Superconducting Sector Magnets for the RIKEN Superconducting Ring Cyclotron

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Abstract

Superconducting sector magnets for the RIKEN superconducting ring cyclotron (SRC) have been designed and a full-scale prototype magnet is now under construction to verify the design. The special features of the sector magnets are, the high magnetic field of 4.5 T maximum in beam orbit with the arrangement of iron-pole and iron-yoke, the cold-pole structure for support the huge magnetic force, the triangle shape superconducting coils stabilized by cryogenic method to avoid coil quench, and the big mass of 5,000 tons for the six magnets total. Present design status and various R&D works are described.

1 Introduction

In the original plan at four yeas before described in [1][2][3], the booster ring cyclotron in the RIKEN RI beam factory was the SRC only, then the conceptual design was changed with further study and the booster was divided into two ring cyclotrons[4] of IRC using normal-conducting four-sectors and SRC using superconducting six-sectors. This change was made mainly to make the central region of the SRC more widely for arrangement of the injection beam channels, and to reduce the mechanical deformations of the main coil, cold-pole and yoke as well as their magnetic forces. As the result, the beam injection radius of the SRC was changed from 2.4 m to 3.6 m, and the length of the main coil's long side from 5 m to 4 m. The arrangement of the cold-pole and yoke, the structures of the superconducting main and trim coils, and the structure of the cryostat were studied and designed in detail. While these design works, various R&D works were also done. Now, the full-scale prototype magnet is under construction. Table 1 shows the main parameters of the sector magnets.

2 Structure

Fig. 1 shows a cross-sectional view of the sector magnet. Main components of the magnet are superconducting and normal conducting coils, coil vessels, cold-poles, a cryostat which consists of 80K thermal shields and vacuum vessels, a beam chamber and a yoke. We use two kinds of superconducting coils; a pair of main coils and a group of trim coils. These main and trim coils are attached to the cold-poles through their coil vessels made of stainless steel SUS316L. The coil vessels are also LHe vessels. Two types of the main coil vessels, one is bolt-type for lower coil and the other weld-type for upper coil, were applied to the prototype magnet, and are being examined in viewpoints of the dimension accuracy, reliability and productivity. A group of normal conducting trim coils for fine magnetic field correction are also arranged in the upper and lower sides of the beam chamber. The vertical magnetic force Fz calculated to be 1,000 tons is supported by two pole-links which are attached to the upper and lower cold-poles. Thermal insulating supports system for the cold-mass consists of eight Fz supports located at upper and lower side, four Fx supports and two Fy supports. The cold mass of 60 tons and an unbalanced magnetic force in z direction are supported by the Fz supports made of Ti-alloy. The shifting force between the cold-mass and yoke in x direction, calculated to be 100 tons, is supported by the Fx

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
Weight of 6 magnets	
cold-mass and cryostats	600 tons
yokes	4,400 tons
total	5,000 tons

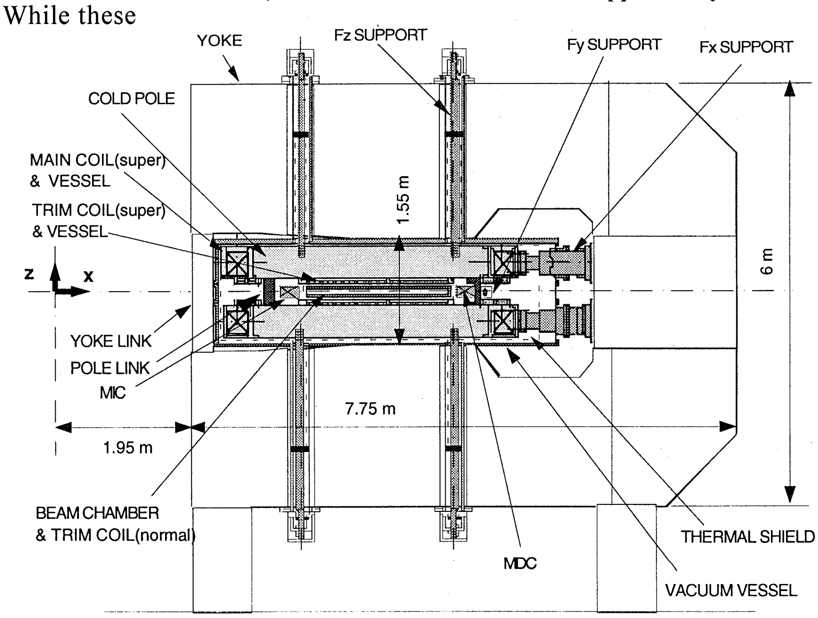

Fig.1 Cross-sectional view of the SRC sector magnet.

supports composed from stainless steel multi-cylinders. The Fy supports made of Ti-alloy are designed to stand a seismic load.

3 Magnetic Field and Forces

Figure 2 shows the calculated dependency of the magnetic field in mid plane to the main-coil's electromotive force. It can be found from Fig. 2, the magnetic field of about 1.7 T is generated by means of the cold-pole/yoke arrangement. We designed and will test the prototype

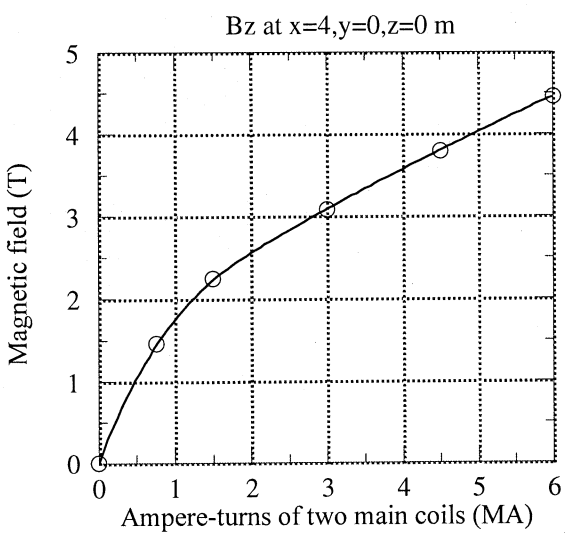

Fig. 2 Calculated Bz versus the electromotive force.

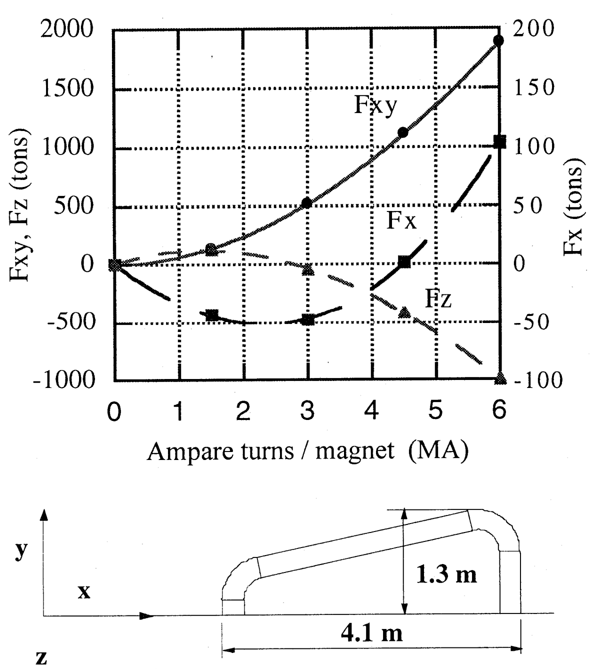

Fig. 3 Magnetic forces exerted on the cold mass. Fxy for half main coil ($=\Sigma(Fx^2+Fy^2)^{1/2}$: expanding force). Fz for one coil and one cold pole. Fx for a magnet.

magnet up to 6 MA, although the real maximum operating rate will be less than 5.4 MA.

The leakage magnetic flux from the sector magnets to the outside region of the SRC-room can be reduced with the yokes, and further we are planning to use active-shield-coils to minimize the leakage flux. The active-shield-coils will consist of a pair of Helmholtz-coil of 23 m in diameter, and will be super-conducting coil to save the electric power.

One of the most critical points of the sector magnet design is how to control and how to support the huge electromagnetic force exerted on the superconducting coils. Especially the shifting force (Fx) is the most critical one, because it should be supported by the thermal insulating supports (Fx supports). In the design, the Fx was minimized adjusting the shape and dimensions of the yoke. Figure 3 shows the calculated magnetic forces on the cold-mass for the final design. 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. This force (Fx) is generated by both the arrangement of six sector magnets and the asymmetric configuration of the coils and irons.

4 Superconducting Coils

The superconducting main coil has almost triangle shape. The outer dimensions are 4.1 m in length, 2.6 m in width, and the cross section of 283 mm by 309 mm. One of our basic design concepts for the sector magnets is to make quench-free superconducting coils to assure the reliable long-period operation of the SRC. For this purpose, we applied partial-stabilization criterion (Maddock's stabilization) for the main coil, and full-stabilization (Stekly's stabilization) for the trim coil. Pure aluminum was selected as the stabilizers for both of the main and trim superconducting wires. Table 2 shows the specifications of the superconducting wires. The gaps in between turns and

Table 2 Specifications of two superconducting wires

Items	For main coil	For trim coil
Operation current (A)	5000	500
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 (MPa)	≧50	≧40
Cooling surface ratio	50 %	40 %
Required total length	77 km	47 km

in between layers of the main coil, which compose the cooling channel and the electric insulation, are designed to be 0.5 mm and 1.5 mm in distance, respectively. These gaps are maintained with a lot of glass-fiber reinforced plates. In case of the trim coil, the superconducting wire is skip-lapped with insulation tape of 0.18 mm thickness. The average current densities of the main and trim coils are 34 A/mm^2 and 39 A/mm^2, respectively.

5 R&D Works

Various R&D and examinations have been done while the design working and the prototype constructing.

5.1 Properties of Pure Iron

Pure iron is used for the cold-pole material. But we had not so much data of the properties at low temperature. So, the mechanical properties; static strength, impact strength, toughness and fatigue strength, were measured at 78 K and 4.2 K. And, the electric resistance at 4.2 K in 0 T to 4 T was also measured to investigate the eddy current loss in the cold-poles.

5.2 Mechanical Strength of the Al-Stabilized Superconducting wire

Static strength, creep characteristics and fatigue strength were measured at room temperature and 78 K.

5.3 Examination of the Stabilized Current of the Coils

The stabilized currents of the main and trim superconducting wires for the prototype magnet were calculated using their measured results about electric resistance and cryogenic heat flux. Next, two small solenoid coils using the superconducting wires for the prototype, were made. These coils have same cooling channels as the real coil design. Then, these coils were tested at 4.2 K in 6 T, and their stabilized currents were measured.

5.4 Study on the Main Coil/Vessel Structure

Mechanical stiffness of the short-straight packs which consist of wires and insulators, were measured to estimate the deformation of the real coil by the cooldown and excitation. Two cross section models, one has the weld-type coil vessel another bolt-type, were made to examine the assembly process and to measure the coil stiffness. These section models have full-size cross section, and length of 0.5 m.

5.5 Mechanical Strength of the Main Coil Vessel

For the bolt-type coil vessel, the static strength and fatigue strength of two kinds bolts were measured at room temperature and 78 K. For the weld-type vessel, the fatigue strength of the welding area was measured at 78 K using the parts of above cross section model.

5.6 Measurement of the Unbalanced Magnetic Forces

Three sets of 1/6-scaled Cu/Iron model magnets were constructed for the measurement of unbalanced magnet forces. The model magnets were cooled down to 78 K, and excited up to 4 T Maximum in pulse for 1 to 2 seconds. The unbalanced magnetic forces in three directions were measured both on one-sector arrangement and three-sectors arrangement. Figure 3 shows the photograph of the three sectors arrangement of the models placed in RIKEN campus for the exhibition after the measurement.

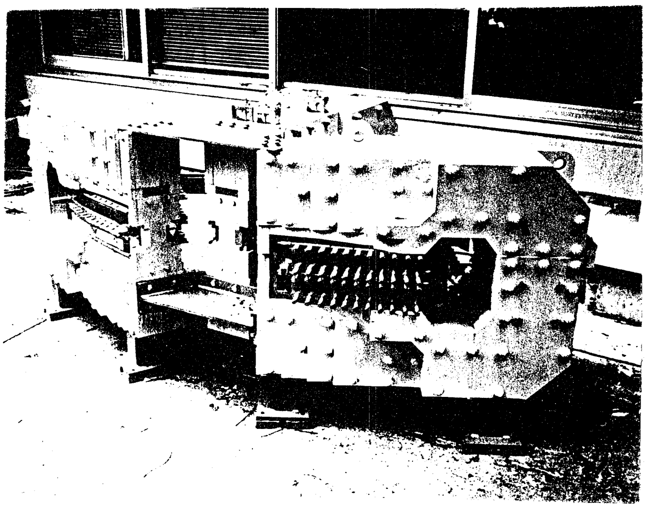

Fig. 4 Three-sets of the 1/6-scale Cu/Iron magnets.

6 Present Status of the Prototype Full-Scale Magnet

The construction status of the prototype at Sep. '99 is as follows: Upper and lower cold mass composed from the main-coil/vessels and cold-poles were completed. Two trim coil/vessels were almost completed. The vacuum vessels divided into three parts were completed. The parts of the cryostat; the 80K thermal shield, thermal insulating supports, many pipings and service ports, are under manufacturing. The sliced pieces of the yoke; the yoke consists of 48 sliced pieces, are almost completed and they are under preassembly. In our present schedule, the cold-mass and cryostat will be assembled together by the end of this year. And, after the assembly of the coil/cryostat and yoke, the cold test of the prototype will be done in next spring.

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