Design of a Sector Magnet for High Temperature Superconducting Injector Cyclotron

Keita Kamakura

Research Center for Nuclear Physics
Osaka University
Overview

• About us
• Current status of RCNP
• Project for New Injector Cyclotron
• Sector Magnet Design
• HTS Magnets
• Summary
About Us

- Research Center for Nuclear Physics
About Us

• RCNP Cyclotron Facility

Grand Raiden Spectrometer

K140 AVF Cyclotron
Features of beam production at RCNP

- **High energy resolution** acceleration for precise nuclear physics experiments
- Together with Grand Raiden Spectrometer
  \[
  \frac{\Delta E}{E} \sim \frac{12.8 \text{ keV}}{295 \text{ MeV}} \sim 4.3 \times 10^{-5}
  \]
  mainly for light ions \((p, d, ^3He, \alpha \ldots)\)
- Intensity of the precise beam is \(~ \text{few nA} \)

- Using **proton beam** to produce secondary particle beam (neutrons, muons)
- Intensity limit of the primary proton beam is \(~ 1 \mu\text{A} \)
Our Goal

• Increase the beam current x10 for both
  – Precise ion beams (*few nA → several tens of nA*)
  – Primary proton beam (1 μA → 10 μA)

AVF cyclotron is not the best for high intensity beam
## New Injector: Conceptual Design

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K value</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Injection Radius</td>
<td>1 m</td>
</tr>
<tr>
<td>Extraction Radius</td>
<td>3 m</td>
</tr>
</tbody>
</table>

### Sector Magnet
- Pole Angle: 33°
- No. of Sectors: 4
- Max. Field: 1.73 T

### RF Cavity
- No. of Cavities: 2
- No. of Gaps: 2
- Harmonic No.: 9, 15 (RING: 6, 10)
- RF Frequency: 30~52 MHz
- Gap Angle: 17°

For technological development, main coil of the new injector will be implemented with HTS coils.
Motivations for HTS Cyclotron

• Magnets can be compact, and can generate high magnetic field
• Low power consumption
• Critical temperature is high: $T_c > 100 \text{ K}$
  – No liquid helium is required
  – Operating Temperature: $T_o \sim 10 \text{ K}$
  – Large margin between operating temperature and $T_c$
    $\rightarrow$ High stability against quenching
• Still, large scale HTS coil used for cyclotron is not available so far
New Injector: HTS Main Coil & Trim coils

- FEM model of the sector magnet.

Trim Coils (normal conductor)

HTS Main Coil

2.8 m
Isochronous Field

• Design Assistant Program
  1. FEM field analysis on 3D model of sector magnet (Opera-3d, TOSCA)
     1. Main Coil
     2. 36 Trim Coils
  2. Orbit simulation on Main Coil and find equilibrium orbit by controlling particle energy (Runge-Kutta)
  3. Calculate $K_B$ and $K_r$ for each radius
  4. Fit isochronous field by trim coils
  5. Excite trim coils in FEM model and calculate the field
Isochronous Field

• Design Assistant Program
  1. FEM field analysis on 3D model of sector magnet (Opera-3d, TOSCA)
     1. Main Coil
     2. 36 Trim Coils

Discussed later
Isochronous Field

- Design Assistant Program
  1. FEM field analysis on 3D model of sector magnet (Opera-3d, TOSCA)
    1. Main Coil
    2. 36 Trim Coils
  2. Orbit simulation on Main Coil and find equilibrium orbit by controlling particle energy (Runge-Kutta)
Isochronous Field

- Design Assistant Program

\[ \bar{B}(R) = \bar{\gamma}(R)\bar{B}_0 = \bar{B}_0 \sqrt{\frac{M^2}{M^2 - (QB_0rc/K_r)^2}} \]

\[ B_{iso}(r) = K_B\bar{B}_0 \sqrt{\frac{M^2}{M^2 - (QB_0rc/K_r)^2}} \]

3. Calculate \( K_B \) and \( K_r \) for each radius

\[ K_B = \frac{B(r)}{\bar{B}(R)} \]

\[ K_r = \frac{r}{R} \]
Isochronous Field

- Design Assistant Program

\[ \Delta B(r) = B_{iso}(r) - B_{main}(r) \]
\[ = \sum_{i=1}^{36} a_i B_{trim}^i(r) + \delta(r) \]
\[ S = \sum_{j=1}^{N} \left\{ \Delta B(r_j) - \sum_{i=1}^{36} a_i B_{trim}^i(r_j) \right\}^2 \]

Least Square Method

4. Fit isochronous field by trim coils
Isochronous Field

- **Design Assistant Program**
  1. FEM field analysis on 3D model of sector magnet (Opera-3d, TOSCA)
     1. Main Coil
     2. 36 Trim Coils
  2. Orbit simulation on Main Coil and find equilibrium orbit by controlling particle energy (Runge-Kutta)
  3. Calculate $K_B$ and $K_r$ for each radius
  4. Fit isochronous field by trim coils
  5. Excite trim coils in FEM model and calculate the field
Isochronous Field

Number of Trim Coils: 15

Fields on this axis
Results

- Isochronous field has been successfully maintained by 15 trim coils.
- Orbit simulation confirmed the result.
Half-meter-size HTS Magnet

- Toy model
- HTS Wire: DI-BSSCO
- Preliminary research

Excitation by pulsed current

- Coil: 600 x 2 turns
- Radius: 400 mm
- Deflection: 60 deg.
- Pole gap: 30 mm
1-meter-size HTS Magnet

- Switching magnet for time sharing between two target rooms
- HTS Wire: BSSCO-2223
- Testing now @RCNP

Coil: 256 x 2 turns
Length: 1,142 mm
Width: 580 mm
Pole gap: 70 mm
Current: 200 A
Field: 1.5 T
Ramping speed: 20 A/s
1-meter-size HTS Magnet

Coil temperature during a pattern operation of the switching magnet

Cooling performance

I_c measurement at 77 K
Perspective for Next-gen Cyclotron

Size: 0.4 m, Toy model

Size: 1 m, Operation: 1.5 T

Size: 2.8 m, Operation: 1.7 T

Next Generation Cyclotron
Compact & High Magnetic Field
Summary

- At RCNP, upgrading cyclotron facility has been planned to increase beam current to $x10$.
- HTS cyclotron is proposed for the new injector.
- Design of sector magnet is completed.
- Magnetic field and orbit simulation confirmed the design.
- Now 1-meter-size HTS magnet is being tested.
- HTS Injector Cyclotron will be the first step to the next generation cyclotrons.
Thank you for your attention

For further discussions, contact me at
keita@rcnp.osaka-u.ac.jp

or as Keita Kamakura