SUPERCONDUCTING MAGNETS FOR THE RIKEN SRC

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Abstract

A K2500 superconducting ring cyclotron with 6-sectors is being constructed at RIKEN as one of the energy boosters of the existing K540 ring cyclotron. Its sector magnets and bending magnet for beam injection should be superconducting because they are required to generate as high fields as about 4 T. Its design was finalised for the real production. In this paper the final design will be described.

1 INTRODUCTION

At RIKEN construction of the Radioactive Isotope Beam Factory (RIBF)[1] has started. The RIBF provides the world's most intensive RI beams at energies of several hundreds MeV/nucleon over the whole range of atomic masses by the projectile fragmentation or fission process. A K2500 superconducting ring cyclotron (SRC) will be installed as the final booster in the proposed cascade which can extract light ions such as carbon and heavy ions such as uranium with the energies of 400 MeV/u and 350 MeV/u, respectively [1]. The design of the SRC was finalised to start the real production. Fig. 1 in the ref [2] shows a schematic layout of the SRC. The SRC consists of six-sector magnets [3], four acceleration resonators and injection and extraction elements and so on. The remarkable point is that iron plates of about 1m thickness cover the valley regions for additional magnetic and radiation shielding. They suppress the leakage field from the sector magnets, decreasing magnetic motive forces for the maximum bending power. The merits of the magnetic shield are described in the ref. [2]. The sector magnets and the bending magnet for beam injections should be superconducting inevitably due to the high fields, although their structure and operation would be complicated. Their finalised designs are overviewed in the following part of the paper.

2 THE SECTOR MAGNET

Cross-sectional and plan views of designed sector magnet are shown in Fig. 1, excluding the magnetic shields. The sector magnet is 7.2 m in length and 6 m in height. The weight is about 800 Ton per each. The sector angle is 25 deg. The maximum sector field is 3.8 T, which is required to accelerate 350 MeV/nucleon U^{88+} ions. Main components of the sector magnet are: a pair of superconducting main coils, four sets of superconducting trim coils, their cryostat, thermal insulation support links, twenty-two pairs of normal conducting trim coils, warm-poles and a yoke.

The superconductor for the sector magnet has a rectangular shape consisting of a Rutherford-type NbTi cable located at the center of conductor and a stabilizer housing. The conductors' cross-sectional area measures 8 mm by 15 mm. The stabilizer material is aluminum alloy with 1000 ppm Ni, which gives a high 0.2 %-yield strength of about 60 MPa at room temperature, keeping the residual resistivity ratio greater than 800. Total length of the conductors for the six sector magnets is 51 km.

396 (22 x 18) turns are wound for the main coils, giving the maximum magneto-motive force per sector of 3.96 MA. A solenoid winding is adopted for the main coil with cooling gaps of 0.8 mm and 1.5 mm horizontally and vertically, respectively. Spacers made of FRP (Fiber Reinforced Plastic) are placed in the both gaps between the conductors; about 50 % of the vertical conductor

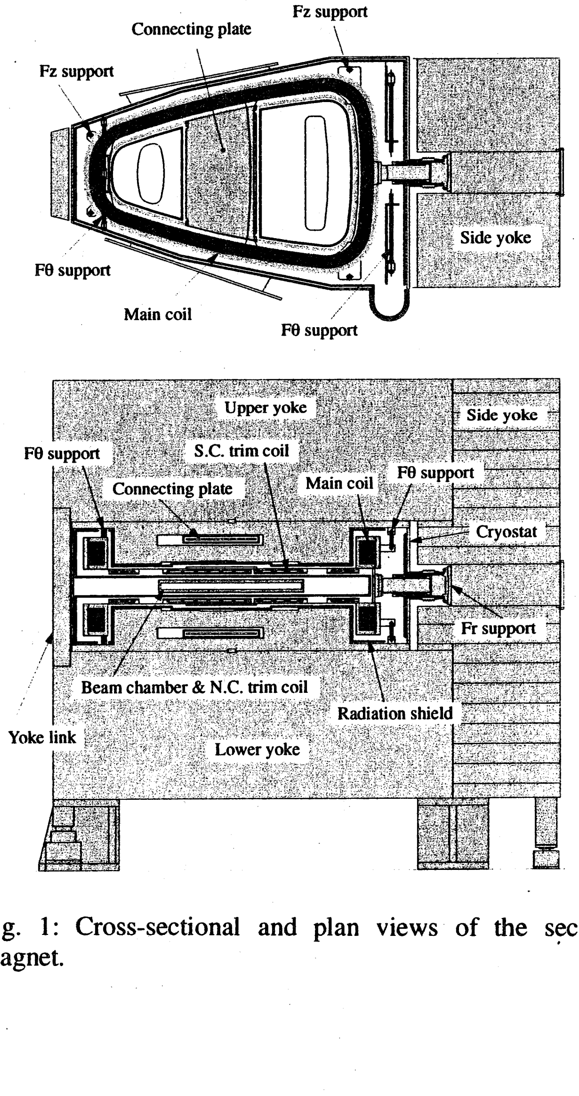

Fig. 1: Cross-sectional and plan views of the sector magnet.

surface are exposed to liquid helium, while no horizontal surface is. The main coil is designed based on Maddock's partial stabilization criterion. The main coil vessel made of stainless steel was designed to be enough rigid to support the electromagnetic force on the coil. The horizontal electromagnetic force of about 260 Ton/m is exerted on the long section of the vessel covering the beam area. In order to sustain this force, a pair of connecting plates is attached to the both sides of this section. The plate is 1 m in width and 25 mm in thickness. One of these plates crosses through the rectangular hole (1.5 m in width and 160 mm in height) of the warm iron pole.

Two types of trim coils are used to help generate isochronous fields for various kinds of ions: superconducting trim coils and normal-conducting trim coils. Superconducting trim coils consist of four sets (parameters). A double-pancake winding of the same conductor as that for the main coil is adopted, in which the coils are indirectly cooled by forced two-phase helium through tubes engraved on the coil case made of alumiun alloy plates of 18 mm in thickness. The four sets of trim coils consist of 2 (layers) x 4 (turns) x 2 (blocks), 2 x 5 x 5, 2 x 7 x 2 and 2 x 8 x 2, respectively. The maximum current is 3,000 A. Twenty-two pairs of normal-conducting trim coils are attached on the surface of the beam chamber that is part of the cryostat, as shown in Fig. 1. The maximum current is 600 A.

The side walls of the cryostat are made of stainless steel. The upper and lower walls, which constitute part of pole, are made of steel. The side walls and the upper and lower walls are welded to each other. The gap distance between the connecting plate and the surface of the hole of the warm pole is 70 mm. These gaps are wide enough to incorporate 70 K thermal radiation shields. The area of the radiation shields is about 85 m^2. The thickness of the beam chamber wall made of stainless steel is 45 mm, and the gap of the chamber is 90 mm in which the injection and extraction elements are placed.

The cold mass is supported with a total of 17 thermal-insulation support links. A multi-cylinder type of support link is used for the radial support. The multi-cylinder made of stainless steel with an outermost diameter of 320 mm and a length of 850 mm is designed to sustain the radial shifting force of 90 Ton. It is fixed on the surface of the back yoke. The vertical (azimuthal) support is performed with four (also four) support links at inner-radius part and four (also four) at outer-radius part are used for the vertical (azimuthal) direction. They are made of titanium-alloy rod are designed to have a spring constant with larger than 140/190 (100/85) kN/mm to sustain the vertical (azimuthal) unbalanced force. The vertical support links are fixed at the upper and lower yokes. The azimuthal links are fixed on the surface of the upper and lower walls of the cryostat. The whole support links are designed to sustain the additional force due to earthquake of 1,000 Gal and 500 Gal in the horizontal and vertical directions, respectively.

The pole is divided into two pieces in order to make a hole that lets the connecting plate of the main coil vessel cross through it. These poles are fixed to the surface of the upper/lower yoke with long screws through the yoke since a total force of 760 Ton due to electromagnetic force and atmospheric pressure is exerted on a pair of poles toward the median plane. The slabs of the upper and lower yokes are stacked in the horizontal direction in order to keep the deformation due to electromagnetic forces as small as possible.

In order to protect the superconducting main and trim coils, the quench characteristics was calculated in terms of current decay, temperature rise, voltage development. The simulation shows that the optimal resistance of dump resistor should be 0.3 Ω and 0.1 Ω for the main coil and the trim coil, respectively. The temperature of the main coil rises up to about 140 K with this dump resistor. The maximum voltage applied between the main coil and the coil vessel can be half of 1,500 V, by taking the earth at the middle point of the dump resistor.

3 SBM

The SBM needs to generate a magnetic field of about 4 T along the beam trajectory which has a curvature of about 1.2 m. Fig. 2 shows a proposed cross section and plan view of the SBM. The two coils, the iron poles and the yokes generate the required fields. Flat coils are adopted since they can be wound and supported easily. Iron poles are used for the mandrel of the coil windings. The yoke is divided into two parts: cold yoke and warm yoke. The cold yoke, which about half of the flux passes through, is H-type. This configuration makes shifting forces and unbalanced forces on the cold mass small, while the weight of the cold mass is not too large (about 3 ton). C-type is adopted for the warm yoke because the available space for the warm yoke in the side of the sector magnet is very narrow as shown in Fig. 1 of the ref. [2]. A warm duct is installed for the ion beams. Iron shims and water-cooled baffle slits are attached to the duct.

Two-dimensional analysis was carried out to optimize the geometry of the coils, yokes and iron shims. It shows that the overall current density of about 150 A/mm^2 can achieve the required field. The value of current density is selected from the experience of the test. The geometry of the yokes is optimized so that shifting forces and unbalanced forces on the cold mass are minimized. Three-dimensional field analysis was carried out to study the maximum fields at the coil end and the effective field lengths. Coupling of the field of the SBM and the sector magnets is also studied using a model that includes the SBM and two sector magnets. Generated field of the SBM decrease by 5 % compared to the stand alone excitation. Shifting forces on the cold mass are estimated to be not as large as about 4 kN. This forces is comparable but opposite sign compared to that from the 2-dimensional analysis. These results indicate that the cold mass is well shielded from the sector magnet system by the warm yoke of the SBM.

Rectangular monolithic NbTi wire of 0.8mm x 2.4mm in size was adopted so as to be wound well-aligned. The conductor was coated with polyimide 50μm in thickness for electrical insulation. Polyimide was adopted because of its strength against radiation. The operation point is less than 30% of the critical current. Coil winding is one of the key issues for the SBM production because the coils of the SBM have negative curvature, which can not be wound with any tension. The following winding method was adopted: 1) the few layers of the coil are wound with a tension in a shape which has no negative curvature (The circumference of the coil should be the same as that of the final shape of the SBM coil.), 2)the layers are pushed to the mandrel to make the proper shape of the coil. The merit of the method is that the time for winding can be saved without the decrease in performance. This method was successfully applied to the real coil production. After completion of the winding, the coil is impregnated in the vacuum vessel. Figure 2 shows the cross section of the coil casing. The radial and vertical pre-compression required to keep the coil compression when the magnet is excited is provided by set-screw bolts and vertical bolts, respectively. This support structure was successfully applied to the test coil. Iron, which shrinks less from 300 K to 4.5 K than stainless steel, will be used for the inner mandrel of the center coil to decrease the degradation of the stress of the coil. The coil casing is partially covered by the seal covers for He tightness. The two coil casings are attached to the cold yoke.

The cold mass of the SBM is installed in the vacuum vessel made of structural iron of 20 mm thickness. It works as a part of the yoke which makes shifting forces and unbalanced forces small. The duct for the beam bore is connected to the vessel at its ends. The cold mass was supported by three types of thermal insulating supports from room temperature as shown in Fig. 2. They are designed to support the cold mass stably against the shifting and unbalanced force as well as against big earthquakes (1 g and 0.5 g in the horizontal and vertical direction, respectively).

Total heat leaks to the cryostat are estimated to be about 56 W at 80 K, about 15 W at 4.5 K and 1.7 l/h for power lead cooling without beam loss of the accelerated ions. Gas He for the thermal shield and 4.5 K liquid He for the coil cooling are supplied to the SBM cryostat by the big refrigeration system for the sector magnet. Current leads are installed in the He reservoirs placed near the SBM magnet. Cooling of the SBM without the reservoir for the sector magnet is also possible by replacing it with a conventional Liq. He dewar.

A quench protection system is installed to dump the current safely. A dump resistance of 2.5 Ω is connected in parallel to the coil. Maximum temperature in the coil is estimated to be about 270 K from the hot spot model and maximum voltage on the coil is about 450 V because the resistor is terminated to ground in the middle of the resistor.

5 REFERENCES

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[2] H. Okuno et al., "Status of the RIKEN SRC", in this proceedings.

[3] A. Goto et al., "Progress on the Sector Magnets for the RIKEN SRC", Proc. 16th Int. Conf. on Cyclotron and Their Applications, Michigan, (2001).

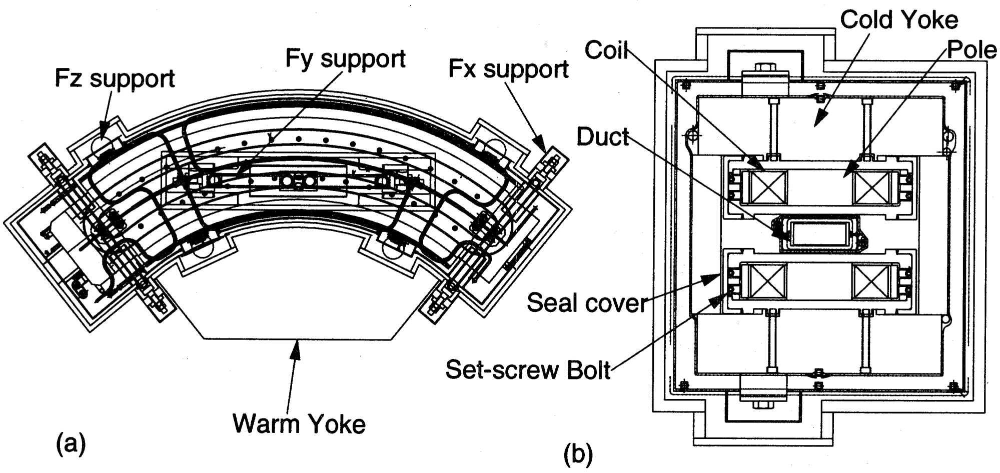

Fig. 2 (a) Plan view and (b) cross sectional view of the SBM.