DESIGN OF THE SECTOR MAGNETS FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON

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A design of the superconducting sector magnets for the RIKEN superconducting ring cyclotron is described. Structures, magnetic forces, superconducting coils, R&D works, and a cryogenic system are described. Special features are the cold pole arrangement for supporting of the huge magnetic forces, and the cryogenic stable coils. A full-scale superconducting model is now under construction as a prototype sector magnet.

1. Introduction

The RIKEN Superconducting Ring Cyclotron (SRC) is one of the main accelerators for the "RIKEN RI Beam Factory Project."[1] Six units of superconducting sector magnets will be used as the main components of the SRC.[2] Each one of sector magnets has to generate a maximum magnetic field of 4.5 T in the beam orbital area. We use superconducting main coils as well as superconducting trim coils to obtain compactness in size and to save the electric power and cooling water. A yoke and poles made of magnetic soft iron are arranged in the sector magnet to reduce ampere-turns of the superconducting coils and to minimize a leakage of magnetic flux. A cold pole arrangement is adopted in order to support the huge magnetic forces. To avoid coil quench, cryogenic stabilizing methods are applied to the superconducting coils. Table 1 shows the main parameters of the sector magnets.

2. Structures of the Superconducting Sector Magnet

Figure 1 shows a cross-sectional view of the sector magnet. Main components of the magnet are superconducting and normal conducting coils, a cryostat which consists of 80K thermal shields and vacuum vessels, poles, and a yoke. We use two kinds of superconducting coils: a pair of main coils and a group of trim coils. Both coils are located upper and lower sides with respect to the mid plane. A group of normal conducting trim coils for fine magnetic field correction is also arranged in the upper and lower sides of the beam chamber. A special feature is the cold-pole arrangement described in a later chapter. A vertical magnetic force Fz is supported by two pole links which are attached to the upper and lower cold poles. We investigated two ways of supporting a magnetic shifting force Fx in the radial direction. One way is to arrange a pair of cold rings which connect the cold masses (coils and cold poles) of the six sector magnets in 4.5 K region. A problem of the cold ring support system is the central space for the cyclotron. This space is reserved for arranging the beam injection elements. Another way is to use large-size thermal insulated supports made of high strength material, in between the cold mass and yoke using the outer space of the sector magnet. The problems of this support system are its large heat leak, and its mechanical deflection which causes a position shift of the magnetic field. An optimization for decreasing the shifting force Fx was continued, and the Fx was successfully decreased to 100 tons from the previous one of 540 tons, by changing the number of the booster cyclotron one (SRC) to two (IRC and SRC), and by modifying the yoke shape. We decided to use the thermal insulated support system, Fx supports arrangement, as shown in Fig. 1.

3. Cold pole arrangement

At the time of preliminary design work, a warm pole arrangement was studied. Then a cold pole arrangement was investigated as an alternative way.

Table 1. Parameters of the sector magnets.

Average radii of beam injection		3.56 m
	extraction	5.36 m
Sector angle of main coil		25 degree
Maximum magnetic field		
	in the beam orbital area	4.5 T
	in the main coil	5.5 T
	in the trim coil	5.0 T
Main-coil's ampere turns per magnet		6.0 MA
Coil cooling method		LHe bath cooling
Magnetic stored energy for 6 magnets		390 MJ
(75 % in air, 17 % in poles, 8 % in yokes)		
Maximum operation currents		
	for main coil	5,000 A
	for trim coil	500 A
Iron weight of 6 magnets		
	poles	216 tons
	yokes	4,300 tons

Fig. 2 shows the schematic drawing of both arrangements. Comparing the magnetic characteristics and especially the mechanical stiffness against the huge magnetic force, we have decided to employ the cold pole arrangement. The compared result is shown in Table 2.

4. Magnetic forces

One of the most serious points of the design is how to control and how to support the huge electromagnetic force exerted on the superconducting coils. The magnetic forces on the cold mass calculated with 3-D TOSCA/OPERA code are shown in Fig. 3. The magnetic forces (Fxy, Fz) exerted on the main coils are all supported by the cold-poles through the coil vessels. The shifting force (Fx) in the radial direction is supported with four sets of the Fx supports which work at the same time as the thermal insulations between the room temperature and 4.5 K regions. This force (Fx) is generated by both of the arrangement of six sector magnets and the asymmetric configuration of the coils and irons.

5. Superconducting coils

The superconducting main coil has a triangle shape with two long straight sections of about 3.5 m long, and its section dimensions are 283 mm in width and 309 mm in height.

We apply a cryogenic stabilizing method for the main coil as well as the trim coil to prevent coil quench. The gaps in between turns and in between layers of the main coil, which are for the cooling channels and the electric insulation, are designed to be 0.5 mm and 1.5 mm in distance, respectively. These gaps are held with a lot of glass-fiber reinforced plates. In case of the trim coil, the superconducting wire is skip-lapped with insulation tapes of 0.18 mm thickness. The average current densities of the main coil and trim coil are 34 A/mm^2 and 39 A/mm^2, respectively. Pure aluminum was selected as the stabilizers for both of the main and trim superconducting wires. Table 3 shows the specifications of the superconducting wires.

6. Cryogenic stabilizing current

To confirm the stabilizing current of real winding, two kinds of the superconducting wires for the prototype magnet were wound into small test coils, and tested in LHe. The wire lengths of a main test coil and of a trim test coils are 115 m and 55 m, respectively. These two test coils have similar configurations of the cooling channel which was designed for the real main and trim coils. The test coils were assembled into a bias superconducting coil to be tested in the magnetic field of 6T, and measured the voltage drop change at the time when the electric heaters inside of the test coils gave a heat to make an origin of quench.

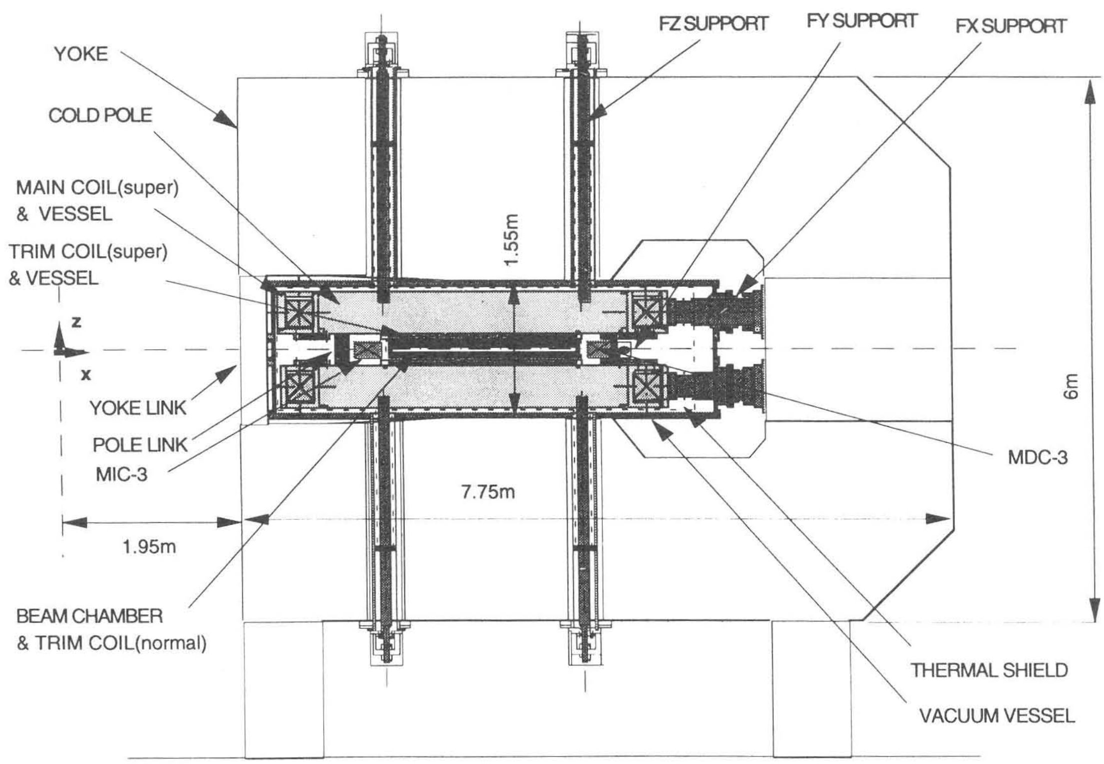

Fig.1. Cross-sectional view of the SRC sector magnet.

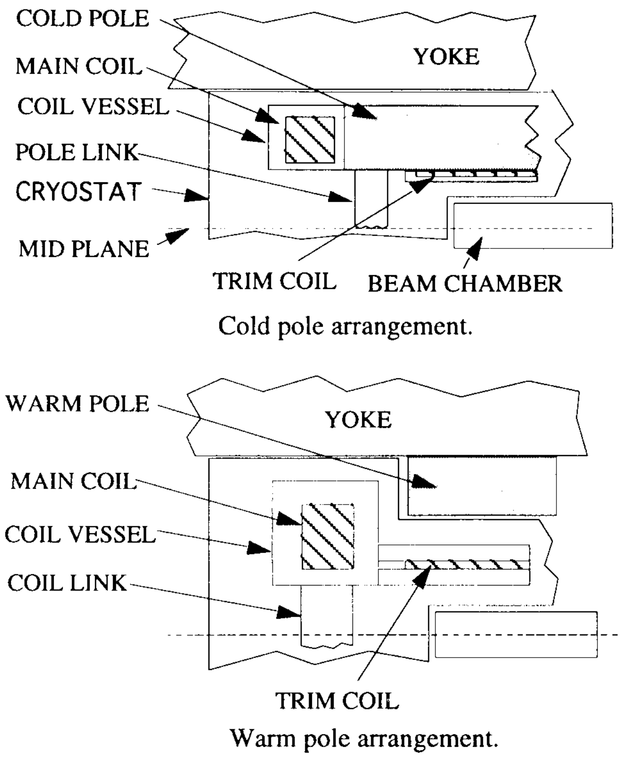

Fig. 2. Comparison of the pole arrangement.

Table 2. Comparison of the magnetic forces and cold mass weight between Cold-Pole method and Warm-Pole one.

* is the ratio.

Items	Cold-P	Warm-P
AT/magnet (MA)	6 *1	7 *1.2
Fxy for half coil (tons)	1800 *1	2900 *1.6
Fz for one coil and one cold-pole (tons)	-970 *1	-610 *0.63
Fx for a magnet (tons)	100 *1	260 *2.6
Wt. of cold mass (tons) (six magnets)	360 *1	270 *0.75

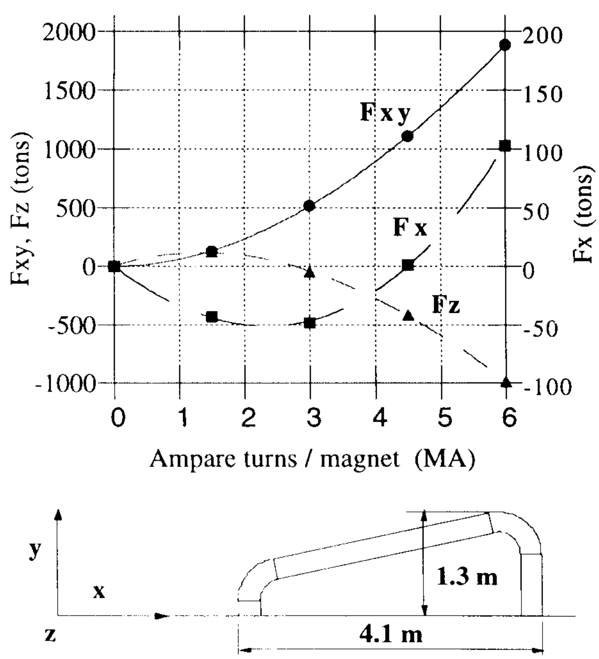

Fig. 3. Magnetic forces exerted on the cold mass. Fxy for half main coil ($=\Sigma(Fx^2+Fy^2)^{1/2}$: expanding force). Fz for one coil and one cold pole. Fx for a magnet.

Table 3. Specifications of two superconducting wires.

Items	For main coil	For trim coil
Operation current (A)	5 0 0 0	5 0 0
Max. magnetic field (T)	6	6
Stabilizing criterion	Partial	Full
Stabilizing current (A) at 6 T, 4.5 K	≧6000	≧550
Critical current (A) at 6 T, 4.3K	≧11500	≧1150
Outer dimension (mm)	8.0 x 15.0	2.9x3.6
Materials	NbTi / Cu / Al	NbTi / Cu/ Al
Section area ratio	1 / 1 / 17	1 / 1 /15
RRR of Al	≧500	≧400
0.2 % yield strength of Al (kg/mm2)	≧5	≧4
Cooling surface ratio	5 0 %	4 0 %
Required total length for 6 magnets (km)	7 7	4 7

Fig. 4 shows the arrangement of the three coils. Typical measured results of the main test coil are shown in Fig. 5. In case of 5500 A excitation, the normal region made by heater returned to the superconducting state. On the other hand, in case of 6000 A, the normal region grew larger. The displayed voltage drop is in the conductor of 5.4 m long. In this stabilizing test, the partial stabilizing current of the main test coil was found to be 5700 A, and the fully stabilizing current of the trim test coil to be 630 A. These results verified the validity of the design on the cryogenic stabilization.

7. R&D works

Various R&D works were done and are under going to examine the design and to make sure the construction of the prototype magnet. Heat flux characteristics and mechanical properties of the superconducting wires were already measured. Two sets of 0.5m-straight models which have full-size cross sections composed from the main coil and the coil vessel, has been made to study the assembly and the mechanical stiffness. Three sets of 1/6 sized normal conducting pulse magnets are now under construction to measure the unbalanced magnetic force in x, y and z directions.

8. Cryogenic system

Two refrigerators having a capacity of 500 W each at 4.5 K are planned to be used for the cooling of the six sector magnets plus of the beam injection and extraction superconducting magnets. The cold-mass of six sector magnets weights 360 tons, and it will take one and a half months for cooling the cold mass from room temperature to 4.5 K. We expect to operate the superconducting ring cyclotron for more than 6,000 hours a year. Therefore, the cold mass should be kept in low temperature as long as possible. When one refrigerator breaks down, the magnets can be kept at 5 to 6 K by the other refrigerator. For the maintenance of power system, one or two days of power-off a year is inevitable, and for that time a recovery compressor with an emergency power source can recover the evaporated helium gas to buffer tanks. In this cryogenic system, we will not use liquid nitrogen for simplicity of the cooling system.

9. Conclusions

A design work of the superconducting sector magnets for the RIKEN superconducting ring cyclotron is being progressed for the construction of a full-scale prototype magnet doing the various R&D works. The coil winding and the cryogenic test of the prototype magnet are going to be done in this summer and in next spring, respectively.

References

[1] Y. Yano et al., Proc. of the 14th int. conf. of cyclotrons and their applications, pp.590-597 (1996).
[2] T. Mitsumoto et al., Proc. of the 14th int. conf. of cyclotrons and their applications, pp. 237-240 (1996).

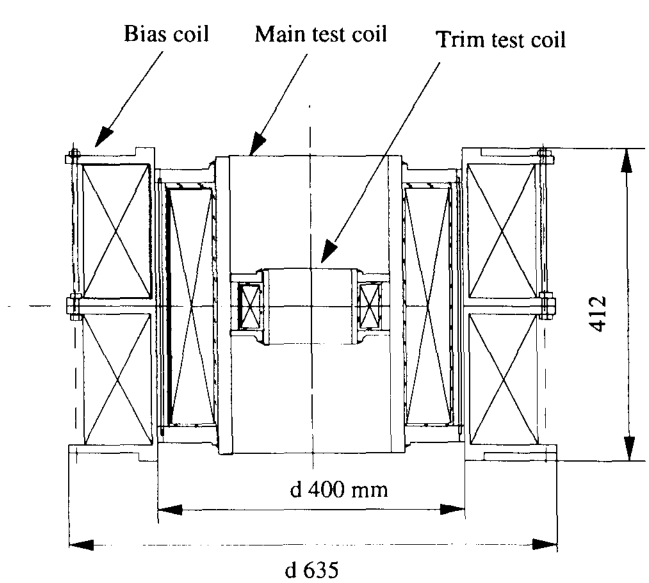

Fig. 4. Coils arrangement for the stabilizing test.

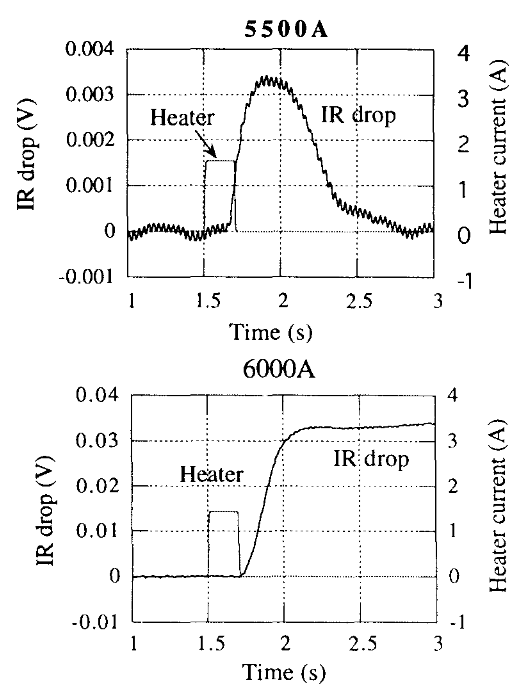

Fig. 5. Measured voltage drop change of the test main coil.