MAGNETS FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON

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Abstract

The RIKEN RI Beam factory is under construction toward the beam commissioning scheduled in the autumn of 2006.[1] The Superconducting Ring Cyclotron (SRC) is the final stage booster for the RIBF accelerator complex. The two superconducting magnets: the sector magnets and the bending magnet for beam injection (SBM), are the key components for the realization of the SRC. All the parts of the sector magnets had been successfully fabricated until the end of March 2003. [2] Now (Oct. 2004) the assembling in due site is going on. The SBM which includes bended coils were successfully completed in the summer of 2003. It was cooled and excited for the first time in RIKEN after the completion, which shows that it can generate the required fields along the injection trajectory. The power supplies and the He cooling system have been installed in the RIBF building. The first cool-down and excitation of the sector magnets will start in the summer of 2005.

INTRODUCTION

Figure 1 shows a bird's eye view of the SRC. It will be the first superconducting ring cyclotron with the largest K-value of 2500 MeV in the cyclotron history. It consists of six sector magnets, four 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 reduce the leakage field from the sector magnets and decrease magneto motive forces for the maximum bending power. The maximum sector field is 3.8 T and the maximum stored energy is 235 MJ. The total weight amounts to 8300 ton. The size is 19 m and 8 m in diameter and height, respectively. This paper focuses on the two superconducting magnet which are the key components for the realization of the SRC. One is the superconducting sector magnet and another is the superconducting bending magnet (SBM) for beam injection. It also describe briefly about power supplies and cryogenic cooling system for the magnets.

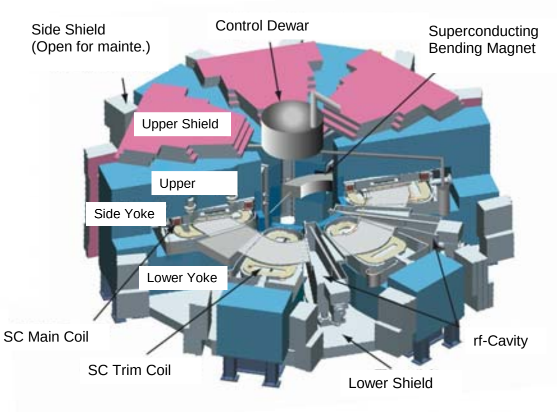


Fig. 1: A bird's eye view of the SRC

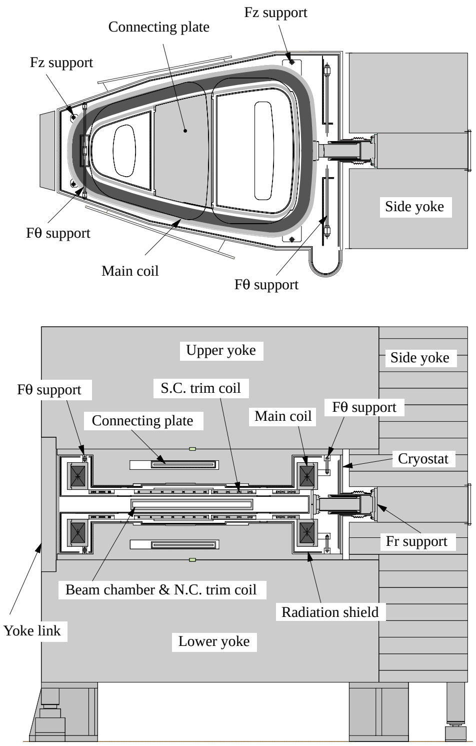


Fig. 2: Cross-sectional and plan views of the sector magnet

SECTOR MAGNETS

General Description of the Components

Figure 2 shows cross-sectional and plan views of the sector magnets. Its sector angle is 25 degree and its height and length are 6 m and 7.2 m, respectively. The weight is about 800 ton per sector. The main coil has magneto motive force of 4 MA at maximum. Cross-sectional area of the coil measures 208 mm by 284 mm and circumference is about 10 m. When the coil is excited, horizontal magnetic force of about 2.6 MN/m is applied on the long section of the coil vessel. To sustain such a force, a pair of connecting plates is attached to the vessel.

The superconducting trim coils are thin and cover the acceleration area in the sector magnet. They are attached to the main coil vessel and the connecting plates. The 4.5 K cold masses (the main coils and the superconducting trim coils) are covered with 70 K thermal radiation shields which suppress the heat load to the 4.5 K cold masses. The 4.5 K cold masses with the 70 K thermal shield are installed in the cryostat. Its side wall is made of stainless steel. The upper and lower walls, which constitute part of pole and yoke, are made of steel. After installation of the cold masses, they are welded together. The beam chamber constitutes part of the cryostat. Its vertical gap aperture is 90mm in which the injection and extraction elements are placed. Twenty-two pairs of normal-conducting trim coils are attached to the surface of the beam chamber. They correct isochronous field with accuracy of 10^{-4}. The cold mass is supported with 17 thermal-insulation supports. Radial shifting force is estimated to be about 300kN at maximum. So the radial support was designed to sustain the force of 900 kN, including safety margin. Vertical and azimuthal supports are designed to have large spring constants enough to sustain unbalanced forces due to small displacements from symmetric planes. Vertical force of 7.6 MN due to electromagnetic force and atmospheric pressure is exerted on a pair of poles toward the median plane. To sustain such a force, the poles are fixed to the yokes with long screws. The yokes are composed of the upper yoke, lower yoke, back yoke and yoke link. The positions of the lower (upper) surfaces of the upper (lower) yokes are determined by the yoke link and the back yoke. Their accuracies are very important to generate accurate field. In the next section, the details of the fabrication of the superconducting coils are described.

Fabrications of the Superconducting Coils

Quench of superconducting coils is catastrophic phenomenon that a normal conducting zone generated locally propagates to the whole of the coil with sudden and huge heat generation. It is very important to create a hard coil to quench. From such a point of view we adopted an aluminum stabilized conductor shown in Fig. 3. A Rutherford-type Nb-Ti superconducting cable is embedded at the centre of a rectangular stabilizer made of Al-alloy. Normal conducting Nb-Ti alloy has more than thousand times resistance of aluminium. When normal zone appears, this configuration can suppress heat generation since current in the conductor can pass the aluminum stabilizer in stead of the Nb-Ti alloy, which provides more opportunities for Nb-Ti alloy to recover from normal conducting phase. Small amount of mineral impurity can make pure aluminum stronger. The adopted stabilizer has impurity of 1000 ppm Ni, which gives high yield strength of about 55 MPa at room temperature while that of pure aluminum is typically 40 MPa. The critical current of the conductor is shown in Fig. 3 as a function of applied field with the operational point of the main coil and the superconducting trim coil, which shows that our design is very conservative.

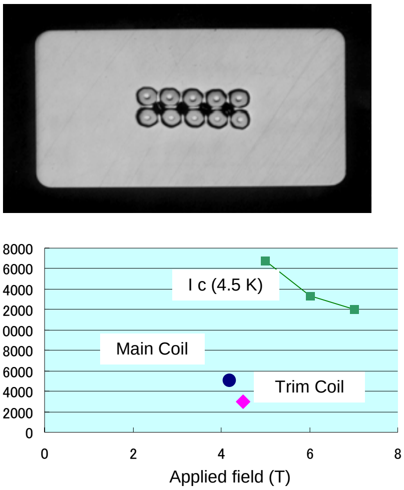


Fig. 3: A cross section and critical currents of the superconducting wire.

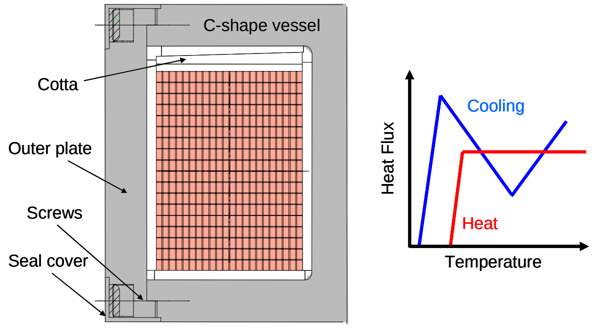


Fig. 4: Cross section and cooling property of the main coil.

The coil block consists of the solenoid winding with 396 turns as shown in Fig. 4. The main coil has gaps for electric insulation between the conductors by placing FRP spaces. The sizes of the horizontal and vertical gaps are 0.8 mm and 1.5 mm respectively. The main coil block is cooled in liquid helium bath made by the coil vessel. Vertical cooling channels are made such that about 50 % of the vertical conductor surface is exposed to liquid helium. Generated heat is removed from the conductor by boiling the liquid He around the conductor. Cooling property by liquid He is schematically drawn in Fig. 4 as function of temperature with heat generation of the conductor. While integral of cooling dominates that of heat generation, th normal conducting zone does not expand to the whole coil and when the origin of the normal disappears, the normal zone also disappears. This is a criterion for stabilization proposed by Madocck.[3] According to this criterion the stabilization current is estimated to be more than 6300A from measured data of heat flux using small models. They are fairy larger values than the maximum operational current of 5000A. This stabilization current has been experimentally confirmed by a small coil test.

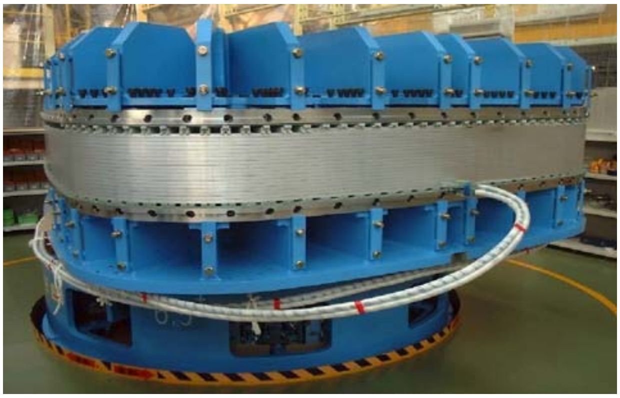


Fig. 5: Completion of the winding.

For the fabrication of the coil, we require that accuracy of the central position of the coil block is less than 1 mm in the long section, taking into account of the field disturbance by the positional error. The main coil vessel, made of the stainless steel, consists of the four parts: C-shaped vessel, outer plate, screws and seal covers as shown in Fig. 4. Each component was machined with accuracy of ±0.2 mm. The C-shape vessel was used for the mandrel in the winding. After installation of the ground insulation, the conductor was wound with a tension of about 20 MPa. After winding of every five (two) layer, the width (height) of the coil block was measured to realize the required accuracy. Figure 5 shows the completion of the winding. After the winding, the outer plate is carefully attached to the coil block and crews put stresses at a pressure of 10 MPa horizontally. Vertical pressure of 10 MPa was also applied with cotta placed in the gap between coil block and the vessel. This stress is important to minimize gaps between the surfaces of the coil block and the vessel in cool-down and excitation and it makes the coil hard to move. Finally seal covers were welded to the vessel. Deformation in the welding could be successfully suppressed to be less than ± 0.2 mm.

Figure 6 shows a profile of the superconducting trim coil covering the beam acceleration area in the sector magnet. It consists of four sets to make various isochronous fields depending on acceleration condition. The maximum current is 3000 A. To make such coils, a double-pancake winding was adopted. The coil blocks are sandwiched by two Al-alloy plates and supported with screws and epoxy glues. The coils are indirectly cooled by forced two-phase helium through tubes engraved on the Al-alloy plate. Bonding together each component of the coil is the key issue in order to make it with high performances. The coil should be bonded to the plate with small thermal resistance, keeping them electrically insulated. Moreover the plane of glue should be strong enough to sustain shearing stress caused by magnetic forces applied to the trim coil in the main coil field. Before the real fabrication we investigate the following three quantities for this structure: breakdown voltage, shearing stress and heat-transfer coefficient using several small models. Bonding structures which satisfied the three conditions were adopted. Accuracy of the trim coil for fabrication is required to be less than 1 mm. Special cares are devoted to suppress deformations in each process since the trim coil is wide and thin. Figure 7 shows a jig which prevents the trim coil from deformation in the process of the coil cure at about 150 degree with a pressure of about 2 MPa.

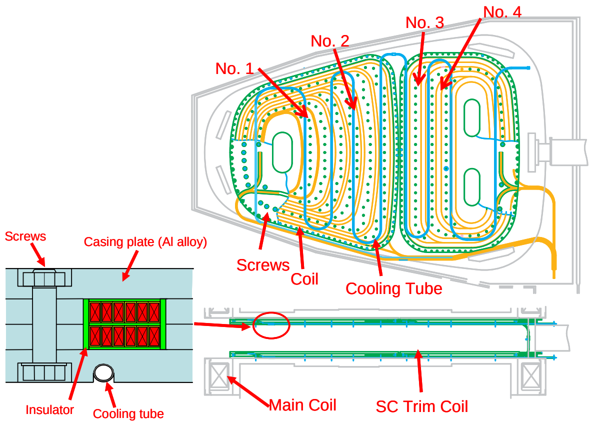


Fig. 6: Profile and structure of the superconducting trim coils.

Fig. 7: A jig for cures of the superconducting trim coils.

Fig. 8: Assembling in due site.

Assembling of the Sector Magnet

After the completion of the components of the sector magnets, the assembling of the cold masses started from the autumn of 2003 in the factories. The cold mass assembly mainly consists of the main coil, the superconducting trim coils, poles and the lower (upper) plate of the cryostat. Of course, thermal insulation support, piping and cabling inside the cryostat are also included. This pre-fabrication reduces the processes in due site and will improved the quality of the alignments and welding in the assembling. The assembling in due site proceeds as follows: Lower yoke, lower cold mass assembly, cryostat, upper cold mass assembly and upper yoke. Figure 8 shows the status of the assembling in November 2004. You can also enjoy its movie from the beginning in http://rarfaxp.riken.jp/~okuno/src/src-h.avi.

The floor level in the SRC vault has been monitored as shown in Fig. 9 to see how much the floor sunk due to such heavy weight as 8300 ton. The data suggest the floor around the north and east wall sunk by 2 mm after the installation of the parts of the SRC, but after the sinking they stay for several months. The lower yoke level was adjusted again after this measurement. The yoke levels were measured again two months later, suggesting that the upper surface of the lower yokes was tilted by 0.5mm in 20 m. But we think that the tilting is not harmful to the performances of the SRC. We will continue the monitoring until the beam commissioning.

SUBERCONDUCTING BENDING MAGNET

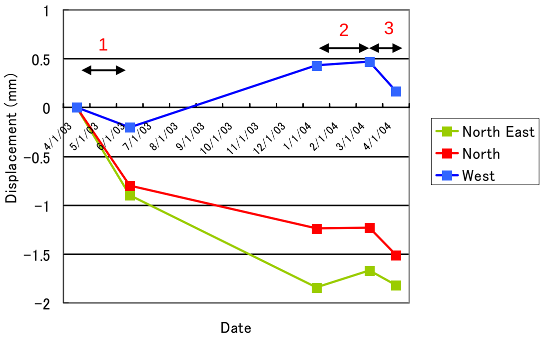


Fig. 9: Subsidence of the floor level in the SRC. Periods 1, 2, and 3 indicate the following. 1: Delivery of slabs for the yoke and the shield into the SRC and Big-RIPS vaults, 2: Assembly of the lower yokes and 3: Transfer of most slabs from the Big-RIPS vaults into the SRC vaults.

Figure 10 shows a plane view and cross-sectional view of the SBM with the main parameters. It needs to generate a field of about 4 T along the beam trajectory which has a curvature of about 1.2 m and an angle of 75 degree. Coil winding is the key issue since the coils are bended shapes which has negative curvature and can not be wound with any tension. The following winding method was adopted. In the first step the coil is 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. After winding of a few layers, the layers are pushed to the mandrel to make the proper shape of the coil. The SBM was completed on August of 2003 and cooled down and excited for the first time. Figure 11 shows the excitation curve with the history of quenches. The magnet reached the designed field with the first quench which occurred at 315 A, and training effects

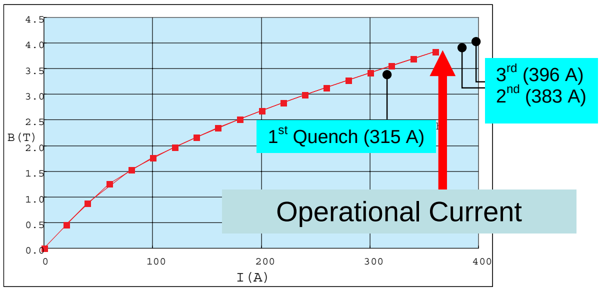
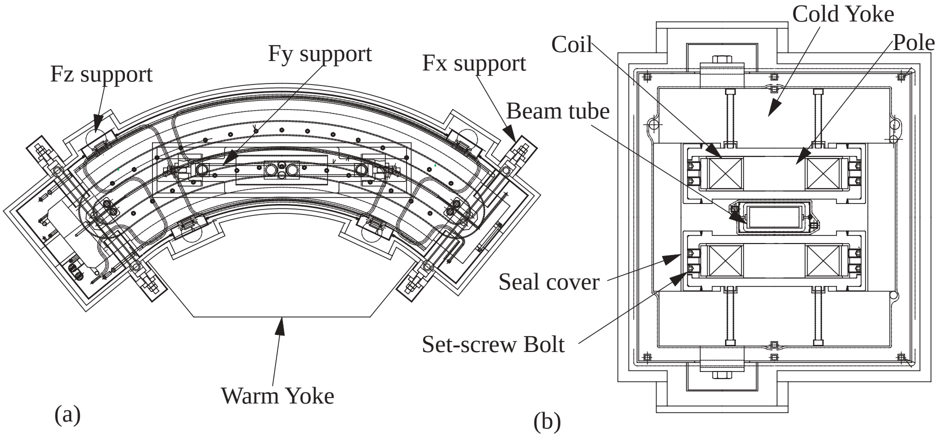


Fig. 11: Excitation curve of the SBM with the history of the quenches.



(a) (b)

Fig. 10: A plan view and cross-sectional views of the SBM

were clearly observed. Magnetic fields along the beam axis were also measured to get effective lengths and field uniformity at various excitation levels. The measured effective length agrees well with the designed value.

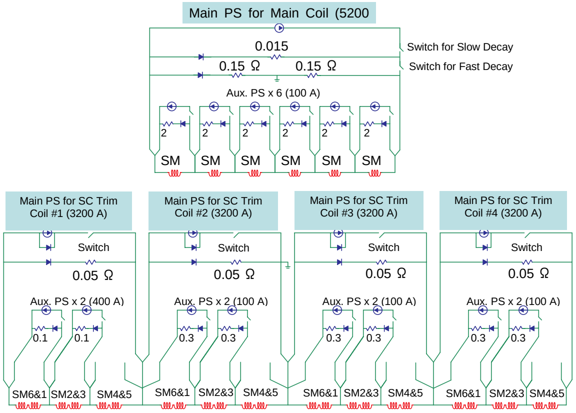


Fig. 12: A schematic diagram of the power supplies for the sectormagnets.

HE REFRIGERATOR AND POWER SUPPLY

Power Supplies and Quench Protection System

Figure 12 shows a schematic diagram for power supplies. The main power supplies feed currents in the main circuit where the coils are connected in series. The auxiliary supplies can adjust differences of magnetic fields among the sector magnets and also correct the magnet field perturbation produced by the injection and extraction elements.

Various troubles are expected in the excitations of the superconducting coils. If they are dangerous to the coils, the circuits should be cut off from the power supply to release the stored energy using dump resister. The most dangerous trouble is quenching. The quench characteristic was calculated in terms of current decay, temperature rise, and voltage development. The simulation shows that the optimal resistance of dump resistor should be 0.3 ohm and 0.05 ohm for the main coil and the trim coil, respectively. The temperature of the main coil rises up to about 140 K. The maximum voltage applied between the main coil and the coil vessel can be half of 1.5 kV, by taking the earth at the middle point of the dump resister. The time constant of the main coil is thus 63s.

Power Supplies and Quench Protection System

The cryogenic cooling system consists of He reservoir tanks, compressor, He refrigerator and control dewar. The control dewar, which is located on the top of the SRC, gathers the pipes and cables from the six sector magnets to make a closed circuit. Cooling capacity of the helium refrigerator is 620 W at 4.5 K, 4000 W at 70 K and 4 g/s gas helium for cooling of current lead cooling. It is estimated that it takes three weeks to cool the cold masses from room temperature to 4.5 K with this cooling system. The cooling capacity of the system was designed to be more than 1.5 times of estimated heat loads of the whole superconducting magnets. We will perform a trial run of He refrigerator in December 2004 to confirm that the capacity of the cooling system is fairly larger than the heat load.

PLAN TO THE FIRST BEAM

The assembling of the sector magnet which is going on finished until July of 2005. The superconducting coils will be cooled from the middle of August and will be excited around October. The field maps will be taken until the end of January 2005. The other components will be installed until the end of May 2006 for high power tests of rf-system. Finally beam commissioning will be performed in the autumn of 2006.

ACKNOLWEGEMENT

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