Proton Beam Delivery Techniques and Commissioning Issues: 

*Scattered Proton Beams*

Roelf Slopsema

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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
spread the beam laterally

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

active scanning
- 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

layer 1

\[ W^1 \propto Q^1 \]

\[ P^+ (E_0) \]

\[ R^1 \]
pullback \((R_1 - R_2)\) set to width of pristine peak at 80% level
weight layer 2 about 1/3 of layer 1: \(W_2 \approx 0.3 \times W_1\)
Range modulation / variable range shifter

layer 3

absorbers

$Q_3$

$P^+(E_0)$

$W_3 \propto Q_3$

pullback typically kept constant over layers (shape same)

weight layer 3 : $W_3 \approx 0.2 \times W_1$
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

Diagram: Chu '93
<table>
<thead>
<tr>
<th>Step#</th>
<th>thickness</th>
<th>angular width</th>
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<tbody>
<tr>
<td>1</td>
<td>1.8 cm.H20</td>
<td>76 deg</td>
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Range modulation / RM wheel

Target

$E = 147$ MeV
E = 147 MeV

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1. $E_1 = 147$ MeV - $w_1 = 89\%$
2. $E_2 = 143$ MeV - $w_2 = 30\%$

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2. $E_2 = 143 \text{ MeV}$ - $w_2 = 30\%$
3. $E_3 = 139 \text{ MeV}$ - $w_3 = 25\%$
4. $E_4 = 135 \text{ MeV}$ - $w_4 = 19\%$
5. $E_5 = 130 \text{ MeV}$ - $w_5 = 16\%$

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<th>Modulation</th>
<th>stop angle</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2 cm.H20</td>
<td>170 deg</td>
</tr>
<tr>
<td>2</td>
<td>7.0 cm.H20</td>
<td>250 deg</td>
</tr>
<tr>
<td>3</td>
<td>11.1 cm.H20</td>
<td>316 deg</td>
</tr>
<tr>
<td>4</td>
<td>“full”</td>
<td>360 deg</td>
</tr>
</tbody>
</table>

Modulation = 3.2 cm, skin dose = 51%
Modulation = 7.0 cm, skin dose = 68%
Modulation = 11.1 cm, skin dose = 80%
Modulation = ‘up to skin’, skin dose = 100%
Range modulation / weight optimization

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

\[ w_2 \downarrow : \text{‘shoulder’} \rightarrow \text{better uniformity} \]

\[ w_1 \uparrow : \text{‘dip\&bump’} \rightarrow \text{sharper distal fall-off} \]

...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:**
  weights 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
Figure 2. A bar ridge filter for the proton beam in the gantry nozzle (a), the cross-sectional shape of the ridge for 6 cm SOBP (b).
<table>
<thead>
<tr>
<th>variable range shifter</th>
<th>RM wheel</th>
<th>ridge filter</th>
</tr>
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<tbody>
<tr>
<td>energy stacking</td>
<td>SOBP delivered with frequency RM rotation</td>
<td>instantaneous delivery SOBP</td>
</tr>
<tr>
<td>no problems with beam time structure</td>
<td>rotational speed should be large compared to beam time structure</td>
<td>no problems with beam time structure</td>
</tr>
<tr>
<td>organ motion is concern</td>
<td>organ motion (typically) no problem</td>
<td>no problems with organ motion</td>
</tr>
<tr>
<td>partial delivery is concern</td>
<td></td>
<td></td>
</tr>
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</table>
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
Advantages:
- little energy (range) loss
- more efficient than SS

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

Diagram: Chu ’93

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

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

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

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)

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 \( \theta \)

[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

80%-20% penumbra is given by

\[ \theta_p \] sigma

of gaussian fit to angular spread
### Dosimetric properties

<table>
<thead>
<tr>
<th></th>
<th>Defined by</th>
<th>Determines</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAD</strong></td>
<td>Average angular spread</td>
<td>Beam divergence (&amp; z fluence)</td>
<td></td>
</tr>
<tr>
<td><strong>Effective Source Size</strong></td>
<td>Variation around average of angular spread</td>
<td>Lateral penumbra (&amp; inhomogeneity)</td>
<td></td>
</tr>
</tbody>
</table>
Single thin scatterer

\[ p^+(E_0) \]
\[ \theta_0 = 0, \sigma_0 = 0 \]

\[ S_1(\theta_1) \]

\[ \Phi(z, r, \theta) = \exp \left\{ -\frac{(r - (z_s - z)\theta)^2}{2\sigma_s^2} \right\} \cdot \exp \left\{ -\frac{\theta^2}{\sigma_1^2} \right\} \]

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

\[ \theta_s = \sqrt{\theta_0^2 + \theta_1^2 + \ldots + \theta_N^2} \]

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

\[ z_s = \left( \frac{z_0 \theta_0^2 + z_1 \theta_1^2 + \ldots + z_N \theta_N^2}{\theta_s^2} \right) \]

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

\[ \text{SAD} = z_1 \]

\[ \sigma_{\text{source}} = 0 \]

\[ \sigma(z) = \theta_1 (z_1 - z) \]
Two thin scatterers

\[ \theta_0 = 0, \sigma_0 = 0, z_0 \]

\[ N = 2 \]

\[ SAD = \frac{z_1 \theta_1^2 + z_2 \theta_2^2}{\theta_s^2} \]

\[ \sigma_{source}^2 = ((z_1 - SAD)^2 \theta_1^2 + (z_2 - SAD)^2 \theta_2^2) \]

\[ \theta_s^2 = \theta_1^2 + \theta_2^2 \]

\[ \sigma(z)^2 = \sigma_{source}^2 + (SAD - z)^2 \theta_s^2 \]
Two thin scatterers: SAD versus scattering power ratio

- $z_1 = 300\,\text{cm}$
- $z_2 = 200\,\text{cm}$
- $\sigma(z=0) = 9.0\,\text{cm}$
Two thin scatterers: source size versus scattering power ratio

\[ \sigma(z=0) = 9.0 \text{ cm} \]
Two thin scatterers: penumbra versus scattering power ratio

- $z_1 = 300\text{cm}$
- $z_2 = 200\text{cm}$
- $\sigma(z=0) = 9.0\text{cm}$
- air gap: $20\text{cm}$

Source size

$80\%-20\%$ penumbra [cm]

$\theta_2 / \theta_1$ [-]
Two thin scatterers: source size versus distance between scatt.

\[ \theta_1 = \theta_2 \]
\[ \sigma(z=0) = 9.0 \text{cm} \]
Contoured second-scatterer

$S_1(\theta_1)$ $S_2(\theta_2(r))$

$\theta_0 \neq 0, \sigma_0 \neq 0$

See Gottschalk: Passive Beam Spreading
Contoured second scatterer: SAD versus range

- E = 196 MeV
- FS lead thickness = 0.81 mm
- Z1 = 280 cm
- Z2 = 180 cm
- Thickness SS: 3.6 cm H2O
- Max. field diameter: 24 cm

- E = 183 MeV
- FS lead thickness = 0.25 mm
Contoured second scatterer: SAD versus range

SS1: 24cm diameter
SS2: 24cm diameter
SS3: 14cm diameter
Contoured second scatterer: source size versus range

![Graph showing the relationship between effective source size (cm) and range (g/cm²)]
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
Measurements – Comparison of Rooms

Range = 8.50 g/cm², Modulation = 8.00 g/cm², depth = 4.5 cm, 10cmx10cm aperture, air gap 10 cm
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 contract

- a limited set, covering random samples of the complete ‘space’ of delivery parameters

- describing in detail the measurement setup and the specified limits

- distinction between design specifications and installation specifications

- do not allow you to treat a single patient
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.
Commissioning

• Verification of the dose distribution over the complete set of prescribed parameters

• Verification of setup and localization equipment
  ▪ patient positioner
  ▪ gantry
  ▪ imaging equipment

• Treatment planning commissioning
  ▪ measurement of the beam data library
  ▪ verification of the modeled dose distribution

• Definition of Quality Assurance and other clinical procedures (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?
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

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

- Depth dose
  - uniformity profile (tilt/flatness)
  - maximum field size
  - lateral penumbra vs. depth
  - field size vs. depth

- Lateral
  - dose per MU
  - dose rate

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

For what subset of prescribed parameters do these need to be verified?
Defining the subset - Range

**Does the range depend on......**

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<td>Modulation</td>
<td>No</td>
</tr>
<tr>
<td>Field size</td>
<td>No</td>
</tr>
<tr>
<td>Snout size</td>
<td>No</td>
</tr>
<tr>
<td>Gantry angle</td>
<td>Unlikely</td>
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<td>Dose rate</td>
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<tr>
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**Measure...**
- 4 SOBP’s per suboption
- 2 SOBP’s for 2 gantry angles
Defining the subset \(\text{– PDD uniformity}\)

*Does the PDD uniformity depend on...*

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*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*
Examples of Commissioning Measurements
Measurements – Range Reproducibility
Measurements – Range Reproducibility
Measurements – Output and Dose Rate
Measurements – Output and Gantry Angle

Variation in Output around mean [%]

R=19.83, M=17.40, B7, 12/04
R=13.34, M=4.40, BRAIN, 12/04
R=19.83, M=17.40, B7, 11/28

Gantry Angle [deg]

Note: lines to guide the eye
Measurements – Dose distribution and snout size

\( P^+ \) - 10-cm snout

\( P^+ \) - 25-cm snout
Measurements – Dose distribution and snout size

Range = 13.70 g/cm², Modulation = full, option B5

- 25 cm snout - 24 cm diameter
- 18 cm snout - 18 cm diameter
- 18 cm snout - 12 cm diameter
- 10 cm snout - 12 cm diameter
- 10 cm snout - 7 cm diameter
Measurements – Dose distribution and snout size
Measurements – Output Model

\[ r = \frac{(R - m \cdot M)}{(m \cdot M)} \]

Kooy et al PMB 2005
Measurements – Output Model
Measurements – Comparison of Rooms

Range = 8.50 g/cm², Modulation = 8.00 g/cm², depth = 4.5 cm, 10cmx10cm aperture, air gap 10 cm
References

I. scattering techniques


II. dosimetric properties

II. commissioning

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