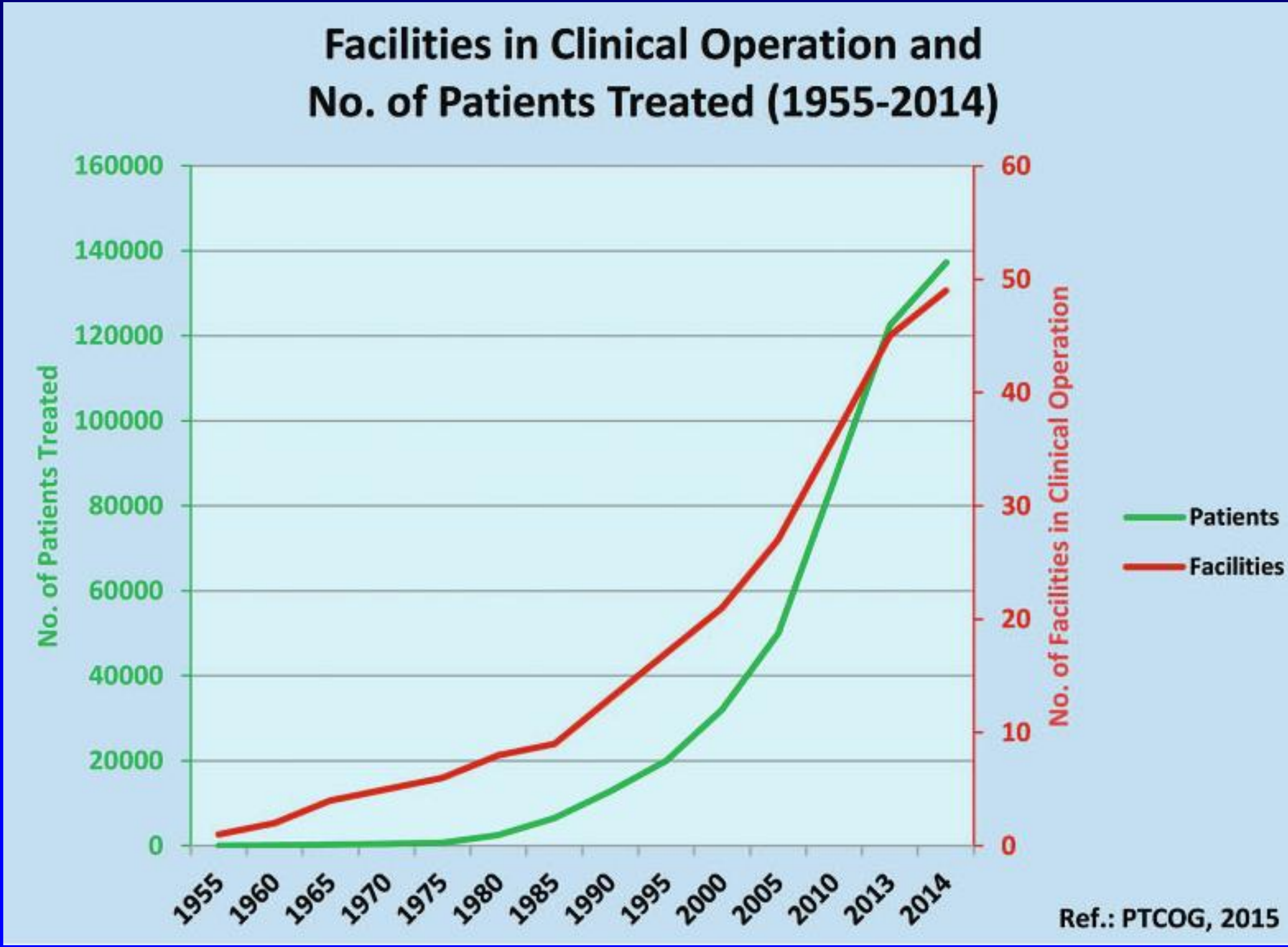
The Basic Interaction Physics of Therapeutic Proton Beams

Wayne Newhauser, Ph. D.

LSU/MBPCC


Facilities in Clinical Operation and
No. of Patients Treated (1955-2014)
160000
140000
120000
100000
80000
60000
40000
20000
0
No. of Patients Treated
60
50
40
30
20
10
0
No. of Facilities in Clinical Operation
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2013
2014
Patients
Facilities
Ref.: PTCOG, 2015

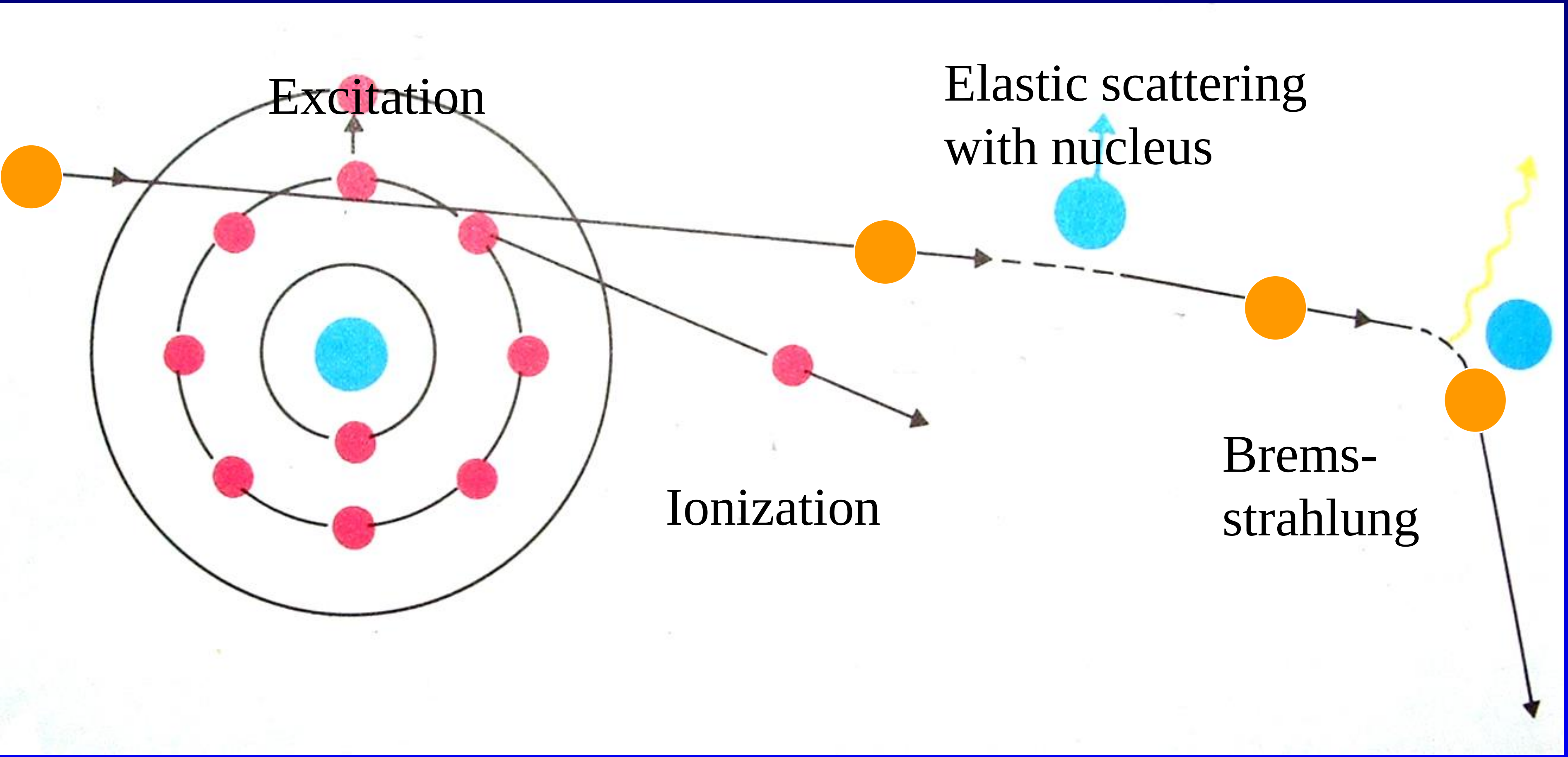
Objectives

- Review basic proton interaction physics
- Understand why protons offer some clinical advantages
- Introduction to some proton therapy equipment and technology

Physics Overview

- Basic interaction physics
  - –Energy loss (penetration range)
  - –Scattering (particle trajectory)
  - –Range straggling
  - –Bragg curves
  - –Spread out Bragg Peaks

Energy Transfer Mechanisms

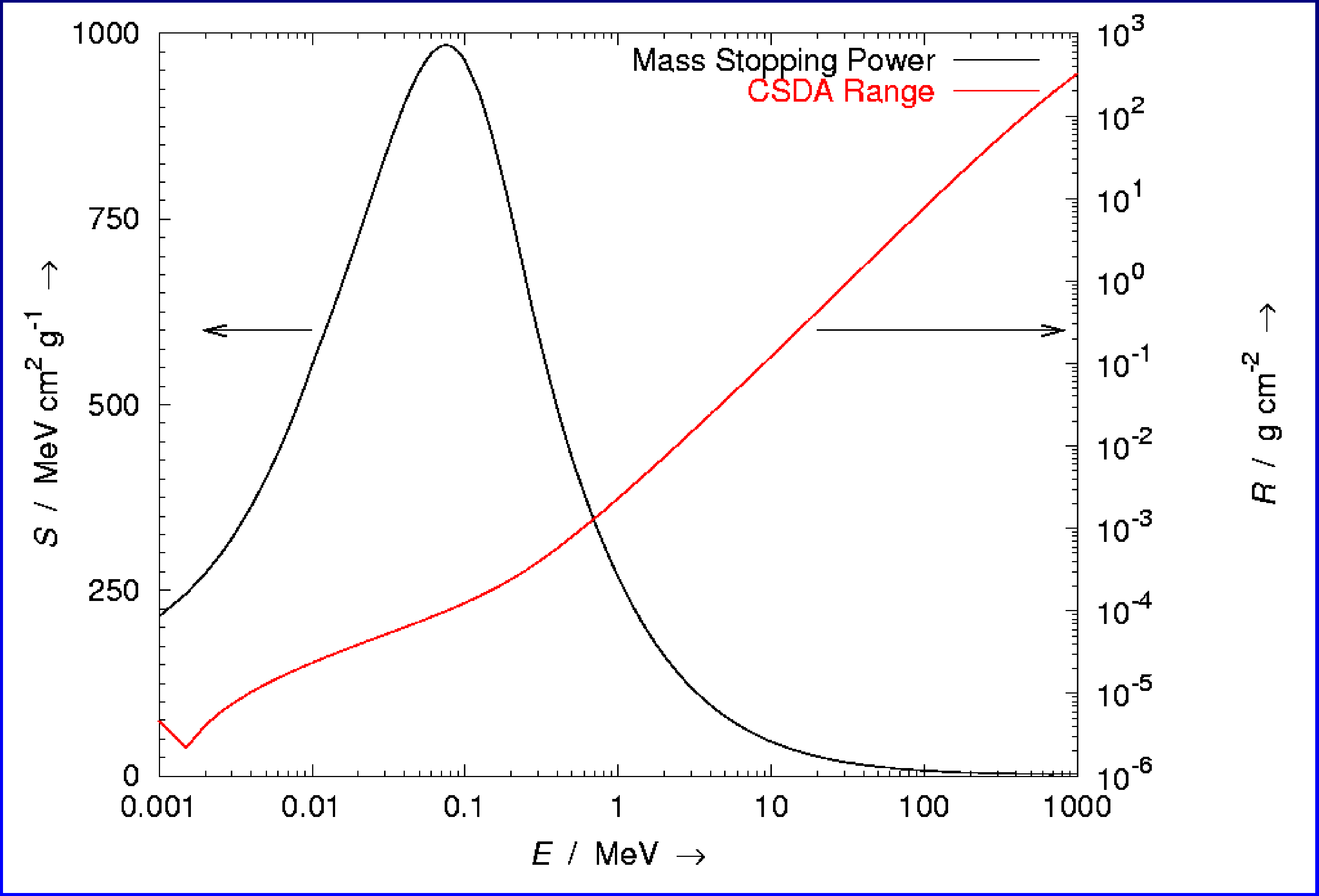


Most *energy loss* is via *coulombic* interactions with atomic electrons.

Small deflections are caused by *coulombic* interactions with nucleus.

Nuclear reactions play only a small role.

Energy-Loss Rate , Proton Range



Range Energy Relation (Geiger's Rule)

$$\boxed{R = \alpha E^{p}}$$

$$\underbrace{R}_{\substack{\text{Range}\\ \text{[cm]}}} = \underbrace{\alpha}_{\substack{\text{Materials}\\ \text{constant}\\ \text{2.2e-3}}} \underbrace{E}_{\substack{\text{Initial}\\ \text{energy}\\ \text{[MeV]}}}{}^{\underbrace{p}_{\text{Constant(1.77)}}}$$

For protons in water where E < 200 MeV.

Stopping Power Calculation: Bethe Bloch

$$-\frac{dE}{dx} = \underbrace{2\pi N_a r_e^2 m_e c^2}_{\text{constants}} \underbrace{\rho \frac{Z}{A} \frac{z^2}{\beta^2}}_{\text{Same as Bohr's}} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right], \qquad (2.27)$$

with

$$2\pi N_a r_e^2 m_e c^2 = 0.1535\ \mathrm{MeV cm^2/g}$$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm

m_e: electron mass

N_a: Avogadro's number $= 6.022 \times 10^{23}\ \mathrm{mol}^{-1}$

I: mean excitation potential

Z: atomic number of absorbing material

A: atomic weight of absorbing material

ρ: density of absorbing material

z: charge of incident particle in units of e

$\beta = v/c$ of the incident particle

$\gamma = 1/\sqrt{1-\beta^2}$

δ: density correction

C: shell correction

W_{max}: maximum energy transfer in a single collision.

W. R. Leo. Techniques for Nuclear and Particle Physics Experiments. Springer, Berlin, 1987.

Stopping Power Calculation: Bethe Bloch

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

W. R. Leo. Techniques for Nuclear and Particle Physics Experiments. Springer, Berlin, 1987.

Dependencies

Ion charge: z^2

Ion velocity: $1/v^2$ ($1/\beta^2$ relativistically)

Ion mass: Buried in the W_{max} term

Absorber: $N_a \rho Z/A = N_e$ = e^- density

$\ln(1/I^2)$

Stopping Power Calculation: Bethe Bloch

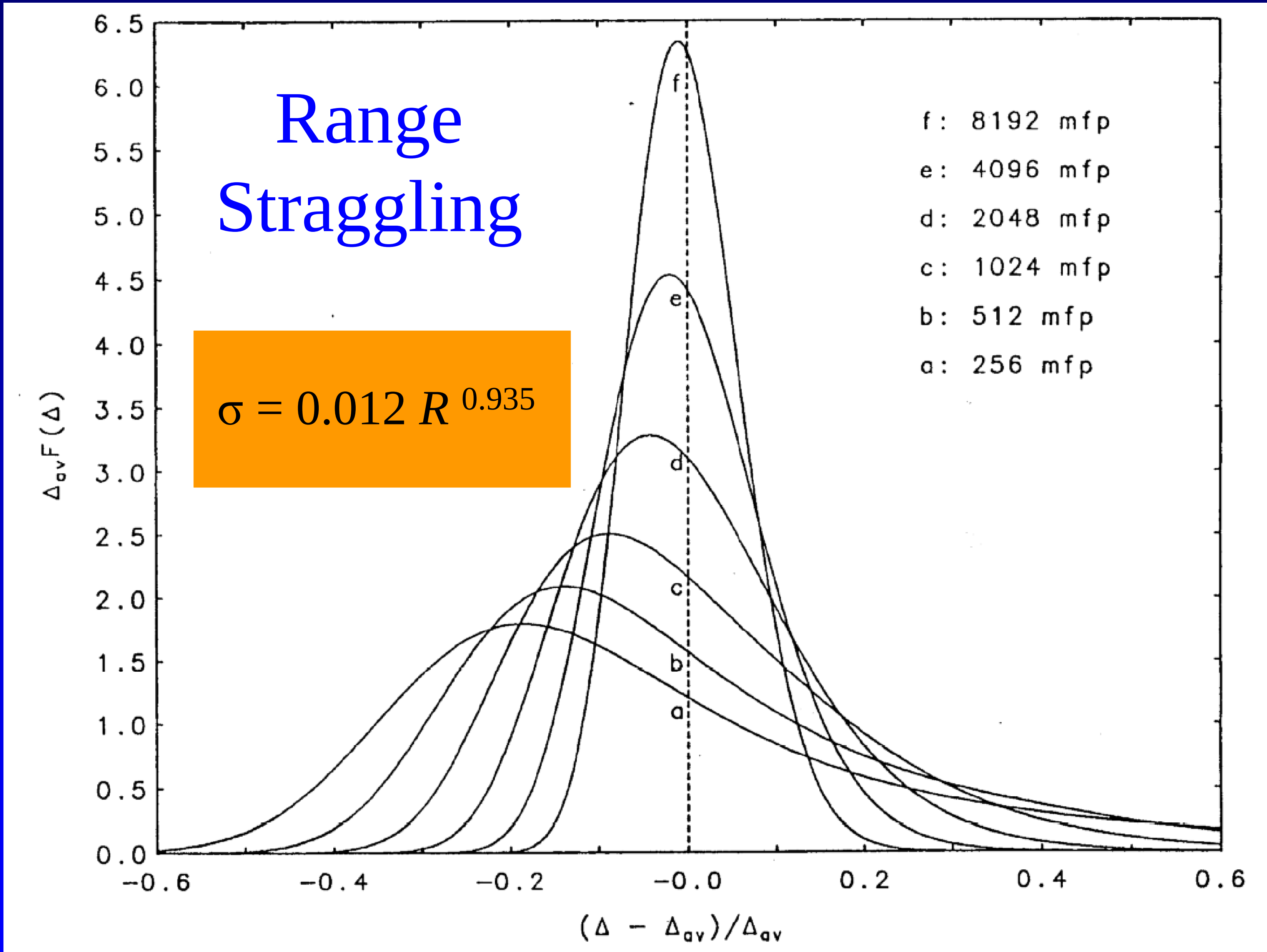
- Mean excitation potential (I)
  - Main parameter of Bethe Bloch formula
  - Theoretically related to logarthmic average of orbital frequencies of electrons, weighted by oscillator strengths of atomic levels.
  - Very difficult theoretical problem. In practice, deduced by fitting measured dE/dx to Bethe Bloch formula.

Stopping Power Calculation: Bethe Bloch

- *Bloch Correction:* Important for low velocity particles. Takes into account departure from first-order Born approximation used by Bethe.
- *Barkas Correction:* Particles of opposite charge have different stopping powers.
- *Shell Correction:* as projectile slows down to velocity of orbital electron, assumption that electrons are stationary breaks down.
- *Density-Effect Correction: E*-field of ion polarizes the atoms along trajectory. Polarization shields distant electrons from full *E* field. Stopping power is reduced.

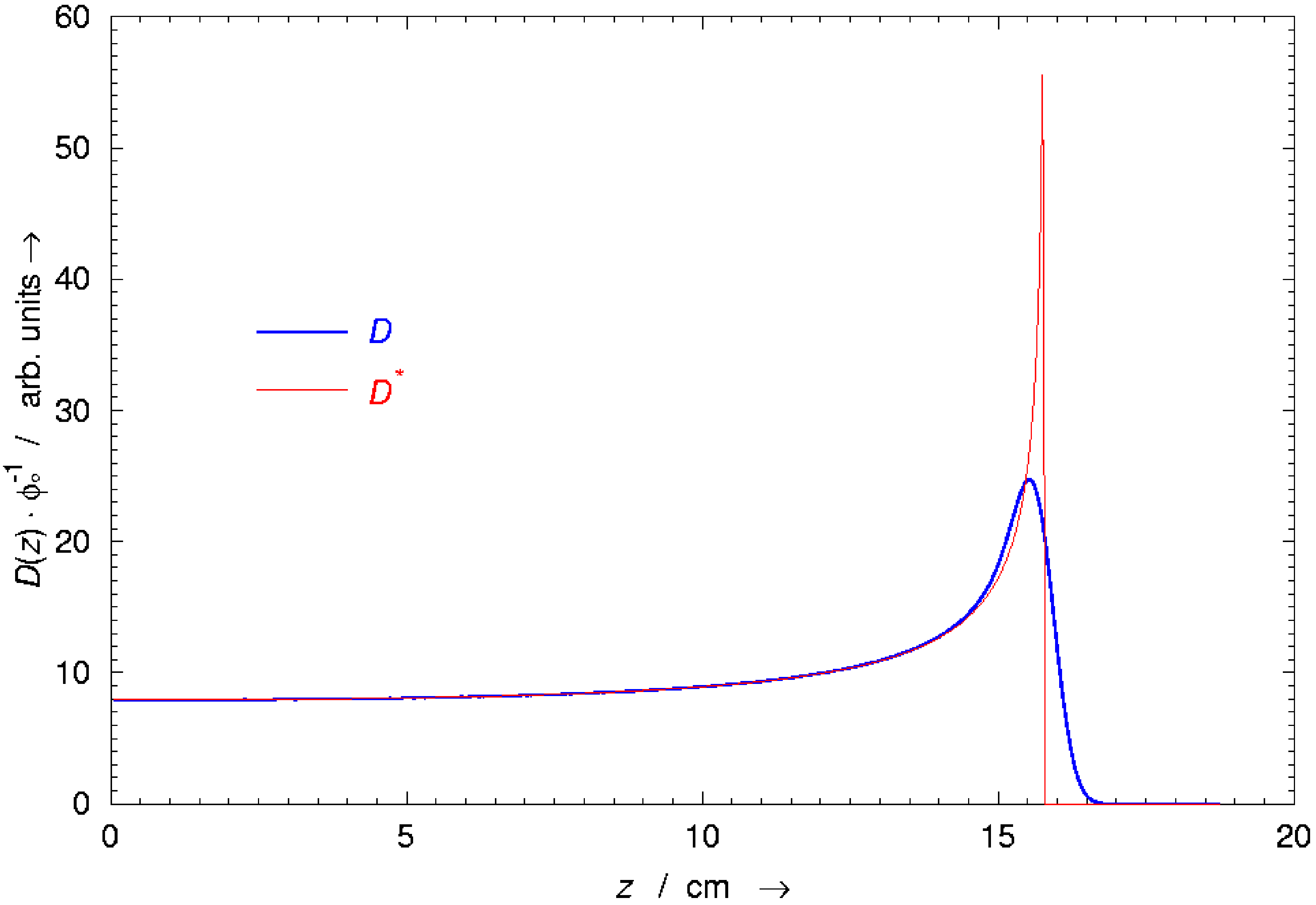
Range Straggling

$\sigma = 0.012\, R^{\,0.935}$



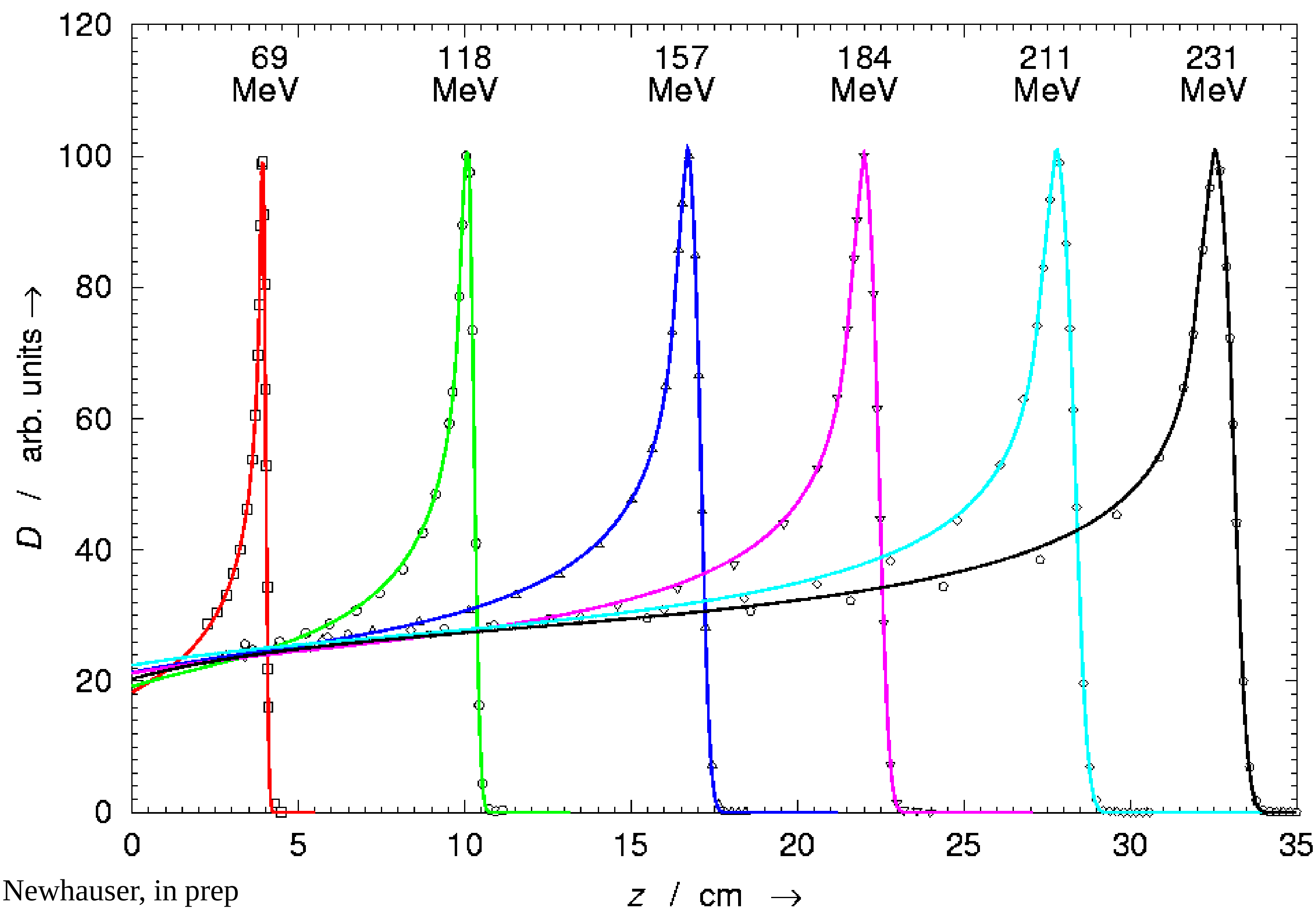
ICRU Report 49, 1993

Range Straggling



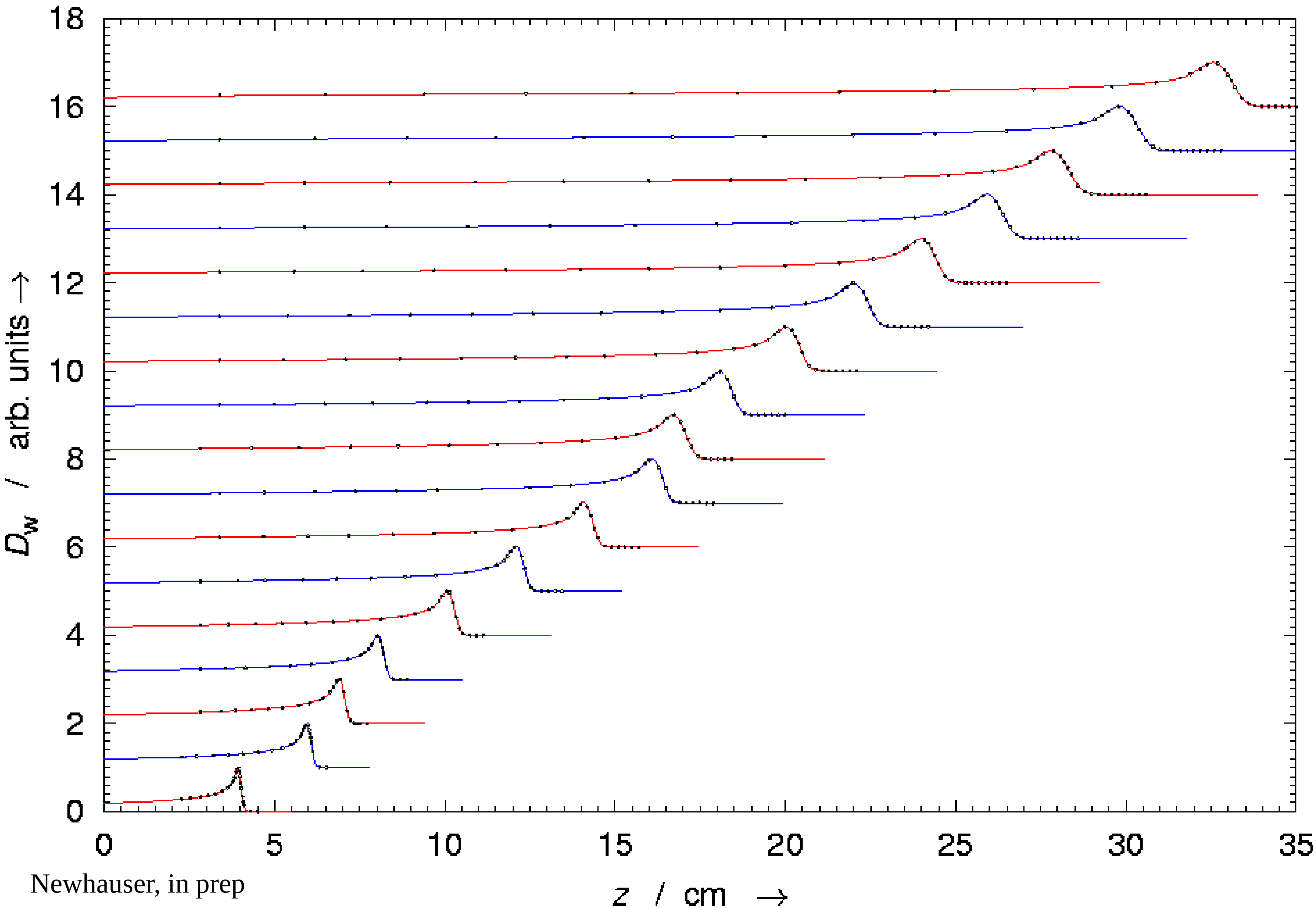
Comparison of SOBP Model with Experimental Data

Pristine Peaks from NPTC cyclotron



Newhauser, in prep

Range Straggling Smears out the Bragg Peak



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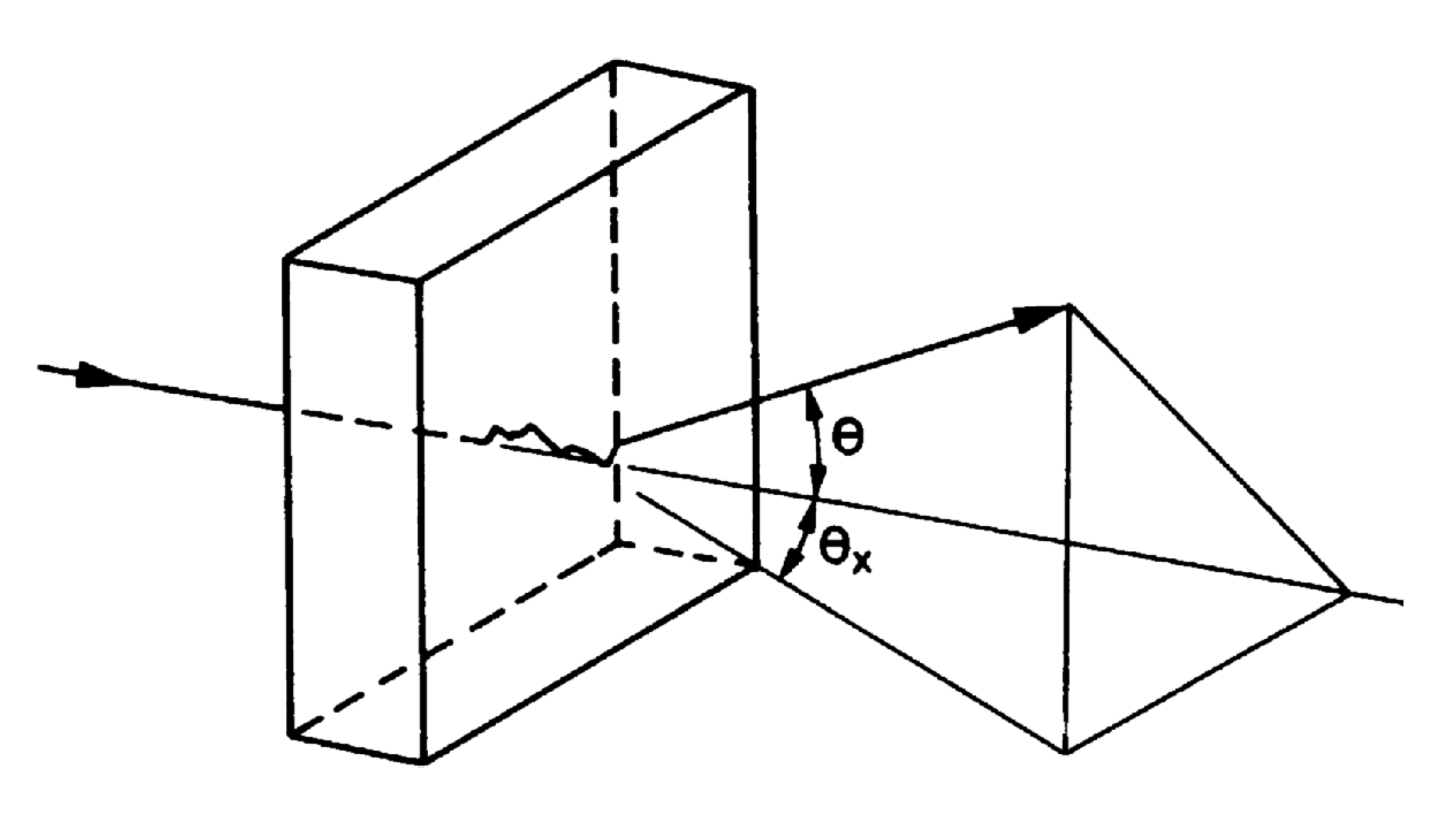
Multiple Coulomb Scattering



Highland's approximation of Moliere's theory as a gaussian:

$$P(r)\mathrm{d}r = \frac{6r}{\langle\theta^2\rangle t^2}\exp\left(\frac{-3r^2}{\langle\theta^2\rangle t^2}\right)\mathrm{d}r$$

Lateral Displacement

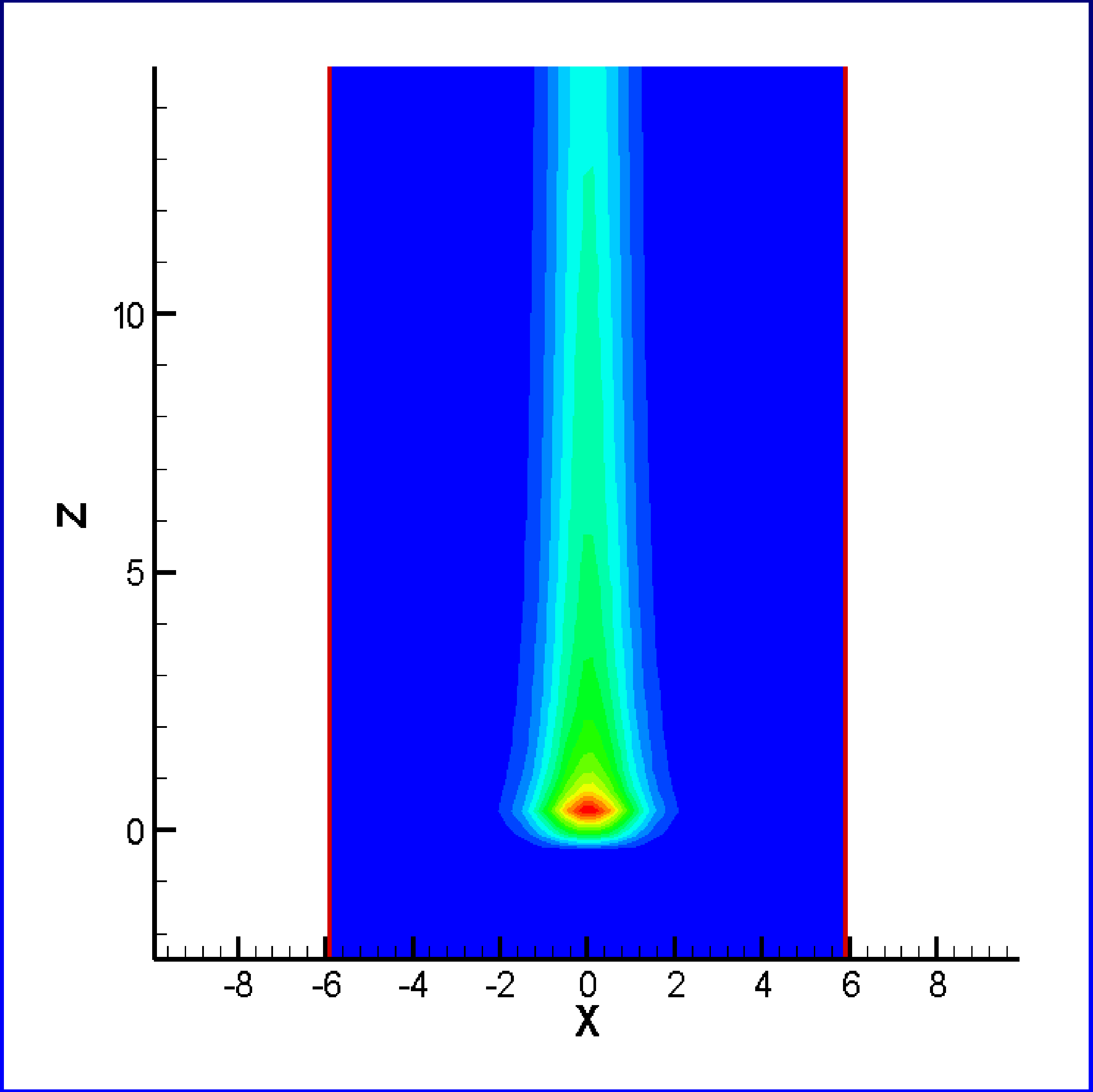
$r_{\mathrm{RMS}} = 0.029\, R^{.896}$

Single Proton Beam

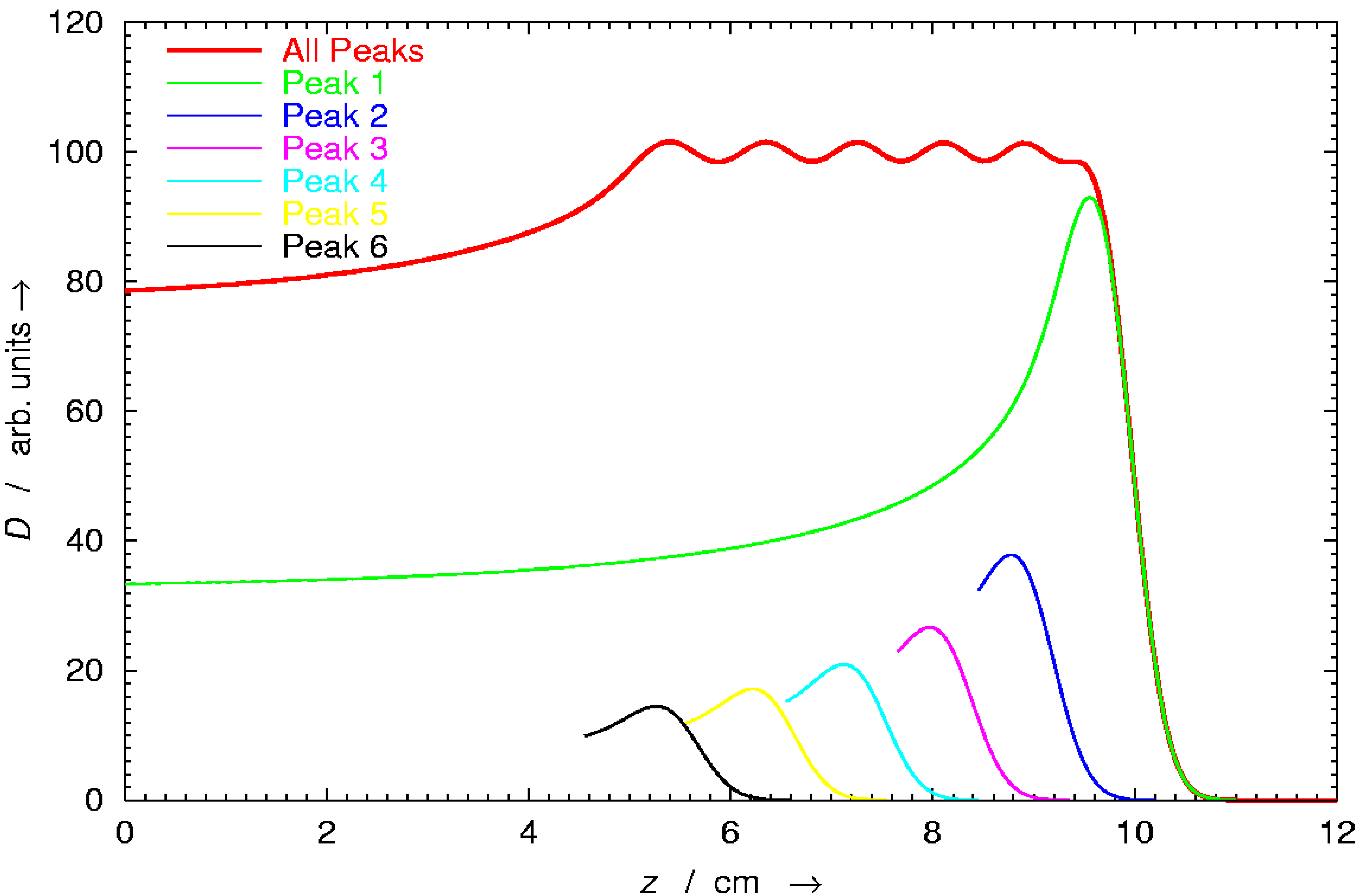
138 MeV initial mean beam energy

Gaussian initial energy distribution (σ_E = 0.5 mev).

Gaussian axially symmetric dose profile (σ = 0.7 cm)



Making a Spread-Out Bragg Peak



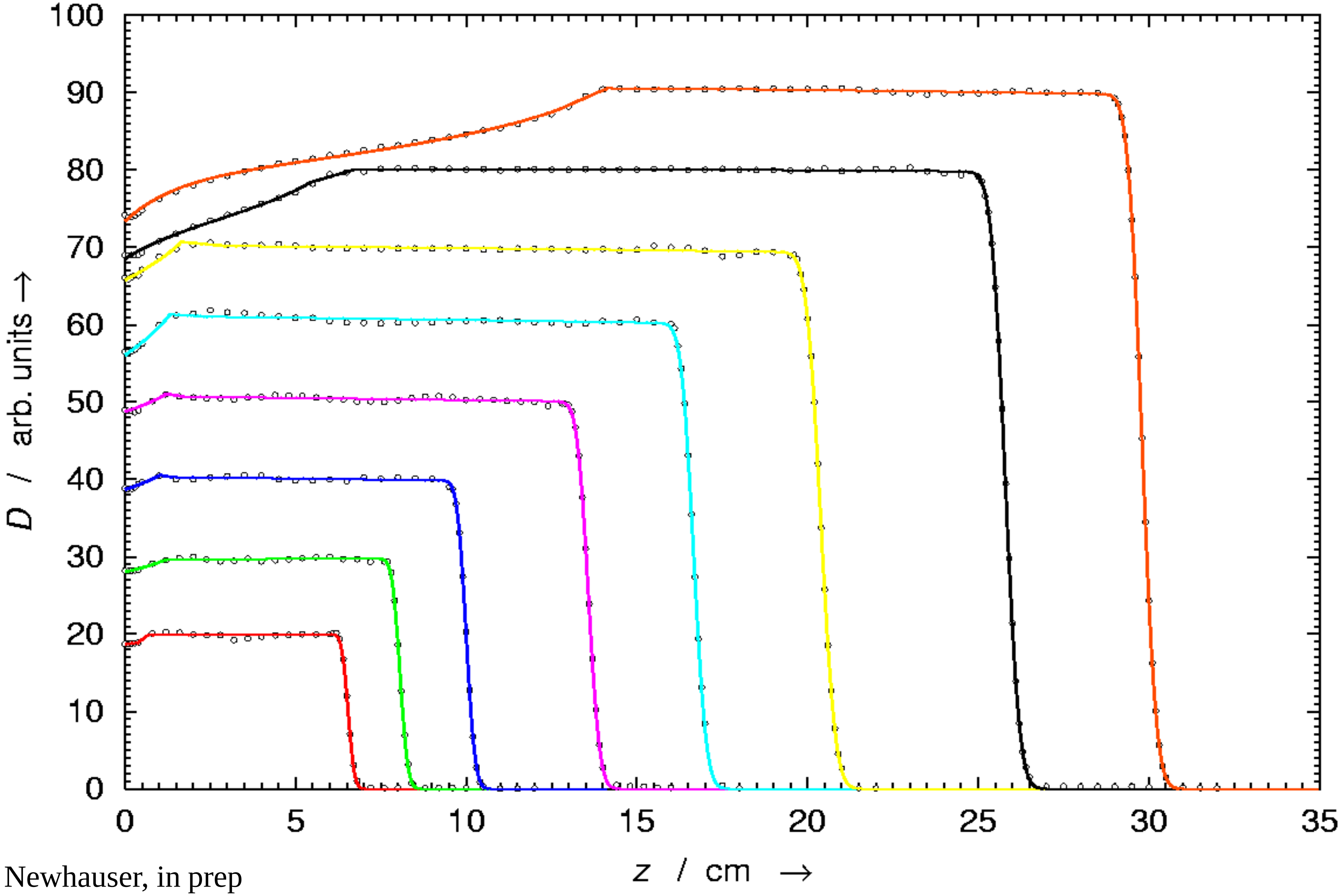
Newhauser, in prep

Making SOBPs

Range Modulator Wheel

Andy Koehler
(Harvard Cyclotron Lab.)

SOBPs: Model v Measurement



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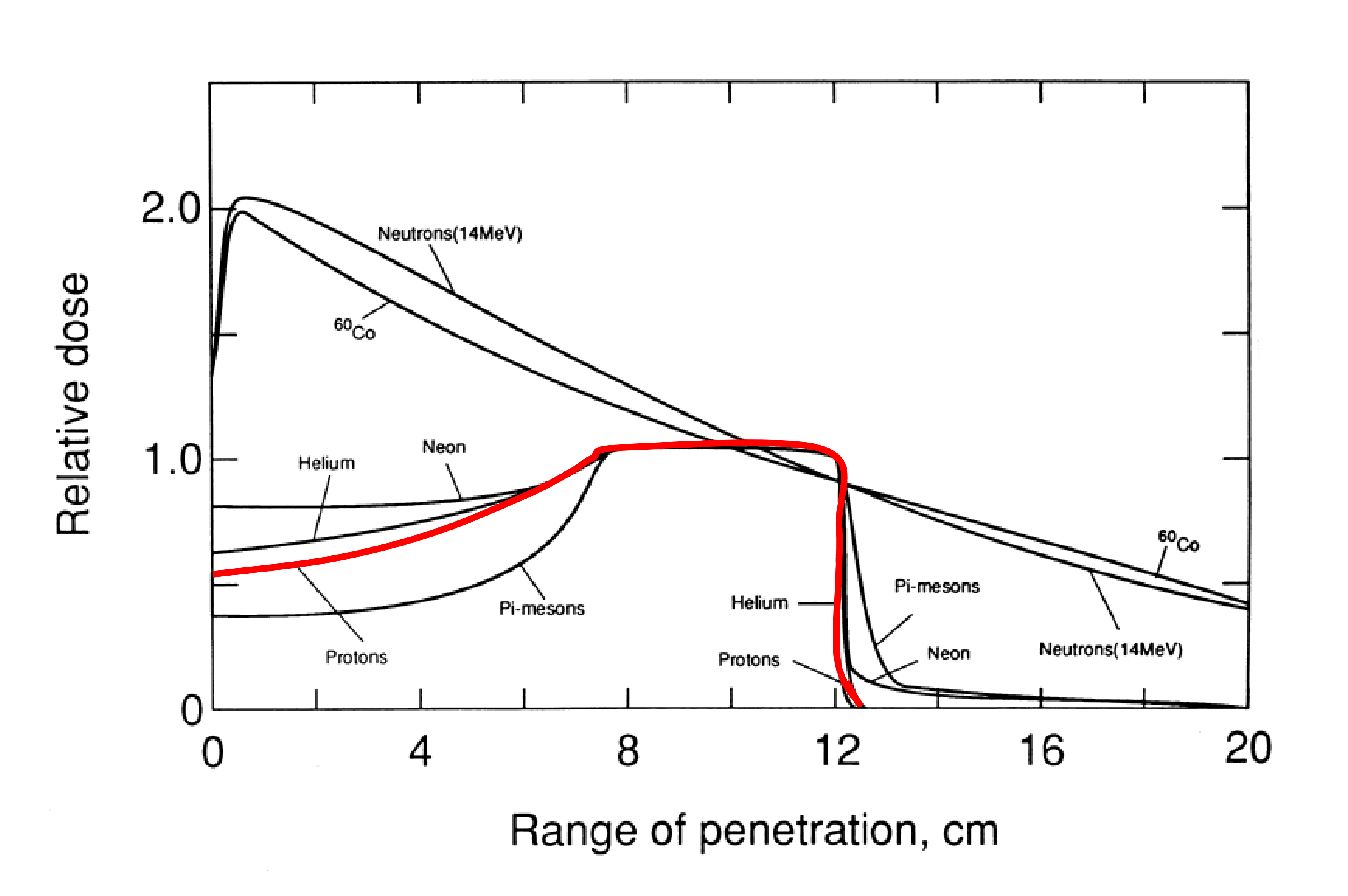
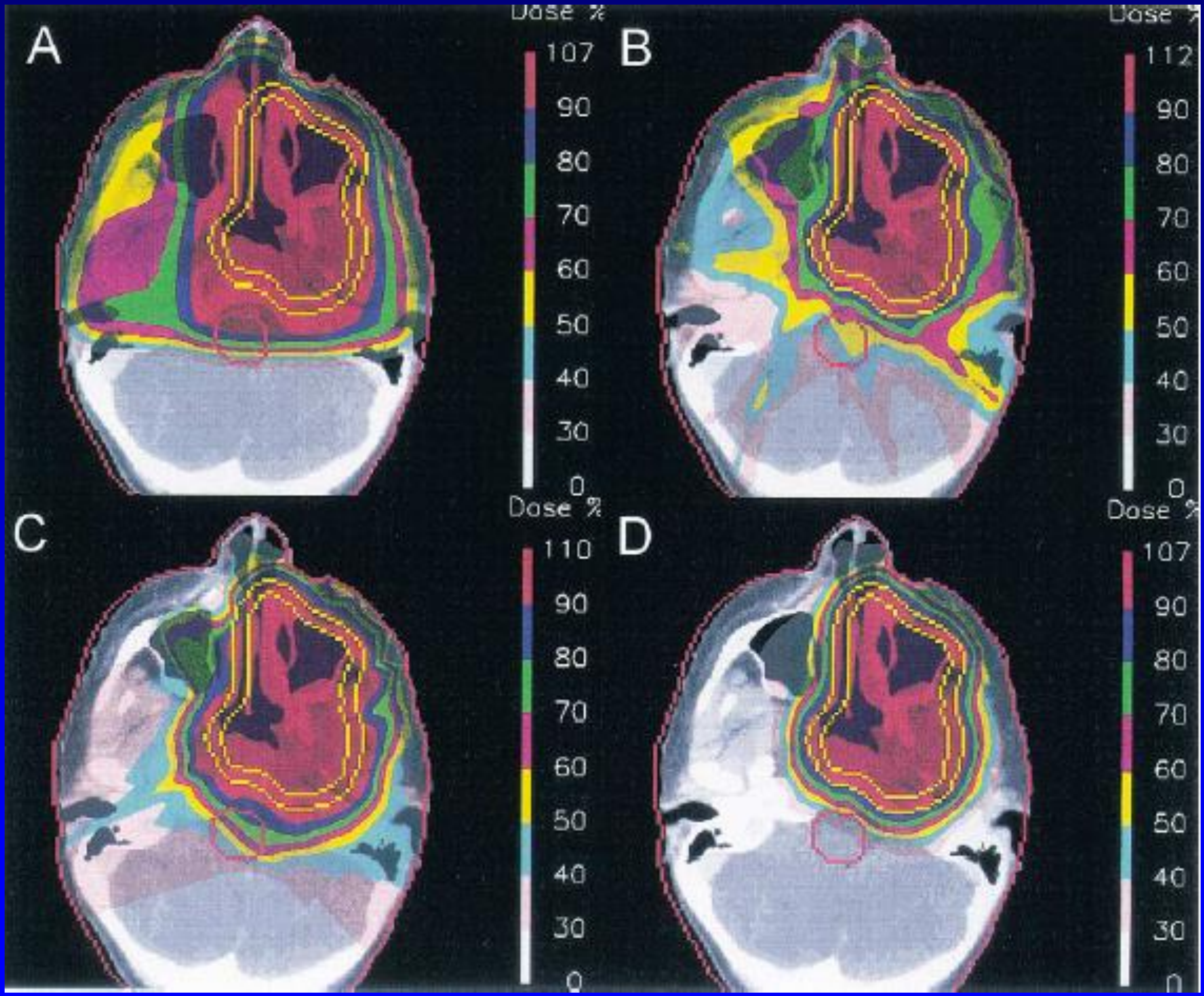
Compare CAX PDD



Rhabdomyosarcoma of Paranasal Sinus (7 y old boy)

6 MV Photons (3 field)

160 MeV Protons (2 field)



Photon IMRT (9 field)

Proton IMRT (9 field)

Miralbell et al., IJROBP 2002

Review of Proton Beam Properties

1) Proton beams stop - no exit dose

2) Laterally, proton beams have sharp penumbra

3) Proton beams provide very uniform target dose distributions

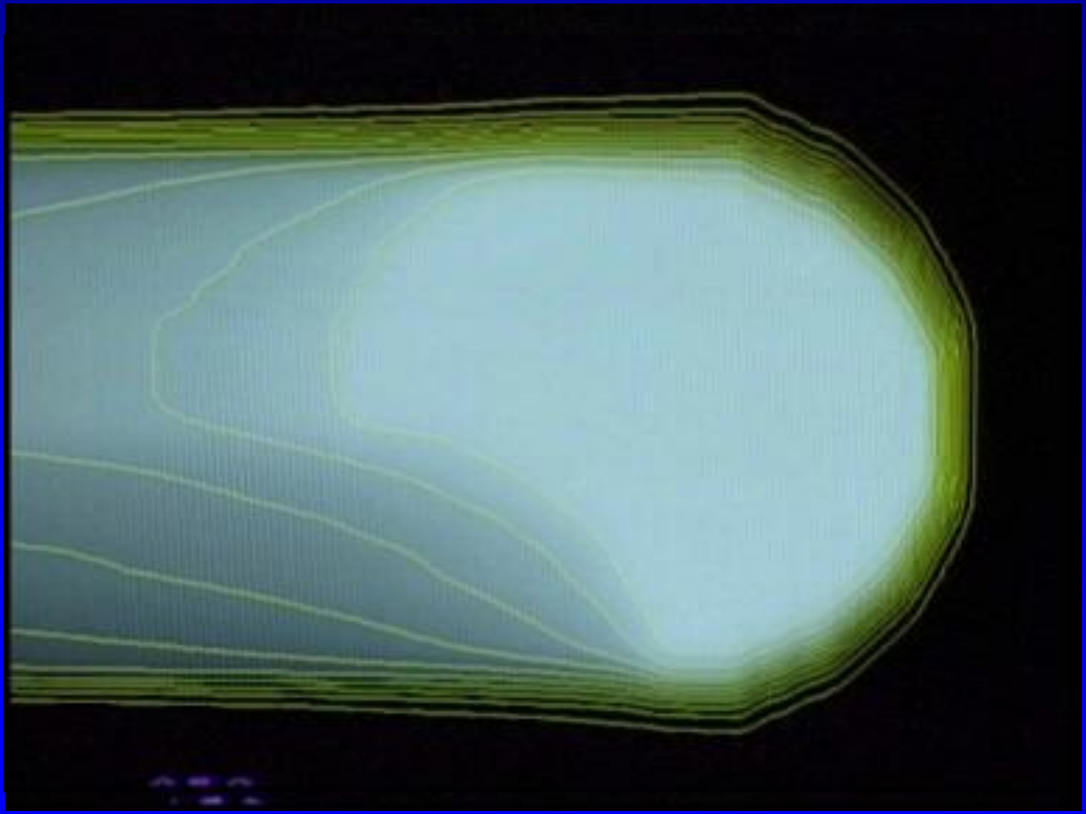
4) Proton dose distributions can be made to conform tightly to irregular target shapes in all three dimensions

4) Clinically, the radiobiology of proton beams is almost identical to that of photon beams

5) Hence, protons offer a significant clinical advantage and it is mainly due the ability sharpshoot with dose.

Dynamic Beam Scanning

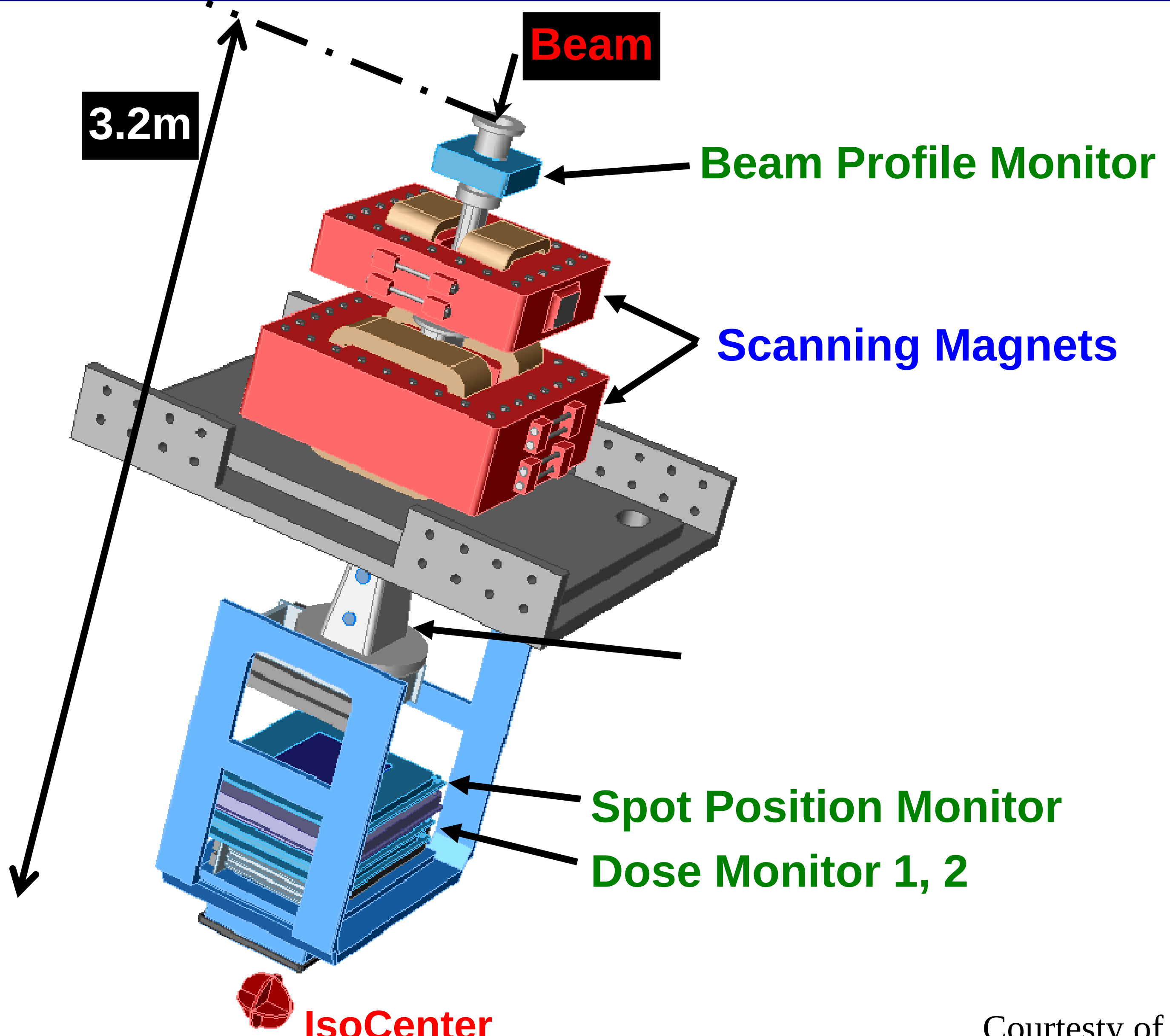
- Sweep small proton beam over a large tumor using magnetic beam deflection.
- Modulate beam range and fluence for each spot.



A full set, with a homogenous dose conformed distally ***and*** proximally

Images courtesy of Eros Pedroni, PSI (Switzerland)

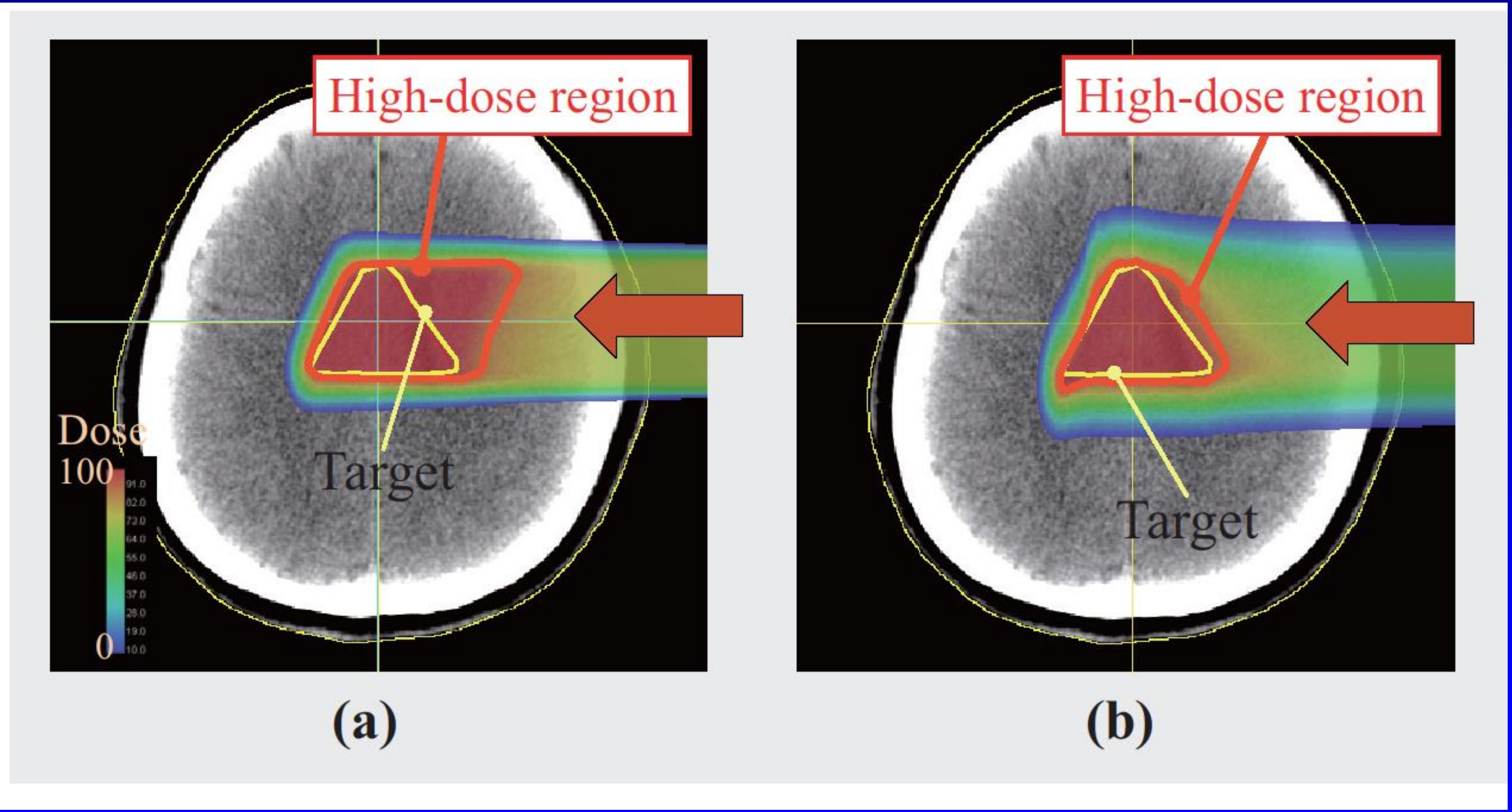
Scanning Nozzle



Courtesty of Hitachi

IMPT versus Passive Scattered Proton Therapy

Passively Scattered Proton Beam | Actively Scanned Proton Beam



Matsuda et al. 2009, Hitachi Reviews ***58*** *(5)*

W. Newhauser, LSU/MBPCC

For More Details …

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Topical Review

The physics of proton therapy

Wayne D Newhauser[1,2] and Rui Zhang[1,2]

[1] Medical Physics Program, Department of Physics and Astronomy, Louisiana State University, 202 Nicholson Hall, Baton Rouge, LA 70803, USA
[2] Mary Bird Perkins Cancer Center, 4950 Essen Lane, Baton Rouge, LA 70809, USA

E-mail: newhauser@lsu.edu

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