Scanning Beam Dose Delivery

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Outline

• Situation/Rationale
• Standard (passive) dose delivery
• Semi-active dose delivery
• Beamscanning
• Implementation@HIT
Situation

- 2/3 patients suffer from a local disease at the time of diagnosis
- In 18% local treatment modalities fail => 280,000 deaths/year in the EC
- Protons and ions have the potential to cure 30,000 patients/year in the EC

Relevance of local tumor control (EC-study 1991)
Rationale / Physics

- Advantageous physical characteristics: inverted depth-dose distribution
Rationale / Physics

- Advantageous physical characteristics: small lateral scattering
Goal
The key element to improve the clinical outcome is **local control!**

Entrance channel:
- low physical dose
- low rel. biol. efficiency

Tumour:
- high physical dose
- high rel. biol. efficiency
Standard Approach

- Facilities being built at existing research accelerators
- Fixed energy machines with moderate flexibility (if at all)
- Dose delivery not tumor-conform
Passive Dose Delivery

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Passive / Longitudinal Spread

- **Passive** static longitudinal spreading via ridge filter or rotating wheels
- spares the distal edge at the expense of the proximal (dose pull-back)
Passive / System + Dose Distr.

**typical set-up (Tsukuba)**

- Scatterer
- Fine degrader
- Ridge Filter
- First collimator
- Bolus
- Final collimator
- Body
- Cancer

**Figure 3-2 Ridge Filter**

**Figure 3-3 Bolus**

**Figure 3-4 Final collimator**

Distal edge shaping using a bolus pulls dose back into healthy tissue.
Situation / Clinical Centers

• In 1994 the first dedicated clinic-based facilities, LLMUC (protons) and HIMAC (carbon), started.
• Nowadays more than 50 proton treatment protocols are approved and reimbursed in the US.
• LLUMC treats up to 180 patients per day.

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Semi-active / Layer-stacking

- developed for Carbon therapy @ HIMAC, Chiba
- combines lateral wobbling plus scattering with stacking of layers (some cm H₂O)
- each layer represents a small spread-out Bragg peak
- each layer may have individual weight
- improved conformity

*Kanai et al., Med Phys. 2006 (33)*

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Semi-active / Layer-stacking

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Semi-active / Layer-stacking

wedge-shaped dose distribution
Active Dose Delivery

The inverse approach:

Dose distributions of utmost tumor conformity can be produced by superimposing many thousands Bragg-peaks in 3D. Sophisticated requirements concerning the beam delivery system, the accelerator, the treatment planning, QA, ... result from this approach.

The basic idea:

Dissect the treatment volume into thousands of voxels. Use small pencil beams with a spatial resolution of a few mm to fill each voxel with a pre-calculated amount of stopping particles taking into account the underlying physical and biological interactions.

=> Extreme intensity modulation

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Active / Longitudinal

- **active** energy variation in the accelerator
- virtual dissection of the tumor (range stepping mm-resolution)
Scanning

Protons (Pedroni et al., PSI):
- spot scanning gantry
- 1D magnetic pencil beam scanning
- plus passive range stacking (digital range shifter)

Ions (Haberer et al., GSI):
- raster scanning, 3D active,
- 2D magnetic pencil beam scanning
- plus active range stacking (spot size, intensity)
in the accelerator

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Active / Lateral

• superpositioning of gaussian beam spots, statistics

10^3 particles

10^5 particles
Active / Lateral

- 2d superpositioning, step size and beam spot size
Active / Lateral

- homogeneity of fluence distributions

**Geometry**

- $\homogeneity \propto \exp(\alpha \delta)$

**Statistics**

- $\homogeneity \propto 1/\sqrt{F}$

- Data points:
  - $F/cm^2$
  - Homogeneity (%)
  - $\delta_{pixel}/\text{fwhm}$
  - $\delta_{FWHM}$
  - $10^5$
  - $10^6$

Data points:
- 1.27
- 1.19
- 1.10
- 1.02
- 0.93
- 0.85
- 0.68
- 0.51
Rasterscan Method

scanning of focussed ion beams in fast dipole magnets

active variation of the energy, focus and intensity in the accelerator and beam lines

Haberer et al., NIM A, 1993
Fluence distribution of a single slice through the target volume

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Scanned Carbon vs. Intensity Modulated Photons

scanned carbon 3 fields

IMRT 9 fields

courtesy O. Jäkel, HIT

- reduced integral dose
- steeper dose gradients
- less fields
- increased biological effectiveness
Therapy @ GSI
Key Developments @ GSI

- Scanning-ready **pencil beam library** (25,000 combinations):
  253 energies (1mm range steps) x 7 spot sizes x 15 intensity steps
- **Rasterscan method** incl. approved controls and safety
- **Beammonitors** follow the scanned beams (v <= 40 m/s) in real-time
- **Biological interaction model** (LEM) based on 25 years of radiobiological research
- Physical beam **transport model**
- **Planningsystem** TRiP
- **In-beam Positron Emission Tomography**
- **QA system**
- Prototype of the **scanning ion gantry**

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Heidelberg Ion Therapy Center

- compact design
- full clinical integration
- rasterscanning only
- low-LET modality: Protons (later He)
- high-LET modality: Carbon (Oxygen)
- ion selection within minutes
- world-wide first scanning ion gantry
- > 1000 patients/year
- > 15,000 fractions/year
pencil beam library:

- **ions**: p, $^3$He$^{2+}$, $^{12}$C$^6$, $^{16}$O$^{8+}$
- **energies (MeV/u)**: 48, 72, 88, 102
  
  (255 steps, 1.0/1.5 mm) -220, -330, -430, -430
- **beam spot size**: 4 – 10 (20) mm, 2d-gaussian
  
  (4 (6) steps) (up to 20 mm for moving organ treatments)

**intensity variation**: chopper system in front of the RFQ, variation factor: 1000

**active energy variation**: in the synchrotron + high-energy beam lines

**beam size variation**: quads directly in front of the scanning systems

**beam extraction**: established RF-knock-out method (Himac > 10 years) gives
high stability in time, position and spot size

**extraction switchable at flat-top level**

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Spot Size Library for Carbon
skull base chordoma, fraction sequence for 2 proton plans
Plan1_CTV_P 50 GyE + Plan2_GTV_P 24 GyE
HIT Scanning Beam Nozzle

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commissioning result, Protons @ H1: 3d dose delivery vs. treatment planning 24 thimble-type ICs in a water phantom, standard deviation 2.2 %
Performance Specifications (1)
- Protons / Carbons for 1 litre cubic / 2 Gy *

<table>
<thead>
<tr>
<th>Spot Spacing mm</th>
<th>Layer Spacing mm</th>
<th>Beam Width (FWHM) mm</th>
<th>Irradiation Time seconds</th>
<th>Lateral Penumbra (80/20%) mm</th>
<th>Dose Uniformity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>9</td>
<td>81/96</td>
<td>7,5</td>
<td>1,5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>10</td>
<td>55/60</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>12</td>
<td>35/42</td>
<td>9</td>
<td>2,5</td>
</tr>
</tbody>
</table>

* - ripple filter adapted to selected layer spacing
- overlap between spots varying from 2.4 to 3
Performance Specifications (2)
- Clinical Case Examples for Protons / Carbons

„skull base chordoma“

<table>
<thead>
<tr>
<th>Spot Spacing mm</th>
<th>Layer Spacing mm</th>
<th>Beam Width (FWHM)</th>
<th>Energies/Positions</th>
<th>Irradiation Time sec.</th>
<th>Lateral Penumbra (80/20%) mm</th>
<th>Dose Uniformity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>35/8200</td>
<td>63</td>
<td>4.9</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>6</td>
<td>35/8200</td>
<td>44</td>
<td>5.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

* typical GSI parameters:*
- ripple filter 3 mm
- overlap between spots 3
- 1 of 2 fields
- dose/ field : 1 Gy
- volume: 300 ccm
skull base chordoma
Motivation
Gantry

Advantage of a rotating beamline

Pancreas, supine position via gantry advantageous
Gantry 1 / PSI

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Gantry 2 / PSI

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Design for HIT

- isocentric barrel-type
- world-wide first ion gantry
- 2D beam scanning upstream to final bending, almost parallel due to edge focussing
- ± 180° rotation
  3° / second
- 13m diameter
- 25m length
- 570 to rotating
  (145 to magnets)

MT Aerospace

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Patient Gantry Room November 2007

Tilt floor, pending on Gantry position

Nozzle

Bumber mats

Patient table, Roboter
Interplay scanned beam - moving target

stationary target – scanned beam  moving target – scanned beam

courtesy C.Bert, GSI
Thank you for your attention!

(Intensity modulated raster scan, $^{12}$C at 430 Mev/u, October 15th 2007)