

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

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photons (bremsstrahlung)  
neutrons

### 2. Proton accelerators

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neutrons

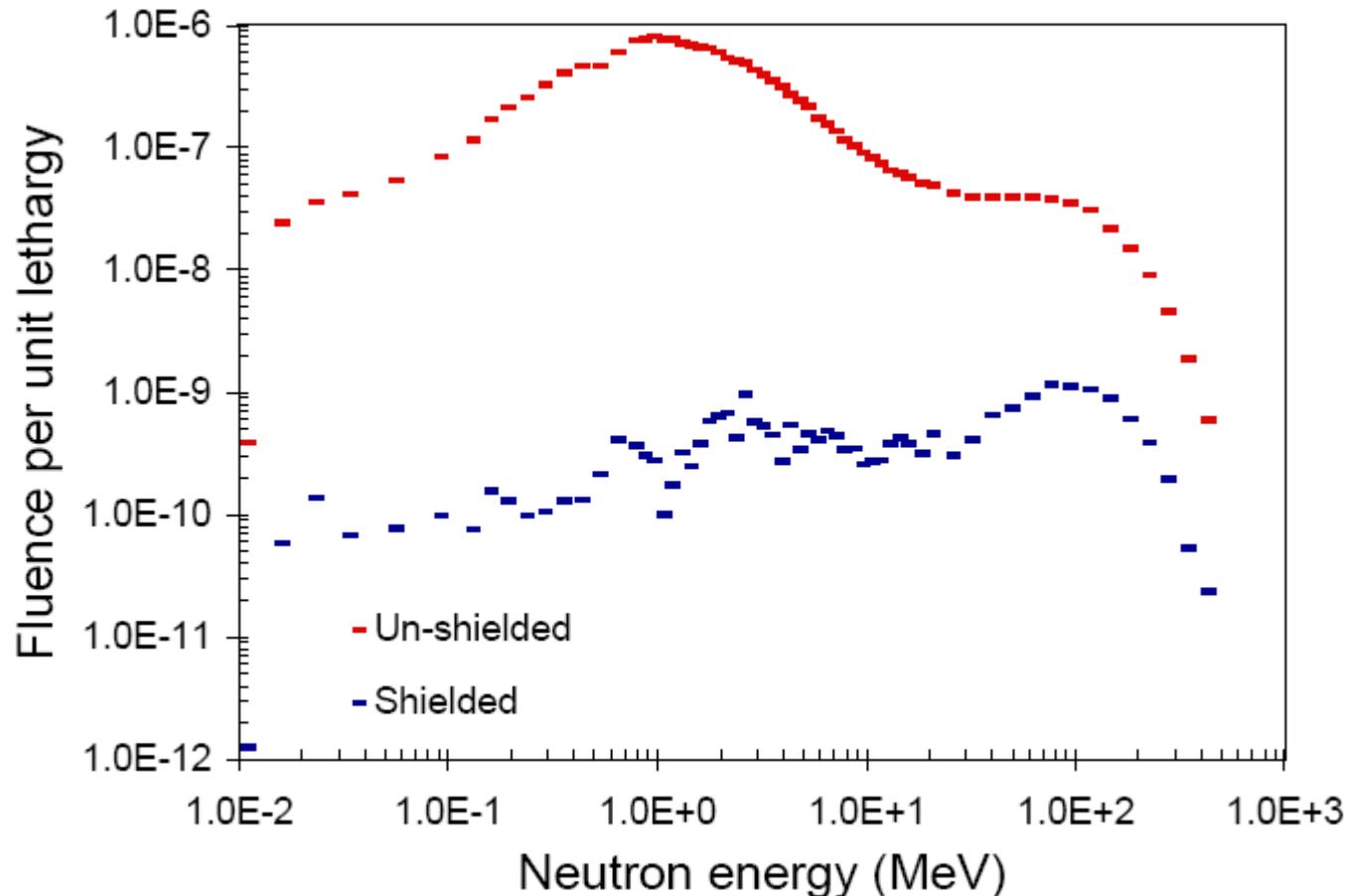
### 3. Synchrotron radiation facilities

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accelerators  
beamlines

# 1. Electron accelerators

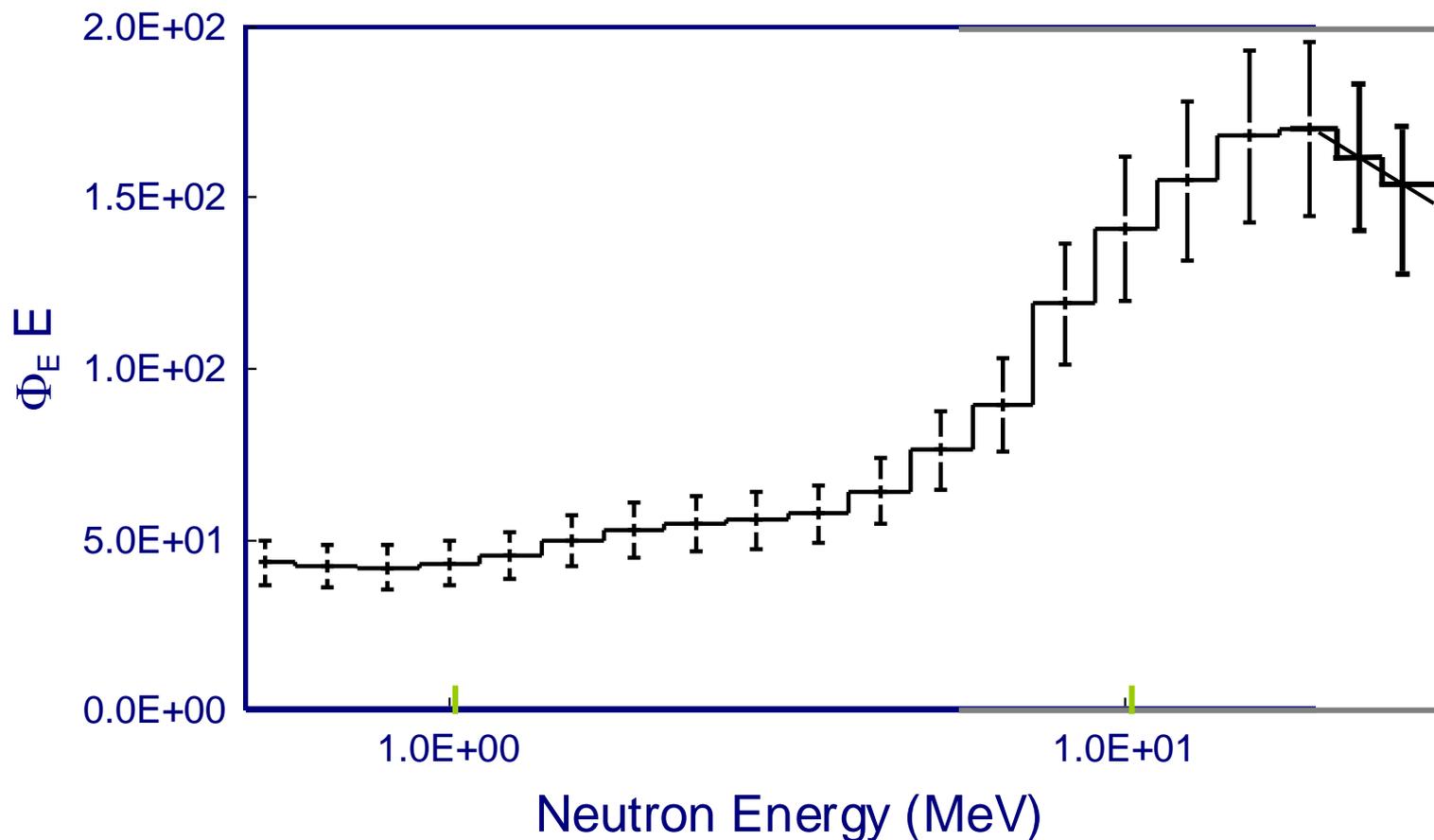
## Examples of neutron spectra



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

# 1. 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)

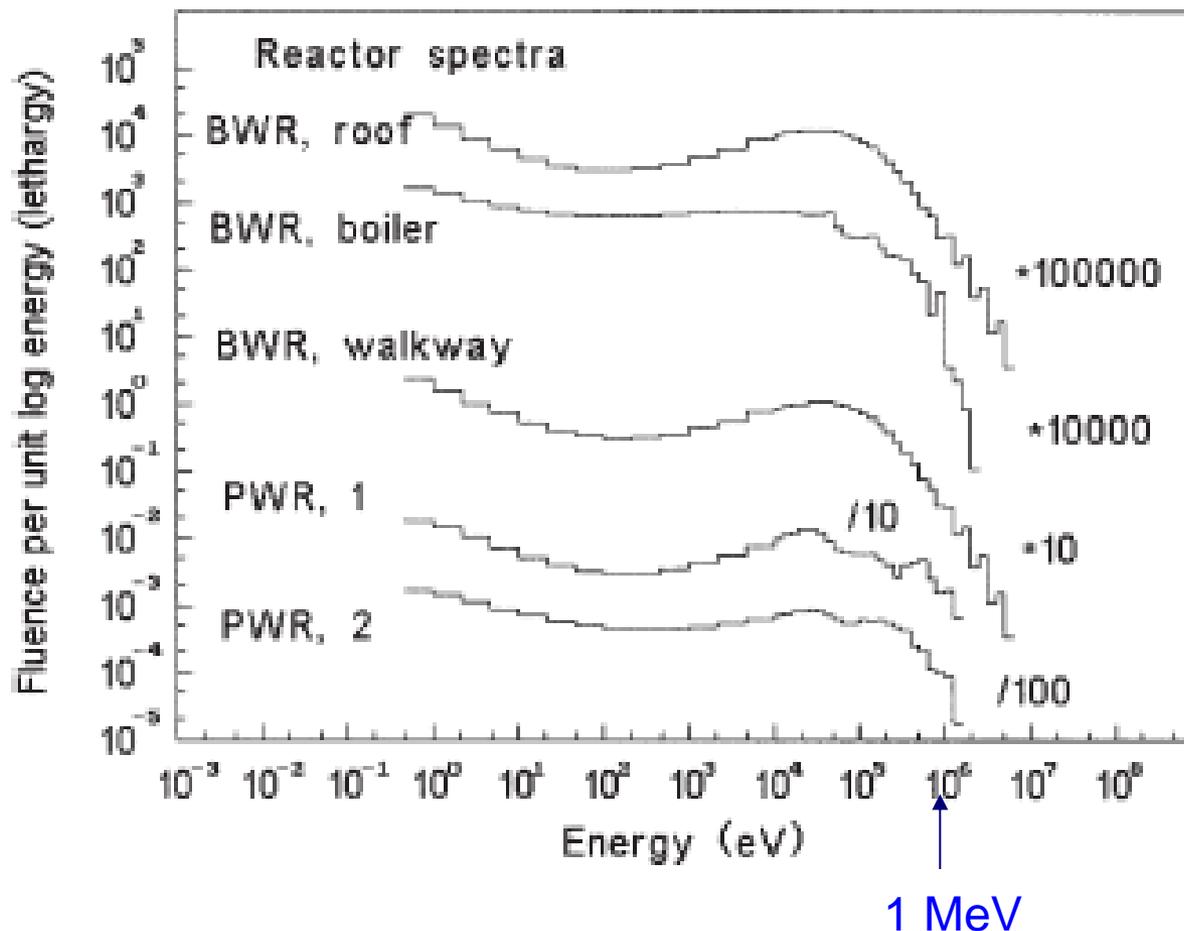
## 2. Proton accelerators

### 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

# 2. Proton accelerators

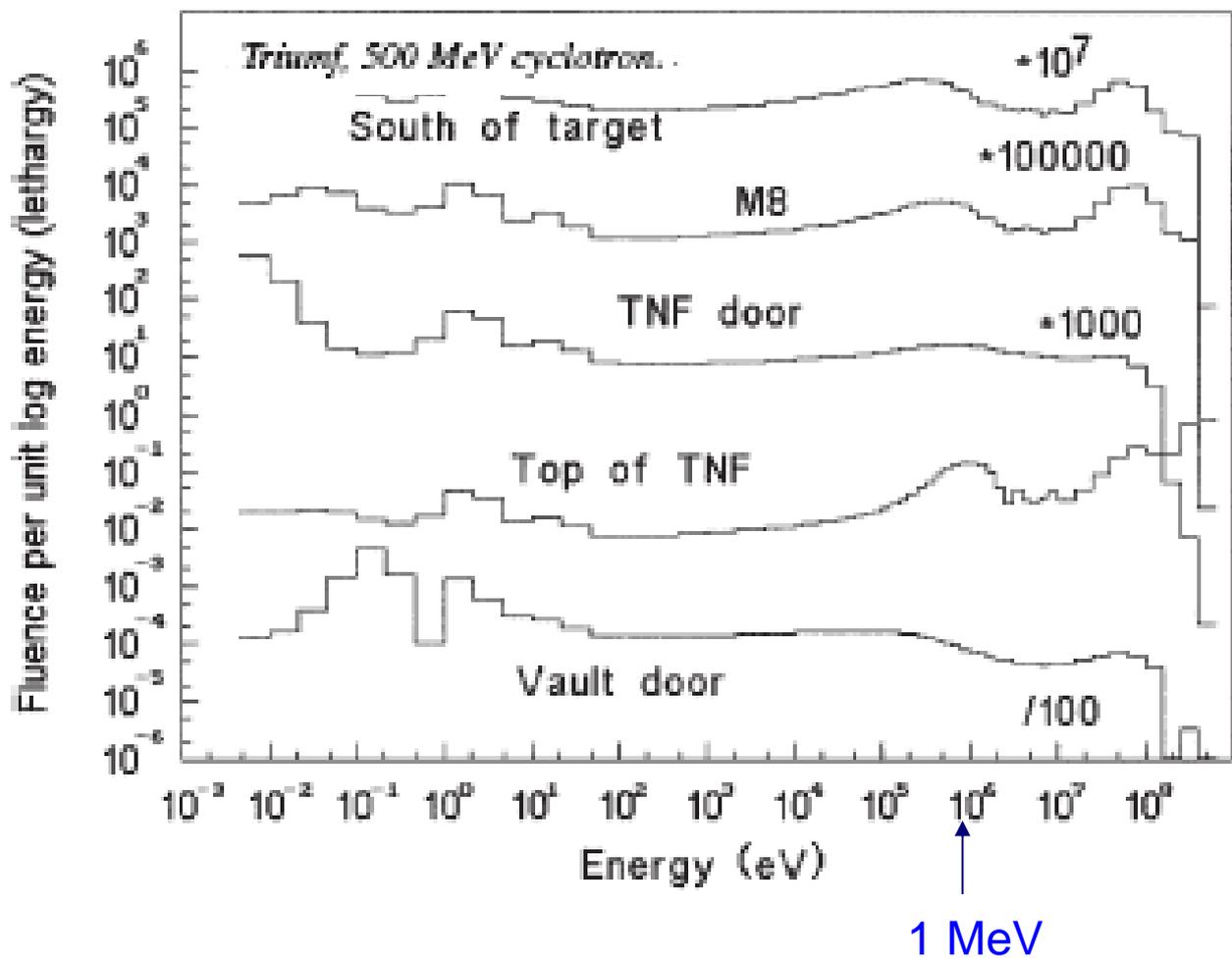
## Examples of neutron spectra



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

# 2. Proton accelerators

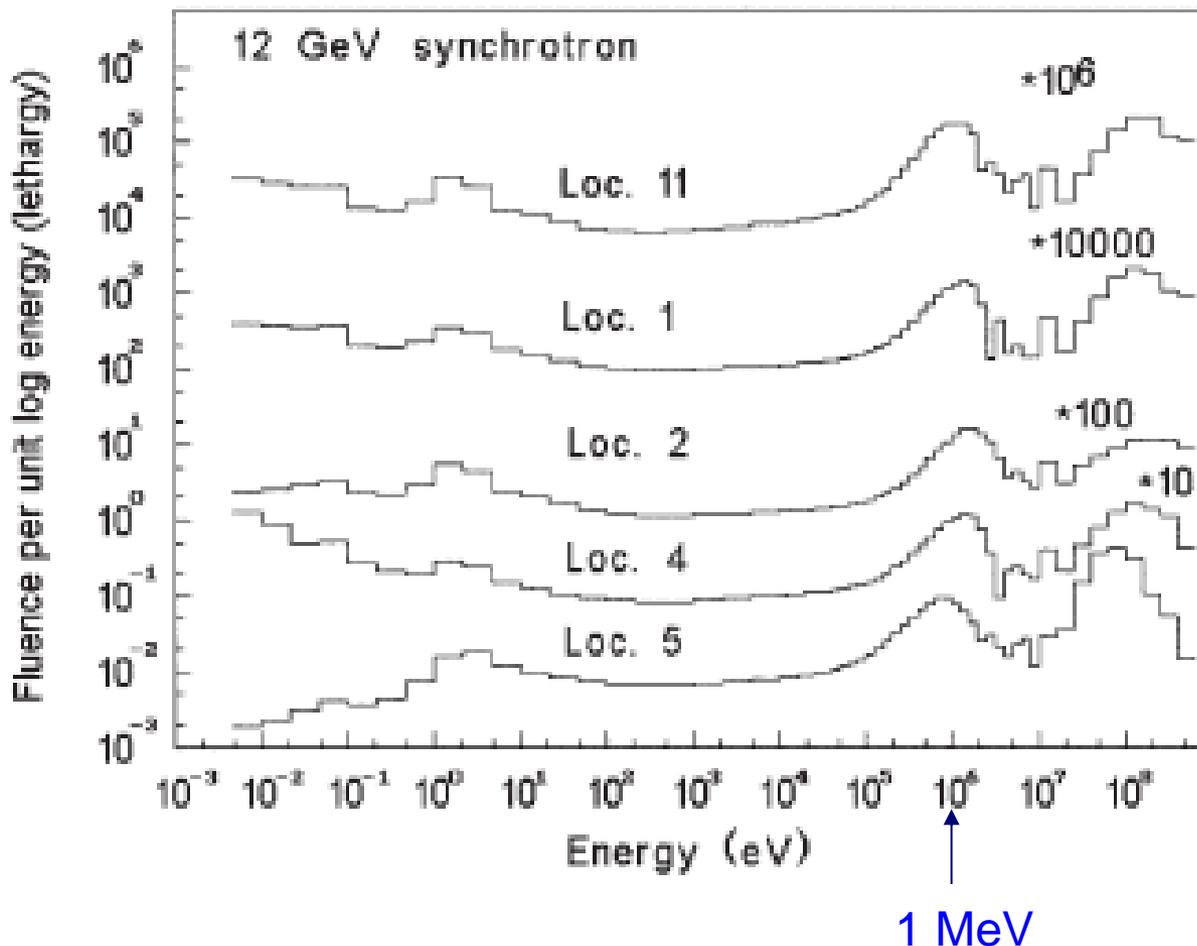
## Examples of neutron spectra



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

# 2. Proton accelerators

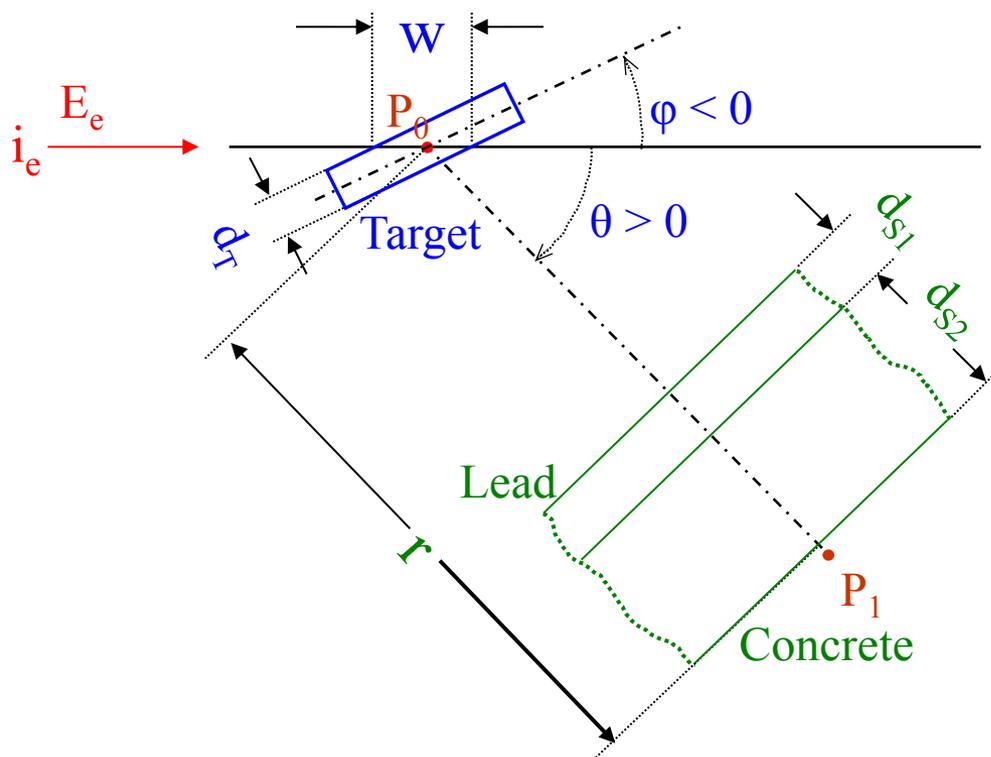
## Examples of neutron spectra



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

# 3. Synchrotron radiation facilities

## ➤ Shielding Scheme Drawing:



## ➤ In the ALBA case:

### Source (for the Storage Ring):

$i_e = 400 \text{ mA}$

$E_e = 3.0 \text{ GeV}$

### Target:

$d_T [cm]$ : depends on the machine point

$\varphi$ : depends on the machine point

$\rho_T [g/cm^3]$ : stain steel

### Shielding:

$r [cm]$ : depends on the machine point

$\rho_{S1} [g/cm^3]$ : lead

$d_{S1} = 5 \text{ cm}$

$\rho_{S2} [g/cm^3]$ : concrete (normal & heavy)

$d_{S2} = 1 \text{ m (side) \& 1.5 m (front) \& 1.4 m (roof)}$

$\Theta$ : depends on machine point

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

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

Analytical models:

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

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

$W$ : primary beam loss rate, in kW

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

$d$ : shield wall thickness, in  $\text{g} \times \text{cm}^{-2}$

$\lambda_i$ : attenuation length for the  $i^{\text{th}}$  radiation component, in  $\text{g} \times \text{cm}^{-2}$

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

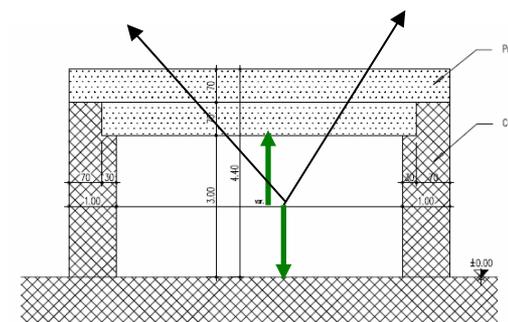
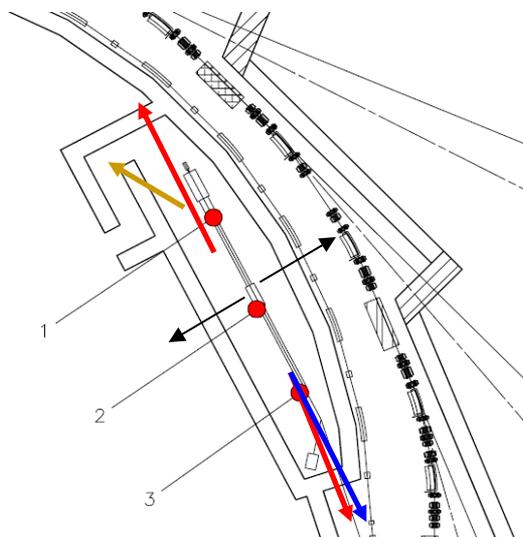
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$i$ : sum over different radiation components

# 3. Synchrotron radiation facilities

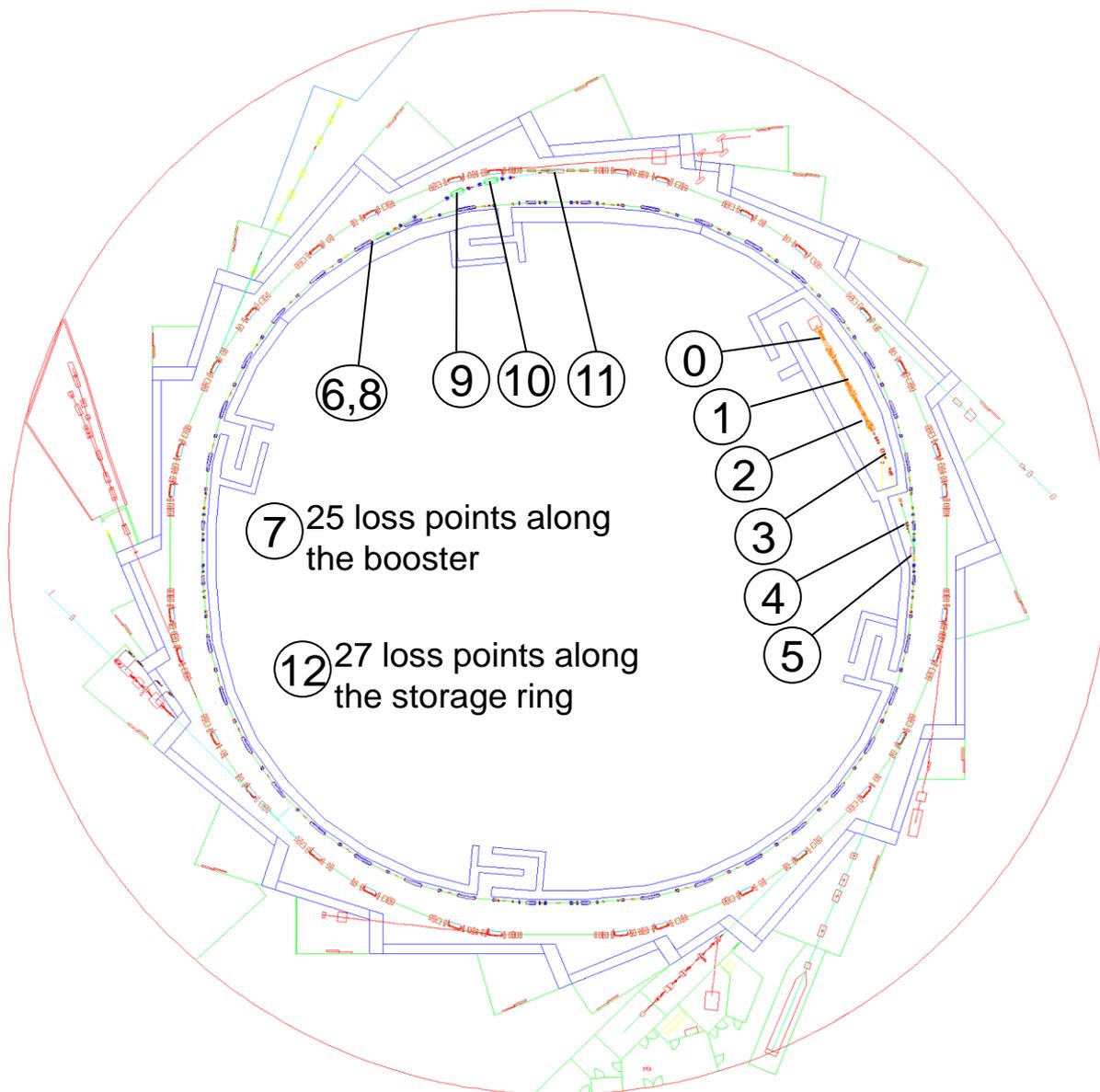
➤ The Ott's code allows to compute the effective annual dose  $D$ , at the following directions:

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



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

# 3. Synchrotron radiation 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

# 3. Synchrotron radiation 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	<b>20%</b>	1.35E+10	6.76E+10	3.38E+10	0,1 to 3
6 Extraction Septum	<b>15%</b>	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	<b>15%</b>	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	<b>40%</b>	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

# 3. Synchrotron radiation 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
<b>Booster operation / year</b>	<b>250 hours</b>
Min. injection time/ injection	169 seconds
Min. injection time/ year	59 hours
Max. injection time/ injection	507 seconds
<b>Max. injection time/ year</b>	<b>176 hours</b>

## Machine Test mode

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

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

# 3. Synchrotron radiation 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:

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

$\vec{s}$  : accelerator point

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

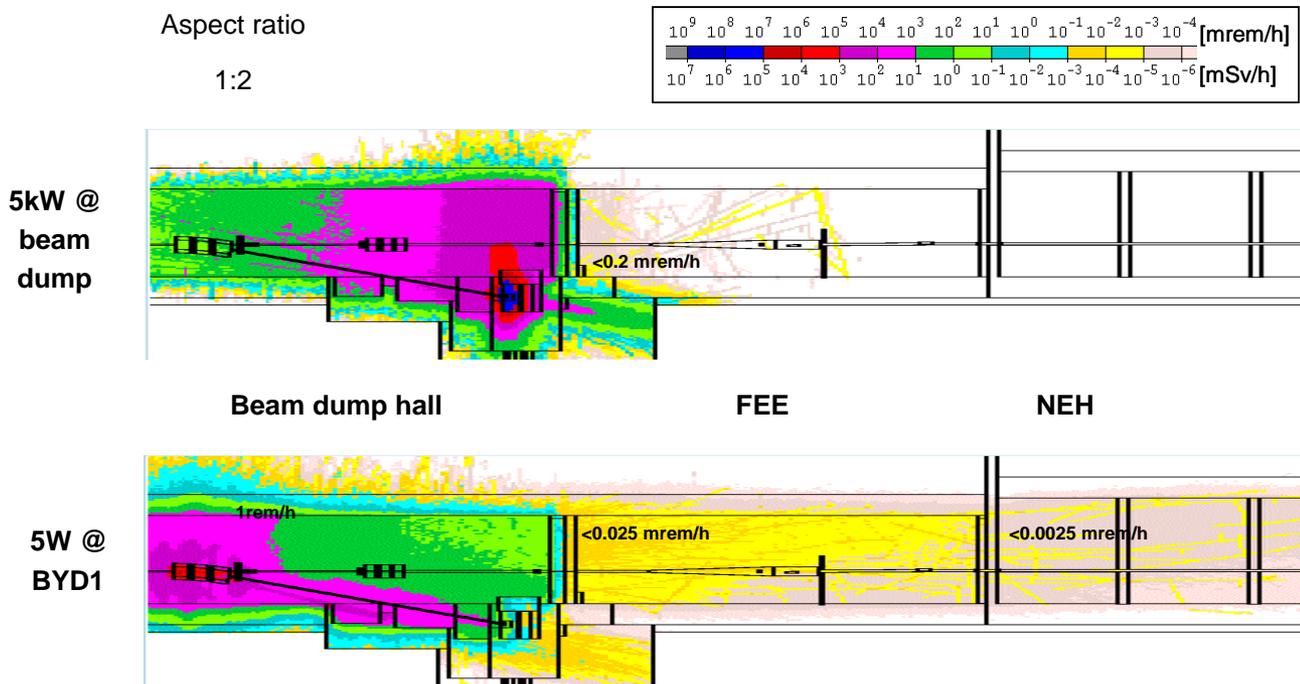
$t(s) = t_{\text{User}}(s) + t_{\text{Machine}}(s)$  : is the time that the e-loss occurs (at s-point)

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

# 3. Synchrotron radiation facilities

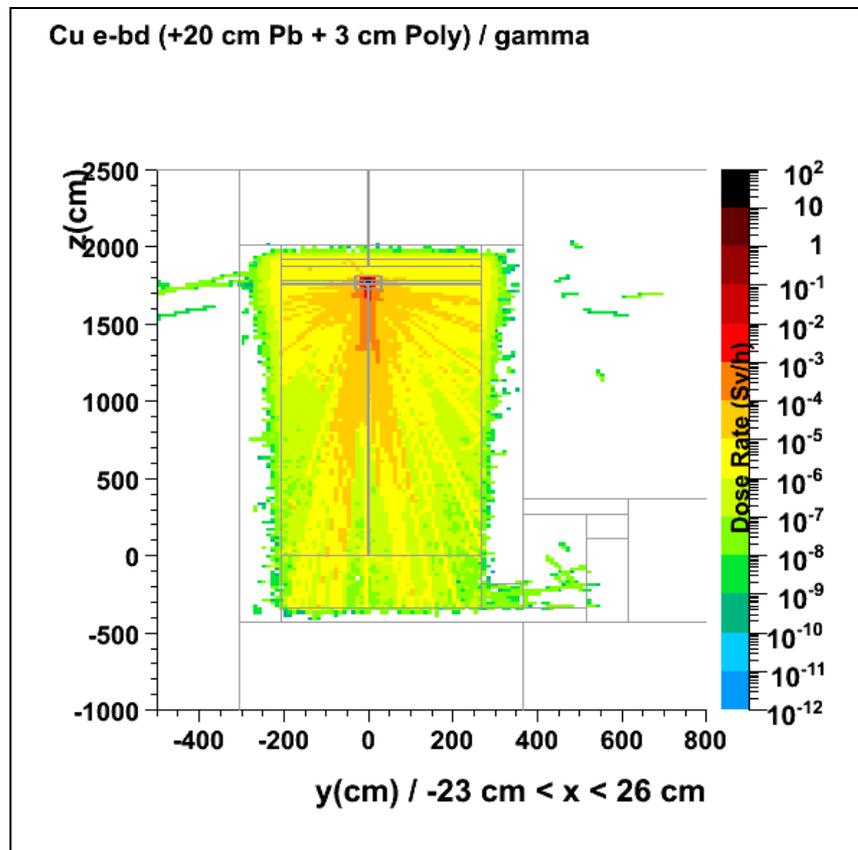
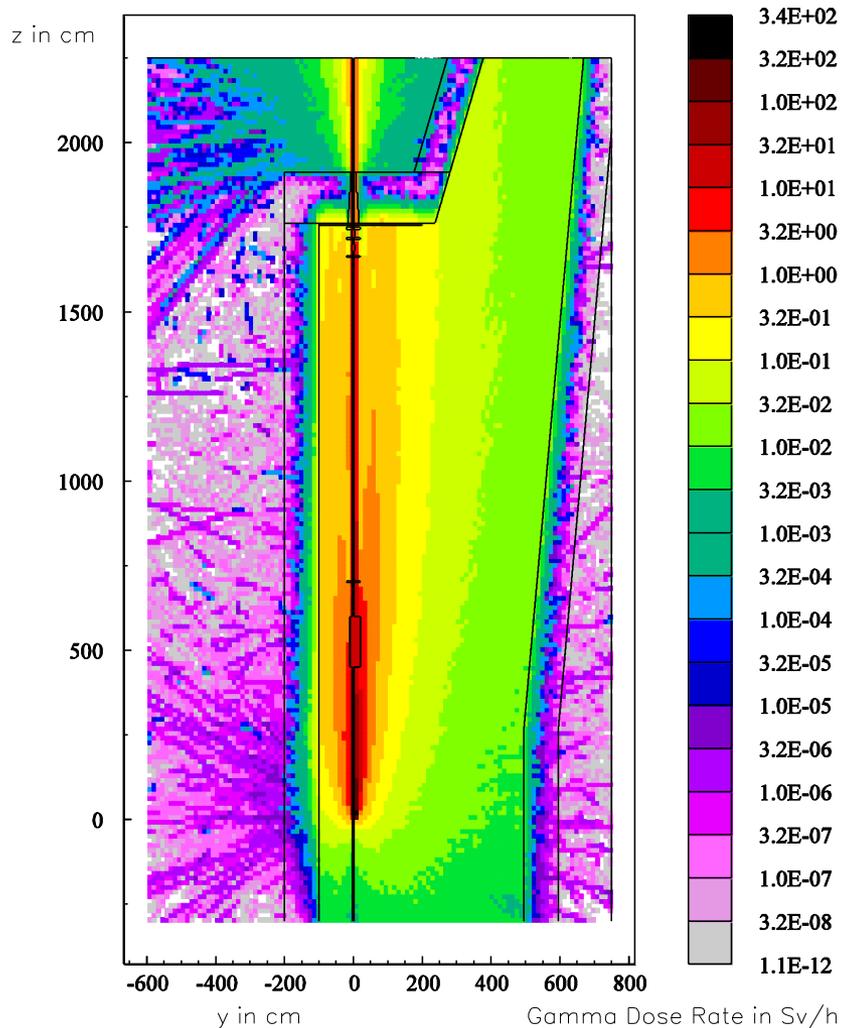
Monte-Carlo codes

- Examples: MCNPX  
 PENELOPE  
 FLUKA  
 MARS



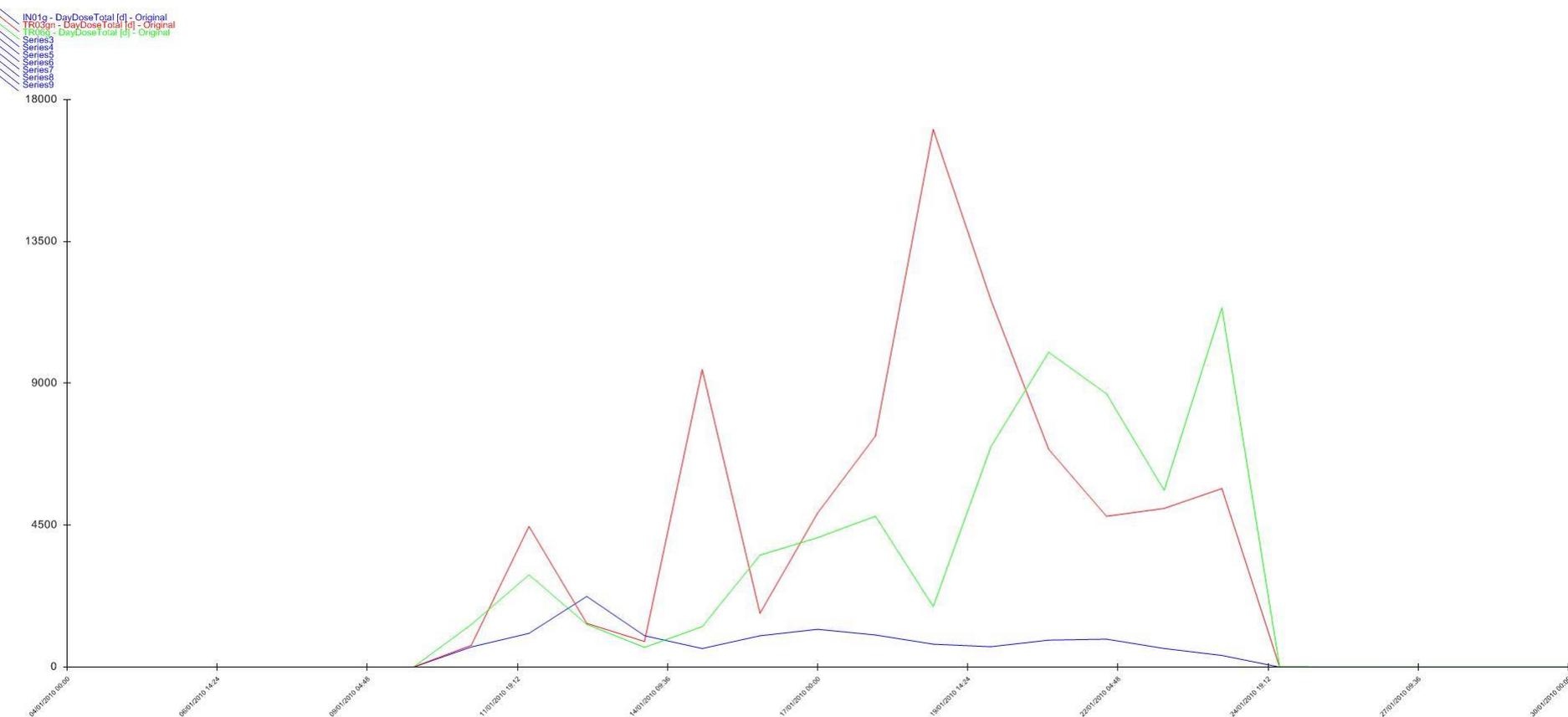
Example: MARS calculation for the electron dump line of the LCLS facility - Courtesy of T. Sanami.

## ➤ FLUKA simulations



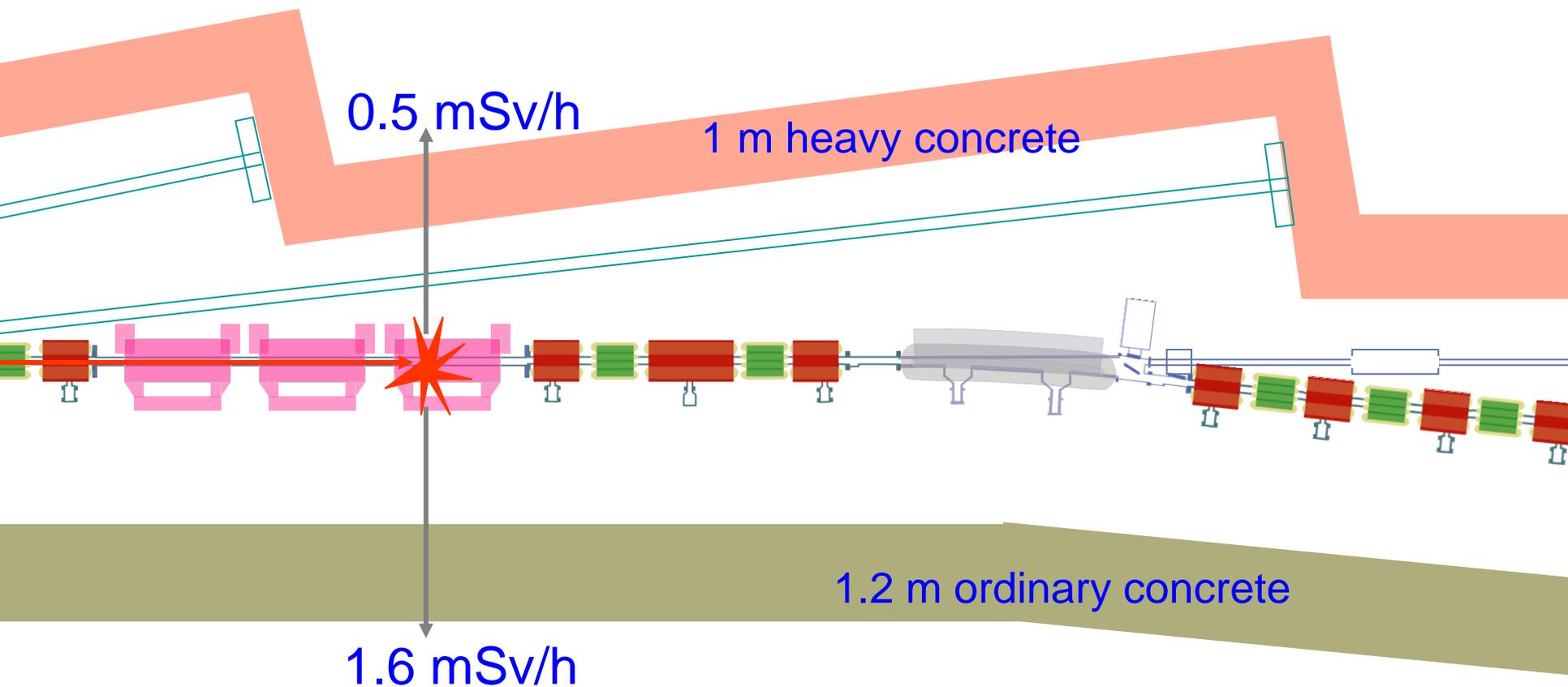
# 3. Synchrotron radiation facilities

## January 2010 daily dose (total) inside the Tunnel



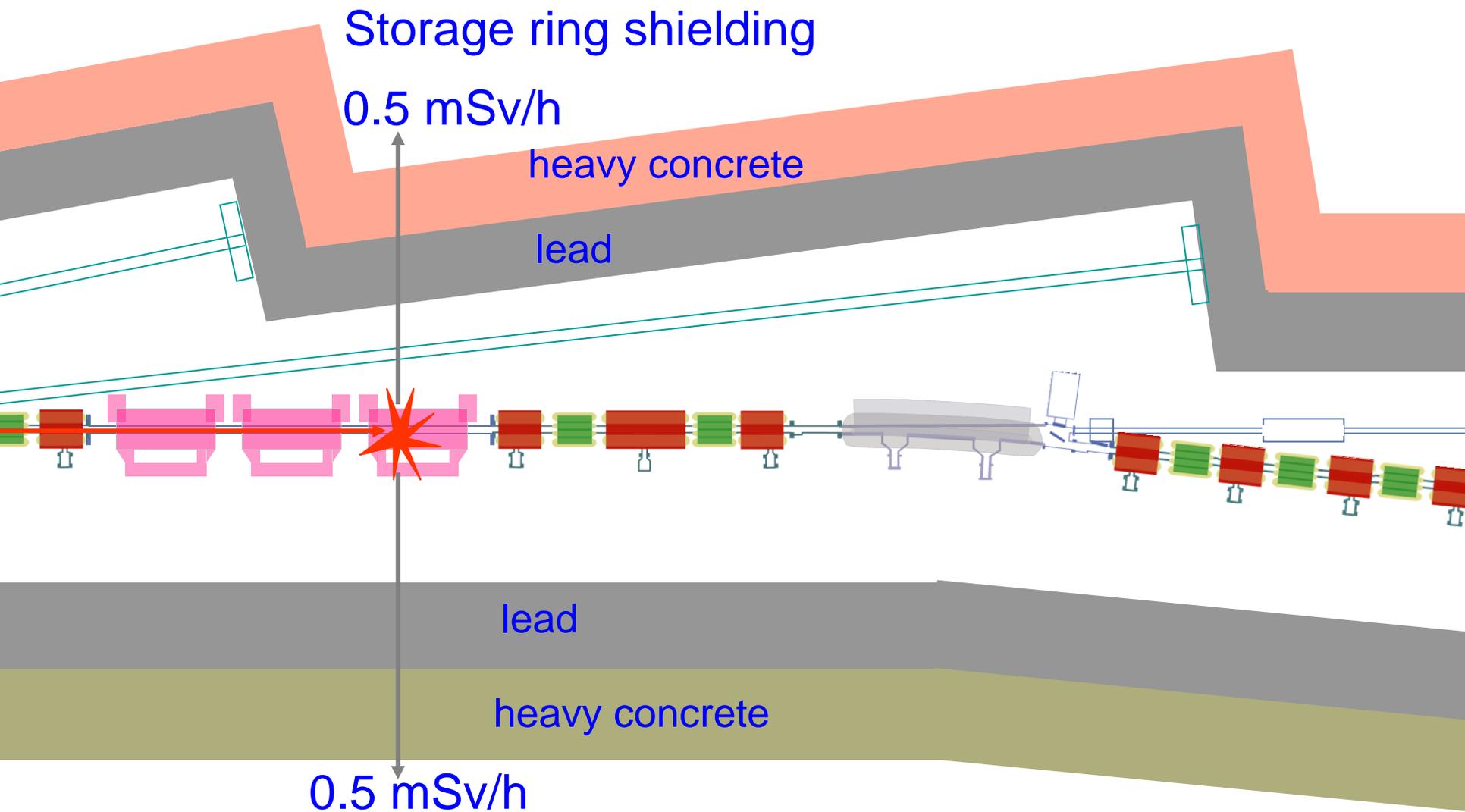
# 3. Synchrotron radiation facilities

## Storage ring shielding



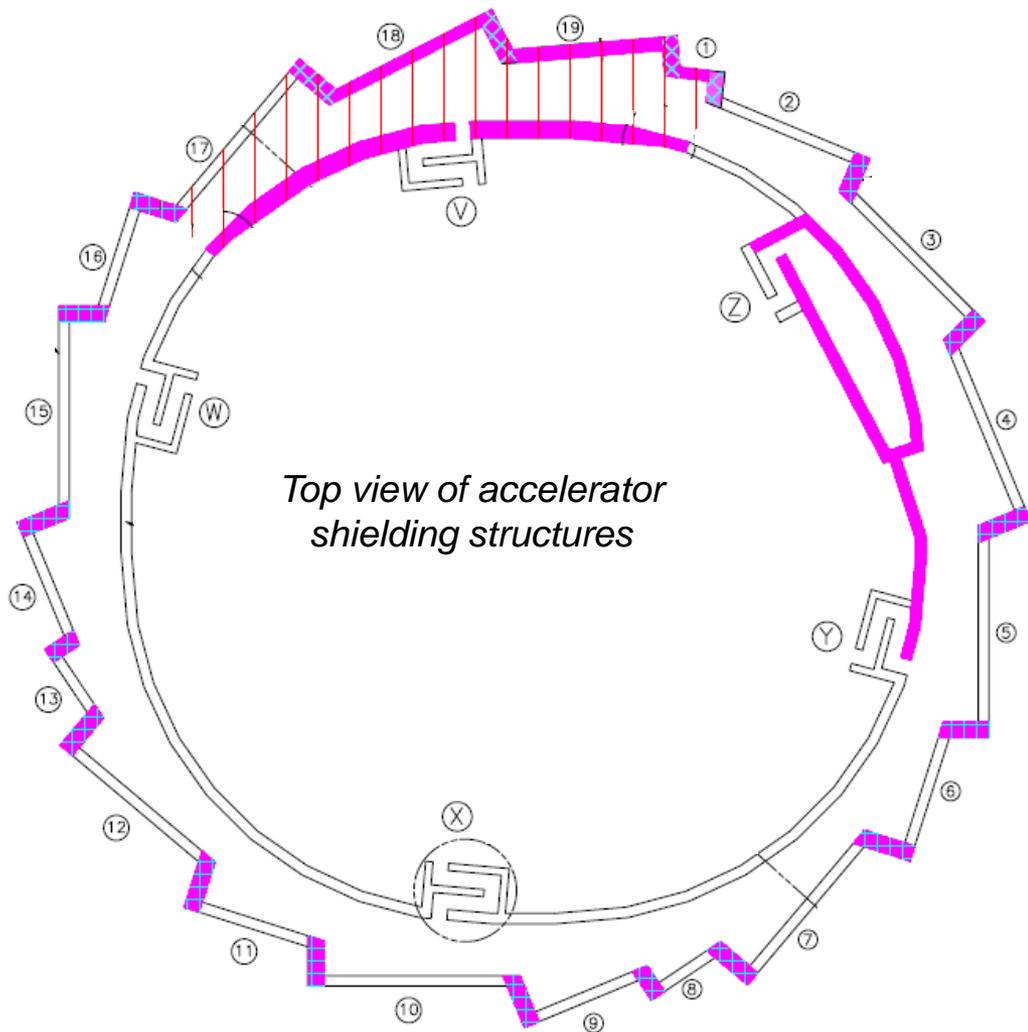
Example: ESRF 6 GeV storage ring, continuous beam loss during injection:  
10 mA, 1 ms, 1 Hz, 6 GeV

# 3. Synchrotron radiation facilities

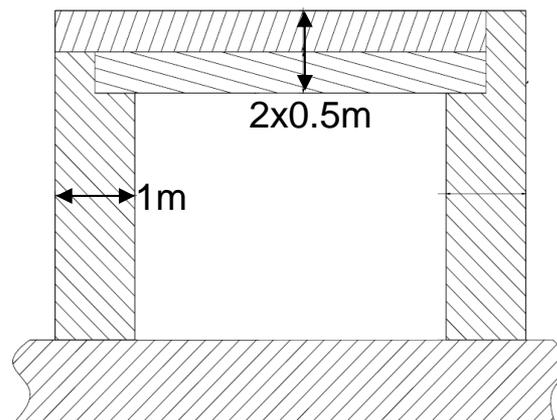


Example: ESRF 6 GeV storage ring, continuous beam loss during injection:  
10 mA, 1 ms, 1 Hz, 6 GeV

## ➤ Concrete structures:

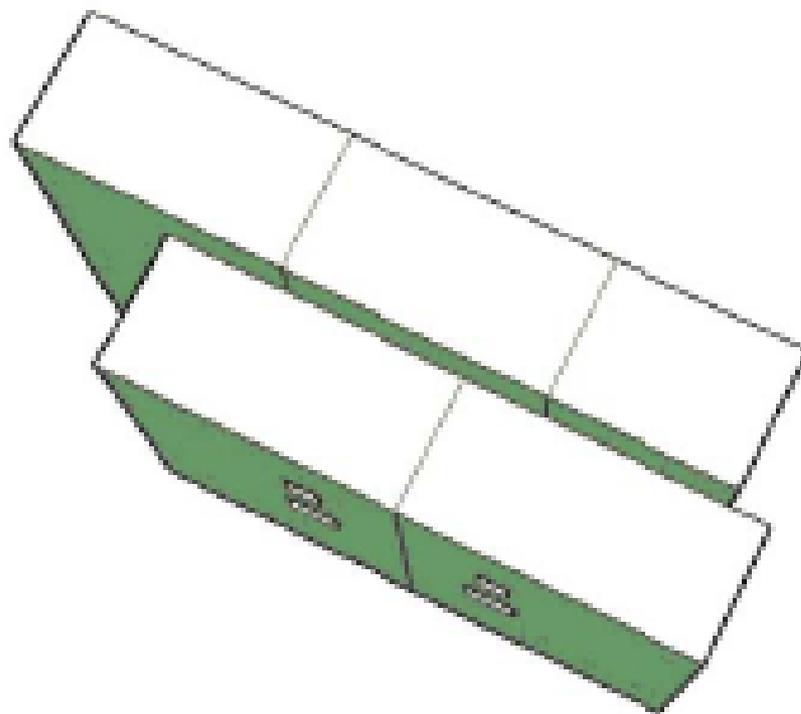
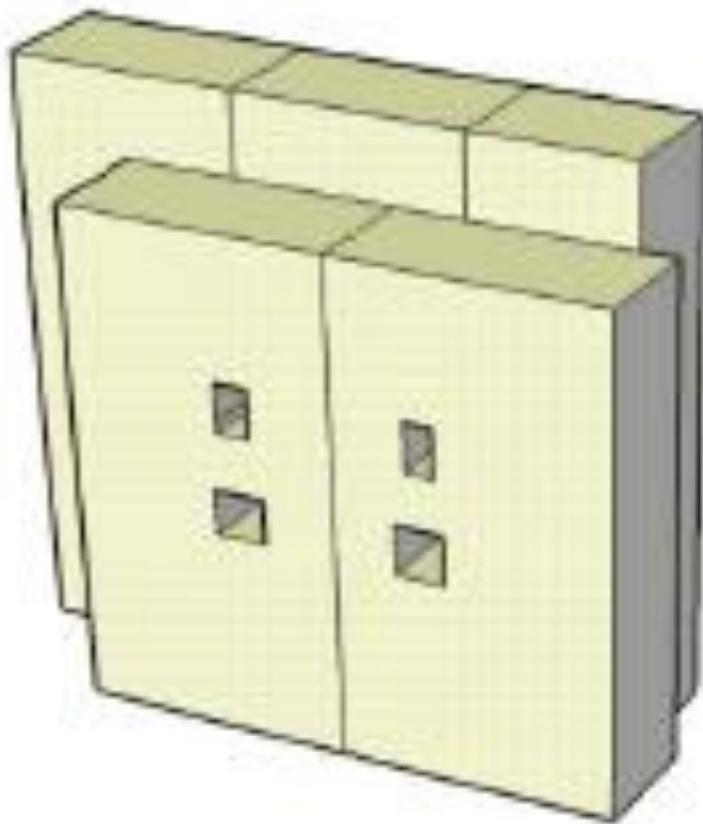


Inner and side walls thickness	1 m
Inner wall thickness at injection	1.65 m
Side wall thickness at injection	1.25 m
Roof thickness	1 m
Roof thickness at injection	1.4 m
Linac walls thickness	1 m
Labyrinths walls thickness	0.7 m
Front walls thickness	1.5 m
Number of side/front walls	19
Concrete density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



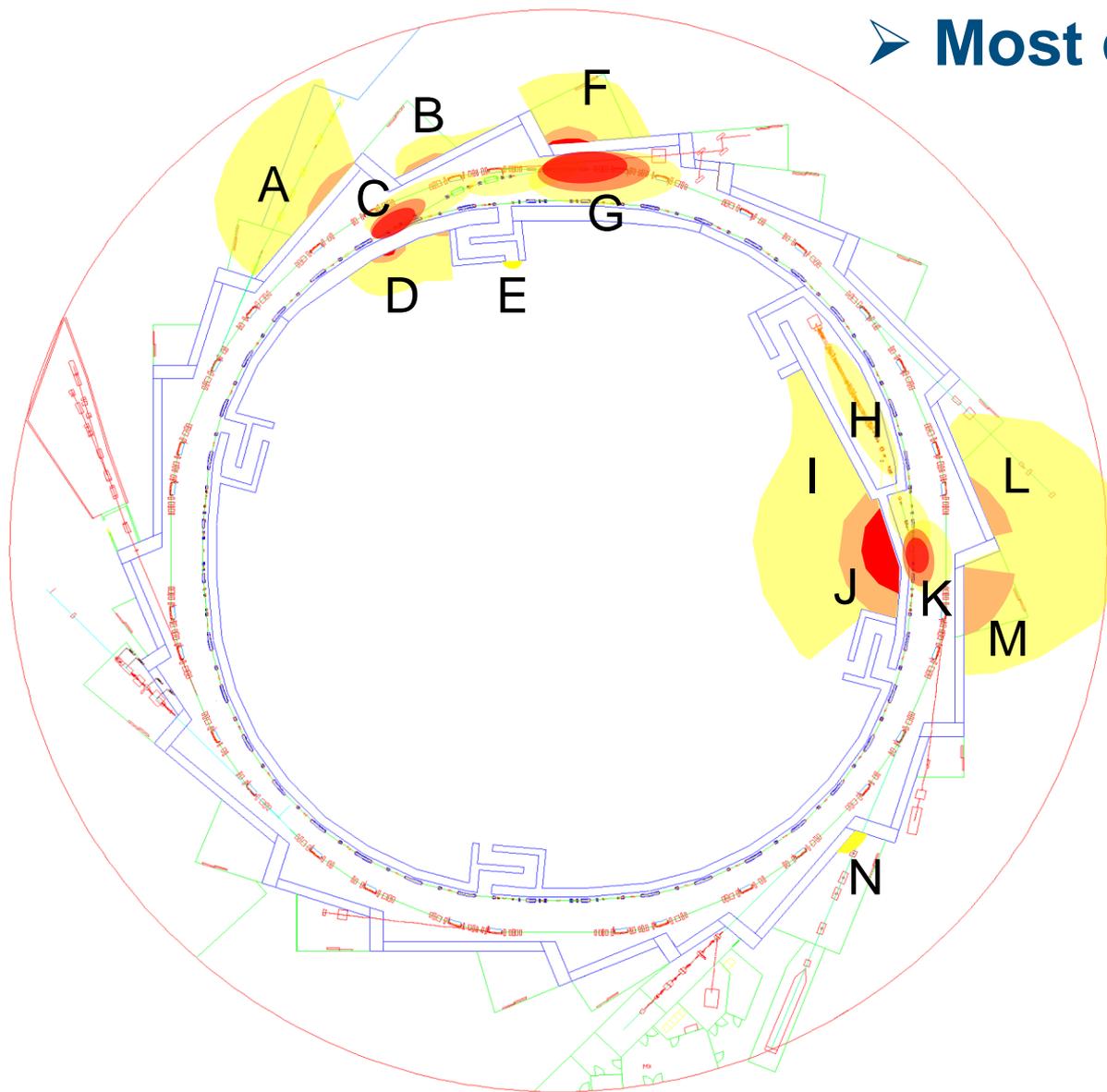
Tunnel section

## ➤ Front wall: final option



# 3. Synchrotron radiation facilities

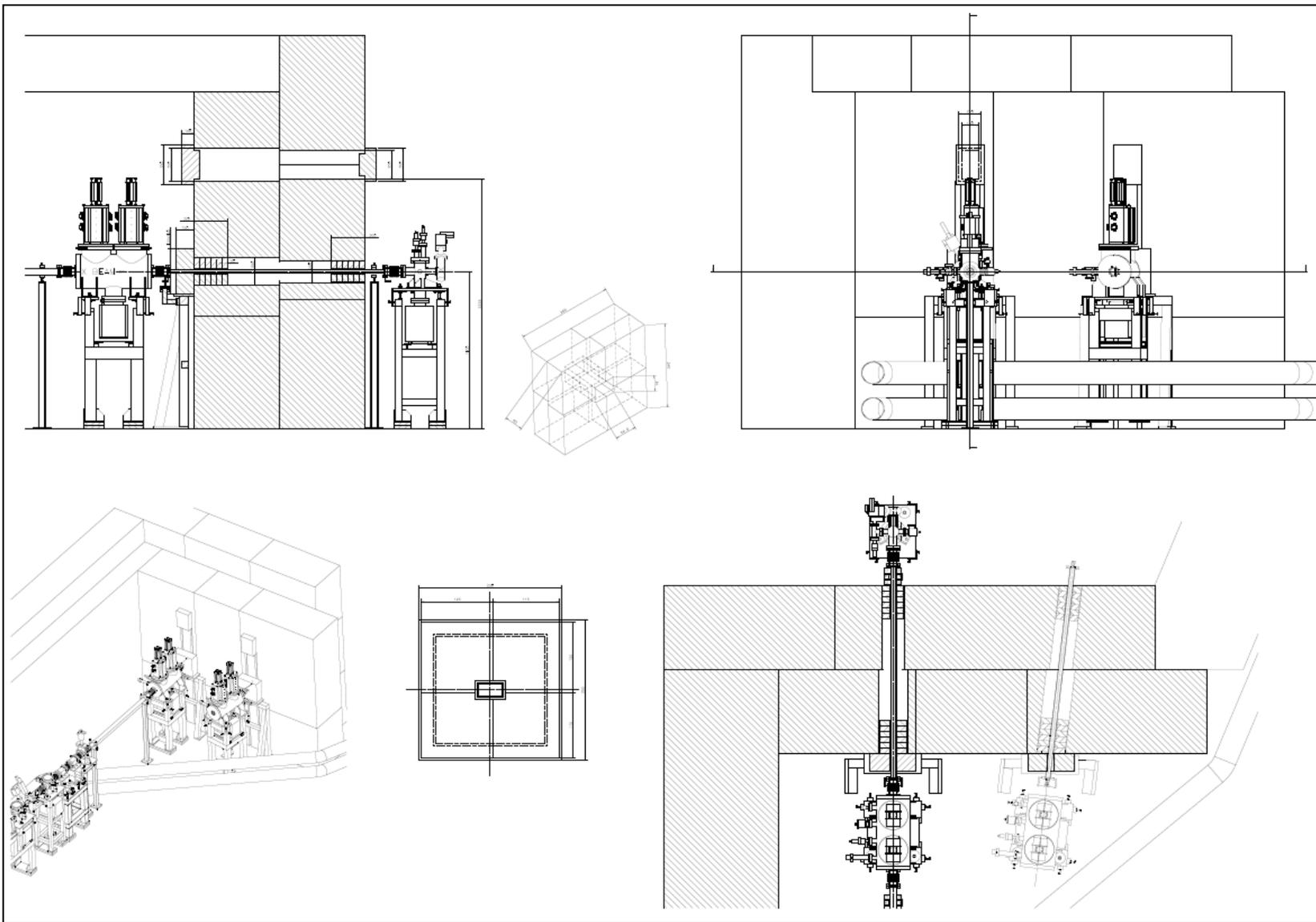
➤ **Most critical areas**



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

# 3. Synchrotron radiation facilities

## ➤ Front wall: a possible filling solution



## 3. EL SINCROTRÓ ALBA: LES LÍNIES EXPERIMENTALS

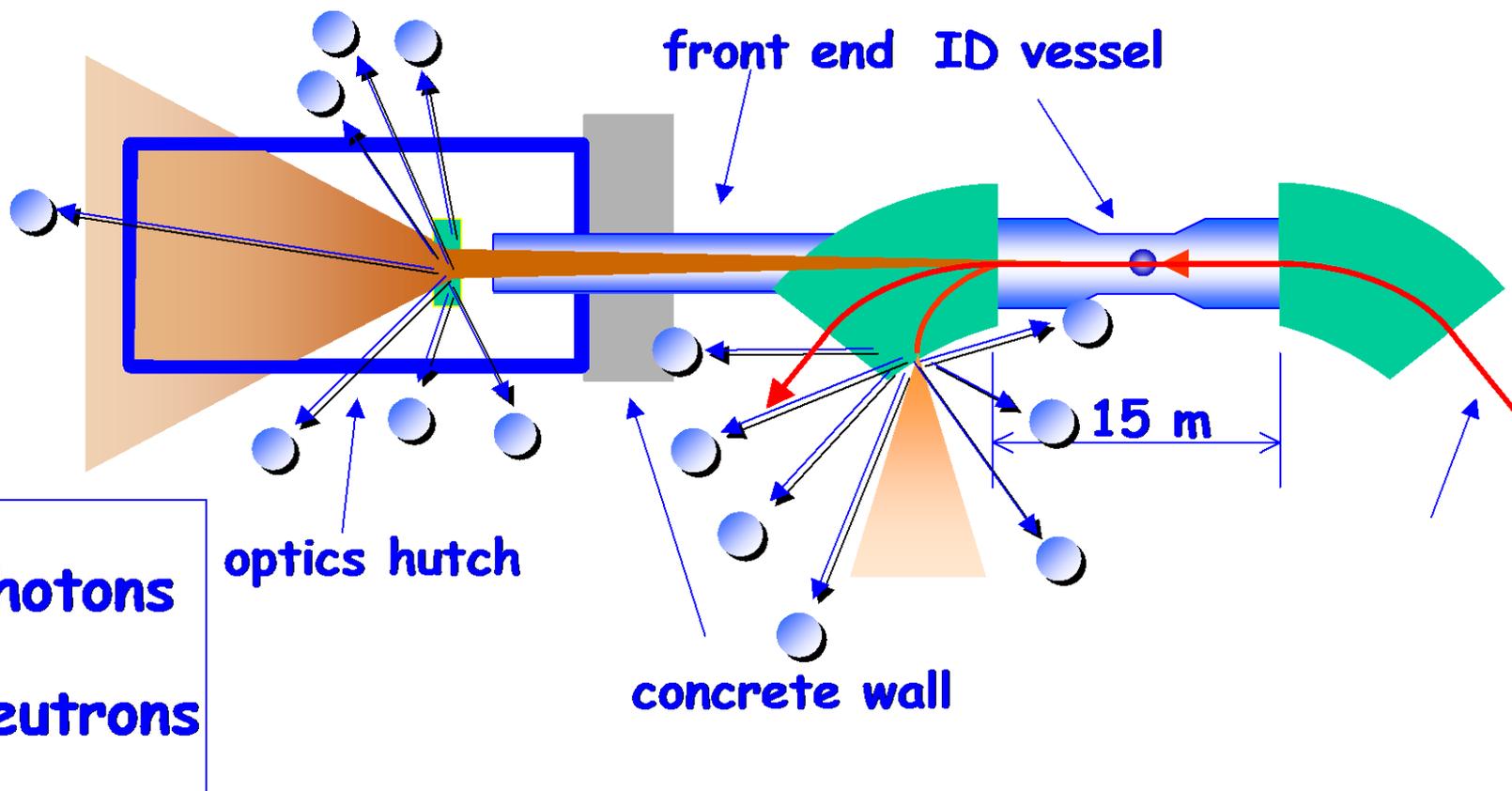


# 3. Synchrotron radiation facilities

Radiation fields

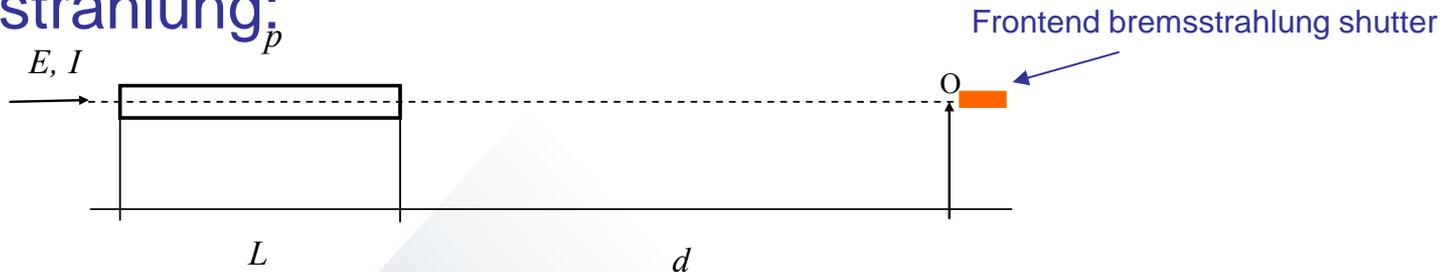
Accelerator tunnels:  
photons, neutrons

Beamlines:  
X-rays, photons, neutrons



## 2. BEAMLINES SHIELDING - SOURCE TERM

➤ Gas bremsstrahlung:



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

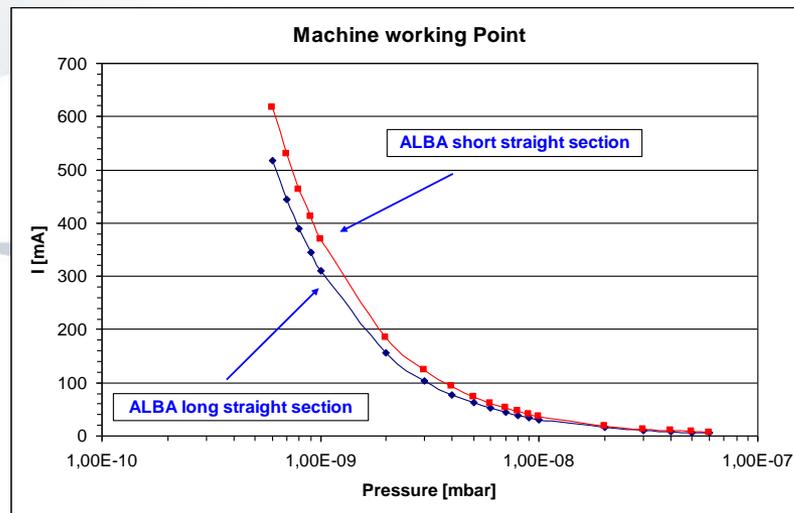
$\dot{D}_0$ : is the dose rate at O-point (Energy/Mass/Time)

✓ If:

- L = 4 m ; d = 18 m
- I = 400 mA
- P = 1.4 · 10<sup>-9</sup> mbar

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

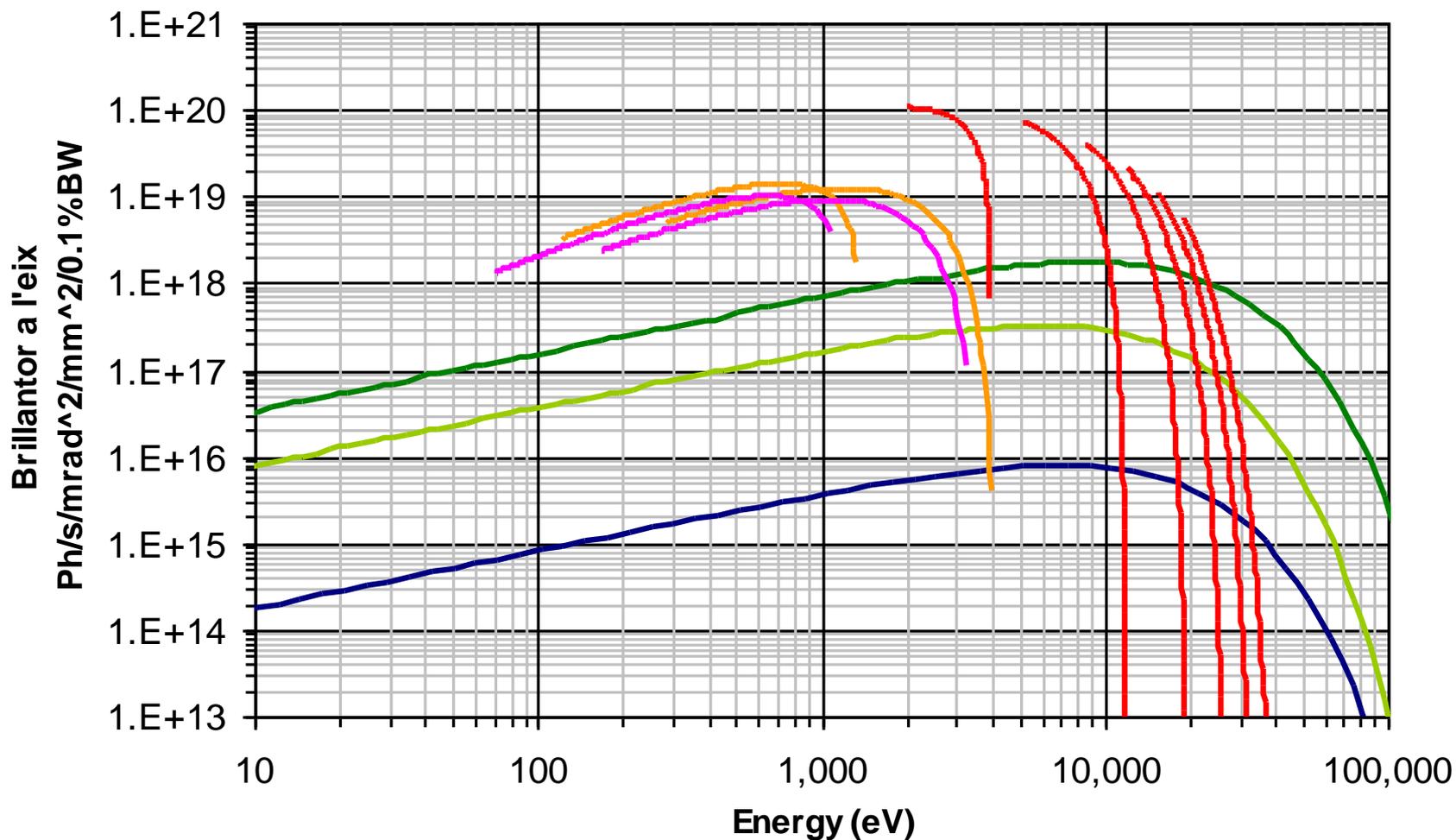
$$\frac{\dot{D}_0 \Big|_{3\text{GeV}}}{\dot{D}_0 \Big|_{2\text{GeV}}} = \frac{3^{2.67}}{2^{2.67}} \approx 3$$



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

# 3. Synchrotron radiation facilities

— Bend — SC-W31 — MPW-80 — IVU-21 — EU-62 — EU-71



# 3. Synchrotron radiation facilities

## ❖ Source term

✓ Internal rules:

1 mSv / year



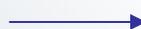
0.5 μSv / h

(2000 hour / year)



✓ Order of the radiation source term

1 Sv / h



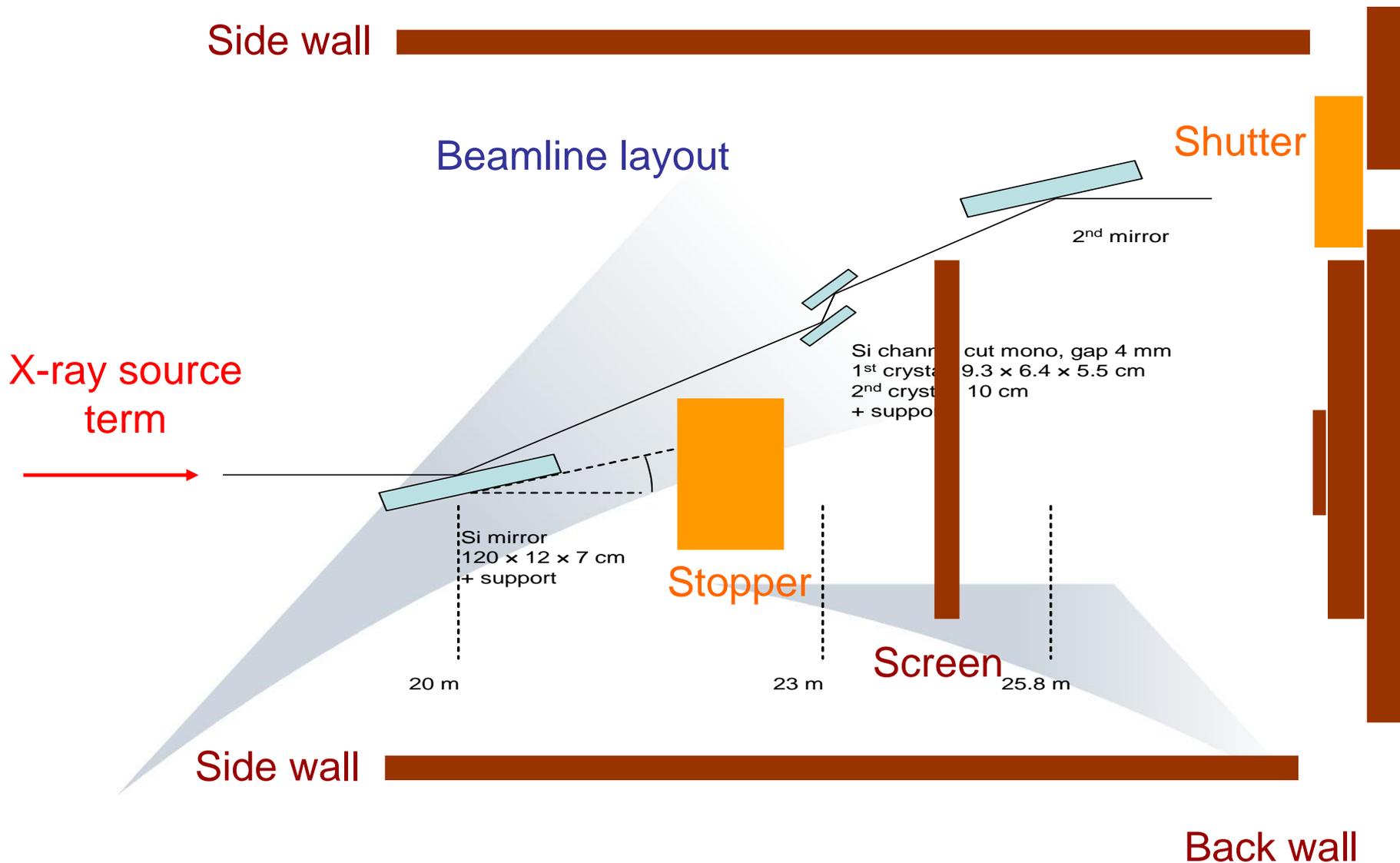
> 10<sup>6</sup> times reduction



✓ Shielding elements required:

- Hutch walls
- Stopper & Shutter

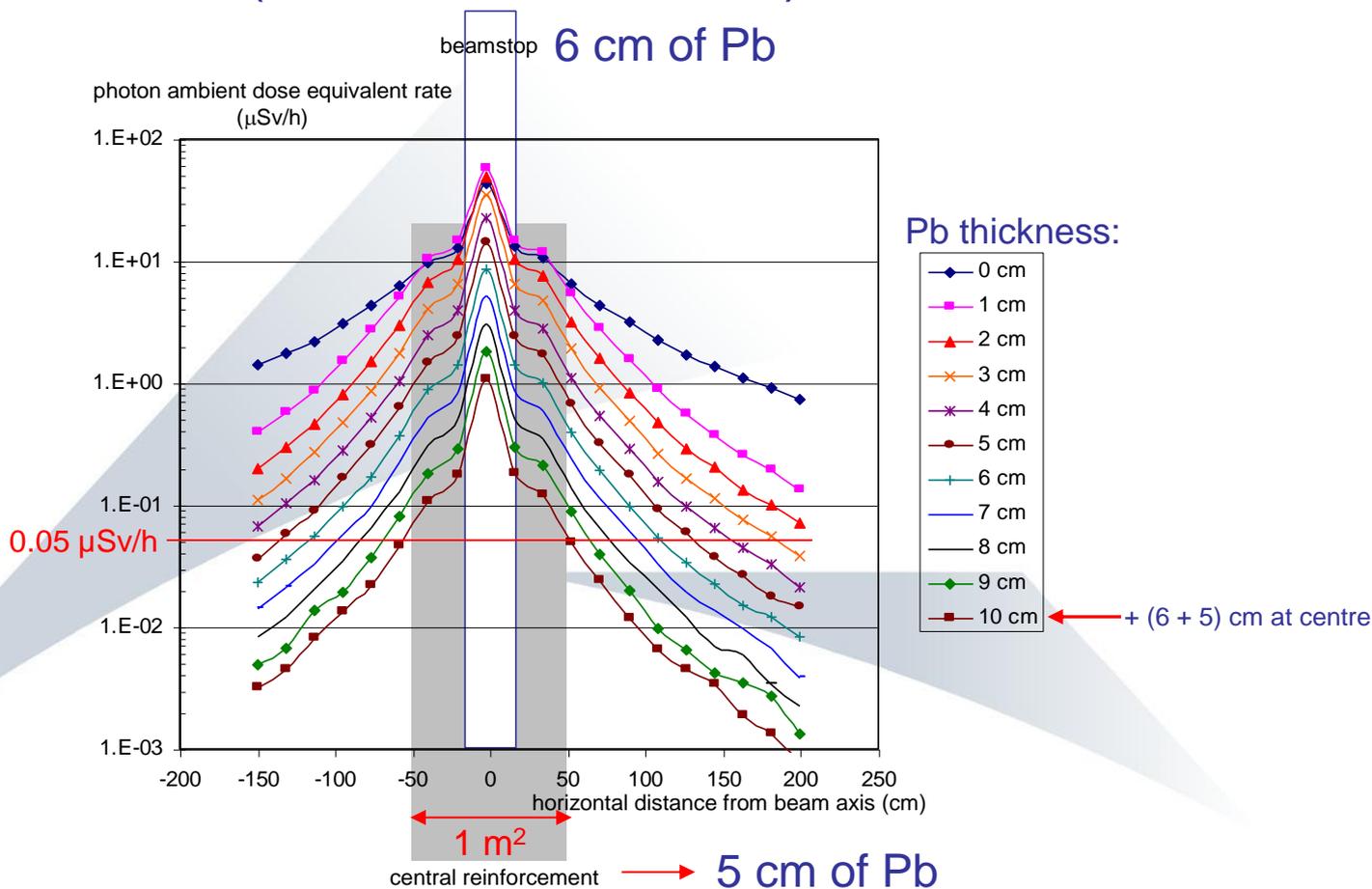
## 2. BEAMLINES SHIELDING - SAFETY ELEMENTS



## 2. BEAMLINES SHIELDING - SAFETY ELEMENTS

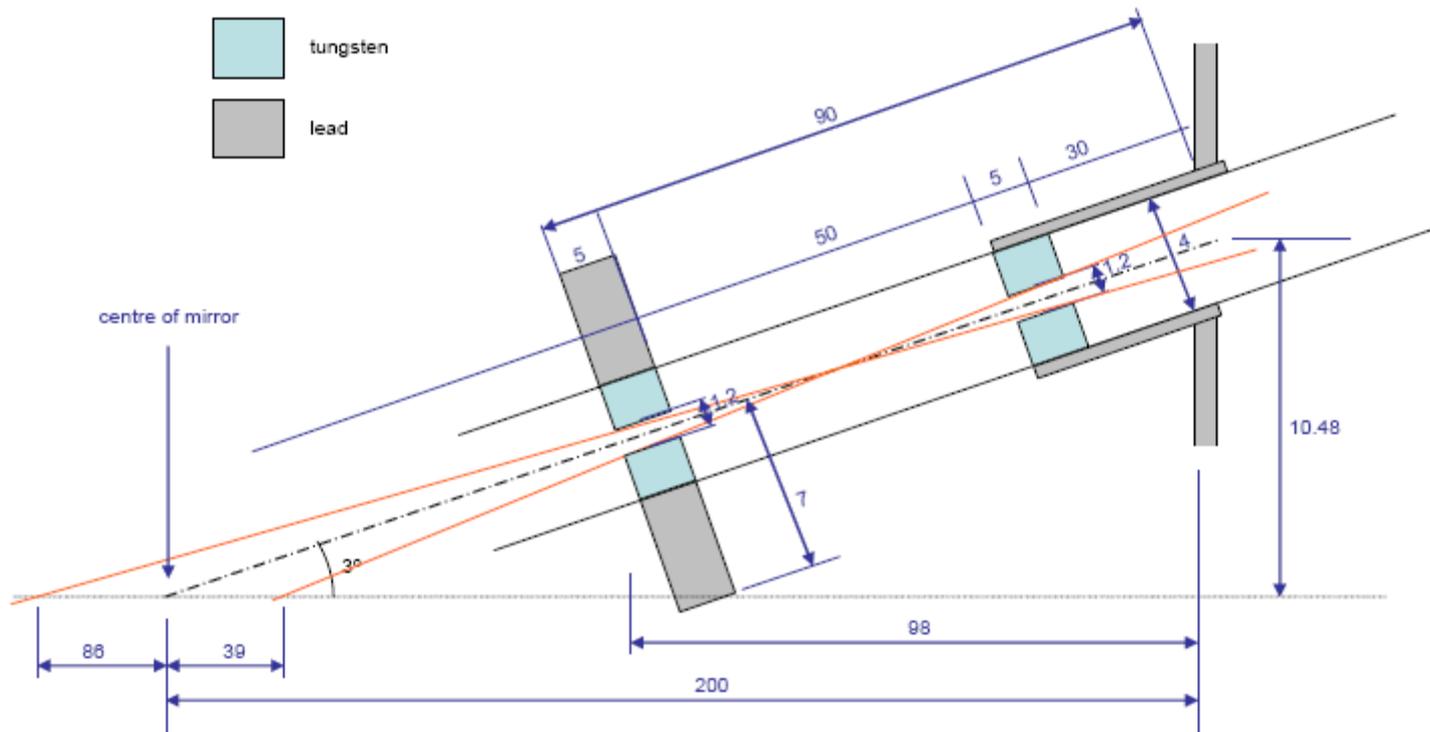
❖ Shielding against gas bremsstrahlung

➤ Backwall thickness (for the HRPD case):



## 2. BEAMLINES SHIELDING - SAFETY ELEMENTS

❖ CIRCE beamline: Bremsstrahlung collimator

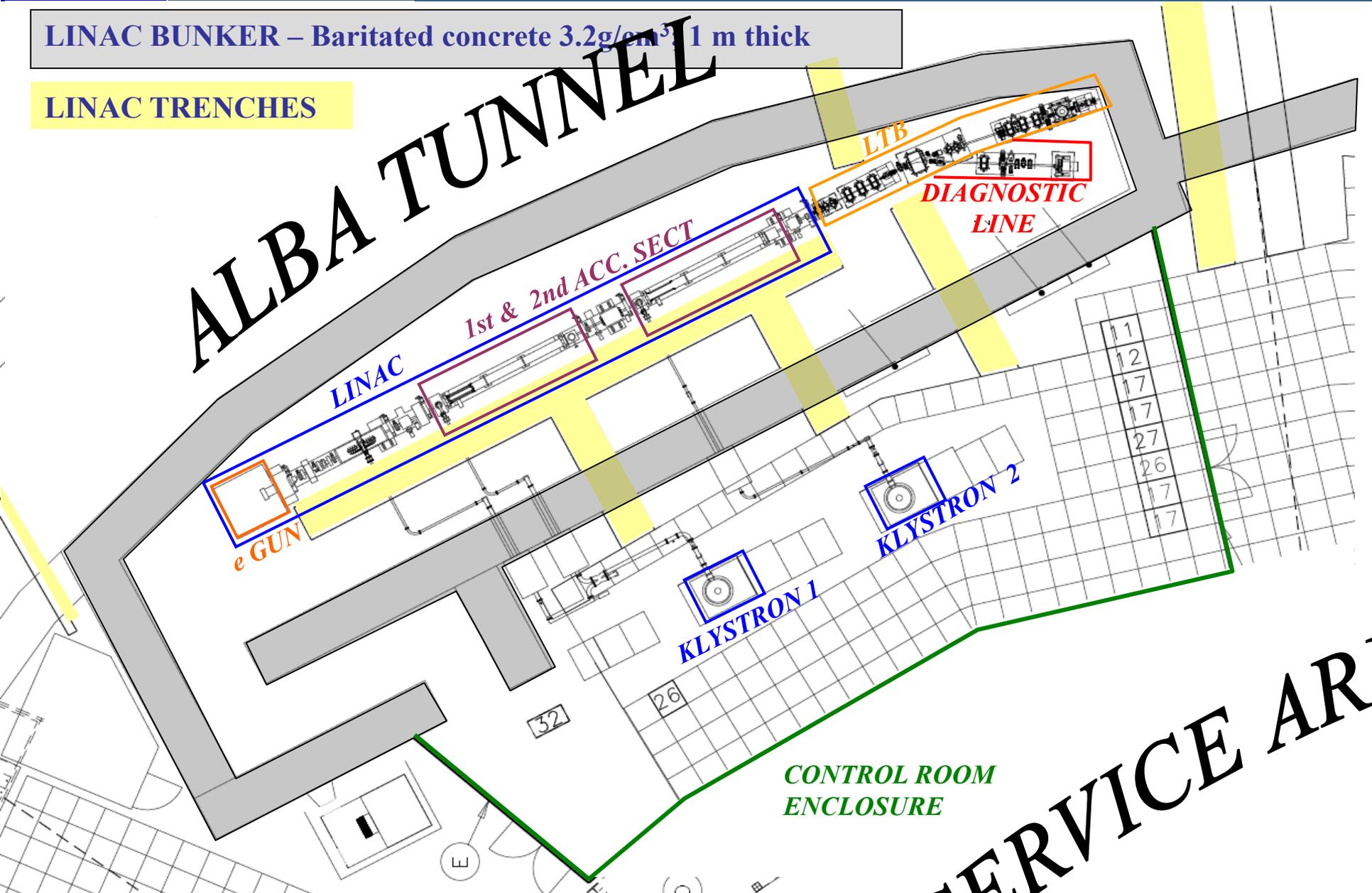


# 4a. Beam dumper

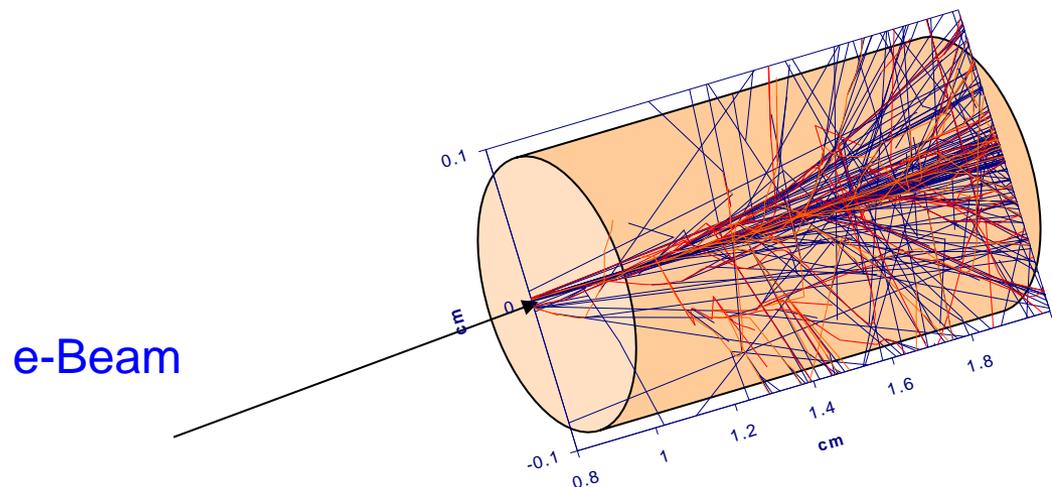
LINAC BUNKER – Baritated concrete  $3.2\text{g/cm}^3$ , 1 m thick

LINAC TRENCHES

# ALBA TUNNEL



## 4a. Beam dumper

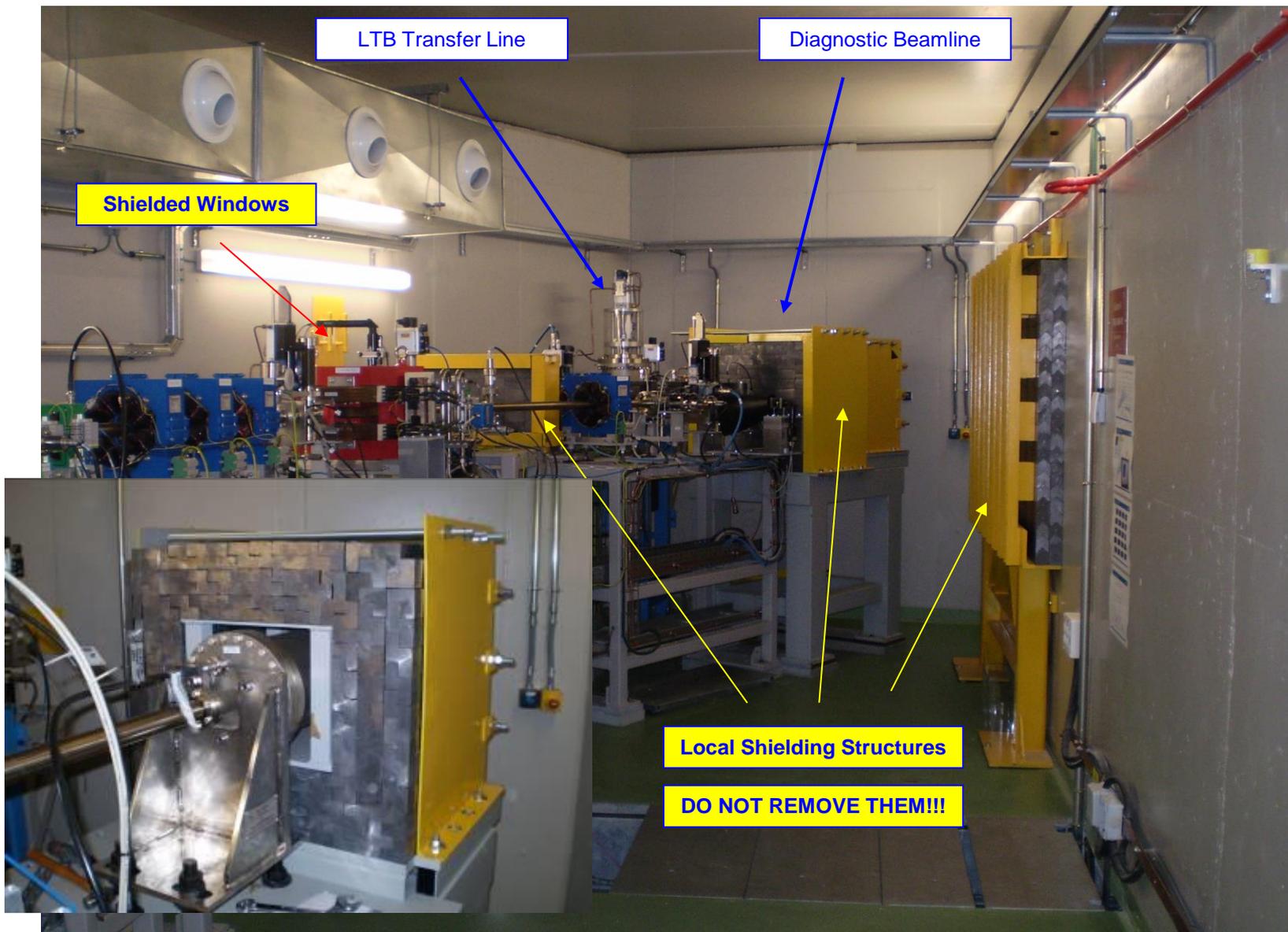


Molière radius ( $\rho_M$ ): it is the radius of a cylinder containing on average 90% of the shower's energy deposition.

$$\rho_M = E_s \frac{X_0}{E_c} \quad E_s = m_e c^2 \sqrt{4\pi/\alpha}$$

$$X_0 \propto A/Z^2, \quad E_c \propto 1/Z \quad \Rightarrow \quad \rho_M \propto A/Z$$

# 4a. Beam dumper



# 4b. Induced Activity

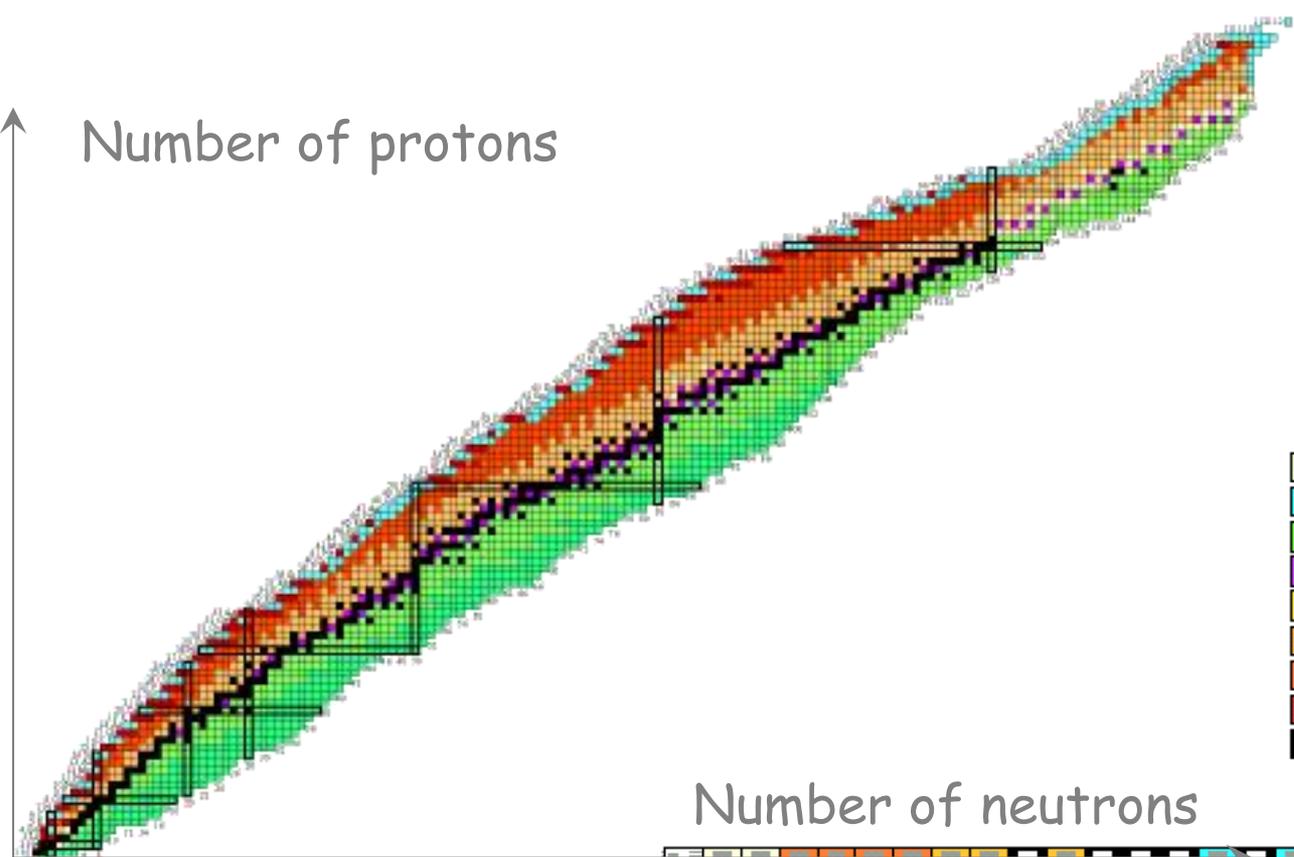
- radiation remains after accelerator switched off
- work permits for people entering tunnels
- radiation protection: personnel and environment
- management of activated accelerator components
- decommissioning of facilities

- 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

Number of protons



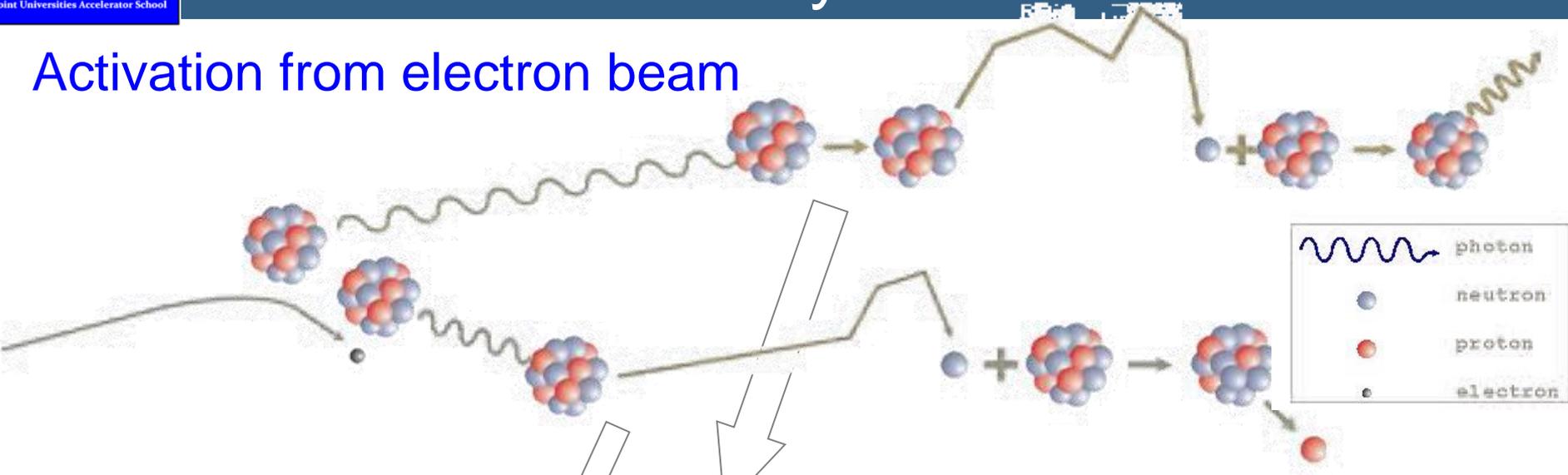
- Decay Q-value Range
- Q(??)
  - $Q(\beta^-) > 0$
  - $Q(\beta^-) - S_N > 0$
  - $Q(\beta^-) > 0 + Q(EC) > 0$
  - Stable to Beta Decay
  - $Q(EC) > 0$
  - $Q(EC) - S_p > 0$
  - $Q(P) > 0$
  - Naturally Abundant

Number of neutrons

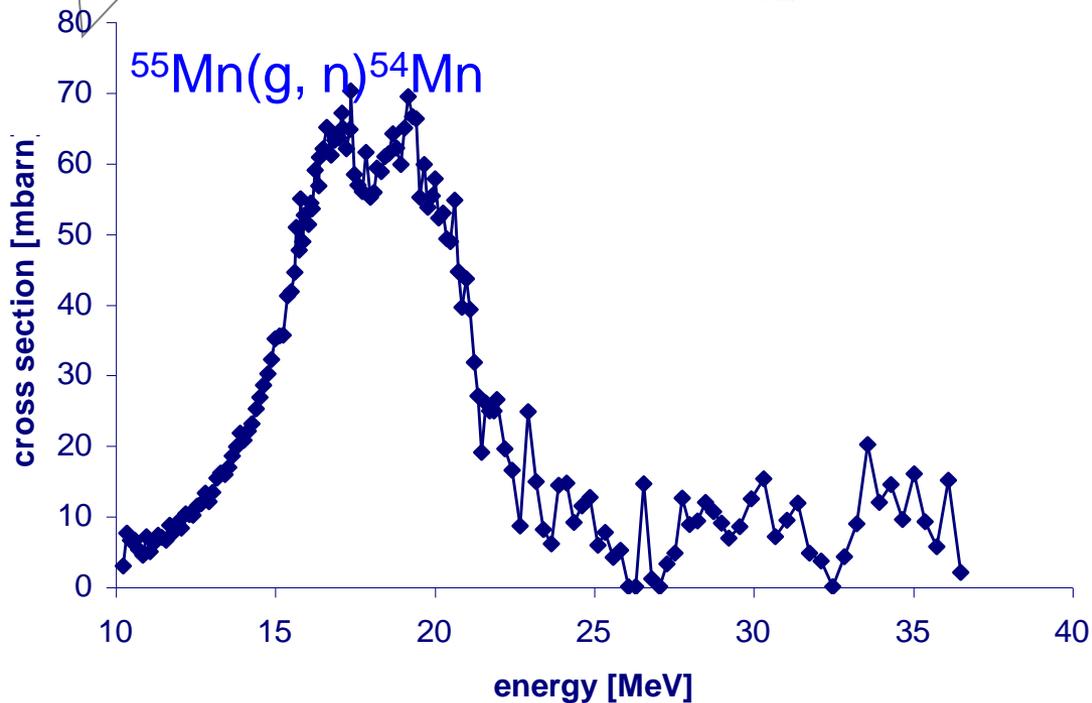
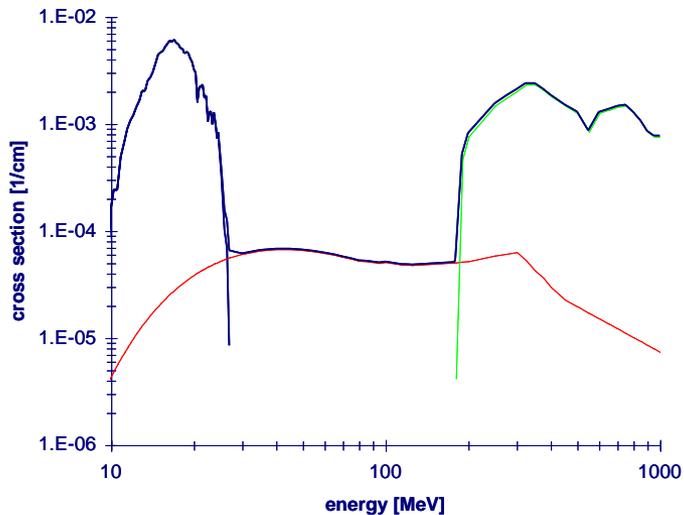


# 4b. Induced Activity

## Activation from electron beam

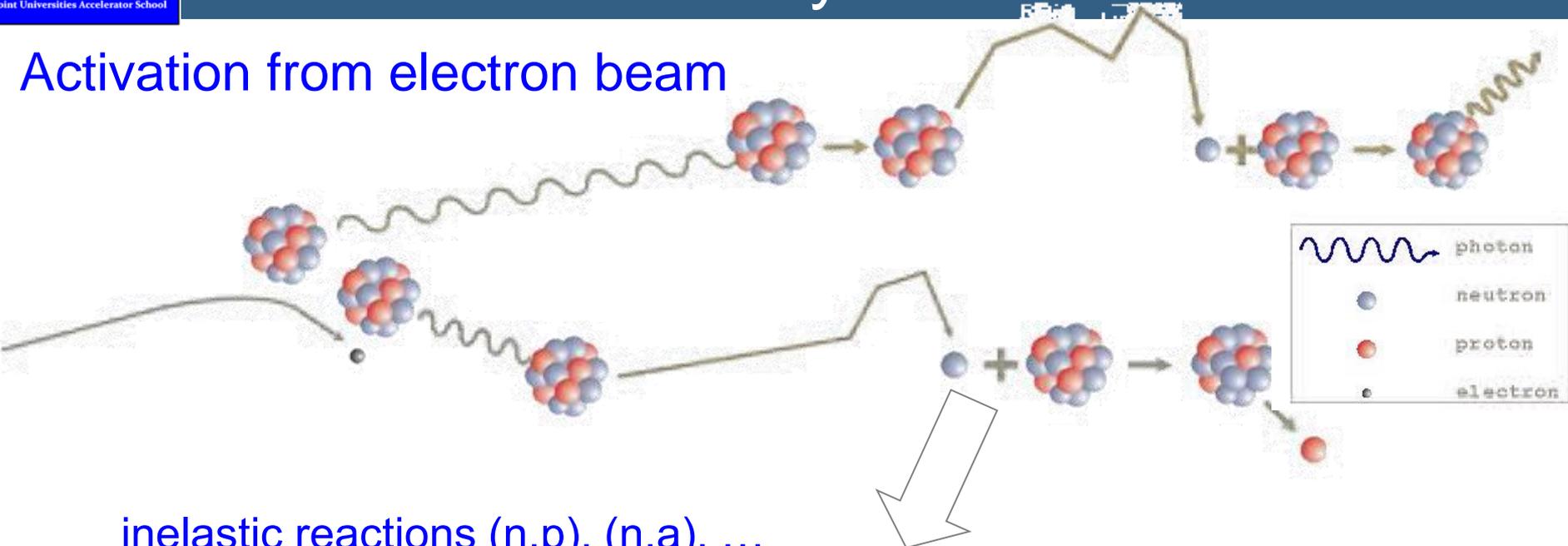


photonuclear reactions  
(g,n), (g,p), (g,np), ...

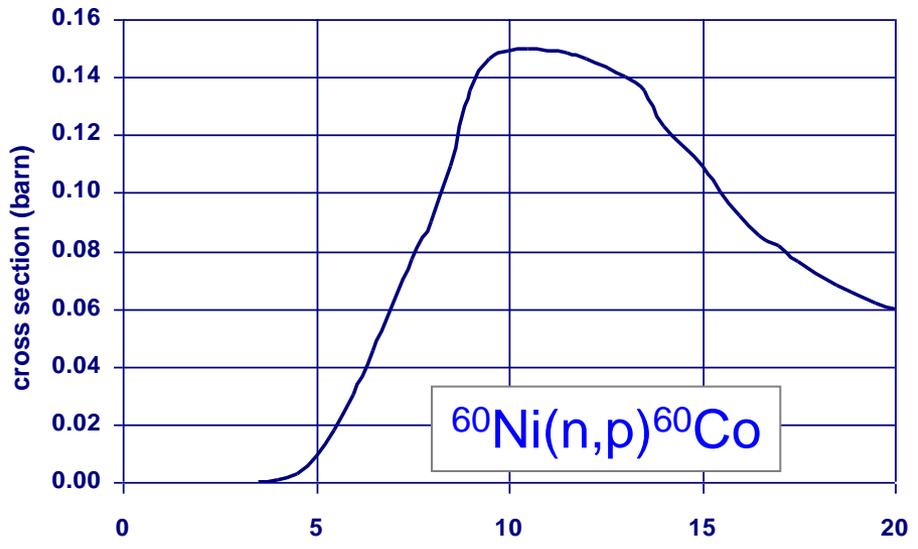
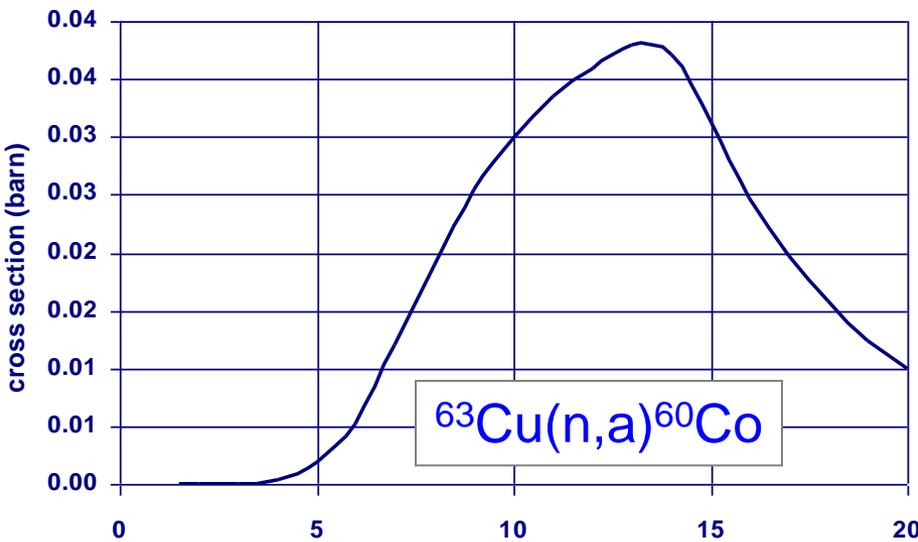


# 4b. Induced Activity

## Activation from electron beam

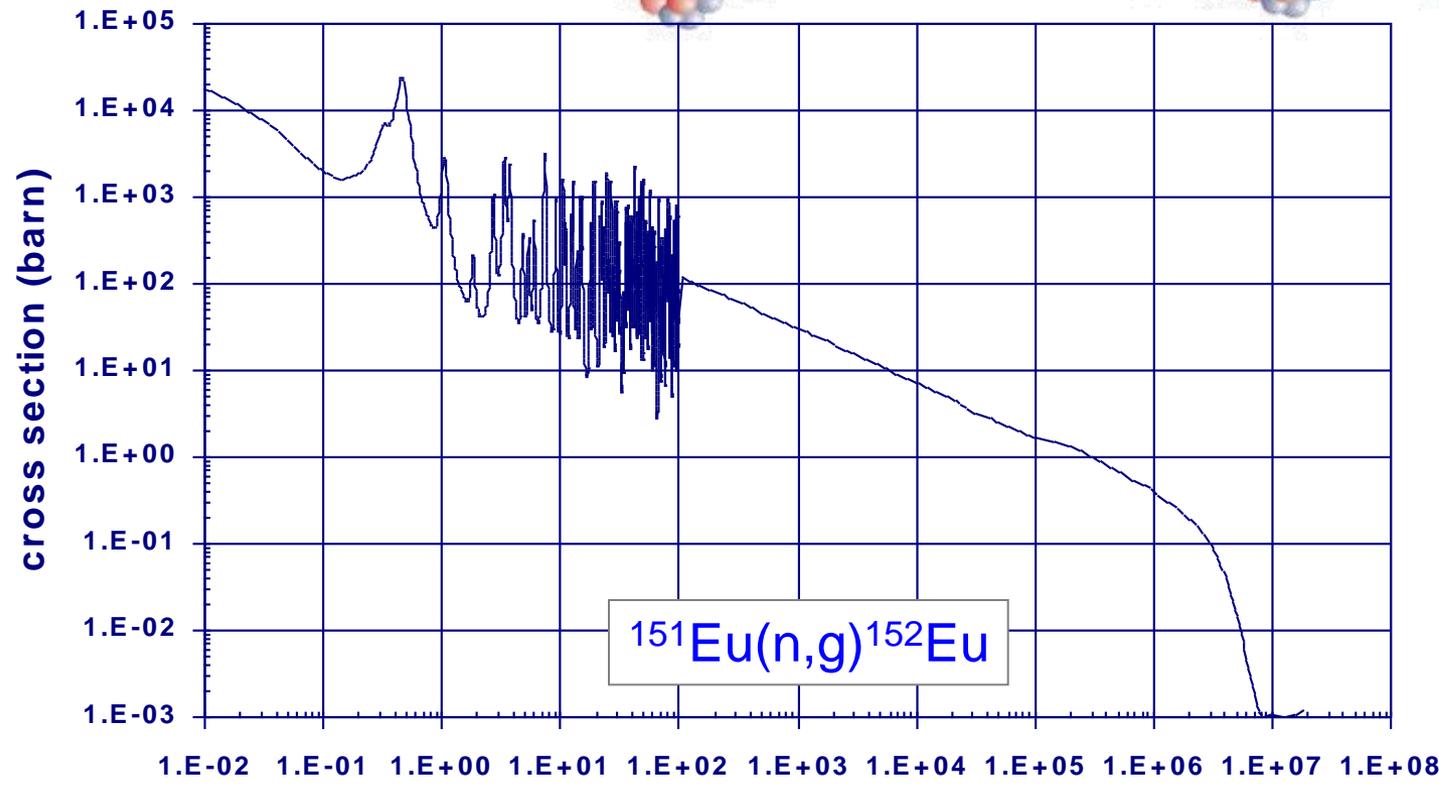
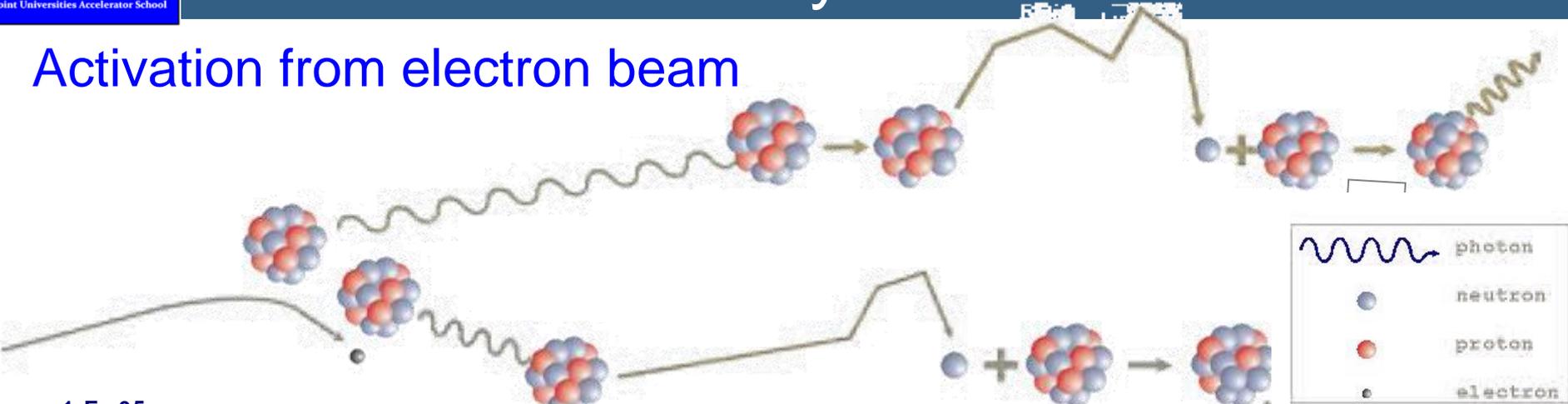


inelastic reactions (n,p), (n,a), ...



# 4b. Induced Activity

## Activation from electron beam

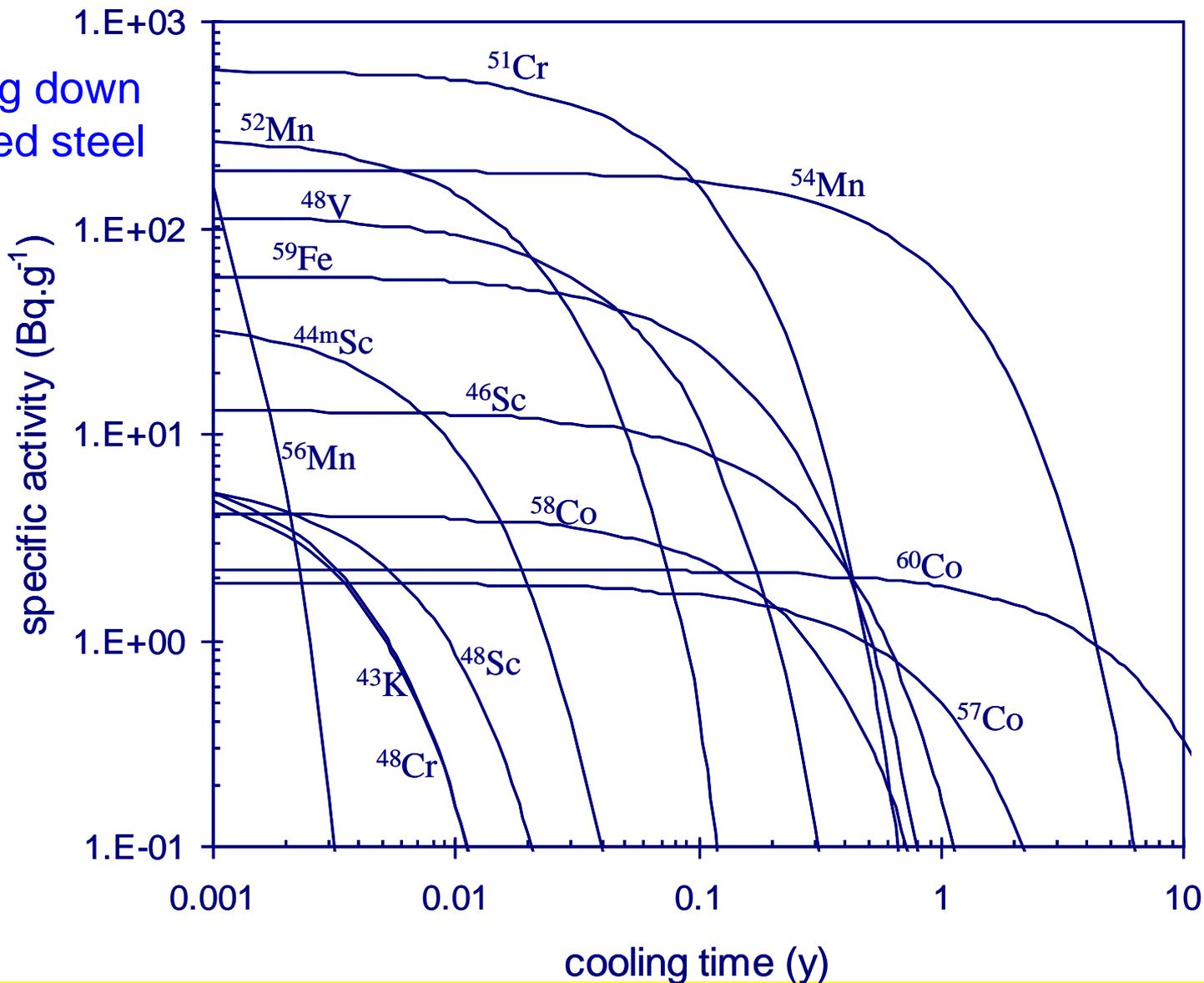


Radioactive capture

# 4b. Induced Activity

## Activation from electron beam

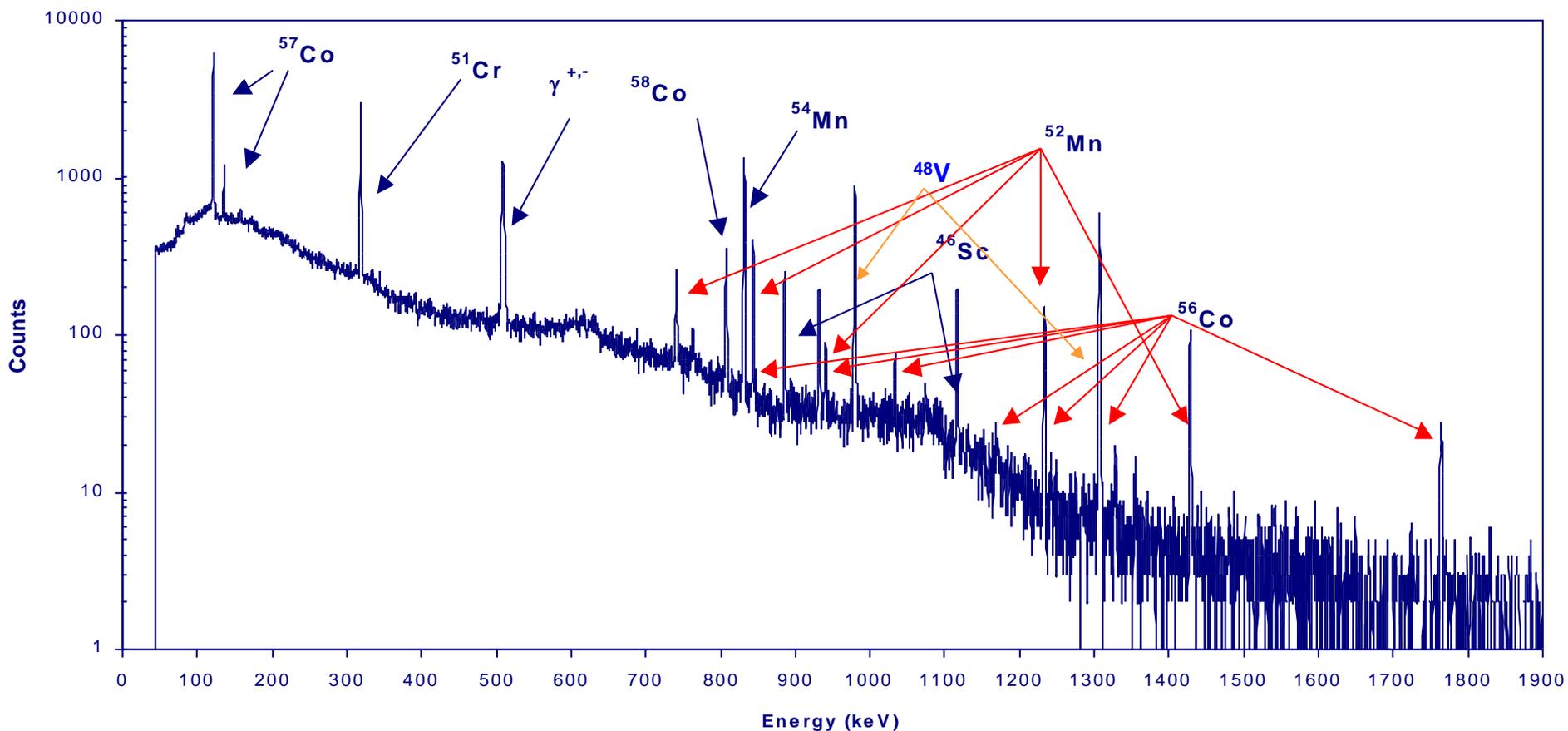
Example: cooling down curve of irradiated steel



# 4b. Induced Activity

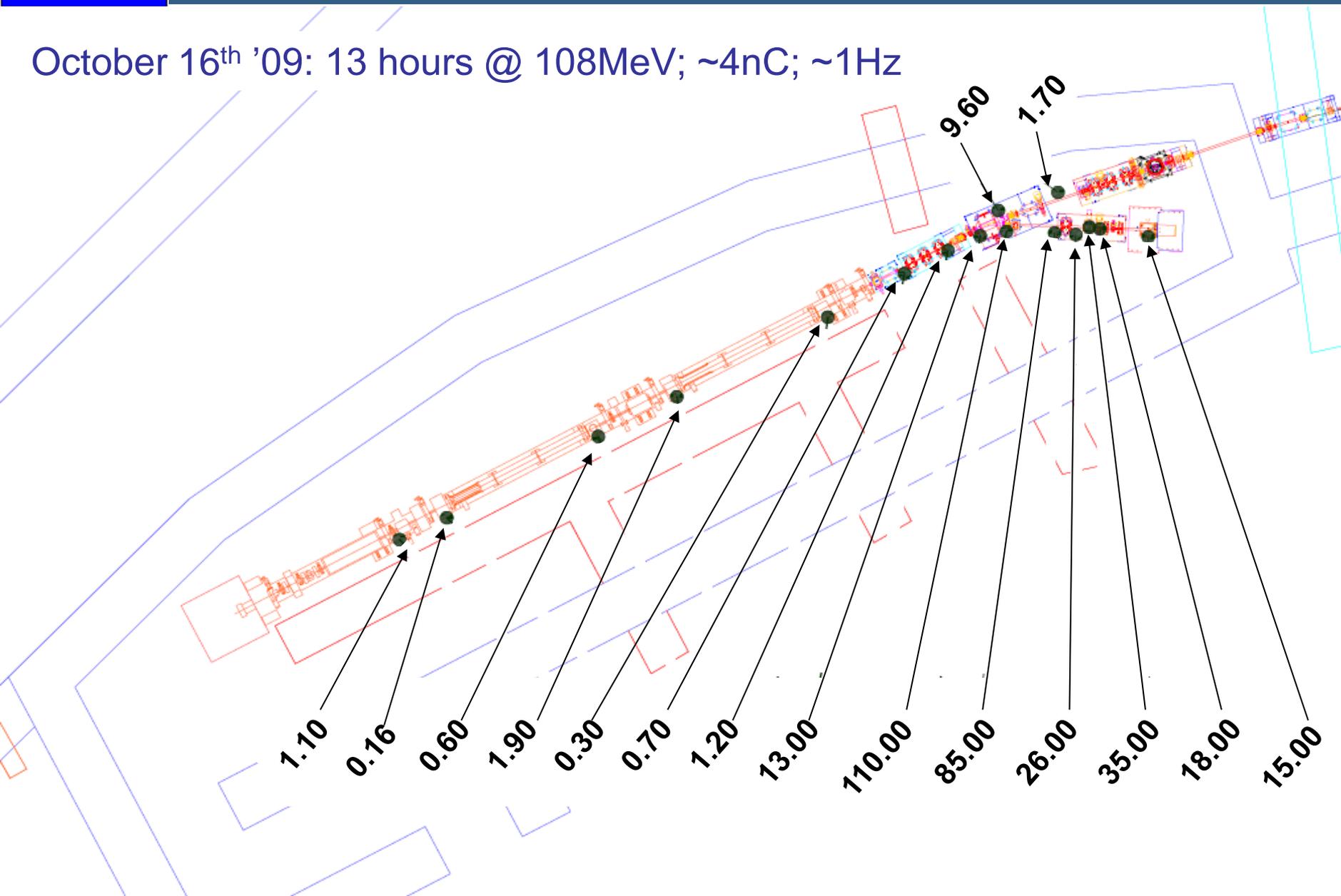
Activation from electron beam

Stainless steel vessel ESRF



# 4b. Induced Activity

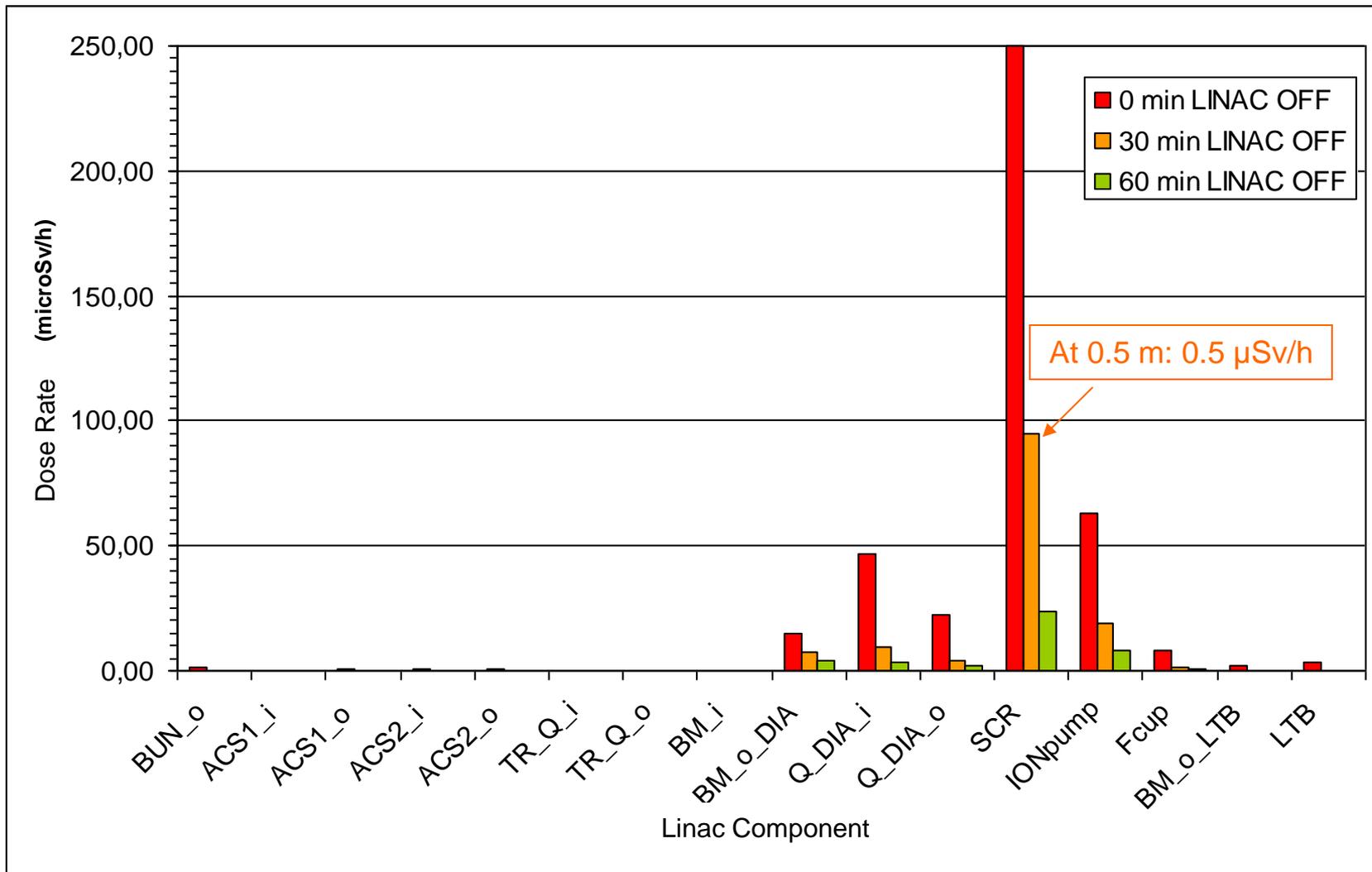
October 16<sup>th</sup> '09: 13 hours @ 108MeV; ~4nC; ~1Hz



# 4b. Induced Activity

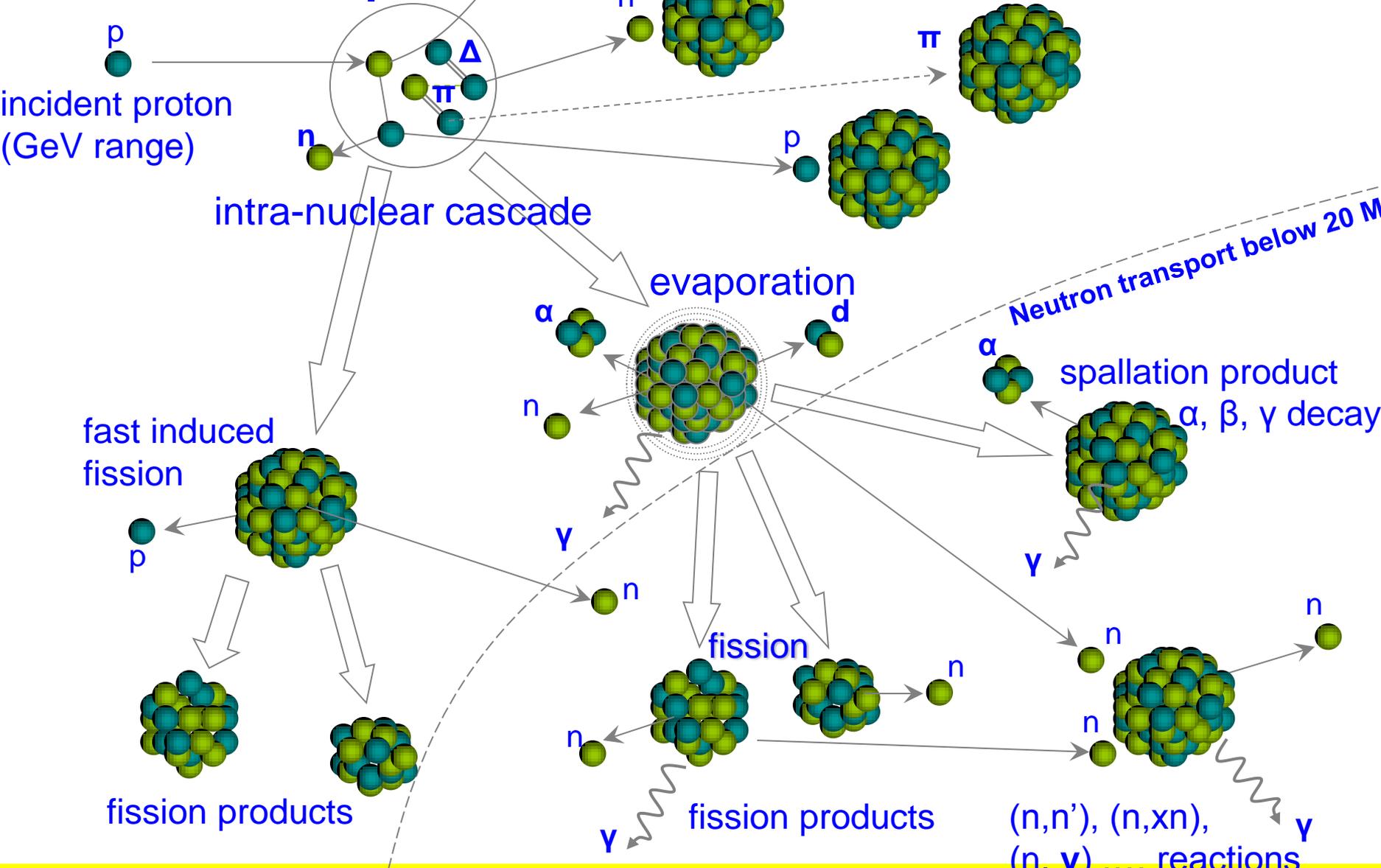
## 3b. PORTABLE DETECTORS: ACTIVATION

Measurements on surface (Sep 26<sup>th</sup> '08):



# 4. Interaction of protons with matter

## Activation from proton beam



# 4b. Induced Activity

## Activation from proton beam

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

Principal radioactive isotopes produced in accelerator structures by spallation reactions

# 4b. Induced Activity: proton beam

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

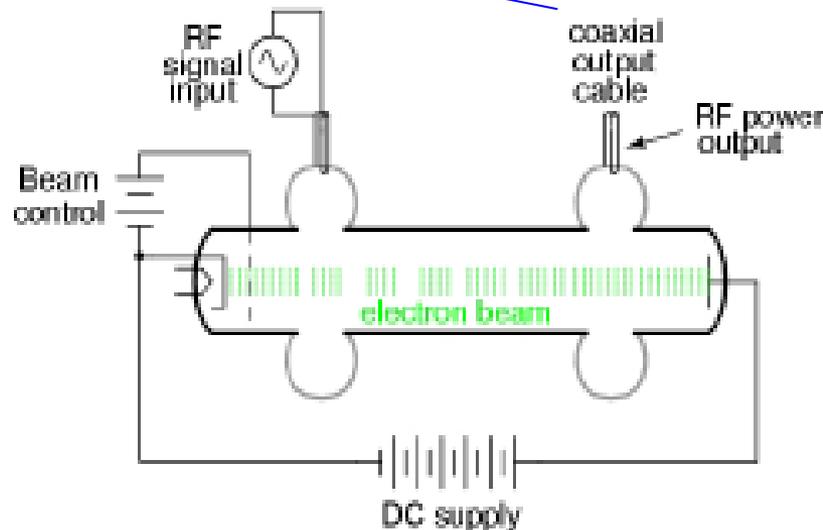
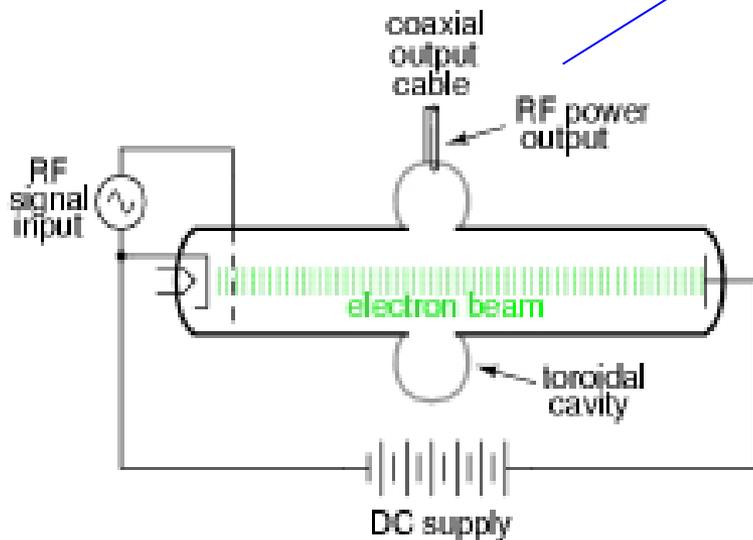
Most important isotopes near high energy particle accelerators formed by thermal neutron capture

# 4a. RF generator plants

a. IOT:

to RF Cavity

b. Klystron:



## IOT (Inductive Output Tube)

$G \approx 23$  dB (for comparison: Tetrode  $G \approx 15$  dB)

Intensity modulated

Class AB

Peak efficiency  $\approx 75\%$

Compact size

## Klystron

$G \approx 40$  dB

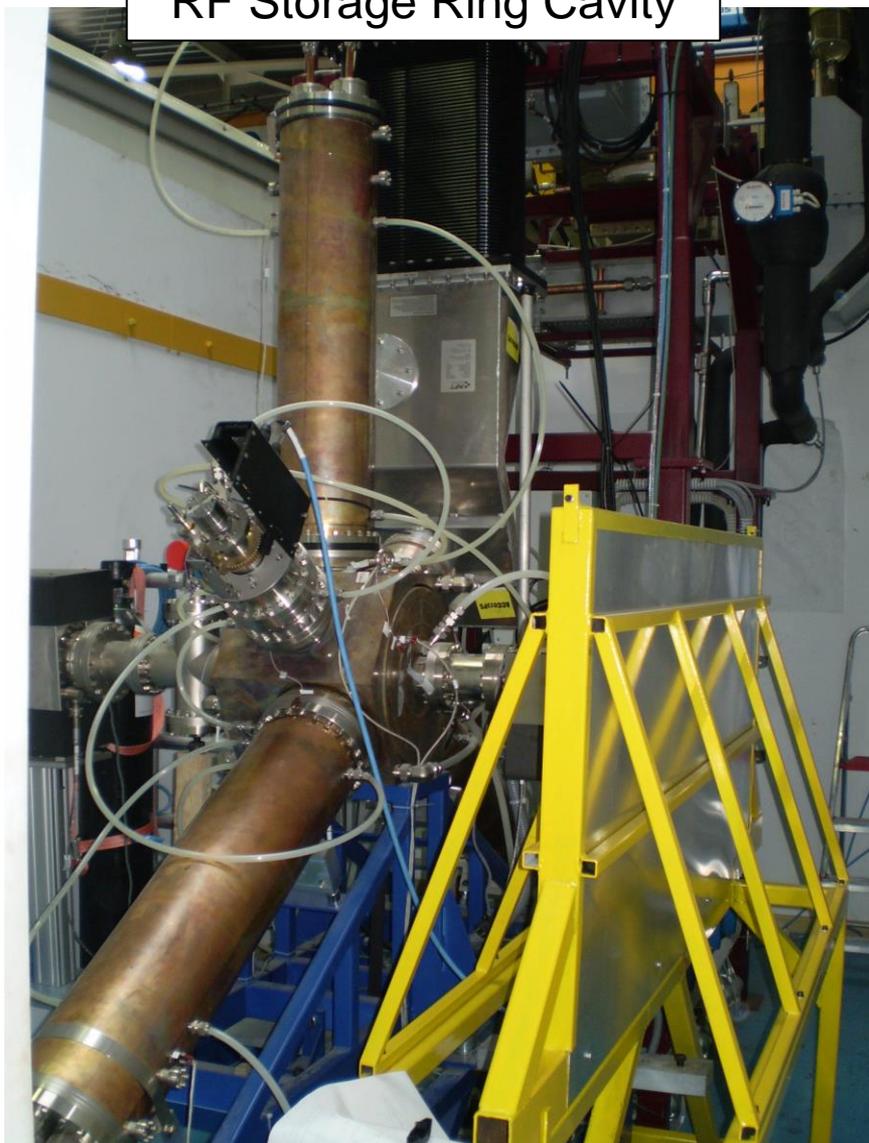
Velocity modulated

Class A

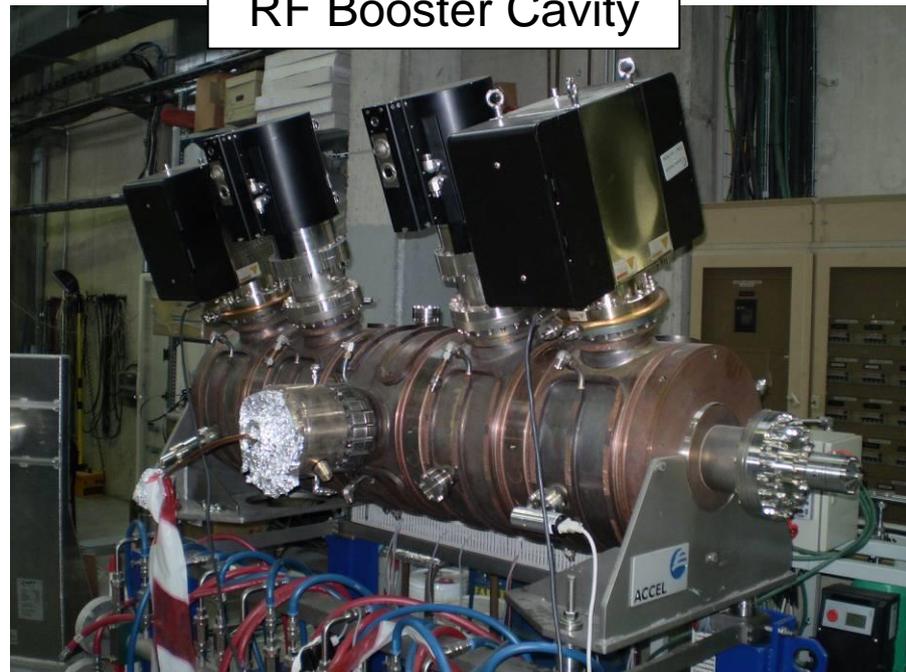
Peak efficiency  $\approx 65\%$

# 4a. RF generator plants

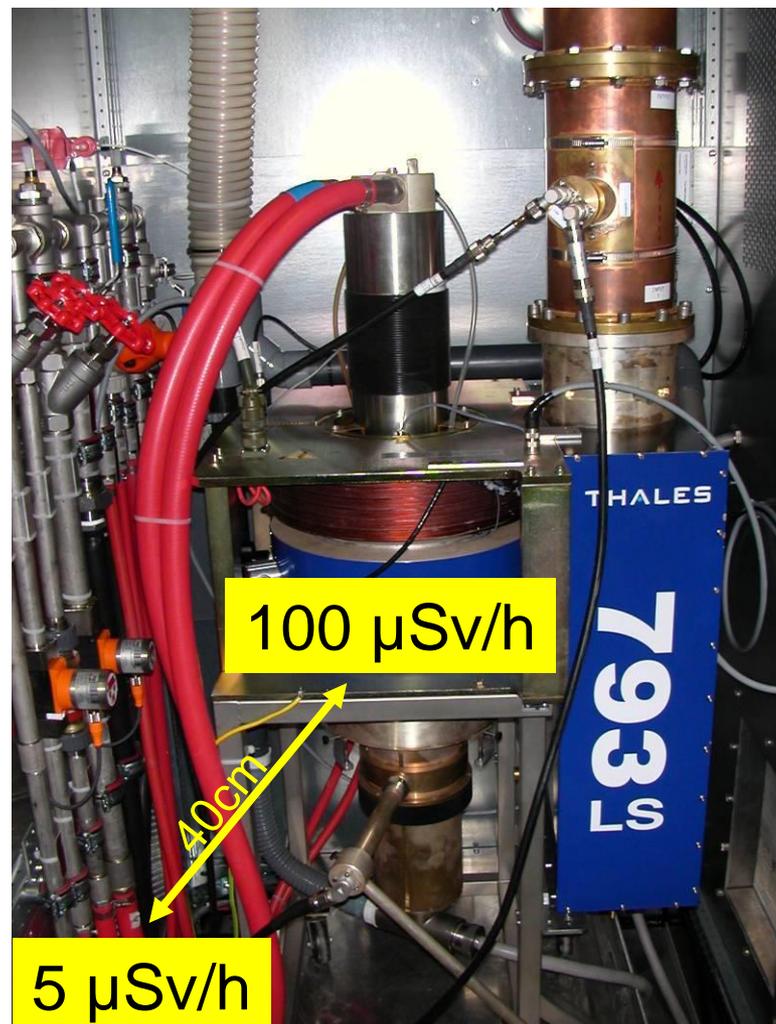
RF Storage Ring Cavity



RF Booster Cavity



## RADIATION MEASUREMENTS: IOT

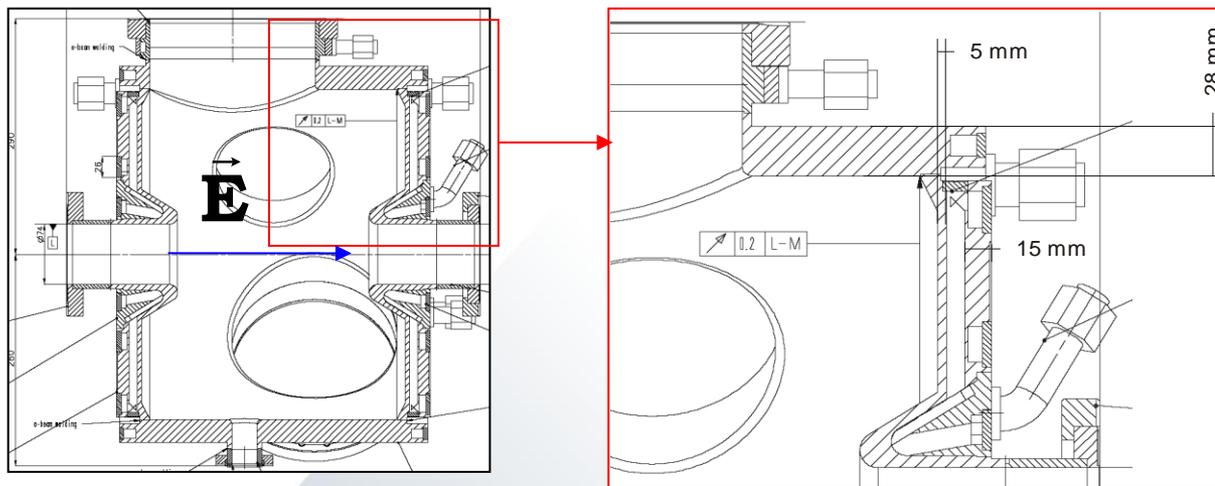


# 4a. RF generator plants

## ALBA linac entrance and control: present configuration



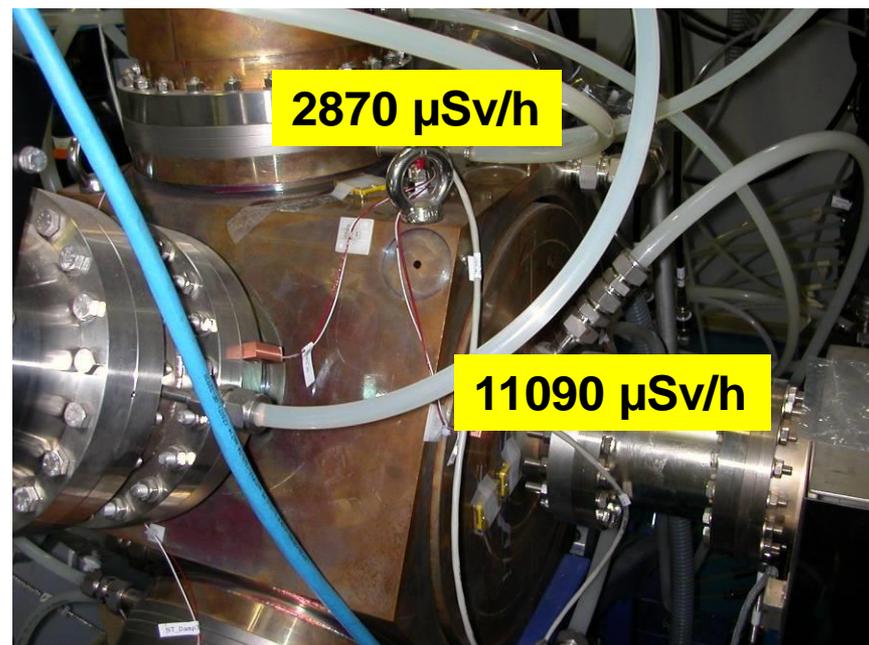
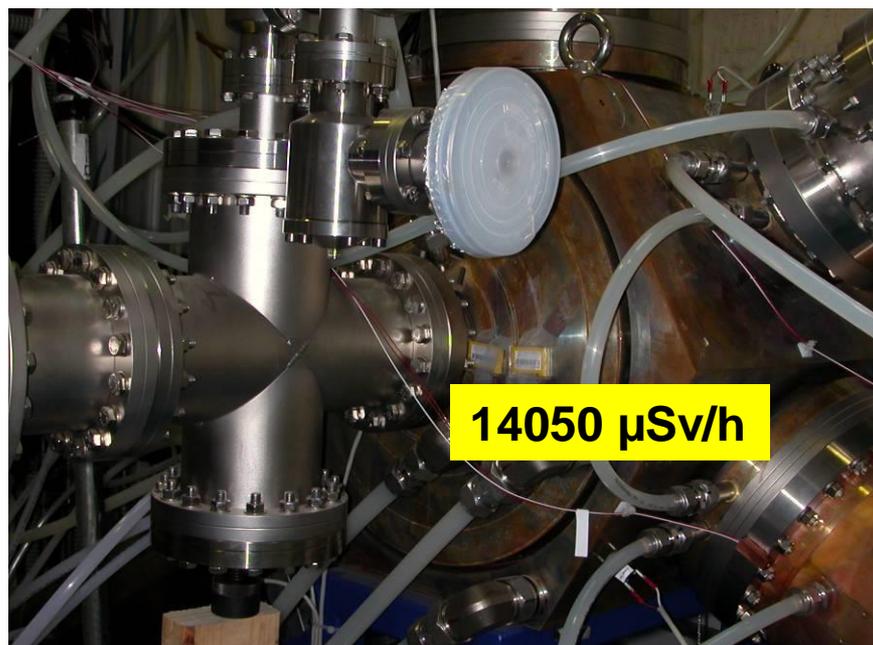
# 4a. RF generator plants



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

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

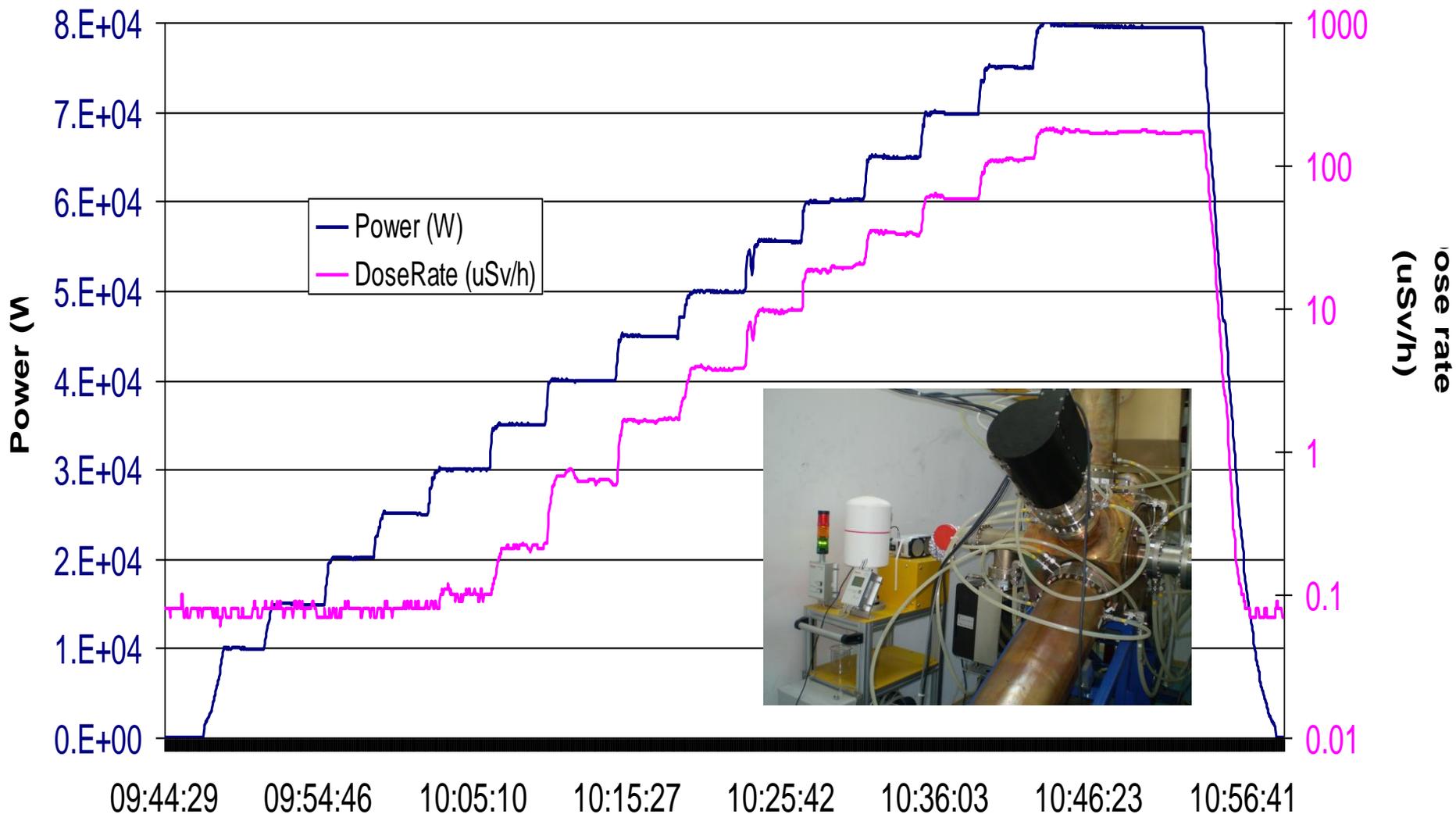
## RAD. MEAS.: DOSE RATE ON SURFACE



80kW (max power) @ 20%

# 4a. RF generator plants

## Power and gamma dose rate vs. time



## Gamma spectrums at different RF powers

