# Part C. Radiation shielding

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

# 1. Electron accelerators

## Prompt radiation fields around accelerators:

### 1. Electron accelerators

photons (bremsstrahlung)
neutrons

### 2. Proton accelerators

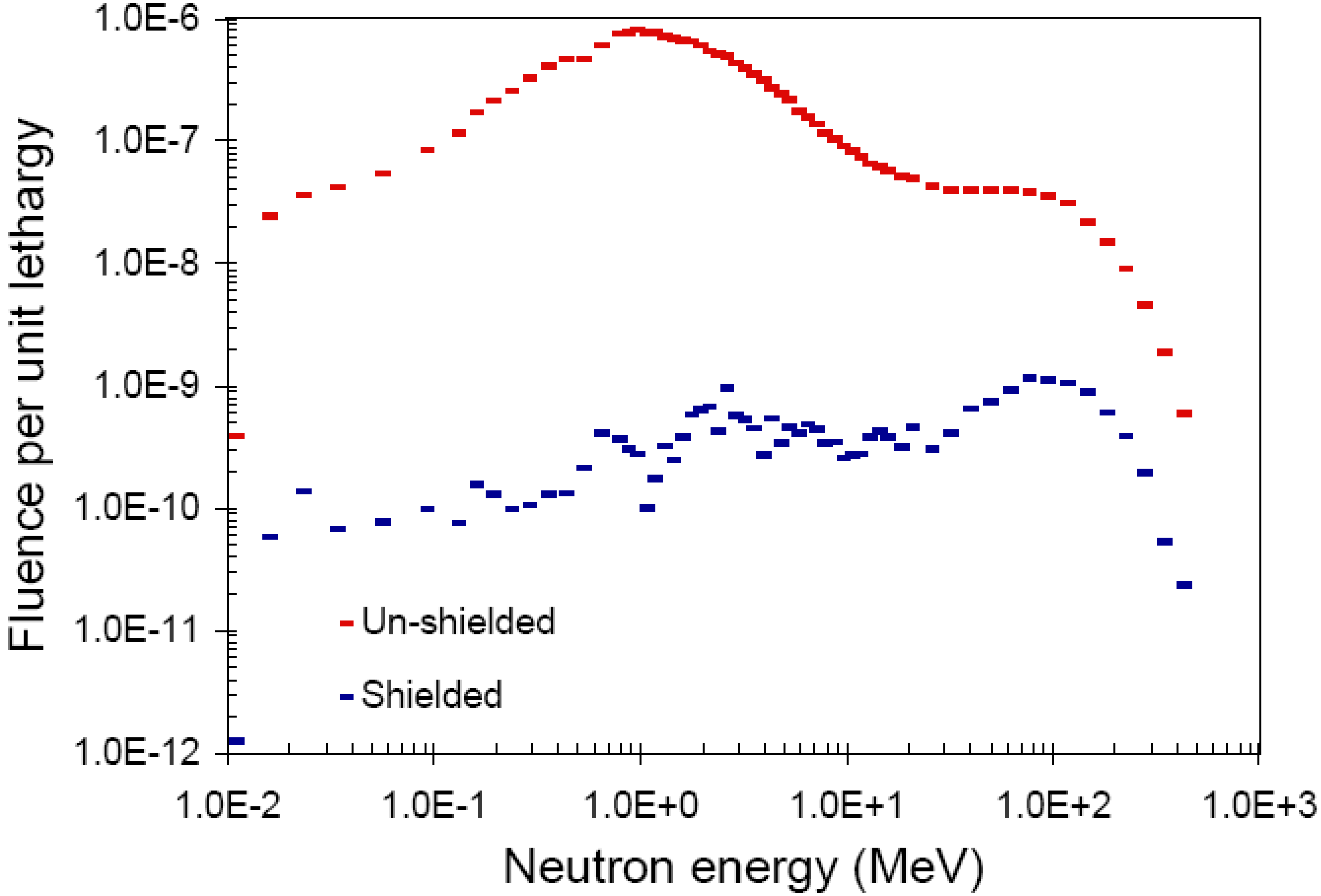
neutrons

### 3. Electron/Proton accelerator facilities

accelerators
beamlines

# 1. Electron accelerators

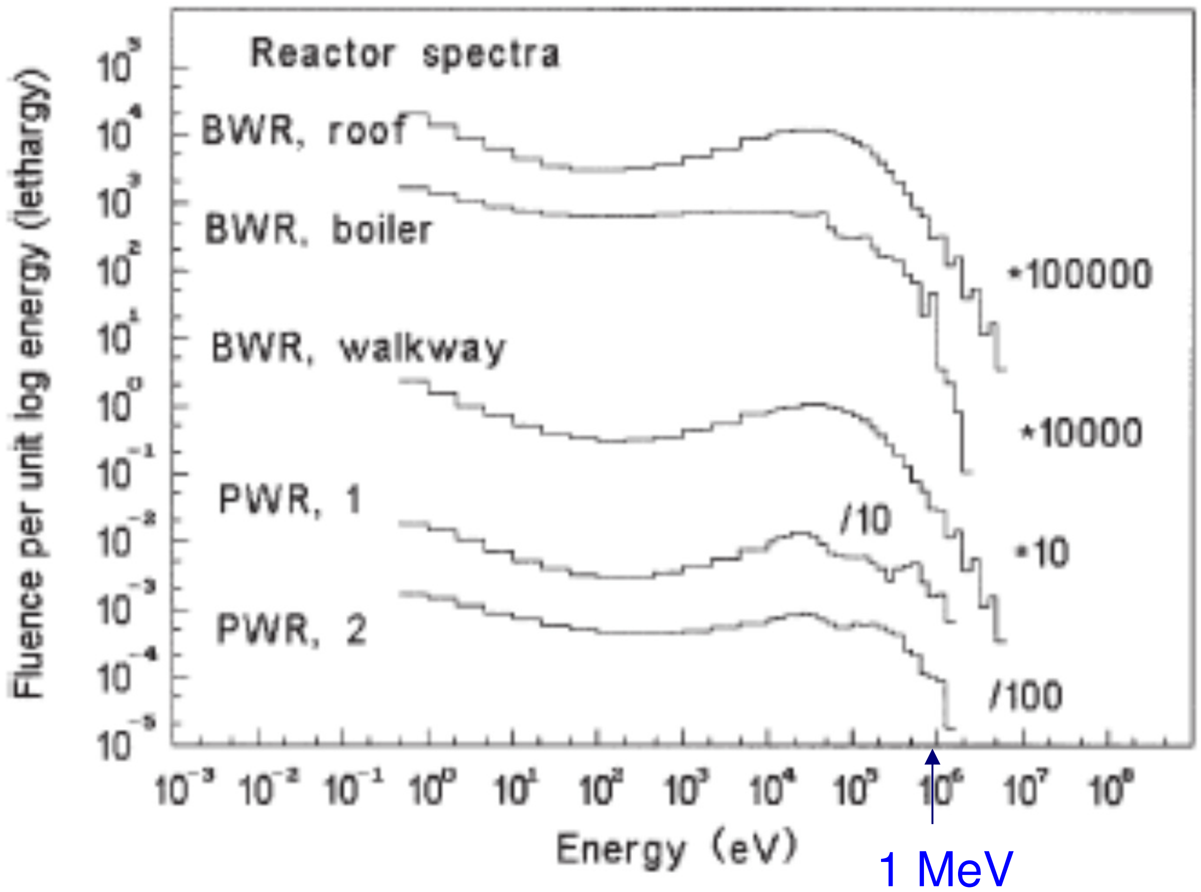
## Examples of neutron spectra




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

# 2. Proton accelerators

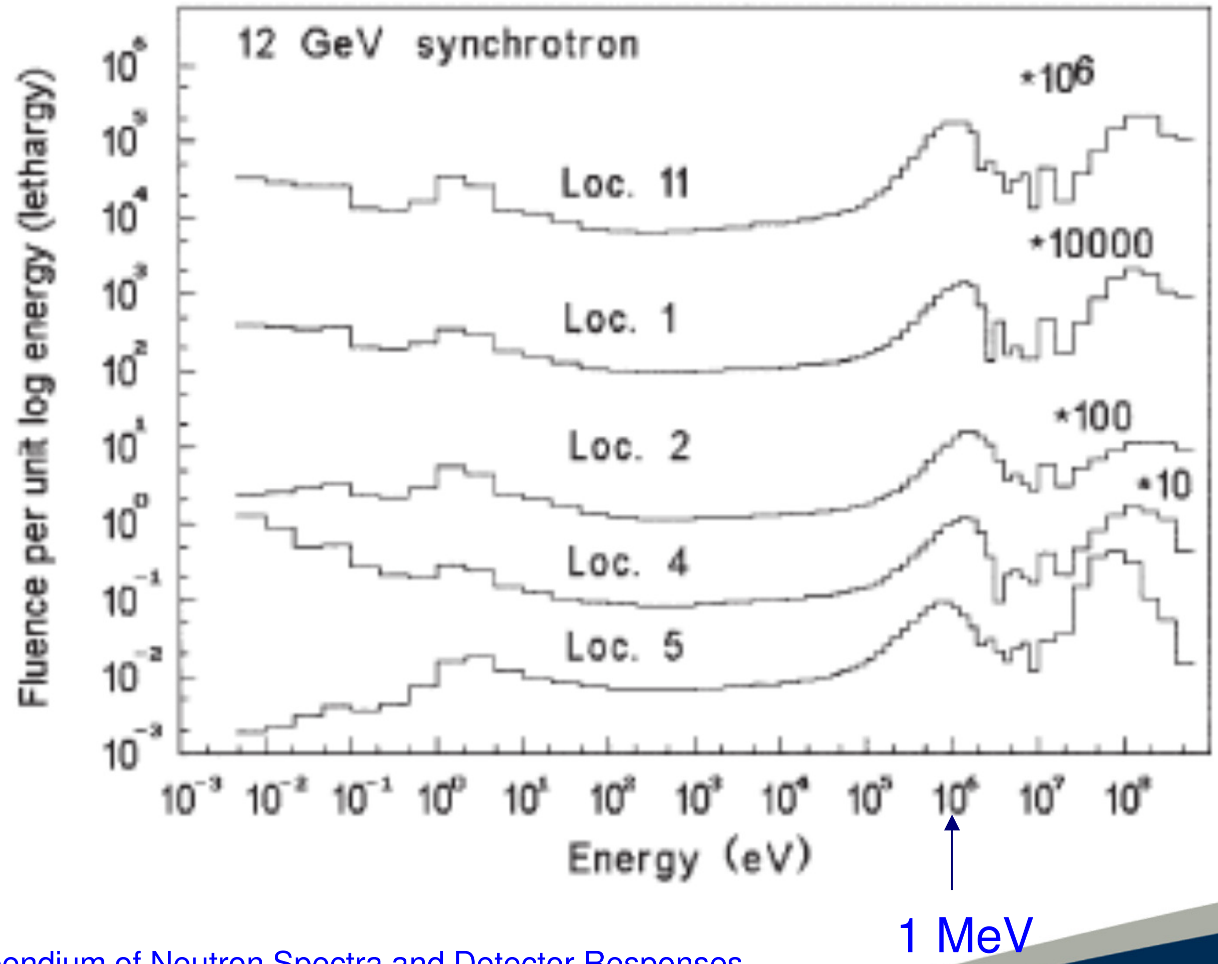
## Examples of neutron spectra




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

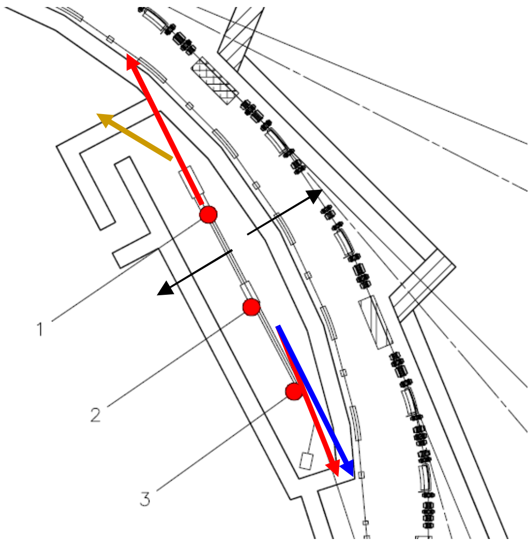


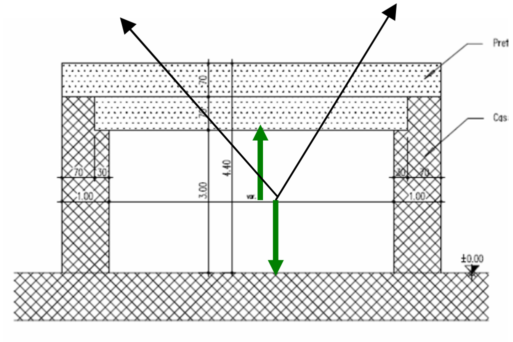

Source: Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes – Technical Reports Series no. 403 , IAEA, 2001

# 1&2. Electron/Proton accelerator facilities

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

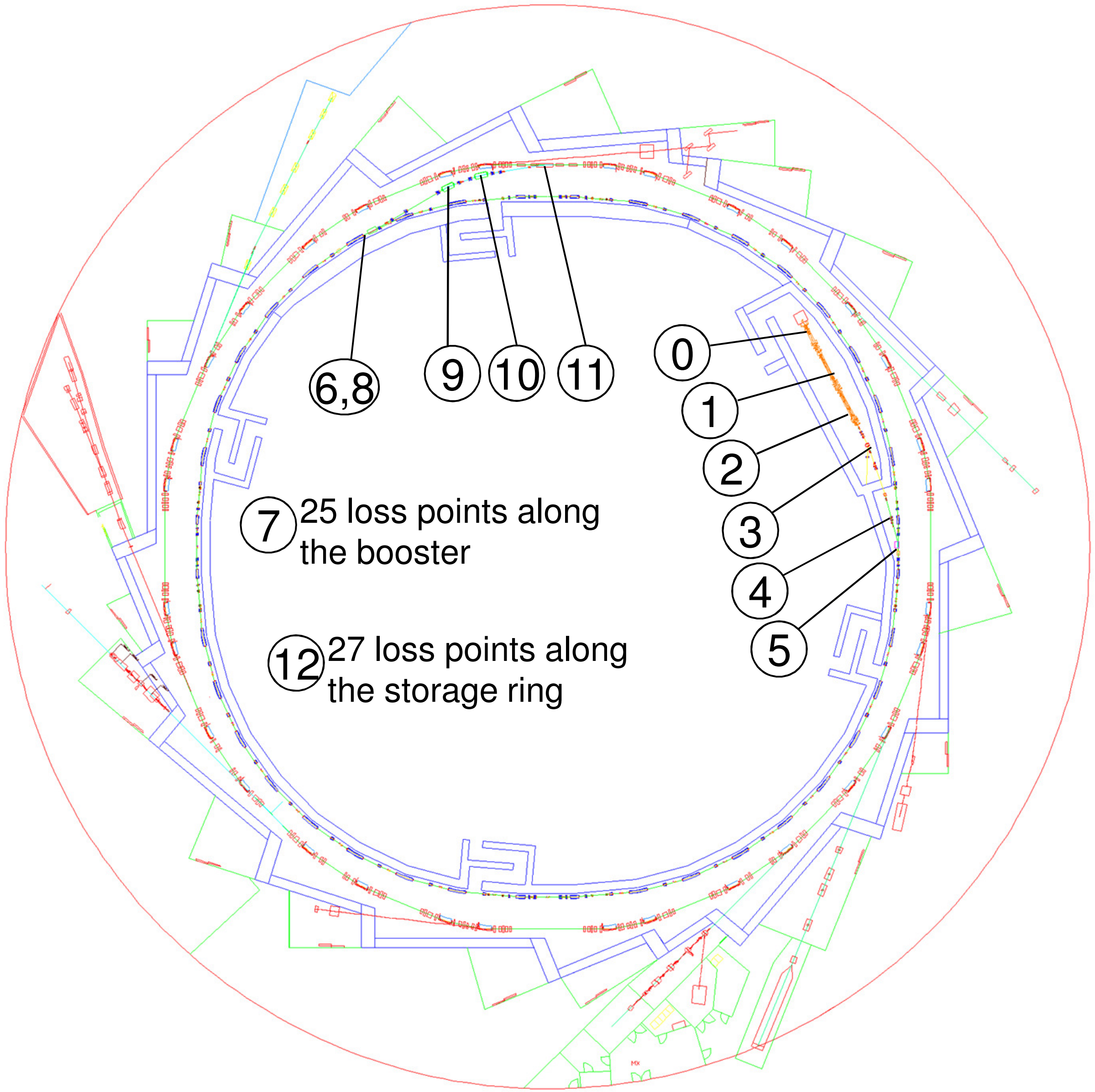
- Front / Back
- Front / Side
- Inside / Outside
- Roof / Floor
- Skyshine
- Labyrinth



(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 | | | Energy [GeV] |
|---|---|---|---|---|---|---|
| | | | LOSS | IN | OUT | |
| 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 |

# 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

# 1&2. Electron/Proton accelerator facilities

- Annual Dose:

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

Where $D_i$ is given by:

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

$s$ : accelerator point

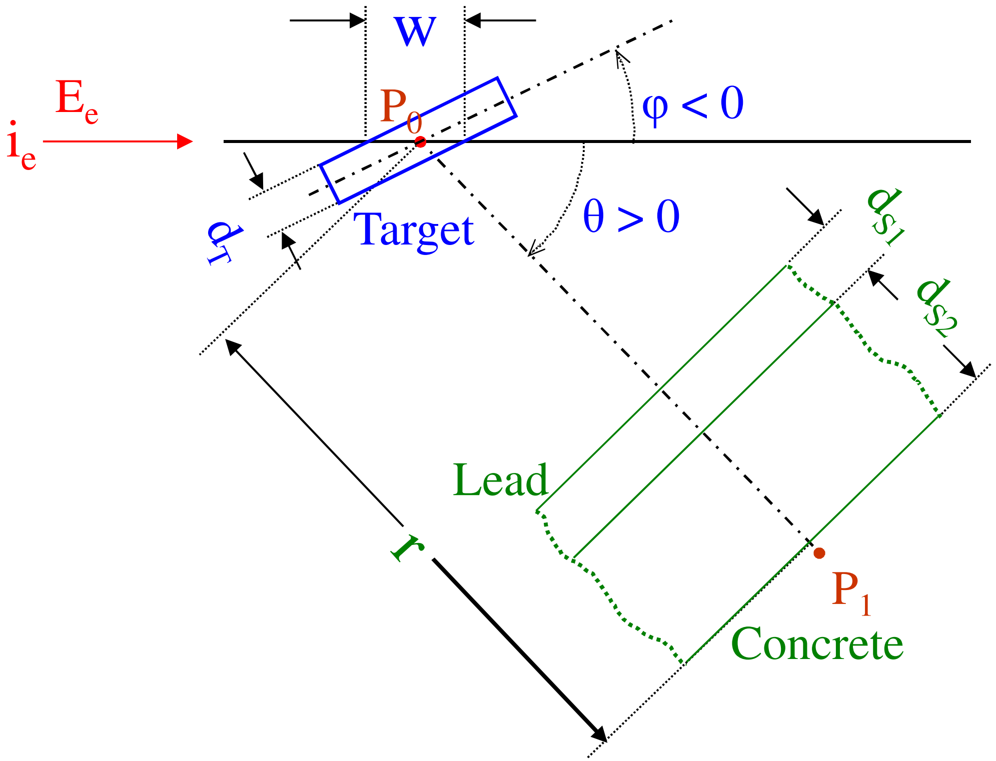
$i_e(s)$: is the electron loss rate at s-point

$t(s) = t_{User}(s) + t_{Machine}(s)$: 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:




➢ 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*
$\rho_T$ *[g/cm3]* : stain steel

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

➢ Dose at $P_1$, (per incident electron at $P_0$):

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

# 1&2. Electron/Proton accelerator facilities

Analytical model (**for photons**):

$$\dot{H}_p = \sum_i \frac{\dot{H}_0 \times e^{\left[-\left(\mu/\rho\right)_i \rho_i \times d\right]}}{{r_p}^2}$$

$\dot{H}_p$: 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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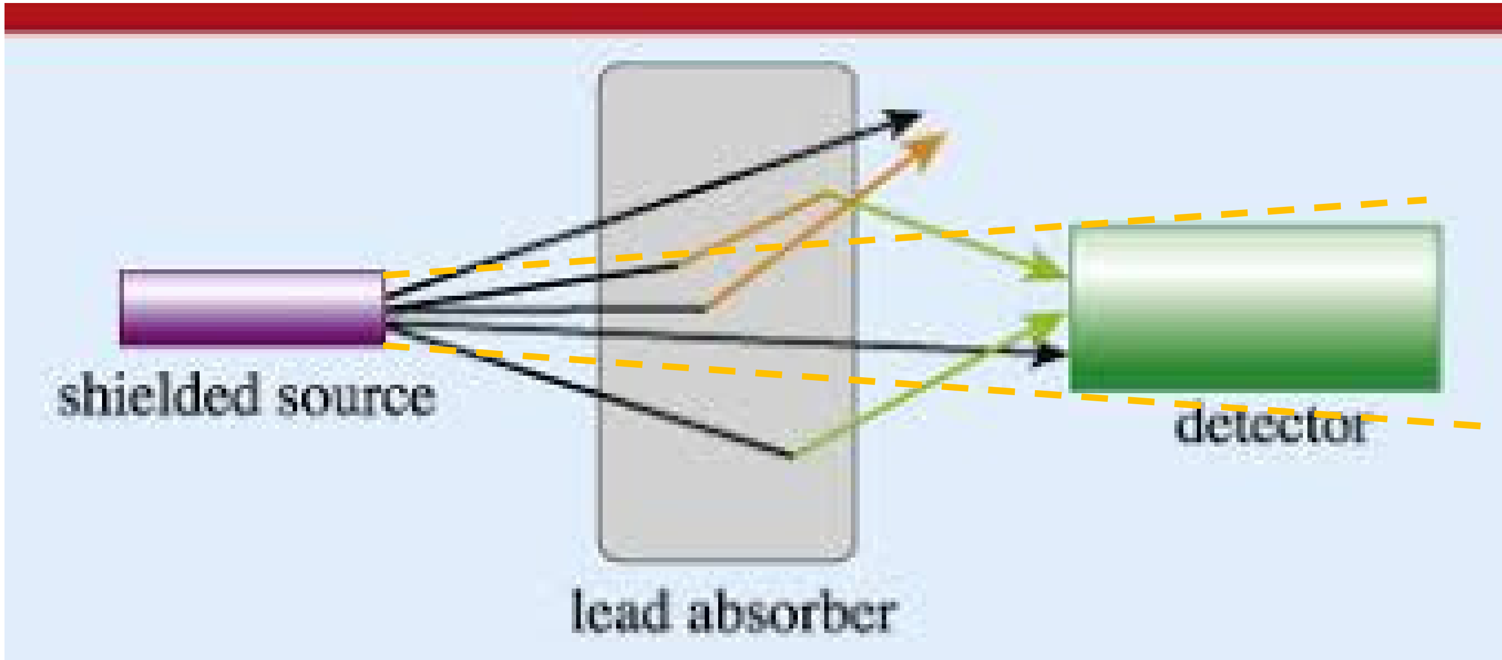
# 1&2. Electron/Proton accelerator facilities

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

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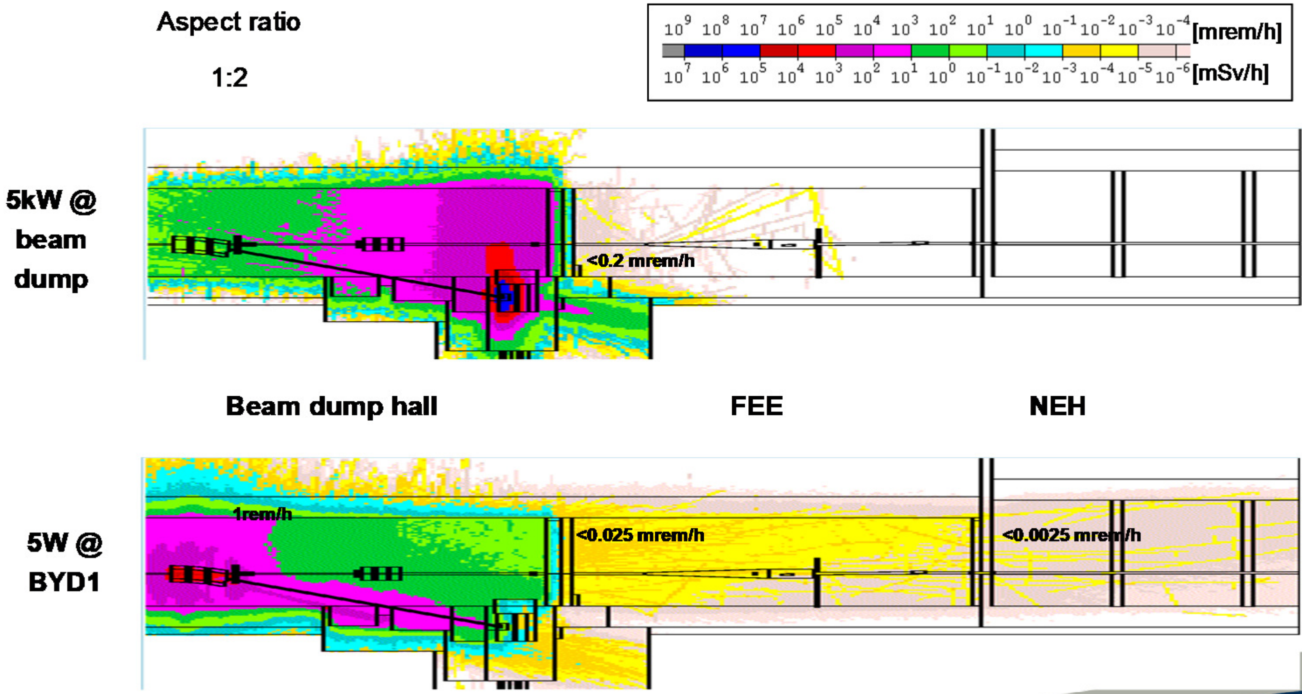
# 3. Synchrotron radiation facilities

## Monte-Carlo codes

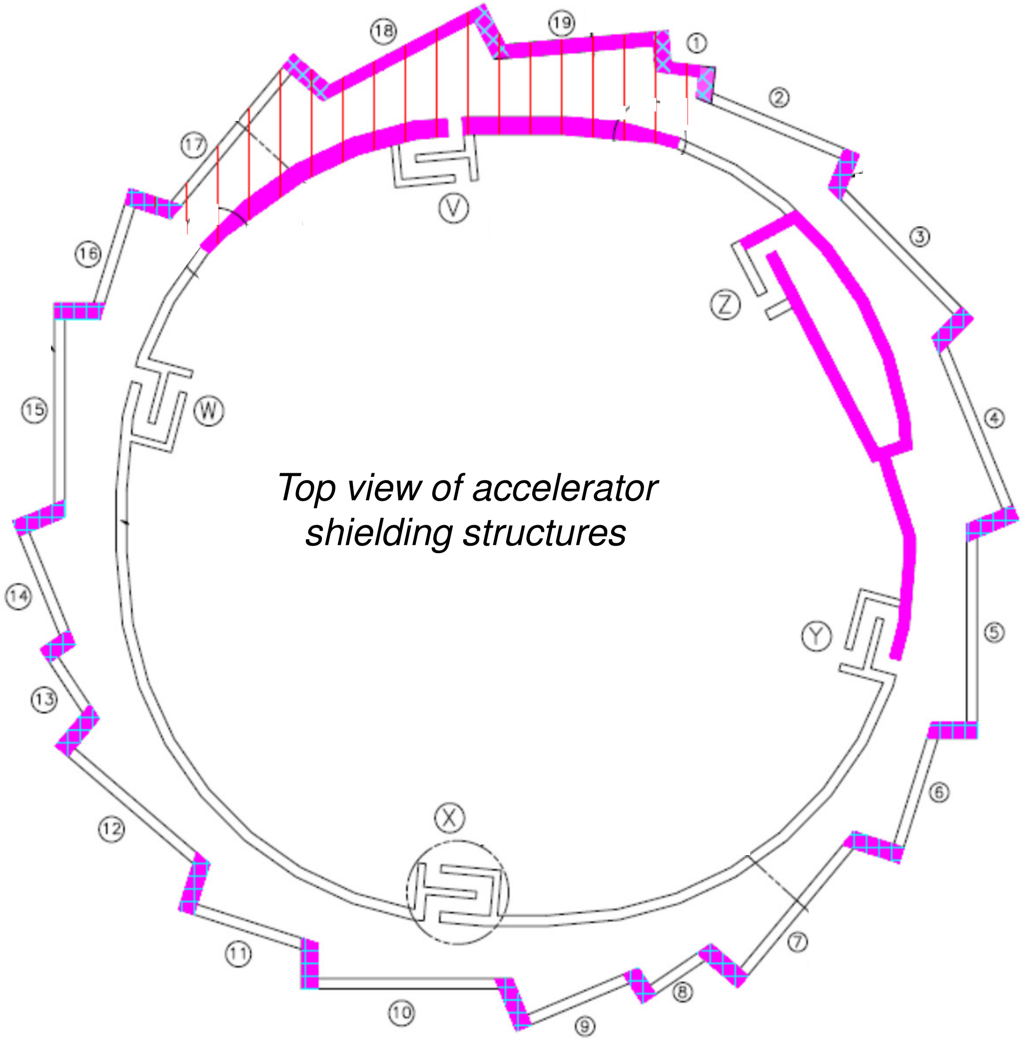
Examples: MCNPX
PENELOPE
FLUKA
MARS




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

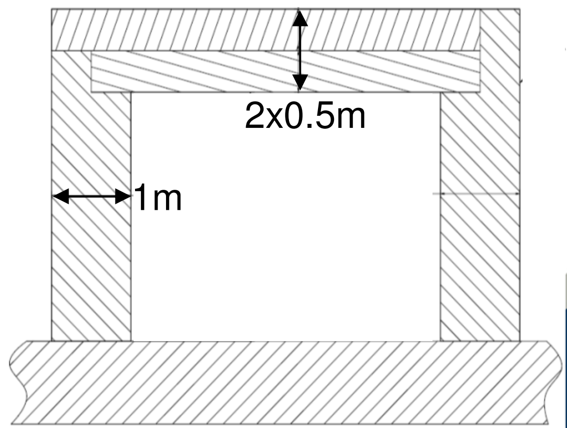
# 3. Synchrotron radiation facilities

## ➢ Concrete structures:



*Top view of accelerator shielding structures*

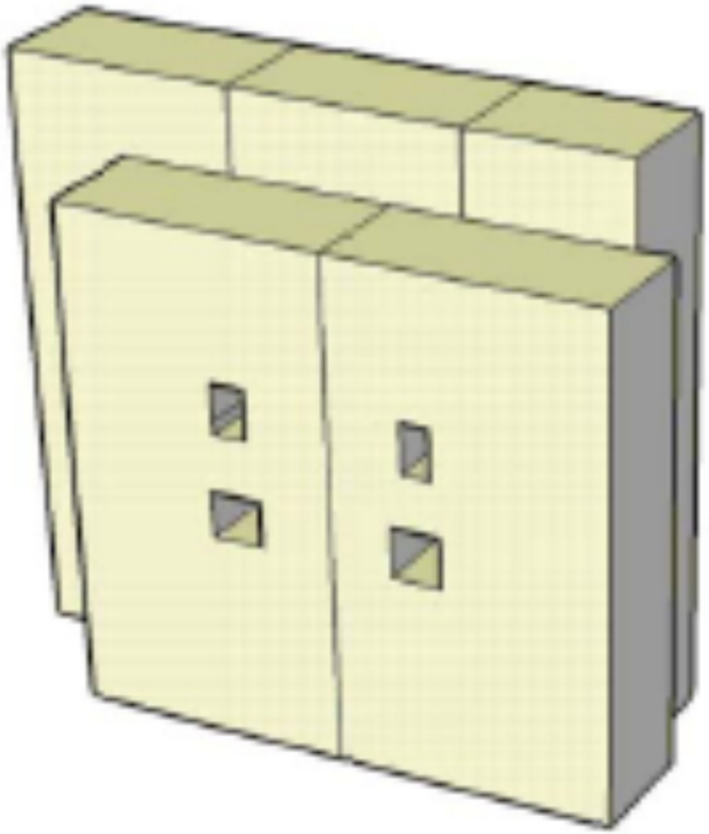
| | |
|---|---|
| Inner and side walls thickness | 1 m |
| Inner wall thickness at injection | 1.65 m |
| Side wall thickness at injection | 1.25 m |
| Roof thickness | 1 m |
| Roof thickness at injection | 1.4 m |
| Linac walls thickness | 1 m |
| Labyrinths walls thickness | 0.7 m |
| Front walls thickness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

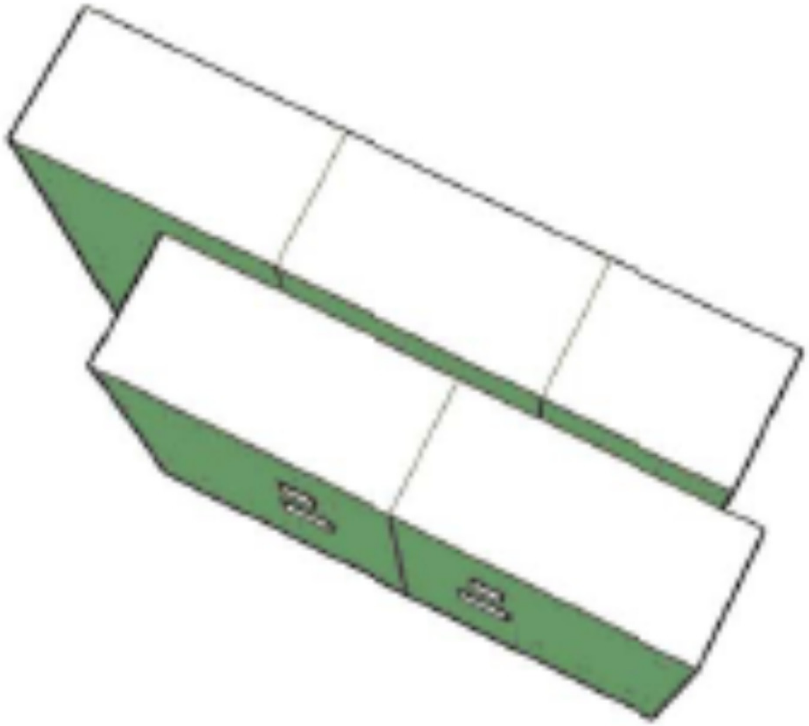


*Tunnel section*

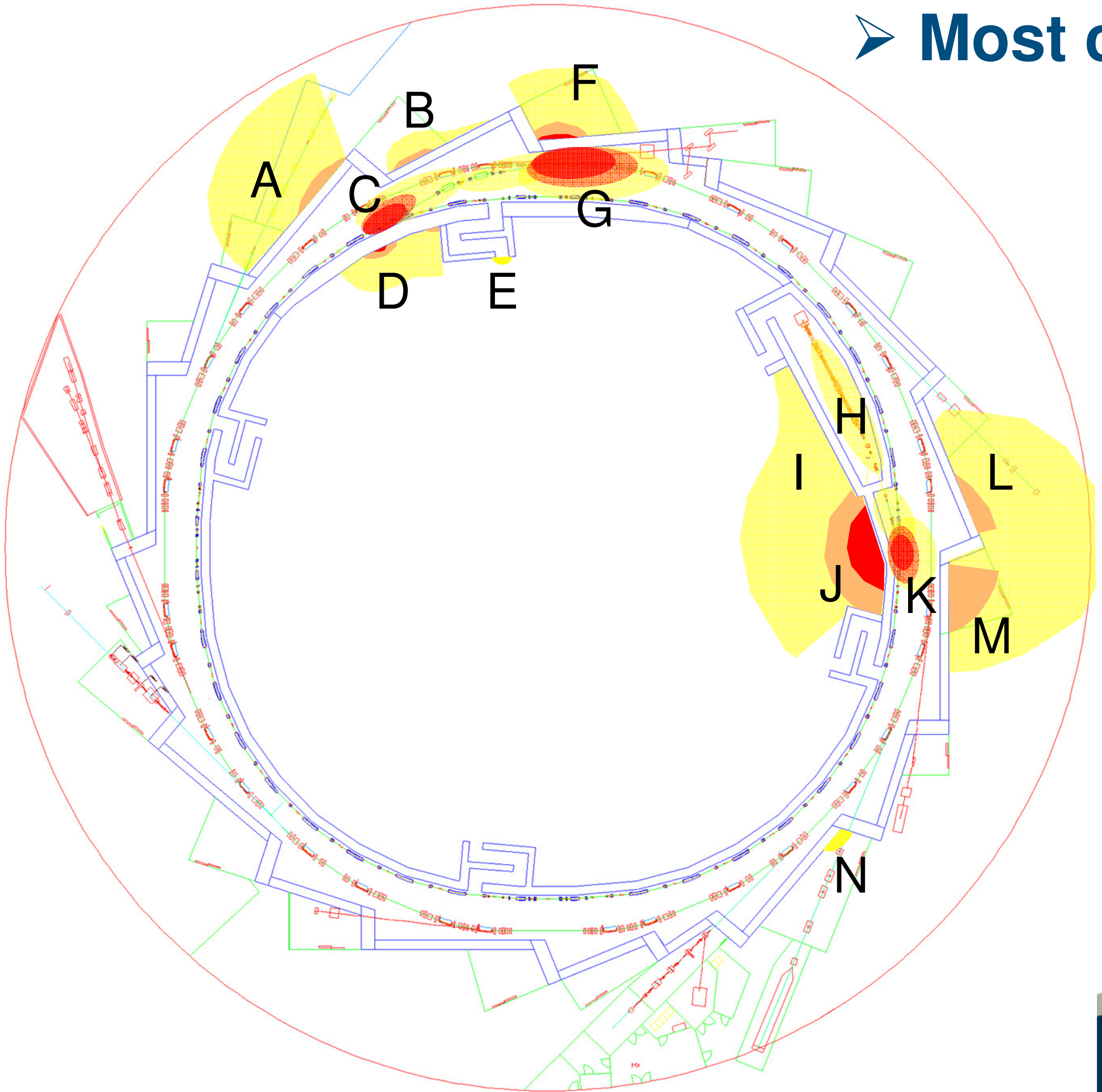
# 3. Synchrotron radiation facilities

- Front wall: final option





# 3. Synchrotron radiation facilities




➤ **Most critical areas**

- 0.1-0.5 mSv/y
- 0.5-1.0 mSv/y
- >1.0 mSv/y

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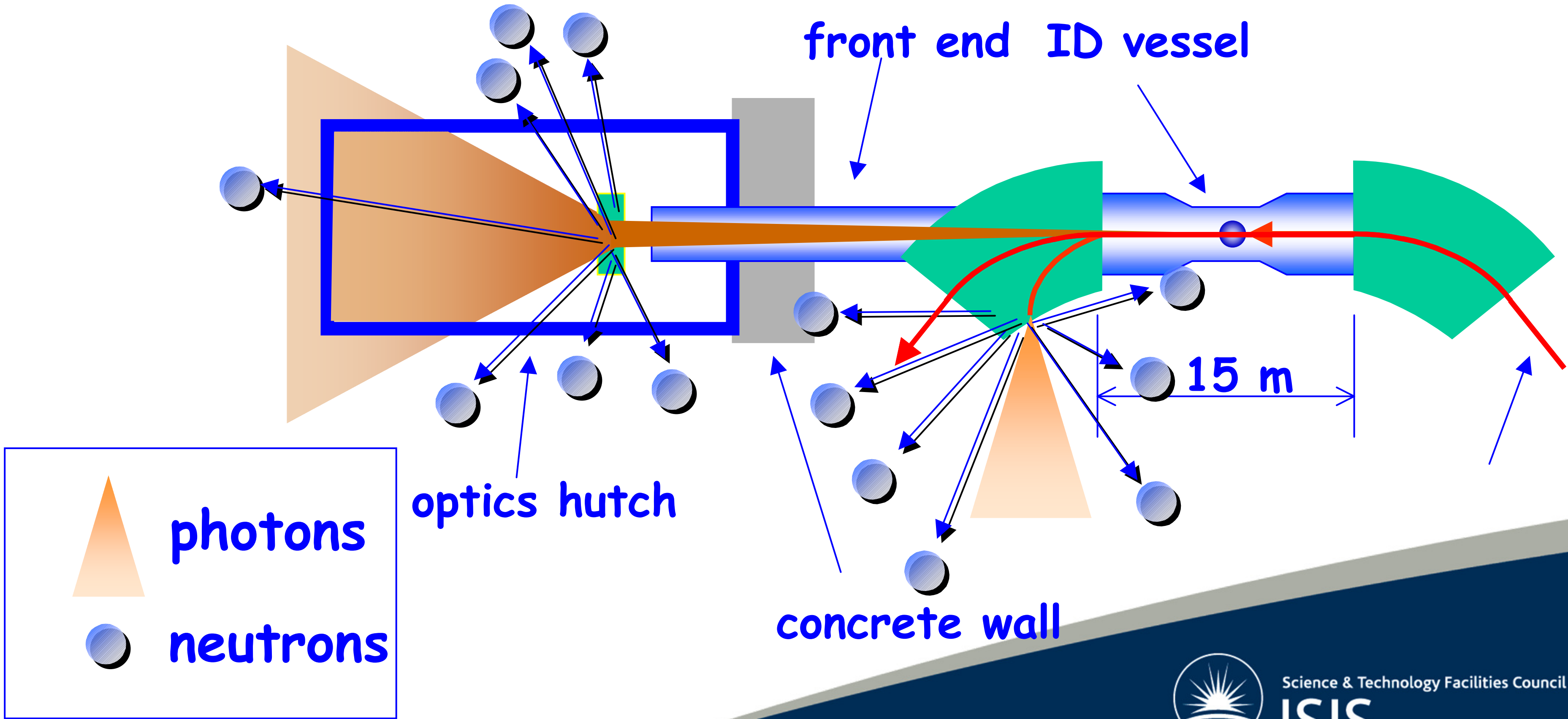
# 3. Synchrotron radiation facilities

## ALBA SYNCHROTRON: EXPERIMENTAL BEAMLINES

# 3. Synchrotron radiation facilities

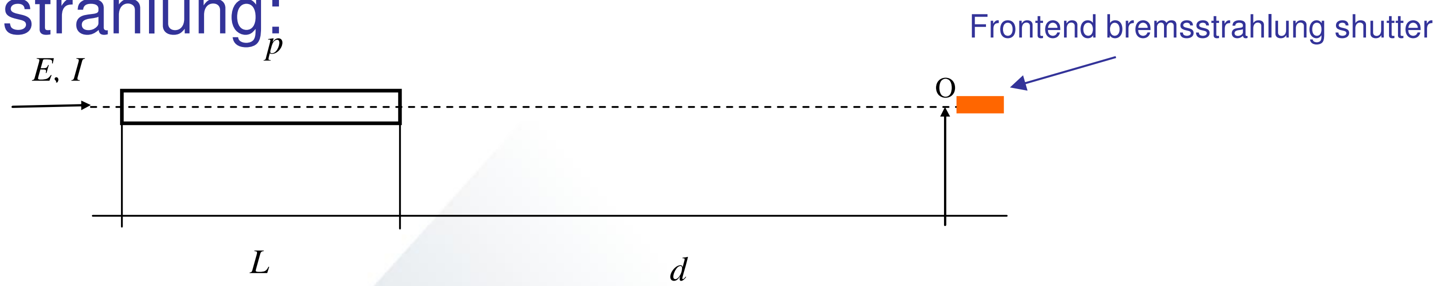
Radiation fields
- Accelerator tunnels:
  - photons, neutrons
- Beamlines:
  - X-rays, photons, neutrons



# 3. Synchrotron radiation facilities

## BEAMLINES SHIELDING - SOURCE TERM

- Gas bremsstrahlung:




$$\dot{D}_0 = 2.5\times10^{-27}\cdot\left(\frac{E}{mc^2}\right)^{2.67}\cdot\frac{L}{d\,(L+d)}\cdot I\cdot\frac{p}{p_0}$$

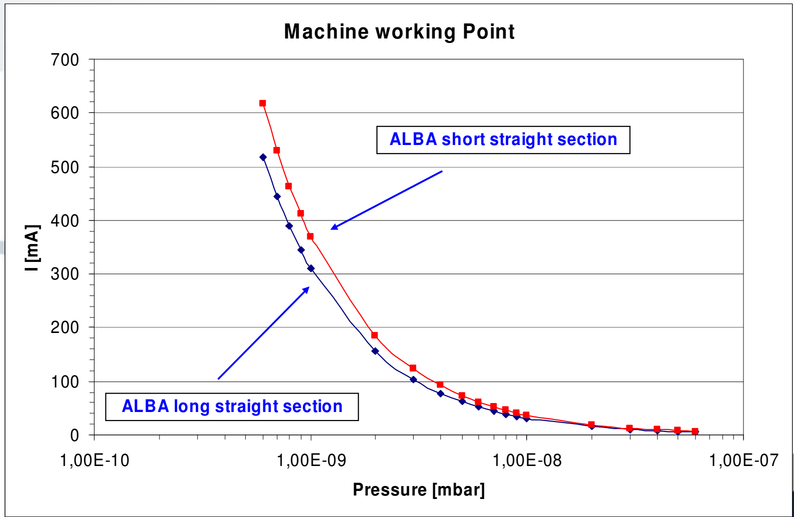
$\dot{D}_0$ : is the dose rate at O-point (Energy/Mass/Time)

✓If:

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

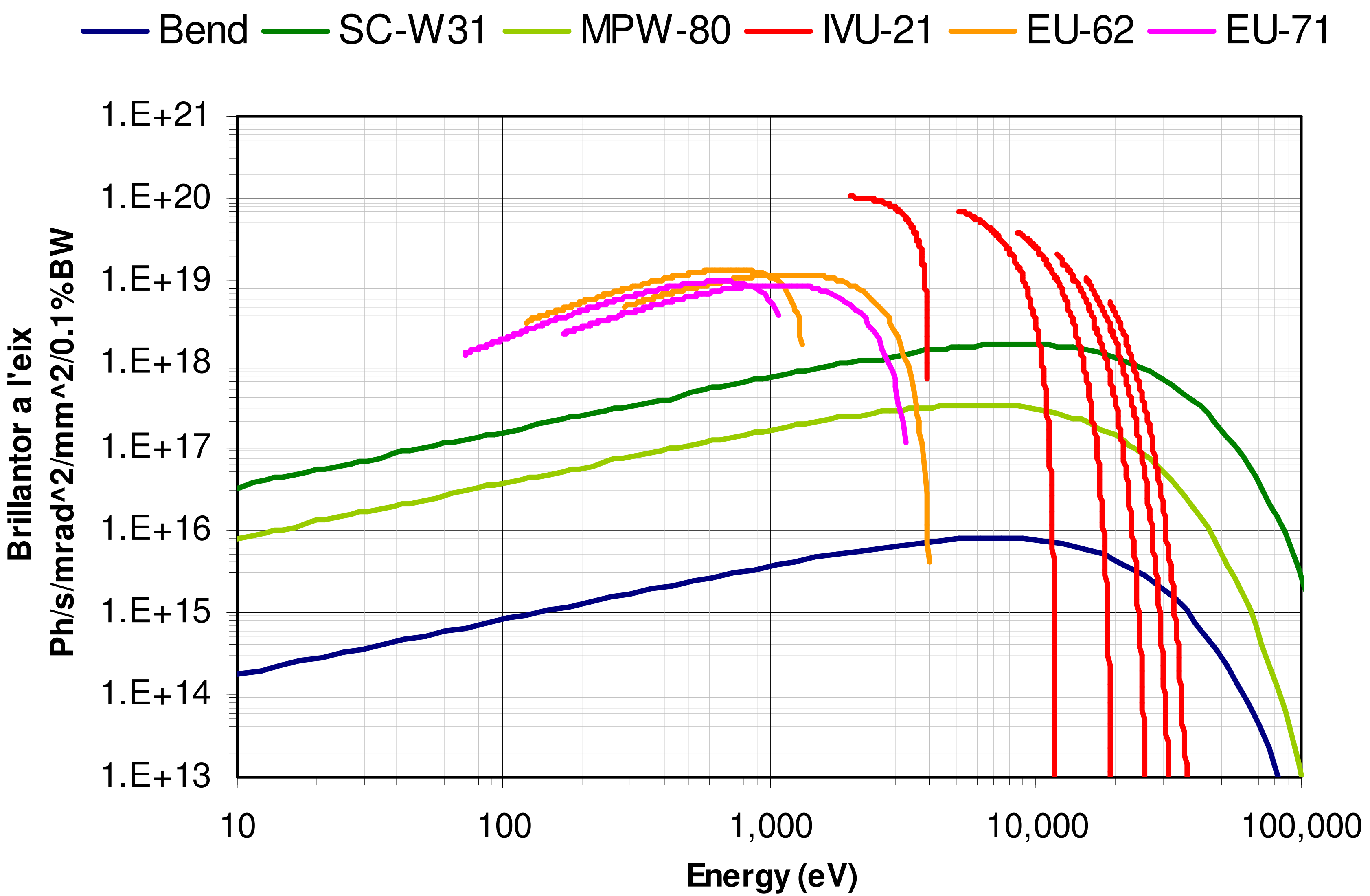
$$\dot{D}_0 = 0.6\ \mathrm{Gy/h}$$

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




✓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

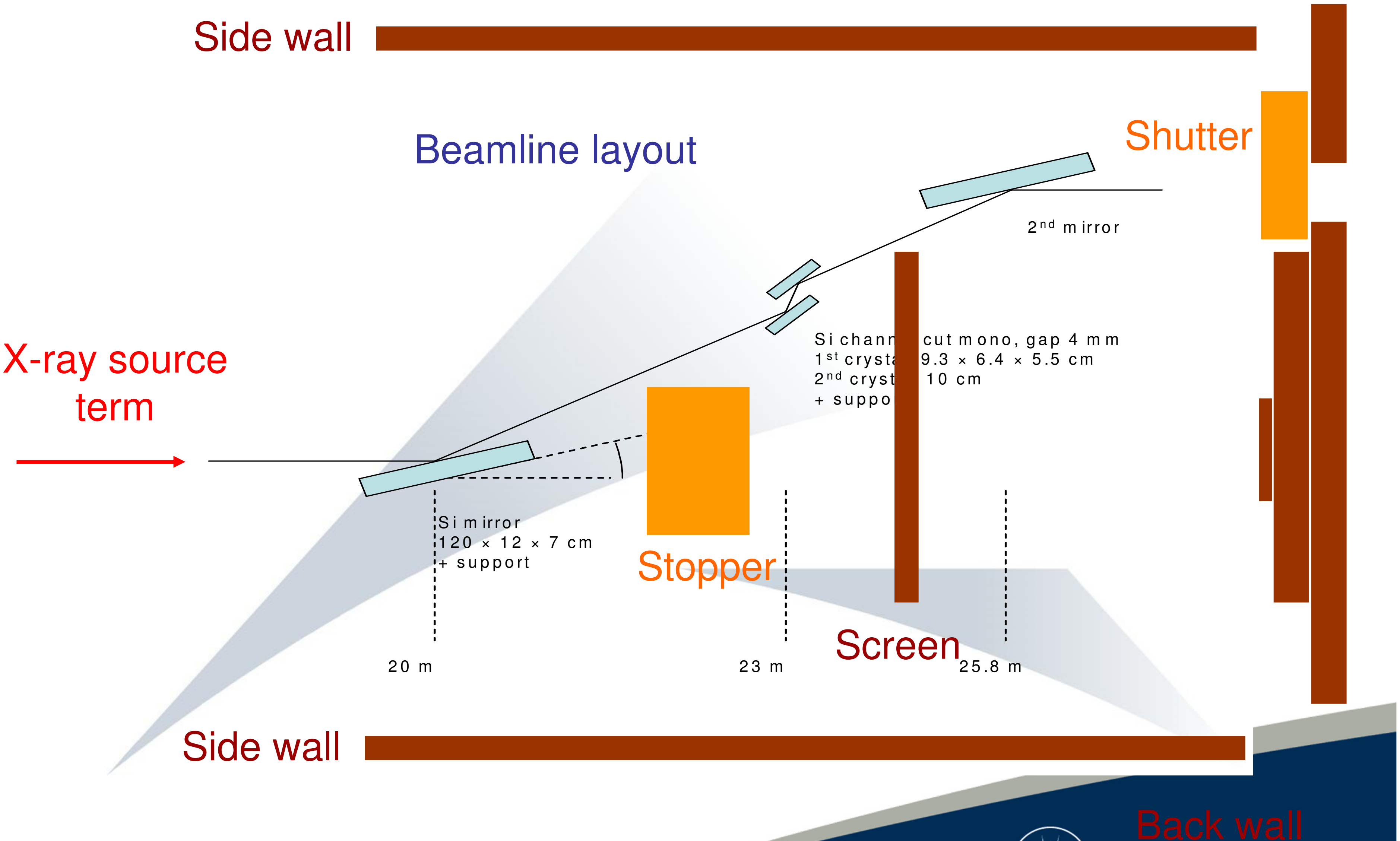
1 Sv / h

✓Shielding elements required:

- Hutch walls
- Stopper & Shutter

# 3. Synchrotron radiation facilities

## 2. BEAMLINES SHIELDING - SAFETY ELEMENTS

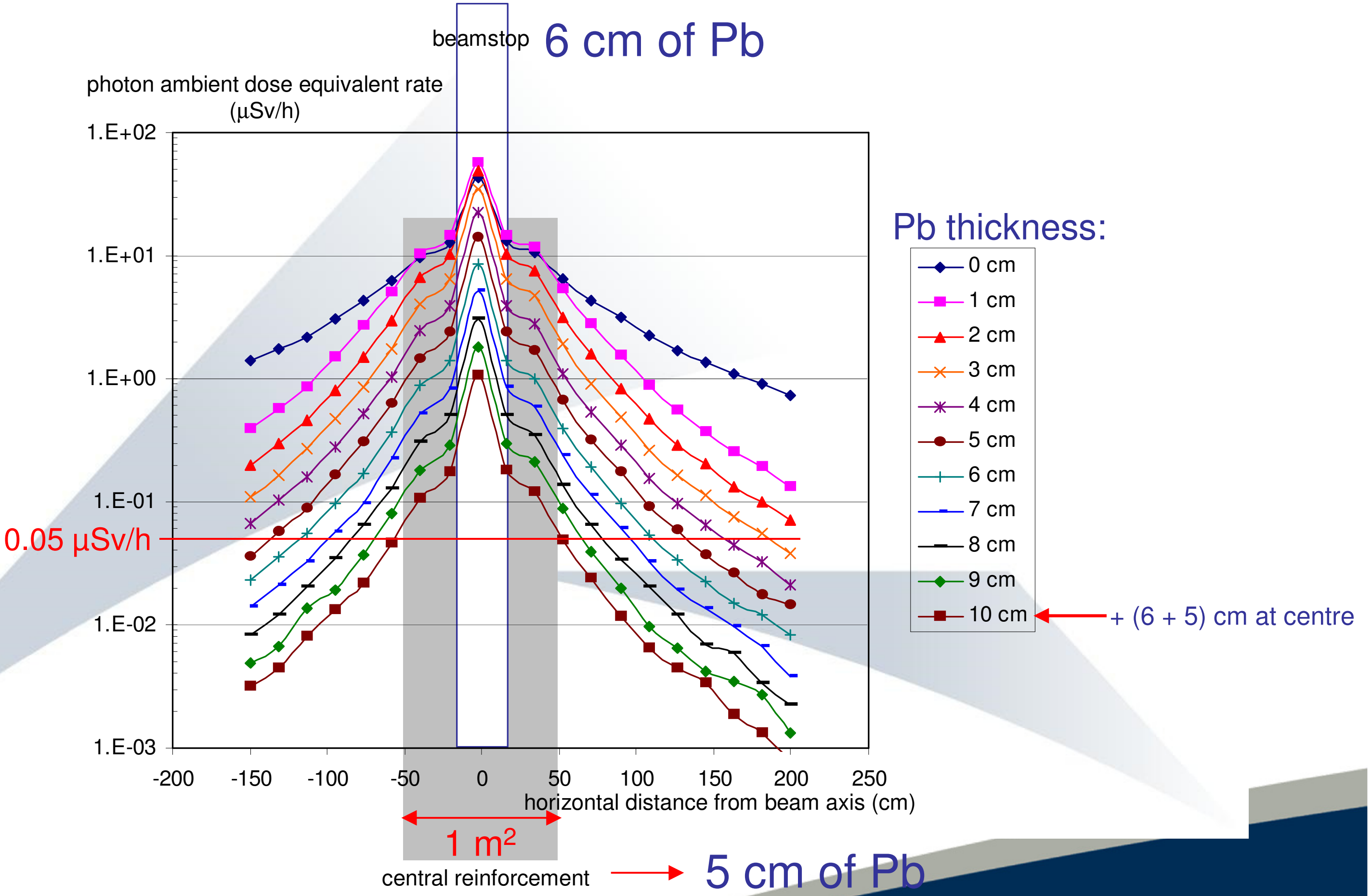


# 3. Synchrotron radiation facilities

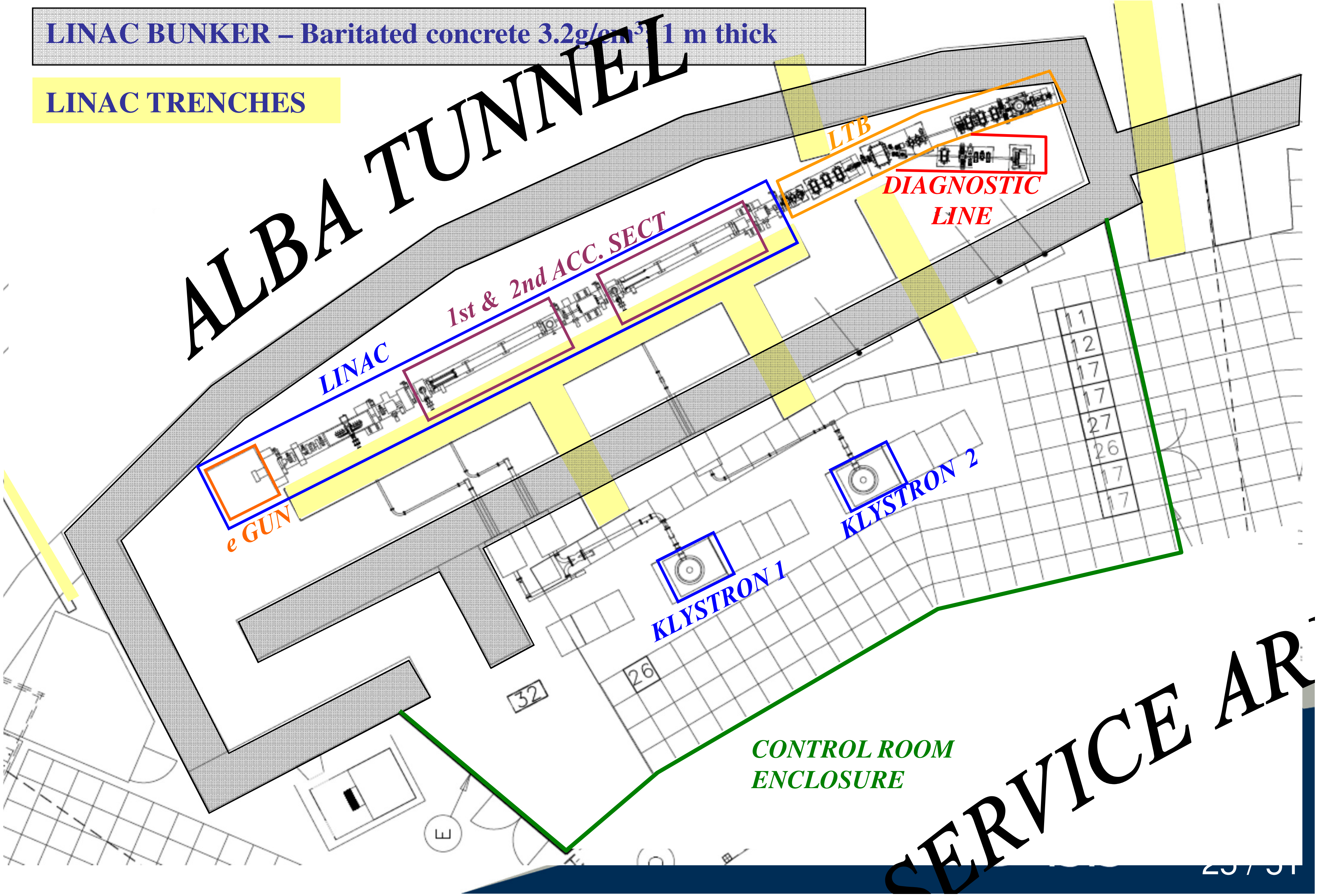
## BEAMLINES SHIELDING - SAFETY ELEMENTS

❖Shielding against gas bremsstrahlung

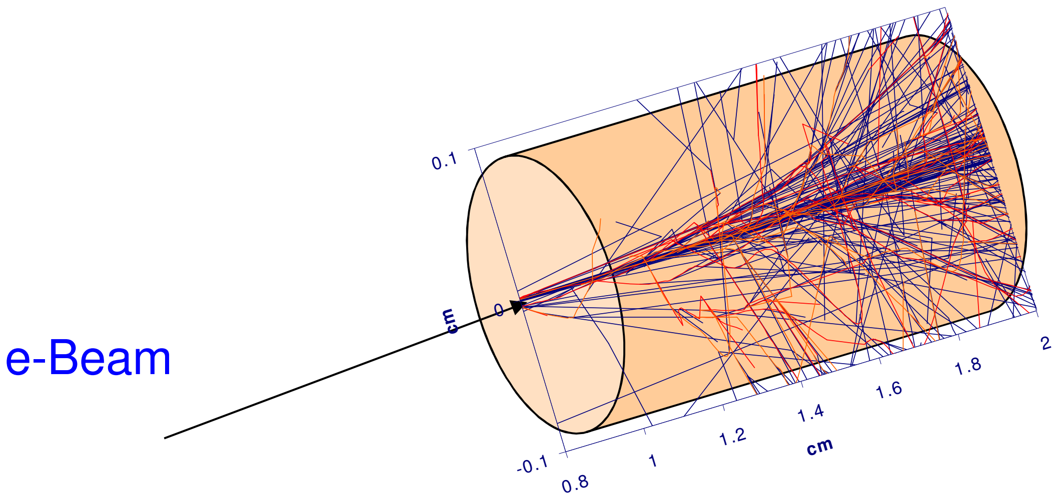
➢Backwall thickness (for the HRPD case):



# 4a. Beam dumper



# 4a. Beam dump cylinder




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

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

Where:

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

Z: atomic number (for Cu: 29)

$\rho_M = 10.29$ cm

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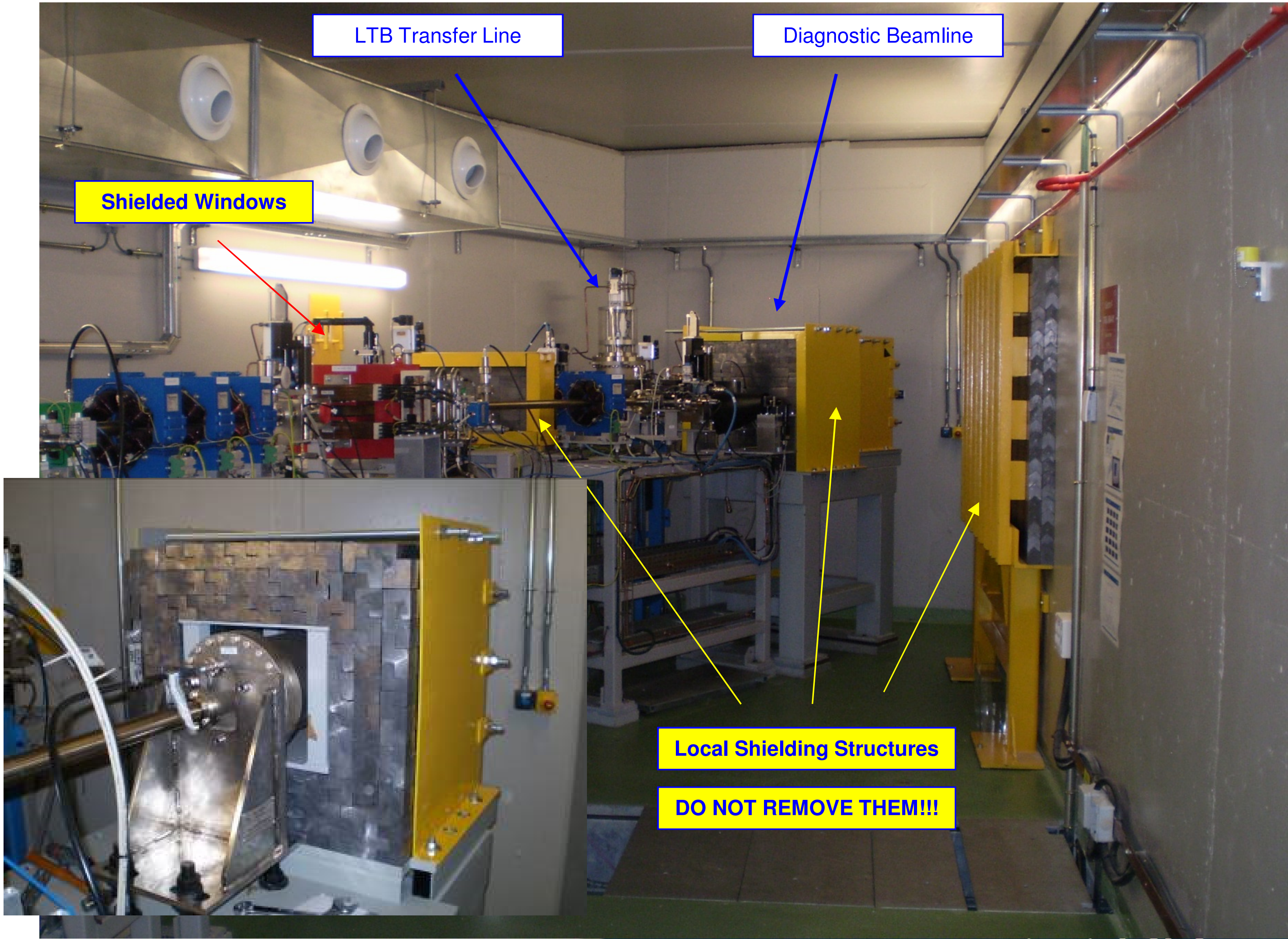
# 4a. Beam dump cylinder



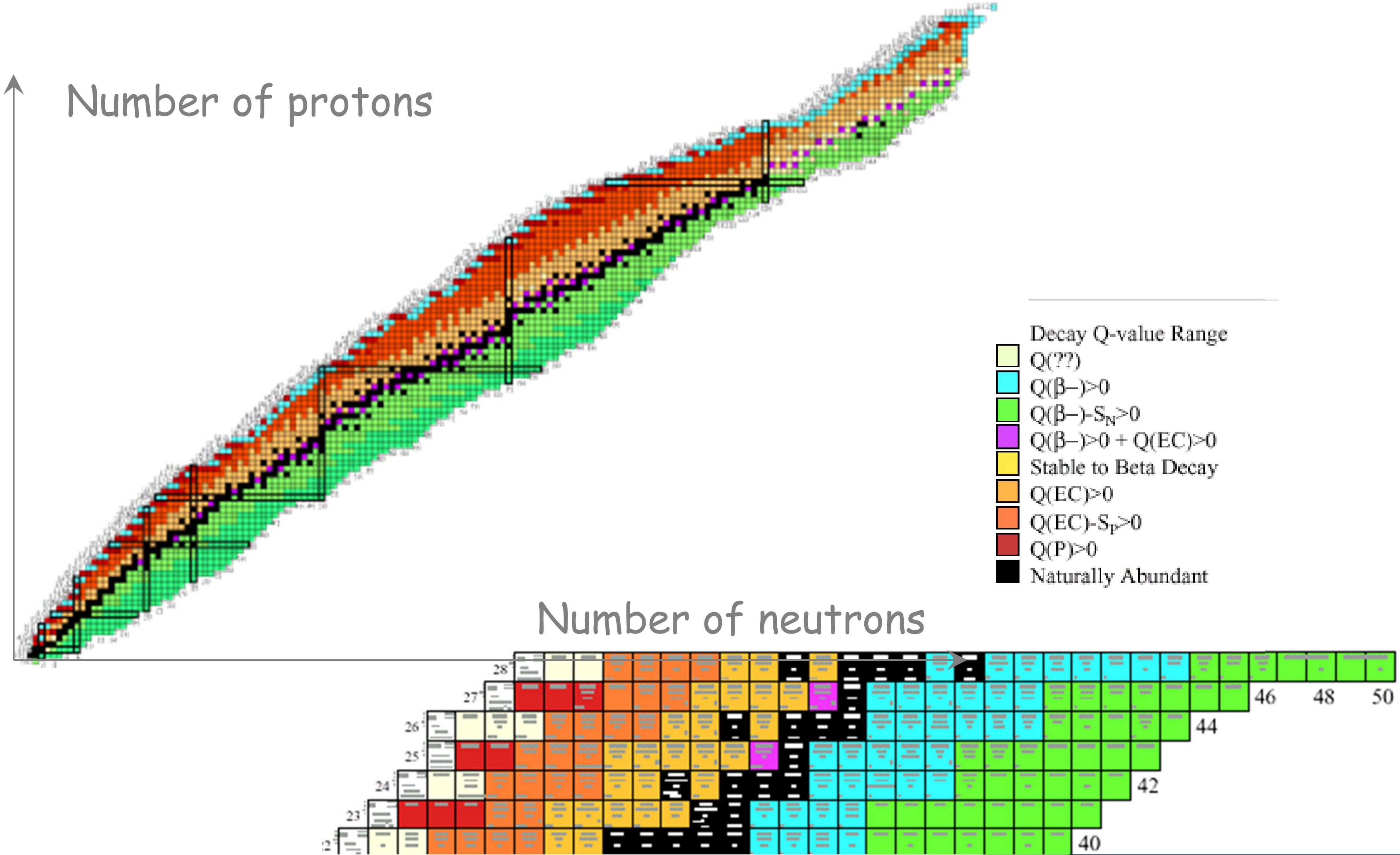
# 4b. Induced Activity

- 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

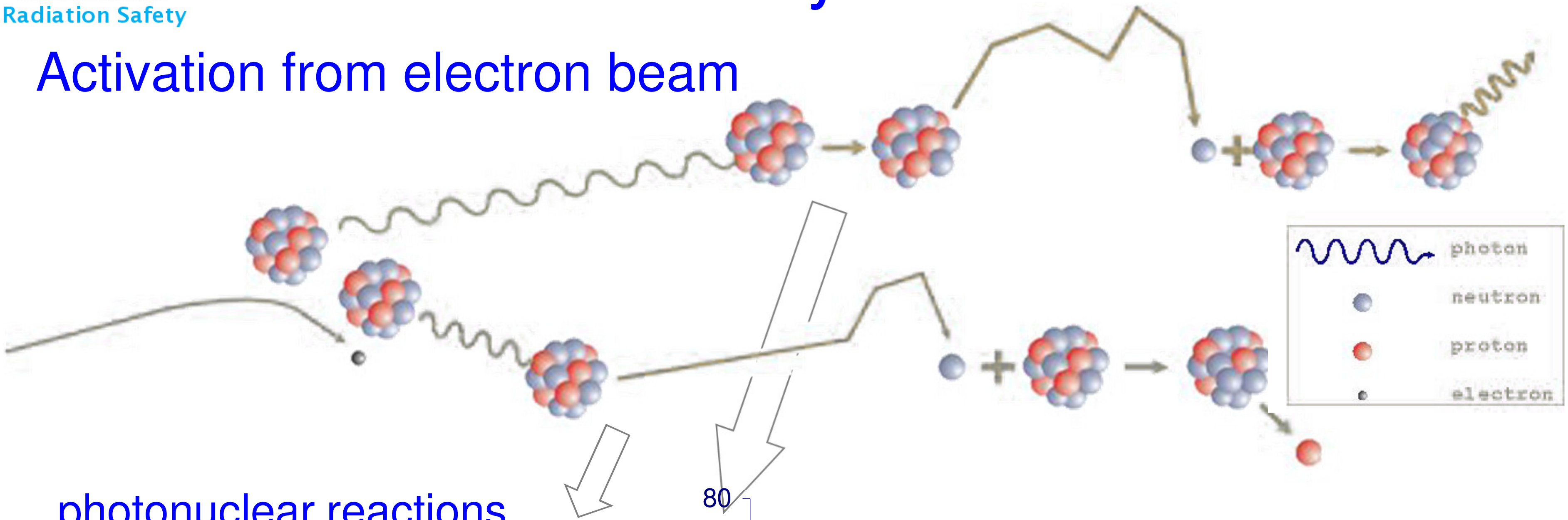
| relatively insensitive to activation | moderately susceptible to activation | highly susceptible to activation | fissionable |
|---|---|---|---|
| ordinary concrete, Pb, Al, wood, plastics | Fe (steel, ferrites), Cu | Stainless steel, W, Ta, Zn, Au, Mn, Co, Ni | U, Pu, Th |

# 4b. Induced Activity

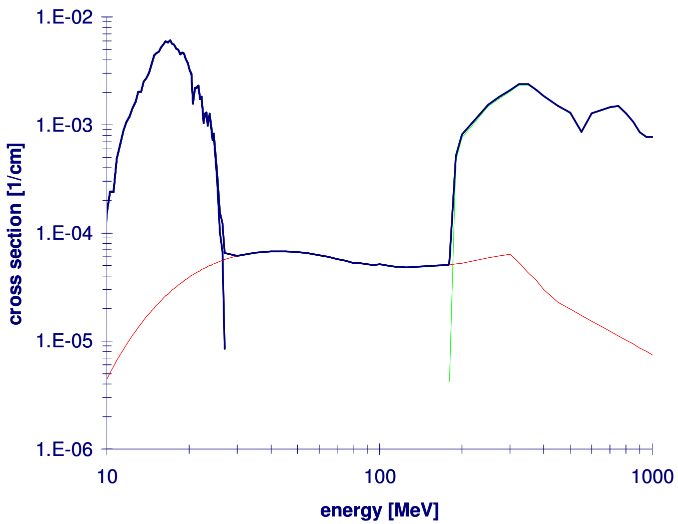


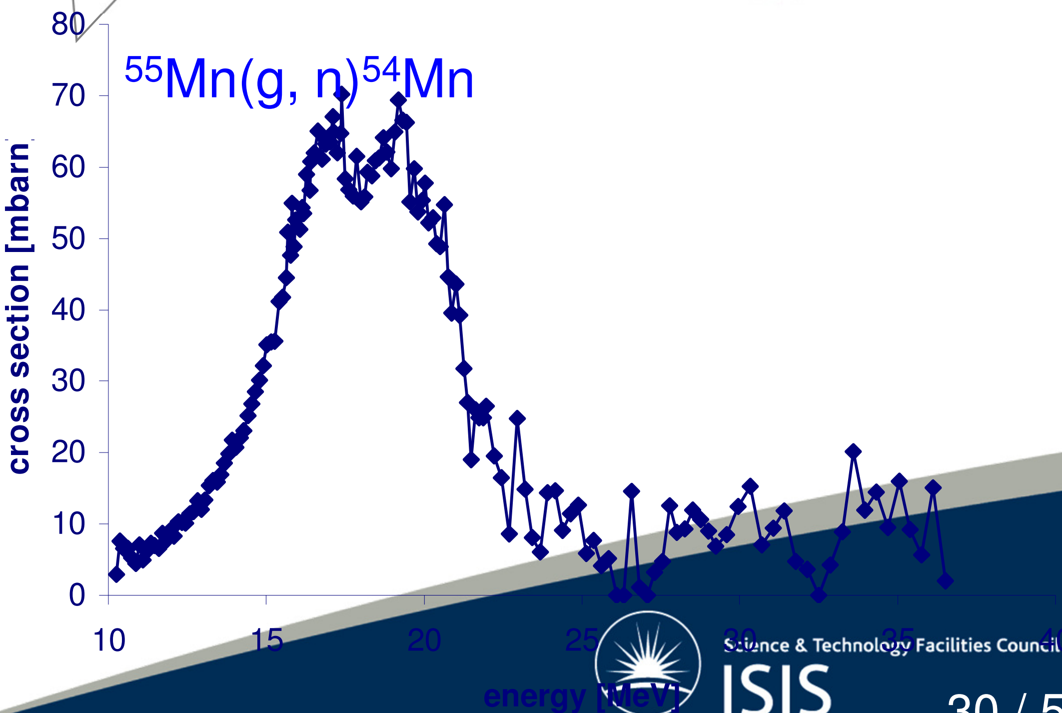
# 4b. Induced Activity

## Activation from electron beam




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

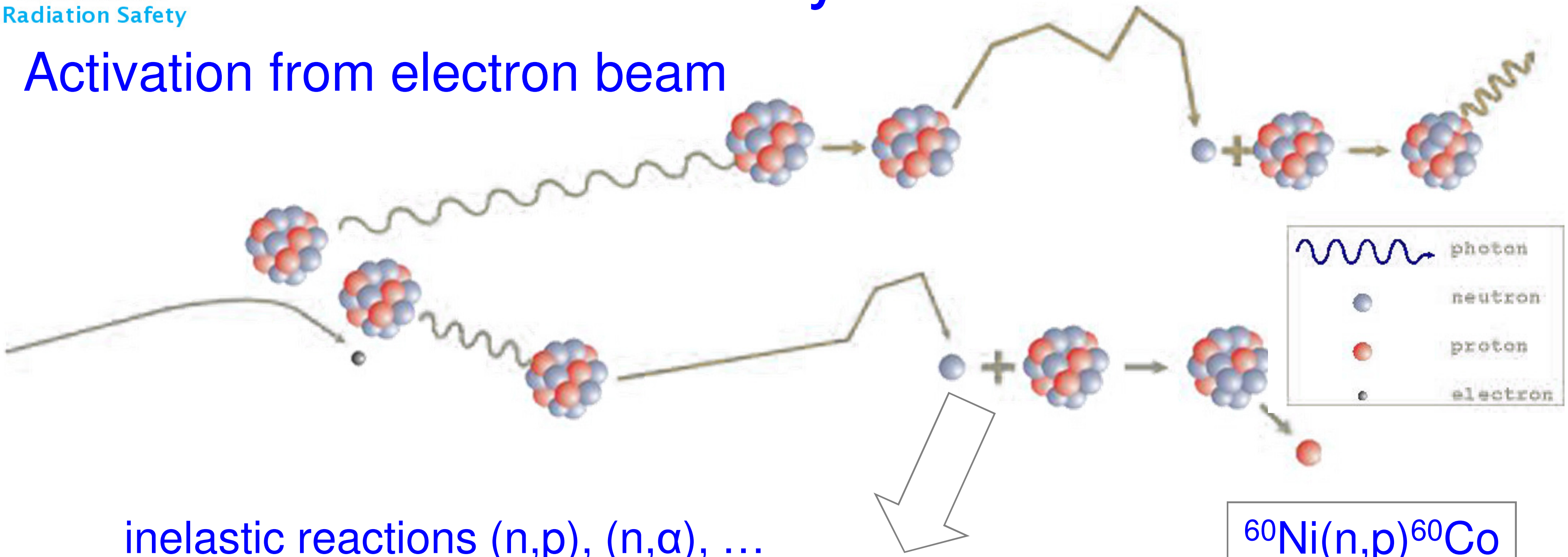


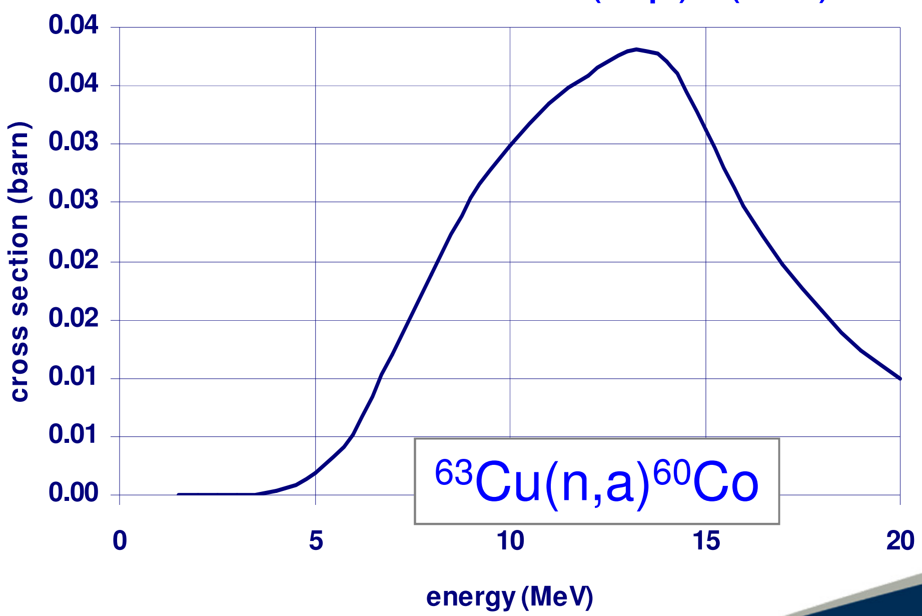
# 4b. Induced Activity

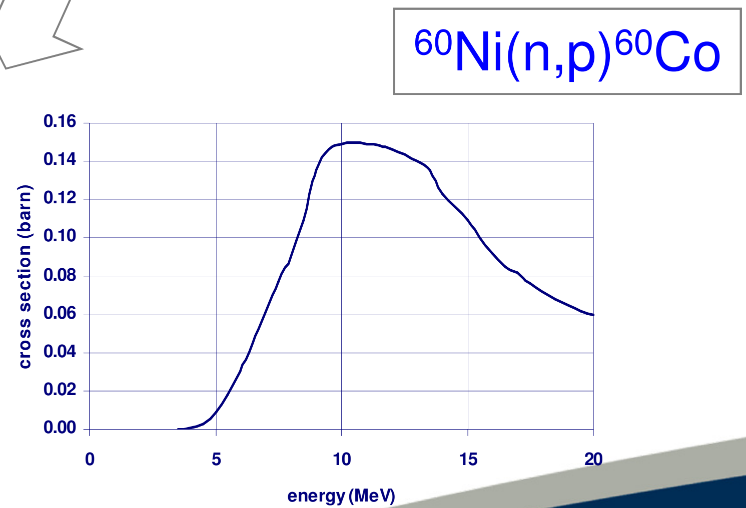
Radiation Safety

## Activation from electron beam




inelastic reactions (n,p), (n,α), …

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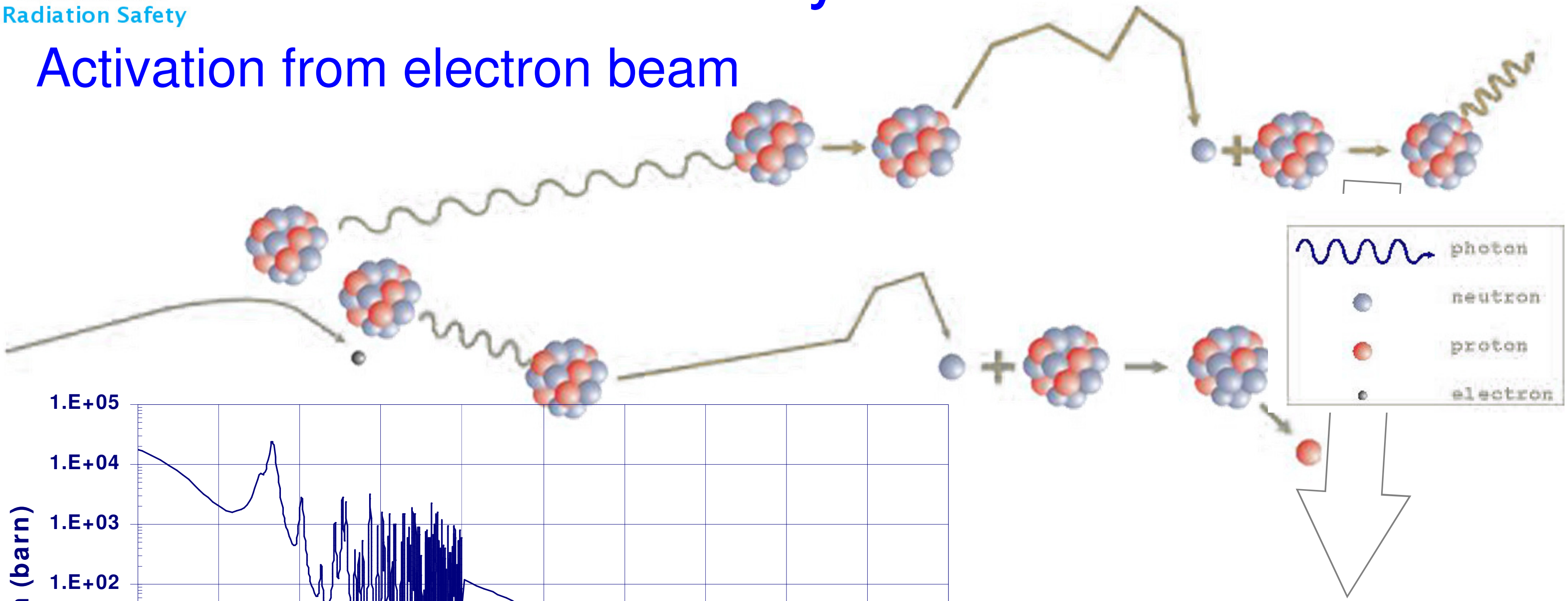
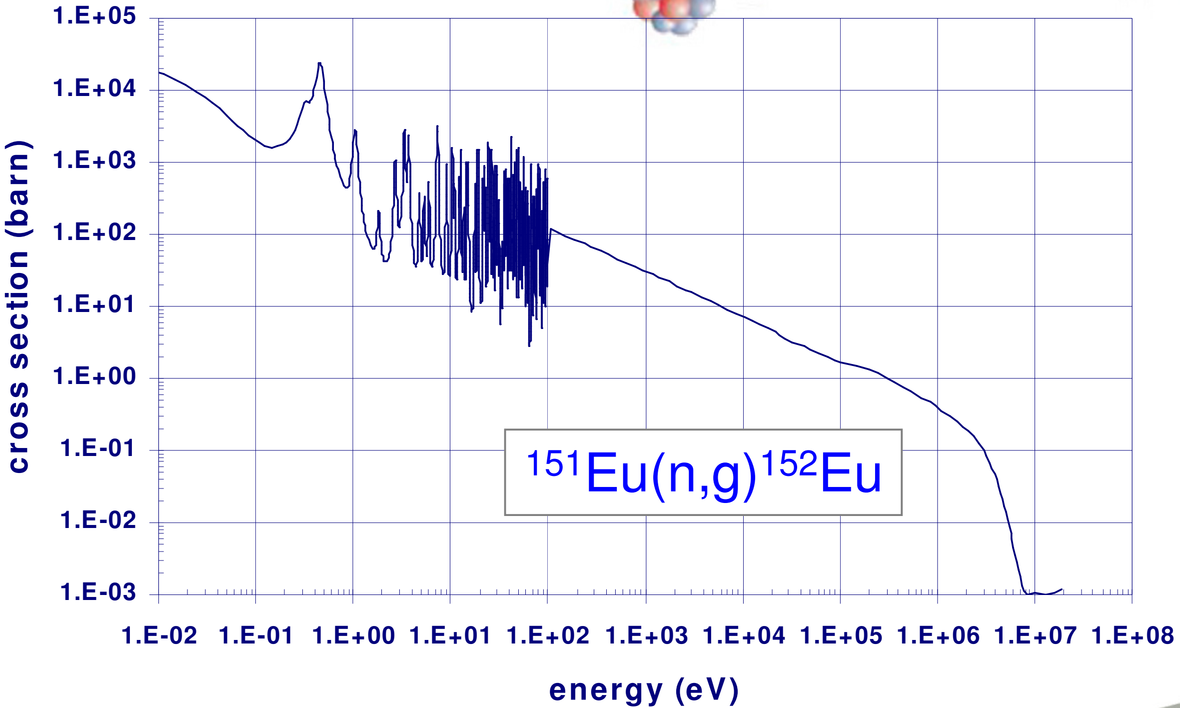
# 4b. Induced Activity

## Activation from electron beam

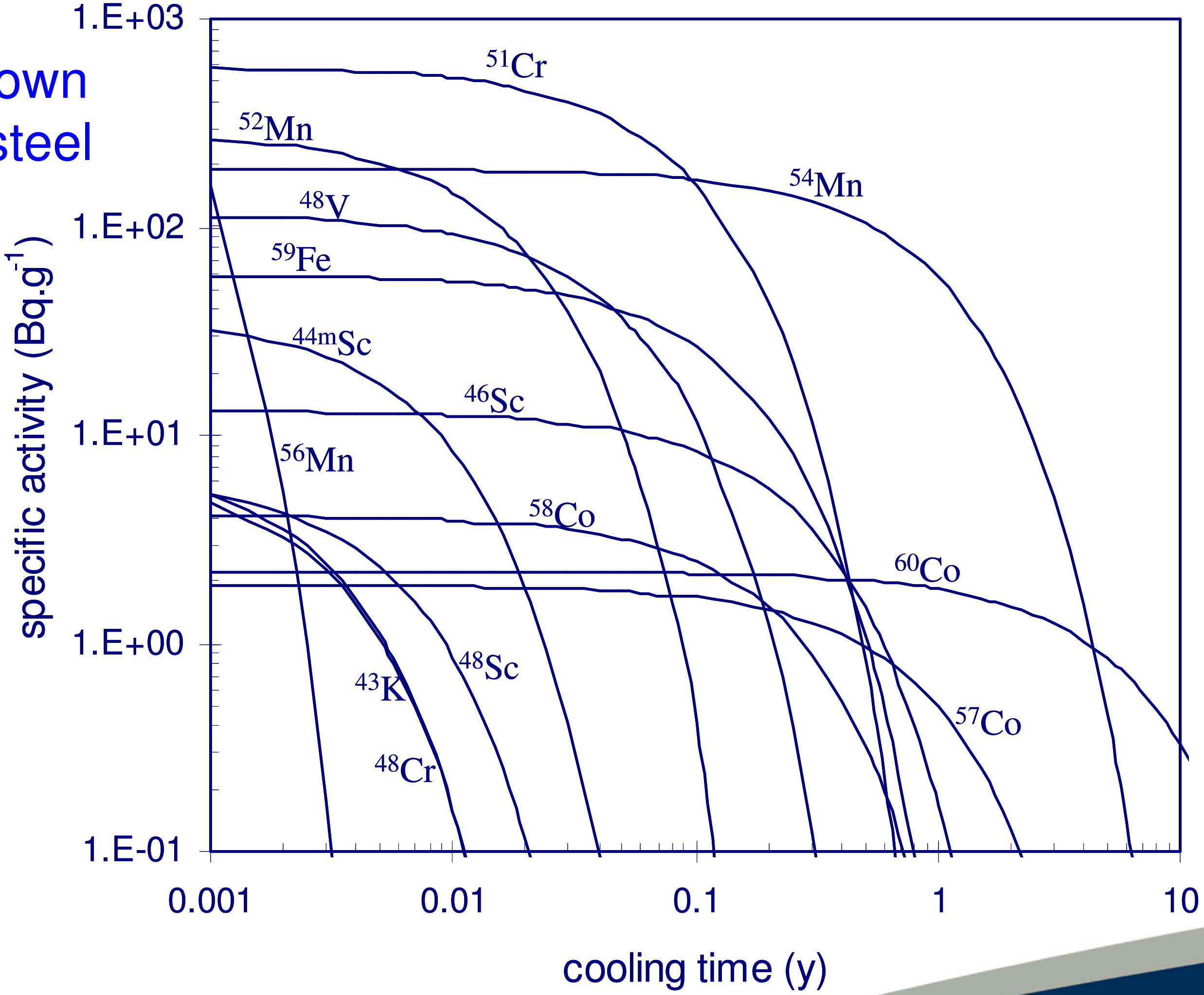


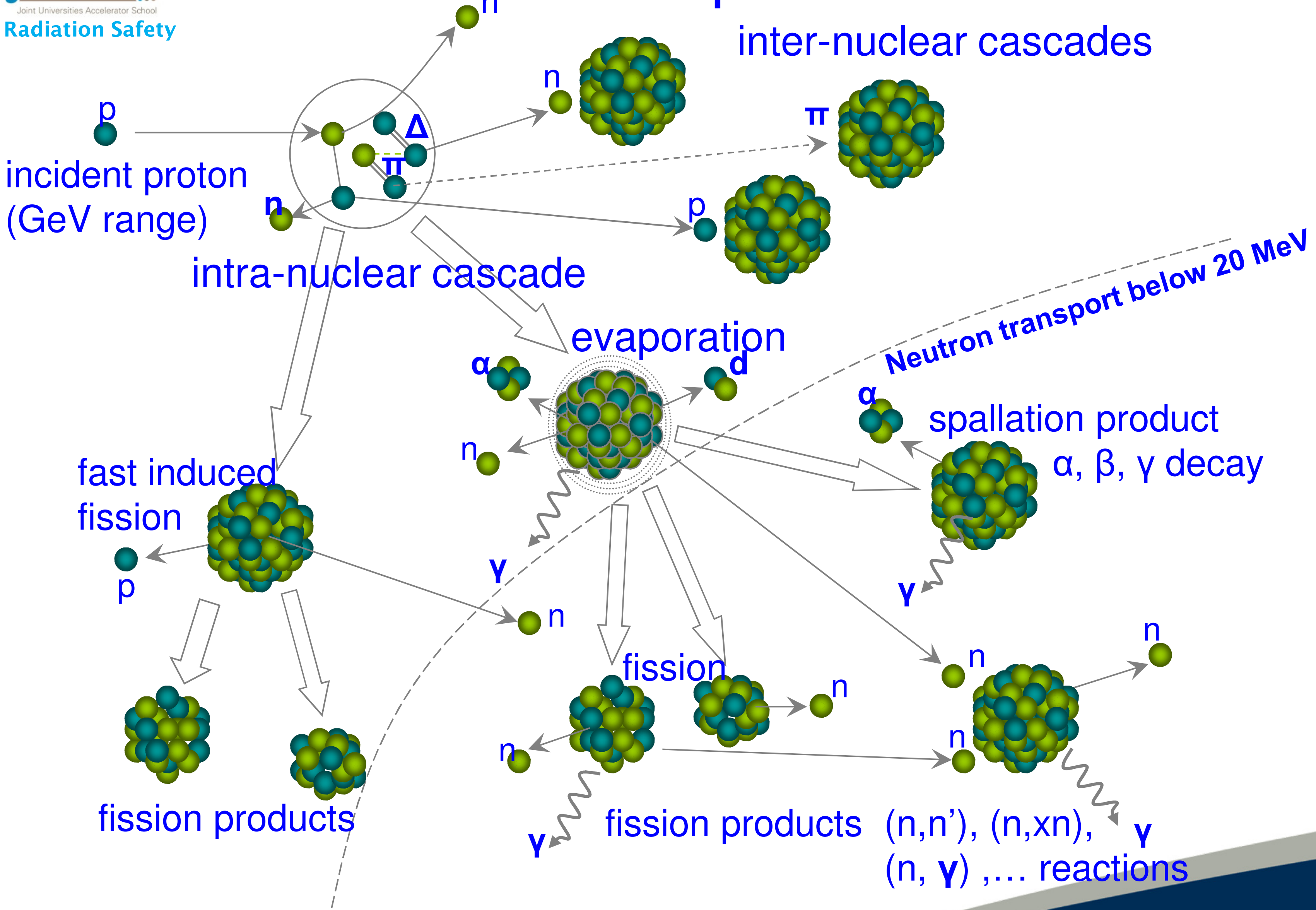

Radioactive capture

# 4b. Induced Activity
## Activation from electron beam

Example: cooling down curve of irradiated steel



# 4b. Interaction of protons with matter




**Activation from proton beam**

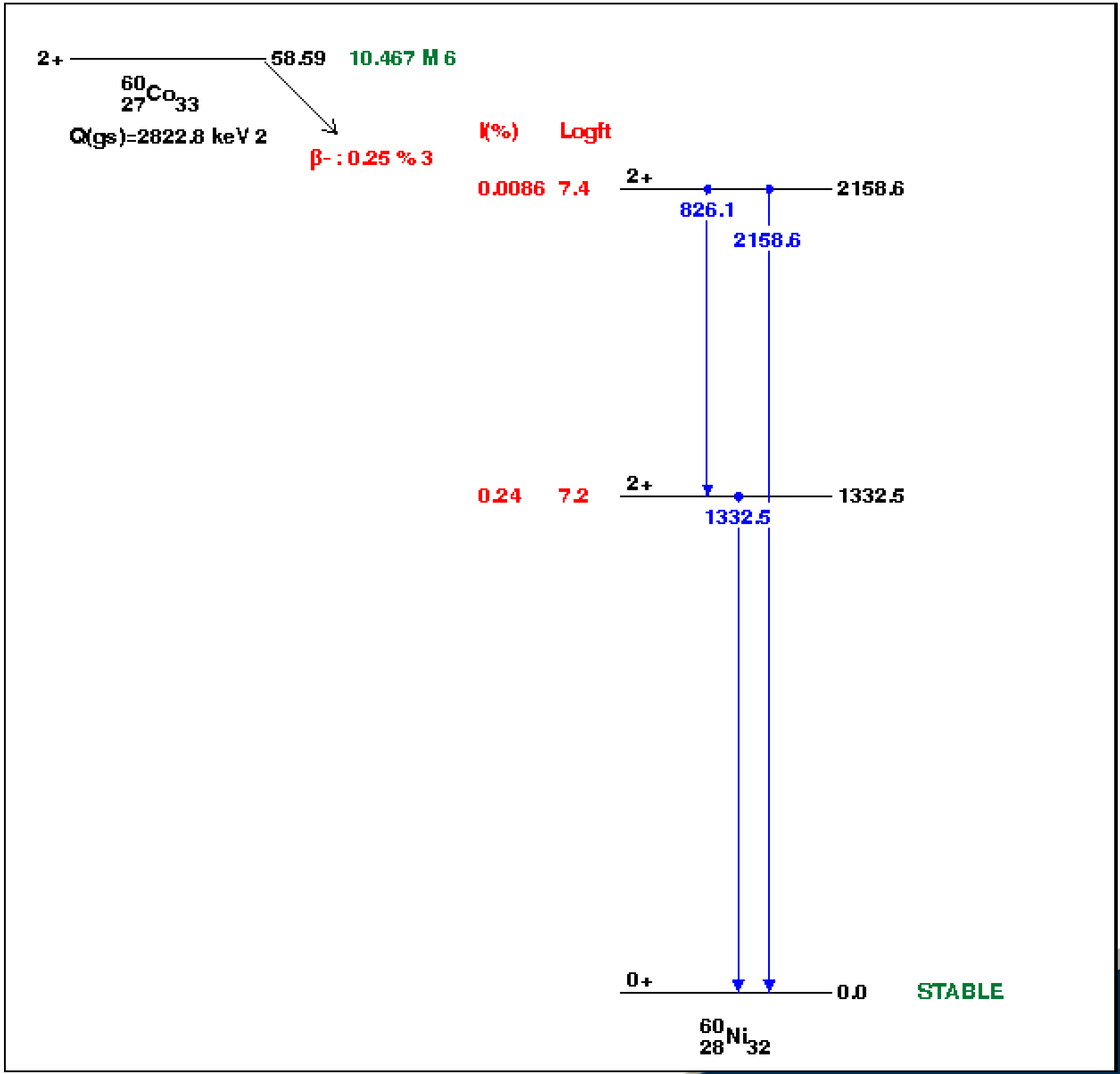
# 4b. Induced Activity

## 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 | $\beta^+$ | 140 |
| $^{18}F$ | 1.8 h | $\beta^+$ | 132 |
| $^{22}Na$ | 2.6 y | $\beta^+$ | 298 |
| $^{24}Na$ | 15 h | $\beta^+$ | 560 |
| $^{46}Sc$ | 84 d | $\beta^+$ | 283 |
| $^{48}Sc$ | 1.8 d | $\beta^+$ | 455 |
| $^{48}V$ | 16 d | $\beta^+$ | 397 |
| $^{51}Cr$ | 28 d | EC | 4.3 |
| $^{52}Mn$ | 5.7 d | $\beta^+$ | 326 |
| $^{54}Mn$ | 303 d | EC | 114 |
| $^{56}Co$ | 77 d | $\beta^+$ | 350 |
| $^{60}Co$ | 5.3 y | $\beta^+$ | 340 |
| $^{65}Zn$ | 245 d | EC | 76 |

Principal radioactive isotopes produced in accelerator structures by spallation reactions

# 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 | $\beta^-$<br>$\gamma$ | 0.32 MeV (100%)<br>1.17 MeV (100%)<br>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

# 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**:

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

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

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

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

Radiation Safety

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

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

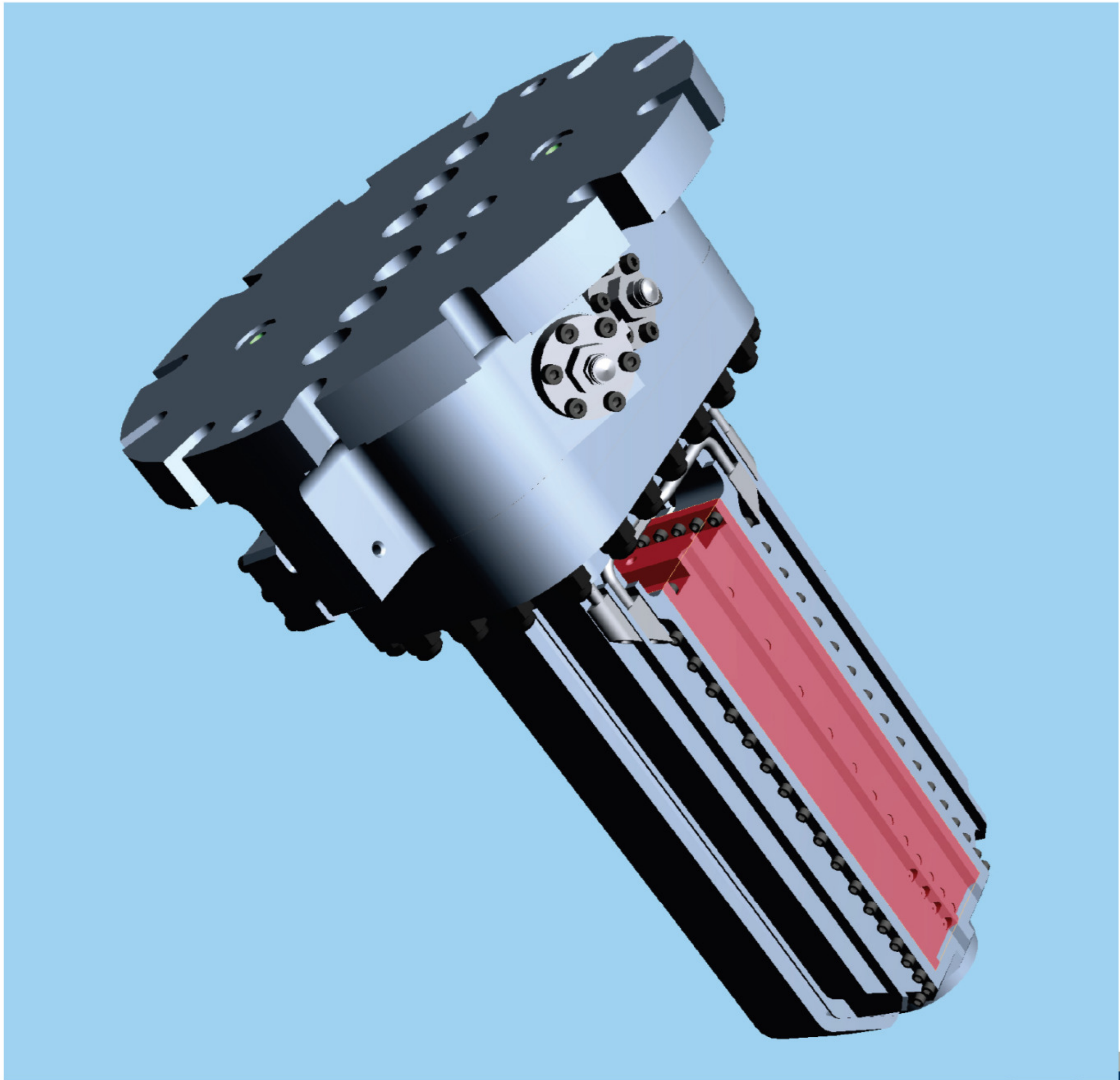
Science & Technology Facilities Council ISIS

# 4b. Induced Activity: proton beam

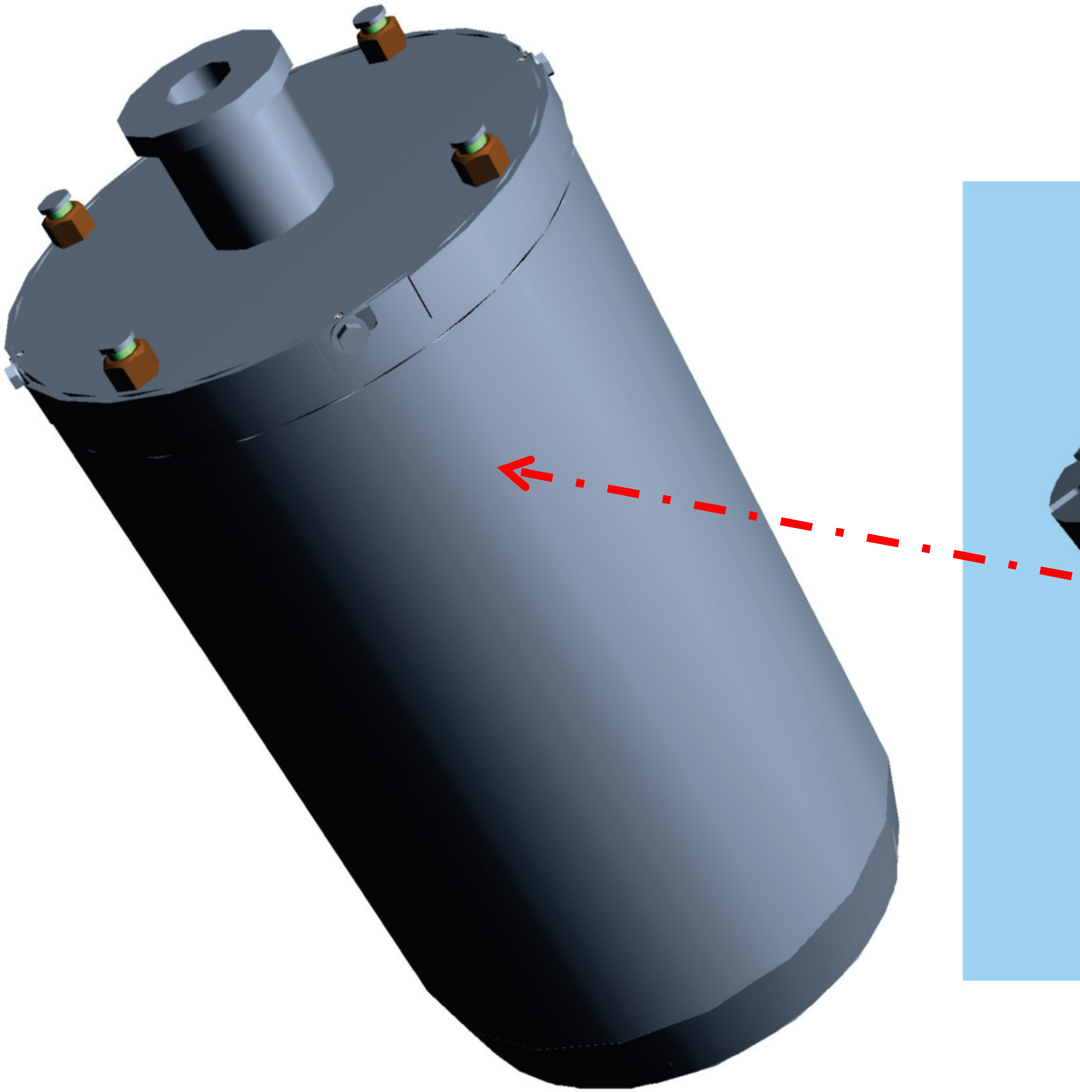
| Parent isotope | Natural (%) | σ (barn) | Active isotope | Half-life | fSv.h-1 at 1m per Bq | per g |
|---|---|---|---|---|---|---|
| $^{23}$Na | 100 | 0.53 | $^{24}$Na | 15 h | 560 | 7.7 |
| $^{40}$Ar | 99.6 | 0.61 | $^{41}$Ar | 1.8 h | 150 | 1.4 |
| $^{44}$Ca | 2.0 | 0.70 | $^{45}$Ca | 165 h | - | - |
| $^{50}$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 |

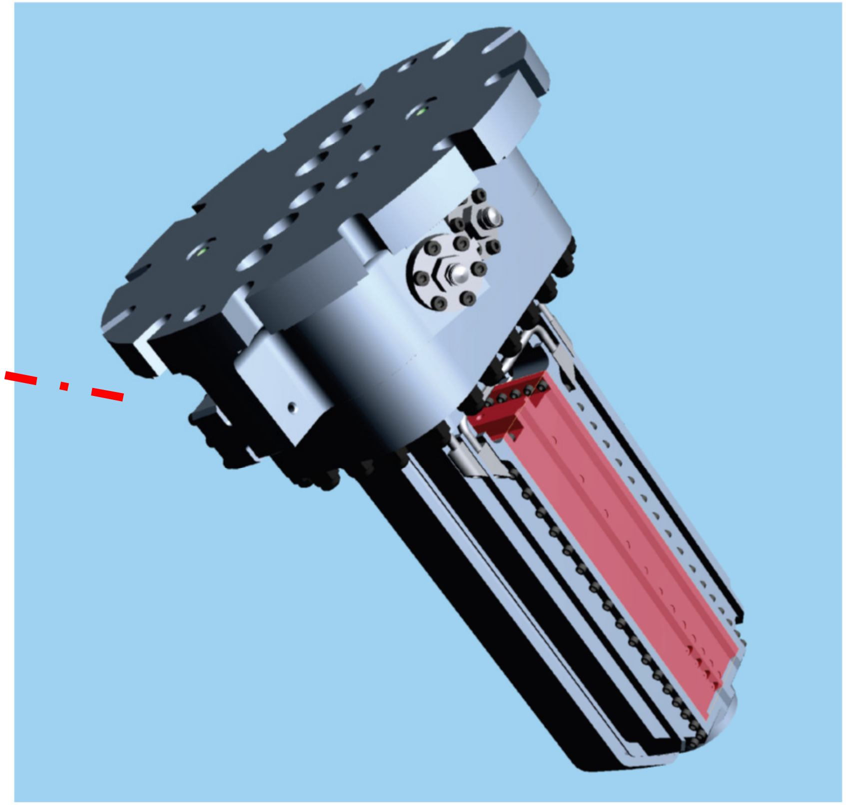
Most important isotopes near high energy particle accelerators formed by thermal neutron capture

# 4b. Example-1: ISIS TS1 target

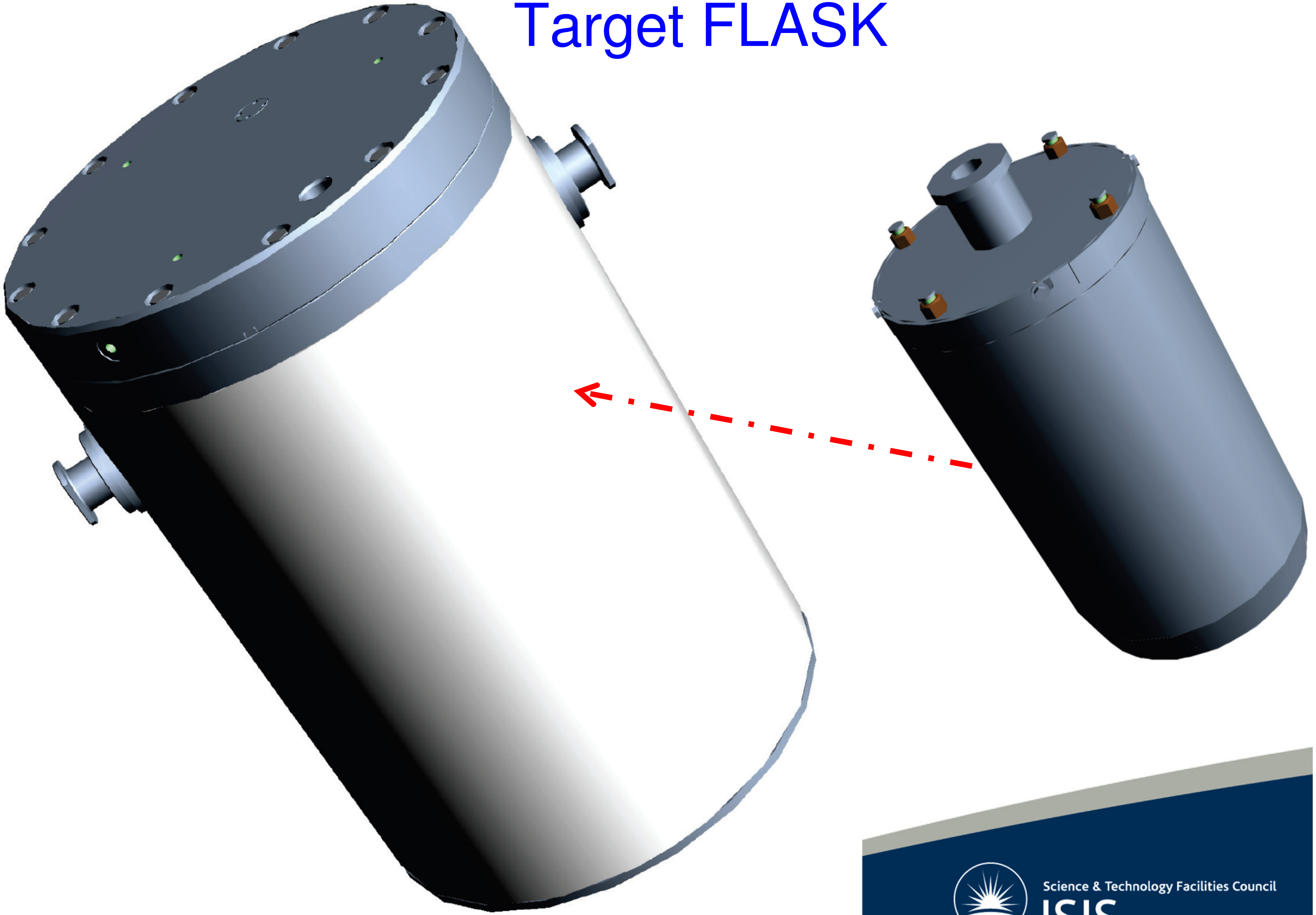


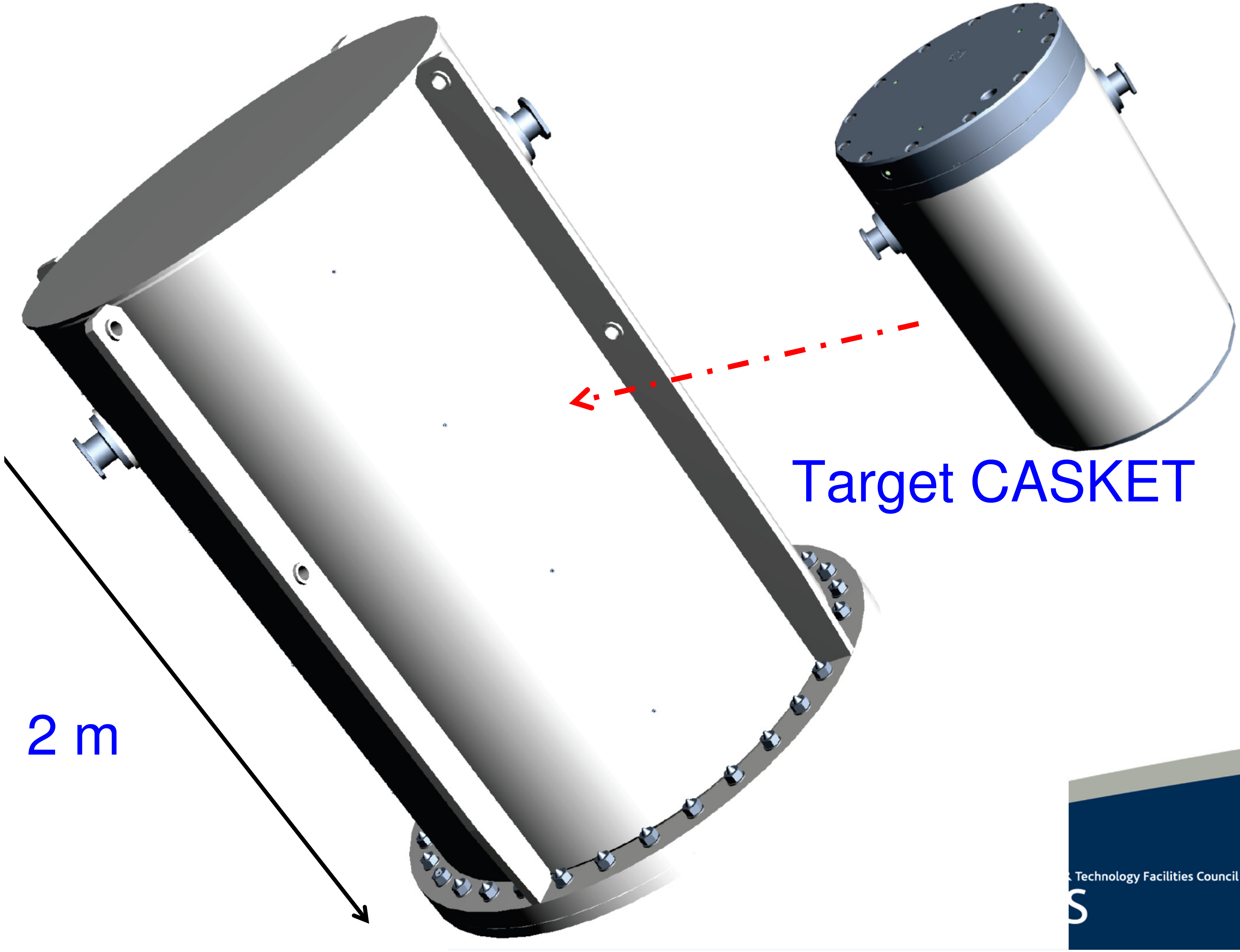
# Target CAN





# Target FLASK




Target CASKET
2 m

juas
Joint Universities Accelerator School
Radiation Safety

# 4b. Example-1: ISIS TS1 target

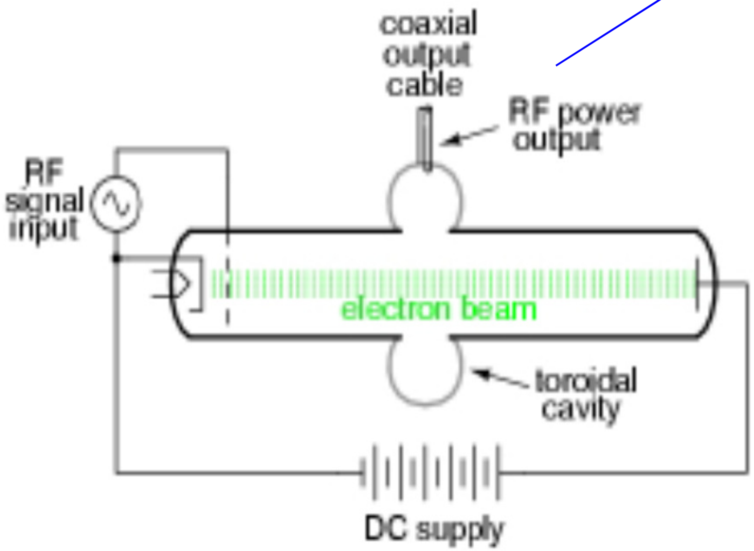
| Irradiation Time | Cooling time | Dose rate TOP | (x5 all the activities values) |
|---|---|---|---|
| [y] | [y] | [mSv/h] | |
| 4 | 0 | 292.42 | |
| 4 | 3 | 1.19 | |
| **4** | **4** | **0.69** | |
| 4 | 5 | 0.48 | |
| 4 | 6 | 0.35 | |
| 4 | 6.5 | 0.30 | |

| | | | | 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% | |

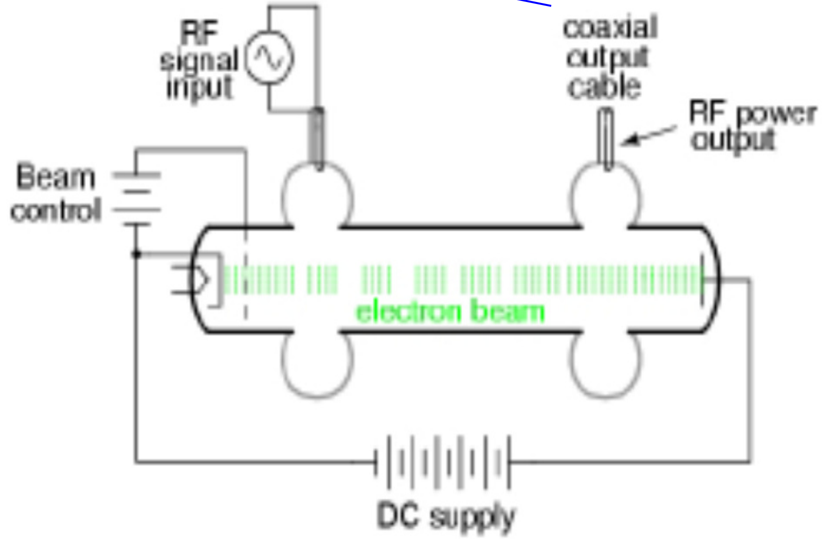
| Total DR after 5 years of cooling | 0.48 | 100.0% | Total DR after 6 years of cooling | 0.3507 | 100.0% | Total DR after 6.5 years of cooling | 0.30 | 100.0% |
|---|---|---|---|---|---|---|---|---|
| A5y[Bq] | DR[mSv/h] | %DR | A6y[Bq] | DR[mSv/h] | %DR | A6.5y[Bq] | DR[mSv/h] | %DR |
| 1.86E+13 | 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% | |

# 4c. RF generator plants

## a. IOT: to RF Cavity b. Klystron:



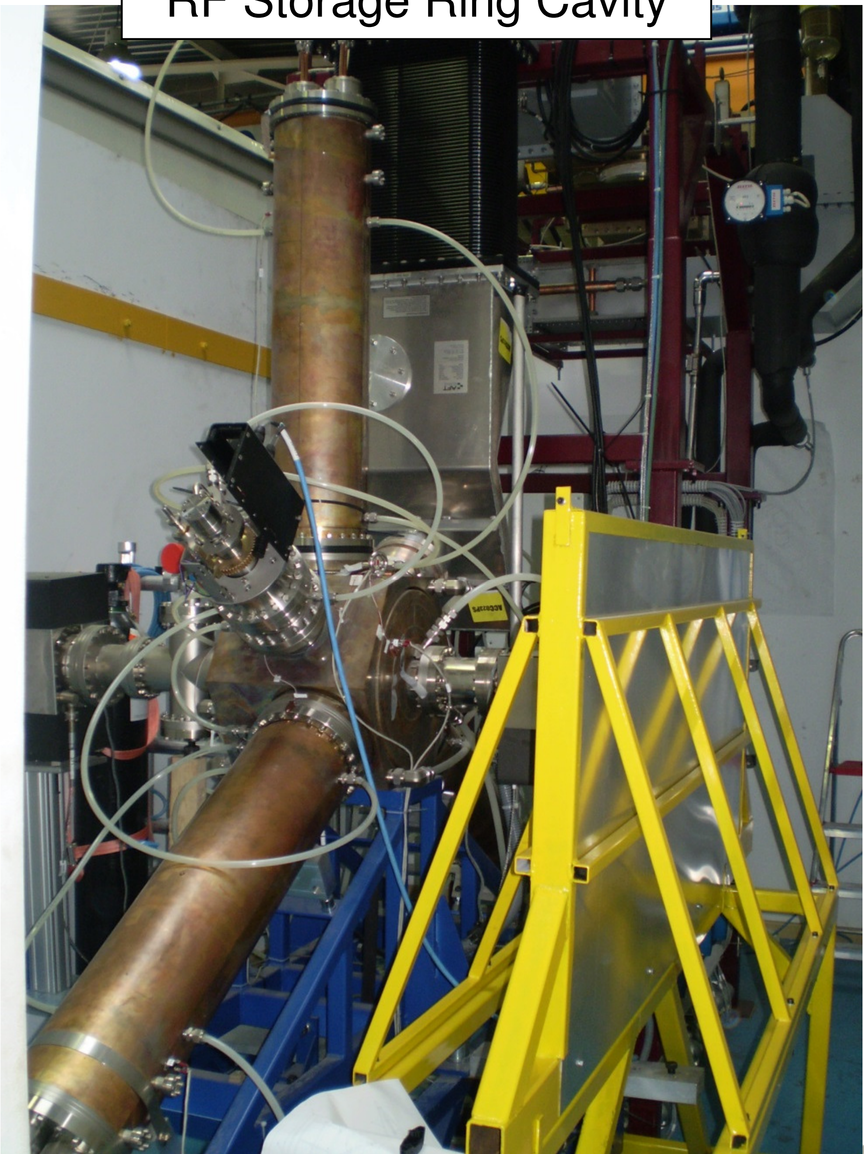

**IOT (Inductive Output Tube)**
G ≈ 23 dB (for comparison: Tetrode G ≈ 15 dB)
Intensity modulated
Class AB
Peak efficiency ≈ 75%
Compact size



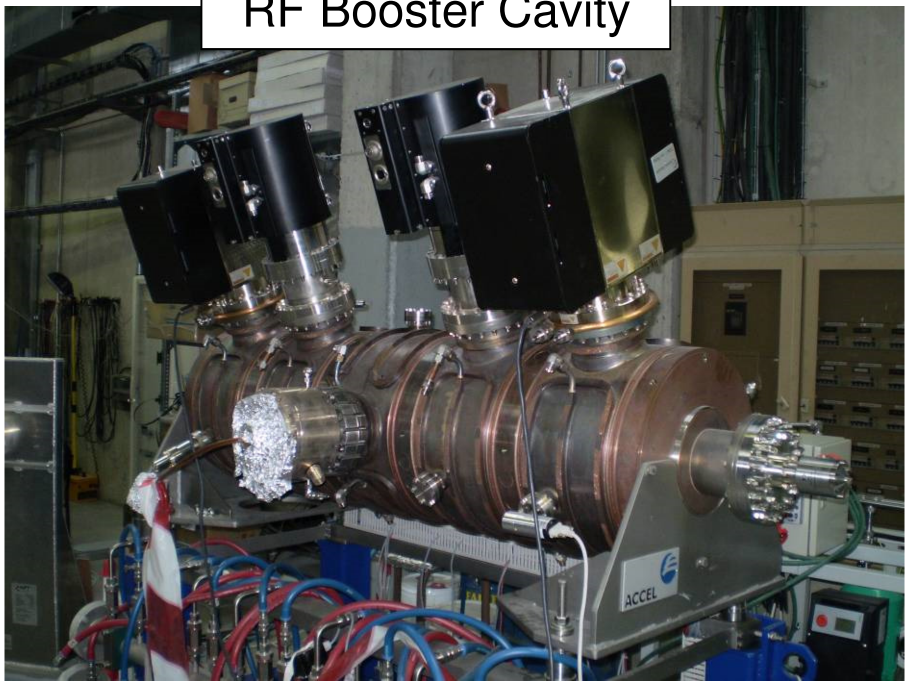

**Klystron**
G ≈ 40 dB
Velocity modulated
Class A
Peak efficiency ≈ 65%

# 4c. RF generator plants

RF Storage Ring Cavity

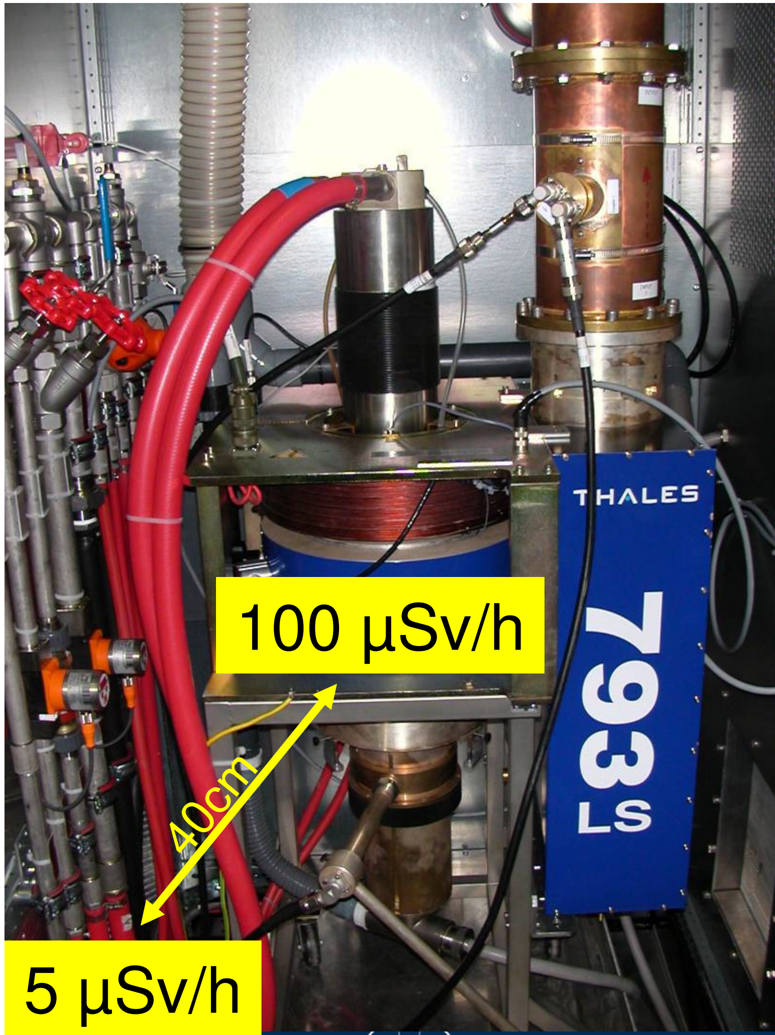


RF Booster Cavity

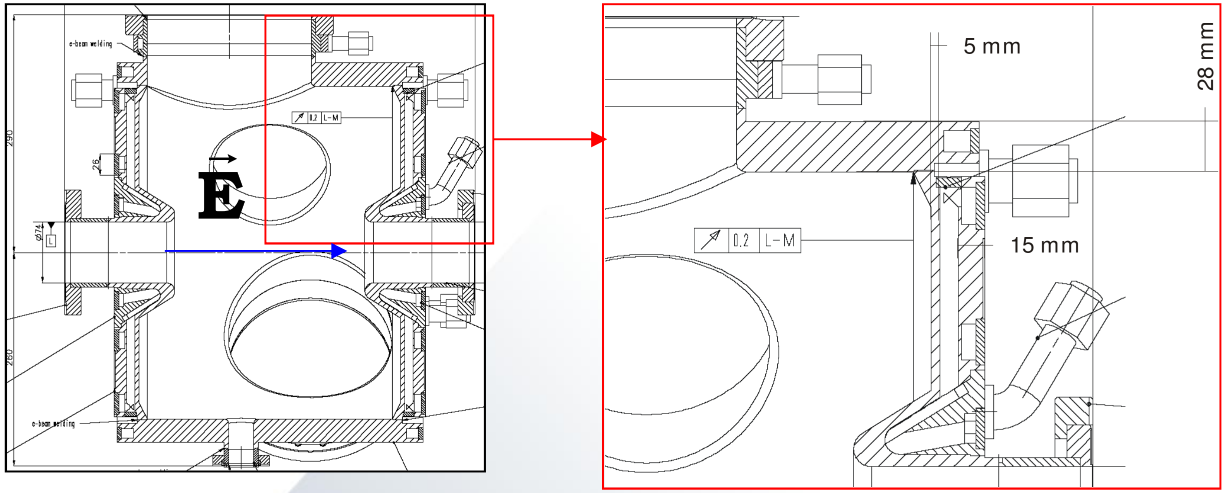


# 4c. RF generator plants

## RADIATION MEASUREMENTS: IOT

# 4c. RF generator plants

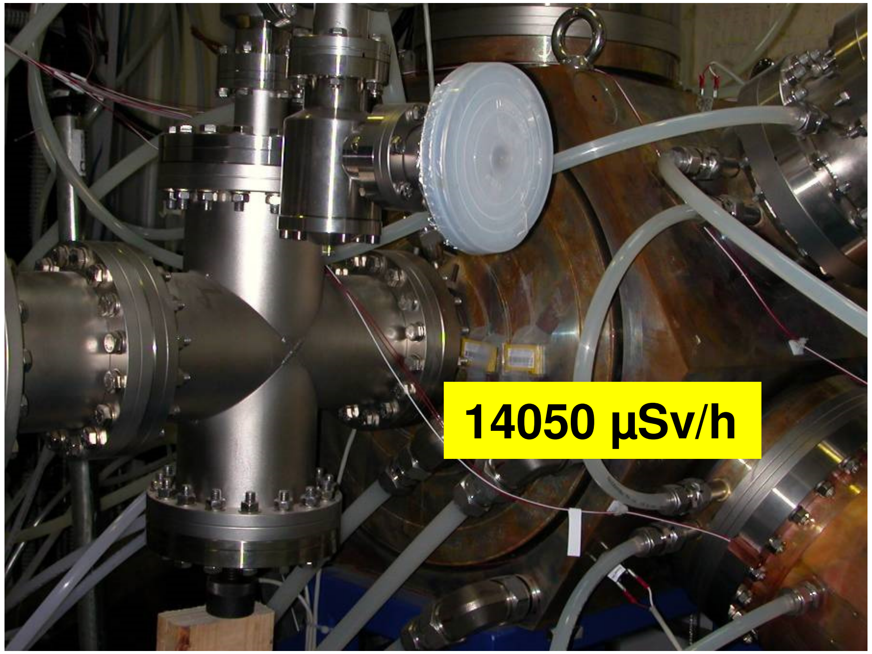


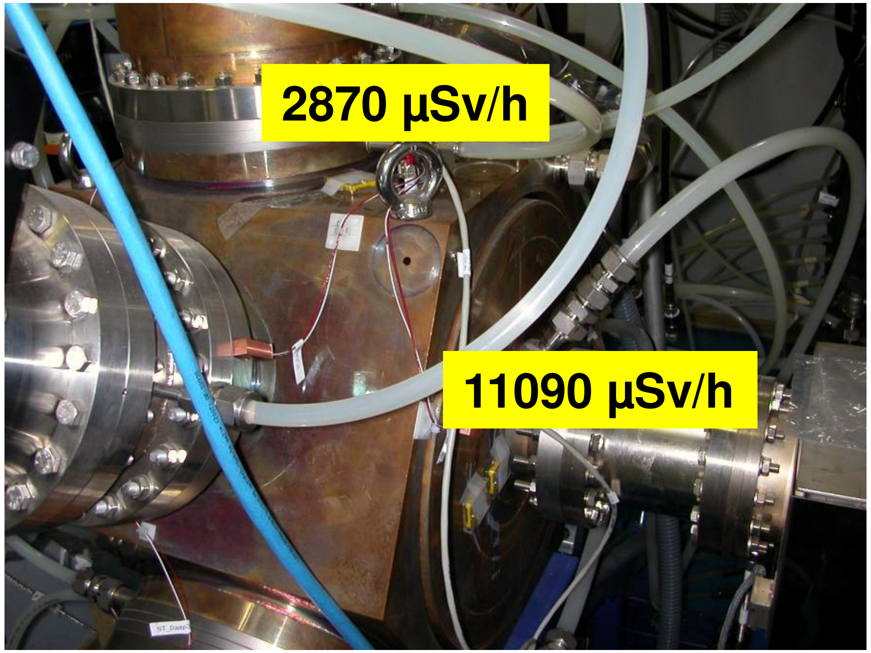

| | *Booster* | *Storage Ring* |
|---|---|---|
| Voltage on axis (kV) | 1350 | 750 |
| Maximum E field on surface (MV/m) | 2.0 | 6.2 |

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

# 4c. RF generator plants

## RAD. MEAS.: DOSE RATE ON SURFACE




**80kW (max power) @ 20%**

# 4c. RF generator plants