Neutron deep-penetration calculations & shielding design of proton therapy accelerators

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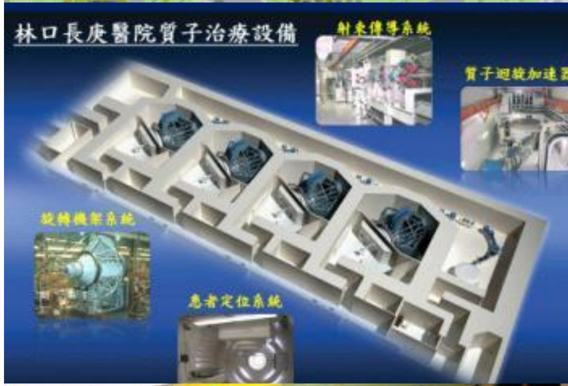
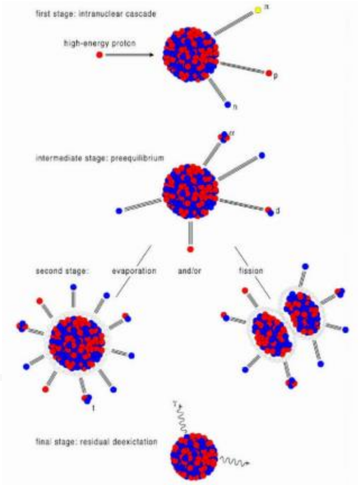
New accelerators in Taiwan

- Taiwan Photon Source
  - NSRRC, Hsinchu
  - 3 GeV electron synchrotron
  - Installation 2013, commissioning 2014
- Proton therapy center
  - Chang Gung Memorial Hospital, Linkou
  - 235 MeV proton cyclotron
  - Commissioning 2013, clinical trial 2014
- Heavy ion therapy center
  - Veterans General Hospital, Taipei
  - 400 MeV/A carbon cyclotron
  - In planning



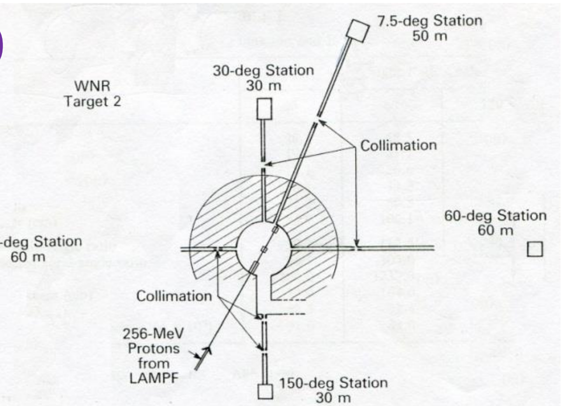


Accelerator shielding

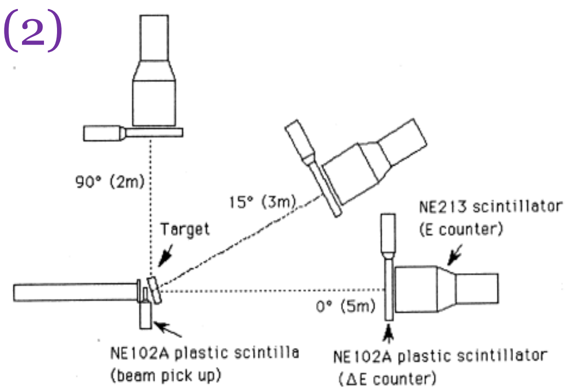
- Key issues in shielding design
  - Neutrons produced from hadronic cascade or EM cascade with photonuclear interaction are dominant dose component
  - Neutron production and deep-penetration calculations

- Selected experiments on thick-target neutron yield
  - 256 MeV proton on iron (Meier et al., 1990)[1]
  - 400 MeV/A carbon on copper (Nakamura et al., 2006)[2]
  - 2.04 GeV electron on copper (Lee et al., 2005)[3]

(1)



(2)



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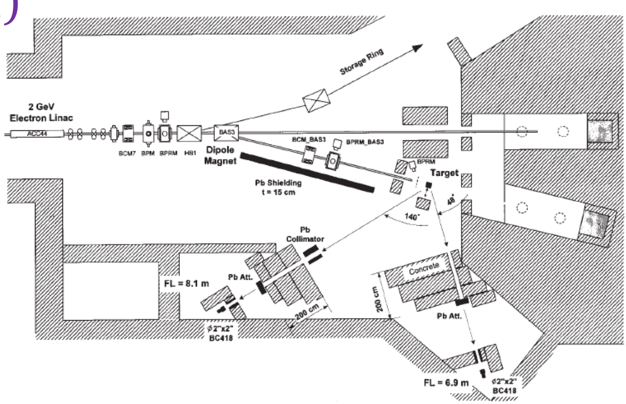
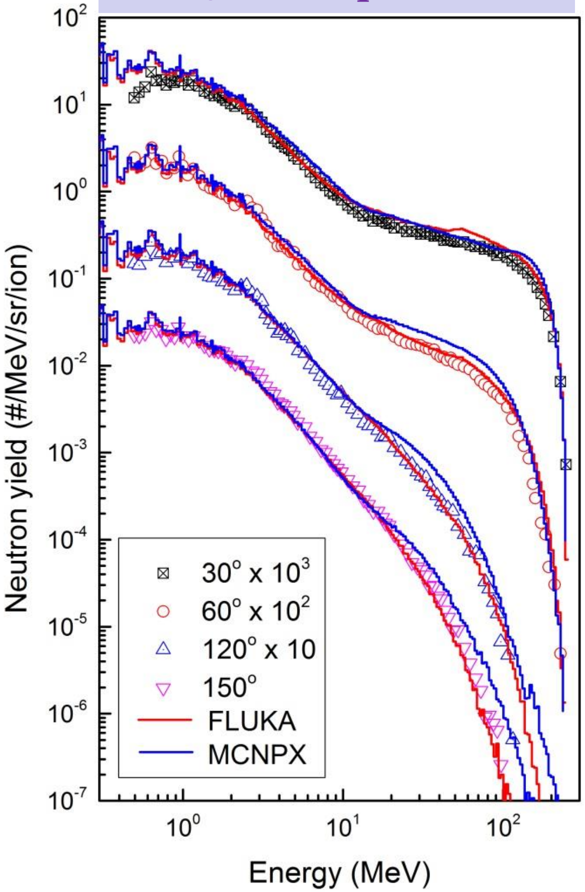


Benchmark calculations for double differential neutron yield

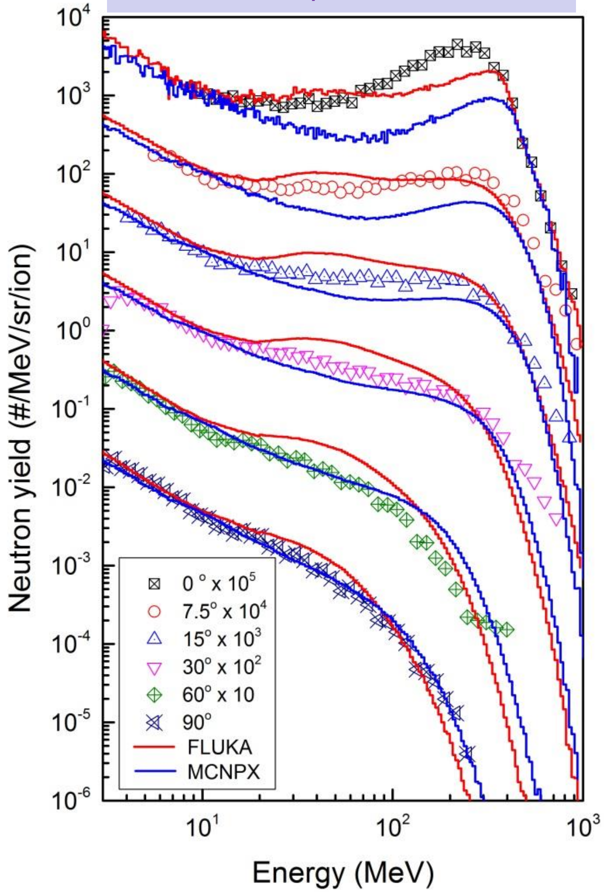
FLUKA v2011.2 & MCNPX v2.7.0

- Comparisons of experimental results with calculations

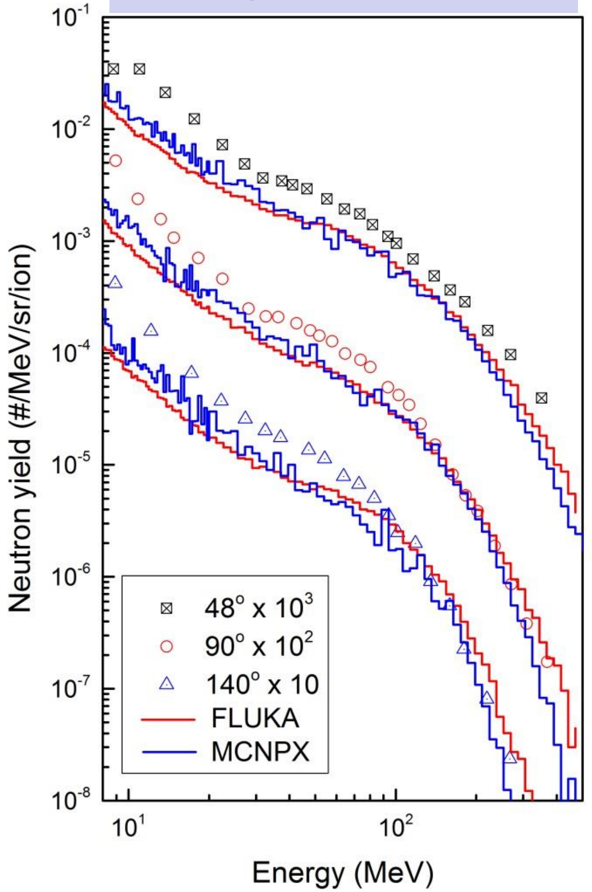
256 MeV p on Fe



400 MeV/A ¹²C on Cu



2.04 GeV e⁻ on Cu



Ranges of neutron source intensities

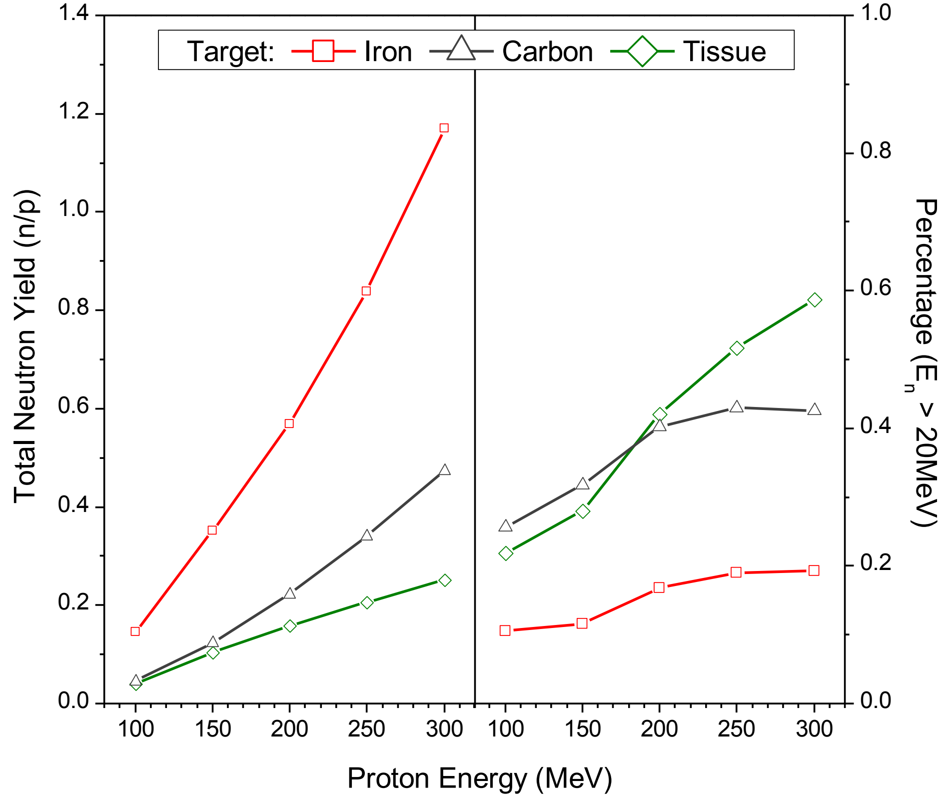
- For three accelerators of main concern
  - 235 MeV proton cyclotron
  - 400 MeV/A carbon cyclotron
  - 3.0 GeV electron synchrotron
  - Total number of neutrons produced per incident primary particle (n/p) calculated by FLUKA and MCNPX:

Beam	Target	FLUKA	MCNPX
235 MeV proton	Iron	$0.70 \pm 0.13\%$	$0.79 \pm 0.24\%$
400 MeV/A carbon	Copper	$9.02 \pm 0.14\%$	$5.92 \pm 0.24\%$
3.0 GeV electron	Copper	$0.63 \pm 0.36\%$	$0.51 \pm 0.21\%$

Neutron production from proton bombardment

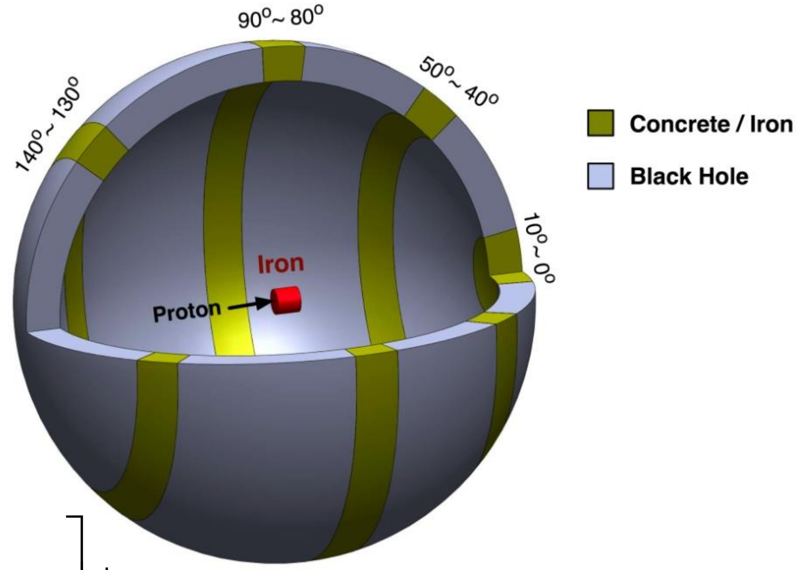
- For various proton energies and target materials
  - LHS: total neutron yield
  - RHS: percentage of high-energy neutrons ($E_n > 20\ MeV$)

- Neutron yield increases significantly as increasing proton energies, especially for high-Z targets.
- Low-Z targets cause harder neutron spectra, i.e. more forward-peaked neutrons and anisotropy of dose distribution.



Parameters for shielding design

Point- source line-of-sight model

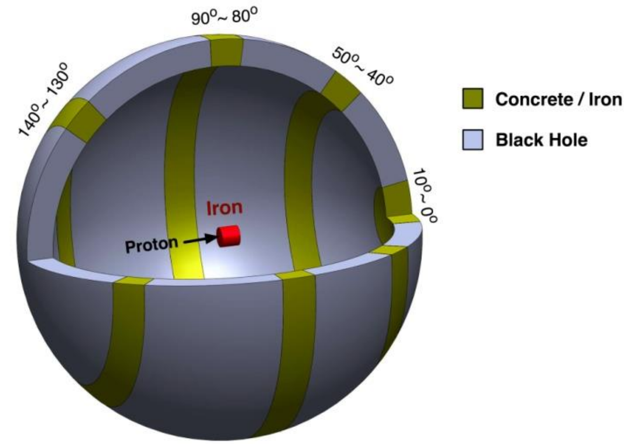


- A simplified method ~

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

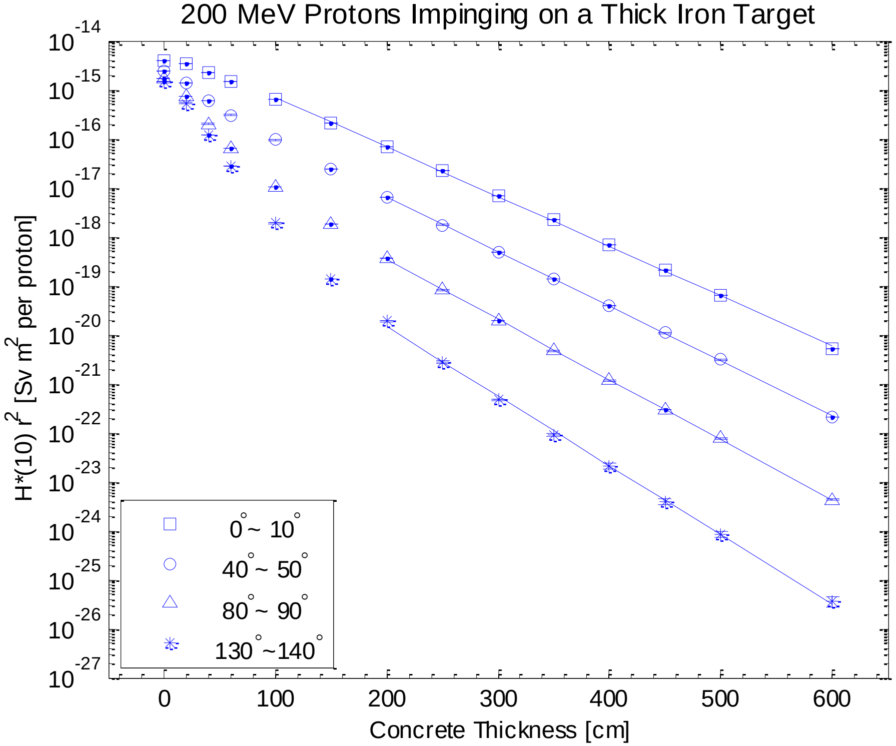
- Source term H_0 and attenuation length λ_θ = ?
  - Literature data (a wide range of variability)
  - Radiation transport calculations (neutron deep penetration)
- Calculation model (Agosteo et al., 2007)
  - Primary beam: 200 MeV protons
  - Shielding material: concrete & iron
  - Use **FLUKA** & **MCNPX** to simulate the production and transport of all secondary radiation produced from proton bombardment
  - Depth dose distributions in shield
    → Curve fitting → Source terms & attenuation lengths

Neutron deep-penetration calc.

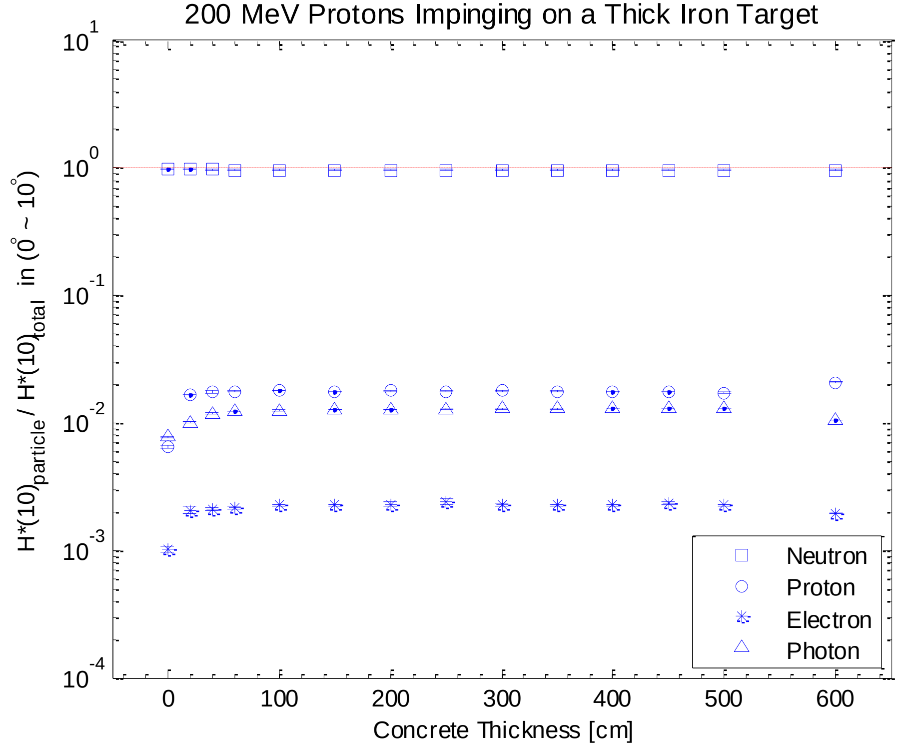


- Concrete shielding
  - Consistent with reference: *NIM-B265, p.581, 2007*

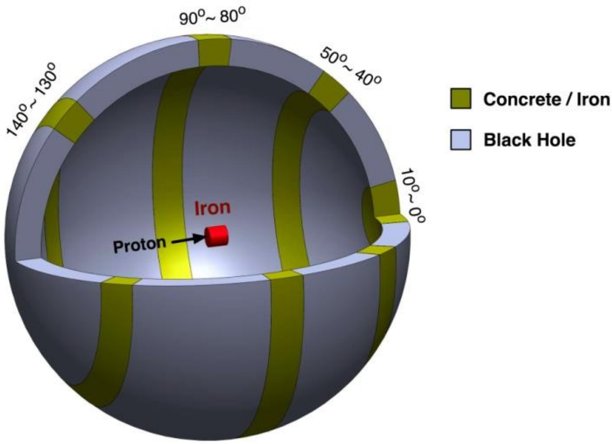
Attenuation of Total Dose Equivalent in Ordinary Concrete for 200 MeV Protons Impinging on a Thick Iron Target



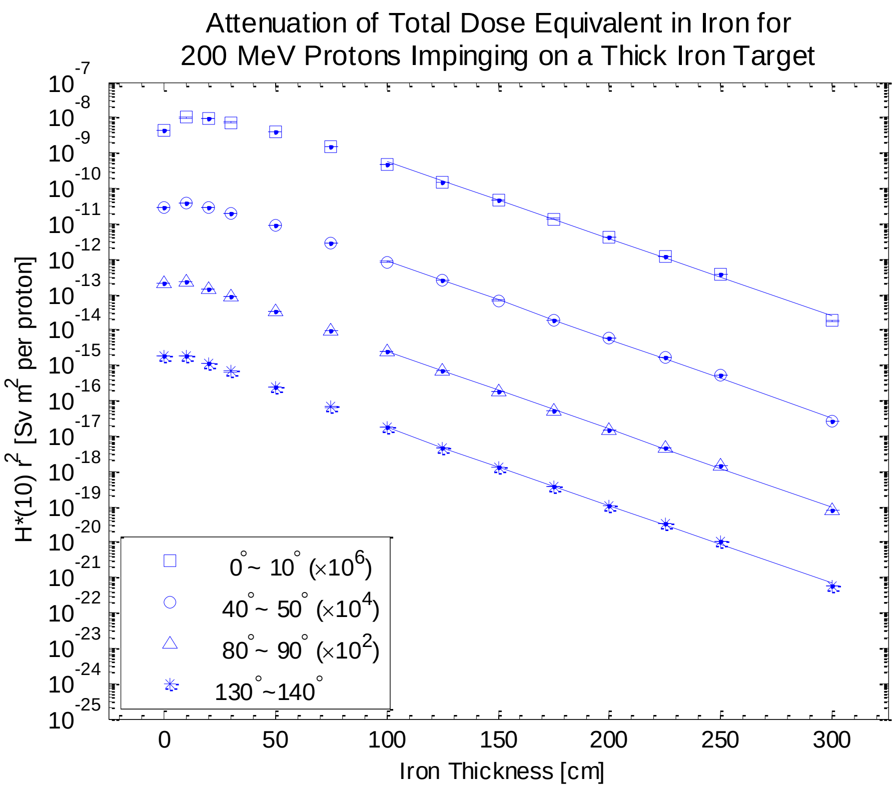
Relative Contribution of Various Particles to Total Dose in Concrete 200 MeV Protons Impinging on a Thick Iron Target



Neutron deep-penetration calc.



- Iron shielding
  - Inconsistent with reference: *NIM-B266, p.3406, 2008*

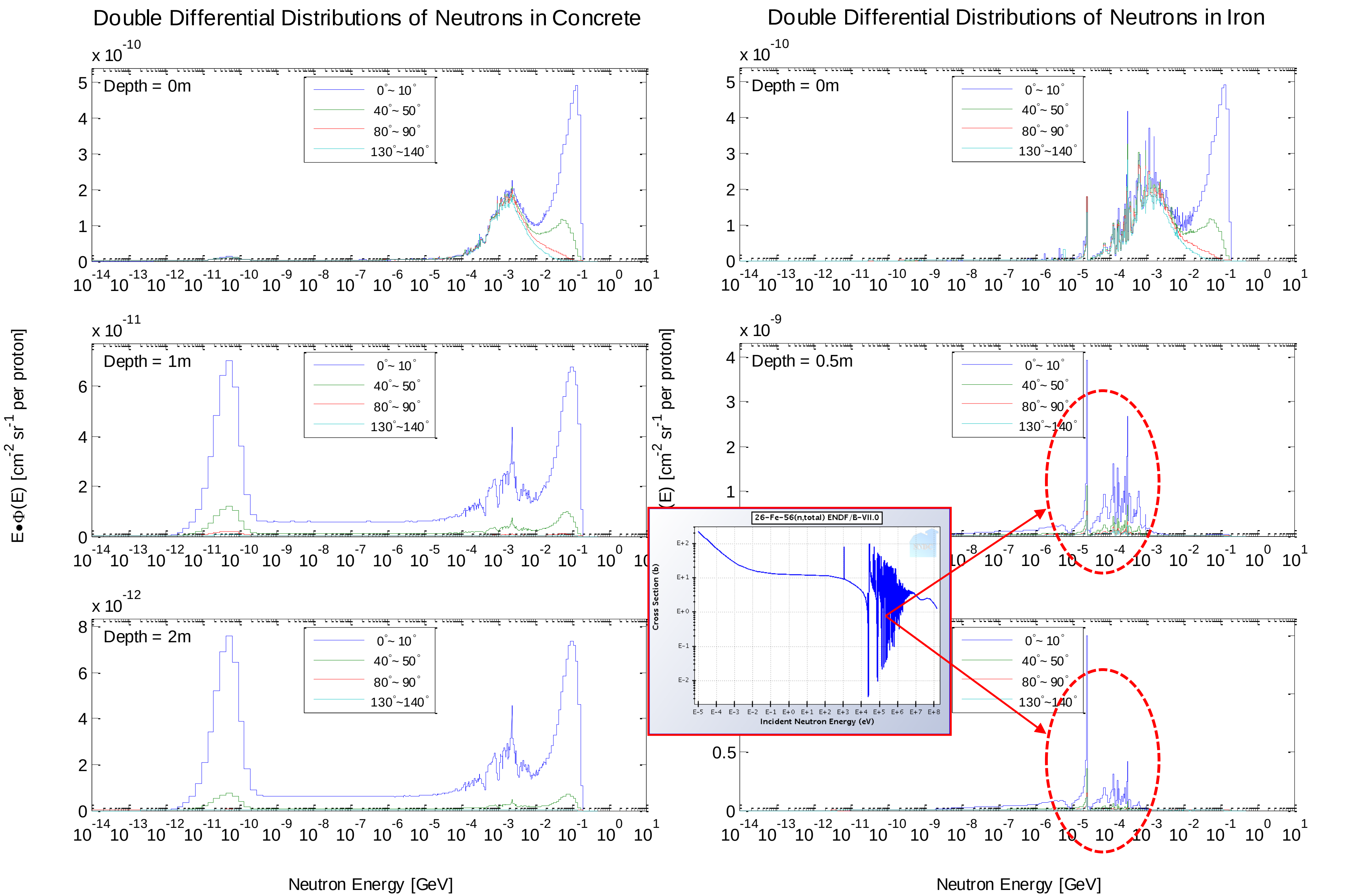


	First exponential		Second exponential	
	H_1 [Sv m^2 per proton]	λ_1 [g cm^{-2}]	H_2 [Sv m^2 per proton]	λ_2 [g cm^{-2}]
0°~10°:	1.9573869e-014	231.26087	8.6791123e-014	156.39452
40°~50°:	7.0531340e-015	184.78711	1.4822132e-014	153.90741
80°~90°:	3.8826802e-015	158.39371	4.0535242e-015	154.48923
130°~140°:	3.0590892e-015	153.40506	2.6849795e-015	155.24485

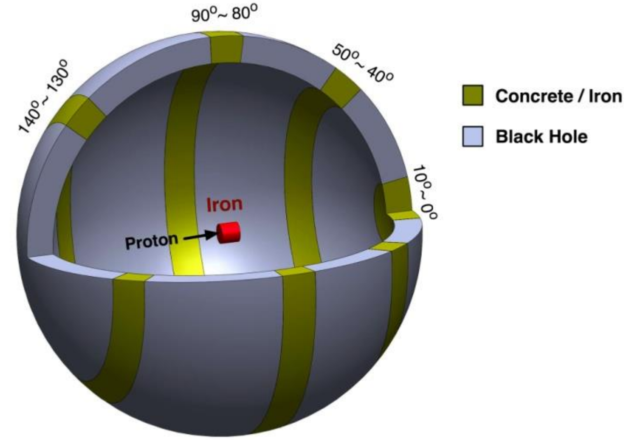
cf. *S. Agosteo et al. NIMB-266 (2008) 3406-3416, Table 3&2*

	First exponential		Second exponential	
	H_1 [Sv m^2 per proton]	λ_1 [g cm^{-2}]	H_2 [Sv m^2 per proton]	λ_2 [g cm^{-2}]
0°~10°:	$(9.7\pm0.07)\times10^{-15}$	222.0 ± 1.0	$(5.5\pm0.04)\times10^{-14}$	140.8 ± 0.2
40°~50°:	$(4.0\pm0.02)\times10^{-15}$	170.1 ± 0.4	$(1.7\pm0.01)\times10^{-14}$	124.5 ± 0.1
80°~90°:	$(2.3\pm0.01)\times10^{-15}$	138.6 ± 0.2	$(1.0\pm0.01)\times10^{-14}$	108.4 ± 0.06
130°~140°:	$(1.6\pm0.01)\times10^{-15}$	133.4 ± 0.2	$(7.5\pm0.03)\times10^{-15}$	104.4 ± 0.03

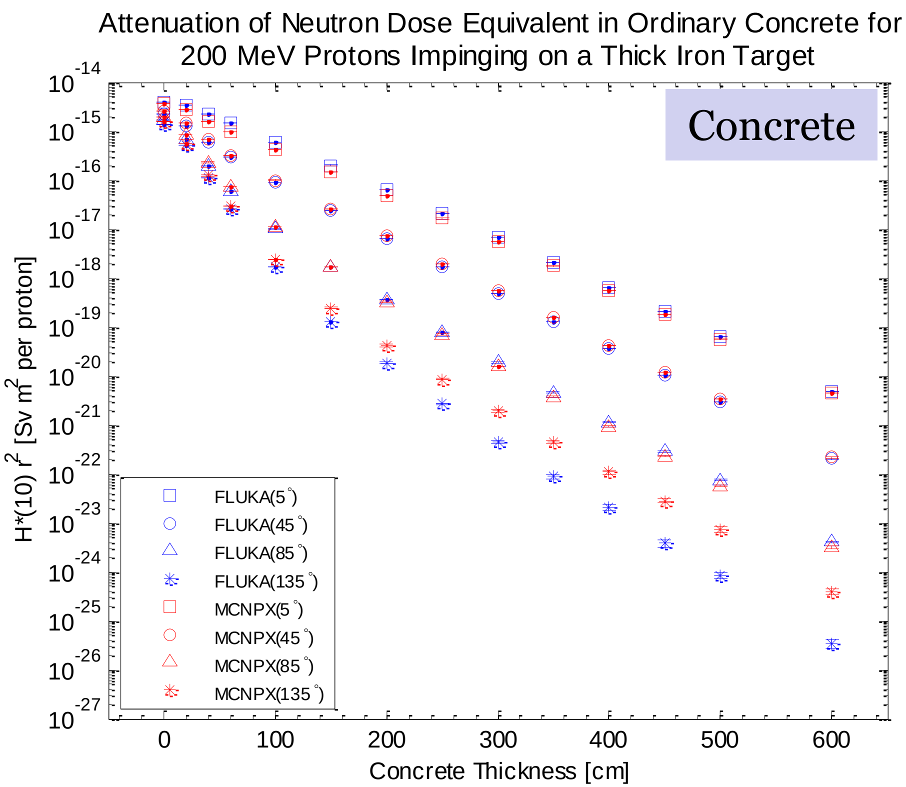
Neutron spectra at various depths in concrete and iron shield

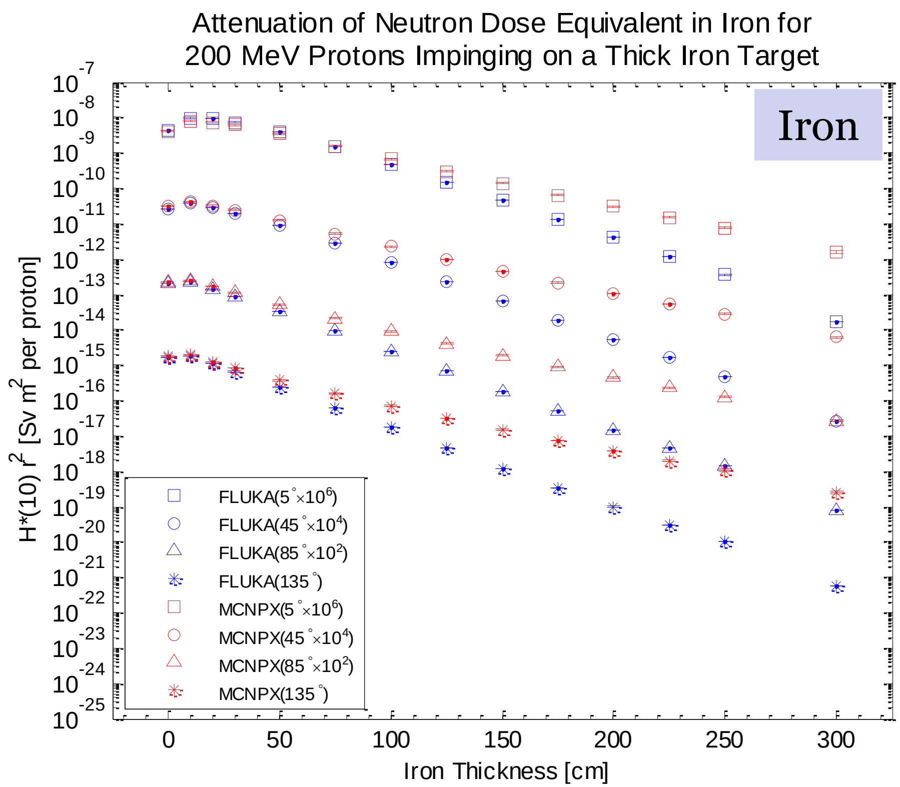


Neutron deep-penetration calc.

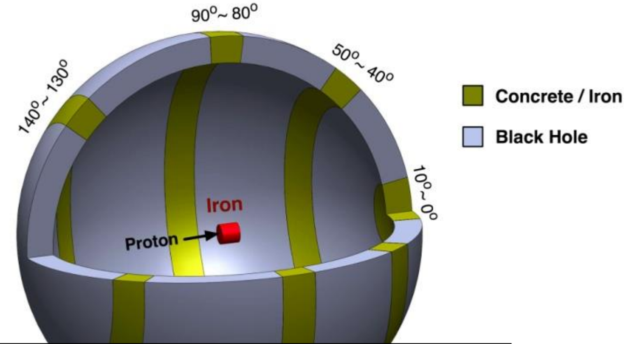


- Comparison: FLUKA & MCNPX
  - E_n<20MeV, multigroup vs. continuous cross sections



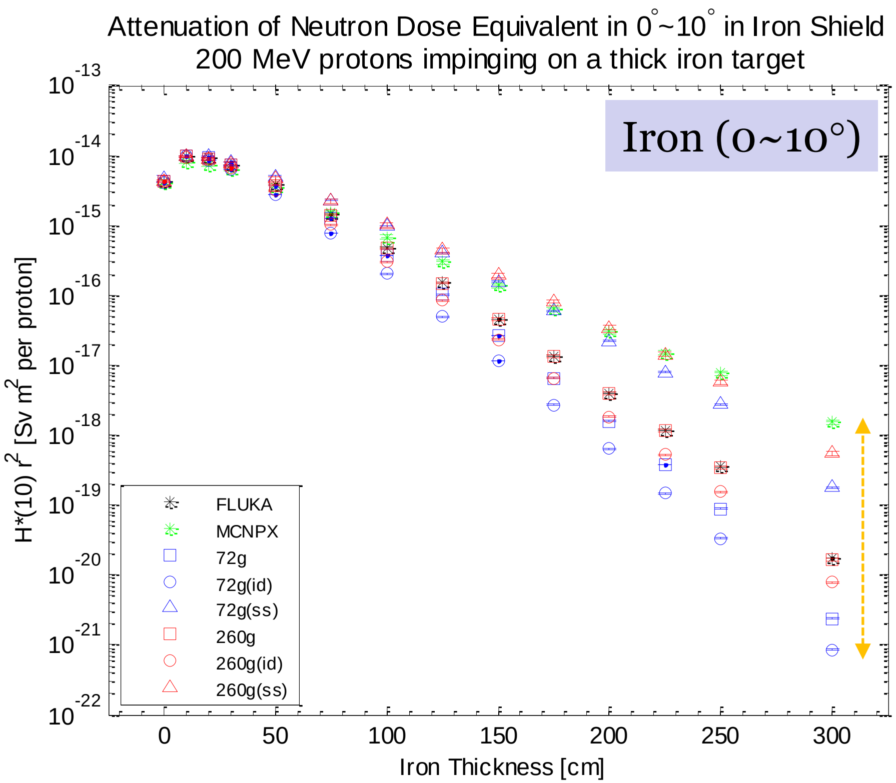


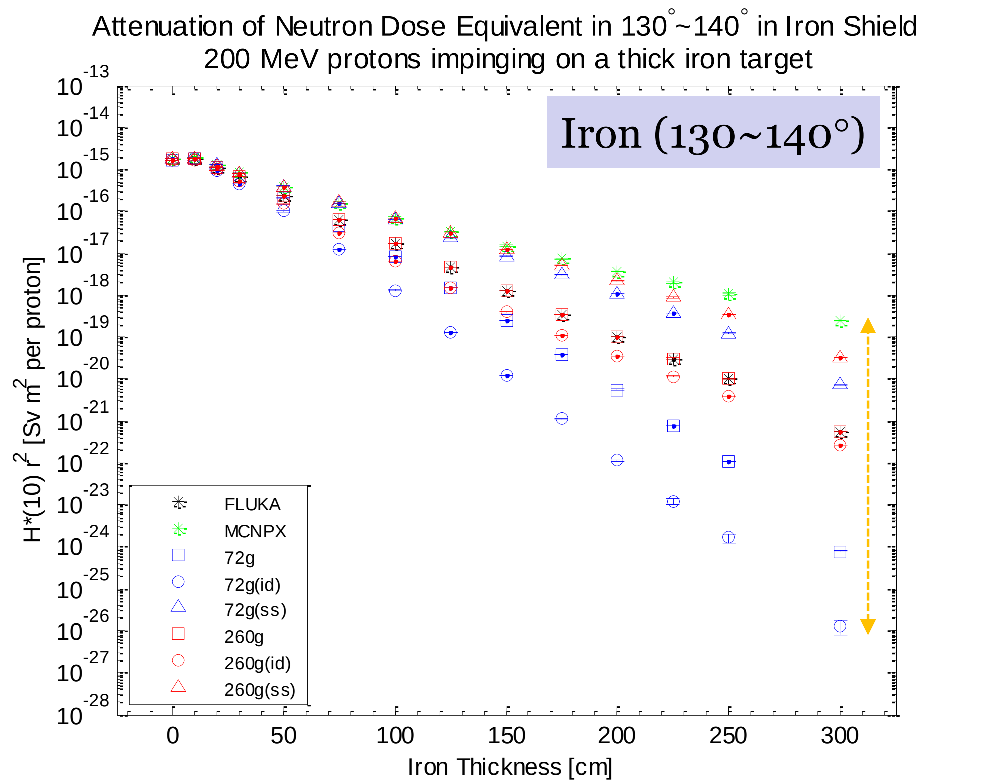
Neutron deep-penetration calc.



Orders of magnitude differences are possible for deep-penetration calculations!

- Effect of iron multigroup cross sections
  - Group structure: 72 or 260 groups
  - Self-shielding: infinitely dilute, partially and fully self-shielded





A shielding database for proton therapy accelerators

- Point-source line-of-sight model

$$H(E_p,\theta,d/\lambda)=\frac{H_1(E_p,\theta)}{r^2}\exp(-\frac{d}{\lambda_1(E_p,\theta)})+\frac{H_2(E_p,\theta)}{r^2}\exp(-\frac{d}{\lambda_2(E_p,\theta)})$$

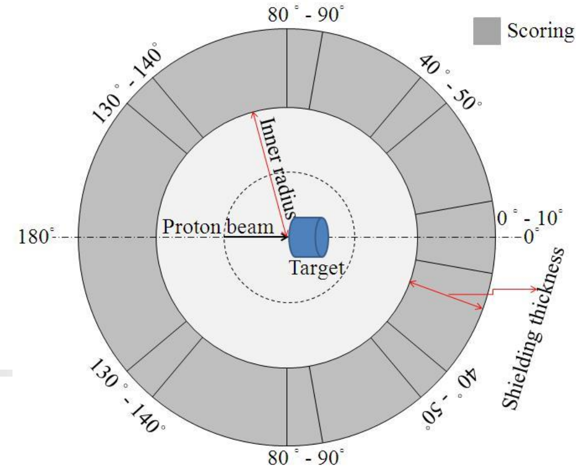
- Source term & attenuation length: (H_1,λ_1) & (H_2,λ_2)

  Reasonable coverage of common beam/target/shielding/angle
  - Proton energies: 100, 150, 200, 250, 300 MeV
  - Target materials: iron, graphite, tissue
  - Shielding materials: concrete, iron, lead
  - Angles of neutron emission: 0°-10°, 40°-50°, 80°-90°, 130°-140°

- Monte Carlo simulations
  - MCNPX with continuous-energy cross sections
  - Generation of shielding parameters → Database
  - Case study and verification

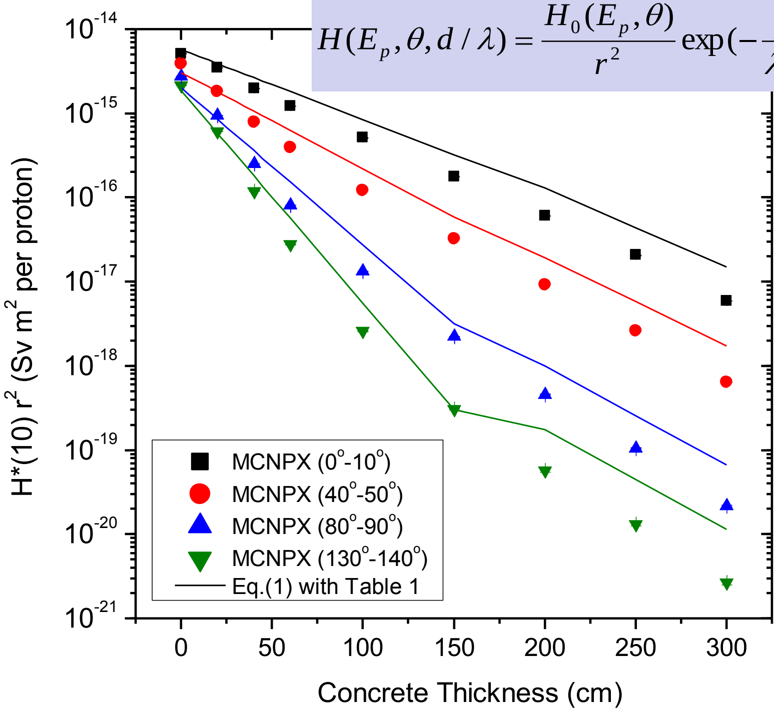
Demo by two simple cases

250 MeV proton on Fe

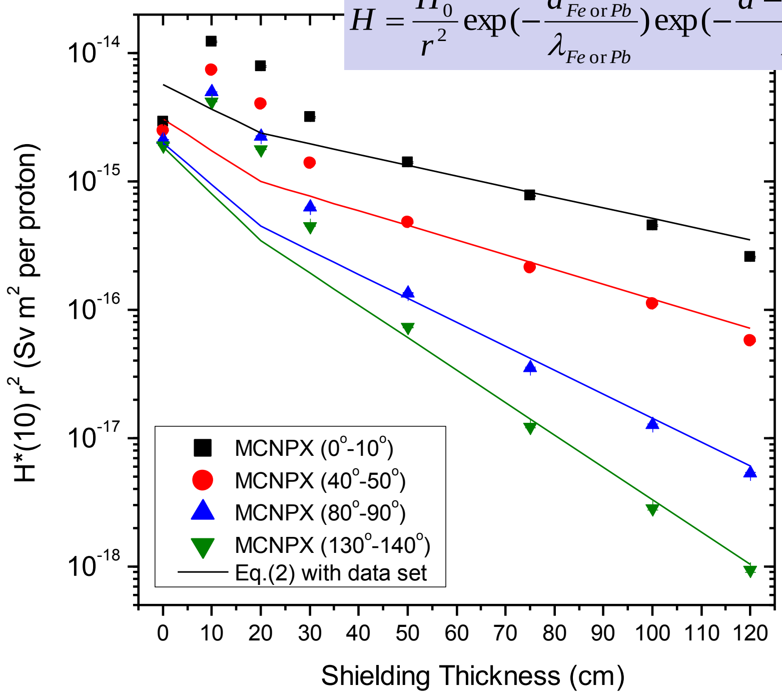


- Single-layer shielding: 3m concrete
  - Overestimation is acceptable and usually preferable
- Double-layer shielding: 20cm iron + 1m concrete
  - Reasonably good agreement with the Monte Carlo results

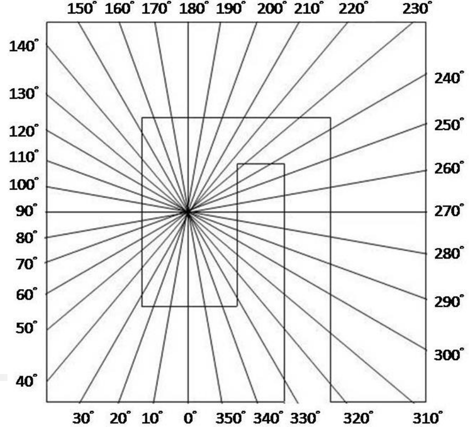
$$H(E_p,\theta,d/\lambda)=\frac{H_0(E_p,\theta)}{r^2}\exp\left(-\frac{d}{\lambda(E_p,\theta)}\right)$$



$$H=\frac{H_0}{r^2}\exp\left(-\frac{d_{Fe\,or\,Pb}}{\lambda_{Fe\,or\,Pb}}\right)\exp\left(-\frac{d-d_{Fe\,or\,Pb}}{\lambda_{Con}}\right)$$

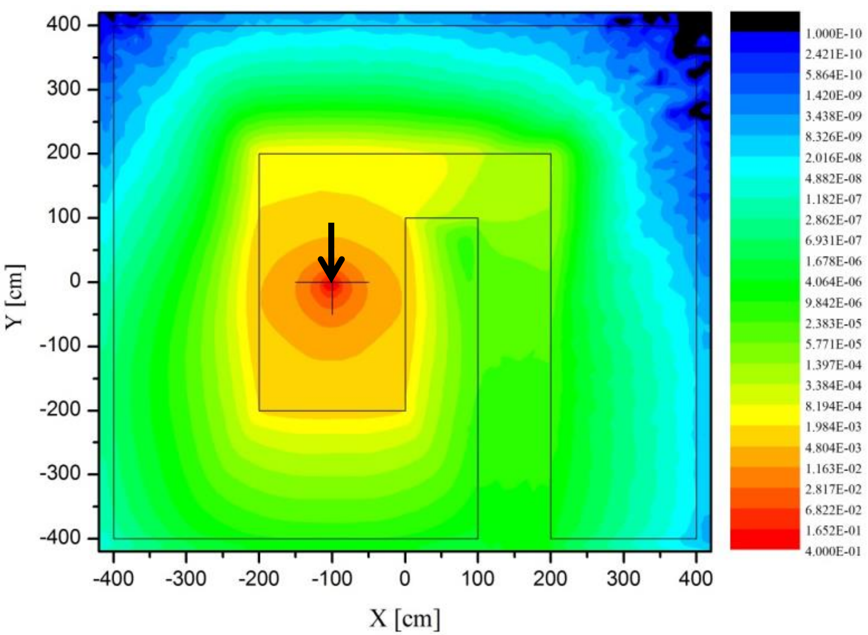


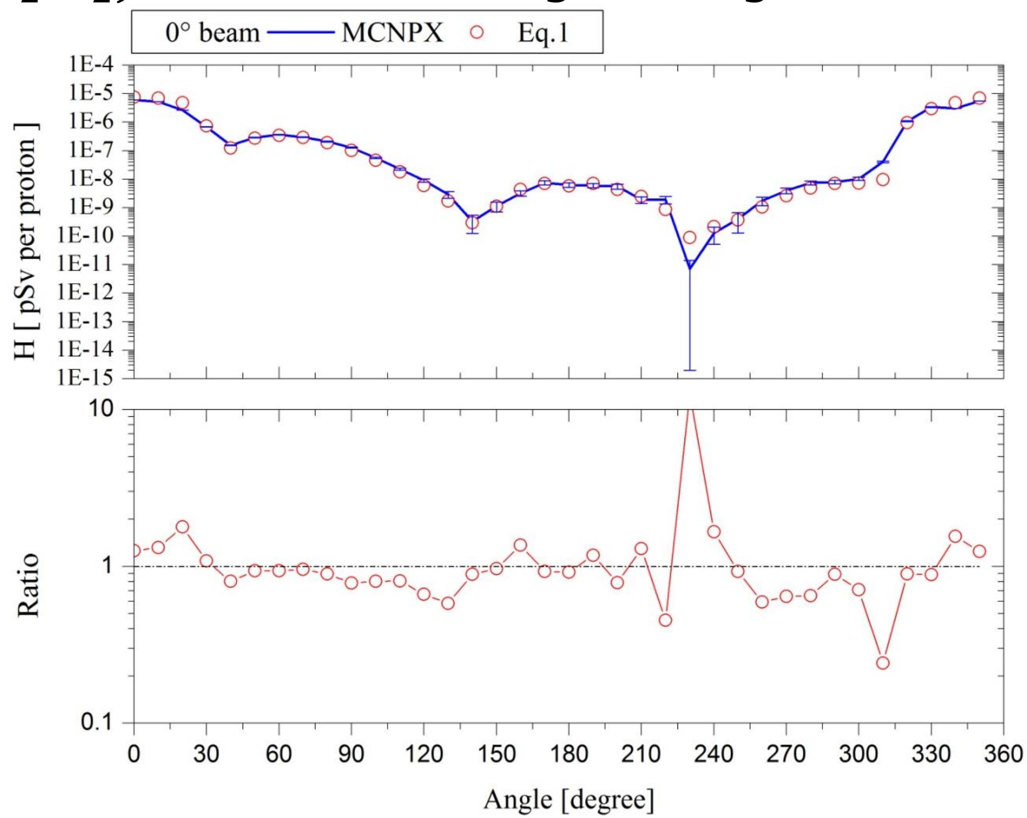
Shielding design & dose analysis



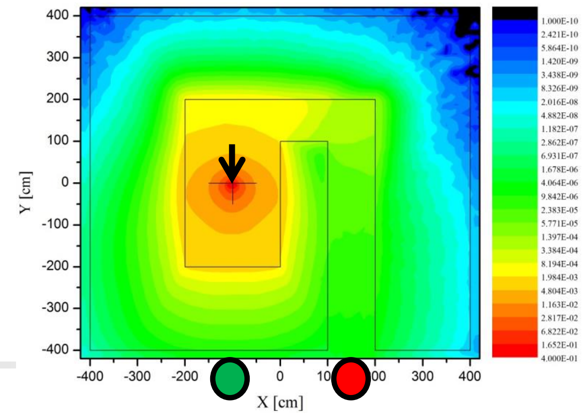
250 MeV proton on Fe, concrete shielding

- Proton therapy treatment room
  - Direct Monte Carlo simulation
  - Database $(H_1, \lambda_1), (H_2, \lambda_2)$ + Point-source light-of-sight model



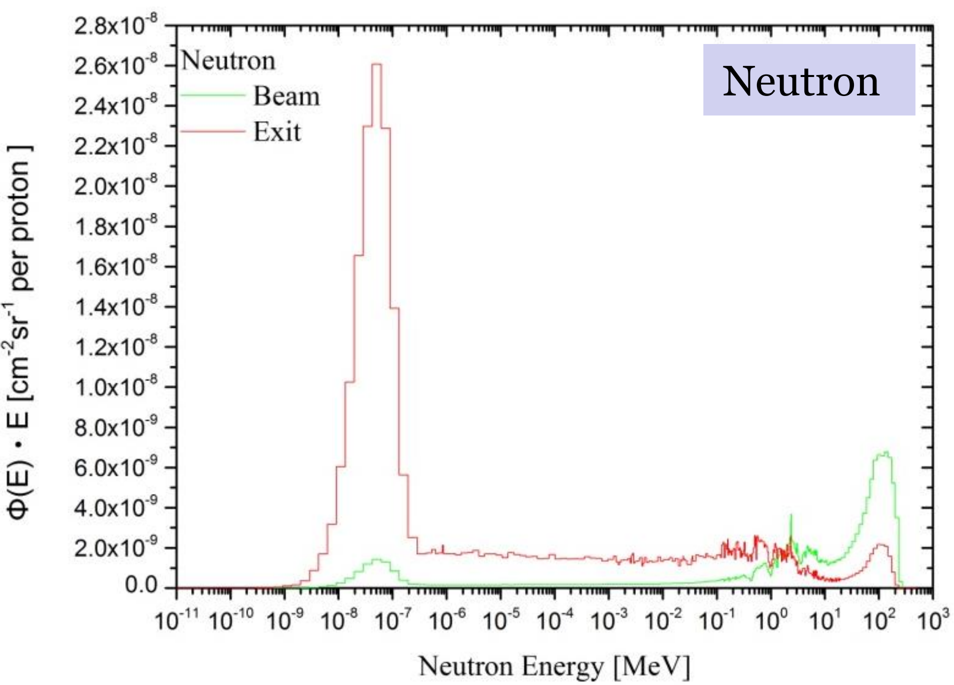


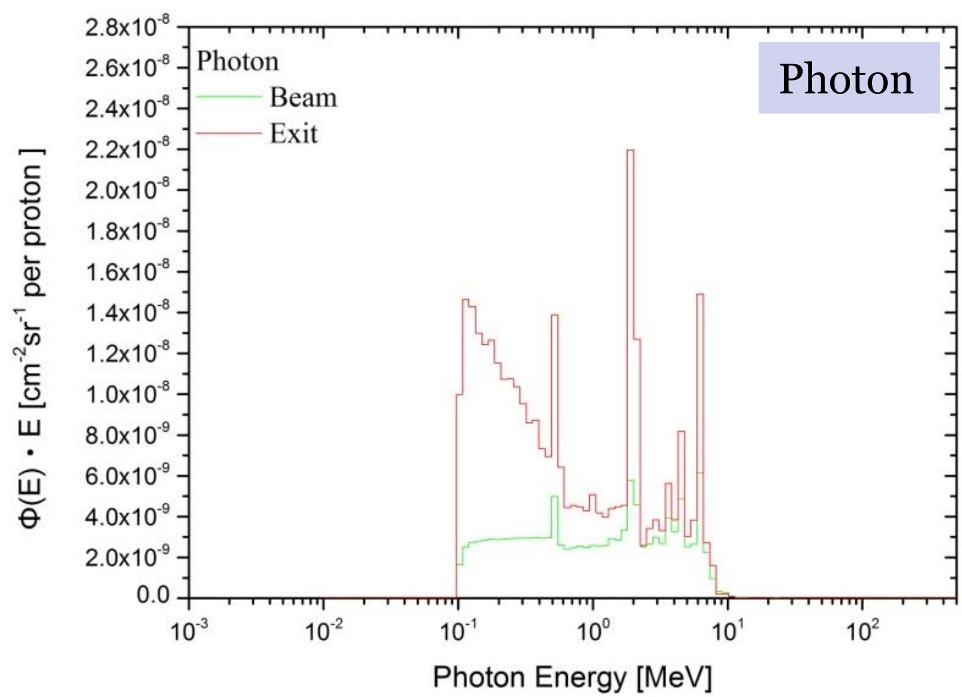
Shielding design & dose analysis



250 MeV proton on Fe, concrete shielding

- Proton therapy treatment room
  - Direct Monte Carlo simulation
  - Energy spectra of neutrons and gamma rays on the surface of the 0° shielding wall and near the maze entrance, respectively





$$H_1(\delta_1) = \left[\frac{r_0}{\delta_1 + r_0}\right]^2 H_0(R) \quad \text{for } 1^{st} \text{ leg}$$

$$H_i(\delta_i) = \left\{\frac{e^{-\delta_i/a} + Ae^{-\delta_i/b} + Be^{-\delta_i/c}}{1 + A + B}\right\} H_{i-1}(\delta_{i-1}) \quad \text{for } i^{th} \text{ leg } (i > 1)$$

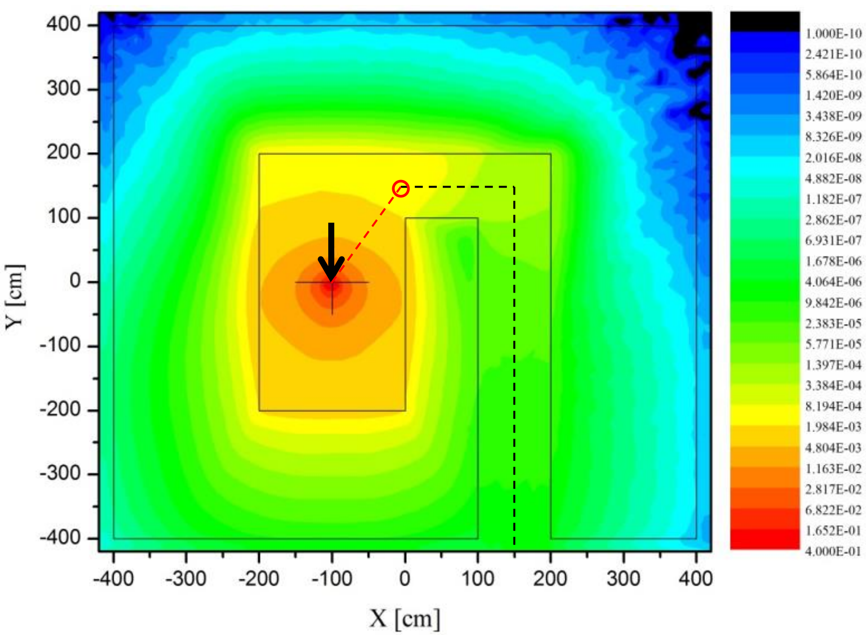
where $\delta_i = d_i/\sqrt{A}$ and the fitting parameters are:

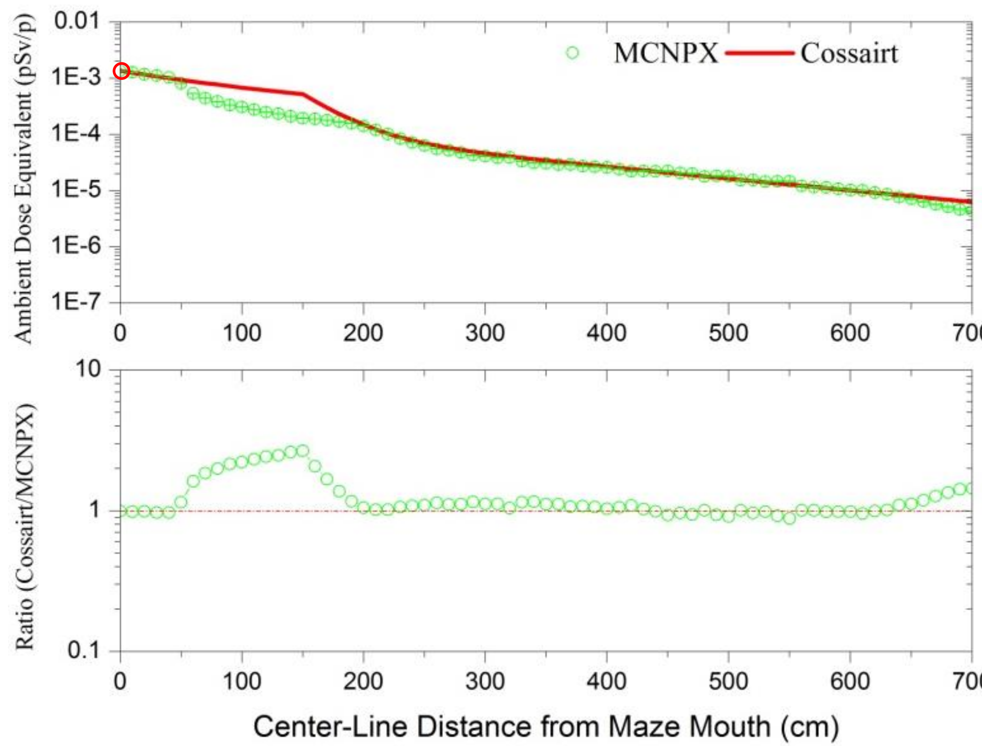
$r_0 = 1.4,\ a = 0.17,\ b = 1.17,\ c = 5.25,\ A = 0.21,\ B = 0.00147$

Radiation streaming

250 MeV proton on Fe, concrete shielding

- Proton therapy treatment room
  - Direct Monte Carlo simulation
  - Database (H_0/r^2) + Cossairt's formula (FermiLab TM-1834, 2005)





Conclusions

- Neutrons are dominant dose component at proton and heavy ion accelerators, also for high-energy electron accelerators with thick shielding.
- Benchmark calculations were performed for neutron production by proton, heavy ion, and electron with energies of our interest and their agreement with experiments are generally satisfactory.
- Selection of proper multigroup cross sections is important to neutron deep-penetration calculations.
- This work provides a set of reliable shielding data with reasonable coverage of common target and shielding materials for 100-300 MeV proton accelerators.
- General characteristics and possible applications of this data set in cases of single- and double-layer shielding are presented.