UNIVERSITY OF FLORIDA
PROTON THERAPY
INSTITUTE

Proton Beam Delivery Techniques and Commissioning Issues:

Scattered Proton Beams

Roelf Slopsema

19 May 2008 – PTCOG Educational Workshop

slopsema@ufl.edu

Disclaimer

- the manufacturer of the UFPTI system is IBA
- I personally have worked for IBA

Learning objectives

After this presentation you…

I. know the basic elements of different proton scattering systems

II. understand the basic dosimetric properties of a proton double scattering system

III. have learned a method of setting up a commissioning plan for a scattering system

Part I

Introduction to scattering delivery techniques

<u>passive scattering</u>

- single scattering
- double scattering
  - block / annulus
  - contoured scatterer

<u>active scanning</u>

- uniform scanning *(wobbling)*
- spot scanning
- continuous scanning

spread the beam laterally

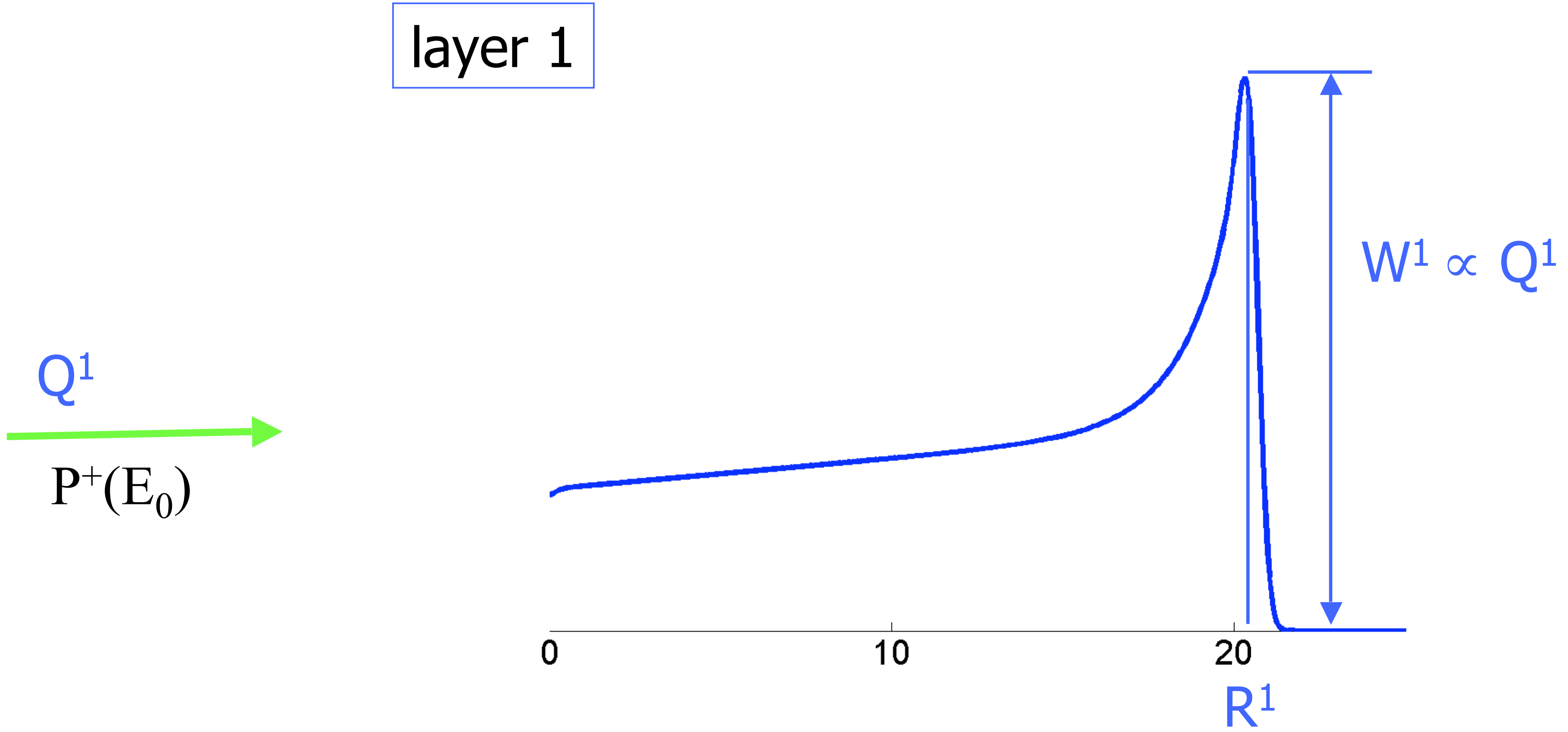
> “creation of the spread-out Bragg peak (SOBP) by adding pulled-back pristine peaks with appropriate weight”

- variable range shifters *energy stacking*
- rotating modulator wheel
- ridge filter

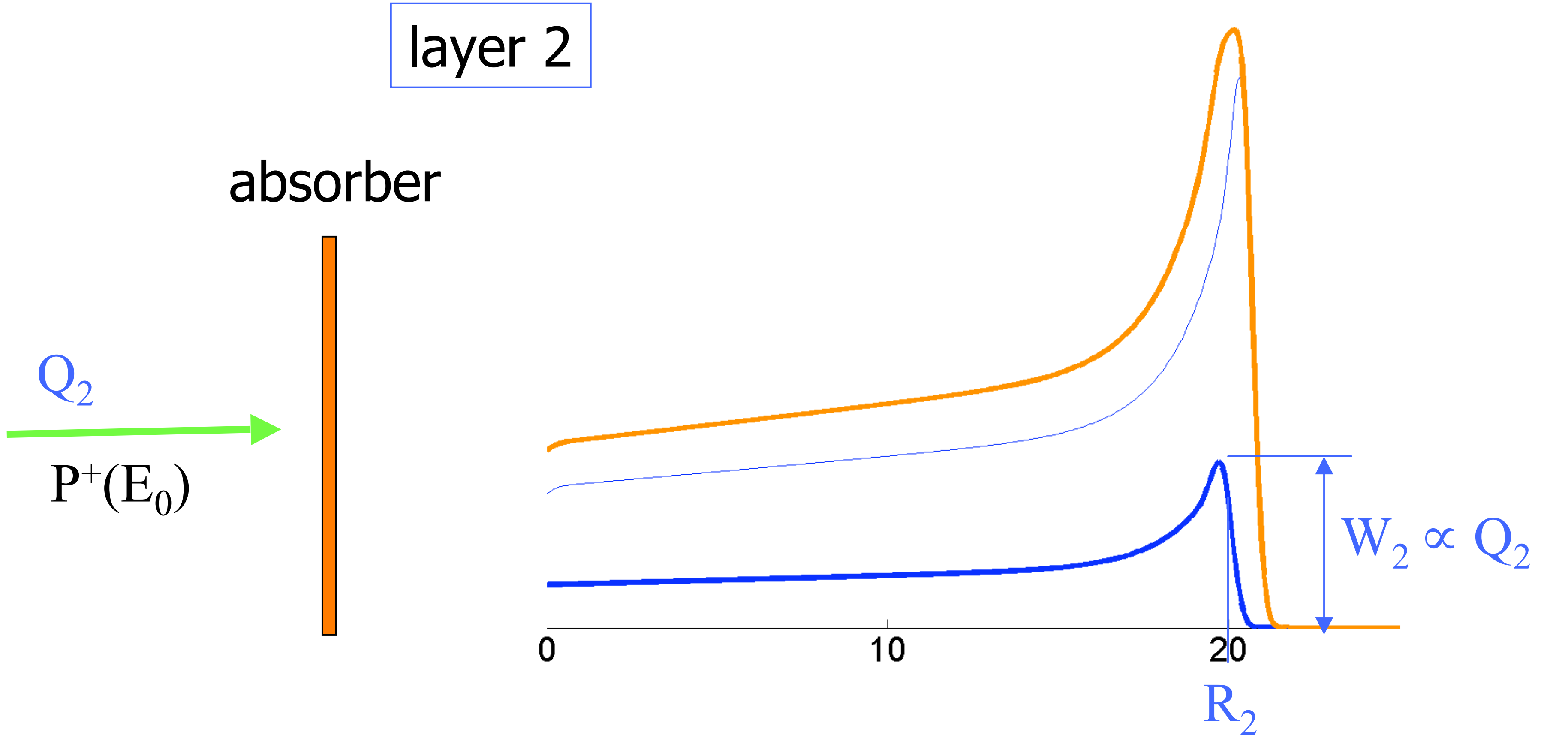
- spread the beam laterally
- modulate beam in depth

- aperture
  → conforming dose in lateral plane
- range compensator
  → conforming dose in depth

Range modulation / variable range shifter



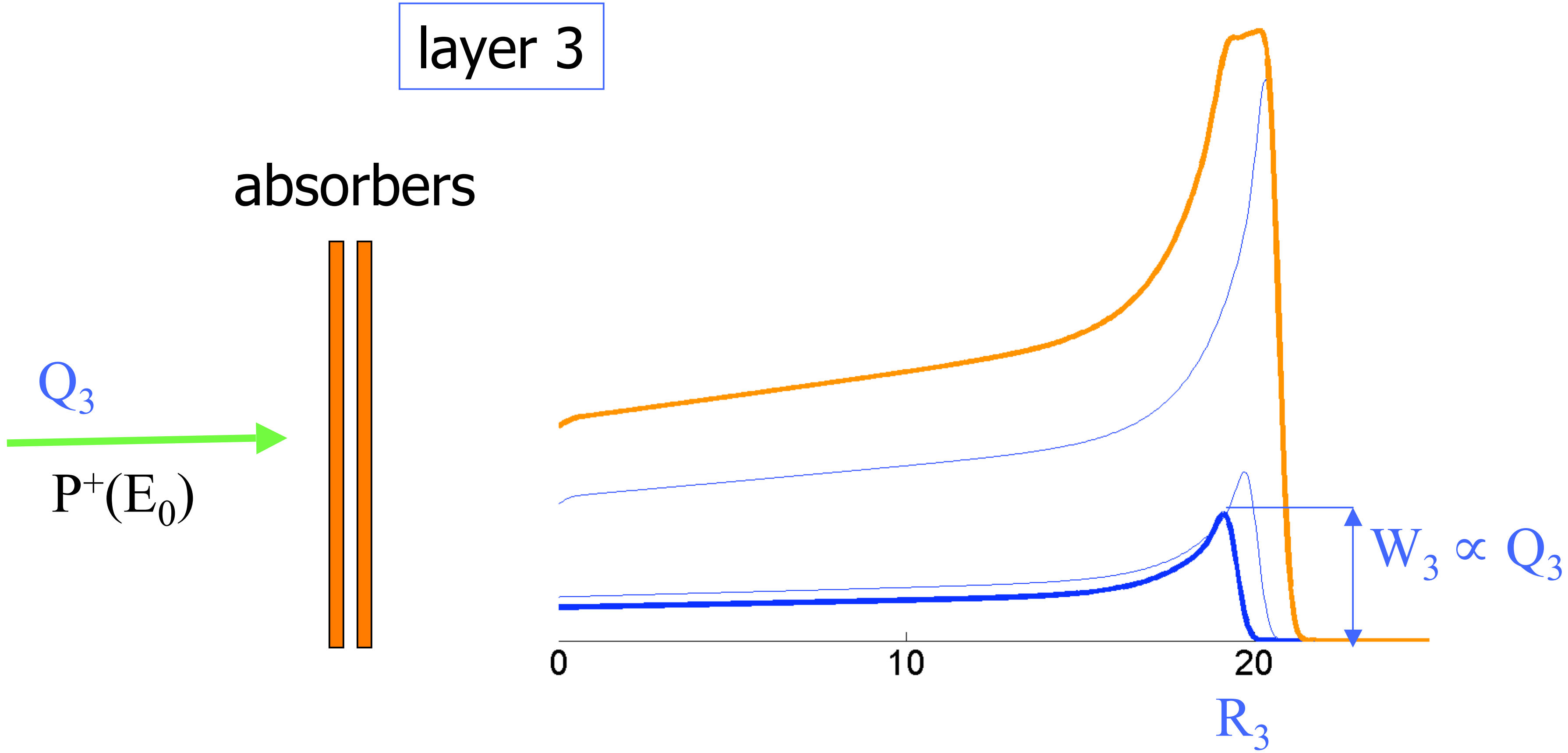
Range modulation / variable range shifter



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

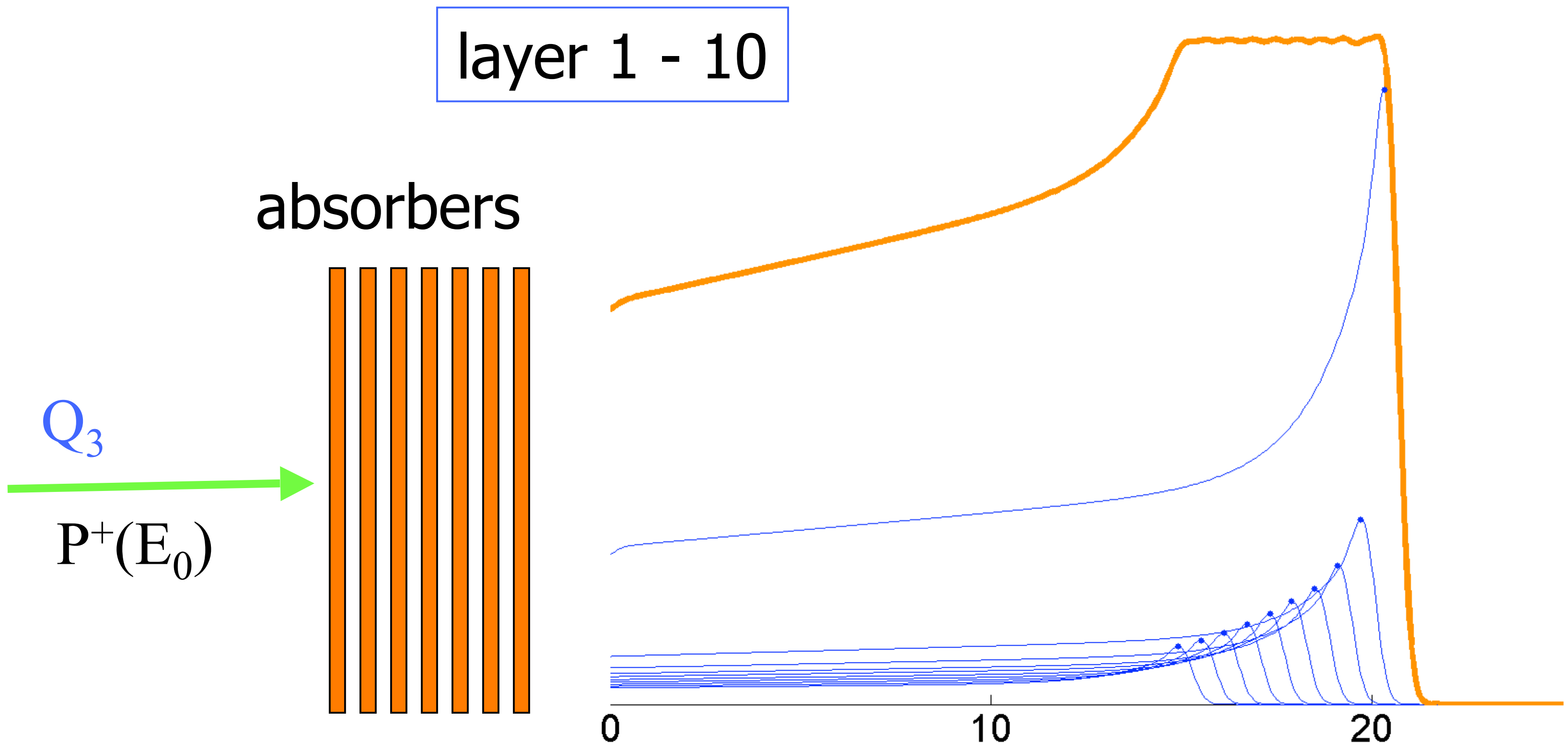
Range modulation / variable range shifter



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 / variable range shifter

- energy shifting at nozzle entrance
  - (synchrotron)
  - upstream energy-selection system (cyclotron)

- variable water column

- binary filter

- double-wedge variable absorber

Made of 'water-like' material (lucite, carbon, …), not perturbing shape pristine peak too much

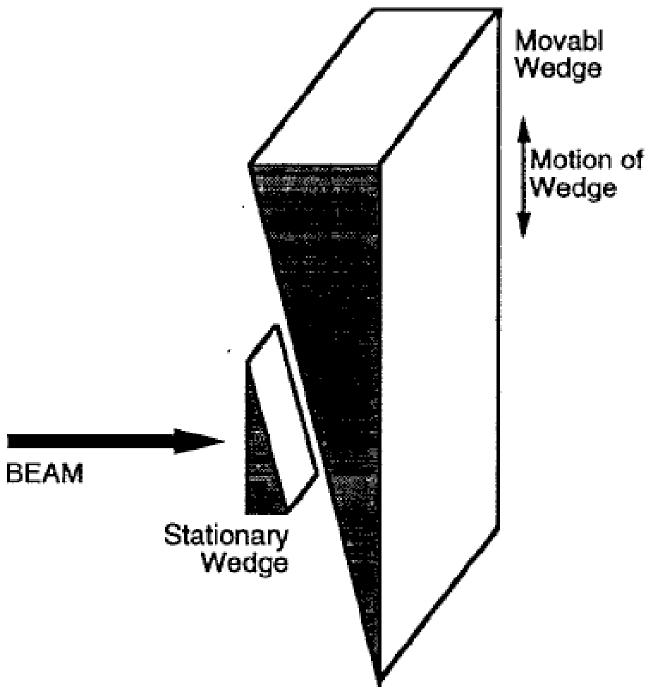
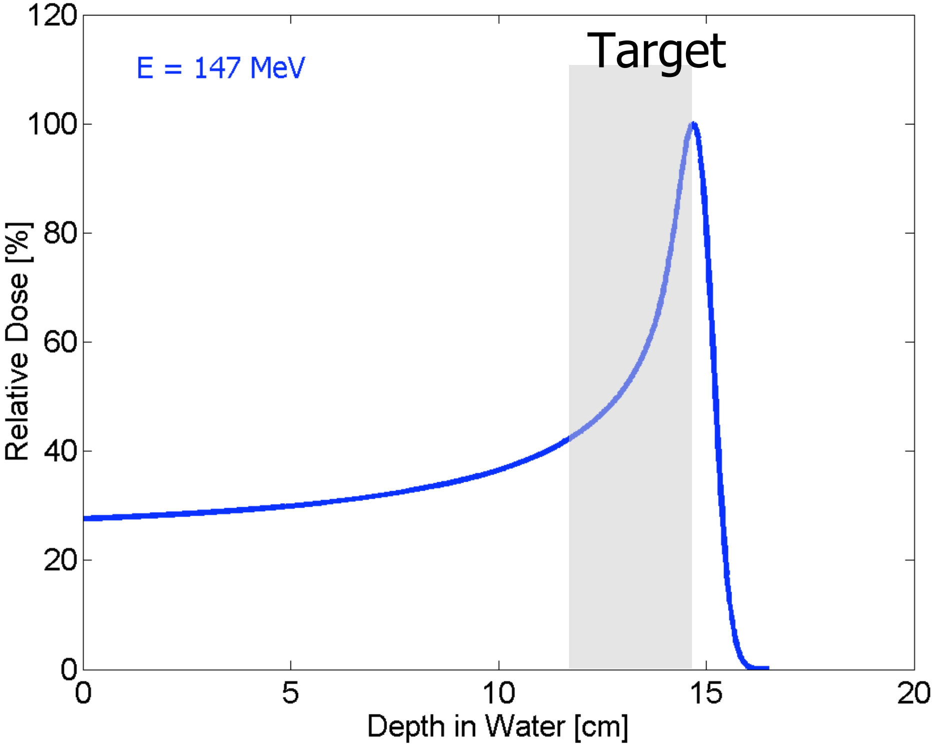
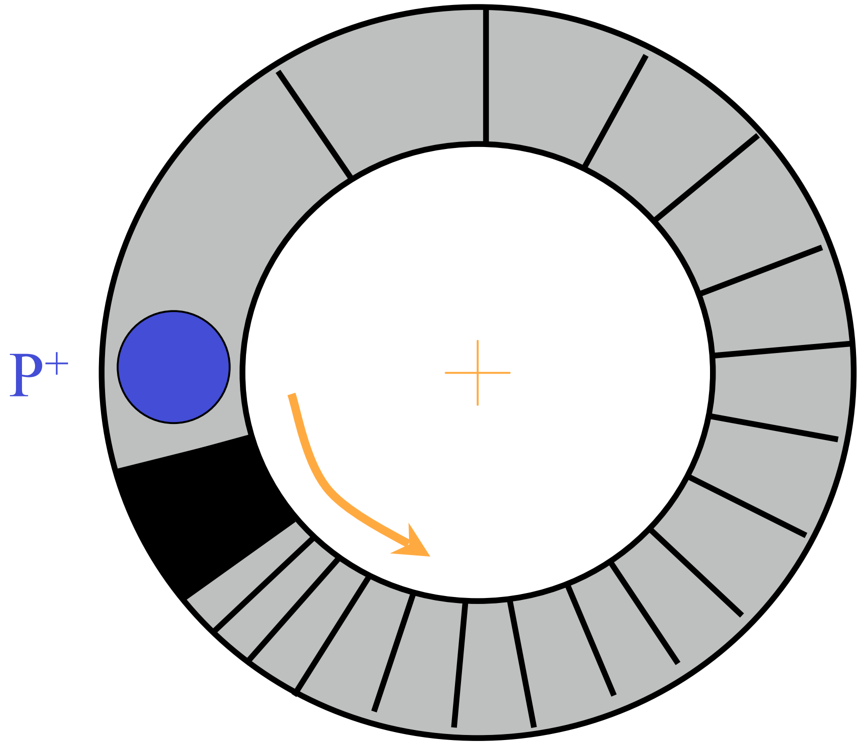


FIG. 18. Schematics of a double wedge system which is used to shift the range of the beam.

Diagram: Chu '93

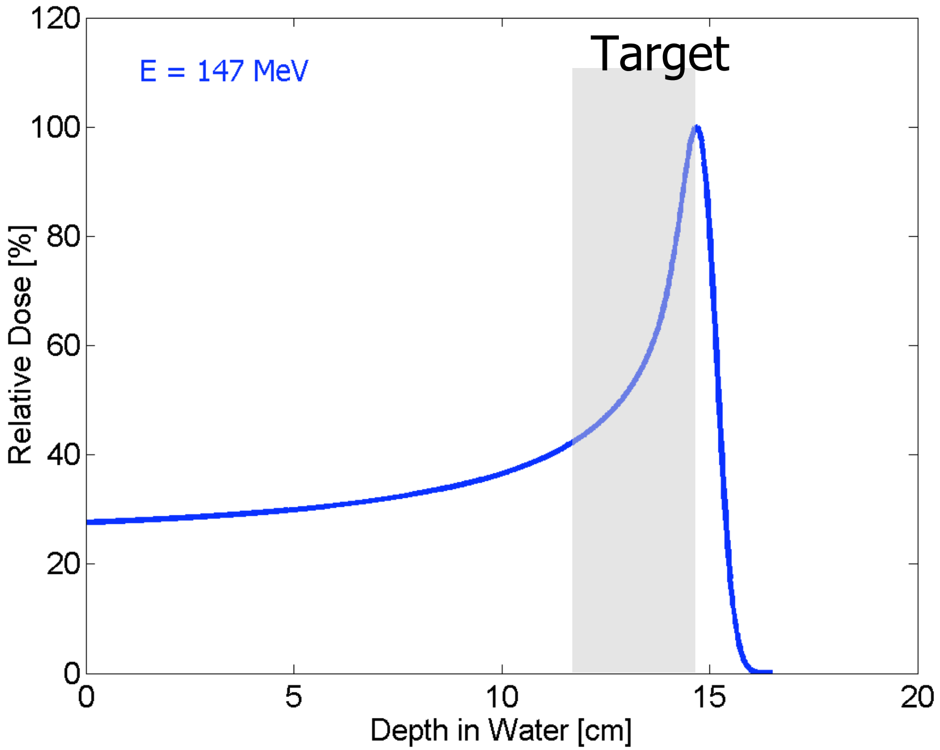
Range modulation / RM wheel

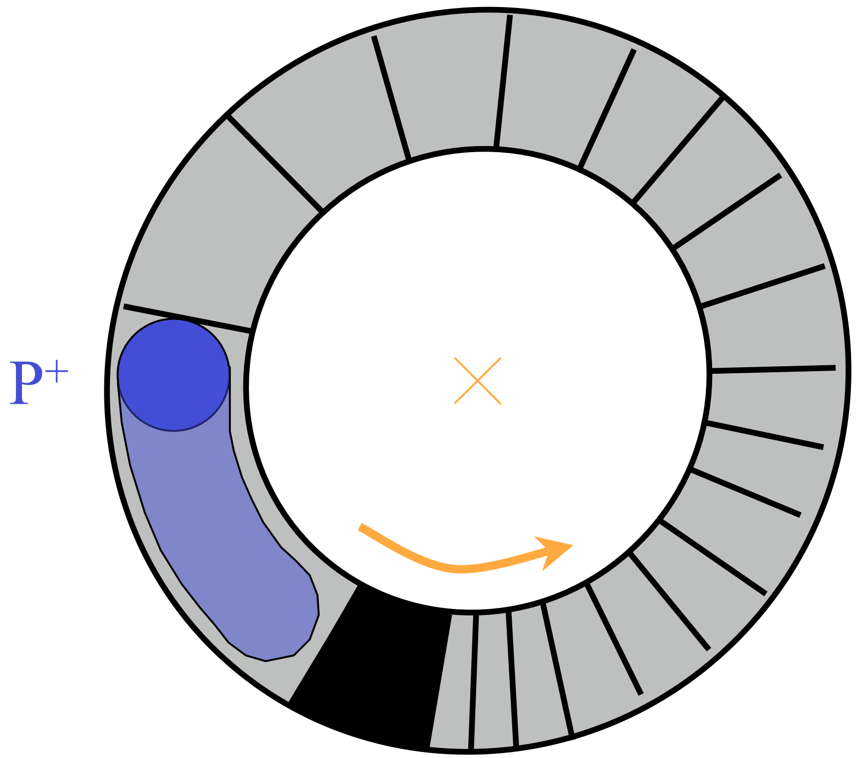




Step#	thickness	angular width
1	1.8 cm.H20	76 deg
2	2.3 cm.H20	27 deg
3	2.9 cm.H20	20 deg
4	3.4 cm.H20	14 deg
5	4.0 cm.H20	11 deg

Range modulation / RM wheel





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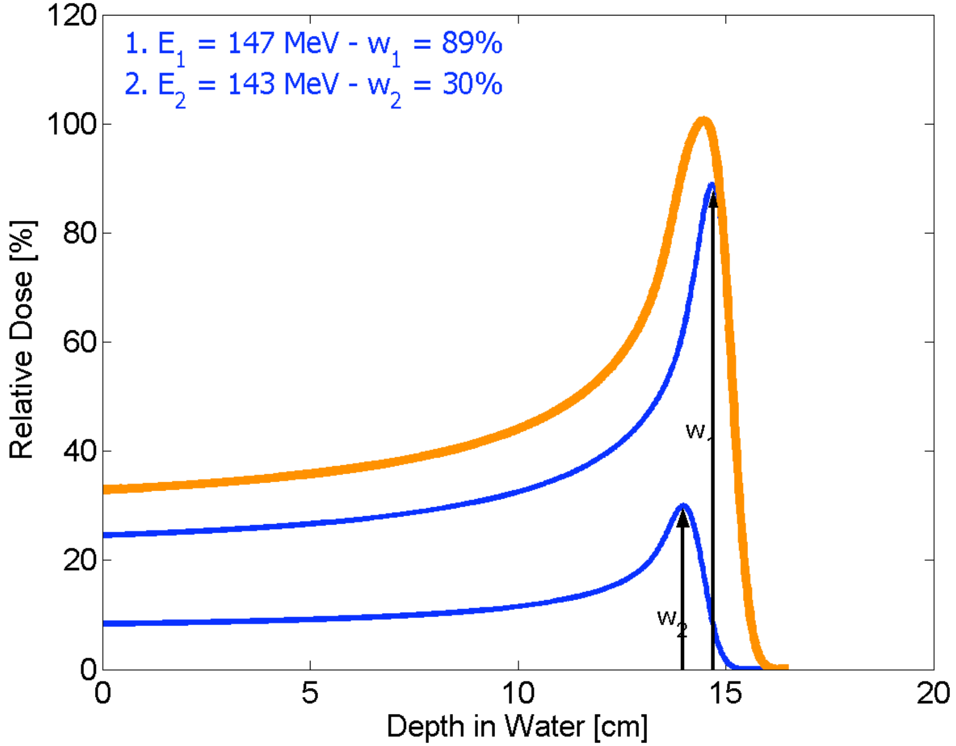

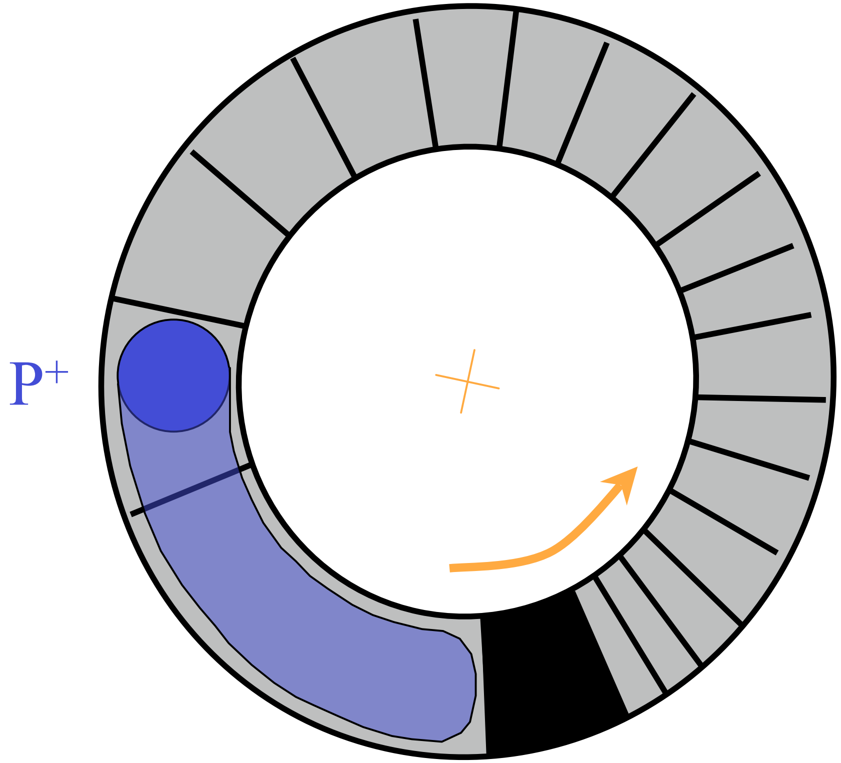

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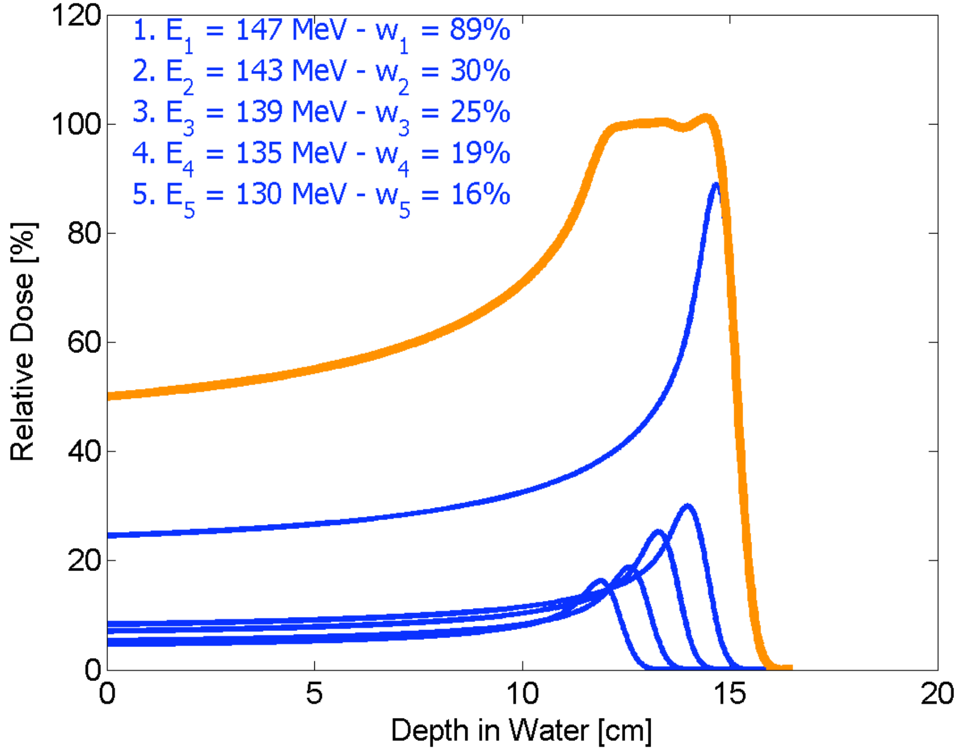

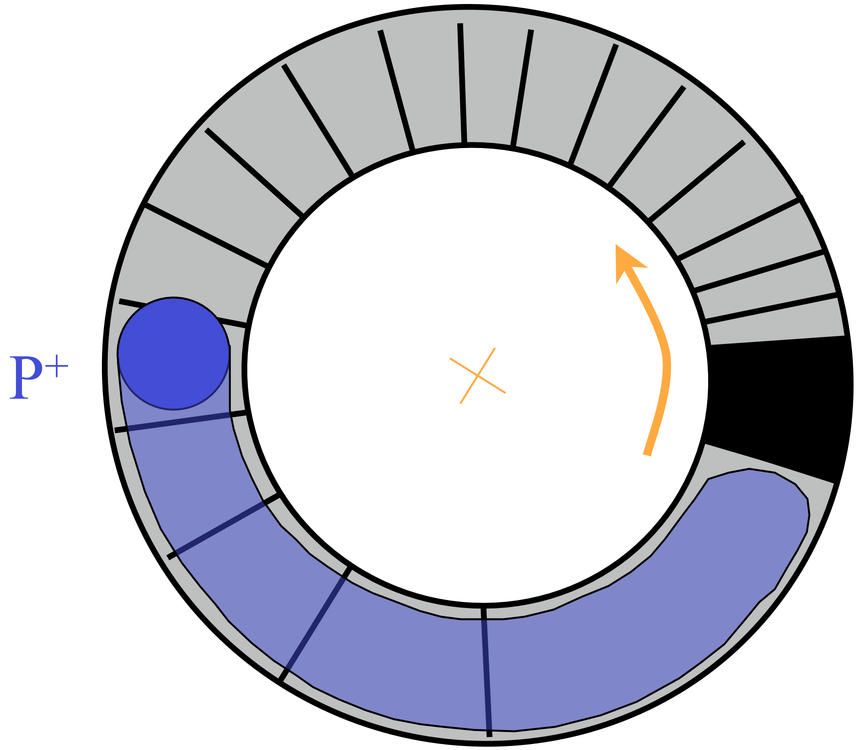

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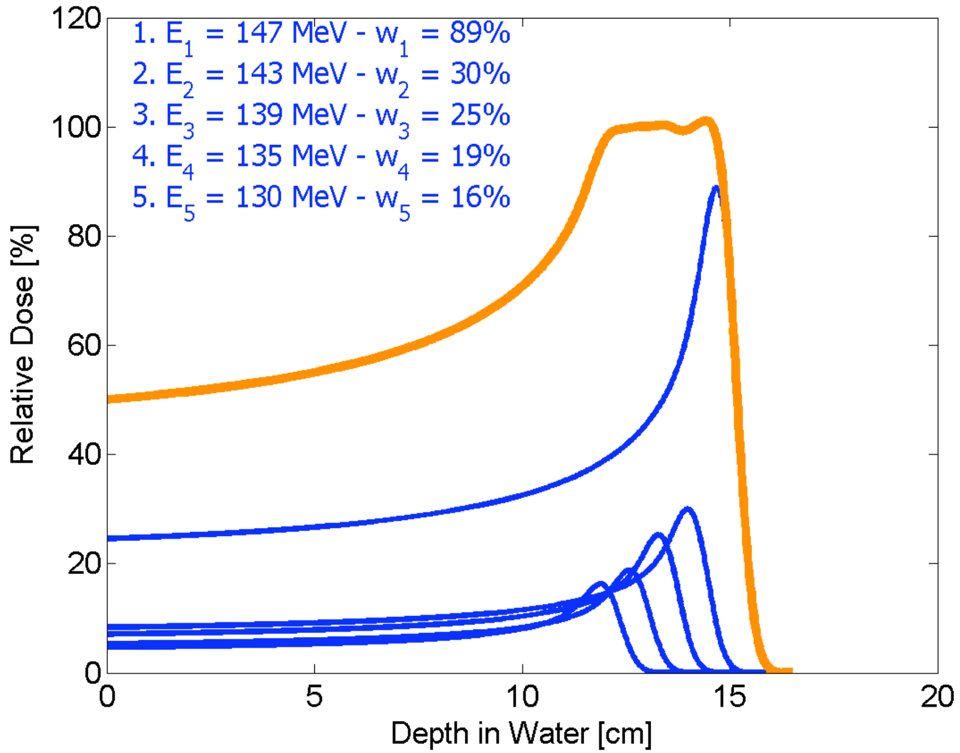

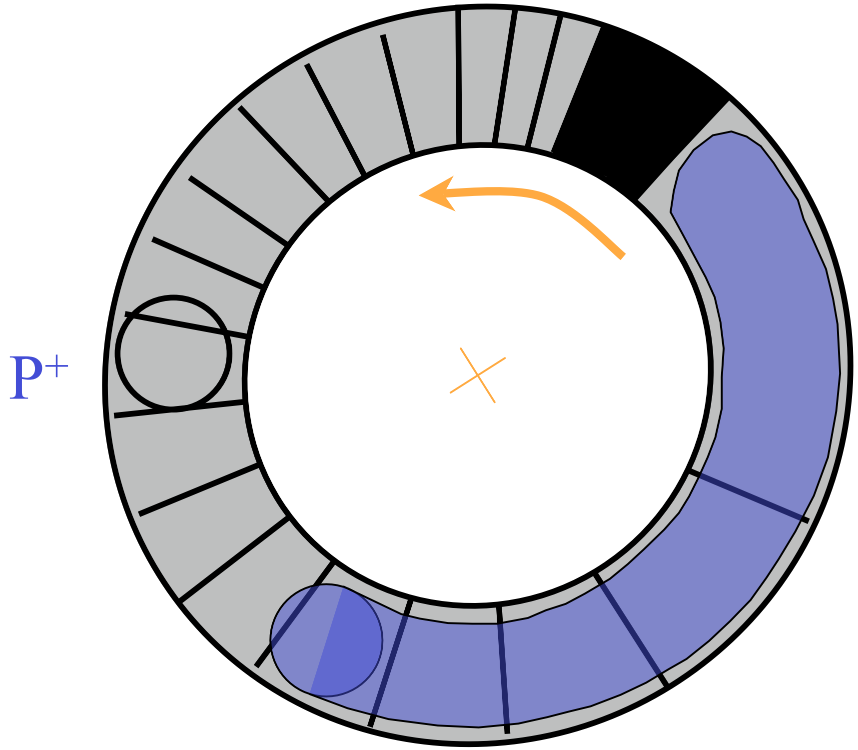

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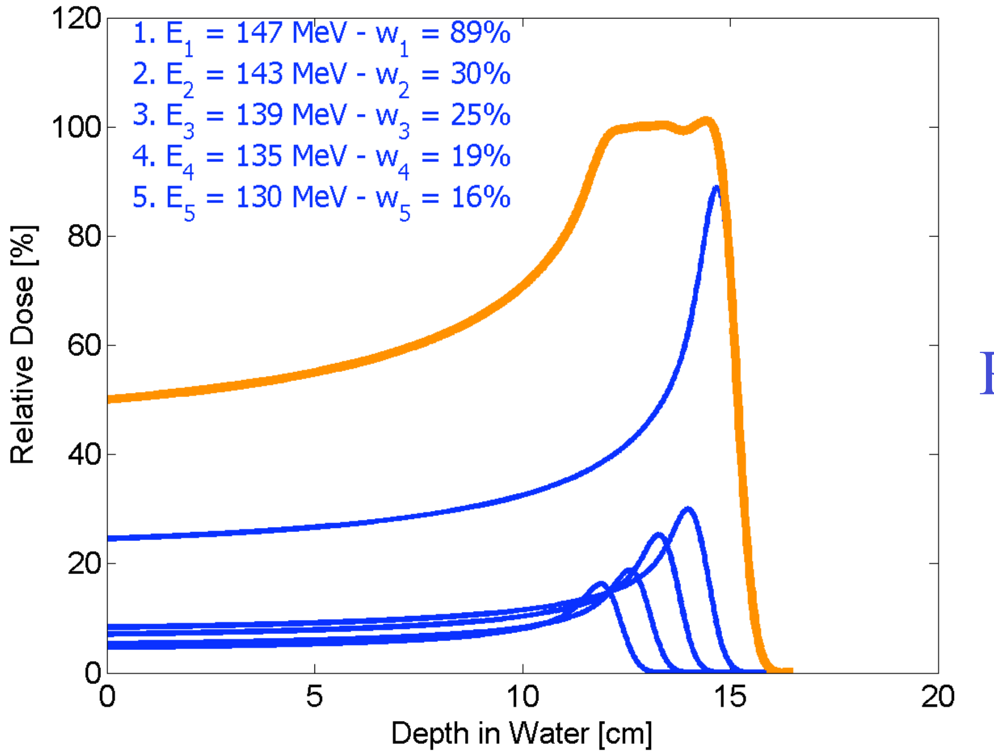

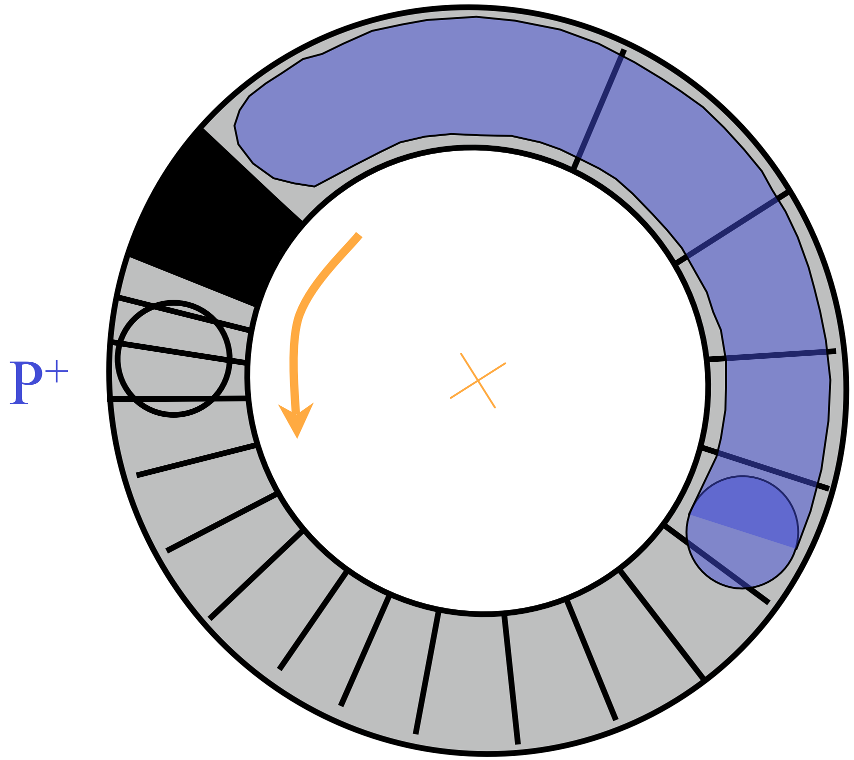

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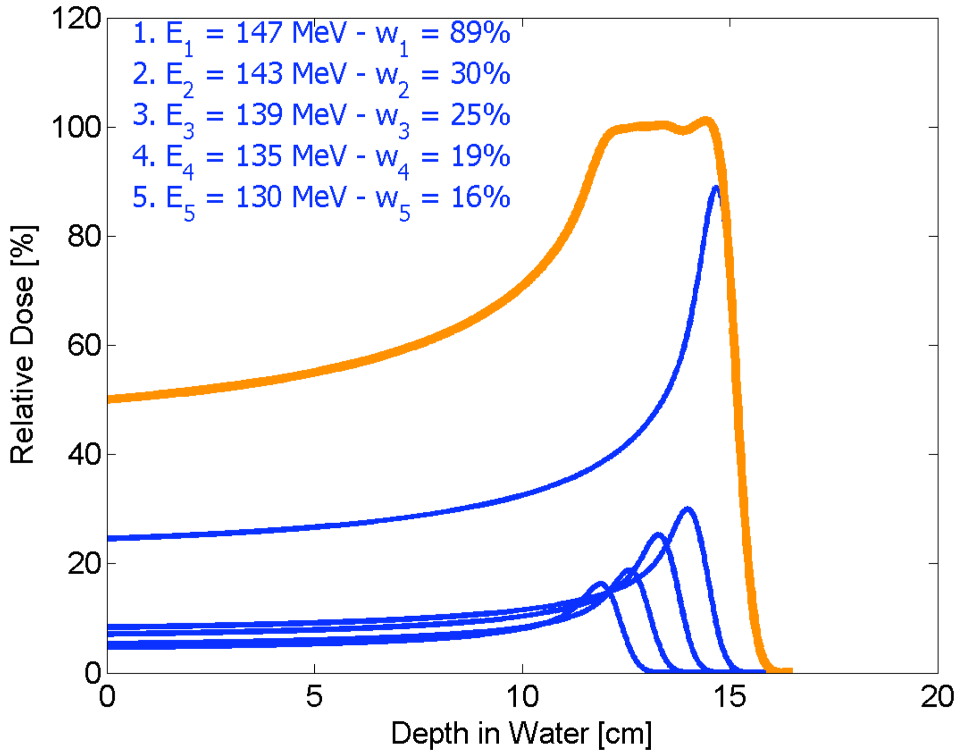

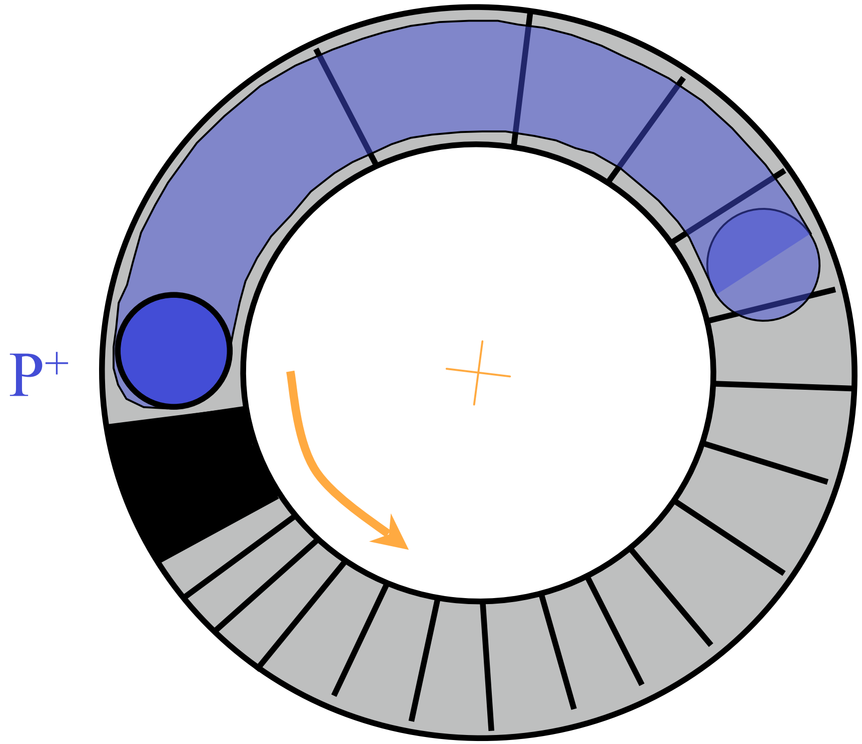

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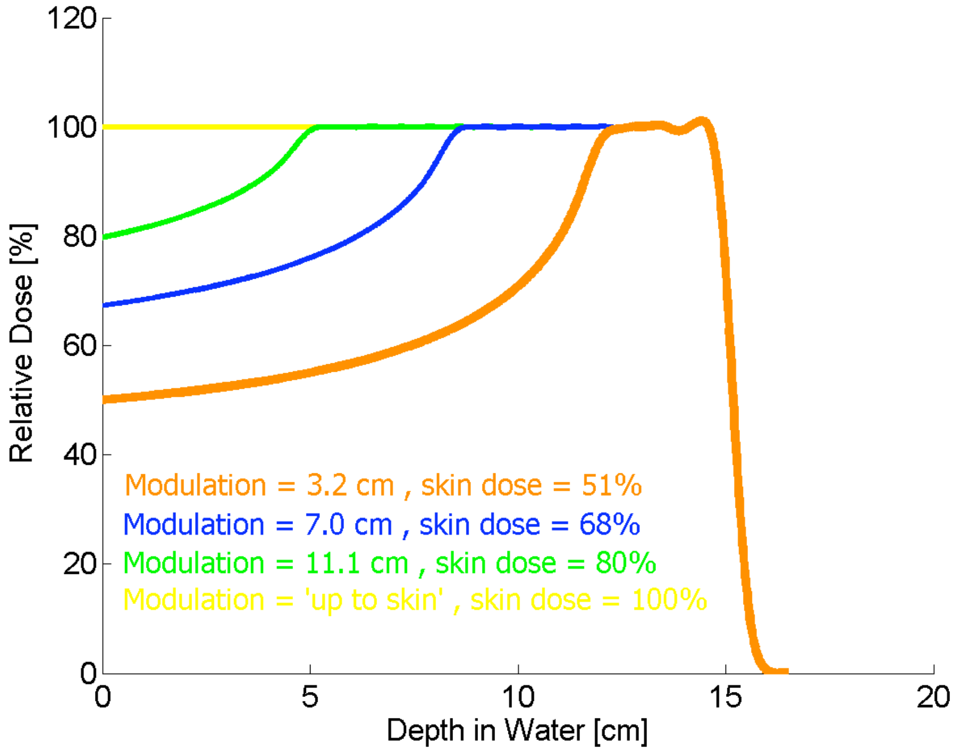
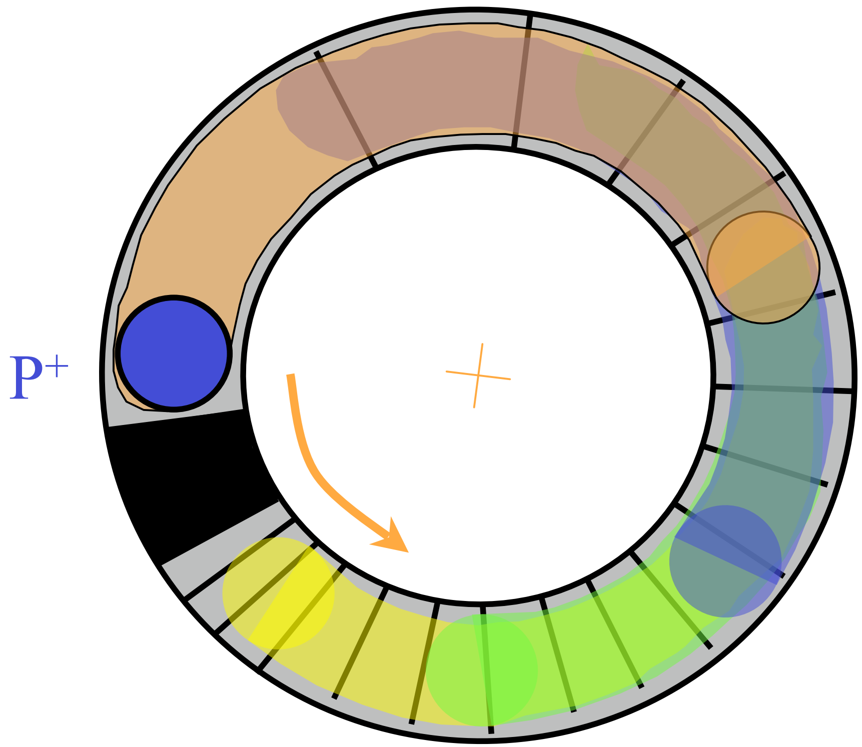
Range modulation / RM wheel

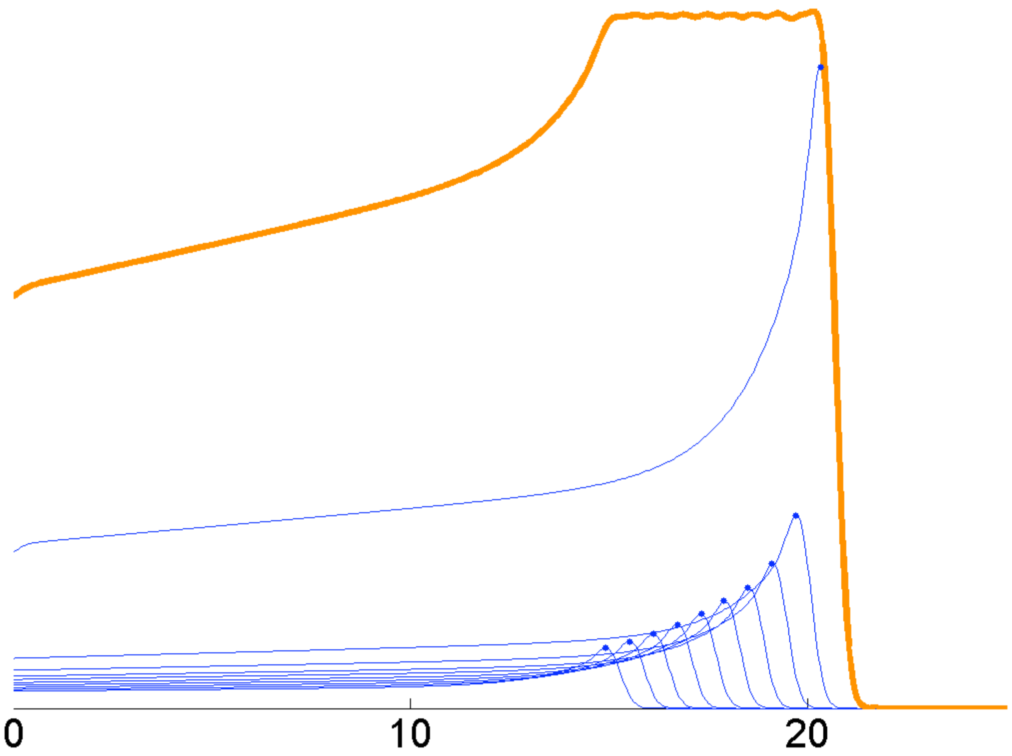




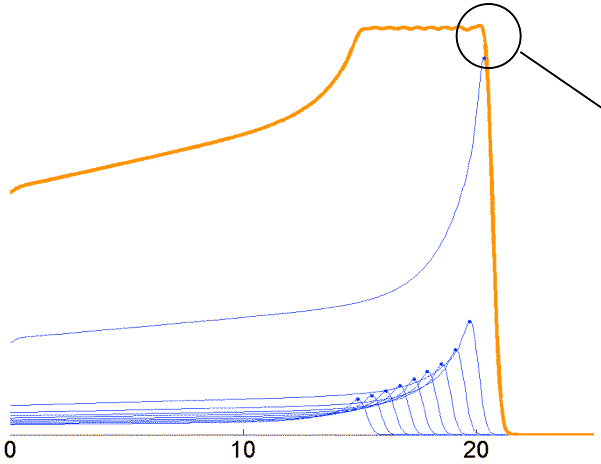
Field#	Modulation	stop angle
1	3.2 cm.H20	170 deg
2	7.0 cm.H20	250 deg
3	11.1 cm.H20	316 deg
4	"full"	360 deg

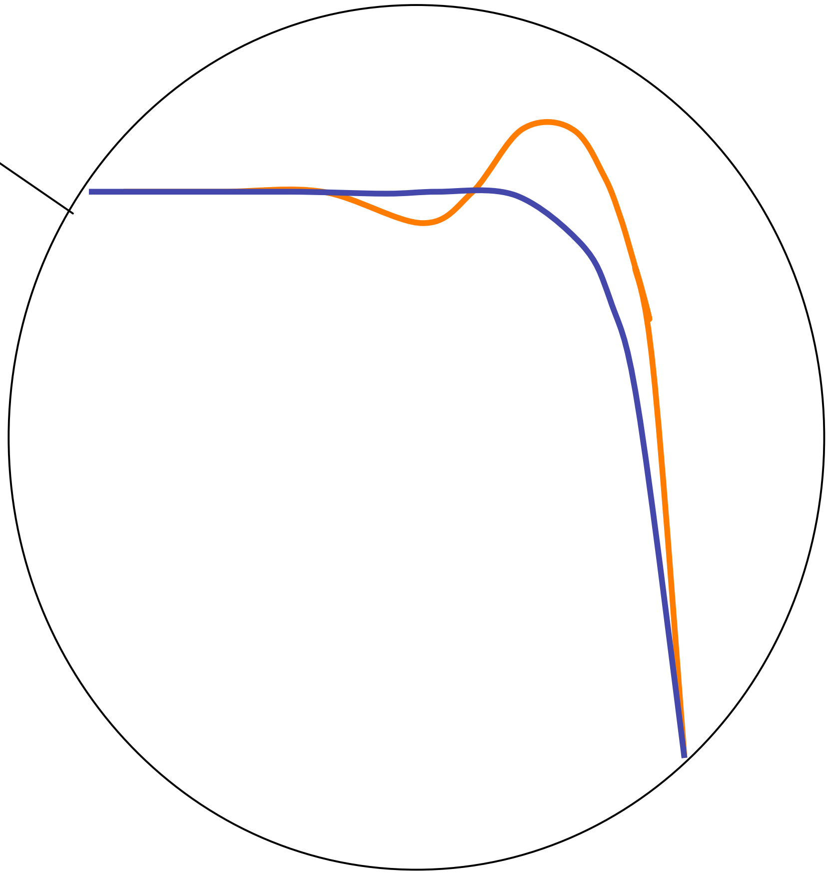
Range modulation / weight optimization

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



Range modulation / weight optimization





Distal-end optimization

w2 ↓ : 'shoulder'

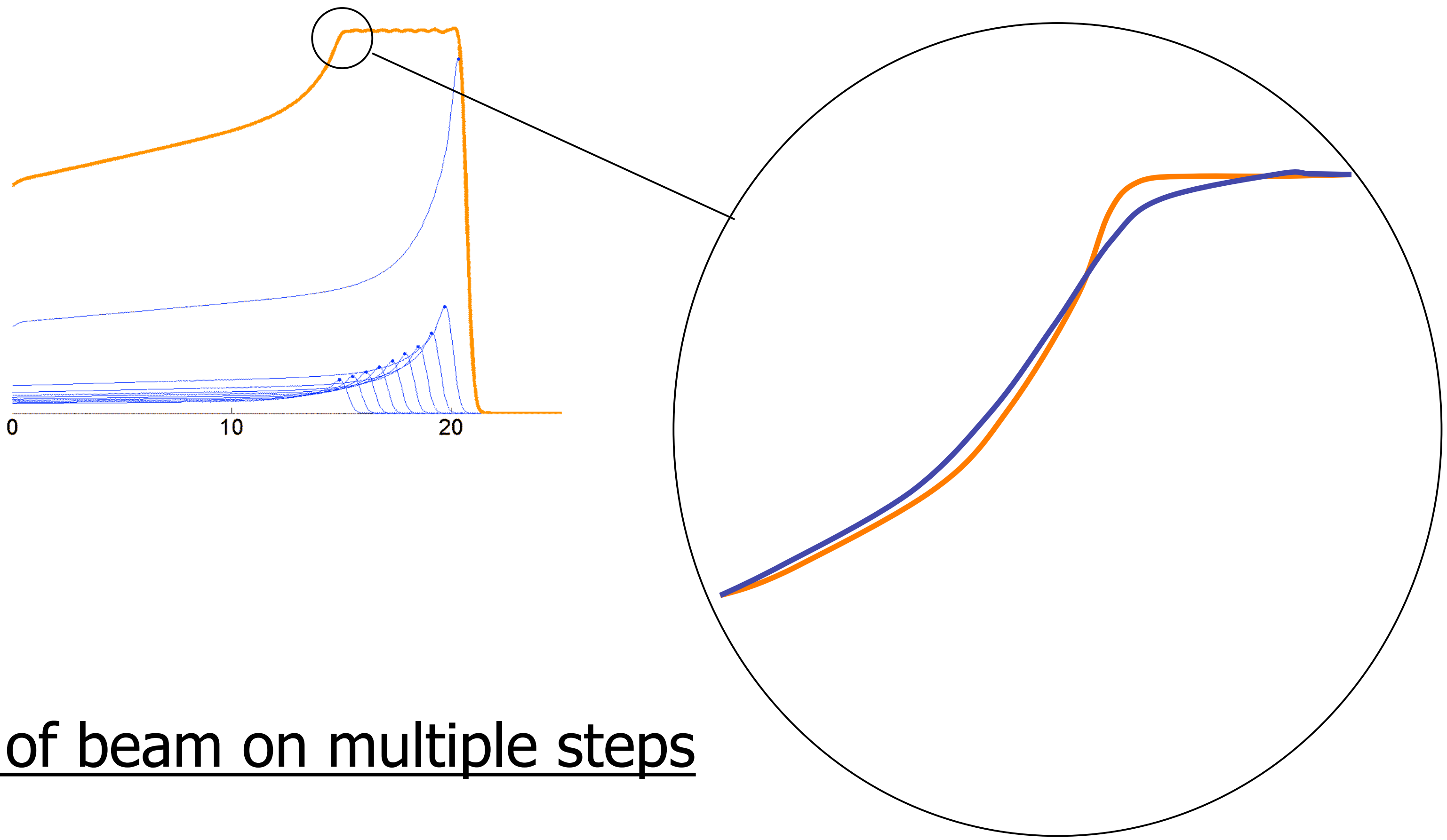
→ better uniformity

w_1 ↑ : 'dip&bump'

→ sharper distal fall-off

…but higher RBE for low energies…

Range modulation / weight optimization



<u>Spilling of beam on multiple steps</u>

Spot size small compared to RM step width

Spot size large compared to RM step width

- 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:

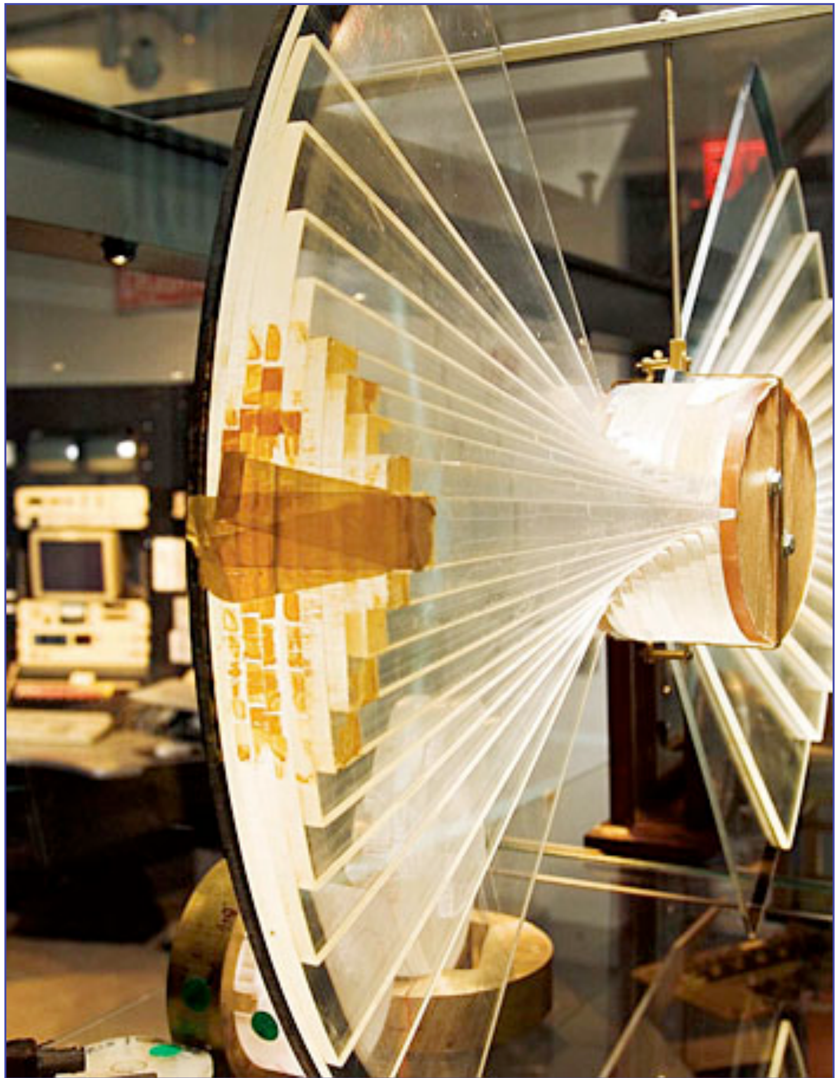
  making scattering power of each step equal by adding high Z material to thinner steps

- rotational speed / multiplication of RM profile:

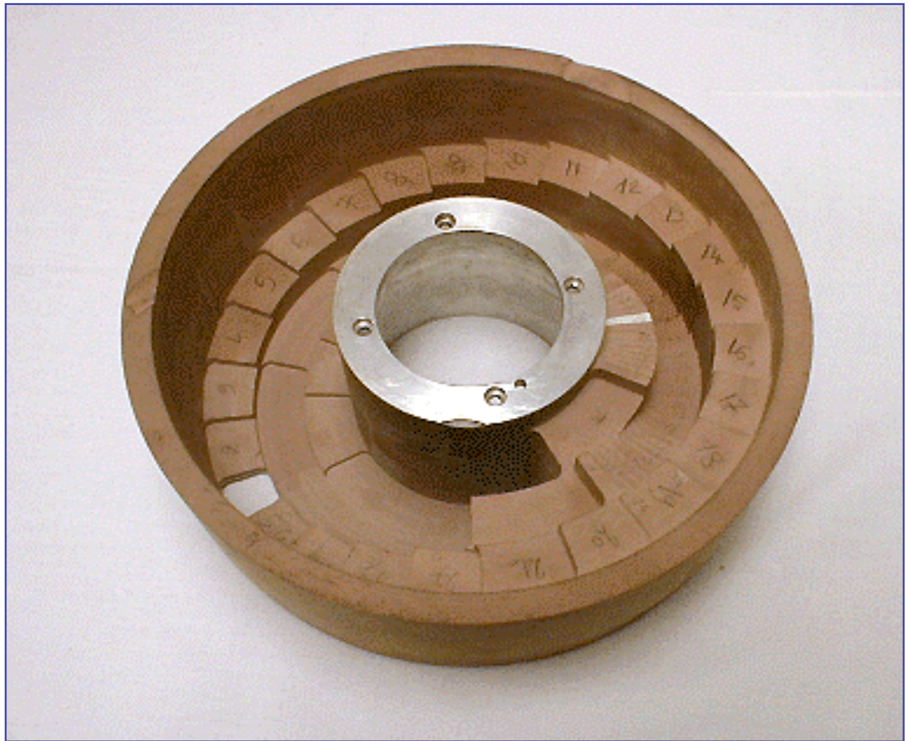
  requirements on frequency are defined by time-structure beam and organ motion

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

Range modulation / RM wheels



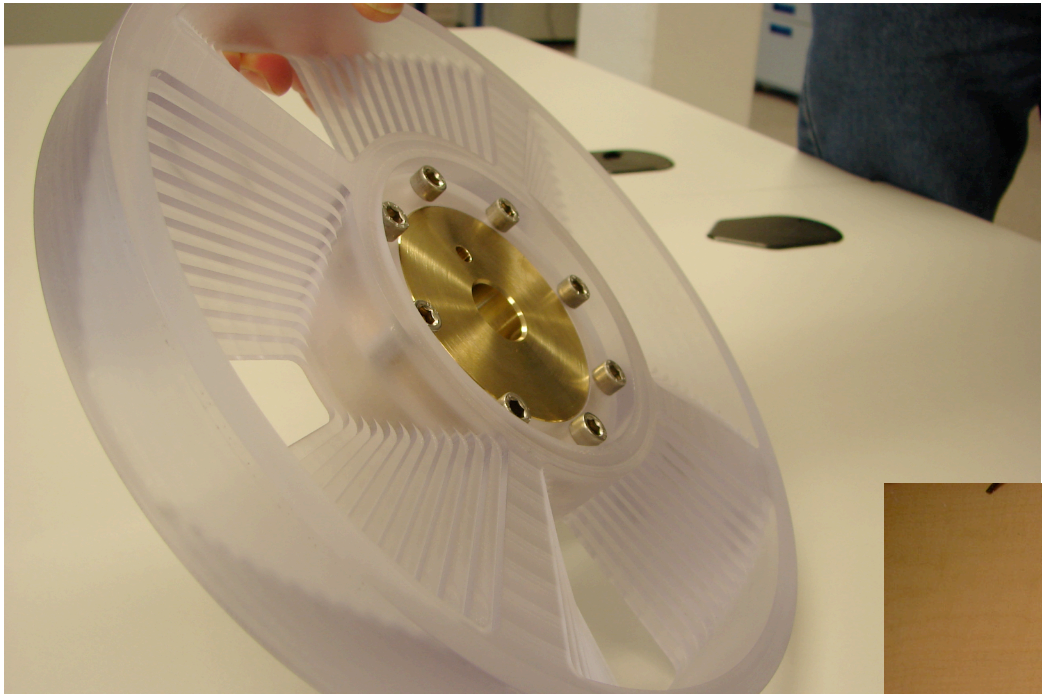
HCL design (single modulation, downstream, 4 repetitions)

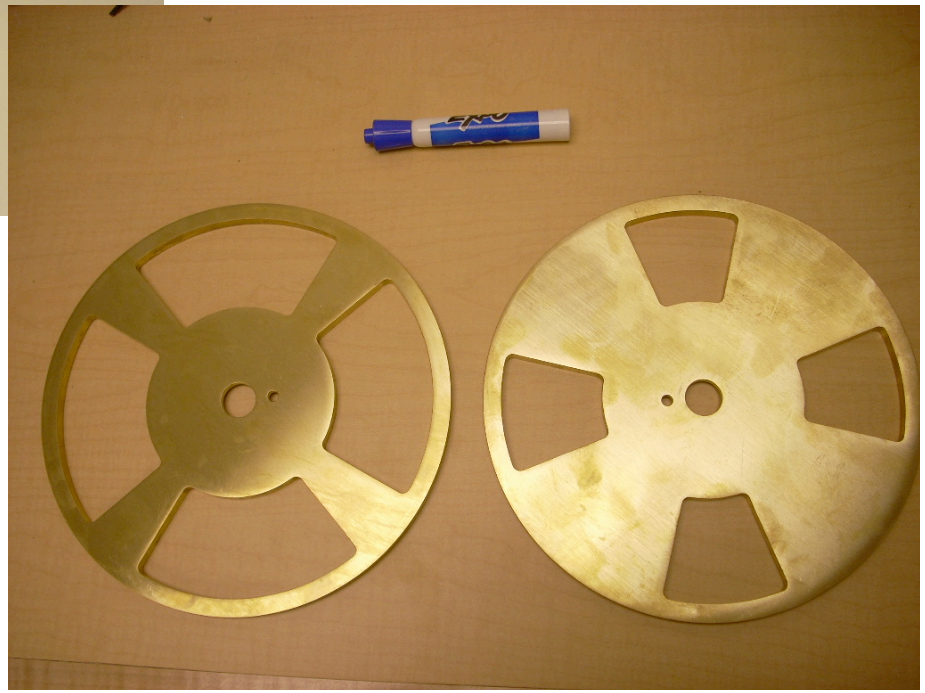


IBA design (3 tracks on single wheel, gating used to adjust modulation)

Photos courtesy MGH / IBA

Range modulation / RM wheels





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

Photos courtesy IBA

Range modulation / ridge filters

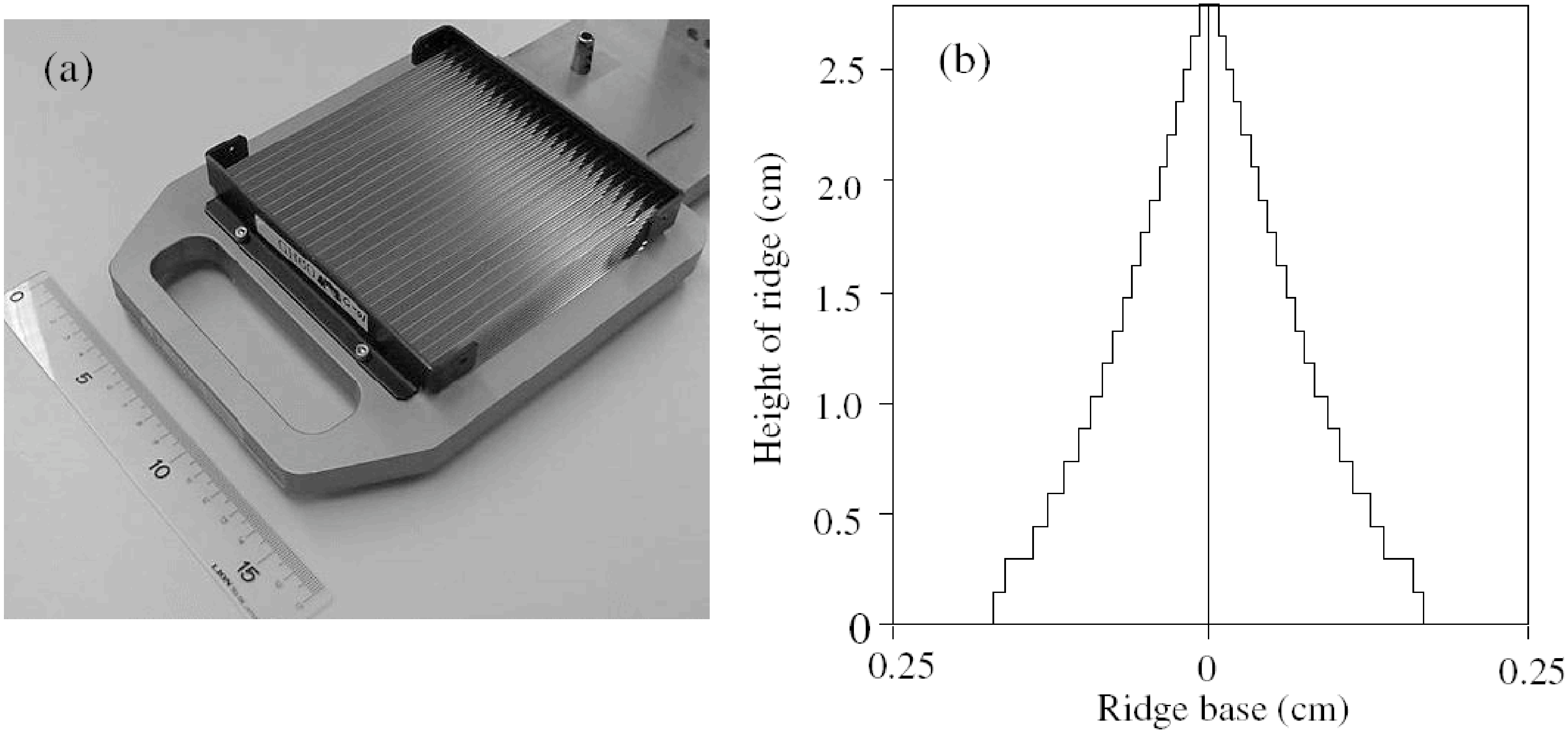


Figure 2. A bar ridge filter for the proton beam in the gantry nozzle (a), the cross-sectional shapes of the ridge for 6 cm SOBP (b).

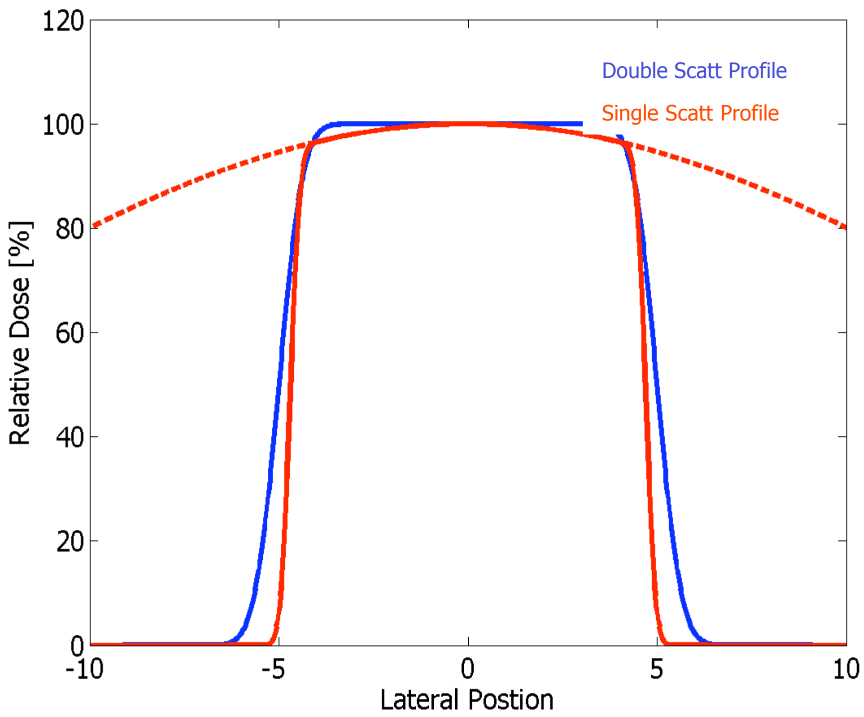
Ridge filter design for proton therapy at Hyogo Ion Beam Medical Center, T.Akagi et al, Phys. Med. Biol. 48 No 22 (21 November 2003) N301-N312

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		

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.



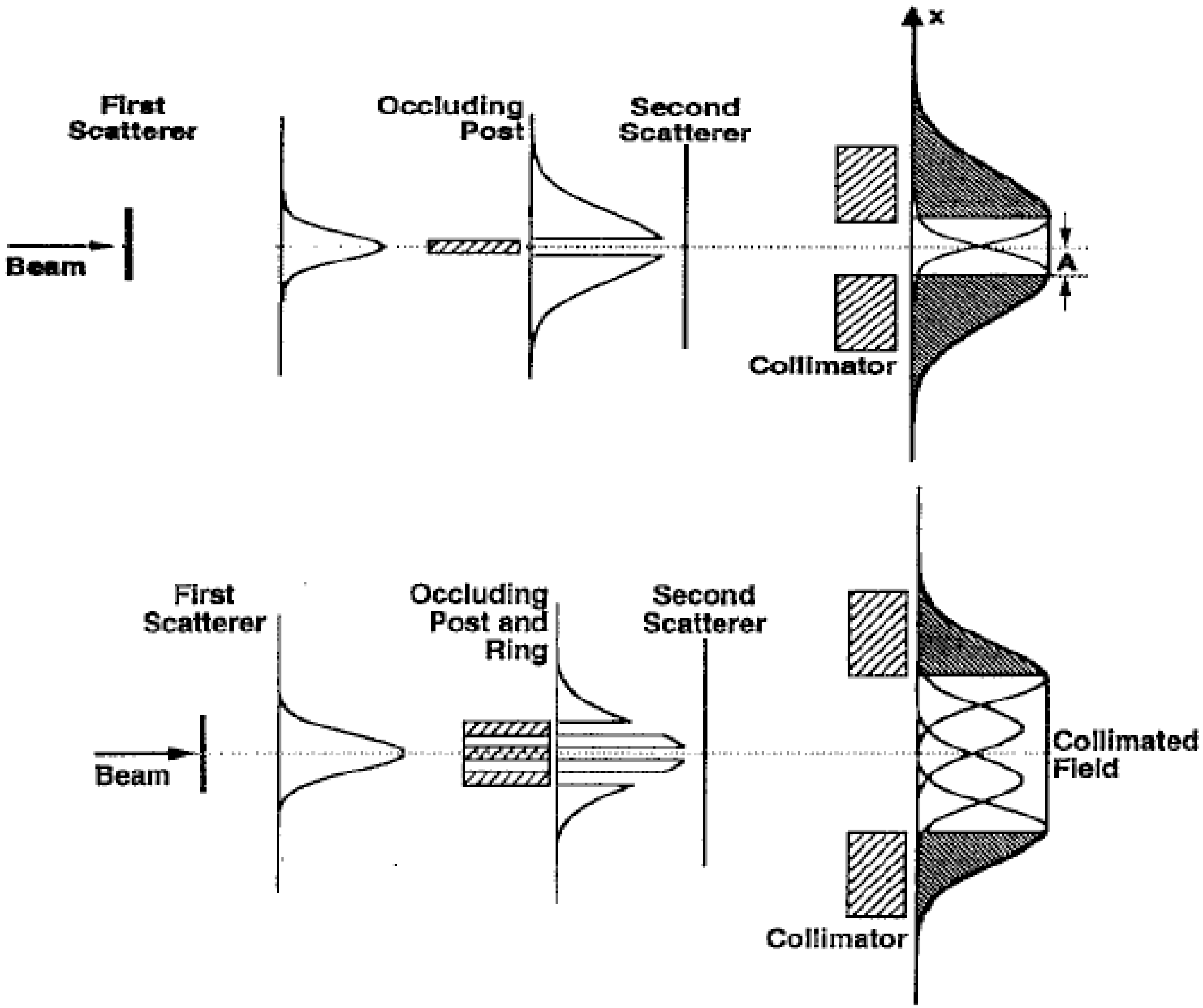
Advantages:

- simple
- sharp lateral fall-off

Disadvantages:

- inefficient
- small field size

Lateral spreading / central block & annulus



Diagrams: Chu '93

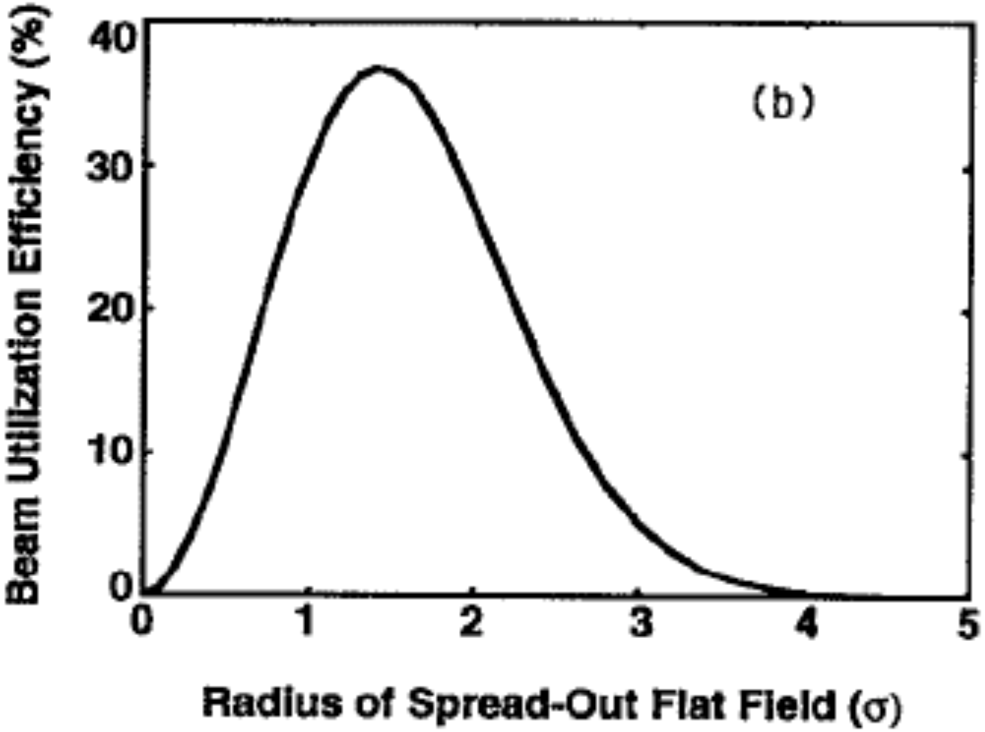
Lateral spreading / central block & annulus

Advantages:

- little energy (range) loss
- more efficient than SS

Disadvantages:

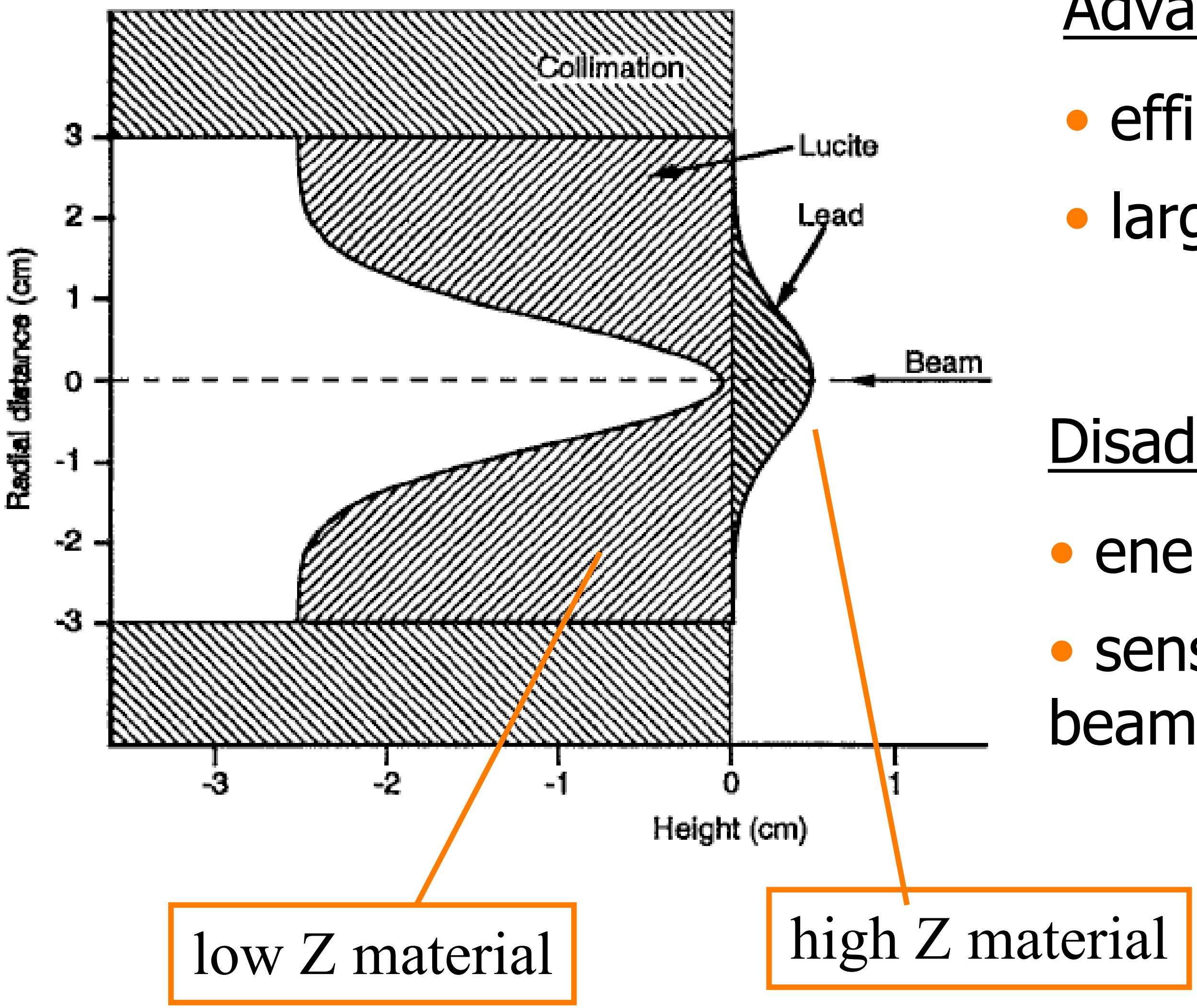
- with increasing field size efficiency reduces
- sensitive to variations beam position



Beam utilization efficiency as a function of the radius of the flat field in units of sigma.

Diagram: Chu '93

Range-compensated contoured scatterer



Advantages:

- efficient
- large field sizes

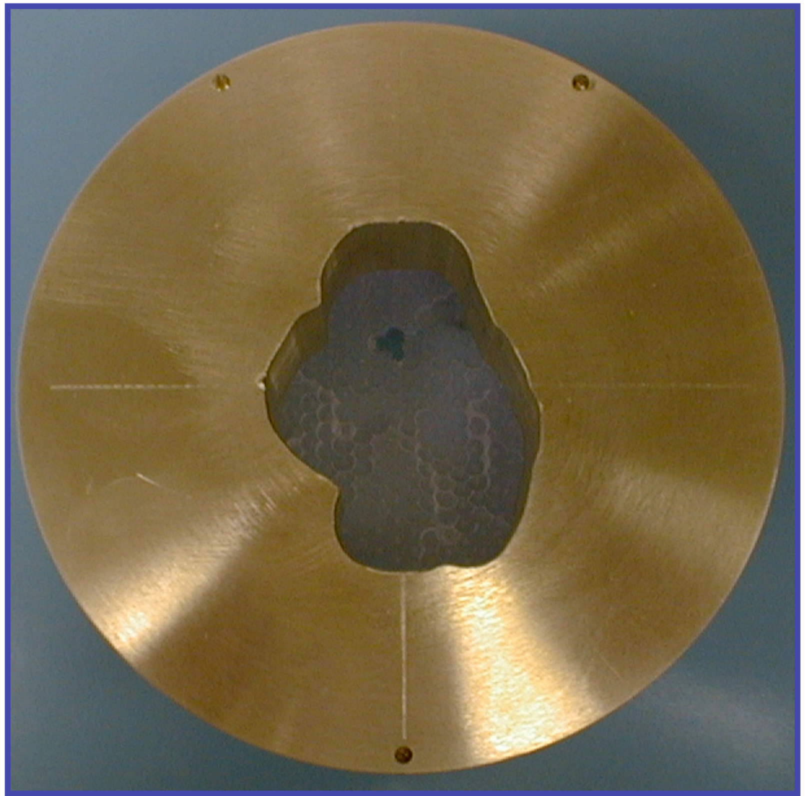
Disadvantages:

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

Diagram: Gottschalk

Conforming to target / field-specific aperture

- milled brass aperture
- poured cerrobend aperture



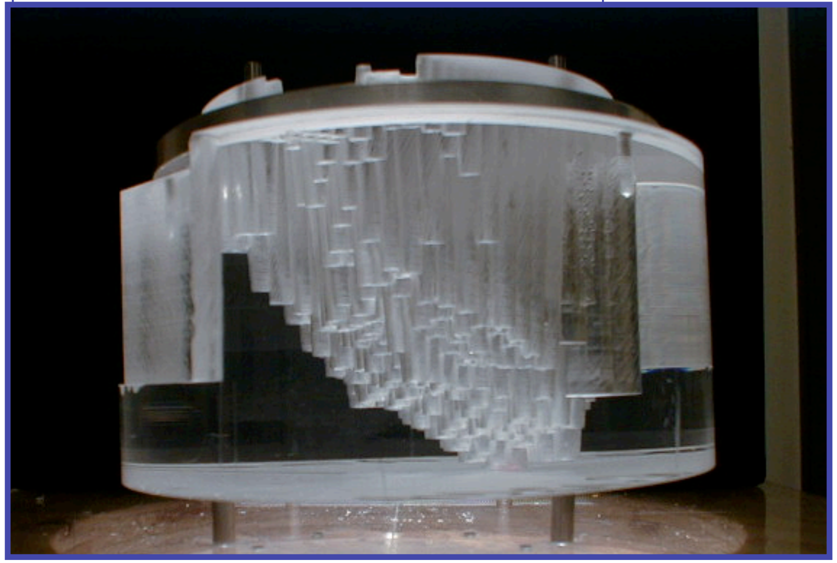
brass aperture

cerrobend aperture

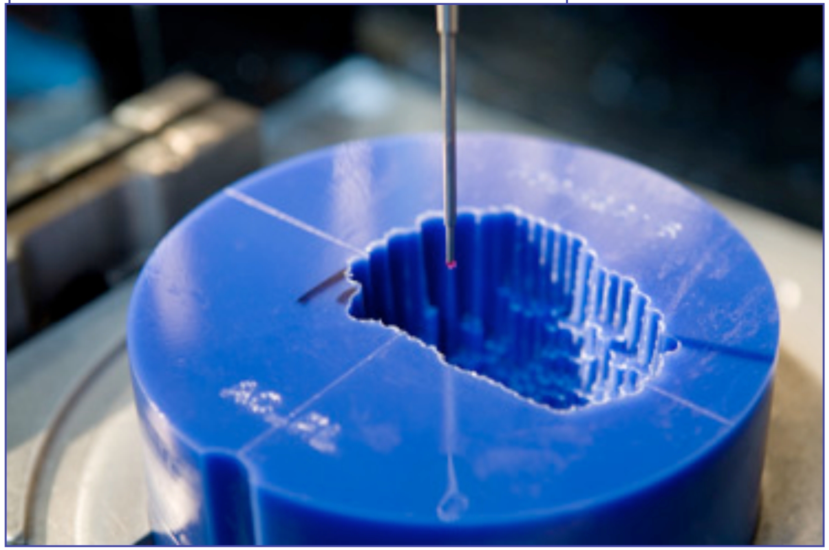
Photos courtesy MGH / LLUMC

Conforming to target / field-specific range compensator

Lucite range compensator



Wax range compensator



Photos courtesy MGH/LLUMC

Conforming to target / field-specific range compensator

RC compensates for:

- shape distal end target
- density variations
- shape body contour

<u>double-sided RC</u>

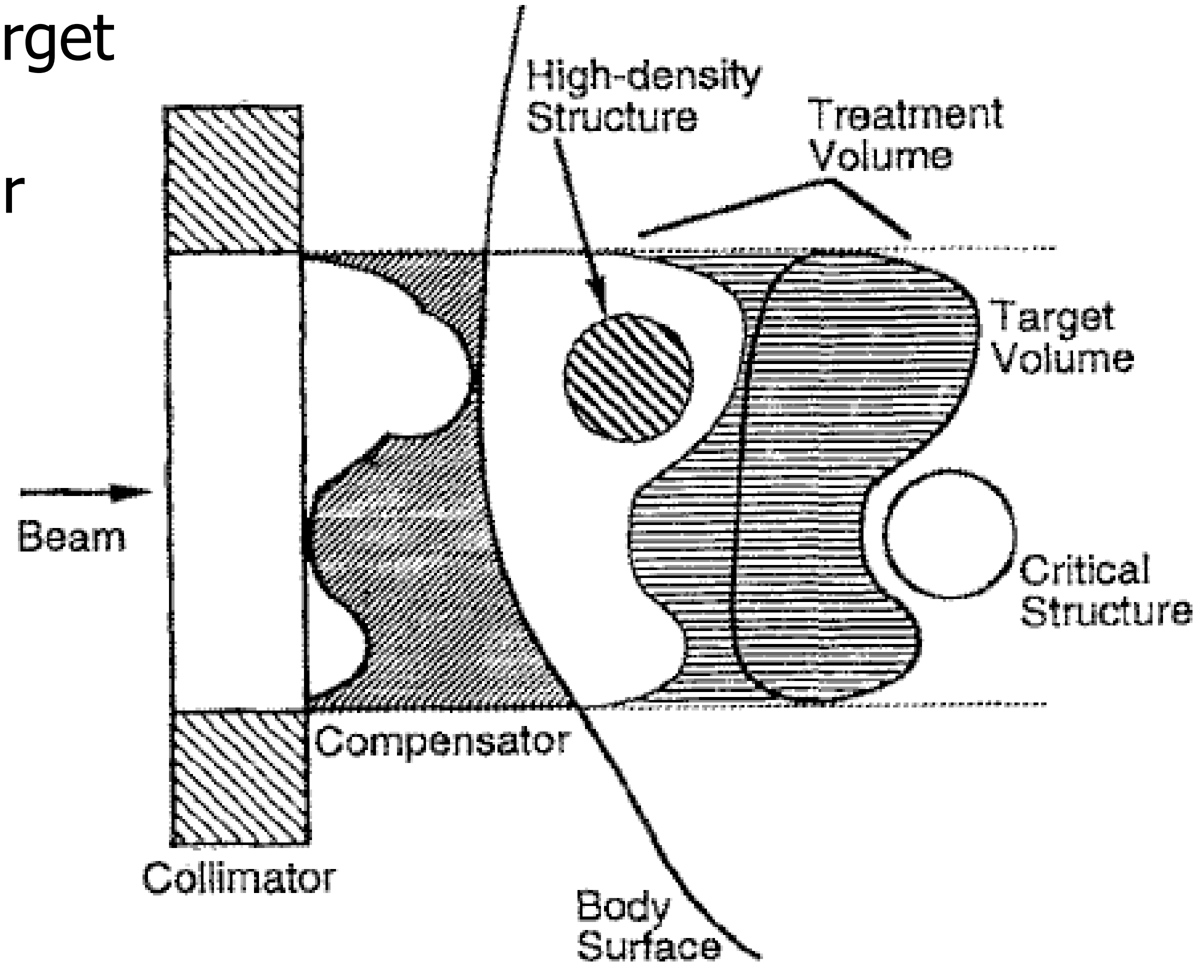
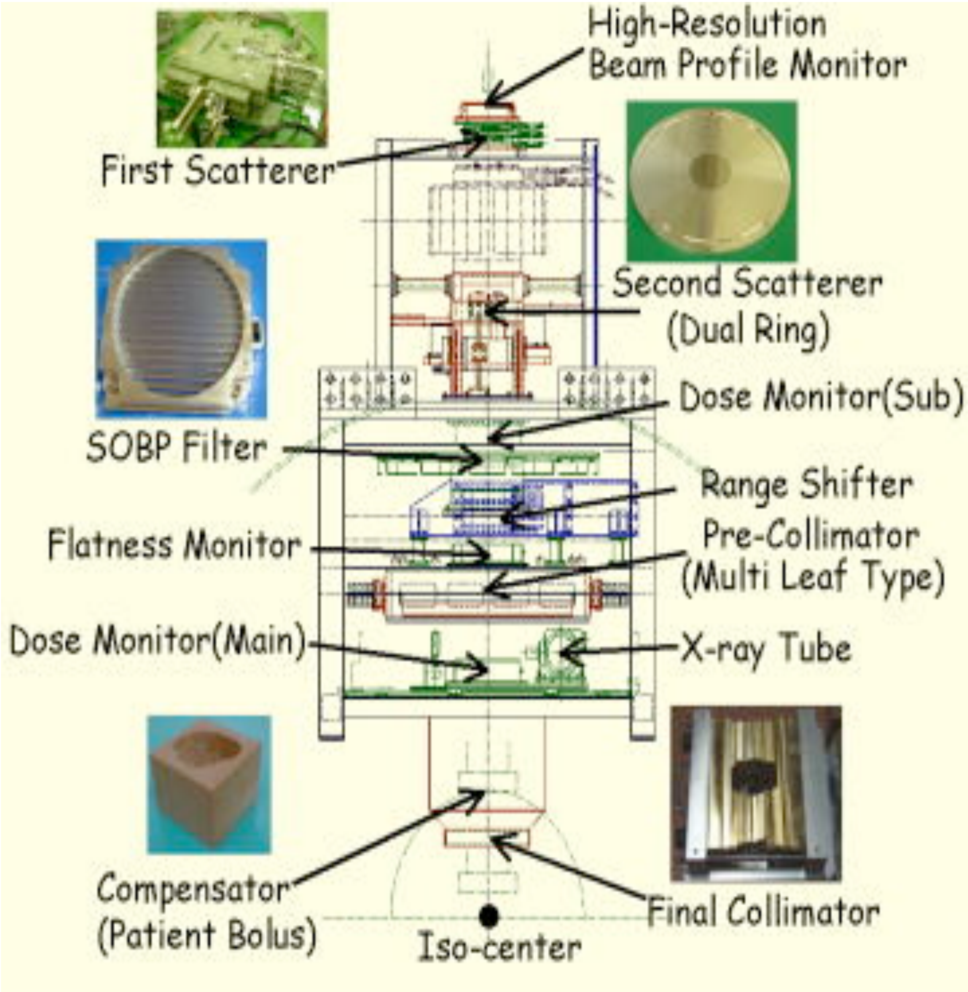


Diagram: Chu '93

Examples of scattering systems / Tsukuba (Hitachi)

Proton Medical Research Center, University of Tsukuba



- double scattering system with dual ring
- ridge filter for energy modulation
- max. field diameter 20 cm

http://www.pi.hitachi.co.jp/rd-eng/product/industrial-sys/accelerator-sys/proton-therapy-sys/probeat/accelerator-technology/technology/2011244_17888.html

Examples of scattering systems / MGH STAR Line

- single-scattering system
- large SAD (~4.5m)
- very sharp penumbra
- variable range shifter
- used for stereo-tactic radio-surgery treatments

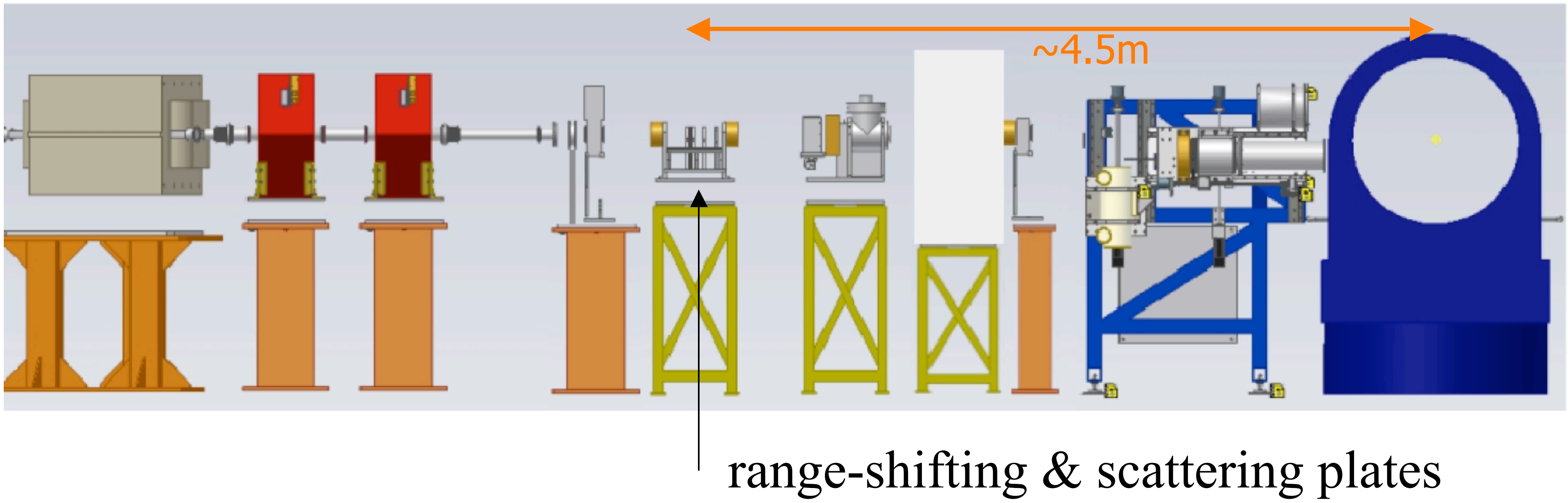
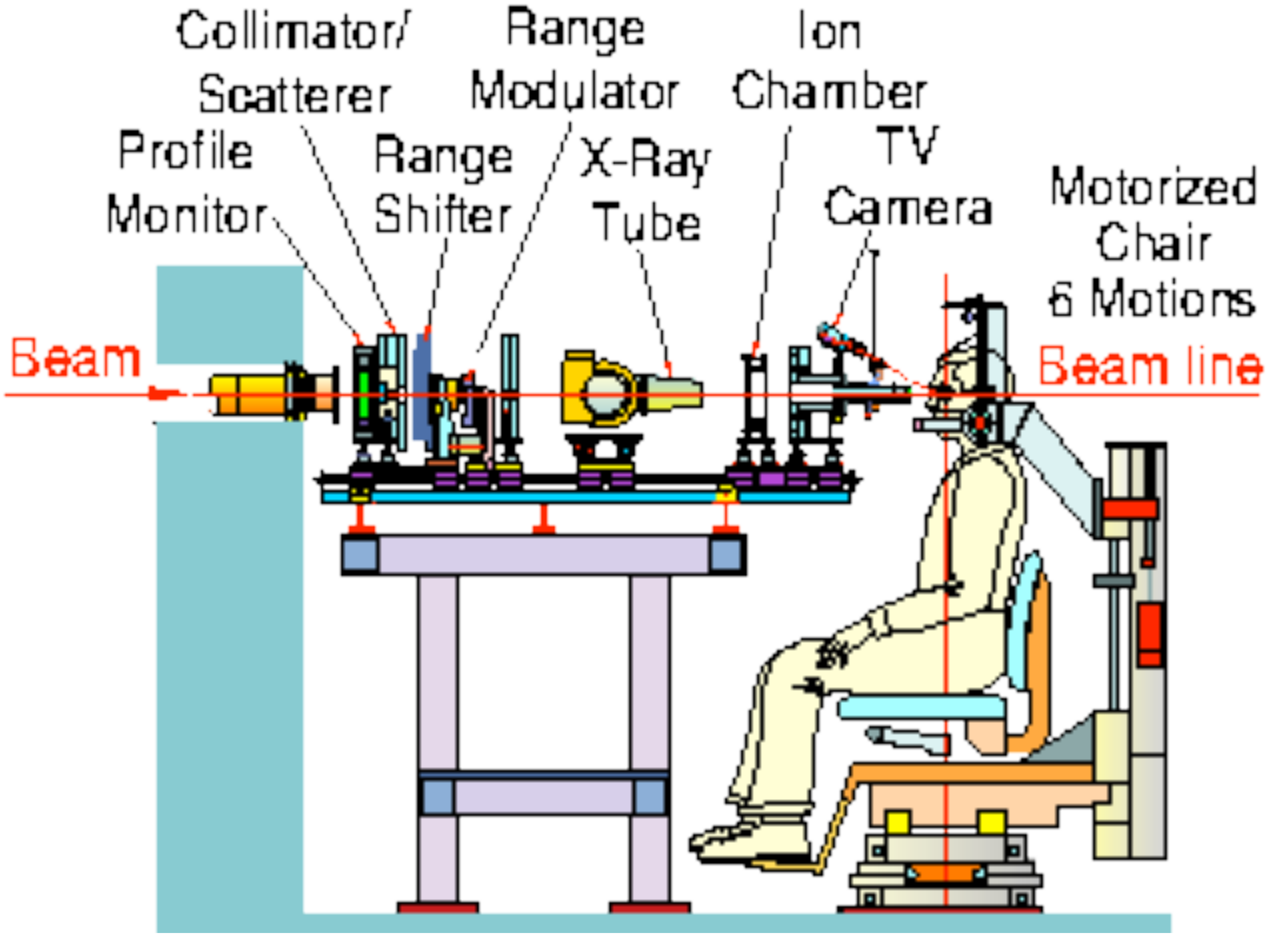
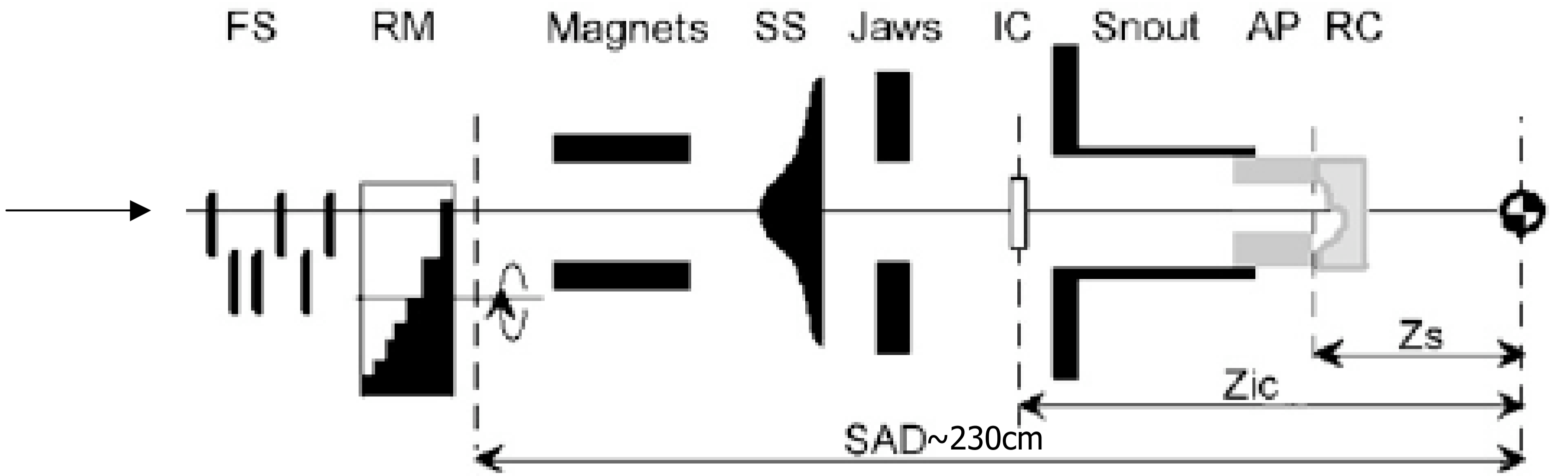


Diagram courtesy M. Bussiere & J. Daartz (MGH)

Examples of scattering systems / TRIUMF eyeline



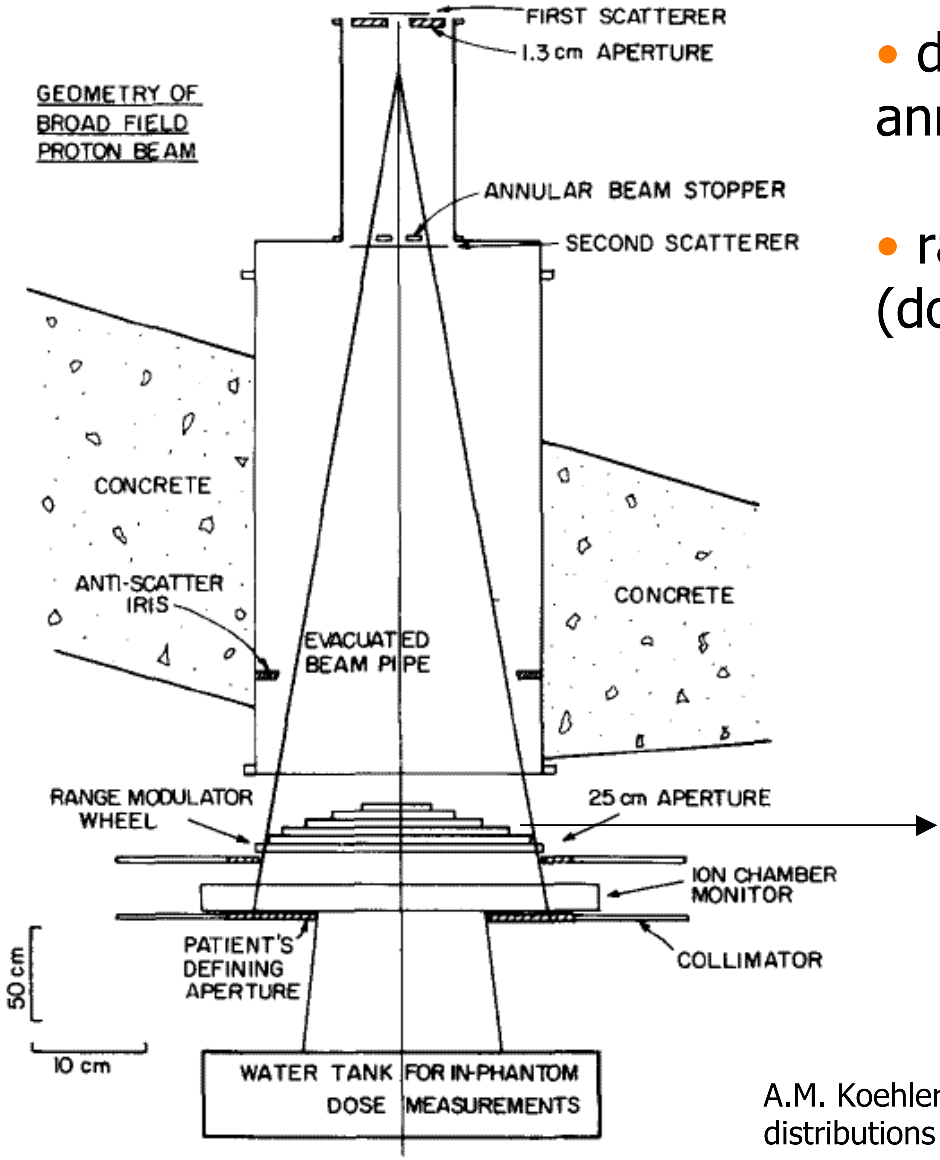
Examples of scattering systems / IBA universal Nozzle



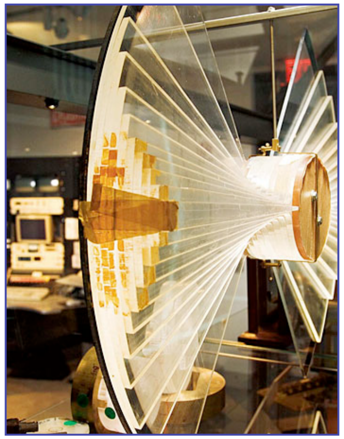
- double-scattering system with contoured second scatterer
- 3 range modulator wheels, each three tracks (RM)
- three contoured scatterers (SS)
- fixed scatterer (FS) for initial spread
- maximum field diameter 24 cm

The prediction of output factors for spread-out proton Bragg peak fields in clinical practice, Hanne M Kooy *et al* 2005 *PMB* 50 5847-5856

Examples of scattering systems / HCL



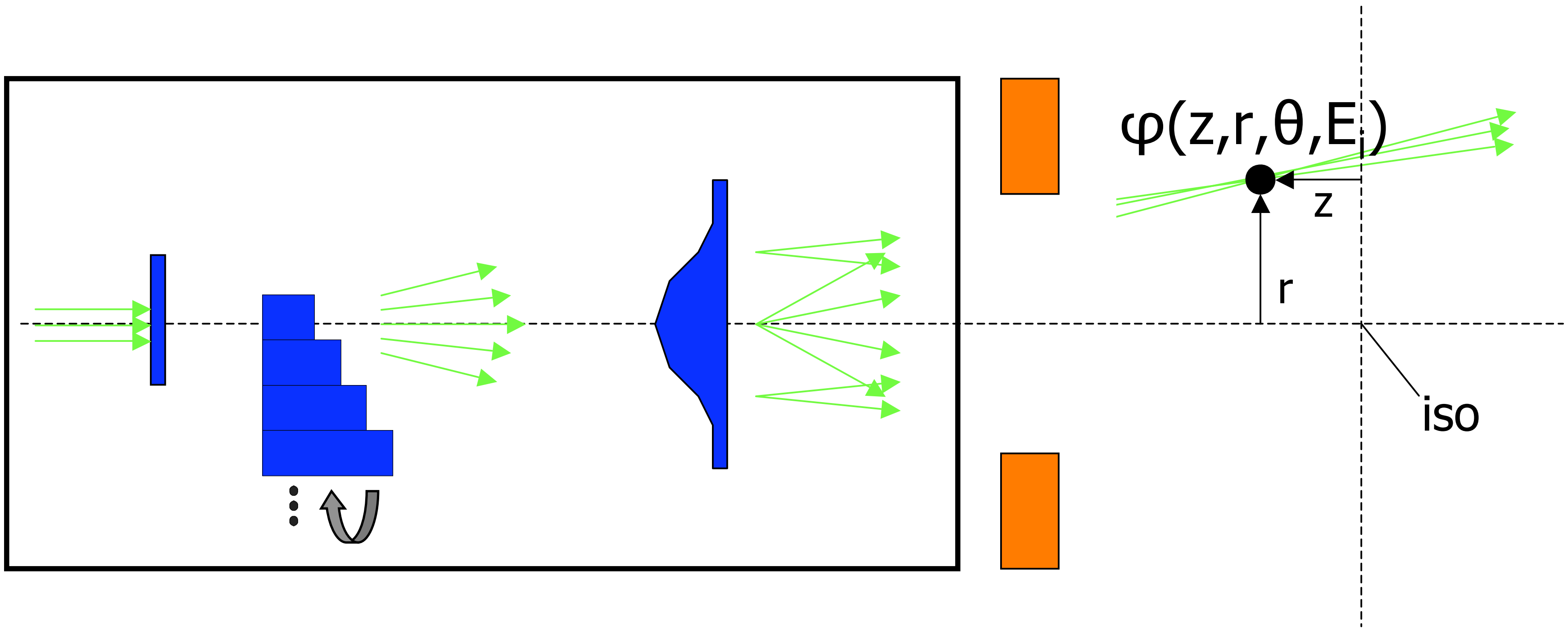
- double-scattering system with annulus
- range modulator wheel (downstream)



A.M. Koehler, R.J. Schneider and J.M. Sisterson, 'Flattening of proton dose distributions for large-field radiotherapy,' Med. Phys. **4(4)** (1977) 297-301.

Part II

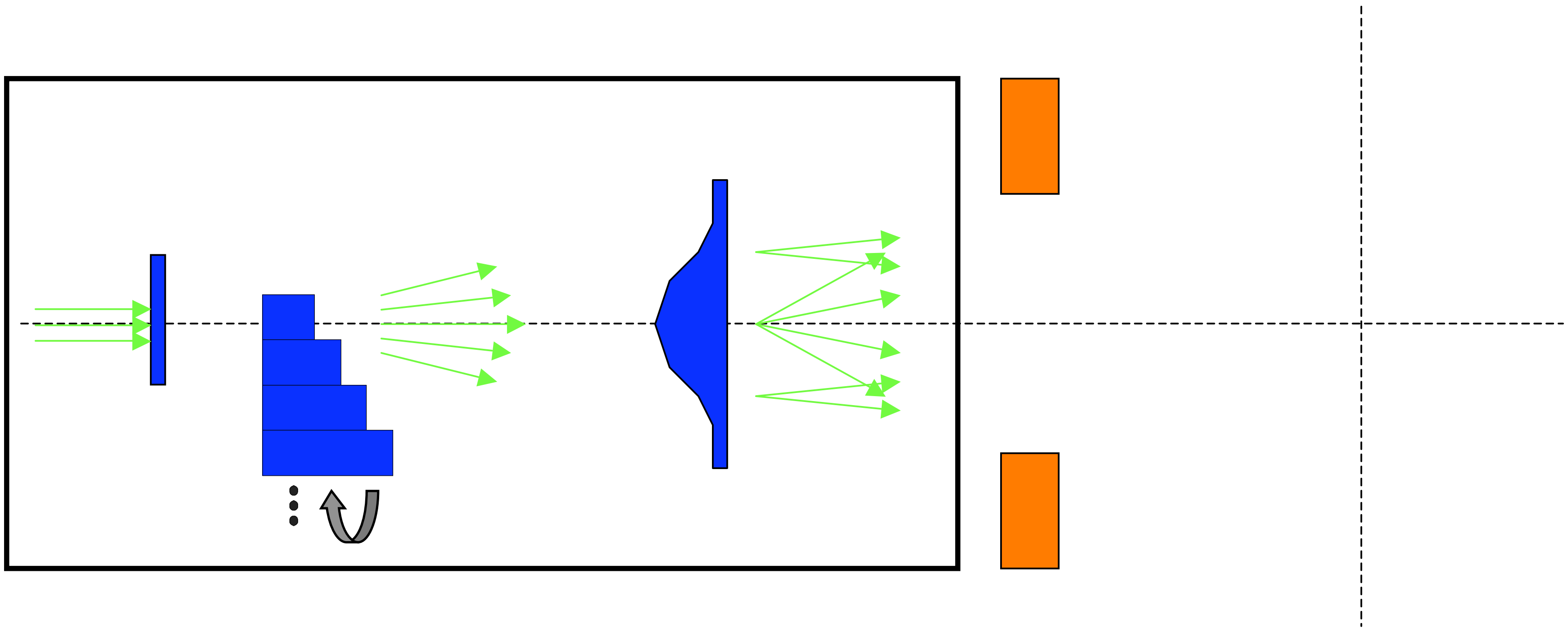
Dosimetric properties of a double-scattering system



$\varphi(z,r,\theta,E_i)$ [protons/m/rad]: number of protons of energy E_i passing (z,r) under an angle θ

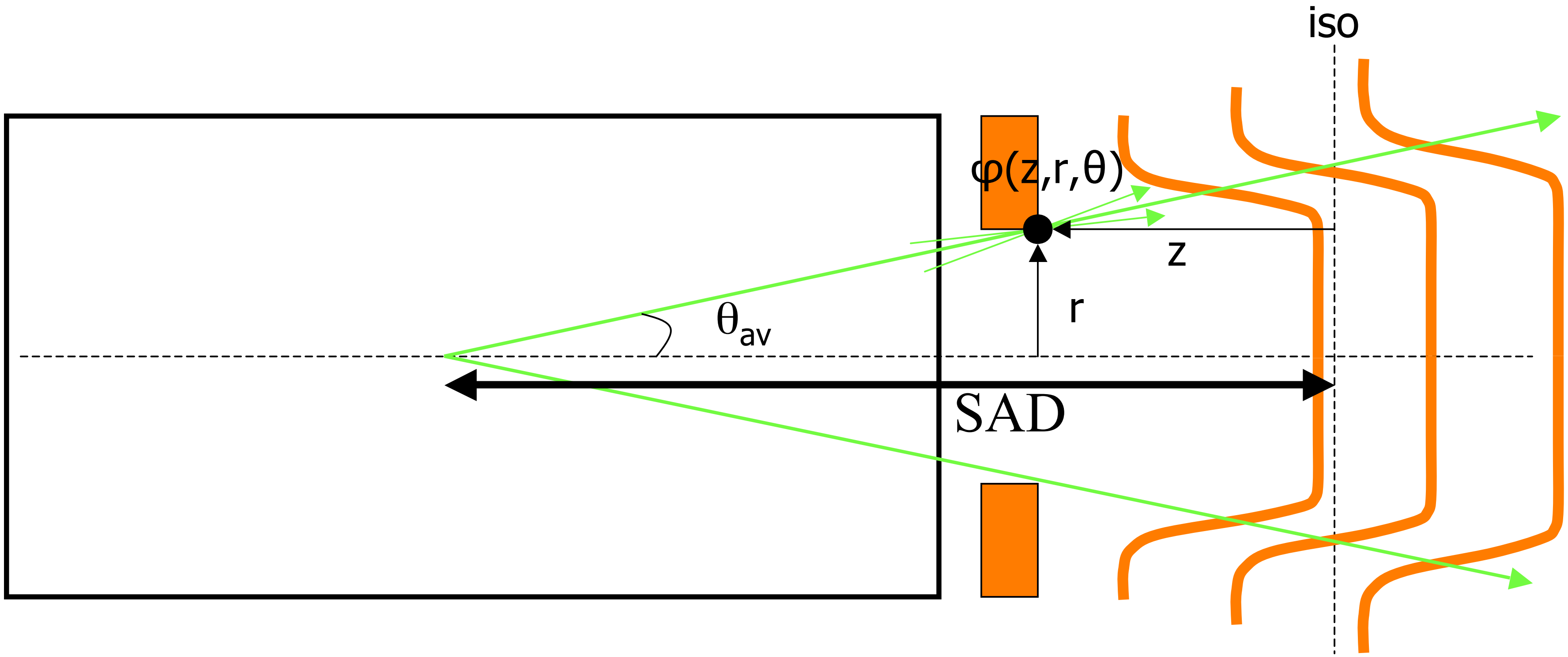
[protons/m]: total number of protons of energy E_i passing (z,r)

Note: we are considering 2D case here, assuming rotational symmetry



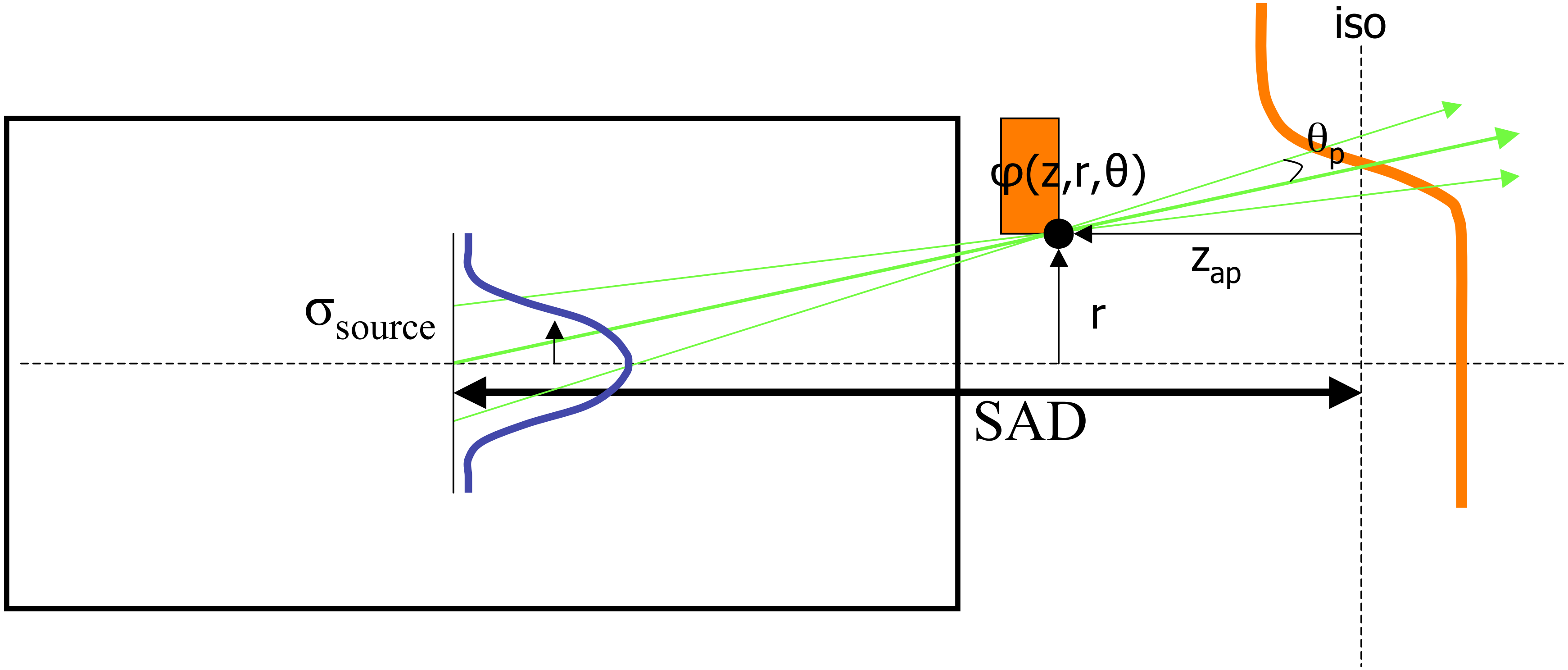
Reduce scattering system to two parameters (per energy layer):

- source position (SAD)
- effective source size



Reduce scattering system to three parameters (per energy layer):

- source position (SAD)
- effective source size



Reduce scattering system to three parameters (per energy layer):

- virtual SAD
- effective source size

with θ_p sigma

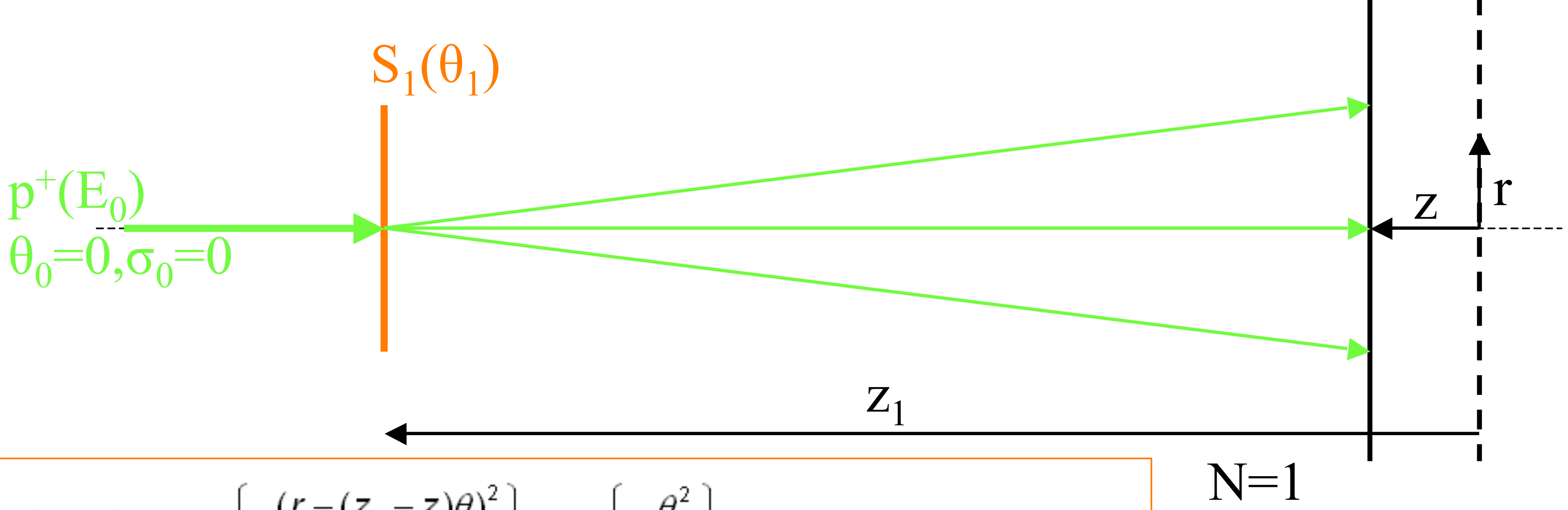
of gaussian fit to angular spread

80%-20% penumbra is given by

Dosimetric properties

	Defined by	Determines	Formula
SAD	Average angular spread	Beam divergence (& z fluence)	
Effective Source Size	Variation around average of angular spread	Lateral penumbra (& inhomogeneity)	

Single thin scatterer



$$\varphi(z,r,\theta) = \exp\left\{-\frac{(r-(z_s-z)\theta)^2}{2\sigma_s^{\,2}}\right\}\cdot \exp\left\{-\frac{\theta^2}{\theta_s^{\,2}}\right\}$$

$$\Phi(z,r) = \int_{-\infty}^{\infty} \varphi(z,r,\theta)\,d\theta = \exp\left\{-\frac{r^2}{2\sigma(z)^2}\right\}$$

$$\theta_s = \sqrt{\theta_0^{\,2} + \theta_1^{\,2} + \ldots + \theta_N^{\,2}}$$

$$\sigma_s = \sqrt{\sigma_0^{\,2} + \theta_0^{\,2}(z_0 - z_s)^2 + \theta_1^{\,2}(z_1 - z_s)^2 + \ldots + \theta_N^{\,2}(z_N - z_s)^2}$$

$$z_s = \left(z_0\theta_0^{\,2} + z_1\theta_1^{\,2} + \cdots + z_N\theta_N^{\,2}\right)/\theta_s^{\,2}$$

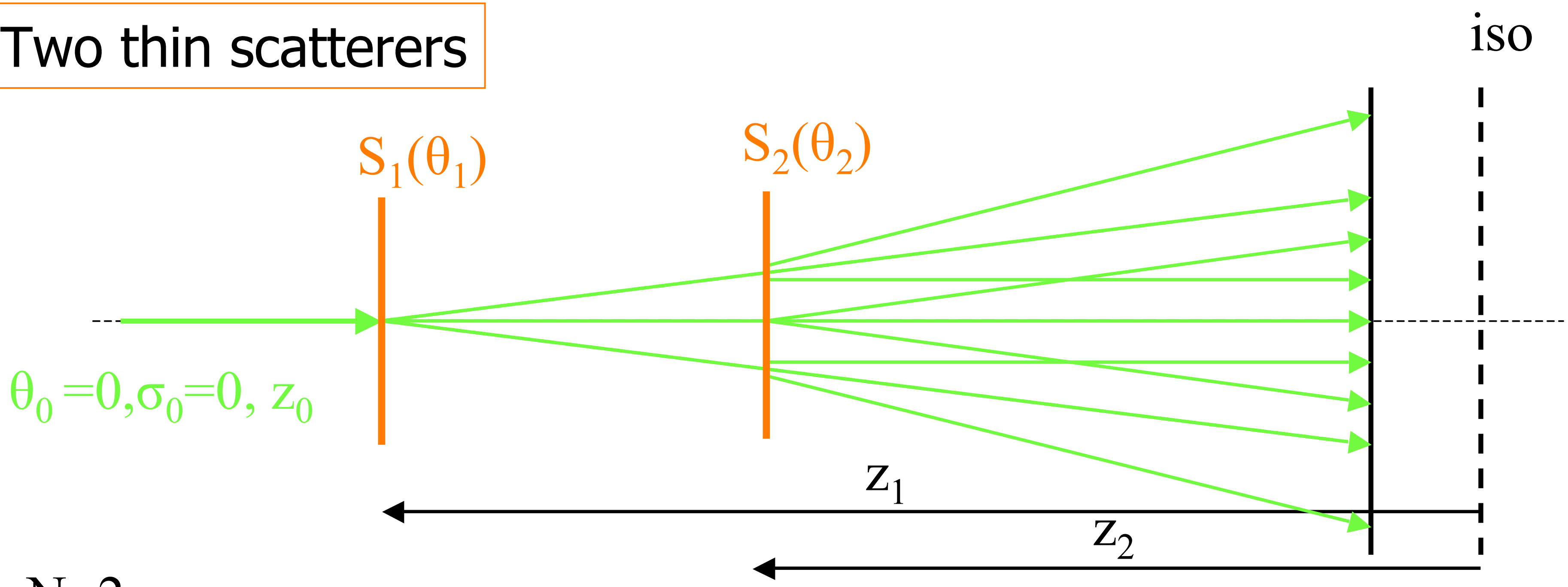
$$\sigma(z) = \sqrt{\sigma_s^2 + (z_s - z)^2\,\theta_s^2}$$

SAD = z_1

σ_{source} = 0

$\sigma(z) = \theta_1\,(z_1 - z)$

Two thin scatterers



N=2

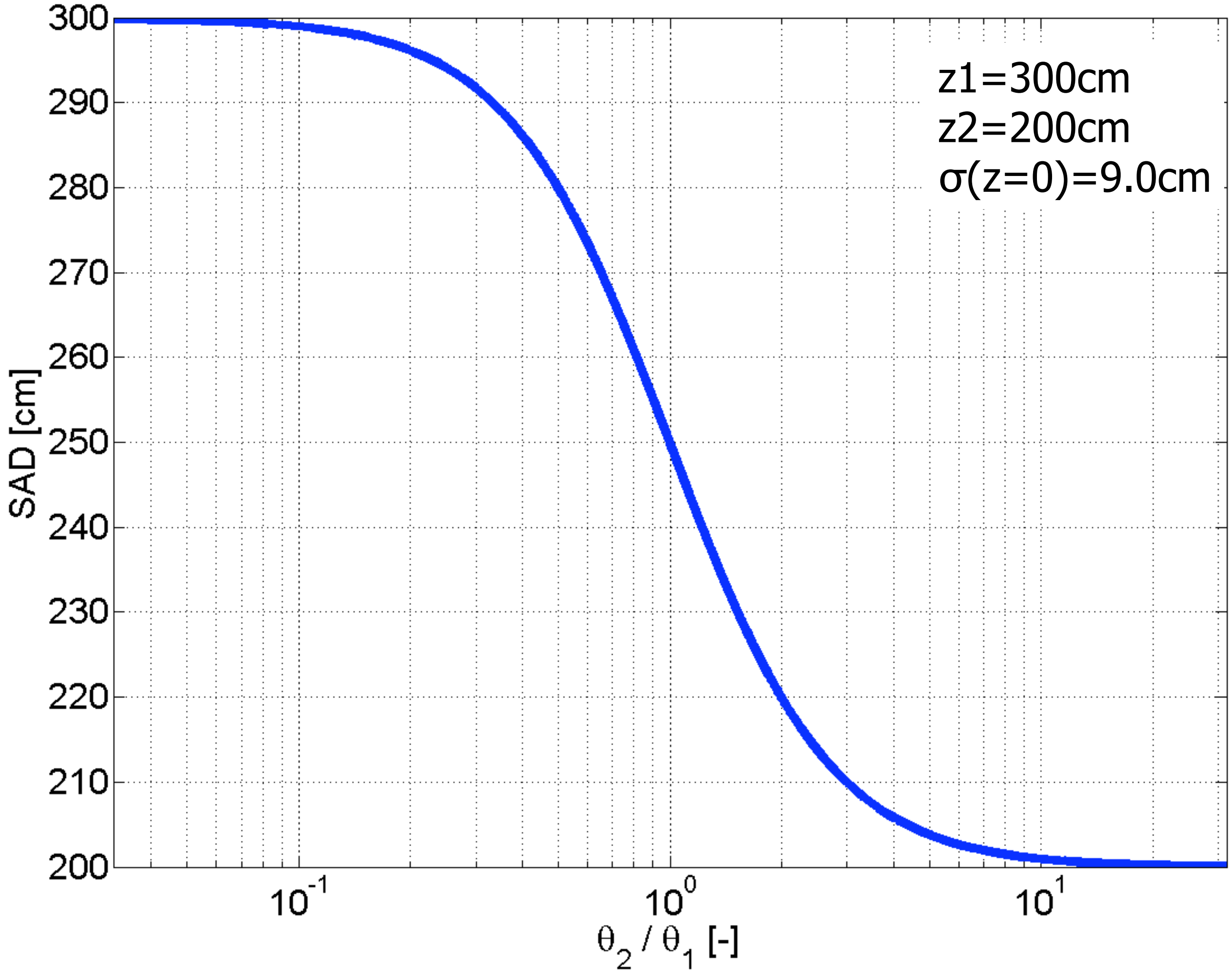
$$SAD = (z_1\,\theta_1^2 + z_2\,\theta_2^2)\,/\,\theta_s^2$$

$$\sigma_{source}^2 = ((z_1\text{-}SAD)^2\,\theta_1^2 + (z_2 - SAD)^2\,\theta_2^2)$$

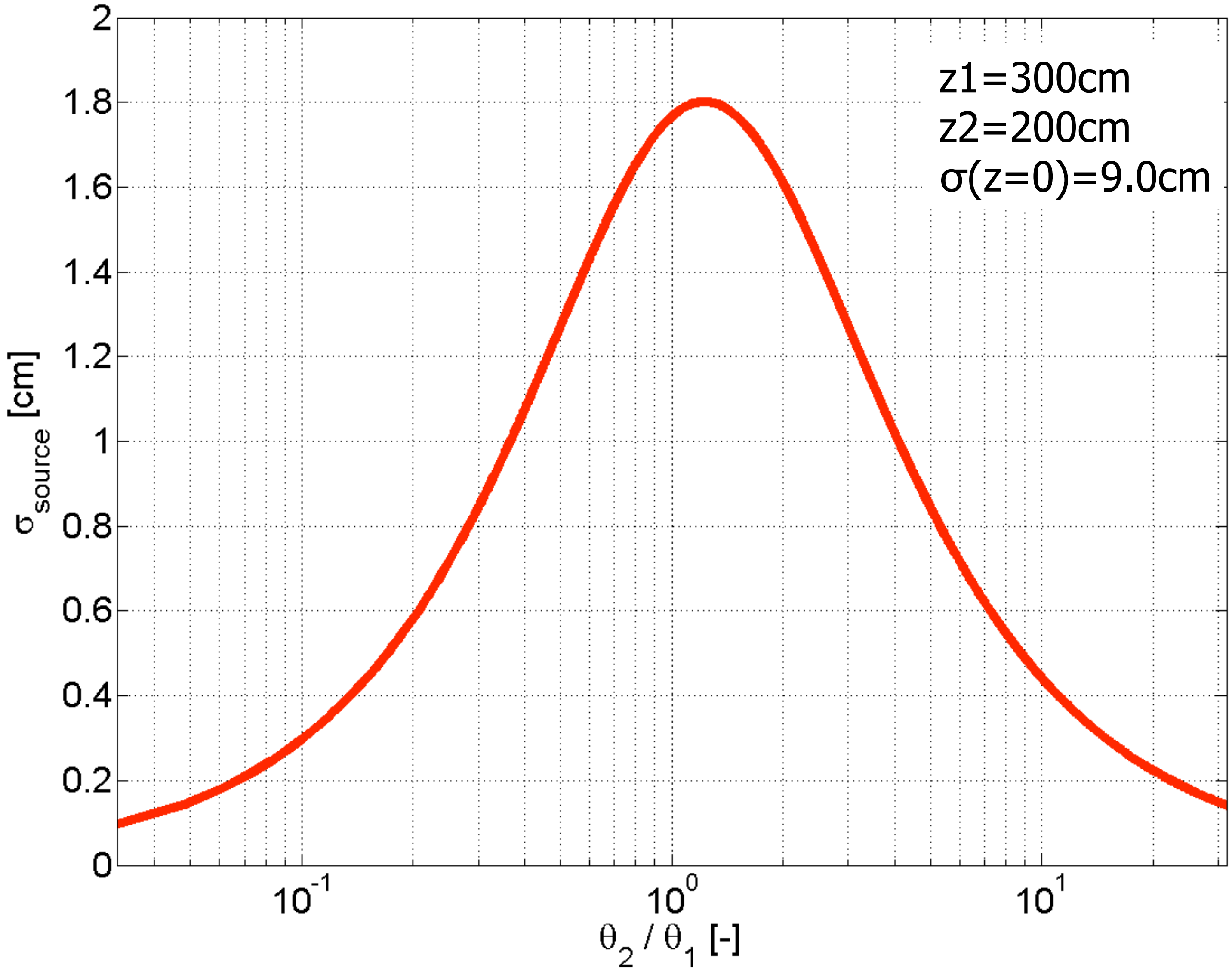
$$\theta_s^2 = \theta_1^2 + \theta_2^2$$

$$\sigma(z)^2 = \sigma_{source}^2 + (SAD\text{-}z)^2\,\theta_s^2$$

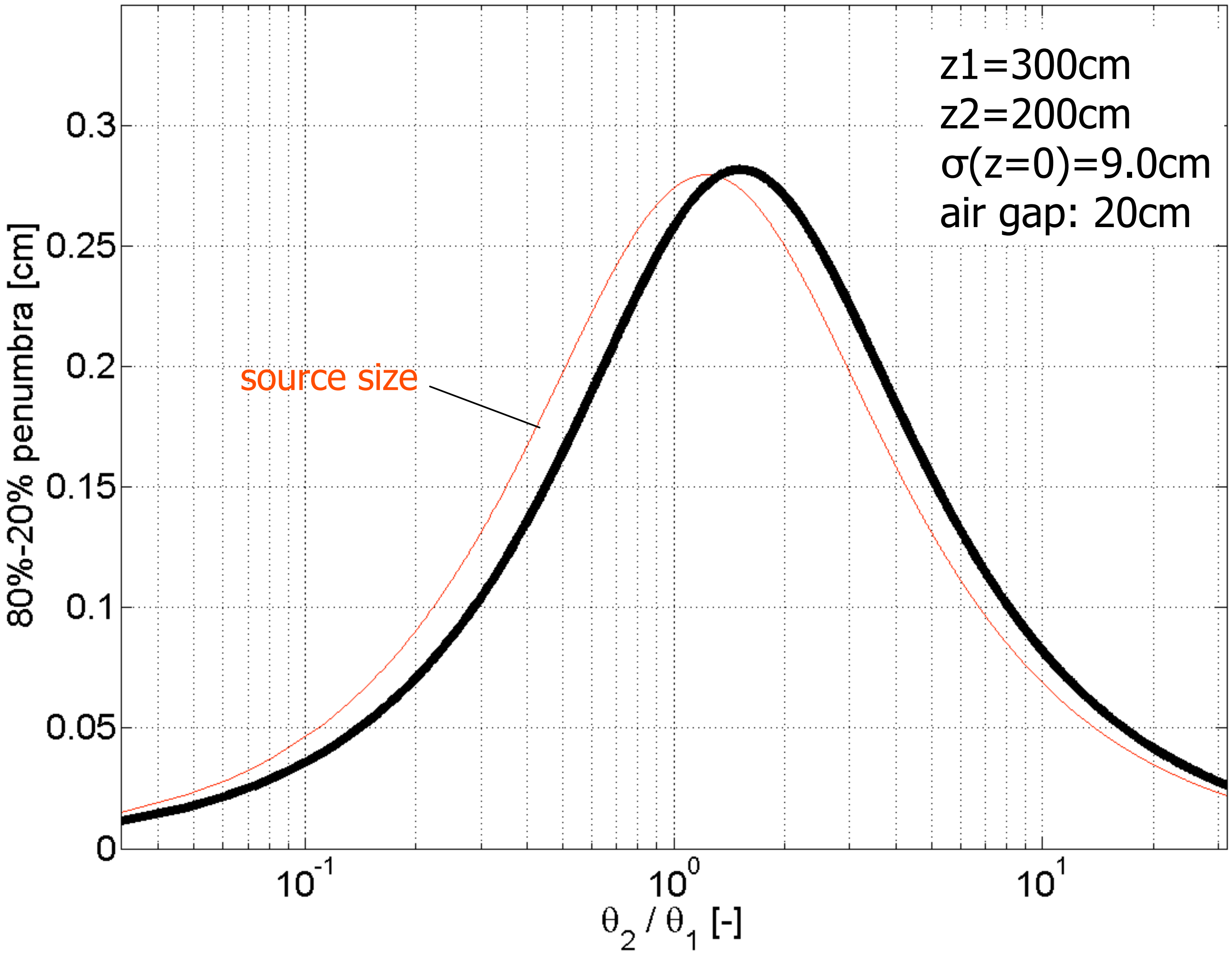
Two thin scatterers: SAD versus scattering power ratio



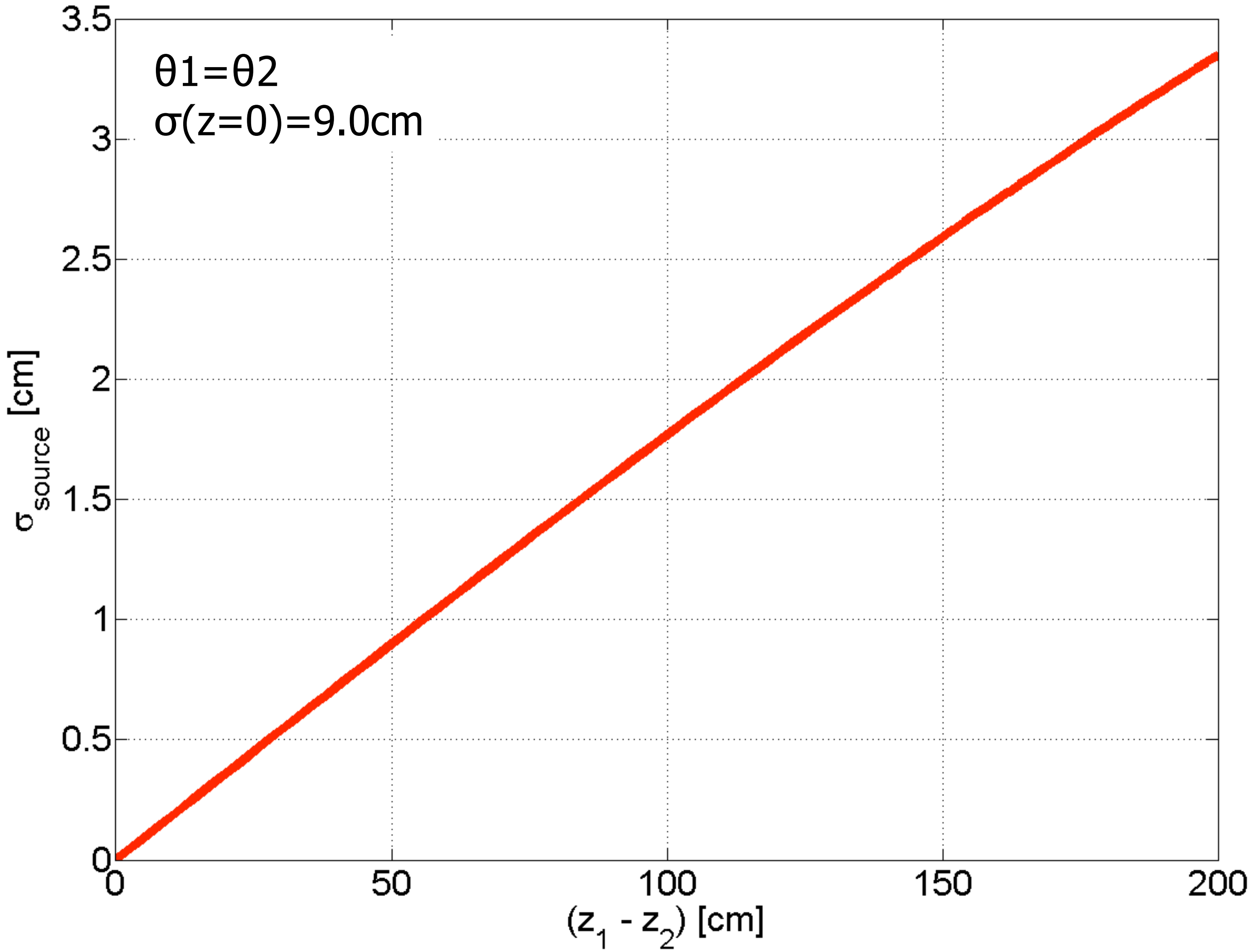
Two thin scatterers: source size versus scattering power ratio



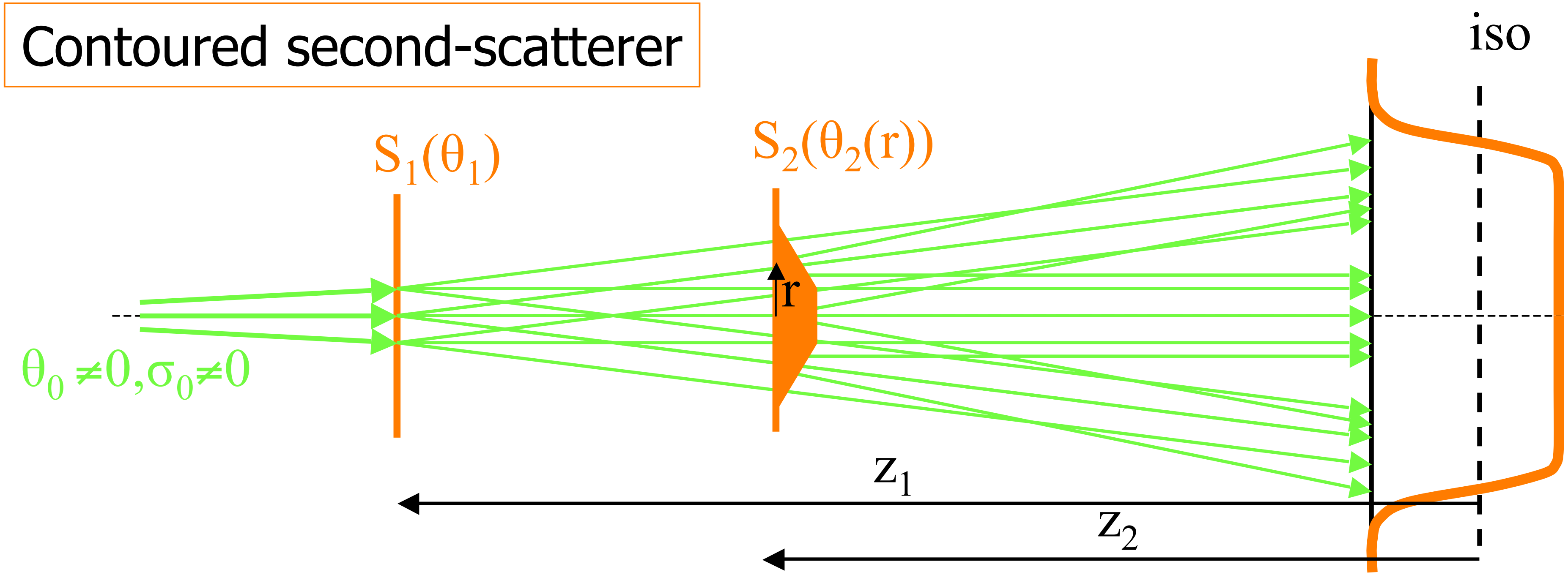
Two thin scatterers: penumbra versus scattering power ratio



Two thin scatterers: source size versus distance between scatt.

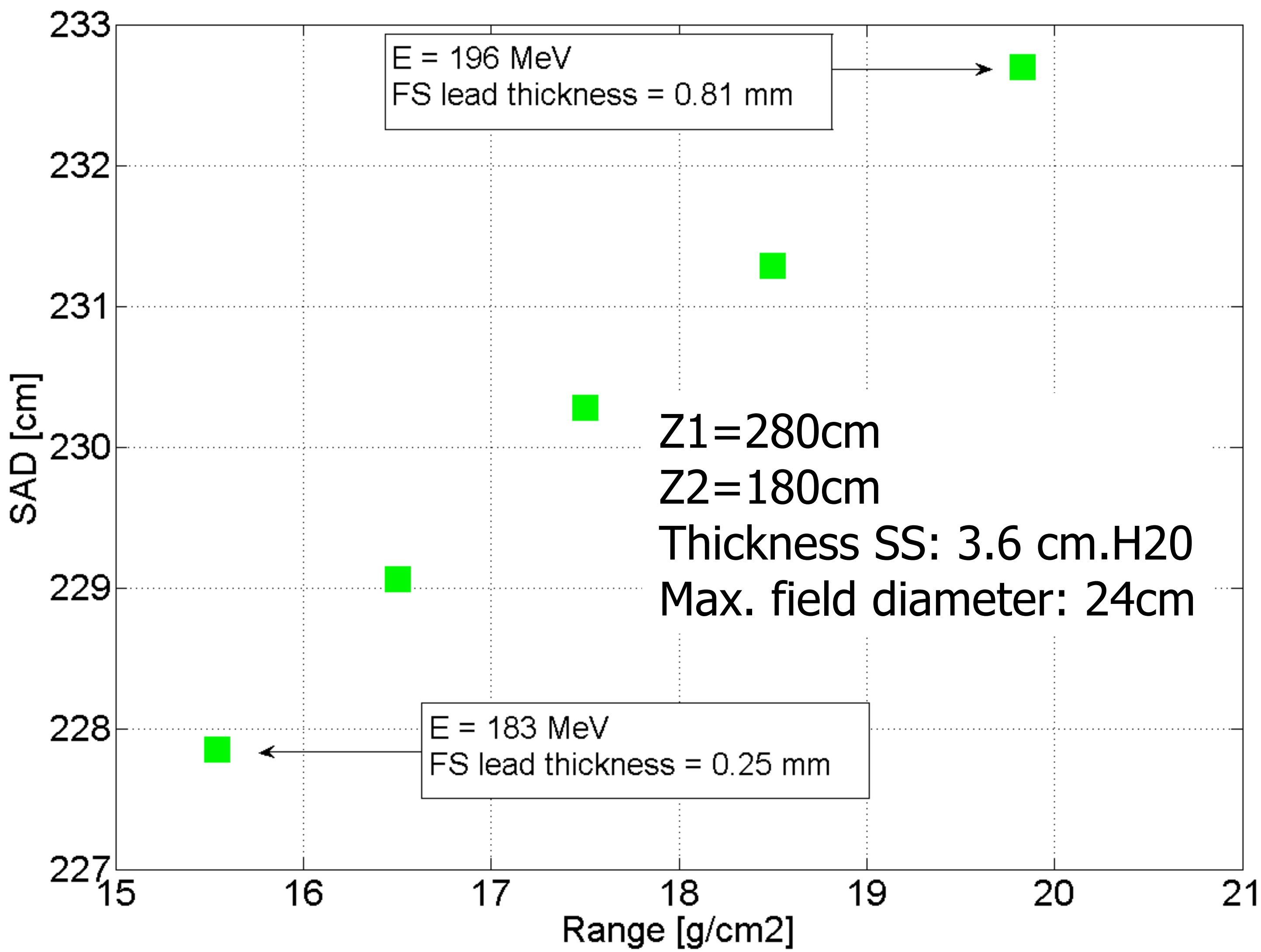


Contoured second-scatterer

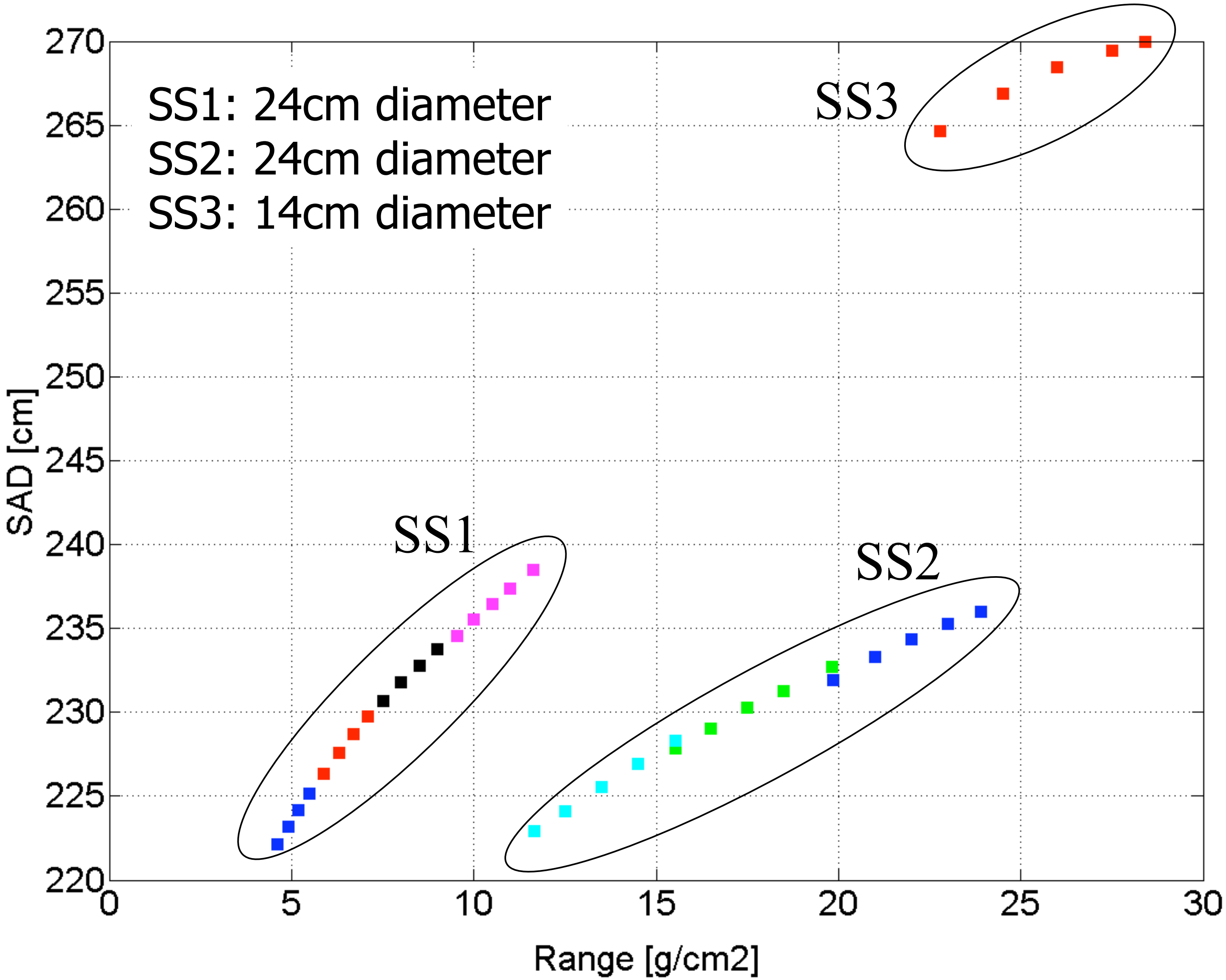


See Gottschalk: Passive Beam Spreading

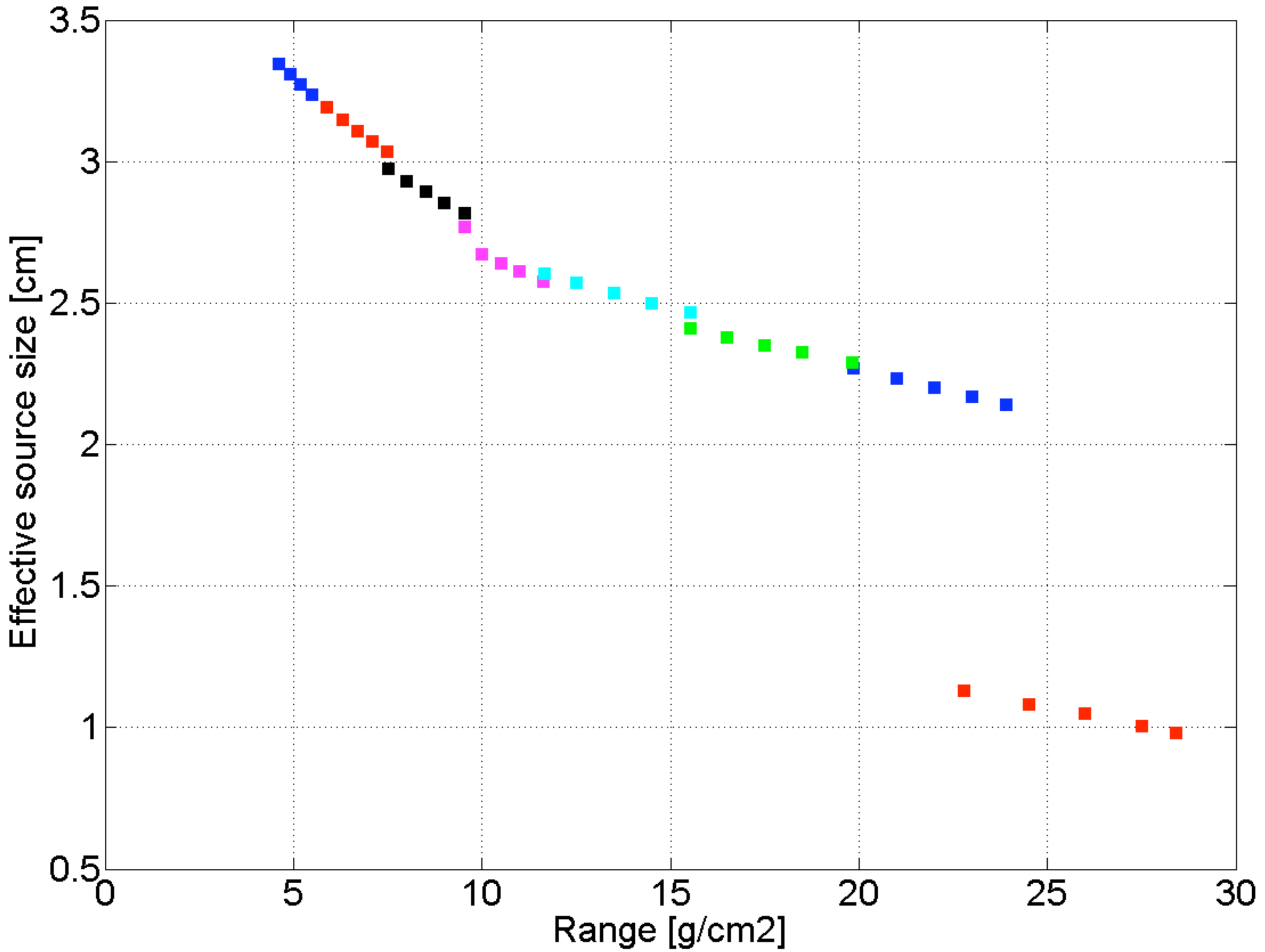
Contoured second scatterer: SAD versus range



Contoured second scatterer: SAD versus range



Contoured second scatterer: source size versus range



Summary of Dosimetric properties

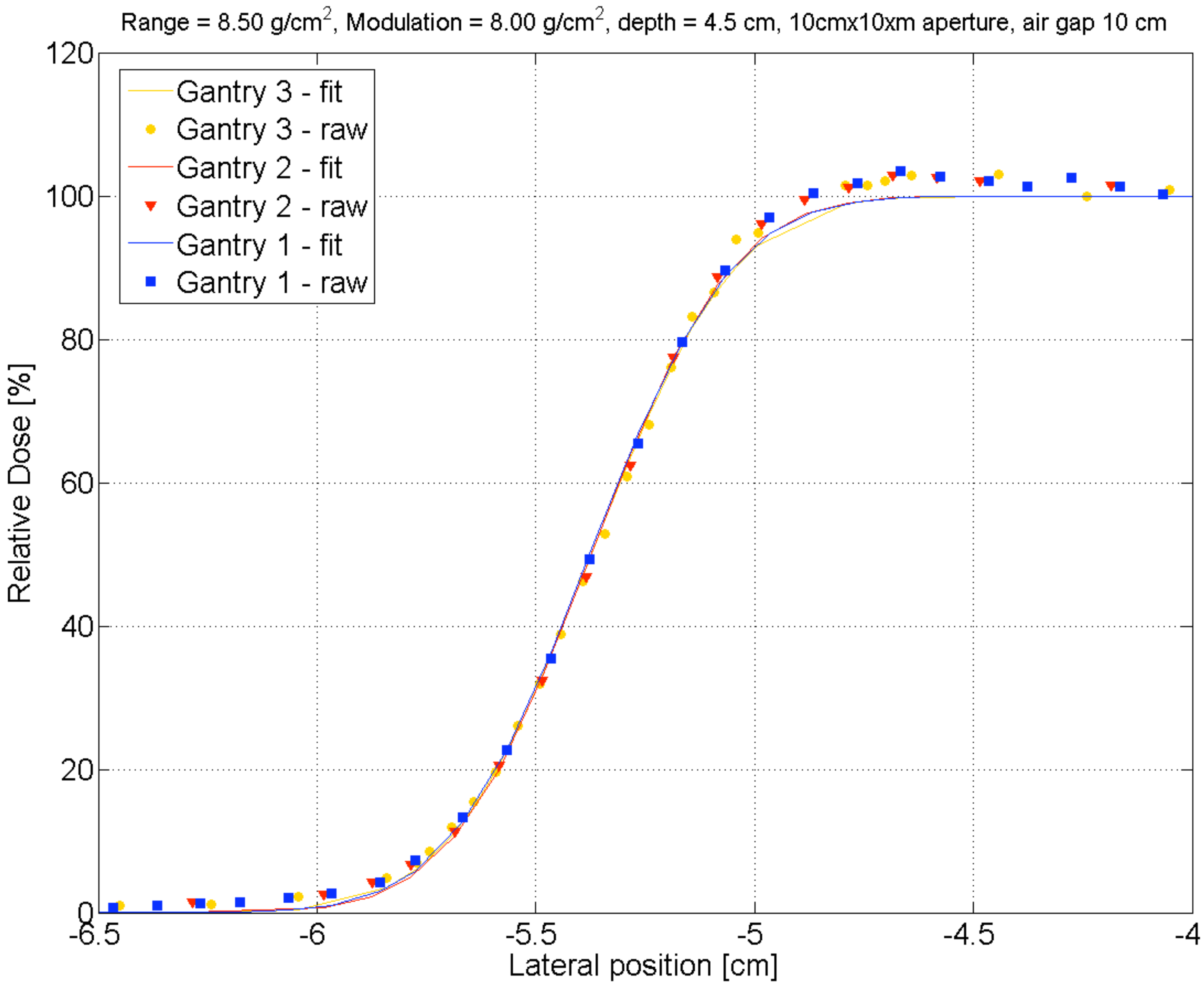
- double-scattering system can be parameterized (per energy layer) as a gaussian source at a certain distance from iso center (SAD)

- source falls between first and second scatterer; increasing scattering power of first (second) scatterer moves source upstream (downstream)

- source size increases with total amount of scattering and distance between first and second scatterer

END

Measurements – Comparison of Rooms



END

Part III

Method of commissioning a double-scattering system

Definitions of acceptance and commissioning

- **Acceptance Testing** → Vendor and customer

  '.. to determine that all applicable radiation safety standards are met or exceeded and that the machine meets or exceeds the contractual specifications.'

  'A satisfactorily completed acceptance test simply assures that the accelerator and its associated systems satisfy all performance specifications and pertinent safety requirements.'

- **Commissioning** → Customer

  '….refers to the process whereby the needed machine-specific beam data are acquired and operational procedures are defined.'

AAPM code of practice for radiotherapy accelerators: Report of AAPM Radiation Therapy Task Group No. 45

Acceptance tests

- specified in the <u>contract</u>

- a <u>limited set</u>, covering random samples of the complete 'space' of delivery parameters

- describing in <u>detail</u> the measurement setup and the specified limits

- distinction between <u>design</u> specifications and <u>installation</u> specifications

- <u>do not allow you to treat a single patient</u>

Example of acceptance tests

- Range accuracy: for a ‘random’ field measure the pdd and verify the observed range is within ±1 mm of requested

- Lateral penumbra: measure the profile in air, at iso center, at 10 cm from the aperture and verify the 20%-80% penumbra

- Reproducibility: measure the dose per MU for a single field on 10 consecutive days and verify the output dose not vary by more than ±2%.

- Safety: All emergency crash buttons are tested.

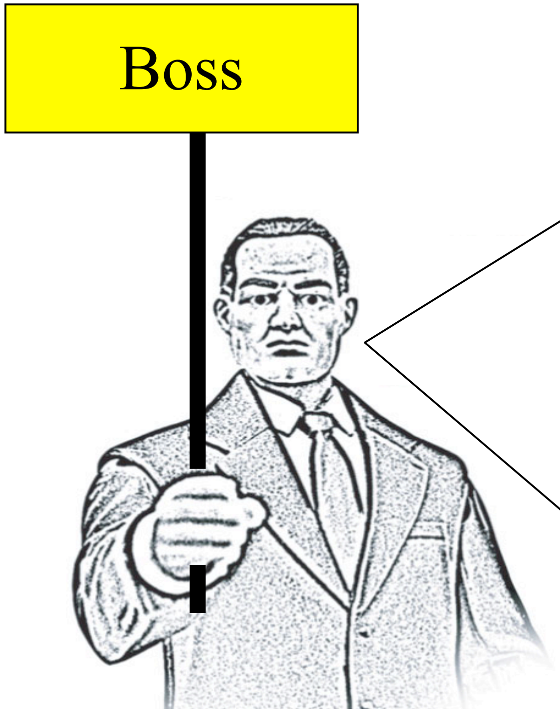
- Verification of the <u>dose distribution</u> over the complete set of prescribed parameters

- Verification of <u>setup</u> and <u>localization</u> equipment
  - patient positioner
  - gantry
  - imaging equipment

- <u>Treatment planning</u> commissioning
  - measurement of the beam data library
  - verification of the modeled dose distribution

- Definition of Quality Assurance and other clinical <u>procedures</u> (simulation, immobilization, setup, …)

Setting up a commissioning plan



We just bought a proton-therapy system!

A cyclotron based system with not one, not two, but three gantries!

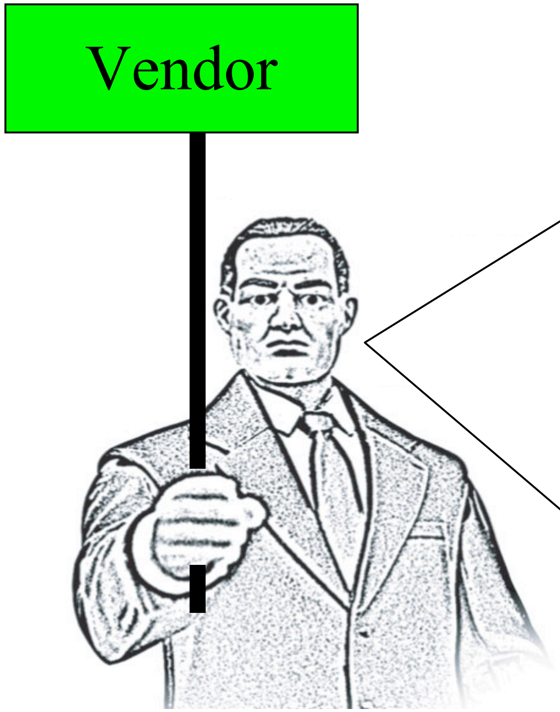
We are going to treat 1200 patients a year, 14 hours a day, and for six days a week.

There will be pediatric cases, prostates, head&neck, lung, radio-surgery…..

We will be starting on September 1.

Can you commission the system for us?

Setting up a commissioning plan



You just bought a proton-therapy system from us. Congratulations!

We will be ready to hand over the first room to you on June 1.

Each room has 8 double-scattering options. Each option has three suboptions that use a different beam current modulation.

Our system is great: the range and modulation width can be varied continuously.

The field size is fixed, but we have variable collimators and three snouts.

Determine the parameters to verify

Prescription → Equipment settings → Delivery

- range
- modulation width
- field size
- dose rate
- dose
- gantry angle
- SSD (air gap)
- snout size

Depth dose

- range
- modulation width
- dose variation uniform region
- ...ll off
- ...ximal region

Lateral

- ...file (tilt/flatness)
- ...um field size
- lateral penumbra vs. depth
- field size vs. depth

Absolute

- dose per MU
- dose rate

For what subset of prescribed parameters do these need to be verified?

Does the range depend on……

Option	Yes
Suboption	Maybe
Modulation	No
Field size	No
Snout size	No
Gantry angle	Unlikely
Dose rate	No
Dose	No
SSD	No

Measure…

- 4 SOBP's per suboption
- 2 SOBP's for 2 gantry angles

Defining the subset – PDD uniformity

Does the pdd uniformity depend on……

Option	Yes
Suboption	Yes
Modulation	No
Field size	Yes
Snout size	Maybe
Gantry angle	Unlikely
Dose rate	Unlikely
Dose	No
SSD	Yes

Measure…

- 1 full-mod SOBP per suboption
- 2 sobp for all snouts
- 1 sobp for 2 gantry angles
- 1 sobp for 3 dose rates
- 2 sobp for varying SSD
- sobp's for small aperture size

Specification and measurement table

Specification and measurement table

Specification and measurement table

Scheduling

- First-patient treatment versus ramp-up
  the sooner you start treating the more commissioning needs to be done in parallel to treatments

- Commissioning effort versus QA effort
  a heavy patient load prevents many QA hours and requires more commissioning (MU model)

- The expected patient mix and ranges (options) to be commissioned
  limiting the type of treatments in a room can reduce the commissioning load

- Commissioning different rooms of the same design
  certain measurements only have to be performed for one room

Setting up a commissioning plan

1. Identify the properties that need to be verified

2. Determine the subset of equipment settings on which the property depends

3. Define the measurements required to verify the property

4. Combine the measurements into a measurement plan

5. Schedule the measurements, taking into account

   - *desired start treatments*
   - *expected patient load*
   - *expected patient mix*

Commissioning schedule - example

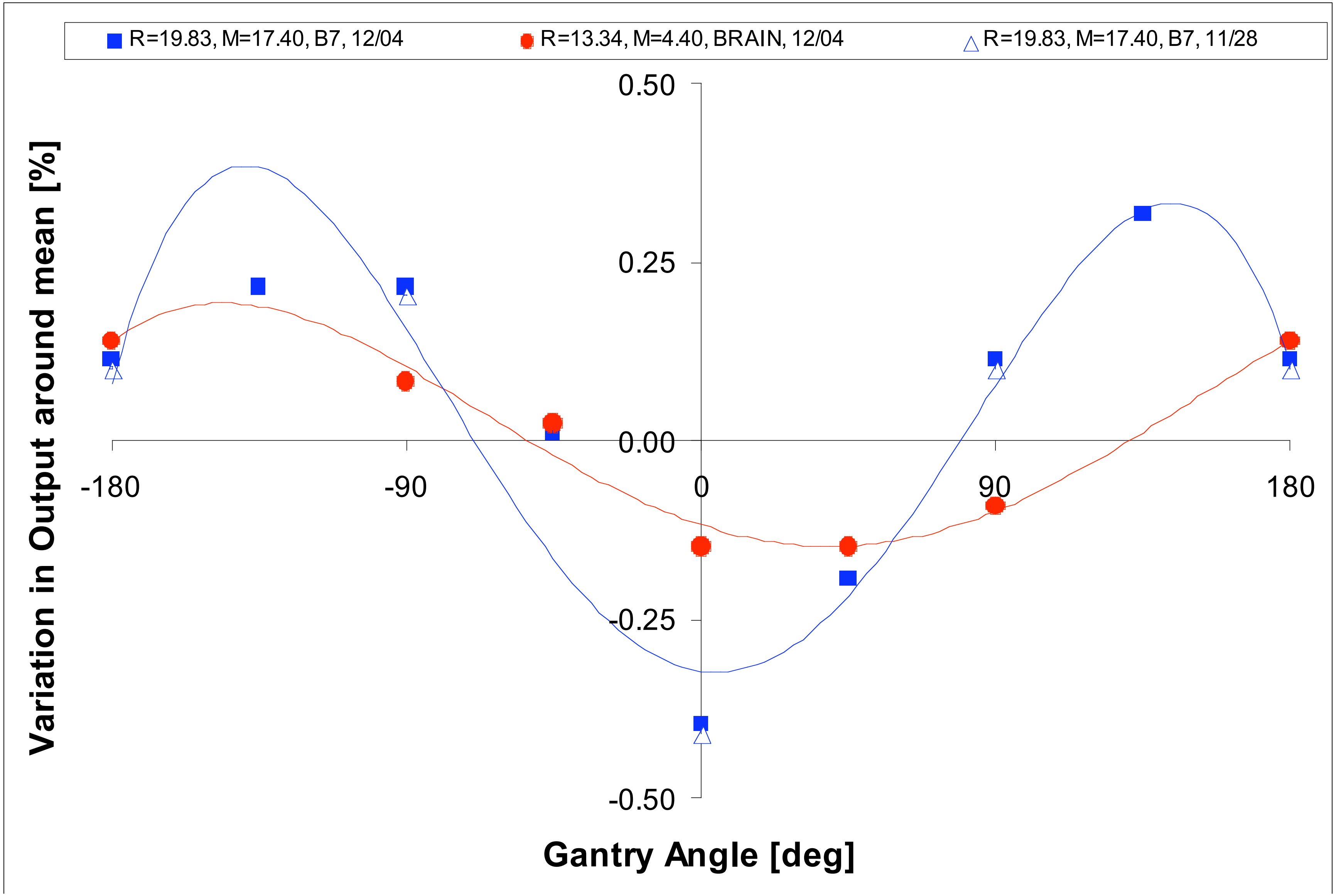
Examples of Commissioning Measurements

Measurements – Range Reproducibility

Measurements – Range Reproducibility

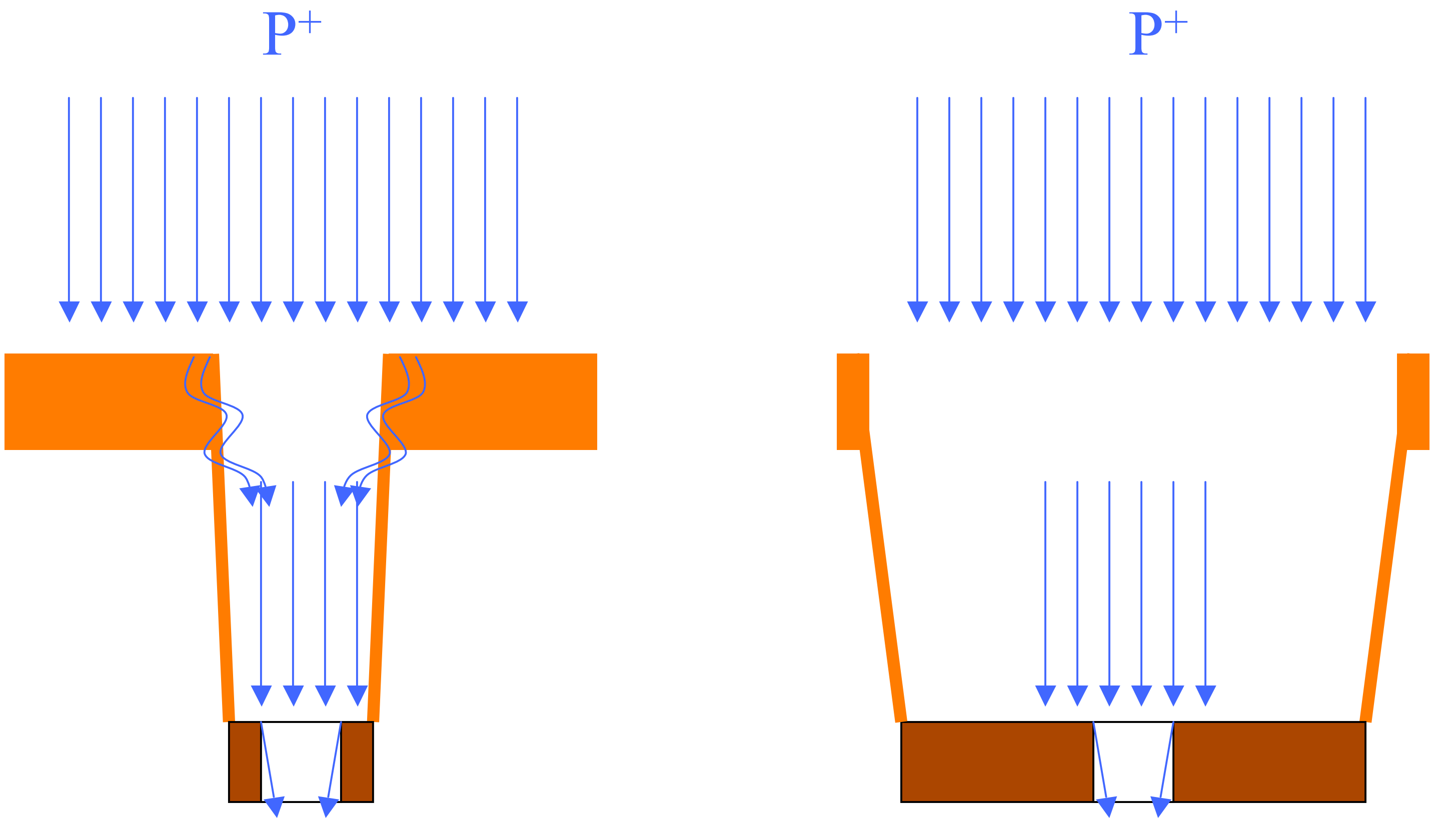
Measurements – Output and Dose Rate

Measurements – Output and Gantry Angle



Note: lines to guide the eye

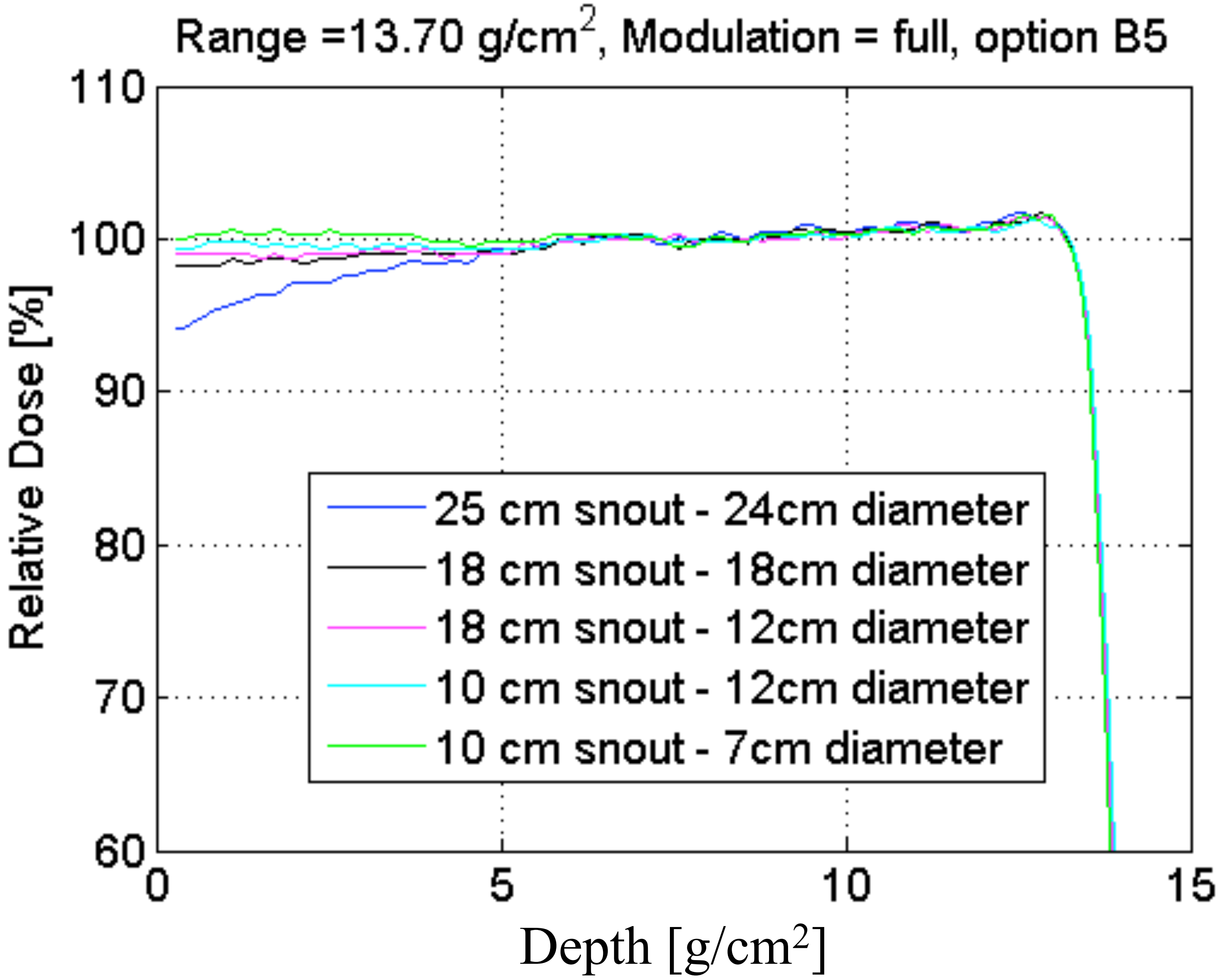
Measurements – Dose distribution and snout size



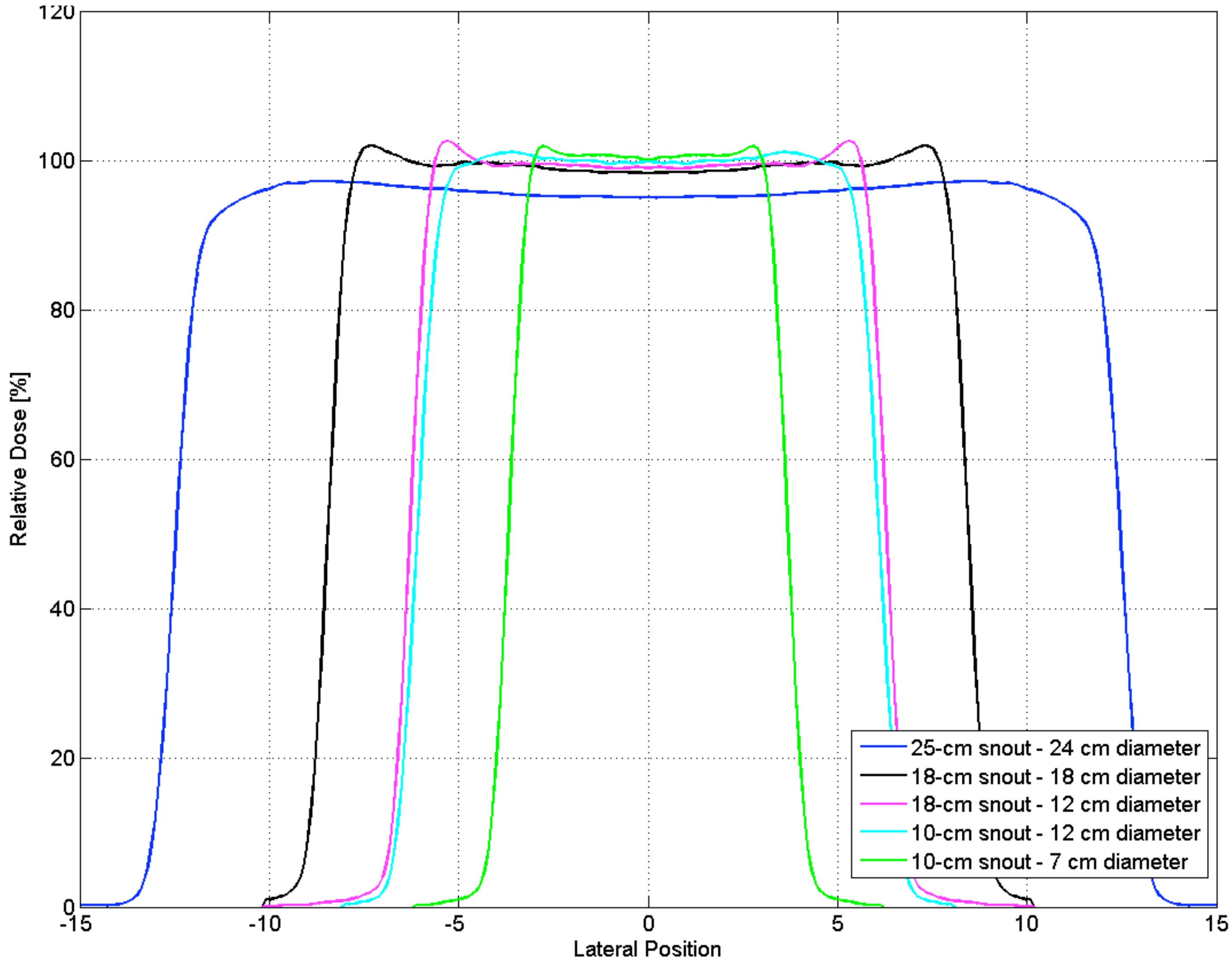
10-cm snout

25-cm snout

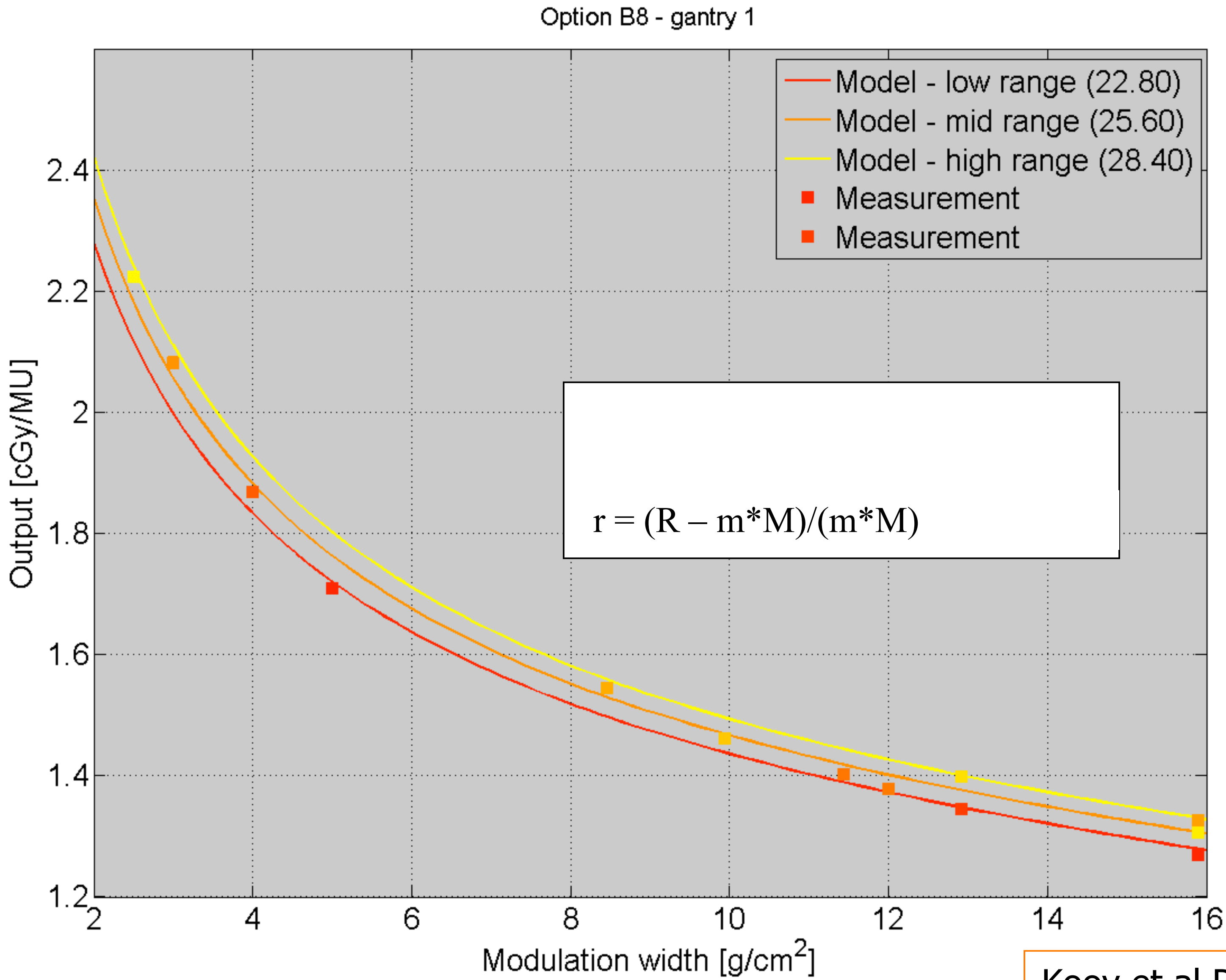
Measurements – Dose distribution and snout size



Measurements – Dose distribution and snout size

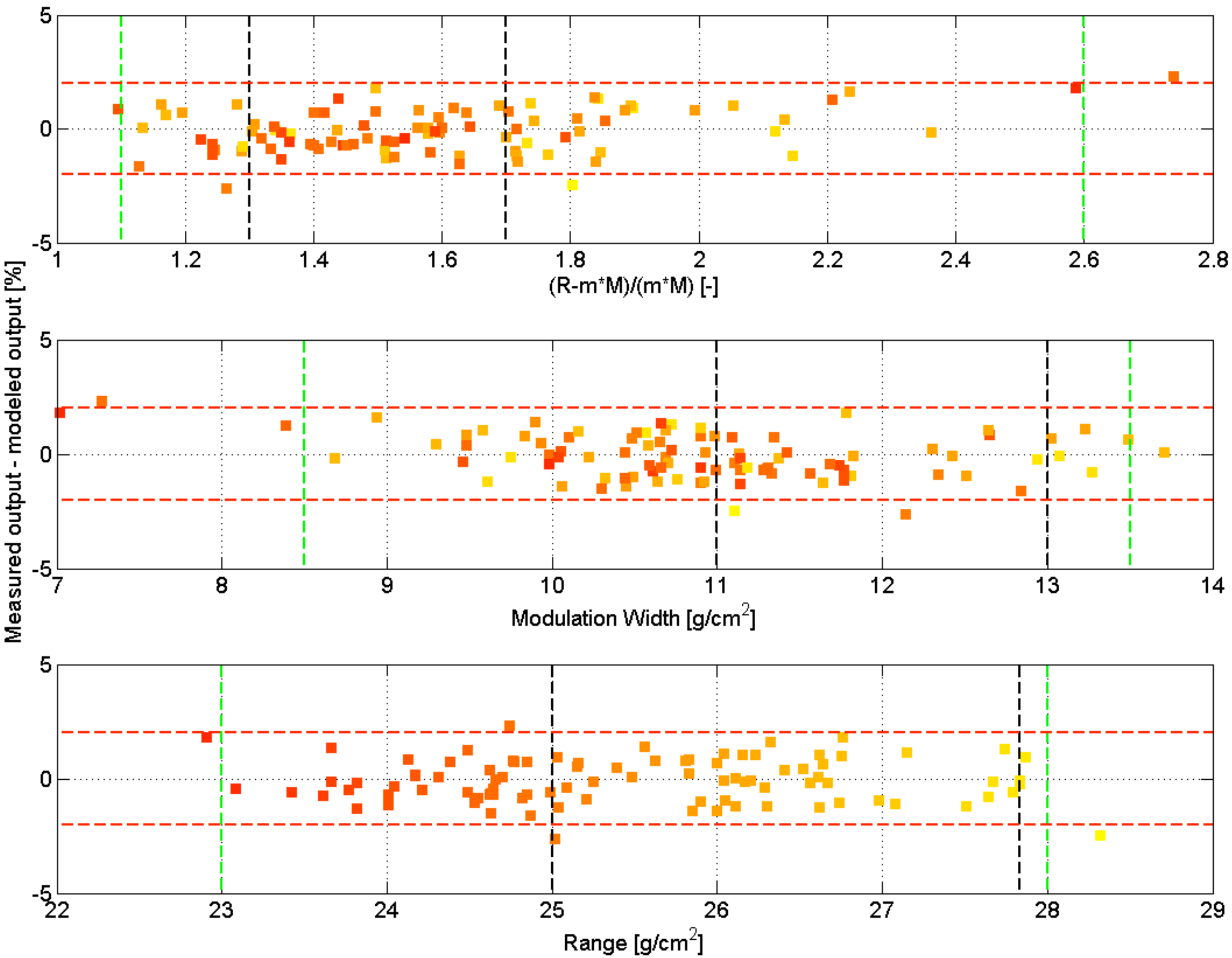


Measurements – Output Model

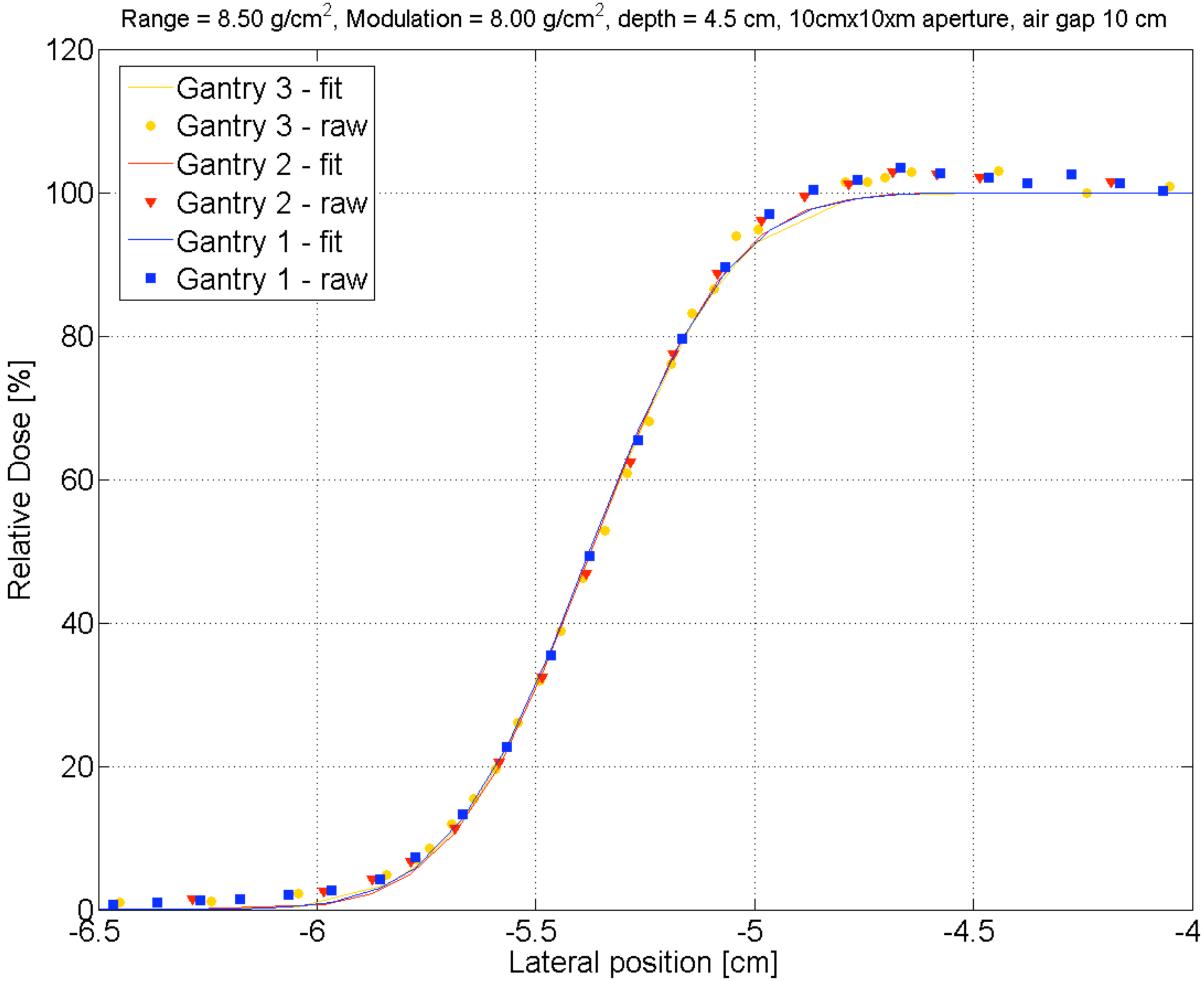


Kooy et al PMB 2005

Measurements – Output Model



Measurements – Comparison of Rooms



References

I. scattering techniques

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- W.T. Chu, B.A. Ludewigt and T.R. Renner, ‘Instrumentation for treatment of cancer using proton and light-ion beams,’ Rev. Sci. Instr. 64 (1993) 2055-2122.
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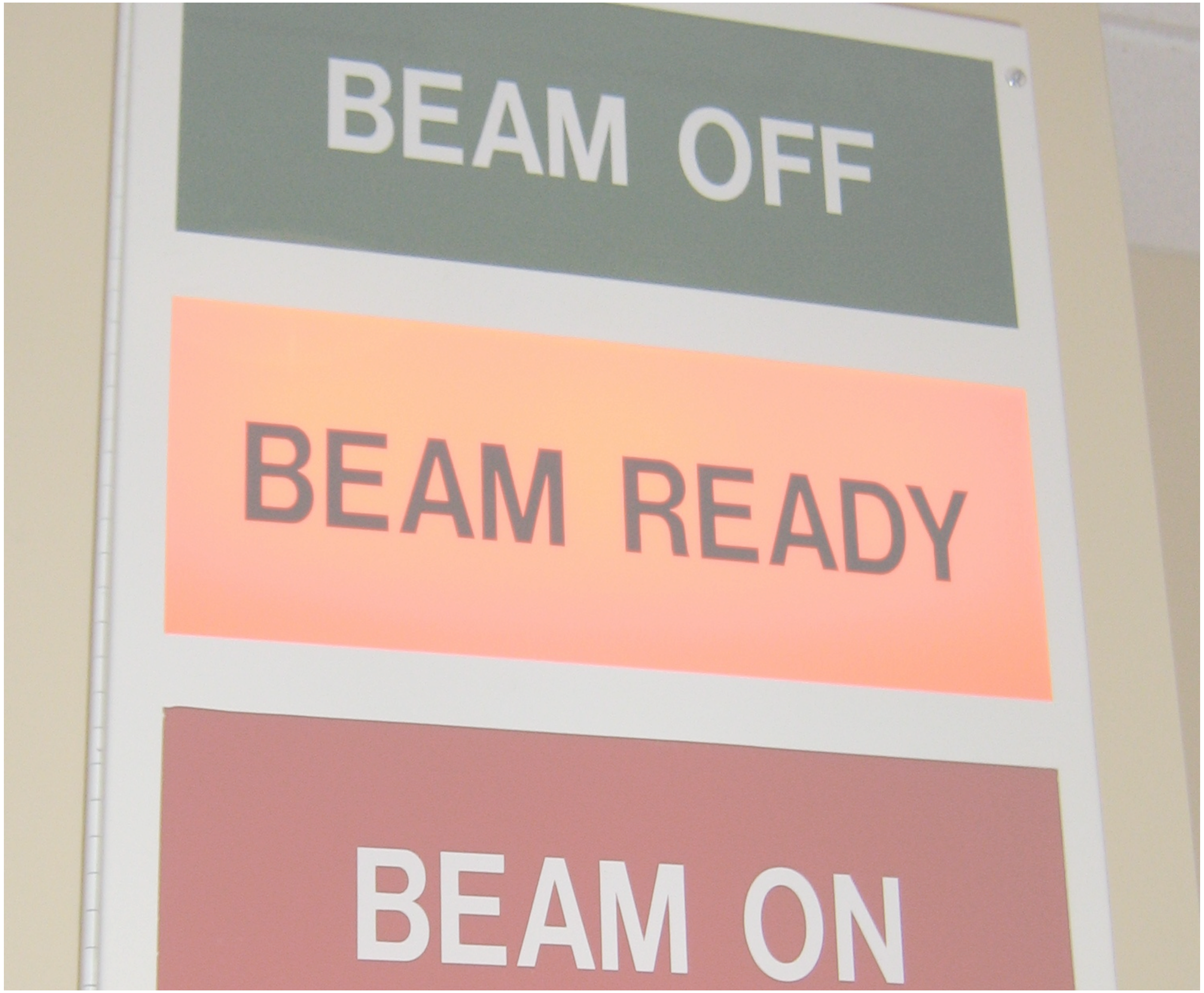
- Ridge filter design for proton therapy at Hyogo Ion Beam Medical Center, T.Akagi et al,Phys. Med. Biol. 48 No 22 (21 November 2003) N301-N312

I. dosimetric properties

II. commissioning

- AAPM code of practice for radiotherapy accelerators: Report of AAPM Radiation Therapy Task Group No. 45



THANK YOU