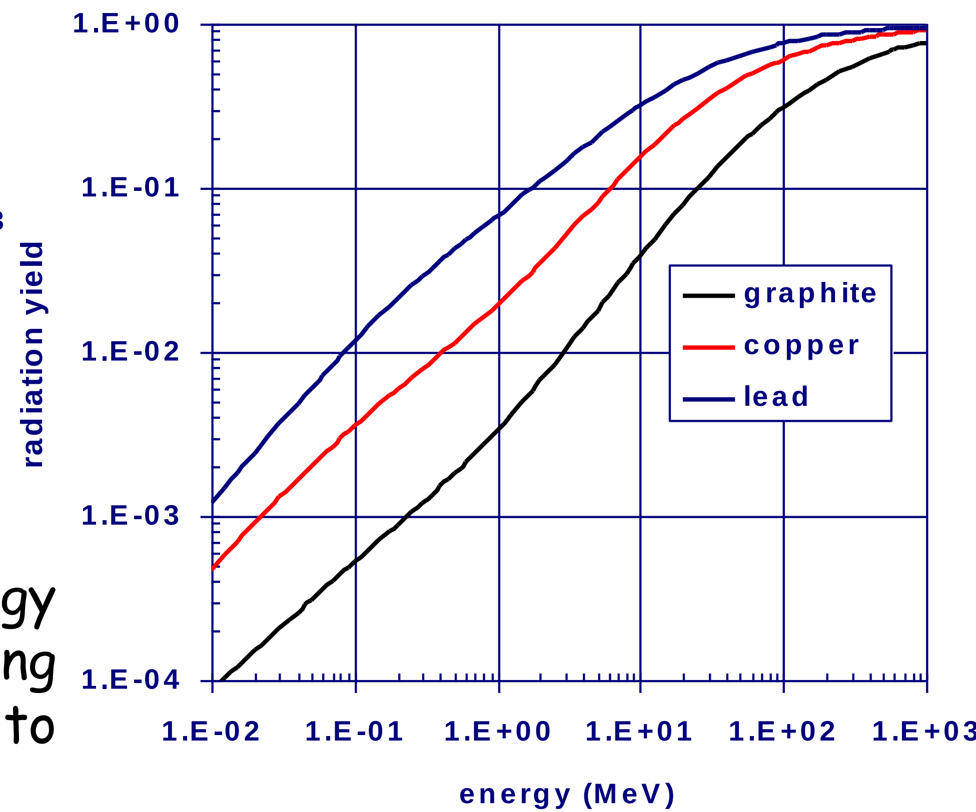






Continuous Slowing Down Approximation range

$$r_{CSDA} = \int_{E_0}^{0} \frac{1}{S_{tot}} dE$$

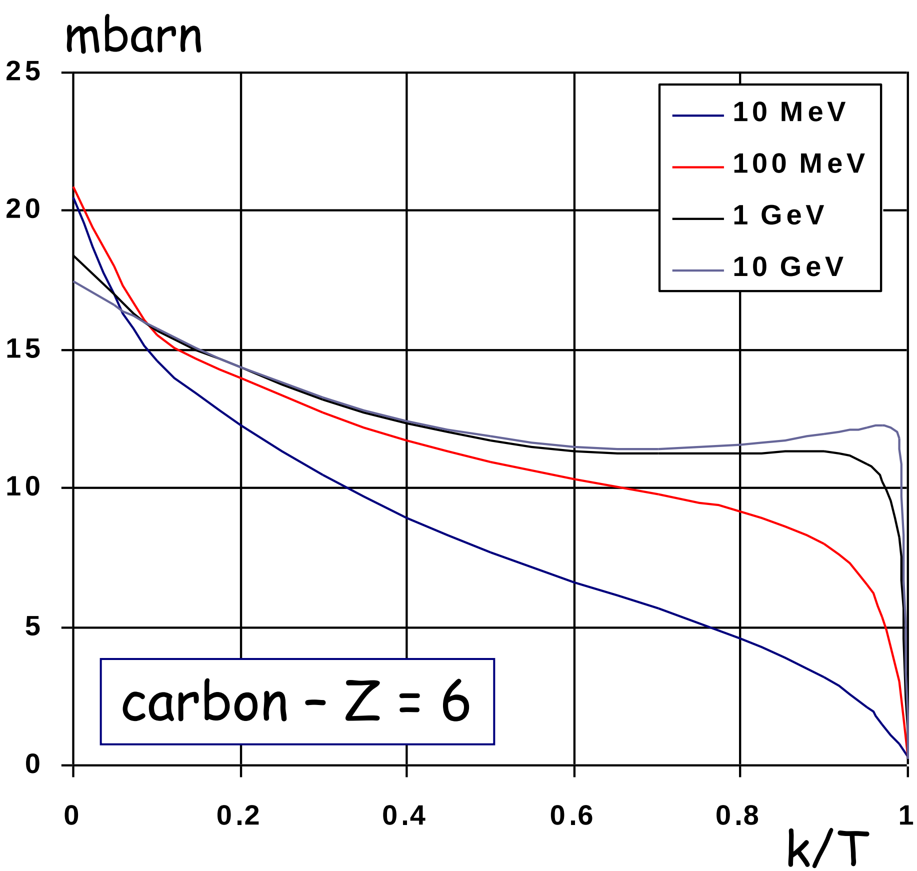


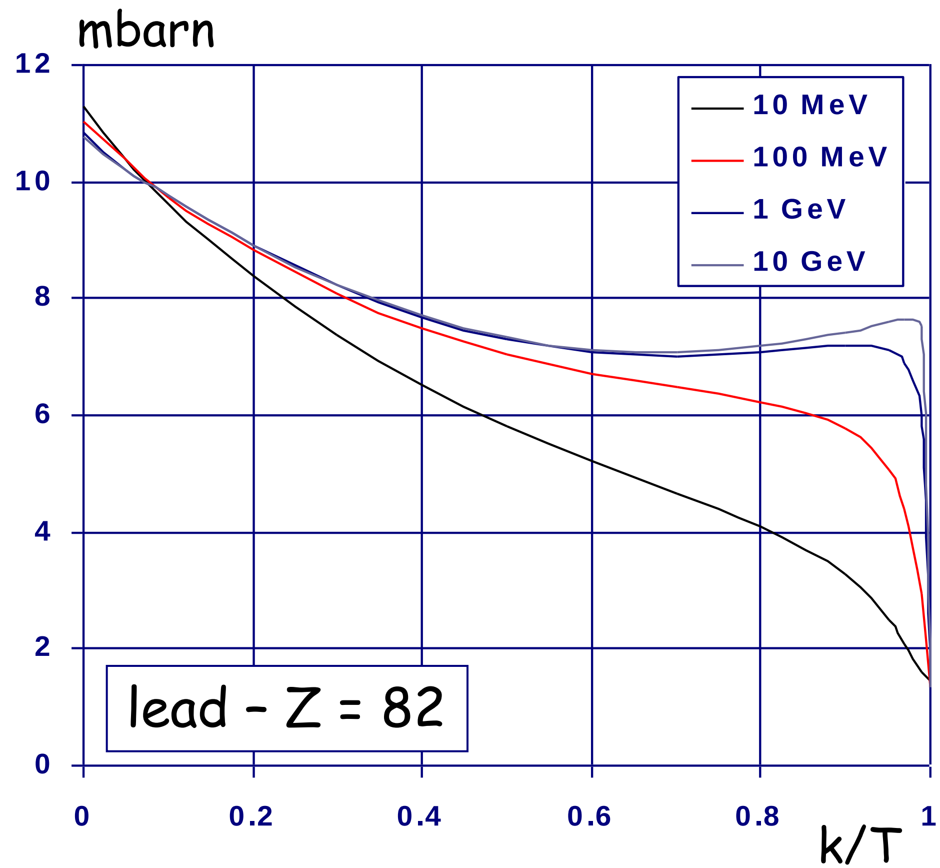
Radiation yield

Fraction of the initial kinetic energy that is converted to bremsstrahlung energy as the electron slows down to rest.

Differential bremsstrahlung cross section

$$\frac{1}{Z^2} k \times \frac{d\sigma}{dk}$$





k: photon energy
T: electron kinetic energy

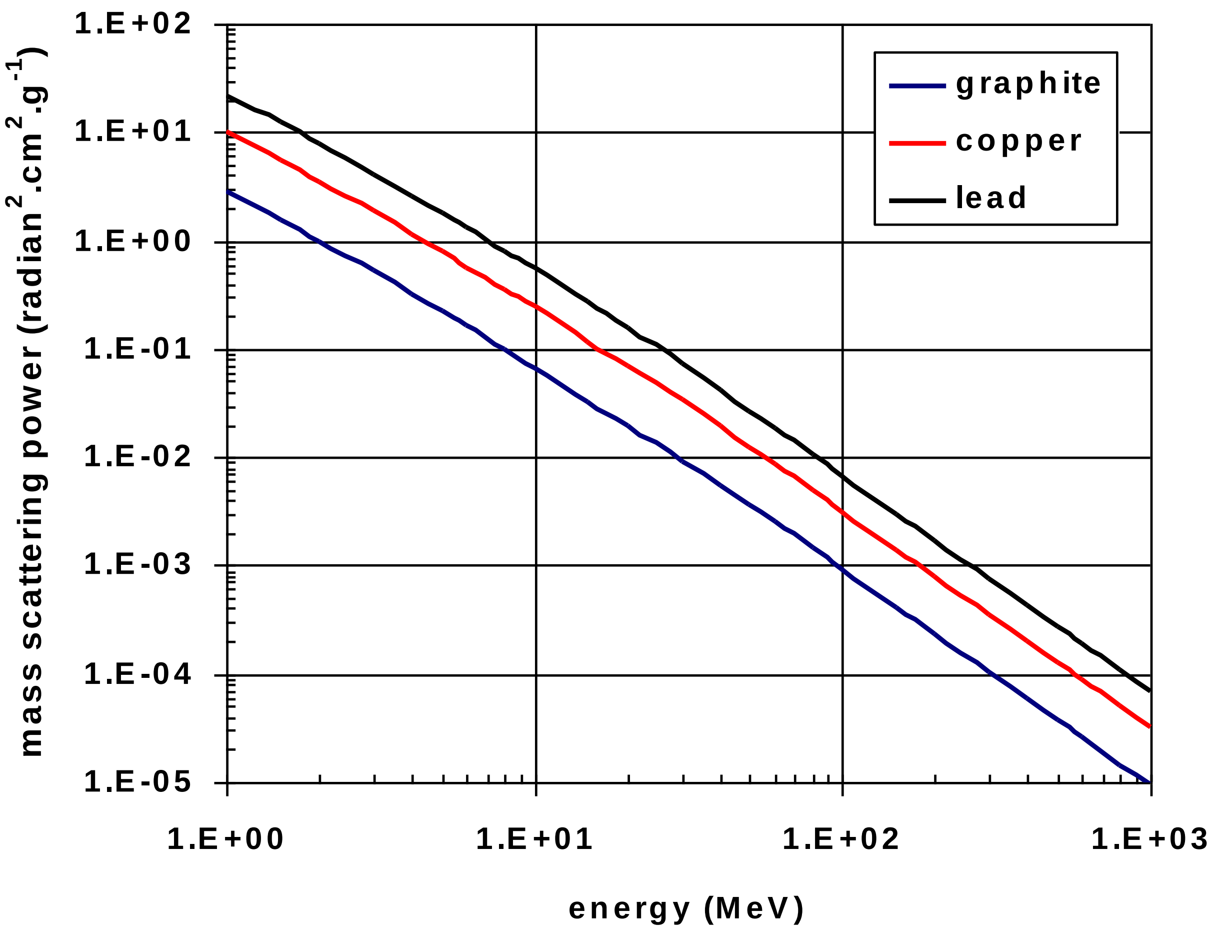
Multiple scattering

mean scattering angle

$$\langle \theta^2 \rangle = \left(\frac{E_s}{\beta p} \right)^2 \frac{X}{X_0}$$

mass scattering power S_{sc}

$$S_{sc} = \frac{1}{\rho} \frac{d\langle \theta^2 \rangle}{dx}$$



E_s = 21.2 MeV
X_0: radiation length
β: v/c
p: momentum

Interaction of photons with matter

The physical processes

1. Photo-electric effect
   removal of an orbital electron of the inner shells (K,L,M)

2. Compton scattering
   inelastic scattering on loosely bound electrons

3. Pair production
   production of e^-/e^+ pair
   essentially with nuclei

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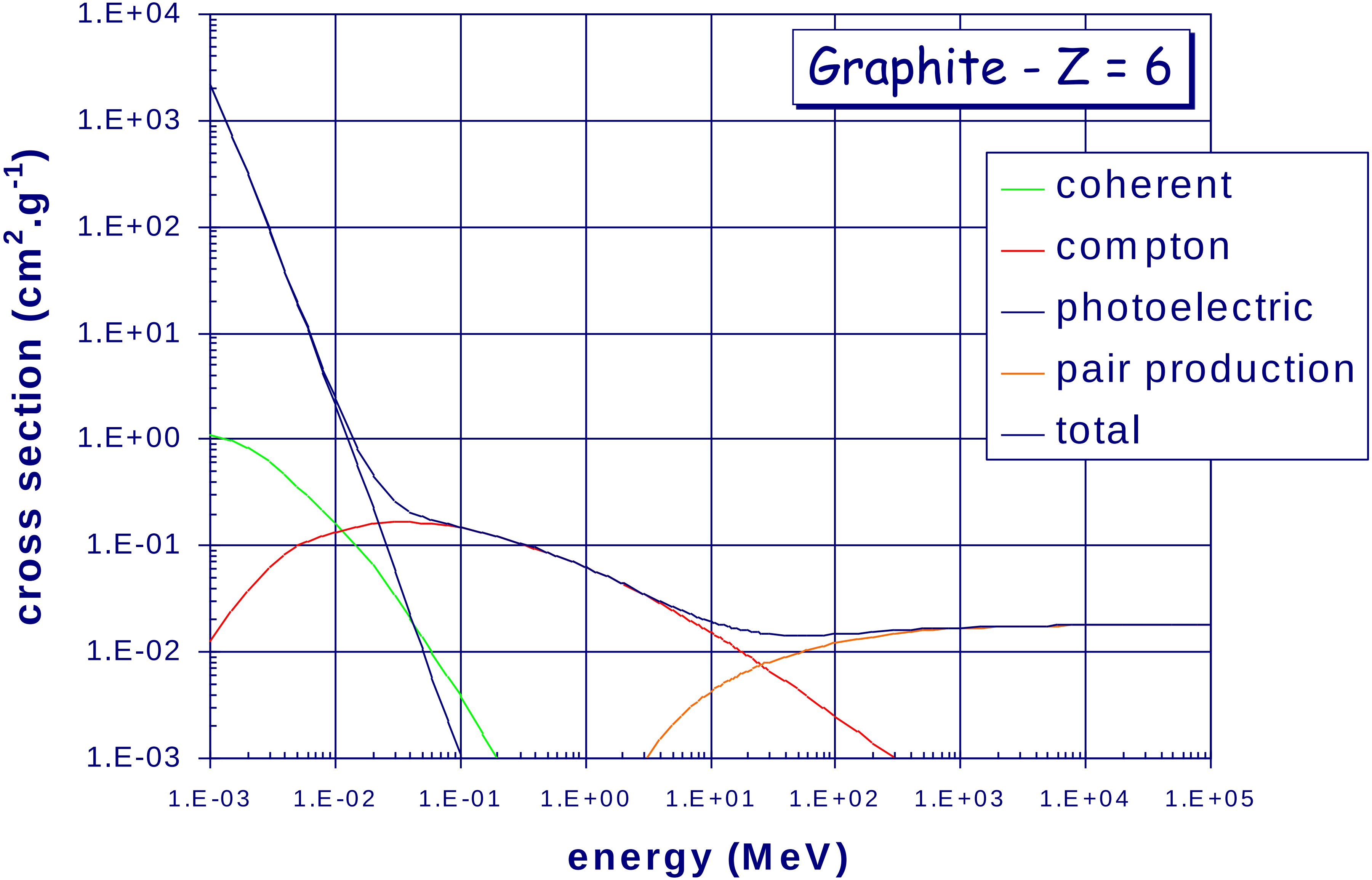
4. Rayleigh scattering
   elastic scattering
   not important for radiation physics

Photon cross sections



Photon cross sections

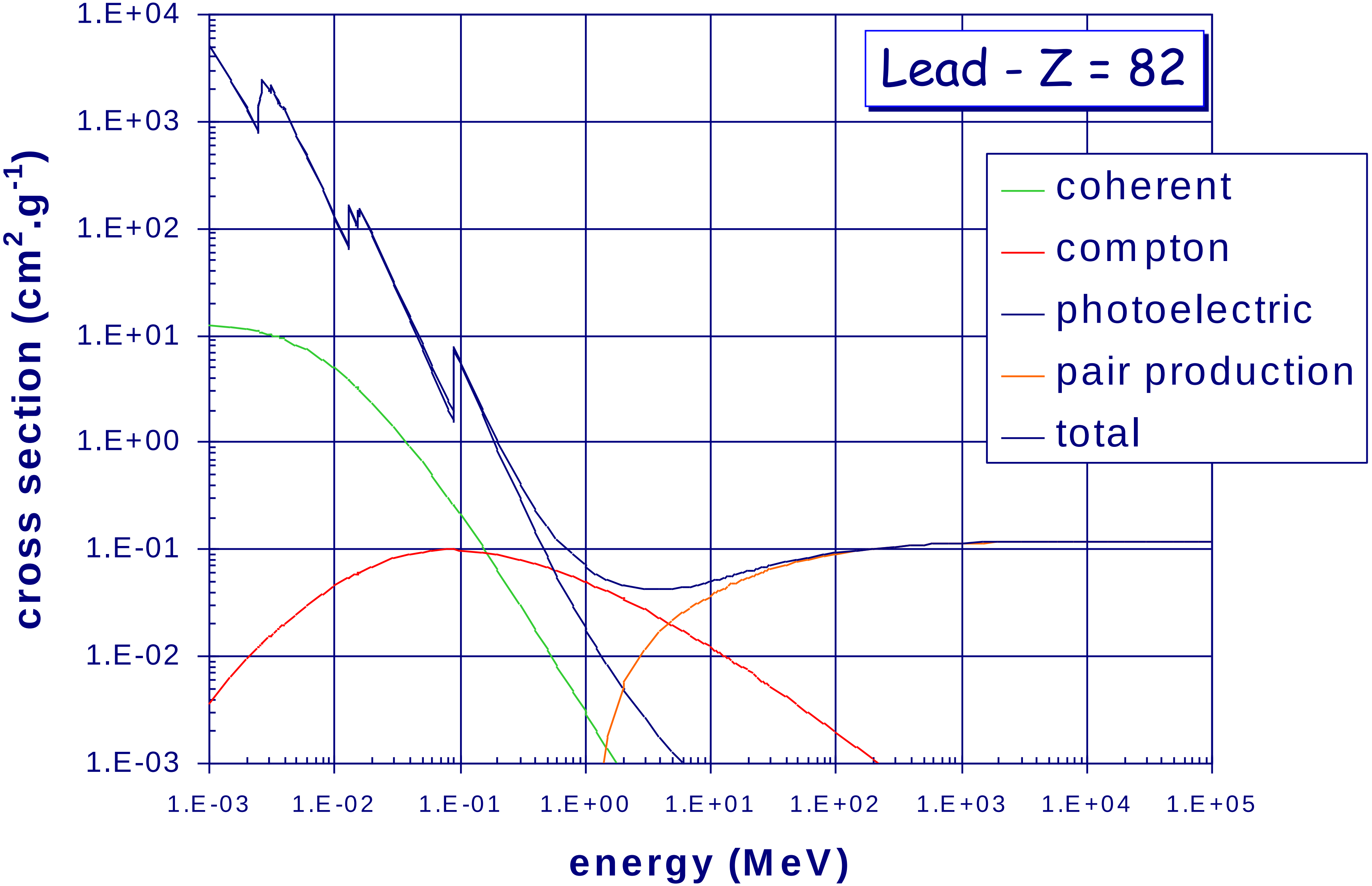
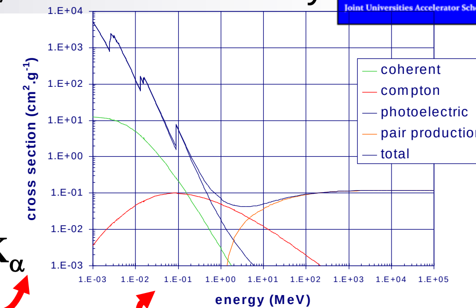
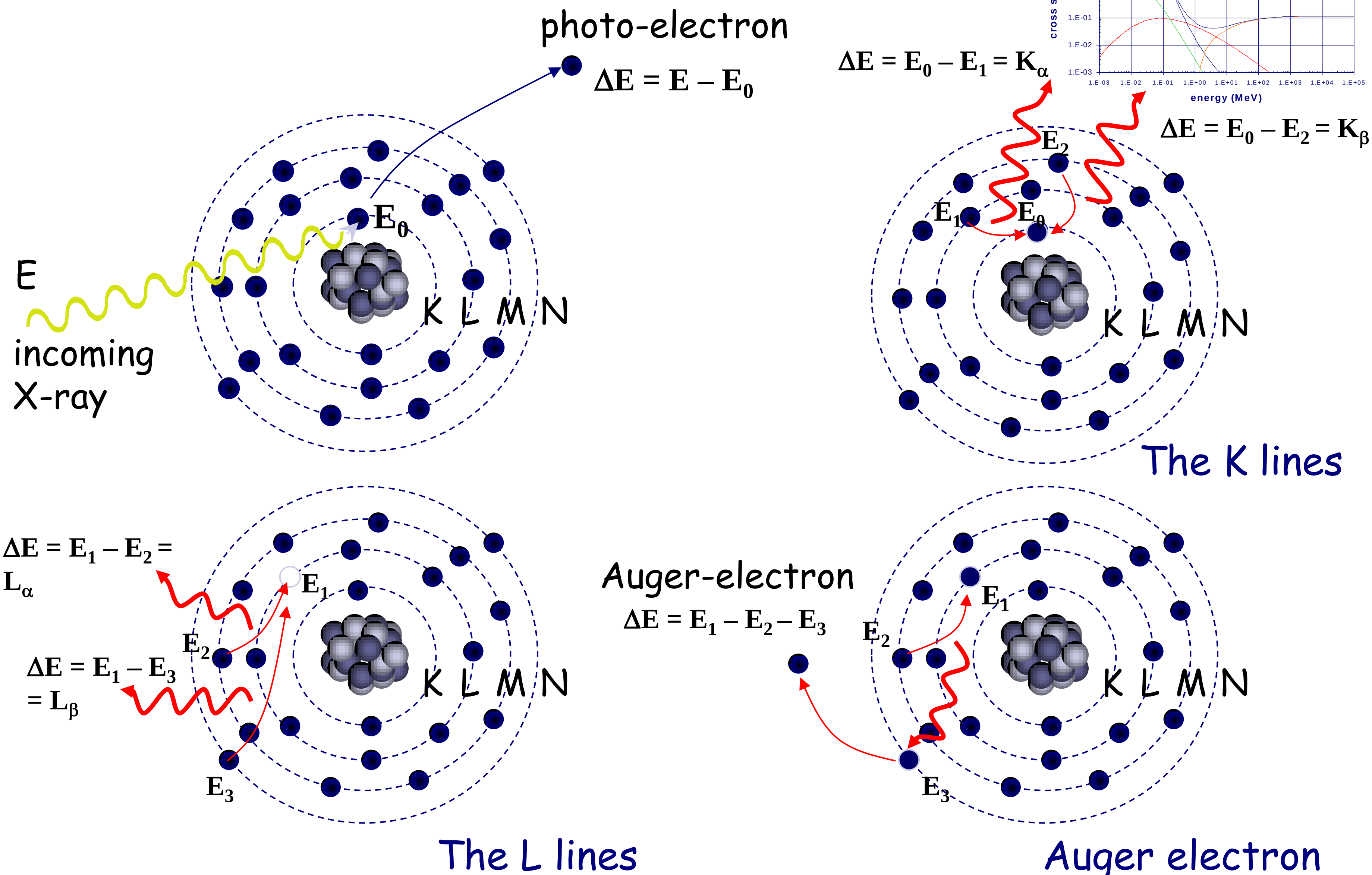
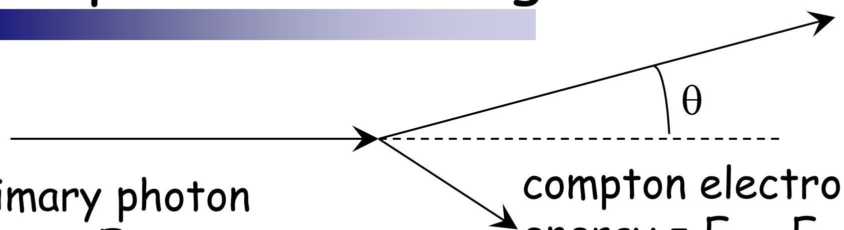


Photo-electric effect





Compton scattering

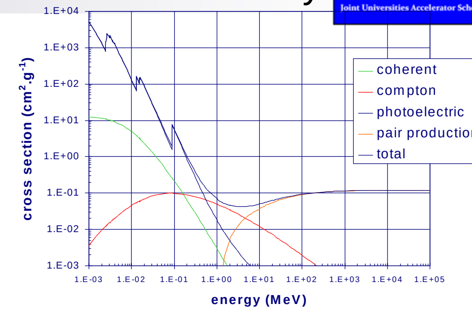


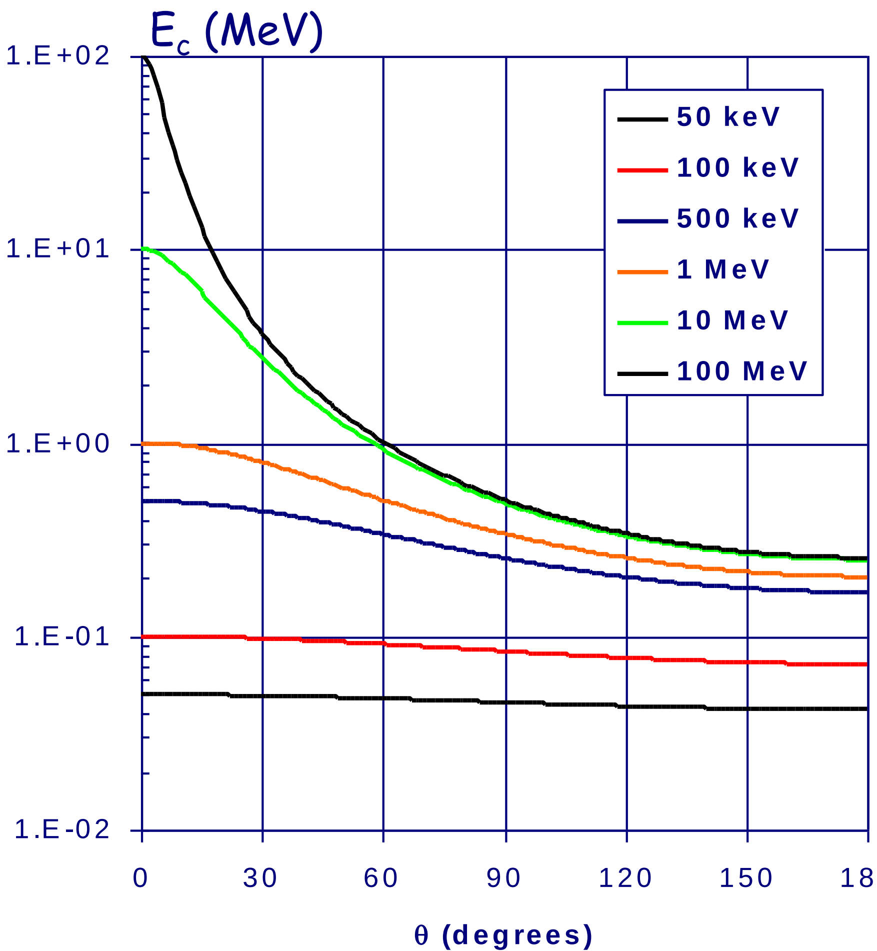
scattered photon energy E_c

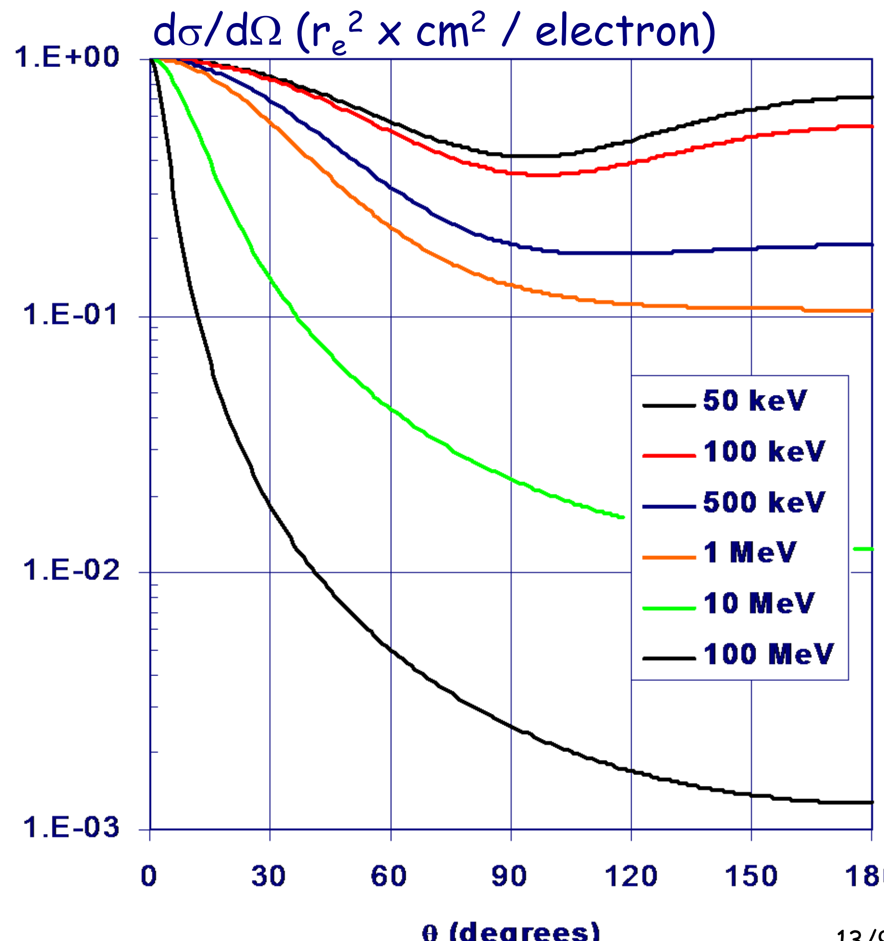
$$E_c = \frac{E_0}{1 + \frac{E_0}{m_0 c^2}(1 - \cos\theta)}$$

primary photon energy E_0

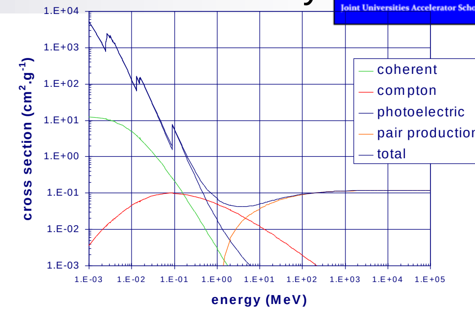
compton electron energy = E_0 - E_c





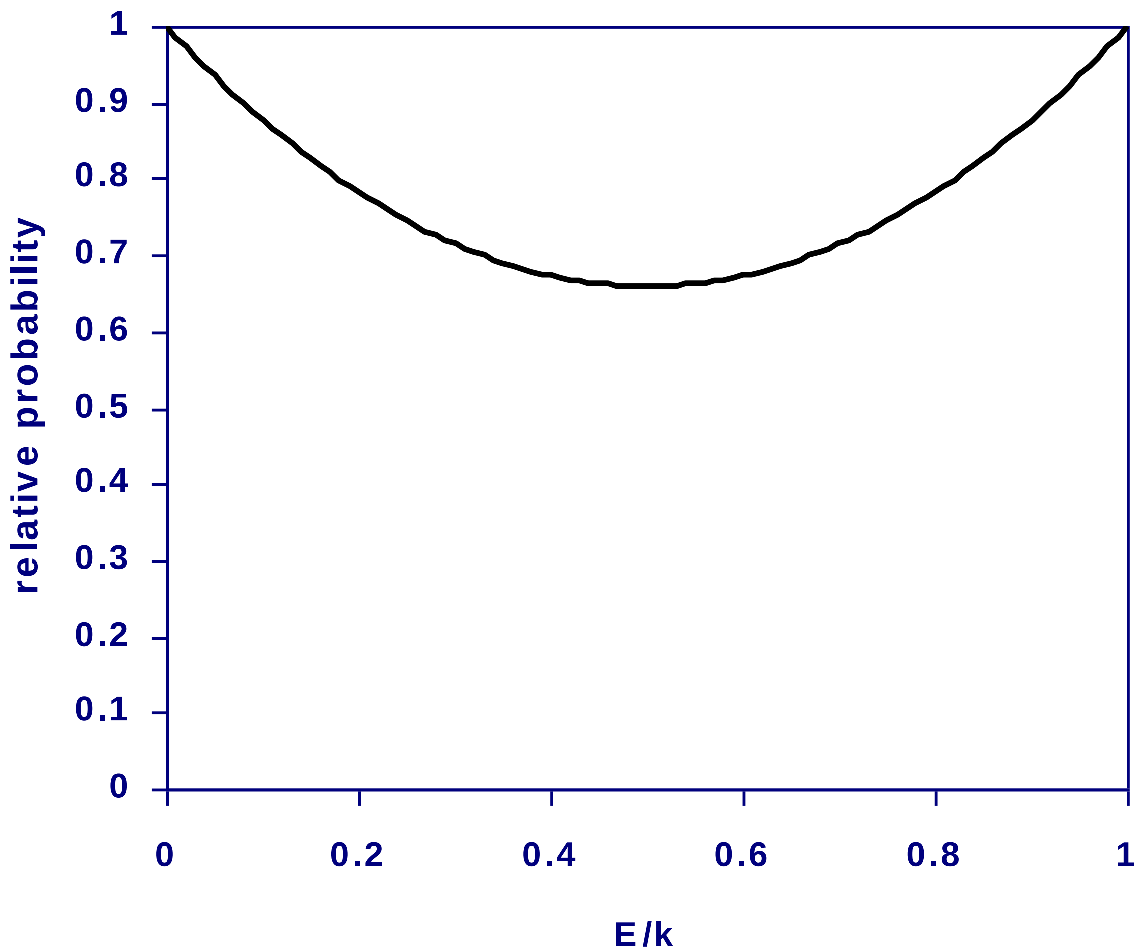


Pair production



$\sigma_{nucleus} \propto Z^2$
threshold: 1.022 MeV

$\sigma_{electron} \propto Z$
threshold: 2.044 MeV



Interaction of photons with matter
Macroscopic description - Attenuation factors

The mass attenuation coefficient μ/ρ:

$$\frac{\mu}{\rho} = \frac{1}{\rho N}\frac{dN}{dl}$$

units: $cm^2.g^{-1}$

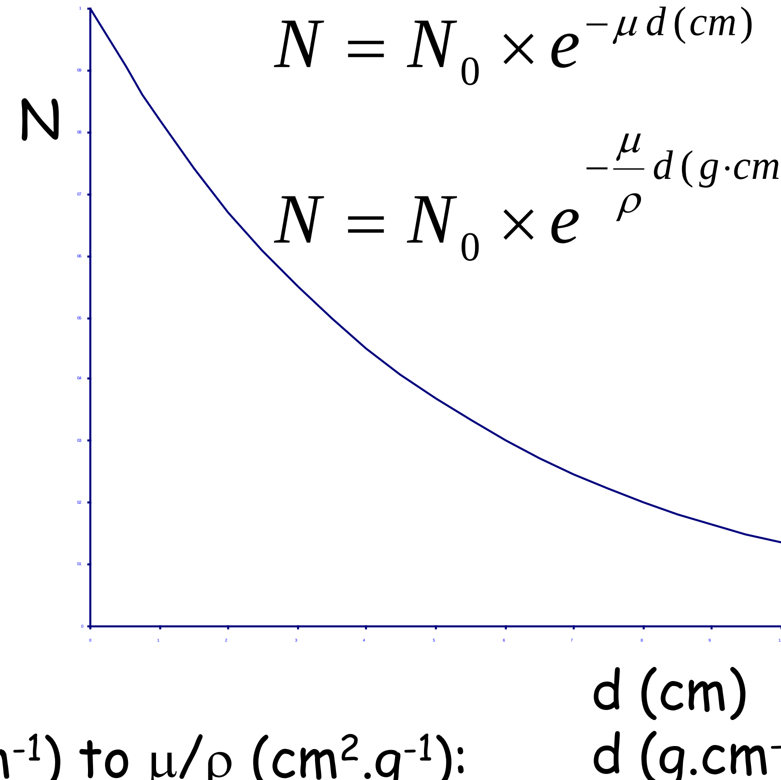
The linear attenuation coefficient μ:

$$\mu = \frac{1}{N}\frac{dN}{dl}$$

units: cm^{-1}

$$N = N_0 \times e^{-\mu d(cm)}$$

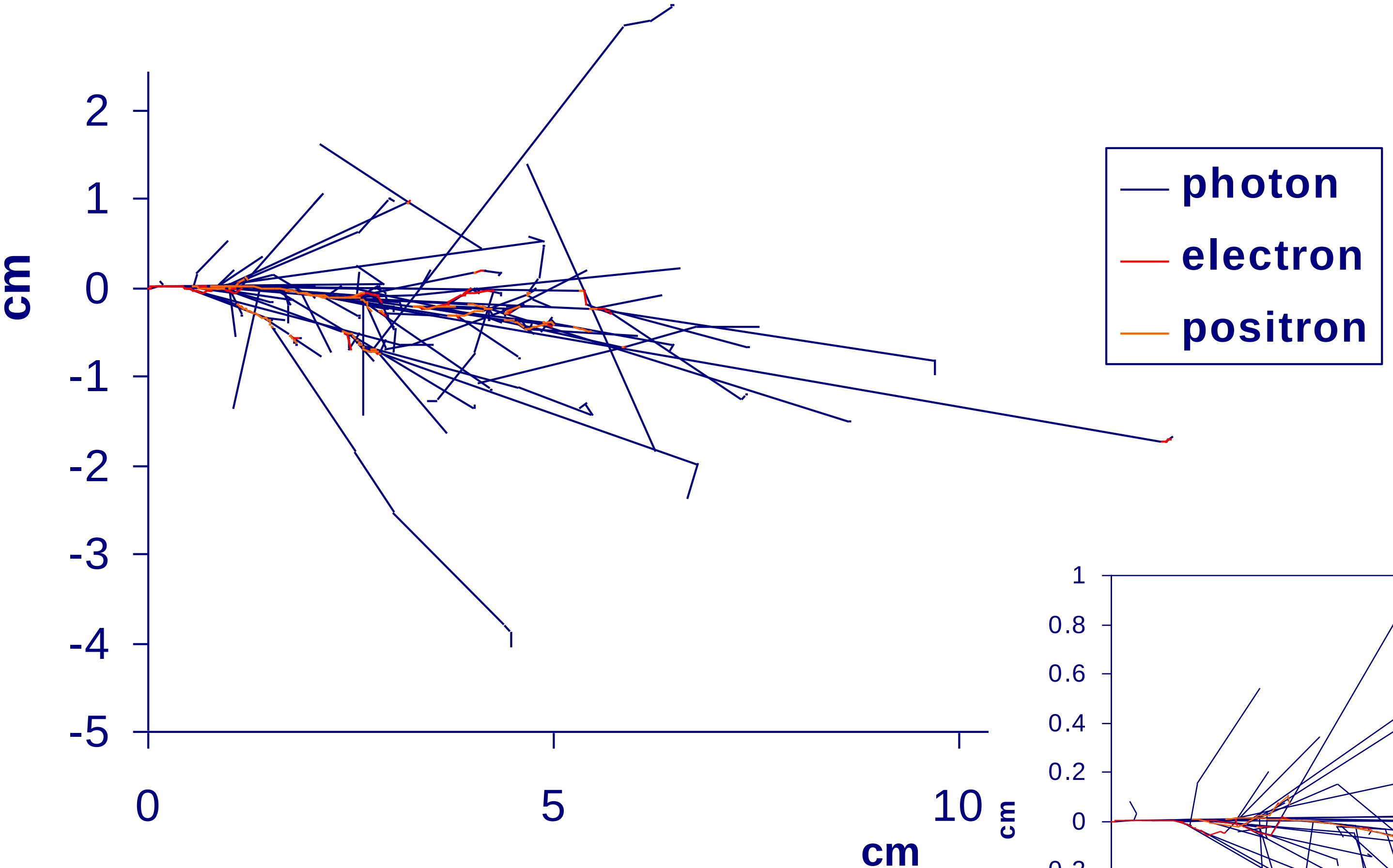
$$N = N_0 \times e^{-\frac{\mu}{\rho} d(g\cdot cm^{-2})}$$

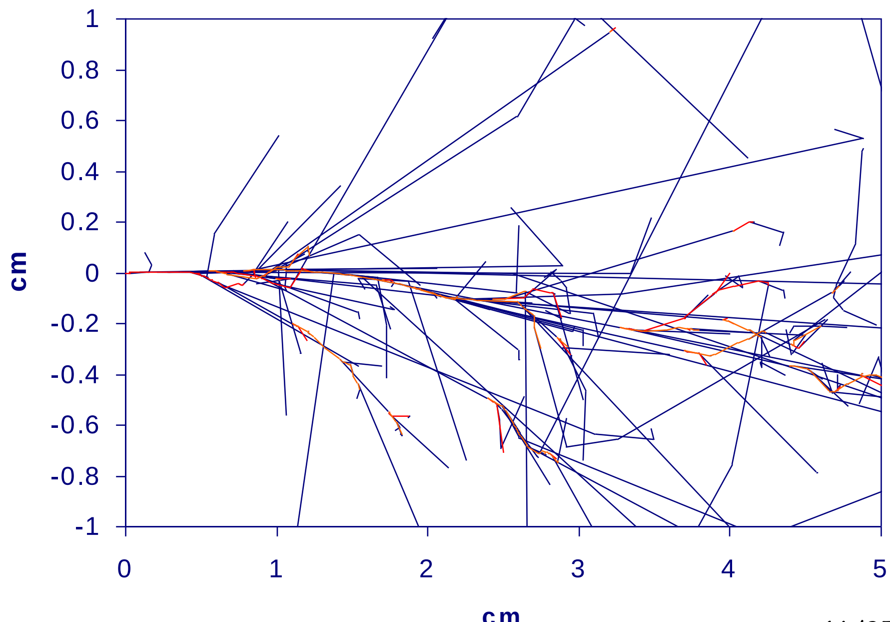


The conversion factor from σ (barns.atom^{-1}) to μ/ρ ($cm^2.g^{-1}$):

$$\frac{\mu}{\rho} = 10^{-24}\frac{N_A}{A}\sigma$$

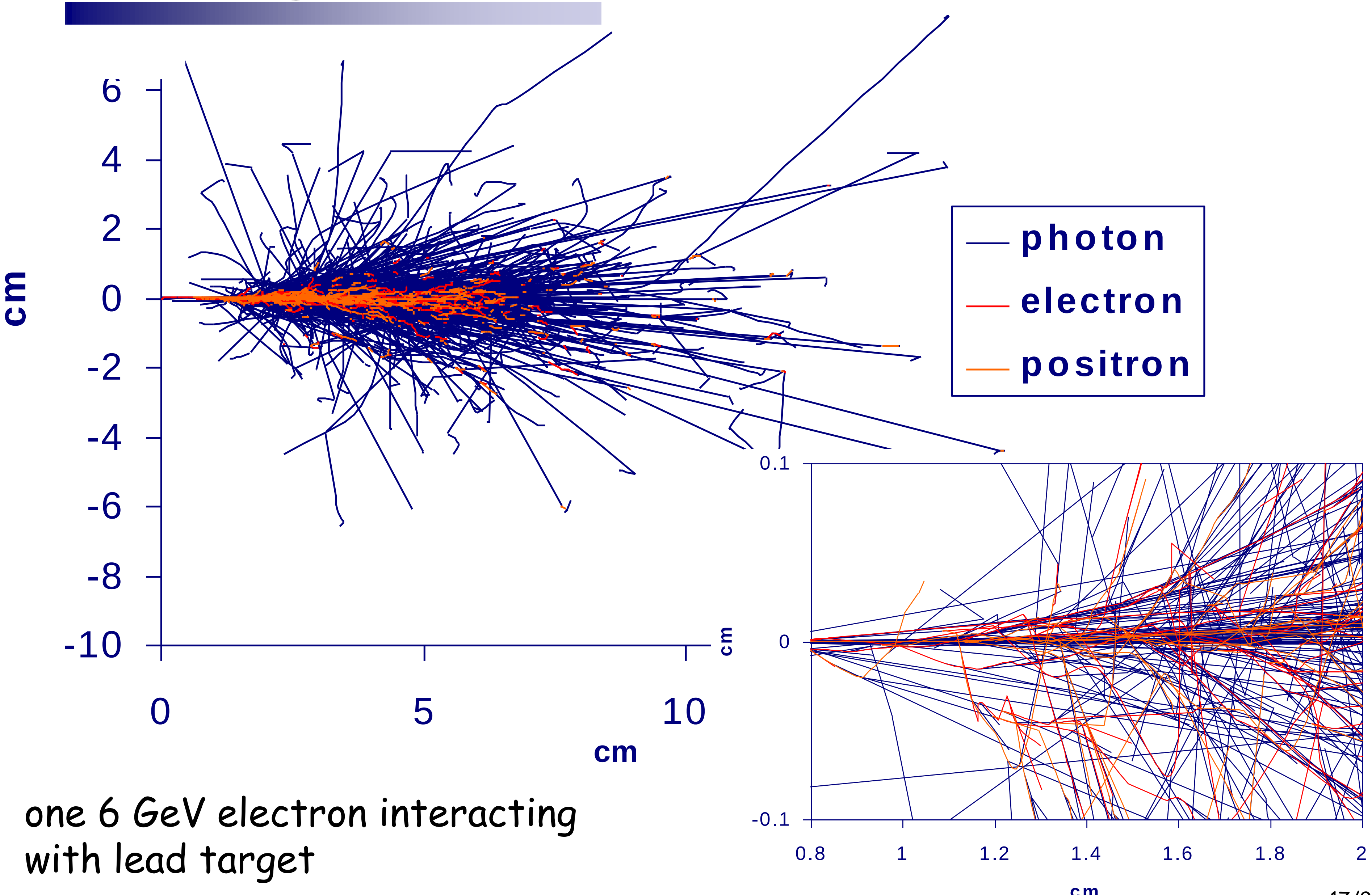
Electromagnetic cascade





one 500 MeV electron interacting with lead target

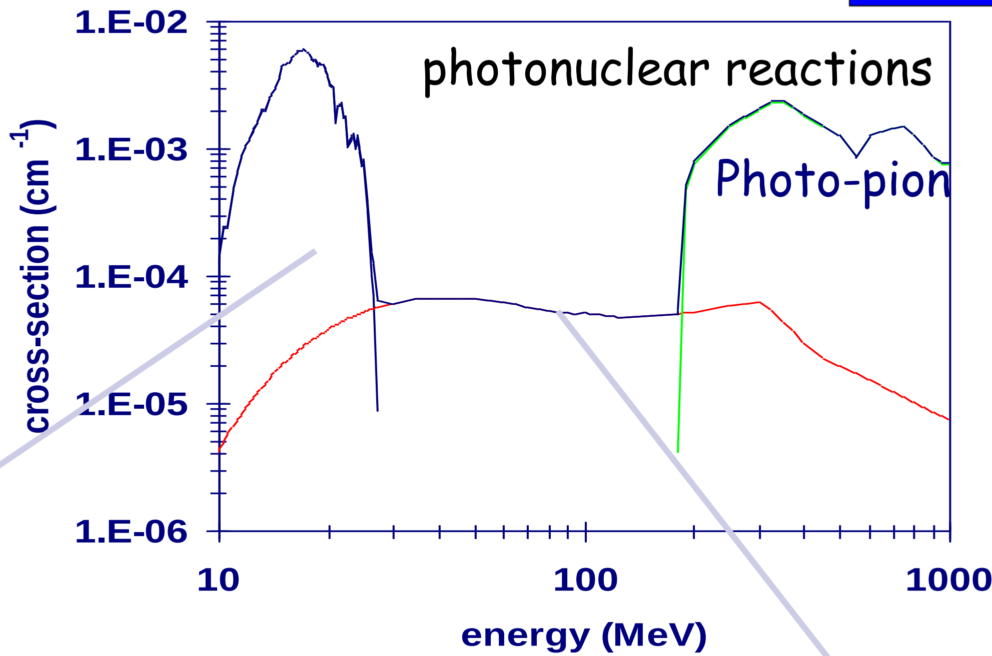
Electromagnetic cascade

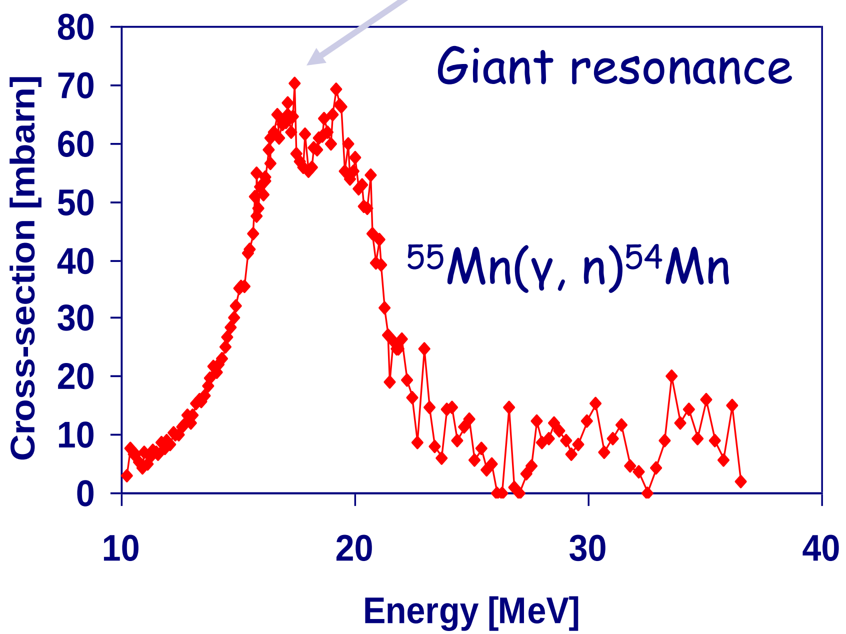


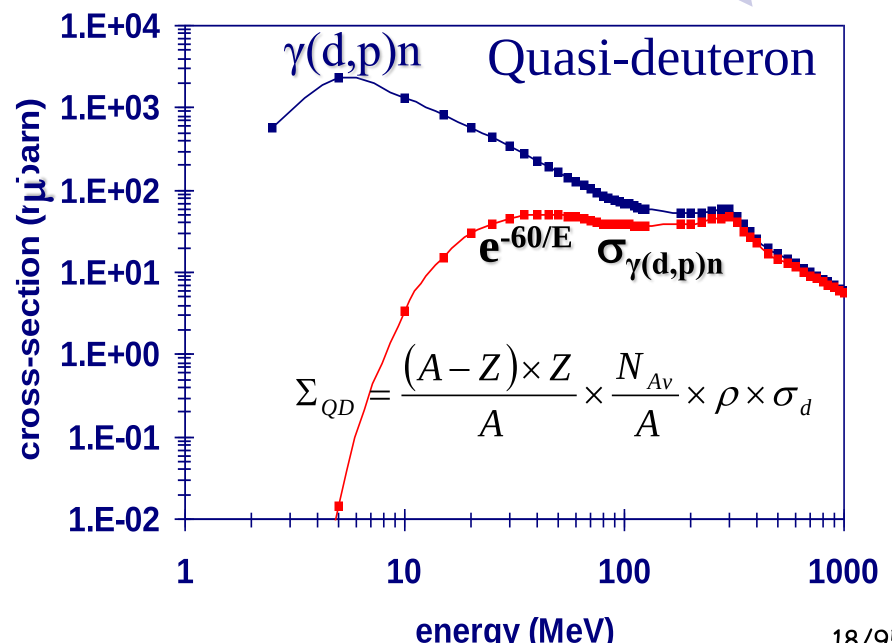
one 6 GeV electron interacting with lead target

Photonuclear reactions

Neutron production

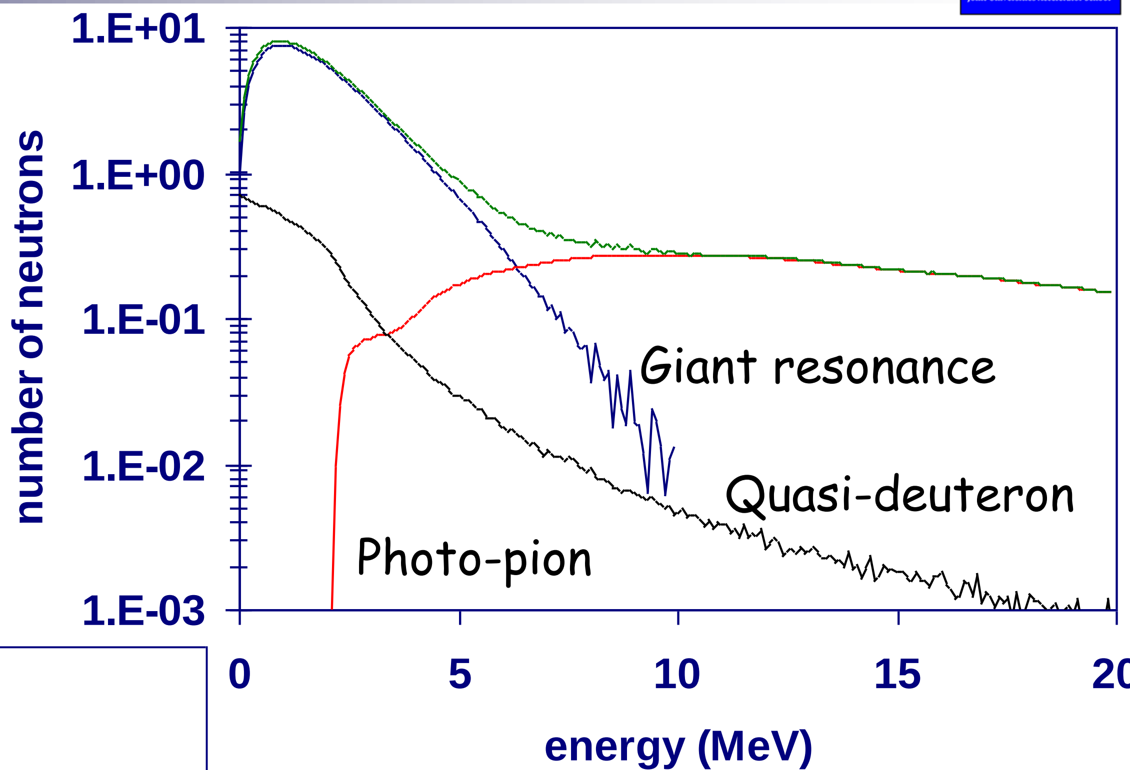


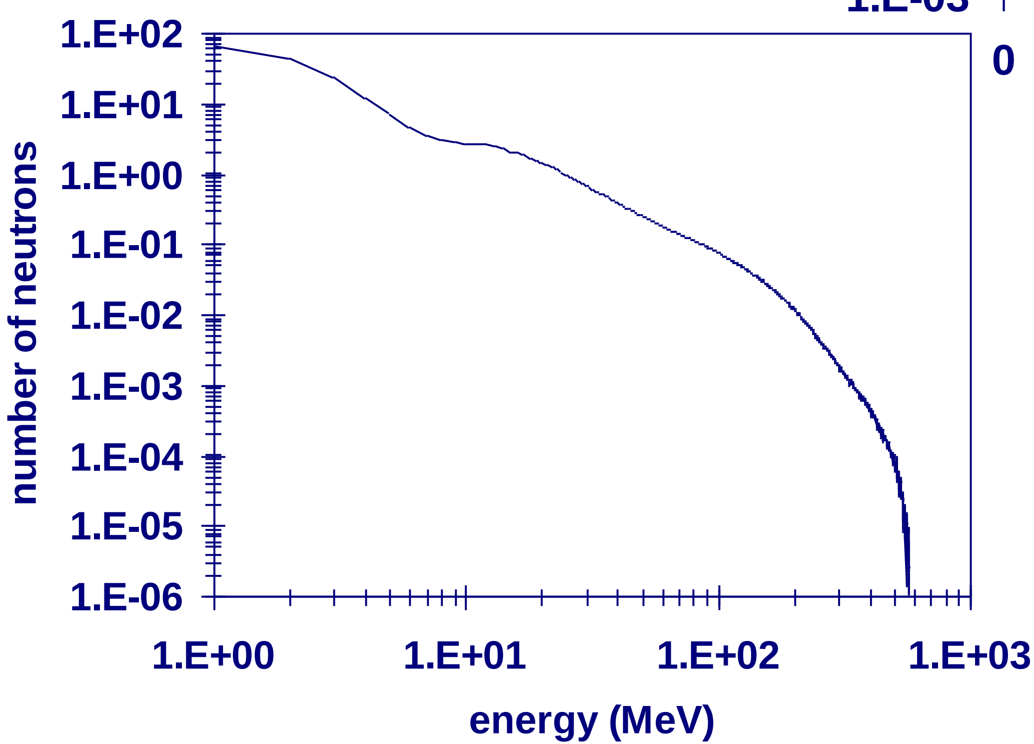




Photonuclear reactions

Neutron production





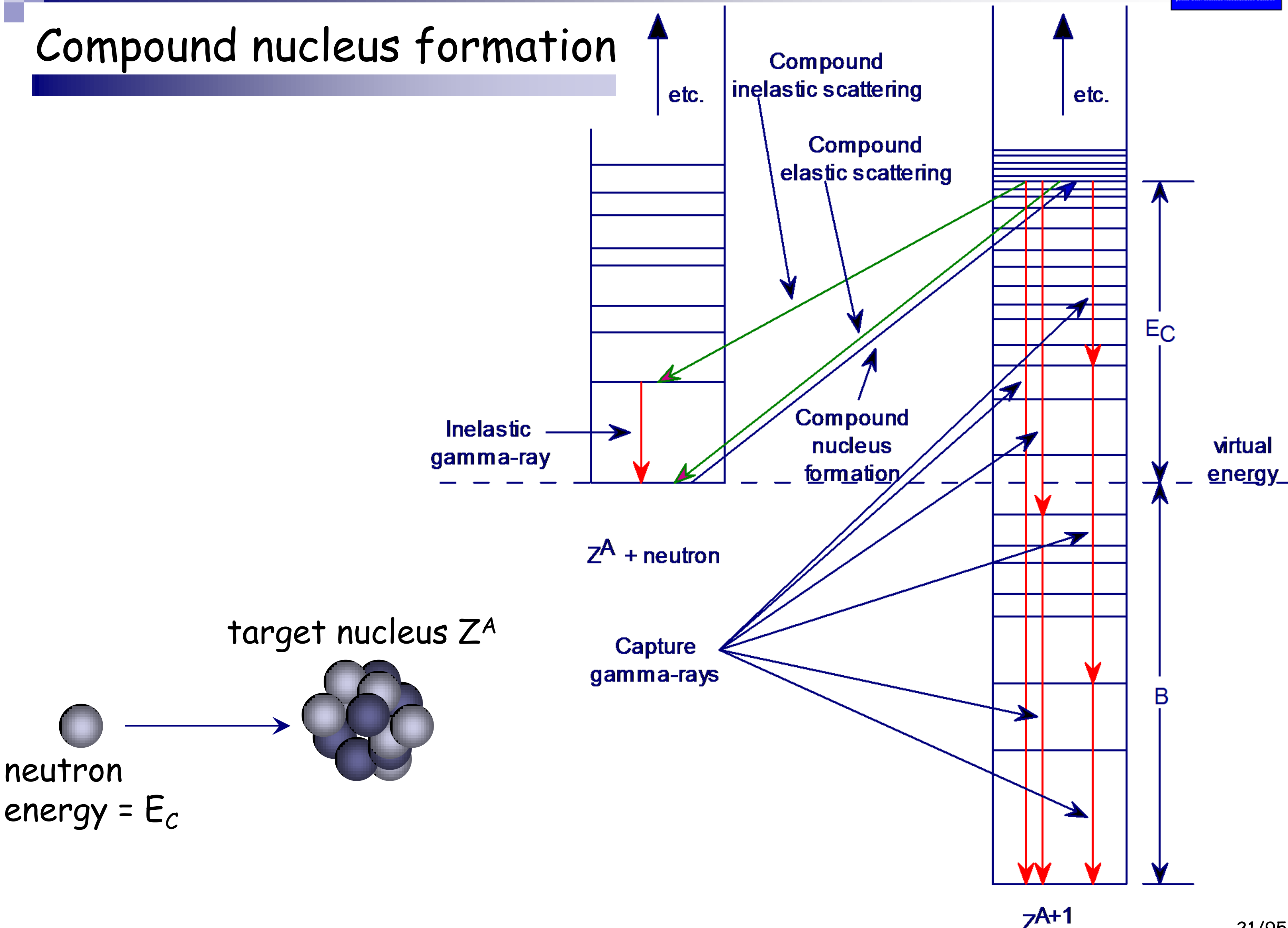
Example: neutron spectrum produced by 600 MeV electrons on Cu target

Interaction of neutrons with matter

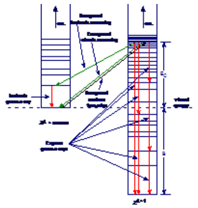
The physical processes

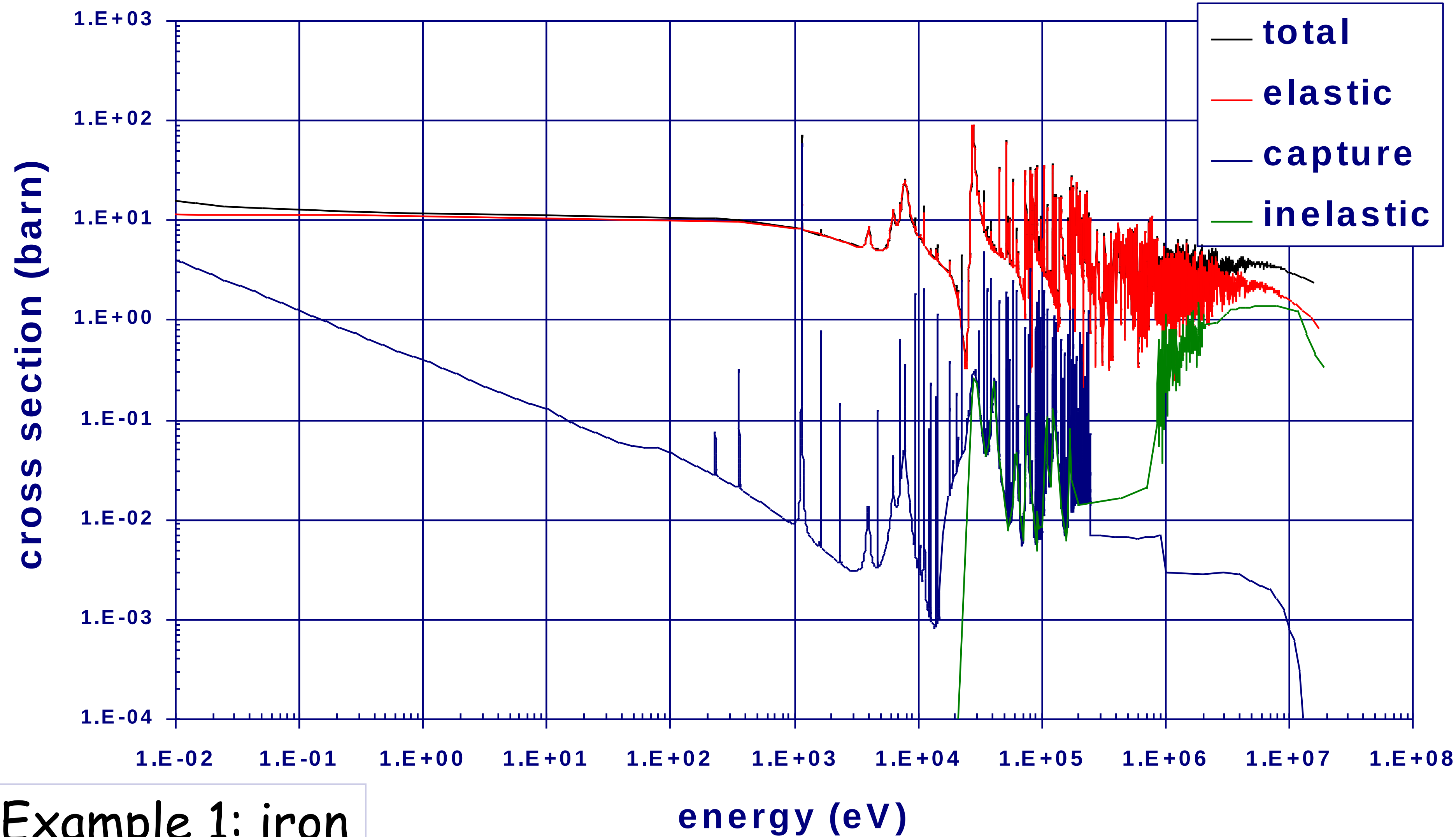
1. elastic scattering
   - compound elastic scattering
   - potential scattering
2. inelastic scattering (n,n')
3. other inelastic reactions: (n,p), (n,α), ...
4. absorption reactions
   - radiative capture
   - charged particle reactions
5. direct reactions: spallation

Compound nucleus formation



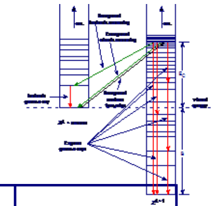
Neutron cross sections

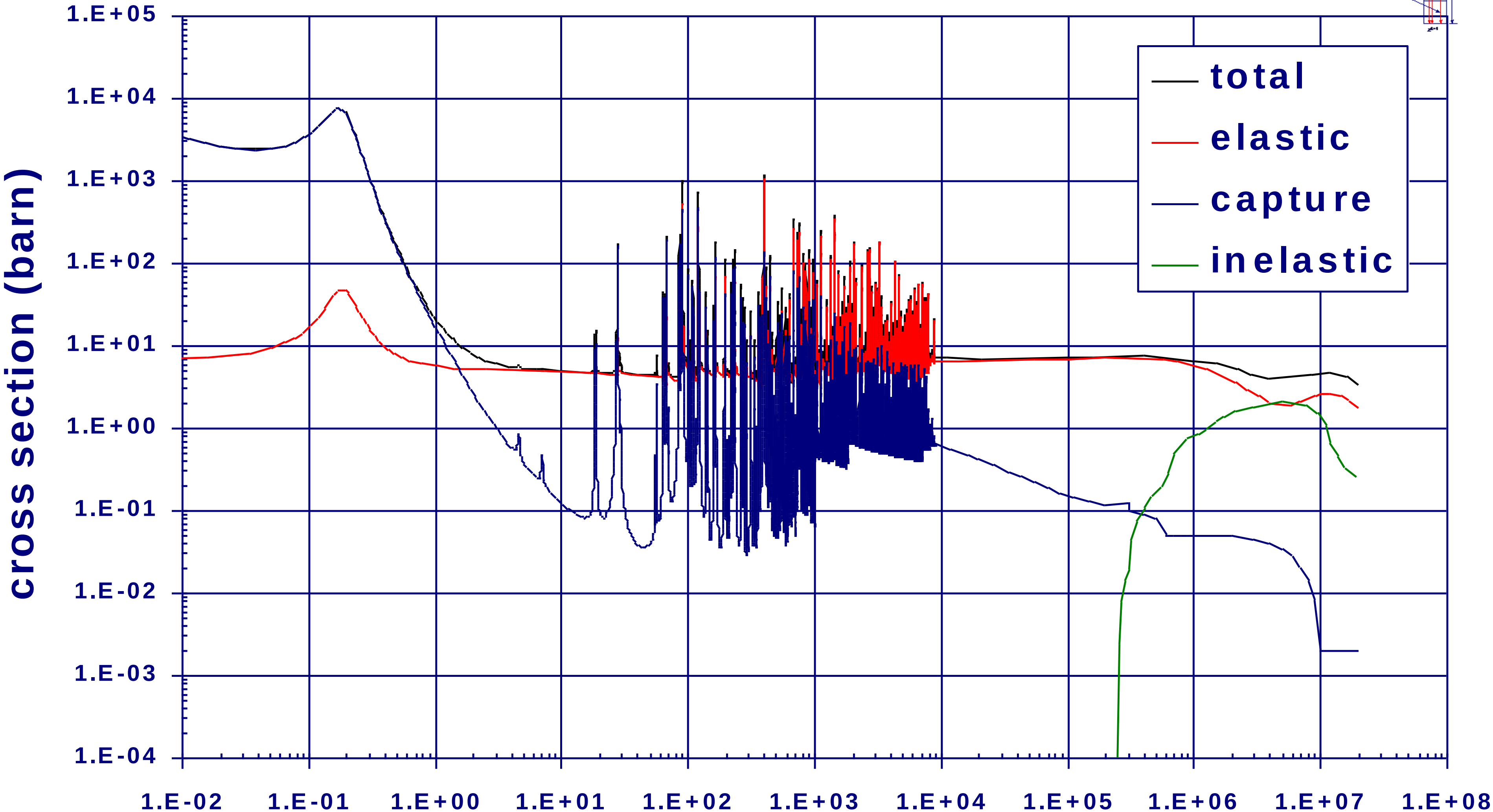




Example 1: iron

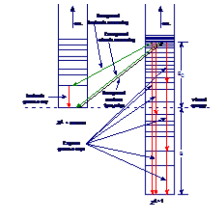
Neutron cross sections

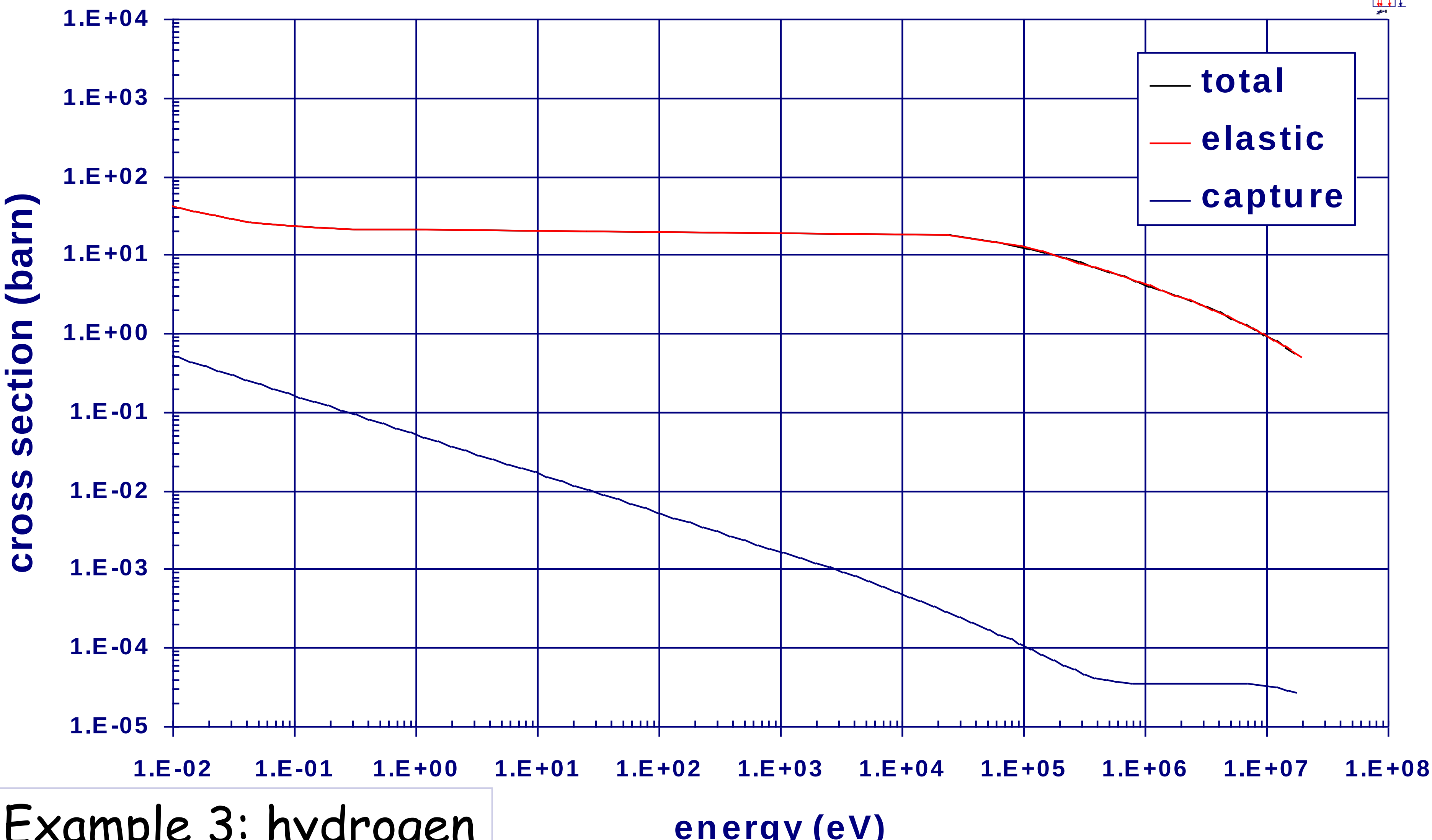




Example 2: cadmium

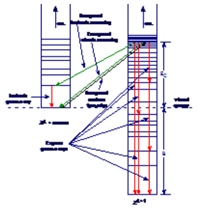
Neutron cross sections

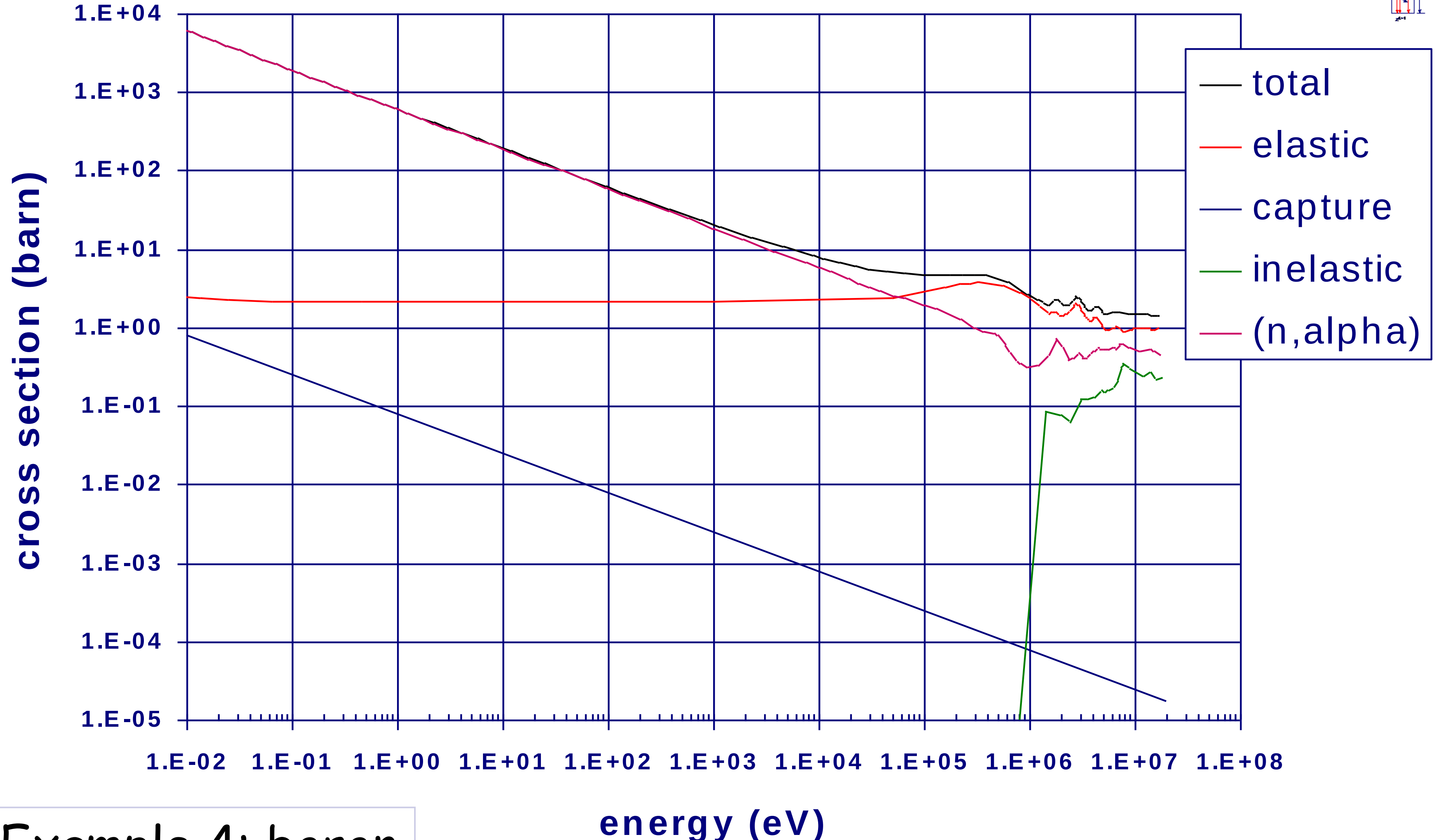




Example 3: hydrogen

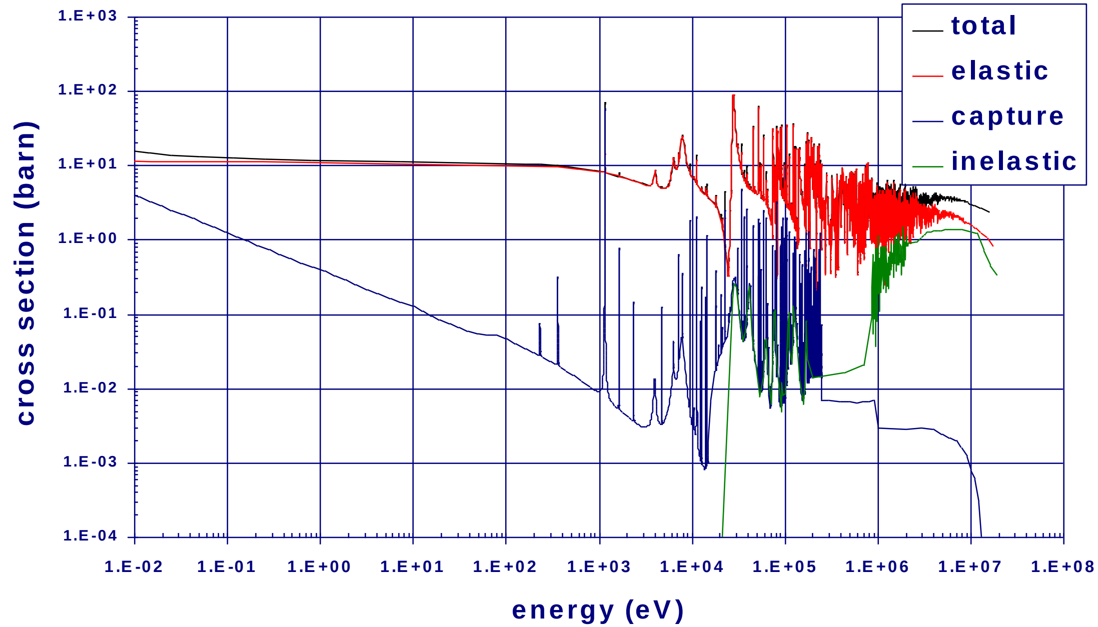
Neutron cross sections



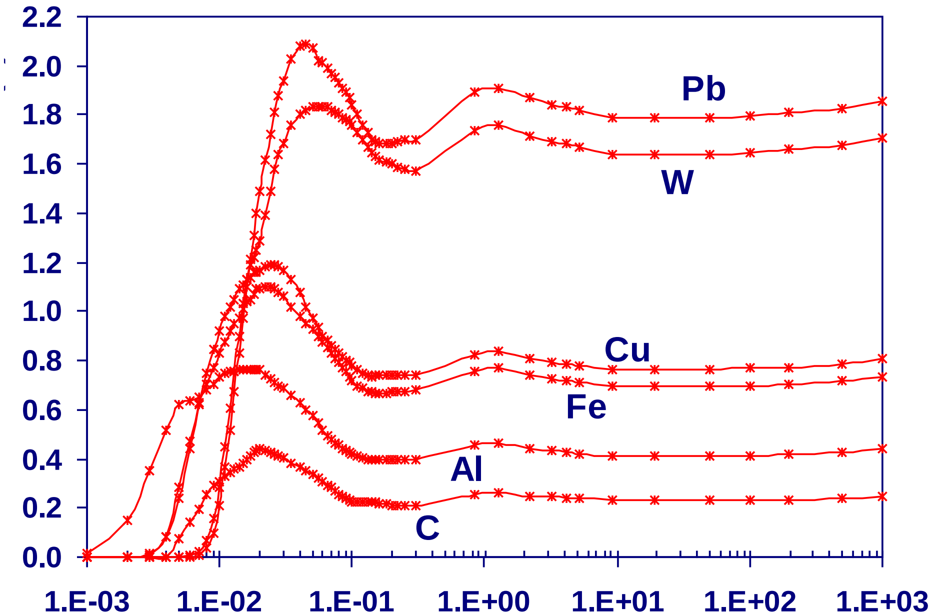


Example 4: boron

Neutron cross sections



inelastic cross section (barn)

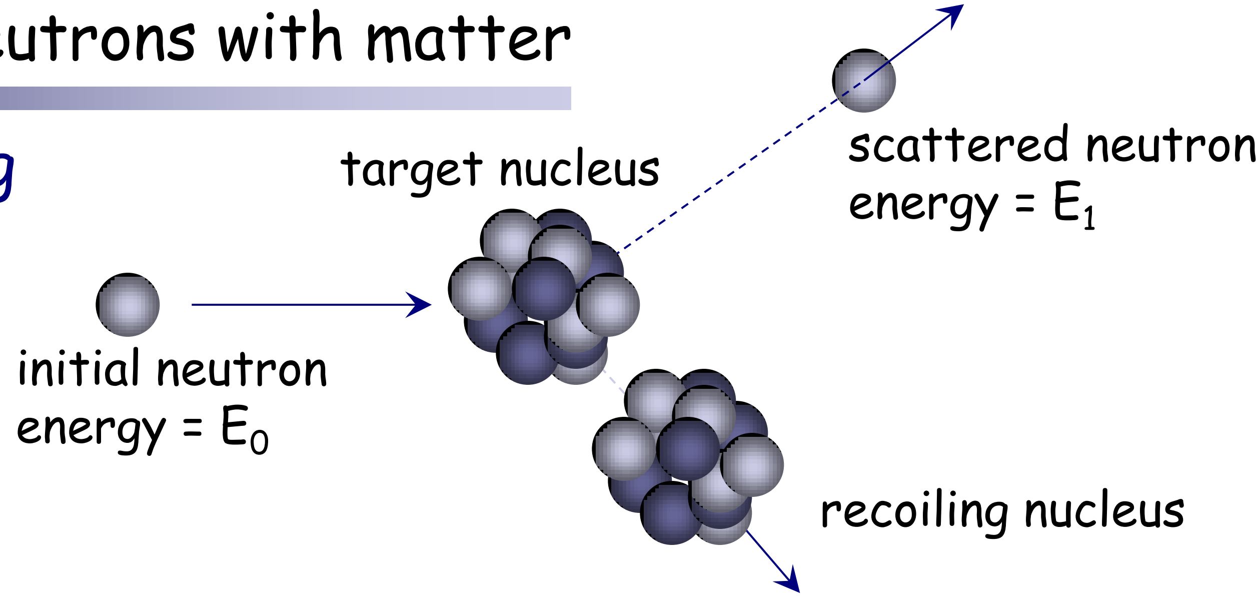


neutron energy (GeV)

Example: iron

Interaction of neutrons with matter

Elastic scattering



Minimum energy of scattered neutron:

$$\mathbf{E}_{1,\mathrm{minimum}} = \left(\frac{\mathbf{A}-1}{\mathbf{A}+1}\right)^2 \mathbf{E}_0 = \alpha \mathbf{E}_0$$

Average energy loss per collision:

$$\overline{\Delta \mathbf{E}} = \frac{1}{2}(1-\alpha)\mathbf{E}_0$$

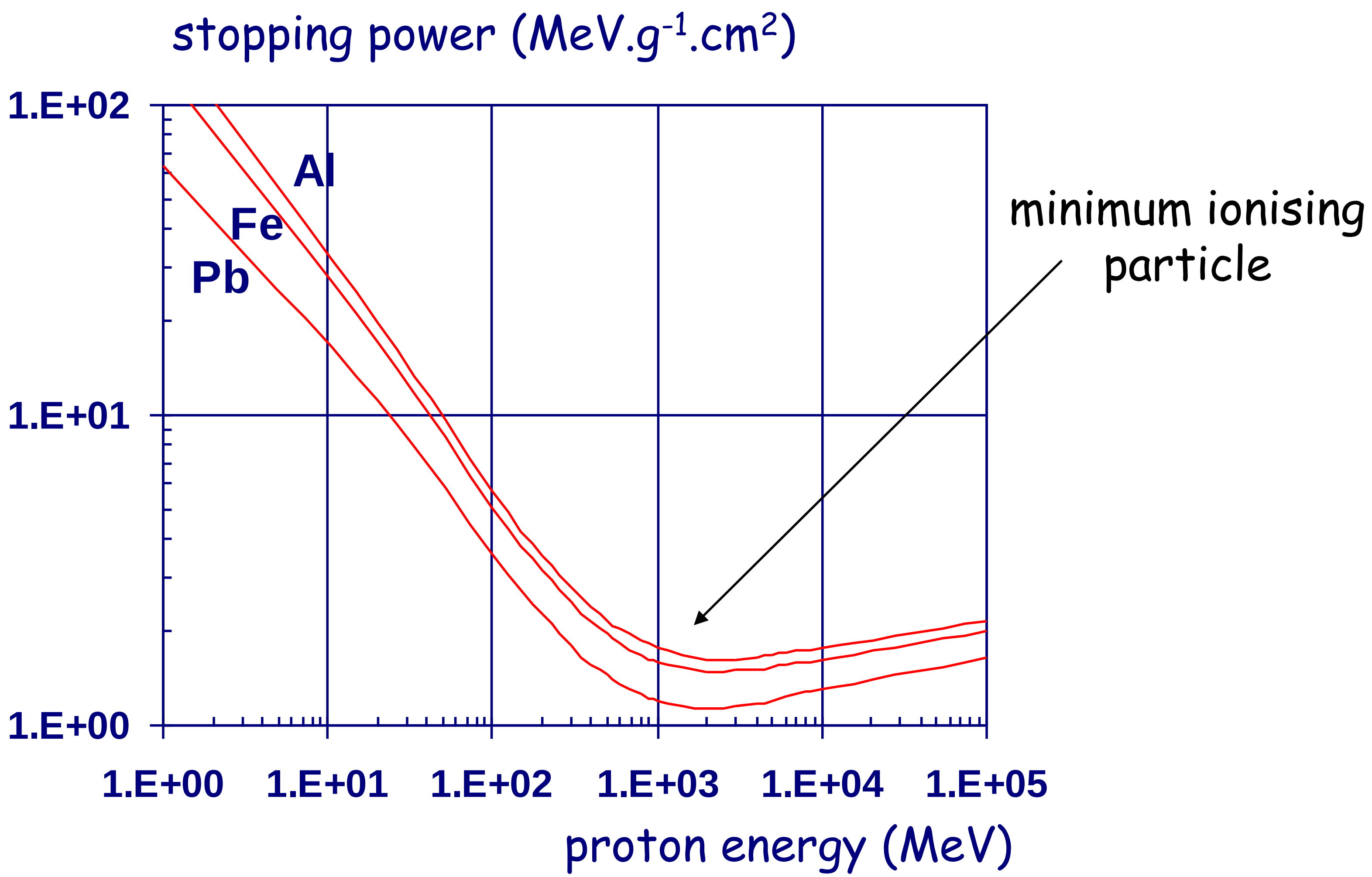
target	$E_{1,minimum}$	$\overline{\Delta E}$
Hydrogen (A=1)	0	0.5 E_0
Iron (A=56)	0.93 E_0	0.034 E_0
Lead (A=207)	0.98 E_0	0.0096 E_0

Interaction of protons with matter

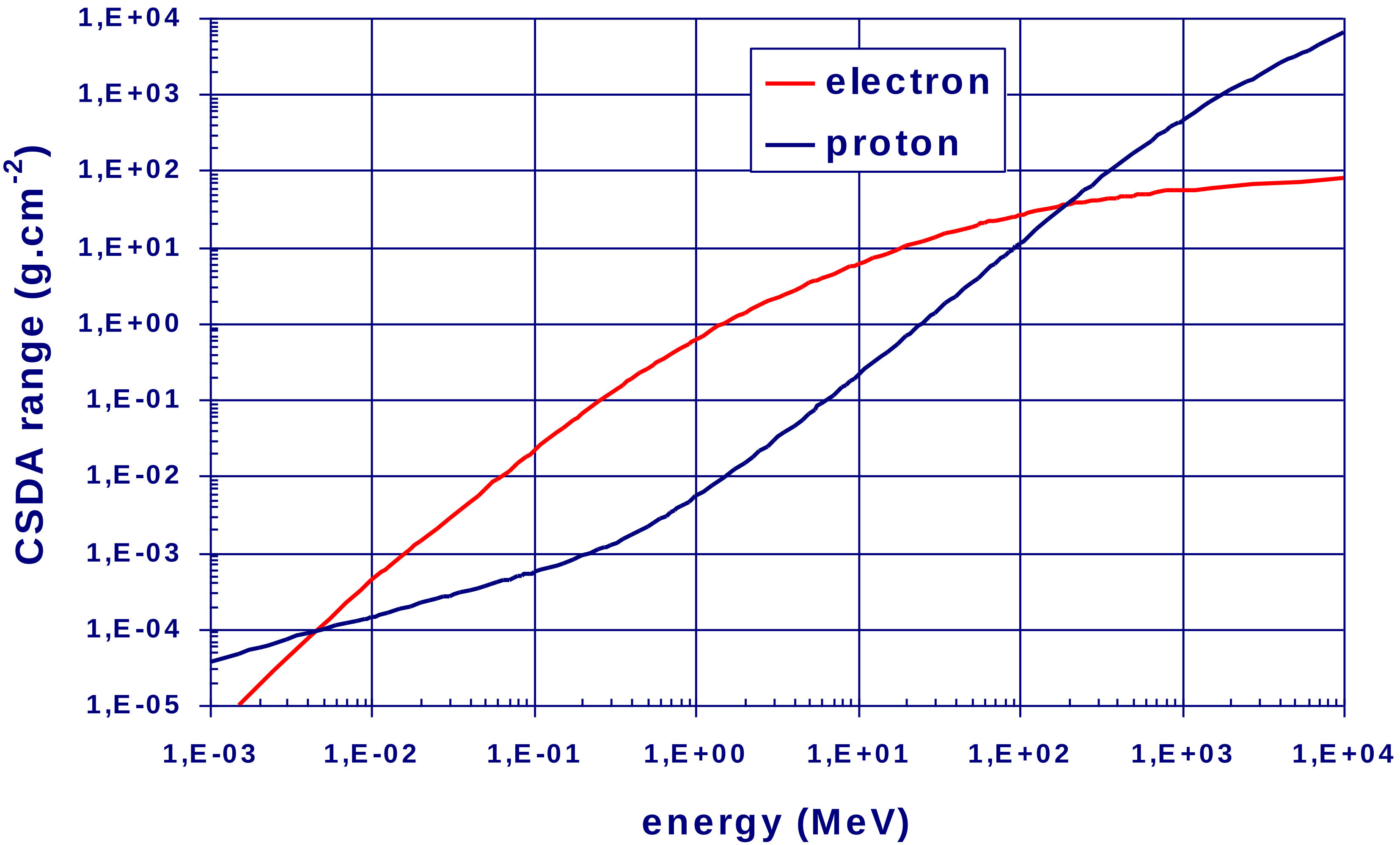
The physical processes

1. ionisation
2. inelastic proton-nucleus scattering
   spallation

Proton ionisation loss - Stopping power

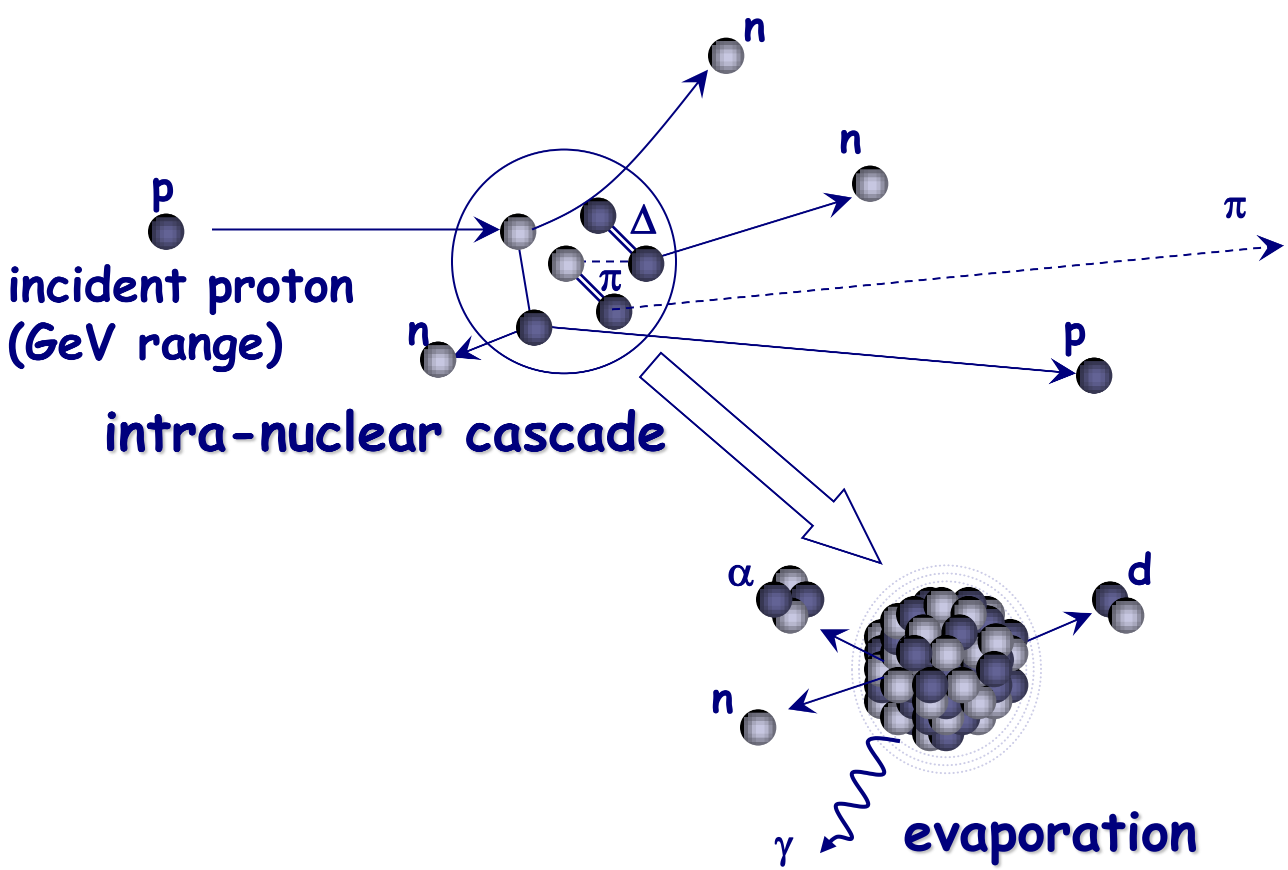


Comparison CSDA range of protons and electrons in iron



Inelastic proton – nucleus scattering

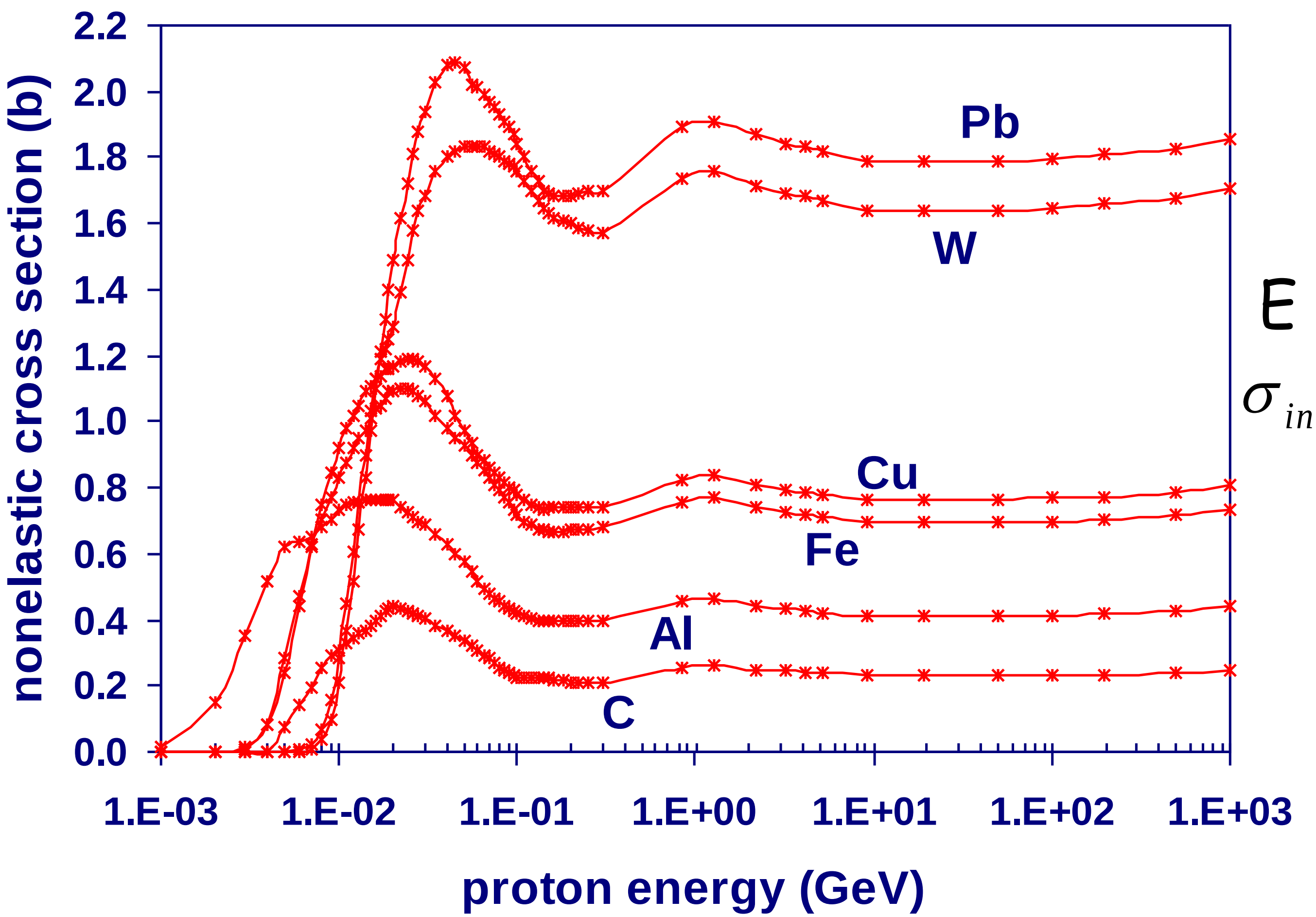
Spallation reaction



Inelastic proton – nucleus scattering

Spallation reaction

Inelastic cross section

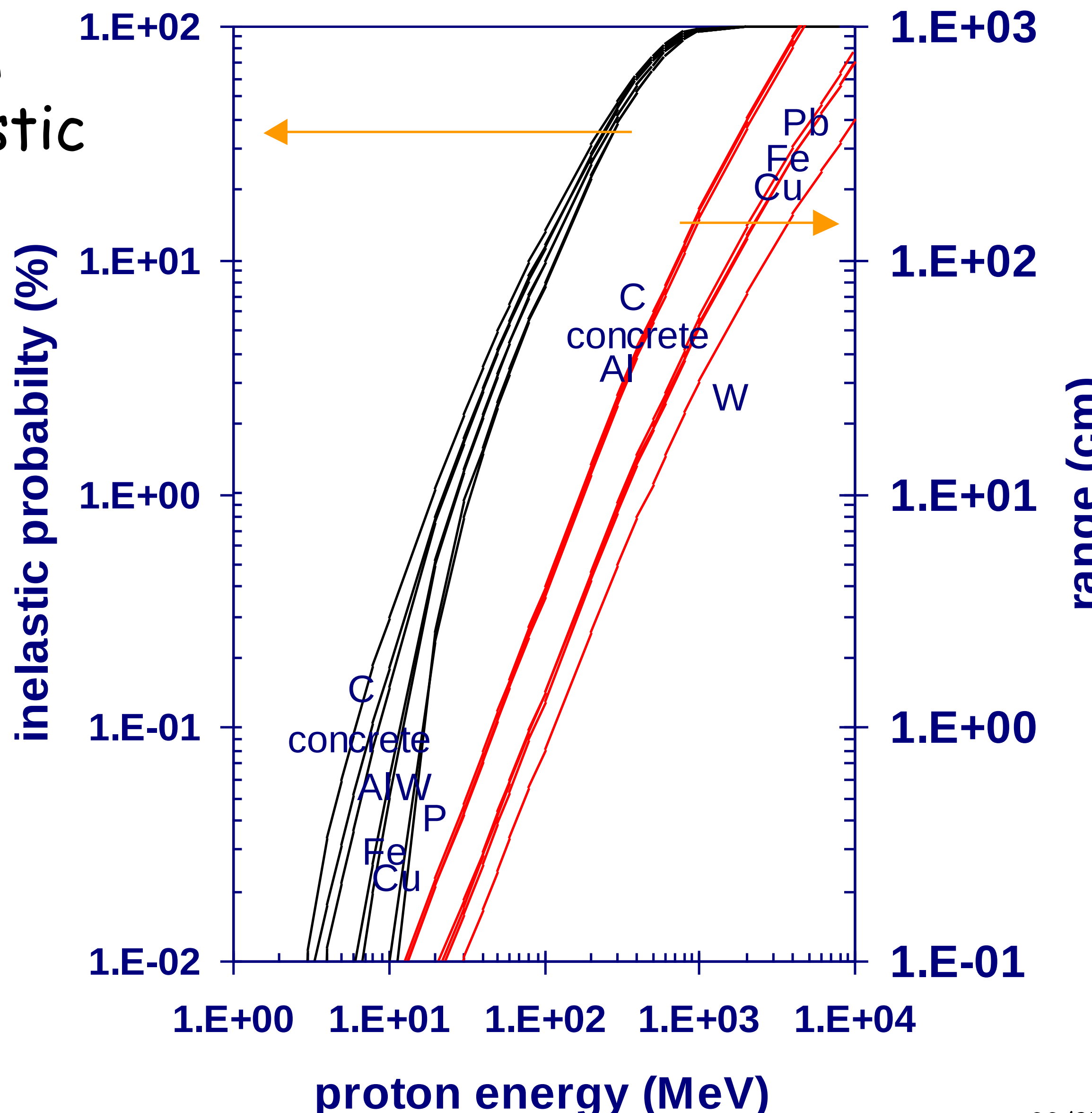


E > 1 GeV

$$\sigma_{inel} = 0.042 \times A^{0.7} barn.$$

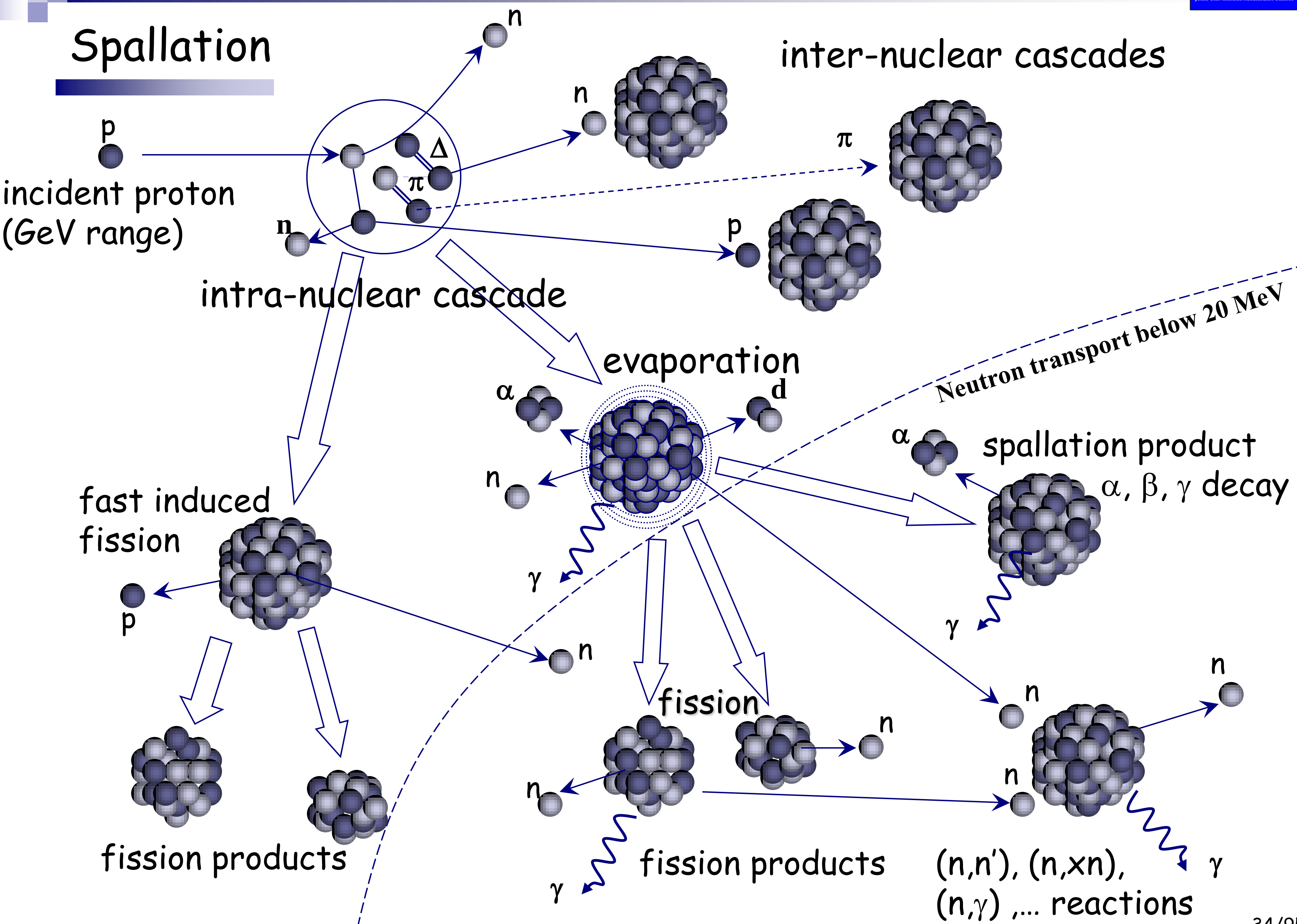
Inelastic proton – nucleus scattering

Comparison ionisation energy loss and inelastic scattering

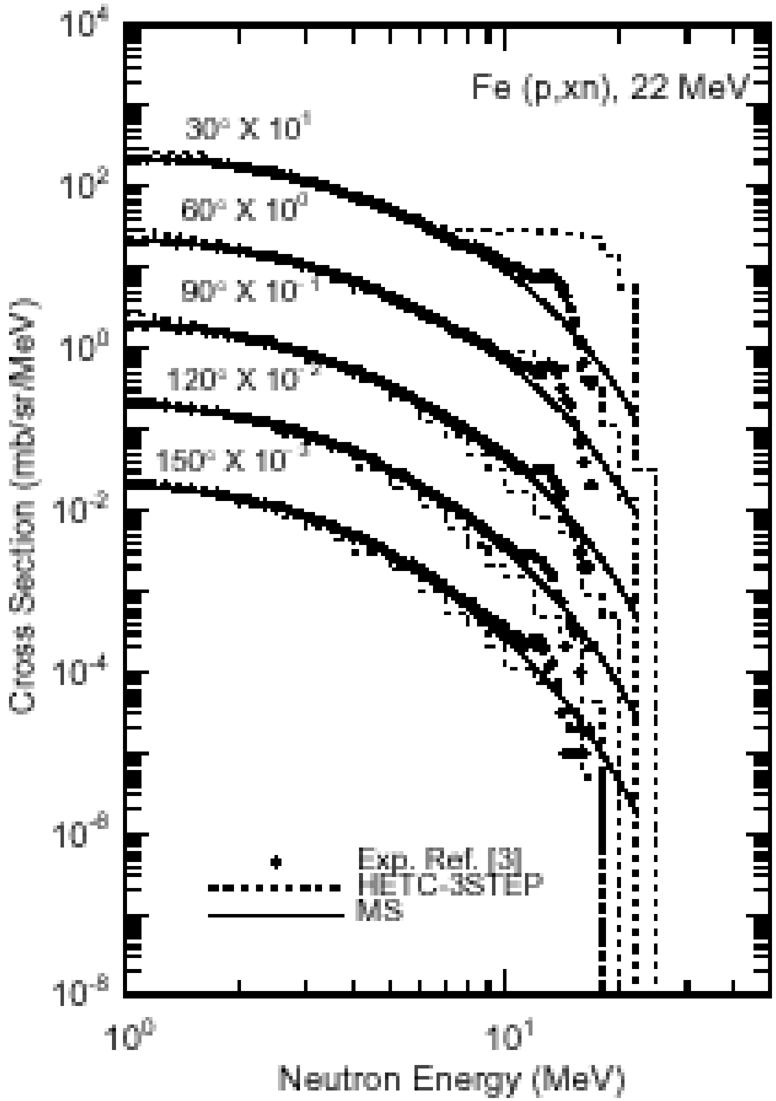


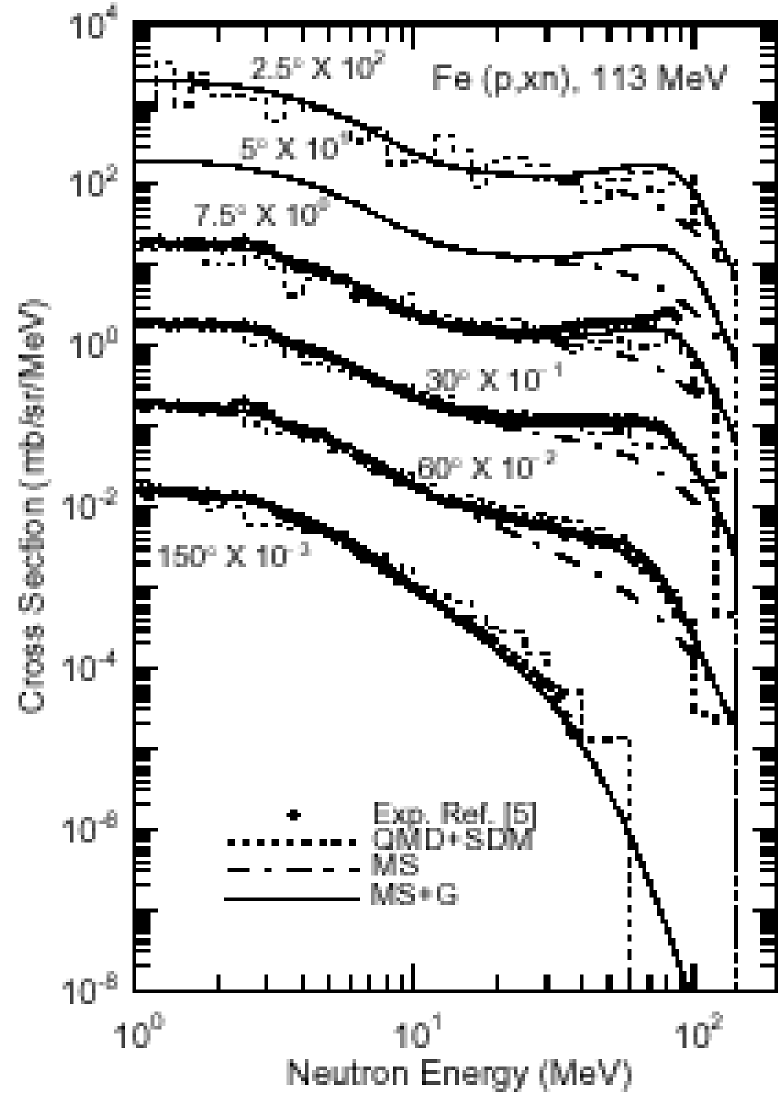
→ E > 1 GeV:
100 % probability
for spallation reaction

Spallation


p
incident proton
(GeV range)
n
Δ
π
n
p
inter-nuclear cascades
n
π
p
intra-nuclear cascade
evaporation
Neutron transport below 20 MeV
α
d
n
γ
α
spallation product
α, β, γ decay
γ
fast induced
fission
p
n
fission
n
n
n
n
n
γ
fission products
fission products
(n,n'), (n,xn),
(n,γ) ,... reactions
γ

Spallation


Fe (p,xn), 22 MeV
30° X 10^1
60° X 10^0
90° X 10^-1
120° X 10^-2
150° X 10^-3
Exp. Ref. [3]
HETC-3STEP
MS
Cross Section (mb/sr/MeV)
Neutron Energy (MeV)


Fe (p,xn), 113 MeV
2.5° X 10^2
5° X 10^1
7.5° X 10^0
30° X 10^-1
60° X 10^-2
150° X 10^-3
Exp. Ref. [5]
QMD+SDM
MS
MS+G
Cross Section (mb/sr/MeV)
Neutron Energy (MeV)

Radiation and Safety

P. Berkvens

1. radiation physics
   - interaction of electrons with matter
   - interaction of photons with matter
   - interaction of neutrons with matter
   - interaction of protons with matter

2. radiation protection
   - definitions
   - rules

3. radiation fields around accelerators
   - electron accelerators
   - proton accelerators
   - synchrotron radiation facilities

4. induced activity

5. radiation monitors

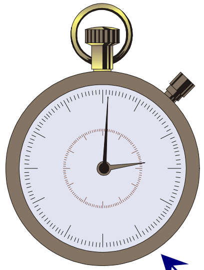
Introduction to radiation protection

$$\frac{dN}{dt} = -\lambda N(t)$$

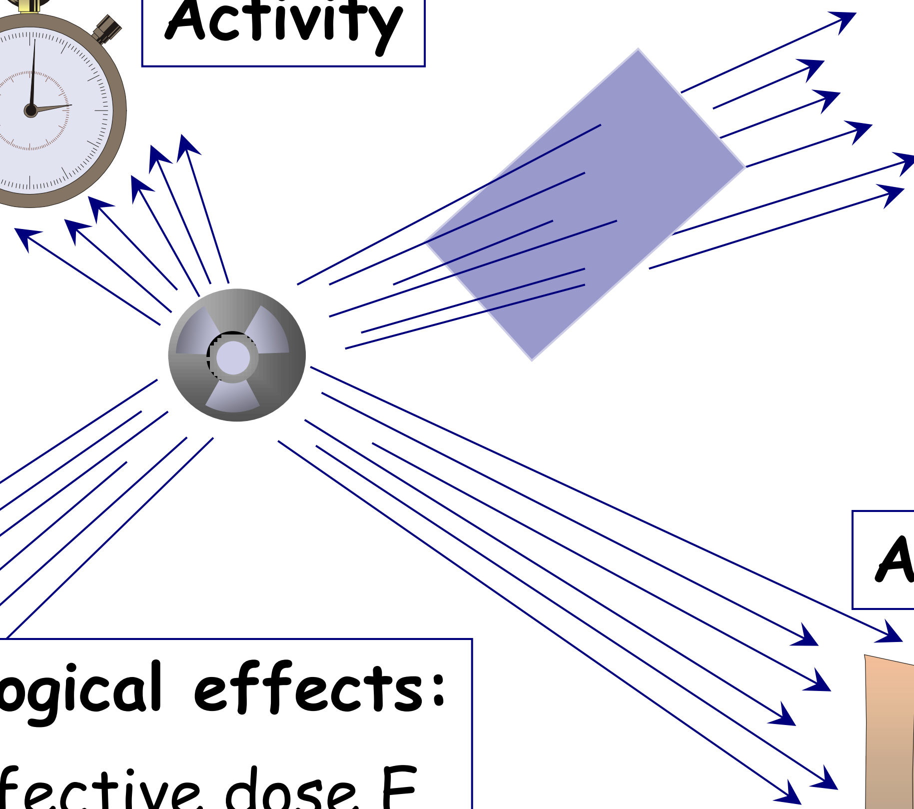
$$N(t) = N(0)e^{-\lambda t}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

becquerel (Bq):
1 Bq = 1 s^{-1}
(curie (Ci):
1 Ci = 3.7 10^{10} Bq)



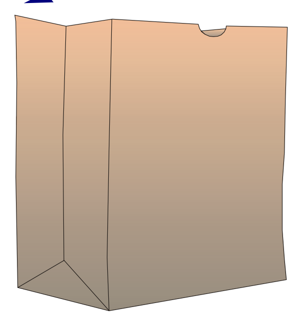
Activity



Fluence F

particles per cm²
~ 1/distance²

Absorbed dose D



$$D = \frac{d\bar{\varepsilon}}{dm}$$

$$\dot{D} = \frac{dD}{dt}$$

gray (Gy): 1 Gy = 1 $J.kg^{-1}$
(rad: 1 rad = 0.01 Gy)

Biological effects:

Effective dose E

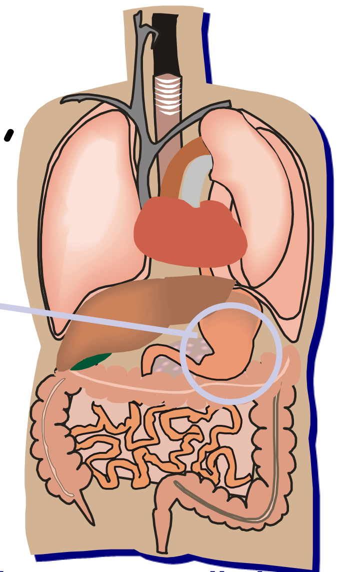
Ambient dose equivalent H*(d)

International Commission on Radiological Protection (ICRP)
Protection quantities - ICRP Publication 60 (1991)

Organ dose D_T

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

Individual organ, e.g. stomach



Tissue or organ equivalent dose $H_{T,R}$

$$H_{T,R} = w_R \cdot D_{T,R}$$

$$H_T = \sum_R w_R \cdot D_{T,R}$$

Unit of equivalent dose: J.kg^{-1}
Special name: sievert (Sv)
Old unit: rem (1 Sv = 100 rem)

Type and energy range of radiation	Radiation weighting factor w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons	
< 10 keV	10
10 - 100 keV	5
> 100 keV to 2 MeV	10
>2 - 20 MeV	20
> 20 MeV	10
	5
Protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

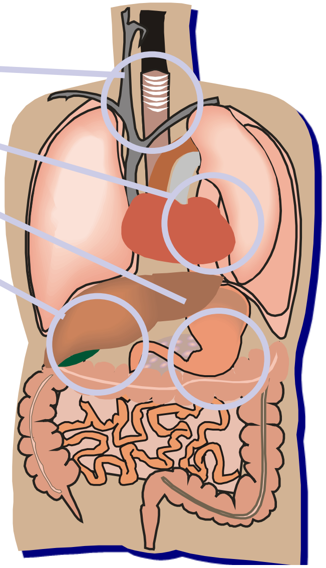
International Commission on Radiological Protection (ICRP)
Protection quantities - ICRP Publication 60 (1991)

Effective dose E

$$E = \sum_T w_T \cdot H_T$$

Unit of effective dose: Sv

Σ different organs

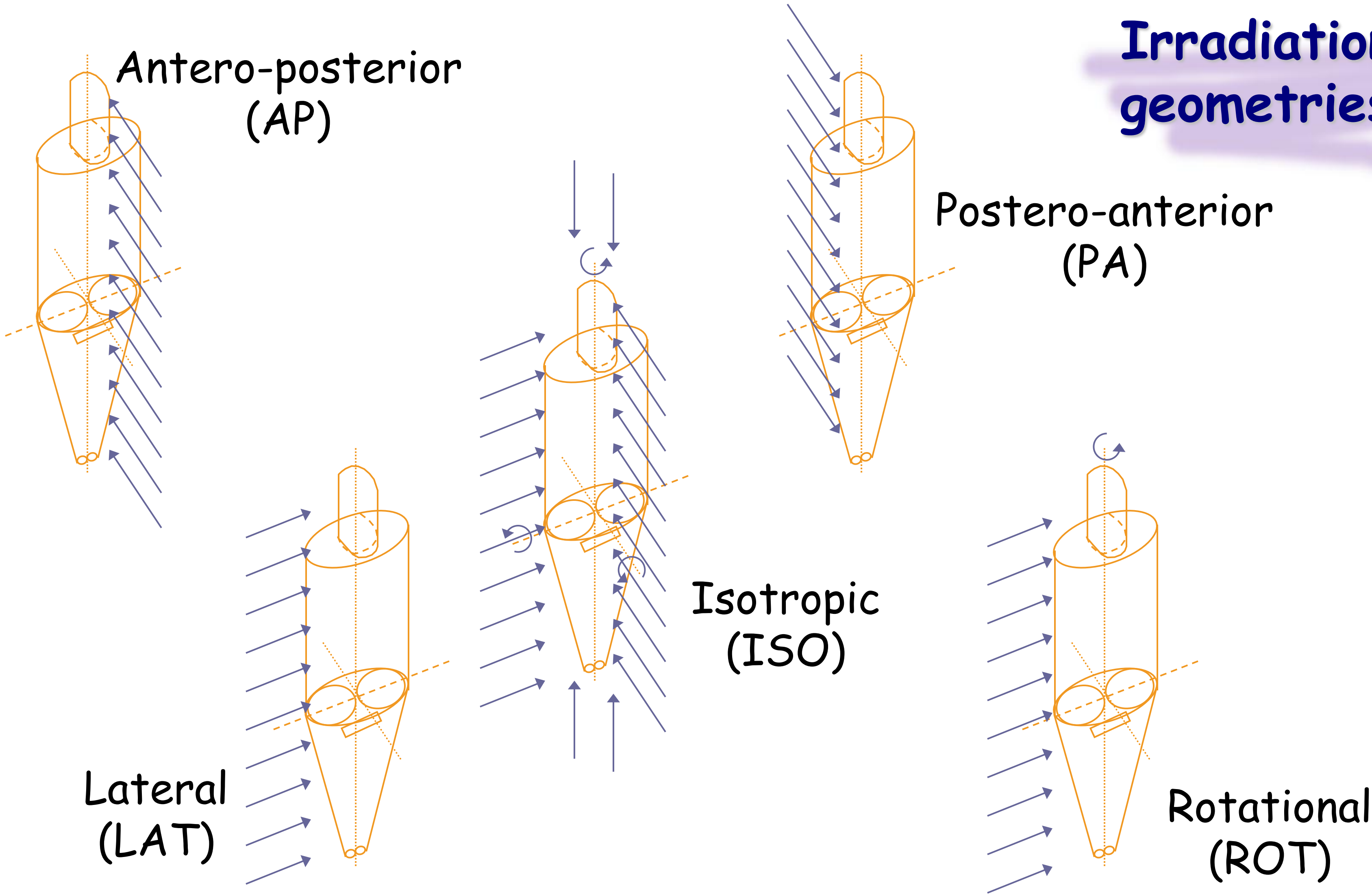


Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Dose limits on:
- *Effective dose E*
- *Tissue or organ equivalent dose H_T*

International Commission on Radiological Protection (ICRP)
Protection quantities - ICRP Publication 60 (1991)

Irradiation geometries



International Commission on Radiological Protection (ICRP) Protection quantities - ICRP Publication 60 (1991)

Basic principles

- Radiation protection measures must guarantee that deterministic radiation damage is avoided. Since deterministic damage appears above a threshold dose, this dose must not be exceeded.
- The probability of stochastic radiation damage, which has no threshold dose according to the dose-effect relationships currently taken as a basis, must not exceed a justifiable size.

ICRP Publication 60

- The necessity of justifying each radiation application by its benefits.
- The demand for optimising radiation protection measures:

  → ALARA principle: As Low As Reasonably Achievable.
- The establishment of individual limits for radiation exposure of people on the basis of a justifiable risk.

International Commission on Radiological Protection (ICRP) Protection quantities - ICRP Publication 60 (1991)

Application	Dose limit	
	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years, not exceeding 50 mSv in any single year	1 mSv in a year
Annual equivalent dose in		
The lens of the eye	150 mSv	15 mSv
The skin	500 mSv	50 mSv
The hands and feet	500 mSv	-

radiation workers	20 mSv $.y^{-1}$ 10 μSv$.h^{-1}$ *
non-exposed workers	1 mSv $.y^{-1}$ 0.5 μSv $.h^{-1}$ *
public	1 mSv $.y^{-1}$ 0.11 μSv $.h^{-1}$ **

* 2000 working hours/year
** 8760 hours/year

International Commission on Radiological Protection (ICRP)
Protection quantities - ICRP Publication 103 (2007)

	ICRP 60	ICRP 103
Gonads	0.20	0.08
Bone marrow (red)	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Oesophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone surface	0.01	0.01
Brain	-	0.01
Salivary gland	-	0.01
Remainder	0.05	0.12
Total	1	1

Tissue weighting factor w_T

$$2.5 + 18.2\, e^{-[\ln E_n]^2/6}, \quad E_n < 1\,\mathrm{MeV}$$
$$5.0 + 17.0\, e^{-[\ln 2E_n]^2/6}, \quad 1\,\mathrm{MeV} \le E_n \le 50\,\mathrm{MeV}$$
$$2.5 + 3.25\, e^{-[\ln 0.04E_n]^2/6}, \quad E_n > 50\,\mathrm{MeV}$$

neutrons

protons: 2

ICRP Publication 103

-

Radiation weighting factor w_R

International Commission on Radiation Units and Measurements ICRU Report 51 (1993)

Protection quantities (ICRP) → operational quantities

Dose equivalent

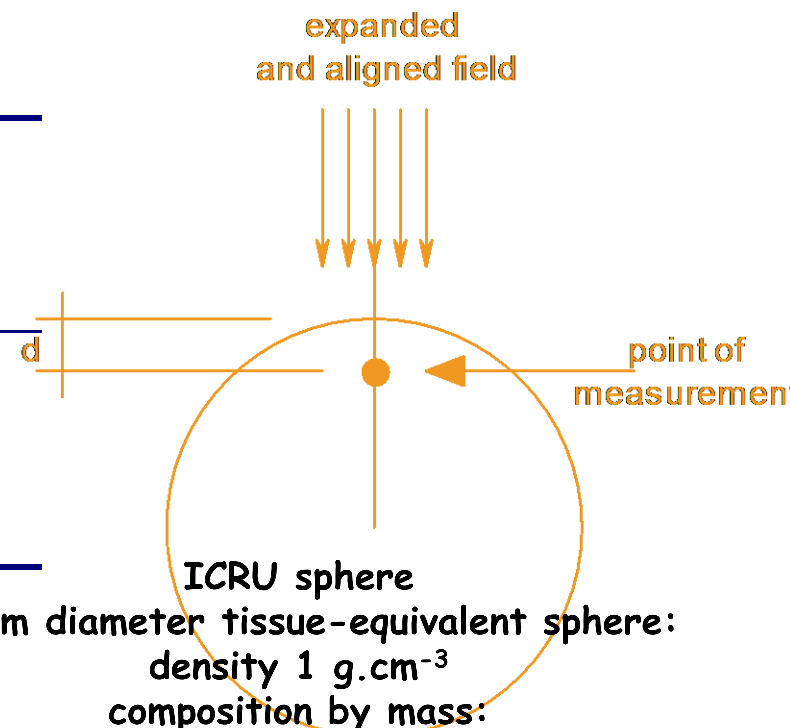
$$H = Q \cdot D$$

Unit of dose equivalent: Sv

Unrestricted linear energy transfer L ($keV \cdot \mu m^{-1}$)	Quality factor Q
$L < 10$	1
$10 \leq L \leq 100$	$0.32\ L - 2.2$
$L > 100$	$300 / L^{1/2}$

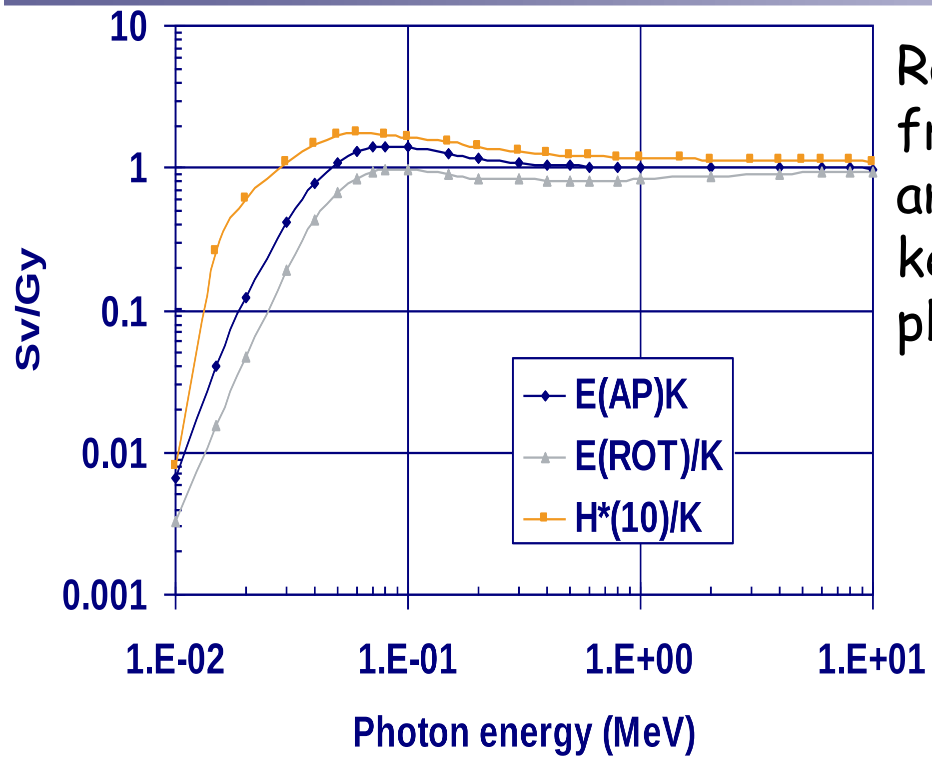
Ambient dose equivalent H*(d)

→ H*(10) ***(d = 10 mm)***



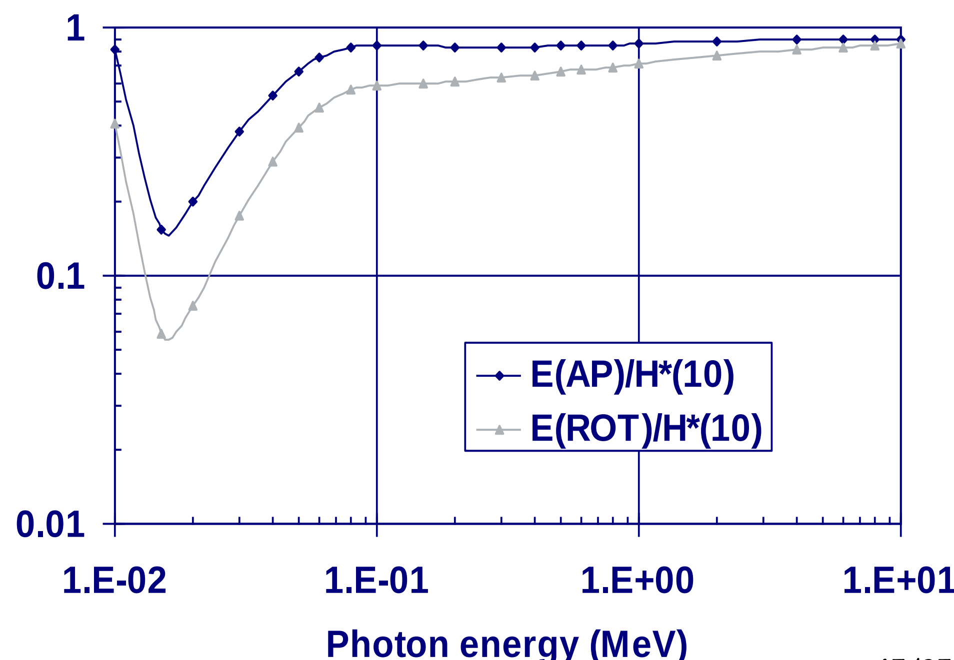
ICRU sphere
30 cm diameter tissue-equivalent sphere:
density 1 $g.cm^{-3}$
composition by mass:
76.2 % O, 11.1 % C, 10.1 % H and 2.6 % N

Comparison between protection quantities (ICRP) and operational quantities (ICRU) - ICRU Report 57 (1998)

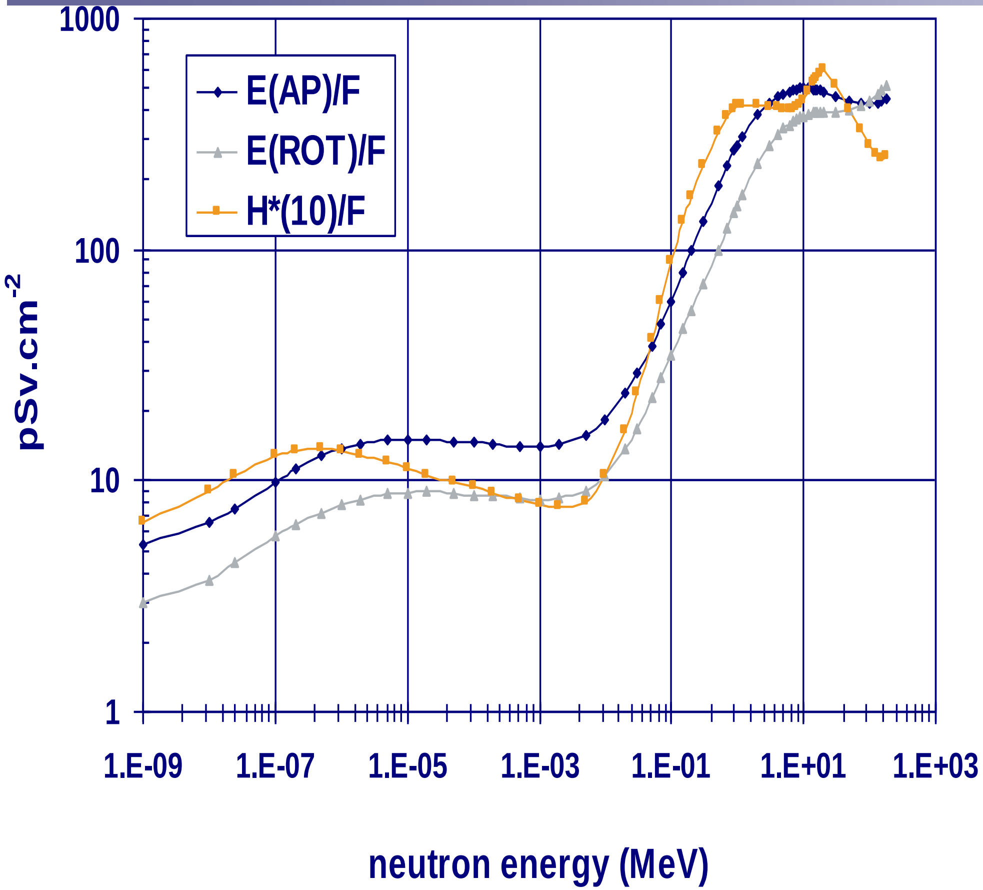


Ratio of effective dose E to air kerma free-in-air (AP and ROT) and ratio of ambient dose equivalent H*(10) to air kerma free-to-air as a function of photon energy.

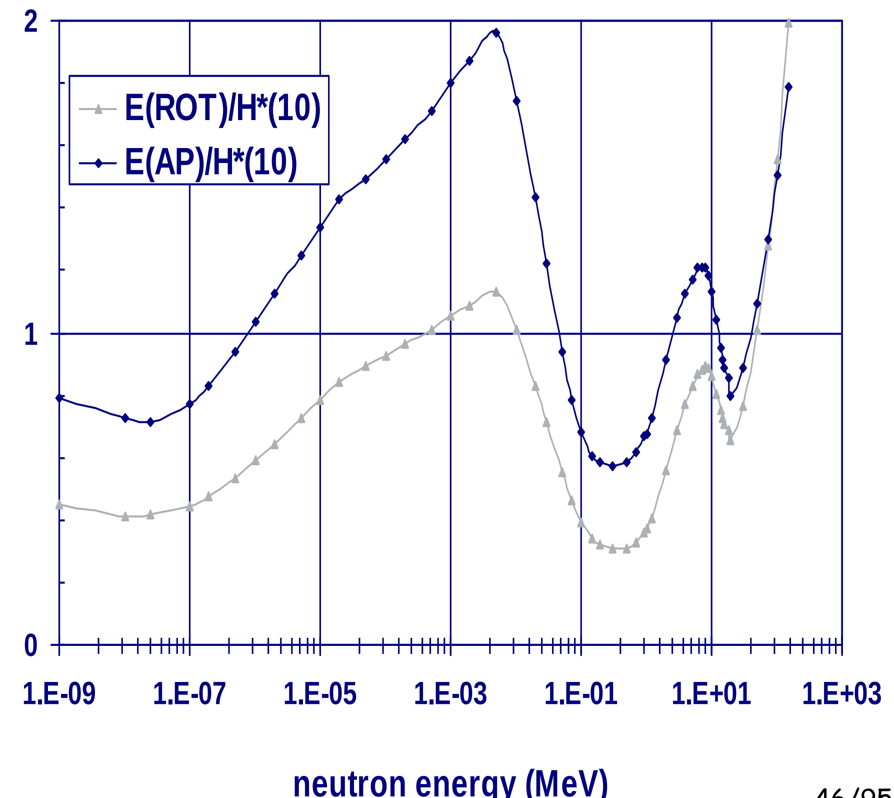
Ratio of effective dose E (AP and ROT) to ambient dose equivalent H*(10) as a function of photon energy.



Comparison between protection quantities (ICRP) and operational quantities (ICRU) - ICRU Report 57 (1998)



Effective dose E per unit neutron fluence (AP and ROT) and ambient dose equivalent H*(10) per unit neutron fluence as a function of neutron energy.



Ratio of effective dose E (AP and ROT) to ambient dose equivalent H*(10) as a function of neutron energy.

Radiation and Safety

P. Berkvens

1. radiation physics
   - interaction of electrons with matter
   - interaction of photons with matter
   - interaction of neutrons with matter
   - interaction of protons with matter
2. radiation protection
   - definitions
   - rules
3. radiation fields around accelerators
   - electron accelerators
   - proton accelerators
   - synchrotron radiation facilities
4. induced activity
5. radiation monitors

Prompt radiation fields around accelerators

electron accelerators

photons (bremsstrahlung)
neutrons

proton accelerators

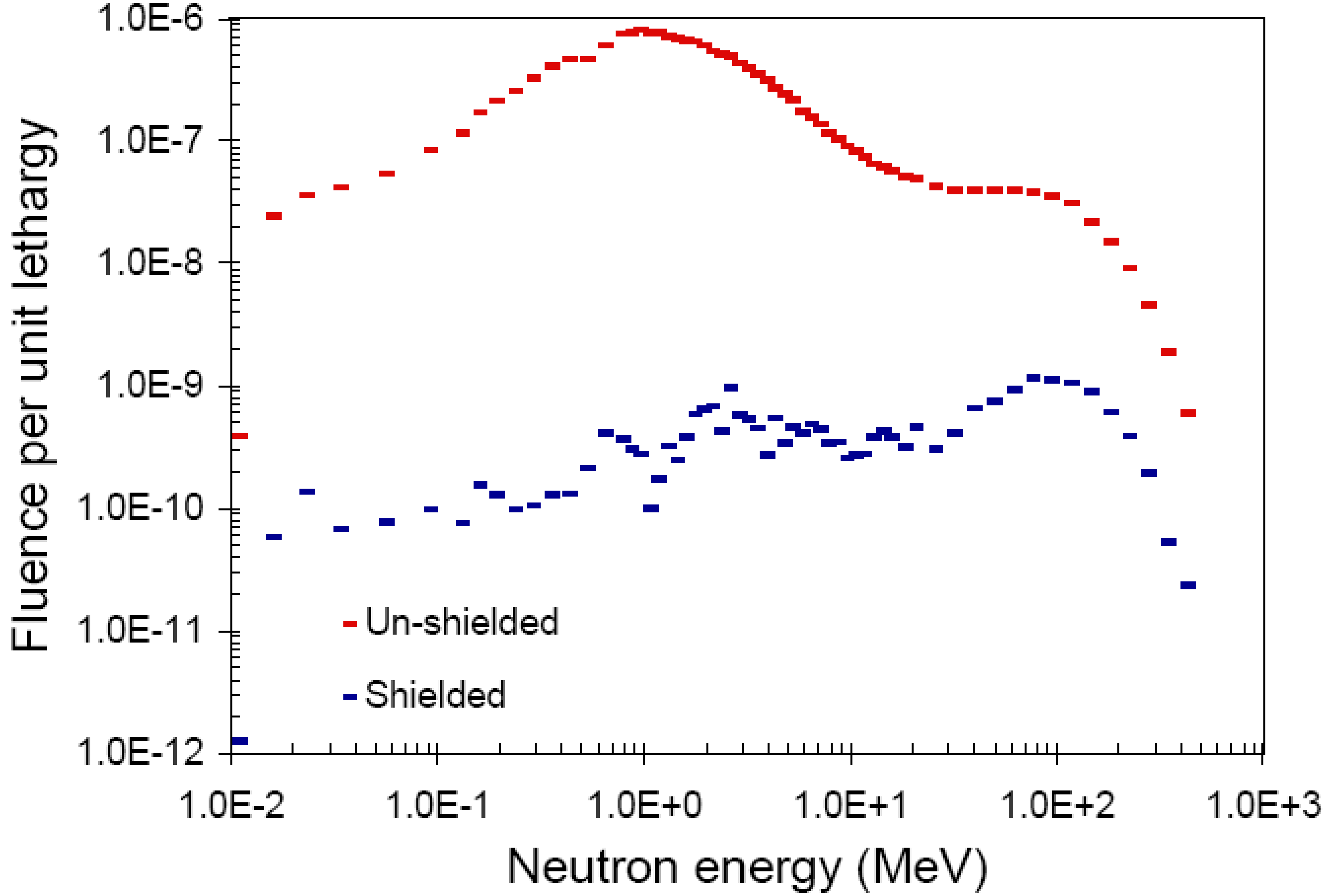
neutrons

synchrotron radiation facilities

accelerators
beamlines

Radiation fields around electron accelerators

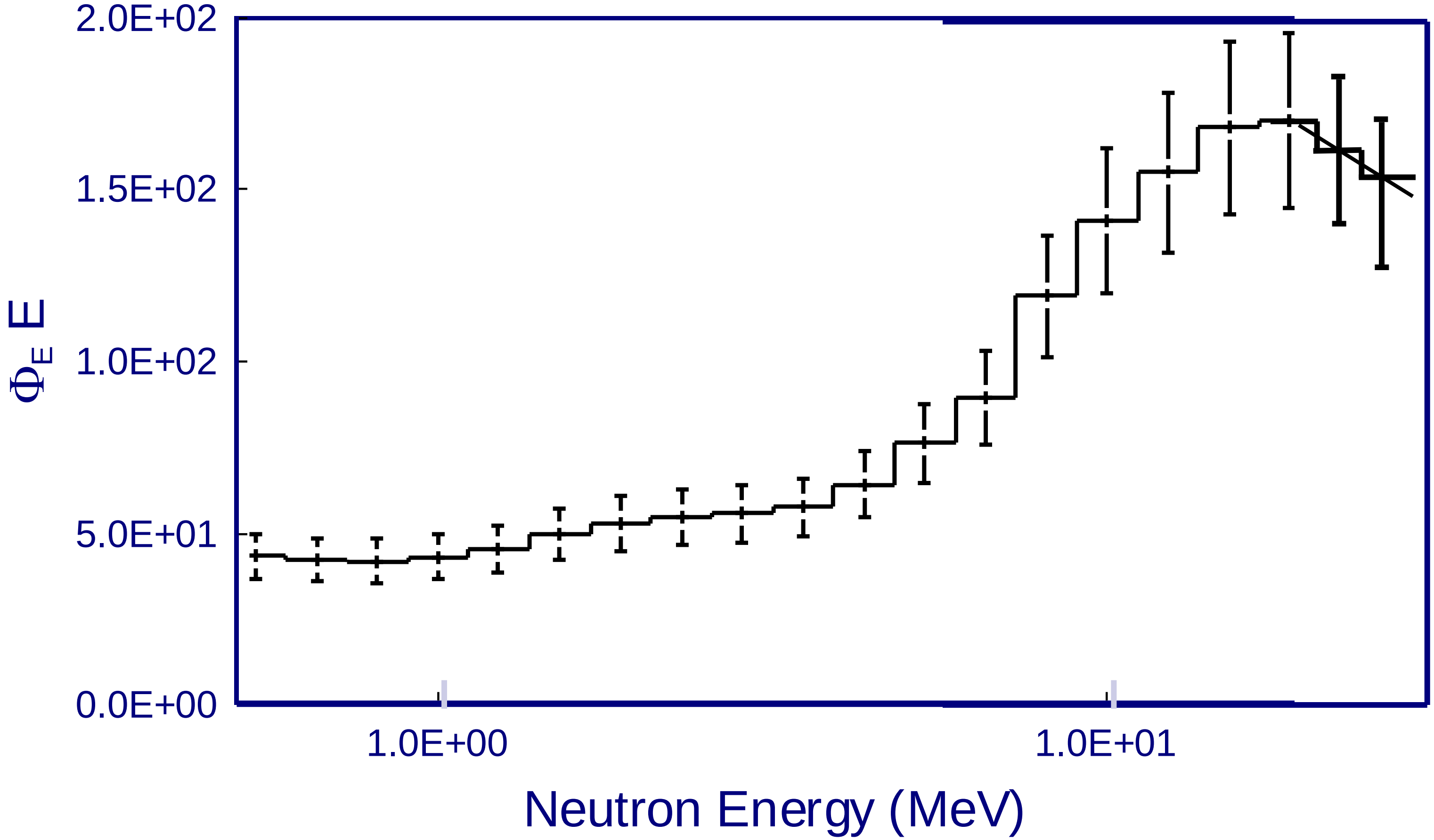
Examples of neutron spectra



Example 1: calculated neutron spectra for the 1.7 GeV BESSY storage ring (Courtesy of Klaus Ott)

Radiation fields around electron accelerators

Examples of neutron spectra



Example 2: measured neutron spectrum on the roof of the 6 GeV ESRF storage ring (behind 1.2 m concrete shielding)

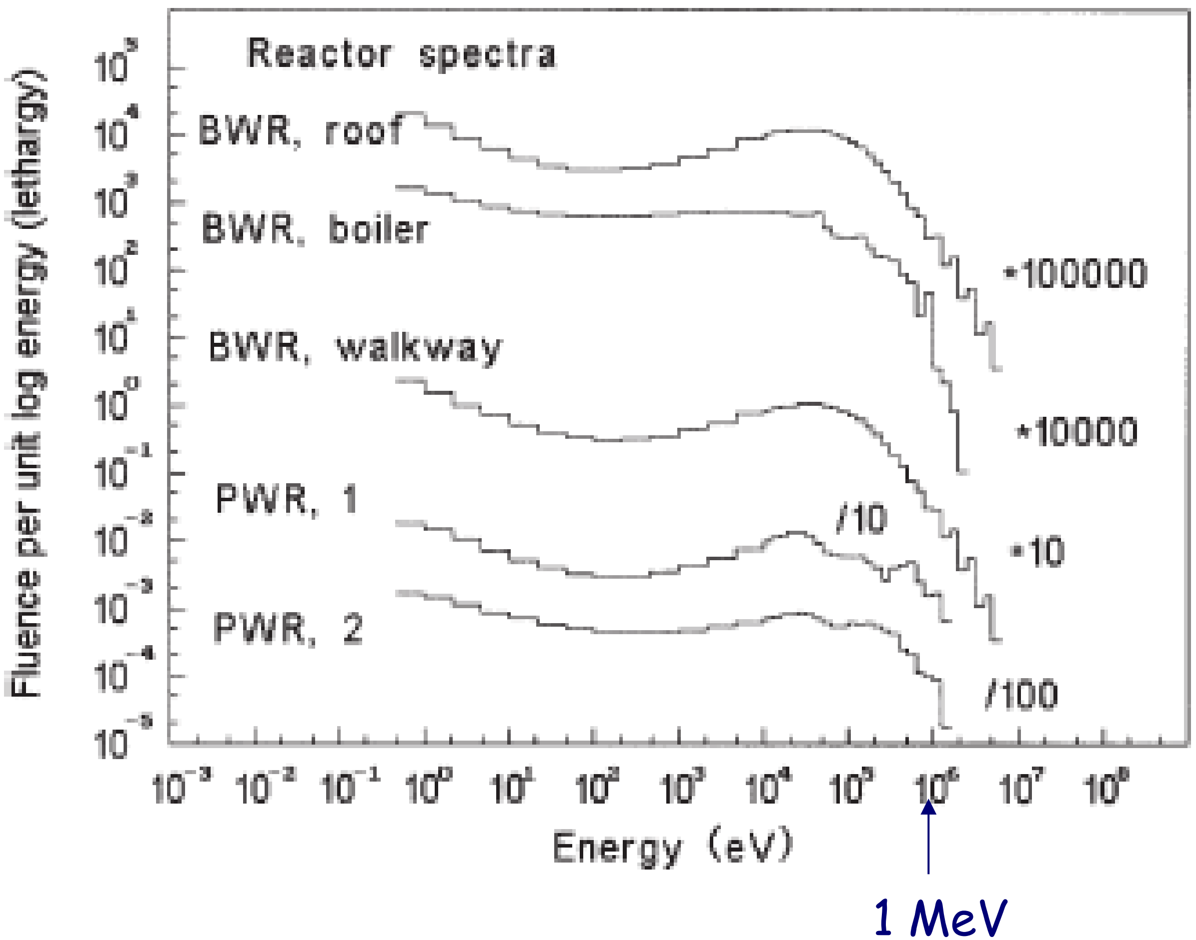
Radiation fields around proton accelerators

7 GeV proton synchrotron NIMROD

Type of radiation	Energy range	Estimated % of neutron flux density	Estimated % of total dose equivalent
Neutrons	< 1 eV	< 7	<1
Neutrons	1 eV – 0.7 MeV	70	20
Neutrons	0.7 – 3 MeV	15	35
Neutrons	3 – 7 MeV	7	25
Neutrons	7 – 20 MeV	1.5	5
Neutrons + protons	20 – 100 MeV	1	5
Neutrons + charged particles	> 100 MeV	0.5	4
Other particles + gammas	-	-	< 2

Radiation fields around proton accelerators

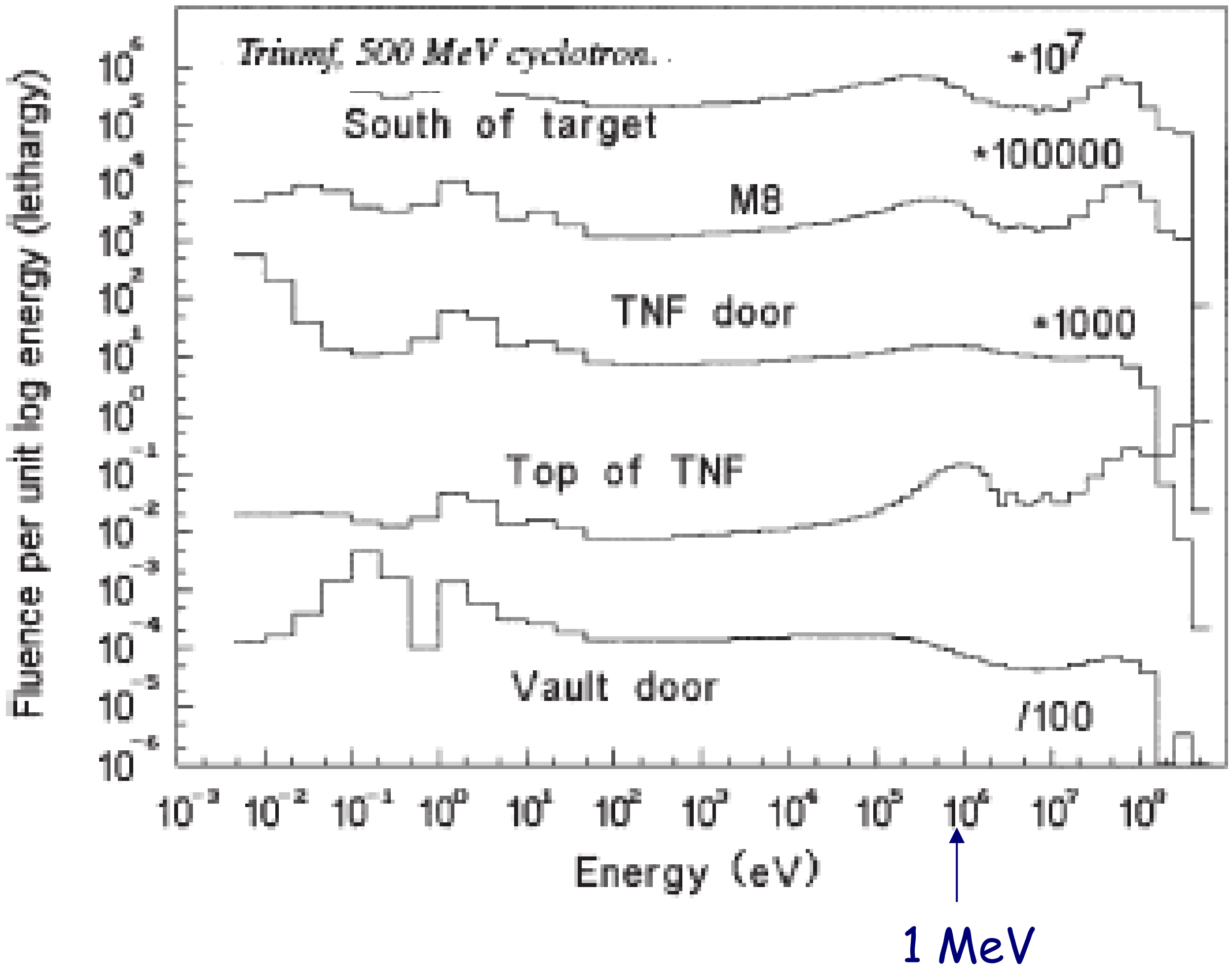
Examples of neutron spectra



Source: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes – Technical Reports Series no. 403 , IAEA, 2001

Radiation fields around proton accelerators

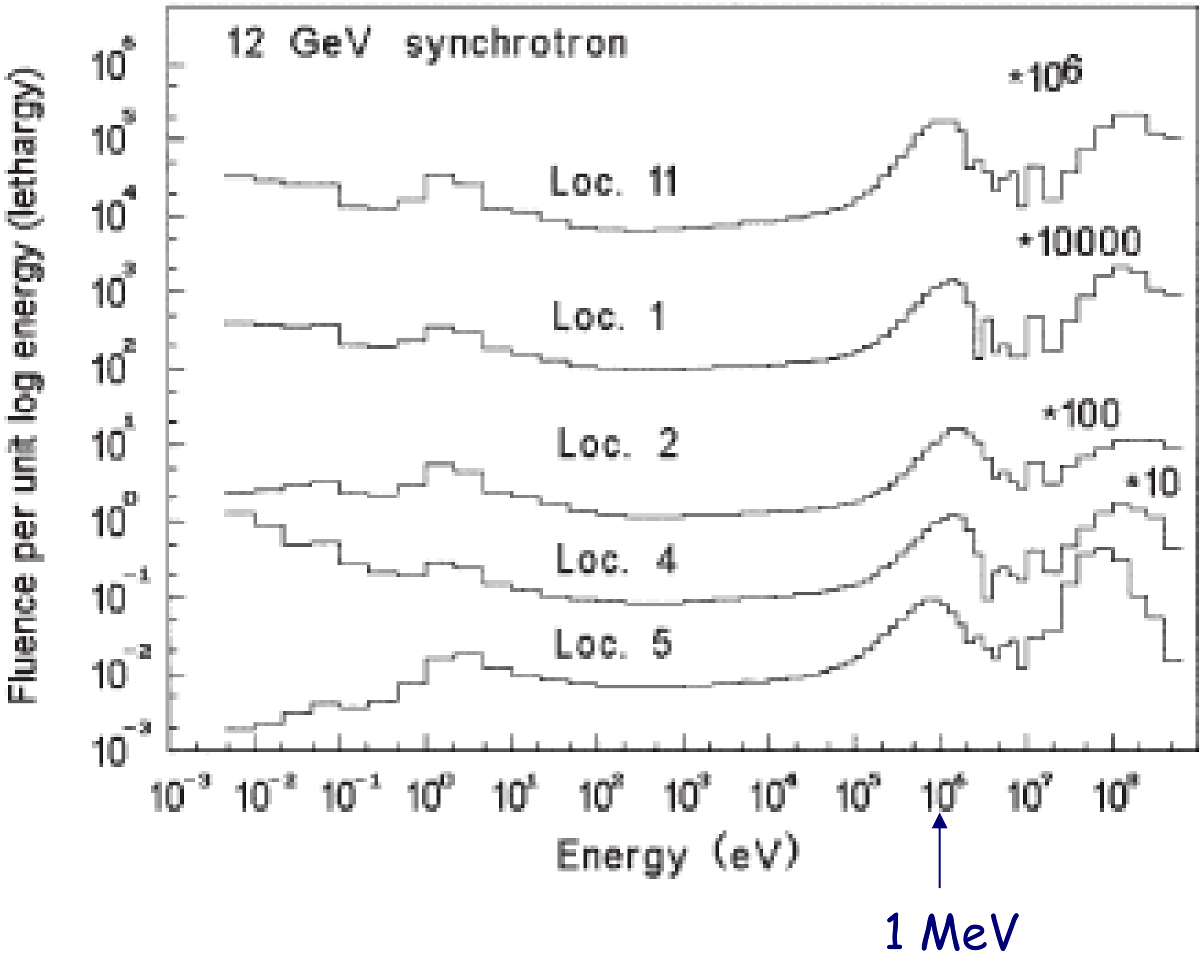
Examples of neutron spectra



Source: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes – Technical Reports Series no. 403 , IAEA, 2001

Radiation fields around proton accelerators

Examples of neutron spectra

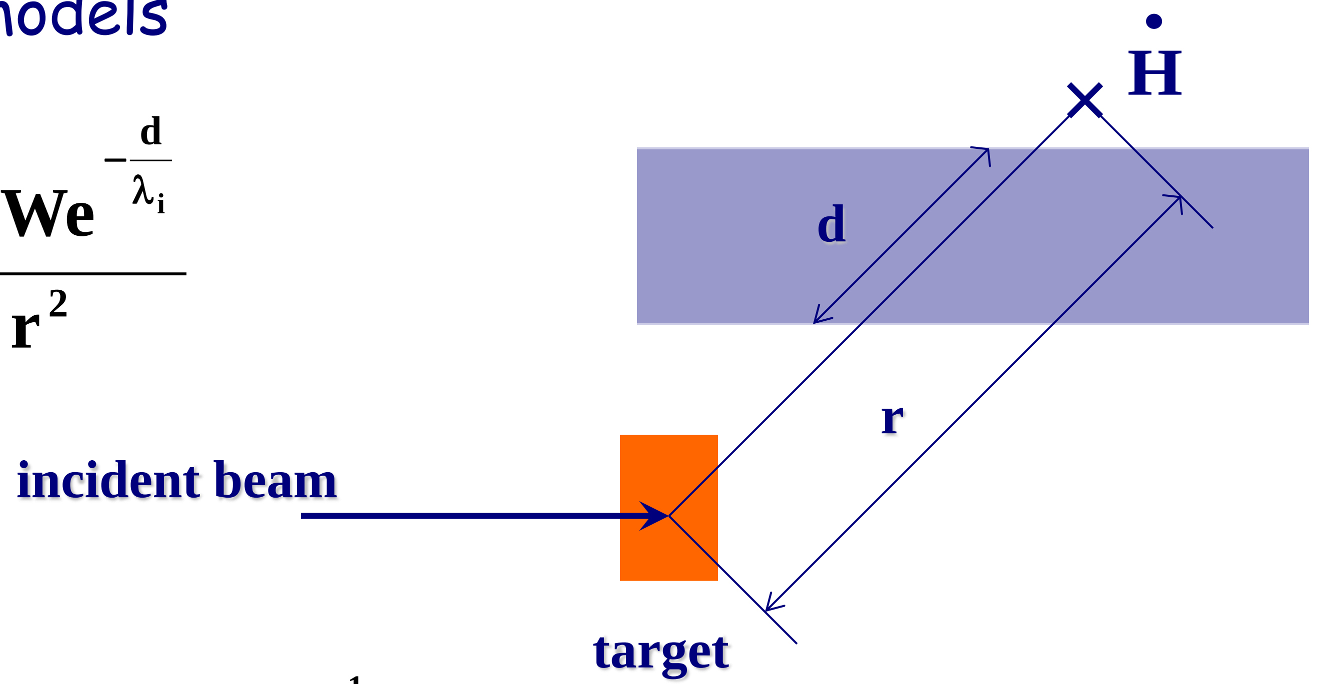


Source: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes – Technical Reports Series no. 403 , IAEA, 2001

Accelerator shielding

Analytical models

$$\dot{H} = \sum_i \frac{F_{H_i} W e^{-\frac{d}{\lambda_i}}}{r^2}$$



$\dot{H}$: dose equivalent rate, in Sv×h^{-1}

W: primary beam loss rate, in kW

F_{H_i} : fluence to (unshielded) dose equivalent conversion factor, in Sv×h^{-1} (kW×m^{-2})$^{-1}$

d: shield wall thickness, in g×cm^{-2}

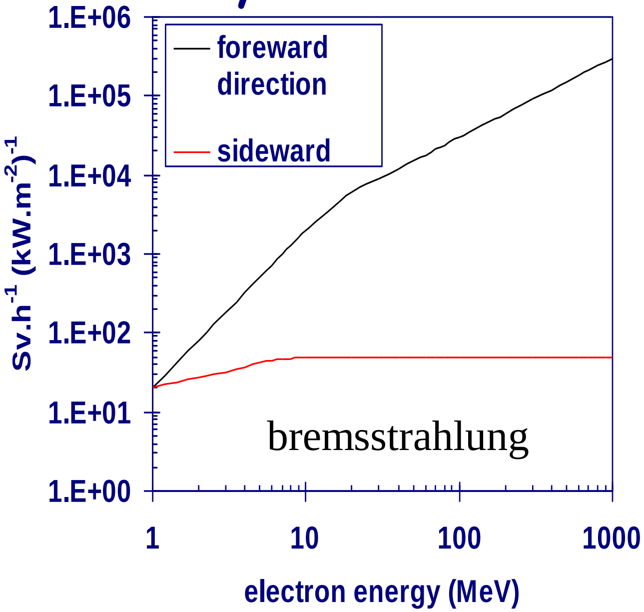
λ_i: attenuation length for the ith radiation component, in g×cm^{-2}

r: distance from the source to the dose point, in m

i: sum over different radiation components

Accelerator shielding: electron accelerator

Analytical models



secondary radiation	$Sv.h^{-1}.kW^{-1}$ at 1 m at 0 deg	at 90 deg
bremsstrahlung	300× E(MeV)	50
neutrons < 25 MeV	20	20
neutrons 25 - 100 MeV	-	2.4
neutrons > 100 MeV	9.2	0.72

F_{H_i} : fluence to (unshielded) dose equivalent conversion factor

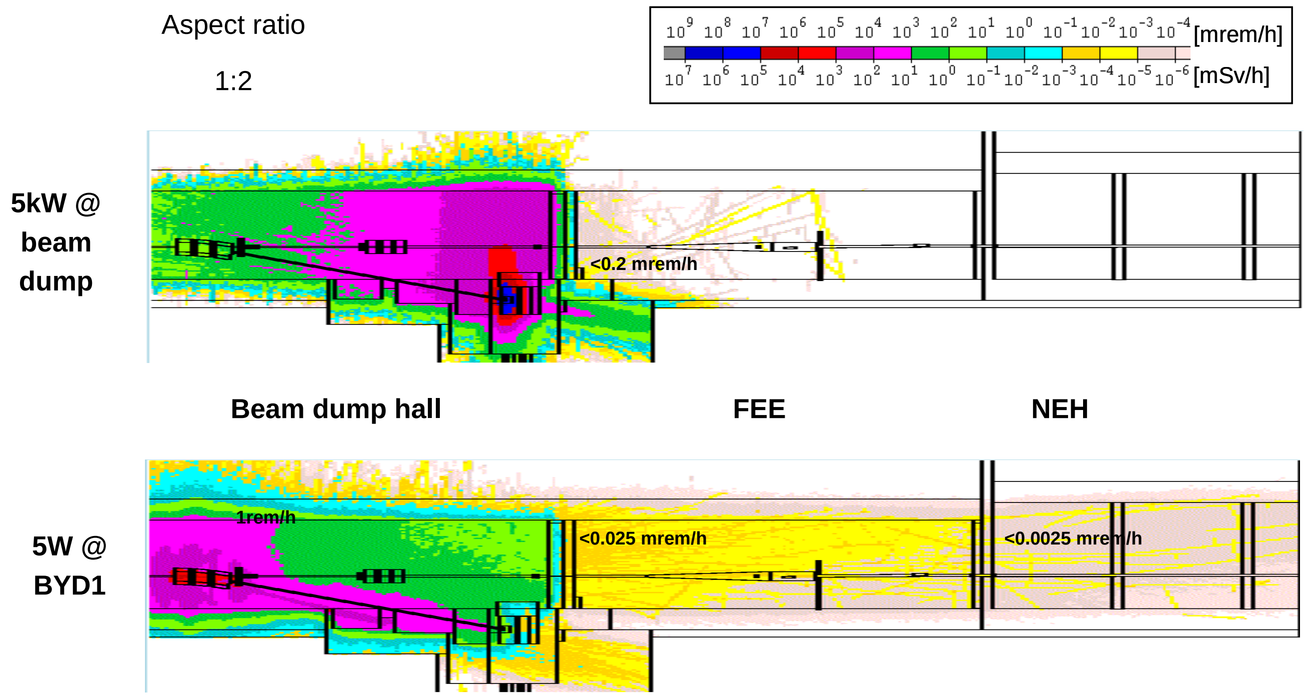
radiation	cm concrete	iron	lead
bremsstrahlung	21	4.7	2.4
neutrons < 25 MeV	18	16	-
neutrons 25 - 100 MeV	28	-	-
neutrons > 100 MeV	43	18	17

λ_i: attenuation length

Accelerator shielding

Monte-Carlo codes

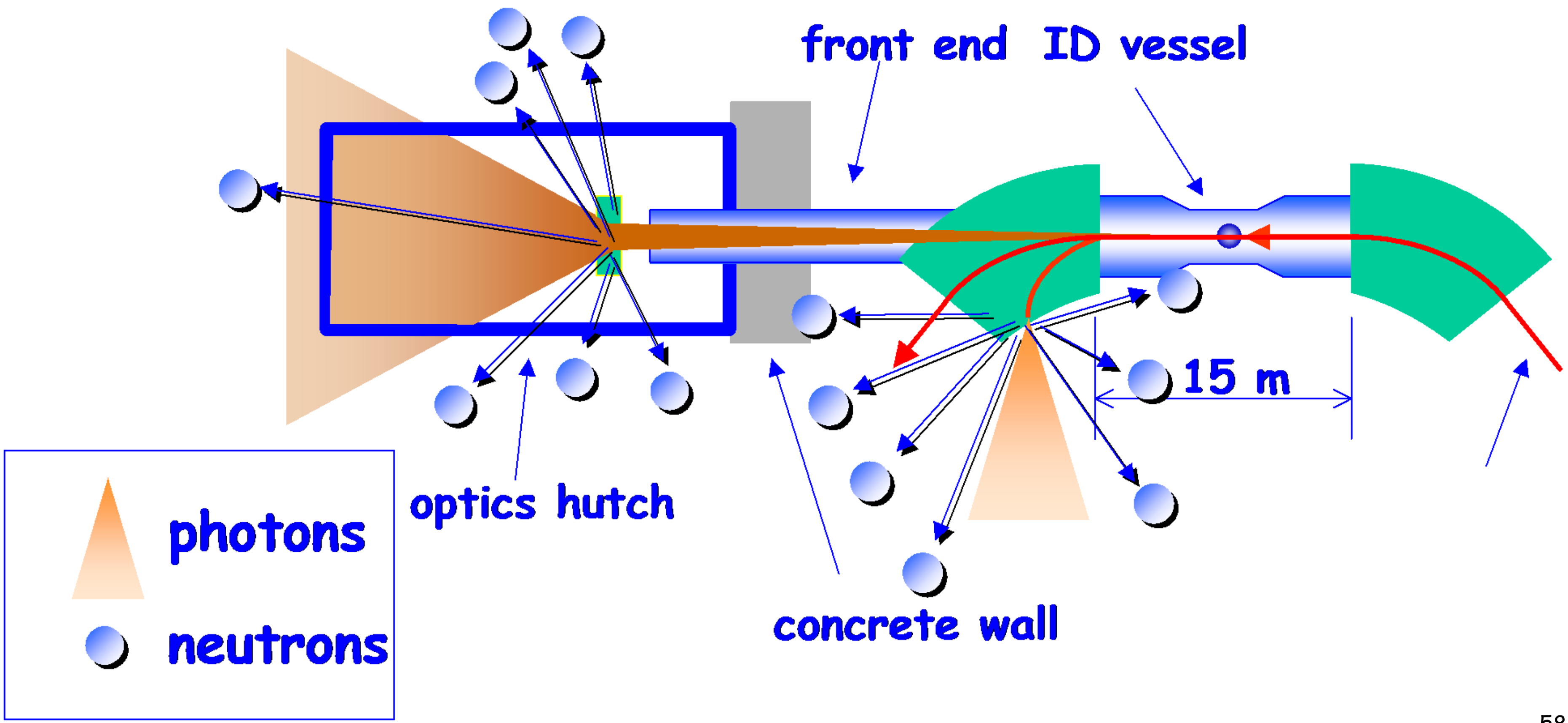
Examples: MCNPX
PENELOPE
FLUKA
MARS



Example: MARS calculation for the electron dump line of the LCLS facility - Courtesy of T. Sanami.

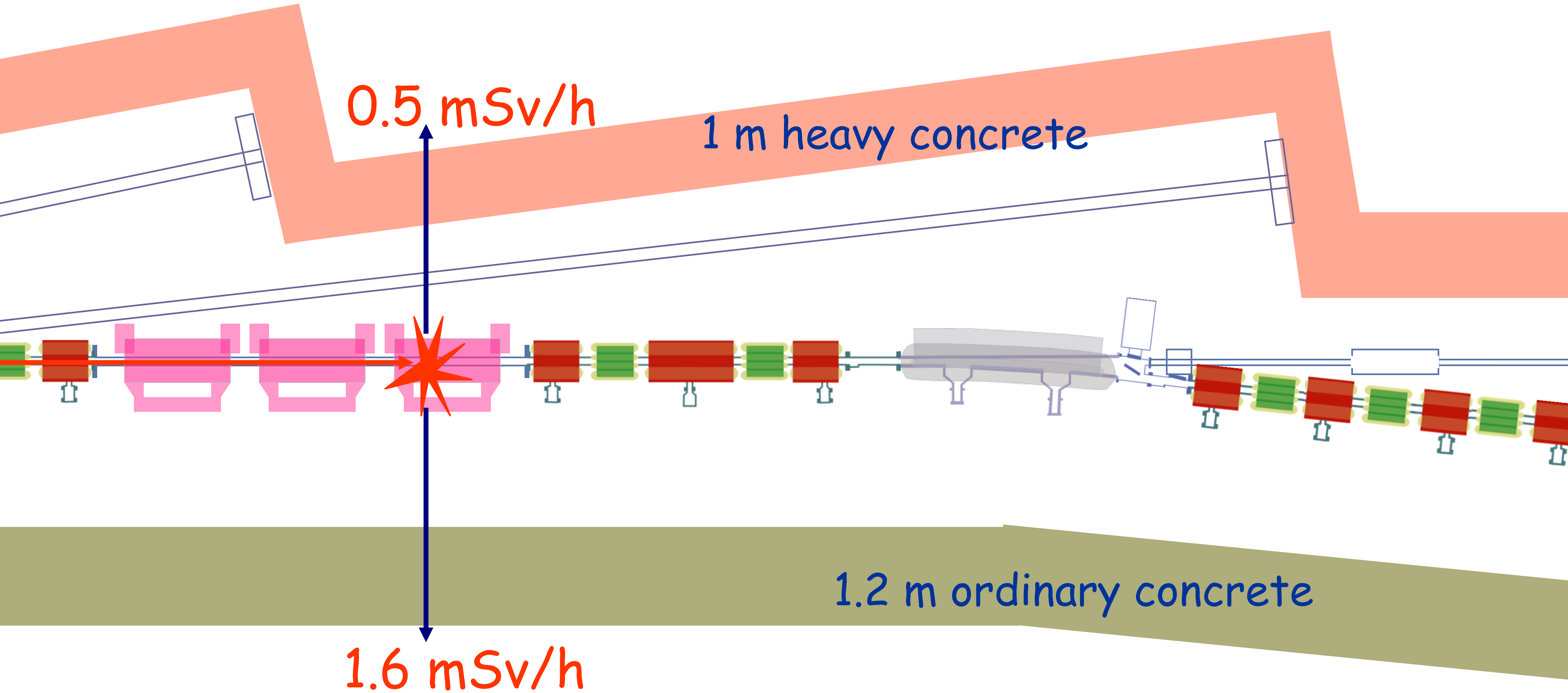
Synchrotron radiation facilities

Radiation fields
- Accelerator tunnels:
  - photons, neutrons
- Beamlines:
  - X-rays, photons, neutrons



Synchrotron radiation facilities

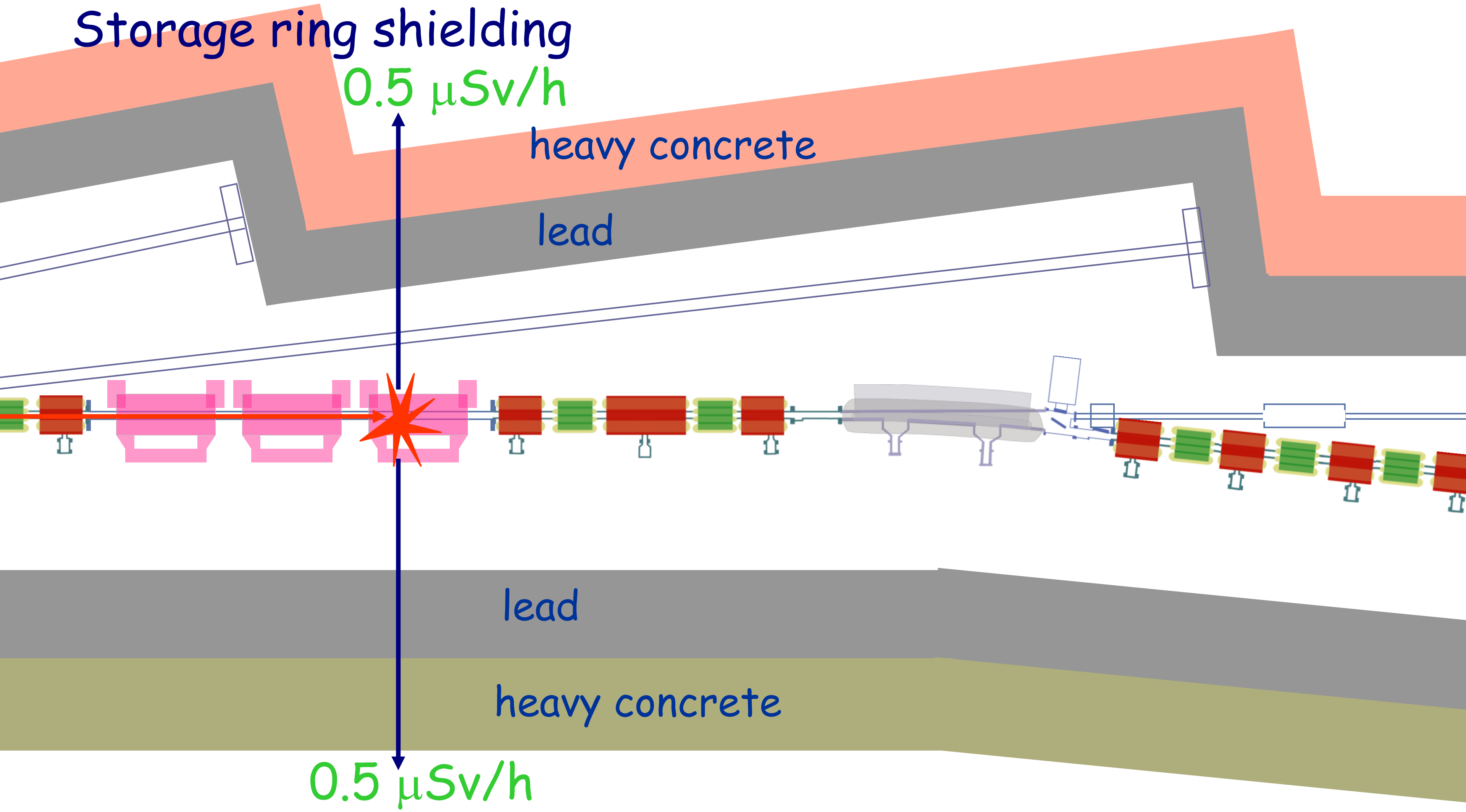
Storage ring shielding



Example: ESRF 6 GeV storage ring, continuous beam loss during injection:
10 mA, 1 μs, 1 Hz, 6 GeV

Synchrotron radiation facilities

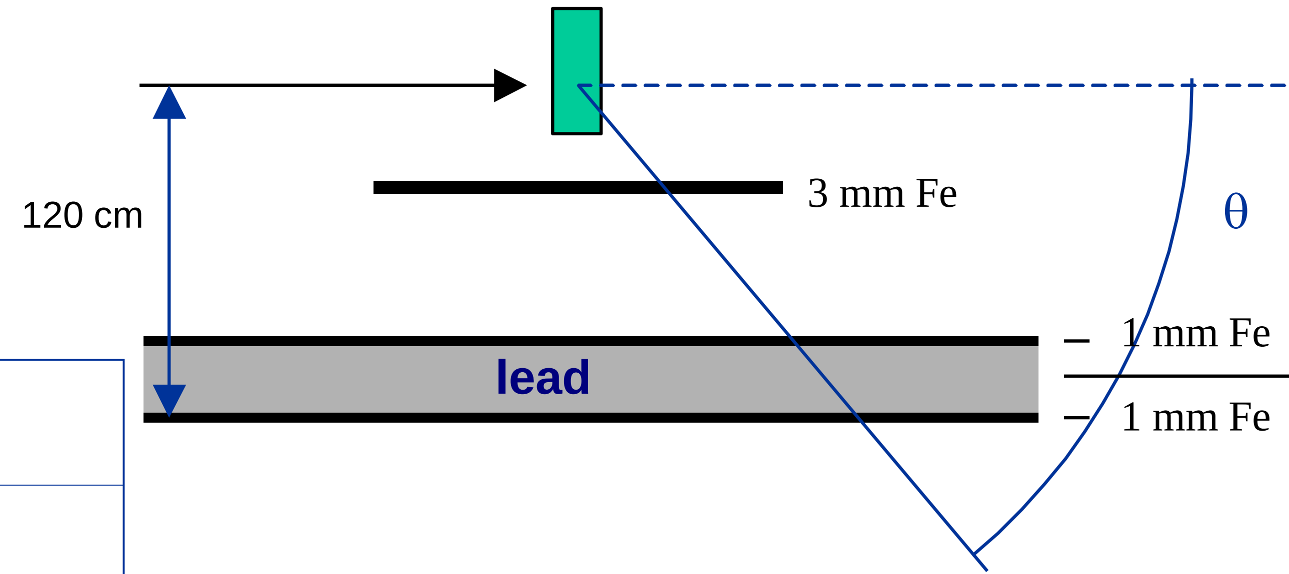
Storage ring shielding

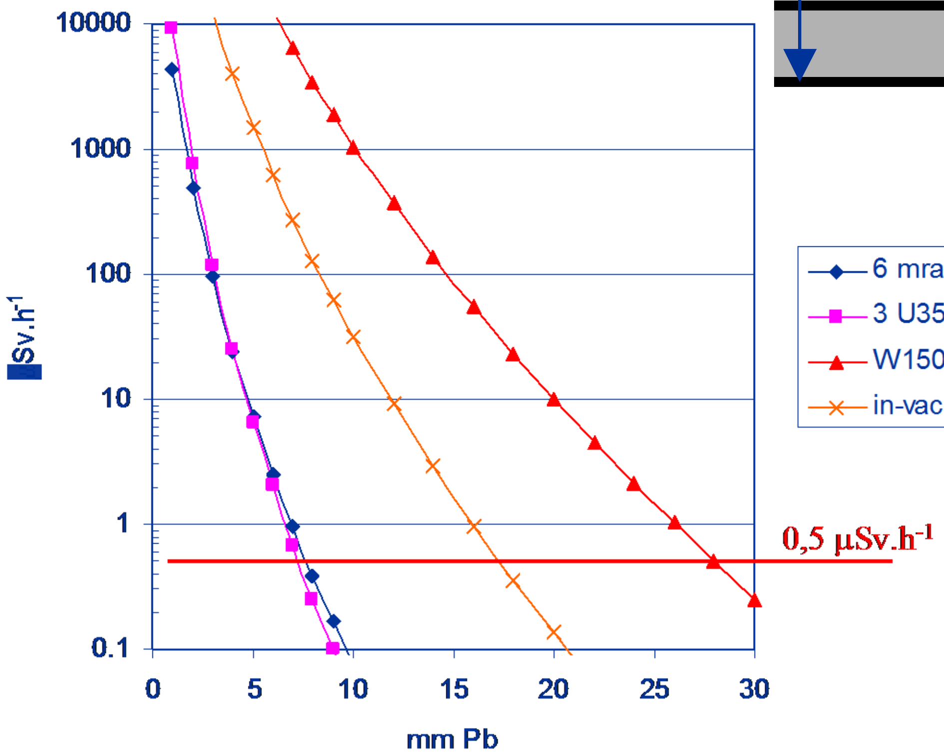


Example: ESRF 6 GeV storage ring, continuous beam loss during injection: 10 mA, 1 μs, 1 Hz, 6 GeV

Synchrotron radiation facilities

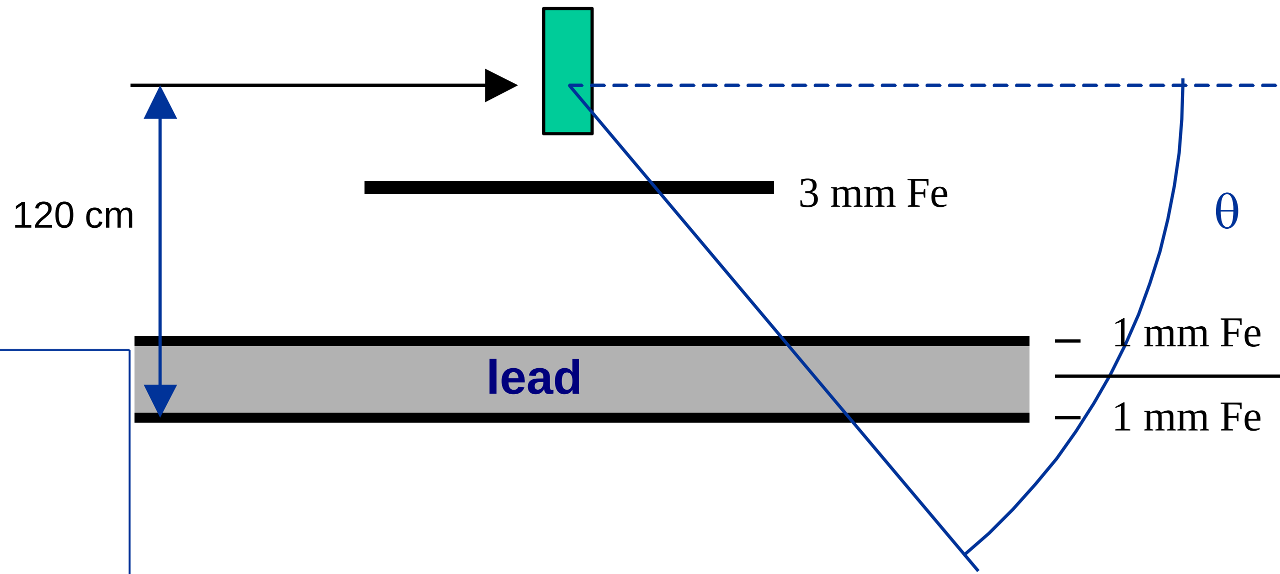
Beamline shielding: synchrotron radiation

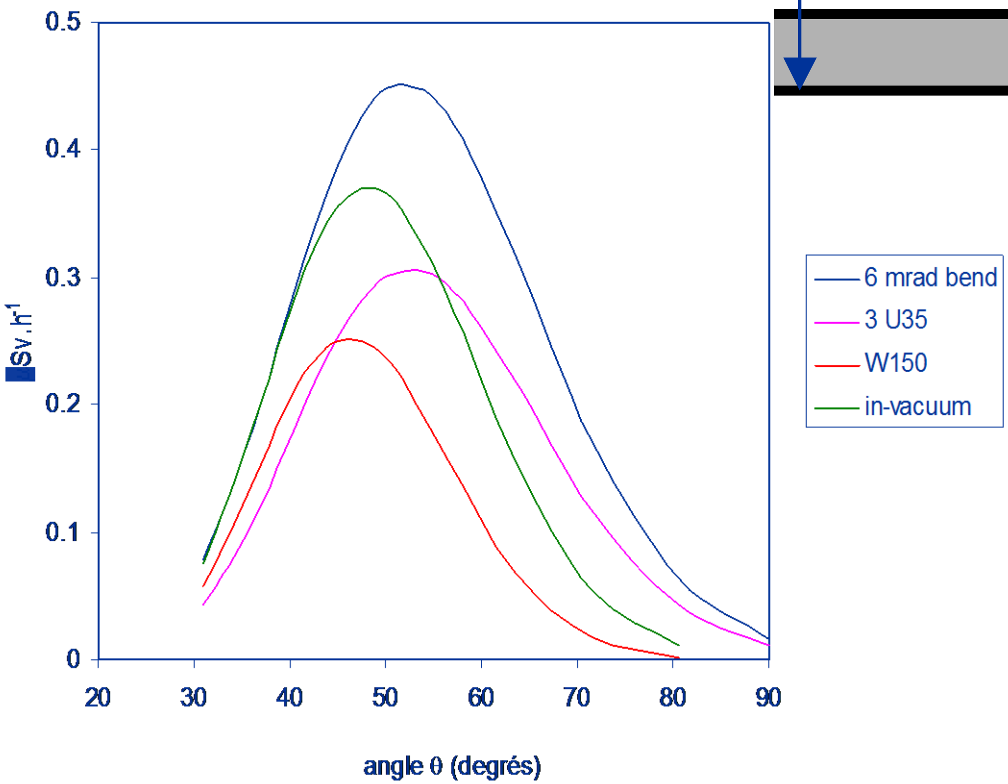




Synchrotron radiation facilities

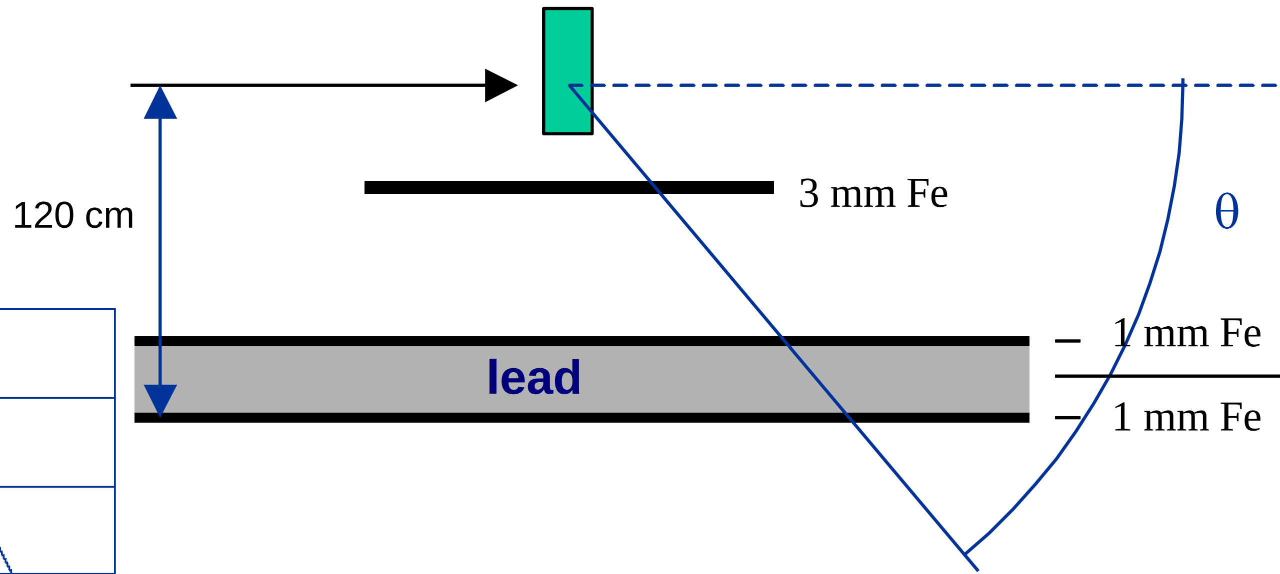
Beamline shielding: synchrotron radiation

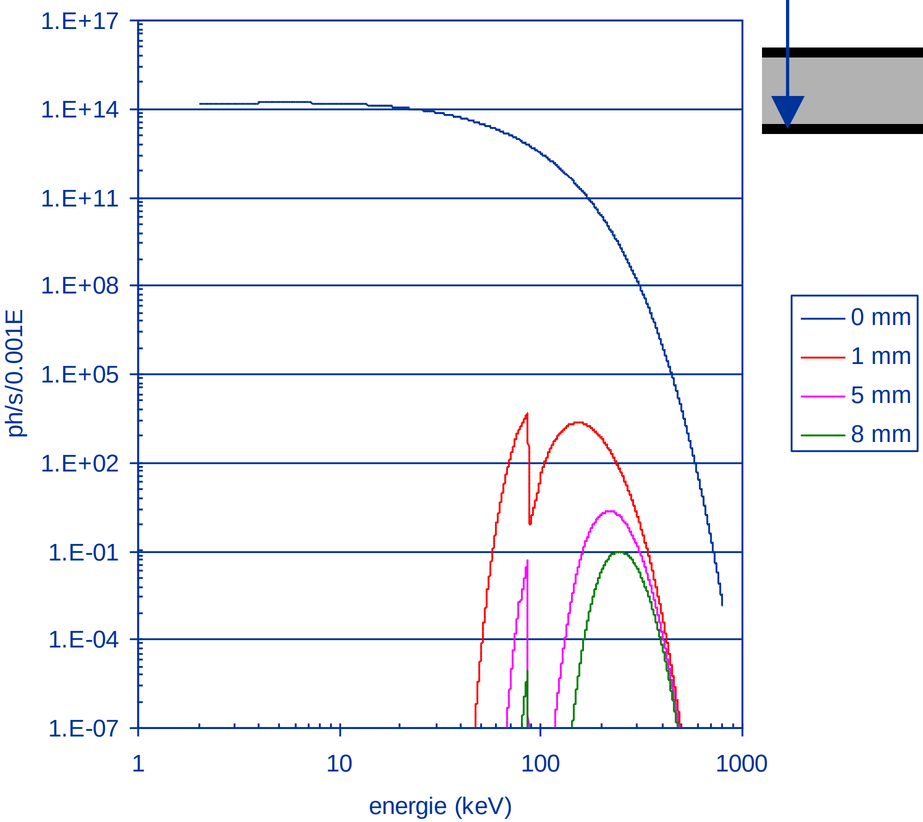




Synchrotron radiation facilities

Beamline shielding: synchrotron radiation





Synchrotron radiation facilities

Beamline shielding: gas-bremsstrahlung

The shielding requirements for the optics hutches of 3rd generation insertion device beamlines are largely determined by gas-bremsstrahlung (and photo-neutrons).

Gas-bremsstrahlung power:

$$P \propto E_e^{\;2} \times I^2 \times L$$

$$P = C \times \frac{dE}{dx}(E_e) \times p \times I \times L,$$

- $\frac{dE}{dx}$: electron stopping power
- p: pressure in straight section
- I: electron beam intensity
- L: length of straight section

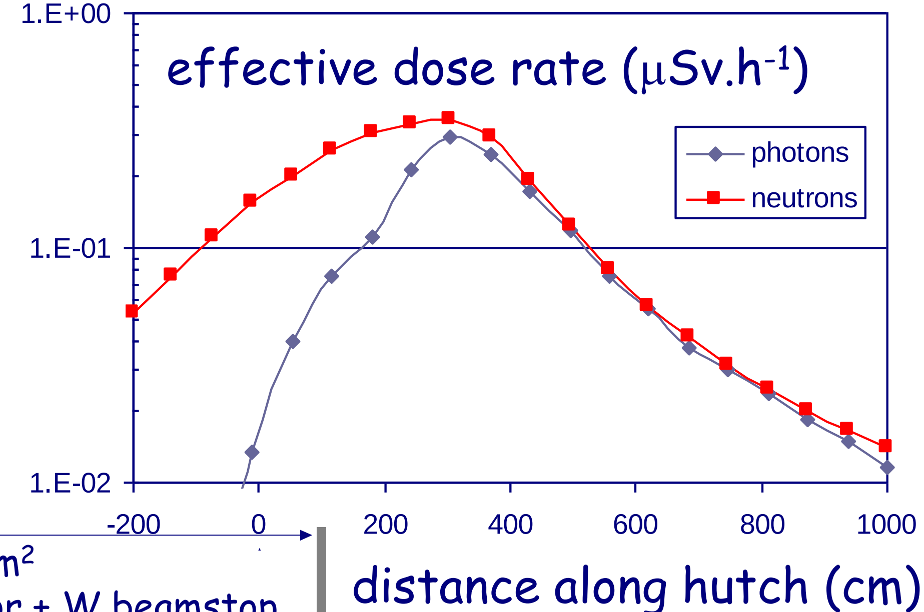
$$\frac{dE}{dx}(E_e) \propto E_e$$

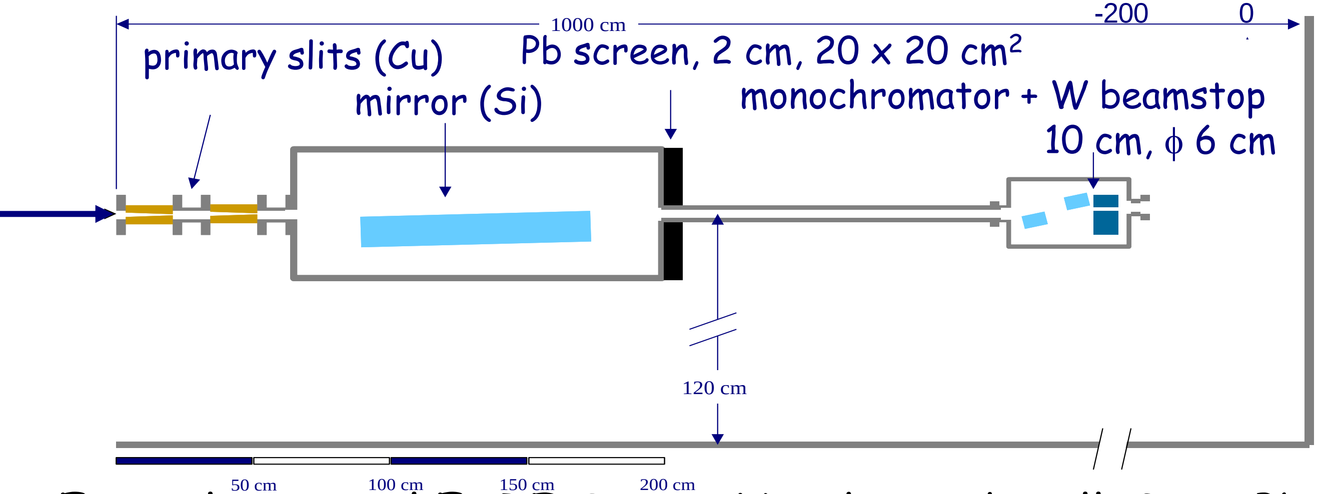
$$p \propto E_e \times I$$

	ESRF	SRS	Diamond		Soleil		
Energy (GeV)	6	2	3		2.75		
Current (mA)	200	250	500		500		
Straight section (m)	15	3.82	15.75	18.75	7.7	12.4	18.5
Bremsstrahlung power (normalised to ESRF)	1	0.044	1.64	1.95	0.67	1.09	1.62

Synchrotron radiation facilities

Beamline shielding: gas-bremsstrahlung



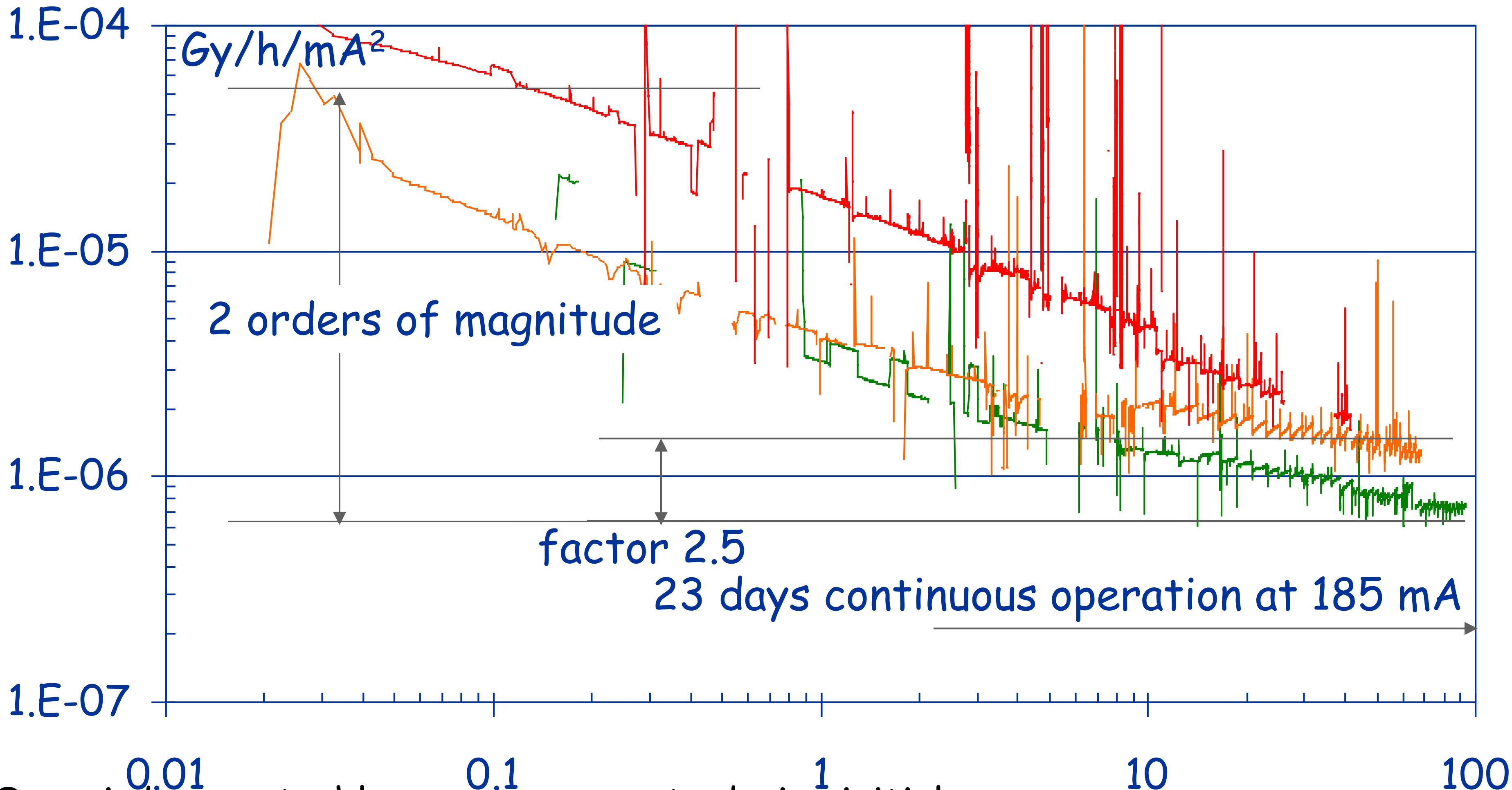


Example: typical ESRF Optics Hutch - Sidewall: 3 cm Pb

6 GeV, 200 mA, average pressure straight section 5×10^{-9} mbar

Synchrotron radiation facilities

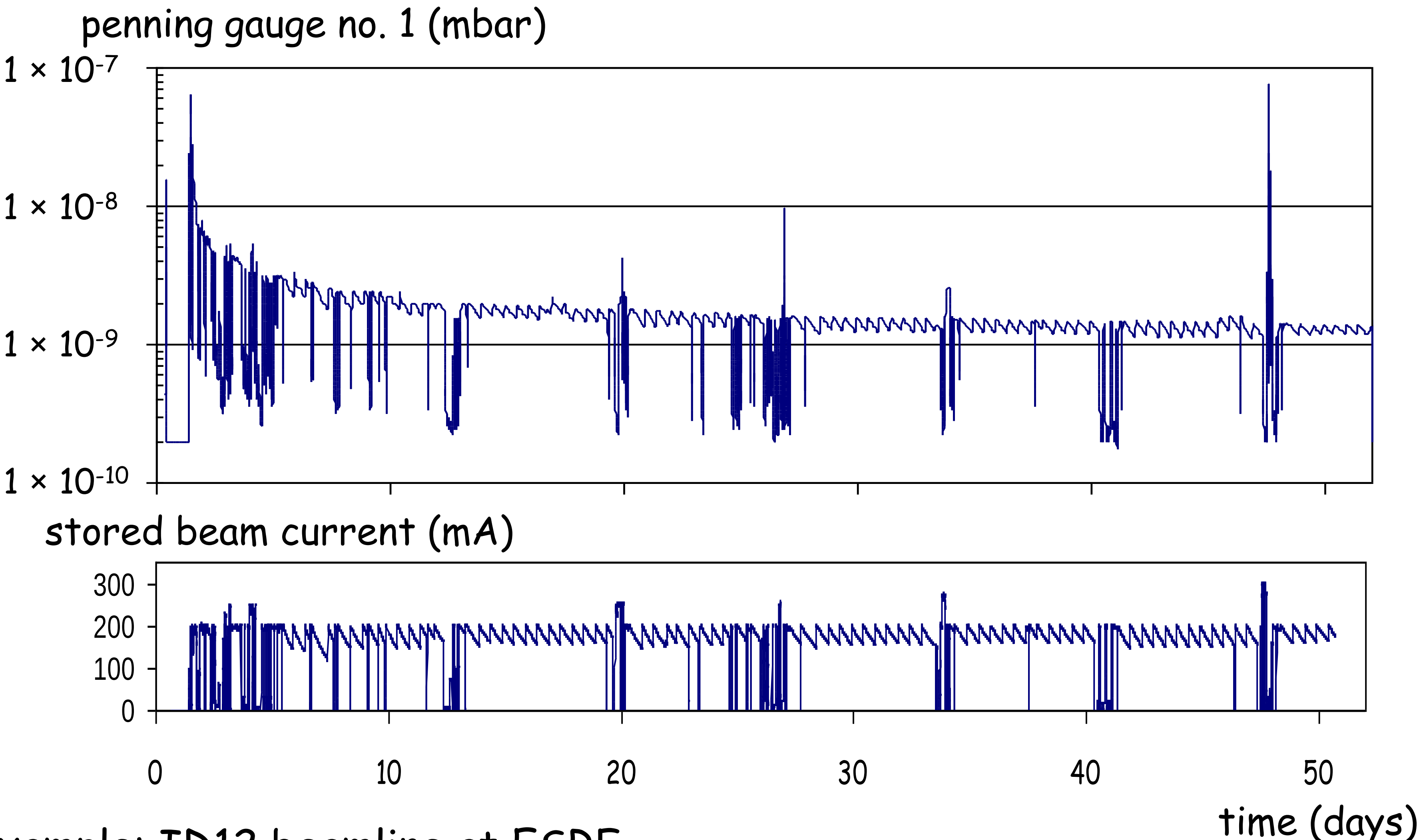
Beamline shielding: gas-bremsstrahlung



On-axis bremsstrahlung measurements during initial conditioning of ESRF 5 m long, 8 mm internal height NEG-coated extruded aluminium ID vessels

Synchrotron radiation facilities

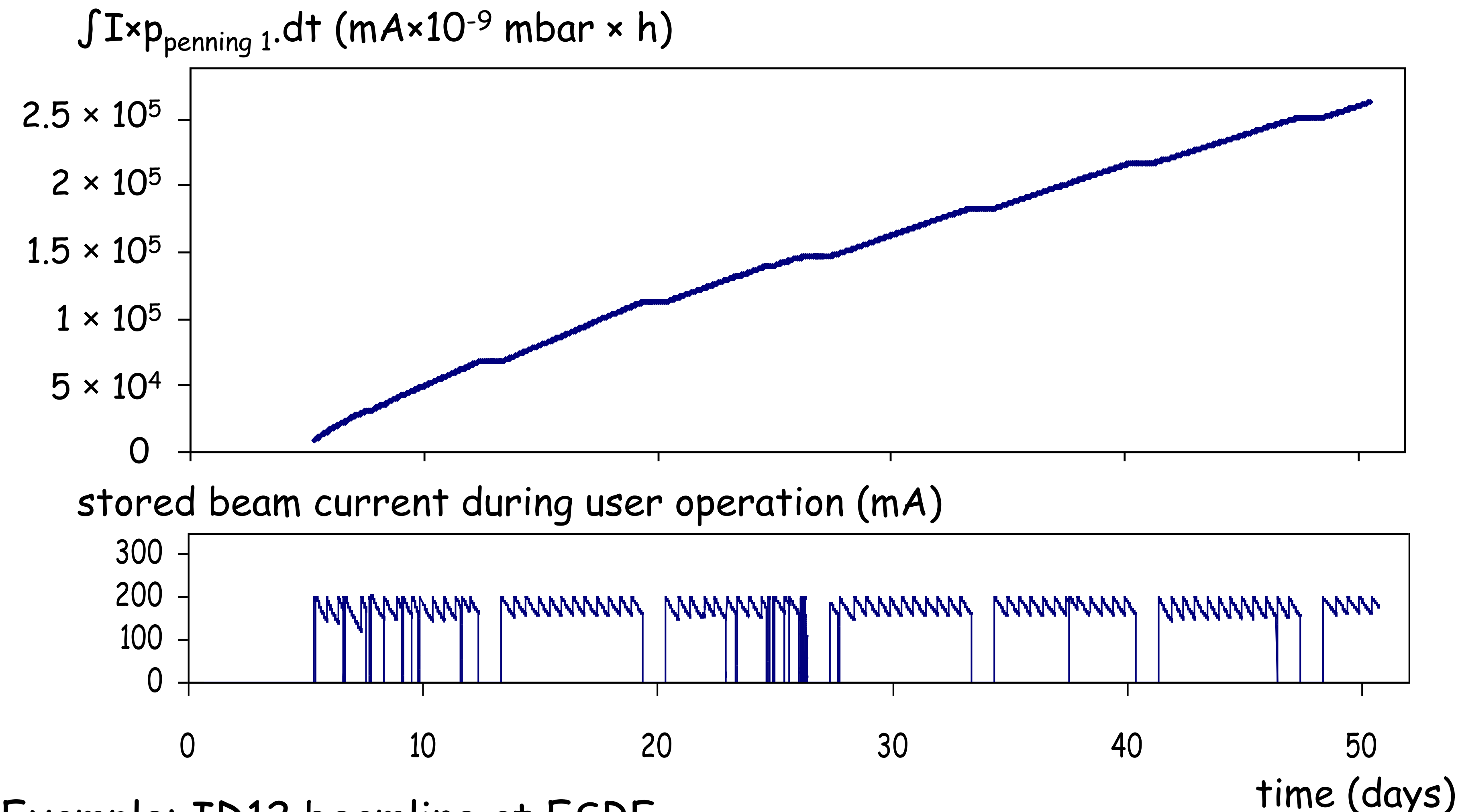
Beamline shielding: gas-bremsstrahlung



Example: ID12 beamline at ESRF

Synchrotron radiation facilities

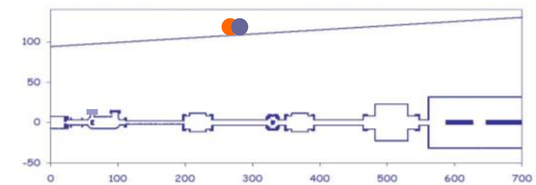
Beamline shielding: gas-bremsstrahlung

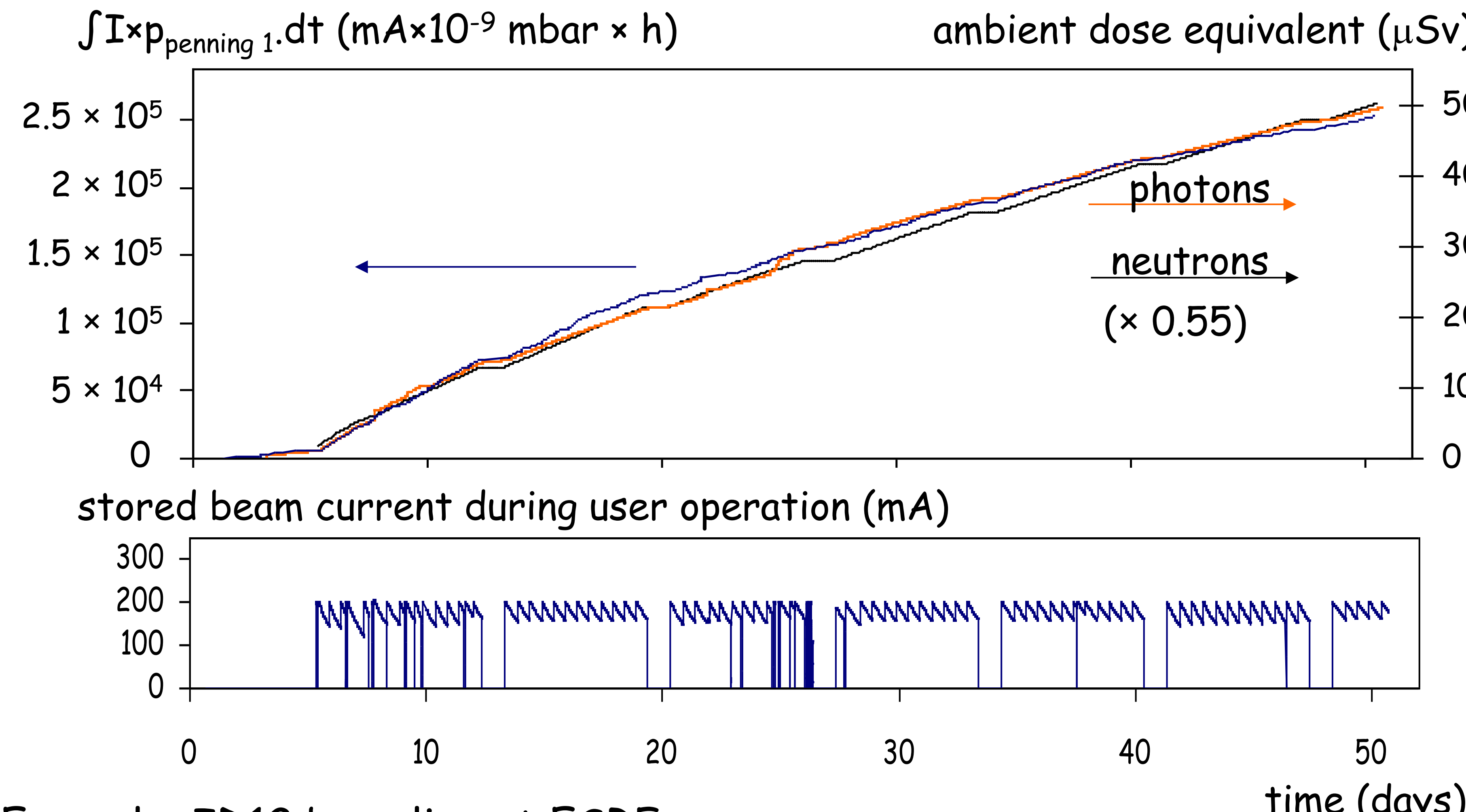


Example: ID12 beamline at ESRF

Synchrotron radiation facilities

Beamline shielding: gas-bremsstrahlung

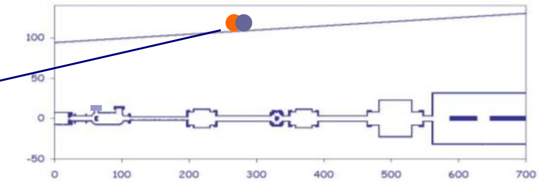


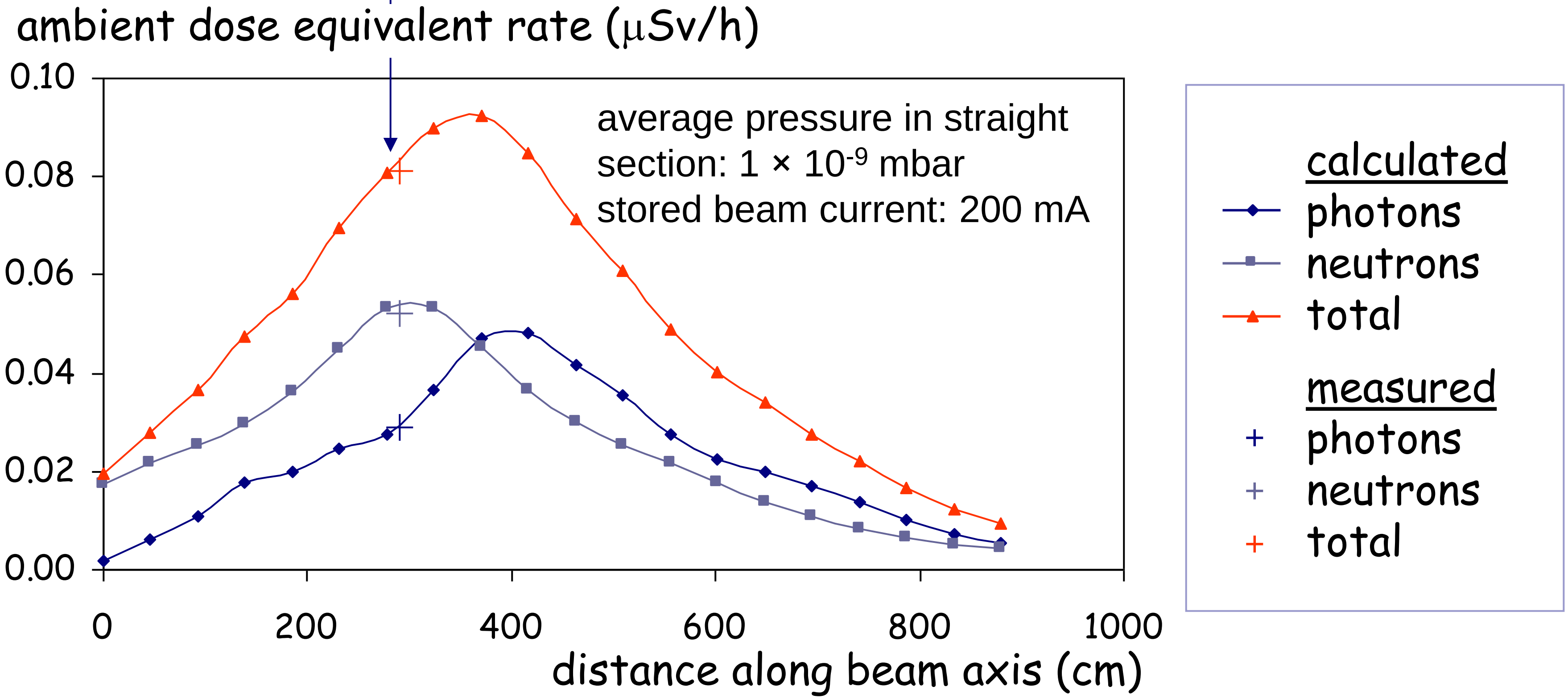


Example: ID12 beamline at ESRF

Synchrotron radiation facilities

Beamline shielding: gas-bremsstrahlung





0.5 μSv/h:
300 mA, 3.8 × 10^{-9} mbar

Example: ID12 beamline at ESRF

Radiation and Safety

P. Berkvens

1. radiation physics
   - interaction of electrons with matter
   - interaction of photons with matter
   - interaction of neutrons with matter
   - interaction of protons with matter

2. radiation protection
   - definitions
   - rules

3. radiation fields around accelerators
   - electron accelerators
   - proton accelerators
   - synchrotron radiation facilities

4. induced activity

5. radiation monitors

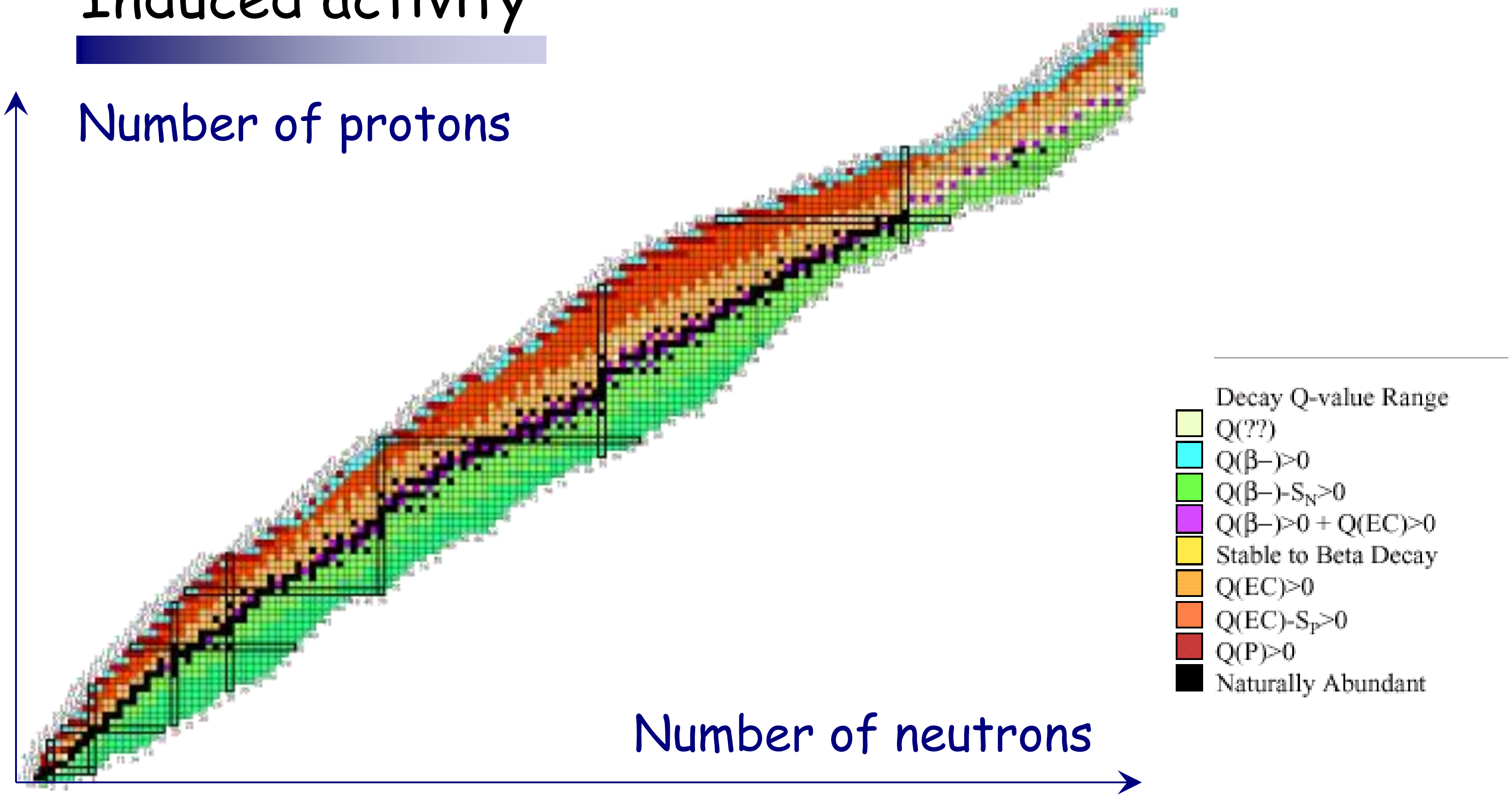
Induced activity

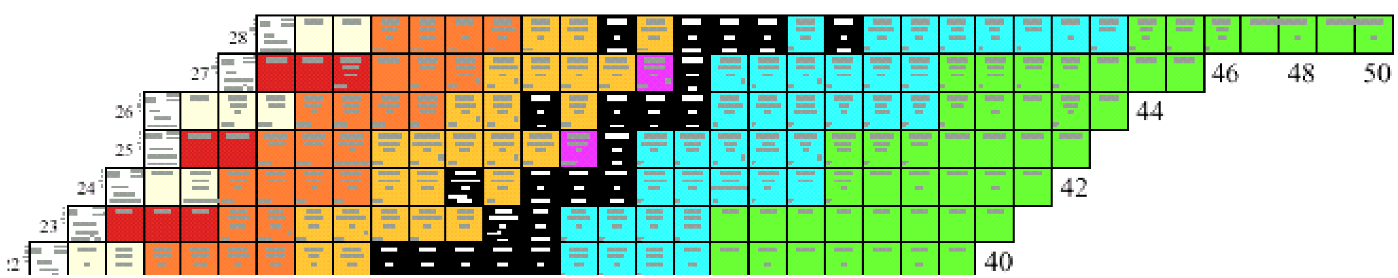
- radiation remains after accelerator switched off
- work permits for people entering tunnels
- radiation protection: personnel and environment
- management of activated accelerator components
- decommissioning of facilities

- thermal and slow neutron reactions
- medium energy neutron reactions
- nuclear reactions at high energy (spallation)
- photonuclear reactions

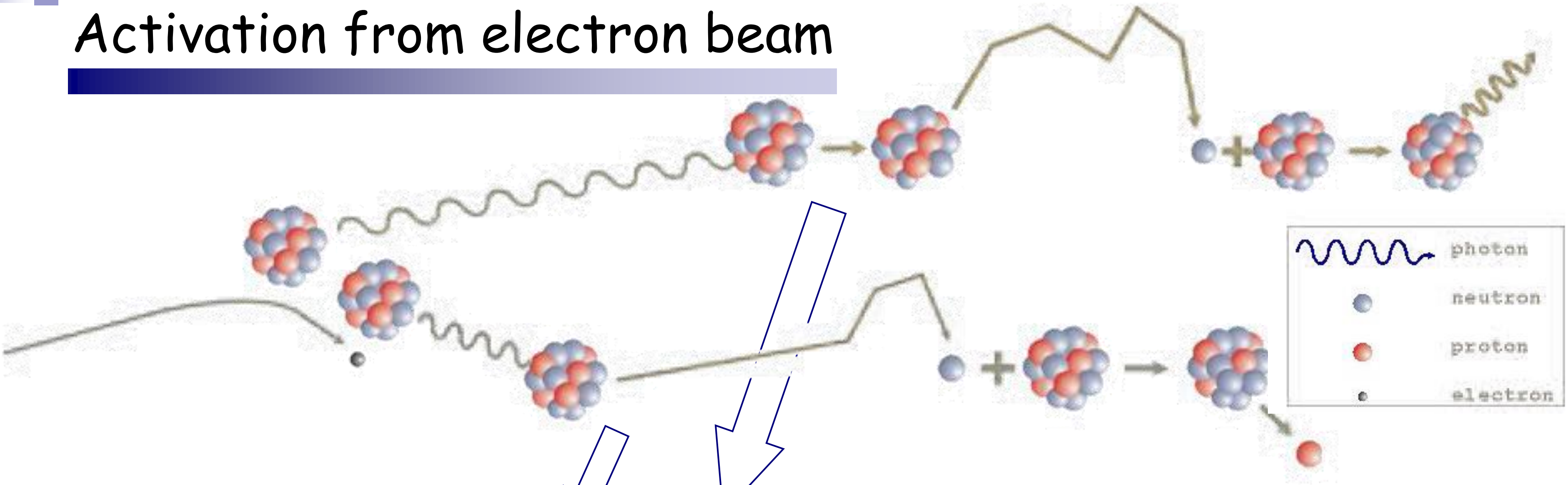
relatively insensitive to activation	moderately susceptible to activation	highly susceptible to activation	fissionable
ordinary concrete, Pb, Al, wood, plastics	Fe (steel, ferrites), Cu	Stainless steel, W, Ta, Zn, Au, Mn, Co, Ni	U, Pu, Th

Induced activity

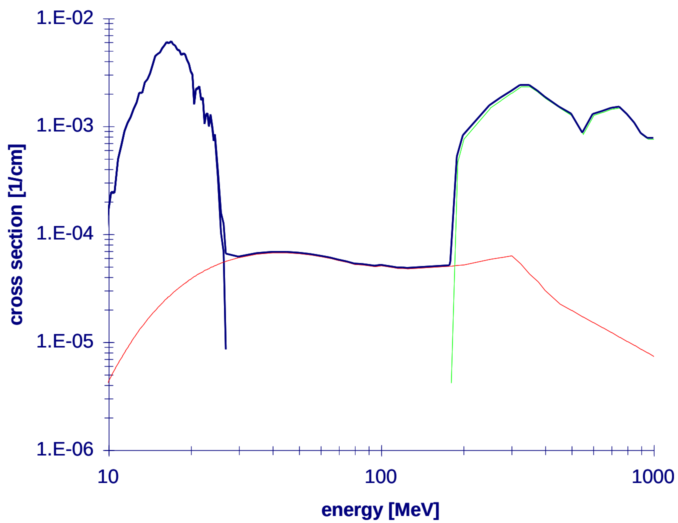


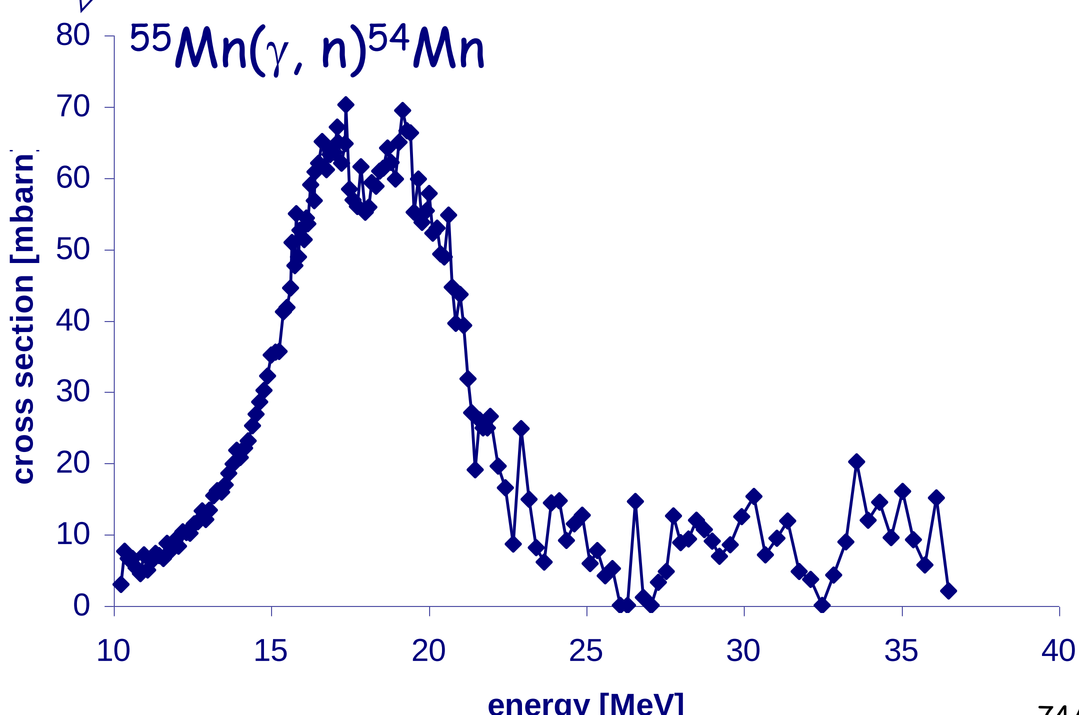


Activation from electron beam

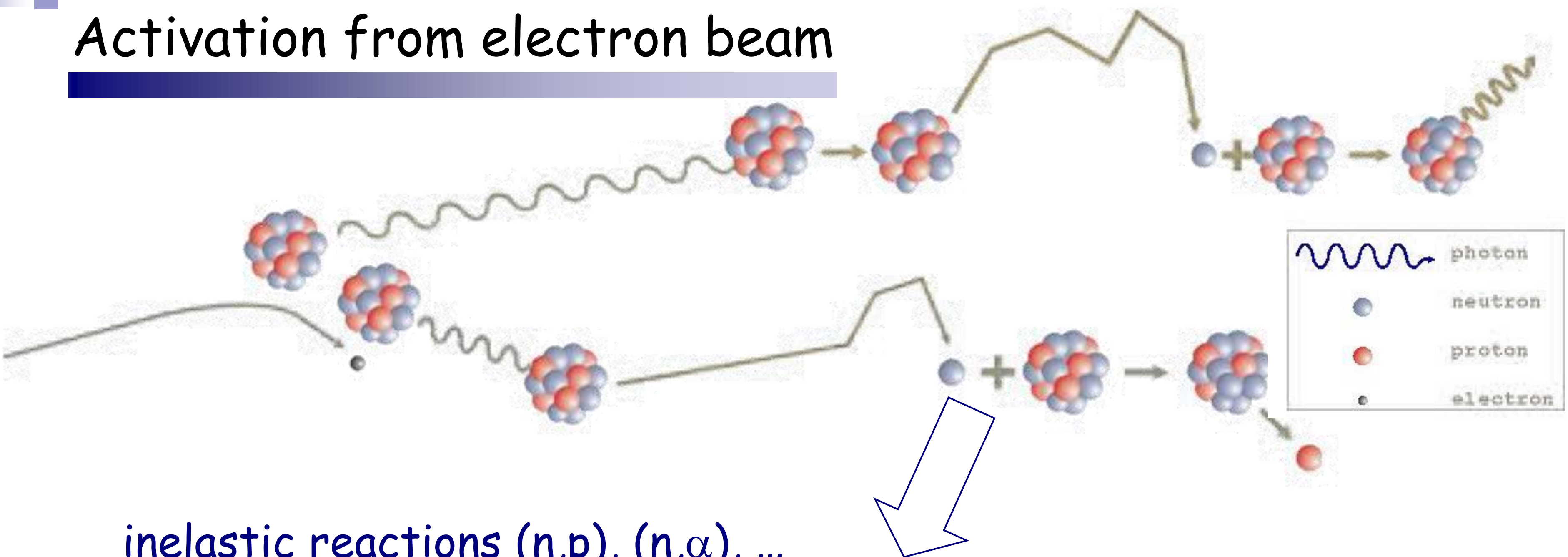


photonuclear reactions
(γ,n), (γ,p), (γ,np), ...

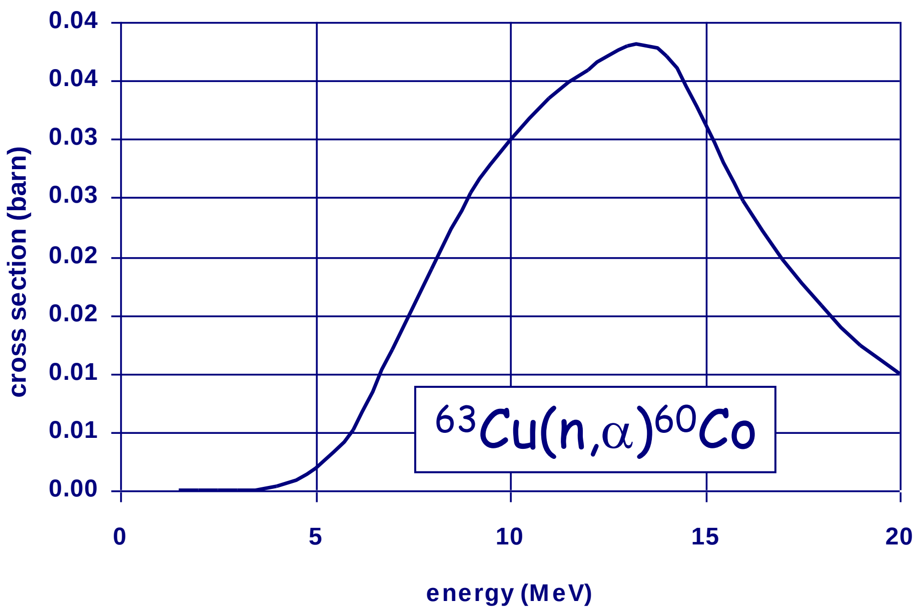


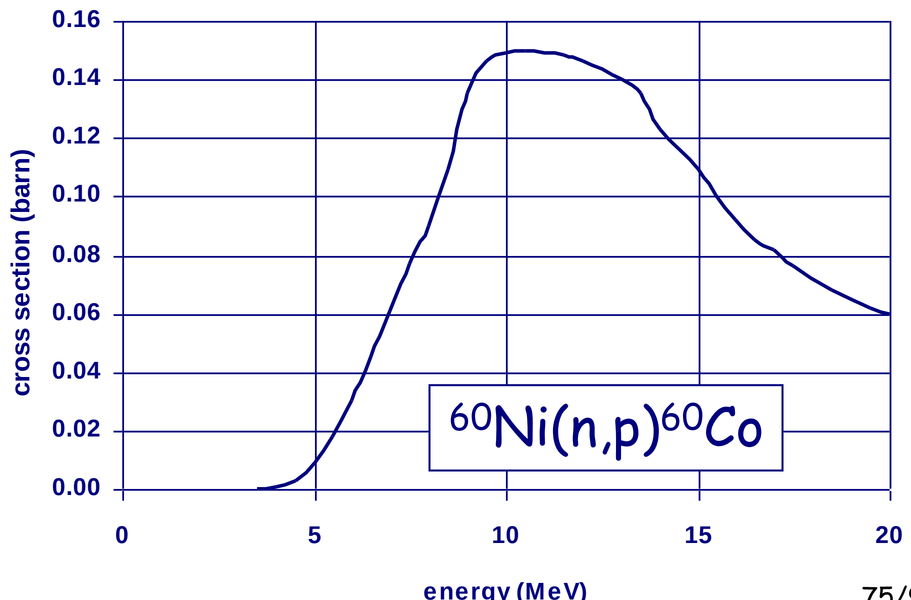


Activation from electron beam

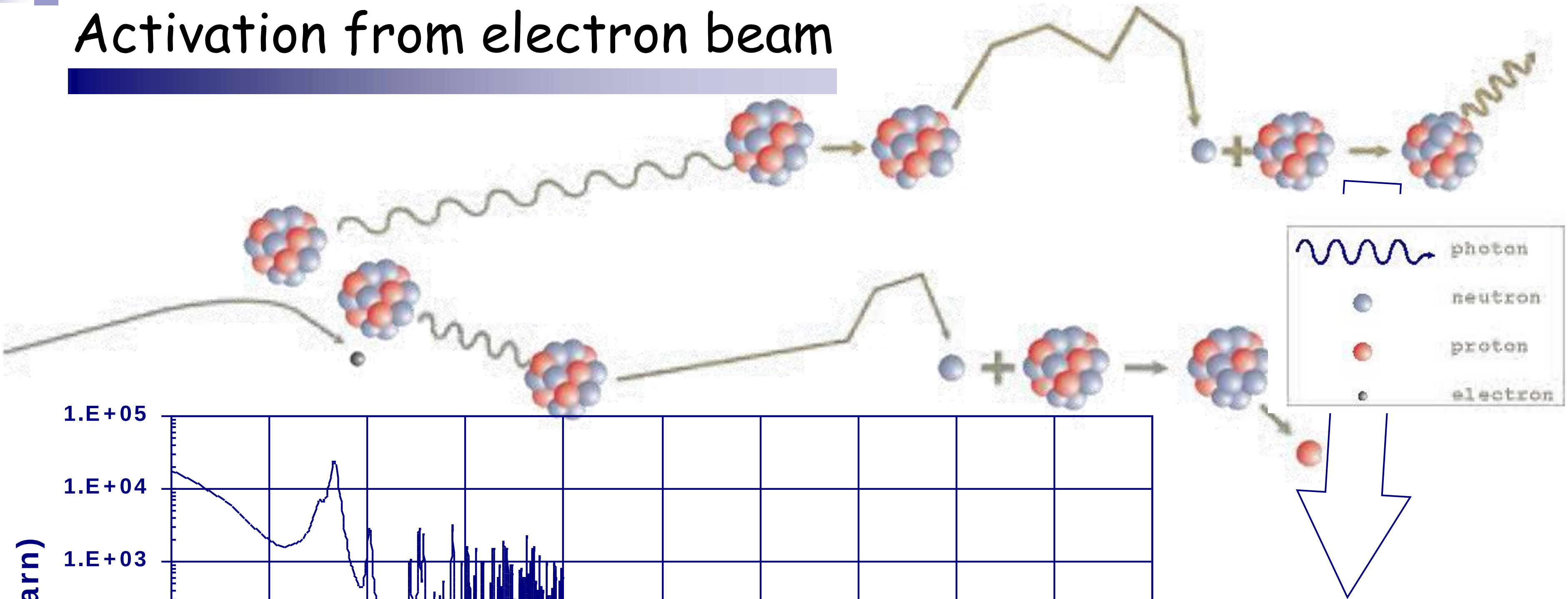


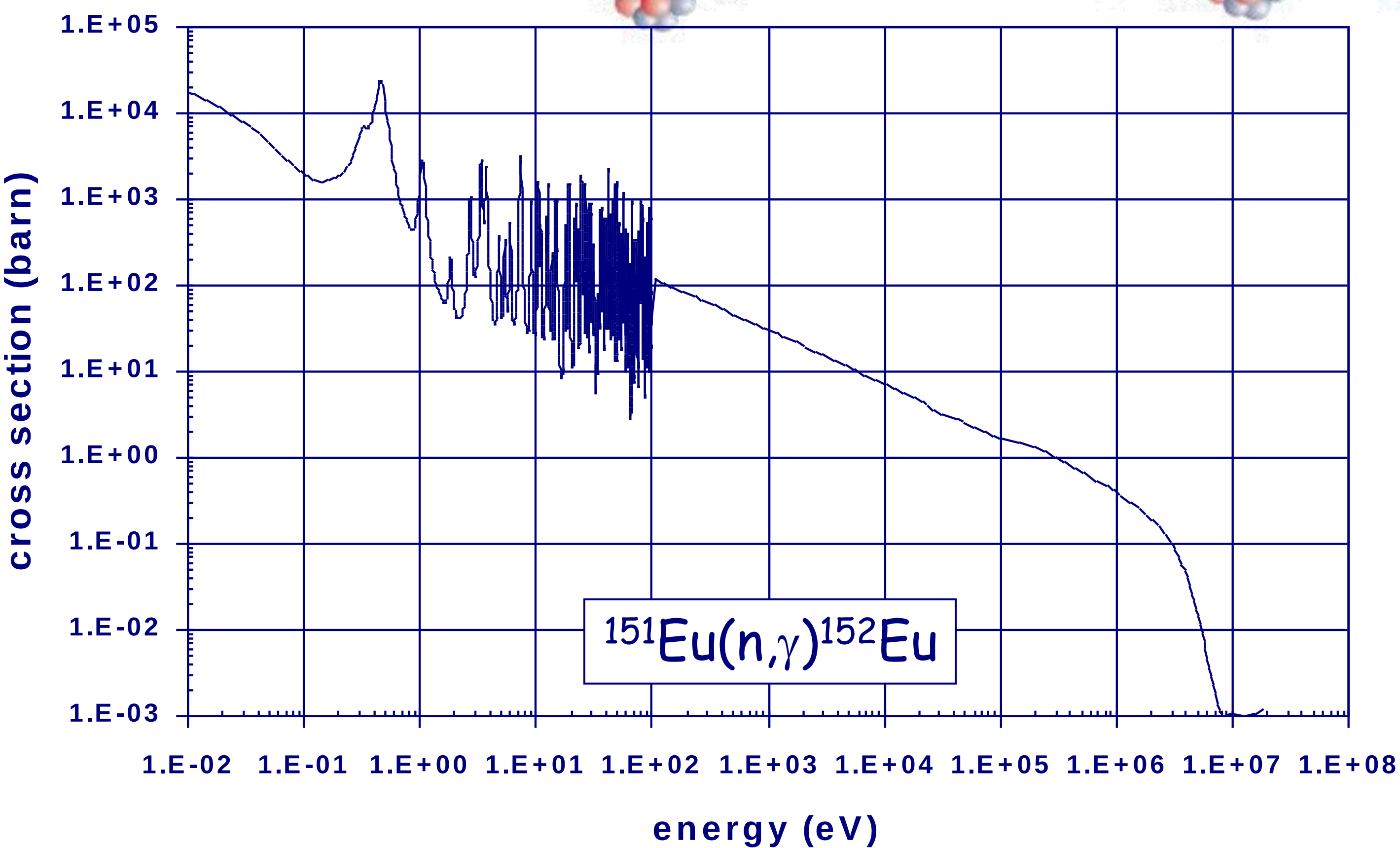
inelastic reactions (n,p), (n,α), …





Activation from electron beam

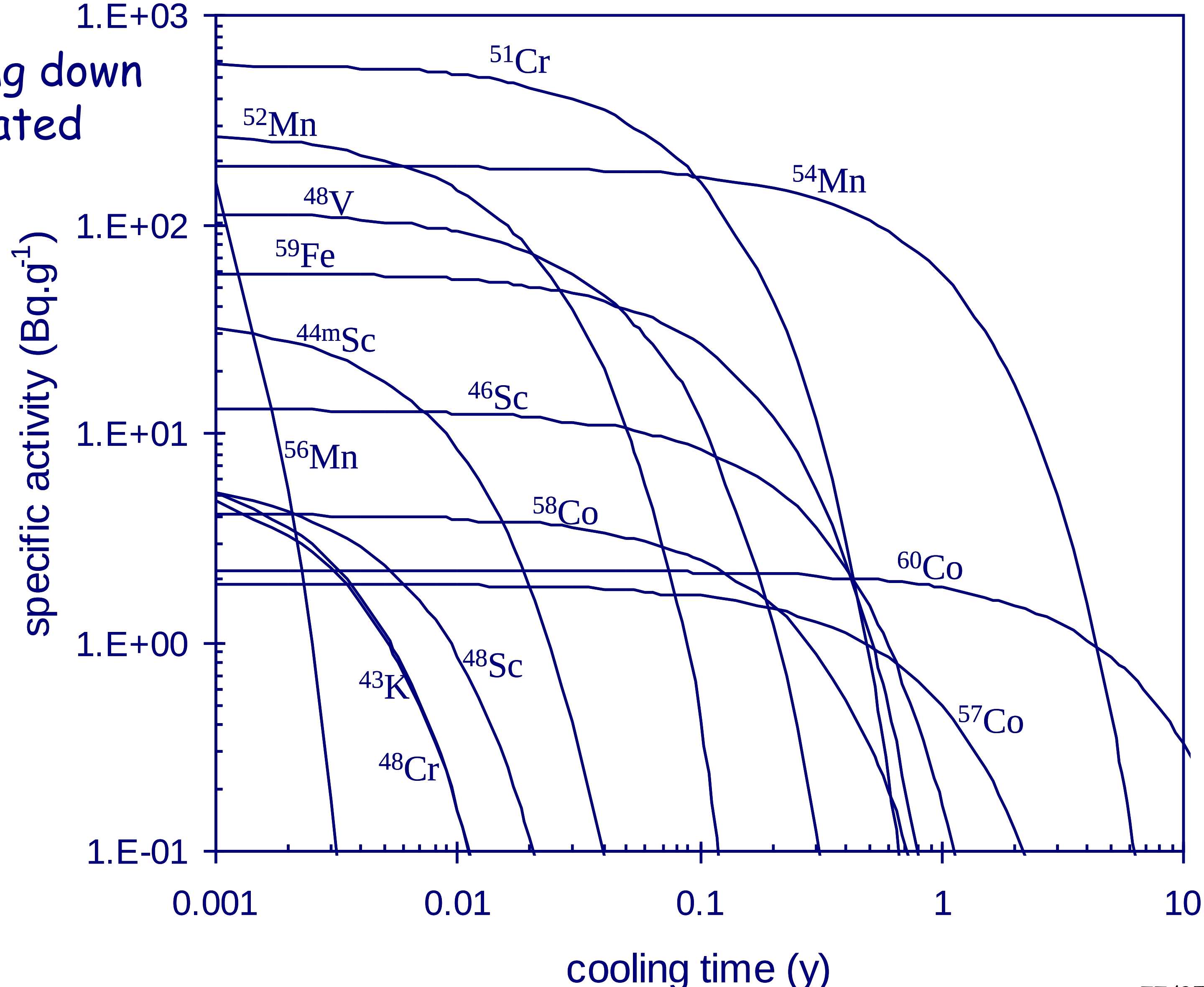




radiative capture

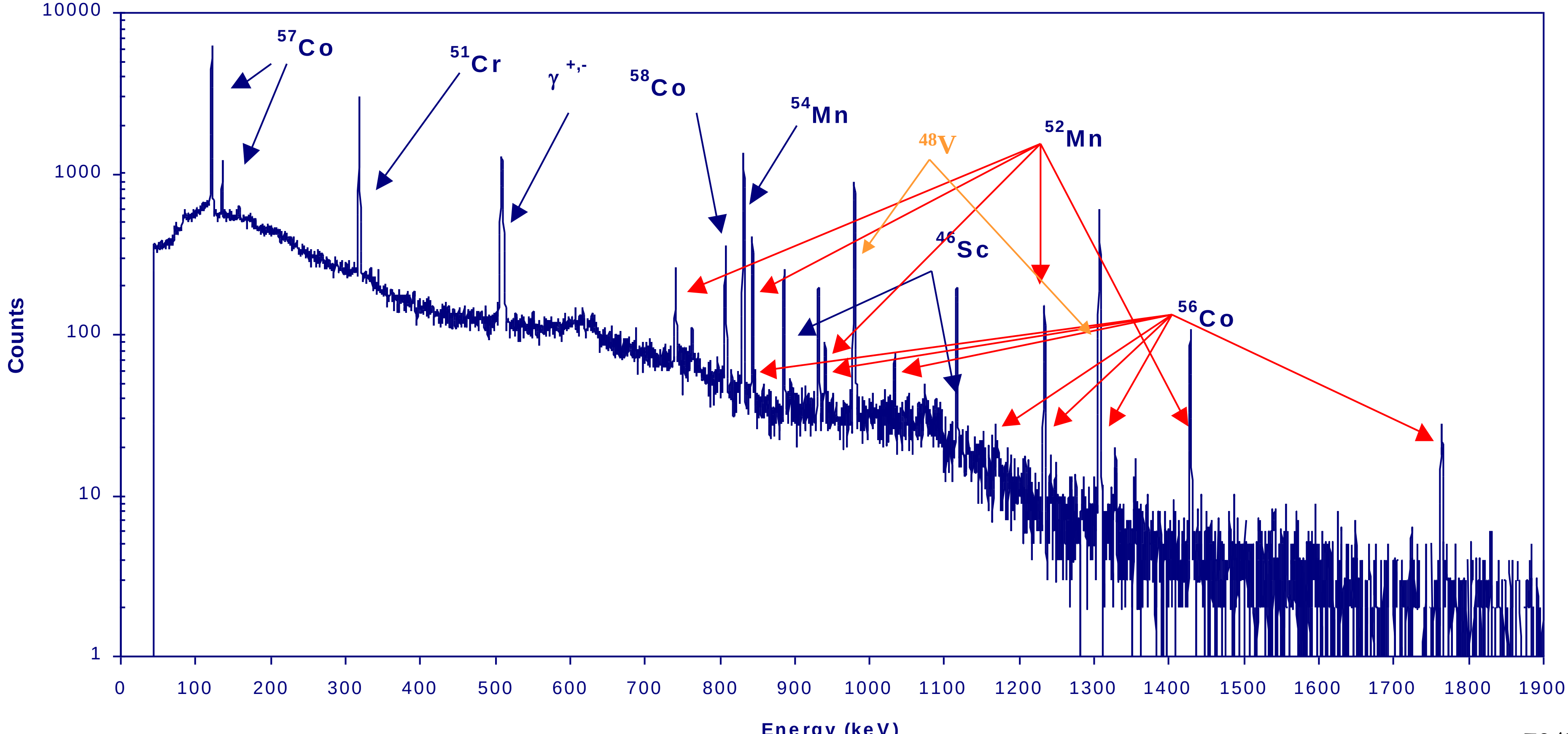
Activation from electron beam

Example: cooling down curve of irradiated steel

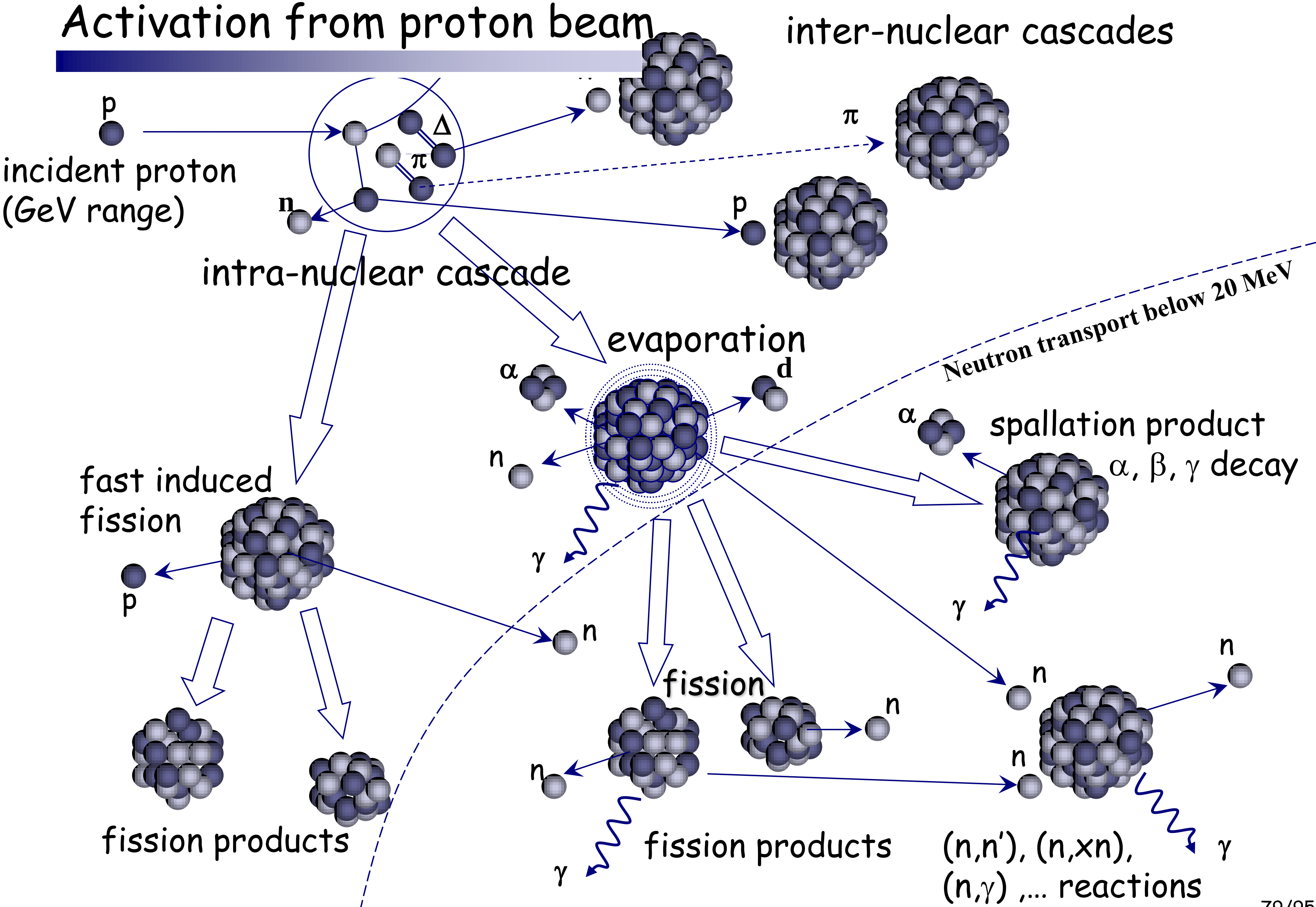


Activation from electron beam

Stainless steel vessel ESRF



Activation from proton beam



Activation from proton beam

Isotope	Half-life	Decay mode	$fSv.h^{-1}.Bq^{-1}$ at 1 m
^{7}Be	53 d	EC	7.8
^{11}C	20 min	β^+	140
^{18}F	1.8 h	β^+	132
^{22}Na	2.6 y	β^+	298
^{24}Na	15 h	β^+	560
^{46}Sc	84 d	β^+	283
^{48}Sc	1.8 d	β^+	455
^{48}V	16 d	β^+	397
^{51}Cr	28 d	EC	4.3
^{52}Mn	5.7 d	β^+	326
^{54}Mn	303 d	EC	114
^{56}Co	77 d	β^+	350
^{60}Co	5.3 y	β^+	340
^{65}Zn	245 d	EC	76

Principal radioactive isotopes produced in accelerator structures by spallation reactions

Activation from proton beam

Parent isotope	Natural (%)	σ (barn)	Active isotope	Half-life	fSv.h-1 at 1m per Bq	per g
^{23}Na	100	0.53	^{24}Na	15 h	560	7.7
^{40}Ar	99.6	0.61	^{41}Ar	1.8 h	150	1.4
^{44}Ca	2.0	0.70	^{45}Ca	165 h	-	-
^{50}Cr	4.3	17	^{51}Cr	28 d	4	0.04
^{55}Mn	100	13	^{56}Mn	2.6 h	2520	35
^{59}Co	100	37	^{60}Co	5.3 y	340	128
^{63}Cu	69	4.5	^{64}Cu	13 h	28	0.84
^{64}Zn	49	0.46	^{65}Zn	245 d	76	0.16
^{121}Sb	57	6.1	^{122}Sb	2.8 d	60	1.0
^{123}Sb	43	3.3	^{124}Sb	60 d	200	1.4
^{133}Cs	100	31	^{134}Cs	2.1 y	116	17
^{151}Eu	48	8700	^{152}Eu	12 y	45	750
^{153}Eu	52	320	^{154}Eu	8 y	286	190
^{186}W	28	40	^{187}W	1d	73	2.6

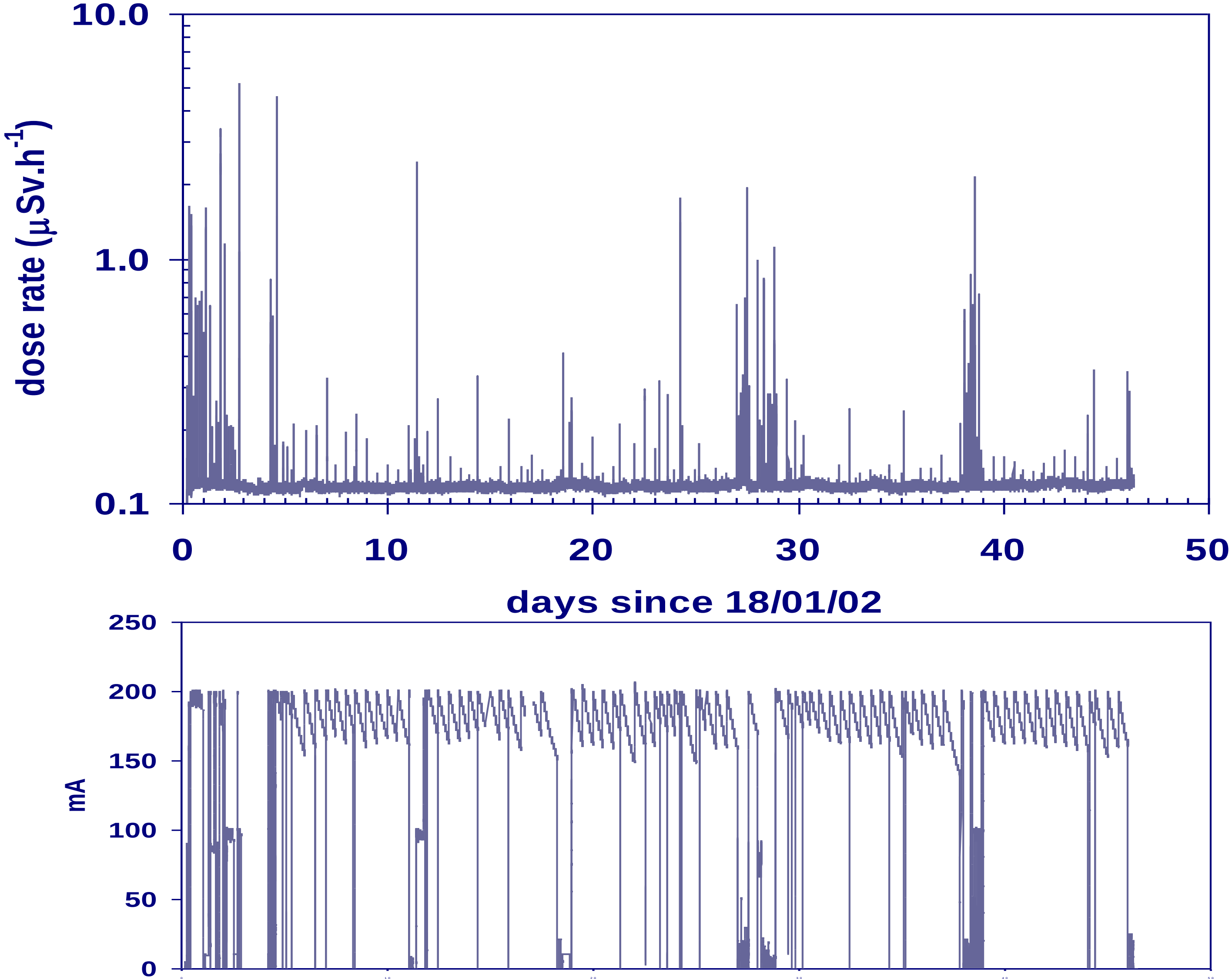
Most important isotopes near high energy particle accelerators formed by thermal neutron capture

Radiation and Safety

P. Berkvens

1. radiation physics
   - interaction of electrons with matter
   - interaction of photons with matter
   - interaction of neutrons with matter
   - interaction of protons with matter
2. radiation protection
   - definitions
   - rules
3. radiation fields around accelerators
   - electron accelerators
   - proton accelerators
   - synchrotron radiation facilities
4. induced activity
5. radiation monitors

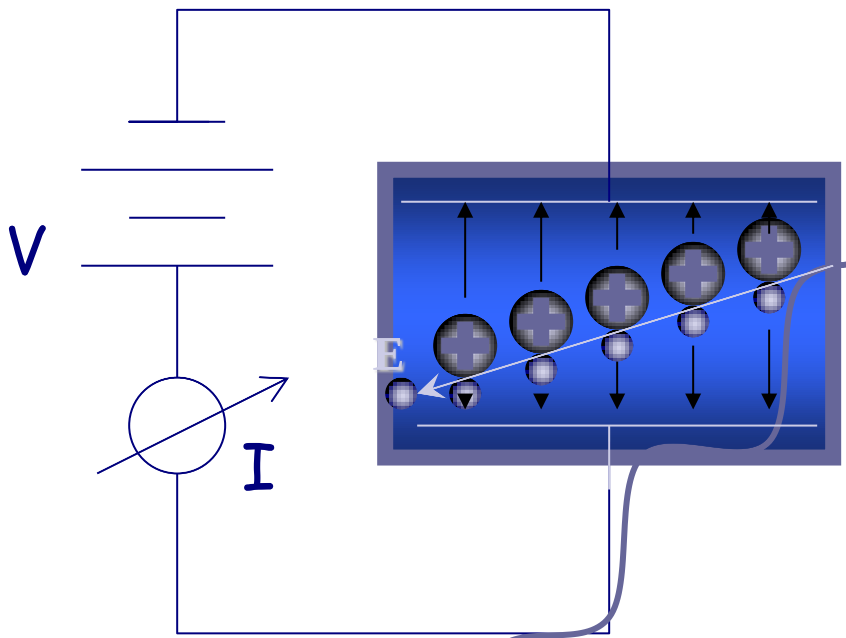
Radiation monitoring

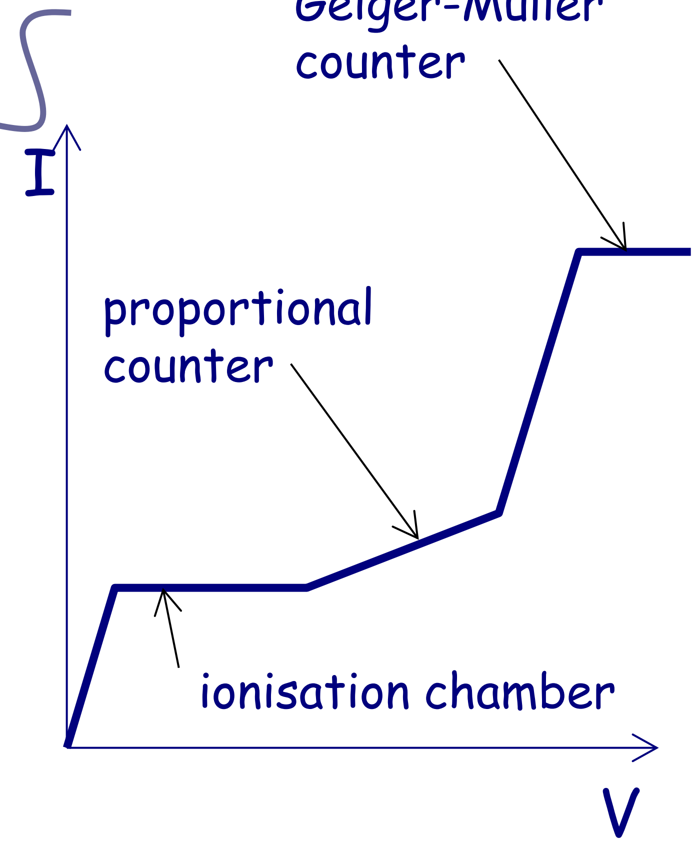


Example: photon dose rate measurement around ESRF storage ring

Radiation monitoring

Gas-filled detectors





$$N_{pairs} = \frac{E}{w}$$

$$\frac{dD}{dt} \propto \frac{w}{\rho_{gas} V_{gas}} \frac{dN_{pairs}}{dt}$$

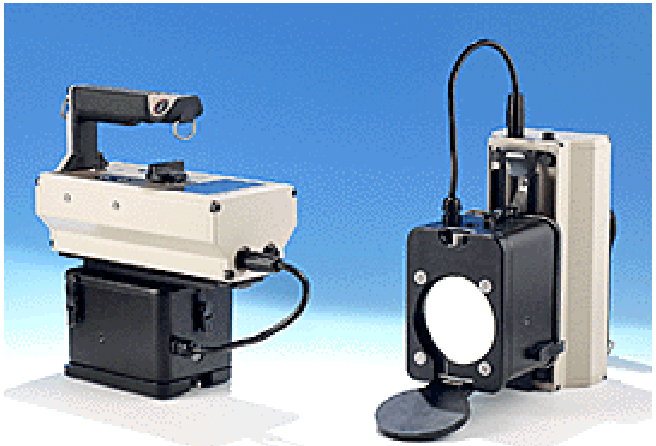
$$\frac{dD}{dt} \propto \frac{w}{e\rho_{gas} V_{gas}} I$$

w	H_2	He	O_2	Ar	Air
electrons	36.3 eV	41 eV	31 eV	26.4 eV	34 eV
alphas	36.5 eV	44 eV	32.4 eV	26.4 eV	35.3 eV

JUAS
Joint Universities Accelerator School

Radiation monitoring

Ionisation chambers



Radiation monitoring

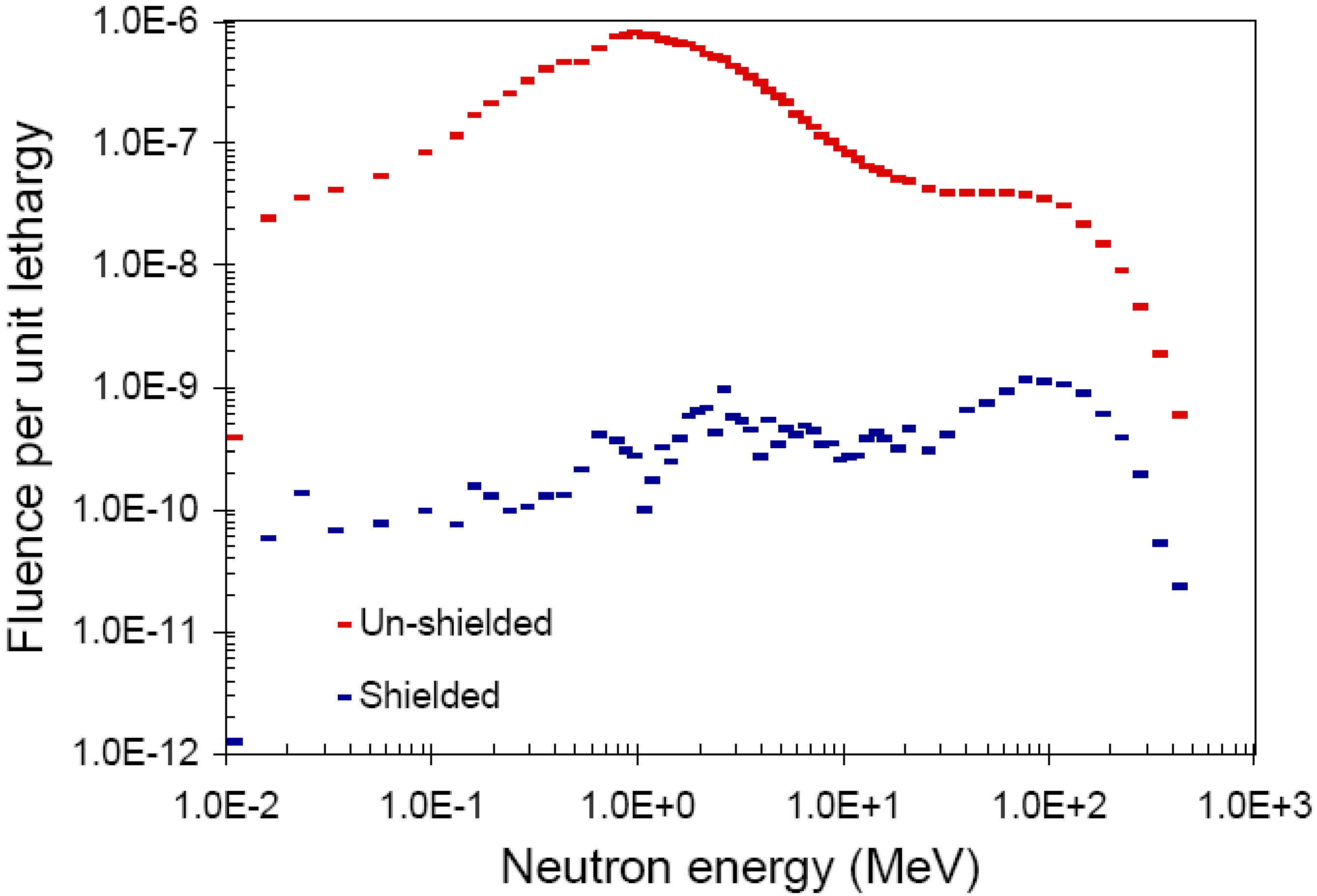
Proportional counter

Radiation monitoring

Geiger - Müller counter


Radiation monitoring

Neutron monitors



Example: neutron spectrum around the 1.7 GeV BESSY storage ring (Courtesy of Klaus Ott)

Radiation monitoring

Moderated neutron monitors

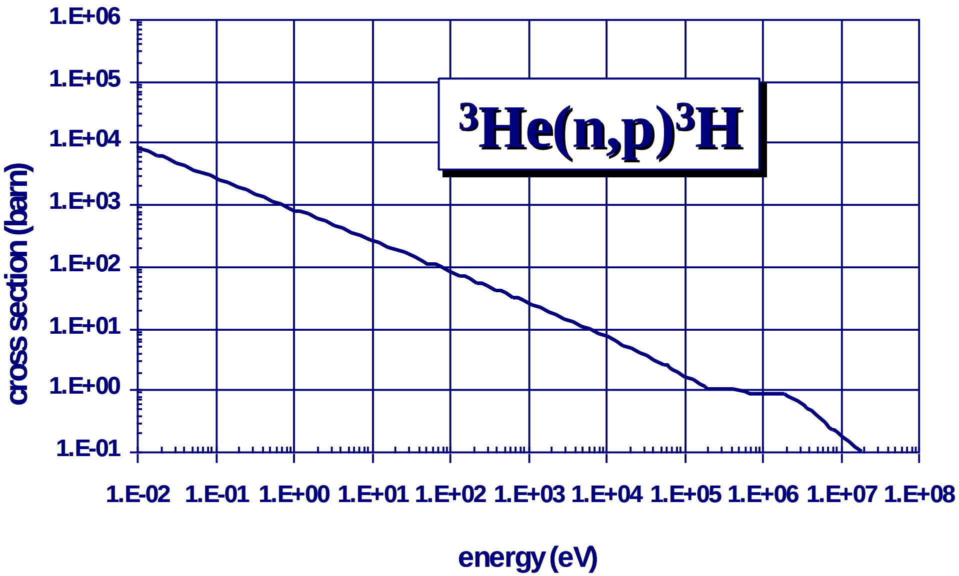
^{3}He-filled proportional counter:

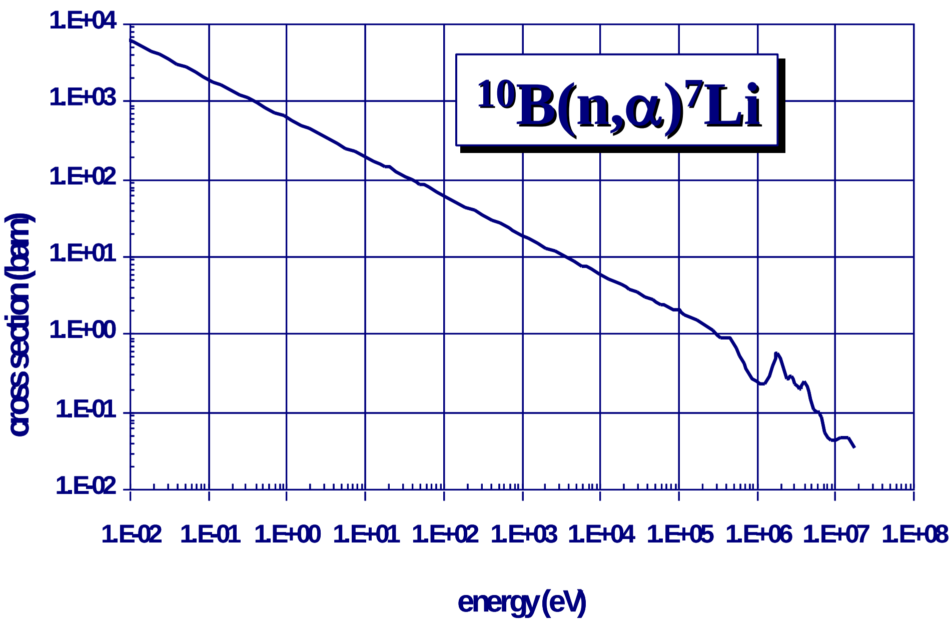
$$n + {}^3He \rightarrow p + {}^3H + 765\,keV$$

BF_3 counter:

$$n + {}^{10}_{5}B \rightarrow \begin{cases} \alpha + {}^{7}_{3}Li + 2.310\,MeV\,(94\%) \\ \alpha + {}^{7}_{3}Li + 2.792\,MeV\,(6\%) \end{cases}$$

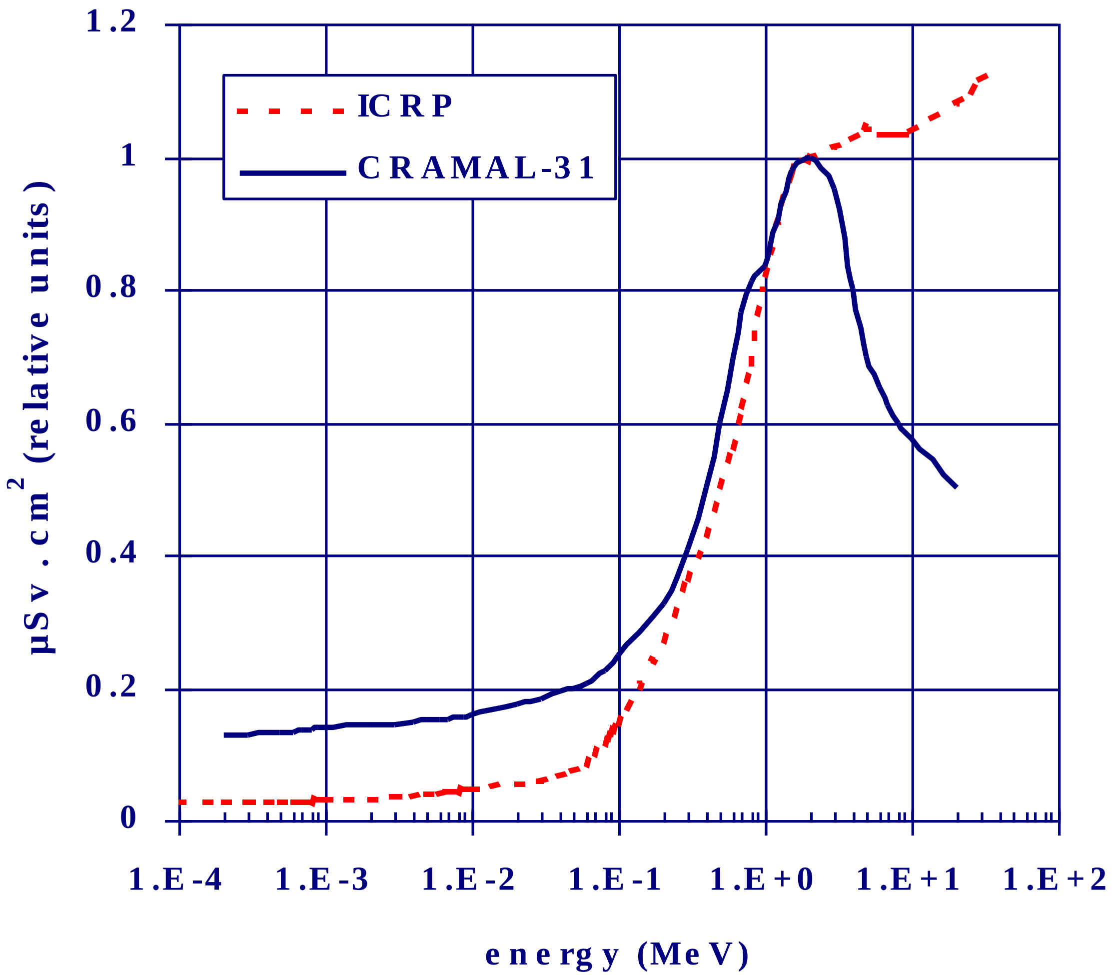
→ Polyethylene moderator





Radiation monitoring

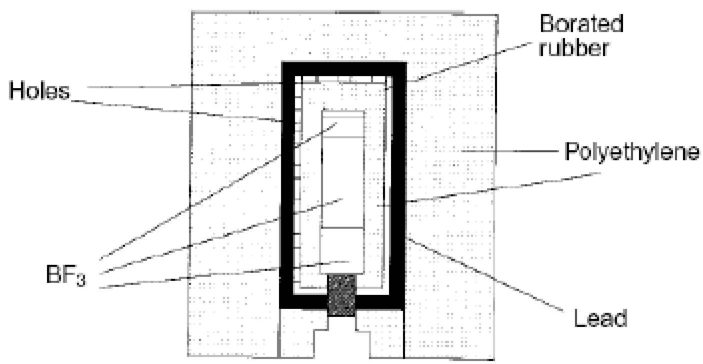
Moderated neutron monitors

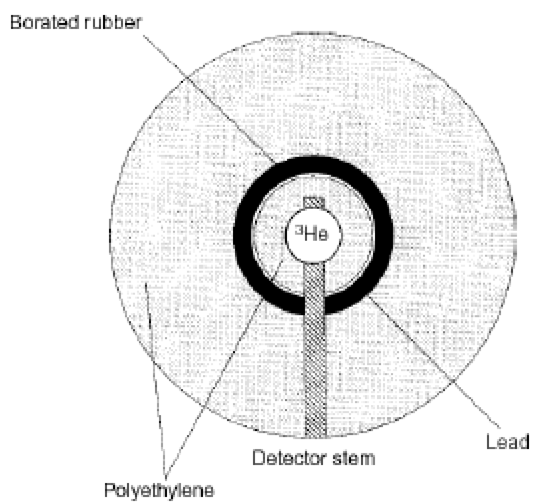


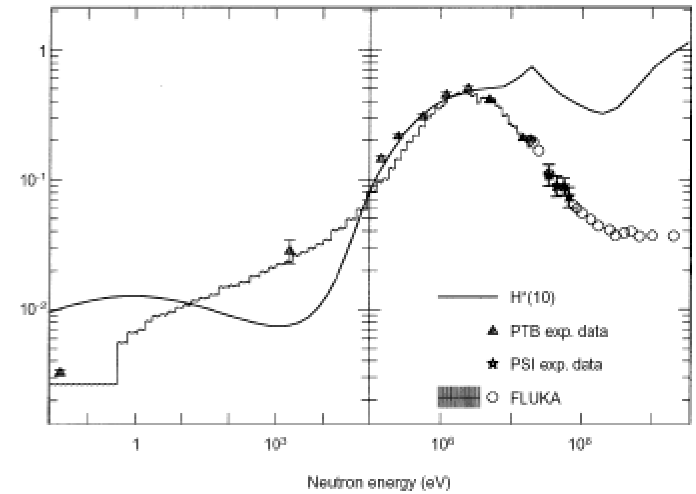
Radiation monitoring

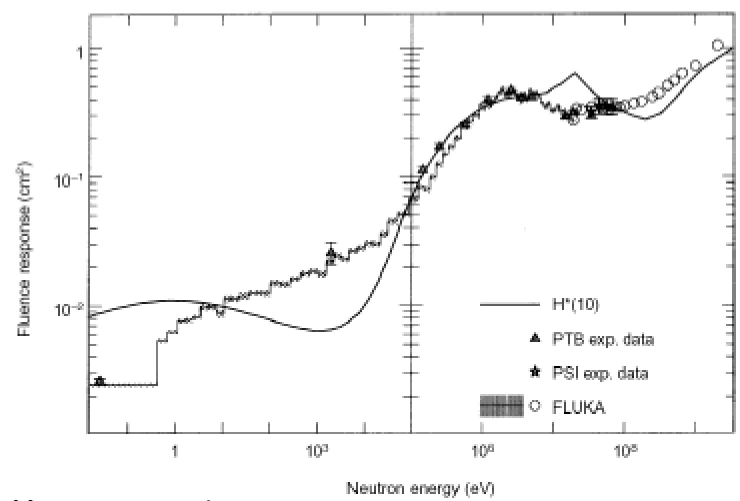
Moderated neutron monitors

Berthold
LB-6411





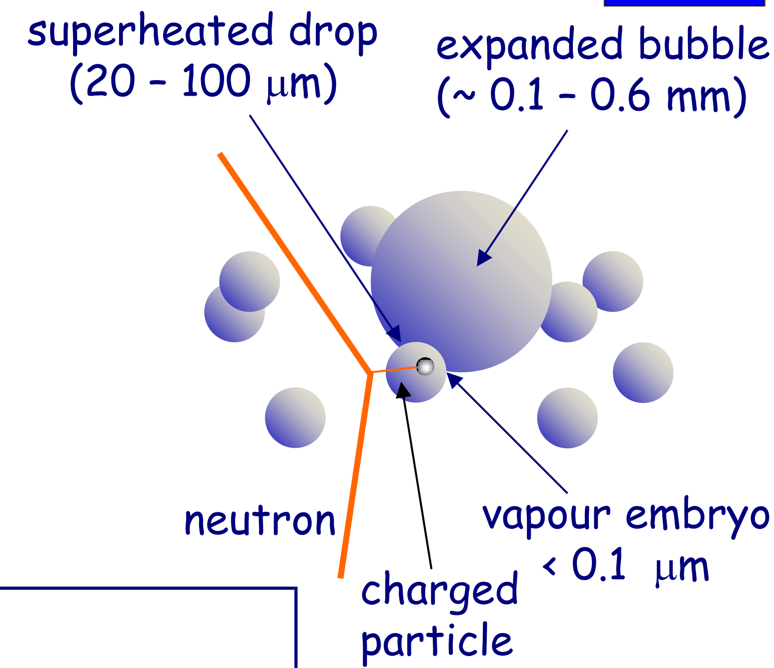


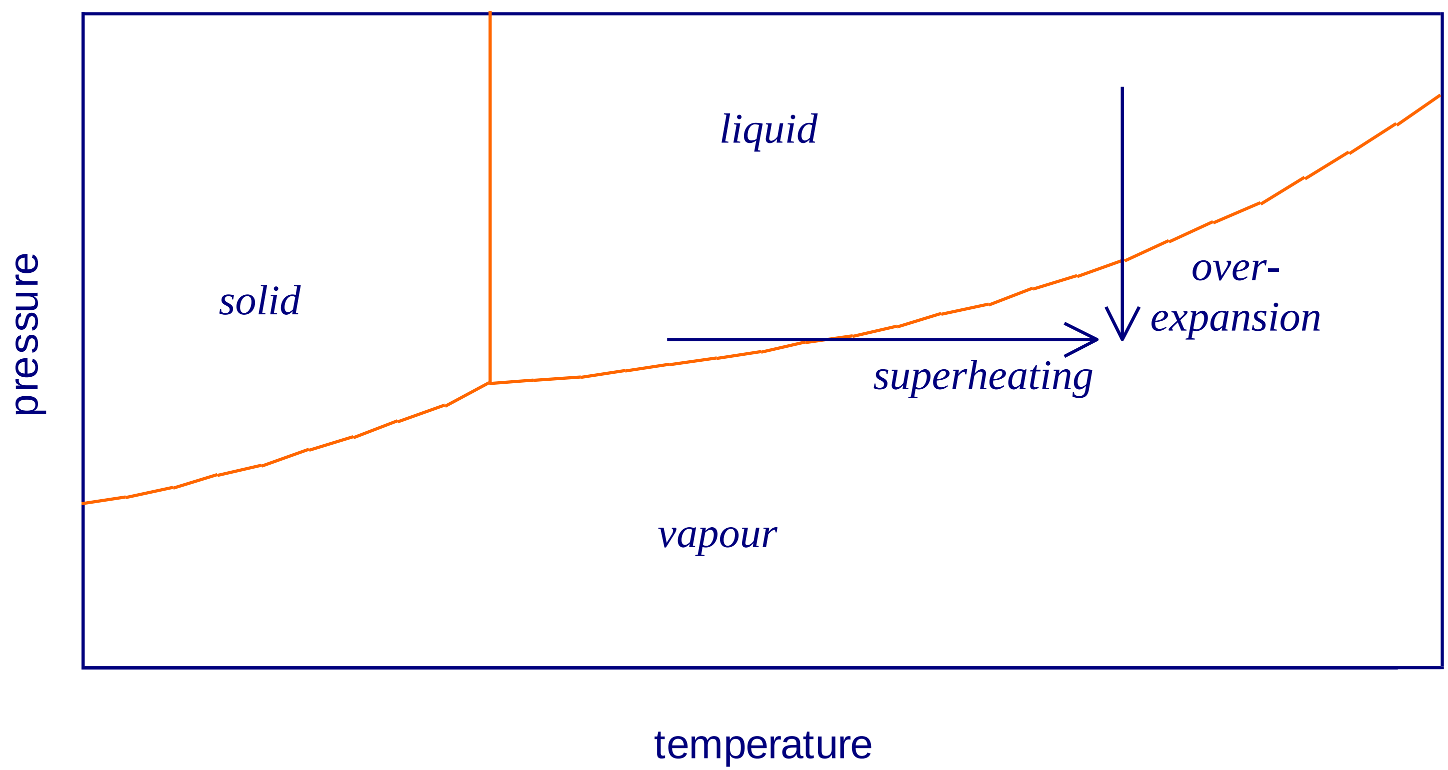


Neutron response enhancement using lead-shell in moderator type counters

Radiation monitoring

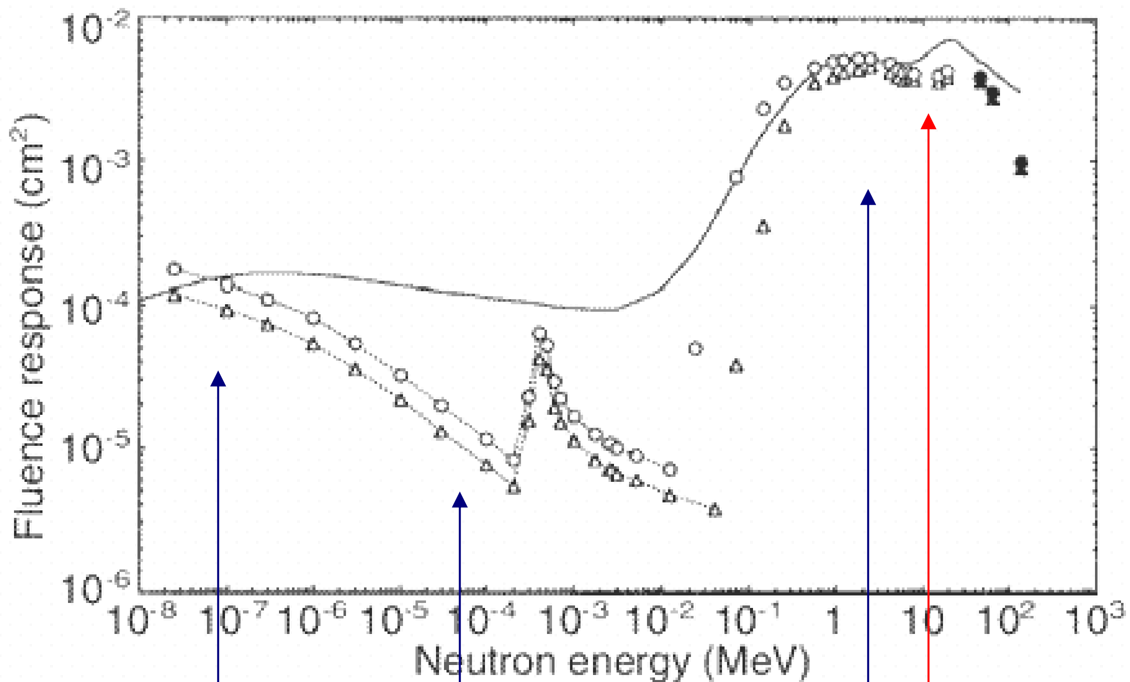
Superheated emulsions





Radiation monitoring

Superheated emulsions



Thermal neutrons: OK

0.1 – 10 MeV: OK

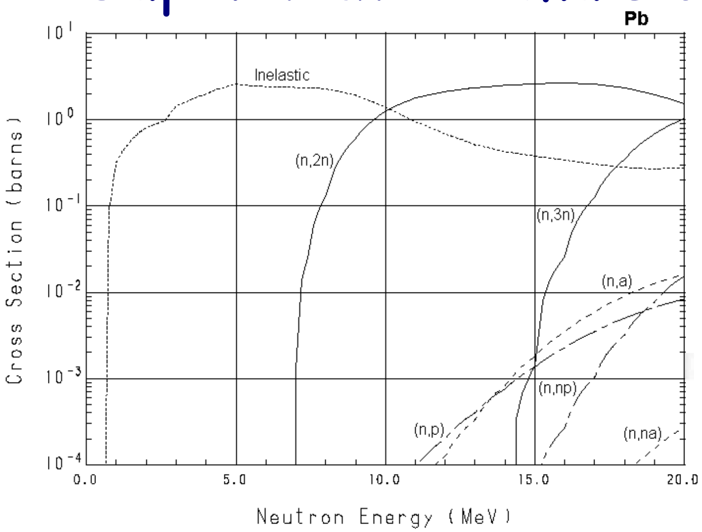
Epithermal neutrons: not important

Under-read > 10 MeV

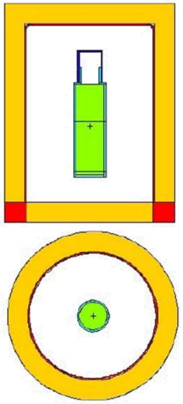
Energy response of SDD100 vials (dichlorodifluoromethane)

Radiation monitoring

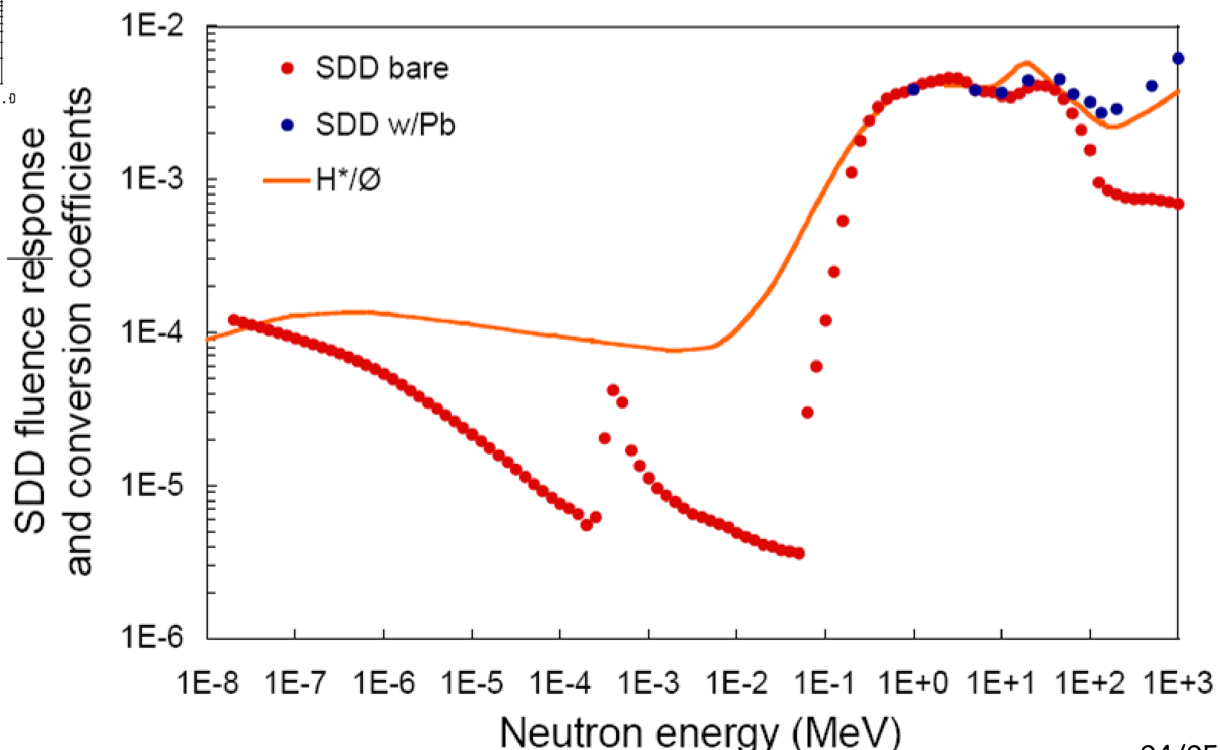
Superheated emulsions



ABC-HE with lead-shell



MCNPX simulation geometry



effect of lead moderator

Radiation monitoring

Superheated emulsions

Acoustic bubble counting

Model ABC1260
Framework Scientific
www.framesci.com