Current Status of Sumitomo’s Superconducting Cyclotron Development for Proton Therapy


Sep. 27, 2019, Cape Town, Cyclotrons 2019
1. Introduction

2. Cyclotron Components

3. Beam Dynamics

4. Summary
Sumitomo Heavy Industries in Japan

Niihama Works

Accelerator Factory

Cranes

800 km

Tokyo Head Office

Chemical Plants

Speed Reducer

Cryocooler

Injection Molding Machine

Hydraulic excavators

Oil Tanker

Speed Reducer

Tokyo Head Office

Chemical Plants

Speed Reducer

Cryocooler

Injection Molding Machine

Hydraulic excavators

Oil Tanker

Speed Reducer
Accelerators Systems for Medical Use

Cancer Therapy

Diagnosis

Proton Therapy System
(230MeV Cyclotron)

30 MeV Cyclotron

Cyclotron-based BNCT
(Boron Neutron Capture Therapy)

PET Cyclotron (7~20MeV)

SPECT Cyclotron (30~70MeV)

RFQ & APF-IH Linacs for Heavy Ion Therapy

Proton Therapy System
(230MeV Cyclotron)
MP-30 Cyclotron for Radio Isotope Production

<table>
<thead>
<tr>
<th></th>
<th>MP-30</th>
<th>HM-20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton</strong></td>
<td>Energy: 15 - 30 MeV</td>
<td>Energy: 20 MeV</td>
</tr>
<tr>
<td></td>
<td>Current: 100 µA</td>
<td>Current: 150 µA</td>
</tr>
<tr>
<td><strong>Deuteron</strong></td>
<td>Energy: 15 MeV</td>
<td>Energy: 10 MeV</td>
</tr>
<tr>
<td></td>
<td>Current: 50 µA</td>
<td>Current: 50 µA</td>
</tr>
<tr>
<td><strong>Alpha</strong></td>
<td>Energy: 32 MeV</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Current: 30 eµA</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Radio Isotopes</strong></td>
<td>+ 62Zn/68Ge/111In/123I/201Pb</td>
<td>18F/15O/13N/11C/64Cu/89Zr</td>
</tr>
<tr>
<td></td>
<td>177Lu/211At</td>
<td>67Ga/76Br/99mTc/111In/124I</td>
</tr>
</tbody>
</table>
# Results of RI Production Tests by MP-30

<table>
<thead>
<tr>
<th>Purpose</th>
<th>PET</th>
<th>PET</th>
<th>SPECT</th>
<th>Therapy $\beta$-emitter</th>
<th>Therapy $\alpha$-emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay mode</td>
<td>EC+(\beta^+)/EC+(\beta^+)</td>
<td>EC/EC+(\beta^+)</td>
<td>IT</td>
<td>$\beta^-$</td>
<td>$\alpha$, EC</td>
</tr>
<tr>
<td>Half life</td>
<td>9.2 h / 9.7 min</td>
<td>271 d / 68 min</td>
<td>6.0 h</td>
<td>6.6 d</td>
<td>7.2 h</td>
</tr>
<tr>
<td>Production reaction</td>
<td>$^{63}\text{Cu}(p,2n)$</td>
<td>$\text{Nat. Ga}(p,2n)$</td>
<td>$^{100}\text{Mo}(p,2n)$</td>
<td>$^{176}\text{Yb}(d,x)$</td>
<td>$^{209}\text{Bi}(\alpha,2n)$</td>
</tr>
<tr>
<td>Target</td>
<td>Cu foil</td>
<td>Natural Ga$_2$O$_3$</td>
<td>$^{100}\text{Mo}-\text{MoO}_3$</td>
<td>$^{176}\text{Yb}-\text{Yb}_2\text{O}_3$</td>
<td>Natural Bi</td>
</tr>
<tr>
<td>Beam energy</td>
<td>p 25 MeV</td>
<td>p 28 MeV</td>
<td>p 19 MeV</td>
<td>d 15 MeV</td>
<td>$\alpha$ 28 MeV</td>
</tr>
<tr>
<td>Irradiation</td>
<td>20$\mu$A $\times$ 60min</td>
<td>20$\mu$A $\times$ 10min</td>
<td>20$\mu$A $\times$ 10min</td>
<td>20$\mu$A $\times$ 20min</td>
<td>20$\mu$A $\times$ 60min</td>
</tr>
<tr>
<td>EOB yield</td>
<td>1,204 MBq</td>
<td>0.53 MBq</td>
<td>180 MBq</td>
<td>6.0 MBq</td>
<td>112 MBq</td>
</tr>
</tbody>
</table>
Sumitomo Particle Therapy Systems in Asia

- Sapporo Teishinkai Hospital (Sapporo, 2016)
- Southern Tohoku General Hospital (Koriyama, 2016)
- Aizawa Hospital (Matsumoto, 2014)
- National Cancer Center (Kashiwa, 1998)
- Takai Hospital (Tenri, 2018)
- Samsung Medical Center (Seoul, 2015)
- Osaka Medical College (Takatsuki, 2018)
- Kyoto University (Kumatori, 2013)
- Chang Gung Memorial Hospital, Linkou (Linkou, 2015)
- Chang Gung Memorial Hospital, Kaohsiung (Kaohsiung, 2018)

19 Treatment Rooms

N: # of Rooms
Year: Treatment start

- Proton
- Neutron
Single-Room Proton Therapy Solution

IMPT Nozzle with Various Options

Cyclotron Underneath

360deg Compact Gantry

Vertical ESS and Beamline

17 m
23 m
20 m
230 MeV Cyclotron P235 for Proton Therapy

P235 cyclotron in National Cancer Center in Japan (1998~)

- Normal conducting (~2T)
- Weight ~220 t
- Diameter ~4.4 m

P235 cyclotrons manufactured in Sumitomo Niihama Works
P235 and New Superconducting Cyclotron

### P235 (Yoke Weight ~ 220 ton)
- Maximum Beam Current: 300 nA
- Power Consumption: 400 kW
- Transport pieces: more than 20
- Installation Period: 30 days

### SC230 (Yoke Weight ~ 65 ton)
- Maximum Beam Current: 1,000 nA
- Power Consumption: 200 kW
- Transport pieces: 2 to 3
- Installation Period: 7 days
Design Parameters

<table>
<thead>
<tr>
<th>Beam</th>
<th>Particle species</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>&gt; 230 MeV</td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>max. 1000 nA</td>
<td></td>
</tr>
<tr>
<td>RMS emittance</td>
<td>~1 $\pi$ mm-mrad</td>
<td></td>
</tr>
<tr>
<td>RMS momentum spread</td>
<td>&lt; 0.1 %</td>
<td></td>
</tr>
<tr>
<td>Extraction efficiency</td>
<td>&gt; 70 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Yoke size</th>
<th>$\phi$2.8 m \times 1.7 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yoke weight</td>
<td>65 t</td>
</tr>
<tr>
<td></td>
<td>Beam extraction radius</td>
<td>0.6 m</td>
</tr>
<tr>
<td></td>
<td>Average B @ center / extraction</td>
<td>3.1 T / 3.9 T</td>
</tr>
<tr>
<td></td>
<td>Number of sectors</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF</th>
<th>Frequency</th>
<th>95.2 MHz (h=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of dees</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Dee voltage @ center / extraction</td>
<td>50 kV / 75 kV</td>
</tr>
<tr>
<td></td>
<td>Cavity wall loss</td>
<td>&lt; 100 kW</td>
</tr>
</tbody>
</table>
Outline

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### SC Coil and Cryostat

- **Conductor Wire material**: Monolith NbTi/OFC
- **Size**: 2.1 mm × 3.4 mm
- **Coil Configuration**: Two solenoids
- **# of Turn**: 2208 Turn/coil
- **Cooling Method**: Conduction cooling
- **Cryocooler**: Four 4 K-GM coolers
- **Operating current**: 442 A
- **Maximum current**: 488 A
- **Peak B in coil @Imax**: 4.4 T
- **Critical temp. @ Imax**: 7.4 K
- **Nominal temperature**: 4.7 K
- **Initial cooling time**: 14 d

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J. Yoshida et al., in Proc. MT26, 2019.
T. Tsurudome et al., in EUCAS 2019.
Cryostat in Cyclotron
Cryostat Cooling Test

Initial cooling time was 14 days
Coil Excitation Test

- Ramp up time from 0 A to 488 A was 1.5 h.
- We have not experienced a quench except during scheduled quench tests.
• Stored energy (=5 MJ) was consumed by SC coil and dump resistor.
• Quench recovery time was 17 h.
- Vertical chopper for fast beam switch on/off (< 50 us).
- Harmonic coils for beam centering.

N. Kamiguchi et al., in Cyclotrons 2019
• RF cavities are being fabricated.
• 120 kW RF power amplifier is being tested.

<table>
<thead>
<tr>
<th>Type</th>
<th>Solid state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>95.2 MHz</td>
</tr>
<tr>
<td>Max. output power</td>
<td>120 kW</td>
</tr>
<tr>
<td>Size of Power Amp.</td>
<td>W3,704 x H2,000 x D1,110</td>
</tr>
</tbody>
</table>
Beam Extraction

- Beam extraction is made by ESD + MC1 + MC2
- C-MC1, C-MC2 for reducing B1 component.
- Harmonic coils for B1 control.

ESD -54 kV, 4 mm gap
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Field Mapping System

Y. Ebara et al., in Cyclotrons 2019

- It took 2.5 h to obtain a full field map by 6 Hall probes
• Sectors were machined three times to obtain isochronous field
• No apparent beam blowup during acceleration.
• Precessional extraction is used to get large turn separation.
• To obtain optimum turn separation at ESD, B1 should be under control.
• B1 at R=600 was corrected by adjusting horizontal position of SC coil.
By adjusting harmonic coils, large turn separation was obtained.
• Optimized beam extraction efficiency was larger than 70%.
• At cyclotron exit, $2\sigma$ emittance will be around 4 $\pi$mm-mrad.
Summary

• Most SC cyclotron components have been designed and are being built.

• SC magnet was built and specified magnetic field was excited.

• Isochronous field was obtained by pole machining.

• In the simulation, the optimized extraction efficiency was larger than 70 %.

• A new building in Saijo plant is under construction for cyclotron beam test. SC cyclotron will be tested at the new site in FY 2020.
Thank you for your kind attention!