Novel Design of Gantry Optics for Carbon Cancer Therapy Accelerator

David Robin

Work by Shlomo Caspi, David Robin, Andy Sessler, Changchun Sun, Weishi Wan and Moohyun Yoon

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Outline

• Introduction to Ion Beam Therapy

• What is a Gantry?

• Novel Superconducting Gantry Magnet Coil Design Optimized with Genetic Algorithms

• Tracking Results

• Future Plans
A Proton Therapy Center (University of Florida)

- Mix of a large accelerator facility and a complex medical treatment facility

Protons.
Three Gantries, One Horiz. Beam
Footprint: 98000 sq ft
$125M
Combined Carbon and Proton Facility Heidelberg Ion Therapy (HIT) Center at Heidelberg University Hospital

- Developed and designed as a collaboration of University of Heidelberg & GSI Accelerator Laboratory in Darmstadt.
Growth Ion Beam Therapy

> 60,000 patients treated with Protons
> 6,000 patients treated with Carbon
Carbon facilities consist of 7 in Europe and 6 in Asia and still more are planned; none in the US.
Goal of radiation therapy is to use radiation to kill cancer tumor tissues while minimizing damage to healthy tissue

Induce significant DNA damage to prevent cell replication
Ion Beam Cancer Therapy

- Ion Beam Therapy (IBT) is the use of ion beams (protons and other ions) to treat tumors.
- IBT was proposed by Robert Wilson to take advantage of the Bragg Peak.

Radiology 47, pp. 487–491, 1946
Energy deposited by different ionizing radiation

Dose versus depth

- X-rays deposit most of their energy near the body entrance
- Ions (such as protons and carbon) concentrate more dose at the tumor
  - Less in front
  - Little or none beyond
The depth of the energy deposition peak (Bragg peak) can be efficiently tuned by changing the ion energy.

Note – For the same penetration depth as protons carbon requires beams with higher magnetic rigidity ➔ larger accelerators.
To deliver the desired dose to the tumor while minimizing dose the healthy tissue

- The desired dose is delivered by scanning a small (few mm) beam in all 3-dimensions ➔ conform dose to the tumor
- Scan from several directions ➔ Gantry
What is a Gantry?

- A gantry is a beam line that directs and focuses the beam onto the patient at whatever angle is required for the treatment plan optimization.

- Possible to access the full $4\pi$ solid angle with a combination of gantry and patient rotation.
Some Existing Proton Gantries

PSI Gantry 2
Heidelberg Ion Therapy Carbon Ion Gantry

Only Carbon Gantry Worldwide

- Gantry can be rotated with ±180° at 3° per second
Gantries are Large

**Weight**
- Proton gantries weight about **100 tons**
- HIT carbon gantry weighs **600 tons**

1/10 of the Eiffel Tower
Gantries are much larger than the accelerator.
Heidelberg Ion Therapy (HIT) Facility

This is even more striking for carbon facilities
Carbon vs Proton

Carbon has two properties resulting in several desirable consequences for many patients

**Carbon Properties**

- Sharper knife  
  *(Sharper Penumbra)*
- Higher rate of energy deposited versus depth  
  *(High Linear Energy Transfer)*

**Consequences**

- Less dose to healthy tissue
- More effective against tumors resistant to X-rays and proton radiation *(hypoxic tumor cells)*
- Shorter overall treatment course

There is a growing interest in carbon therapy worldwide (and in the Bay Area)
Challenge

• Advantages of gantries are such that many new proton facilities are being built with multiple gantries

• Gantries are very expensive
  – Large structures, large power, with large heavily shielded rooms

• *Unlikely that many facilities will be able to afford multiple carbon gantries the size of the HIT gantry. If the size of the gantry the situation could be very different*

• Therefore developing more cost effective, compact gantries has the potential for big payoffs
Gantry Properties and Considerations

1. Active Scanning
2. Large Good-Field Region
3. Parallel Scanning
4. Full Range of Gantry Angles
5. Isocentric versus Exocentric Gantries
1. Active Scanning

- Active spot or pencil scanning - the desired dose is delivered by scanning a small (few millimeter) beam in all 3-dimensions
2. Good Field Region

Good field region is the lateral region that can be scanned without moving the gantry or patient.

Lateral plane (Dispersive and Transverse Dimensions)
Field Patching

- Large Field: Scan in one go
- Small Field: Scan and move couch (PSI gantry 1)

- Field patching is slower
- Large field requires larger magnet apertures and higher costs

What is an optimal size for the good field region?
3. Parallel versus Angular Scanning

- To minimize normal tissue dose → Parallel scanning is preferable

- But some small angle might be acceptable

- Source to Axis Distance (SAD)

**What is the Minimal Allowable SAD?**

40% increase in skin dose for 2 meter SAD
Scanning Magnets Location

- Large aperture dipole
- Heavier
- Higher operating costs

- Larger gantry radius
- Larger room size
4. Angular Coverage

• How important is full $360^\circ$ coverage?

• Limiting angular coverage could reduce space and reduce costs
Gantry Functional Specifications

• As part of the Union of Light Ion Centers in Europe (ULICE), CNAO physicians completed a survey

• Some of the survey results are shown on the next page and are useful in understanding the gantry functional specifications
<table>
<thead>
<tr>
<th>Gantry functional specifications</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Good field size</td>
<td>15 x 15 cm² or 10/15 x 20 cm²</td>
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<tr>
<td>Number of fields per session</td>
<td>4</td>
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<tr>
<td>Penetration depth (range)</td>
<td>3 – 30 cm (corresponding energy: p = 60 - 220 MeV; C ion = 120 – 430 MeV/u)</td>
</tr>
<tr>
<td>Voxel dose accuracy</td>
<td>±1%</td>
</tr>
<tr>
<td>Dose uniformity</td>
<td>±2.5%</td>
</tr>
<tr>
<td>Voxel characterization</td>
<td>3 x 3 x 3 mm³</td>
</tr>
<tr>
<td>Voxel out of range</td>
<td>1%</td>
</tr>
<tr>
<td>Field position accuracy</td>
<td>±0.5 mm</td>
</tr>
<tr>
<td>SAD</td>
<td>4 m</td>
</tr>
<tr>
<td>Maximum treatment time</td>
<td>30 min</td>
</tr>
<tr>
<td>Required space around isocenter</td>
<td>60 cm</td>
</tr>
<tr>
<td>Achieved beam directions</td>
<td>4π</td>
</tr>
</tbody>
</table>
Isocentric Gantry

Focal point is at the same position for each gantry angle

*Patient does not move vertically when gantry rotates*
Exocentric Gantries

- Not a new concept
  - Gantry 1 at PSI is an exocentric gantry
  - More compact than Gantry 2
Compact Excocentric Gantry serving 4 rooms
(A. Brahme)
Riesenrad Gantry

- Rotating structure (room with the patient) probably lighter
- 90° magnet alignment is easier in case of magnet rotation around its axis rather than in case of complete rotation of the line;
ETOILLE (LYON)
(Superconducting 90 degree Bend)

- 3.2 Tesla Superconducting Dipole
- 2 meter bending radius
- Significantly lighter than HIT dipole

M. Bajard, EPAC08, (2008 )1779-1781
Present State of the Art

- Fast Conformal Scanning with Volumetric Repainting
- Active and Parallel scanning
- Short (few minute) treatment time per field (including repaintings)
- Large Lateral Good-Field Regions > 10cm x 10cm
- Isocentric
- Full $4\pi$ angular coverage

*PSI Gantry 2 and the HIT Gantry are the state of the art*

- Derivatives of the same design - Pavlovic Type
Radially very compact by having the last magnet a 90 degree magnet. All the other magnets – quadrupoles, dipoles, and steering magnets, do not take up additional radial space.

The radial size is determined by only three things – (1) the space between the patient and the last magnet, (2) the bending radius of the 90 degree dipole, and (3) how wide that dipole is.
Pros and Cons of Pavlovic Design

Pros
• Efficient use of Magnets
• Radially compact
• Parallel Scanning

Cons
• Last bending magnet needs to have a large aperture to accommodate the scanning
  – Heavy (~90 tons for the HIT gantry)
Heidelberg Gantry and Final 90° Dipole

Weighs 90 tons
(65% of all rotating beamline components)
Superconducting Magnets

• Attraction
  – Superconducting magnets can achieve many times the magnetic field strength compared with normal conducting magnets
    – more compact systems

• Some major challenges such as
  – Rotatable cryogenic systems
  – Rapid field scanning

• Several groups are looking at Superconducting Gantry Magnets (CEA, U. Genoa, HIMAC, and LBNL)
Can the size of a carbon gantry be reduced to about the size and weight of existing proton gantry?

PSI-2 (Proton)

HIT (Carbon)

- Weight:
  - Proton: 100 tons
  - Carbon: 600 tons
A Proton sized Carbon Gantry

5 Tesla Bend fields would allow to reduce the size to that of PSI
Required Properties

- Large Good Field Region
- Point-to-Parallel from scanning magnets to the patient in transverse (x and y) directions
- Minimal beam shape distortion when scanning over good field region
- Ability to field ramp reasonably quickly (seconds)
  - Bend beams of magnetic rigidity of 2.5 to 6.6 Tm
Tilted Solenoidal Pair on a Toroid

Curved superconducting dipole

- **Straight superconducting dipole:**
  - Two layer helical wires on a straight cylinder
  - Solenoid magnet component are canceled
  - Cos-theta current distribution on cross-section
  - Pure dipole field

- **Curved superconducting dipole:**
  - Two layer helical wire on a torus
  - Solenoid magnet component are canceled
  - Pure dipole?
  - Quadrupole? sextupole?
Parameters

- Magnetic rigidity (400 MeV/u fully stripped carbon) is 6.347 Tm.
- Bending radius (for 5 T) is 1.269 m.
- Bore diameter > 21 cm
First Attempts (Wrong Linear Focusing)

- S. Caspi
- W. Wan

<table>
<thead>
<tr>
<th></th>
<th>C0</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
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<td>5.0000</td>
<td>-2.26</td>
<td>1.30</td>
<td>0.00</td>
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</tbody>
</table>
**Correcting the linear term (First Attempt)**

- Offset iron with respect to the coil
- Changing the Iron cross section shape from circular to elliptical
Particle Tracking: Initial particle tracking distribution

Histogram of the gaussian distributed 5000 particles at the gantry entrance

5000 particles
Gaussian
\( \epsilon_x \text{ max } = 1 \text{ mm mrad} \)
\( \epsilon_y \text{ max } = 5 \text{ mm mrad} \)
\( \Delta p/p \text{ max } = 0.2 \% \)
Large nonlinearities and distortion at the patient location

Severe distortion is mostly due to 6-pole components.
Need to correct linear and nonlinear terms

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<th>C3</th>
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<td>9.0278</td>
<td>-25.25</td>
</tr>
<tr>
<td>“Ideal” red</td>
<td>5.0000</td>
<td>-2.26</td>
<td>1.30</td>
<td></td>
</tr>
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Genetic algorithms

• Genetic Optimization is a method to generate optimum solutions using techniques inspired by natural evolution, such as inheritance, mutation, selection and crossover.

• A typical GA is describe as follows:
  1: Randomly generate the first generation
  2: Evaluate the first generation
  3: Sort the first generation
  4: Repeat
  5: select parent to generate child (cross over)
  6: mutate child
  7: evaluate child
  8: merge the parent and child
  9: sort the mixed population
 10: select the first half of the mixed populations
 11: Until reach maximum generation
Torus

$I = 18 \text{ kA}, n = 216 \text{ turns, } a_0 = 0.168, a_1 = -5.74e-03, a_2 = 2.345e-04$
inner pitch: 8.5 mm, outer: 10 mm
Current distributions on the center cross-section
Magnetic fields

\[
B_z = 4.9965 - 2.2597x + 1.2959x^2
\]

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Tracking with optimized windings
Tracking with optimized windings

Scanning magnet settings

Resulting positions and distributions at the patient

More nonlinear and less distorted
Comparison of the two cases

Initial Attempt          Genetically Optimized       Comparison of 3\textsuperscript{rd} order terms

Improvement due to large reduction in 3\textsuperscript{rd} order term
Next Steps

- Increase bore radius to 13 cm
- Add Iron
- Evaluate
  - Stored Energy
  - Stresses
  - Inductance
    - Quench protection
    - Ramping rate limits
  - Cryogenic system
Initial Estimate Size and Weight

- Torus radius = $c = 1.269\text{m}$
- Bore radius = $a_0 = 0.1\text{m}$
- Coil thickness = $d=0.02\text{m}$
- Central dipole field = $B_0 = 5\text{T}$
- Iron outer radius = $0.37\text{m}$
- Torus outer radius = $1.639\text{m}$
- Total weight = iron $(6.25 \text{ ton}) + \text{Coil} (\sim 1 \text{ ton}) + \text{Cryo}(\sim 1 \text{ ton}) = 8.25 \text{ ton}$
- Weight depends on the bore radius square.
Conclusion

• Gantry optimization can yield significant benefits for carbon ion beam therapy
• Goal reduce size and weight of carbon gantry to the level of a proton gantry
• Novel superconducting dipole has the promise to reduce the significantly reduce the size and weight.
• Coil geometry (optimized using genetic algorithms) resulted in minimal field distortions
• Future work in progress to assess the feasibility of this magnet
Sources

**GENERAL**

**PSI**
- E. Pedroni, Presentation at the Workshop on Hadron Therapy (Erice, 2009)

**HIT (Heidelberg)**
- [U. Weinrich, EPAC 06 (2006) 964-968
- U. Weinrich, private communication
- U. Weinrich, Presentation at the Workshop on Hadron Therapy (Erice, 2009)

**ETOILLE (Lyon)**
- M. Bajard, EPAC08, (2008) 1779-1781

**HIMAC (Chiba)**
- Furukawa et al., Nucl. Inst. and Meth B 266 (2008) 2186-2189

**Other**
- A. Brahme, “Potential Developments of Biologically optimized Light Ion Therapy”
- D. Trbojevic, Presentation at the Workshop on Hadron Therapy (Erice, 2009)