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Radiation Safety

Part C. Radiation shielding

1. Electron accelerators
2. Proton accelerators
3. Synchrotron radiation facilities
4. Specific:
   a. Beam dump
   b. Induced Activity
   c. RF generator plants

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1. Electron accelerators

Prompt radiation fields around accelerators:

1. Electron accelerators

photons (bremsstrahlung)
neutrons

2. Proton accelerators

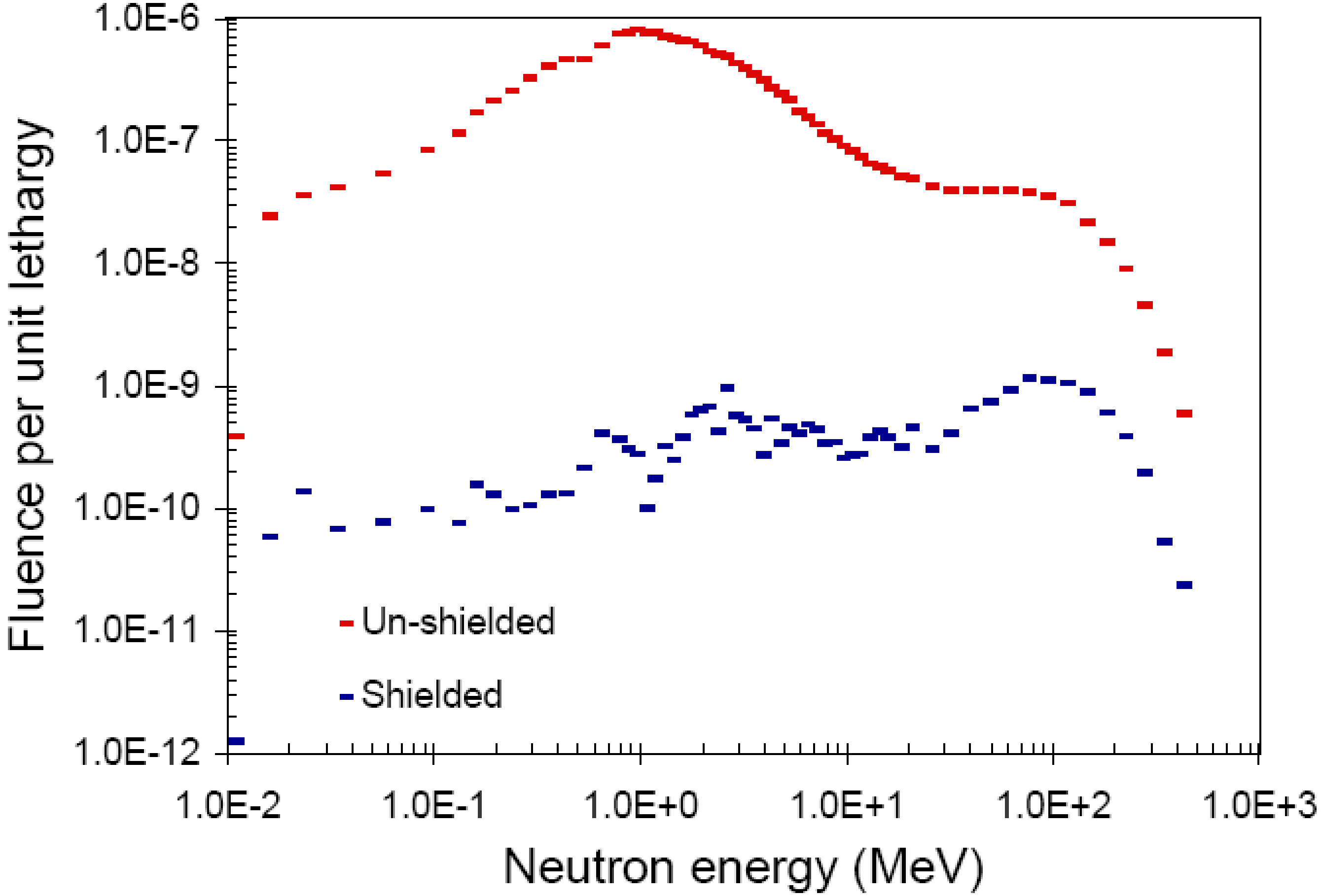
neutrons

3. Electron/Proton accelerator facilities

accelerators
beamlines

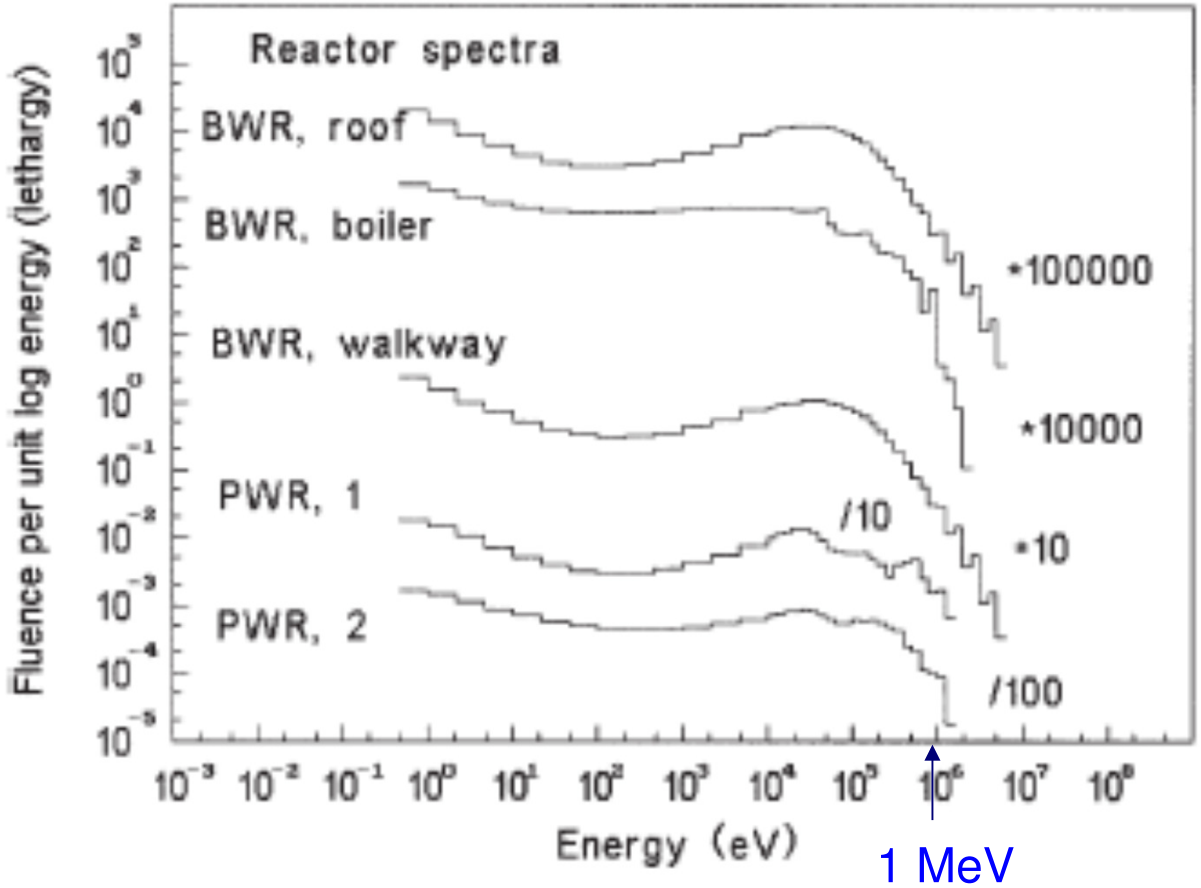
1. Electron accelerators

Examples of neutron spectra



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

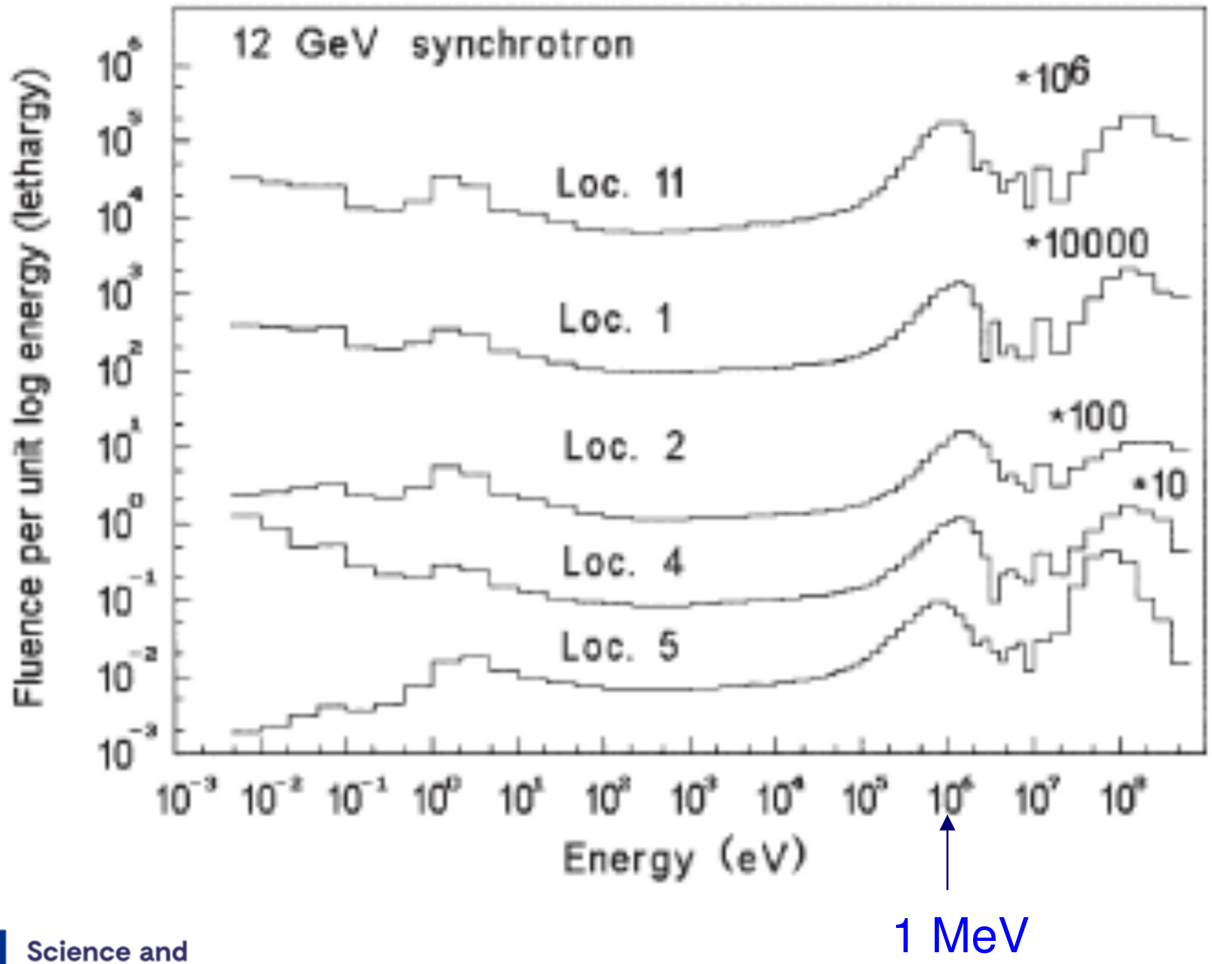
2. Proton accelerators
Examples of neutron spectra



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

2. Proton accelerators

Examples of neutron spectra



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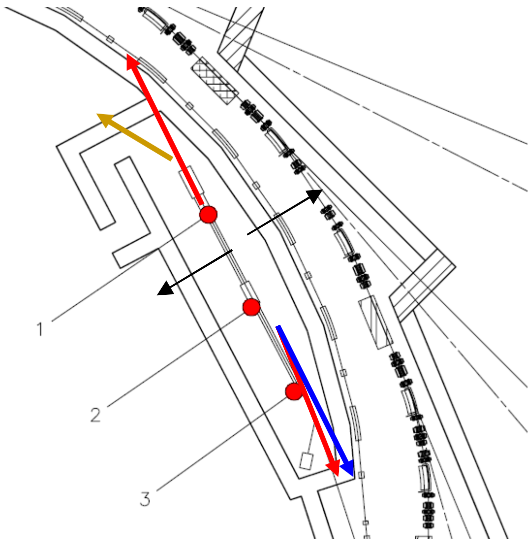
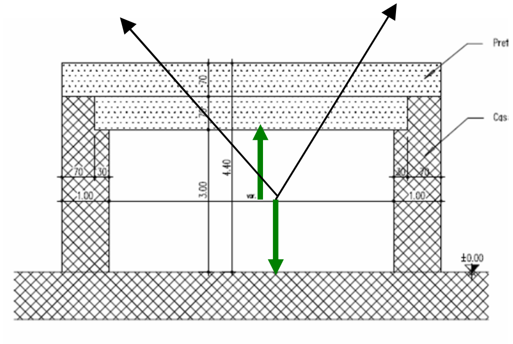
Source: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes – Technical Reports Series no. 403 , IAEA, 2001

1&2. Electron/Proton accelerator facilities

➢ The Ott's code allows to compute the effective annual dose D, at the following directions:

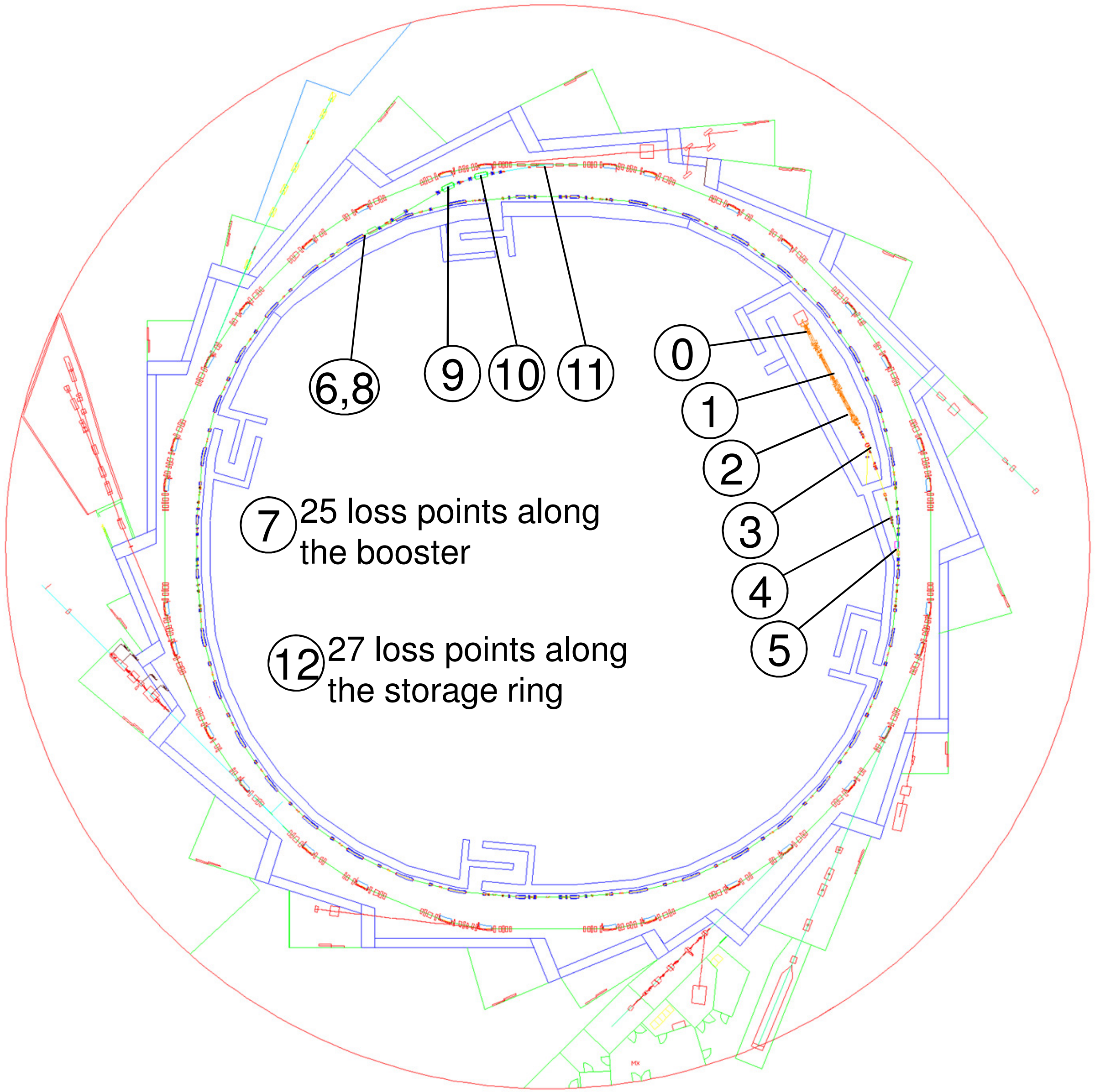
- Front / Back
- Front / Side
- Inside / Outside
- Roof / Floor
- Skyshine
- Labyrinth





(For a given: $i_e\,(P_S)$, $t_{User}\,(P_S)$, $t_{Machine}\,(P_S)$, E_e and shielding conditions)

1&2. Electron/Proton accelerator facilities



➢e-Loss Points:

	Machine Point
0	LINAC prebuncher
1	LINAC-1
2	LINAC-2
3	Transferline LINAC->Booster
4	Transferline LINAC->Booster
5	Injection Septum
6	Extraction Septum
7	Point Sources-Booster
8	Extraction Septum
9	Transferline Booster->SR-1
10	Transferline Booster->SR-2
11	Injection Septum
12	Point Sources-Storage Ring

1&2. Electron/Proton accelerator facilities

- Electron losses estimation during injection:

	Machine Point	% loss	Electron per second LOSS	IN	OUT	Energy [GeV]
0	LINAC prebuncher	-		7.02E+10	9.24E+10	0,00009
1	LINAC-1	10%	9.24E+09	9.24E+10	8.32E+10	0,05
2	LINAC-2	10%	8.32E+09	8.32E+10	7.49E+10	0,1
3	Transferline LINAC->Booster-1	5%	3.74E+09	7.49E+10	7.11E+10	0,1
4	Transferline LINAC->Booster-2	5%	3.56E+09	7.11E+10	6.76E+10	0,1
5	Injection Septum	**20%**	1.35E+10	6.76E+10	3.38E+10	0,1 to 3
6	Extraction Septum	**15%**	1.01E+10	3.38E+10	3.38E+10	0,1 to 3
7	Point Sources-Booster	15%	1.01E+10	3.38E+10	3.38E+10	0,1 to 3
8	Extraction Septum	**15%**	5.07E+09	3.38E+10	2.87E+10	3
9	Transferline Booster->SR-1	5%	1.44E+09	2.87E+10	2.73E+10	3
10	Transferline Booster->SR-2	5%	1.36E+09	2.73E+10	2.59E+10	3
11	Injection Septum	**40%**	6.48E+09	2.59E+10	1.30E+10	3
12	Point Sources-Storage Ring	30%	6.48E+09	1.30E+10	1.30E+10	3

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1&2. Electron/Proton accelerator facilities

- Operation time, depending on the machine mode:

User mode

Operating time /day	24	hours
Operating time/year (250 days/year)	6000	hours
Storage time /filling	5	hours
Injections / day	5	
Injections / year	1200	
Booster operation / injection	12	minutes
Booster operation / year	**250**	**hours**
Min. injection time/ injection	169	seconds
Min. injection time/ year	59	hours
Max. injection time/ injection	507	seconds
Max. injection time/ year	**176**	**hours**

Machine Test mode

Machine test weeks / year	12	hours
Injections / day	10	hours
Injections / year	600	hours
Synchrotron operation / injection	48	minutes
Synchrotron operation / year	**476**	**hours**
Min. injection time / injection	169	seconds
Min. injection time / year	28	hours
Max. injection time / injection	2535	seconds
Max. injection time / year	**422**	**hours**

- The dose limit objective at ALBA (following the ALARA principle) is **1 mSv/a** in all the site

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1&2. Electron/Proton accelerator facilities

- Annual Dose:

$$D = \sum_{i=1}^{3} D_i = D_{\gamma-\text{ray}} + D_{\text{giant-neutron}} + D_{\text{fast-neutron}}$$

Where D_i is given by:

$$D_i(\vec{s}) = i_e(s) \cdot t(s) \cdot H_i(\vec{s})$$

s : accelerator point

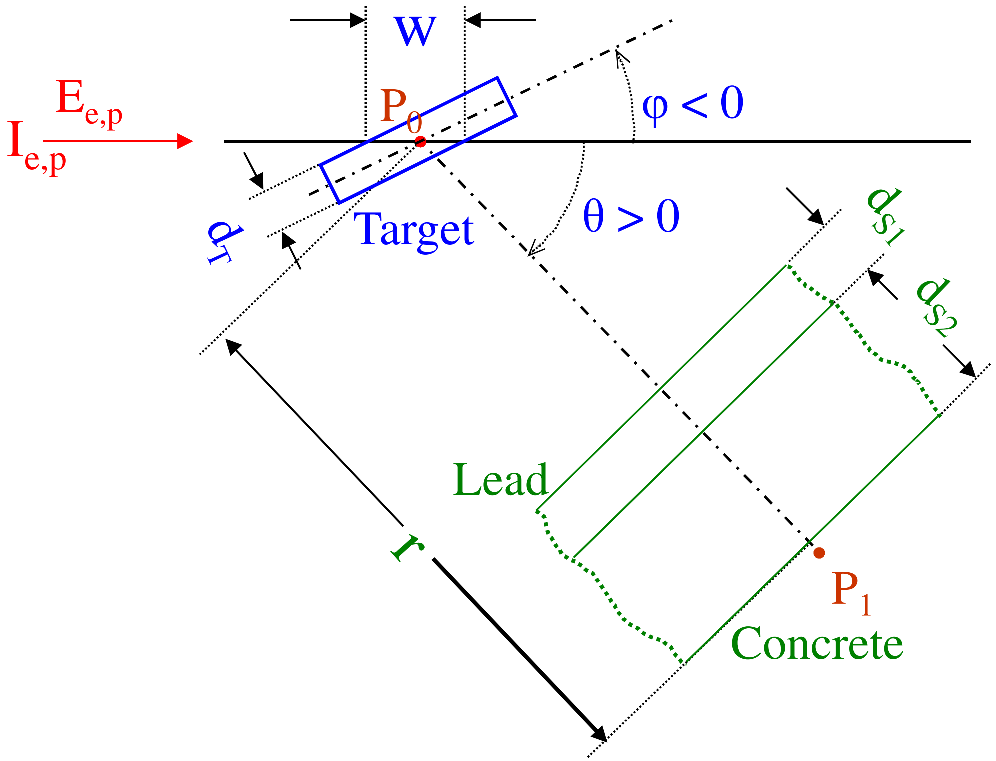
$i_e(s)$: is the electron loss rate at s-point

$t(s) = t_{User}(s) + t_{Machine}(s)$: is the time that the e-loss occurs (at s-point)

$H_i(\vec{s})$: is the dose rate (at s-point) for i-particle

1&2. Electron/Proton accelerator facilities

- Shielding Scheme Drawing:



- Dose at P_1, (per incident electron at P_0):

$$H = H(E_e;\ w\ (d_T,\varphi),\ \rho_T;\ r,\ \rho_{S1},\ d_{S1},\ \rho_{S2},\ d_{S2},\ \theta)$$

- In the ALBA case:

Source (for the Storage Ring):
Ie = 400 mA
Ee = 3.0 GeV

Target:
d_T *[cm]*: *depends on the machine point*
φ: *depends on the machine point*
ρ_T *[g/cm3]* : stain steel

Shielding:
r *[cm]*: *depends on the machine point*
ρ_{S1} *[g/cm³]*: lead
d_{S1} = 5 cm
ρ_{S2} *[g/cm3]* : concrete (normal & heavy)
d_{S2} = 1 m (side) & 1.5 m (front) & 1.4 m (roof)
Θ: *depends on machine point*

1&2. Electron/Proton accelerator facilities

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Analytical model (**for photons**):

$$\dot{H_p} = \prod_i \frac{\dot{H_0} \times e^{\left[-\left(\mu/\rho\right)_i \rho_i \times d\right]}}{{r_p}^2} = \frac{\dot{H_0}}{{r_p}^2} \prod_i e^{\left[-\left(\mu/\rho\right)_i \rho_i \times d\right]}$$

$\dot{H_p}$: Dose rate equivalent rate (in Sv/h) in a given point-p, out of the shielding area

$\dot{H_0}$: Dose rate equivalent rate (in Sv/h) at 1 m from the source, without the shielding

d : Shield thickness (in cm)

$(\mu/\rho)_i$: mass attenuation coefficient (in cm^{-1}) for the material-i

r_p: distance from the source point to the dose point-p (in m)

i: sum over different materials

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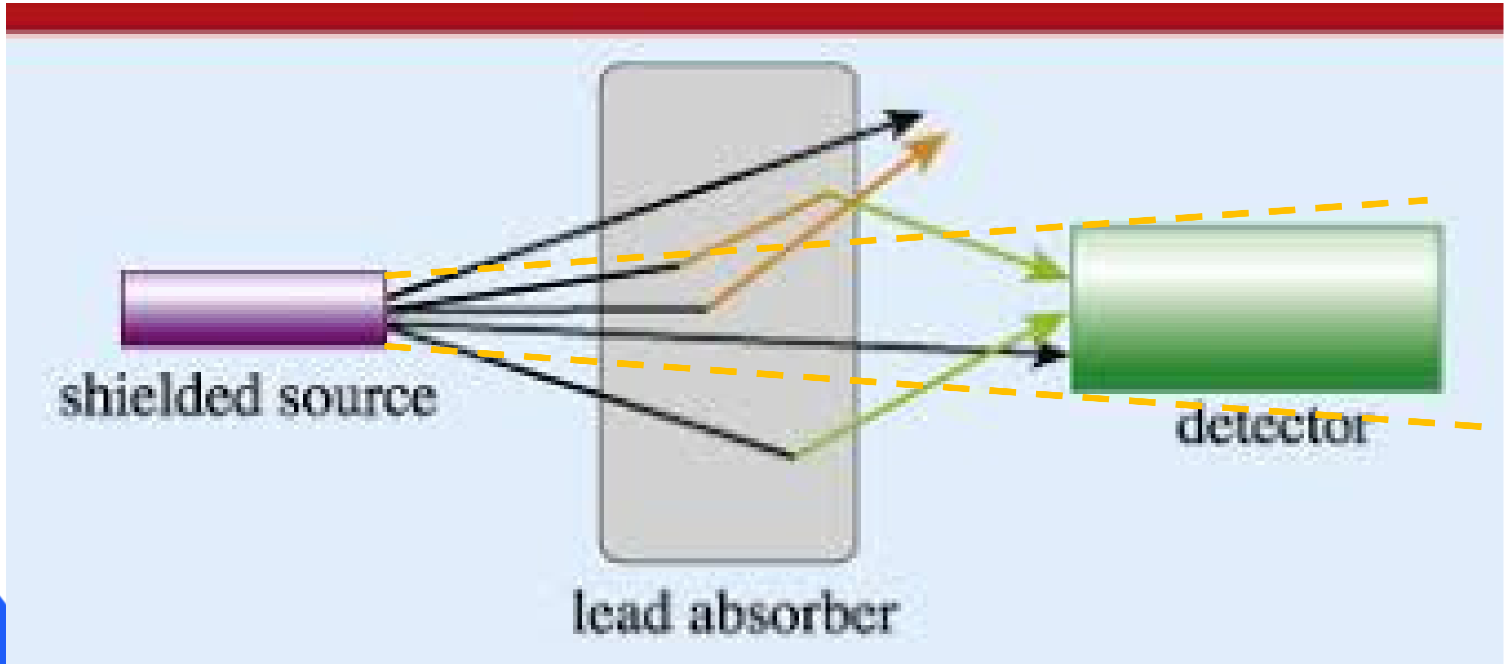
1&2. Electron/Proton accelerator facilities

Example (**in air**): a 1 Sv/h (at 1 meter in vacuum) 100 keV photon source, at 10 m?

$$\dot{H}_p = \frac{1 \times e^{[-(0.1541 \times 0.00123) \times 1000]}}{10^2} = 8.3 \text{ mSv/h}$$

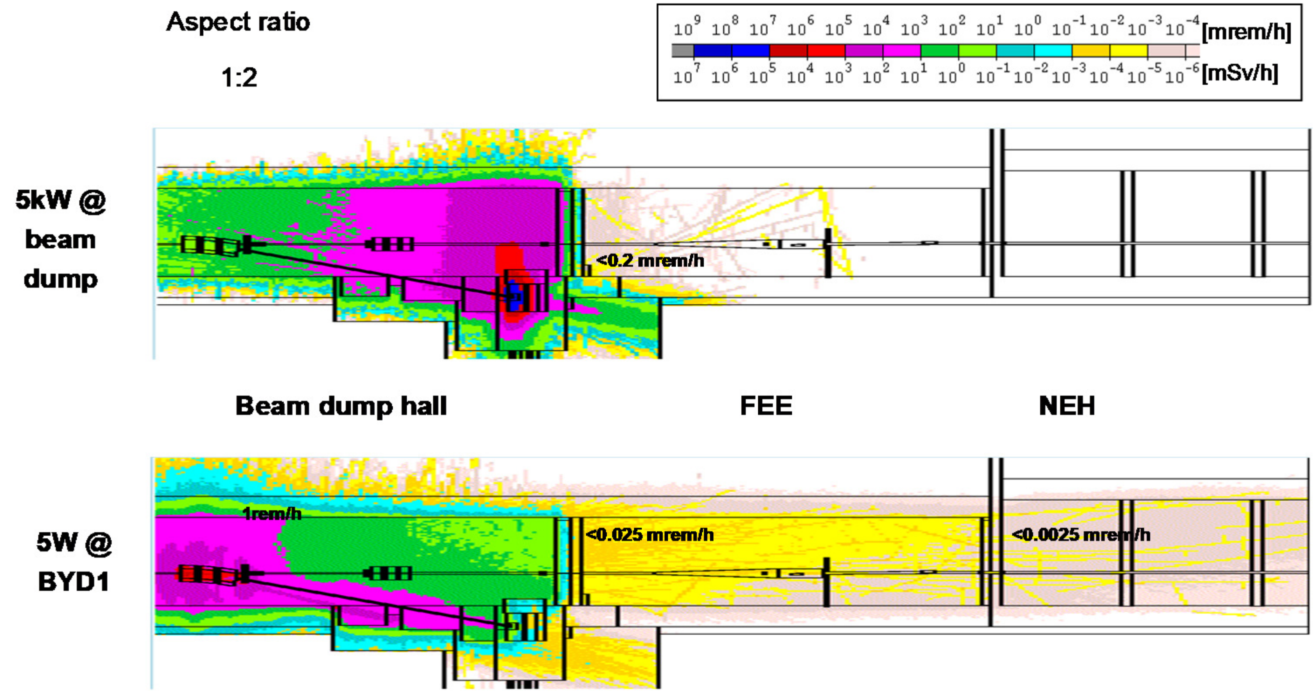
Buildup factor effect: how the shielding 'unshield' the source



3. Synchrotron radiation facilities

Monte-Carlo codes

Examples: MCNPX
PENELOPE
FLUKA
MARS



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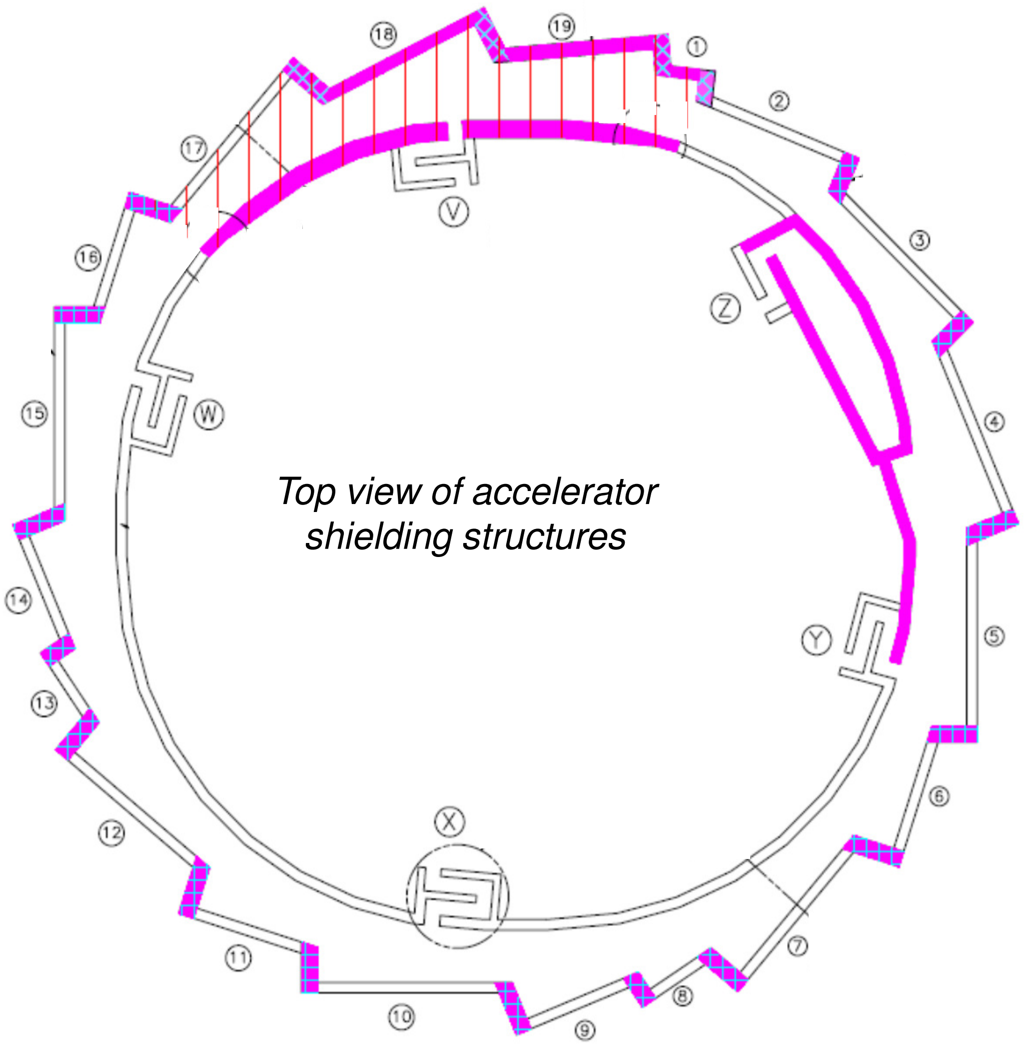
Example: MARS calculation for the electron dump line of the LCLS facility - Courtesy of T. Sanami.

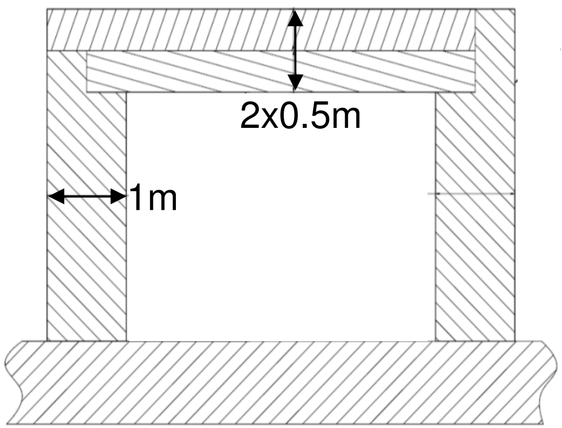
3. Synchrotron radiation facilities

➢ Concrete structures:



Top view of accelerator shielding structures

Inner and side walls thickness	1 m
Inner wall thickness at injection	1.65 m
Side wall thickness at injection	1.25 m
Roof thickness	1 m
Roof thickness at injection	1.4 m
Linac walls thickness	1 m
Labyrinths walls thickness	0.7 m
Front walls thickness	1.5 m
Number of side/front walls	19
Concrete density	2.4 g/cm^3
Heavy concrete density	3.2 g/cm^3



Tunnel section

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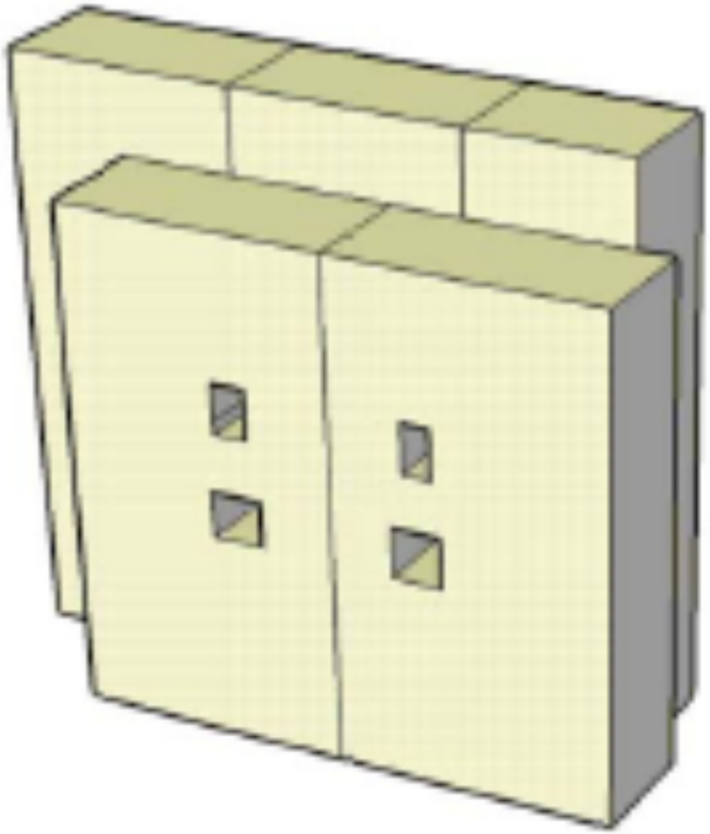
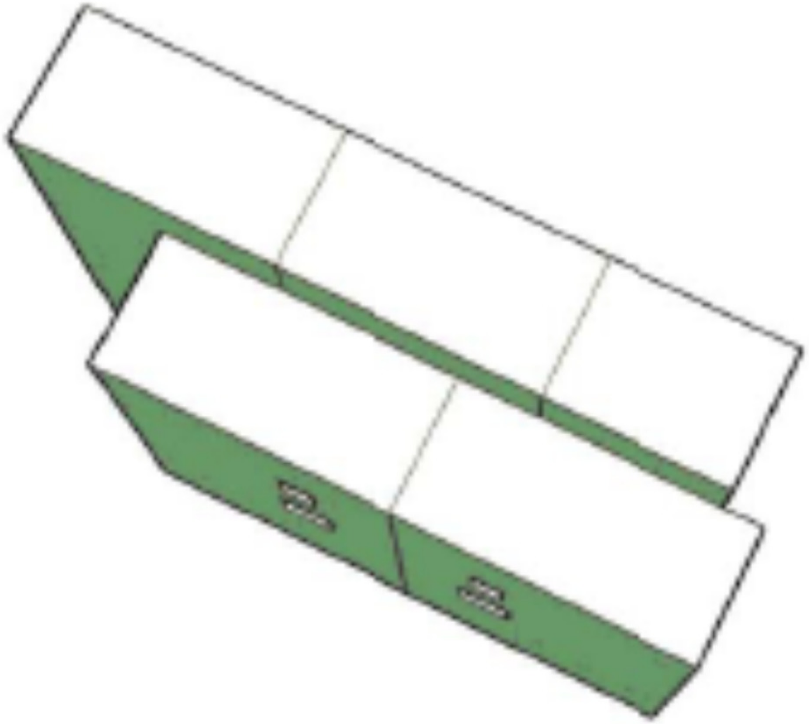
3. Synchrotron radiation facilities

- Front wall





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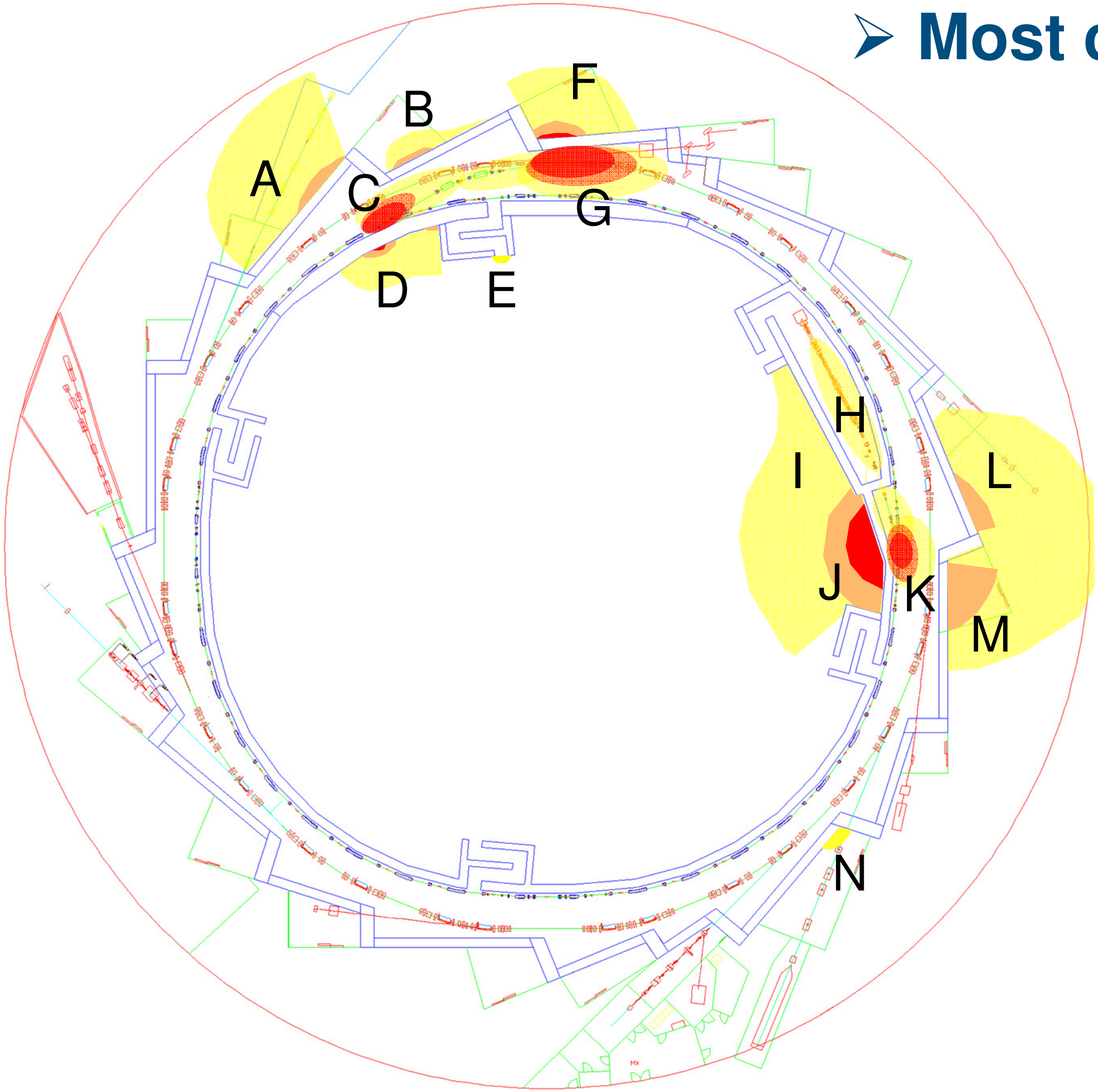
3. Synchrotron radiation facilities



➢ **Most critical areas**

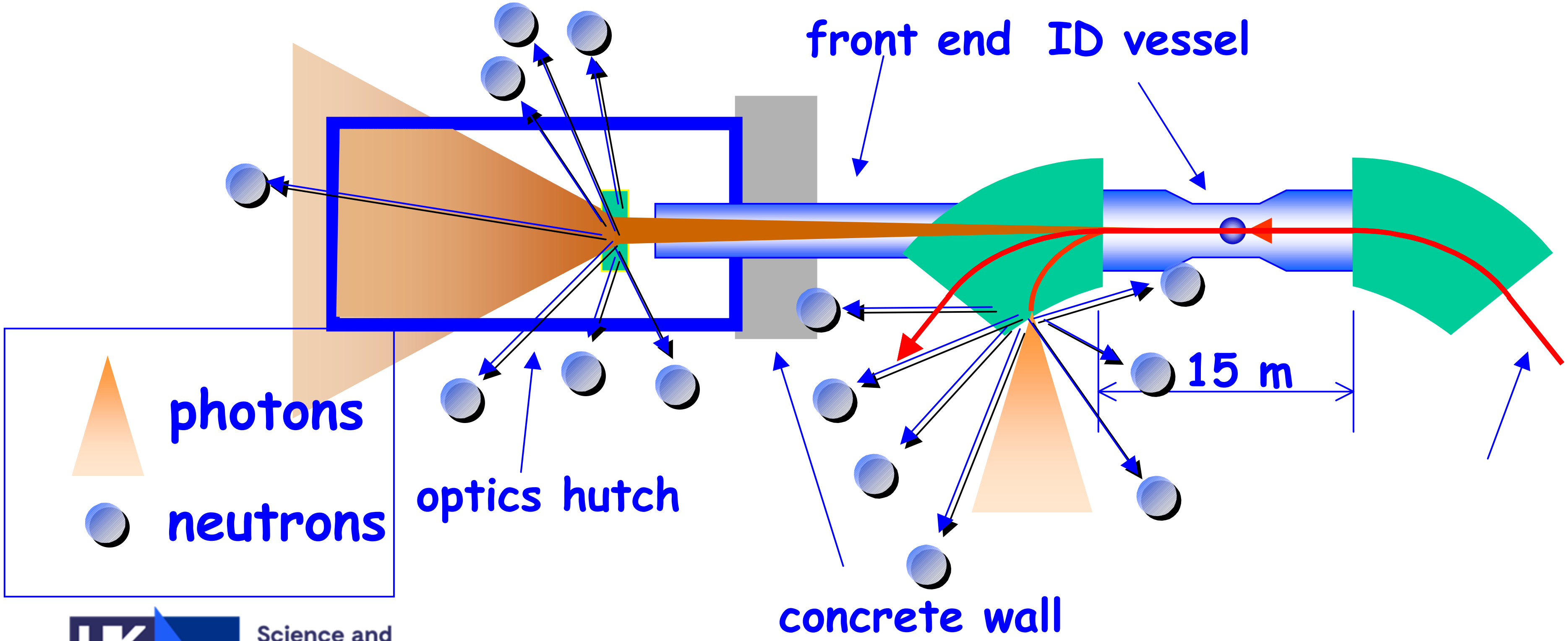
3. Synchrotron radiation facilities

ALBA SYNCHROTRON: EXPERIMENTAL BEAMLINES

3. Synchrotron radiation facilities

Radiation fields

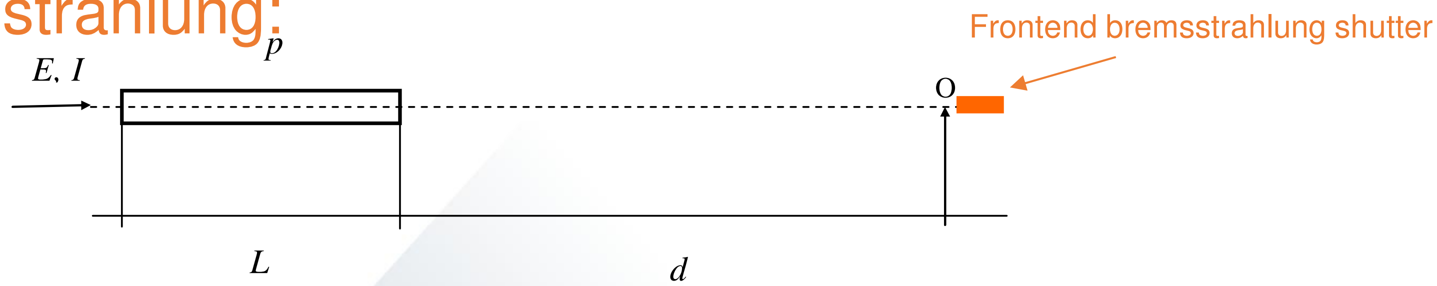
- Accelerator tunnels:
  - photons, neutrons
- Beamlines:
  - X-rays, photons, neutrons



3. Synchrotron radiation facilities

BEAMLINES SHIELDING - SOURCE TERM

➢Gas bremsstrahlung:



$$\dot{D}_0 = 2.5 \times 10^{-27} \cdot \left(\frac{E}{mc^2}\right)^{2.67} \cdot \frac{L}{d(L+d)} \cdot I \cdot \frac{p}{p_0}$$

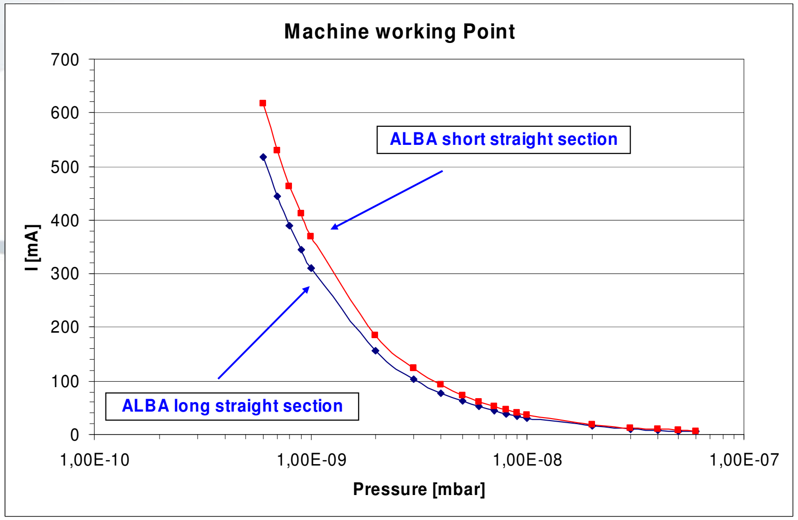
$\dot{D}_0$: is the dose rate at O-point (Energy/Mass/Time)

✓If:

- L = 4 m ; d = 18 m
- I = 400 mA
- P = 1.4 10^{-9} mbar

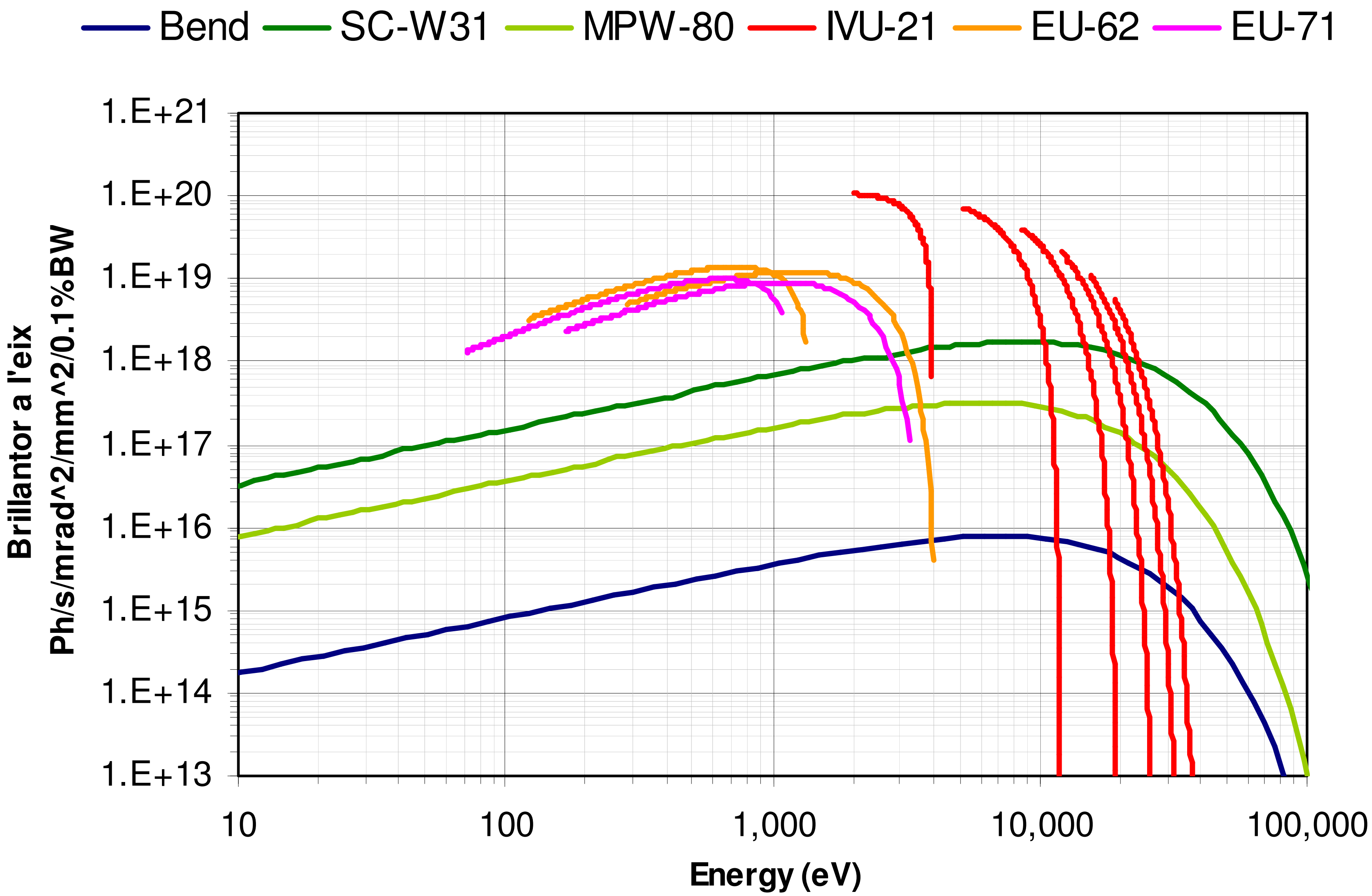
$$\dot{D}_0 = 0.6 \text{ Gy/h}$$

$$\frac{\left.\dot{D}_0\right]_{3\,\text{GeV}}}{\left.\dot{D}_0\right]_{2\,\text{GeV}}} = \frac{3^{2.67}}{2^{2.67}} \approx 3$$



✓Strong dependence with the machine condition (E, I and P)

3. Synchrotron radiation facilities



3. Synchrotron radiation facilities

❖Source term

✓Internal rules: → 0.5 µSv / h

1 mSv / year (2000 hour / year)

✓Order of the radiation source term → > 10^6 times reduction

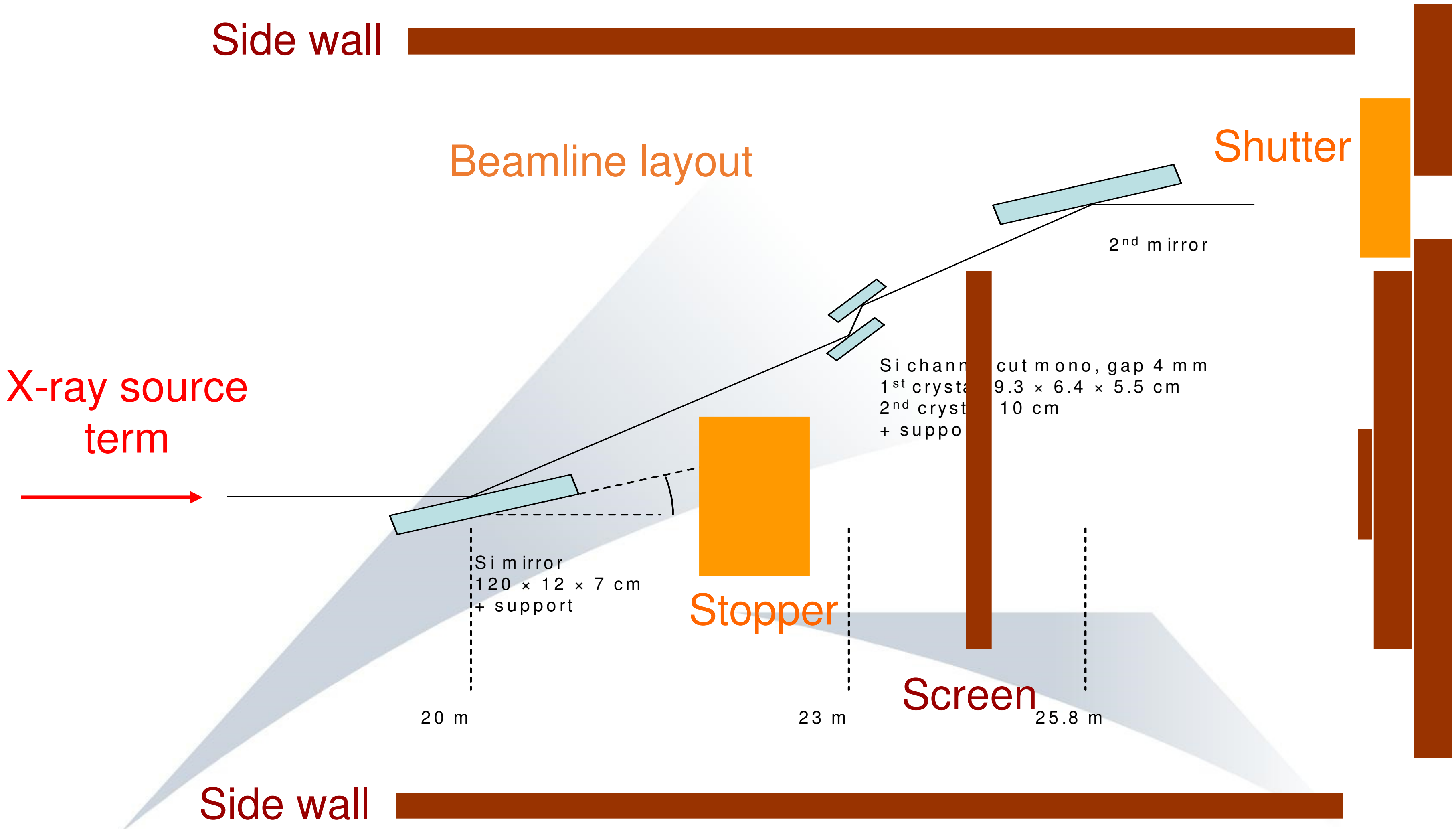
1 Sv / h

✓Shielding elements required:

- Hutch walls
- Stopper & Shutter

3. Synchrotron radiation facilities

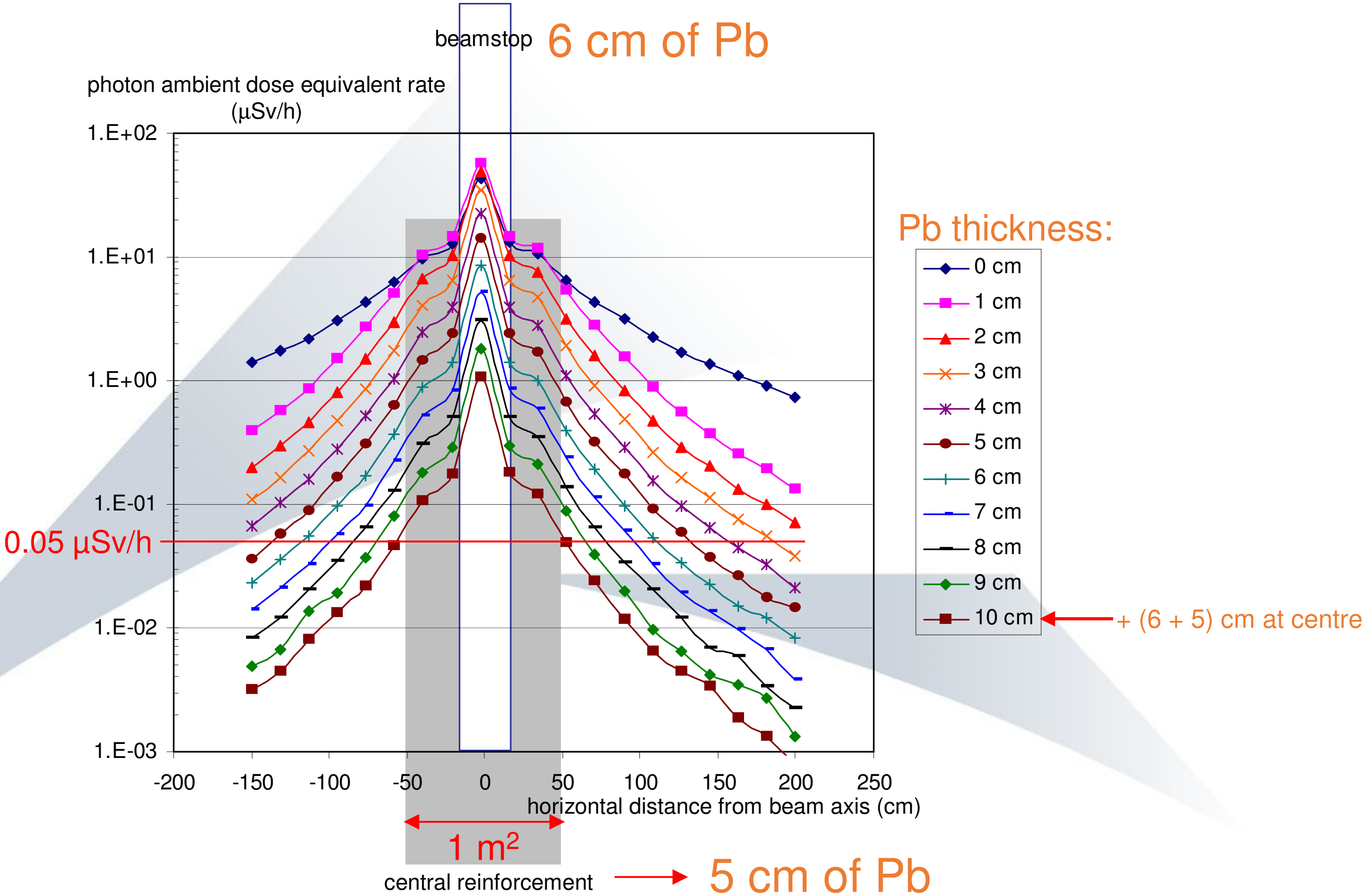
BEAMLINES SHIELDING - SAFETY ELEMENTS



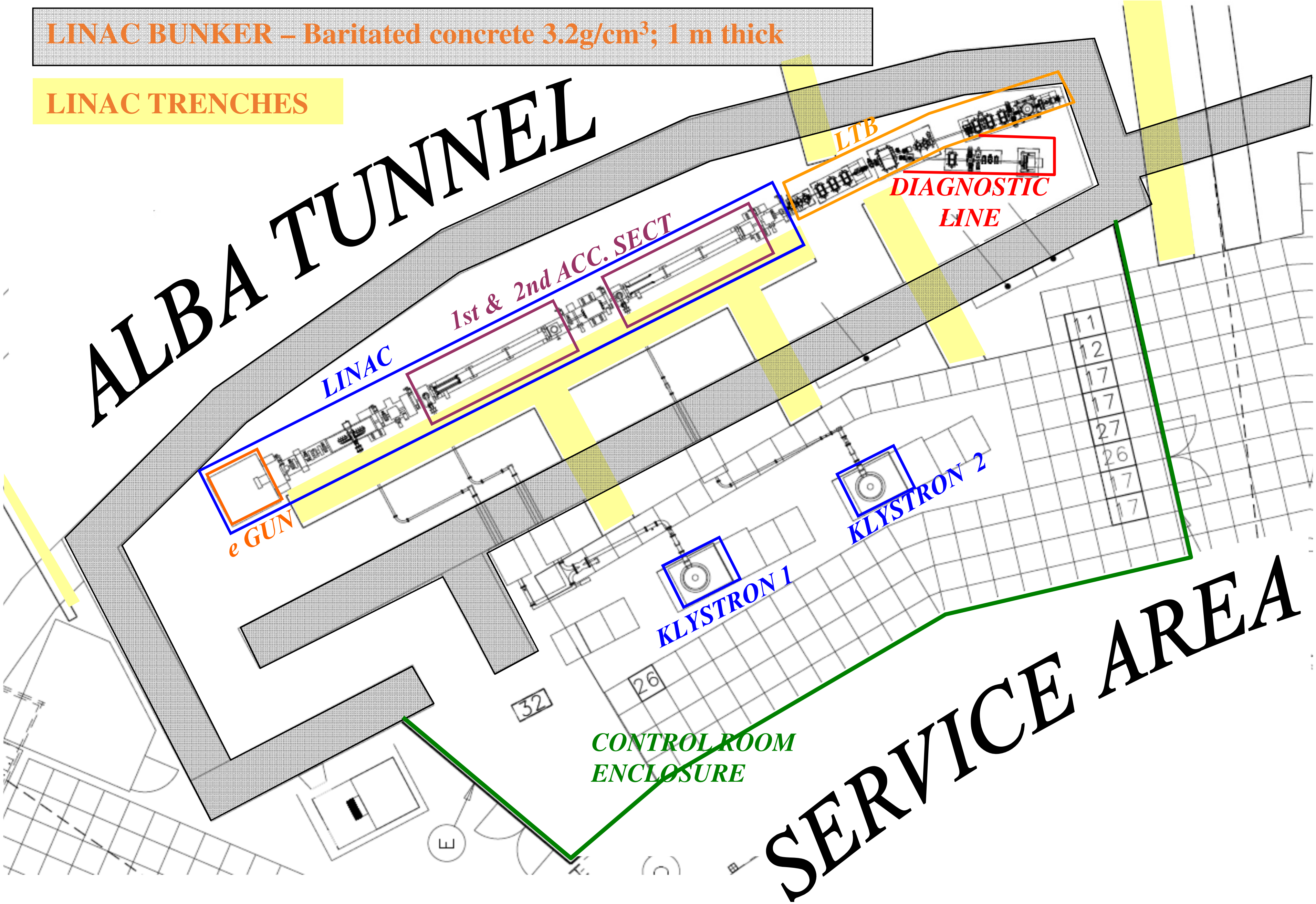
3. Synchrotron radiation facilities

BEAMLINES SHIELDING - SAFETY ELEMENTS

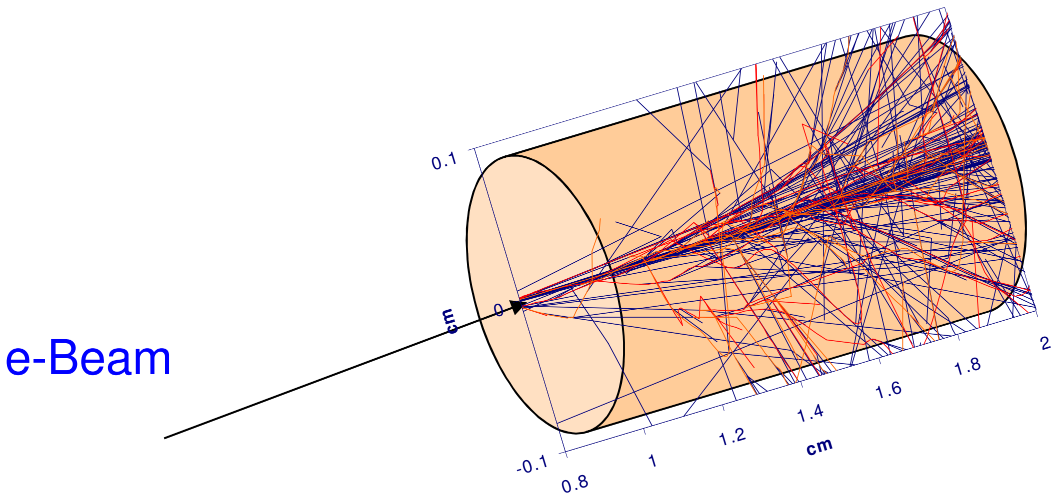
- ❖Shielding against gas bremsstrahlung
  - ➢Backwall thickness (for the HRPD case):



4a. Beam dump


LINAC BUNKER – Baritated concrete 3.2g/cm³; 1 m thick
LINAC TRENCHES
ALBA TUNNEL
LTB
DIAGNOSTIC LINE
1st & 2nd ACC. SECT
LINAC
e GUN
KLYSTRON 2
KLYSTRON 1
CONTROL ROOM ENCLOSURE
SERVICE AREA

4a. Beam dump cylinder



Molière radius (ρ_M): it is the radius of a cylinder containing on average 90% of the shower's energy deposition.

$$\rho_M\,[cm] = 0.0265\,[cm^3/g]\,X_0\,(Z + 1.2)$$

Where:

X_0 [g/cm^2]: Radiation length (for Cu: 12.86 g/cm2)

Z: atomic number (for Cu: 29)

ρ_M = 10.29 cm

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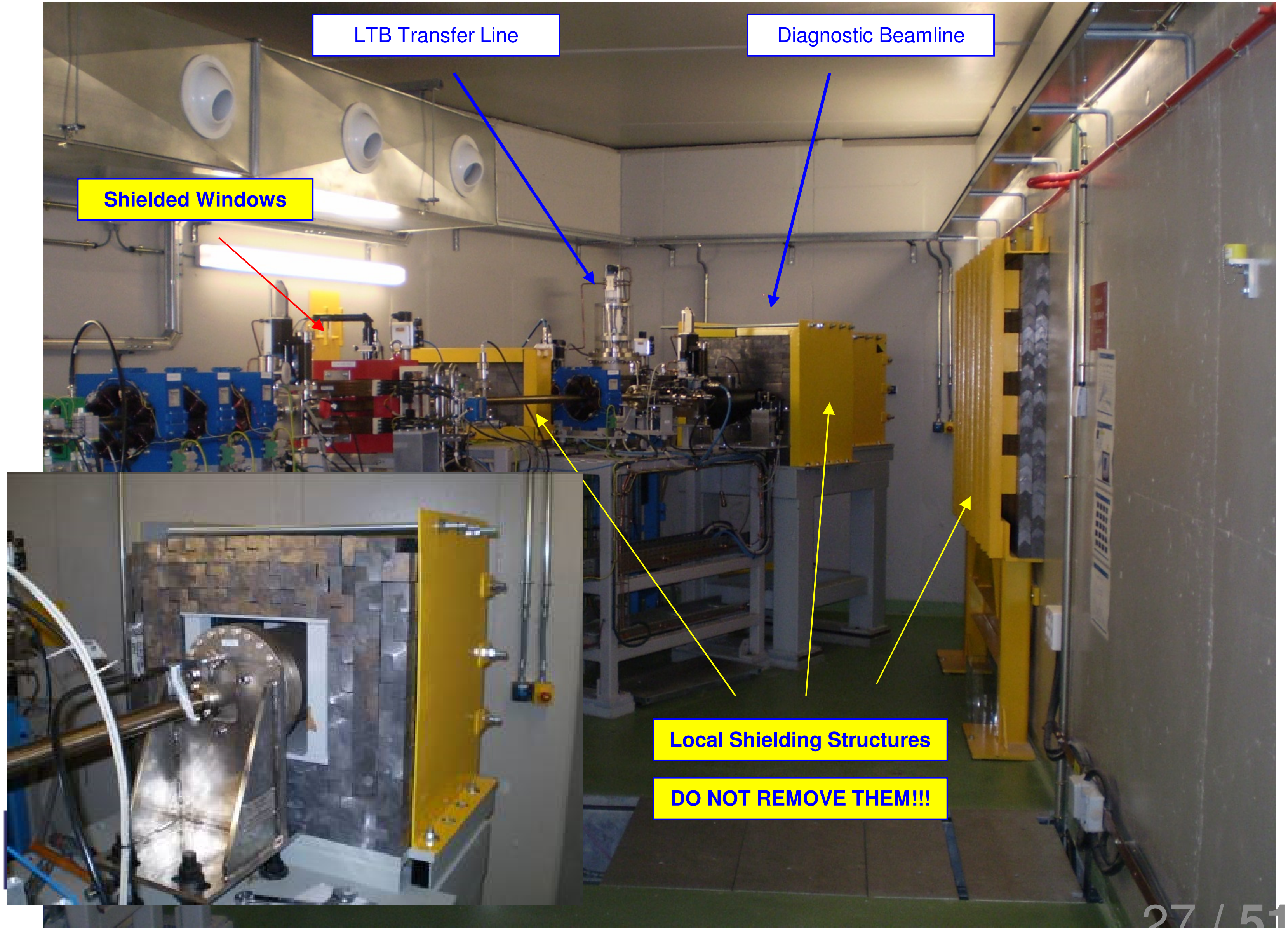
4a. Beam dump cylinder



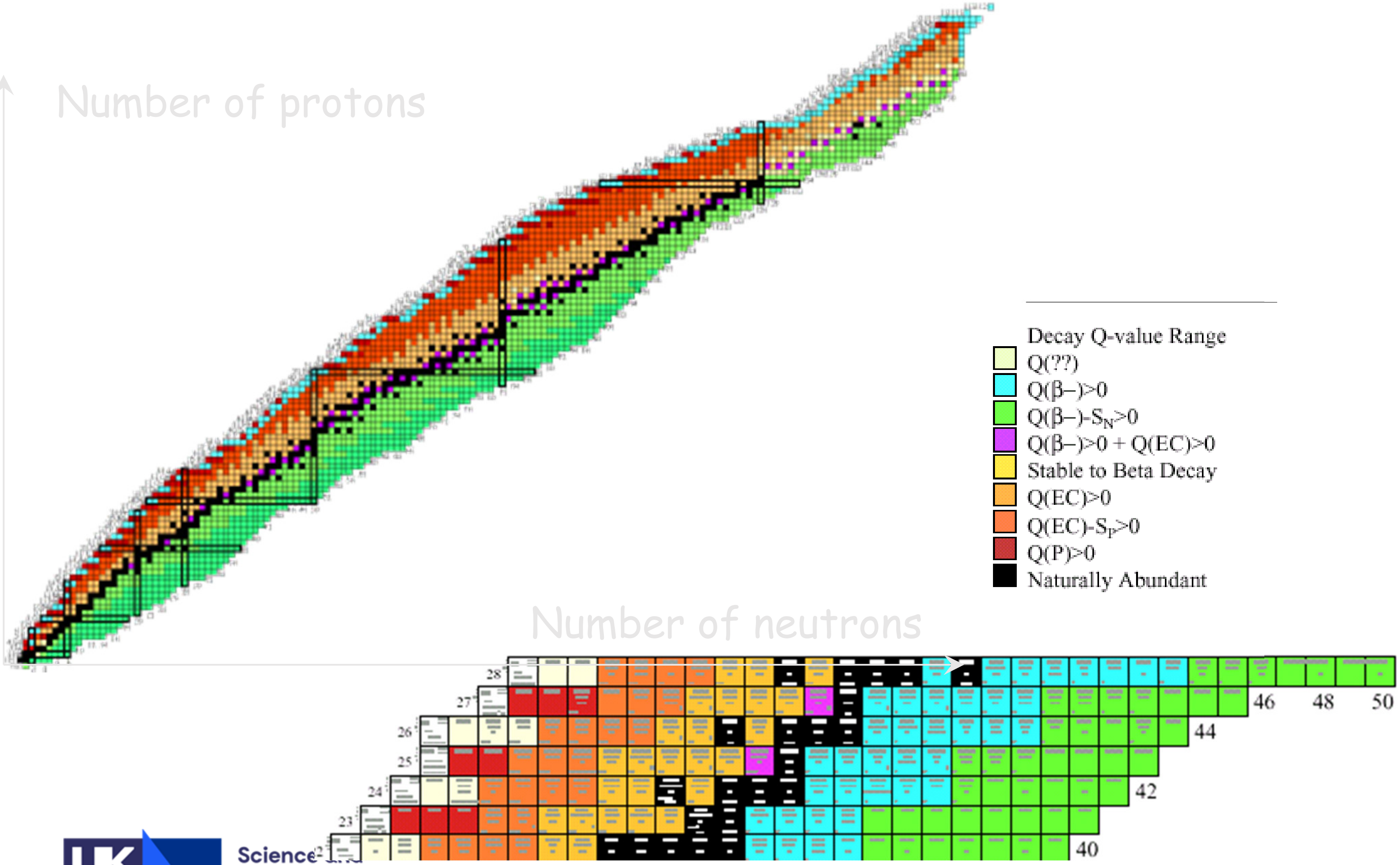
4b. Induced Activity

- 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

4b. Induced Activity



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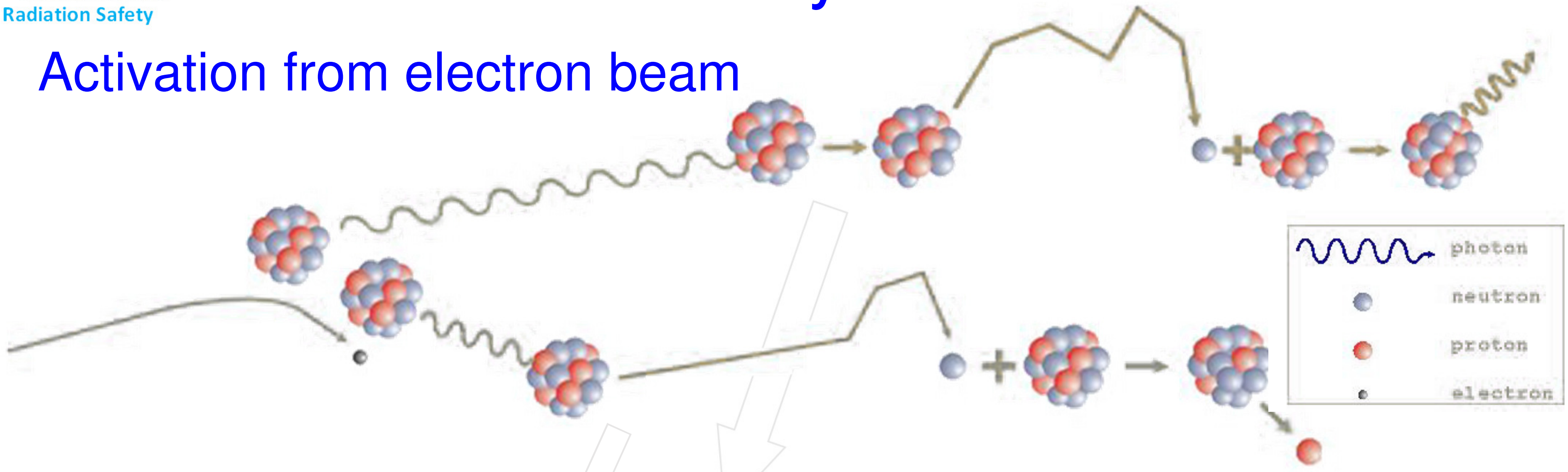
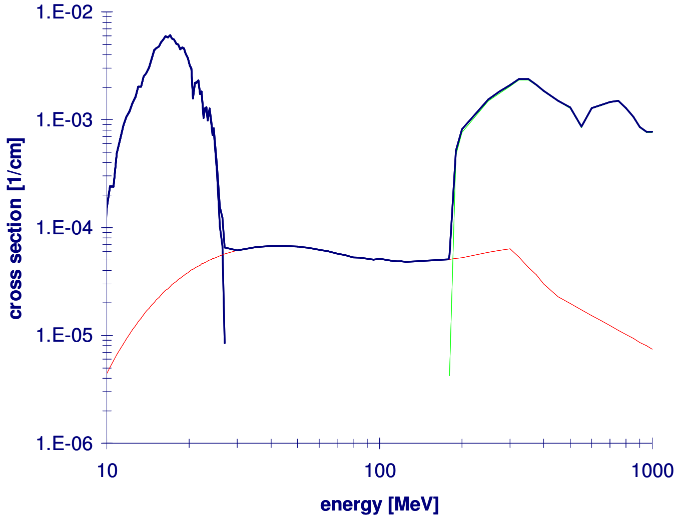
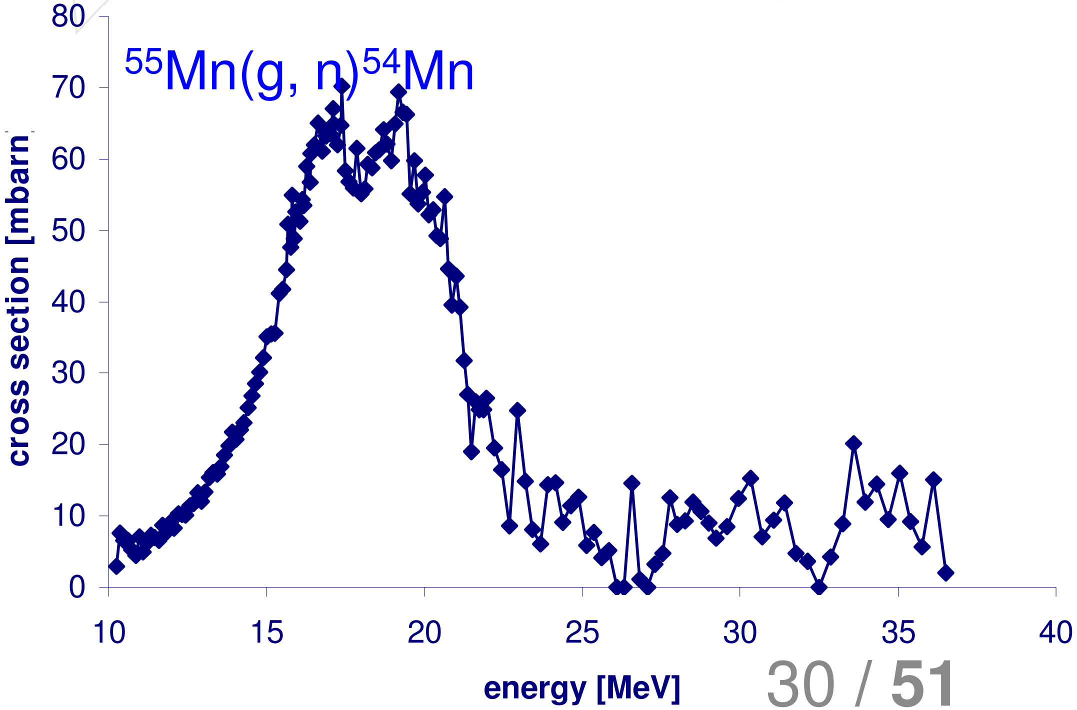
4b. Induced Activity

Activation from electron beam



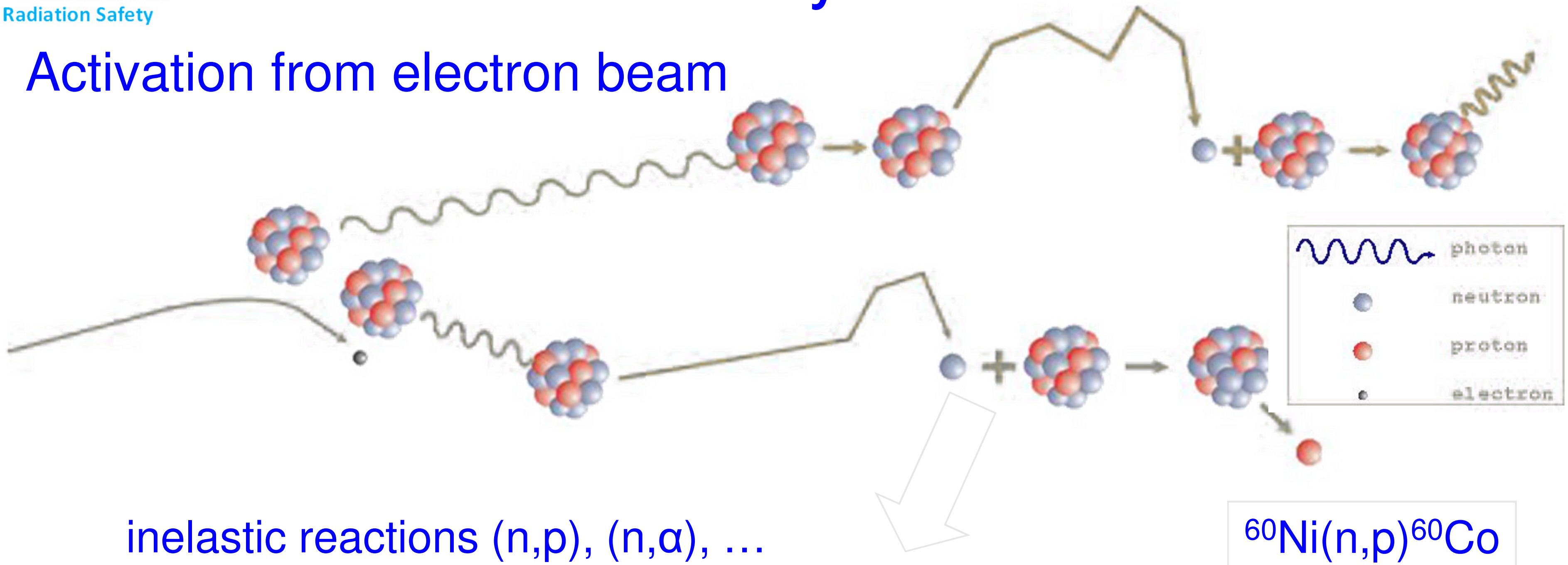
photonuclear reactions
(γ,n), (γ,p), (γ,np), …



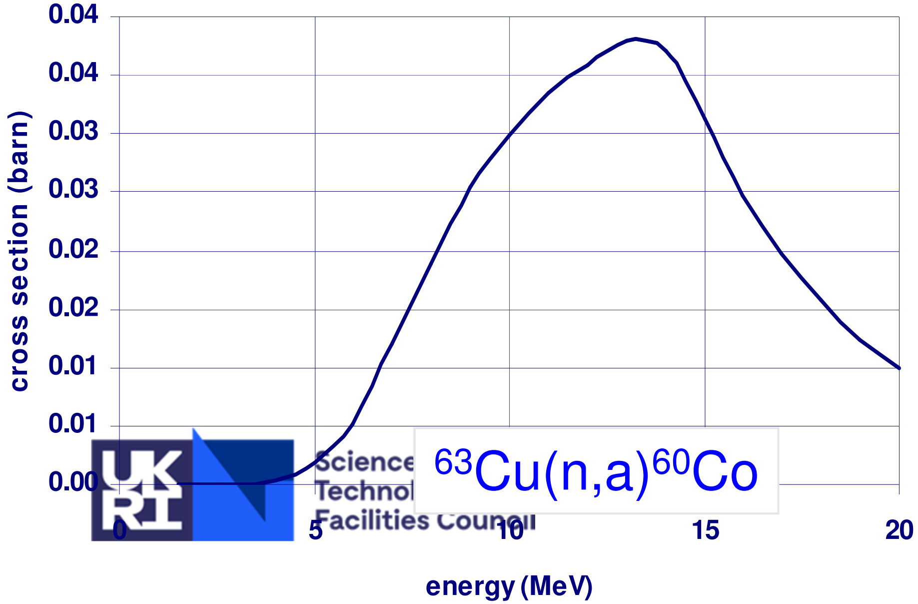


4b. Induced Activity

Activation from electron beam

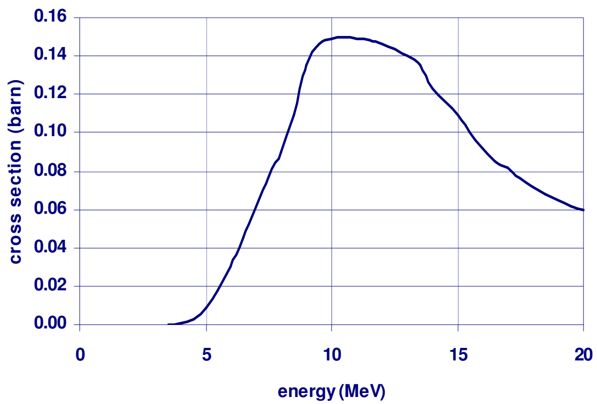


inelastic reactions (n,p), (n,α), …



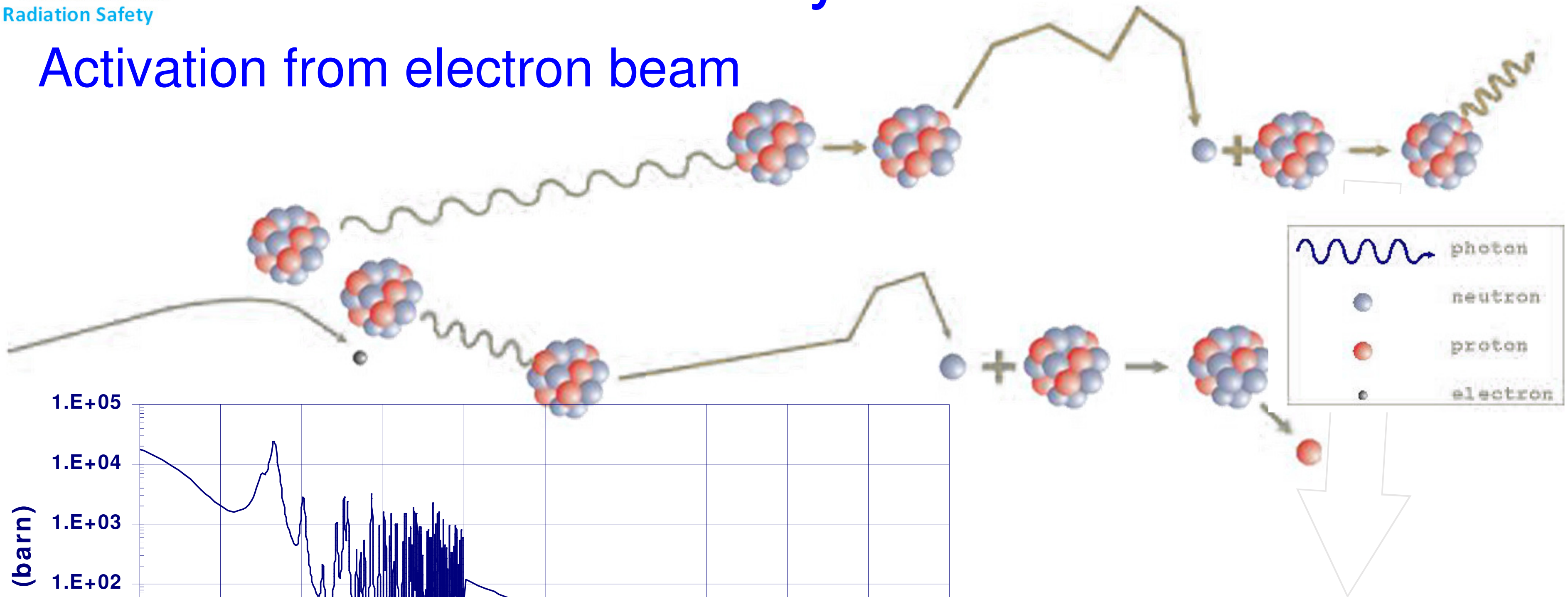
$^{63}Cu(n,a)^{60}Co$

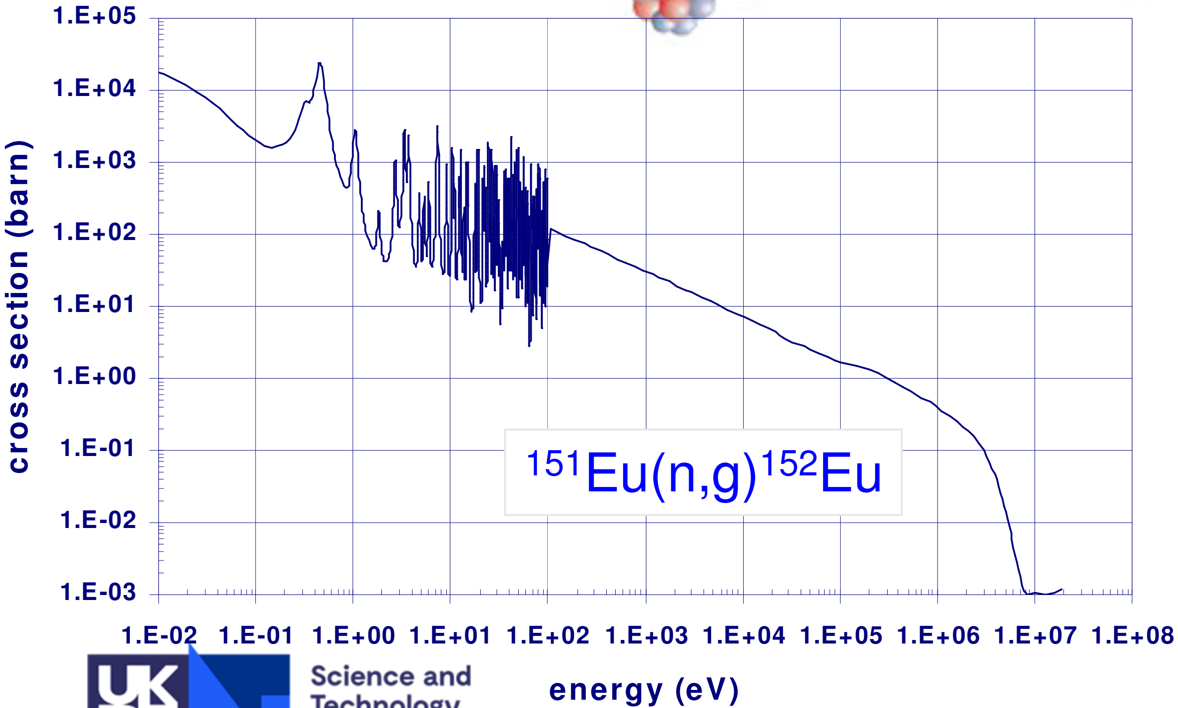
$^{60}Ni(n,p)^{60}Co$



4b. Induced Activity

Activation from electron beam

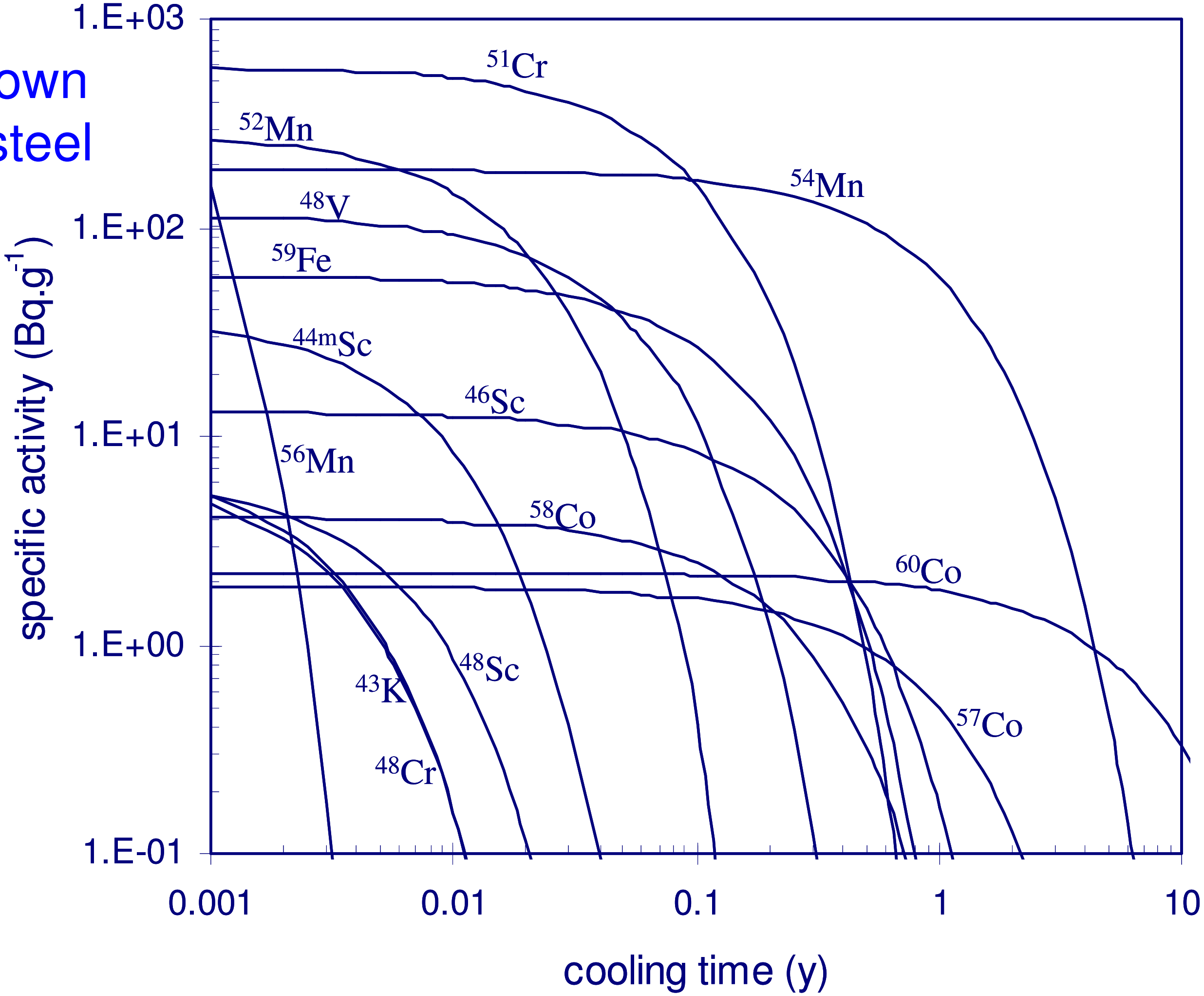




Radioactive capture

4b. Induced Activity
Activation from electron beam

Example: cooling down curve of irradiated steel



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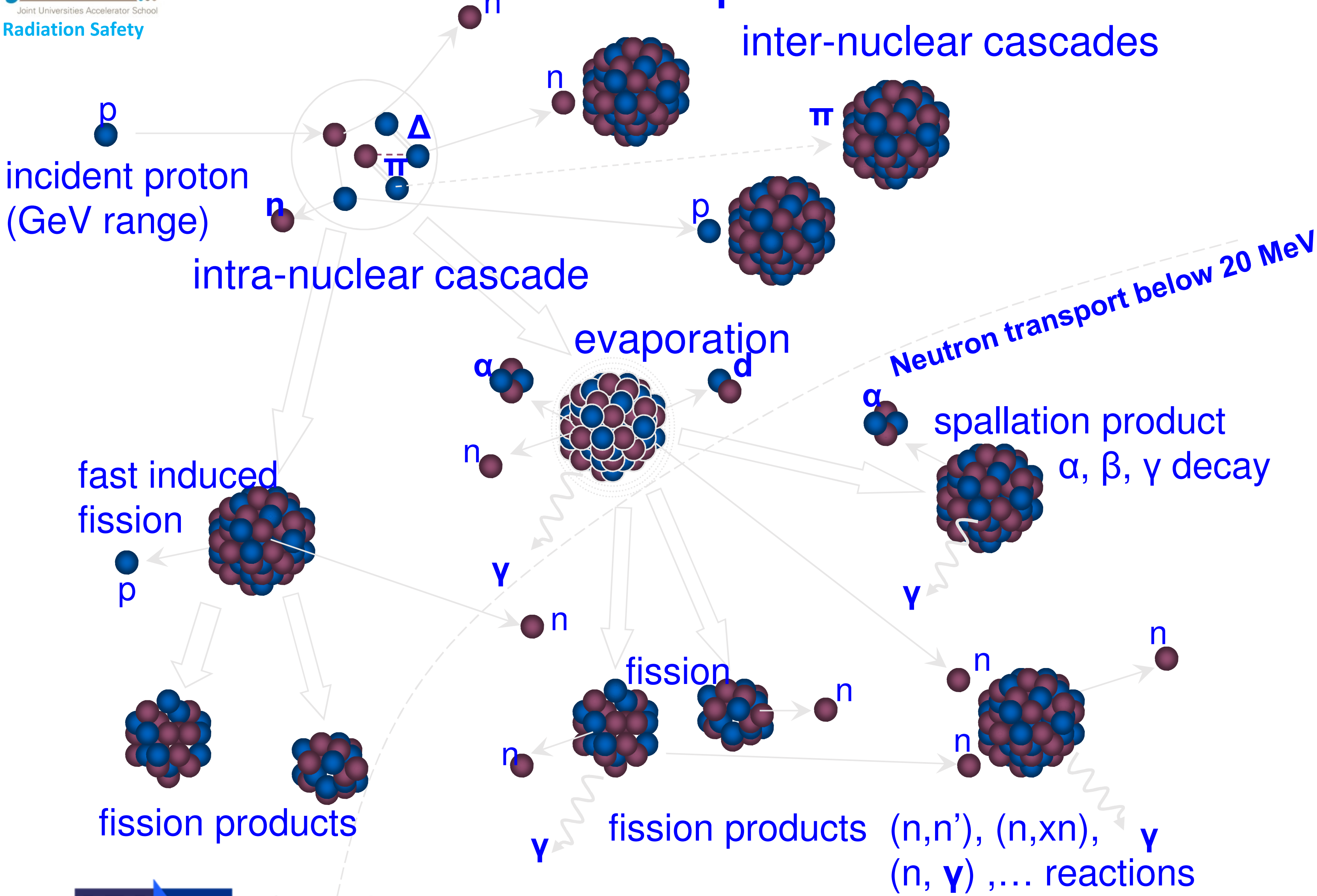
4b. Interaction of protons with matter



Activation from proton beam

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4b. Induced Activity

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

Main radioactive isotopes produced in accelerator structures by spallation reactions

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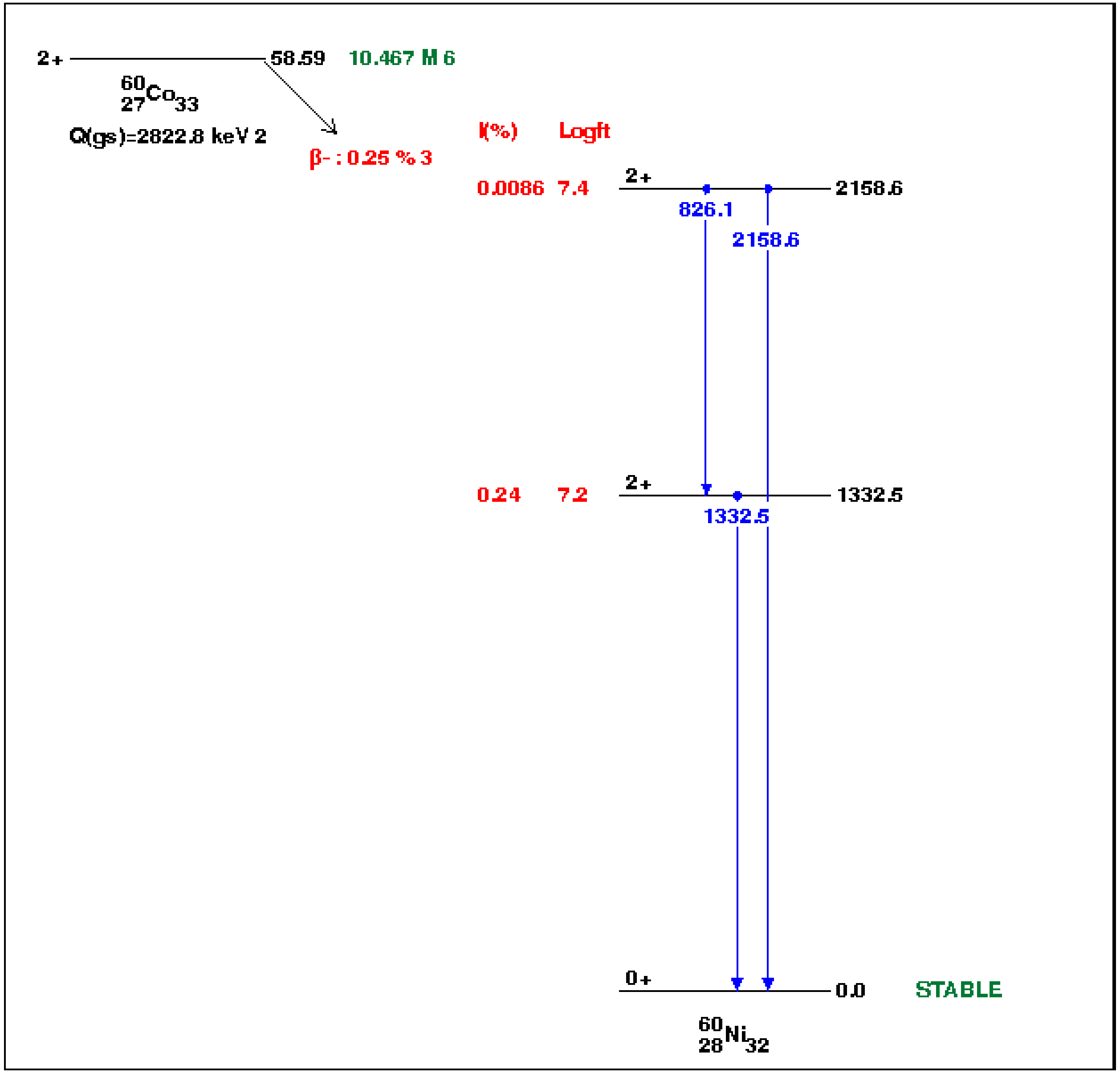
4b. Particular case: $^{60}Co = {}^{60}_{27}Co_{33}$



A = 60
Z = 27
N = 33

$^{60}_{28}Ni_{32}$

A = 60
Z = 28
N = 32

4b. ^{60}Co Radiation term

Radionuclide activity [A]: number of decays per unit time.

International Unit: becquerel **[Bq],** one nucleus decay per second [s^{-1}].

Nuclide	half-life	radiation	principal energies	gamma dose rate at 1 metre (μSv/h/GBq)
Co-60	5.27 y	β^- γ	0.32 MeV (100%) 1.17 MeV (100%) 1.33 MeV (100%)	357

Therefore the dose rate of a 60Co source of 1 Bq at 1 m in air is: $3.57 \cdot 10^{-7}$ µSv/h

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4b. ^{60}Co Radiation term

It means that, the dose rate [µSv/h] produced by a radioactive source of **1 kBq** of ^{60}Co in air is $357 \cdot 10^{-6}$ µSv/h:

$$\dot{D}(t) = k \times A(t)$$

And the **accumulated dose over a year is**:

$$D(t) = \int_0^t k \times A(t) = \int_0^t k \times A_0 \times e^{-\lambda \cdot t}$$

$$D(t) = \frac{k \cdot A_0}{\lambda}\left[1 - e^{-\lambda \cdot t}\right]; \; t_{1/2} = \frac{Ln2}{\lambda} = \tau \, Ln2$$

$$\tau = \frac{t_{1/2}}{Ln2} = 2.398 \cdot 10^8 \, s \quad ; t_{1\,year} = 0.315 \cdot 10^8 \, s$$

$$\boldsymbol{D(t_{1\,year}) = 10.5 \, mSv}$$

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4b. ^{60}Co Radiation term

$$D(t) = k \cdot A_0 \cdot \tau \cdot \left[1 - e^{-t/\tau}\right]$$

Two Limit cases:

a. $t << \tau$: $e^{t/\tau} \cong 1 + \frac{t}{\tau}$

$$\boldsymbol{D(t) = k \cdot A_0 \cdot t}$$

b. $t >> \tau$: $e^{-t/\tau} \cong 0$

$$\boldsymbol{D = k \cdot A_0 \cdot \tau}$$

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4b. Induced Activity: 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

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

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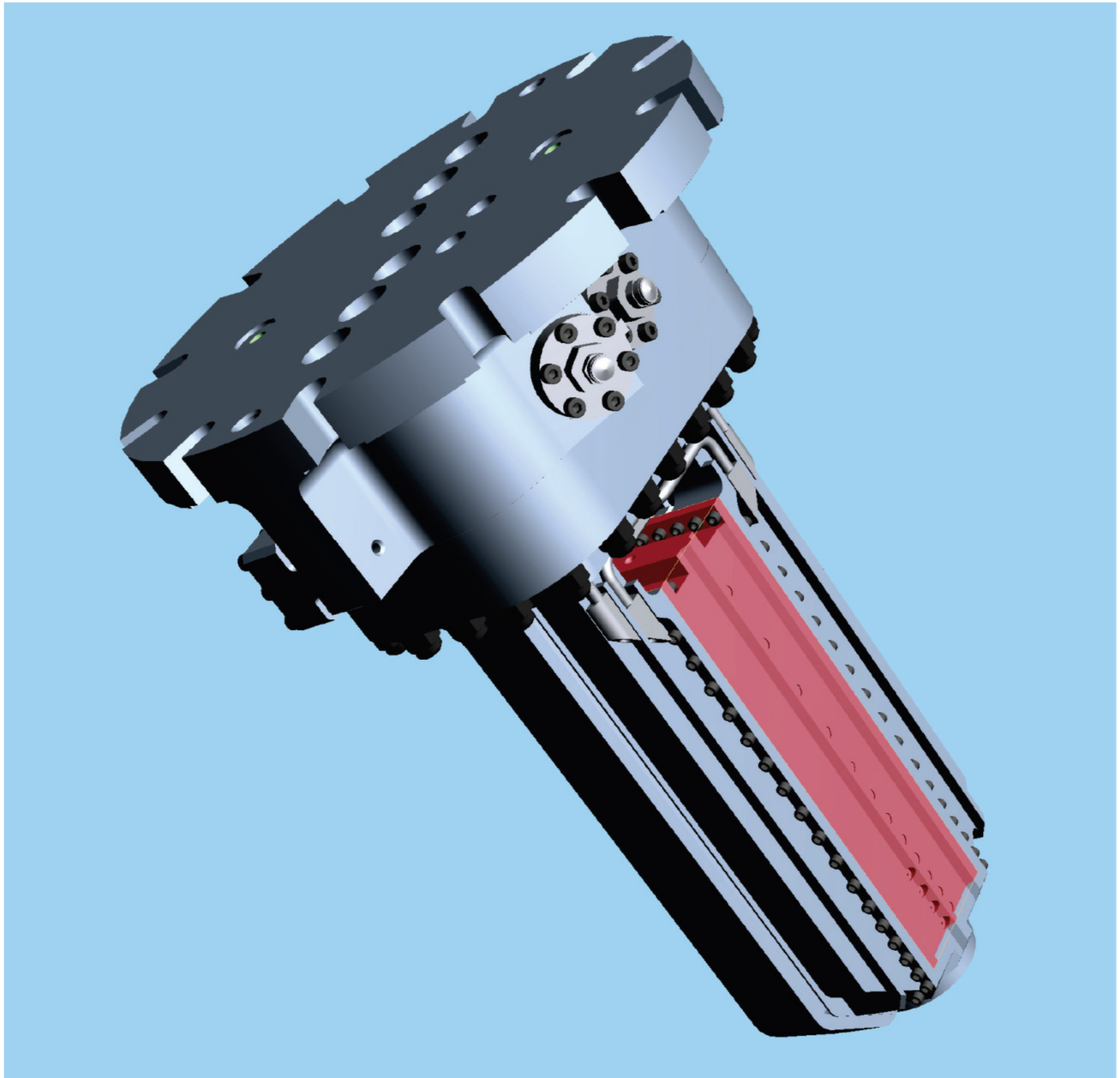
4b. Example-1: ISIS TS1 target



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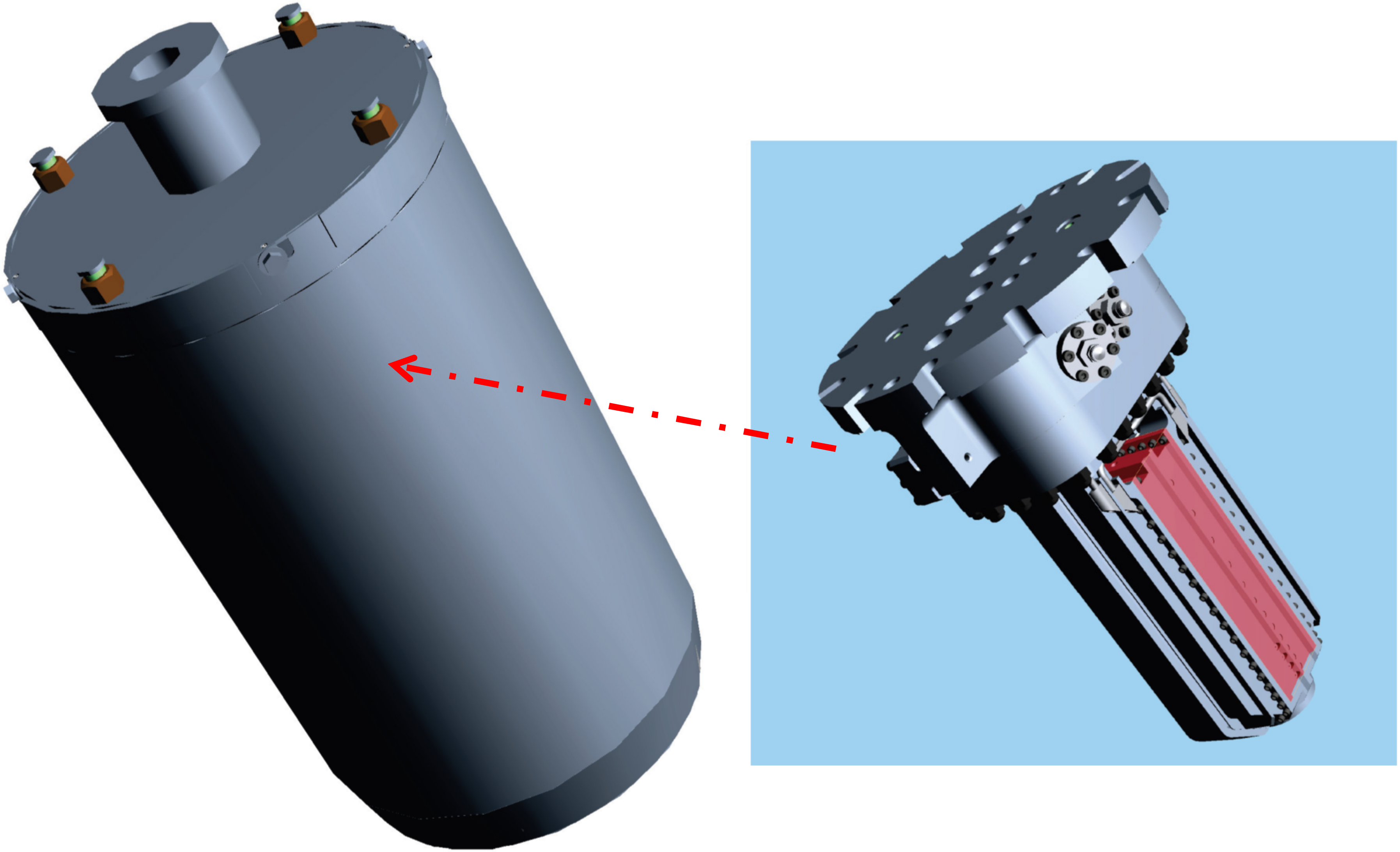
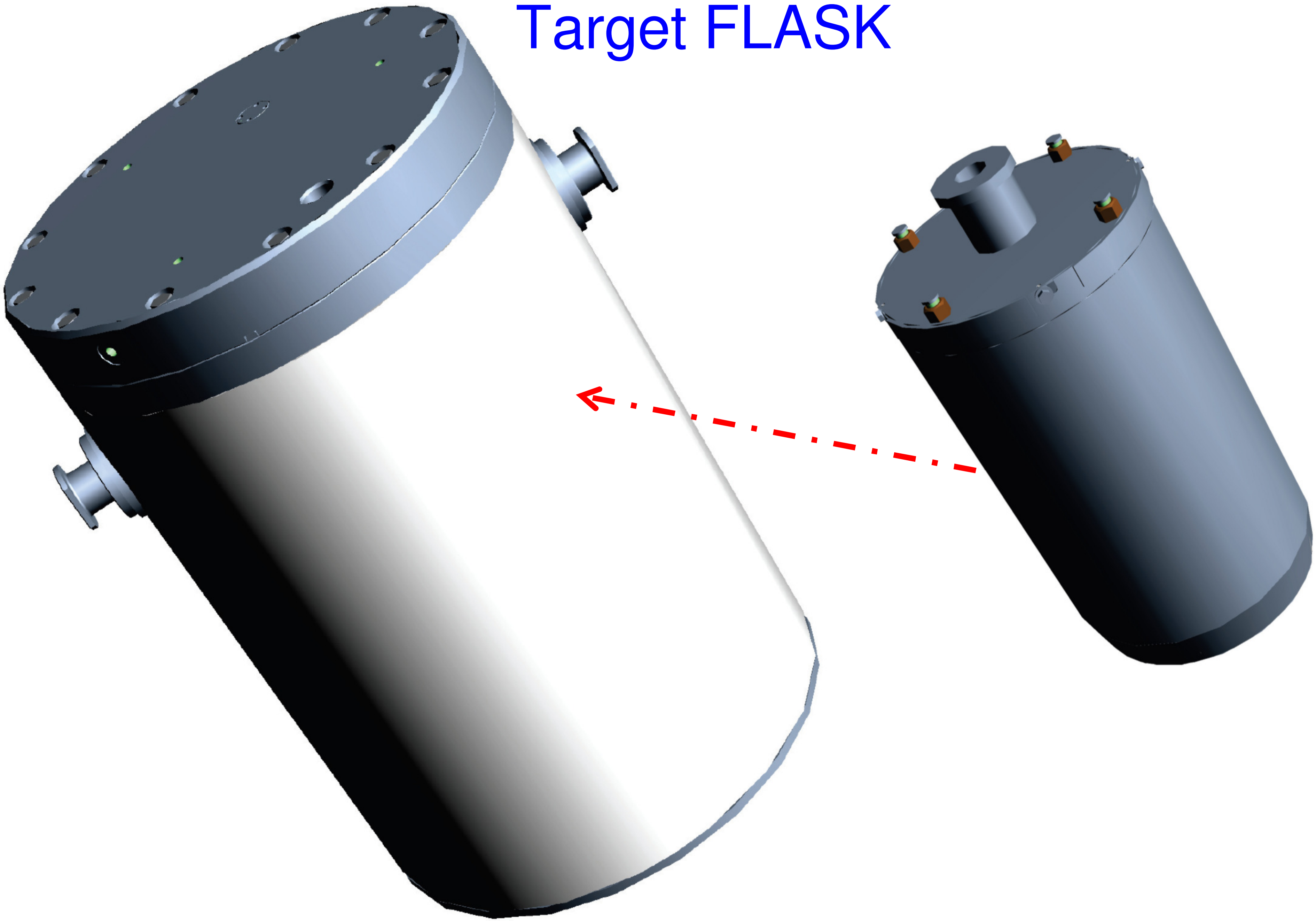
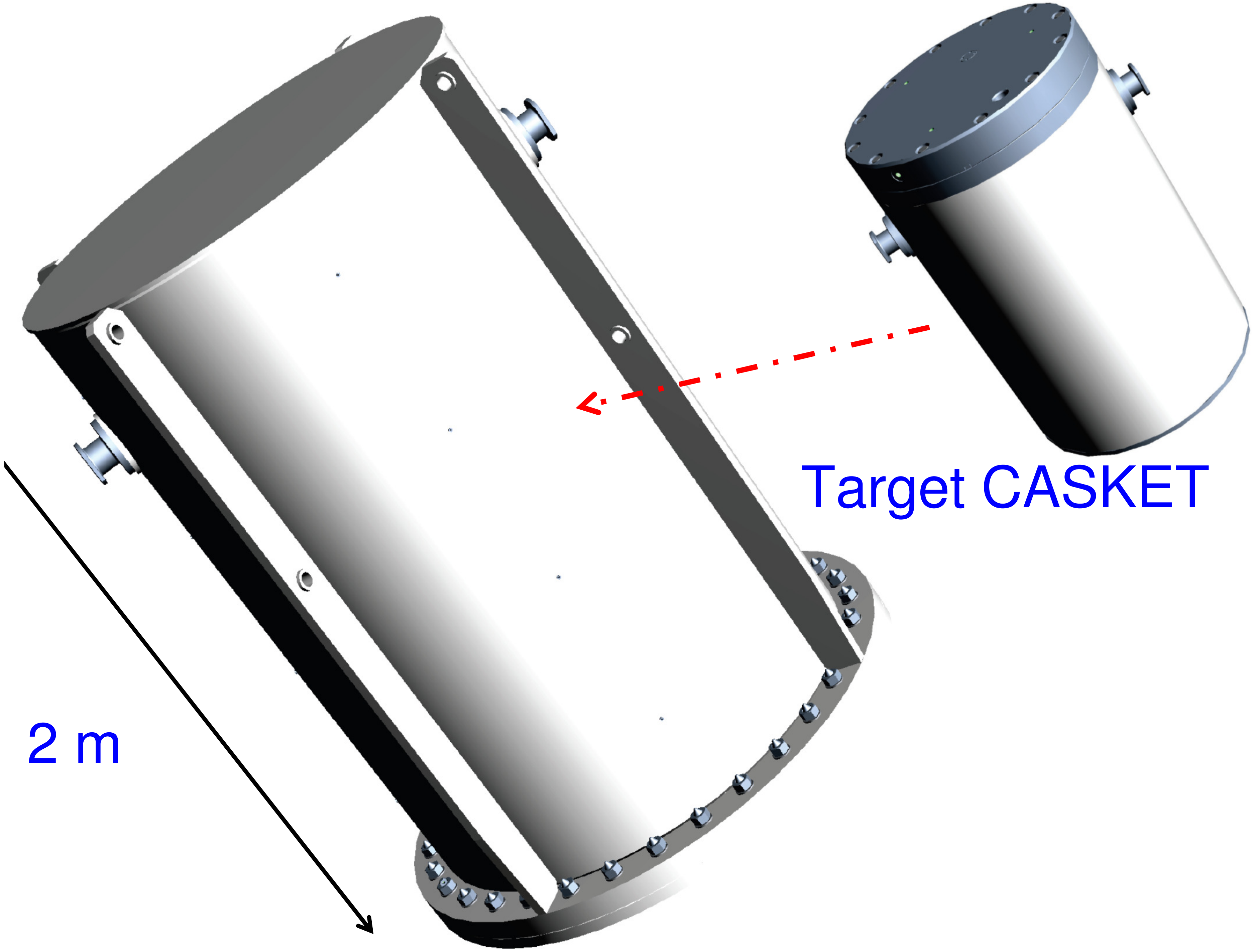
Target CAN



Target FLASK




Target CASKET
2 m

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4b. Example-1: ISIS TS1 target

(x5 all the activities values)

Irradiation Time	Cooling time	Dose rate TOP
[y]	[y]	[mSv/h]
4	0	292.42
4	3	1.19
4	**4**	**0.69**
4	5	0.48
4	6	0.35
4	6.5	0.30

				Total DR after 0 seconds of cooling [mSv/h]	292.42	100.0%	Total DR after 3 years of cooling	1.19	100.0%	Total DR after 4 years of cooling	0.69	100.0%
#CL	Nuclide	Halflive [s]	A0 (after 4 years irradiation)	DoseRate[mSv/h;3.7E10Bq]	DR[mSv/h]	%DR	A3y[Bq]	DR[mSv/h]	%DR	A4y[Bq]	DR[mSv/h]	%DR
1	Lu172	5.79E+05	1.62E+14	7.25E-04	3.18E+00	1.09E-02	3.69E+13	7.24E-01	6.06E-01	2.62E+13	5.137E-01	7.42E-01
2	Co60	1.66E+08	1.26E+12	3.28E-03	1.12E-01	3.81E-04	8.42E+11	7.46E-02	6.25E-02	7.45E+11	6.605E-02	9.54E-02
3	Hf172	5.90E+07	1.14E+14	9.38E-05	2.88E-01	9.87E-04	3.66E+13	9.27E-02	7.76E-02	2.60E+13	6.579E-02	9.50E-02
4	Ta182	9.89E+06	4.44E+16	2.13E-04	2.55E+02	8.74E-01	5.07E+13	2.92E-01	2.44E-01	6.55E+12	3.767E-02	5.44E-02
5	Lu174	1.05E+08	8.91E+12	4.76E-05	1.15E-02	3.92E-05	4.73E+12	6.08E-03	5.09E-03	3.90E+12	5.015E-03	7.24E-03
6	Eu152	4.21E+08	1.53E+11	7.86E-04	3.26E-03	1.11E-05	1.31E+11	2.78E-03	2.33E-03	1.25E+11	2.650E-03	3.83E-03
7	Mn54	2.70E+07	1.31E+14	6.77E-06	2.40E-02	8.22E-05	1.10E+13	2.00E-03	1.68E-03	5.17E+12	9.462E-04	1.37E-03
8	Sc44	1.41E+04	1.55E+13	4.67E-04	1.96E-01	6.70E-04	2.42E+10	3.06E-04	2.56E-04	2.39E+10	3.015E-04	4.35E-04
9	Ti44	1.49E+09	2.53E+10	1.56E-04	1.06E-04	3.64E-07	2.42E+10	1.02E-04	8.52E-05	2.39E+10	1.004E-04	1.45E-04
10	Co56	6.81E+06	1.60E+13	1.71E-02	7.38E+00	2.52E-02	8.57E+08	3.95E-04	3.31E-04	4.38E+07	2.022E-05	2.92E-05
					266.64			**1.19**			**0.69**	
					8.8%			0.005%			0.003%	

Total DR after 5 years of cooling	0.48	100.0%	Total DR after 6 years of cooling	0.3507	100.0%	Total DR after 6.5 years of cooling	0.30	100.0%
A5y[Bq]	DR[mSv/h]	%DR	A6y[Bq]	DR[mSv/h]	%DR	A6.5y[Bq]	DR[mSv/h]	%DR
1.86E+13	3.65E-01	7.56E-01	1.32E+13	2.587E-01	7.38E-01	1.11E+13	2.18E-01	7.25E-01
6.60E+11	5.85E-02	1.21E-01	5.84E+11	5.180E-02	1.48E-01	5.50E+11	4.87E-02	1.62E-01
1.84E+13	4.67E-02	9.68E-02	1.31E+13	3.313E-02	9.45E-02	1.10E+13	2.79E-02	9.28E-02
8.46E+11	4.87E-03	1.01E-02	1.09E+11	6.287E-04	1.79E-03	3.93E+10	2.26E-04	7.51E-04
3.21E+12	4.14E-03	8.58E-03	2.65E+12	3.412E-03	9.73E-03	2.41E+12	3.10E-03	1.03E-02
1.19E+11	2.53E-03	5.24E-03	1.13E+11	2.407E-03	6.86E-03	1.11E+11	2.35E-03	7.81E-03
2.44E+12	4.47E-04	9.27E-04	1.15E+12	2.110E-04	6.02E-04	7.93E+11	1.45E-04	4.82E-04
2.35E+10	2.97E-04	6.17E-04	2.32E+10	2.934E-04	8.37E-04	2.31E+10	2.91E-04	9.69E-04
2.35E+10	9.91E-05	2.05E-04	2.32E+10	9.774E-05	2.79E-04	2.31E+10	9.71E-05	3.23E-04
2.24E+06	1.03E-06	2.14E-06	1.15E+05	5.287E-08	1.51E-07	2.59E+04	1.20E-08	3.97E-08
	0.48			**0.35**			**0.30**	
	0.002%			0.001%			0.001%	

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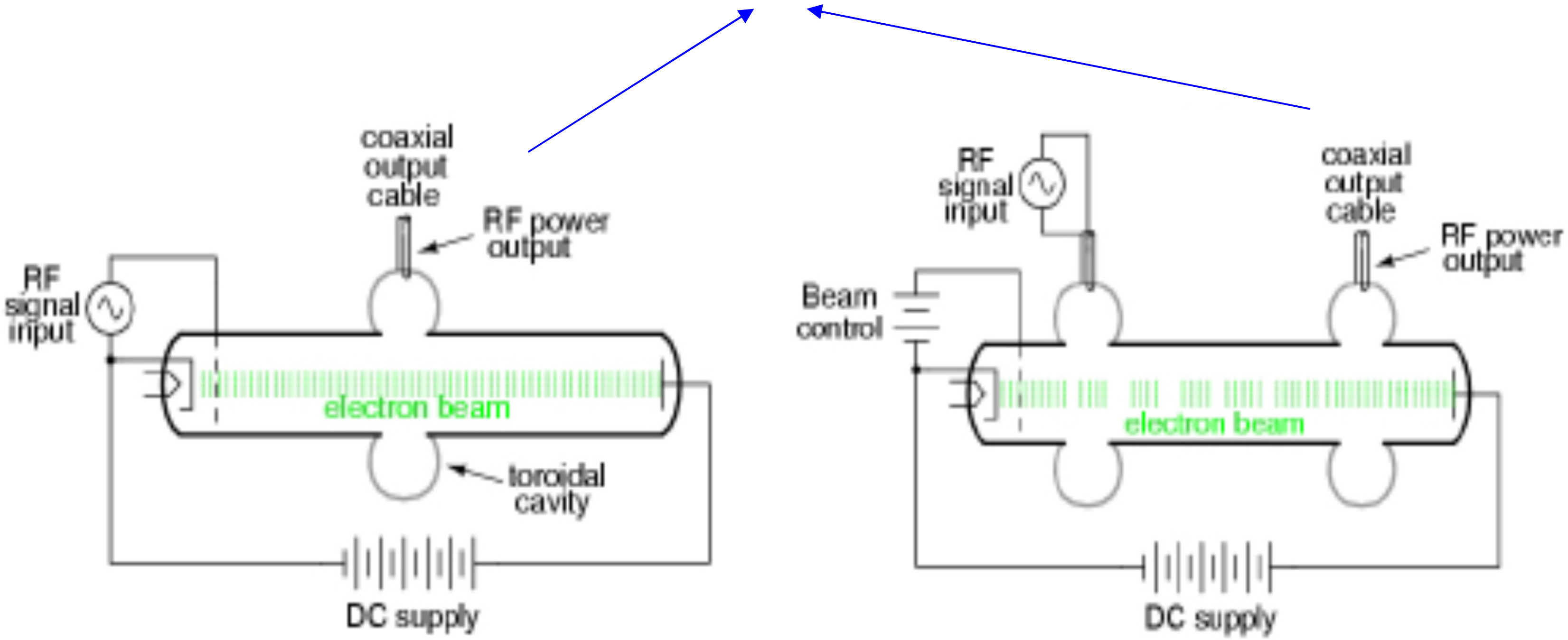
4c. RF generator plants

a. IOT: to RF Cavity b. Klystron:



IOT (Inductive Output Tube)
G ≈ 23 dB (for comparison: Tetrode G ≈ 15 dB)
Intensity modulated
Class AB
Peak efficiency ≈ 75%
Compact size

Klystron
G ≈ 40 dB
Velocity modulated
Class A
Peak efficiency ≈ 65%

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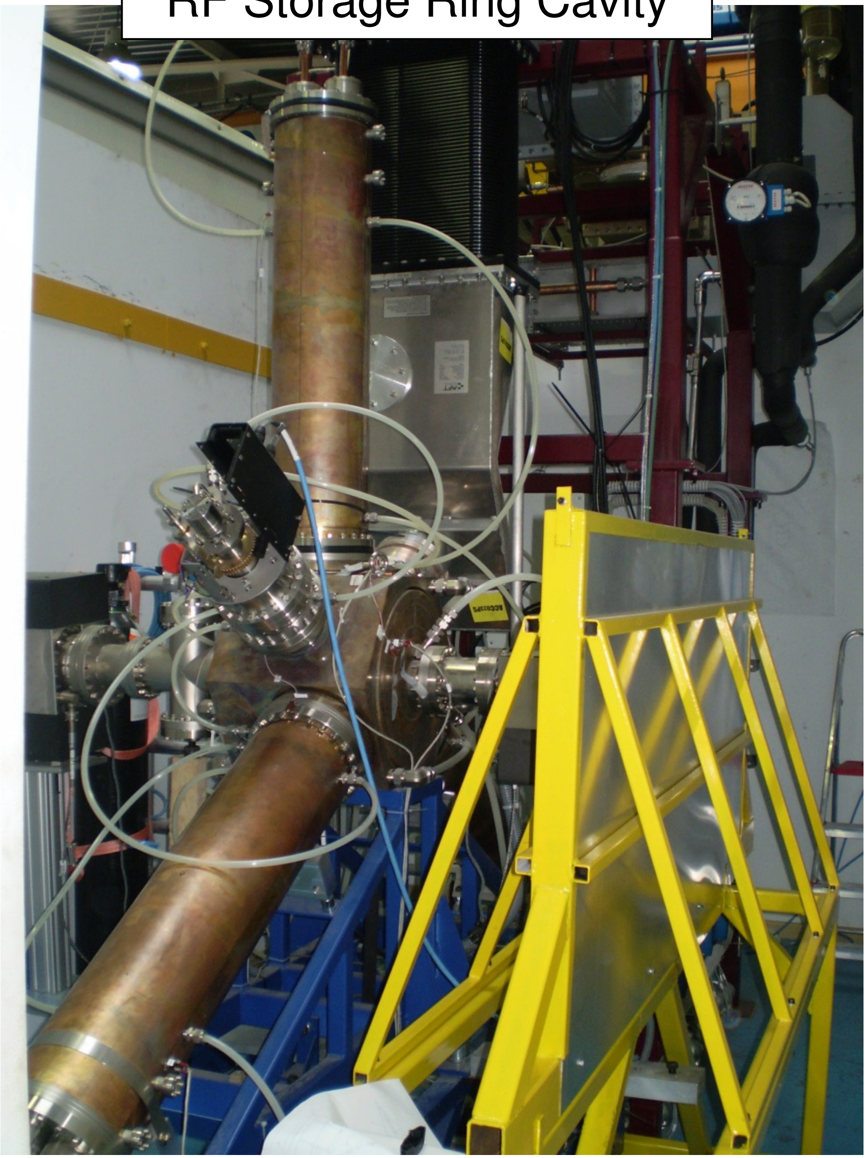
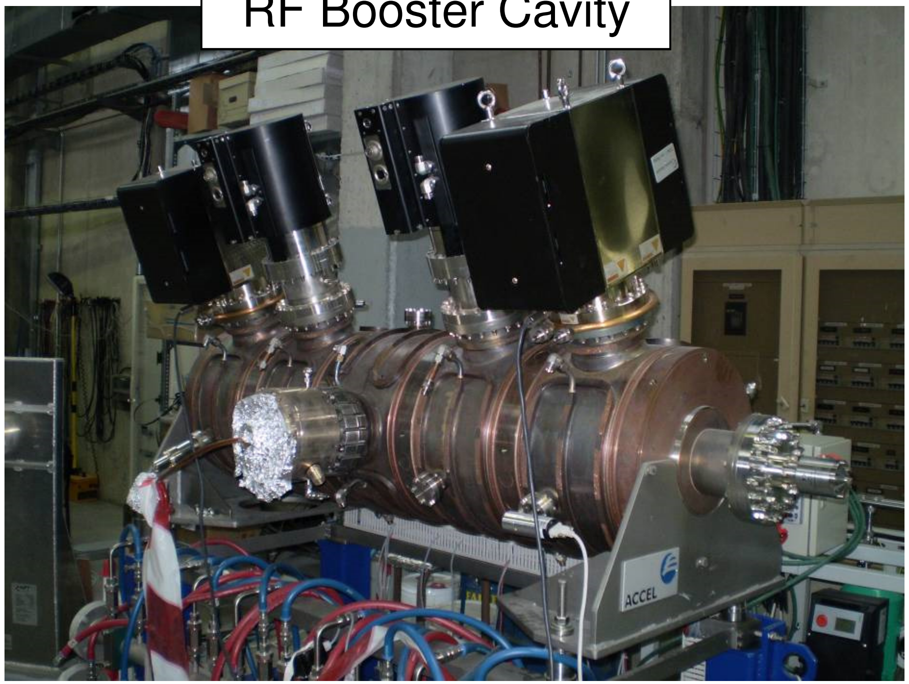
4c. RF generator plants

RF Storage Ring Cavity

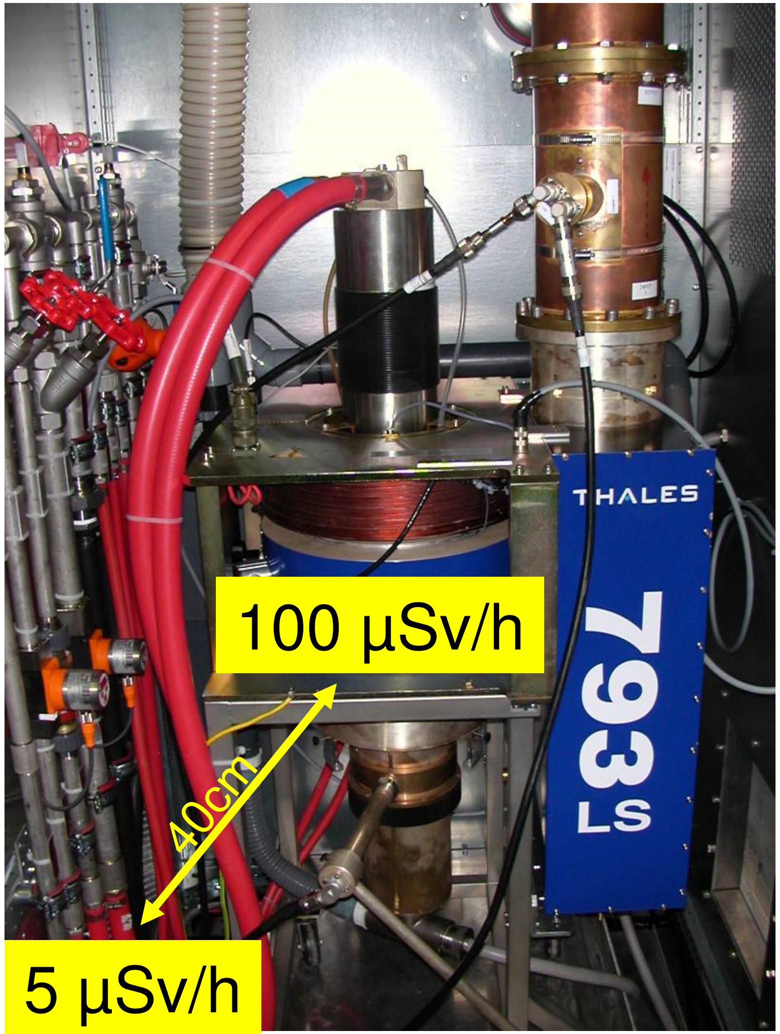


RF Booster Cavity

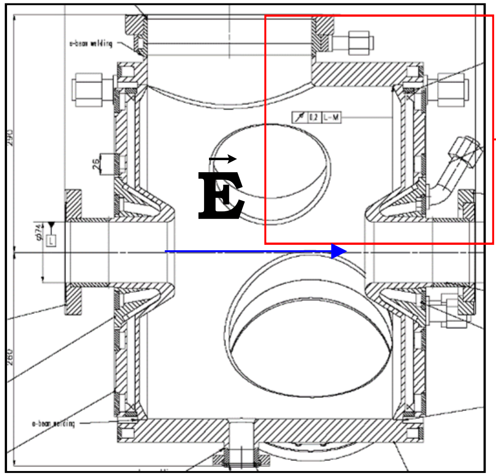


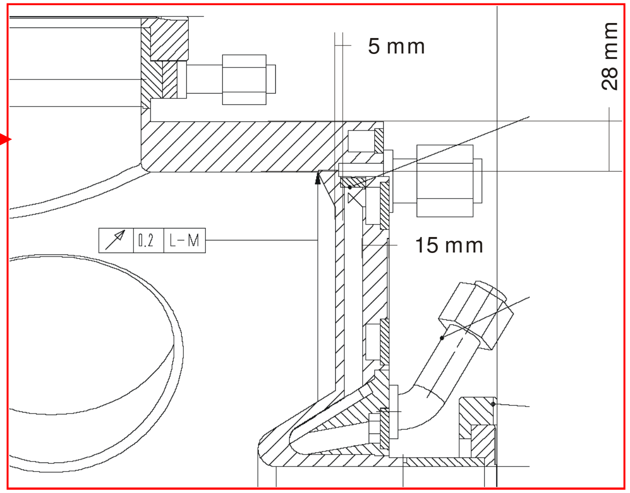
4c. RF generator plants

RADIATION MEASUREMENTS: IOT



4c. RF generator plants



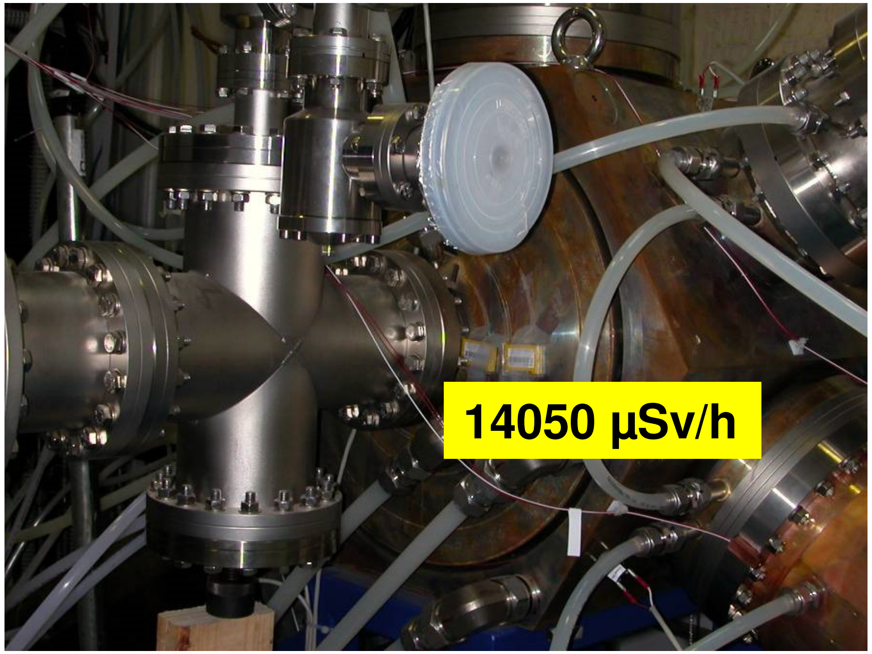


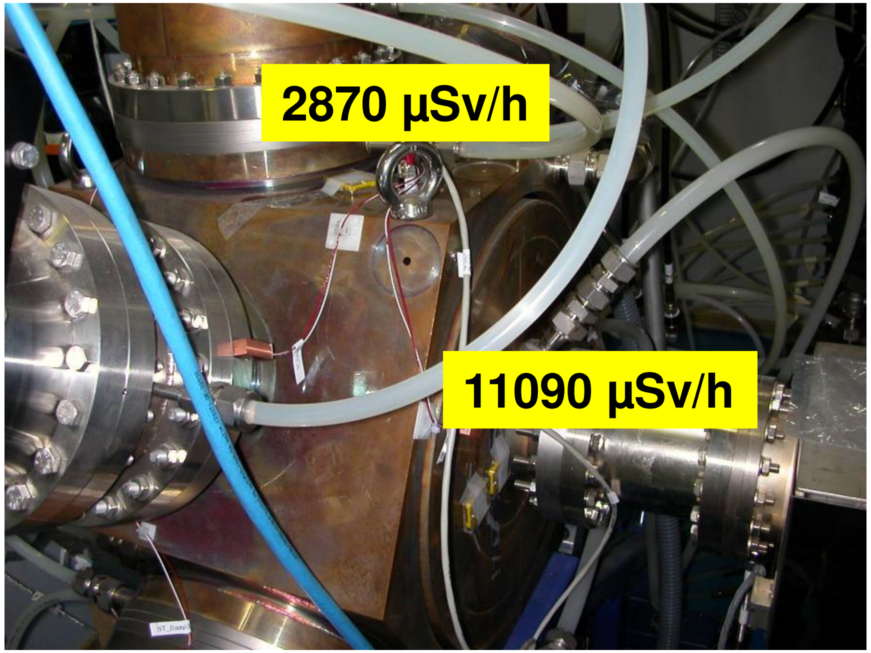
	Booster	*Storage Ring*
Voltage on axis (kV)	1350	750
Maximum E field on surface (MV/m)	2.0	6.2

$$j(E_{SUP}) = \frac{A_{FN} \cdot (\beta \cdot E_{SUP})^2}{\phi} \times \exp\left[- \frac{B_{FN} \cdot \phi^{3/2}}{\beta \cdot E_{SUP}} \right]$$

4c. RF generator plants

RAD. MEAS.: DOSE RATE ON SURFACE





80kW (max power) @ 20%

4c. RF generator plants