Radiation Protection Studies for Proton Therapy Centres

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Outline

- Introduction
- Radiation sources
- Neutron attenuation in concrete
- Shielding design for a PT centre
- Monte Carlo code validation
- Neutron-induced activation
- Conclusions

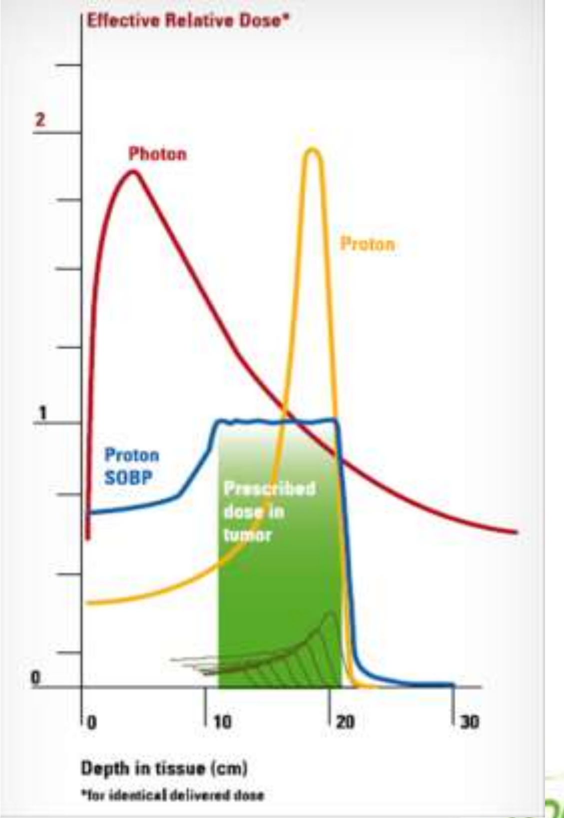
Hadron/Proton Therapy Advantages

Hadron interactions with matter:

- Maximal energy losses at the end of hadron range (Bragg peak);
- Particle range changing with energy
  - ➔ ^{1}H: 70 MeV to 230 MeV (32 cm in water)
- Highly ionizing particles.

Advantages wrt classical RT:

- Precise control of the dose delivered to the tumor
- Reduction of dose delivered to healthy tissue, sparing critical organs located behind tumor.
- Larger radiobiological efficiency (RBE ~ 2 to 3 for ^{12}C ions).

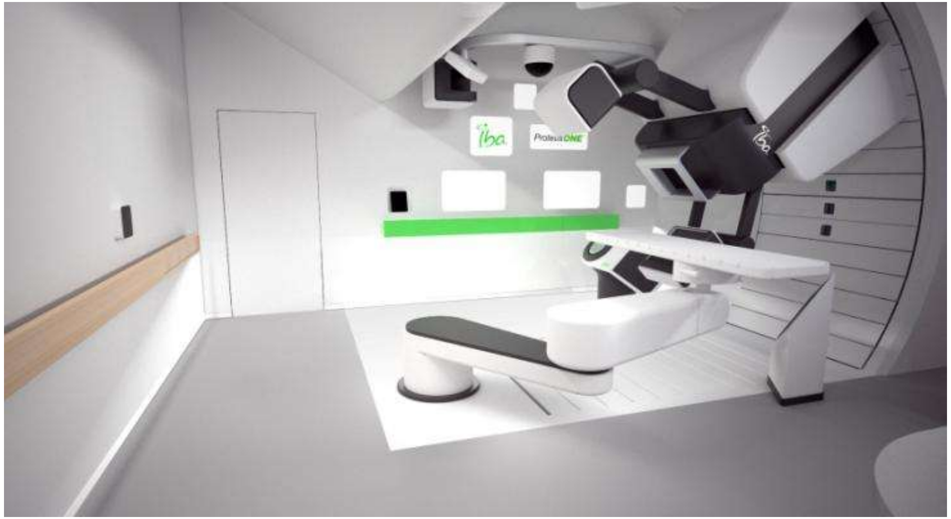


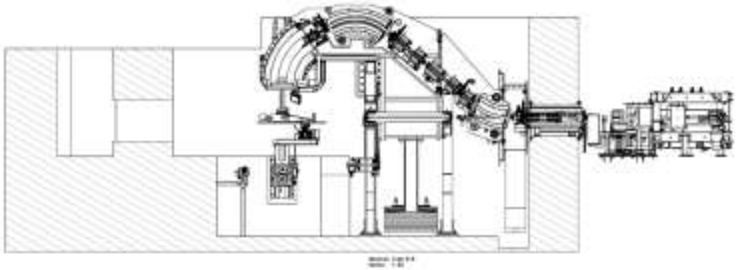
Proton Therapy Center by IBA

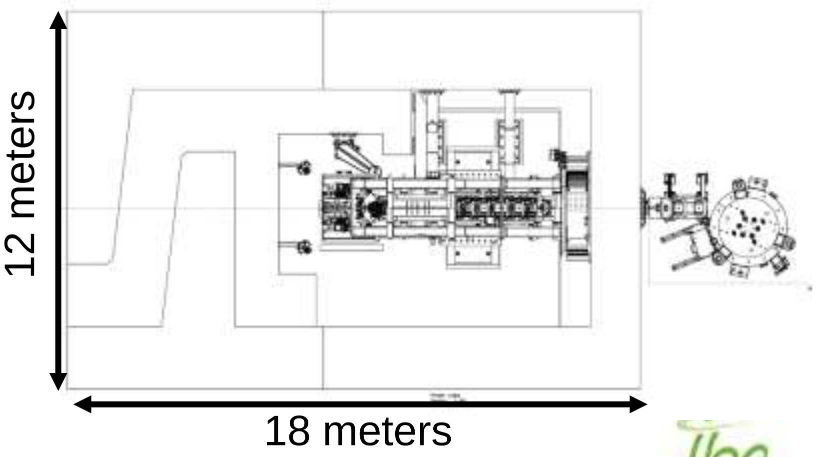
- **IBA has installed its first PT system at Massachusetts General Hospital (MGH) in Boston (2000).**
- **IBA is now the world leader in Proton Therapy with more than 20 centers already installed or in construction in USA (10), Europe (8) and Asia (3).**

ProteusONE: Compact PT System

Single-room system equipped with a superconducting cyclotron and a compact gantry.

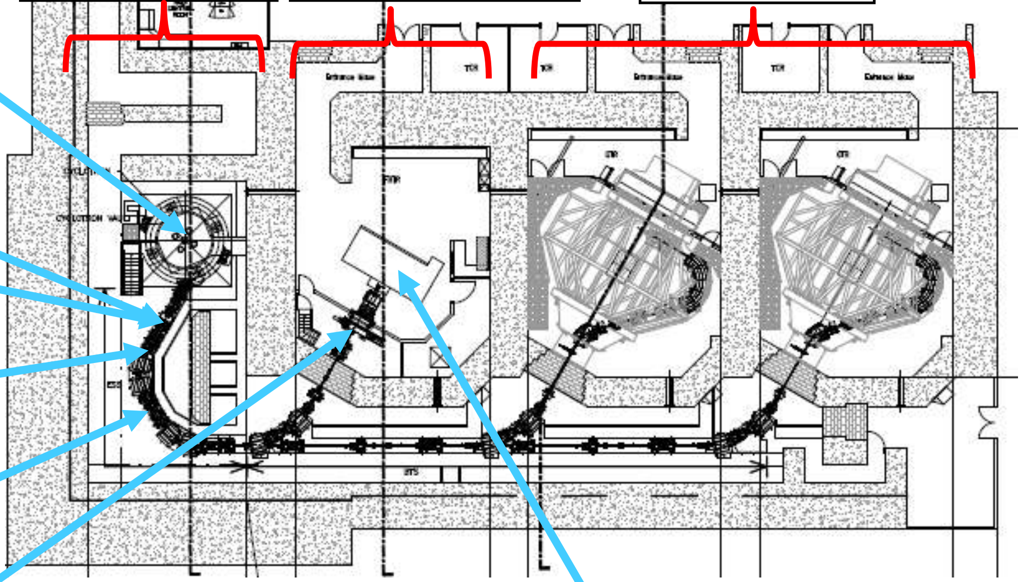






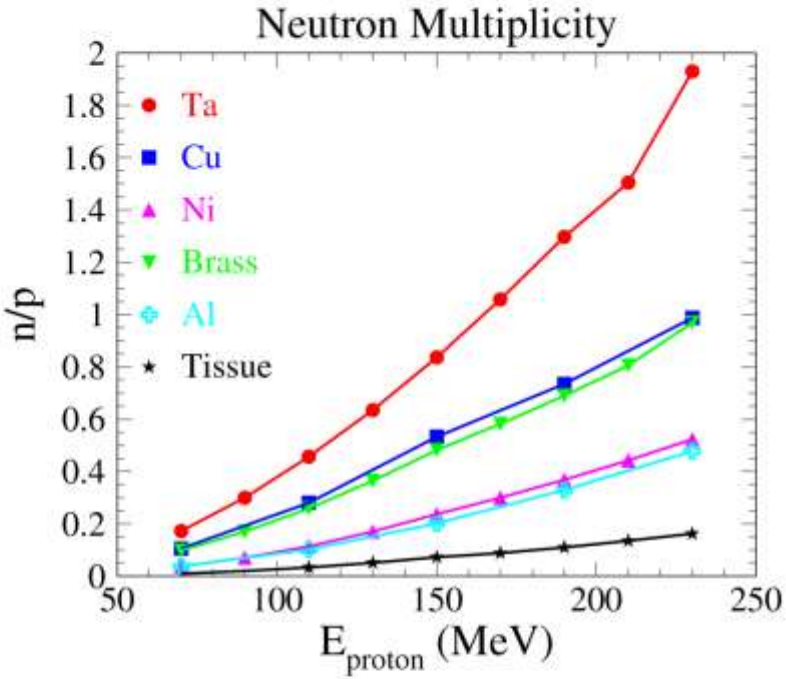
Radiation Sources in Cyclotron & Treatment Rooms

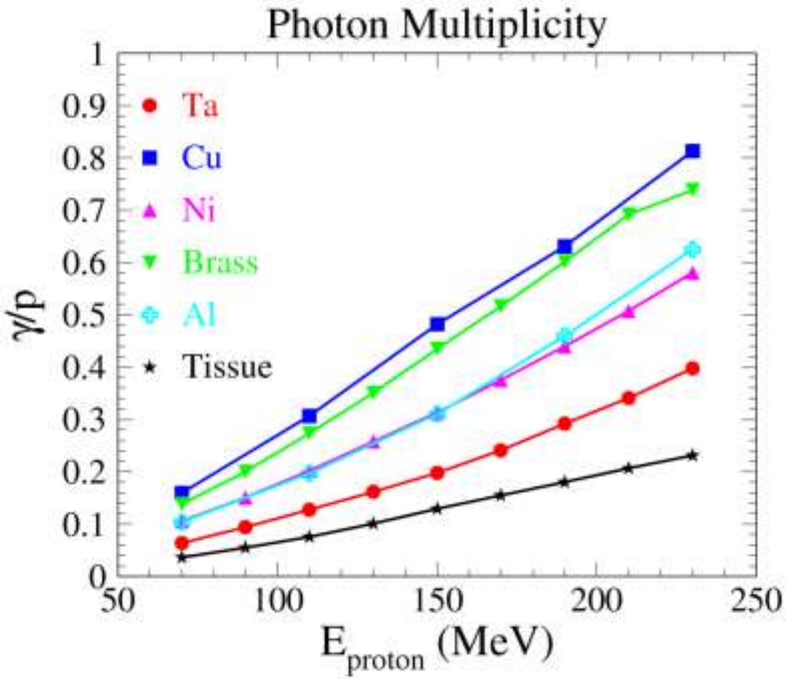
Neutrons and photons are produced at various locations along beam path when protons hit matter



Secondary Radiation (1)

Yields of secondary particles depend on beam energy and target materials

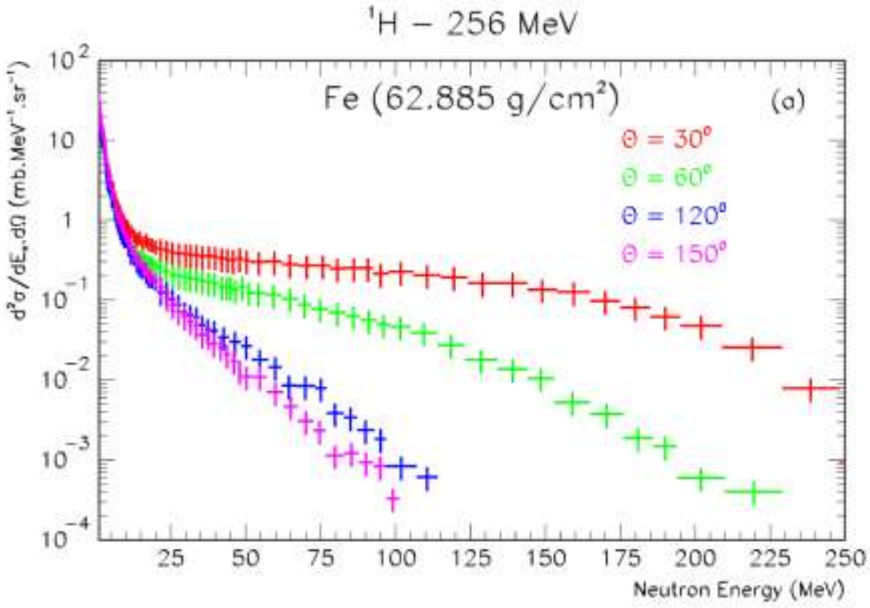




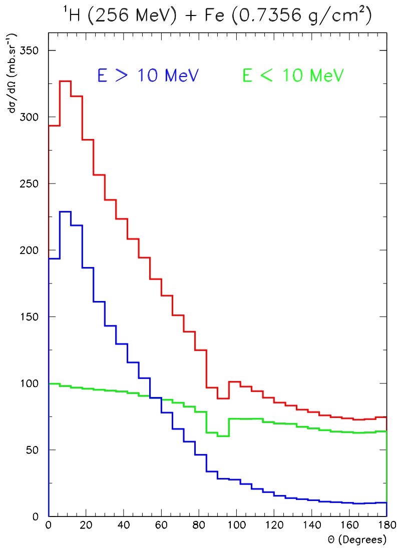
Secondary Radiation (2)

Production of secondary neutrons:

- Intranuclear cascade ➔ high-energy neutrons, mostly forward emission
- Target nuclei evaporation ➔ neutrons < 10 MeV, isotropic emission



M.M. Meier et al, Nucl. Sci. Eng. **104**, 339 (1990)

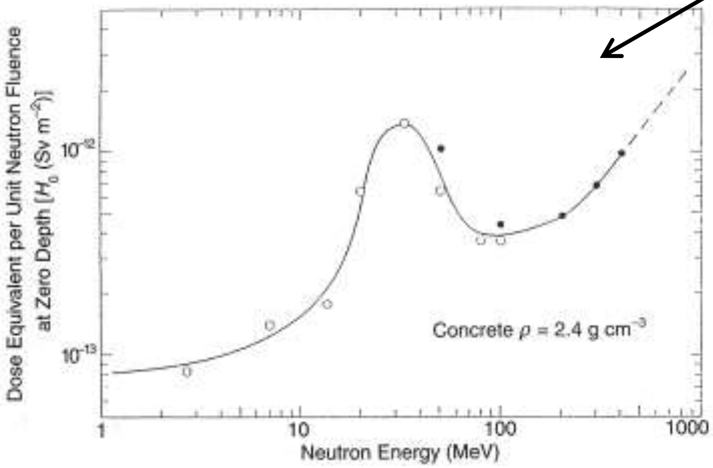


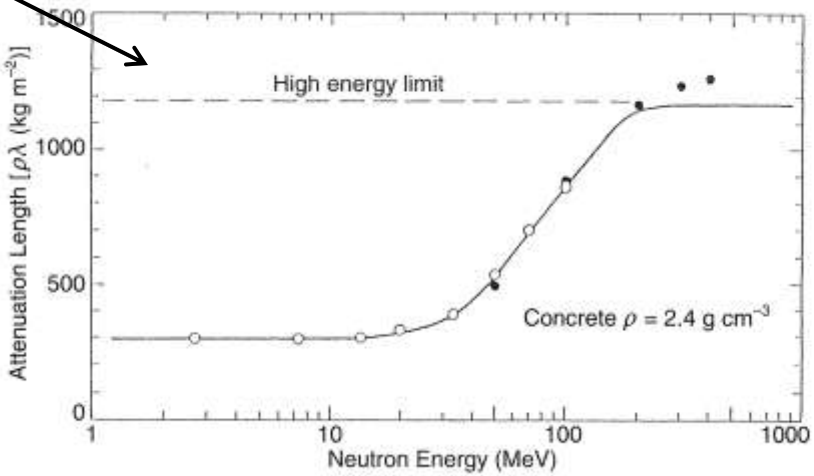
MCNPX simulation

Neutron Attenuation in Concrete (1)

- **Proton Interactions with matter:**
  - Secondary neutrons with energies up to 230 MeV
  - Continuous energy spectra and strong Θ variations
- **For a wide and monoenergetic neutron beam traversing a shielding with thickness z:**

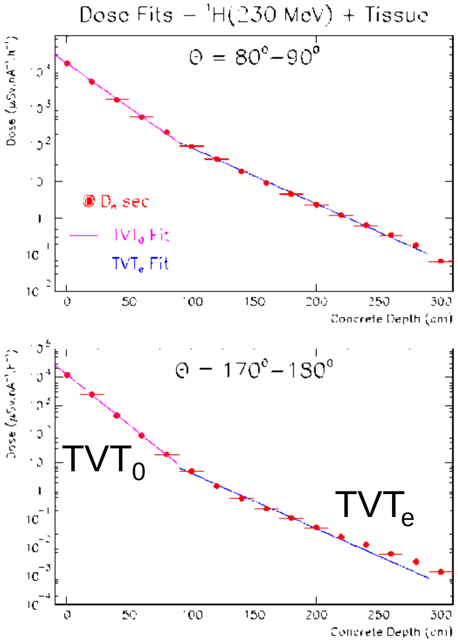
$$H(z) = H_0 e^{-z/\lambda}$$



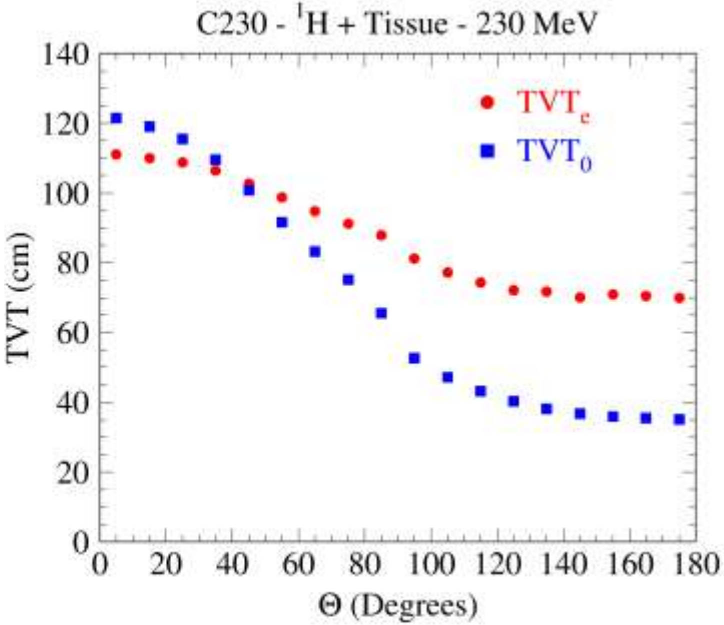


NCRP-144: Radiation Protection for Particle Accelerator Facilities (2005)

Neutron Attenuation in Concrete (2)



$H(z) = H_0\, 10^{-z/TVT}$



- Strong variation of TVT_0 with Θ due to differences in energy spectra.
- $TVT_0 \neq TVT_e$ because of neutron spectrum hardening with shielding depth.

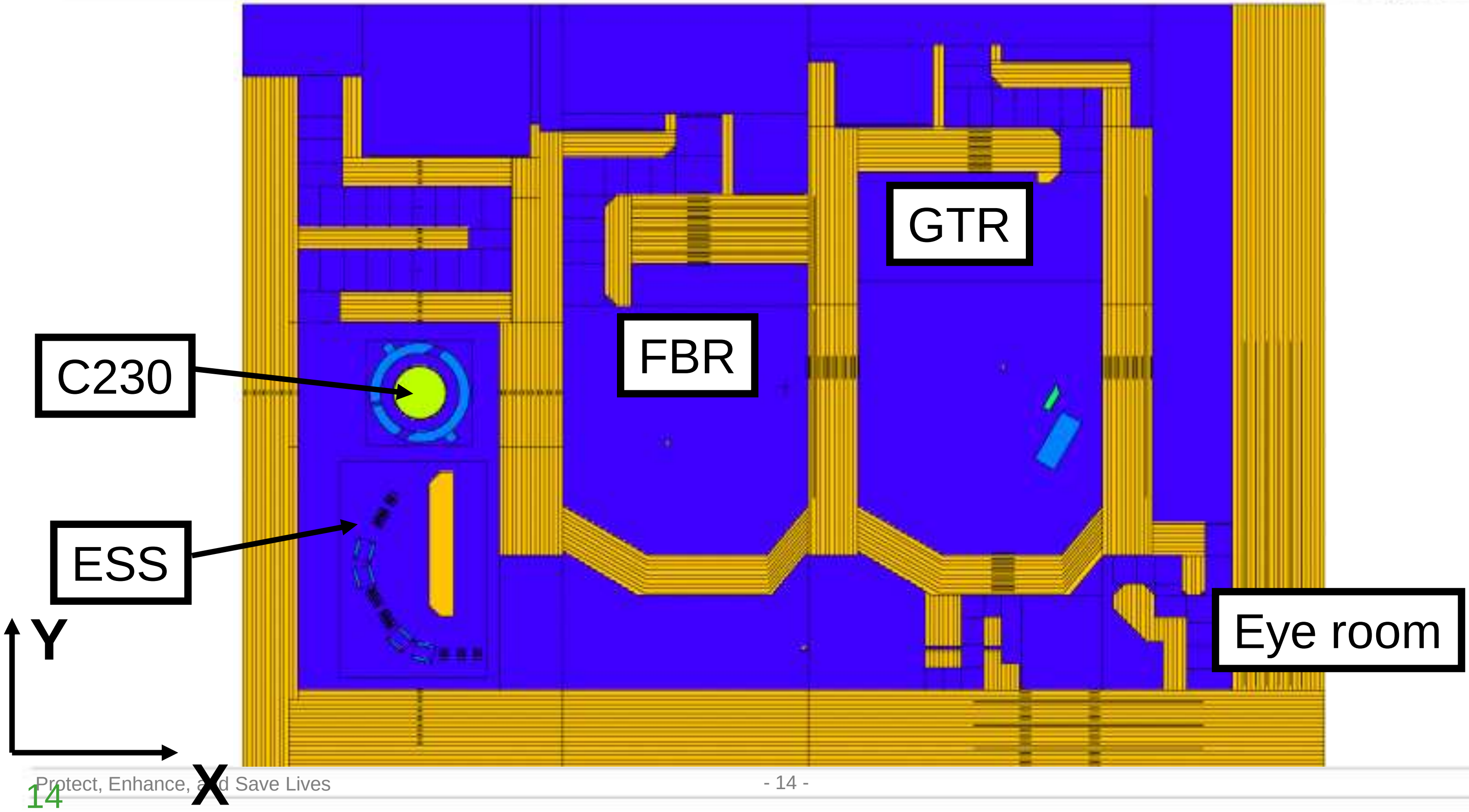
Monte Carlo Transport Codes

- **General purpose Monte Carlo (MC) codes allow the transport of electrons, photons, neutrons, protons and heavy ions in matter from low energy (1 keV) to the TeV range:**
  - MCNPX – FLUKA – GEANT4 – PHITS
- **These codes simulate all possible interactions + generate and transport secondary particles.**
- **Proton and neutron transport in MCNPX (Mix&Match):**
  - Based on nuclear database LA150 up to 150 MeV
  - Based on nuclear models above 150 MeV
- **Various intranuclear cascade and evaporation models available in MCNPX 2.7.0 (Bertini, INCL4, CEM03)**

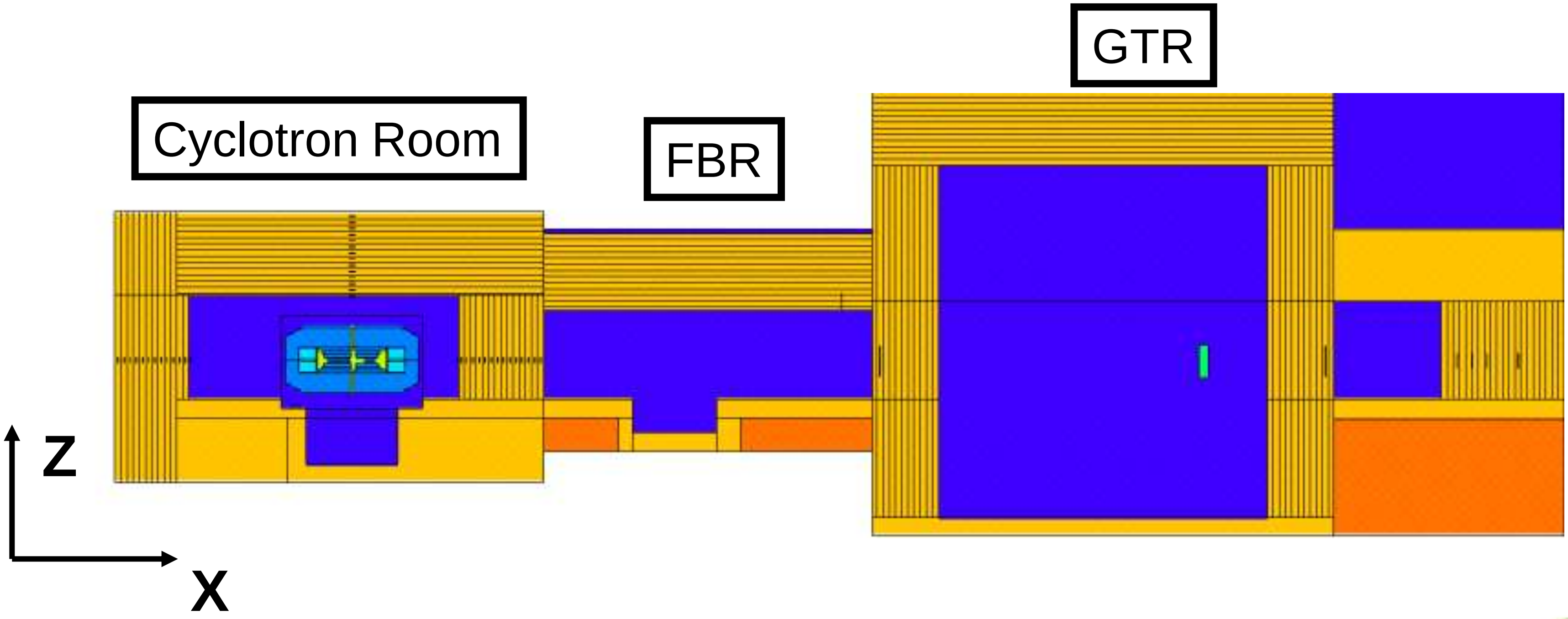
Shielding Design for PT Centre

- 3D modelling of whole facility using MCNPX: cyclotron room and treatment rooms.
- Development of a patient case mix based upon clinical requirements.
- Conversion to beam data → set of beam energies and workloads.
- Simulation of all major radiation sources for each clinical indication and computation of resulting ambient dose equivalent H*(10) or effective dose E(AP), using ICRP-74 fluence-to-dose conversion factors for neutrons and photons.
- Sum of all radiation sources and clinical indications to determine the annual H*(10) values.
- Determination of shielding thicknesses based upon local regulations for controled and public areas.

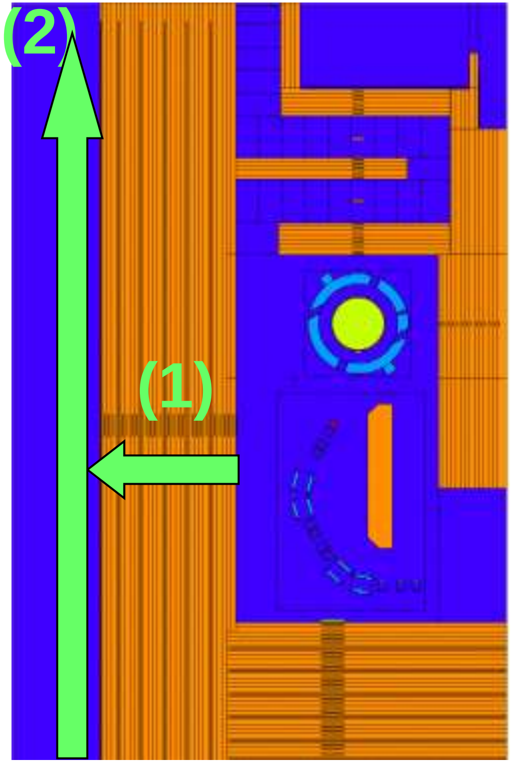
PT Centre Modelling with MCNPX (1)

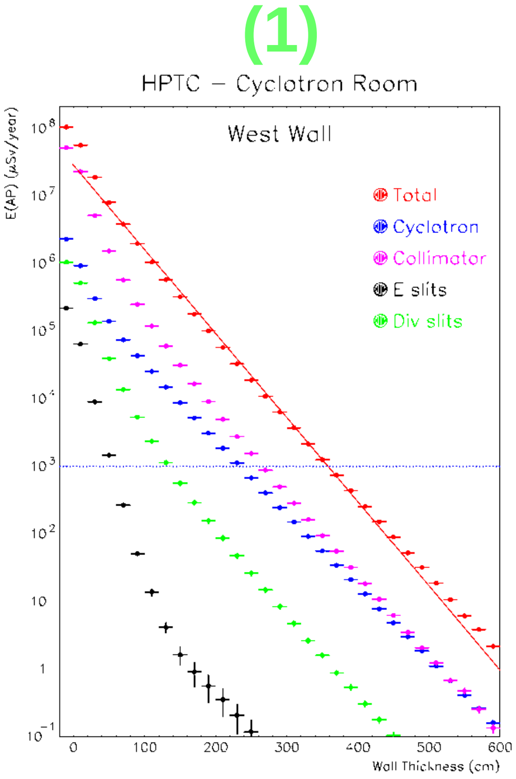


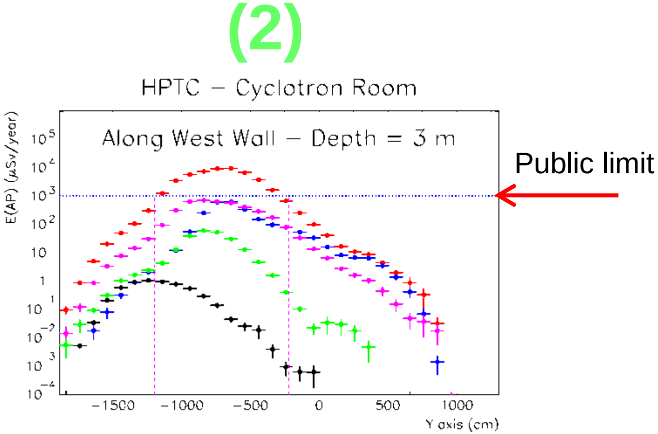
PT Centre Modelling with MCNPX (2)

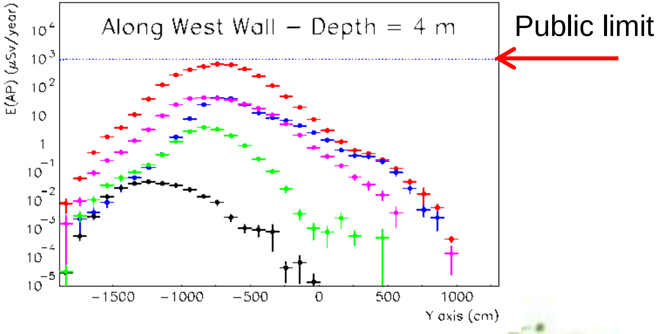


Cyclotron Room: Side Wall

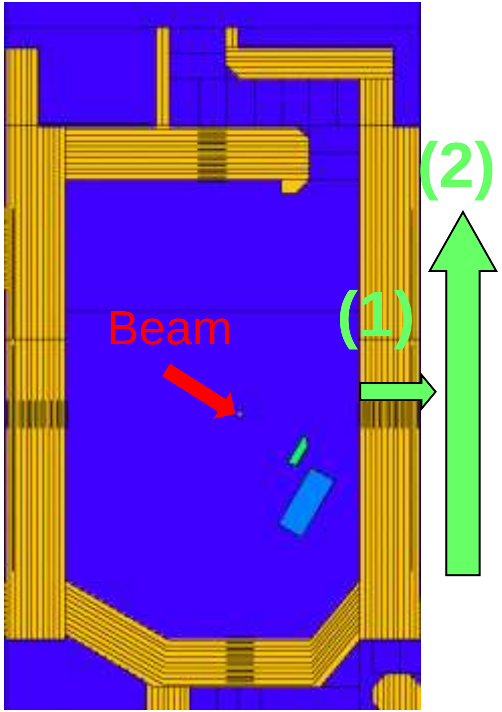


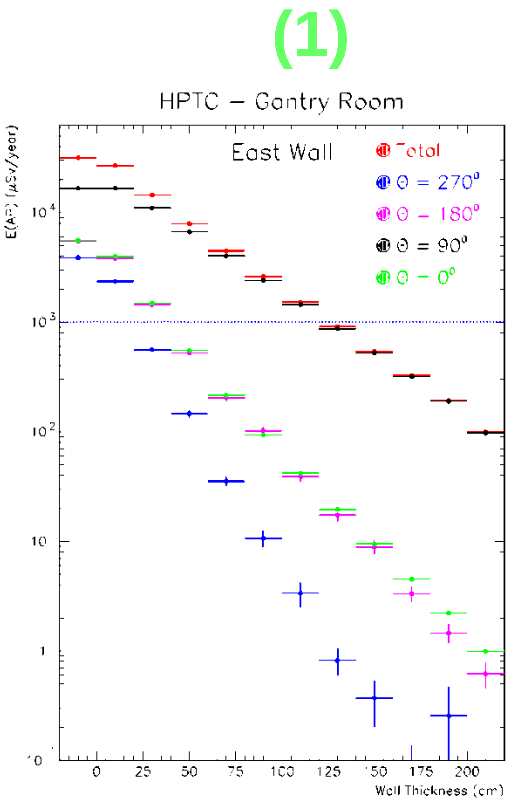


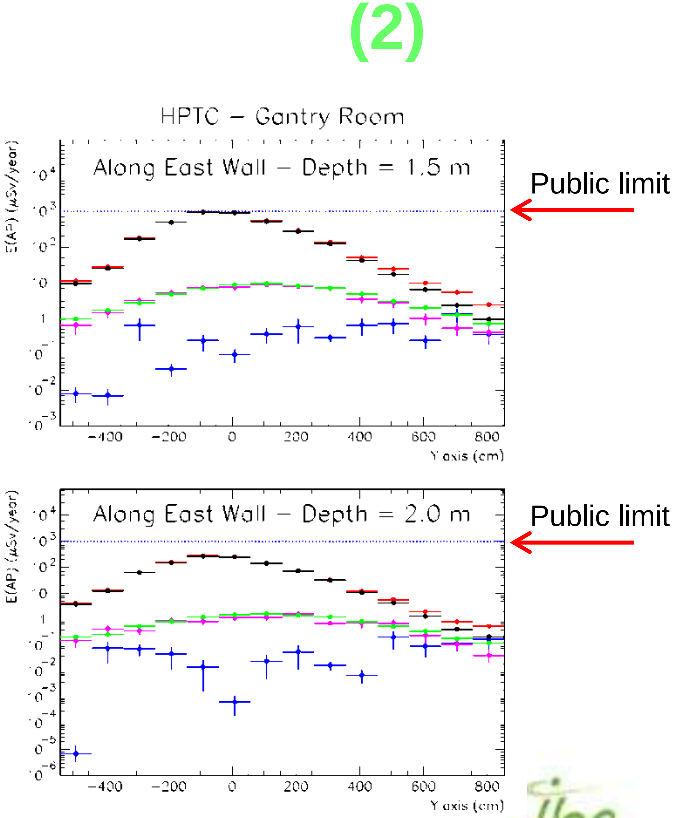




Gantry Room: External Wall







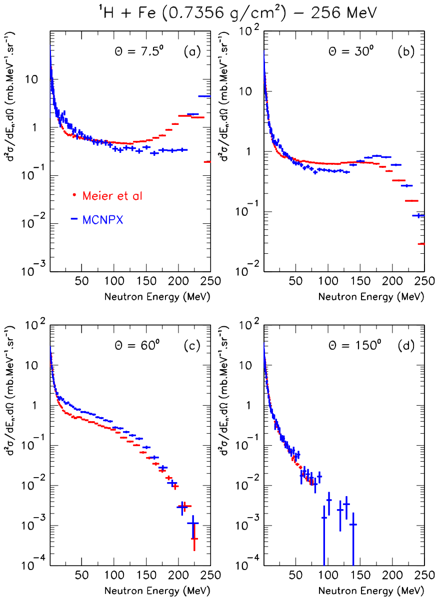
Validation of MC Codes

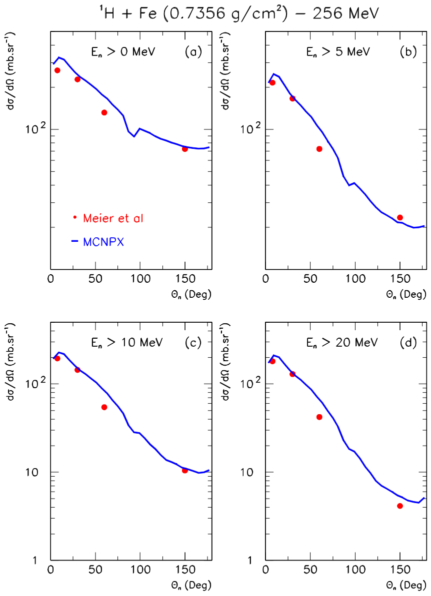
- **Shielding design of our PT centres relies mostly on MC simulations using MCNPX.**
- **Validation of these simulations:**
  - Benchmarking of MCNPX for the production of secondary neutrons using LANL data.
  - Measurements of ambient dose equivalents around PT equipment using wide-energy range neutron detectors (FREDONE project - ISIB-ULB-IBA collaboration)

MC Validation: Neutron Generation (1)

Secondary neutron yields measured by Meier's team at LANL:

- Proton beams 113, 256, 597 and 800 MeV
- Stopping-length and thin targets Be, B, C, Al, Fe, W, Pb, ^{238}U
- Measured data available in EXFOR database

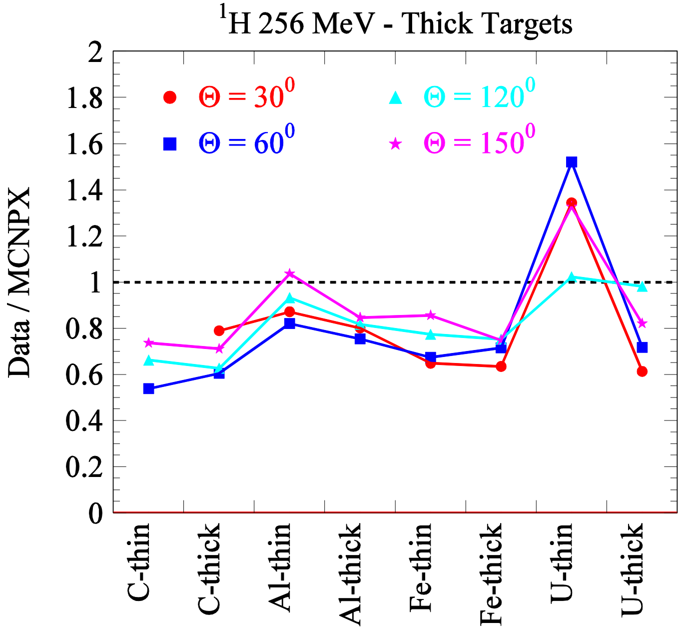


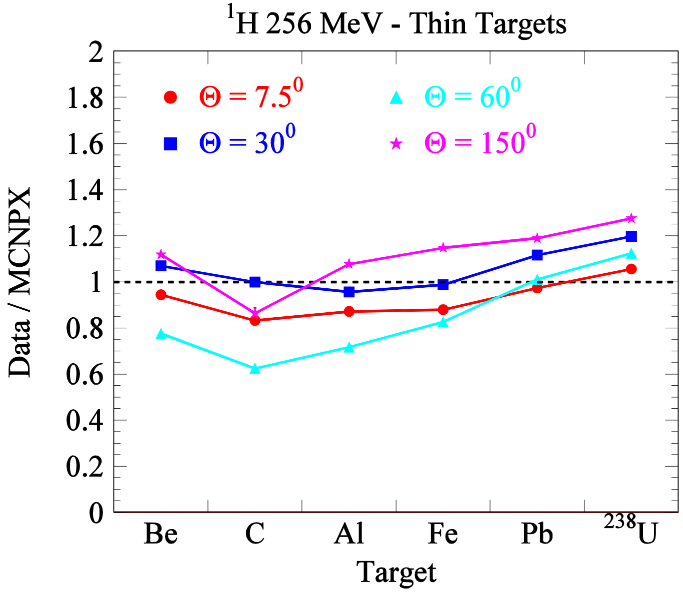


M.M. Meier et al,
Nucl. Sci. Eng. **110**, 289 (1992)

MC Validation: Neutron Generation (2)

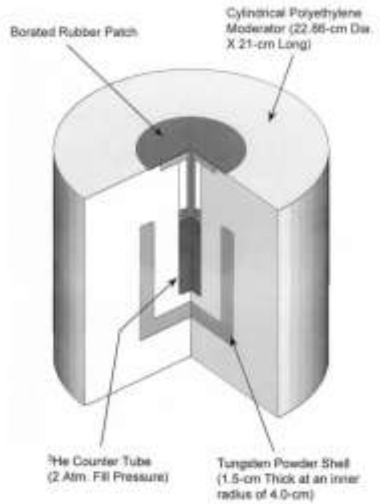
Comparison of energy-integrated yields obtained for 256 MeV protons impinging on various thick and thin targets

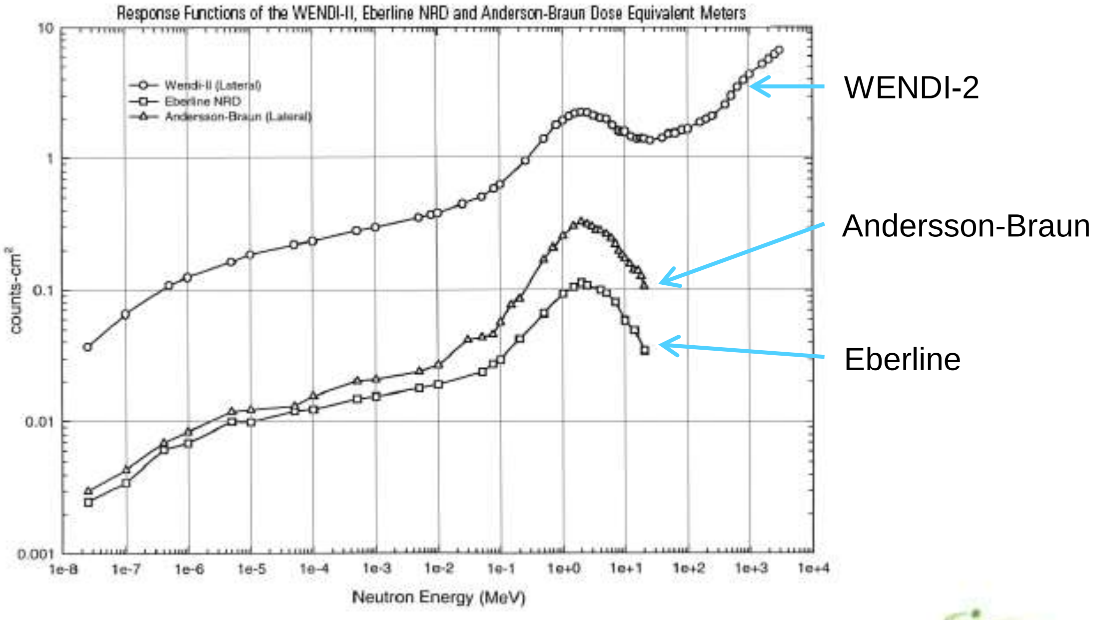




MC Validation: Neutron Detection (1)

Special neutron detector needed to measure H*(10) with high-energy neutrons
➔ WENDI-2 from Thermo Scientific able to detect neutrons up to 5 GeV.

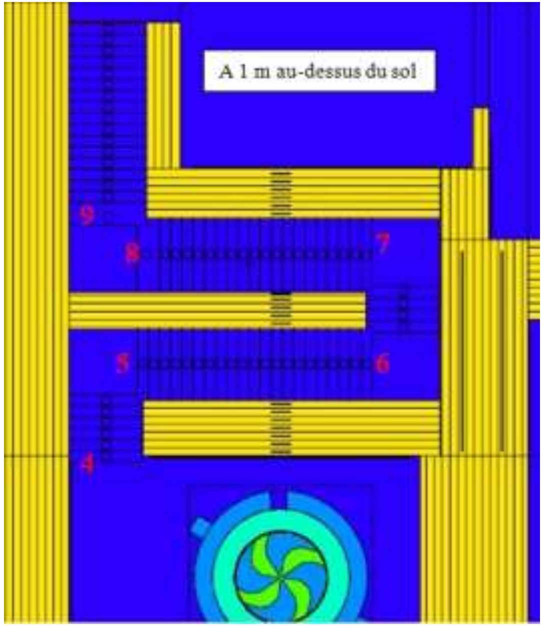


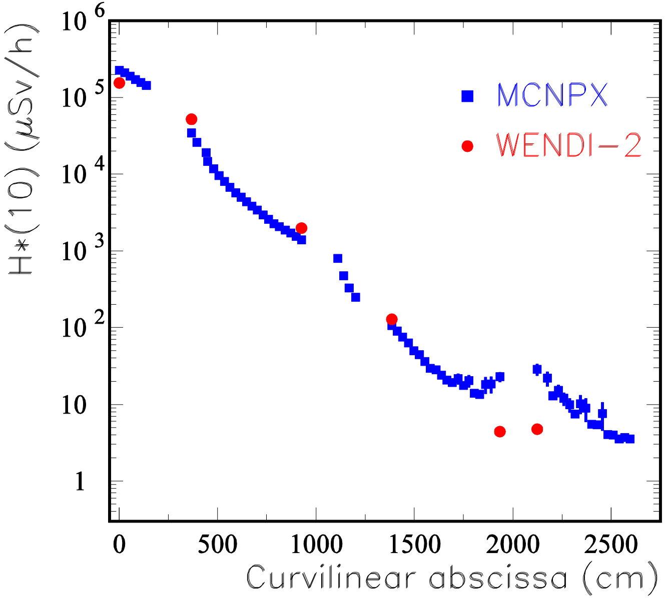


Tungsten powder shell to generate (n,xn') reactions

MC Validation: Neutron Detection (2)

- Measurements performed at WPE in Essen, Germany.
- Comparison of ambient dose equivalent H*(10) measured along cyclotron access maze and MCNPX prediction.





Activation Studies

- **Neutron-induced activation processes:**
  - Inelastic collisions (spallation processes)
  - Neutron capture (n,γ)
- **MC codes are also very usefull for these activation studies:**
  - Air and cooling water activation ➔ release strategy.
  - Shielding concrete activation ➔ building decommissioning.
  - Activation of PT components (Cyclotron, magnets, beam shaping devices) ➔ personal radioprotection and long-term decommissioning.
- **Codes such as FLUKA and PHITS allow the prediction of the whole history, from nuclear reactions to specific activities or dose rates after some cooling period.**

Conclusions

- **Proton therapy offers significant improvements in cancer therapy compared to classical radiotherapy.**
- **Interaction of medium-energy protons leads to the production of complex fields of secondary neutrons and photons.**
- **General purpose Monte Carlo simulation codes are ideal tools to deal with these mixed fields for radioprotection studies:**
  - Shielding design for PT facilities
  - Neutron-induced activation mechanisms
- **MC benchmarking generally shows good agreement between MC predictions and measured data.**

Thank you