University of Florida Proton Therapy Institute

Basic Physics of Proton Therapy

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overview

I. basic interactions
  - energy loss
  - scattering
  - nuclear interactions

II. clinical beams
  - pdd
  - lateral penumbra

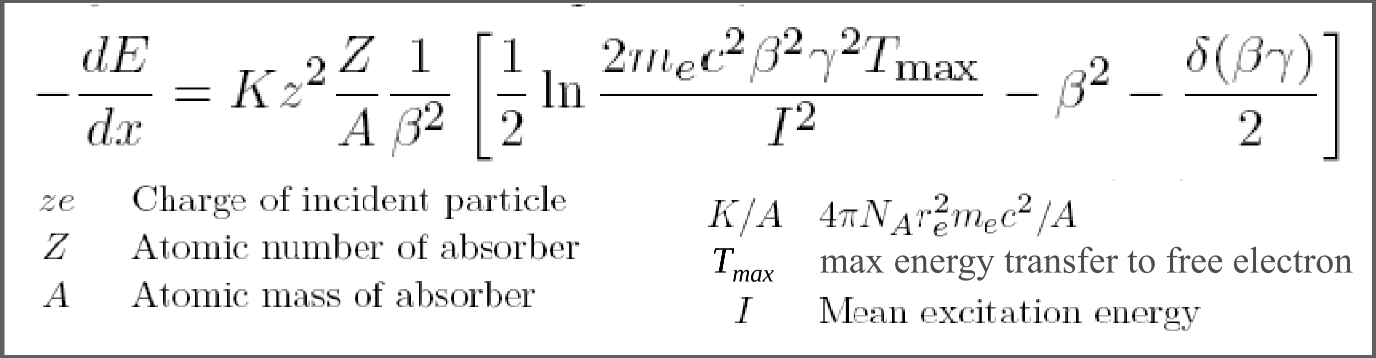
interactions / energy loss

Primarily protons lose energy in coulomb interactions with the outer-shell electrons of the target atoms.

- excitation and ionization of atoms
- loss per interaction small → 'continuously slowing down'
- range secondary e^+ <1mm → dose absorbed locally
- no significant deflection protons by electrons

interactions / energy loss

Energy loss is given by Bethe-Bloch equation:



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

+ corrections

ze	Charge of incident particle	K/A	$4\pi N_A r_e^2 m_e c^2/A$
Z	Atomic number of absorber	T_{max}	max energy transfer to free electron
A	Atomic mass of absorber	I	Mean excitation energy

- to first order: $-dE/dx \propto 1/\text{speed}^2$
- max electron energy: $T_{max} \approx 4\ T\ m_ec^2 / m_pc^2$

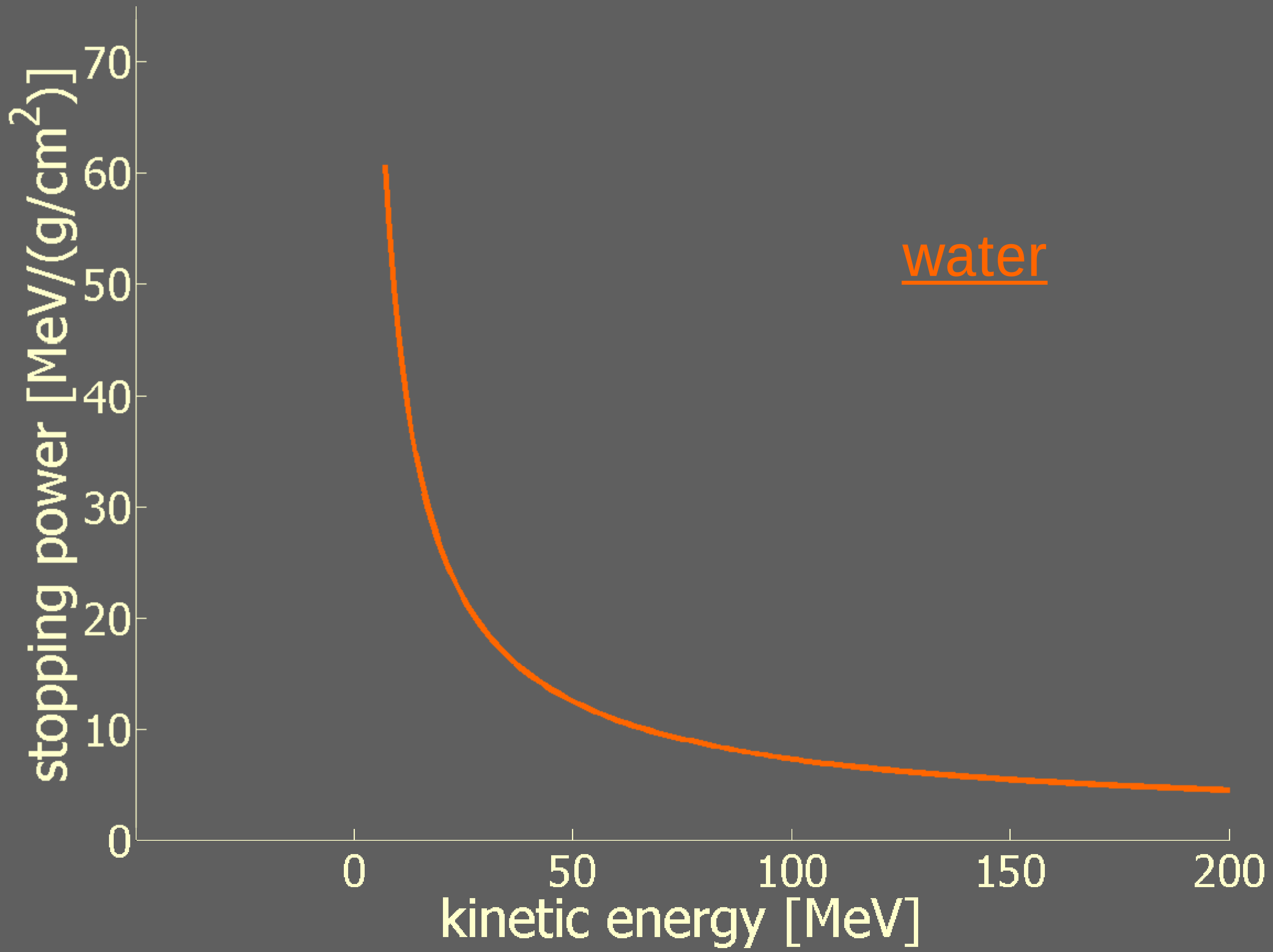
T=200 MeV → $T_{max} \approx 0.4$ MeV → range ≈ 1.4mm

....but most electrons far lower energy

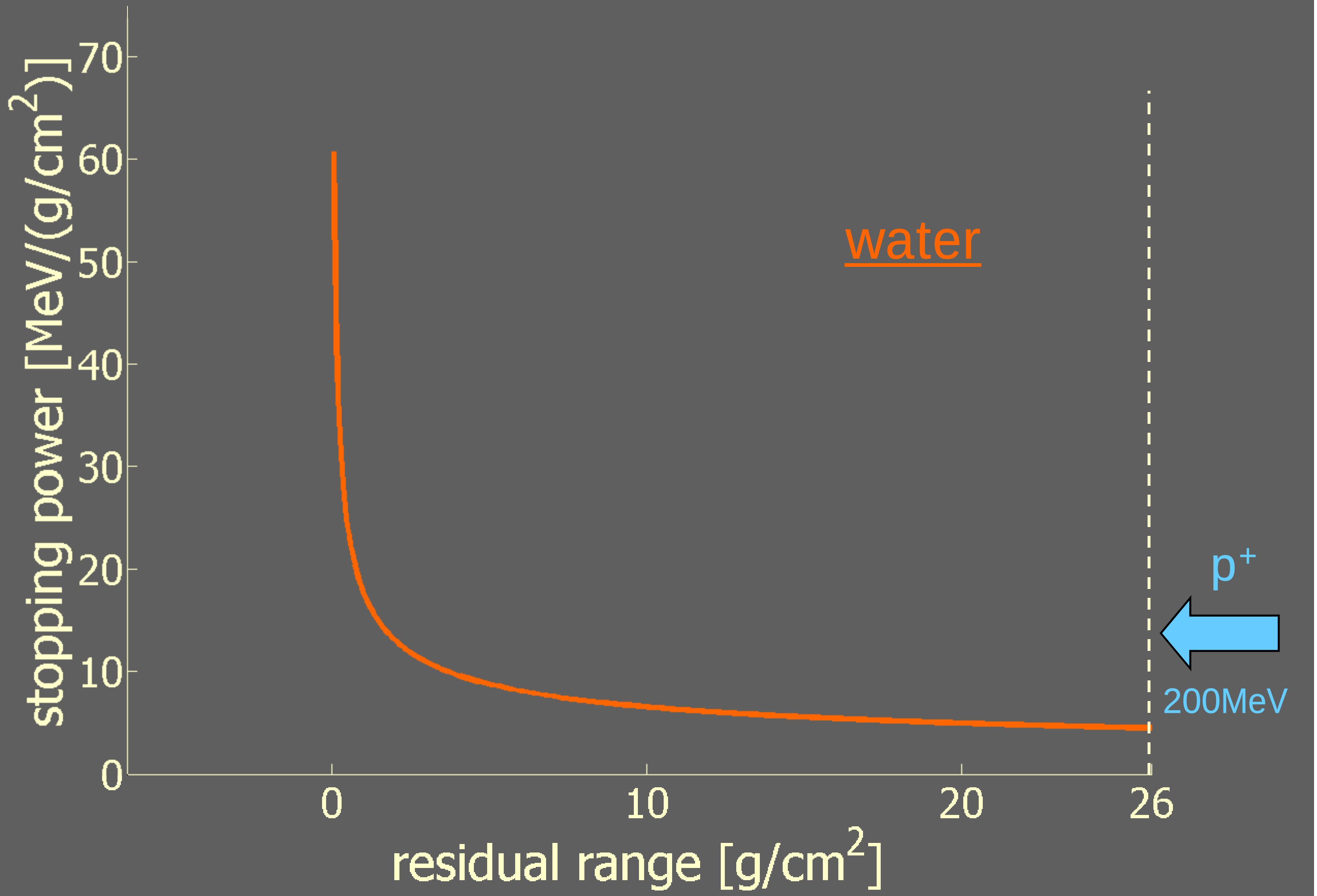
in practice we use range-energy tables and measured depth dose curves.

Equations from Review of particle physics, C. Amsler et al., Physics Letters ***B667****, 1 (2008)*

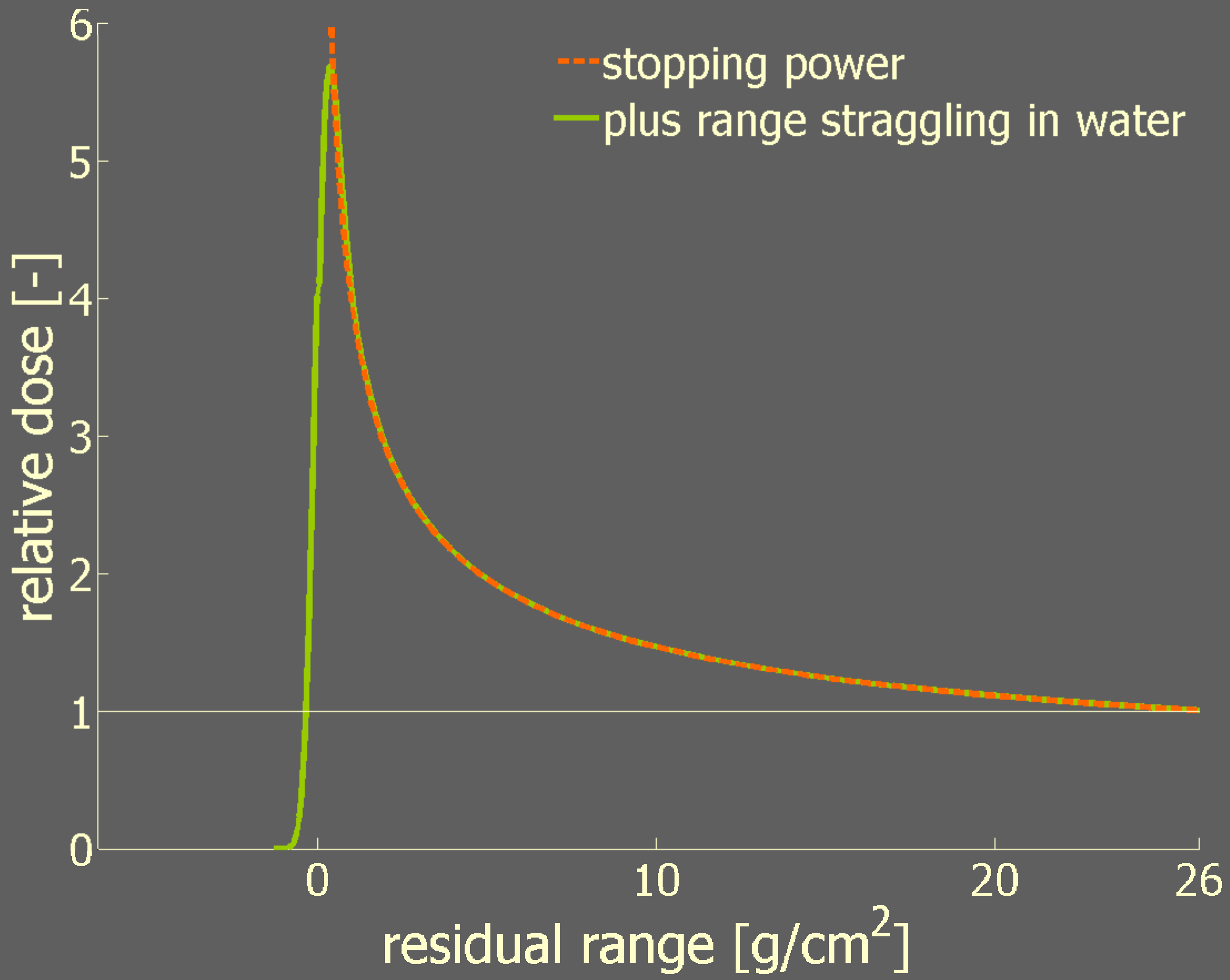
stopping power



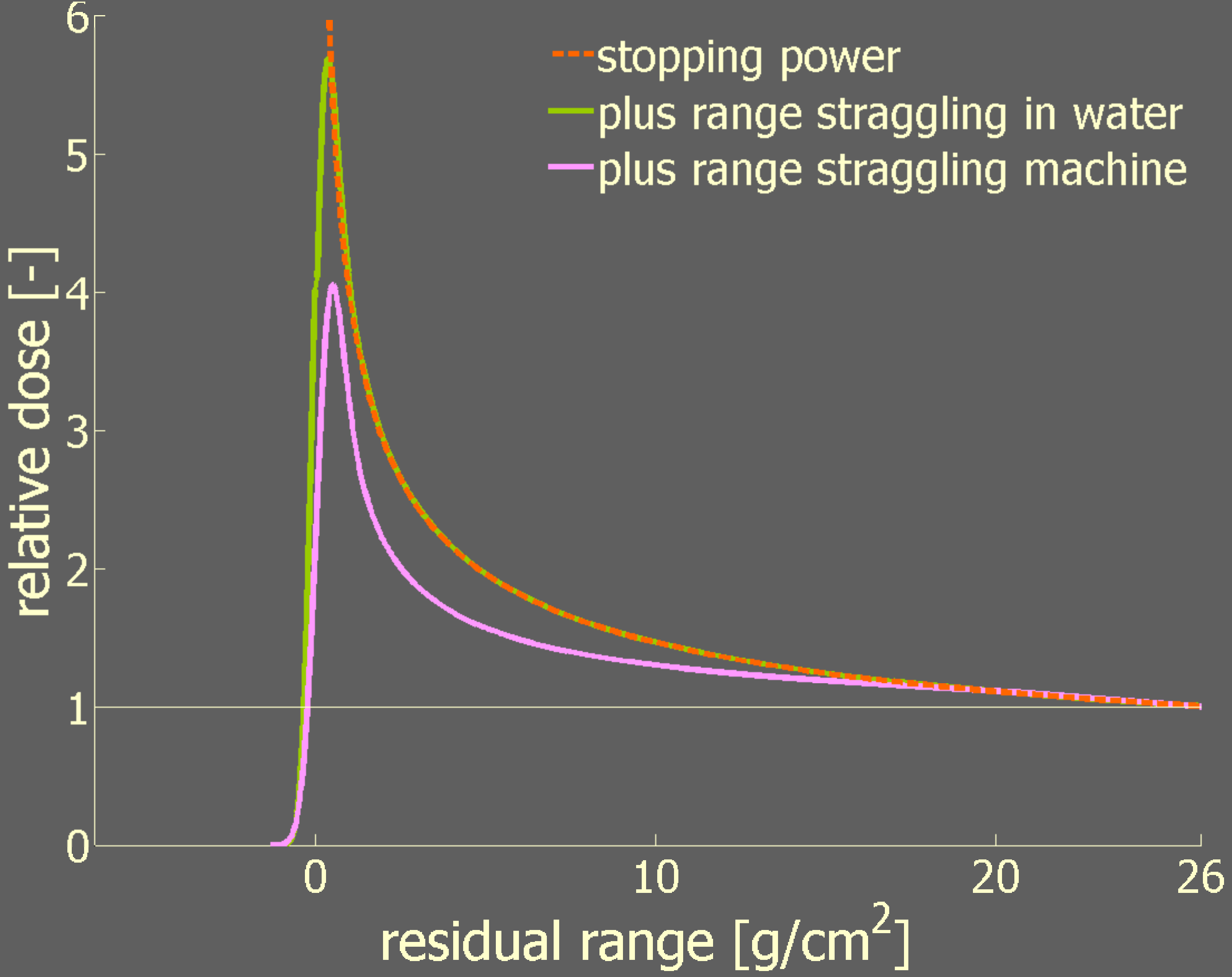
● stopping power



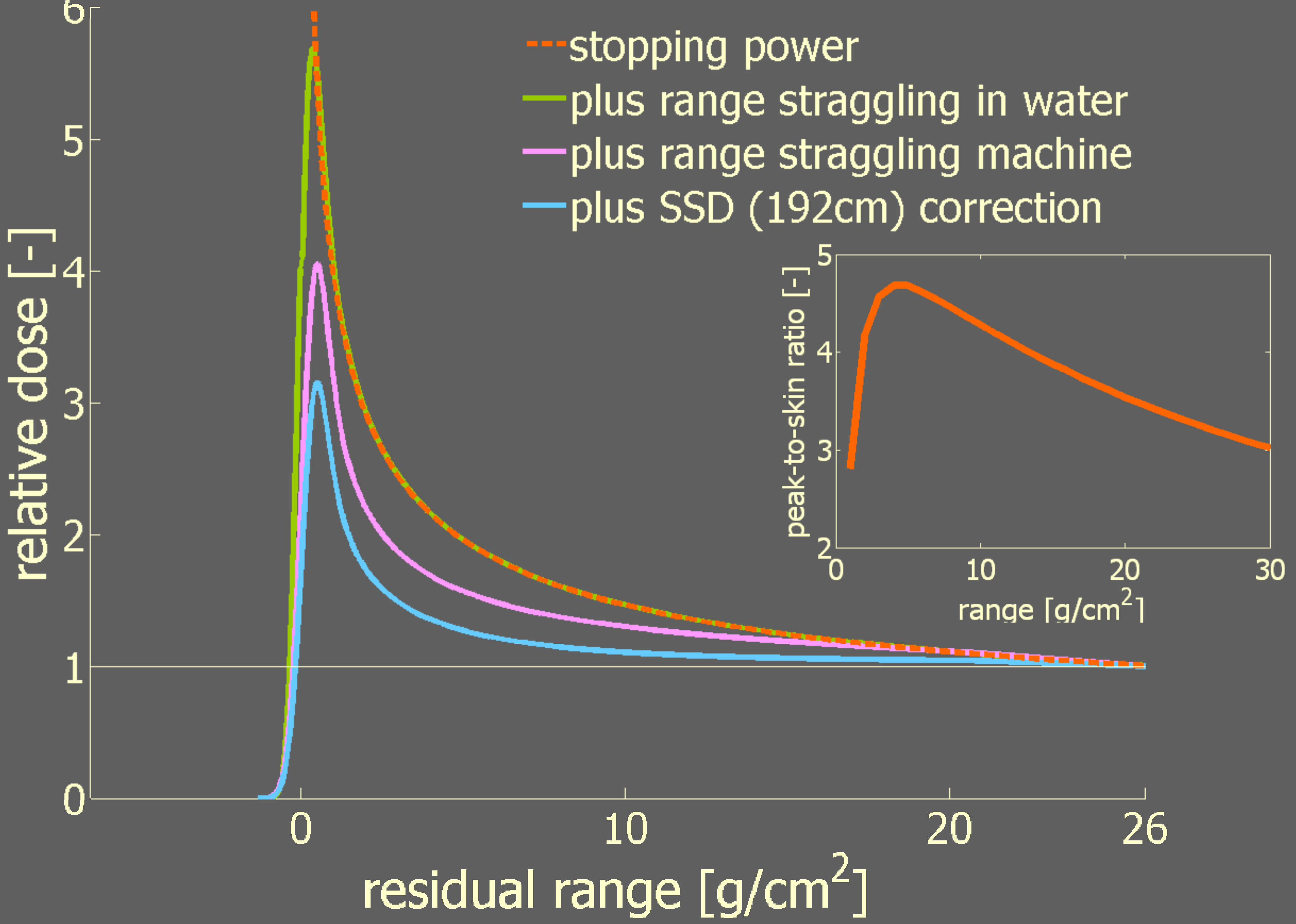
Bragg peak


stopping power
plus range straggling in water
relative dose [-]
residual range [g/cm²]
6
5
4
3
2
1
0
0
10
20
26

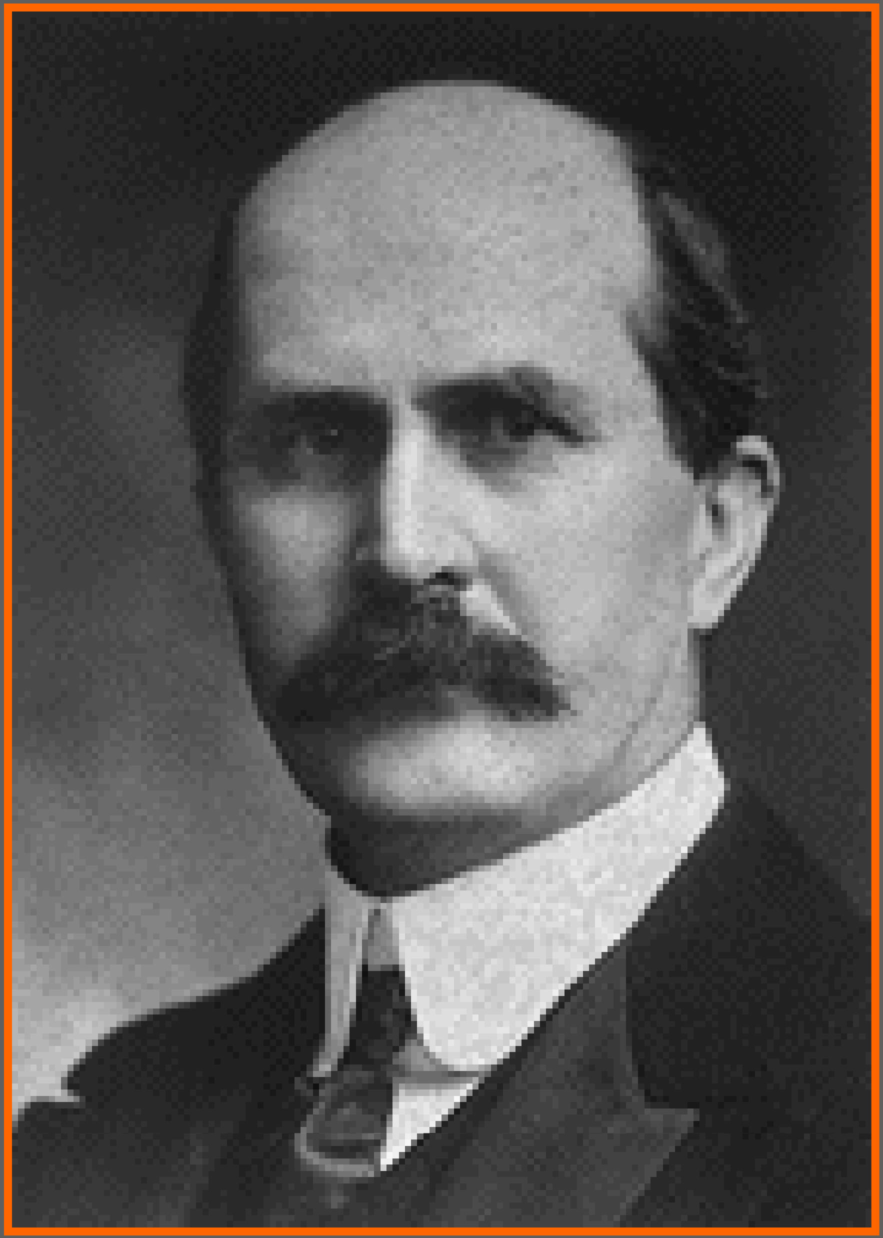
Bragg peak

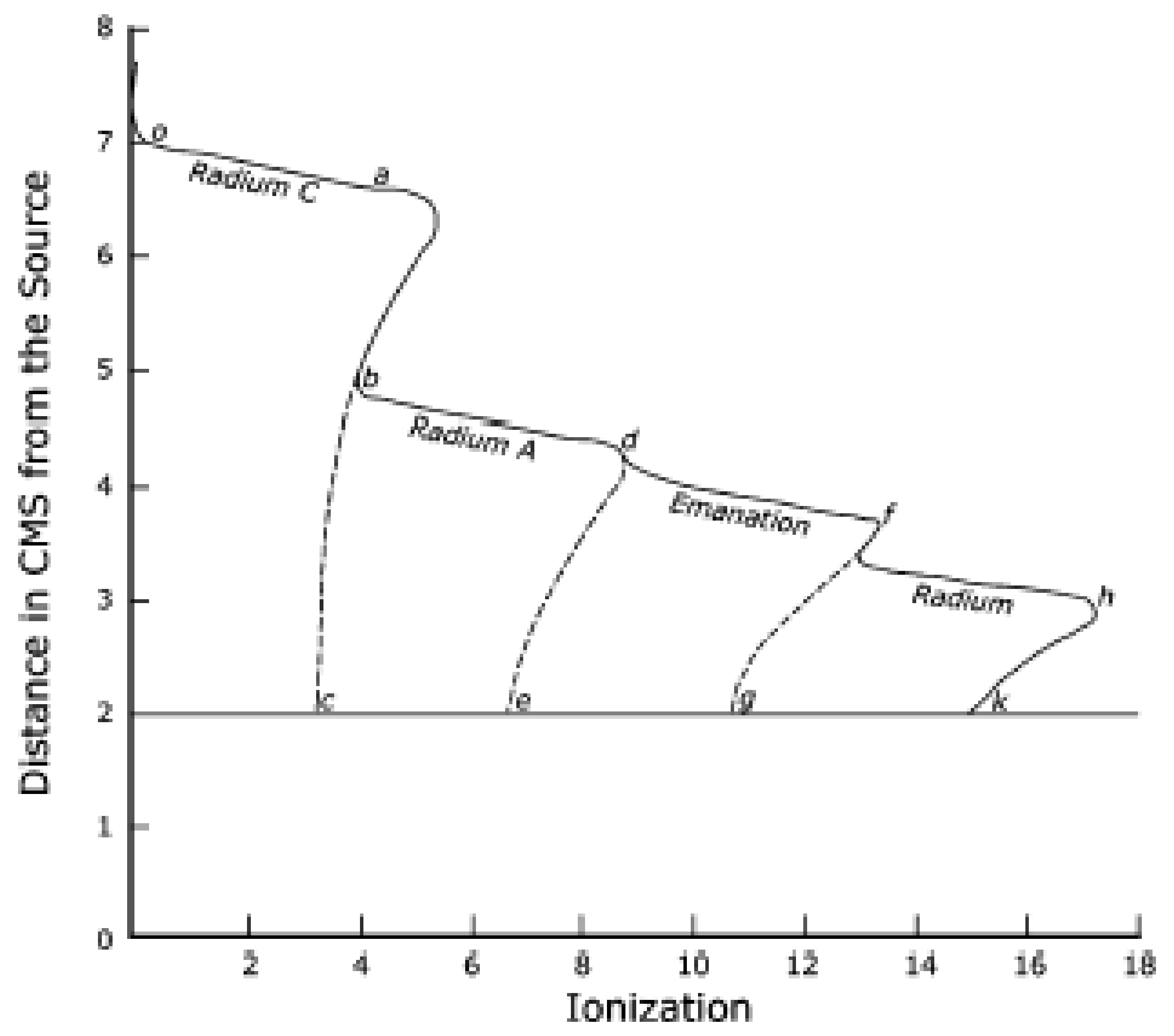

stopping power
plus range straggling in water
plus range straggling machine
relative dose [-]
0
1
2
3
4
5
6
0
10
20
26
residual range [g/cm²]

Bragg peak


stopping power
plus range straggling in water
plus range straggling machine
plus SSD (192cm) correction
relative dose [-]
6
5
4
3
2
1
0
0
10
20
26
residual range [g/cm^2]
peak-to-skin ratio [-]
5
4
3
2
0
10
20
30
range [g/cm^2]

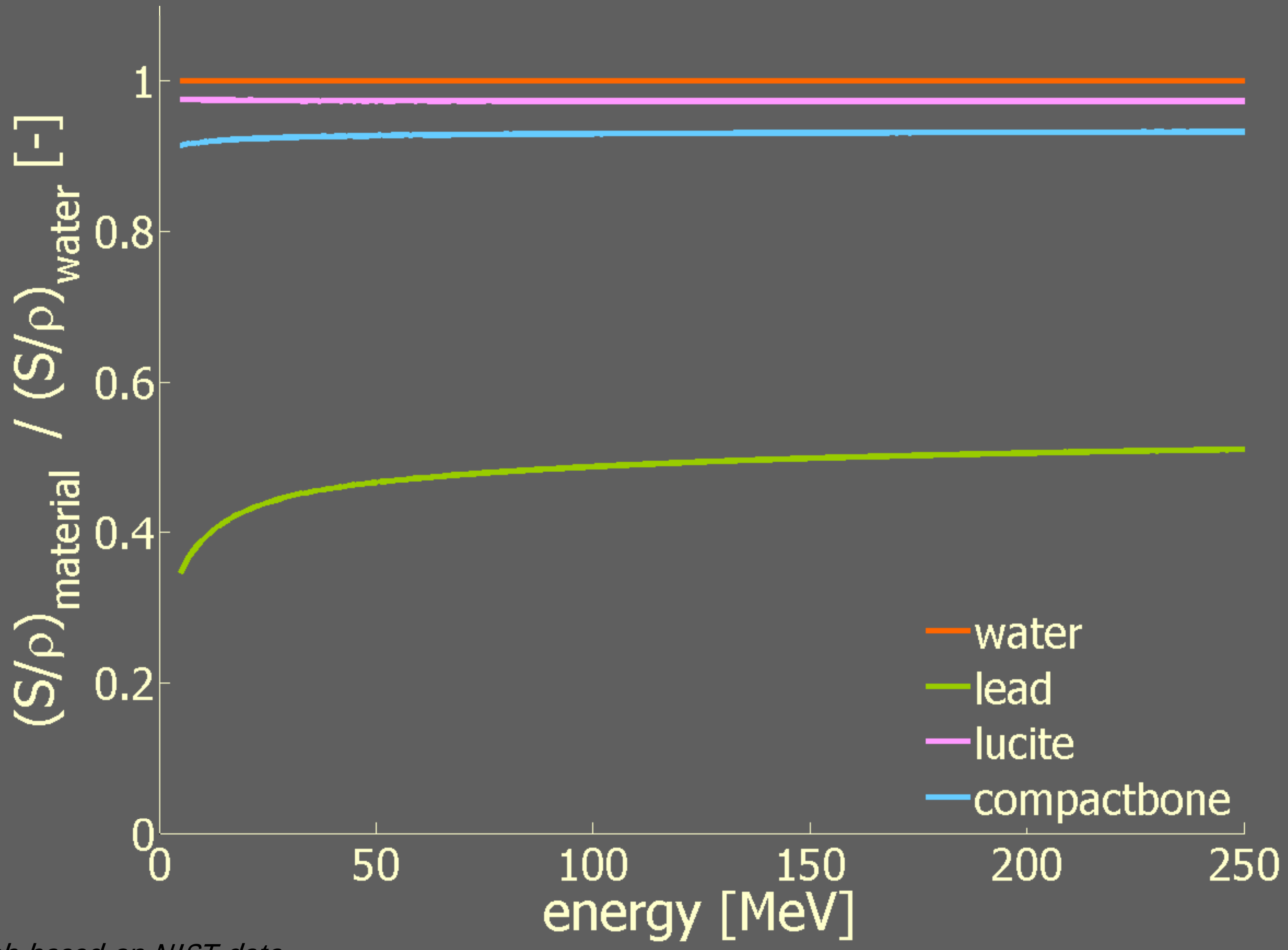
William Bragg





W.H. Bragg and R. Kleeman, On the ionization curves of radium, Philosophical Magazine S6 (1904), 726-738

stopping power



Graph based on NIST data

interactions / scattering

Primarily protons scatter due to elastic <u>coulomb interactions</u> with the target <u>nuclei</u>.

- many, small angle deflections
- full description → Moliere, gaussian approx. → <u>Highland</u>

$$\theta_0 = \frac{14.1\ \mathrm{MeV}}{pv}\, z \sqrt{\frac{L}{L_R}} \left[1 + \frac{1}{9} \log_{10}\left(\frac{L}{L_R} \right) \right]$$

p	proton momentum
v	proton speed
L	target thickness
L_R	target radiation length

  - $\theta_0 \propto 1/pv \approx 1/(2*T)$ T<<938MeV
  - material dependence: $\theta_0 \propto 1/L_R^{-0.5}$

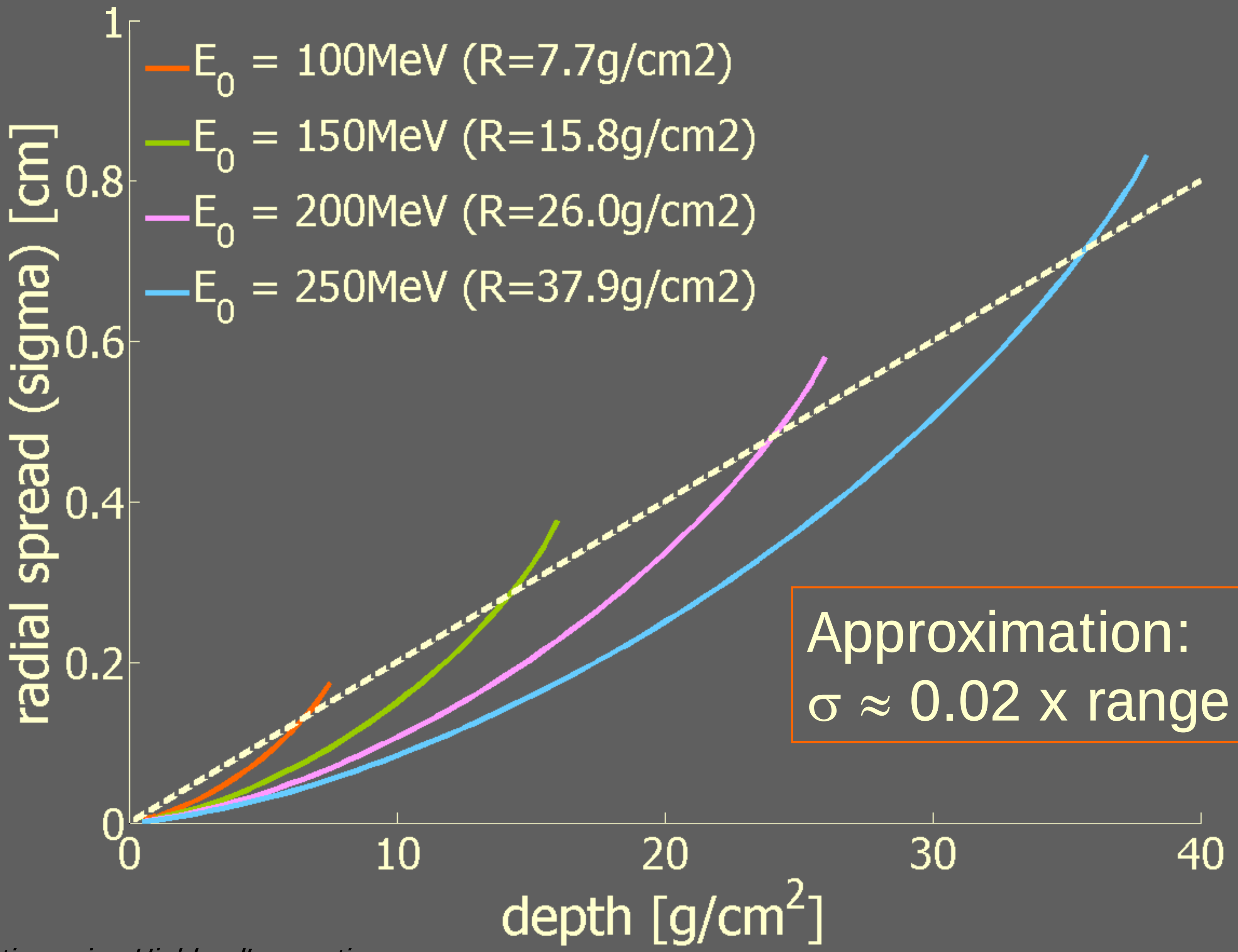
    1 g/cm^2 of water (L_R =36.1 g/cm^2) → θ_0=5mrad for T=200MeV

    1 g/cm^2 of lead (L_R = 6.37 g/cm^2) → θ_0=14mrad for T=200MeV

Highland neglects large-angle tails, but works well in many situations...

Equation from Gottschalk (Passive beam spreading)

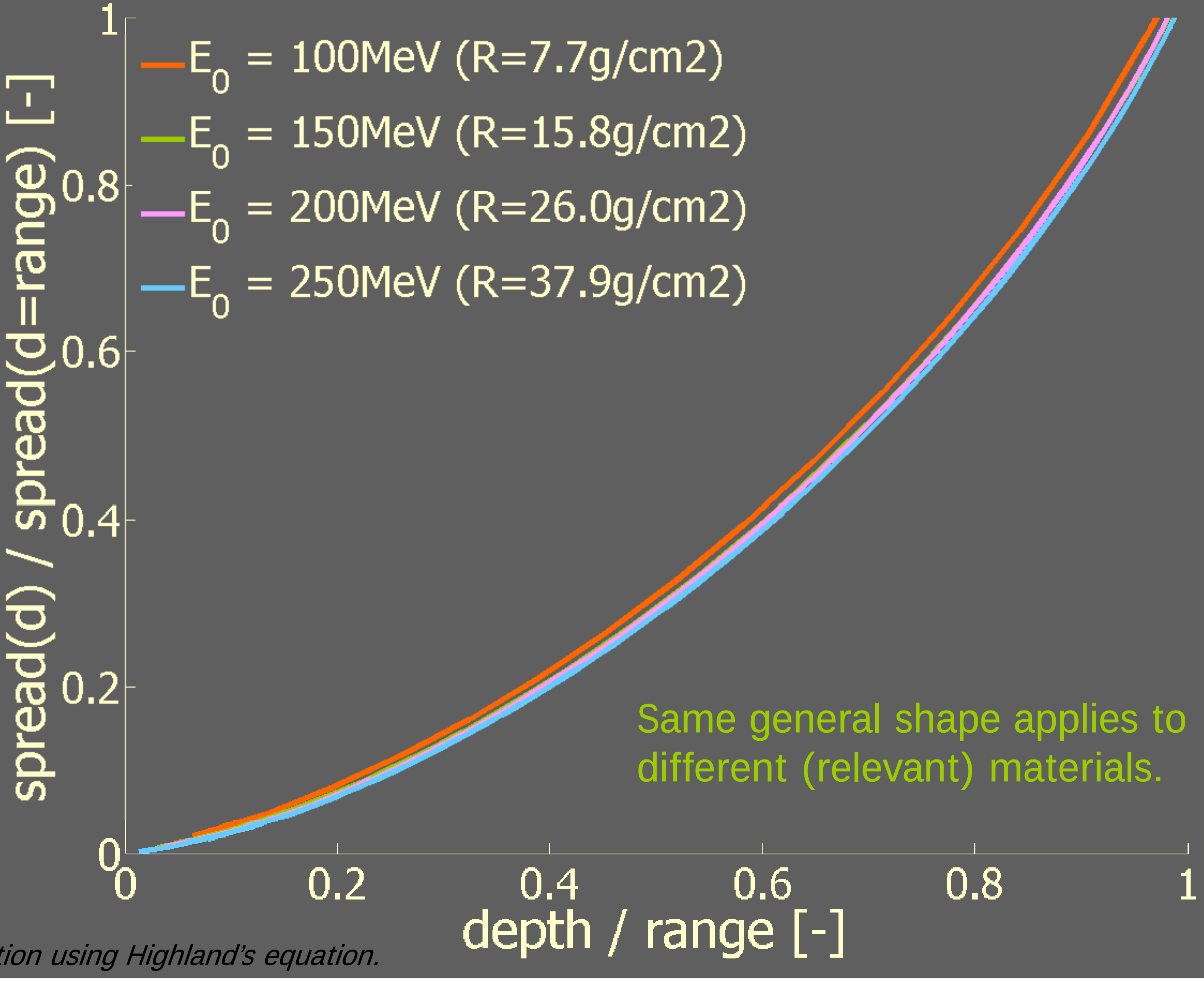
radial spread in water



Approximation:
$\sigma \approx 0.02 \times \text{range}$

Calculation using Highland's equation.

radial spread in water



Same general shape applies to different (relevant) materials.

Calculation using Highland's equation.

interactions / nuclear

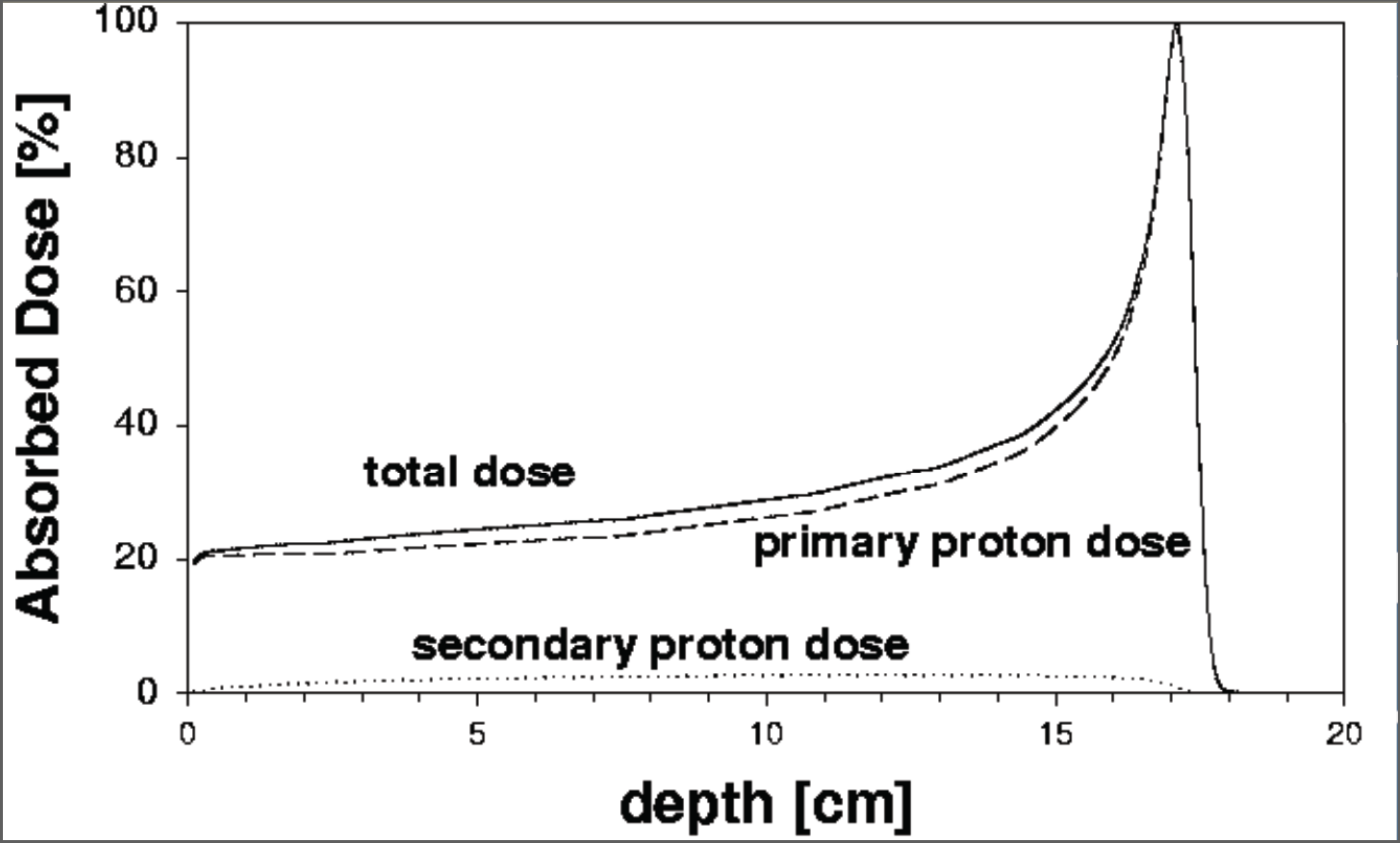
About 20% of the incident protons have a nonelastic nuclear interaction with the target nuclei.

- reduction of proton fluence with depth → shape Bragg peak
- secondaries:
  - charged (p,d,α,recoils) ~60% of energy → absorbed ‘locally’
  - neutral (n,γ) ~40% of energy → absorbed ‘surroundings’
- production of unstable recoil particles (activation)
  - radiation safety
  - dose verification using PET/CT

interactions / nuclear

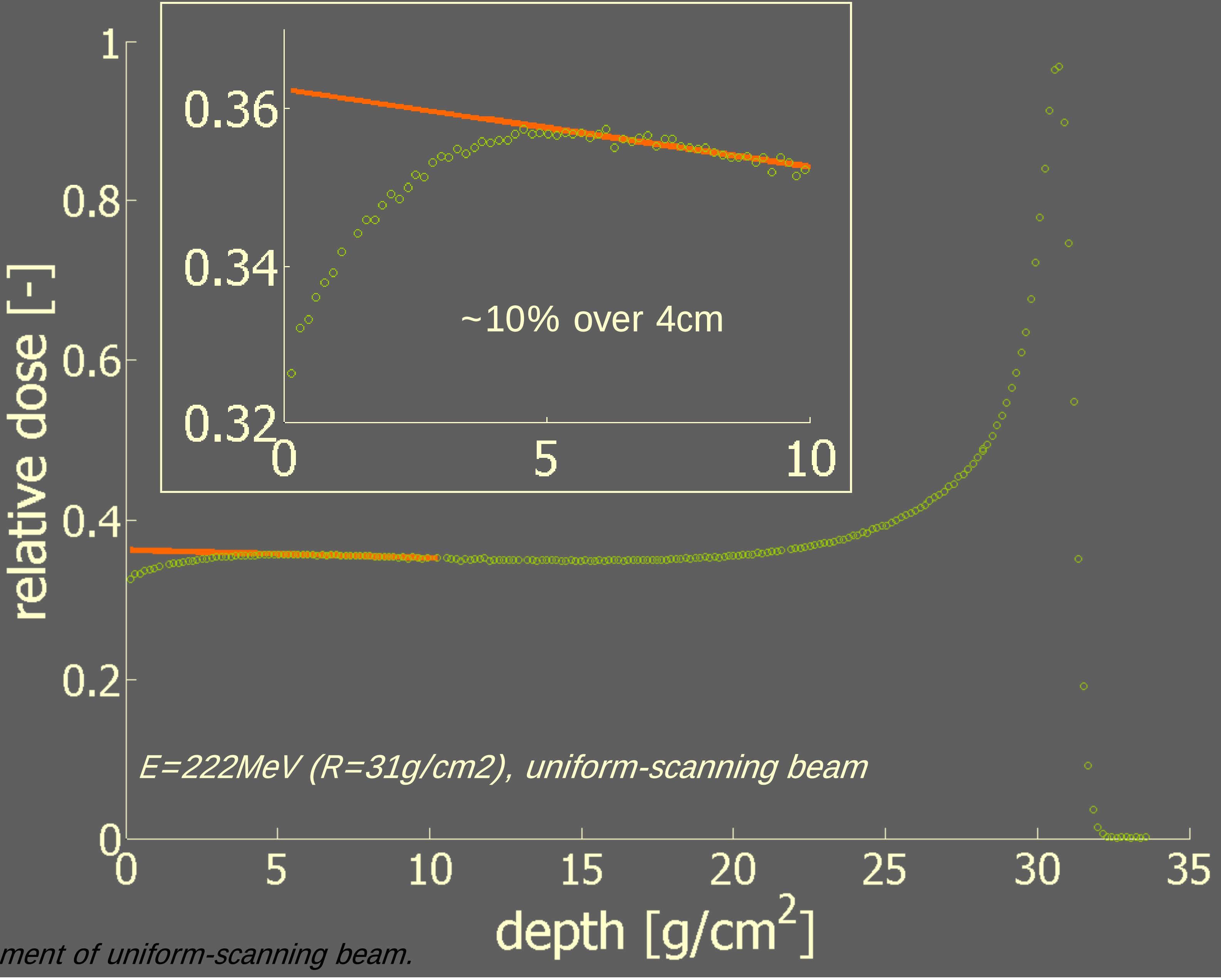
Relevant channels

nuclear interactions



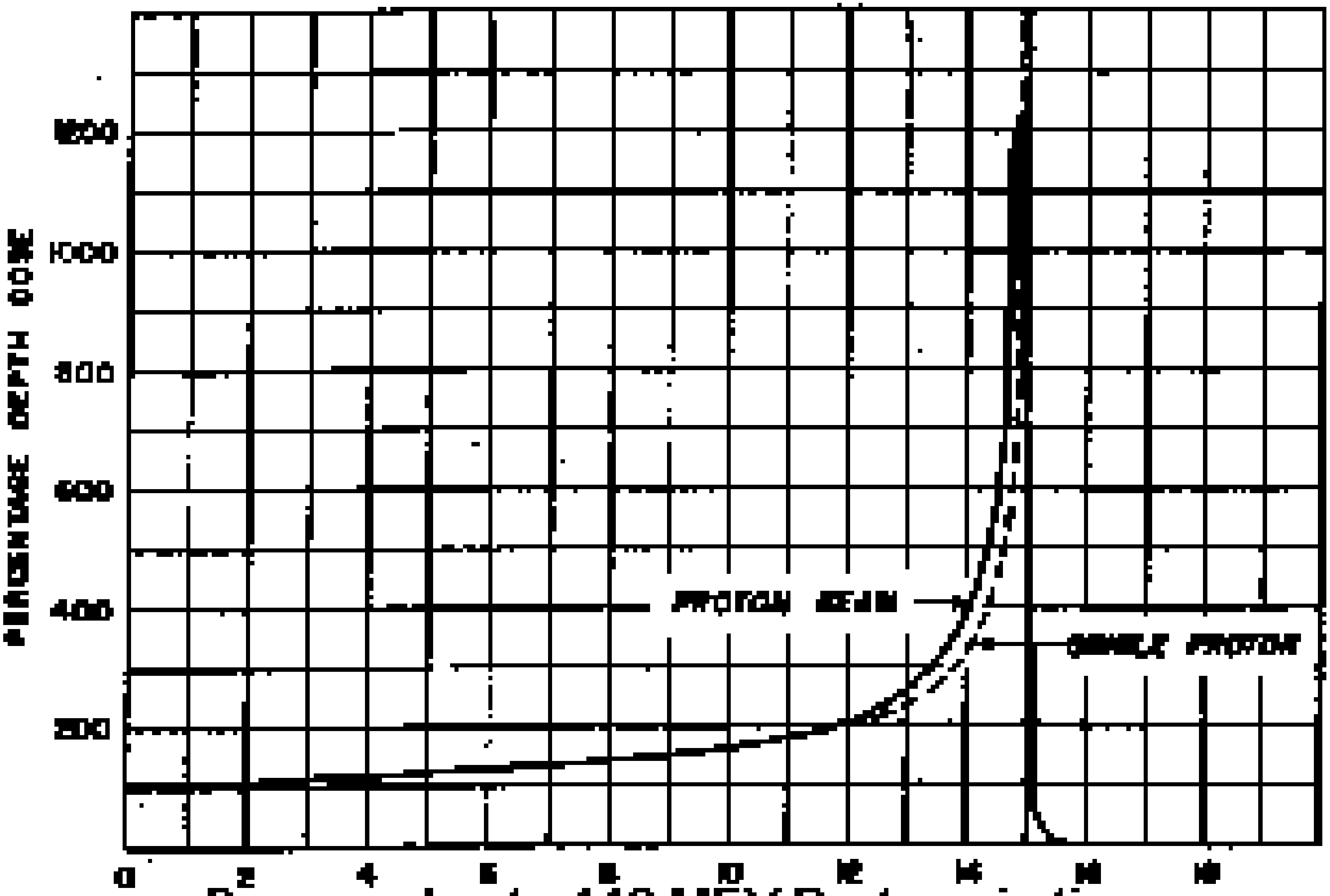
Graph courtesy Harald Paganetti.

nuclear buildup



Measurement of uniform-scanning beam.

Robert Wilson

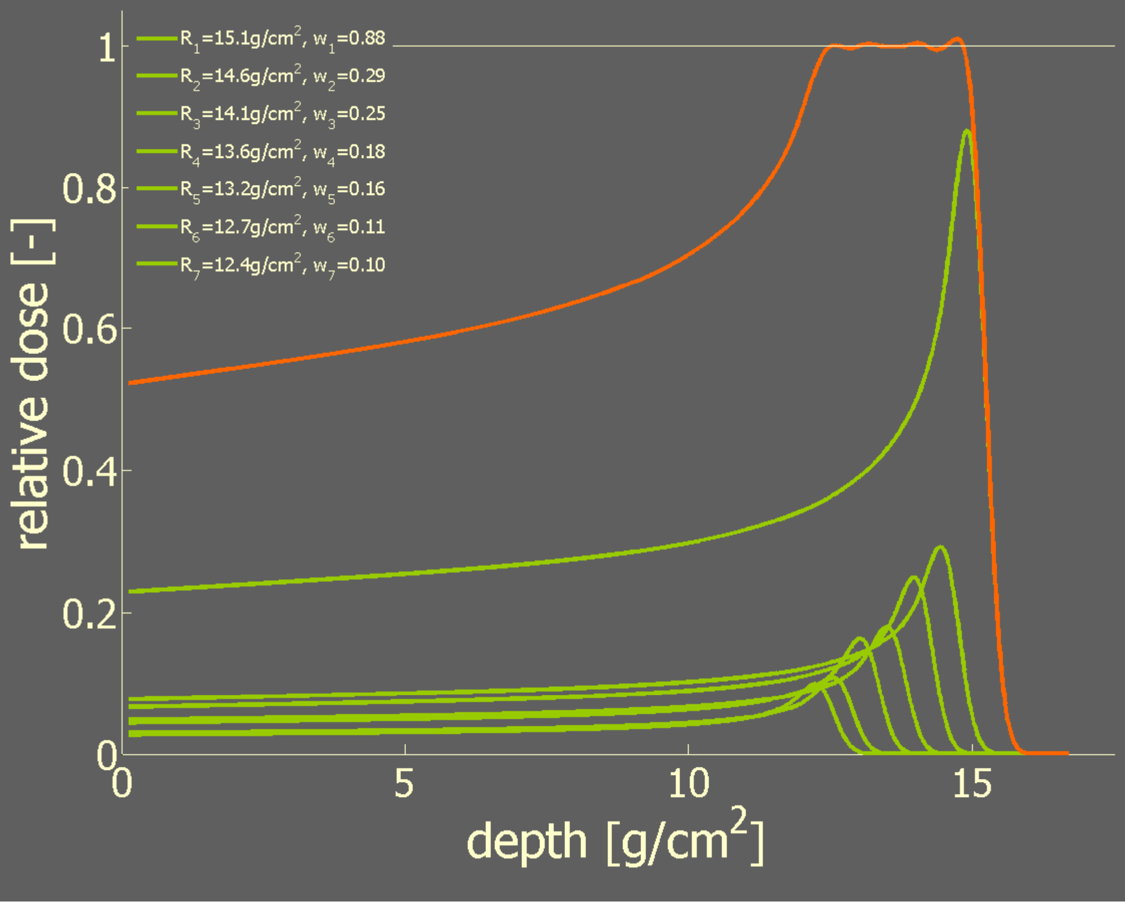


Dosage due to 140 MEV Protons in tissue

R.R. Wilson, Radiology 47(1946), 487-491

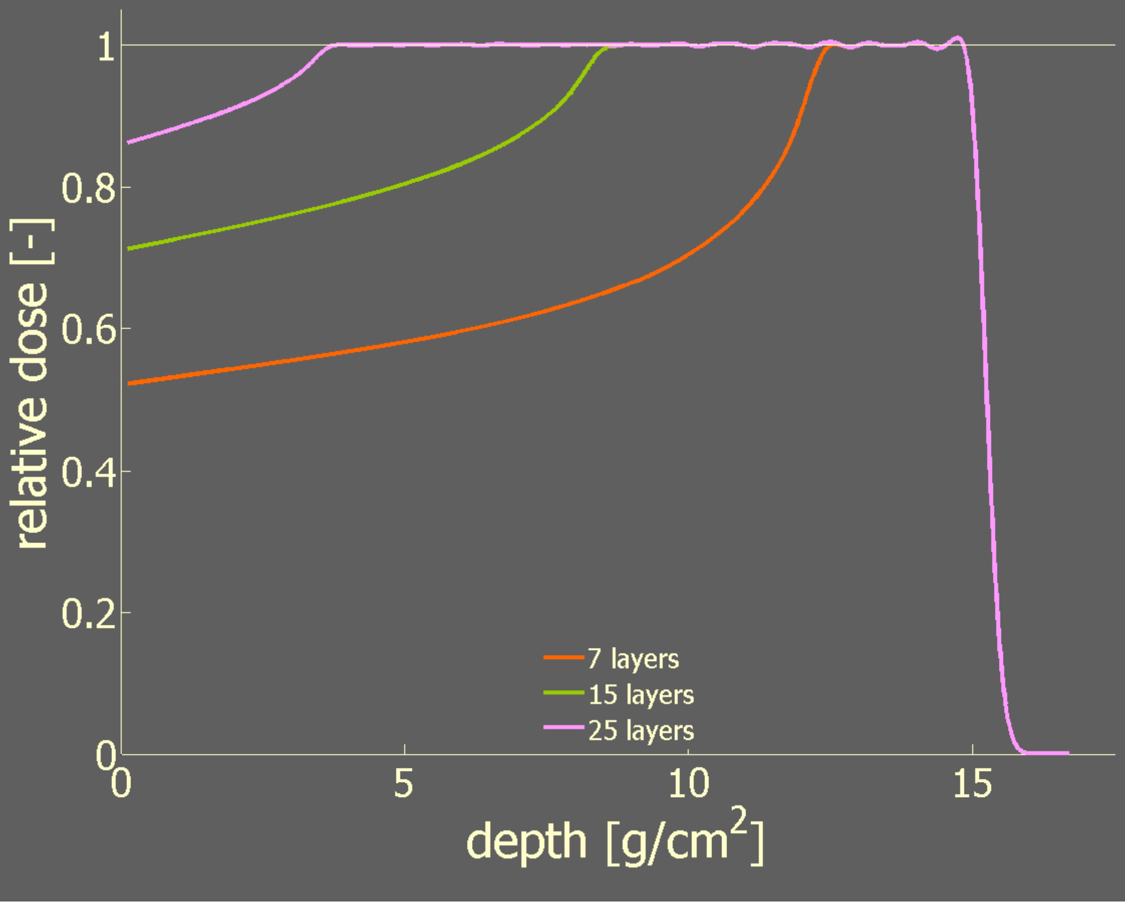
clinical beams / pdd

By adding Bragg peaks that are shifted in depth and weighted, a ‘spreadout Bragg peak’ (SOBP) is created.

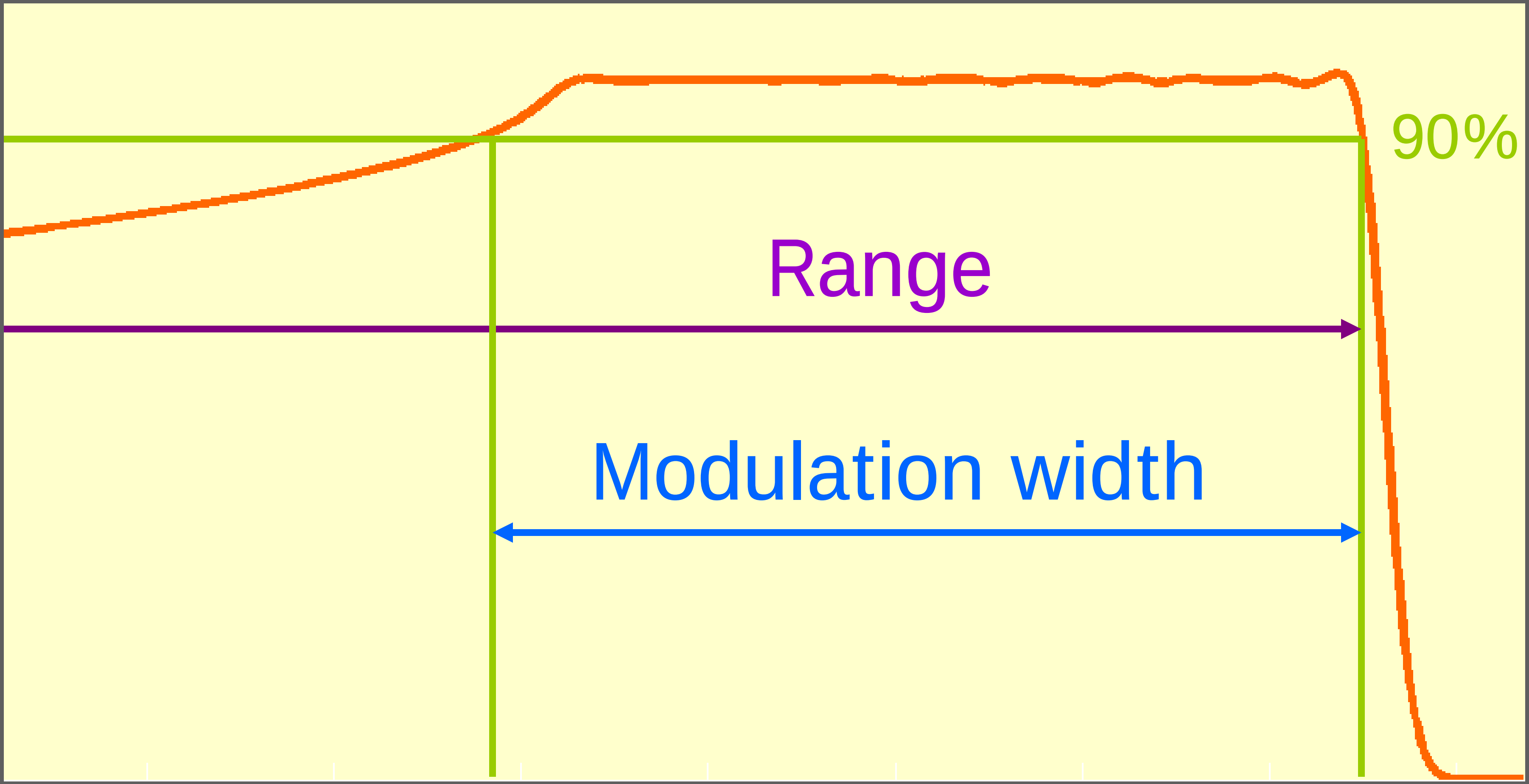


clinical beams / pdd

By varying the number of peaks, the extent of the uniform region (modulation) can be varied.



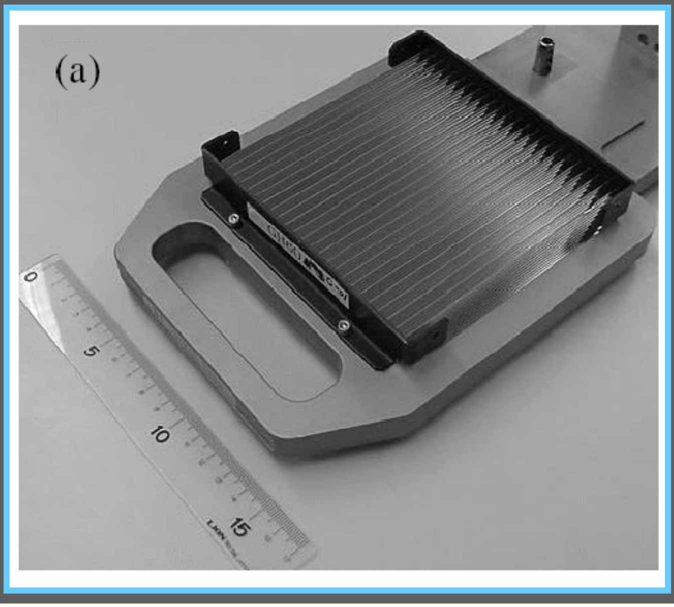
clinical beams / pdd

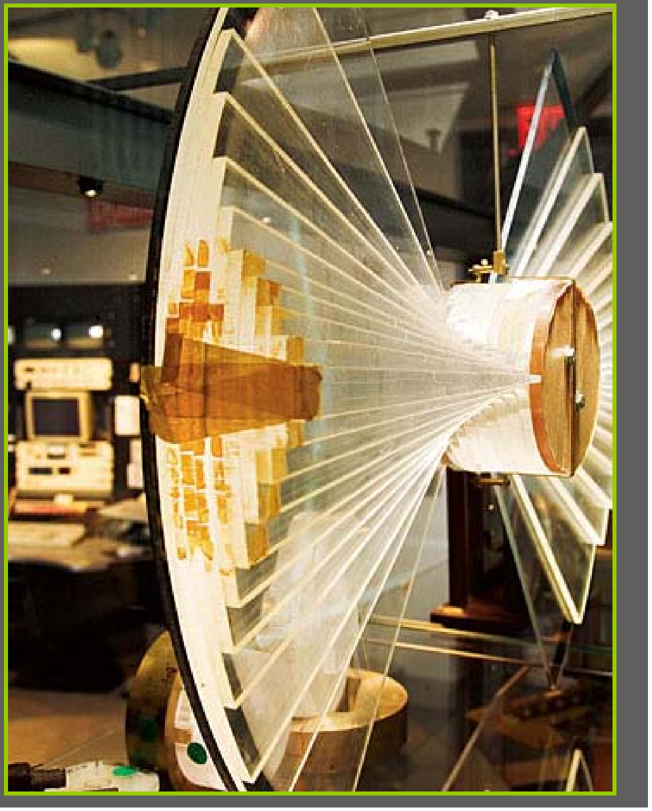


...alternative definitions of modulation width are not uncommon...

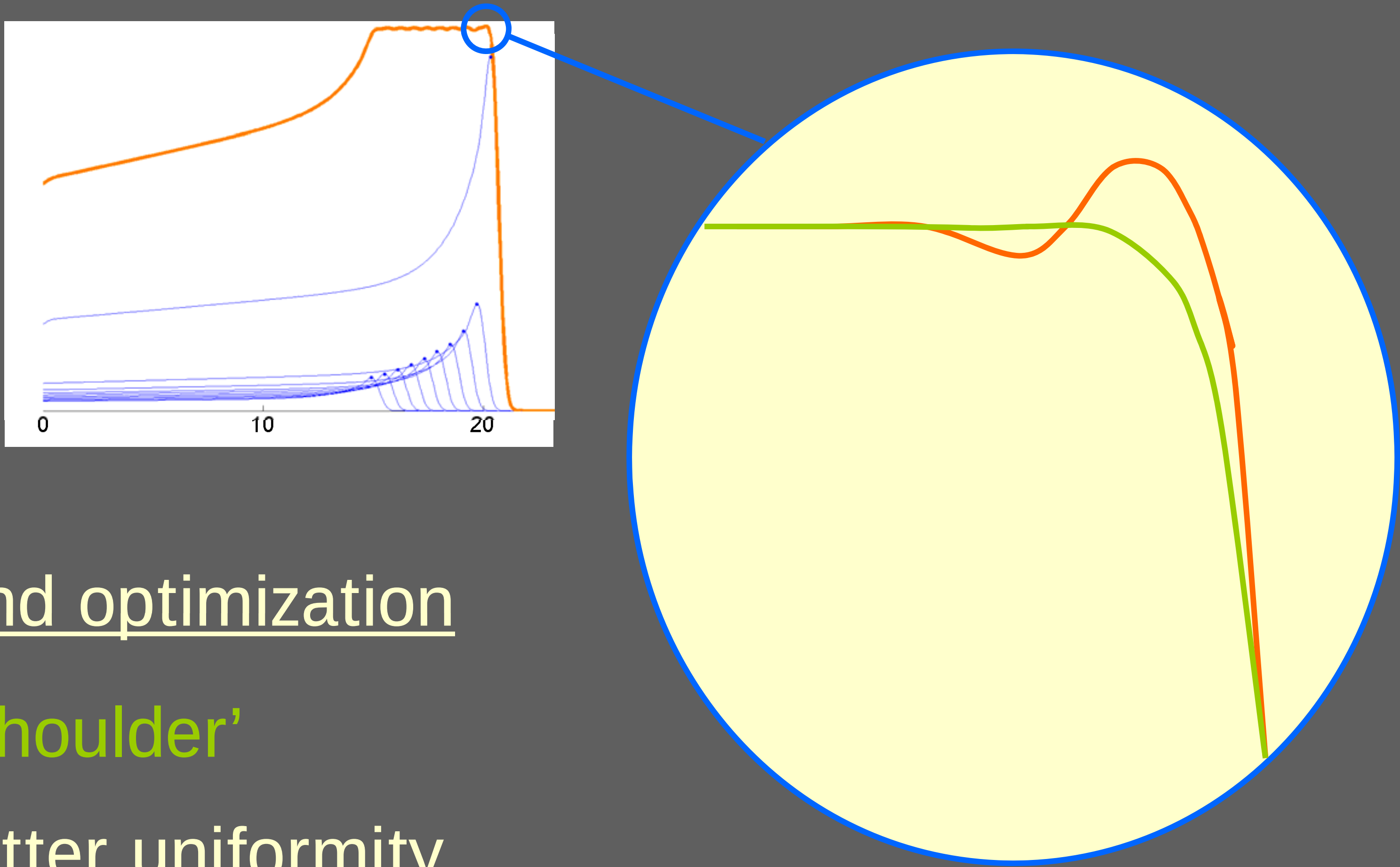
technical implementation of SOBP creation:

- energy stacking: energy change upstream of nozzle
- range modulator wheel
- ridge filter





clinical beams / pdd



Distal-end optimization

w_1 ↓ : ‘shoulder’

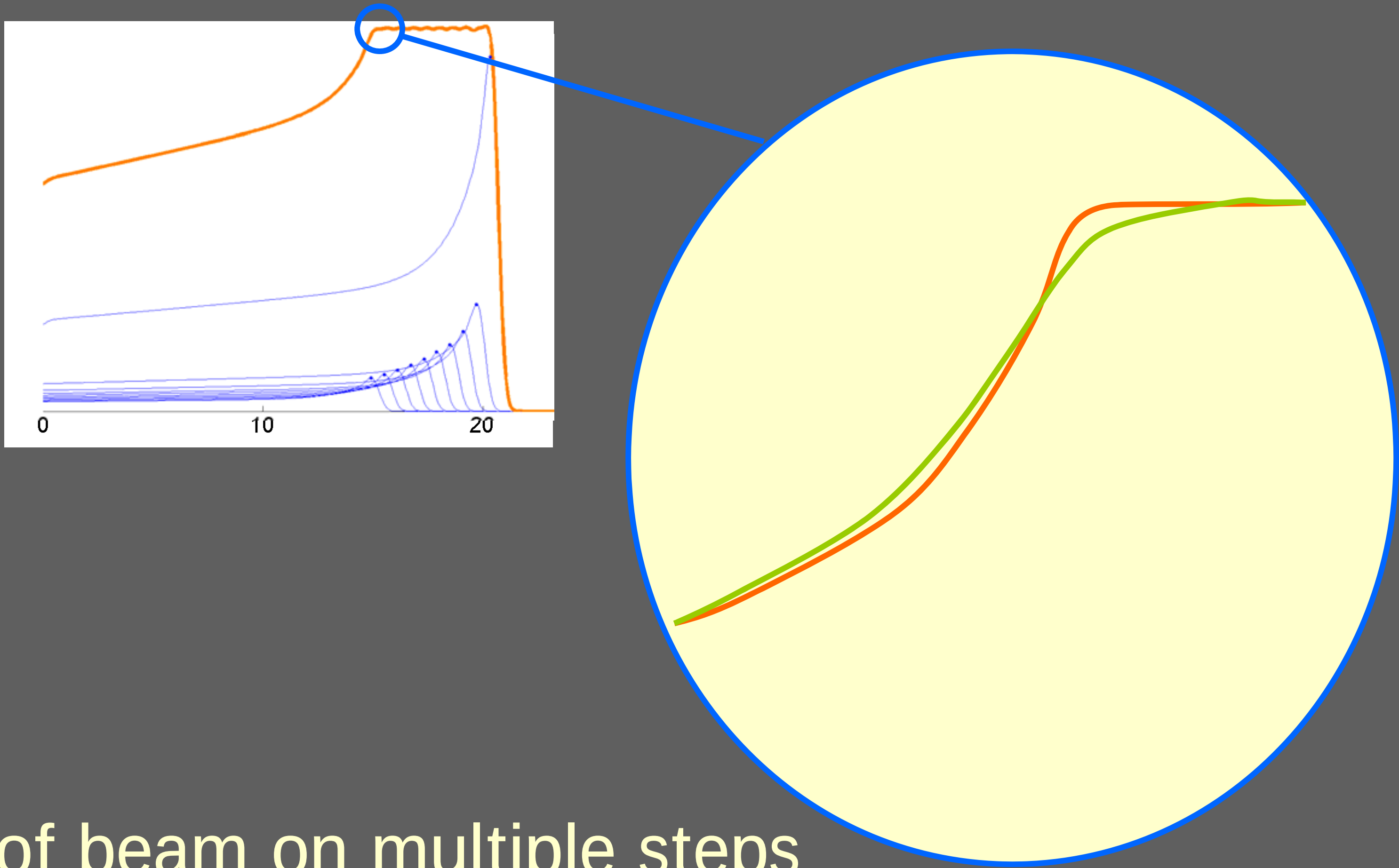
→ better uniformity

w_1 ↑ : ‘dip&bump’

→ sharper distal fall-off

...but higher RBE for low energies...

clinical beams / pdd

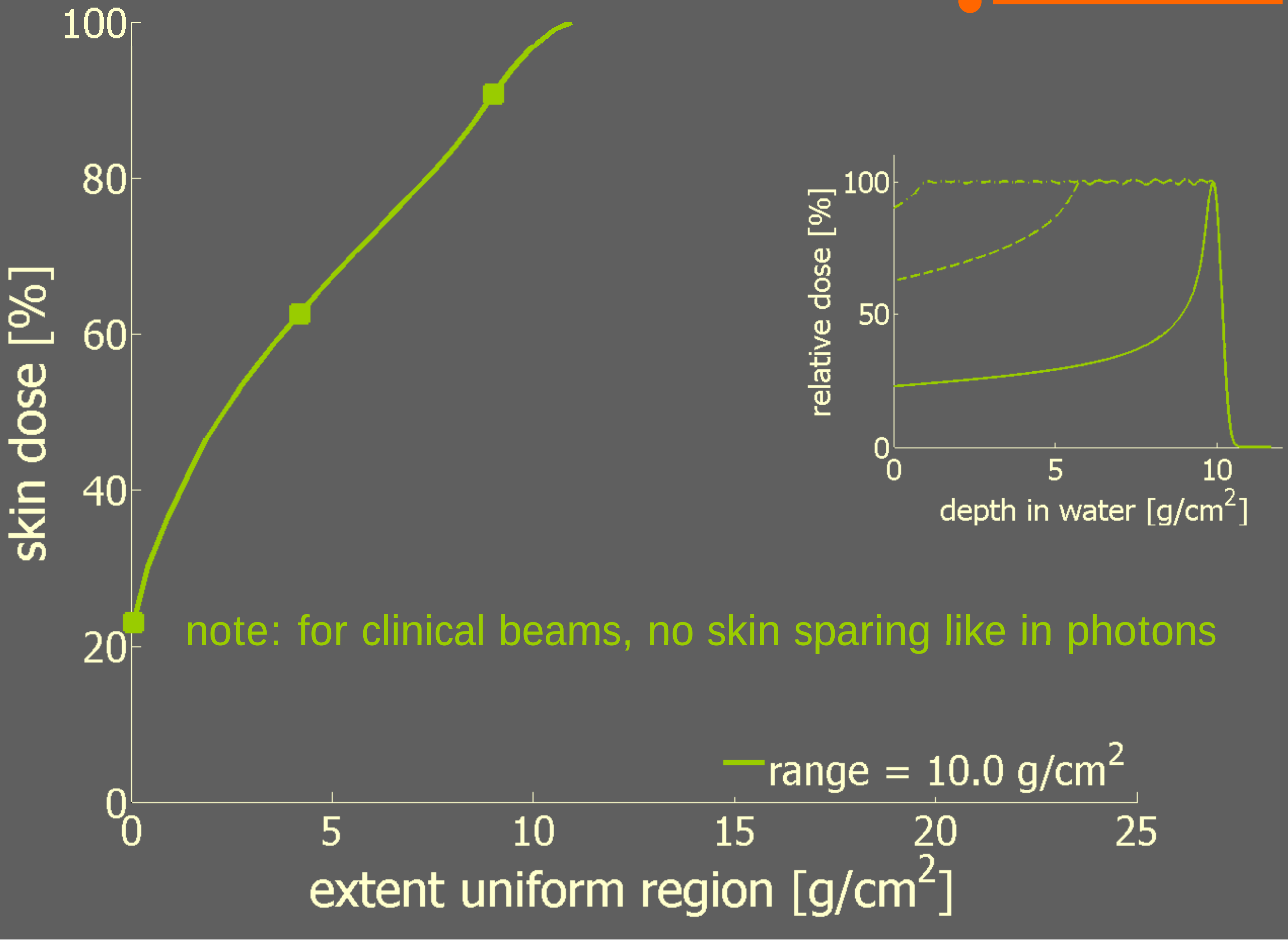


Spilling of beam on multiple steps

Spot size small compared to RM step width

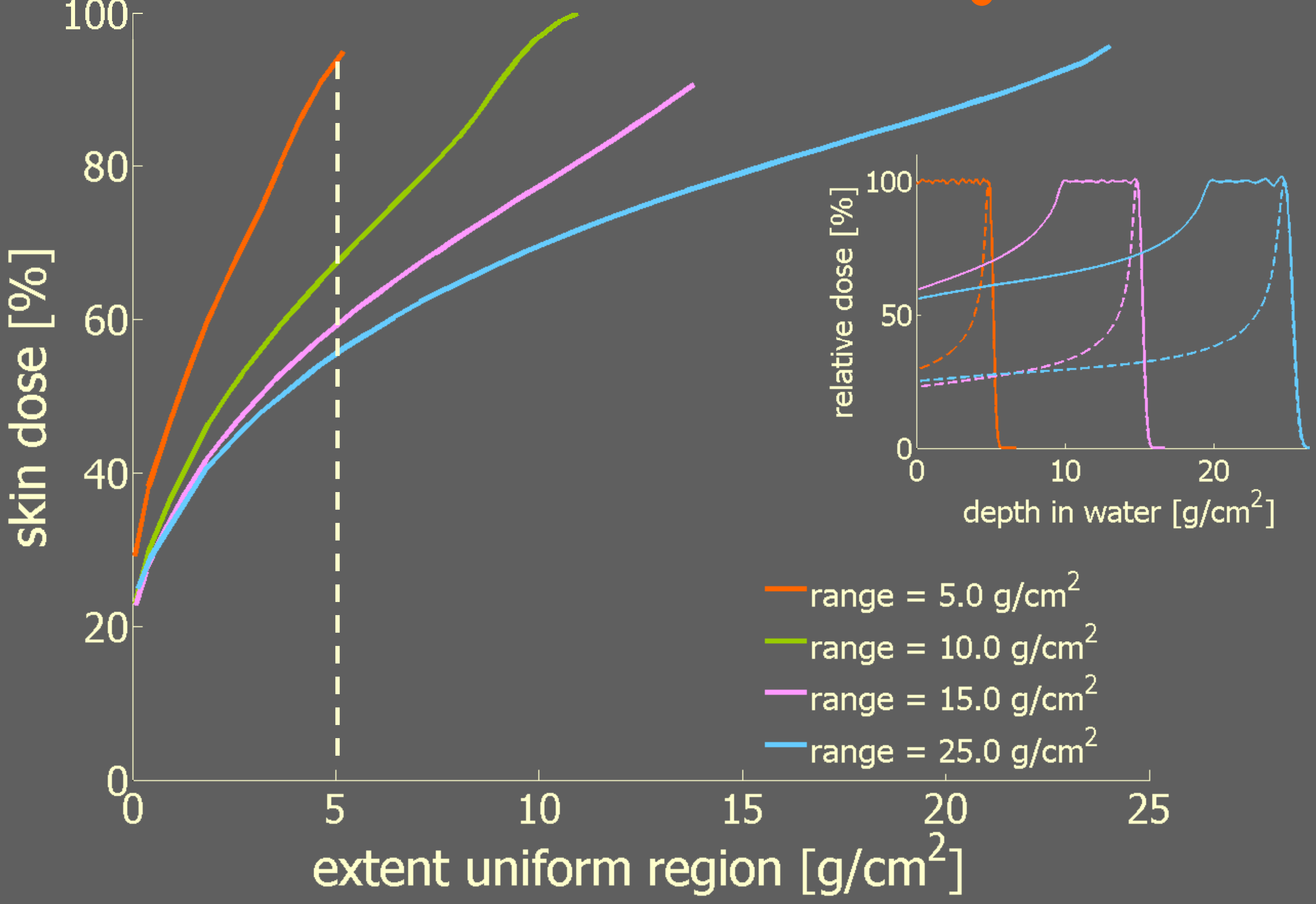
Spot size large compared to RM step width

skin dose

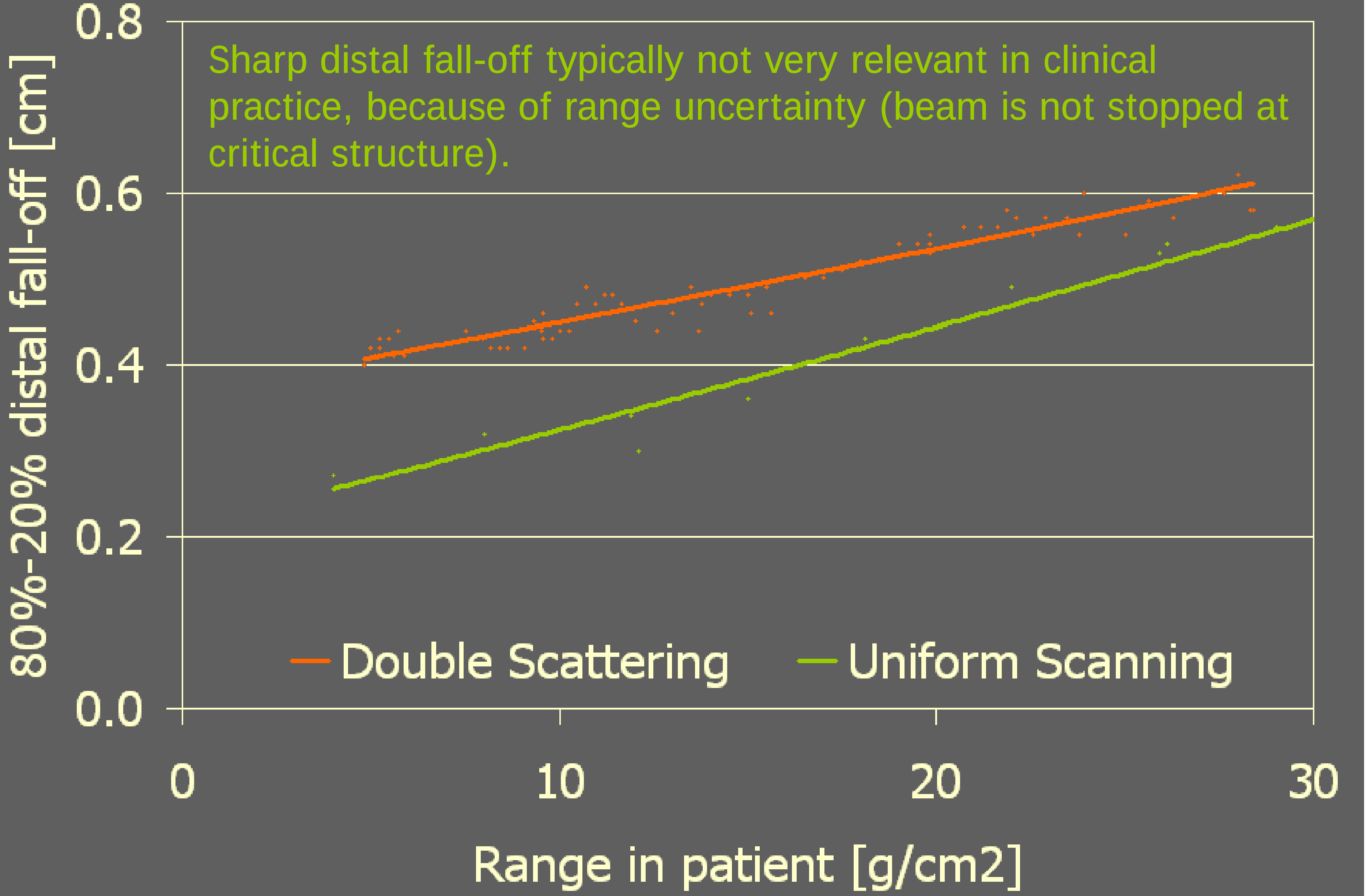


note: for clinical beams, no skin sparing like in photons

skin dose


skin dose [%]
100
80
60
40
20
0
0
5
10
15
20
25
extent uniform region [g/cm^2]
range = 5.0 g/cm^2
range = 10.0 g/cm^2
range = 15.0 g/cm^2
range = 25.0 g/cm^2
relative dose [%]
100
50
0
0
10
20
depth in water [g/cm^2]

distal fall-off



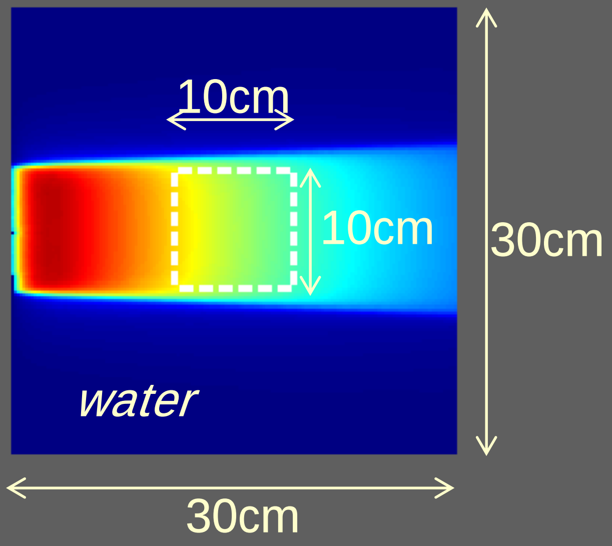
Sharp distal fall-off typically not very relevant in clinical practice, because of range uncertainty (beam is not stopped at critical structure).

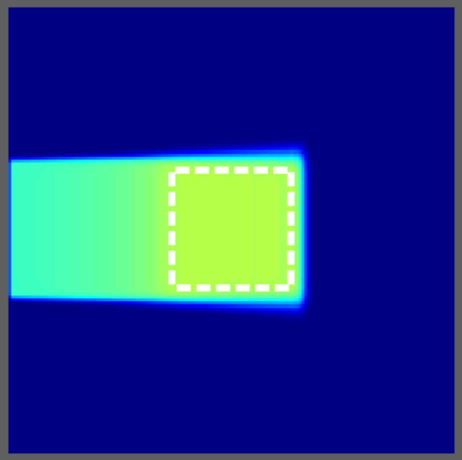
proton vs. photon pdd

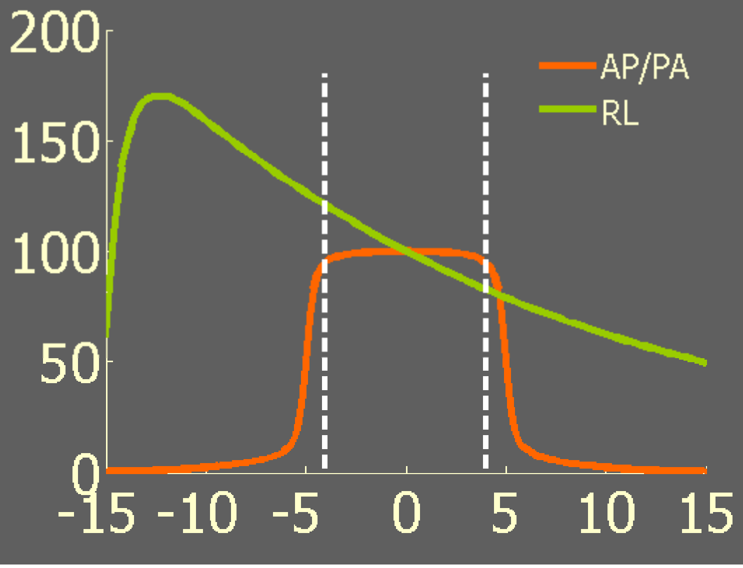
15MV photons

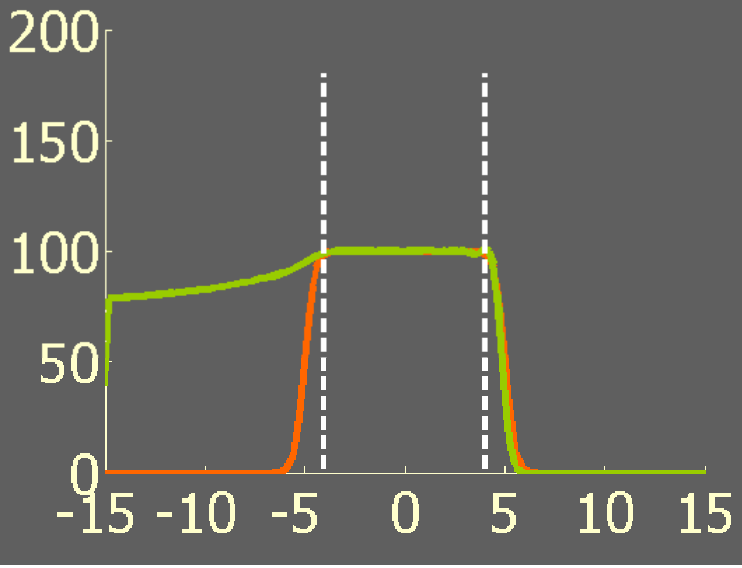
protons (R=20,M=10)

1 field





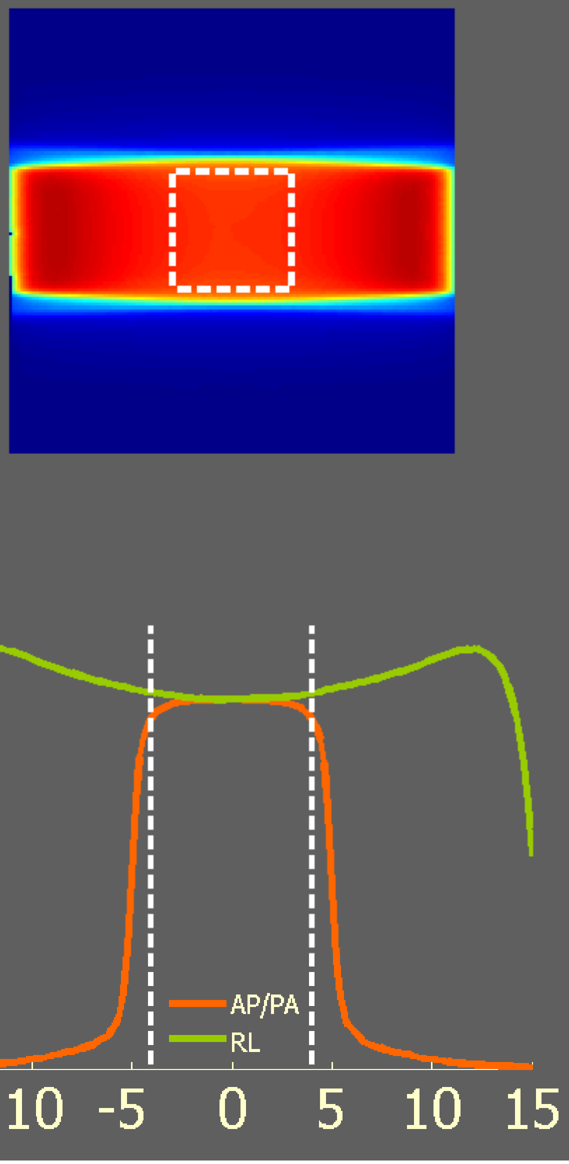




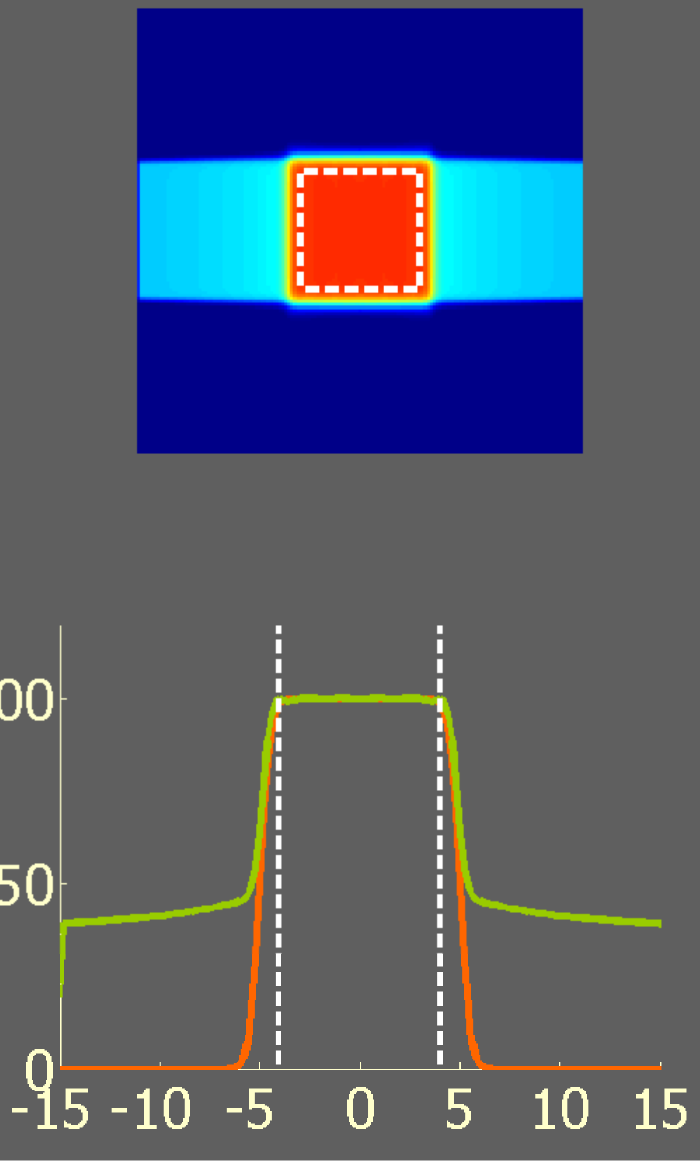
proton vs. photon pdd

2 fields

15MV photons



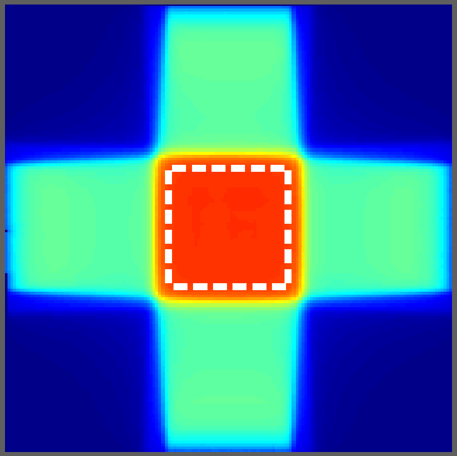
protons (R=20,M=10)

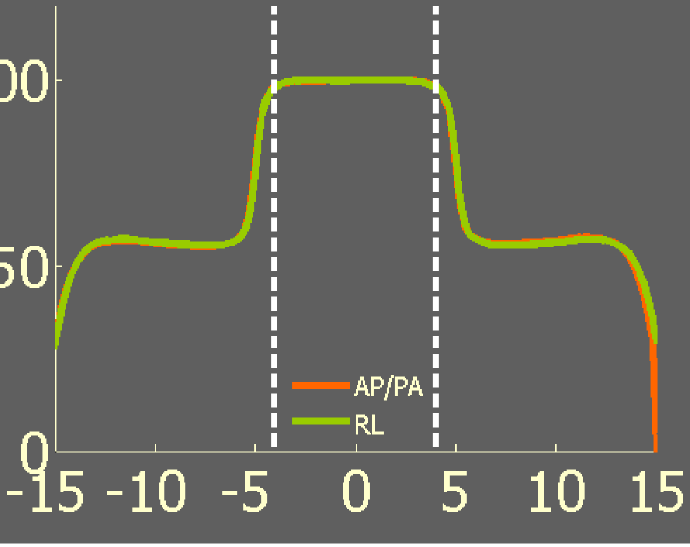


proton vs. photon pdd

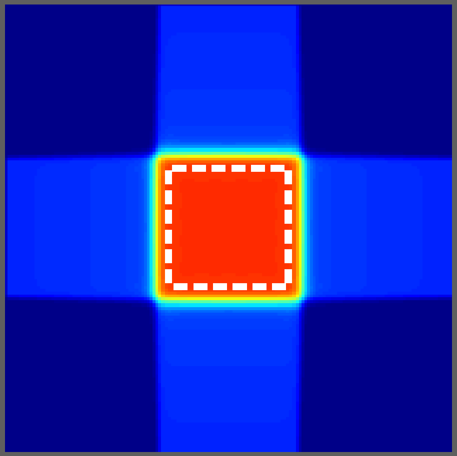
4 fields

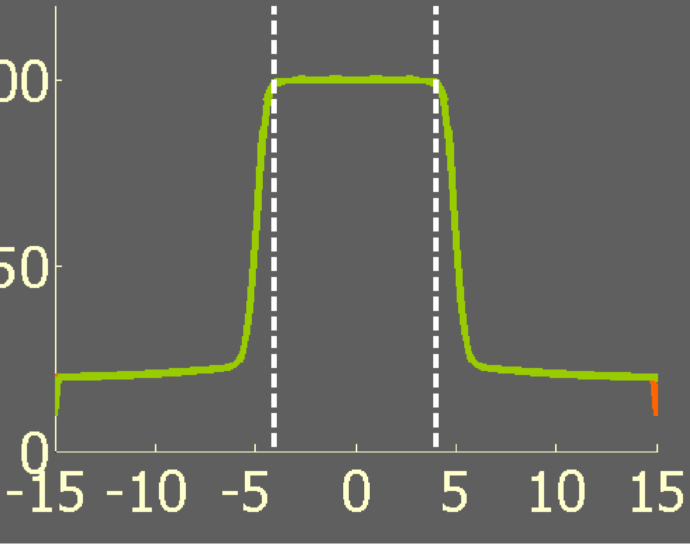
15MV photons





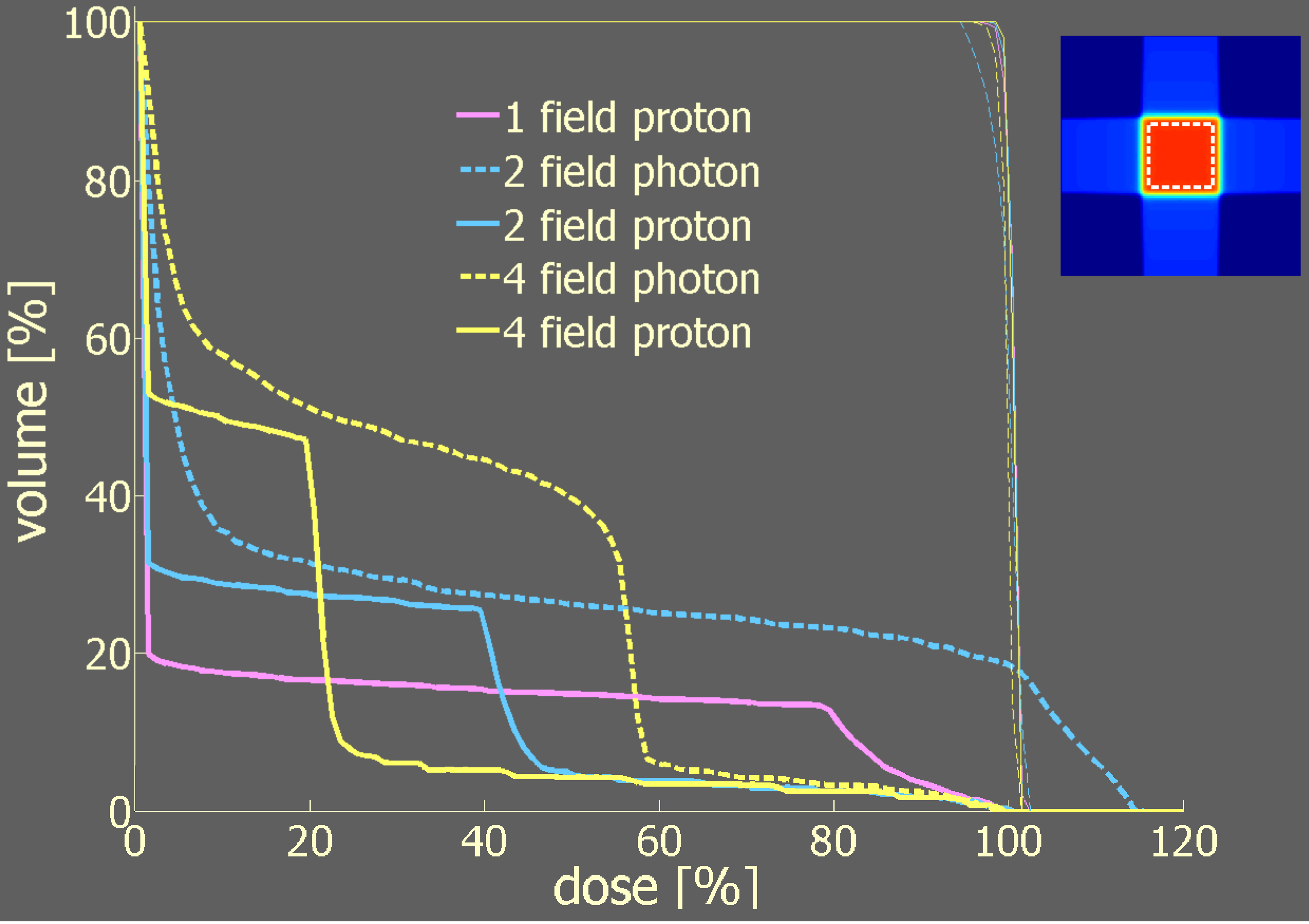
protons (R=20,M=10)





Non-target dose

- proton vs. photon pdd



proton vs. photon pdd

the intrinsic properties of the proton pdd ...

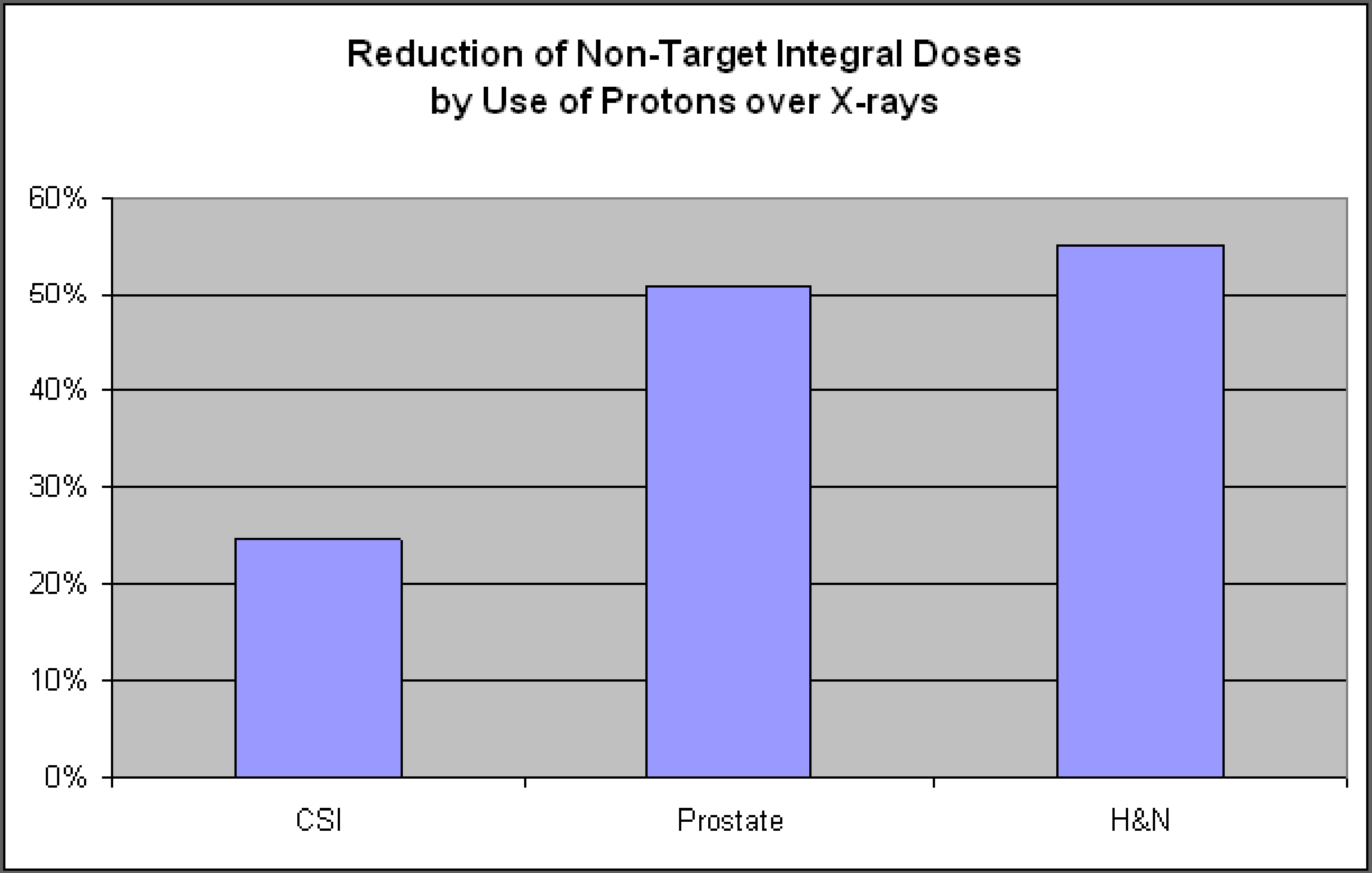
- the absence of dose distal to the uniform region and
- the lower dose proximal to the uniform region

... result in a lower integral non-target dose

→ allowing for a larger flexibility in the selection (number and direction) of beams

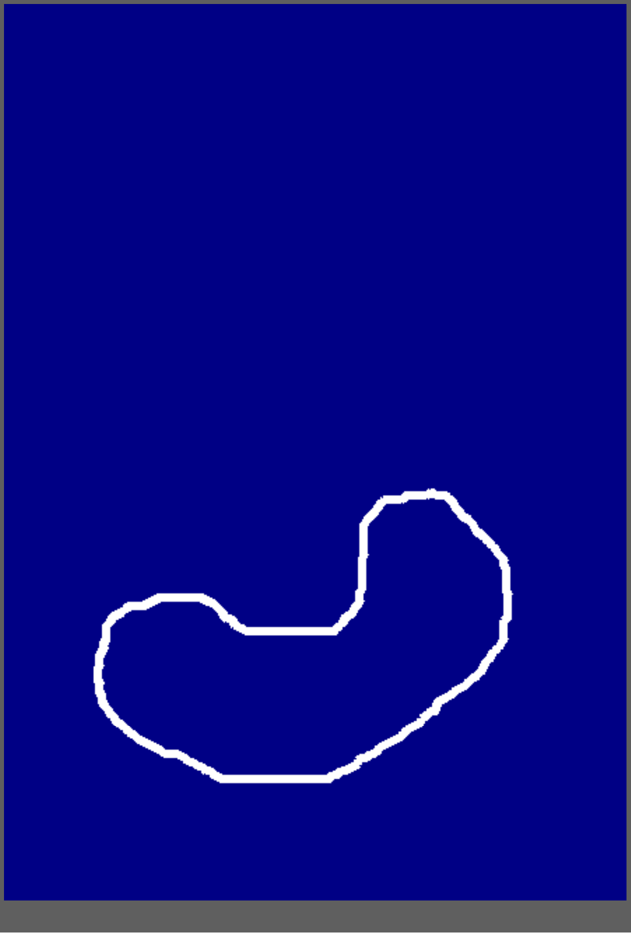
→ allowing for a larger flexibility in distributing the non-target dose

integral dose

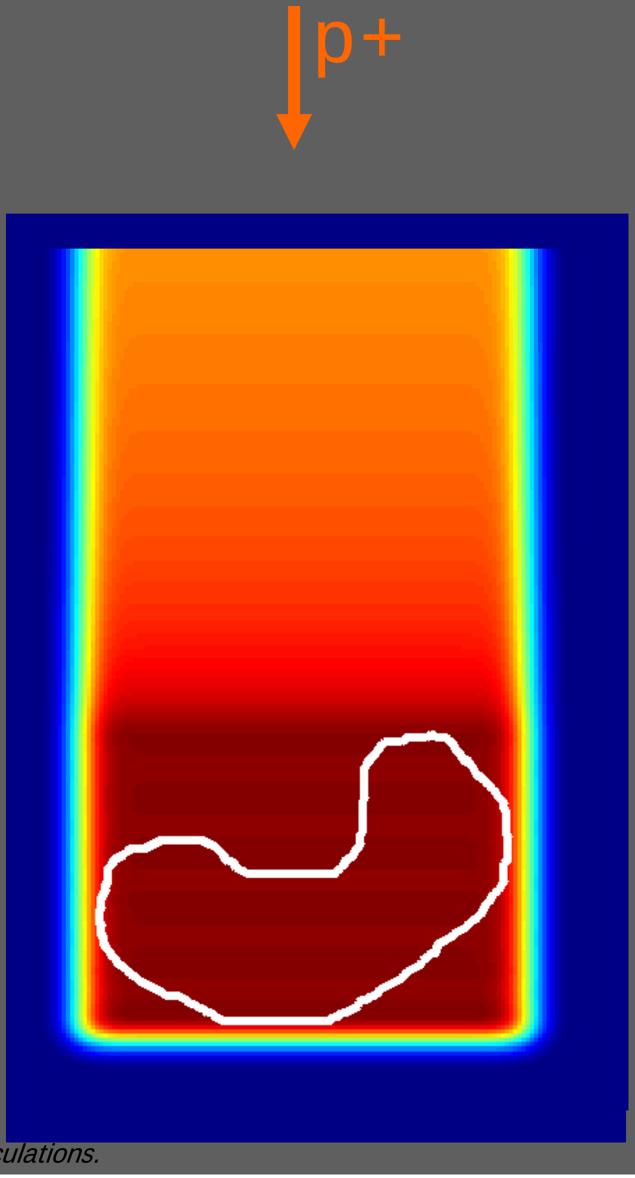


Graph courtesy of Zuofeng Li

conforming pdd



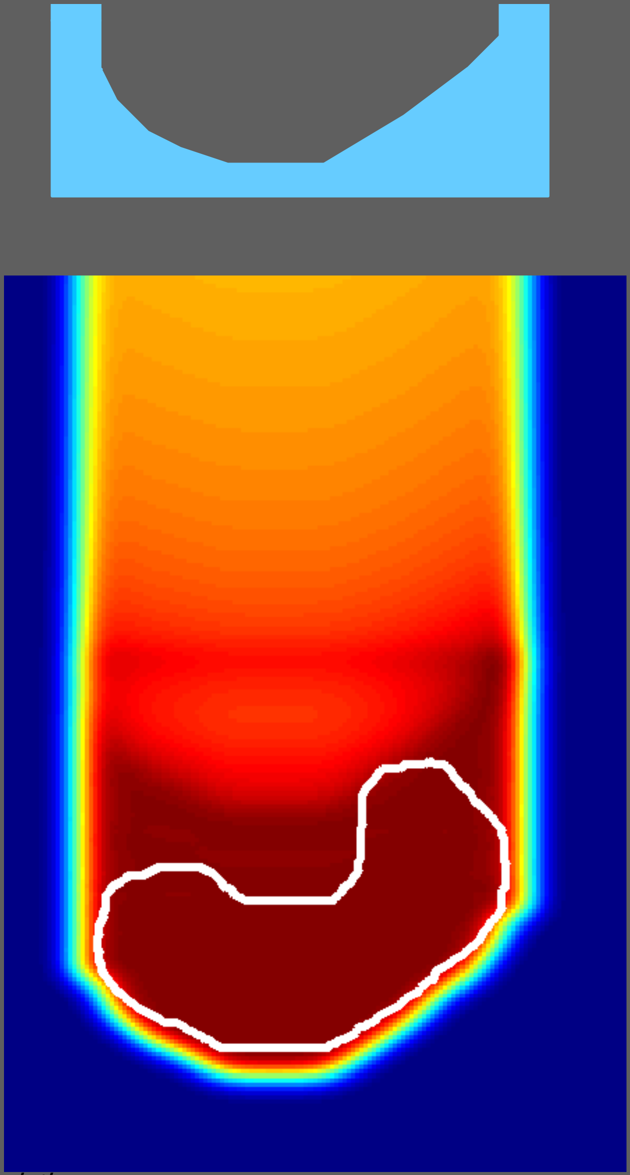
conforming pdd



Theoretical calculations.

conforming pdd

beams with range compensator & fixed modulation



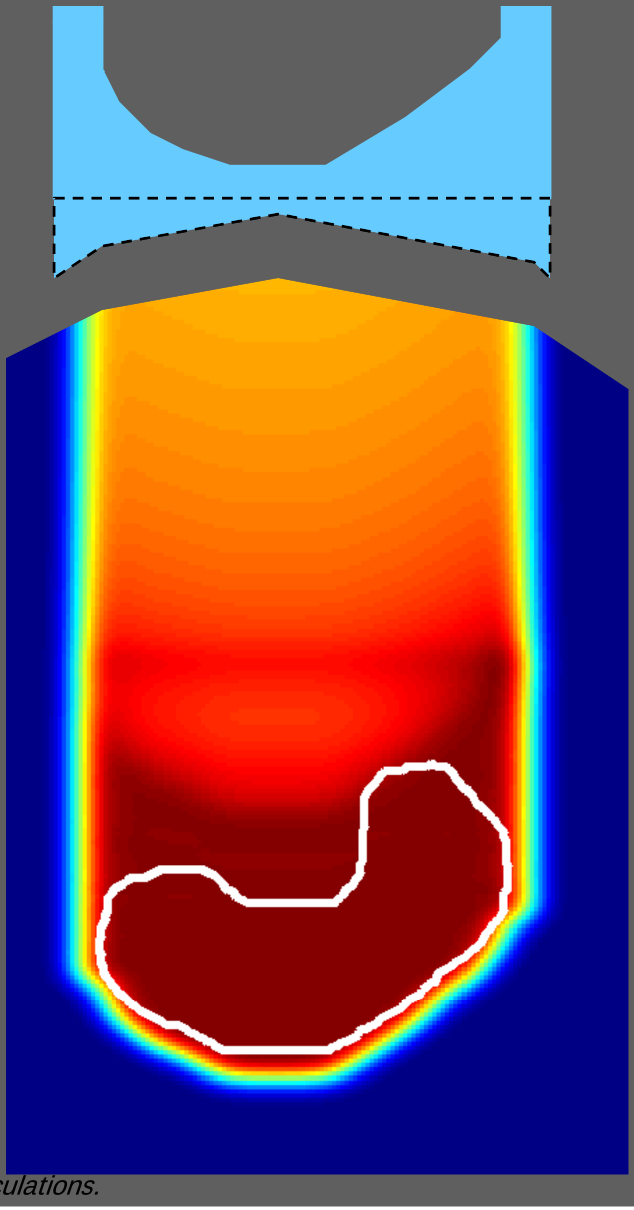
Theoretical calculations.

compensation for...

- shape distal end

conforming pdd

beams with range compensator
& fixed modulation



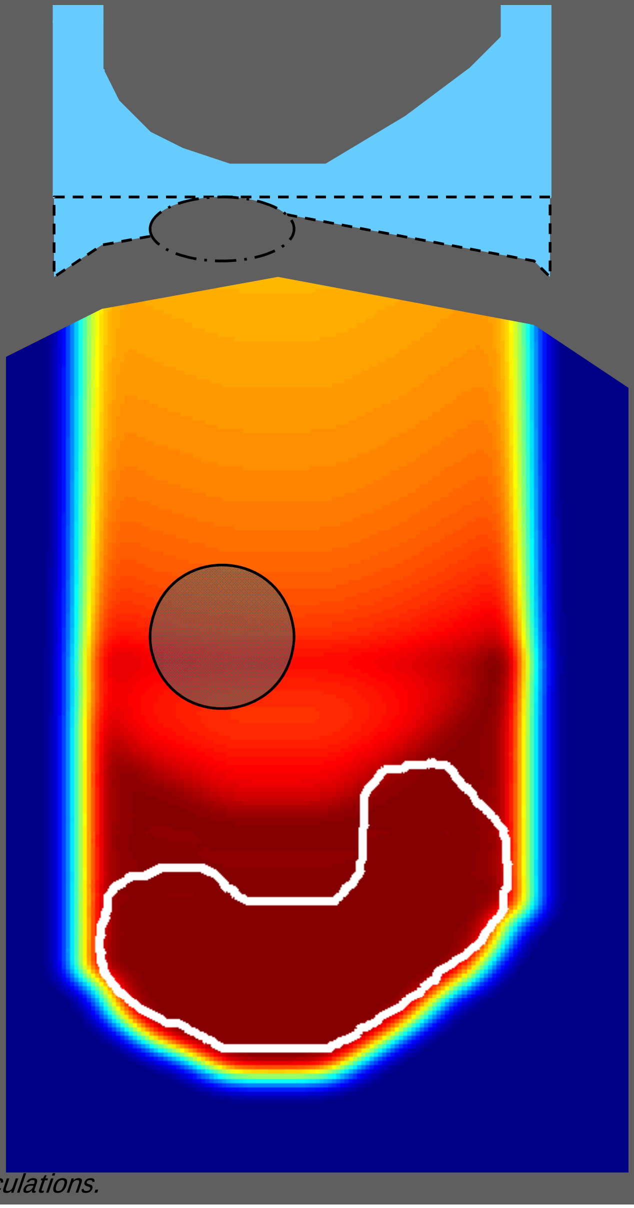
Theoretical calculations.

compensation for...

- shape distal end
- shape entrance

conforming pdd

beams with range compensator
& fixed modulation



Theoretical calculations.

compensation for...

- shape distal end
- shape entrance
- inhomogeneities

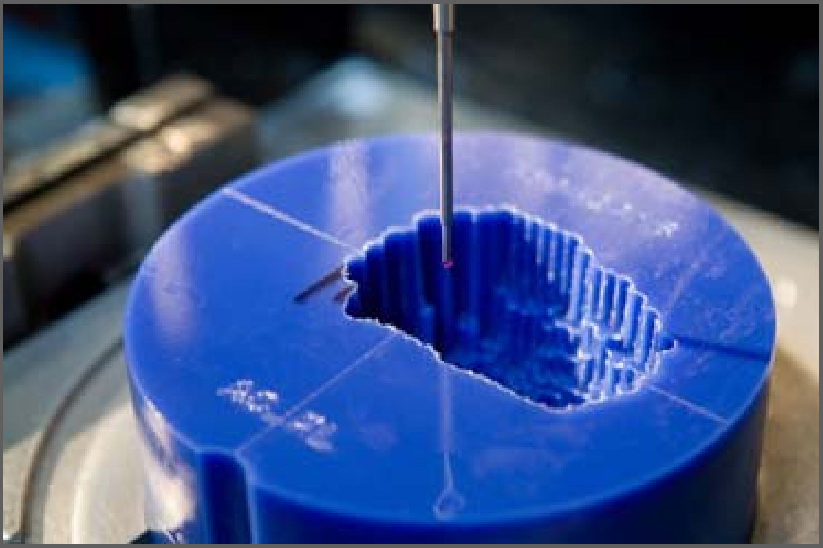
but...

- no proximal conformity
- scattering from RC leads to hot/cold spots

range compensator

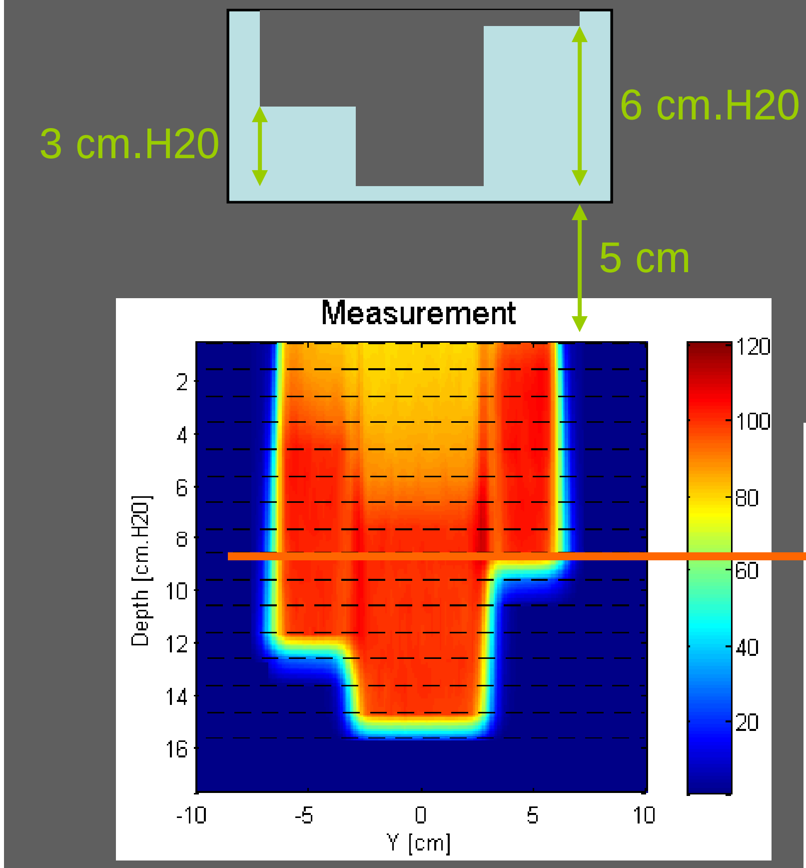
lucite

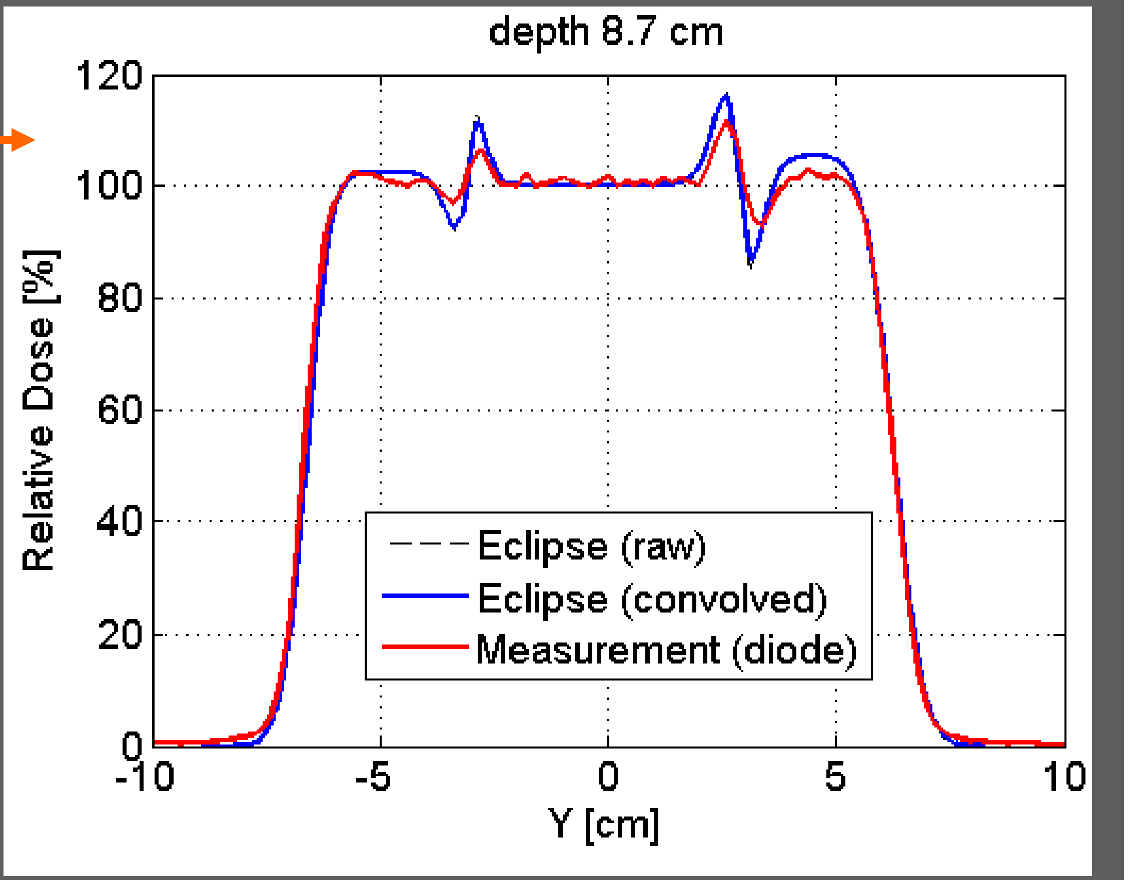
wax



Photos courtesy MGH/LLUMC

compensator scatter



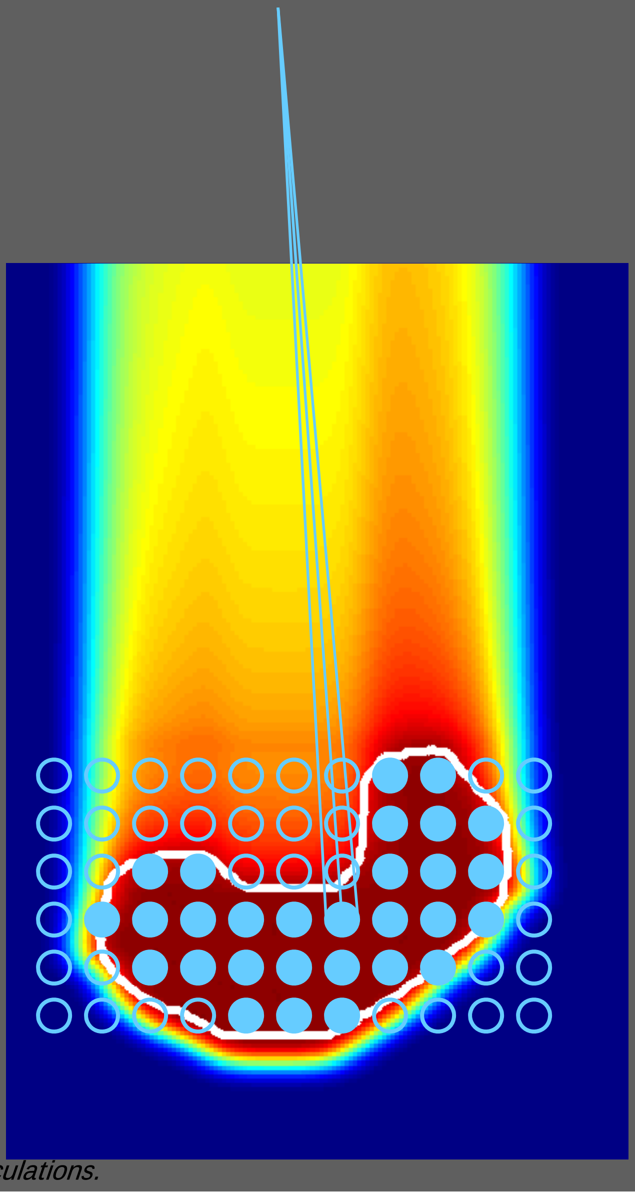


In clinical cases RC gradients smaller...

UFPTI measurement and tx planning data.

conforming pdd

pencil beam scanning

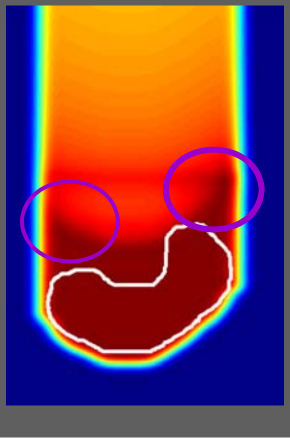


fluence optimized per energy layer

→ beam only turned on inside target

- better proximal conformity
- no compensator scatter

compensator



Theoretical calculations.

clinical beams / penumbra

Lateral penumbra is defined by...

beams with aperture

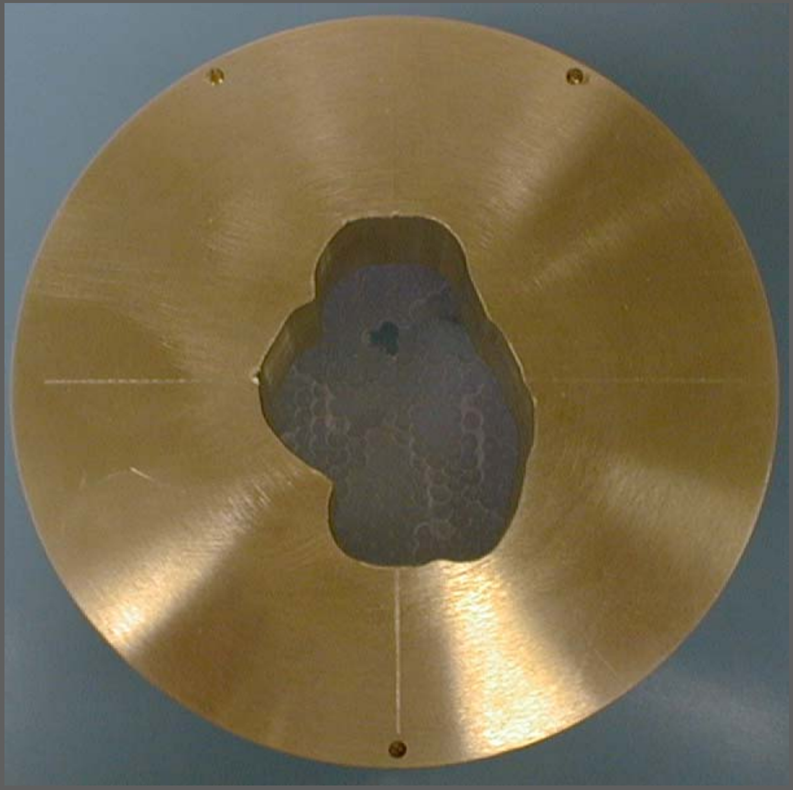
- angular spread protons at aperture (geometric source)
  - system design: source size, source position
  - air gap
- scattering in range compensator
- in-patient scattering

beams without aperture (scanning)

- in-air spot size
- in-patient scattering
- optimized fluence pattern

aperture

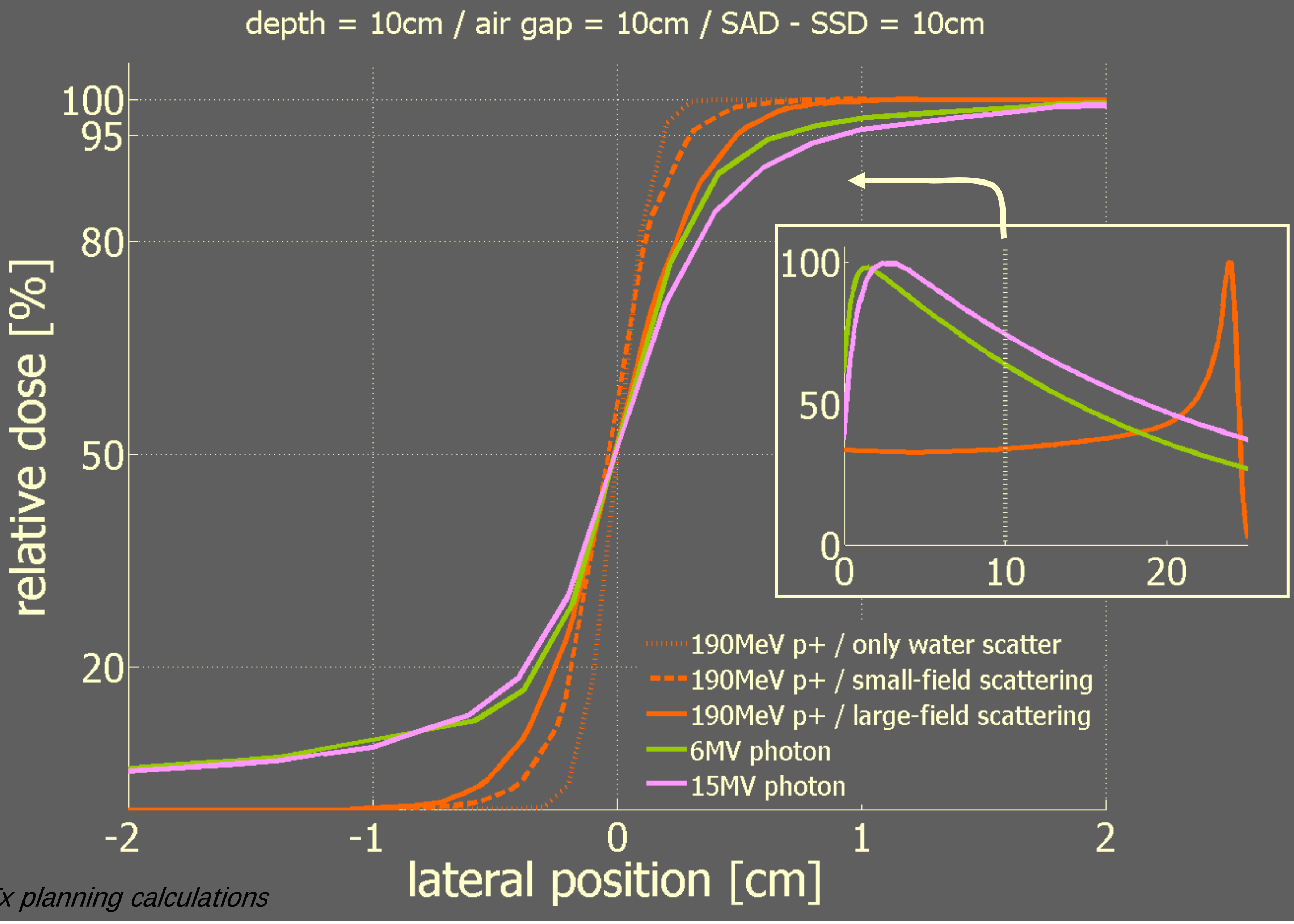
brass (milled)



cerrobend (poured)

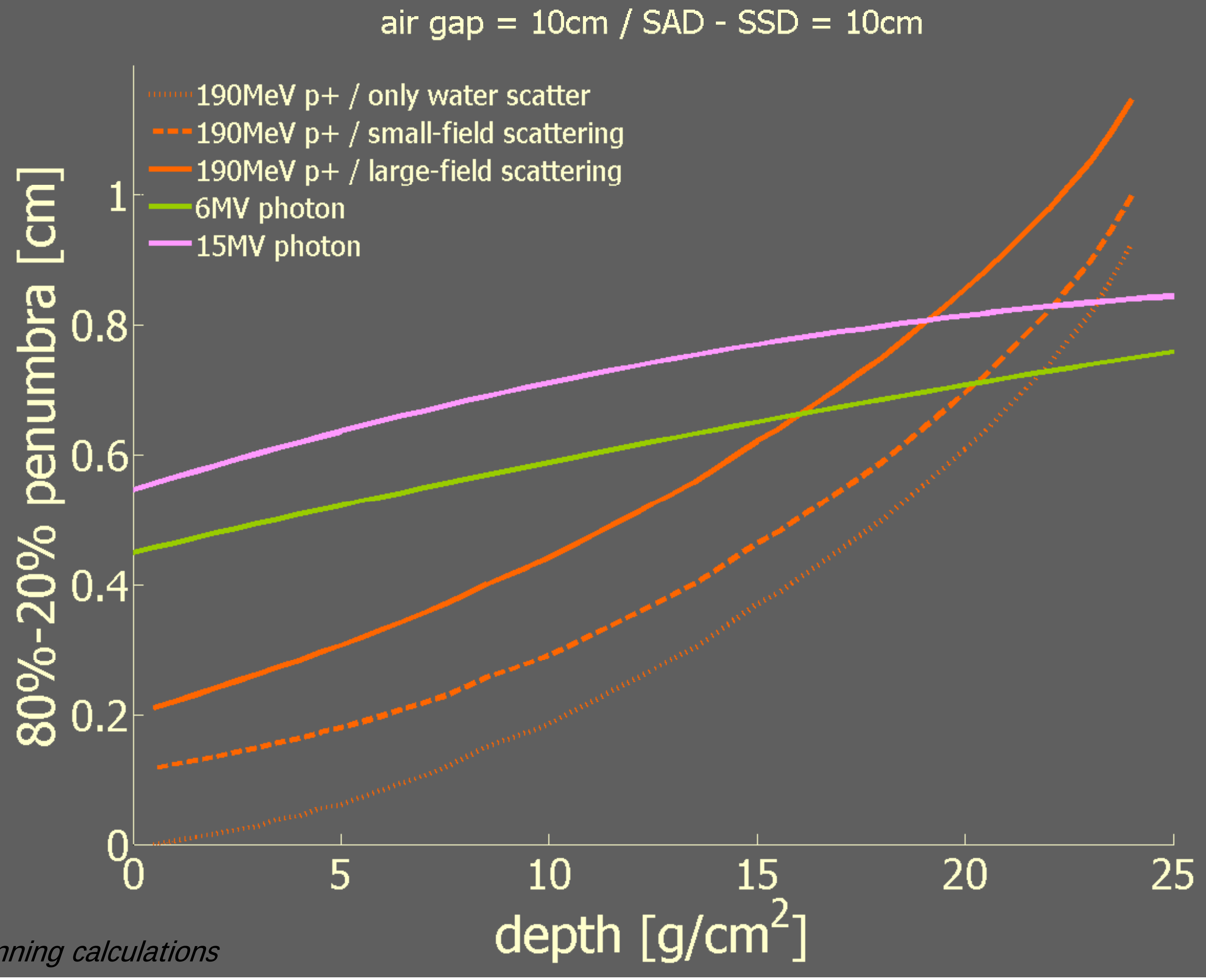
Photos courtesy MGH/LLUMC

clinical penumbra



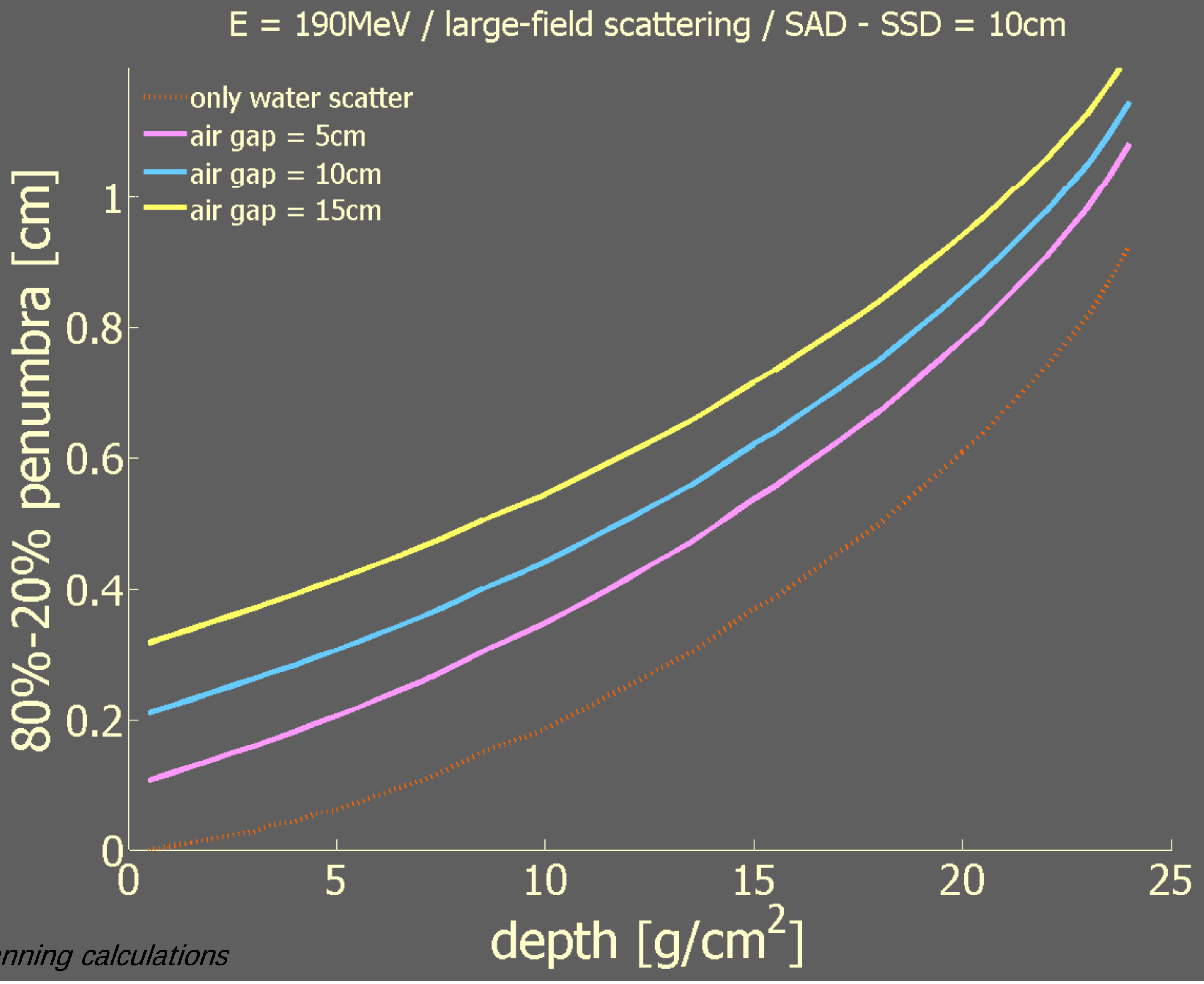
Tx planning calculations

clinical penumbra



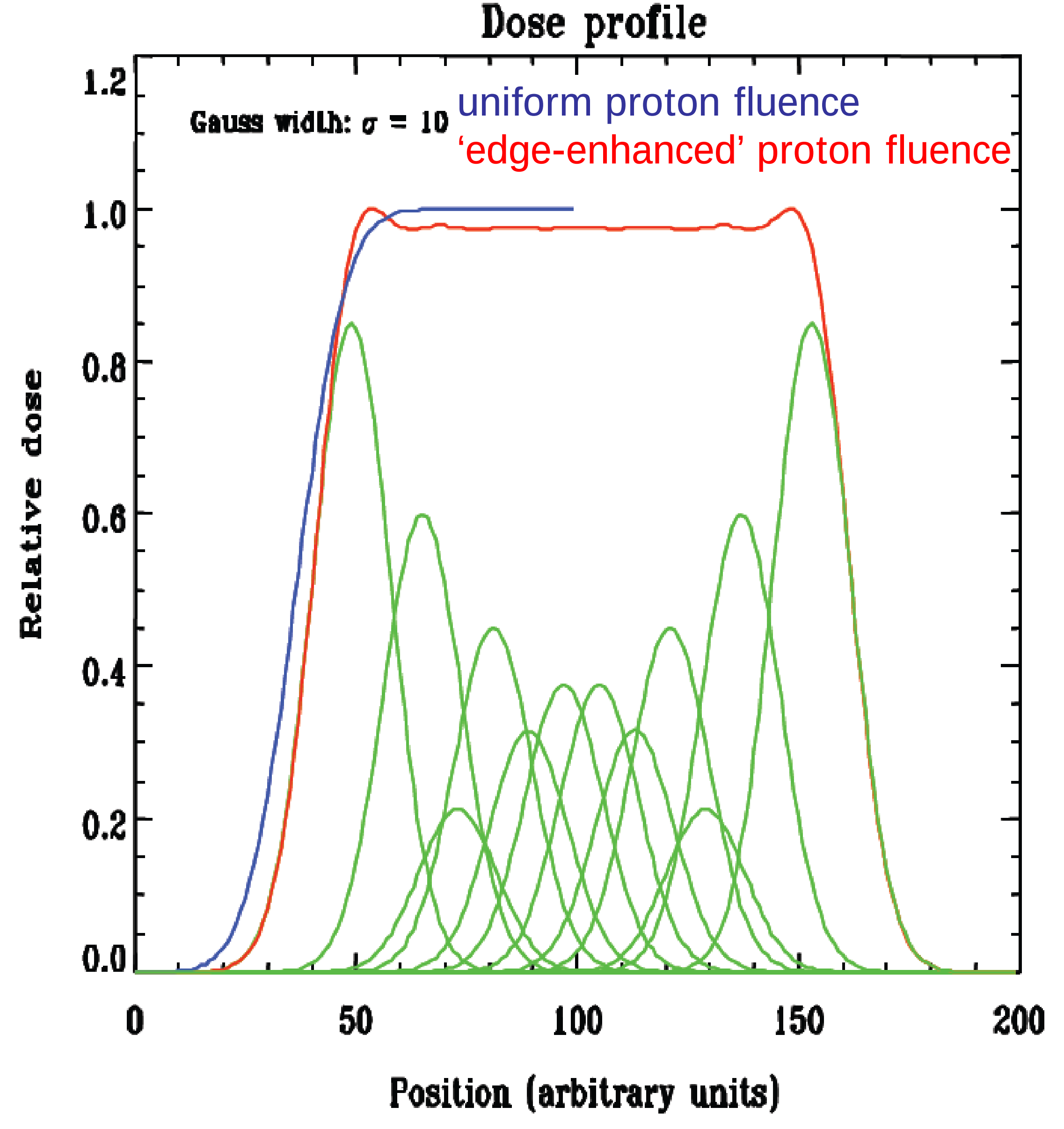
Tx planning calculations

air gap & penumbra



Tx planning calculations

scanning penumbra



Graph courtesy E. Pedroni

proton vs. photon lateral penumbra

- the proton penumbra depends on system design and setup parameters

- in general, the proton penumbra is not significantly sharper than the photon penumbra

- the low-dose ‘tails’ of the proton field are not as pronounced as for photon fields

1954: John Lawrence treats first patients at Berkeley

References

historical

- On the ionization curves of radium, W.H. Bragg and R. Kleeman, Philosophical Magazine S6 726-738, 1904
- Radiological use of fast protons, R.R. Wilson, Radiology 47 487-491, 1946
- Moliere’s theory of multiple scattering, H.A. Bethe, Phys. Rev. 89 1256-1266, 1953

stopping power / Bragg peak

- An analytical approximation of the Bragg curve for therapeutic proton beams, T. Bortfeld, Med. Phys 24 (12), December 1997

scattering

- Some practical remarks on multiple scattering, V.L. Highland, Nucl. Instr. Meth. 129 497-499, 1975
- Multiple Coulomb scattering of 160 MeV protons, Gottschalk et al, Nucl. Instrum. Method B 74 467–90, 1993

books on proton therapy

- passive beam spreading in proton therapy, B. Gottschalk, http://huhepl.harvard.edu/˜gottschalk
- proton therapy and radio-surgery, H. Breuer and B. Smit, Springer (2000)