Summary of Synchrotron for Hadron Therapy

April 30, ‘09
Koji Noda

1. G.H. Rees ; A New Tracking Gantry-Synchrotron Idea
2. K. Noda ; Overview of NIRS Accelerator Activity
3. T. Haberer ; The Heidelberg Ion Therapy Centre
4. K. Hiramoto; PROBEAT, Hitachi Proton-Therapy System
5. S. Peggs ; Rapid Cycling Medical Synchrotron
6. M. Pullia ; The Design of CNAO
7. J. Wei ; Recent Ion-Beam Therapy Proposals in China
8. M. Herforth; Synchrotron based on PT Solutions from Siemens AG

Synchrotron types as mentioned above are categorized to two groups:
A)Rapid Cycle Synchrotron
B)Slow Cycle Synchrotron
• 50-70 Hz repetition rate required through spot-scanning experiences.
• Small beam size & Lighter Gantry

Racetrack design
  2 super-periods
  Strong focusing minimizes the beam size
  FODO/combined function mags with edge focusing
  2x7.6m straight sections, zero dispersion, tune quads
  Working tunes: 3.38, 3.36

Compact footprint
  Circumference: 27.8 m
  Area: 37 sq m
Not so rapid, but 5 Hz dual rings

5 Hz synchrotrons (low voltage rf systems)

C₁ = 43.68 m
C₂ = 49.92 m
Apertures:
42 x 60 mm²

H⁻ steering to foils
C⁴⁺

H⁺ continuous extraction
C⁶⁺

Inner ring: H⁻ ions 5 - 250.0 MeV/u
RFQ linac injector for H⁻ and C⁴⁺

Inner ring: C⁴⁺ 4.965 - 31.18 MeV/u
Outer ring: C⁴⁺ 31.18 - 400 MeV/u
Features of the 5 Hz rings

- Each ring has six FODO combined function lattice cells
- Ring magnets have small (42 mm x 60 mm) apertures
- Injection of $H^-$ or $C^4^+$ to Ring 1 is from a common RFQ
- Ring 1 has 1-turn $H^-$ injection & outward stripping ejection
- Ring 1 has 1-turn injection for $C^4^+$ ions and fast extraction
- Ring 2 has fast inject of $C^4^+$ & inward $C^6^+$ stripping ejection
- Max. field in Ring 1 is < 5 kG for low, $H^-$ Lorentz stripping
- Both rings require vacuum pressures of a few $x$ 10^{-10} Torr
Debates in possible approaches

- **Goal**: ion-beam therapy with capability of 3D stereo-tactic scanning
- **At least 5 ways to build the machine**
  - Cyclotron with *mechanical degrader*: PSI practice
  - Slow-cycling synchrotron with *energy-programming slow extraction*: GSI practice
  - Rapid cycling synchrotron: resonance acceleration with *adjustable extraction timing*
  - FFAG-ring based
  - Linac based
Rationale to choose the RCS approach

- **Well established technology**  
  – proven example of ISIS (50Hz), J-PARC (25Hz)
- **New to the therapy world**  
  – smaller beam size, lighter gantry … (e.g. Peggs)
- **Share the R&D efforts in China**  
  – China Spallation Neutron Source (CSNS)
- **Primary challenge:**  
  – Lower cost (30 – 50%), quality production  
  – World-wide collaboration, domestic fabrication
- **Possible weakness:**  
  – Large amount of RF (C: < 100 kV for 50 Hz)
Energy Modulation Ion Therapy (EMIT) layout

Energy: 7-250 MeV @ p
7-450 MeV/n @ C
Repetition: 50 Hz
RF_V : 16 kV @ p
<100 kV @ C
Lanzhou HIRFL-CSR Layout

1) SCS by Wei

Surface tumor
100MeV/n C

Deeply seated tumor
430MeV/n C
Cooler-Synchrotron

12.1 Tm
CSRm (161m)
1.1GeV/u—C⁶⁺
2.8Gev--p

9.4 Tm
CSRe (128.8m)
500MeV/u—U⁹²⁺

- Cooling Stacking
- Variable Energy
The Heidelberg Ion Therapy Centre
• treatment both with low and high LET-ions
• fast change of ion species
• 3 treatment areas to treat a large number of patients
• integration of an isocentric gantry
• ion-species : p, He, C, O
• ion-range (in water) : 20 - 300 mm
• ion-energy (*) : 50 - 430 MeV/u
• extraction-time : 1 - 10 s
• beam-diameter : 4 - 10 mm (h/v)
• intensity (ions/spill)(*) : 1*10^6 to 4*10^10
(*) (dependent upon ion species)
pencil beam library:

- **ions**: 
  - \(p\), \(^{3}\text{He}^{2+}\), \(^{12}\text{C}^{6}\), \(^{16}\text{O}^{8+}\)

- **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
Accelerator & Gantry have already been fully commissioned. First treatment is scheduled on October ’09.
Revised HIT Accelerator Design by Siemens

The HIT accelerator design has been modified
To improve technical capabilities
To reduce construction and operating costs
Examples
1) 12 dipoles (each 8 tons) instead of 6 (each 25 tons)
   - cost reduction, easier installation and handling
2) Smaller and lighter quadrupoles
   - cost reduction, less power consumption
3) Optimized injection and extraction system
   - Higher intensity, shorter treatment times
4) 3 sources
   - more flexibility, other ions species
New Project by Siemens

3) SCS by Herforth

Marburg

Kiel
Synchrotron for light ions ($z \leq 6$)
Active scanning
Range $\leq 27$ g/cm$^2$

3 treatment rooms
Space for 2 gantries

Injector: GSI design
Synchrotron: PIMMS design
How it looks in reality
## Basic Parameters I

<table>
<thead>
<tr>
<th>Protons (&lt; $10^{10}$ per spill)</th>
<th>LEBT (*)</th>
<th>MEBT</th>
<th>SYNC</th>
<th>HEBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV/u]</td>
<td>0.008</td>
<td>7</td>
<td>7-250</td>
<td>60-250</td>
</tr>
<tr>
<td>Imax [A]</td>
<td>$1.3 \times 10^{-3}$ (0.65, 0.43)</td>
<td>$0.7 \times 10^{-3}$</td>
<td>$5 \times 10^{-3}$</td>
<td>$7 \times 10^{-9}$</td>
</tr>
<tr>
<td>Imin [A]</td>
<td>$1.3 \times 10^{-3}$ (0.65, 0.43)</td>
<td>$70 \times 10^{-6}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>$17 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{rms,geo}}$ [π mm mrad]</td>
<td>35</td>
<td>1.9</td>
<td>0.67-4.2</td>
<td>0.67-1.43 (V)</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot,geo}}$ [π mm mrad]</td>
<td>180</td>
<td>9.4</td>
<td>3.34-21.2</td>
<td>3.34-7.14 (V) 5.0 (H)</td>
</tr>
<tr>
<td>Magnetic rigidity [T m]</td>
<td>0.013 (0.026, 0.039)</td>
<td>0.38</td>
<td>0.38-2.43</td>
<td>0.38-2.43</td>
</tr>
<tr>
<td>$(\Delta p/p)_{\text{tot}}$</td>
<td>±1.0‰</td>
<td>±(1.2-2.2)%</td>
<td>±(1.2-3.4)%</td>
<td>±(0.4-0.6)%</td>
</tr>
</tbody>
</table>

* (H$_2^+$, H$_3^+$)
## Basic Parameters II

<table>
<thead>
<tr>
<th></th>
<th>LEBT (C⁴⁺)</th>
<th>MEBT</th>
<th>SYNC</th>
<th>HEBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV/u]</td>
<td>0.008</td>
<td>7</td>
<td>7-400</td>
<td>120-400</td>
</tr>
<tr>
<td>Imax [A]</td>
<td>0.16 × 10⁻³</td>
<td>0.15 × 10⁻³</td>
<td>1.5 × 10⁻³</td>
<td>2 × 10⁻⁹</td>
</tr>
<tr>
<td>Imin [A]</td>
<td>0.16 × 10⁻³</td>
<td>15 × 10⁻⁶</td>
<td>28 × 10⁻⁶</td>
<td>4 × 10⁻¹²</td>
</tr>
<tr>
<td>(\varepsilon_{\text{rms,geo}}) [π mm mrad]</td>
<td>35</td>
<td>1.9</td>
<td>0.73-6.1</td>
<td>0.73-1.43 (V)</td>
</tr>
<tr>
<td>(\varepsilon_{\text{tot,geo}}) [π mm mrad]</td>
<td>180</td>
<td>9.4</td>
<td>3.66-30.4</td>
<td>3.66-7.14 (V)</td>
</tr>
<tr>
<td>Magnetic rigidity [T m]</td>
<td>0.039</td>
<td>0.76</td>
<td>0.76-6.34</td>
<td>3.25-6.34</td>
</tr>
<tr>
<td>((\Delta p/p)_\text{tot})</td>
<td>± 1.0‰</td>
<td>± (1.2-2.0)‰</td>
<td>± (1.2-2.9)‰</td>
<td>± (0.4-0.6)‰</td>
</tr>
</tbody>
</table>
7-250 MeV p
7-400 MeV/u C

I ~ 0.1-5 mA (p)
I ~ 0.03-1.5 mA (C)

Slow extraction

Betatron core
HEBT

60-250 MeV p
120-400 MeV/ u C
$10^{10}$ p/ spill (~2nA)
$4 \times 10^8$ C/ spill (~0.4nA)

different settings for

• Treatment Line
• Horizontal beam size
• Vertical beam size
• Extraction energy

Settings interpolation
Charged Particle Therapy in Japan
- based on synchrotron -
HITACHI PBT System

- Injector: LINAC 7 MeV
- Synchrotron: Slow Cycle and Slow Extraction
- High Energy Beam Transport
- Irradiation System: Rotating Gantry /Fixed Course

5) SCS by Hiramoto
University of Tsukuba

- Two Passive Nozzles with Rotating Gantries
- Operation Started in 2001
- Over 1000 Patients Treated

Synchrotron (70-250MeV)

39m

Exp. Room

Treatment Room

Rotating Gantries

5) SCS by Hiramoto
M.D. Anderson Cancer Center

- Three Rotating Gantry and One Fixed Beam Rooms
  > Spot Scanning: G3, and Passive: G1, G2 and Fixed
- Operation Start: Passive in ‘06 and Scanning in ‘08, May
- Treatment over 100 Patients/Day

Synchrotron (70-250MeV)  Gantry Treatment Room
Synchrotron

Lattice Type | Strong Focus
---|---
Circumference | 23m
Repetition | 2 – 7 sec
Inj. Beam Energy | 7MeV
Ext. Beam Energy | 70-250MeV
Intensity | $10^{11}$ ppp

Injection from Linac

Pulse to Pulse Energy Change
Variable Spill Length 0.5 – 5 sec

Decel.

Injection

Time

BM
ESD
QF
QD
RF-for Acc.
7m
SX
R1.4m

Extraction to Beam Transport

RF-for Extraction.
Variable Timing and Op. Length

- Timing and length of beam extraction and operation can be varied flexibly.
  - Respiration gating operation
  - Spot scanning

Operational Cycle Length: Variable

Synchrotron Pattern: Variable Repetition Period

5) SCS by Hiramoto
Example of Gating Operation

Data obtained at Univ. of Tsukuba

Respiration signal

Extraction gate signal

Synchrotron operation pattern

Irradiated Beam*

*With passive scattering and ridge filter
Pulse to Pulse Energy Change

- Range Modulation for Scanning
- Cooperation with HEBT

Extraction
operation pattern
Injection
Extracted Beam Signal

155MeV 150MeV 145MeV 140MeV 135MeV

Pulse to pulse energy change

0 4 8 12 16 20

5) SCS by Hiramoto
Mitsubishi_Synchrotron for Hadron Therapy

~Week focusing: High intensity (17nA)
Accel_driven extraction
Carbon/Proton Therapy System

- Application of technologies used in the proton system to carbon therapy system
  
  > Acceleration, Extraction and Beam Scanning

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Lattice Type</th>
<th>Strong Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td></td>
<td>60m</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>P &lt;250MeV</td>
<td>C &lt;480MeV/u</td>
</tr>
<tr>
<td>RF Freq. for Extraction</td>
<td>P :0.7 - 1.1 MHz</td>
<td>C :0.75 - 1.3 MHz</td>
</tr>
<tr>
<td>Repetition</td>
<td>2 – 7 sec</td>
<td></td>
</tr>
</tbody>
</table>
Gunma University Heavy-Ion Medical Center

6) SCS by Noda
Main parameters of the synchrotron.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Type</td>
<td>FODO</td>
</tr>
<tr>
<td>Max. intensity</td>
<td>$2 \times 10^9$ pps</td>
</tr>
<tr>
<td>Cell number</td>
<td>6</td>
</tr>
<tr>
<td>Long straight section</td>
<td>$3.0m \times 6$</td>
</tr>
<tr>
<td>Circumference</td>
<td>62m</td>
</tr>
<tr>
<td>Injection energy</td>
<td>4 MeV/u</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>140-400 MeV/u</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>0.450-3.483MHz</td>
</tr>
<tr>
<td>Emittance/Δp/p of injection beam</td>
<td>10 $\pi$ mm mrad $\pm 0.2%$</td>
</tr>
<tr>
<td>Acceptance</td>
<td>240/30 $\pi$ mm mrad</td>
</tr>
<tr>
<td>Qx/Qy</td>
<td>1.68-1.72/1.13</td>
</tr>
<tr>
<td>transition gamma</td>
<td>1.72</td>
</tr>
<tr>
<td>$\xi_x/\xi_y$</td>
<td>-0.5/-1.5</td>
</tr>
</tbody>
</table>

BM filling factor of 43% is much larger than that of 31% in HIMAC, which brings a compact synchrotron.
HIMAC Facility

• Ion species: High LET (100keV/μm) charged particles → He, C, Ne, Si, Ar
• Range: 30cm in soft tissue → 800MeV/u (Si)
• Maximum irradiation area: 22cm Φ
• Dose rate: 5Gy/min/l
• Beam direction: horizontal, vertical

HIMAC (Heavy Ion Medical Accelerator in Chiba)
New Treatment Facility

- 3D Scanning with Gating (H&V): 2 rooms
- Rotating Gantry: 1 room

3D Scanning with Gating (H&V)

New treatment facility

Rotating Gantry
Toward Variable-Energy Operation Pattern

11-steps Energy Operation

Operation Pattern

430 MeV

140 MeV

Flattop

Inj. → Accel. → Decel. → Flattop

7) SCS by Noda
11-steps Energy Operation

C$^6^+$, 290 MeV/n

11-steps Beam Extraction

Operation Pattern (SX)

Stored Beam

Beam Spill

7) SCS by Noda
RF-KO Slow-Extraction from Synchrotron

Unstable region

Moving resonance

Induction acceleration

Amplitude growth due to RF-KO

Q-Driven
CNAO (PIMMS)
Mitsubishi_p
Mitsubishi_C/p

Acc. Driven

RF-KO Driven
HIMAC
HIT
Hitachi_p
Rapid Cycle Synchrotron for Hadron Therapy

Features

- Highly averaged intensity
- Compact magnet and machine due to one-turn injection
- Variable energy operation
- Many experiences: ISIS, J-PARC, KEK12GeV Booster
- Pulse machine → Dose-
- High RF voltage → Dep
- Eddy current problem: M
  → Depend on repeti

![Graph showing dose per cycle and cumulative dose over cycles]
Slow Cycle Synchrotron for Hadron Therapy

Features

- Variable energy operation
- Modified FT operation
- Many experiences as therapy machine
- Easy dose management
- Relatively low intensity
Thank you for your attention!!