Beam Delivery Techniques: Scattering Proton Beams

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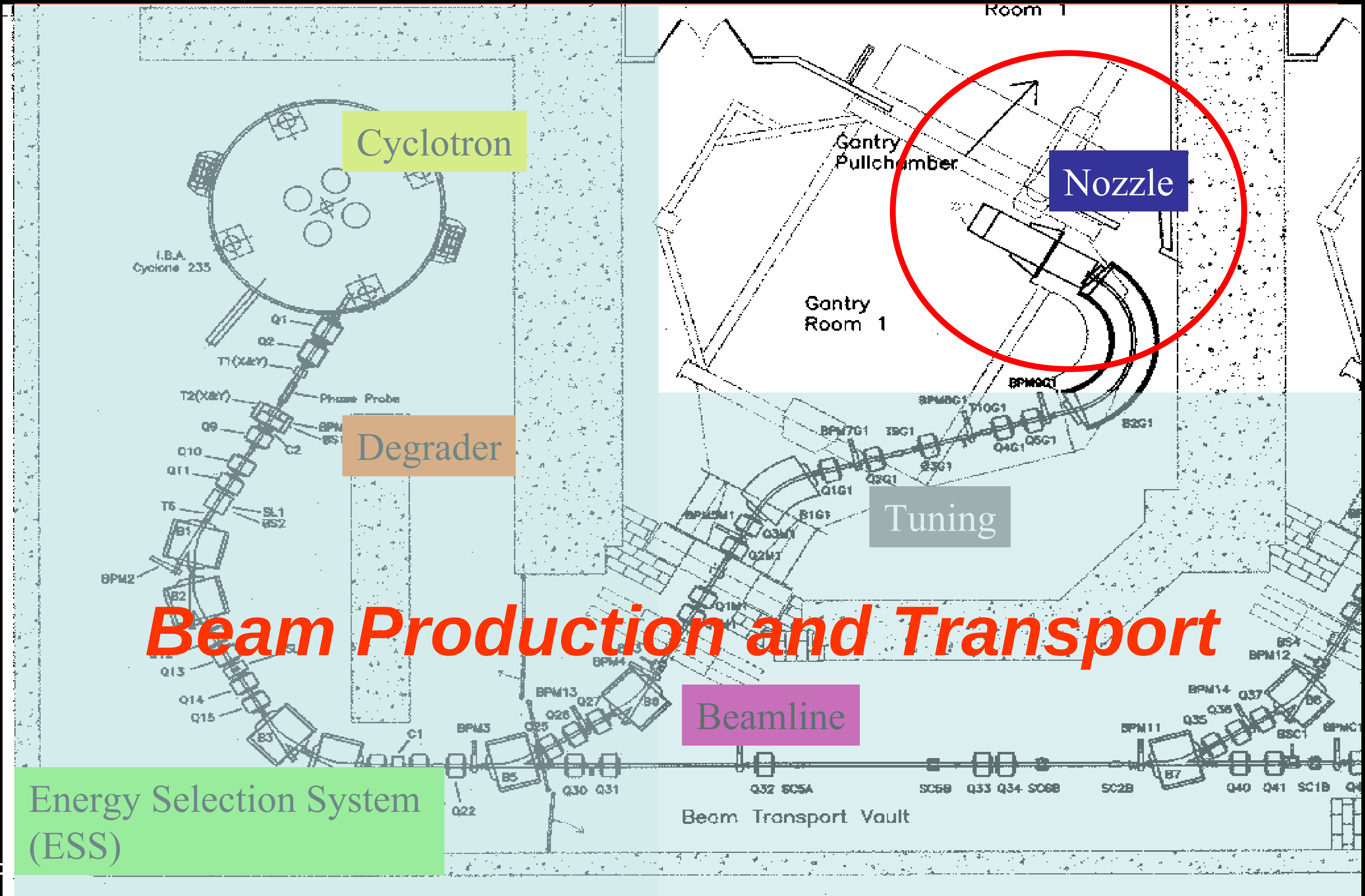
Disclaimer

- UFPTI uses IBA Proton Therapy System
- The work of golden beam dataset library is supported by IBA

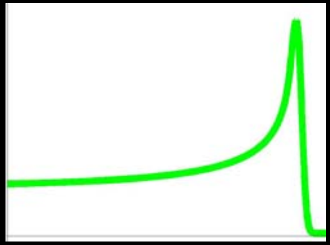
Proton Beam: production, transport, and delivery



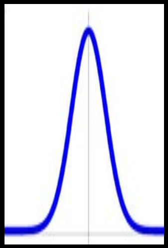
Proton Delivery Techniques

Mono-energetic pencil beam

3D dose distribution



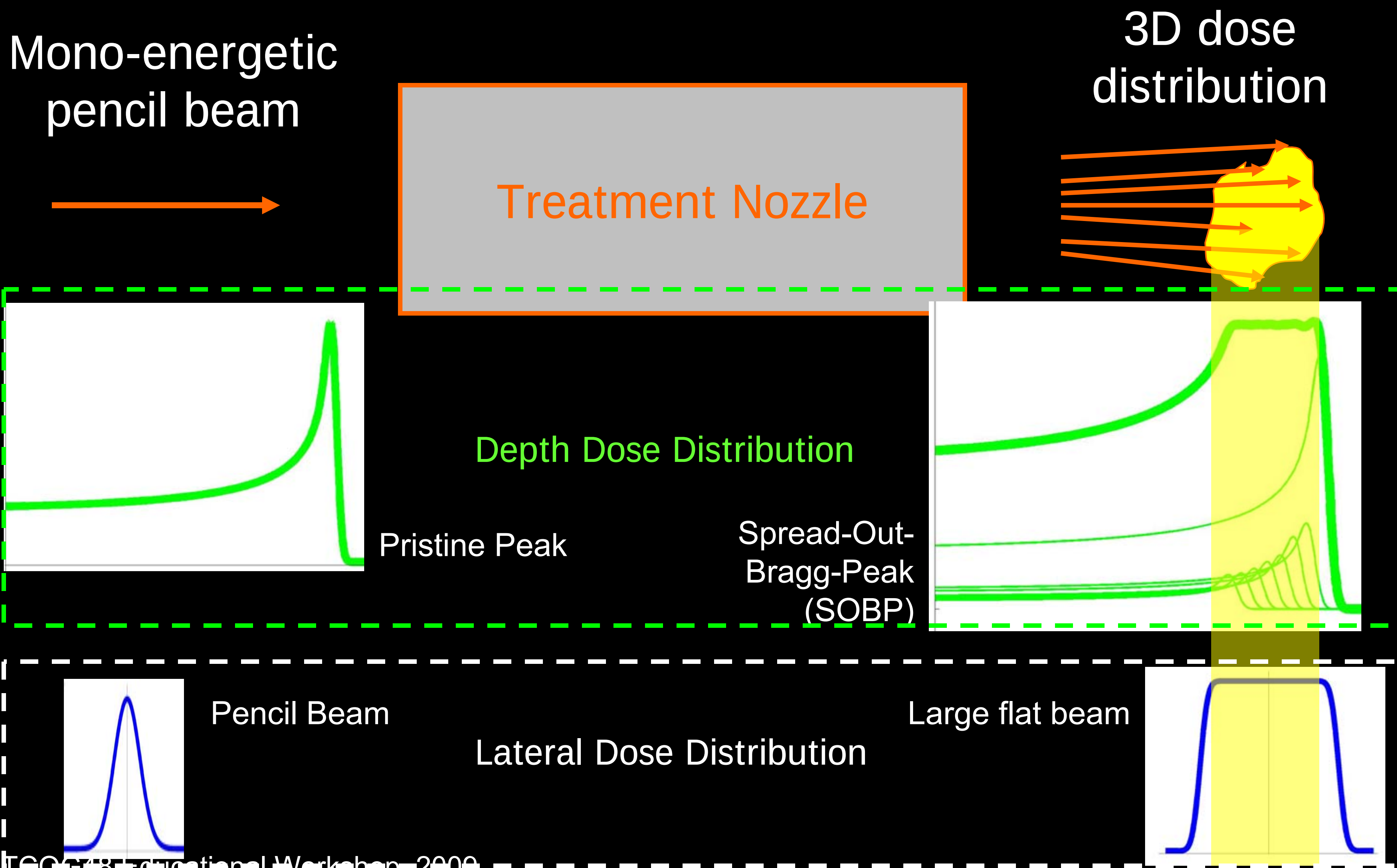
Depth Dose Distribution



Lateral Dose Distribution

Modified from R. Slopsema

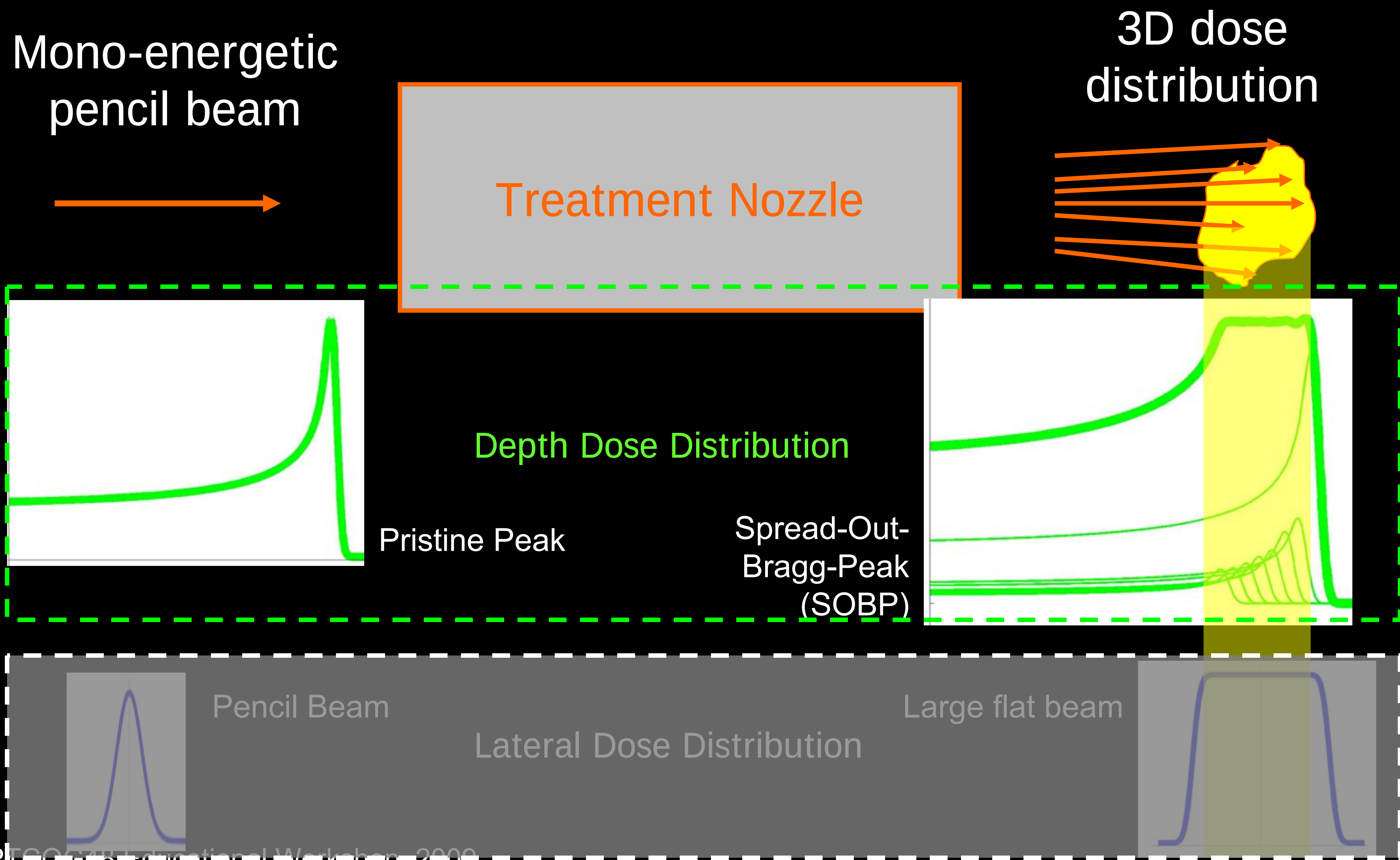
Scattering Beam



Proton Delivery Techniques

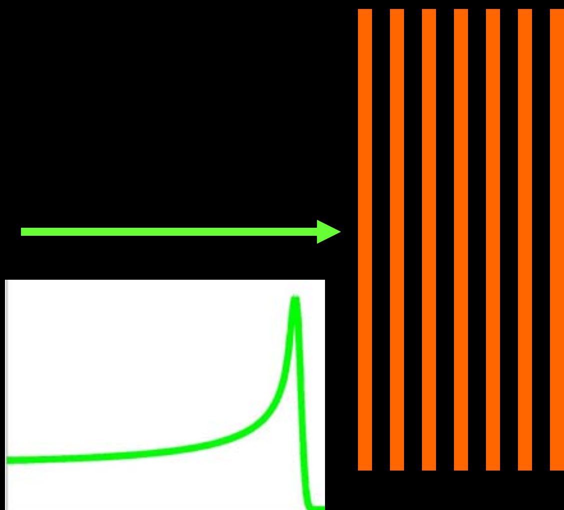
- Double Scattering Beam
- Single Scattering Beam
- Uniform Scanning/Wobbling
- Pencil Beam/Spot Scanning
  - Allowing intensity modulated proton therapy
- *Selections performed in treatment nozzle*
  - *Dedicated nozzle*
  - *Universal nozzle*

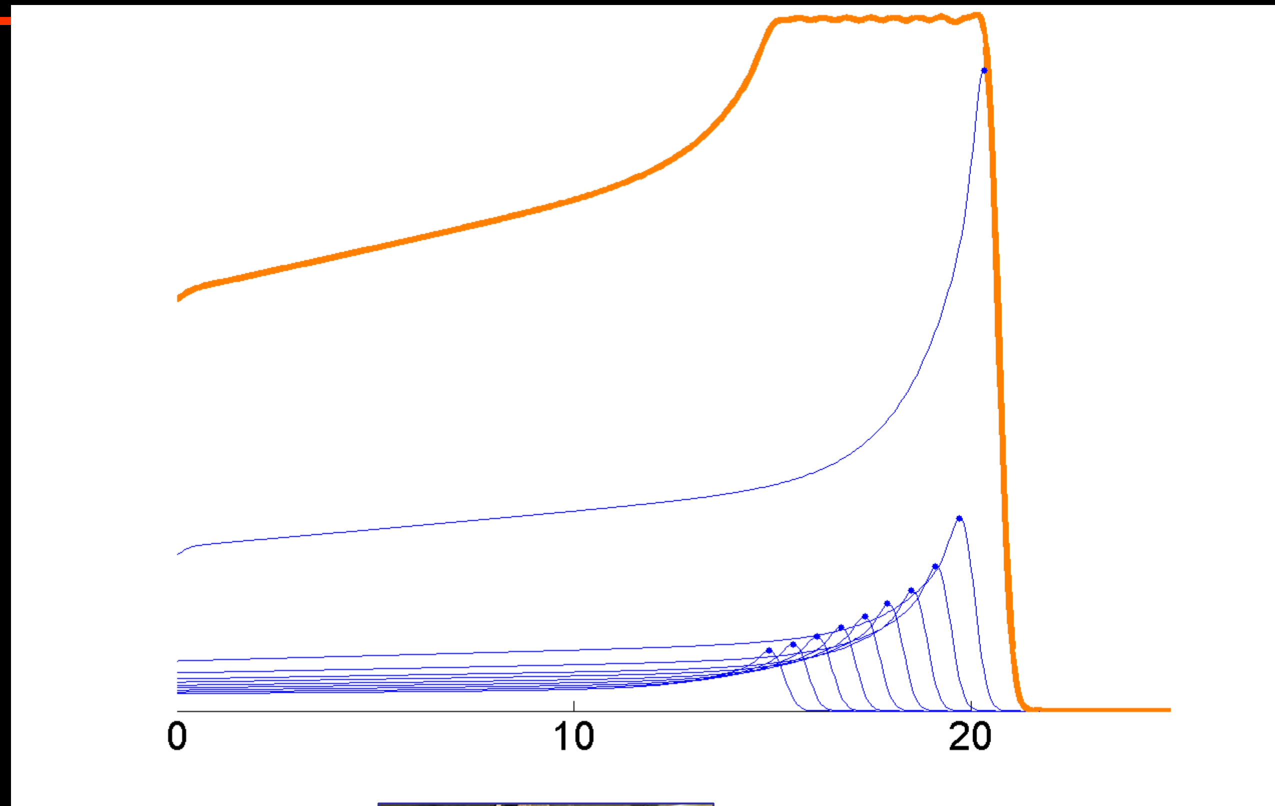
Scattering Beam

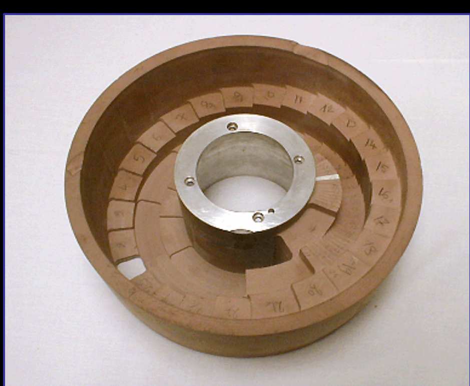


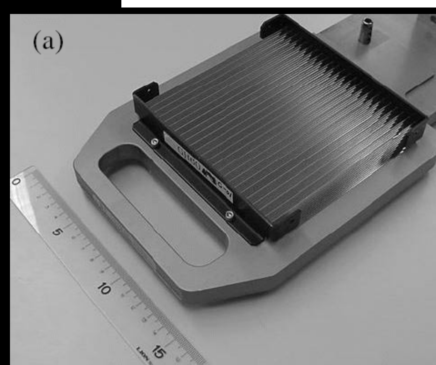
Formation of SOBP

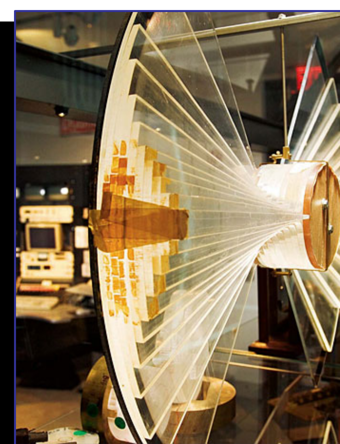
Absorbers of pre-determined thickness added successively into beam to “pull back” individual pristine peaks











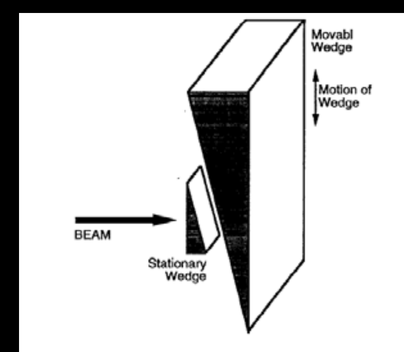
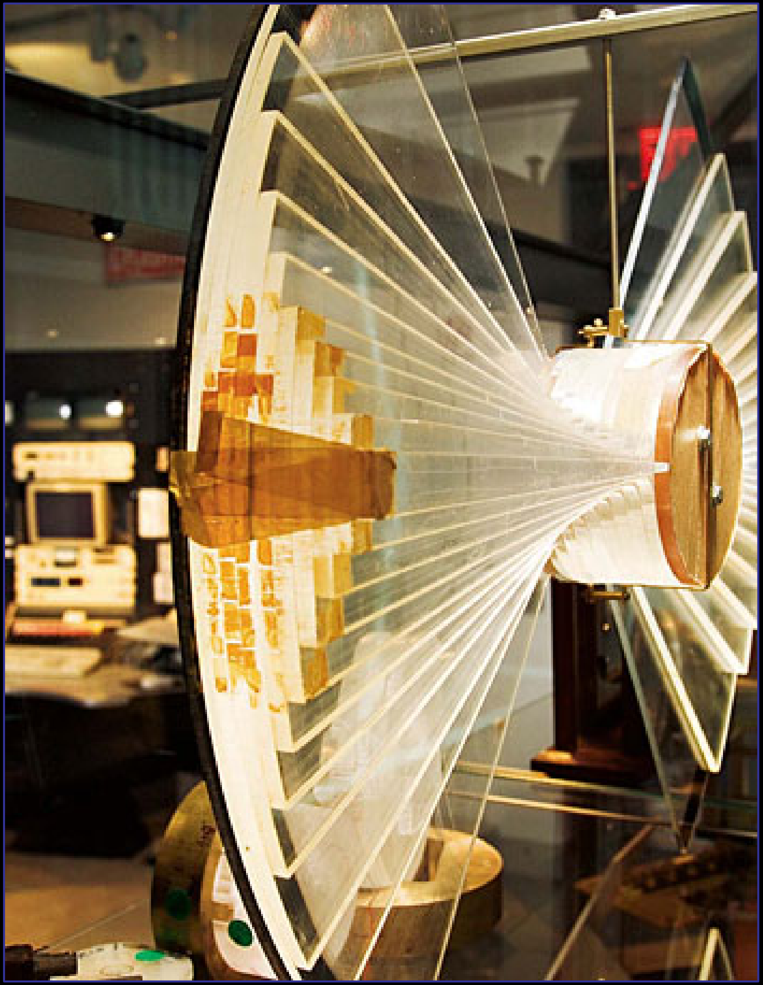
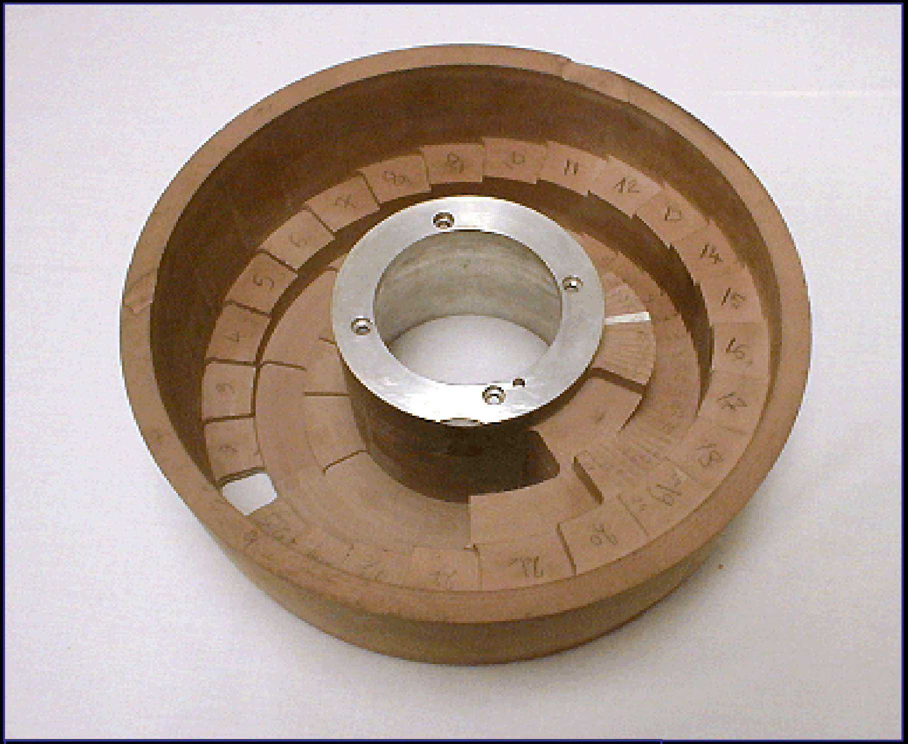


FIG. 18. Schematics of a double wedge system which is used to shift the range of the beam.

Range modulation / RM wheel

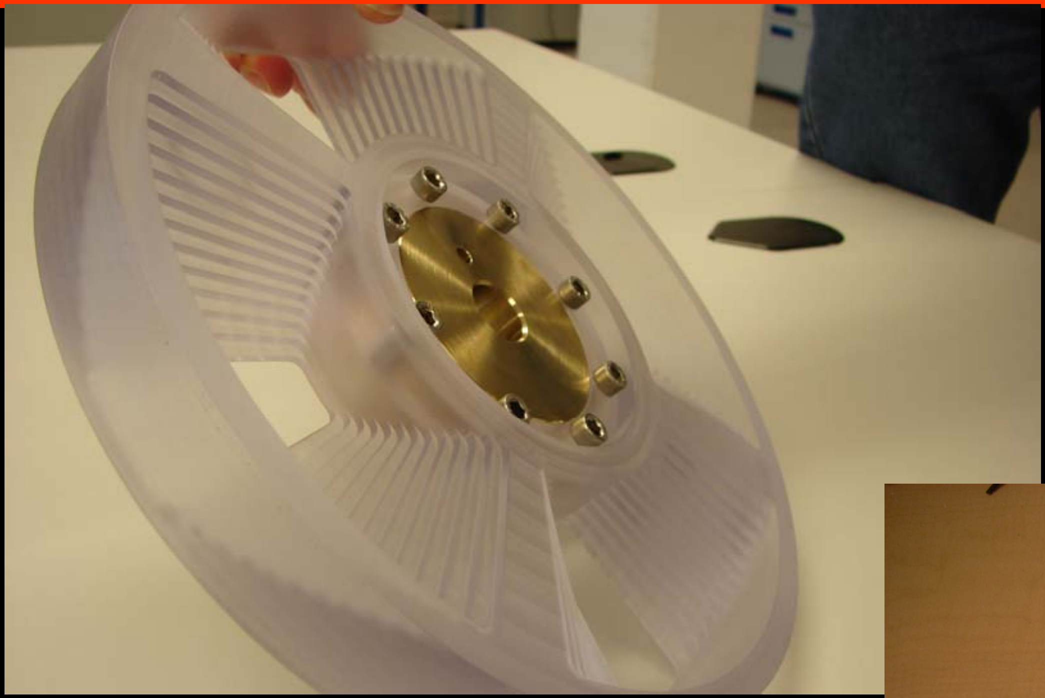


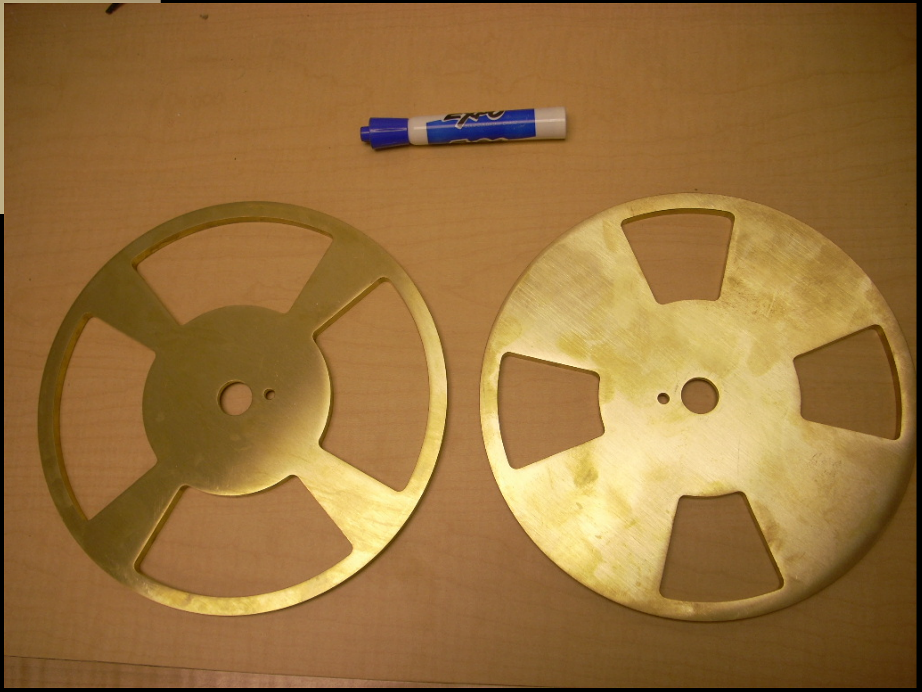
HCL design (single modulation, downstream, 4 repetitions)



IBA design (3 tracks on single wheel, gating used to adjust modulation)

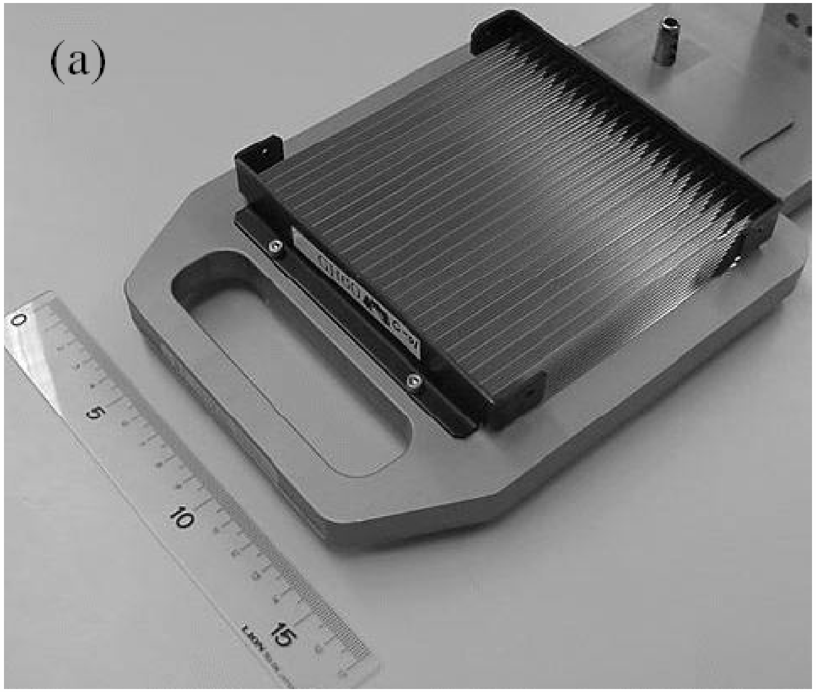
Range modulation / RM wheel





IBA eye-line:
RM wheel with 8 repetitions,
blocks to vary modulation

Range modulation / ridge filters



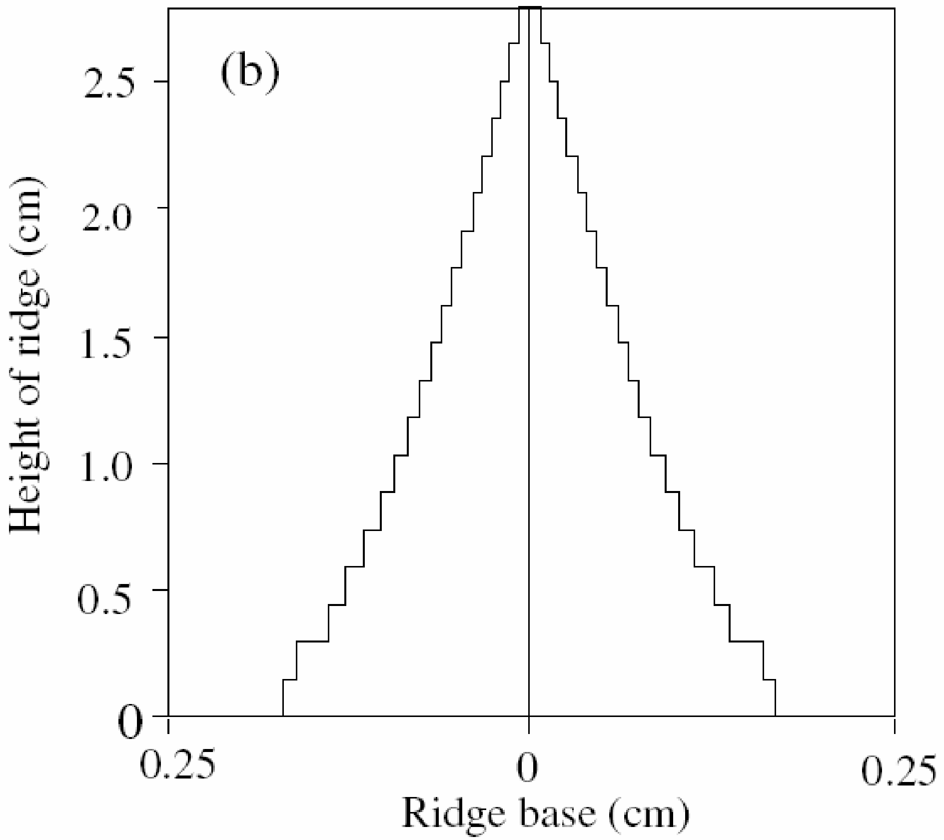


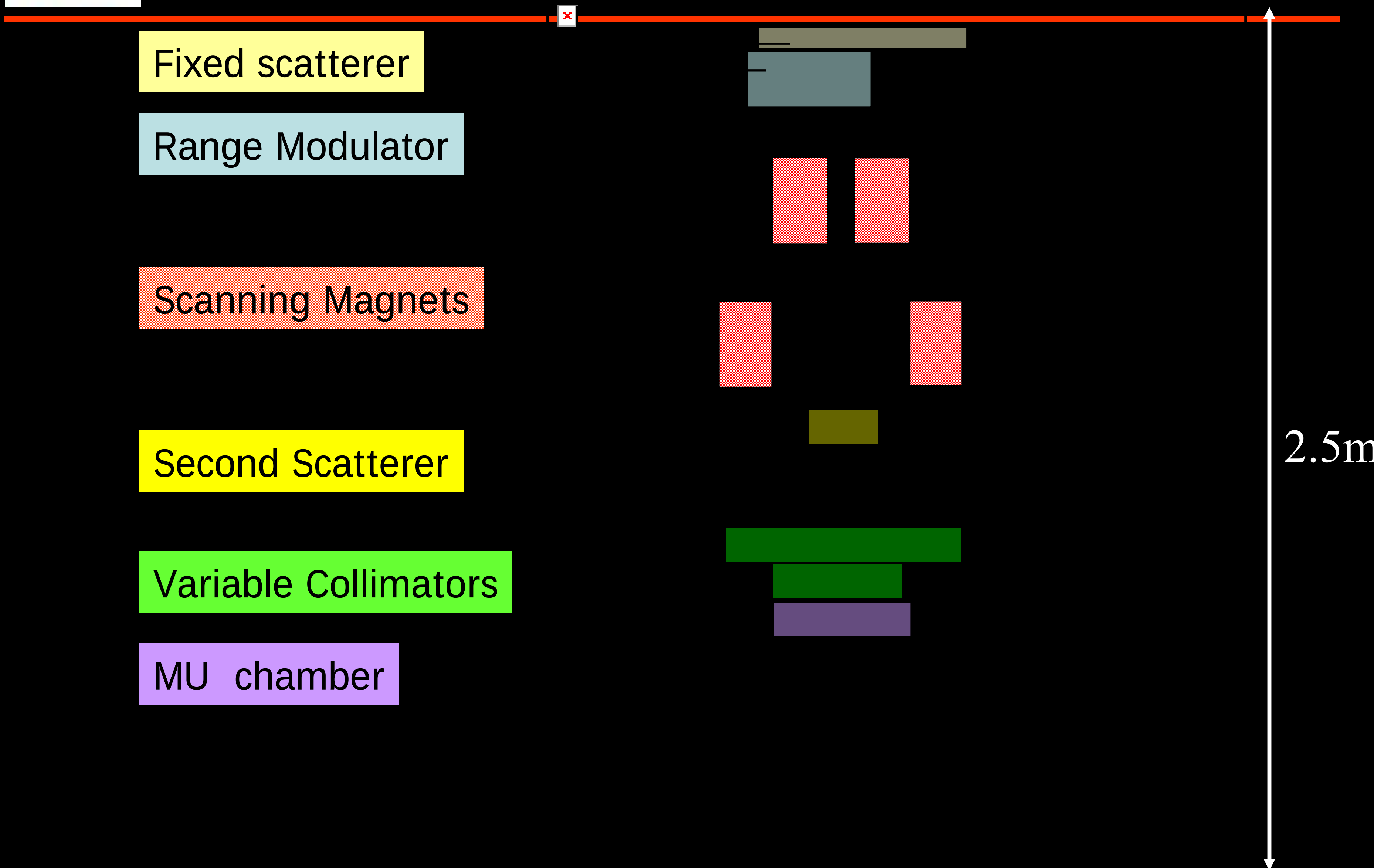
Figure 2. A bar ridge filter for the proton beam in the gantry nozzle (a), the cross-sectional shapes of the ridge for 6 cm SOBP (b).

Akagi et al 2003

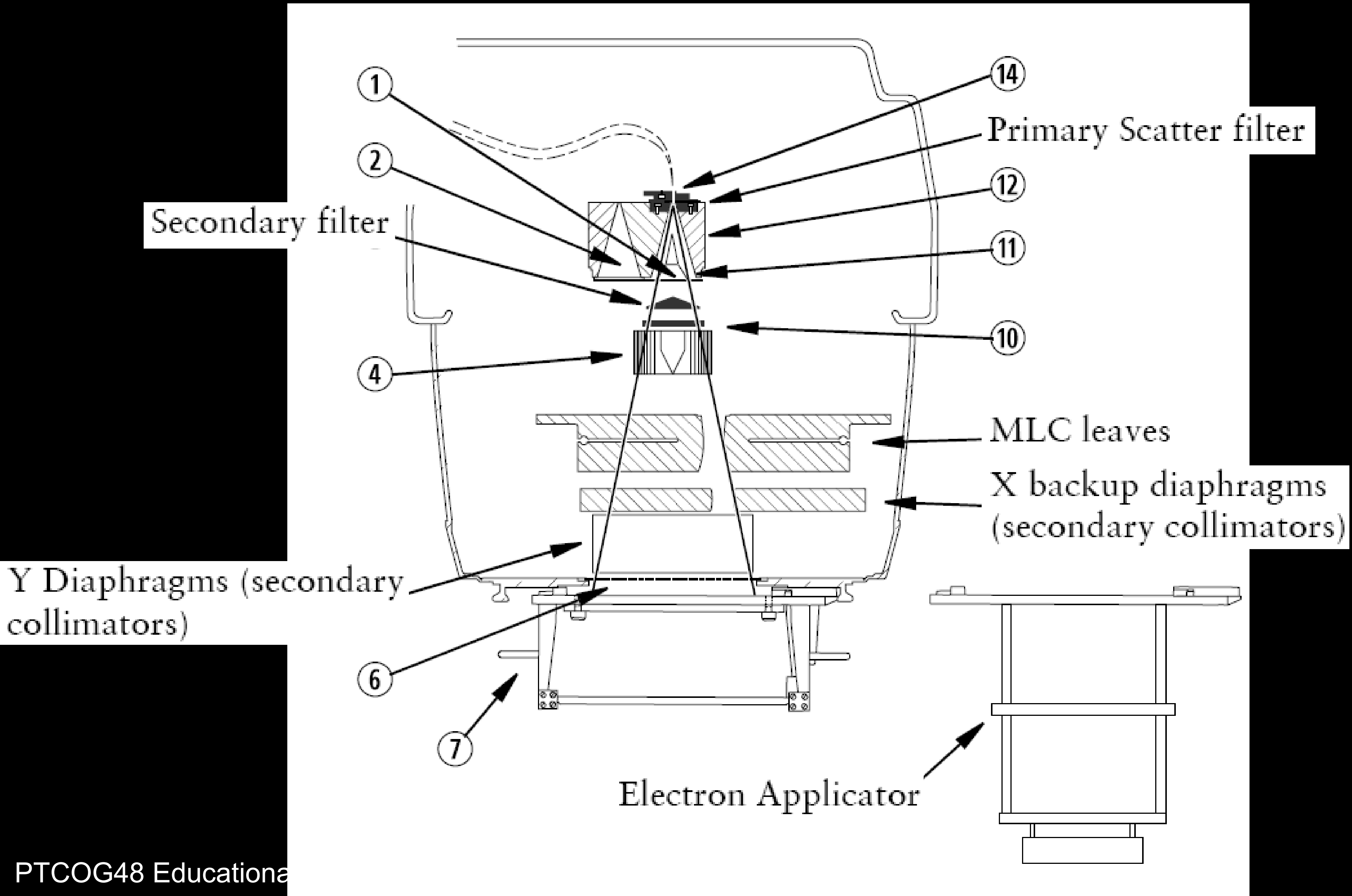
Range modulation / time structure

variable range shifter	RM wheel	ridge filter
energy stacking	SOBP delivered with frequency RM rotation	instantaneous delivery SOBP
no problems with beam time structure	rotational speed should be large compared to beam time structure	no problems with beam time structure
organ motion is concern	organ motion (typically) no problem	no problems with organ motion
partial delivery is concern		

IBA Universal Nozzle



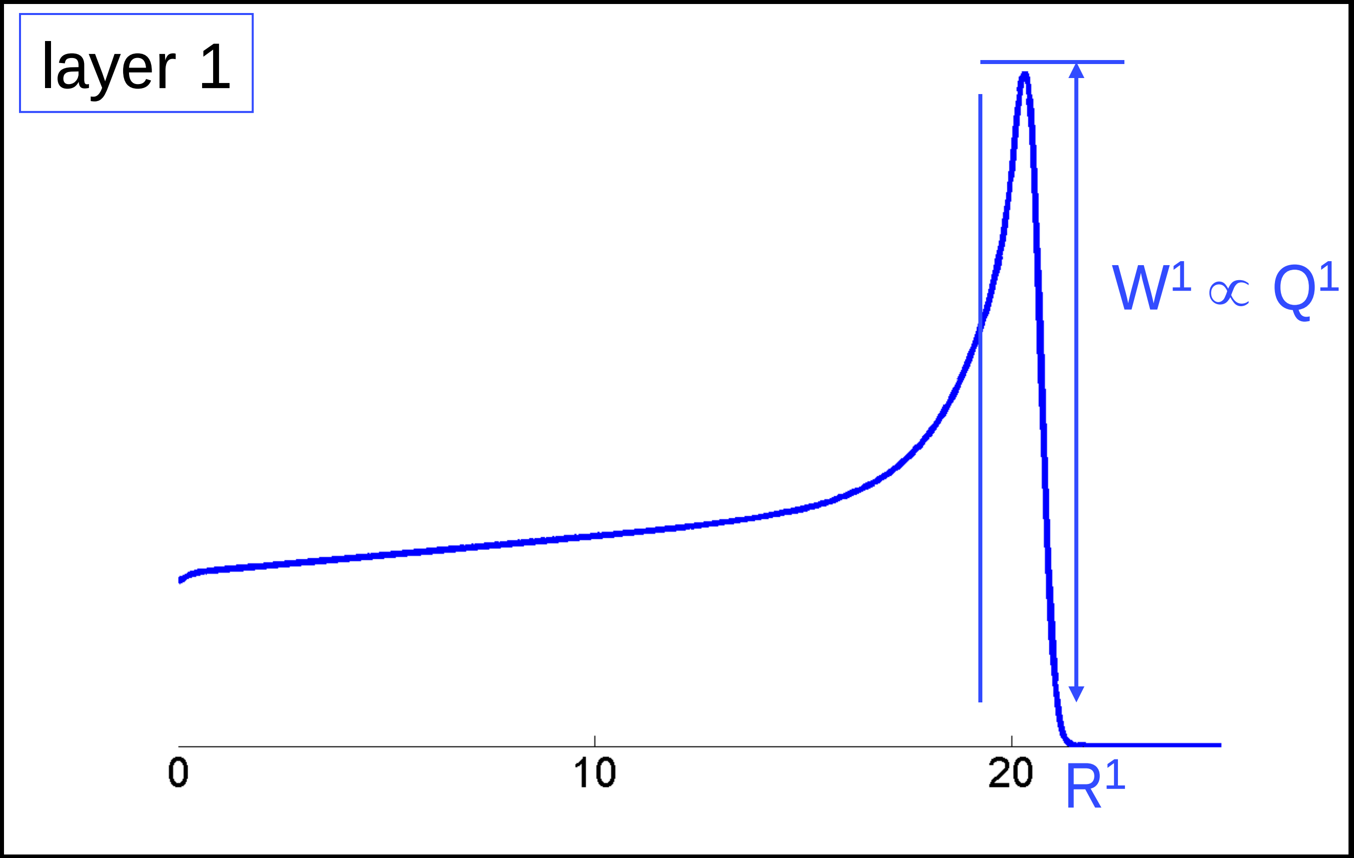
Linear accelerator head



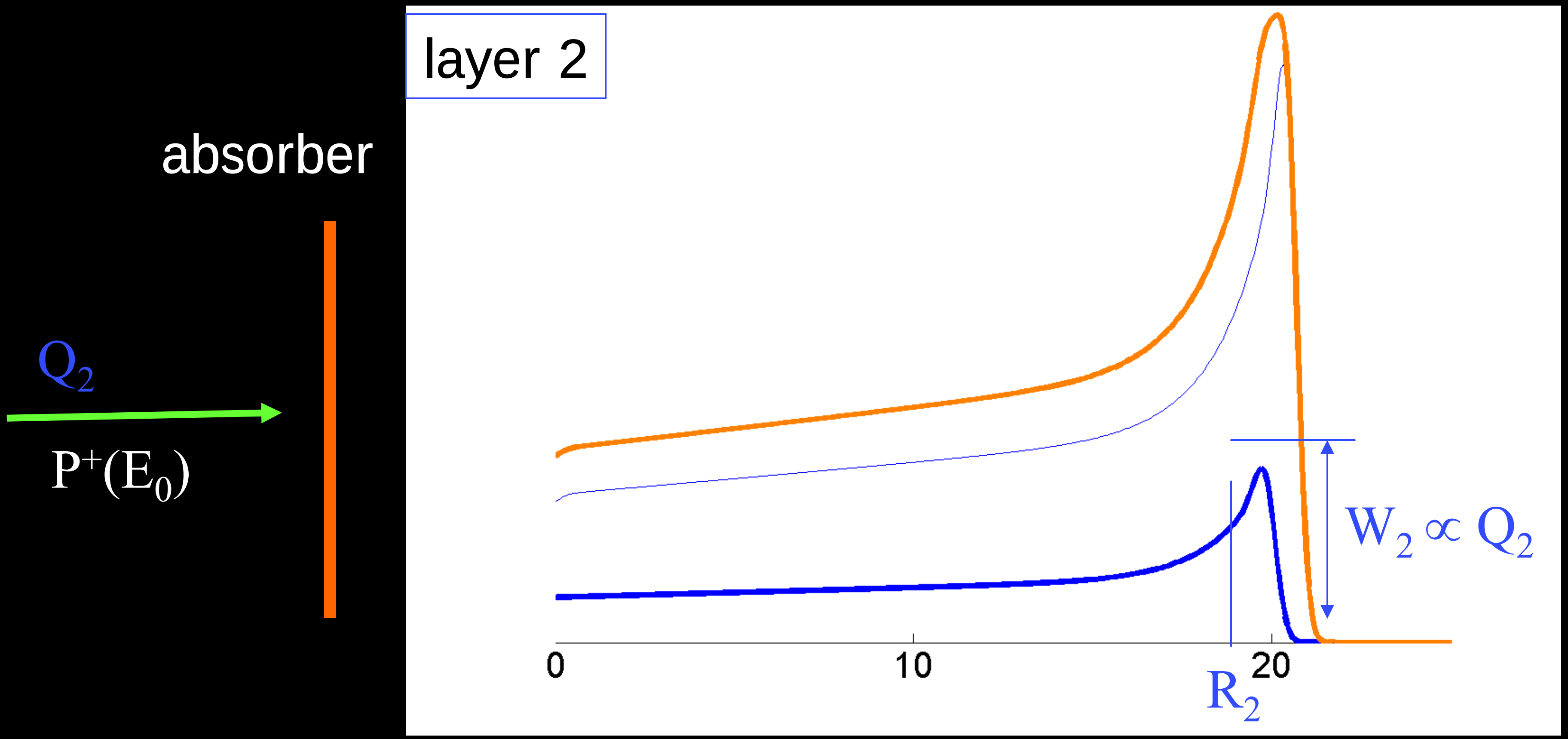
Range modulation / variable range shifter

Q^1

$P^+(E_0)$



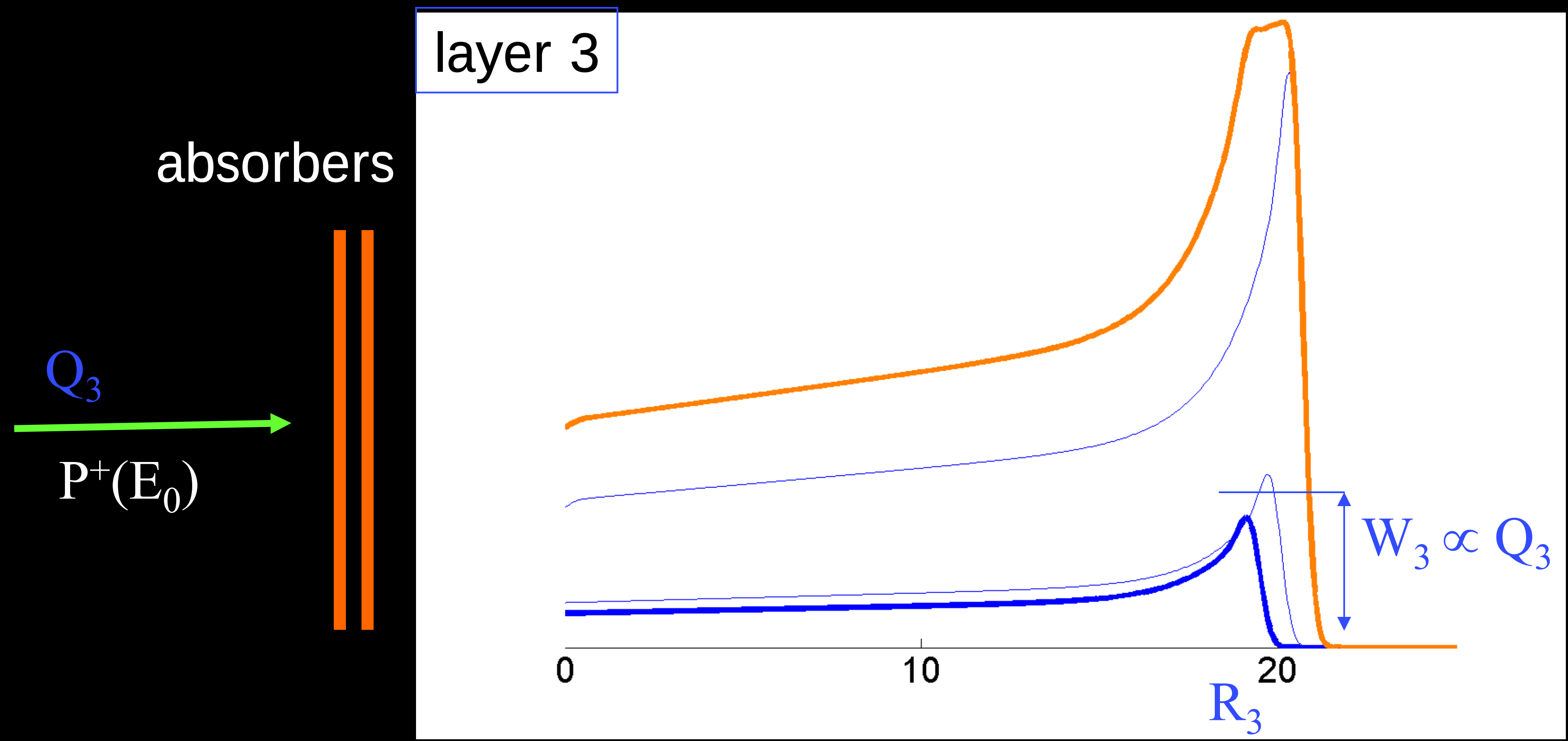
Range modulation / variable range shifter



pullback (R_1-R_2) set to width of pristine peak at 80% level

weight layer 2 about 1/3 of layer 1: W2 ≈ 0.3 x W1

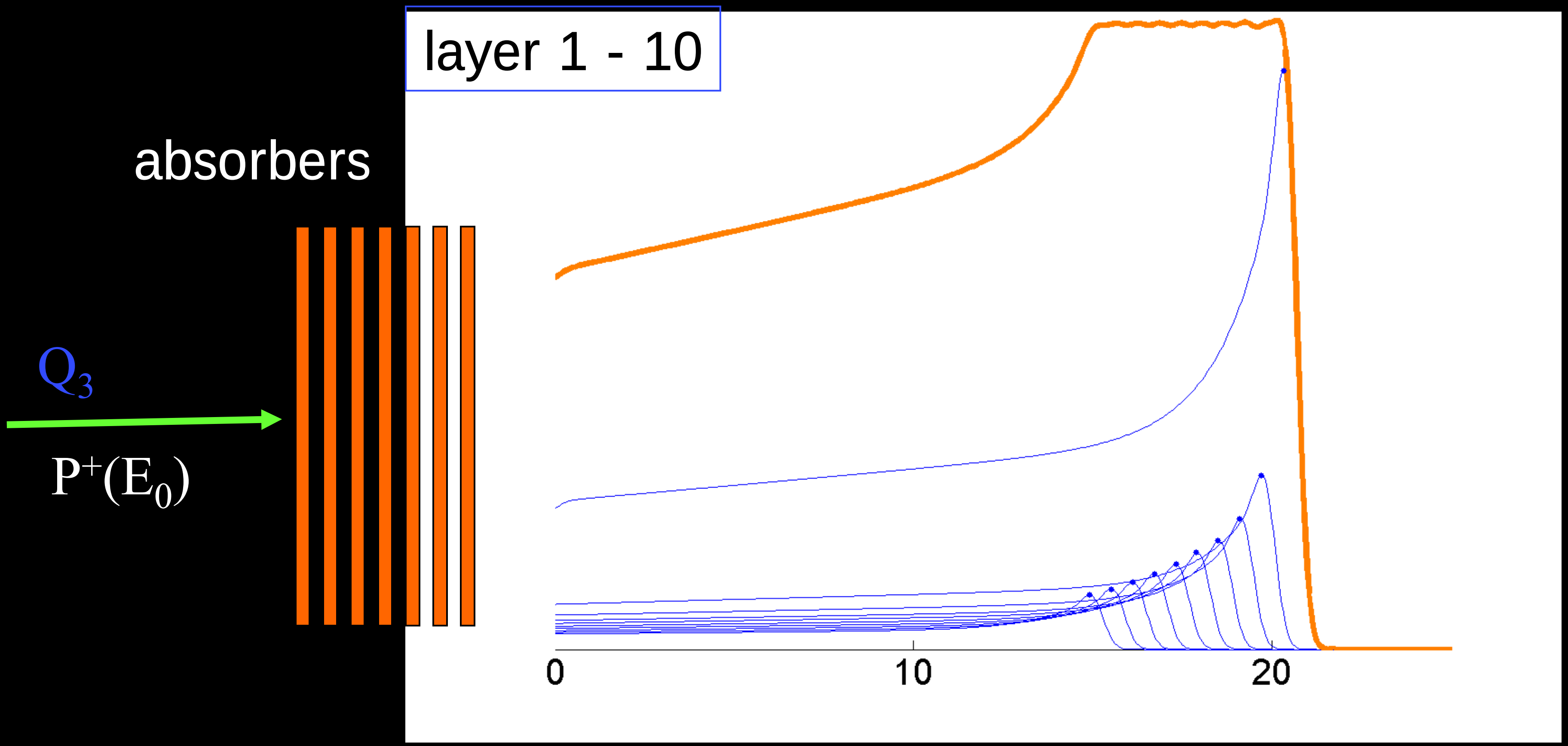
Range modulation / variable range shifter



pullback typically kept constant over layers (shape same)

weight layer 3 : W3 ≈ 0.2 x W1

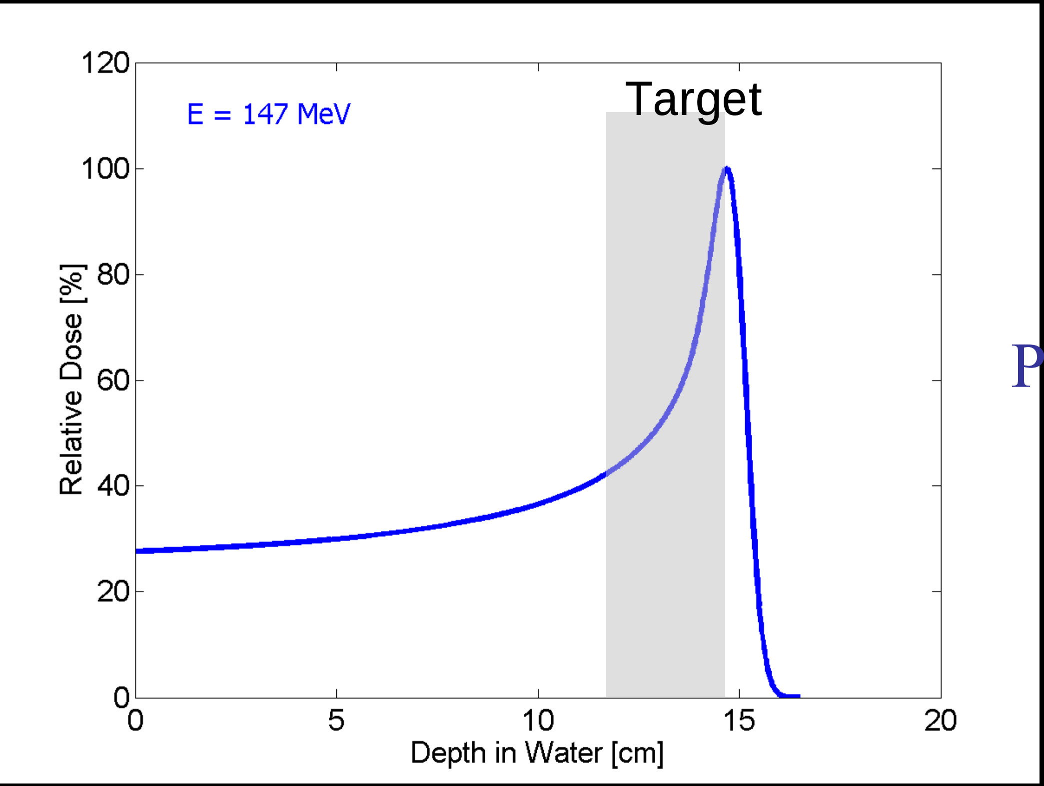
Range modulation / variable range shifter

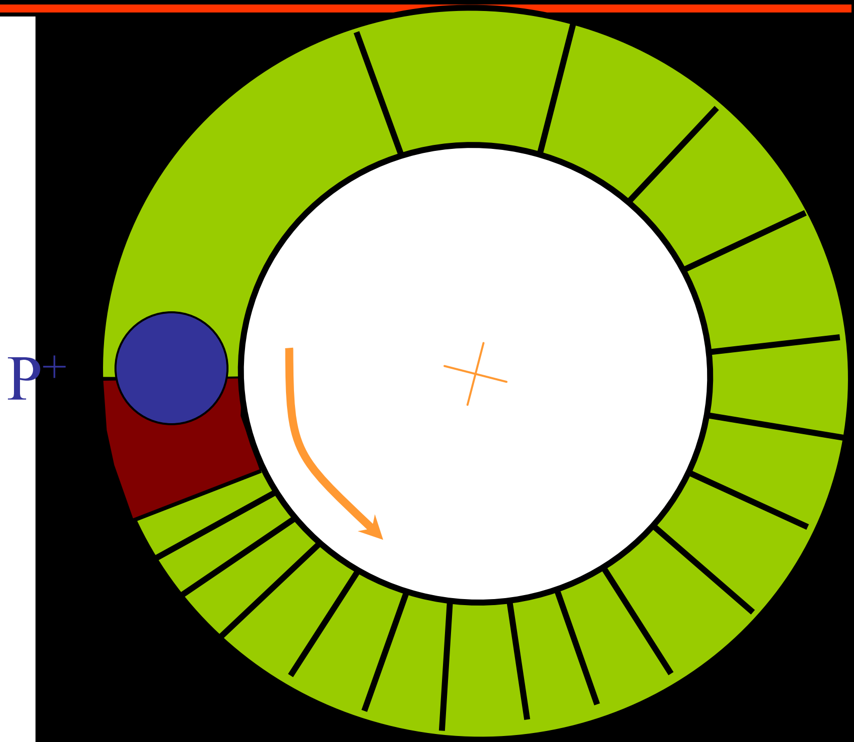


extend uniform region proportional to number of layers

dose delivered sequentially over all layers: *energy stacking*

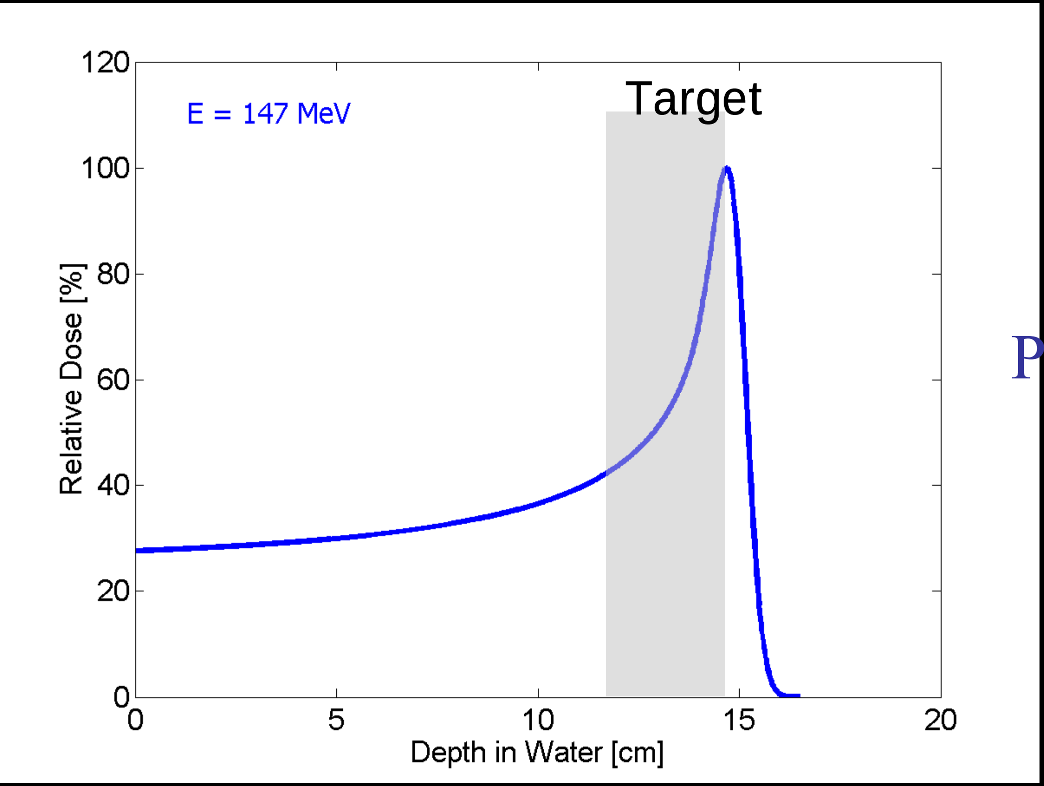
Range modulation / RM wheel

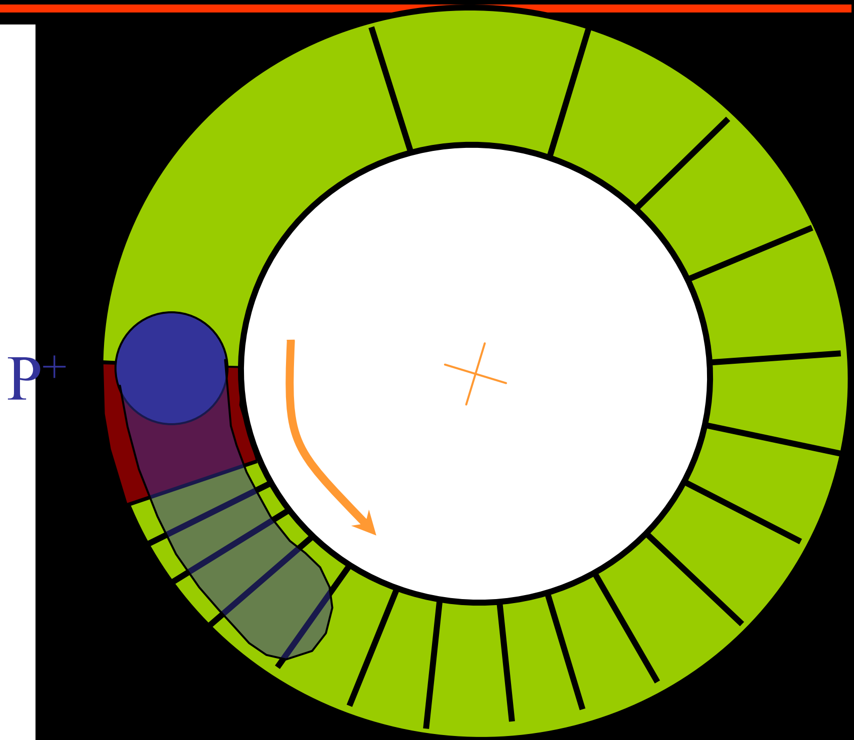




Step#	thickness	angular width
1	1.8 cm.H20	76 deg
2	2.3 cm.H20	27 deg
3	2.9 cm.H20	20 deg
4	3.4 cm.H20	14 deg
5	4.0 cm.H20	11 deg

Range modulation / RM wheel





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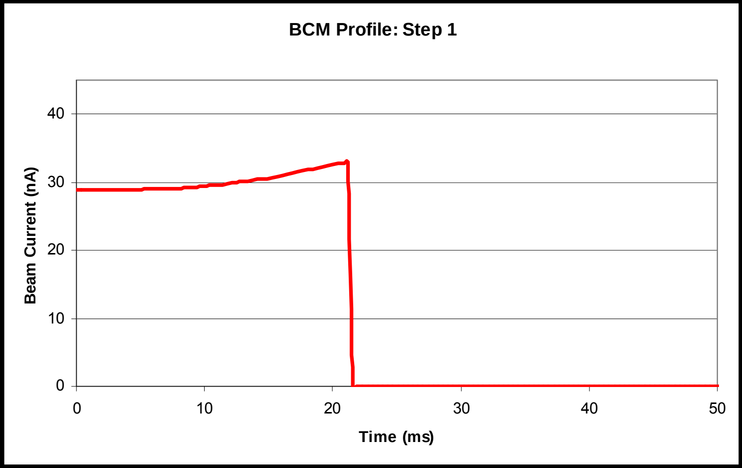
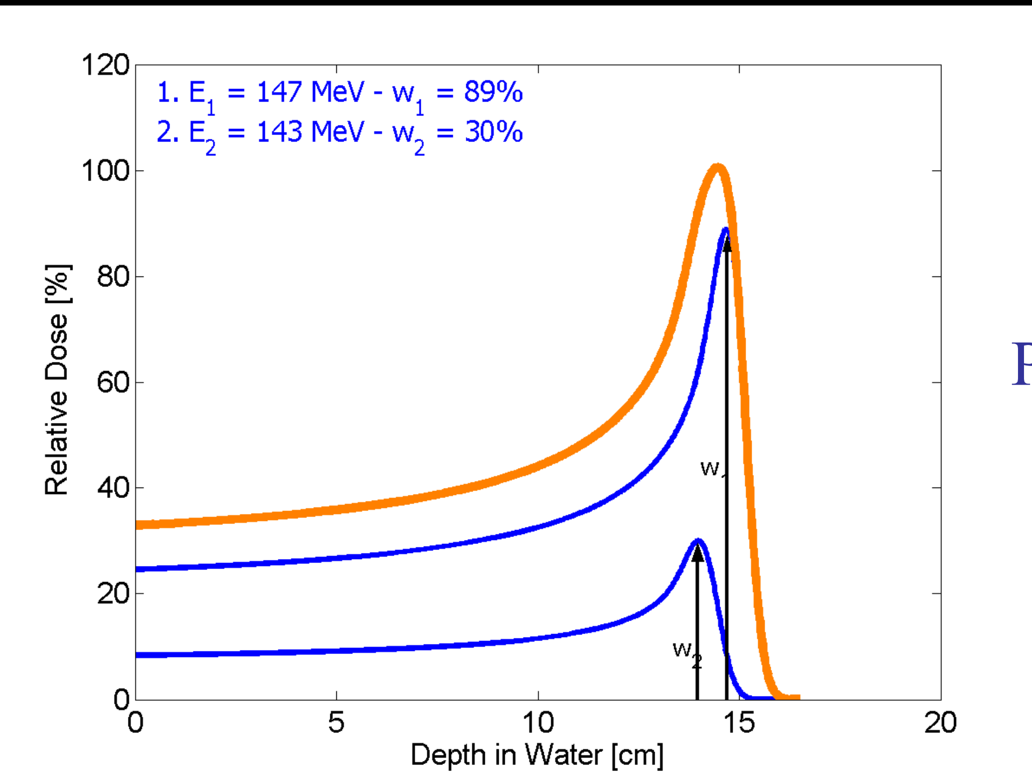
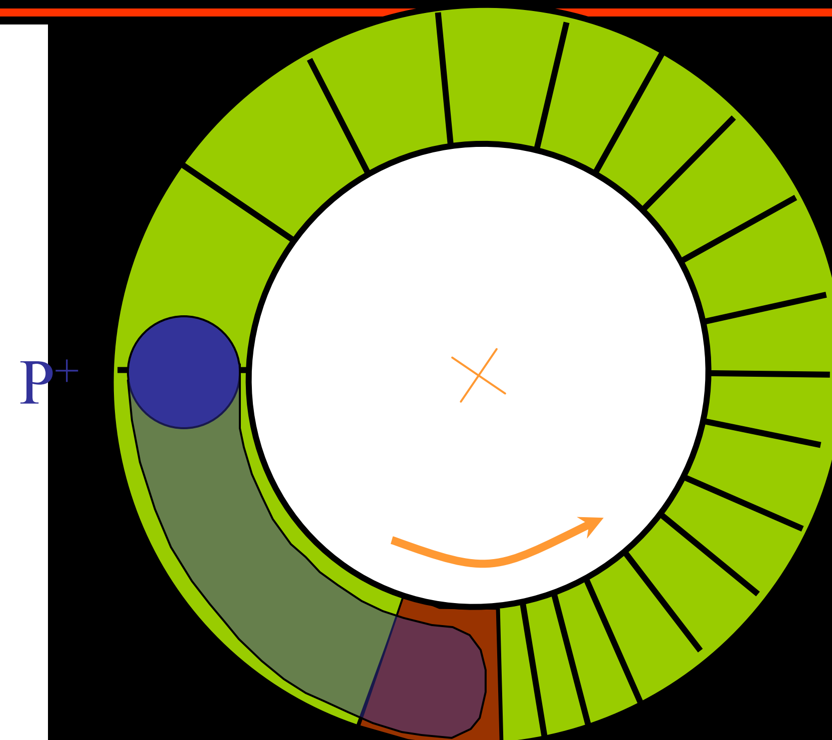


Range modulation / RM wheel





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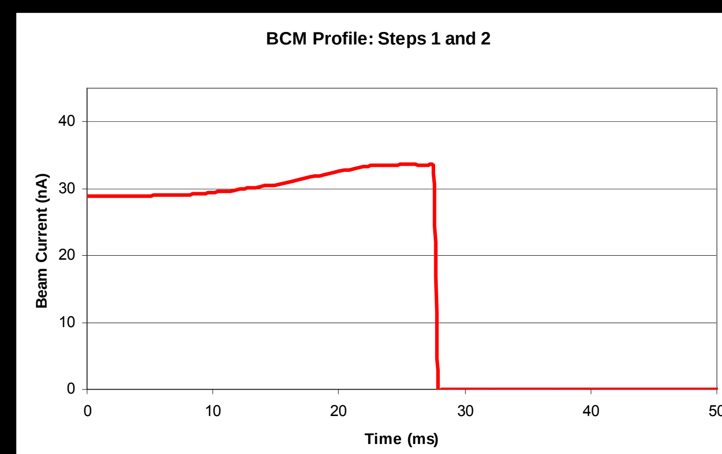
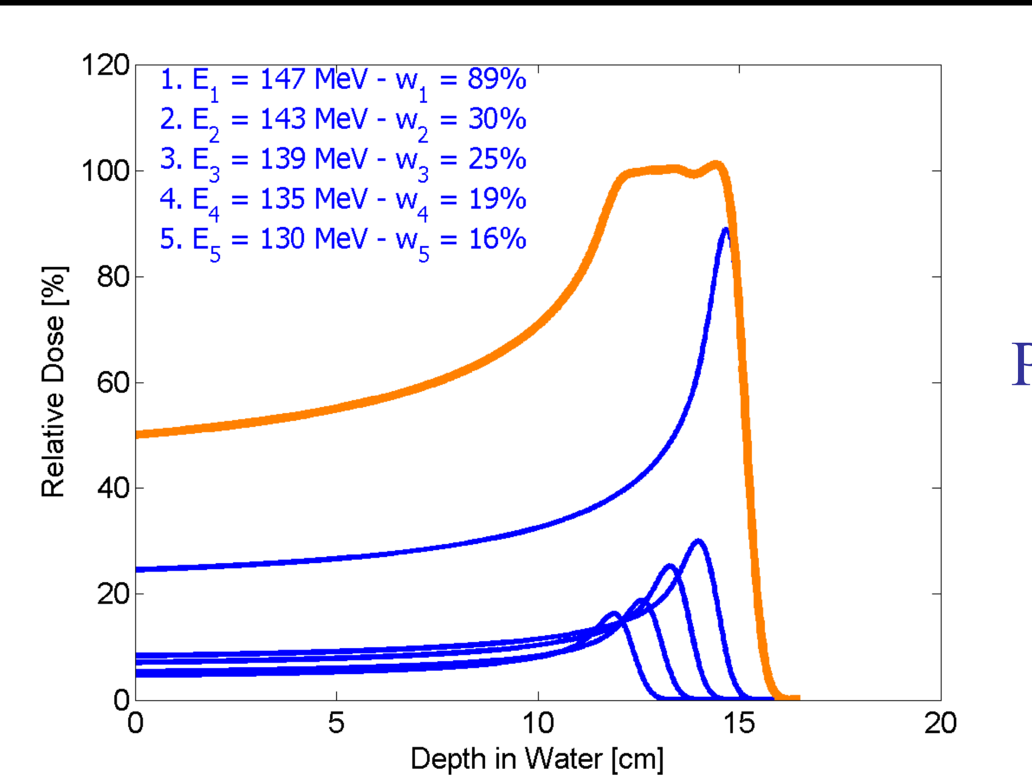
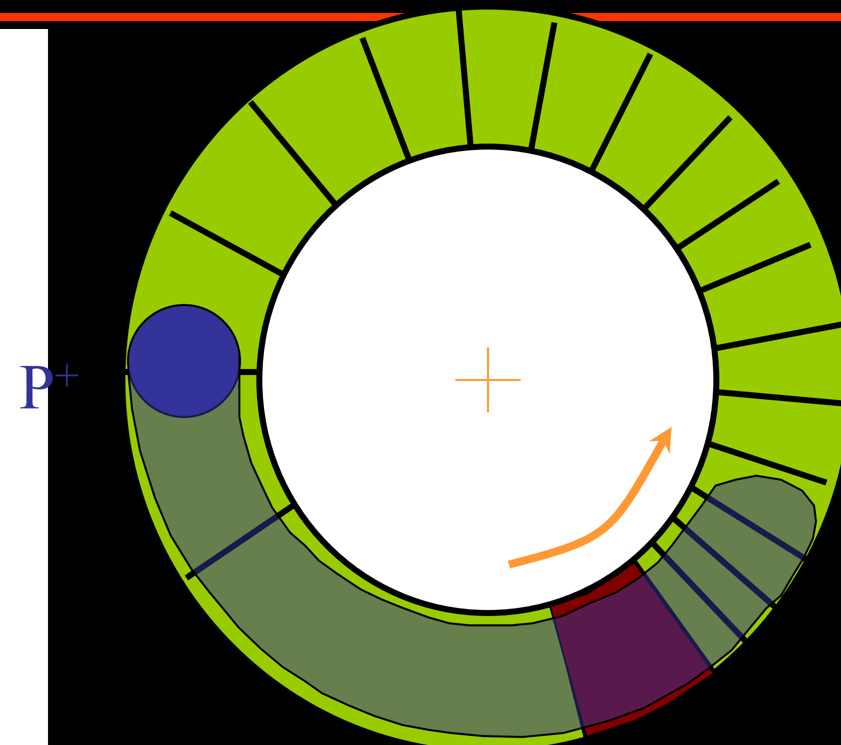


Range modulation / RM wheel





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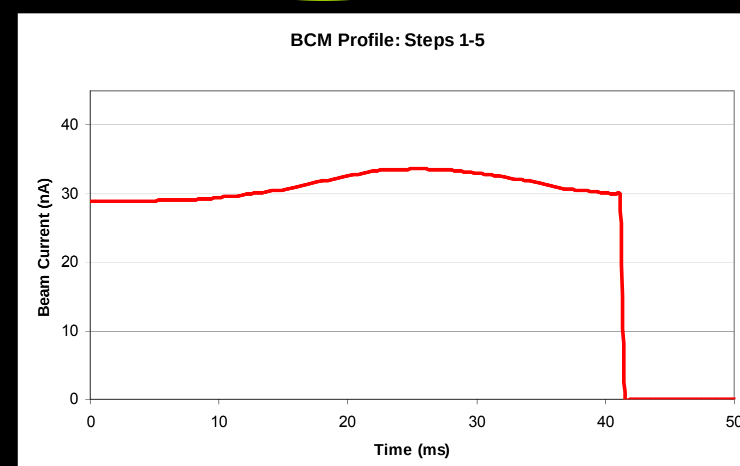
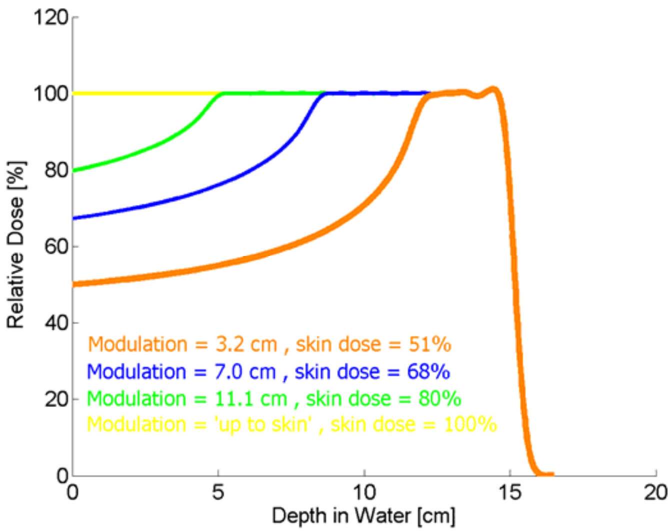
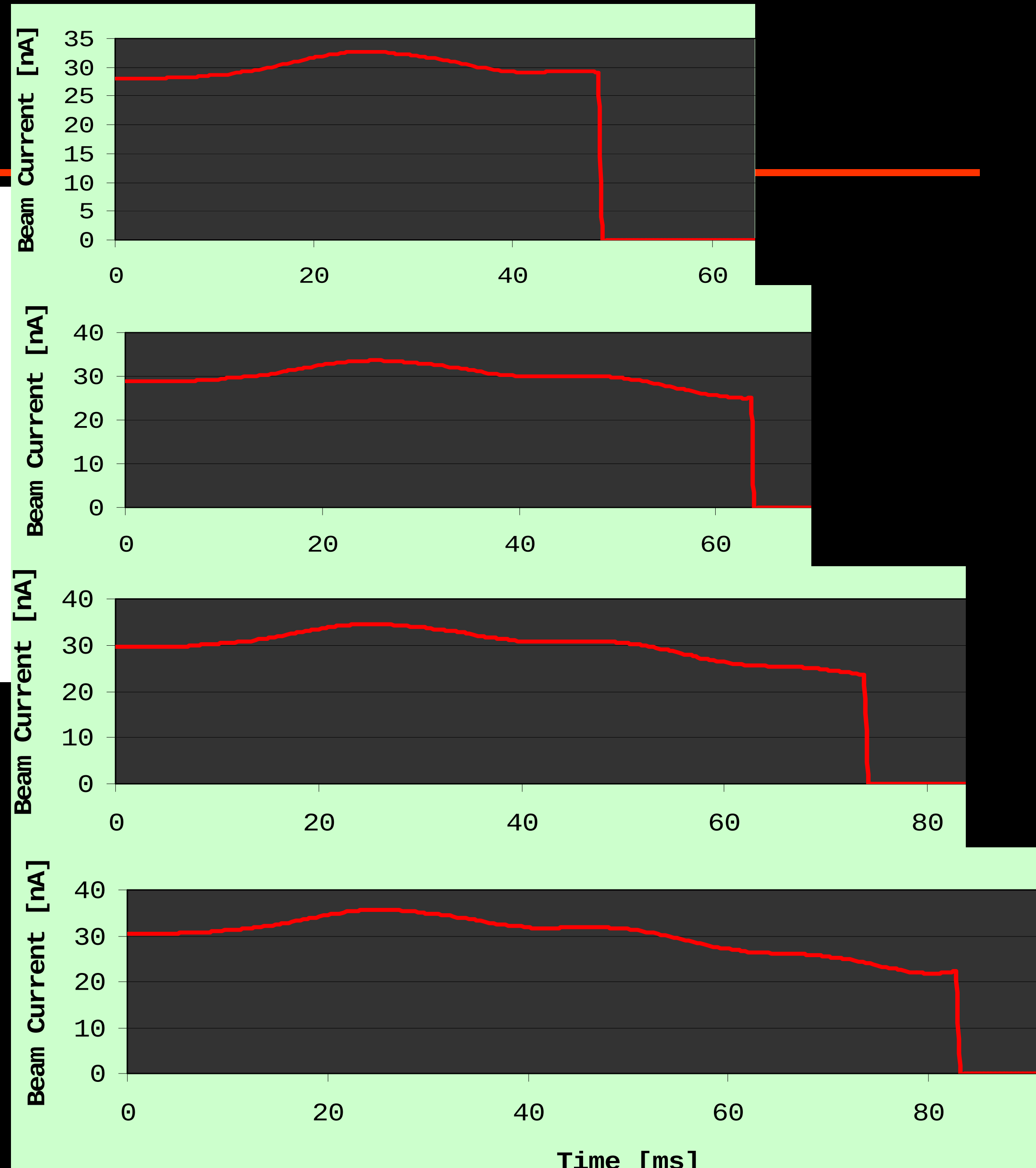


Range modulation / Beam Current Modulation

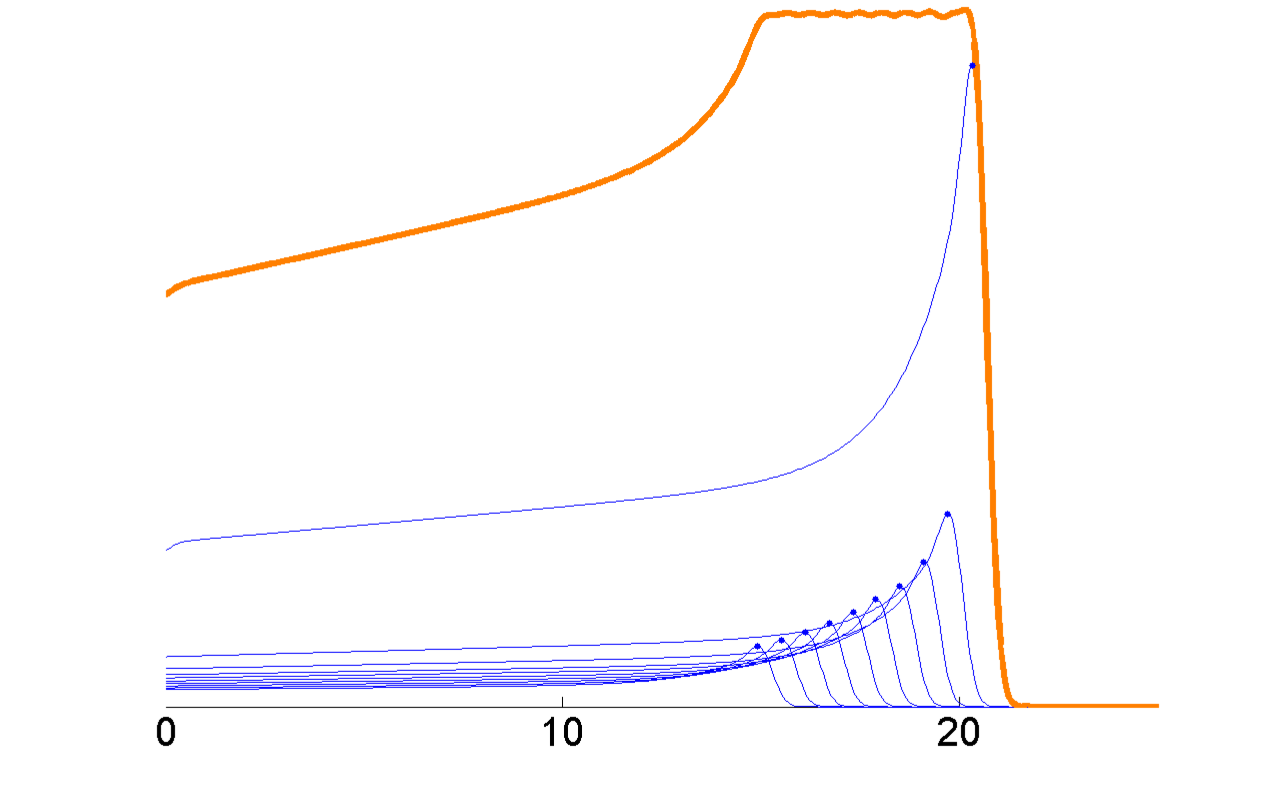


Field#	Modulation	stop angle
1	3.2 cm.H20	170 deg
2	7.0 cm.H20	250 deg
3	11.1 cm.H20	316 deg
4	"full"	360 deg

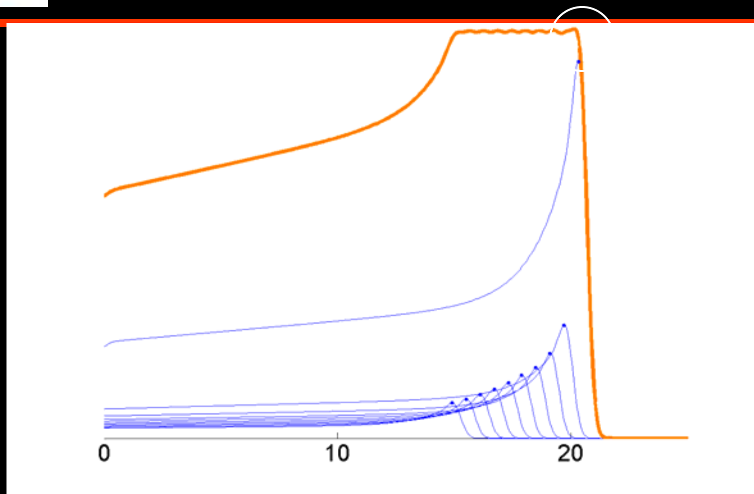


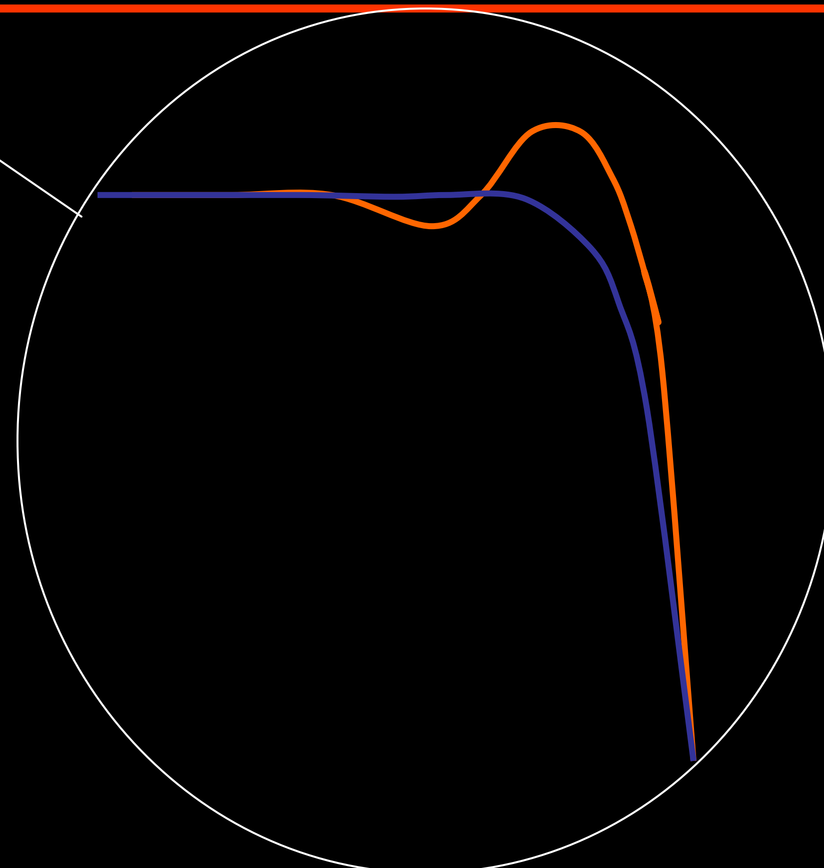
Range modulation / weight optimization

$$sobp(d) = \sum_{i=1}^{N} w_i \cdot pdd(d + (i-1)\cdot pb)\cdot\left(\frac{SSD+d}{SAD}\right)^2$$



Range modulation / weight optimization





Distal-end optimization

w2 ↓ : 'shoulder'

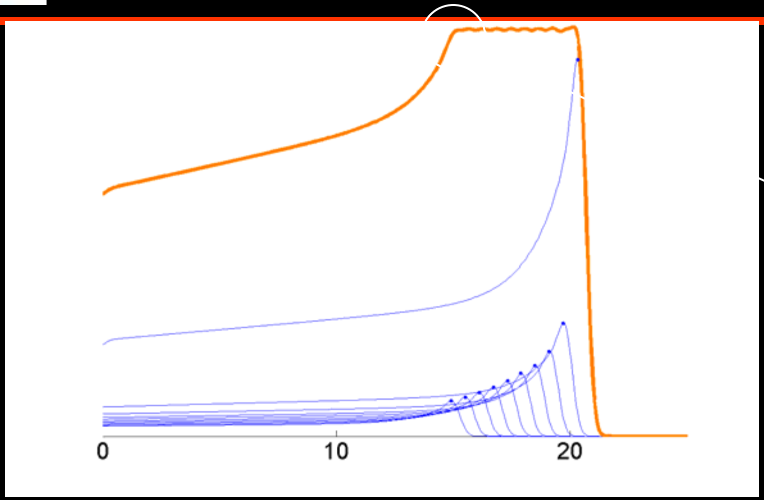
→ better uniformity

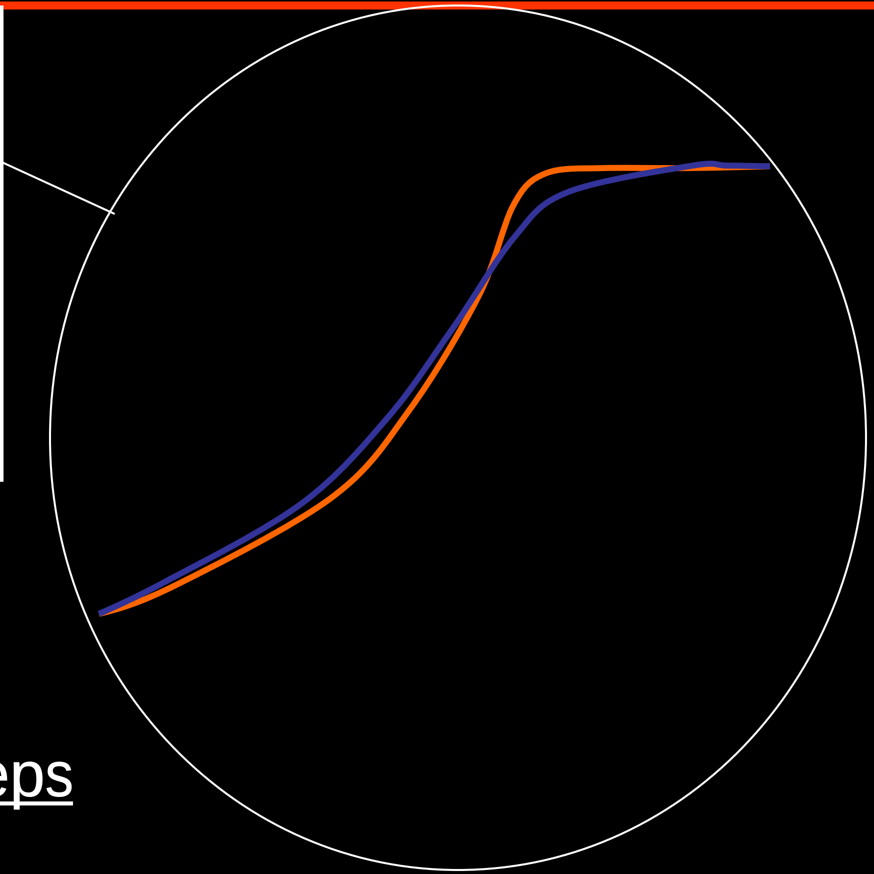
w_1 ↑ : 'dip&bump'

→ sharper distal fall-off

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

Range modulation / weight optimization





Spilling of beam on multiple steps

Spot size small compared to RM step width

Spot size large compared to RM step width

Range modulation / RM wheel

- beam current modulation:

  weigths are optimized for single energy (range); variation of beam current as function of RM angle can increase range span

- scatter compensation:

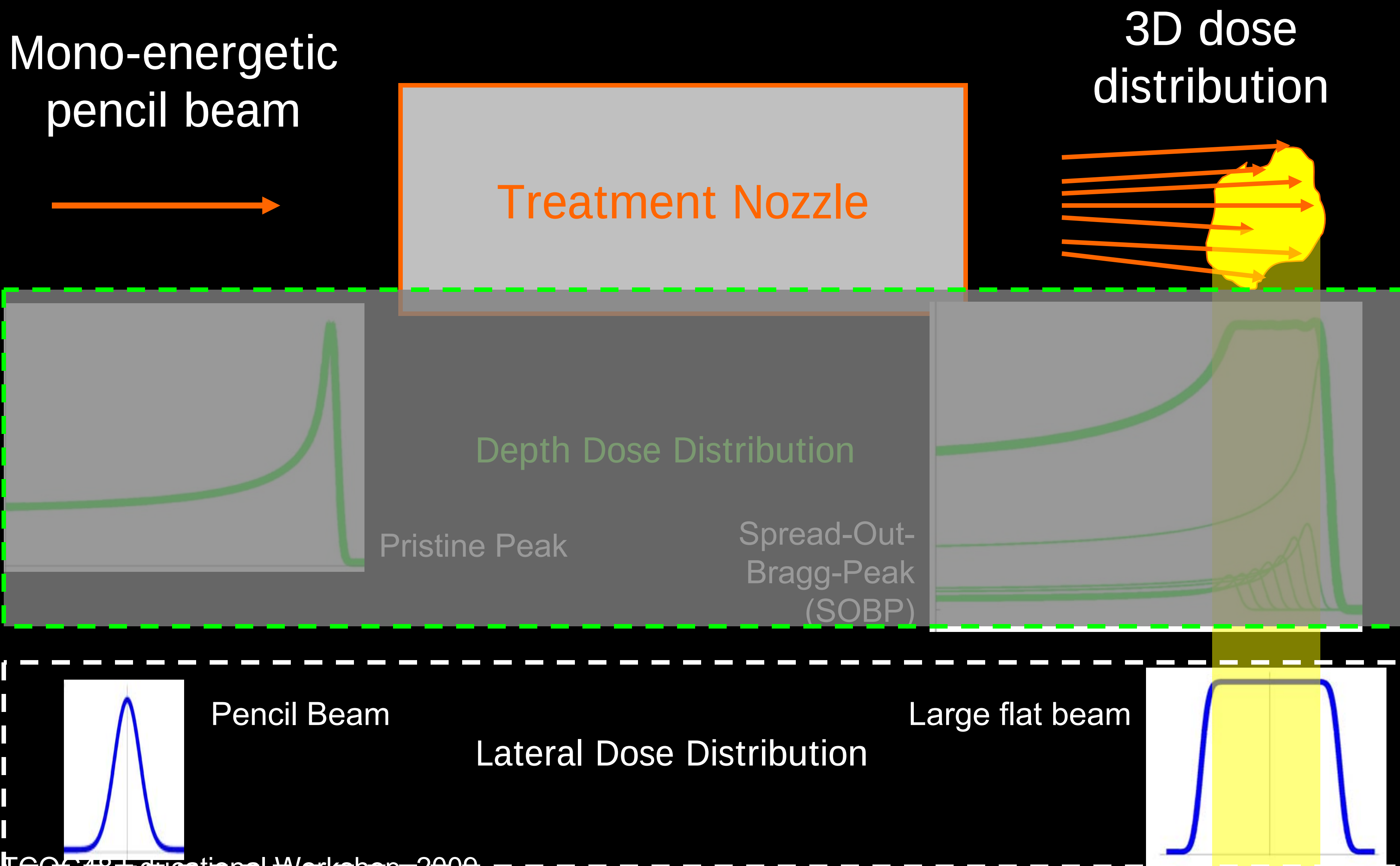
  making scattering power of each step equal by adding high Z material to thinner steps

- rotational speed / multiplication of RM profile:

  requirements on frequency are defined by time-structure beam and organ motion

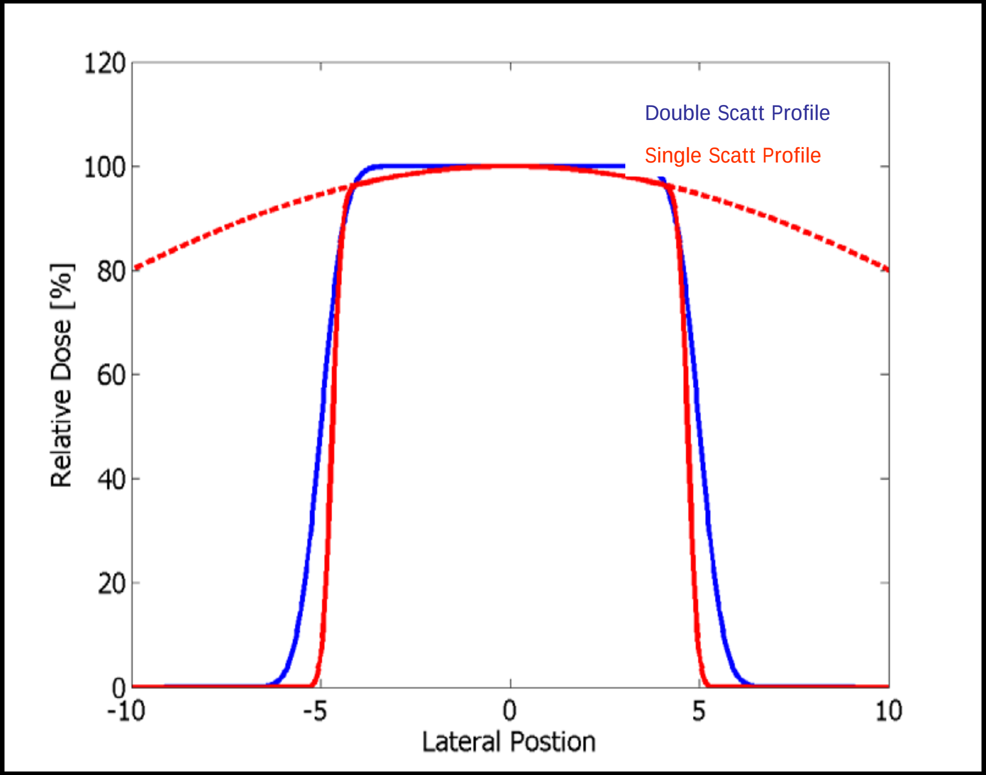
- alternative approaches:
  - single-modulation wheel (instead of gating)
  - blocking part of RM wheel (instead of gating)

Scattering Beam



Lateral spreading / single scattering

Flat scatterer spreads the beam to a large Gaussian profile, of which all protons outside the central 'flat' region are collimated.



Advantages:

- simple
- sharp lateral fall-off

Disadvantages:

- inefficient
- small field size

8 first scatterers used in IBA universal nozzle

First scatterers of IBA nozzle

- Scatters beam into large spot
- Used in single scattering
- Lexan and lead foils may be combined

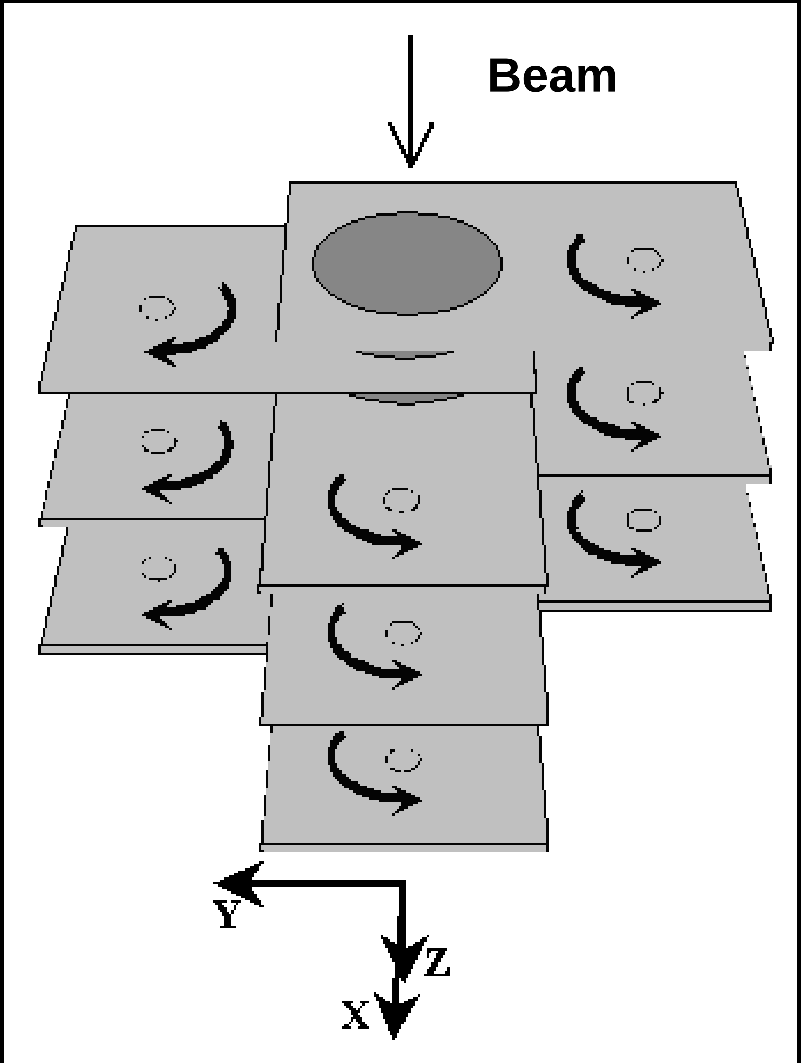
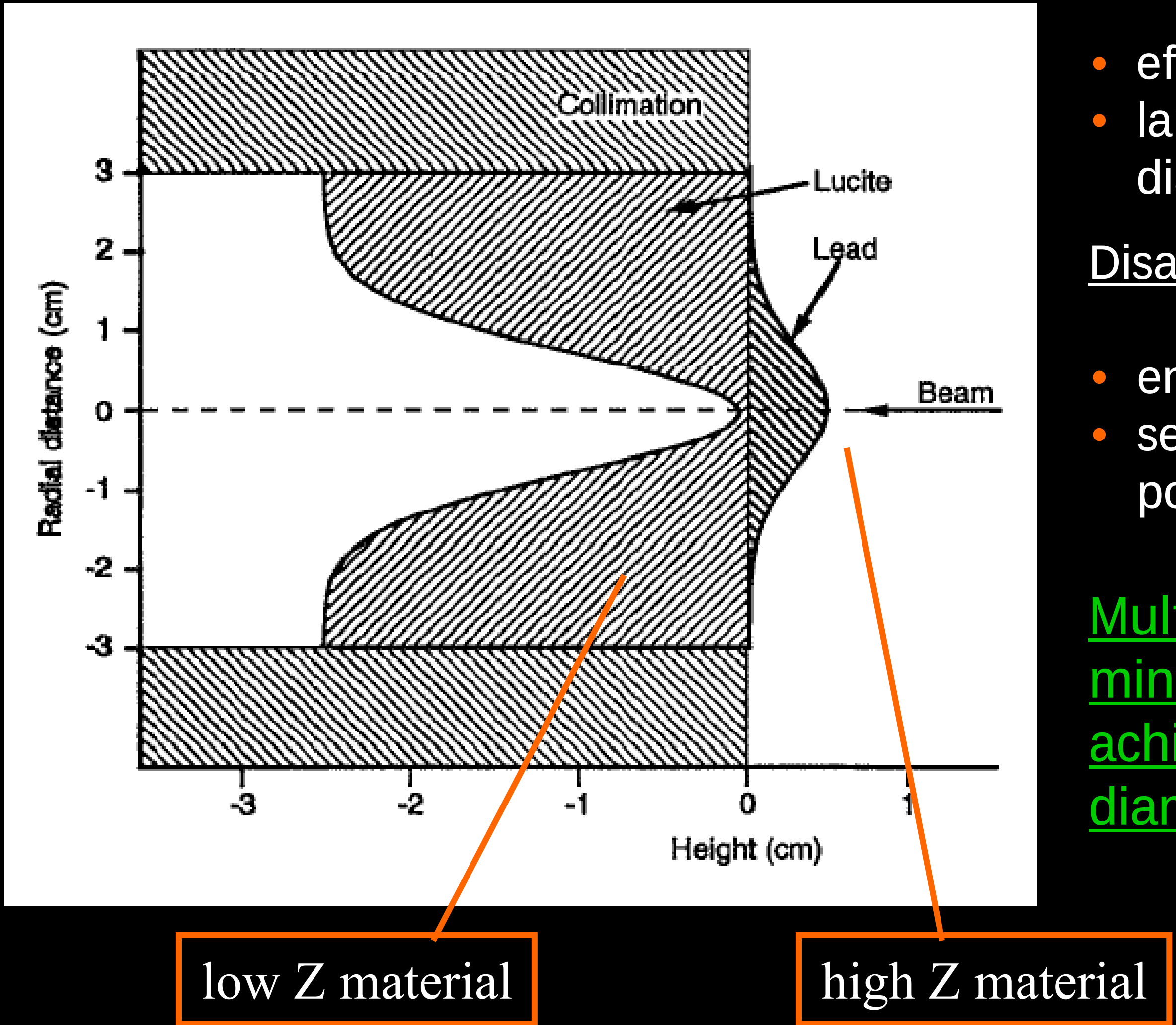


Diagram by IBA

Lateral spreading / contoured scatterer

Range-compensated contoured scatterer



Advantages:

- efficient
- large field sizes (up to 25 cm diameter)

Disadvantages:

- energy (range) loss
- sensitive to variations beam position and size

Multiple scatterers used to minimize range loss and achieve large (up to 25 cm diameter) field size

- 3 in IBA universal nozzle

Diagram: Gottschalk

Energy options

A combination of a range modulator and second-scatterer gives a 'perfect' dose distribution for a given initial energy (range)

- with changing range the <u>shape</u> of the pristine peaks changes, resulting in a non-uniform SOBP
  - first: correct using bcm
  - then: new RM track

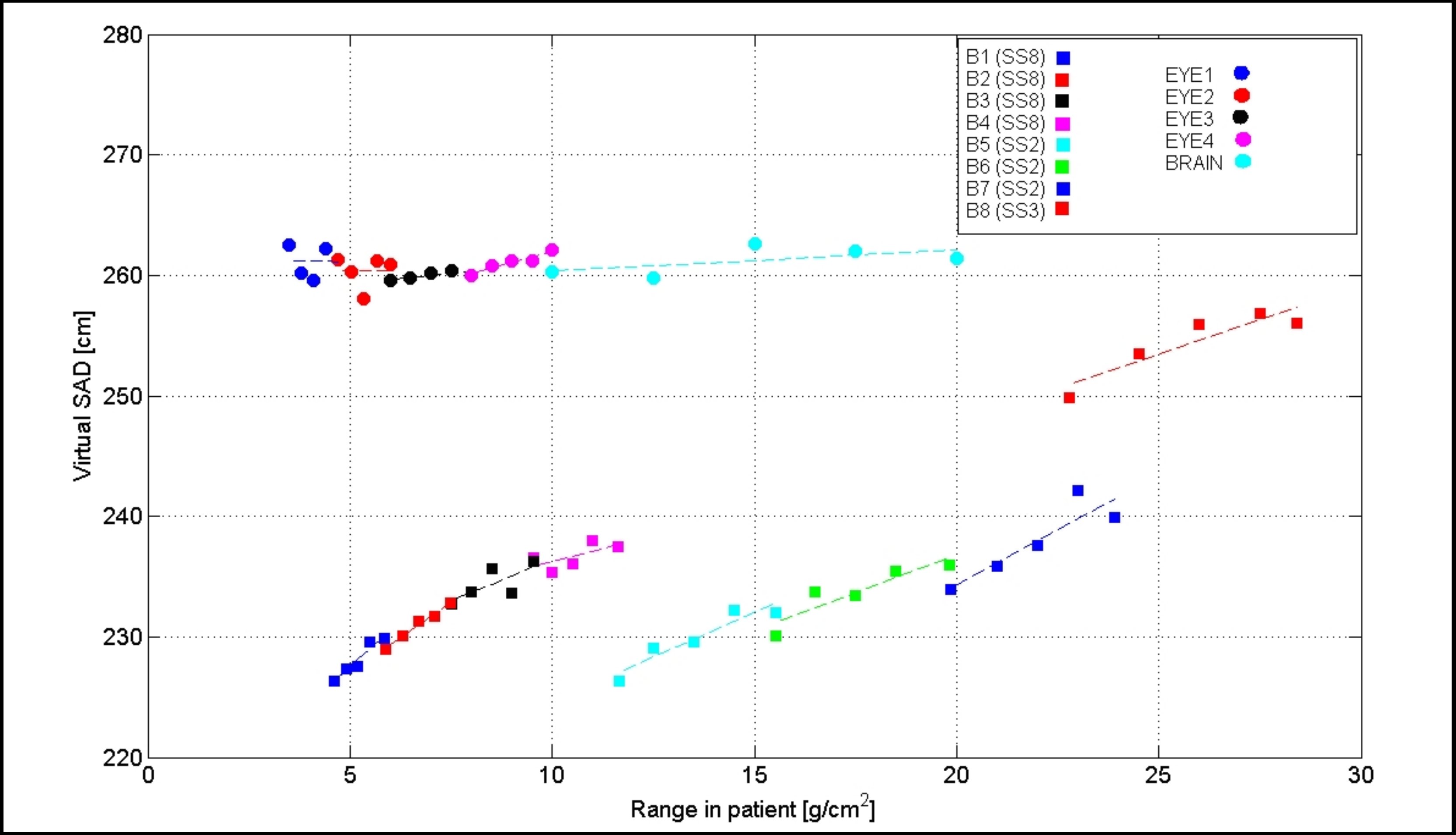
- with increasing energy the scattering decreases, resulting in 'domed' profiles
  - first: correct using 'fixed scatterer'
  - then: new second scatterer

→ To cover a wide range of clinical cases a library of RM and SSC combinations is required

Dosimetric characteristics of scattering beams

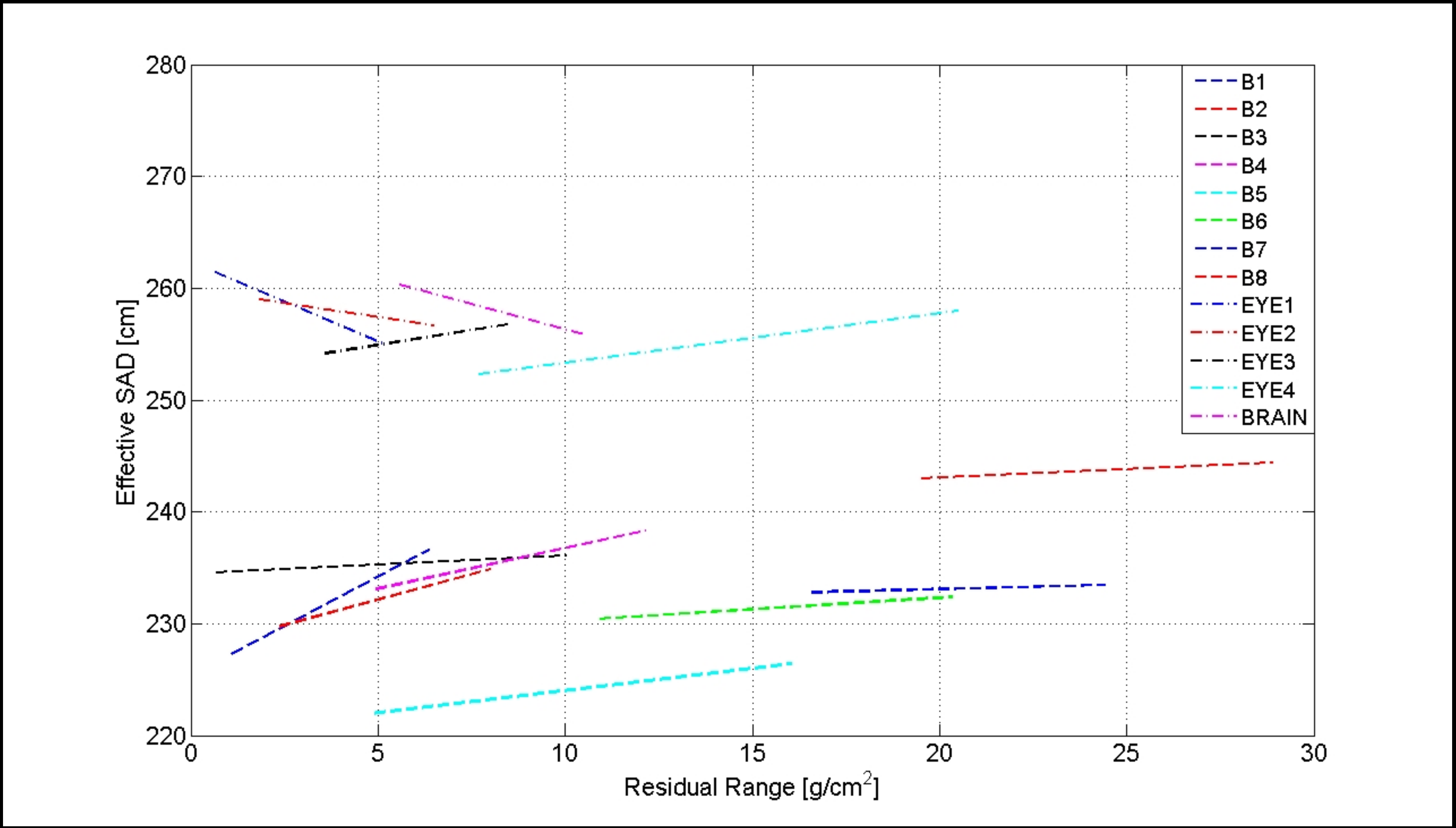
- The total water-equivalent thickness of nozzle components (1st scatterer, RMW, 2nd scatterer) directly impact beam quality parameters
  - Virtual SAD
  - Effective SAD
  - Source size
  - Energy spread
  - Distal falloff
  - Penumbra

Virtual SAD vs. options



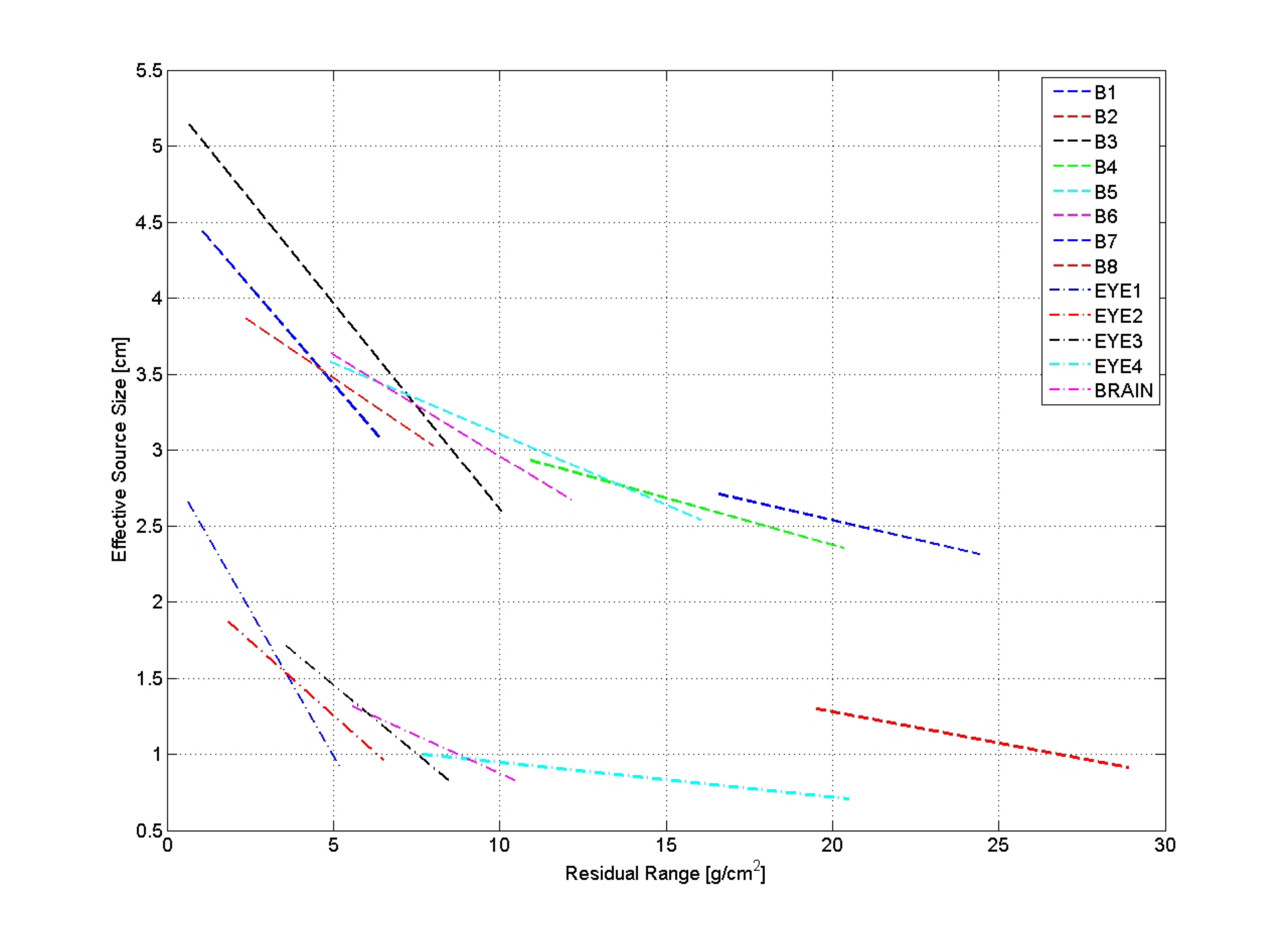
UFPTI data, 2006

Effective SAD vs. options



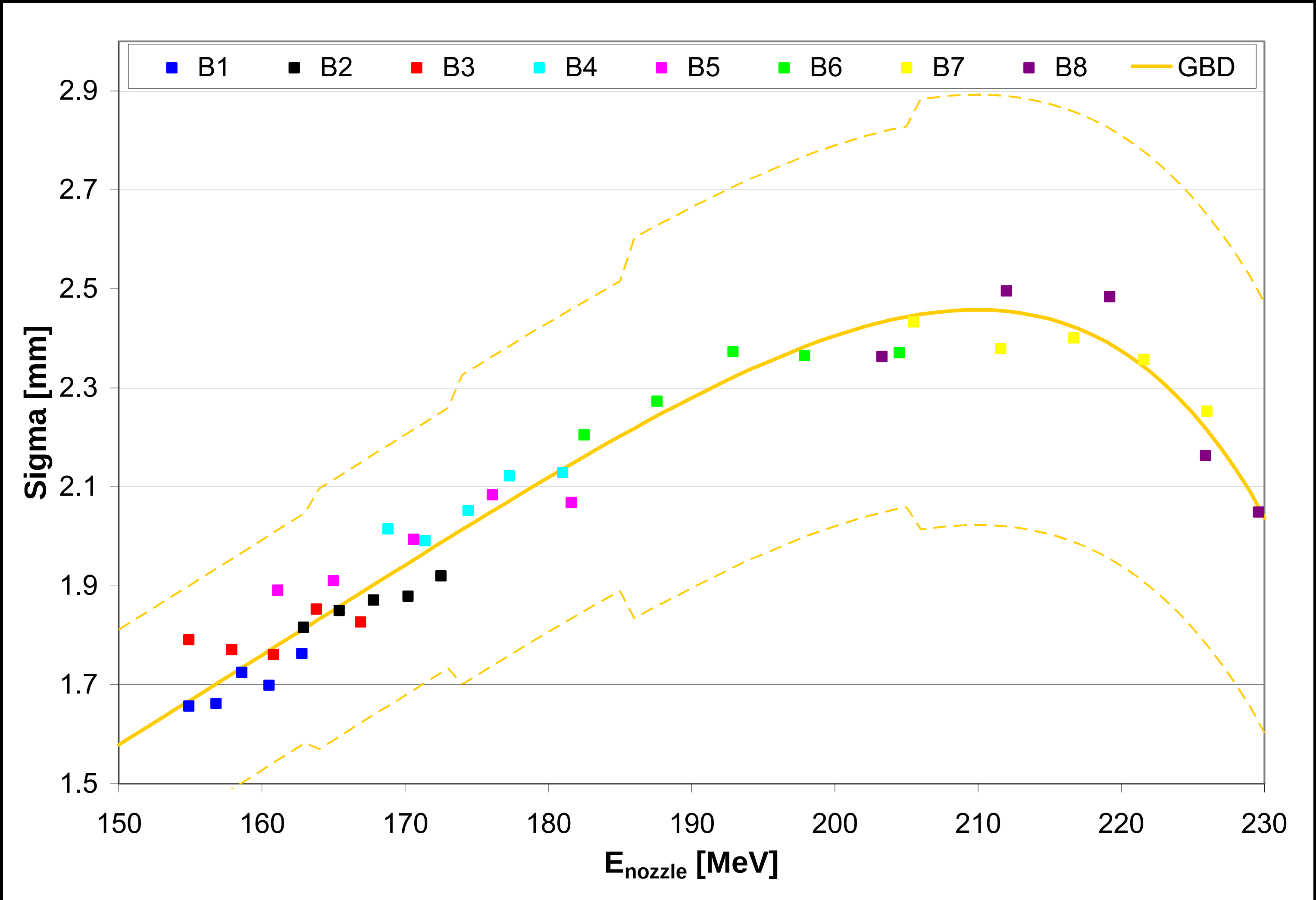
UFPTI data, 2006

Effective source size vs. options

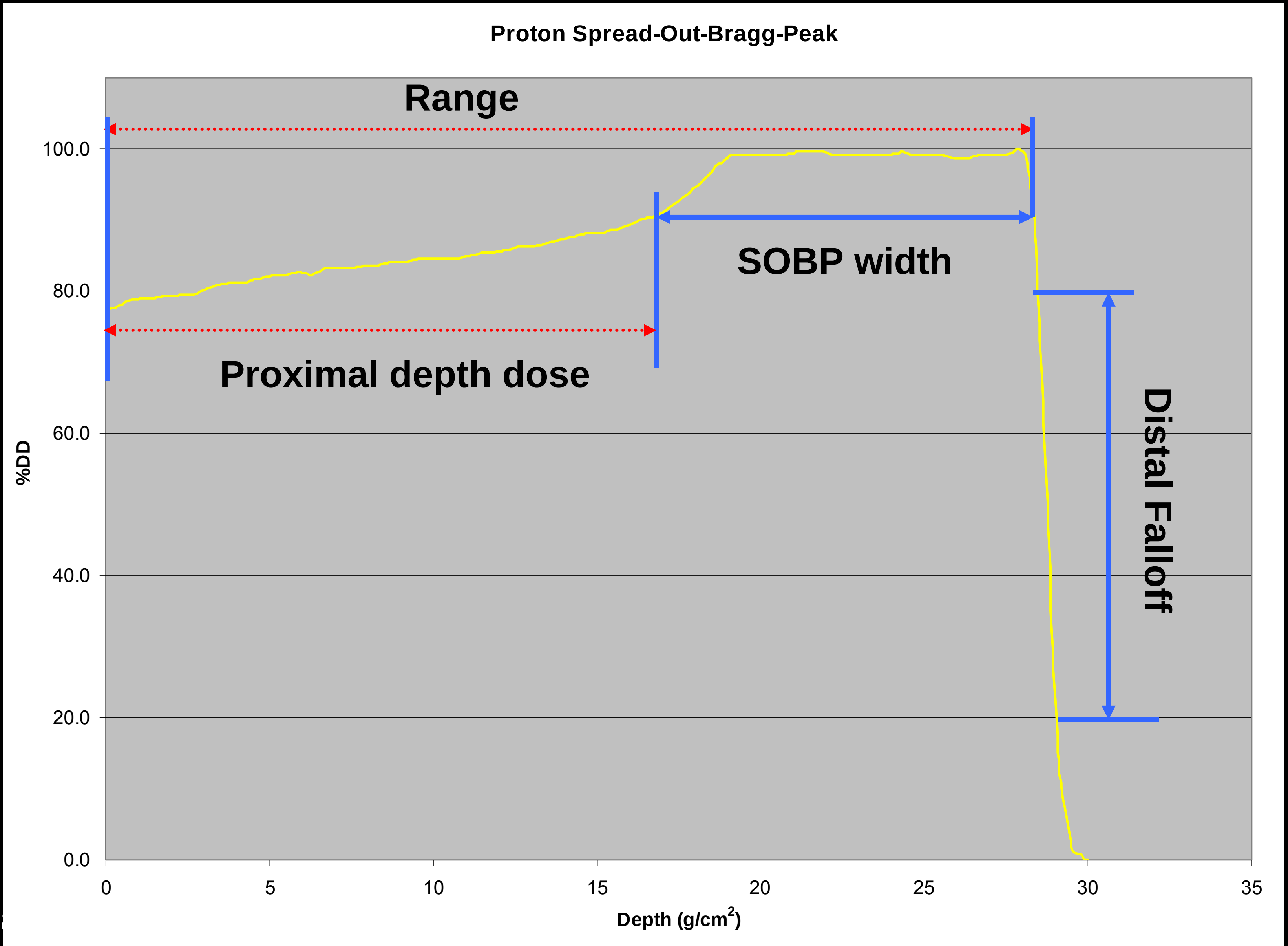


UFPTI data, 2006

Energy spread vs. energy at nozzle entrance



Dosimetric properties of proton beams: %DD

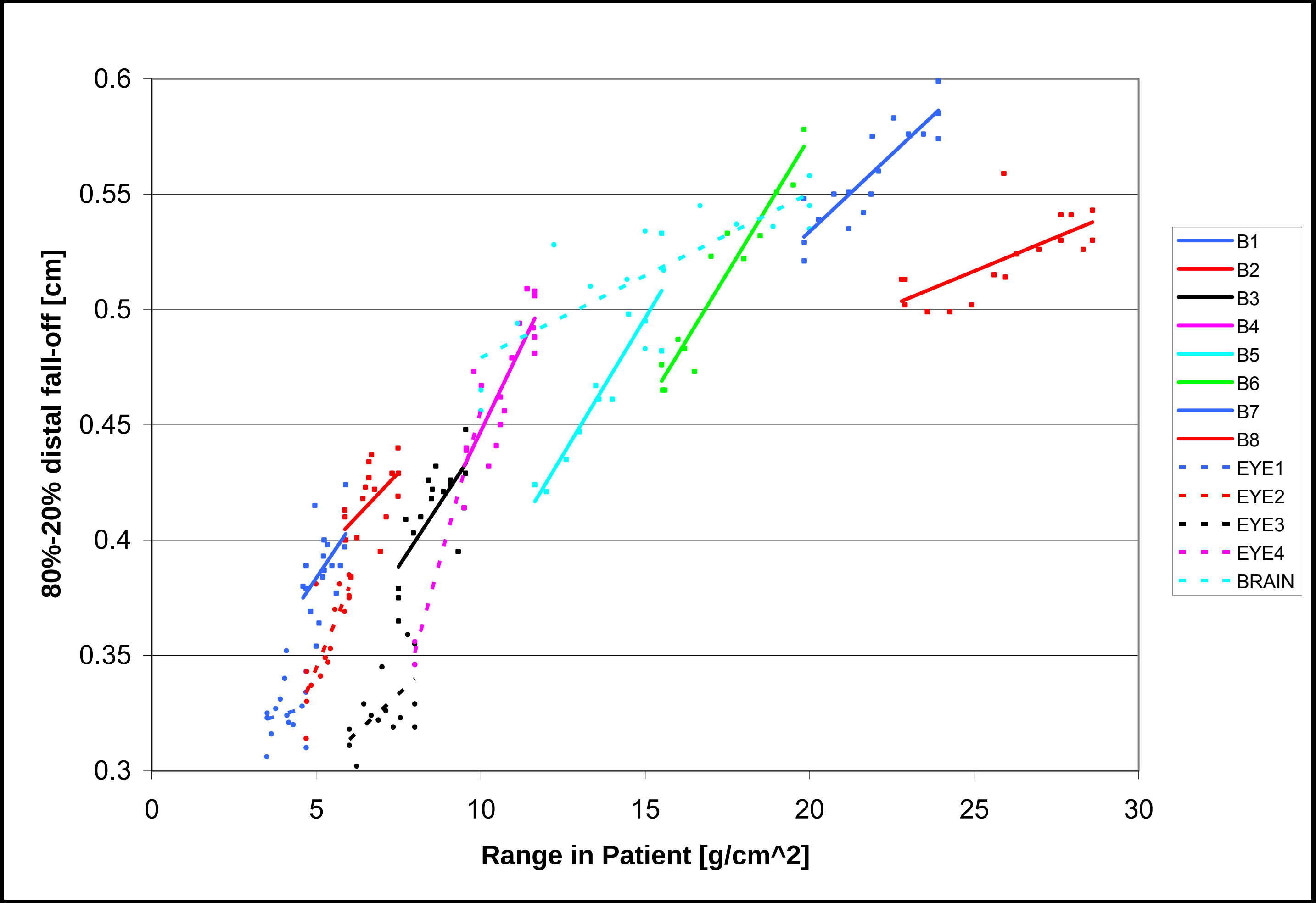


SOBP depth dose characteristics

- Width of distal falloff is a function of
  - proton beam energy spectrum/angular spread, and
  - energy straggling in tissue
- Dose gradient in distal falloff @ 10% - 20%/mm

- Dose gradient in proximal depth dose significantly smaller than distal falloff
  - Function of SOBP formation mechanism and ratio of range/SOBP width
  - ~ 0.5%/mm

Distal falloff vs. options

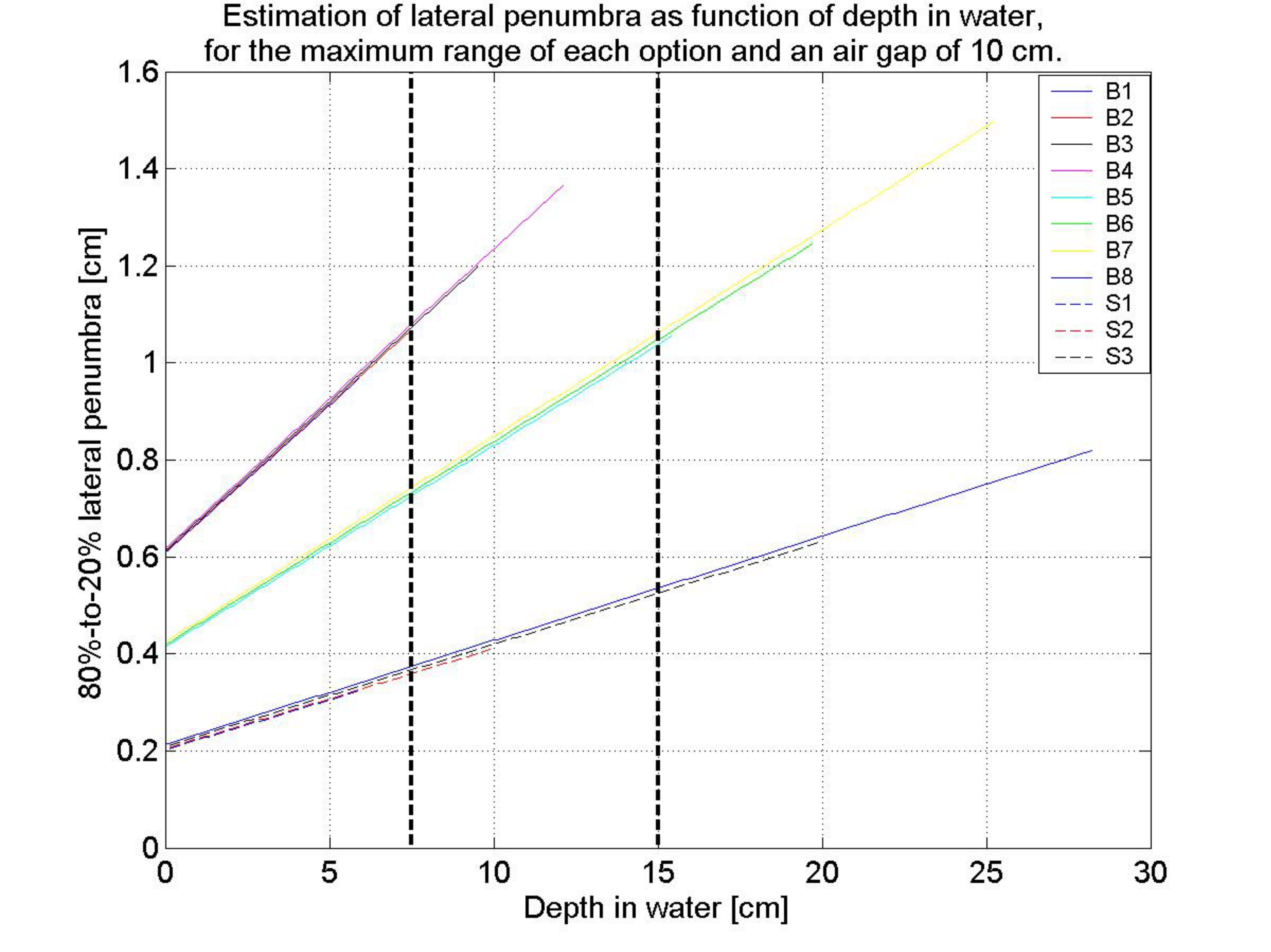


B7 option PDD has larger distal falloff than B8 PDD due to larger nozzle equivalent thickness values

Proton beam penumbra characteristics

- Is a function of beam delivery technique
  - Single scattering
  - Double scattering
  - Uniform scanning
  - Pencil beam scanning
- Is a function of target depth
  - In-water increase of penumbra ~=3% of range
- Is a function of air gap
- Is a function of heterogeneities

Beam penumbra in air vs. options



Parameterization of scattering beam dosimetry: Golden beam data for proton beams

- Is it possible to use a single beam data set ('golden') to commission treatment planning for different installations of a PT system?

- Yes, by parameterizing and fitting of
  - Energy spread
  - Virtual SAD
  - Effective source size
  - Effective SAD

UFPTI project in collaboration with IBA

Golden beam data for proton beams

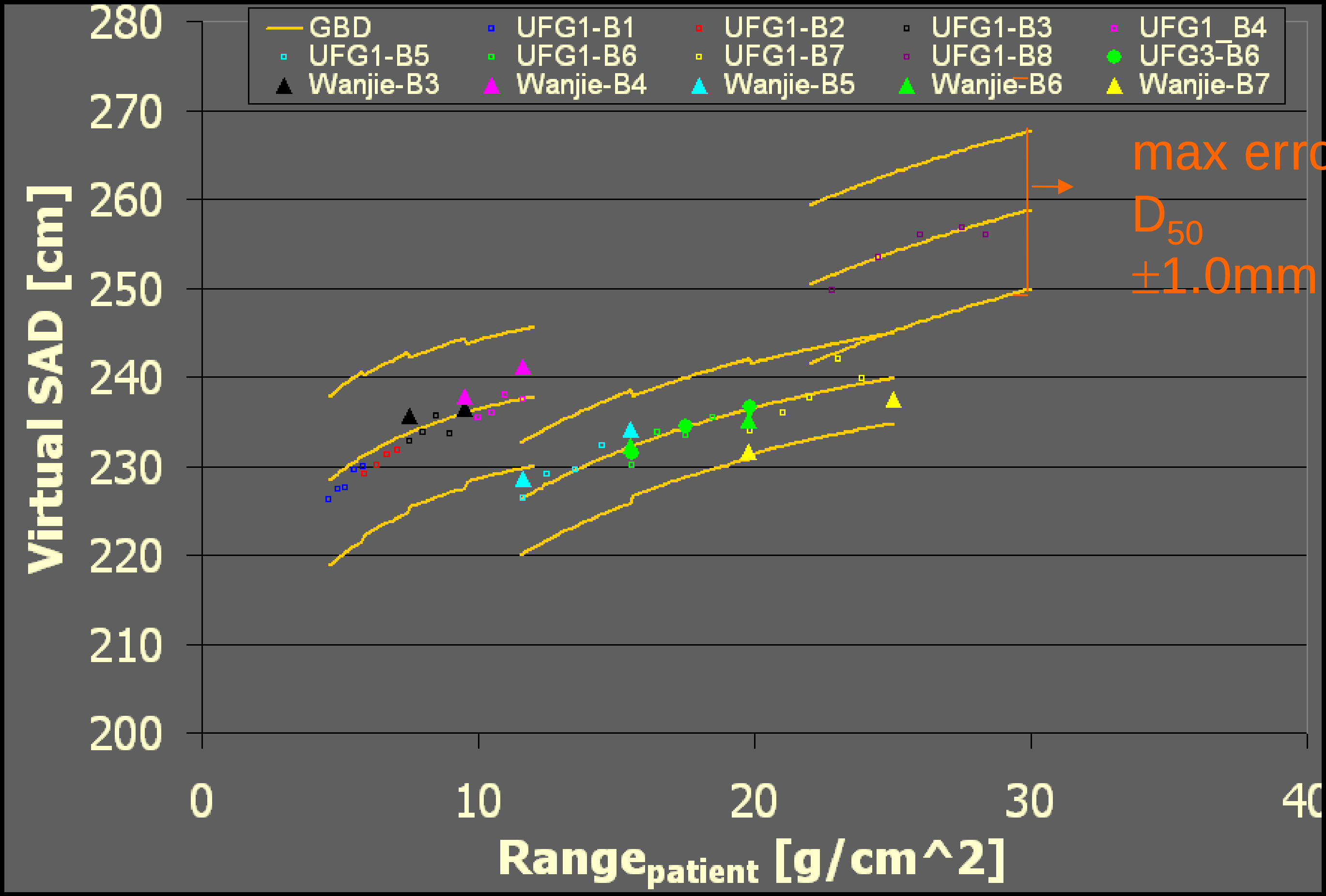
- Accuracy

- max error in pdd dose due to error in the pristine energy spread ±1.0%
- max error in 50% field radius due to error in the virtual SAD ±0.5mm
- max error in 80-20% penumbra due to error in the eff. source size ±0.5mm
- max error in pdd dose due to error in effective SAD ±0.5%

- Fitting tolerances

Option ID	$\Delta\Sigma$	ΔSAD	$\Delta\sigma_s$	ΔSAD_{eff}
	mm	cm	cm	cm
B1	±0.2	±9.5	±0.3	±27.7
B2	±0.3	±9.0	±0.3	±21.3
B3	±0.3	±8.4	±0.3	±16.2
B4	±0.3	±7.8	±0.3	±12.9
B5	±0.3	±6.3	±0.2	±8.3
B6	±0.4	±5.6	±0.2	±6.4
B7	±0.4	±5.1	±0.2	±5.3
B8	±0.4	±8.9	±0.3	±4.8

Golden beam data for proton beams



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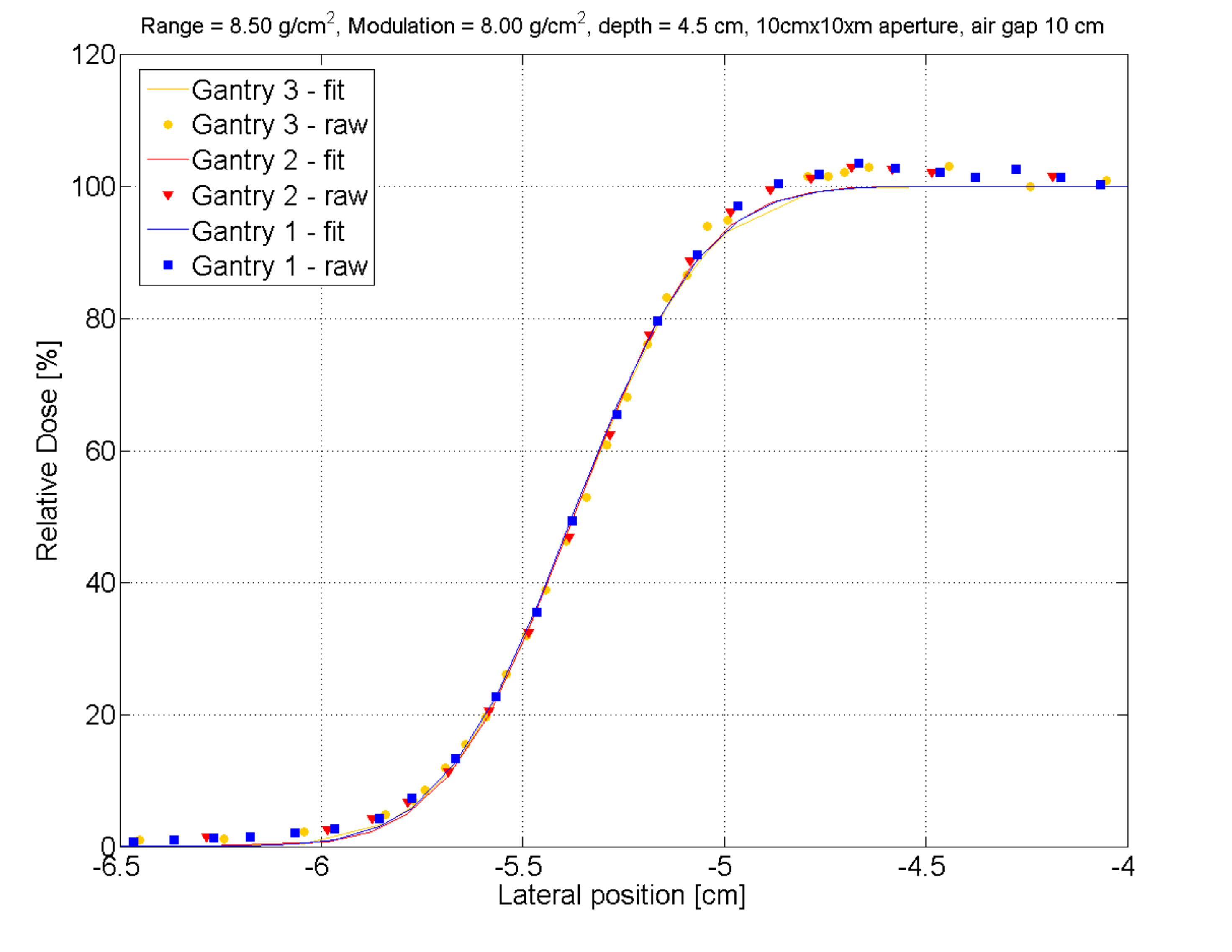
Golden beam data for proton beams



Parameterization of scattering beam dosimetry: MU calculation

- No general framework for proton beam MU calculation available
  - Semi-empirical models exist
    - MGH (*Kooy, 2003; Kooy, 2005)* model (for IBA machine)
    - Empirical fitting of measured data
  - Model partially validated during machine commissioning for limited ranges of beam energy and modulation
    - Additional validation performed as patient QA measurements are performed

MU calculation model

$$\Psi(r,R,\Delta z,DR)=\frac{CF\cdot\Psi_c\cdot D_c}{100/(1+a_1r^{a_2})}\cdot(s_1+s_2(R-R_L))\cdot\left(\frac{SAD}{SAD-\Delta z}\right)^2\cdot\Gamma(r,DR)\quad[cGy/MU]$$

with

$$r=\frac{R_{90}-m\cdot M_{90}}{m\cdot M_{90}}$$

$$\Gamma_i(r,DR)=\cdot\frac{DR}{DR+d_1+d_2\Psi_0(r)}\qquad(9)$$

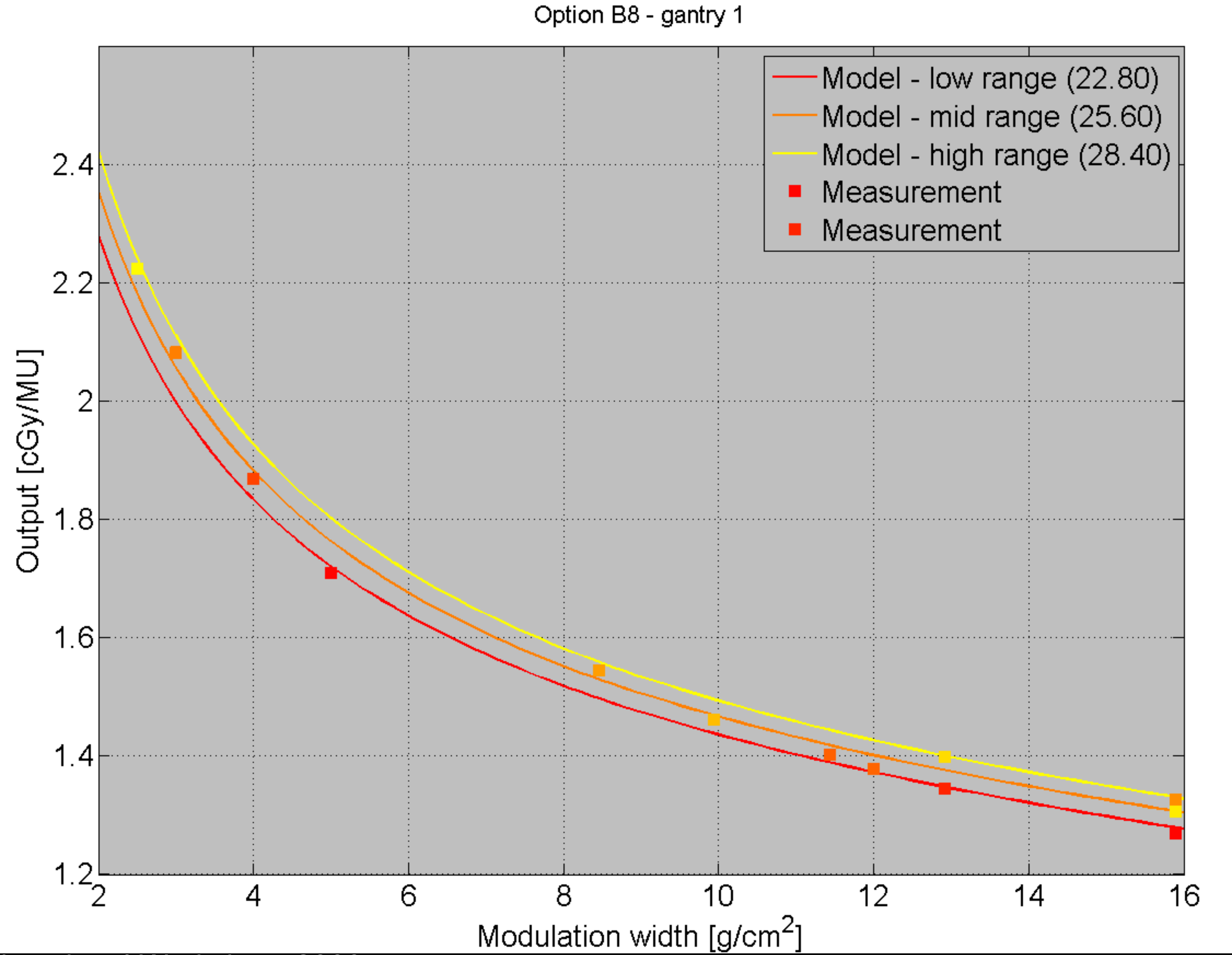
$$\Psi_0(r)=\frac{CF\cdot\Psi_c\cdot D_c}{100/(1+a_1r^{a_2})}$$

- Model fitted for
  - Options
  - Source shift between options
  - Skin dose vs M_{90}
  - Cyclotron dark current
  - Mid-SOBP shift away from isocenter

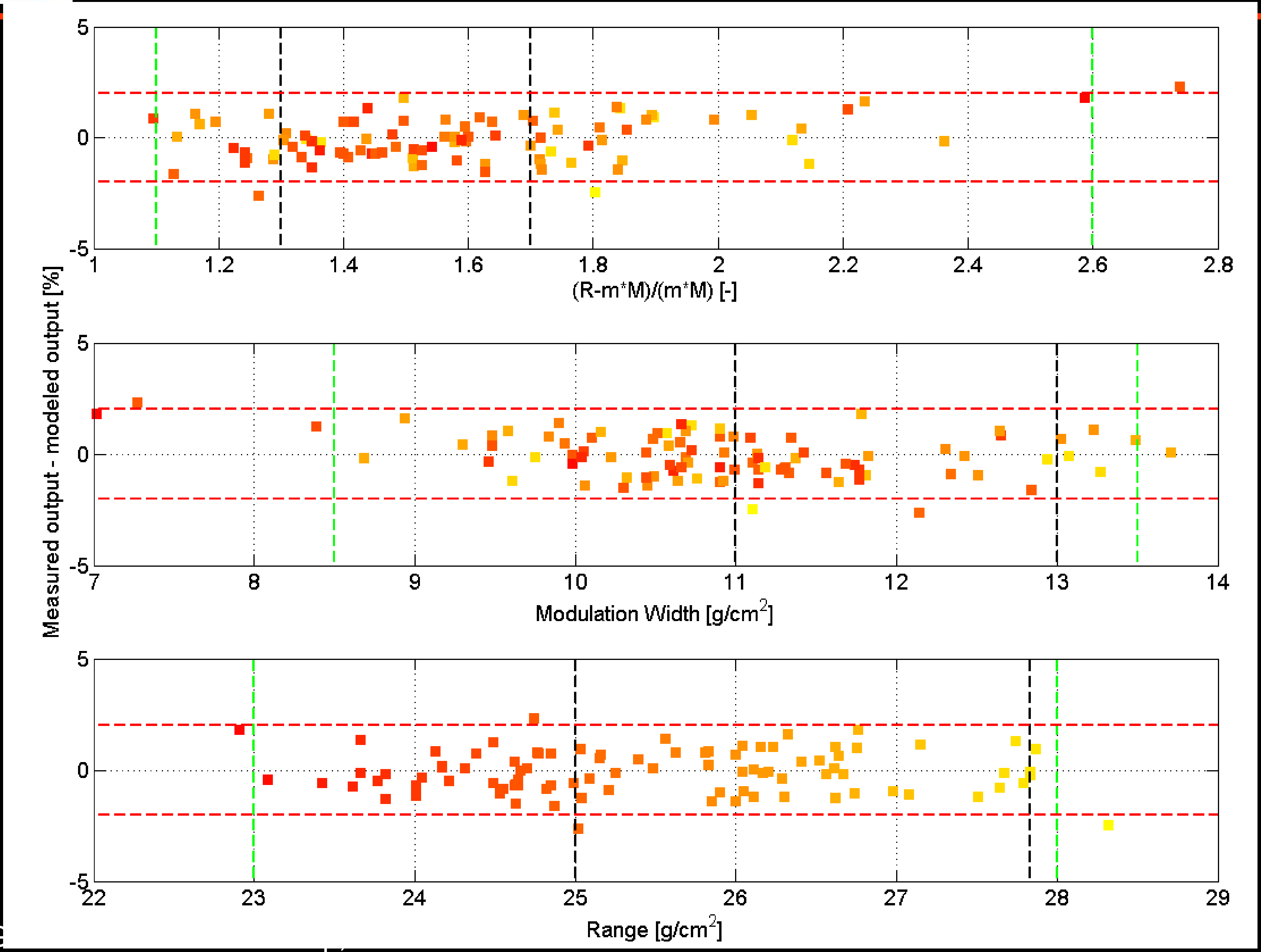
Parameters of MU Calculation Model

Parameter	Unit	Description	Option Specific	Determination
R_{90}	g/cm^2	Range (depth of distal 90% of SOBP)	N/A	Field-specific input
M_{90}	g/cm^2	Modulation width (distance between proximal and distal 90%)	N/A	Field-specific input
Δz	cm	Iso center shift: distance between center SOBP and iso center (positive for shift SOBP upstream)	N/A	Field-specific input
DR	Gy/min	Required dose rate (TCS parameter)	N/A	Field-specific input
m	-	Proportionality parameter relating M_{90} and M_{100}	Yes	Calculated based on: $m = \left(1 + \left(\left(\frac{1}{0.9} - 1\right)/a_1\right)^{1/a_2}\right)^{-1}$
CF	-	Parameter correlating output between different options	Yes	
Ψ_c	cGy/MU	Output for the reference field	No	Will be set to 1 cGy/MU
D_c	%	Relative skin dose for the reference field	No	Measured for reference field
a_1	-	Parameter to model skin dose for given R_{90} and M_{90}	Yes	Optimization model to measured output per option (commissioning)
a_2	-	Parameter to model skin dose for given R_{90} and M_{90}	Yes	Optimization model to measured output per option (commissioning)
s_1	-	Parameter relating source shift to range	Yes	Optimization model to measured output per option (commissioning)
s_2	(g/cm^2)$^{-1}$	Parameter relating source shift to range	Yes	Optimization model to measured output per option (commissioning)
R_L	g/cm^2	Minimum range for an option (used to determine source shift)	Yes	Based on convalgo
SAD	cm	Source-to-axis distance	Yes	Based on air-fluence measurements (commissioning)
d_1	Gy/min	Parameter relating dark current to output	Yes	Calculation based on equation 7 [3]
d_2	(Gy/min)/(cGy/MU)	Parameter relating dark current to output	Yes	Calculation based on equation 7 [4]

MU calculation model



Validation of MU calculation model



Conforming to target / field-specific aperture

brass aperture

- milled brass aperture
- poured cerrobend aperture

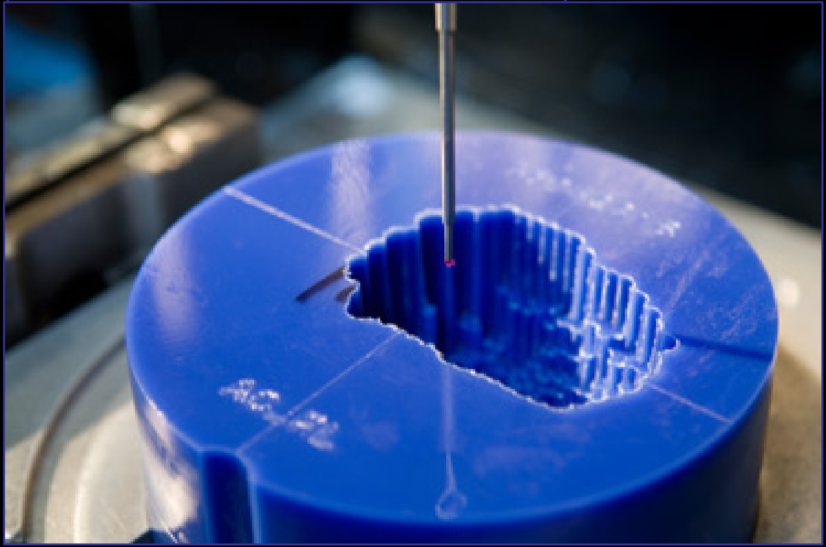
cerrobend aperture

Photos courtesy MGH / LLUMC

Conforming to target / field-specific range compensator

Lucite range compensator

Wax range compensator



Thank You!