Radiation safety of the Danish Center for Proton Therapy (DCPT)

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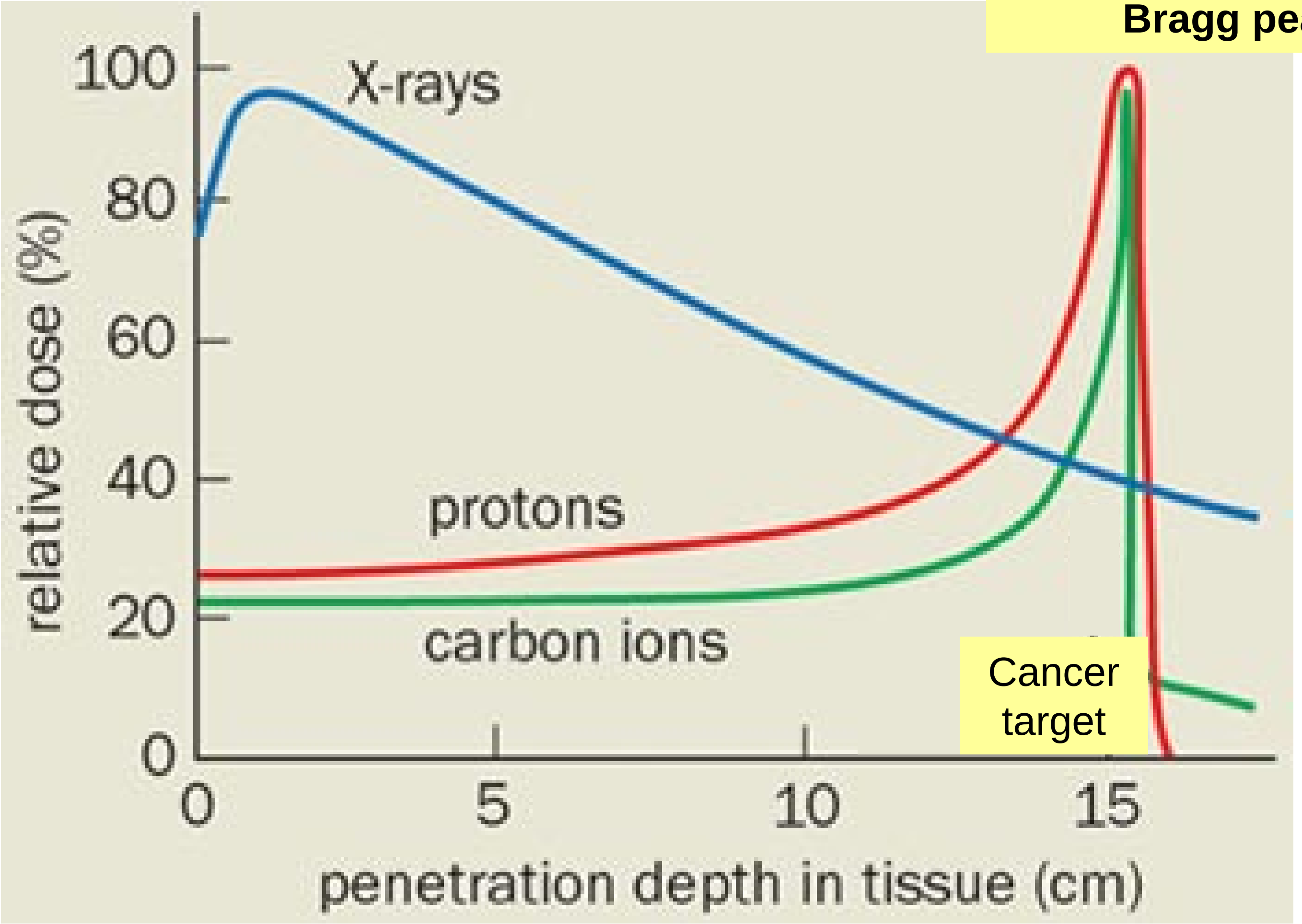
Rationale of proton therapy

Dose deposition versus depth in patient:

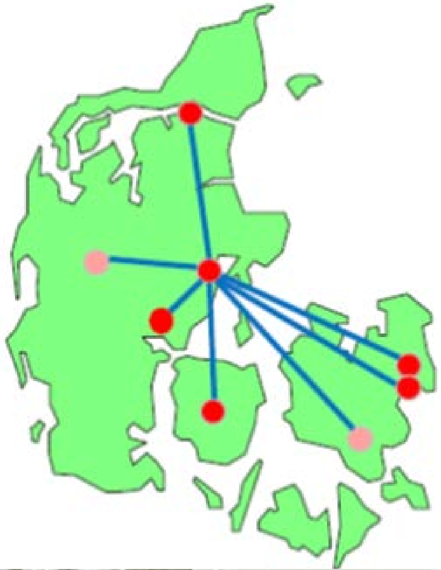
Intense localized dose deposition = **Bragg peak**



Bragg peak position: Initial proton energy

The Danish Center for Proton Therapy (DCPT)

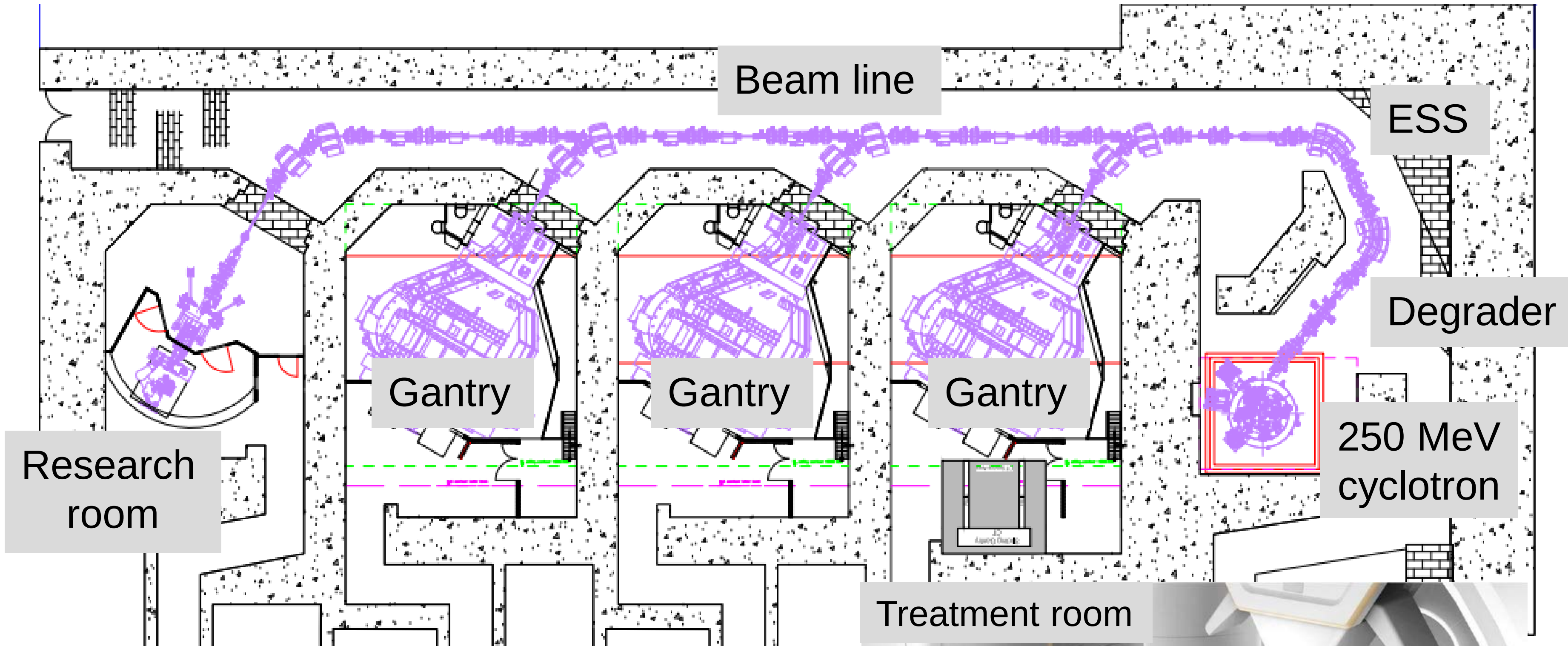
- National center for all Danish patients referred to proton therapy
- Located at Aarhus University Hospital in Skejby
- 3 treatment rooms with gantry and one fixed-beam research room
- Proton therapy system is based on a 250 MeV cyclotron from Varian Medical Systems



Time line:

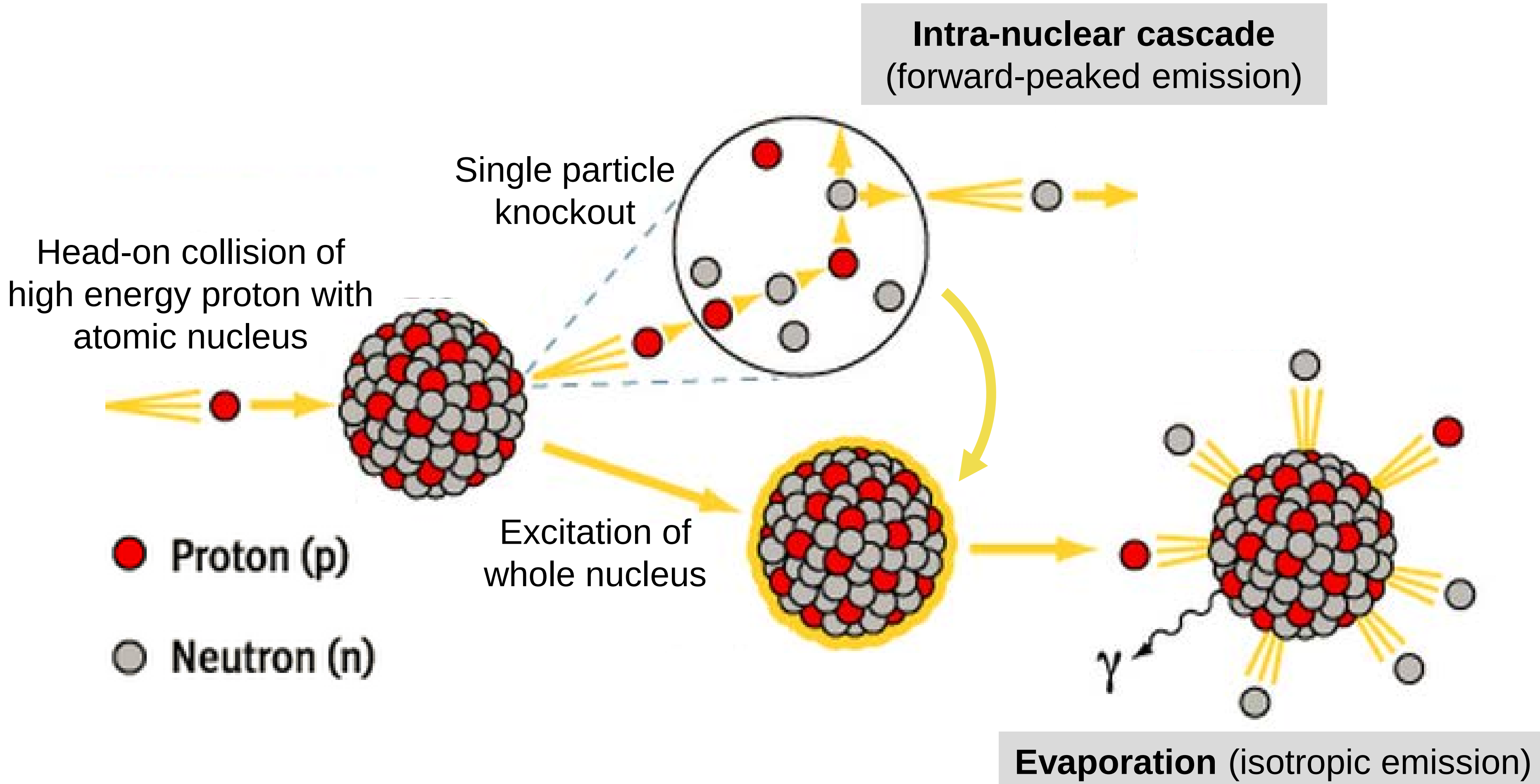
- August 2015: Selection of contractor for the building
- July 2017: Installation of equipment
- October 2018: First patient

Layout of DCPT treatment bunker



- **Degrader:** Energy adjustment
- **ESS:** Energy selection system
- **Gantry:** Variable treatment angle

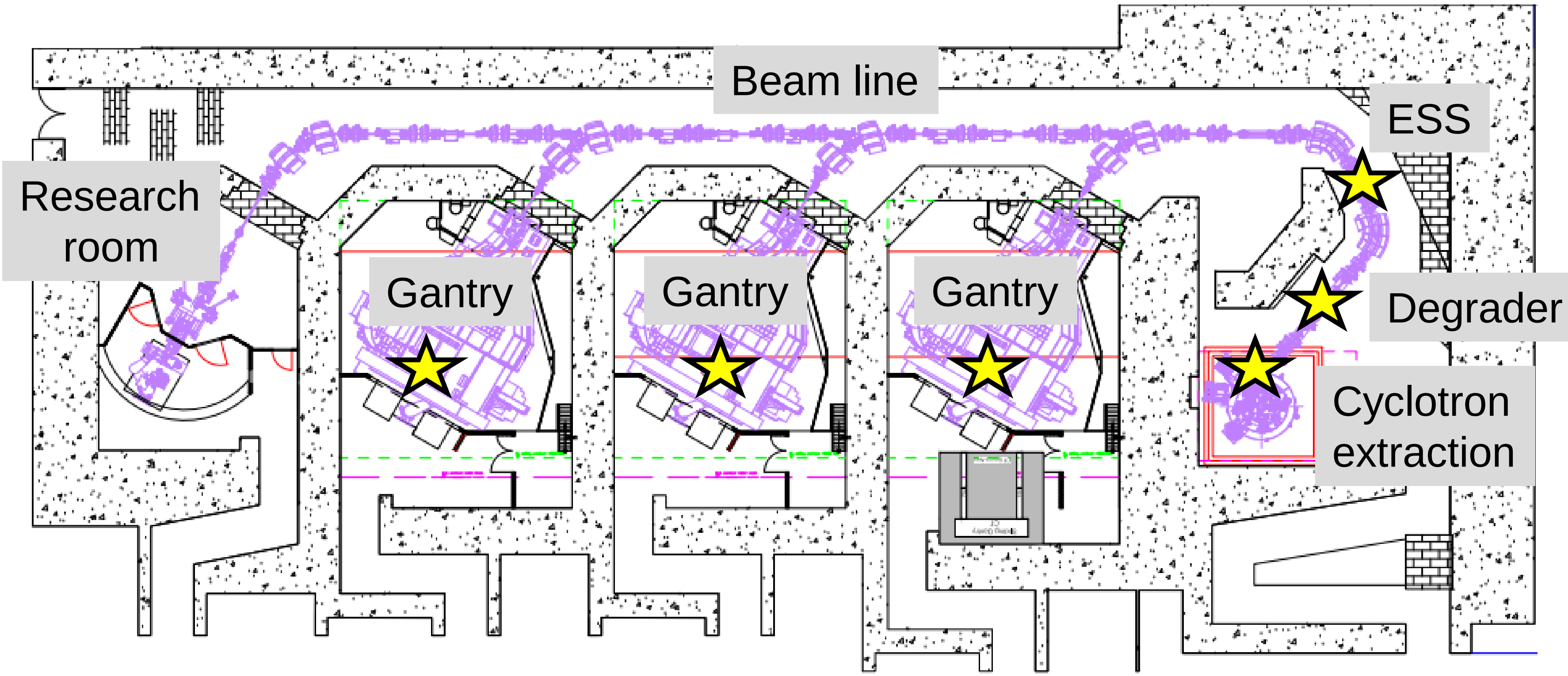
Secondary radiation



Main radiation hazards: Neutrons + induced radioactivity

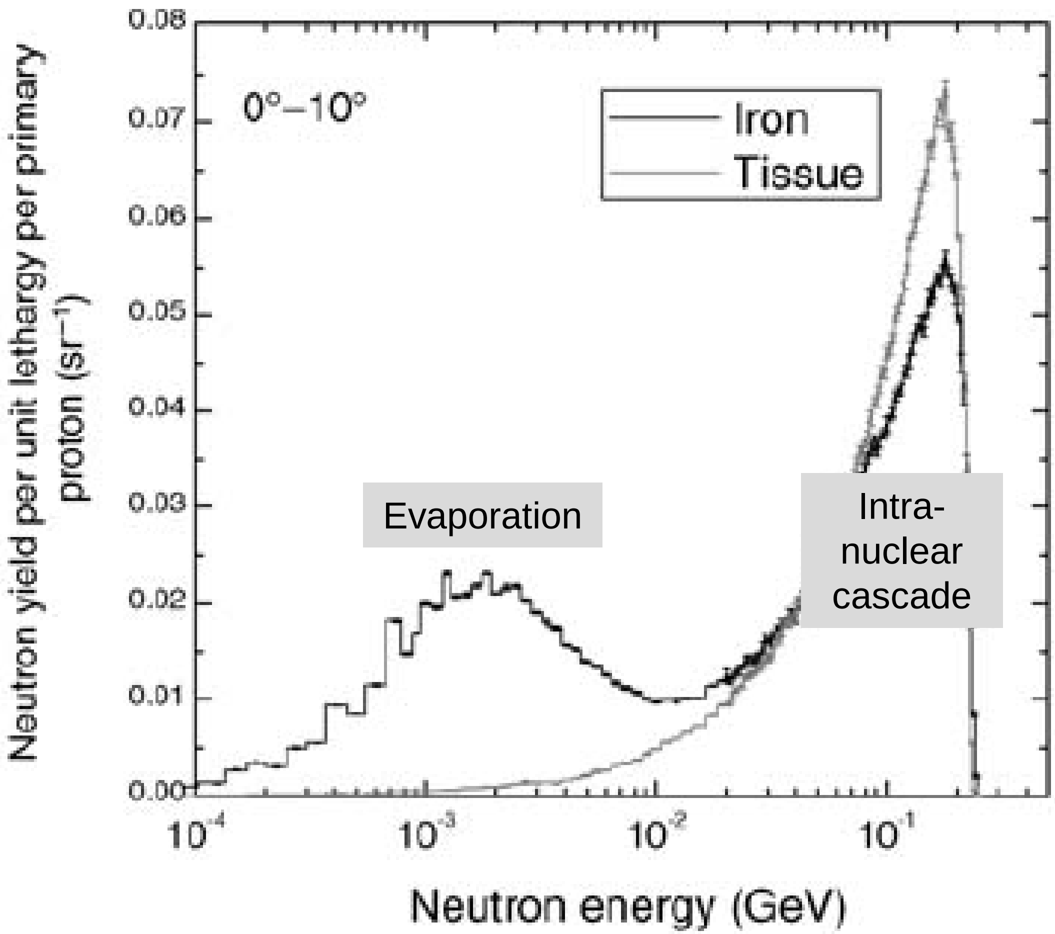
Main neutron sources

Neutron source = Location with large proton loss



Secondary neutron spectrum

Energy distributions of neutrons generated by 250-MeV protons:



Low energy peak (~1 MeV):

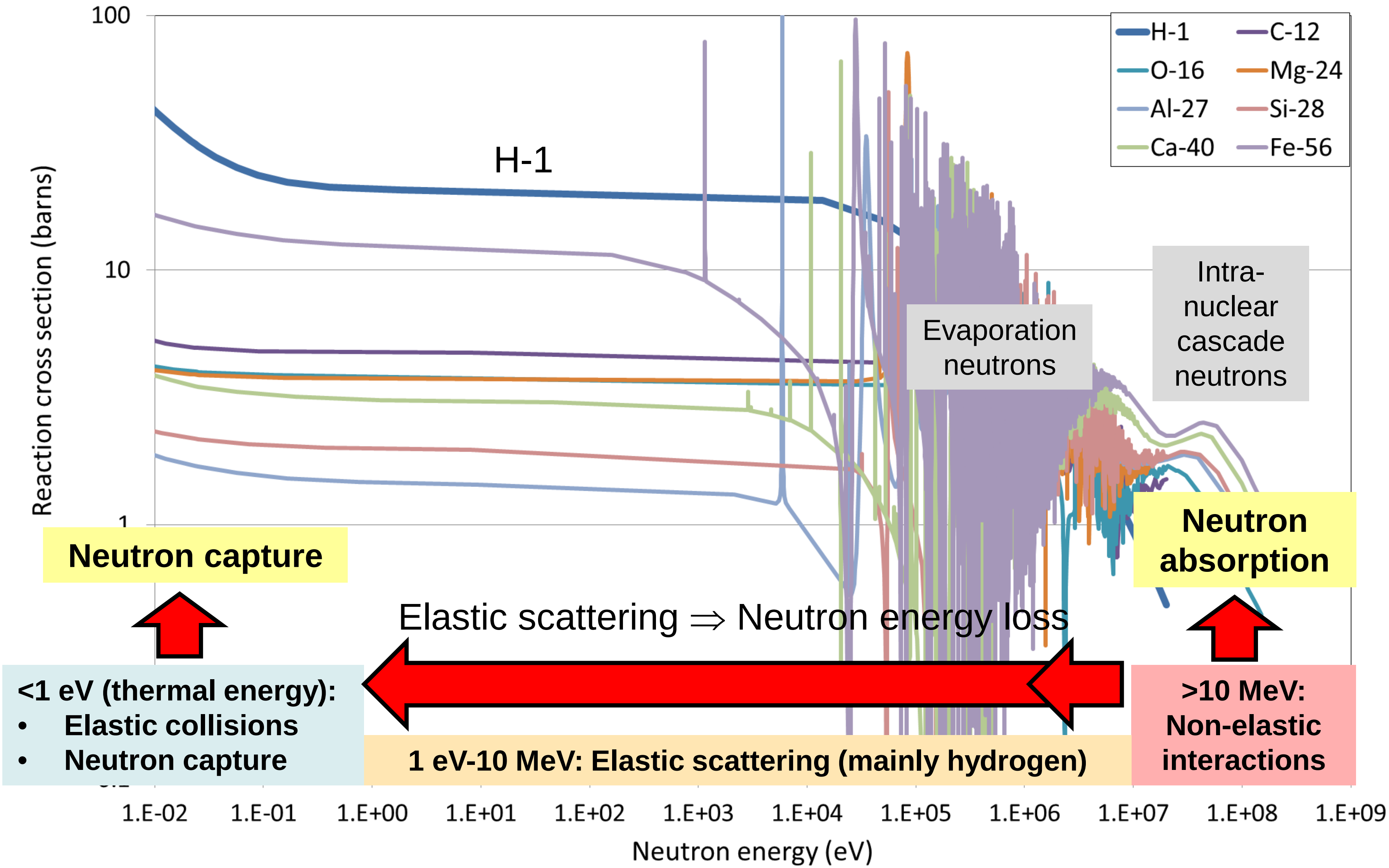
- Evaporation neutrons
- Only present for heavy elements (high nuclear level density)
- Emitted isotopically

High-energy peak (~100 MeV):

- Intra-nuclear cascade neutrons
- Mainly emitted in the forward direction with respect to the incident proton beam

Radiation Protection Dosimetry (2009), Vol. 137, No. 1–2, pp. 167–186

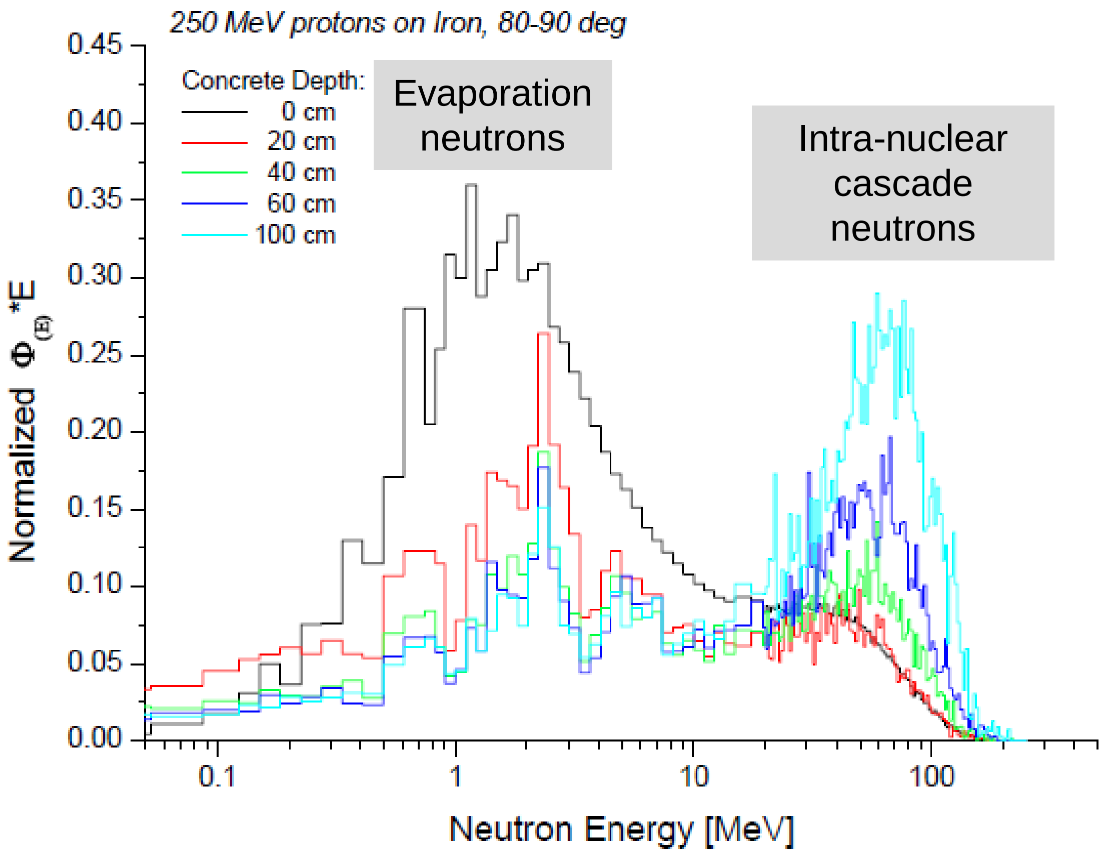
Neutron interactions in shielding barrier



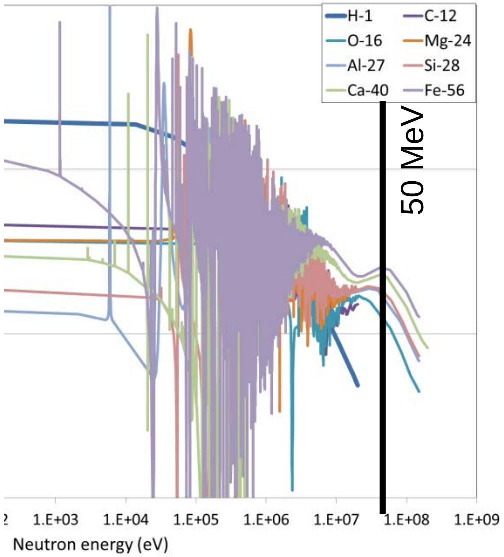
High energy neutron interactions

Lowest neutron interaction probability >50 MeV

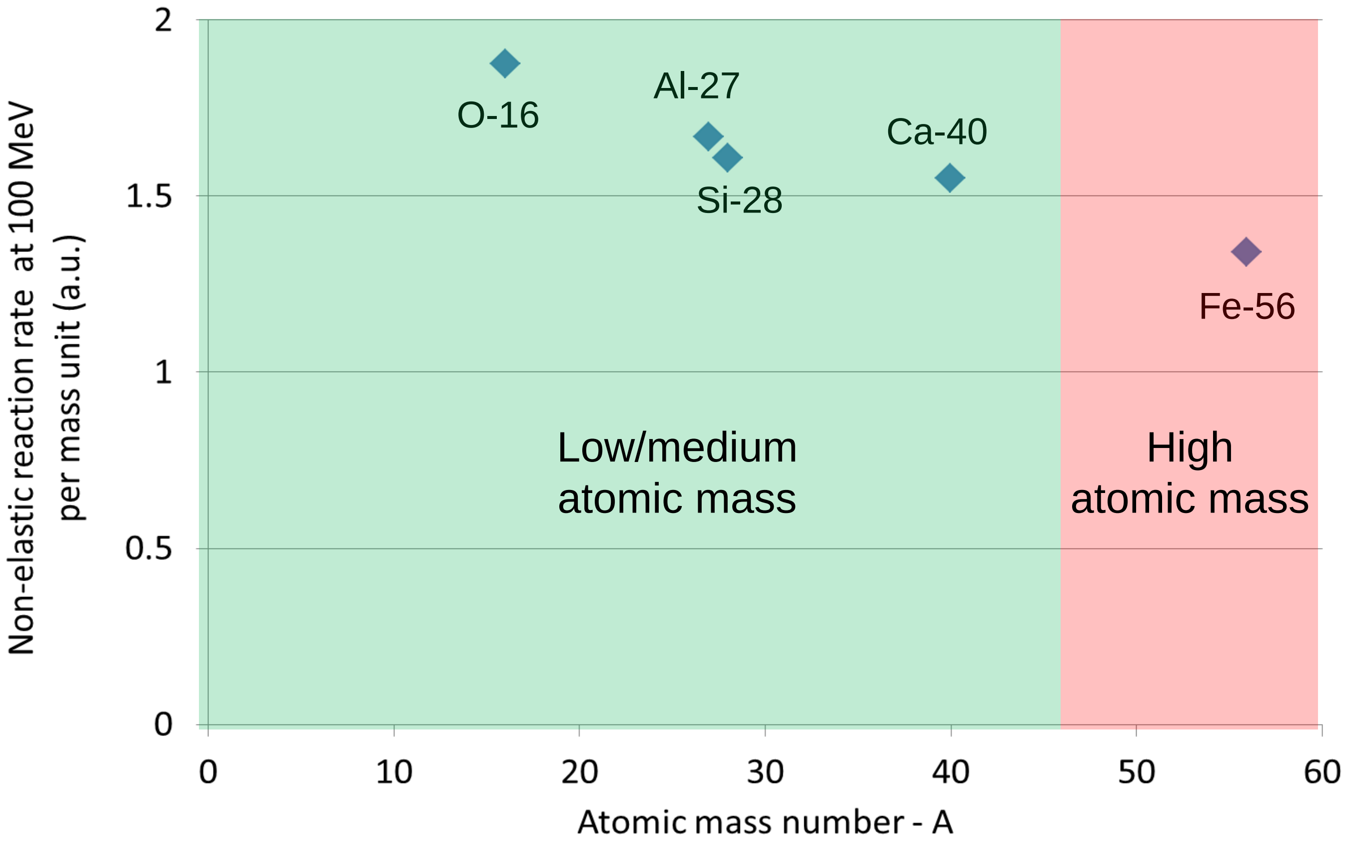
$\Rightarrow$ Neutrons with **energies >50 MeV** drive the shielding thickness



Total neutron reaction cross section:



High-energy neutron reaction rate



- Low/medium atomic mass: The reaction rate is mainly determined by density · wall thickness (total weight)
- High atomic mass: Less efficient shielding per unit mass

$\Rightarrow$ Concrete is an efficient shielding material (only low/medium atomic mass)

Why concrete shielding for DCPT?

- Efficient shielding of high-energy neutrons (>50 MeV) by low/medium atomic masses
- Very good structural properties
- Relatively cheap material per mass unit
- High hydrogen content providing efficient neutron energy loss
- Well-known material used for almost all existing proton therapy facilities

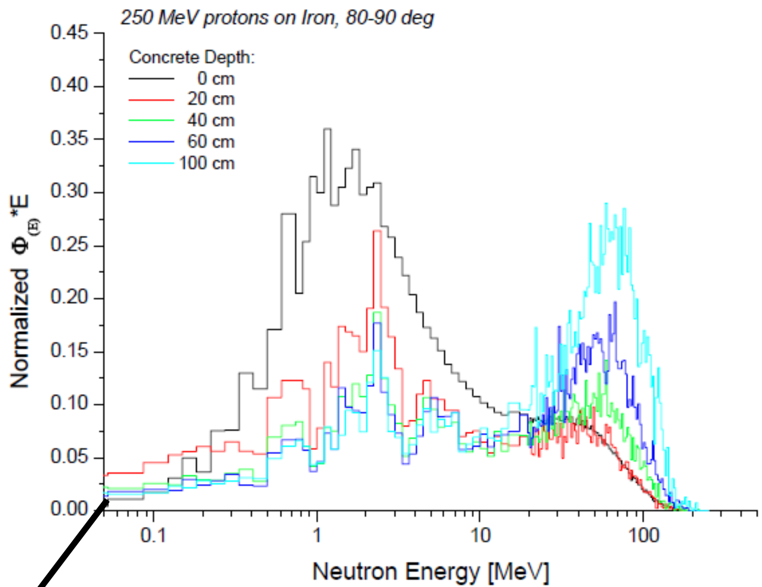
Modelling of neutron attenuation in concrete

Fixed neutron spectrum beyond 1-2 m depth in concrete

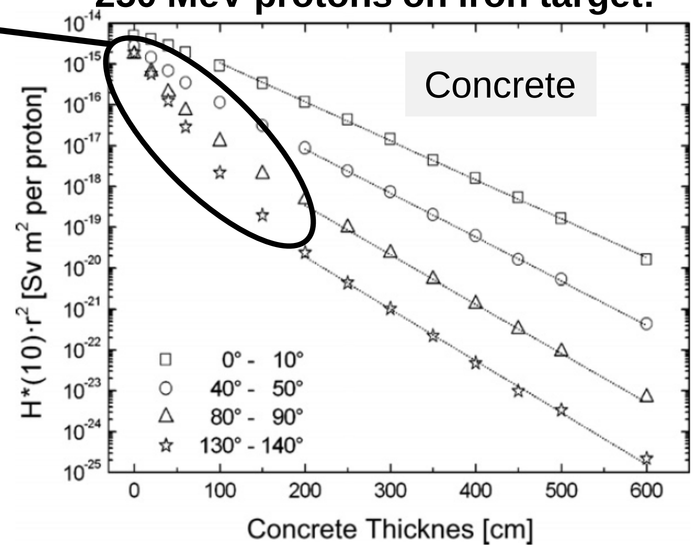
Neutron equilibrium

Exponential attenuation of neutron dose

No equilibrium at low depth: Many low energy neutrons



250 MeV protons on iron target:

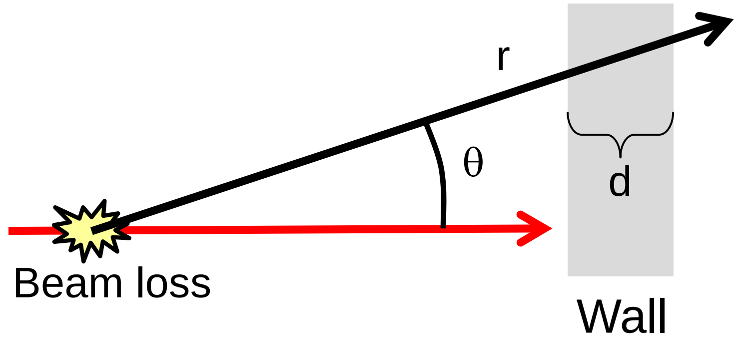


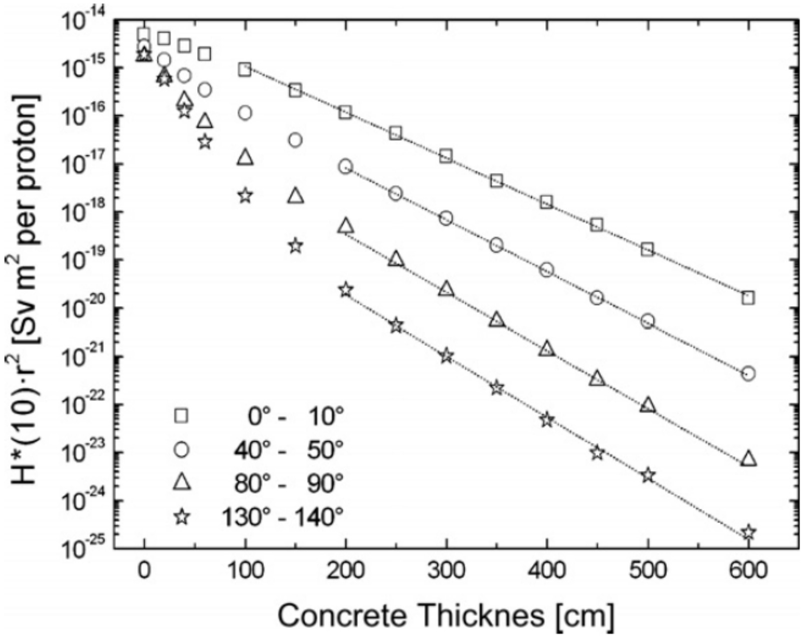
Exponential attenuation model

Neutron ambient dose equivalent from point source:

$$H(E_p, \theta, d/\lambda) = \frac{H_0(E_p, \theta)}{r^2} \exp\left[-\frac{d}{\lambda(\theta) g(\alpha)}\right]$$

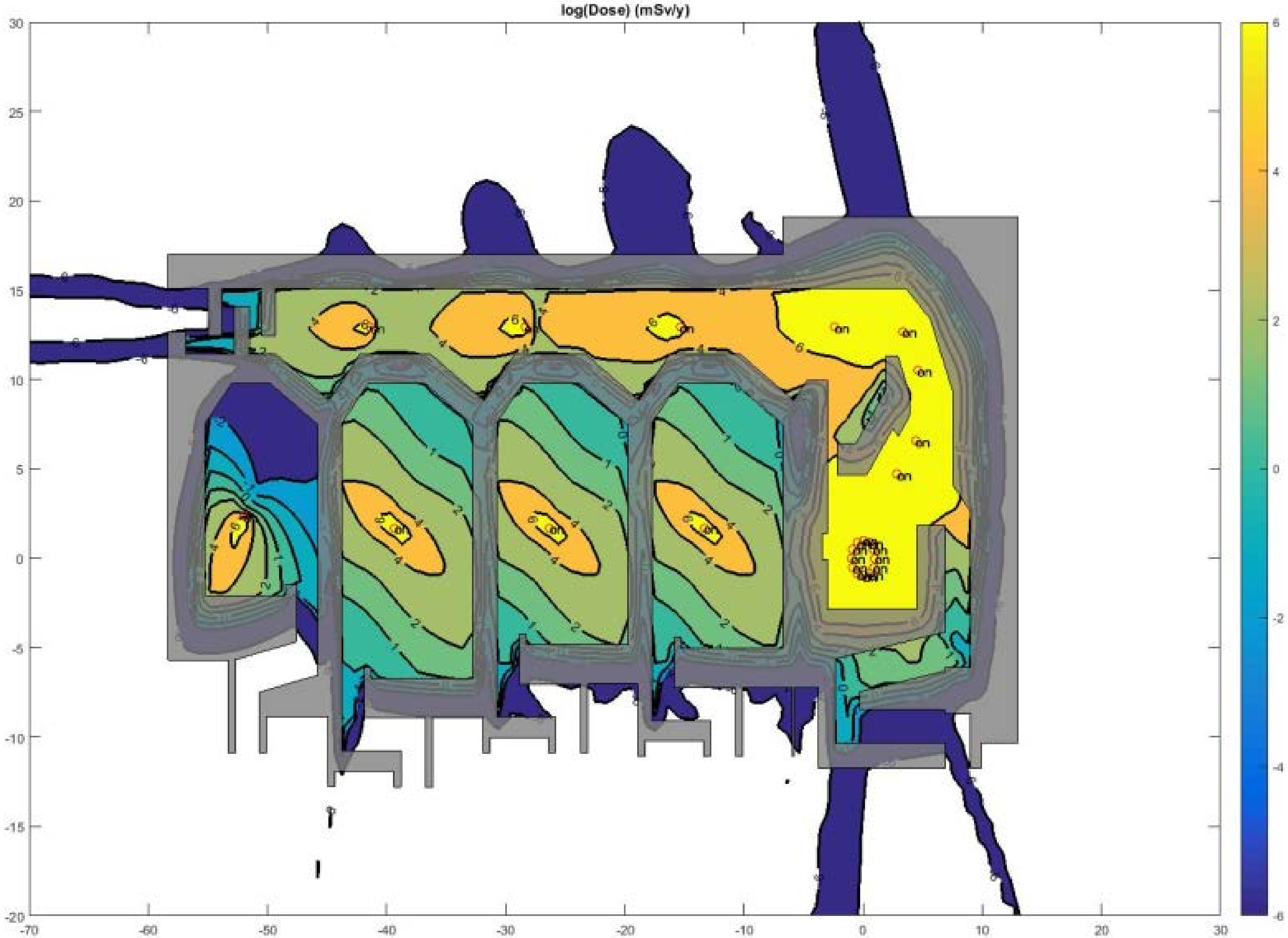
H_0 and λ are determined from Monte-Carlo simulations





E_p: Proton energy
r: Distance to the radiation source (m)
θ: Angle with respect to incident beam
H_0: Dose source term per proton
d: Density-weighted shield thickness (g/cm^2)
$\lambda(\theta)$: Attenuation length (g/cm^2)
$g(\theta)$: Forward wall: $\cos(\theta)$: Lateral wall: $\sin(\theta)$

Example: Dose calculation for DCPT bunker



Induced radioactivity in building structures

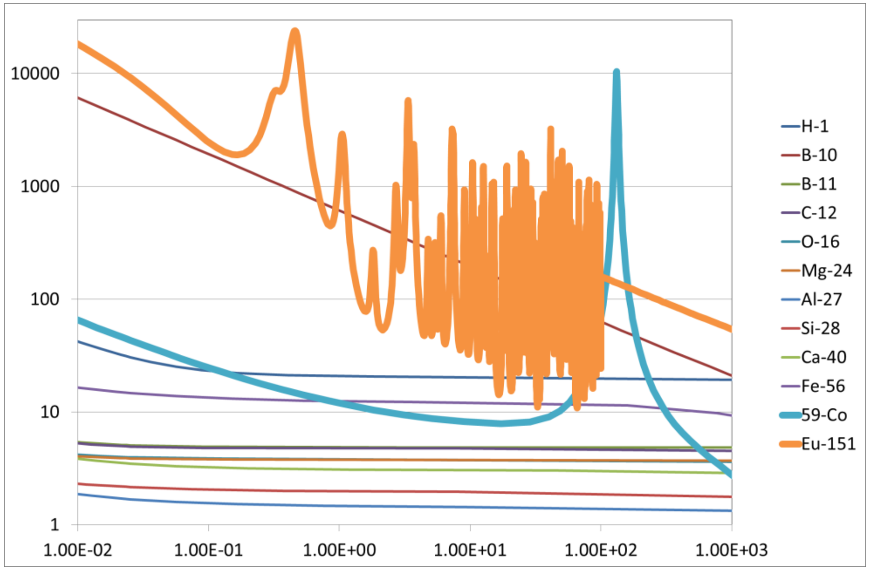
Most common long-lived radionuclides in concrete and steel:

Radionuclide	Dominant reactions	Half life	Material	Expected main contributors to residual radioactivity
^{134}Cs	$^{134}Ba(n,p)$, $^{133}Cs(n,g)$	2.06 yr	Barite concrete	
^{22}Na	$^{23}Na(n,2n)$, $^{27}Al(n,2p4n)$	2.60 yr	Concrete	Long-term
^{60}Co	$^{59}Co(n,\gamma)$	5.27 yr	Concrete, steel	Long-term
^{154}Eu	$^{153}Eu(n,\gamma)$	8.59 yr	Concrete	
^{3}H	Spallation of N and O	12.3 yr	Concrete	
^{152}Eu	$^{151}Eu(n,\gamma)$	13.5 yr	Concrete	Long-term

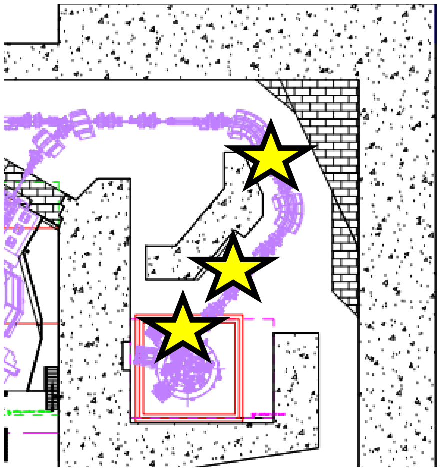
Co, Eu:
High capture σ + Half live > 5 yr $\Rightarrow$ Long-lived activation (decommissioning issue)

Allowed content of Eu and Co in concrete at the cyclotron and ESS:

- Eu: Weight fraction < 0.5 ppm
- Co: Weight fraction < 20 ppm



Activation of air



Air activation

Most common radionuclides produced by neutrons in air:

Nuclide	Dominant production reaction	Half-life	Dominant decay reaction and dominant gamma energies
H-3	Spallation of O	12.3 years	β^-, No gamma radiation
Be-7	Spallation of O	53.3 days	EC, 0.5 MeV (10 %)
C-11	Spallation of O	20.4 min	EC β^+, No gamma radiation
N-13	Spallation of O	9.97 min	EC β^+, No gamma radiation
O-14	Spallation of O	1.18 min	EC β^+, 2.3 MeV (99%)
O-15	Spallation of O	2.04 min	EC β^+, No gamma radiation
F-18	$^{18}O(p,n)^{18}F$	1.83 hour	EC β^+, No gamma radiation
Ar-41	$^{40}Ar(n,\gamma)$	1.82 hour	β^-, 1.3 MeV (99%)

Short lifetime!

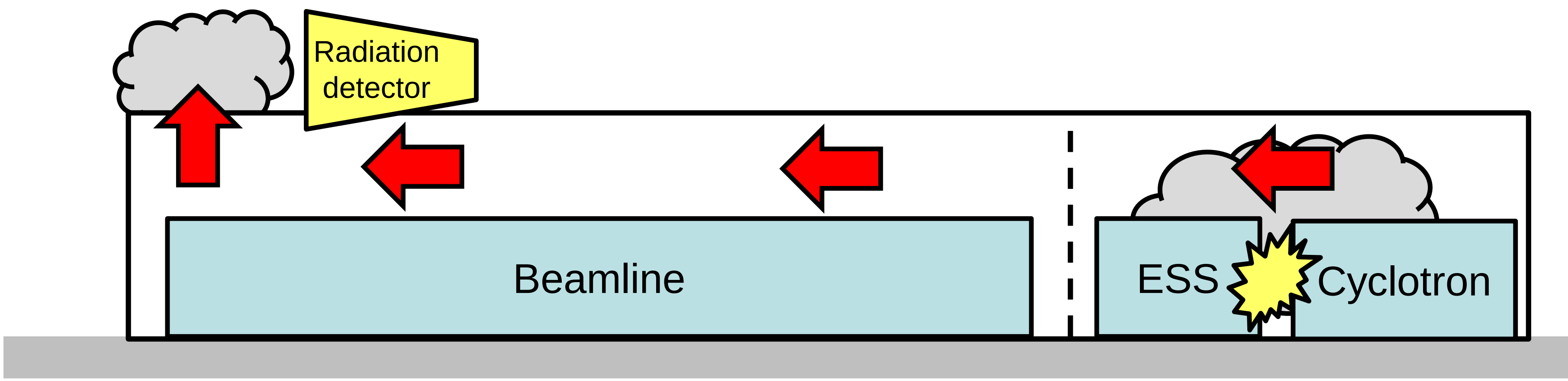
Discharge of activated air

Legal requirement:

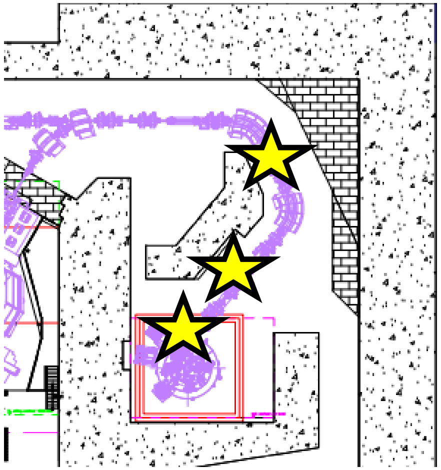
- The dose to individuals in the population < 0.1 mSv/year

Design of DCPT ventilation system:

- Air discharge should be located > 50 m from any building air intake
- Air from the cyclotron and ESS bunker should be transported to the far end of the beamline $\Rightarrow$ Decay of radionuclides before air discharge
- Continuous monitoring of discharged air by a radiation detector.



Activation of cooling water



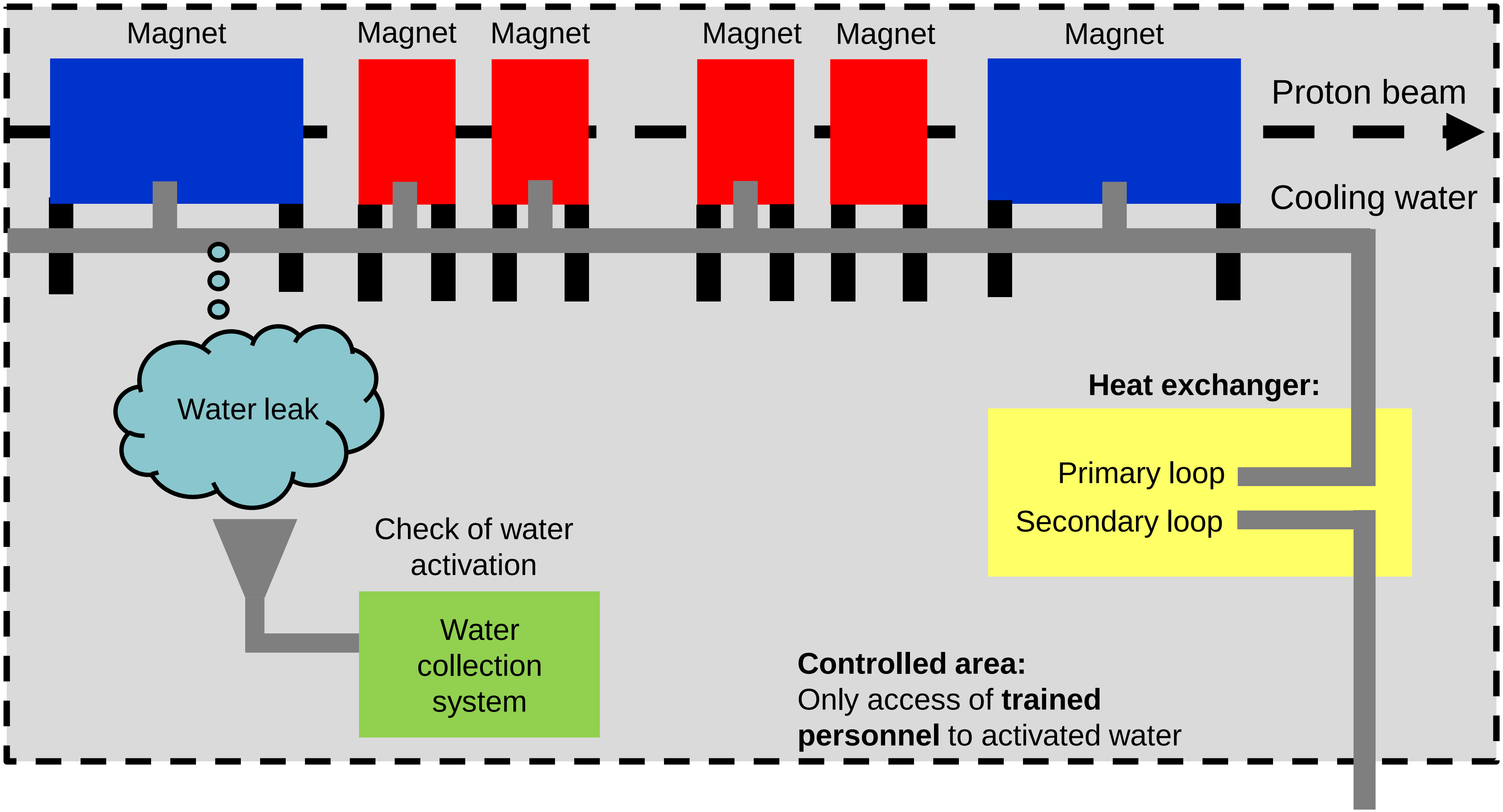
Cooling water activation

Most common radionuclides produced by neutrons in water:

Nuclide	Dominant production reaction	Half-life	Dominant decay reaction and dominant gamma energies
H-3	Spallation of O	12.3 years	β^-, No gamma radiation
Be-7	Spallation of O	53.3 days	EC, 0.5 MeV (10 %)
C-11	Spallation of O	20.4 min	EC β^+, No gamma radiation
N-13	Spallation of O	9.97 min	EC β^+, No gamma radiation
O-14	Spallation of O	1.18 min	EC β^+, 2.3 MeV (99%)
O-15	Spallation of O	2.04 min	EC β^+, No gamma radiation
F-18	$^{18}O(p,n)^{18}F$	1.83 hour	EC β^+, No gamma radiation

Design of DCPT cooling water system

Special design features ⇒ Reduce radiation risk from activated cooling water



Thankyou for your attention