Status of 150-MeV FFAG Accelerator of Kyushu University

Center for Accelerator and Beam Applied Science of Kyushu University

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Overview of Center for Accelerator and Beam Applied Science of Kyushu University
New campus plan and construction of new accelerator facility

http://www.kyushu-u.ac.jp
Establishment of Center for Accelerator and Beam Applied Science

To promote activity in nuclear science and engineering, medical field and accelerator science at Kyushu University
Construction History of Accelerator Facility

1st Stage (2008-2011)
Construction History of Accelerator Facility

1.5\textsuperscript{st} Stage (2011-2013)
Construction History of Accelerator Facility
2nd Stage (2013-2014)
Center for Accelerator and Applied Beam Science

- 150 MeV FFAG
- Injector cyclotron
- 8 MV tandem accelerator
- New $^{60}\text{Co}$ gamma-source
150 MeV FFAG accelerator and injectors

- **Internal Ion Source**
- **Cyclotron**
- **Ion Source** (p, d, Heavy Ion)
- **8 MV Tandem Accelerator**
- **14 MeV Proton or Heavy Ion**
- **150 MeV Proton or Heavy Ion beam**
- **10 MeV Proton**
- **125 MeV Proton**
- **Experimental Hall**
150 MeV FFAG Accelerator (2017)

<table>
<thead>
<tr>
<th>magnet</th>
<th>Radial sector type (DFD-triplet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell</td>
<td>12</td>
</tr>
<tr>
<td>K-value</td>
<td>7.62</td>
</tr>
<tr>
<td>Beam energy</td>
<td>10 ⇒ 125 MeV (12 ⇒ 150 MeV)</td>
</tr>
<tr>
<td>Radius</td>
<td>4.47 ⇒ 5.20 m</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>H: 3.69<del>3.80 V: 1.14</del>1.30</td>
</tr>
<tr>
<td>Max. field</td>
<td>F-field: 1.63 T</td>
</tr>
<tr>
<td></td>
<td>D-field: 0.78 T</td>
</tr>
<tr>
<td>Circ. freq.</td>
<td>1.55~4.56 MHz</td>
</tr>
<tr>
<td>Repetition</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Mean current</td>
<td>1.5 nA</td>
</tr>
</tbody>
</table>
### Injector Cyclotron

#### Technical Specifications:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>10 MeV (proton)</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>AVF Cyclotron</td>
</tr>
<tr>
<td><strong>Ion Source</strong></td>
<td>Internal PIG (LaB6 cathode)</td>
</tr>
<tr>
<td><strong>RF Dee Voltage</strong></td>
<td>40 kV</td>
</tr>
<tr>
<td><strong>Extraction Radius</strong></td>
<td>300 mm</td>
</tr>
<tr>
<td><strong>Magnetic Field</strong></td>
<td>Max. 1.54 T</td>
</tr>
<tr>
<td><strong>RF Frequency</strong></td>
<td>47 MHz (2\textsuperscript{nd} harmonic)</td>
</tr>
<tr>
<td><strong>Beam Current</strong></td>
<td>15 μA</td>
</tr>
</tbody>
</table>
8-MV tandem accelerator

Beam operation for low energy experiments has been started in 2016.

<table>
<thead>
<tr>
<th>Accelerator Type</th>
<th>Horizontal Tandem Van de Graaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>NEC pelletron (8UDH)</td>
</tr>
<tr>
<td>Terminal Voltage</td>
<td>7 MV (max. 8 MV)</td>
</tr>
<tr>
<td>Accelerator Tank</td>
<td>Diameter: 3.0 m</td>
</tr>
<tr>
<td></td>
<td>Length: 13.6 m</td>
</tr>
<tr>
<td>Insulation Gas</td>
<td>SF₆ (Pressure: 0.6 MPa)</td>
</tr>
<tr>
<td>Ion Source</td>
<td>Sputter Ion Source (NEC MC-SNICS)</td>
</tr>
<tr>
<td></td>
<td>RF Ion Source (NEC Alphatross)</td>
</tr>
<tr>
<td>Injection Voltage</td>
<td>-70 kV</td>
</tr>
<tr>
<td>Beam</td>
<td>P, d, Heavy Ion</td>
</tr>
<tr>
<td>Current</td>
<td>1 nA (→ 1µA)</td>
</tr>
<tr>
<td>Terminal Stripper</td>
<td>C Foil and N₂ Gas</td>
</tr>
<tr>
<td>Charging Device</td>
<td>Double Pellet Chains (Current: 150 mA x 2)</td>
</tr>
</tbody>
</table>

Low energy beam lines
### Construction and Beam Commissioning Log

<table>
<thead>
<tr>
<th>Year</th>
<th>1st stage</th>
<th>1.5 stage</th>
<th>2nd stage</th>
</tr>
</thead>
</table>

#### Cyclotron
- Maintenance & Reassembling (2008.9 - 2009.3)
- Radiation Inspection (2014.6)
- In Operation

#### FFAG
- Construction of FFAG (2009.5 – 2012.2)
- Test of Power sources & Beam injection (2011.12 – 2012.12)
- Construction of Tandem- FFAG Injection line (2015.2 – 2015.6)
- Construction of extraction beam lines (2016.8 – 2017.9)
- Beam Acceleration (2013.7 – 2014.12)

#### Tandem
- Construction of Tandem (2011.3 – 2013.6)
- Test of ion source & Beam acceleration (2014.4 – 2015.3)
- In Operation
Construction status of beam lines

Black: Construction completed  
Red: Under construction  
Orange: Construction will be started  
Green: In the planning stage
Present Status of
150-MeV FFAG Accelerator

1. Status of beam commissioning
2. Construction of beam extraction system
Status of Beam Commissioning of 150-MeV FFAG Accelerator

Beam acceleration was demonstrated (~80MeV) in 2013. Radiation safety inspection was passed in Jun. 2015.

2016
Beam commissioning was suspended due to construction of extraction beam line and development of tune correction system.

2017
Test of tune correction system will be carried out. Beam extraction will be demonstrated.

Operation time: about 200 hours / year
(Limitation of budget)
Timing Chart of the FFAG accelerator

Cycrotron RF

Cycrotron Ion Source

Injection Bump

Main Ring RF

Extraction Kicker

Extraction Septum

Repetition rate 100 Hz

Timing:
- Cycrotron RF: 400 μs
- Injection Bump: 50 μs
- Main Ring RF: 10 μs
- Sawtooth capture: 0.1 ms
- Acceleration: 9.0 ms
- Extraction: 9.5 ms
- Square wave: 100 ns
- Half sine-wave: 0.7 ms
Timing Chart of 150 MeV-FFAG

- **Cycrotron RF:** 400 μs
- **Cycrotron Ion Source:** 50 μs
- **Injection Bump:** half sine-wave
- **Main Ring RF:** Sawtooth capture, acceleration to 125 MeV
- **Extraction Kicker:** square wave 100 ns
- **Extraction Septum:** half sine-wave

**In operation:**
- 0 ms to 0.7 ms

**In preparation:**
- 9.5 ms
Extraction method: Fast Extraction
Phase advance between kicker and septum: 440 deg. (4 cells) \(\approx 3\pi\)
• Rise time should be less than 150 ns in order to prevent beam loss at the extraction septum.
• Time width of flat top is larger than 100 ns.
• Required beam separation is larger than 13 mm.
Requirements for Extraction kicker (2)

Kicker magnet developed at KEK in 2006

The kicker magnet consists of air core

Rise Time: 270 ns
Time width of flat top: 80 ns

Beam loss rate was 10 %

Charge Voltage $< 40 \text{ kV (in air)}$

\[ V = -L \frac{dI}{dt} \]

\[ \frac{dI}{dt} \propto \frac{1}{\text{rise time}} \]

Rise time can be decreased if inductance $L$ is reduced.
Development of new type Extraction kicker magnet

New type of kicker magnet with 3 coils has been developed.

600 mm x 70 mm

Development of new type of kicker magnet has been developed in 2012, however, High power test with rapid cycling operation has not been performed.

In ideal condition,

\[ L' = \frac{1}{9} L \]

Measured \( L = 0.95 \, \text{uH} \) \[1\]

Power test of Extraction Kicker (1)

The kicker coils has been installed in the main ring, and high power test has been carried out.

<table>
<thead>
<tr>
<th>Design Parameters of power source of extraction kicker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Current</td>
</tr>
<tr>
<td>Charging Voltage</td>
</tr>
<tr>
<td>Switching device</td>
</tr>
<tr>
<td>Wave form</td>
</tr>
<tr>
<td>Type of Output circuit</td>
</tr>
</tbody>
</table>
Power test of extraction kicker (2)

Power test with 100 Hz operation has been performed

Installed Kicker magnet

Before

Rise Time: 270 ns
Time width of flat top: 80 ns
Peak current: 1700 A

Measured output current

Rise Time: 160 ns
Time width of flat top: 140 ns
Peak current: 5140 A = 1713 A/coil

Rise time was 7 % larger than required rise time.
Results

At the entrance of the septum magnet

Extracted beam
Circulating beam

Technical issues

Enough beam separation was obtained.

Electric discharge around the thyratron was occurred when charging voltage was larger than 42.5 kV. (Operation voltage = 42 kV)
We are now investigating of the cause of the discharge.

100 Hz, 42.5kV
Power test of extraction Septum (1)

The maintenance of the power supply was carried out using the additional budget in 2016.

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Eddy current type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output waveform</td>
<td>Half-sin wave</td>
</tr>
<tr>
<td>Magnet Length</td>
<td>460 mm</td>
</tr>
<tr>
<td>Gap width / height</td>
<td>70 mm / 23 mm</td>
</tr>
<tr>
<td>Switching device</td>
<td>Mitsubishi FT1500EY-24</td>
</tr>
<tr>
<td>Wave length</td>
<td>155 us</td>
</tr>
<tr>
<td>Peak current</td>
<td>8600 A</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>3.7 kV</td>
</tr>
</tbody>
</table>

Power source

New output cables

Power source
Power test of extraction septum magnets (2)

Installation into vacuum chamber and alignment has been performed.
Power test of Extraction Septum (3)

Power test with 100 Hz operation has been carried out.

Required current (8600A) for beam extraction was obtained.
Upgrading of Trigger system

Trigger system consists of 6 function generators. Measured Time jitters are less than 4 ns. Trigger timing can be controlled arbitrary in 10 ns.
Construction of extraction beam line

Since additional construction budget was secured, construction of the extraction beam line has been started in 2016.

Reuse of old magnets in KEK

TRISTAN
- Dipole magnets
- Quadrupole magnets

PS Pre-injector
- Triplet quadrupole
- Dipole magnet
- Power sources

However, Because we did not get enough budget to manufacture new magnets and power sources, used magnets and power sources have been transported from KEK.

Transportation from KEK in Jan. 2016
Vacuum pump and chamber are ready to install.

Construction has been almost completed. Beam commissioning for beam extraction will be started soon.
Hardware developments for 150-MeV FFAG

Tune Correction system
Vertical tune correction patches
Horizontal tune correction coils
Beam loss caused by resonances

\[ \nu_x + \nu_y = 5, \ \nu_y = 1.5 \text{ and } \nu_x - 2\nu_y = 1 \]

are strong resonance line.
Tune variation during acceleration

To reduce the tune variations is important in order to prevent beam loss.
Development of additional pole (patch) for vertical tune correction

The variation of vertical tune has been decreased with the iron plate installed in both side of the magnet.

Optimization of shape of the plate with Opera 3d has been carried out by Motohashi-san in 2016.
Improvement of additional patch

Developed pole in KEK in 2005

New additional pole
Calculation results indicate that Vertical tune variation has been reduced from 0.2 to 0.09.

Tune measurements will be carried out in the next beam time from Nov.
Development of horizontal tune correction coils

In order to reduce horizontal tune variation, correction magnet with multilayered coils has been developed.

Detail of development of the correction coils and results of field measurements will be reported in Ueda-san’s presentation in September 10.
Summary

• Construction status
  – Construction of beam extraction system has been completed.
  – High power test of the extraction kicker and the extraction septum has been demonstrated.

• Hardware development
  – Tune correction system has been developed successfully.

Beam commissioning for beam extraction will be stared.