DESIGN OF A SECTOR MAGNET FOR HIGH TEMPERATURE SUPERCONDUCTING INJECTOR CYCLOTRON

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Abstract

We propose a separated sector cyclotron (SSC) using high temperature superconducting (HTS) magnet for a next generation cyclotron. From its stability and low operating cost, HTS cyclotrons are expected to apply for accelerator-driven subcritical reactors or beam cancer treatment systems. On the other hand, we still have a variety of issues and challenges to implement them. As a first step, we are planning to develop an HTS cyclotron as an injector for K400 ring cyclotron at RCNP. It will be the first attempt in the world. This plan will improve beam intensity in our facility and also contribute to component developments for the next generation cyclotron. The most serious issues are development of large-size HTS magnets that can be used in SSC. One-meter-size HTS dipole magnet is made for testing. Now we are going to exam the magnet and evaluate the characteristics of large HTS magnets. The result of the test will be incorporated with the sector magnet design. Moreover, we have been working on conceptual design of the new injector, developed magnetic field and orbit analysis programs. In this session, the current status of designing HTS injector cyclotron at RCNP will be discussed.

CURRENT STATUS OF RCNP

At RCNP, K140 AVF cyclotron and K400 ring cyclotron are used to accelerate various ion species from proton to Xe (Figure 1). Those beams are used for nuclear physics experiments, neutron irradiation, isotope production, etc.

One of the most important features of our facility is the precise nuclear measurement with high energy resolution beam and Grand Raiden Spectrometer. It makes us possible to achieve resolution shown in formula (1).

$$\frac{\Delta E}{E} \sim \frac{12.8\ \text{keV}}{295\ \text{MeV}} \sim 4.3 \times 10^{-5} \qquad (1)$$

Beam intensity of the precise beam is about few nA.

For secondary beam production, intensity limit of primary proton beam is 1.1 μA which is not that high.

NEW INJECTOR PROJECT

Currently, we are planning to upgrade our facility by increasing the beam current up to 10 times of present values. One crucial factor of our problem is the low transmission of AVF injector cyclotron. So we decided to implement a new separated sector cyclotron as injector, as shown in Figure 2.

Conceptual Design

Considering requirements from the K400 ring cyclotron downstream, we finished a conceptual design on the new injector cyclotron [1].

For heavier ion acceleration, K value is raised up to 200 MeV. Maximum magnetic field is 1.7 T. It can be generated by normal conductor, but we decided to apply HTS coils for technological development.

Motivations for HTS Cyclotron

High temperature superconductors have several advantages over normal conductors and low temperature superconductors, which are:

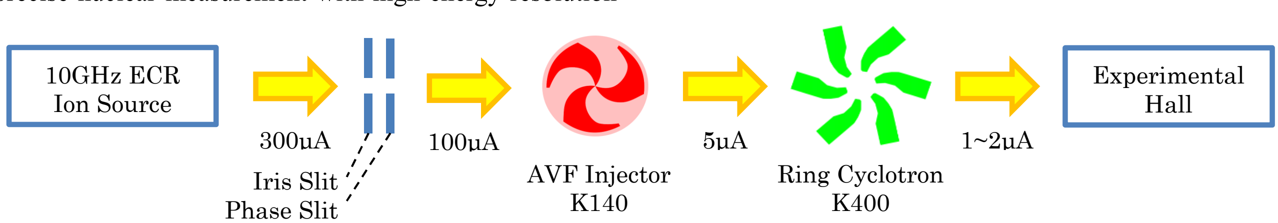

Figure 1: One example of proton acceleration in current RCNP cyclotron cascade.

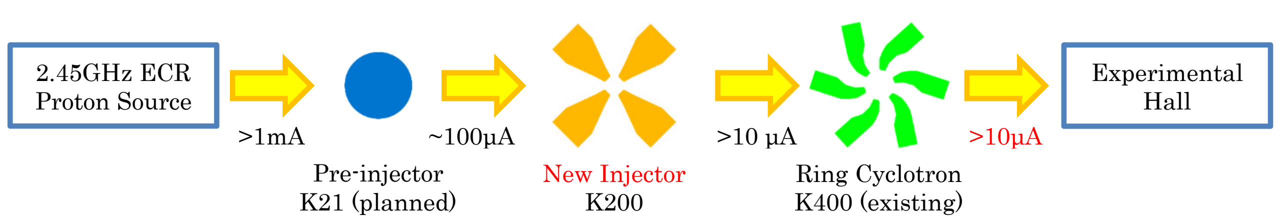

Figure 2: One example of proton acceleration in current RCNP cyclotron cascade.

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- Magnets can be compact, and can generate higher magnetic field.
- Low power consumption.
- Critical temperature is higher than 100 K, no liquid helium is needed for cooling.
- When the operation temperature is set around 10 K, large margin against quenching.

However, large scale HTS coil used for cyclotron is not yet available. Development of such coil will be the challenging part in the project.

Main Coil and Trim Coils

Based on the conceptual design, I designed 3D model of the sector magnet. On one pole, it has 1 set of HTS main coil, and 36 sets of trim coils of normal conductor which will be reduced later to moderate number, as shown in Figure 3.

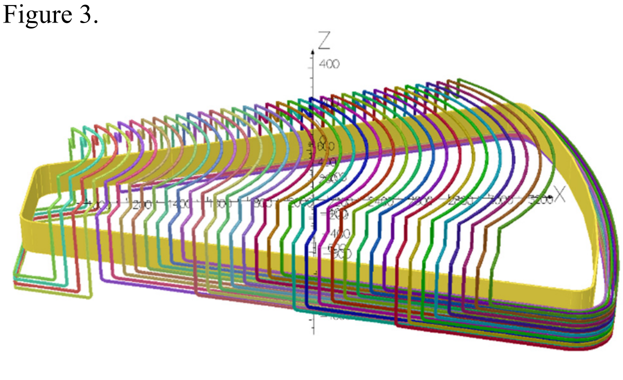

Figure 3: HTS main coil and 36 trim coils on one pole of sector magnet. Main coil size is 2.8 m along X axis.

Isochronous Field

Isochronous field should be maintained on the median plane as shown in (2). I developed a design assistant program to determine currents in the trim coils [2][3].

$$\bar{B}(R) = \gamma(R)\overline{B_0} = \overline{B_0}\sqrt{\frac{M^2}{M^2 - (Q\overline{B_0}Rc)^2}} \quad (2)$$

To control the average field ($\bar{B}$) on average radius (R), we have to know the shape of equilibrium orbits. I used finite element method analysis to obtain main coil field, and did an orbit simulation using Runge-Kutta method to get equilibrium orbit for each radius. Now we know the relationship between average field $\bar{B}(R)$ and field $B(r)$ on X axis; formula (3), also the average radius R and the position r on X axis; formula (4).

$$K_B = B(r)/\bar{B}(R) \quad (3)$$

$$K_r = r/R \quad (4)$$

Now, we can use K_B and K_r to convert the isochronous formula (2), and get isochronous field on X axis; (5).

$$\bar{B}(R) = K_B\overline{B_0}\sqrt{\frac{M^2}{M^2 - (Q\overline{B_0}rc/K_r)^2}} \quad (5)$$

We have to fit formula (5), which is also shown in Figure 4, by magnetic field of main coil (Figure 4) and trim coil contributions (Figure 5).

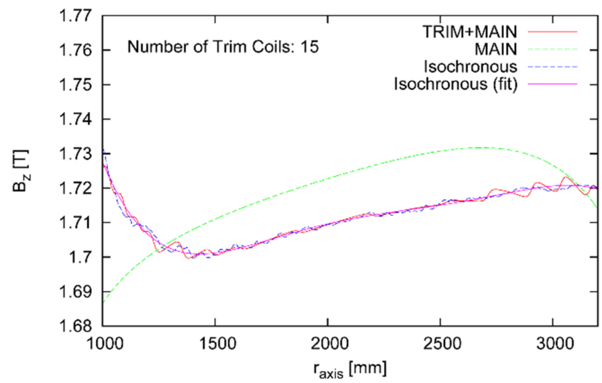

Figure 4: Vertical field B_z along X axis (see Figure 3). TRIM+MAIN: Field generated by main coil and trim coils by optimized parameters. MAIN: Field generated by main coil alone. Isochronous: Isochronous field shown in Formula using raw K_B, K_r. Isochronous (fit): Isochronous field using K_B, K_r fit by quintic curves.

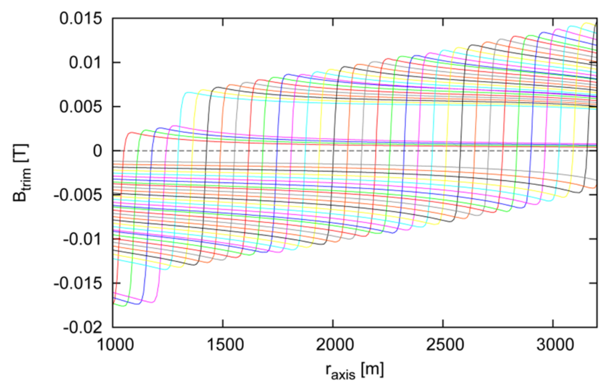

Figure 5: Contributions on vertical field by 36 trim coils excited to 504 A. Trim coils are exited one by one on main field and subtracted main coil contribution.

I used least square method for fitting. ΔB_z: shown in Figure 6 is the subtraction of isochronous field and main coil field.

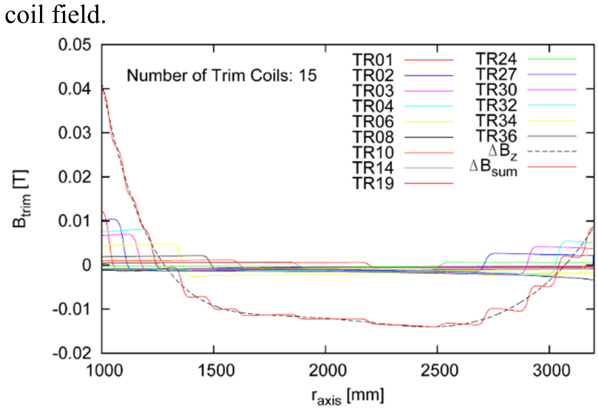

Figure 6: Excitation level of 15 trim coils to fit ΔB_z.

Around r=2000 mm, ΔB_z is very flat so we don't need many trim coils to fit it. So I reduced trim coils mainly from that region down to 15 coils.

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The isochronous field generated by those currents is shown in Figure 6. I did the orbit simulation including impulse acceleration at RF cavities to evaluate the isochronous field. $^{12}C^{4+}$ beam is successfully accelerated up to extraction energy (Figure 7). It confirmed the field generated by 15 trim coils.

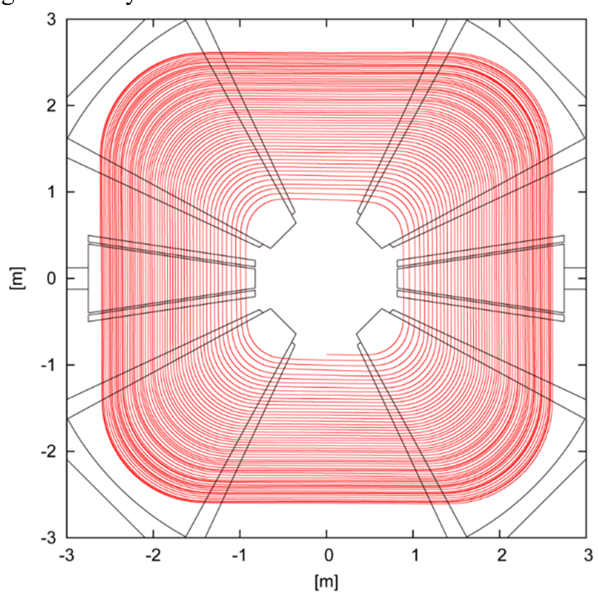

Figure 7: Orbit simulation on isochronous field.

DEVELOPMENT OF HTS MAGNETS

A lot of HTS magnets have been developed in RCNP. [4] Two of them are shown in Figure 8. These experiments are important steps for large scale HTS magnet improvements.

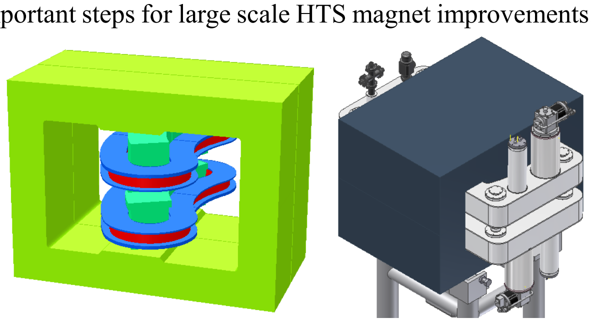

Figure 8: 40 cm toy model magnet (left), and 1 m switching magnet (right).

Half-meter-size HTS Magnet

The left drawing in Figure 8 is a half-meter-size bending magnet model with DI-BSCCO. It has 60 degrees of bending angle and 40 cm radius of curvature. This magnet is made for preliminary research. We did thermal and magnetic field measurements during ramping operation.

One-meter-size HTS Magnet

The left drawing in Figure 8 is a one-meter-size switching magnet for time sharing between two experimental halls. It is developed with BSCCO-2223. Now this magnet is being tested at RCNP. One of the results is shown in Figure 9. It shows coil temperature stays in the operating temperature during switching operation. The result confirmed the thermal design.

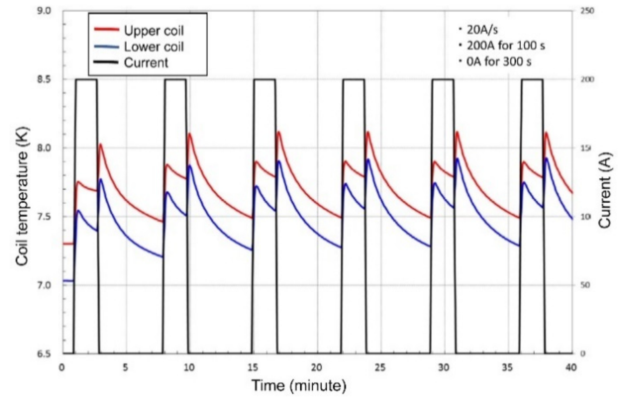

Figure 9: Coil temperature during ramping operation. Ramping rate is 20 A/s.

Perspective for Next Generation Cyclotron

We have been developed half-meter toy magnet, one-meter switching magnet with weak field operation (1.5 T). Next we are going to build three-meter sector magnet with weak field operation (1.7 T).

This HTS cyclotron is an important step for the next generation compact and high field cyclotron.

CONCLUSION

At RCNP, upgrading cyclotron facility has been planned to increase beam currents up to 10 times of present value. HTS cyclotron is proposed for the new injector. Design of sector magnet is completed, and confirmed by magnetic field and orbit simulations. Now 1-meter-size HTS magnet is being tested. The HTS injector cyclotron will be the first step to the next generation cyclotrons.

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