Development of Six-Cell FFAG

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Introduction
Introduction

- PRISM-FFAG ring is muon phase rotator aiming at search for Lepton Flavour Violation process.
- At PRISM-FFAG, muon bunch is rotated quarter turn in $\Delta t$-E phase space and energy spread is squeezed from 20% to 2%.

Longitudinal phase space rotation
Six-Cell FFAG Ring

- Full scale of PRISM-FFAG is 10 cell. However, we will start with scaled down ring of six cell due to budget limitation.

- Characteristics
  - Use of full scale magnets.
  - Use of alpha particle emitted from RI source as beam
  - Sawtooth phase rotation

- Purpose of commissioning
  - Beam orbit study
  - Demonstration of Longitudinal Phase Space Rotation
  - Establishment of commissioning method with alpha ray from RI source.
Phase Rotation on Six-Cell Ring

• 1st step
  • DC alpha particle is used and measure modulation of $E$ vs. $\Delta t$ by RF

• 2nd step
  • Alpha particle is injected by pulsed kicker and measure phase rotation.

Phase Rotation Simulation for \( ^6 \)-particles
\[ P_{\alpha} = 90 \text{MeV/c} \]
RF 100kV/m 2MHz Sawtooth
## Parameters of Six-Cell FFAG RING

<table>
<thead>
<tr>
<th></th>
<th>Six-Cell FFAG</th>
<th>Full PRISM-FFAG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># of Cells</strong></td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td><strong>Particles</strong></td>
<td>Alpha</td>
<td>Muon</td>
</tr>
<tr>
<td><strong>Momentum</strong></td>
<td>MeV/c</td>
<td>100</td>
</tr>
<tr>
<td><strong>Ring Radius</strong></td>
<td>m</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Magnet Aperture</strong></td>
<td>cm</td>
<td>100 x 30</td>
</tr>
<tr>
<td><strong>BL (F)</strong></td>
<td>x10⁴ Gauss/cm</td>
<td>8.53 @r=3.3m</td>
</tr>
<tr>
<td><strong>BL (D)</strong></td>
<td></td>
<td>-1.37</td>
</tr>
<tr>
<td><strong>Field index (k_F/k_D)</strong></td>
<td>1.8 / 1.3</td>
<td>4.6 / 4.6</td>
</tr>
<tr>
<td><strong>Δk_F/Δk_D</strong></td>
<td>±0.2 / ±0.3</td>
<td>const.</td>
</tr>
<tr>
<td><strong>F/D ratio</strong></td>
<td>6~7</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Field Clamp</strong></td>
<td>Attached to 2 Magnets</td>
<td>Attached to All Magnets</td>
</tr>
</tbody>
</table>
Layout of Six-Cell Ring

Cross sectional view of the beam-duct

Cell 1
Cell 2
Cell 3
Cell 4
Cell 5
Cell 6

RF Cavity
Field clamp
Beam Direction
Injection Chamber

Distance from ring center to magnet center
R 2000
R 3080.8
R 3272.4
R 3557.4
R 4022.4
Apparatus
Construction of six-cell FFAG ring

• The six-cell FFAG ring has been constructed at RCNP, Osaka University.
PRISM-FFAG Magnet

- Full scale size of 10 cell PRISM-FFAG magnet
- Consist of six magnets
- 2 magnets have a field clamp
- 4 magnets have no field clamp
Individual difference between FFAG magnets

Variance of magnetic fields between magnets in Six-cell-FFAG ring.
- D magnet: rms=2.2 Gauss (0.2 %)
- F magnet: rms=1.9 Gauss (0.1 %)
Profiles of Magnetic Field

Measured field profile of F magnets

Coefficient of multi-pole expansion around r=3500 mm

Cell 2 (Clamp)

<table>
<thead>
<tr>
<th>Order</th>
<th>Unit</th>
<th>Measurement</th>
<th>TOSCA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>Gauss</td>
<td>3230.7</td>
<td>3218.6</td>
<td>0.38%</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>Gauss/mm</td>
<td>2.109</td>
<td>2.0724</td>
<td>1.8%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>Gauss/mm²</td>
<td>1.146e-3</td>
<td>1.1948e-3</td>
<td>-4.1%</td>
</tr>
<tr>
<td>k</td>
<td></td>
<td>2.28</td>
<td>2.25</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Cell 5 (No Field Clamp)

<table>
<thead>
<tr>
<th>Order</th>
<th>Unit</th>
<th>Measurement</th>
<th>TOSCA</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>Gauss</td>
<td>3225.3</td>
<td>3219.8</td>
<td>0.17%</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>Gauss/mm</td>
<td>2.093</td>
<td>2.080</td>
<td>0.62%</td>
</tr>
<tr>
<td>Sextupole</td>
<td>Gauss/mm²</td>
<td>1.257e-3</td>
<td>1.188e-3</td>
<td>5.8%</td>
</tr>
<tr>
<td>k</td>
<td></td>
<td>2.27</td>
<td>2.26</td>
<td>0.4%</td>
</tr>
</tbody>
</table>
Development Status of RF System

- RF operation test has been performed after construction of 6 cell ring.
- For phase-rotation experiment, the duty factor are increased to 0.3%. Duration and repetition were increased to 30 us and 100 Hz.
- 33 kV has been obtained. (RF frequency=2.1MHz)
- Next step is a generation of sawtooth wave.

Obtained gap voltage : 33 kV
Development status of pulsed kicker

- Pulsed kicker electrode has been installed in the Six-cell FFAG ring.
- Test with DC voltage will be performed soon.

Side view of injection kicker
Beam-Optics Measurement
Motivation of Beam Optics Measurement

- Measurement of the phase rotation
  - Measure $\Delta t$ and $E$ with SSD (solid state detector) located on beam orbit
  - To rotate alpha particles more than one turn, betatron oscillation will be used.
  - To determine position of SSD, beam orbit should be measured.
Procedure of Beam-Optics Measurement

1. Detection of Alpha Particle with Large Acceptance Detector.
Large Acceptance Alpha-ray Detector

- To detect alpha particle with large acceptance, a long detector has been developed.

- Effective Region: 360 mm (cover 90% of beam duct width)
- Position: Charge ratio between two photo multipliers.
- Phosswitch type: Effectively select alpha from background
- Position resolution: \( \sigma_{\text{det}} \sim 3 \text{ cm (1MeV } \alpha\text{-ray)} \)
Photograph of large acceptance alpha-ray detector

Detection window
Large acceptance alpha ray detector was installed into the six cell ring. Alpha particles were successfully detected after cell-2 and cell-4.

Obtained position of $\alpha$ particle signals

- After cell2: 3020 mm
- After cell4: 3000 mm
Measurement of Closed Orbit

- **Collimator**

- Injector and SSD are aligned to a line on a same stage.

- Alpha ray is degraded by Aluminum foil degrader from 5 MeV to 1 MeV

![Diagram of measurement setup]

- Collimator
- Injector and SSD are aligned to a line on a same stage.
- Alpha ray is degraded by Aluminum foil degrader from 5 MeV to 1 MeV.

**Degrader** $^{241}$Am $\rightarrow$ SSD

**Rotation center of stepping motor**

**Circular slit**
- $\phi 10$ mm
- $\phi 7$ mm

**Beam Stopper** $\phi 10$ mm
Measurement of Closed Orbit

• **Procedure**

  • Angle of closed orbit is determined by searching maximum detection rate as a function of rotating angle of the stage.

  • Radial position is changed and angle of a closed orbit is searched again.
Location of measurement device

241 Am source and SSD

Beam Direction

Injection Chamber

RF Cavity

Cell 1

Cell 2

Cell 3

Cell 4

Cell 5

Cell 6

Distance from ring center to magnet center

R 3272.4

R 3080.8

R 2000

R 3557.4

R 4022.4

\[ \alpha \]
Picture of measurement device for closed orbit
Typical data
• Measurement results are between the two simulations.
• Difference between simulation and measurements : 40 mm

* G4beamline: Beam-line design code based on Geant4
Measurement of Phase Adv.

- We measured betatron phase advance of alpha particles after one turn in the six-cell ring
  - Injector is fixed.
  - SSD is moved in radial direction, and $E$ and count rate are measured. We obtain
    - Energy
    - $r$ position
  - SSD is shifted by 160 mm in beam direction and scanned again. We obtain
    - $r'$
Photograph of collimator
Profiles of $\alpha$-particle rate as a function of SSD radial position

- 検出された$\alpha$線のtotal rateとADC分布から各energyのrateを計算
- Gauss分布でFitして$\alpha$線検出位置を決定

$\gamma' = \frac{\Delta r}{L} = \frac{r_2 - r_1}{L} = 19 \pm 7 \text{ mrad}$
Change of betatron phase after 1 turn

• Injection Points \((r,r')\)
  - \(A(3020\text{mm},0\text{mrad})\),
  - \(B(3044\text{mm},-27.8\text{mrad})\)

\[1310 < E < 1320\text{keV}\]
Tune

- Transfer matrix is obtained by solving following equations. The two equations are consist of data where phase space of injection are different each other.

\[
\begin{pmatrix}
\begin{array}{c}
r_f \\
\cdot_f
\end{array}
\end{pmatrix} = \begin{pmatrix}
\begin{array}{cc}
\cos \mu + \alpha \sin \mu & \beta \sin \mu \\
-\gamma \sin \mu & \cos \mu - \alpha \sin \mu
\end{array}
\end{pmatrix}
\begin{pmatrix}
\begin{array}{c}
r_i \\
\cdot_i
\end{array}
\end{pmatrix}
\]

\( \nu = \frac{\mu}{2\pi} \)

\( \nu_H = 0.412 + n \pm 0.02 \) @\( p = 99.0 \) MeV/c

n: unknown integer
Comparison with Simulation

vertical tune

horizontal tune

vertical tune

O: Measurement

Preliminary

75 87.5 100 112.5 125

momentum (MeV/c)

0.5 1 1.5 2 2.5 3 3.5

tune

../rz/n6_tr969-sfm_ro325.0_p0.08.rm100.rz
Summary

- Six-Cell FFAG ring is a machine for test of phase rotation and beam optics study.
- Six-Cell ring has been constructed.
- Beam optic has been measured.
  - Large acceptance alpha beam position detector developed.
  - Closed orbit are obtained. Obtained closed orbit was comparable to two simulation within 40 mm.
  - Tune was obtained, the value was $\nu_H = 0.412 + n \pm 0.02$
Next plan

• Generation of Sawtooth RF wave.
• Measurement of modulation by RF wave.
• Development of kicker system.
• Measurement of phase rotation.