Optimisation of the ion optical range adaptation method for tracking of moving tumours with scanned ion beams

Anna Constantinescu, GSI
Overview

• Motivation

• GSI beam tracking system
• Ion optical solution

• Beam characteristics after energy degrader: shape, material
• Semi-automatical magnet determination

• Summary
• Outlook
Tracking with scanned ion beams

Scanned beam tracking: \((x, y, z) + (dx, dy, dz)\)

Adaptation different for each spot: fast and accurate

Scanning speed: 10 ms
Therapy beam line
Lateral deflection: scanning magnets (x,y)

Longitudinal adaptation: double-wedge system
GSI beam tracking

Lateral deflection: scanning magnets (x,y)

Longitudinal adaptation: double-wedge system
GSI beam tracking

Lateral deflection: scanning magnets (x,y)
Longitudinal adaptation: double-wedge system
GSI beam tracking

Lateral deflection: scanning magnets (x,y)
Longitudinal adaptation: double-wedge system
Drawbacks of double wedge system

- Mechanical solution (limited speed)
- Moving device in front of patient
- Exposure to secondary particles

Ion optical solution
Ion optical solution

Diagram showing a beam path with components such as D1, D2, and a target, with labels for Dose and Range.
Ion optical solution
Ion optical solution
Ion optical solution

- No mechanical solution
- No moving device in front of patient
- Minimal exposure to secondary particles
Ion optical solution

- Initial feasibility study: Naved Chaudhri (dissertation 2010)
- Comparison: experiments, simulations (beam spot, range)
- Ramp degrader $\rightarrow$ non-Gaussian component in beam profile

✓ Principle confirmed
✗ Systematic studies (tail) $\iff$ optimisation

N. Chaudhri, “Ion optical studies for a range adaptation method in ion beam therapy using a static wedge degrader combined with magnetic beam deflection”, PMB, 2010
MOCADI – simulation toolkit

- Transport of ions through ion optical systems, matter
- Monte-Carlo code
- Developed by T. Schwab, N. Iwasa, H. Weick at GSI
  - Modules: magnets, degrader, target, drift, …
  - Energy loss calculation: ATIMA
  - Fragmentation: EPAX
  - Result: - beam profiles at isocenter
    - position (x, y), angle (a, b)
    - energy
    - transmission
    - range
    - fragments (A,Z)

Scheidenberger et al., Phys.Rev.Lett.73, 1990

www-linux.gsi.de/~weick/mocadi
Systematic studies: selected parameters

Shape:

- \( x_{\text{shift}} : 0, \pm 15, \pm 25, \pm 30 \text{ [mm]} \)
- Slope \( \tan \theta = 0.58, 0.47, 0.35 \text{ [mmH}_2\text{O/mm]} \)
- Middle thickness \( t_0 = 9.0, 6.8, 6.38, 13.19 \text{ [mm]} \)

Material:

- Be, C, Al, plastic

\[
t_i = t_0 + x_{\text{shift}} \cdot \tan \theta
\]

<table>
<thead>
<tr>
<th></th>
<th>( ^{9}_{4}\text{Be} )</th>
<th>( ^{12}_{6}\text{C} )</th>
<th>( ^{27}_{13}\text{Al} )</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular straggling</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Resistance</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Known profile</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>/</td>
</tr>
</tbody>
</table>

V. Anferov, Indiana University Cyclotron Facility, 2002
R. Neumann, NIMB 151, 1999
M. Maier, Uni Giessen, Diss, 2004
Overview: Results

- **Lateral beam profile:**
  - Beam distribution \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - Size of tail (at Gaussian 1\(\sigma\), 2\(\sigma\), 3\(\sigma\)) \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - Parametrisation of beam profile

- **Particle range:**
  - Range distribution
  - Range shift \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - FWHM \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Transmission:** \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Fragmentation yield:** (material)

- **Magnet strength determination**
Beam profile: $x_{\text{shift}}$

- $x_{\text{shift}} = -15$ mm
- $x_{\text{shift}} = 15$ mm
- $x_{\text{shift}} = 25$ mm
Beam profile: slope

\[ \tan \theta = 0.58 \]
\[ \tan \theta = 0.47 \]
\[ \tan \theta = 0.35 \]
Beam width: $x_{\text{shift}}$ & slope

Material thickness increases: FWHM increases, total beam gets wider
Slope increases: FWHM decreases, increased tail part
Difference between data and Gaussian Fit: $1\sigma$, $2\sigma$, $3\sigma$
Difference $\Delta$ (data – fit) : $1\sigma$

$\Delta$ increases with $\sigma$ (tail)

**Shape:** $\Delta$ increases with slope (dispersion)

**Material thickness:** $\Delta$ bigger for $x_{\text{shift}} > 0$ mm than for $x_{\text{shift}} < 0$ mm (scattering)
Difference $\Delta$ (data – fit) : $2\sigma$

$\Delta$ increases with $\sigma$ (tail)

**Shape:** $\Delta$ increases with slope (dispersion)

**Material thickness:** $\Delta$ bigger for $x_{\text{shift}} > 0$ mm than for $x_{\text{shift}} < 0$ mm (scattering)
Difference $\Delta$ (data – fit) : $3\sigma$

$\Delta$ increases with $\sigma$ (tail)

**Shape**: $\Delta$ increases with slope (dispersion)

**Material thickness**: $\Delta$ bigger for $x_{\text{shift}} > 0$ mm than for $x_{\text{shift}} < 0$ mm (scattering)
Beam profile: materials (same thickness in WEL)

- Beryllium
- Graphite
- Plastic
- Aluminium

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Beam profile (x,y) | Range | Transmission | Fragmentation | Determination

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Difference $\Delta (data - fit) : 3\sigma$

<table>
<thead>
<tr>
<th>Beam profile (x,y)</th>
<th>Range</th>
<th>Transmission</th>
<th>Fragmentation</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference $\Delta$</td>
<td>$\sigma$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta (data - fit) : 3\sigma$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing beam profile with differences](image-url)
Laterial distribution: well fitted by sum of 3 Gaussians
Lateral distribution: well fitted by sum of 3 Gaussians
Difference data/fit at 3σ: simple & sum of 3 Gaussian

For a simple Gaussian fit:

For fit with sum of 3 Gaussians:

Analytical parametrisation with 3 Gaussians → **Implementation in TRiP**
Overview: Results

- **Lateral beam profile:**
  - Beam distribution \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - Size of tail (at Gaussian \(1\sigma, 2\sigma, 3\sigma\)) \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - Parametrisation of beam profile

- **Particle range:**
  - Range distribution
  - Range shift \((x_{\text{shift}} / \text{slope} / \text{material})\)
  - FWHM \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Transmission:** \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Fragmentation yield:** (material)

- **Magnet strength determination**
**Range distribution**

- $x_{\text{shift}} = -30 \text{ mm}, 0.35 \text{ mmH}_2\text{O/mm}$
- $x_{\text{shift}} = 0 \text{ mm}, 0.47 \text{ mmH}_2\text{O/mm}$
- $x_{\text{shift}} = 25 \text{ mm}, 0.58 \text{ mmH}_2\text{O/mm}$
Range shift: 0.35 mmH$_2$O/mm
Range shift: 0.35 mmH$_2$O/mm

Range shift: 19 mm WEL
Range shift: 0.47 mmH$_2$O/mm

Range shift: 23 mm WEL
Range shift: 0.58 mmH$_2$O/mm
FWHM of range: $x_{\text{shift}}$ and slope

- FWHM R independent of material thickness
- FWHM R bigger with steeper slope
FWHM of range, slope = 0.35 mmH$_2$O/mm: materials

- All materials: FWHM < 1.8 mmH$_2$O
- Smallest FWHM: Be, Al
FWHM of range, slope = 0.47 mmH$_2$O/mm: materials

- All materials: FWHM < 1.8 mmH$_2$O
- Smallest FWHM: Be, Al
Motivation | GSI Beam Tracking | Ion Optical Solution | Optimisation | Summary & Outlook
Beam profile (x,y) | Range | Transmission | Fragmentation | Determination

FWHM of range, slope = 0.58 mmH$_2$O/mm: materials

- All materials: FWHM < 1.8 mmH$_2$O
- Smallest FWHM: Be, Al
Overview: Results

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  - Range shift \( (x_{\text{shift}} \text{ / slope} \text{ / material}) \)
  - FWHM \( (x_{\text{shift}} \text{ / slope} \text{ / material}) \)

- **Transmission:** \( (x_{\text{shift}} \text{ / slope} \text{ / material}) \)

- **Fragmentation yield:** (material)

- **Magnet strength determination**
Transmission: slope $= 0.35 \text{ mmH}_2\text{O/mm}$

**Shape:**
- no effect due to slope (see $x_{\text{shift}} = 0 \text{ mm}$)
- transmission dependent on deflection and material thickness

**Materials:** Be highest transmission, Al lowest
Transmission: slope = 0.47 mmH₂O/mm

Shape:
- no effect due to slope (see $x_{\text{shift}} = 0$ mm)
- transmission dependent on deflection and material thickness

Materials:
Be highest transmission, Al lowest
Transmission: slope = 0.58 mmH₂O/mm

**Shape:**
- no effect due to slope (see $x_{\text{shift}} = 0$ mm)
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**Materials:** Be highest transmission, Al lowest
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  - FWHM \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Transmission:** \((x_{\text{shift}} / \text{slope} / \text{material})\)

- **Fragmentation yield:** \(\text{material}\)

- **Magnet strength determination**
Fragmentation yield for ion optical solution

After degrader

Beryllium

Graphite

Aluminum

<table>
<thead>
<tr>
<th>Element</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>4.23%</td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td></td>
</tr>
<tr>
<td>He</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
</tr>
</tbody>
</table>

Motivation | GSI Beam Tracking | Ion Optical Solution | Optimisation | Summary & Outlook

Beams profile (x,y) | Range | Transmission | Fragmentation | Determination

Normalised by number of incident 12C particles

He 3 4 5 6 7 8 He
H 1 2 3 H

He 3 4 5 6 7 8 He
H 1 2 3 H

He 3 4 5 6 7 8 He
H 1 2 3 H

Total yield: 4.23% 3.24% 2.20%
Fragmentation yield for ion optical solution

**Motivation** | **GSI Beam Tracking** | **Ion Optical Solution** | **Optimisation** | **Summary & Outlook**

- Beam profile \((x,y)\)
- Range
- Transmission
- Fragmentation
- Determination

**Motivation**

- **GSI Beam Tracking**
- **Ion Optical Solution**
- **Optimisation**
- **Summary & Outlook**

**Fragmentation yield for ion optical solution**

**Beryllium**
- At isocenter: total yield: 0.10%
- After degrader: total yield: 4.23%

**Graphite**
- At isocenter: total yield: 0.07%
- After degrader: total yield: 3.24%

**Aluminum**
- At isocenter: total yield: 0.04%
- After degrader: total yield: 2.20%

**Normalised by number of incident \(^{12}\text{C}\) particles**

**Higher Z**

- Beryllium: total yield: 4.23%
- Graphite: total yield: 3.24%
- Aluminum: total yield: 2.20%

**W/o slit**

- Beryllium: total yield: 0.10%
- Graphite: total yield: 0.07%
- Aluminum: total yield: 0.04%

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Fragmentation yield: slit
Motivation | GSI Beam Tracking | Ion Optical Solution | Optimisation | Summary & Outlook

Beam profile (x,y) | Range | Transmission | Fragmentation | Determination

Fragmentation yield: slit
Fragmentation yield for ion optical solution

After degrader

- Beryllium: total yield: 4.23 %
- Graphite: total yield: 3.24 %
- Aluminum: total yield: 2.20 %

At isocenter

- Beryllium: total yield: 0.11 %
- Graphite: total yield: 0.08 %
- Aluminum: total yield: 0.05 %

Normalised by number of incident $^{12}$C particles

Motivation | GSI Beam Tracking | Ion Optical Solution | Optimisation | Summary & Outlook

Beam profile (x,y) | Range | Transmission | Fragmentation | Determination

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Fragmentation yield at isocenter

<table>
<thead>
<tr>
<th>Material</th>
<th>Beryllium</th>
<th>Graphite</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion optical solution (degrader between D1 and D2):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At isocenter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Be</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Li</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>He</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>total yield:</td>
<td>0.04%</td>
<td>0.03%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

| Double wedge (90 mm WEL) at isocenter (22 cm upstream): | | |
| At isocenter | | |
| C | 9 | 10 | 11 | 12 | C |
| B | 8 | 9 | 10 | 11 | B |
| Be | 7 | 8 | 9 | 10 | Be |
| Li | 6 | 7 | 8 | 9 | Li |
| He | 3 | 4 | 5 | 6 | 7 | 8 | He |
| H | 1 | 2 | 3 | H |
| total yield: | 18.07% | 15.89% | 12.16% |
Fragment distribution: Be degrader
Overview: Results

- **Lateral beam profile:**
  - Beam distribution ($x_{\text{shift}}$ / slope / material)
  - Size of tail (at Gaussian 1σ, 2σ, 3σ) ($x_{\text{shift}}$ / slope / material)
  - Parametrisation of beam profile

- **Particle range:**
  - Range distribution
  - Range shift ($x_{\text{shift}}$ / slope / material)
  - FWHM ($x_{\text{shift}}$ / slope / material)

- **Transmission:** ($x_{\text{shift}}$ / slope / material)

- **Fragmentation yield:** (material)

- **Magnet strength determination**
Magnet strength

Manual setting of magnet strength (0, ± 15, ± 25, ± 30 [mm]) → beam characteristics

semi – automatically magnet strength determination ← arbitrary positions for therapy
Magnet strength

Manual setting of magnet strength (0, ± 15, ± 25, ± 30 [mm]) → beam characteristics

semi – automatically magnet strength determination ← arbitrary positions for therapy
Magnet strength

Manual setting of magnet strength (0, ±15, ±25, ±30 [mm]) → beam characteristics

semi–automatically magnet strength determination ← arbitrary positions for therapy
Manual setting of magnet strength (0, ± 15, ± 25, ± 30 [mm]) → beam characteristics

semi–automatically magnet strength determination ← arbitrary positions for therapy
Magnet strength: $E_{D1}$

The diagram shows a quadratic fit to the data with the equation $y = ax^2 + bx + c$.

The coefficients are as follows:

- $a = 0.000601017$, $a_{err} = 0.000348987$
- $b = -0.005924$, $b_{err} = 0.0048627$
- $c = 99.988$, $c_{err} = 0.199773$
Magnet strength: $E_{\text{out}}$

\begin{align*}
a &= -0.000208207 \\
b &= -0.232309 \\
c &= 98.6143 \\
d &= -0.000541015 \\
e &= -0.302299 \\
f &= 98.6587 \\
i &= -0.00059423 \\
j &= -0.370987 \\
k &= 98.6989
\end{align*}

\begin{align*}
a_{\text{err}} &= 0.00013188 \\
b_{\text{err}} &= 0.0013481 \\
c_{\text{err}} &= 0.0791038 \\
d_{\text{err}} &= 0.00240454 \\
e_{\text{err}} &= 0.000178096 \\
f_{\text{err}} &= 0.031013 \\
i_{\text{err}} &= 0.00038451 \\
j_{\text{err}} &= 0.00700978 \\
k_{\text{err}} &= 0.123332
\end{align*}

\begin{align*}
slope &= 0.35 \text{ mmH2O/mm} \\
f(x) &= ax^2 + bx + c \\
slope &= 0.47 \text{ mmH2O/mm} \\
g(x) &= dx^2 + ex + f \\
slope &= 0.58 \text{ mmH2O/mm} \\
h(x) &= ix^2 + jx + k
\end{align*}
Magnet strength: $E_{D2}$ (rel. $E_{in}$)

![Graph showing relationship between $E_{D2}$ and $E_{in}$ with various parameters and equations for graphing lines.

Parameters and equations:
- $a = -0.000813493$, $a_{err} = 5.65719e^{-05}$
- $b = 0.0657115$, $b_{err} = 0.000791644$
- $c = 90.5892$, $c_{err} = 0.0329674$
- $d = -0.00124854$, $d_{err} = 0.000630935$
- $e = -0.00771491$, $e_{err} = 4.31951e^{-05}$
- $f = 90.6224$, $f_{err} = 0.0211031$
- $i = -0.00176006$, $i_{err} = 0.00030138$
- $j = -0.0084203$, $j_{err} = 0.00710789$
- $k = 90.6045$, $k_{err} = 0.123633$

Slopes:
- $f(x) = ax^2 + bx + c$
- $g(x) = dx^2 + ex + f$
- $h(x) = ix^2 + jx + k$

Slopes:
- $0.35$ mmH2O/mm
- $0.47$ mmH2O/mm
- $0.58$ mmH2O/mm

Range, Transmission, Fragmentation, Determination
Magnet strength: $E_{D2}$ (rel. $E_{\text{out}}$)

Elastic electron scattering on Au at 400 MeV. E$_{D2}$ is obtained from a fit of the energy distribution to a power law. The fit parameters are:

- $a = 0.00013612$, $a_{\text{err}} = 0.000125226$
- $b = 0.329749$, $b_{\text{err}} = 0.00175236$
- $c = 99.9632$, $c_{\text{err}} = 0.0716475$
- $d = 0.00035639$, $d_{\text{err}} = 0.00417558$
- $e = 0.32646$, $e_{\text{err}} = 0.00028869$
- $f = 99.945$, $f_{\text{err}} = 0.139663$
- $i = 0.00057597$, $i_{\text{err}} = 0.000194628$
- $j = 0.321489$, $j_{\text{err}} = 0.00194977$
- $k = 99.9709$, $k_{\text{err}} = 0.0339176$

The slope of the fit is:

- $0.35$ MeV/MeV
- $0.47$ MeV/MeV
- $0.58$ MeV/MeV

The equations for the fit are:

- $f(x) = ax^2 + bx + c$
- $g(x) = dx^2 + ex + f$
- $h(x) = ix^2 + jx + k$
Verification of determined settings: lateral beam profile

\( x_{\text{shift}} = -15 \, \text{mm} \)

\( x_{\text{shift}} = -8 \, \text{mm} \)

\( x_{\text{shift}} = 15 \, \text{mm} \)

\( x_{\text{shift}} = 18 \, \text{mm} \)

\( x_{\text{shift}} = 25 \, \text{mm} \)
Verification of determined settings: Particle range

![Graph showing the relationship between range and x-shift for different materials (Be, C, Plastic, Al) with predictions for Be, C, Plastic, and Al for a slope of 0.47 mm/m.](image-url)
Verification of determined settings: Particle range

![Graph showing FWHM of range vs. x-shift in mm.](image)
Verification of determined settings: Transmission

![Graph showing transmission percentage vs. x-shift in nanometers]

- Be
- C
- Plastic
- Al

- Be prediction
- C prediction
- Plastic prediction
- Al prediction

Transmission [%] vs. x-shift [nm]
Summary

- **Lateral beam profile:**
  - Beam distribution \( (x_{\text{shift}} / \text{slope} / \text{material}) \)
  - Size of tail \( (1\sigma, 2\sigma, 3\sigma) \) \( (x_{\text{shift}} / \text{slope} / \text{material}) \)
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- **Particle range:**
  - Range distribution
  - Range shift \( (x_{\text{shift}} / \text{slope} / \text{material}) \)
  - FWHM \( (x_{\text{shift}} / \text{slope} / \text{material}) \)

- **Transmission:** \( (x_{\text{shift}} / \text{slope} / \text{material}) \)

- **Fragmentation yield:** \( \text{(material)} \)

- **Magnet strength determination**

**Summary & favored settings:**

- Small \( x_{\text{shift}} \): smaller scattering
- Shallower slope favored
- Be: smallest angular scattering
- Sum of 3 Gaussians

- Range shift: middle slope favored
- FWHM \( R < 3 \text{ mmH}_2\text{O} \): materials
- FWHM \( R < 3 \text{ mmH}_2\text{O} \): slope

- Be: biggest transmission
- Ion optical \( << \) double wedge
- Be (with Slit)

- Analytical determination possible
Outlook

• Dose calculation in TRiP using sum of 3 Gaussians

• Implementation of Be degrader in beam line

• Simulation for HIT and Marburg beam line?

• Design of ideal beam line
Thank you for your attention!

Thank you to the “Motion Team”….
Christoph Bert, Naved Chaudhri, Sebastian Hild, Robert Luechtemborg, Dirk Muessig,
Johnny Nguyen, Daniel Richter, Nami Saito, Peter Steidl, Jan Trautmann