Commissioning of carbon ion treatment accelerator with a superconducting rotating gantry

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Introduction of Carbon Ion Radiotherapy
Short History of Carbon Ion Therapy

• 1946 R. R. Wilson presented the idea of proton therapy using Bragg peak
• 1954 First Proton Therapy at LBL 340MeV Synchrocyclotron
• 1975-1992 Ion therapy (He, Ne, etc.) at Bevatron, LBL, USA
  – Difficulties in imaging, dose calculation, biological modeling, machine time
• 1994- Carbon Ion Therapy at HIMAC, Japan
  – Successful clinical results by CT-based dose calculation, biological model based on neutron therapy, dedicated machine
• 2010- Compact Carbon Ion Treatment Facilities
• 2017 1st Superconducting Gantry for carbon
• 2023- Multiple ion therapy (He, C, O, Ne) started at HIMAC

Operating Facility: 11 in Asia (Japan 7, China 2, Taiwan 1, Korea 1) (Apr. 2024) 4 in Europe (Germany 2, Italy 1, Austria 1) 0 in US (1 under construction)
Carbon Ion radiotherapy

- Radiotherapy, Irradiate carbon ions of up to 430 MeV/u into human body for cancer therapy

- Strong points compared with conventional X-ray Therapy...
  - High LET (Linear Energy Transfer)
    → Cause severe damage to DNA
    → Effective for radioresistant cancer
  - Bragg Peak
    → Dose concentration to target
    → Protect normal tissues close to target
    → Higher dose than X-ray is available

Effective damage concentrated to target!
Characteristic of carbon ion therapy

Physics Level
- High Charge State (C⁶⁺)
- Large Mass (¹²C)

Dosimetric Level
- High LET
- Small Scattering
- Sharp Bragg Peak
- Large Size Accelerator

Biological Level
- Low OER
- High RBE
- Sharp dose distribution

Medical Level
- Effective to radioresistant cancer
- Reduce Damage to Normal Organ
- Deliver Higher dose safely

High cost but effective therapy

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Target of Carbon Ion Radiotherapy

• Radioreistant Cancer
  – Sarcoma (Bone & Soft tissue cancer)
  – Adenocarcinoma (Prostate, Uterus, Etc..)

• Cancer with Huge Mass
  – Liver, etc.
  – Huge tumor → Hypoxia in the center → low damage by OH radical → Radioreistant

• Close to important Organ
  – Head (Optic Nerve)
  – Pancreas(Duodenum)
  – Prostate(Rectum)

For some types of cancer, Carbon Ion Radiotherapy is the only way to treat
Introduction of Accelerator and Treatment System
Evolution of Heavy Ion Medical Accelerator

1st Generation
1974 Bevatron (Bevalac)
Parasite to research accelerator

2nd Generation
1994 HIMAC
Treatment dedicated machine

3rd Generation
2010 GHMC
Dedicated for carbon ion therapy

3.5th Generation
2015 KCC
Advanced irradiation system (Scanning)

Similar to the evolution of Synchrotron Radiation Facility as User Machine...
1st Gen: INS-SOR
2nd Gen: SOR-RING
3rd Gen: ESRF (Low E)
4th Gen: MAX IV (MBA)

Parasiting
Dedicated
Increase brightness for user application

Medical Accelerator is a User Machine, End User is Patient
East Japan Heavy Ion Center

• East Japan Heavy Ion Center, Faculty of Medicine, Yamagata University
  – 3.9th generation carbon ion therapy facility
  – World Smallest Carbon Ion Facility (45 x 45 m)
  – Full energy Scanning Irradiation
  – Superconducting Rotating Gantry

Exported to
• Yonsei University Health System,
• Seoul National University Hospital in Korea

New Standard model of Today’s Compact Carbon Ion Therapy Facility

Manufacturer: Toshiba Energy Systems & Solutions Co.
Ion Source

- Kei2 series 10 GHz ECR Ion source
- Permanent magnet of mirror and sextupole field, designed to maximize $C^{4+}$ beam current.
- 150-300μA $C^{4+}$ available
- Maintenance interval: 2 years

<table>
<thead>
<tr>
<th>Magnetic Field</th>
<th>All Permanent Magnet Max. Mirror Field: 0.8 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction Electrode</td>
<td>25 mm Diameter</td>
</tr>
<tr>
<td>Anode Electrode</td>
<td>φ6 mm hole</td>
</tr>
<tr>
<td>RF Amplifier</td>
<td>Travelling Wave Tube (TWT) NEC LD79X75A1 (Max.750 W)</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>10 GHz</td>
</tr>
<tr>
<td>RF Power</td>
<td>200 W (typ.)</td>
</tr>
<tr>
<td>Gas species</td>
<td>Methane (CH$_4$)</td>
</tr>
<tr>
<td>Ion Species</td>
<td>$C^{4+}$</td>
</tr>
<tr>
<td>Ext. Voltage</td>
<td>30 kV (10 keV/u)</td>
</tr>
<tr>
<td>Norm. Emittance</td>
<td>$\sim 1 \pi \cdot \text{mm} \cdot \text{mrad}$</td>
</tr>
</tbody>
</table>
Injector Linac

- Compact Injector inside the synchrotron
- RFQ + APF (Alternate Phase Focusing) IH-DTL
- Electropolished surface (Discharge reduced)
- Charge stripper carbon foil after IH-DTL: $C^{4+} \rightarrow C^{6+}$

<table>
<thead>
<tr>
<th></th>
<th>RFQ</th>
<th>IH-DTL</th>
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</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>200 MHz</td>
<td>200 MHz</td>
</tr>
<tr>
<td>RF Power</td>
<td>150 kW</td>
<td>500 kW</td>
</tr>
<tr>
<td></td>
<td>All Solid State</td>
<td>Solid State + Tetrode</td>
</tr>
<tr>
<td>Inj. Energy</td>
<td>10 keV/u</td>
<td>600 keV/u</td>
</tr>
<tr>
<td>Ext. Energy</td>
<td>600 keV/u</td>
<td>4 MeV/u</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>~35 cm</td>
<td>~35 cm</td>
</tr>
<tr>
<td>Tank Length</td>
<td>2.5 m</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Max. Surface field</td>
<td>23.6 MV/m</td>
<td>23.6 MV/m</td>
</tr>
<tr>
<td></td>
<td>(x1.6 Kilpatrick)</td>
<td>(x1.6 Kilpatrick)</td>
</tr>
</tbody>
</table>
Synchrotron

- Synchrotron with intensity-modulated slow extraction system
- Circumference: 63 m
- 600 extraction energy (55.6 – 430 MeV/u)
- Reduce bending magnet gap length → Energy saving operation

<table>
<thead>
<tr>
<th>Ion</th>
<th>C^6+</th>
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<tbody>
<tr>
<td>Inj. Energy</td>
<td>4 MeV/u</td>
</tr>
<tr>
<td>Ext. Energy</td>
<td>55.6 - 430 MeV/u (600 step)</td>
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<tr>
<td>Circumference</td>
<td>63.3 m</td>
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<tr>
<td>Ope. Cycle</td>
<td>&lt; 6 s, Extended flattop &gt; 30 s</td>
</tr>
<tr>
<td>Beam current</td>
<td>$3 \times 10^9$ ppp</td>
</tr>
<tr>
<td>Ext. Intensity</td>
<td>$3 \times 10^7$ ~ $1 \times 10^9$ pps</td>
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</tbody>
</table>
Multiple-Energy Synchrotron Operation

- Many energies are used in one treatment to control beam range
- Multiple energy extraction in one acceleration cycle to shorten irradiation time
- Extended Multiple Flattop Operation was developed in QST (200 energies for 1.5 or 2 mm step)
- In Yamagata, 600 energies for 0.5 mm step


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Irradiation System

- Scanning Irradiation System
  - Scan pencil beam (2-3 mm in $1\sigma$) to paint 200 x 200 mm
  - Range control by synchrotron energy (~300 mm, 0.5 mm step) without any range shifter (plastic block)
  - Main/Sub Dose Monitor (ionization chamber): Measure irradiated dose
  - Position Monitor (MWPC): Monitor beam position, size for interlock and position feedback
Rotating Gantry

- Rotating Gantry enables flexible 360 degree beam angle with no tilting of patient
- Gantry for carbon ion \((Bp = 6.62 \, \text{T} \cdot \text{m})\) by normal conducting magnet is too large
- Superconducting Combined-Function Magnet
  - \((6 \, \text{BM} + 12 \, \text{QM})\) up to 3.5 T
  - \(~3.5 \, \text{K}\) achieved by 3 GM cryocooler (1 redundancy)


Commissioning of Accelerator
Final Goal of Medical Accelerator

• Treatment irradiation: to deliver correct dose to correct position
• Control and measure beam size, beam position, particle number

• Accelerator commissioning: fix the extraction and transport parameter
• Acceptance Test: Verification of each device and irradiation performance
• Clinical Commissioning: Verification of dose distribution of treatment plan
Importance of Accelerator Commissioning

• ~2010 Broad Beam Irradiation
  – 1~3 synchrotron energies
  – Large Tolerance for Beam Size (~10 mm), Beam Position (~3 mm), Beam Current (25 - 200%)
  – Fixed beam port: only one boundary condition many adjust knob

• Now: Spot Scanning Irradiation
  – 600 energies in Yamagata
  – Small Tolerance for Beam Size (~30%), Beam Position (~1 mm), Beam Current (75-150%)
  – Rotating Gantry: many boundary conditions and limitation of tuning

For advanced irradiation, advanced accelerator is needed
Commissioning History

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1-Q2</th>
<th>Q3-Q4</th>
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<tbody>
<tr>
<td>2019</td>
<td>Q1</td>
<td>2</td>
</tr>
<tr>
<td>2020</td>
<td>Q1</td>
<td>3</td>
</tr>
<tr>
<td>2021</td>
<td>Q1</td>
<td>4</td>
</tr>
<tr>
<td>2022</td>
<td>Q1</td>
<td>3</td>
</tr>
<tr>
<td>2023</td>
<td>Q1</td>
<td>4</td>
</tr>
</tbody>
</table>

**Building**
- Building Complete
- Synchrotron Acceleration
- First Patient Treatment

**Accelerator**
- Initial beam test
- Fine tuning
- Acceptance Test
- User Clinical Commissioning

**Fixed Room**
- Beam tuning
- User Clinical Commissioning

**Gantry**
- User Beam tuning
- 15deg step operation

- Linac First Beam
- First Beam in Treatment Room
- First Gantry Treatment
Commissioning of the Synchrotron and HEBT

- **Synchrotron**
  - Only one pattern
  - Stop the clock as any energy (timing)
  - Extraction Parameter (RF-KO Frequency, Amplitude) tuned for each energy

- **HEBT**
  - Parameter table for 73 devices $\times$ 600 energies (=$43,800$)
  - For gantry, 104 devices $\times$ 600 energies $\times$ 360 angles
  - Full manual optimization is impossible
  - Interpolation and automation is necessary
Extraction Control

- Based on HIMAC Advanced RF-KO system

K. Noda et al., NIM A492, 253 (2002)

Pre-heat extraction to reduce spike after deceleration
Commissioning of Fixed beam port

- Beam Data Measurement
  - Depth dose distribution
  - Spot Profile
  - Absolute Physical Dose

- Validation of beam modeling of treatment planning system (Uniform physical dose plan)

- Patient QA
- Stopping Power Ratio Measurement

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Commissioning of the Superconducting Rotating Gantry
Optics design of the gantry

• In the rotating gantry, x-y coordinate will rotate, x-y beam size should be symmetric

• At the extraction from the synchrotron, X emittance is smaller than Y emittance by the beam loss by Electrostatic Septum.

• X-Y symmetric emittance is realized by a thin scatterer at the point \( \beta_x \gg \beta_y \)
  
  – X emittance will be enlarged by the scattering, because initial divergence is small
  
  – Y emittance will be kept by the scattering, because initial divergence is large

• Betatron phase control is extremely important
Gantry Optics

- Deviation of initial beta and dispersion at the extraction will be compensated in the upstream section of transport line
- $\beta_x \sim 30 \text{ m}, \beta_y \sim 0.5 \text{ m}$ at emittance compensator (thin foil)
- $\beta_x = \beta_y$ at gantry entrance $\rightarrow$ No angular dependence
- $\beta_x = \beta_y = 5 \text{ m}$ at the patient position (isocenter) $\rightarrow$ Beam size: $2\sim 3 \text{ mm} (1\sigma)$
Actual Commissioning of Gantry

- In design, the beam size is independent from gantry angle by emittance compensation
- But actually, beam size varies by orbit deviation
  - Quadrupole effective length changes by radial position for sector combined function magnet
  - It is difficult to perfectly correct gantry orbit
    - Transverse kick by dipole field tilting
    - Limit of steering magnet current (±70A)
    - No screen monitor after final bend
  - Beam size optimization using interpolation was carried out
    - At subsequent facility, these problems improved and commissioning time reduced
Commissioning steps

- **1\textsuperscript{st} step**: Prostate by 2 angles
  - Make initial experience
- **2\textsuperscript{nd} step**: Head and Neck by 7 angles (30° step)
  - With tilting patients slightly
- **3\textsuperscript{rd} step**: Pelvis by 12 angles (30° step)
  - Beam passing through the couch
- **4\textsuperscript{th} step**: Lung, Liver, Pancreas by Respiratory Gating
  - All treatment site accepted
- **5\textsuperscript{th} step**: 24 angles (15° step)

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**Step-by-step commissioning to Start new treatment safely**
Beam Position Measurement

• Beam Position must be aligned to the center of X-ray patient positioning system
• Must be kept within \( \pm 1 \text{ mm} \)
• Iron Ball placed on the center by X-ray system
• Beam is steered to hit the center of the iron ball
• Beam position changes by seasonal temperature
• Need correction
  – Measure beam position for 600 energies
  – Calculate correction currents of Steering mangets
  – Automatic correction tool was developed
Beam Size

- Beam size deviation from the reference (fixed port) within ±20% (±30% max tolerance)
- Measured by scintillation screen
Uniformity Measurement

- 2-dimensional uniformity
  - Important as basic beam performance
  - If the beam drift (position deviation during one spill) is large, uniformity is worse
  - Less than 3% for 32 energies, well stable

Beam Position Drift

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Validation of physical dose distribution

- Dose distribution measurement using 3-dimensional water phantom and ionization chamber
- Can only measured at gantry 90 deg (horizontal beam)
- For other angles, beam compatibility is proven for beam position and size

SOBP Dose: ±3%, Uniformity: ±3%, Field Size: ±2 mm was achieved for 20 conditions.

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600 energy - 24 angle commissioning

- 30 degrees step operation: need slight tilting of patient
- 15 degrees step operation → 600 energies × 24 angles, need long time...
- Efficient position correction by interpolation (143 → 600 energies)
- Interpolation of angles of 15 degrees step from 30 degrees step

“Starshot” measurement by cylindrical plastic scintillator
13 angles of 15 degrees step: <1mm position achieved
Measure all Items for many gantry angles (GA) and 600 energy ID (EID) is practically impossible. It is important to make plan to reduce measurement items. To decide to reduce items, it is important to find what parameter is enough stable.
Operation Status
Treatment Status

• 1551 patients treated by March 2024
• 662 patients treated in JFY2023
  – 4~20 irradiations/patient
• Many Patients for Prostate, Liver, Pancreas
Clinically used Beam Energy and Gantry Angle

- Mode of Beam Energy: 358.2 MeV/u
- Minimum Energy (55.6 MeV/u) is used frequently, close to the skin
- Gantry Angle 0 deg (from top) is mostly used
- 135, 225 deg is difficult to use by interference with patient couch

Prostate plan

Max energy ever used: 411.8 MeV/u
Machine Availability

- Machine availability for treatment is 95.8%
- Usually 4 irradiations/week/patient
- Minimum 6 irradiations/2 week/patient should be done in case of trouble
- Longest machine stop was 3 days (simultaneous trouble of ion source gas flow controller and scanning magnet power supply)

\[
\text{Availability} = 1 - \frac{T_{\text{delay}}}{T_{\text{treat}} + T_{\text{delay}}}
\]
Reliability of Superconducting Gantry

• Quench: quench protection by voltage or temperature
  – Current change and mechanical rotation: severe condition for SC
  – $T_{\text{coil}} = 3.5 \rightarrow 20$ K; Need $\sim 90$ min for recovery
  – 146 quenches in the operation, only 10 caused treatment delay
  – To reduce quench, daily training of full excitation

• Rotation: mechanical problem
  – Water leak from flexible hose $\rightarrow$ small leak, continued operation 1 day
  – Damage to power cable of cryocooler $\rightarrow$ 1 of 3 cryocooler stopped, but kept superconducting by other 2 cryocooler, treatment continued successfully.

• In total, stable operation has been achieved as the first mass production model superconducting gantry!
Future Prospect

• Carbon Ion Therapy made good machine performance and clinical result ...
  What we do next?

1. Compact System
   Superconducting Synchrotron is under construction at QST
   → Many machines to small hospital for widespread use

2. Higher LET to Target
   Multipurpose-Ion Therapy using He, C, O, Ne, started at QST in 2023
   → More Effective Treatment for Radioreceptive Cancer

3. Improve Patient Positioning
   3D computed tomography (CT) - based patient positioning
   → Improve irradiation precision

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H. Souda et al., 24 May 2024, IPAC’24, Nashville

Y. Iwata et al., Nucl. Inst. Meth., A1053, 168312 (2023)
Summary

- Carbon ion therapy is an effective radiotherapy to cure radioresistant cancer using high LET and tumor close to important organ by sharp dose distribution.
- In Yamagata University, 430 MeV/u synchrotron with 600 variable energy operation realized 0.5 mm step range control.
- For gantry commissioning, emittance compensation and beam size optimization considering the perturbation of focusing force due to orbit change was the key technology.
- The machine is very challenging but achieved successful operation for 3 years to treat more than 1500 patients.
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• Accelerator Engineering Company
• B-dot Medical Inc.

08 March 2022: 1st Treatment at Gantry room

Thank You For Listening!