4. Superconducting sector magnets for the SRC

4.1 Introduction

The key components for the realization for the SRC are: the superconducting sector magnet and the superconducting bending magnet (SBM) for beam injection.

Construction of the sector magnet of the SRC is challenging in the sense that the SRC is the world's first superconducting ring cyclotron. After the design change that is described in Section 3.4 of Chapter 3 ("Overview and construction status of the RIBF accelerators"), newly designed sector magnets started to be fabricated in 2000. Installation of them into the SRC vault started in the spring of 2003 and their assembly was completed in September 2005. As of October, the sector magnets are cooled at 4.5 K and their excitation is scheduled to carry out soon.

Fabrication of the SBM is also challenging because it has a negative curvature, for which the coil winding is very difficult. The SBM was completed in 2003 and successfully tested.

In this report are described the status of the sector magnets of the SRC as well as that of the SBM. For some more details, refer to the corresponding reports in the attached document "Collected papers on the accelerators for the RIKEN RI beam factory (2003-2005)".

4.2 Superconducting sector magnet

Outline

Cross-sectional and plan views of the sector magnet are shown in Fig. 4.2.1. The sector magnet is 7.2 m in length and 6 m in height. The weight is about 800 t per each. The sector angle is 25 deg. The maximum sector field is 3.8 T, which is required to accelerate U^{88+} ions at 350 MeV/nucleon. 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. Figs. 4.2.2 and 4.2.3 show a cross section of these components and a bird's-eye view of their assembly, respectively. A photograph of the whole sector magnets assembled in the SRC vault is shown in Fig. 4.2.4

Superconductor

The superconductor that is used for the superconducting main and trim coils has a rectangular shape consisting of a Rutherford-type Nb-Ti 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 Al-alloy with 1,000 ppm Ni, which gives a high 0.2 %-yield strength of about 55 MPa at room temperature. The residual resistivity ratio is greater than 800-900. The cable is composed of ten strands of 1.18 mm in diameter, each being composed of about 960 filaments of 28 mm in diameter. The Cu/Nb-Ti ratio, the residual resistivity ratio of Cu stabilizer and the critical currents of the strand are 0.84, 100 and >16,000 A (5 T), >13,000 A (6 T) and >9,500 A (7 T) at 4.3 K, respectively. The conductor's cross section is shown in Fig. 4.2.5.

Main Coil

A solenoid winding with a total turn number of 396 (22x18 in the horizontal and vertical directions, respectively) is adopted for the main coil with cooling gaps of 0.8 mm and 1.5 mm horizontally and vertically, respectively. The maximum current of the main coil is 5,000 A, giving the maximum magneto-motive force per sector of 4.0 MA. Cross-sectional area of the coil measures 208 mm by 284 mm. The maximum current density is 34 A/mm^2. The main coil is designed based on Maddock's partial stabilization criterion. Cryogenic stabilized current at 6 T estimated from the measured resistivity and heat flux is greater than 6,000 A, which has been confirmed by the test using a small model coil. Operational point of the main coil is shown in Fig. 4.2.6 along with that of the trim coil. The maximum total stored energy of the main coils is 235 MJ.

The main coil vessel, the cross section of which is shown in Fig. 4.2.7, is made of stainless steel; its thickness is 50 or 60 mm. The C-shaped vessel is made first, and then the coil winding is performed with a tension stress of 20 MPa. Next, the outer plate is attached with screws made of high-strength stainless steel (A286), and finally thin seal covers with an L-shaped cross section are welded to the vessel. Pre-stress to the coil is applied at a pressure of 10 MPa with a wedge and the outer plate vertically and horizontally, respectively. The vessel is designed in such a way that there is no straight section for the coil winding.

The horizontal electromagnetic force of about 2.6 MN/m is exerted on the long section of the vessel covering the beam acceleration 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. The maximum deformation of the vessel is 1.8 mm.

Fabrication of the coil vessel, coil winding and welding of the seal covers were conducted with an accuracy of ±0.2 mm, ±0.6 mm and ±0.2 mm, respectively. Figs. 4.2.8 and 4.2.9 show photographs of the coil winding and the welding of the L-shaped seal covers, respectively.

Trim coil

Superconducting trim coils consist of four sets (parameters) as shown in Fig. 4.2.10. A double-pancake winding is adopted, in which the coils are indirectly cooled by forced two-phase helium through tubes engraved on the coil case as shown in Fig. 4.2.11. The maximum current is 3,000 A. The coil case is made of two Al-alloy plates that sandwich the trim coils. The LHe cooling tubes are arranged with a pitch of 300 mm. The heat-transfer coefficient measured with a model is over 50 $\Omega/m^2/K$. Operational point of the trim coil is shown in Fig. 4.2.6. A photograph of the winding of the trim coils is shown in Fig. 4.2.12.

The coil case is divided into two parts, each containing two of the four sets. The calculated maximum deformation of the case due to electromagnetic forces is about 1 mm. These coil cases are attached to the main coil vessel with screws.

Twenty-two pairs of normal-conducting trim coils are attached on the surface of the beam chamber. The maximum currents of the trim coils are 600, 800 and 1,200 A according to the region where they are placed. The coil is made of a double-tube consisting of a copper conductor of 10 mm in diameter covered with a stainless steel of 17 mm in diameter with an insulator in between.

Power supply

The power supplies of the main coils are composed of one main power supply with a maximum current of 5,200 A and six auxiliaries with that of 100 A which are used to adjust differences of magnetic fields among the sector magnets. The power supplies of the trim coils are composed of four main power supplies with the maximum current of 3,200 A, two auxiliaries with that of 400 A, and six auxiliaries with that of 100 A. The stability of the main power supplies for the main and trim coils is within 10 ppm per 8 h.

In order to protect the superconducting main and trim coils, the quench characteristics were calculated in terms of current decay, temperature rise, and voltage development. The simulation shows that the optimal resistance of the dump resistor should be 0.3 Ω and 0.05 Ω 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 1,500 V, by taking the earth at the middle point of the dump resistor. The time constant of the main coil is thus 60 s (the self-inductance of the main coil is 18.8 H). The dump resistor is made of steel with a weight of 2 t and is air-cooled.

Thermal shield

The 4.5 K cold masses are covered with a total area of 110 m^2 (per sector magnet) of 70 K thermal radiation shields. The thermal shields are composed of stainless steel plates of 3 mm in thickness and multi-layer insulators. GHe cooling tubes are attached to the surfaces of the plates. For the multi-layer insulators, two types are used according to the radiation environment: one is polyimide sheets that are vacuum-evaporated with Al on both sides, and the other polyester sheets. The former is used for a quarter of their total areas that would be exposed to high radiation.

Cryostat

Conceptual drawing of the cryostat, beam chamber and normal-conducting trim coils is shown in Fig. 4.2.13; a photograph of them is shown in Fig. 4.2.14.

The side walls of the cryostat are made of stainless steel. The upper and lower walls, which constitute part of a pole, are made of steel. The side walls and the upper and lower walls are welded to each other. The maximum deformation of the walls due to atmospheric pressure is 5 mm. The beam chamber, which constitutes part of the cryostat, is made of stainless steel. The gap aperture of the chamber is 90 mm in which the injection and extraction elements are placed.

Thermal-insulation support

The cold mass is supported with a total of 17 thermal-insulation support links as shown in Fig. 4.2.15. A multi-cylinder type of support link used for the radial support is designed to sustain the radial shifting force of 90 kN. It is fixed on the surface of the back yoke. The vertical and azimuthal supports are made of titanium-alloy rod. The structural analysis shows that the minimum natural frequency (22 Hz) is larger than 20 Hz, which is adopted as the threshold value for reactors in Japan. The entire system of support links is thus designed to sustain the additional force due to an earthquake of 980 Gal and 490 Gal in the horizontal and vertical directions, respectively.

Pole and yoke

The pole is divided into two pieces in order to make a hole through which the connecting plate of the main coil vessel passes, as shown in Fig. 4.2.16.

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. The typical slab is 5.7 m (length) x 0.3 m (thickness) x 2.2 m (width). The weight of the yoke per sector is about 750 t.

The carbon content of the pure iron is less than 0.01 %.

Magnetic shield

For magnetic shielding, iron slabs are bridged on the top and bottom pf the valley regions between the neighboring sector magnets. Other slabs are placed vertically between these top and bottom slabs and between the back yokes of the sector magnets. Cross-sectional and plan views of the magnetic shield are shown in Fig. 4.2.17. The vertical outside slabs are assembled to form a double-leafed hinged door to be opened when the maintenance is carried out for the rf resonators, vacuum pumps and so on in the valley region.

Instrumentation

A total of about 350 temperature sensors and 430 strain gauges are mounted at the periphery of the cold mass. They have a possibility of being exposed to high radiation doses. Therefore, radiation effects on the cryogenic temperature sensors such as Cernox^{TM}, Carbon-glass^{TM} resistor (CGR) and PtCo were tested using 210 MeV prton beams from the RRC.

Cryogenic cooling system

The cryogenic cooling system is a closed-circuit system without liquid nitrogen; it consists of a control Dewar vessel connected to the six cryostats of the sector magnets and the cryostat of the SBM, a refrigerator, three compressors and four reservoir tanks for GHe. Figure 4.2.18 shows photographs of the refrigerator, the compressors and the buffer tanks.

The control Dewar vessel is located on the top of the six sector magnets. The outer cryostat vessel of the control Dewar measures 2.5 m in diameter by 3.7 m in height; the volume of the helium vessel is about 2300 L, in which about 1700 L of LHe is stored. The connection of the main and trim coils among the six sector magnets is made inside the Dewar (see Fig. 4.2.19), and all of six types of current leads for the coils are set on the top of the Dewar.

The total heat load is 350 W at 4.5 K: 295 W for the sector magnets, 10 W for the control Dewar vessel and 45 W for the transfer tubes.

The refrigerator has a cooling power of 620 W at 4.5 K for the coils, 4000 W at 70 K for the thermal radiation shields, 4 g/s for the current leads. The total equivalent refrigeration capacity at 4.5 K is approximately 1,100 W, which was confirmed by the recent test on the refrigerator. The refrigerator is of TCF200S type of LINDE. Each of the three compressors (one is a spare) has an electric power of 315 kW and a gas flow rate of 74 g/s. Each of the four reservoir tanks has a volume of 100 m^3; its size is 15 m in height and 3 m in diameter. The designed pressure of the tank is 2 MPa. One of the four reservoir tanks is used as a buffer tank in regular operation, and the other three are used to recover evaporated helium as through a recovery tube line when the coils quench.

It is estimated that it takes 21 days to cool a total of 140 t of the cold masses from room temperature to 4.5 K with this system.

Change of the floor level

The floor level of the SRC vault has been monitored as shown in Fig. 4.2.20 to see how much the floor sunk due to such heavy weight as 8300 t. The data suggests that the floor around the north and east wall sank by 2 mm after the installation of the parts of the SRC, and then they stayed there for several months. The lower yoke level was re-adjusted after this measurement. The yoke levels were measured again two months later, suggesting that the upper surface of the lower yokes was tilted by 0.5 mm in 20 m. However, we judge that this tilt is not harmful to the performance of the SRC. We plan to continue the monitoring.

Cool-down test

The assembly of the sector magnets was completed in September 2005. The cool-down started on September 19. The temperature of the sector magnets has been decreased smoothly by keeping the temperature difference between the inlet and outlet of the coil vessels as well as between the upper and lower parts less than 50 K and 20 K, respectively. On October 13, the resistance of the coils became zero (superconducting), which means that the temperature at that time was less than 10 K. As of October 15, the temperature of the main coil and trim coil has reached around 4.5 K and the total volume of them is filled with liquid He. The excitation test of the sector magnets is scheduled for a week from around October 20, after which the magnetic field mapping will be carried out for about three months.

Figures 4.2.21-24 show a schematic diagram for the cool-down, trend graphs of the temperature, the pressure of the cryostat vacuum chamber and the resistance of the coil, respectively.

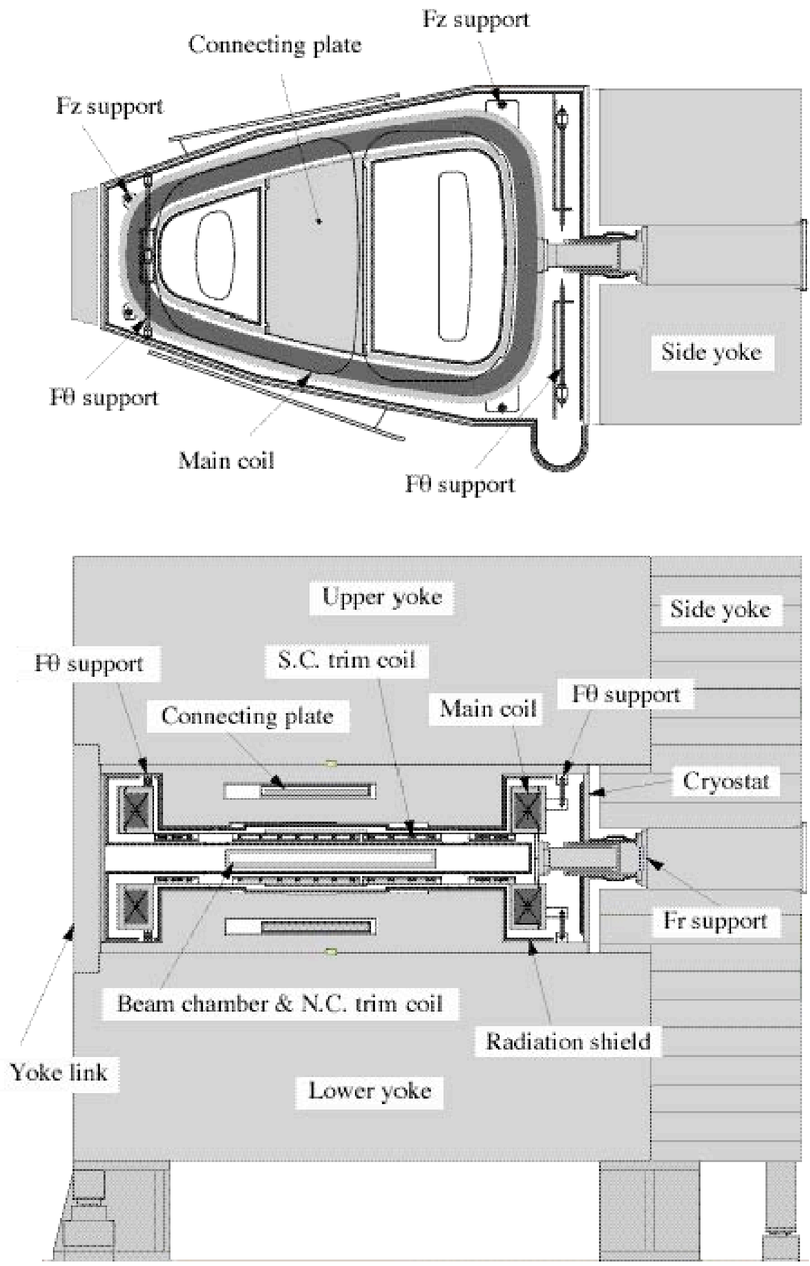

Figure 4.2.1. Cross-sectional (lower figure) and plan (upper figure) views of the sector magnet.

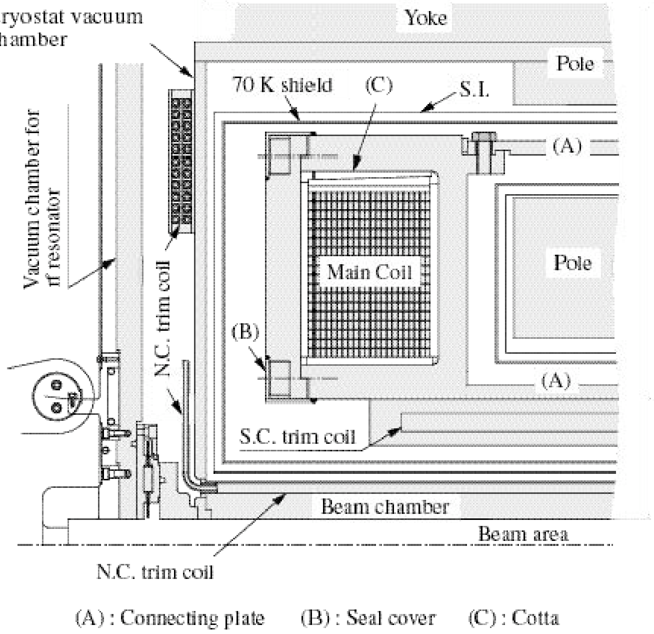

Figure 4.2.2. Cross-sectional view of the main coil, trim coil, pole, yoke and others.

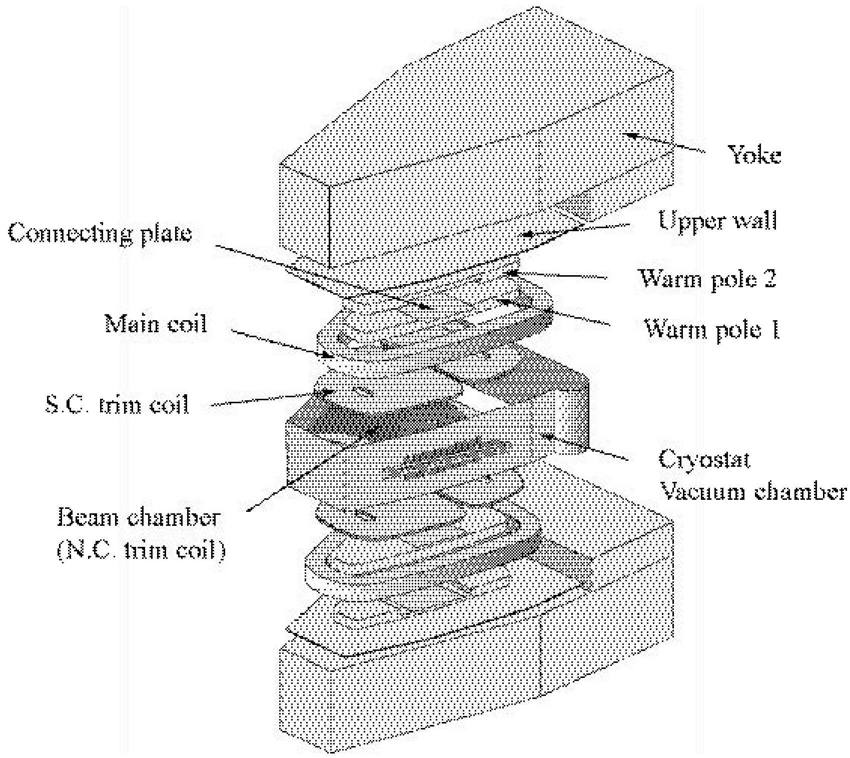

Figure 4.2.3. Bird's eye view of the sector magnet assembly except for the back yoke.

Figure 4.2.4.a. Photograph of the completed sector magnets in the SRC vault.

Figure 4.2.4.b. Same as for Fig. 4.2.4.a.

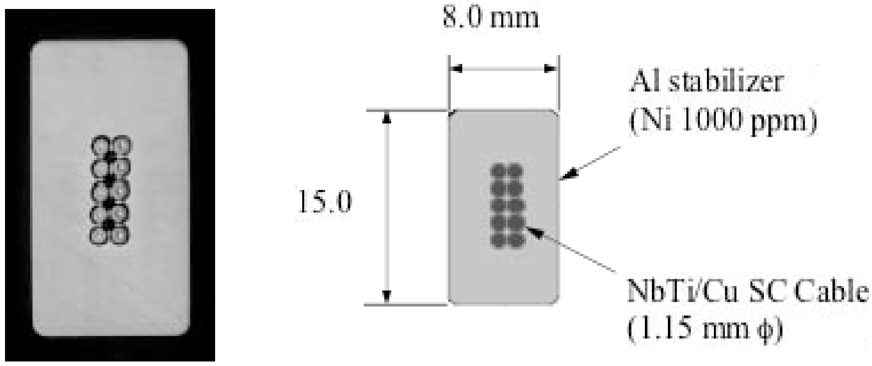

Figure 4.2.5. Cross section of the superconductor.

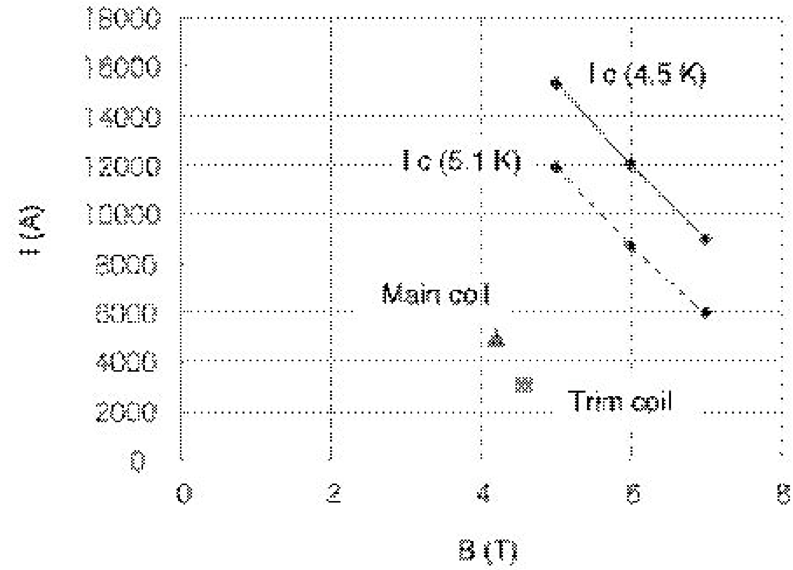

Figure 4.2.6. Operational points of the main and trim coils.

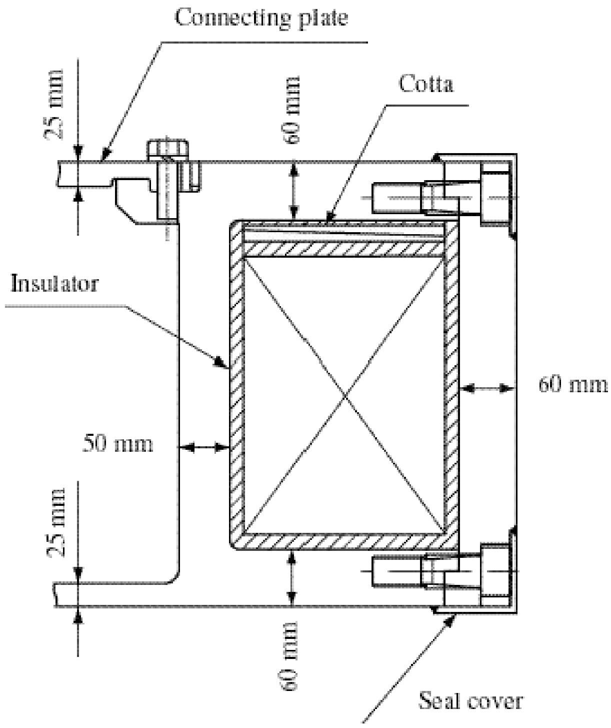

Figure 4.2.7. Cross section of the main coil vessel.

Figure 4.2.8. Photograph of the main coil winding. Vertical GFRP spacers can be seen.

Figure 4.2.9. Photograph of the welding of the L-shaped seal covers.

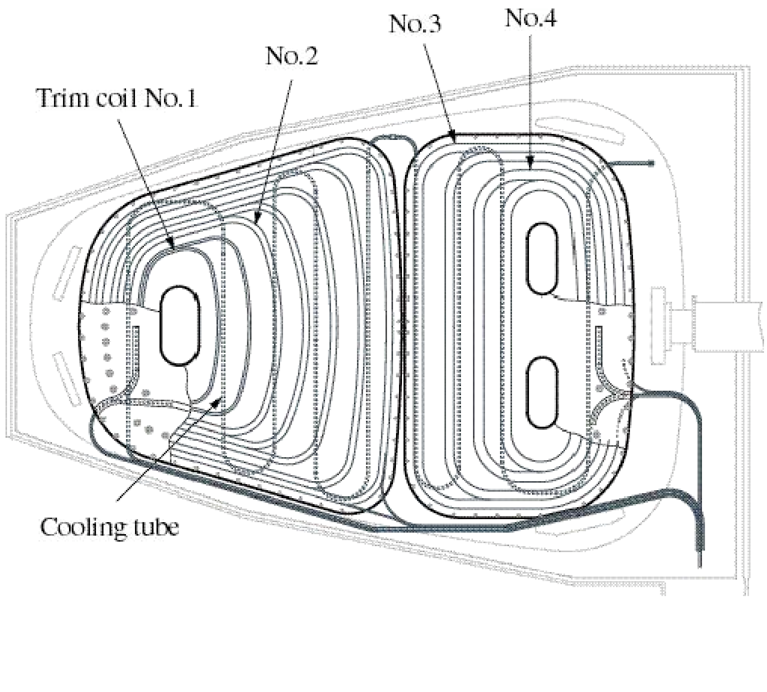

Figure 4.2.10. Plan view of the superconducting trim coils.

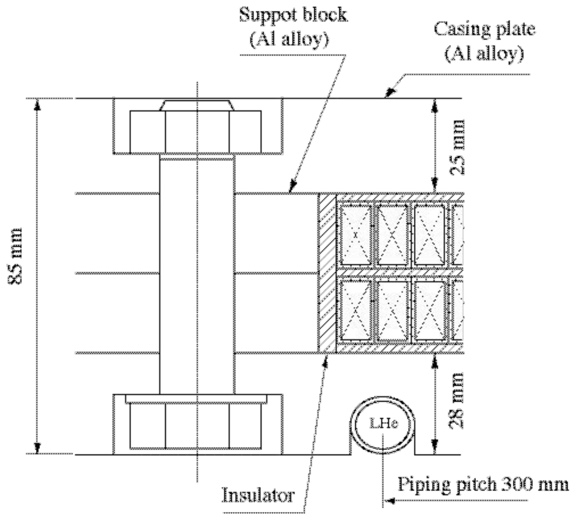

Figure 4.2.11. Cross-sectional view of the superconducting trim coil.

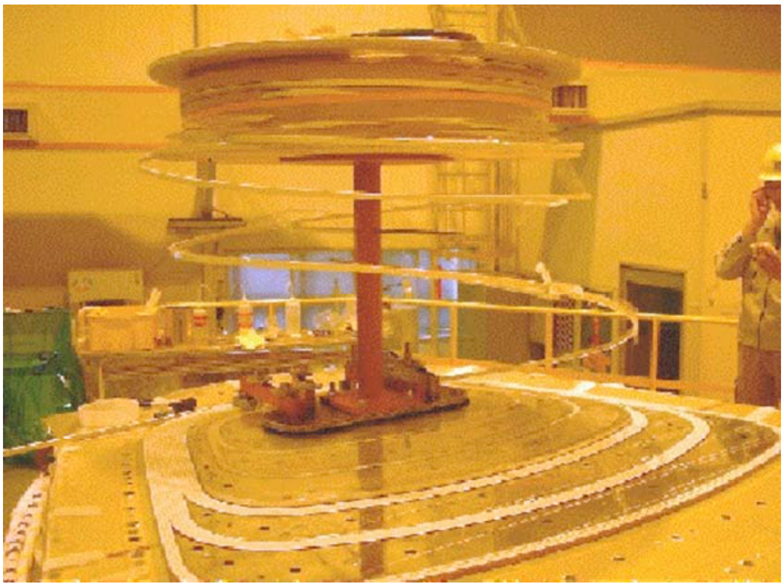

Figure 4.2.12. Photograph of the rim coil winding.

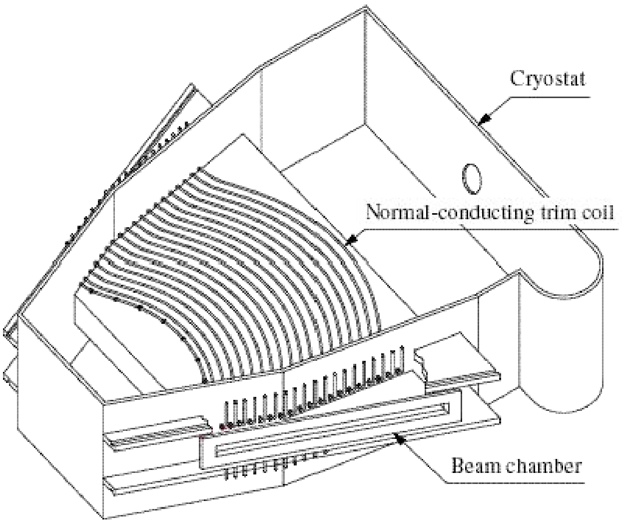

Figure 4.2.13. Conceptual drawing of the cryostat, beam chamber and normal-conducting trim coils.

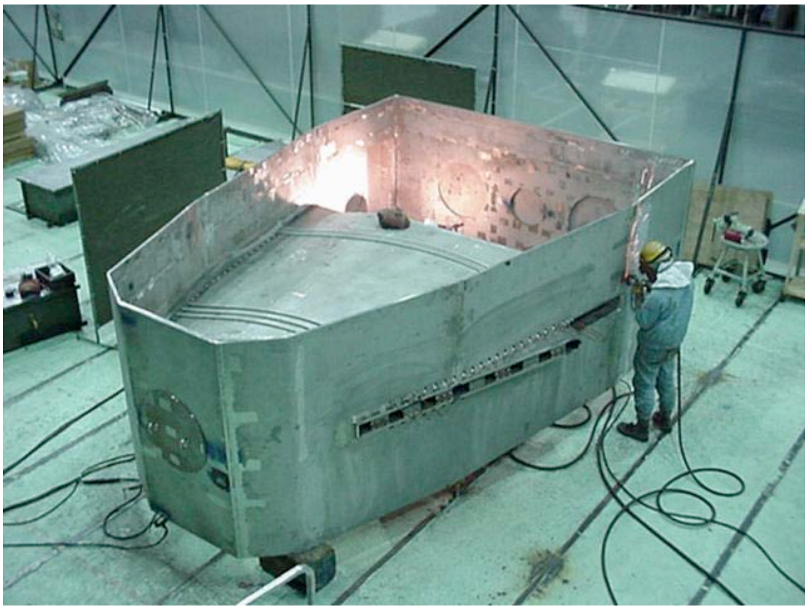

Figure 4.2.14. Photograph of the cryostat and beam chamber. Some normal-conducting trim coils can be seen on the surface of the beam chamber.

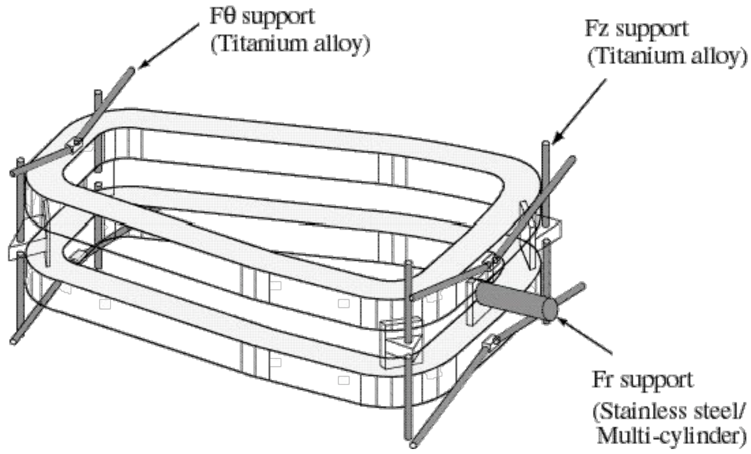

Figure 4.2.15. Thermal insulation supports.

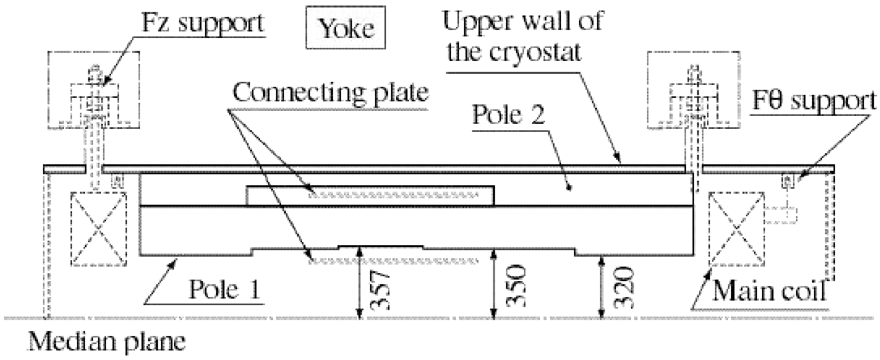

Figure 4.2.16. Cross-sectional view of the pole, connecting plate and thermal insulation supports.

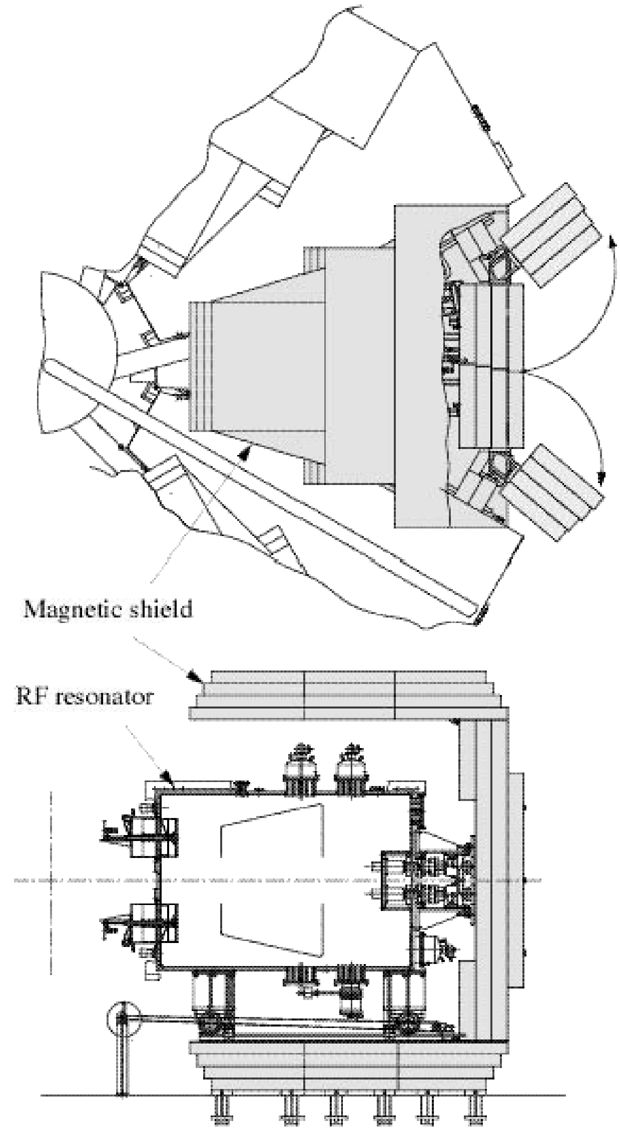

Figure 4.2.17. Cross-sectional and plan views of the magnetic shield.

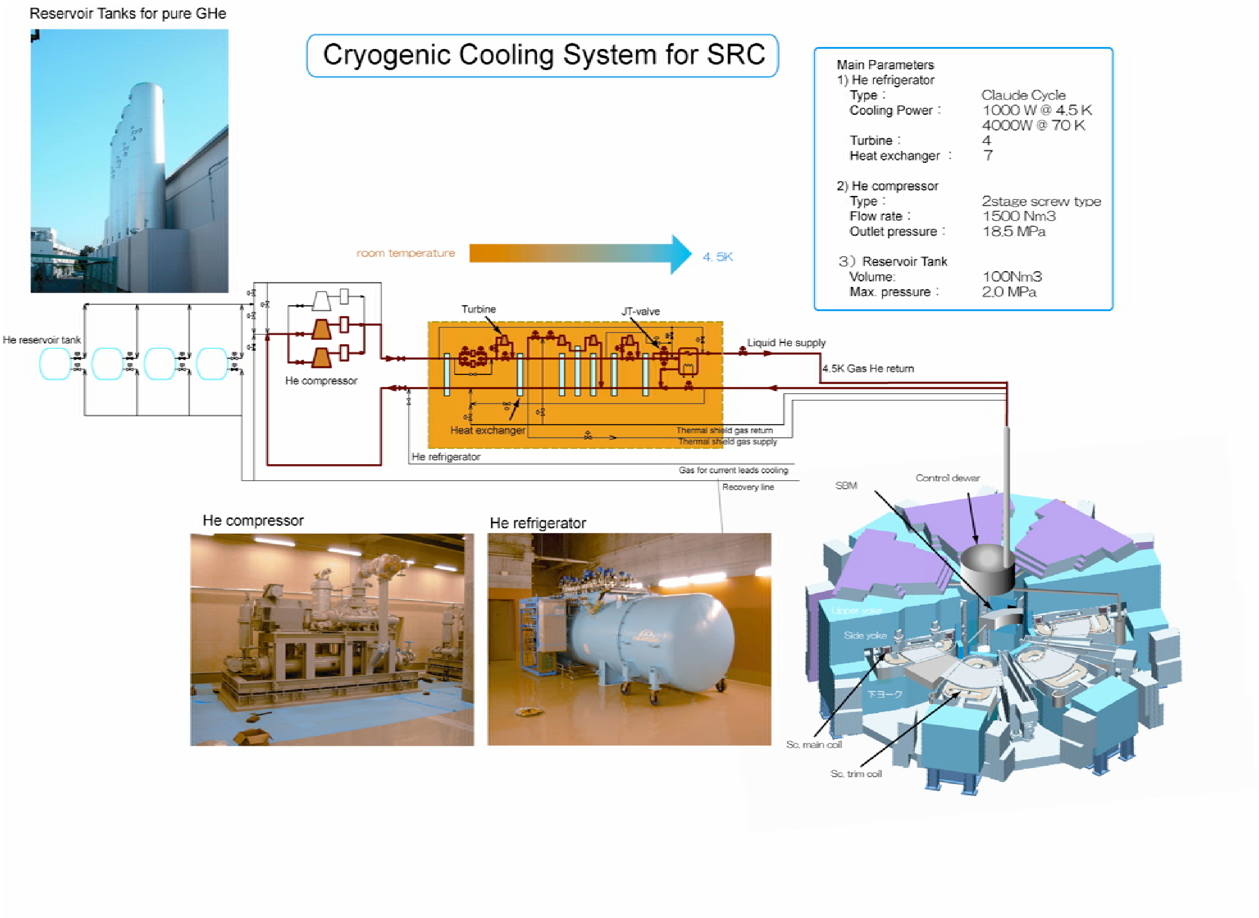

Figure 4.2.18. Cryogenic cooling system.

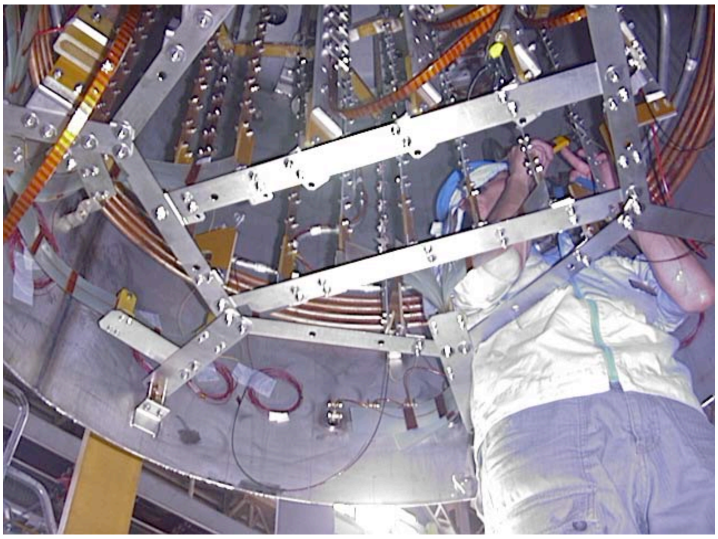

Figure 4.2.19. Photograph of the inside of the control Dewar. The main and trim coils for the six sector magnets are connected here in series. A heat transfer device consisting of four turns of tubes to produce two-phase helium for the trim coils can be seen on the inner surface of the vessel.

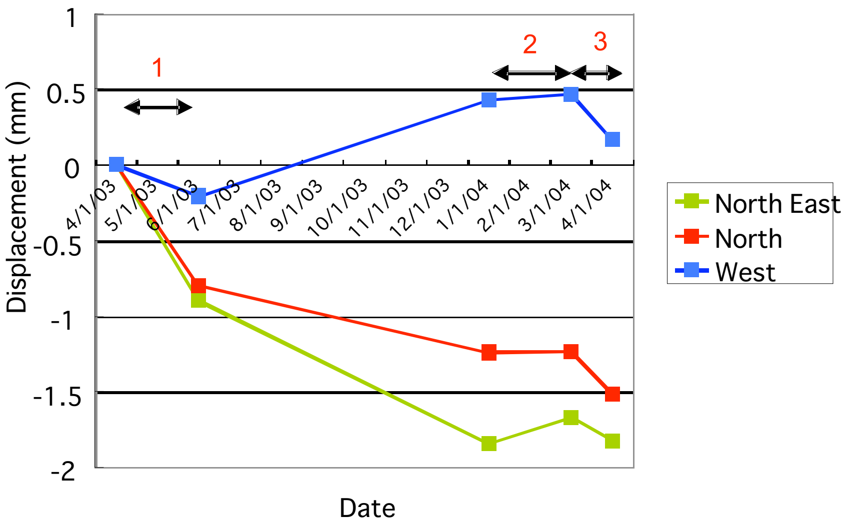

Figure 4.2.20. Subsidence of the floor level in the SRC. Periods 1, 2, and 3 indicate the following. 1: Delivery of slabs for the yoke and the shield into the SRC and Big-RIPS vaults, 2: Assembly of the lower yokes and 3: Transfer of most slabs from the Big-RIPS vaults into the SRC vaults.

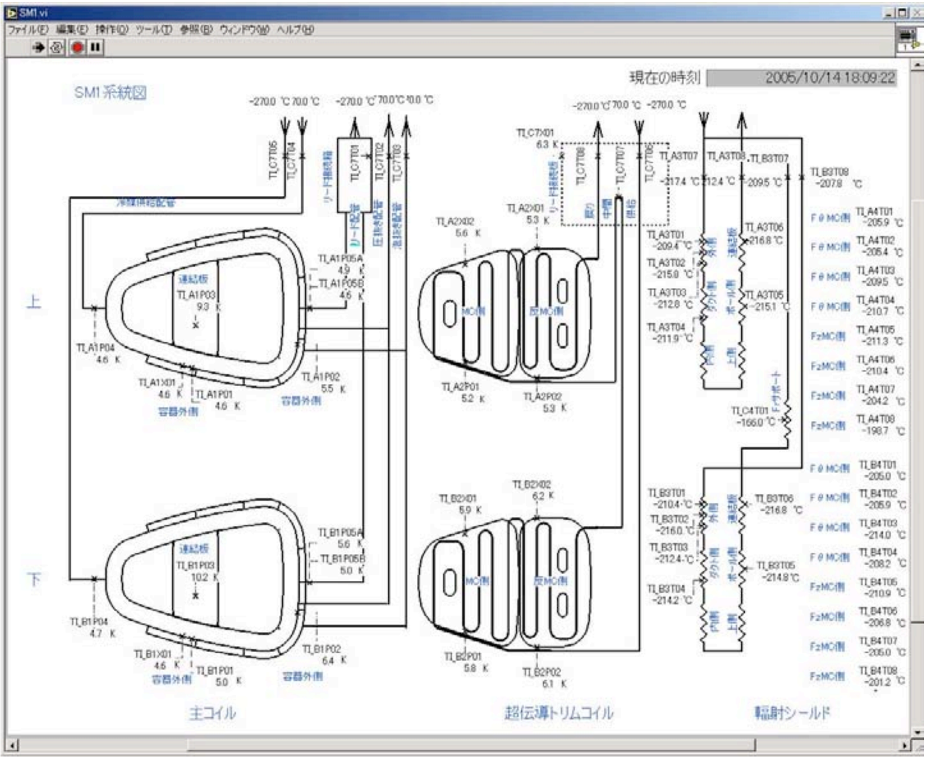

Figure 4.2.21. Schematic diagram for the cool-down of the sector magnet.

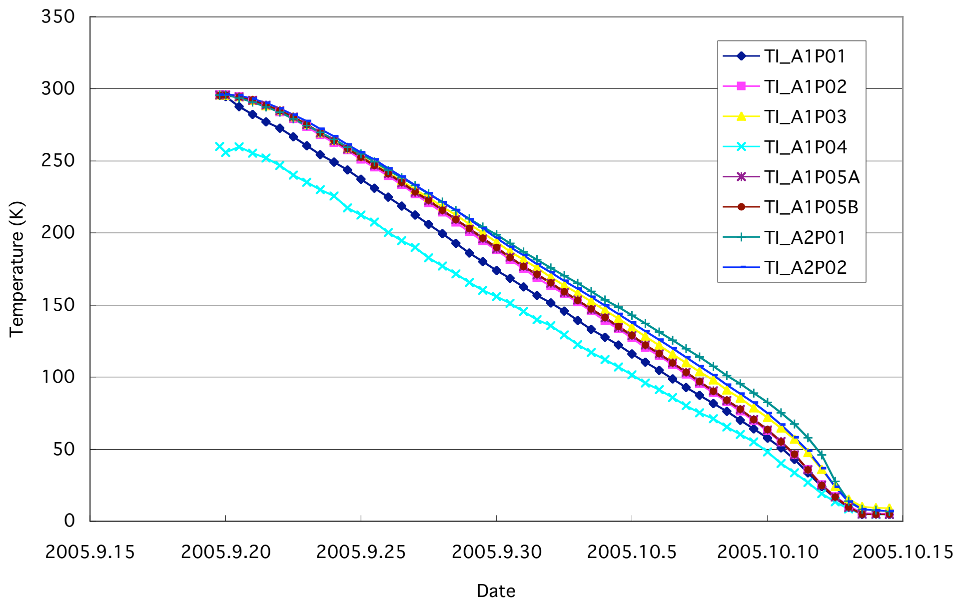

Figure 4.2.22. Trend graph of the temperature during the cool-down.

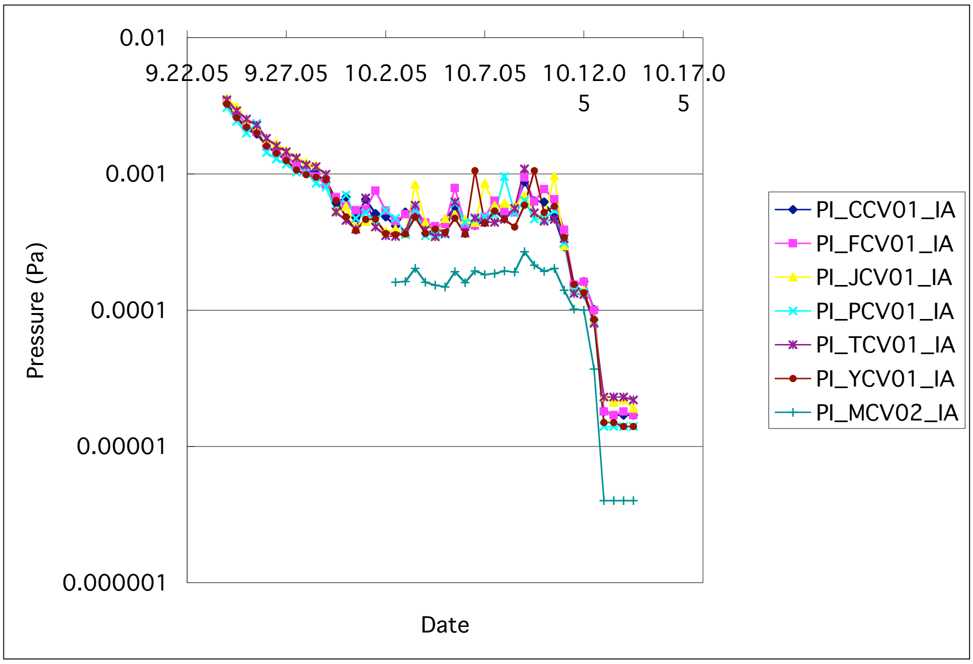

Figure 4.2.23. Trend graph of the pressure in the cryostat chamber.

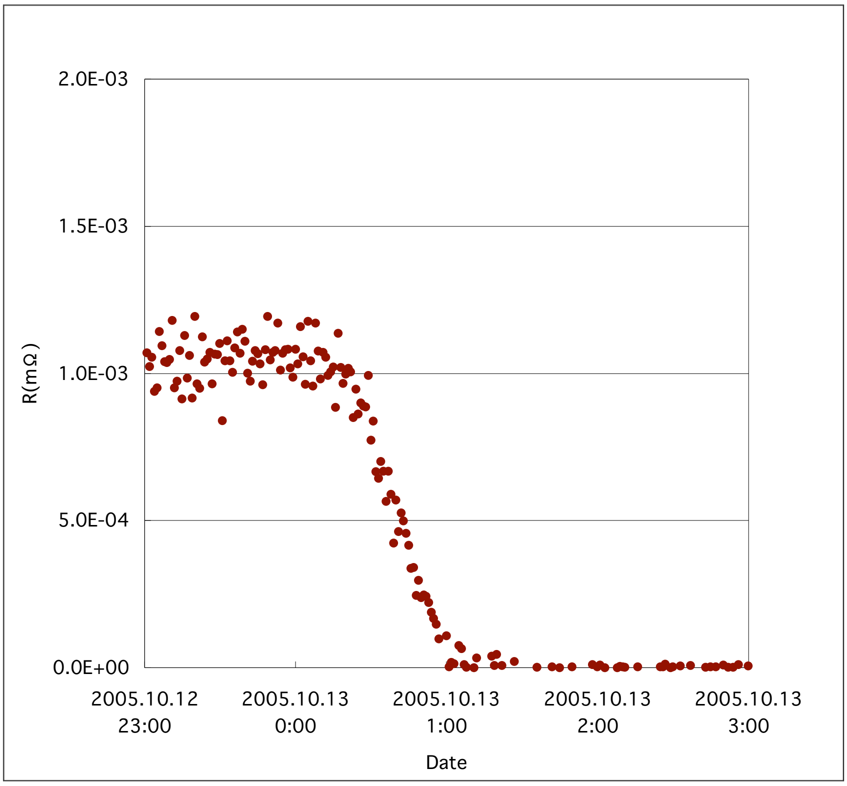

Figure 4.2.24. Trend graph of the resistance of the coil. The resistance drops to zero on October 13 at around 1:30.

4.3 SBM

Outline

The superconducting bending magnet (SBM) is used as one of the beam injection elements. It guides beams into the sector magnet. The main parameters of the SBM are listed in Table 4.3.1. It needs to generate a magnetic field of 3.8 T along the beam trajectory that has a curvature of 1.2 m.

Structure

Figure 4.3.1 shows a cross-sectional and plan views of the SBM. The SBM consists mainly of coil, iron pole and yoke. Flat coils are adopted for the coils since they can be wound and supported easily. The iron pole is cold and used as the mandrel for the coil winding. The yoke is divided into two parts: cold yoke and warm yoke. The cold yoke is of an H-type. This configuration makes shifting forces and unbalanced forces on the cold mass small. The weight of the cold mass is about 3 t. The two coil casings including the cold poles are attached to the cold yoke. A C-type design is adopted for the warm yoke because the available space in the side of the sector magnet is very limited. A warm duct for ion beams is installed in the gap of the poles. Iron shims and water-cooled baffle slits are attached to the duct.

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 and unbalanced forces small. The beam tube is connected to the vessel at its ends. The cold mass is supported by three types of thermal insulation supports from room temperature as shown in Fig. 4.3.1. They were designed to support the cold mass stably against the shifting and unbalanced force as well as against an earthquake of as big as 980 Gal and 490 Gal in the horizontal and vertical direction, respectively.

Two-dimensional analysis was carried out to optimize the geometry of the coils, yokes and iron shims. Magnetic forces on the cold mass were calculated for the mechanical design. 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 with those from the sector magnets is studied using a model that includes the SBM and two sector magnets. The generated field of the SBM decreases by 5 % compared to the stand-alone excitation.

Superconductor, coil winding and fabrication

Rectangular monolithic NbTi wire of 0.8 mm x 2.4 mm in size was adopted for easier winding. The conductor is coated with polyimide of 50 μm 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. The overall current density of the coil to achieve the required field is about 150 A/mm^2. This value of current density was selected from the experience of the test coil.

Coil winding is one of the key issues for the fabrication of the SBM because the coils of the SBM have negative curvature, which is impossible to wind with any tension. The winding method shown in Fig. 4.3.2 was adopted. In the first step the coil is wound with a tension in a shape that has no negative curvature. The circumference of the coil is taken to 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 merit of this 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 4.3.3 shows the completed coil. The coil casing is partially covered by seal covers for He tightness.

Difference of the real coil shape from the designed one was less than 1 mm, which is allowable to keep the flattness of the field along the trajectory. After the installation of the coils, pre-stresses are applied on the coils by about two hundred set bolts. Figure 4.3.4 shows the process of the assembling of the cold mass and piping. The SBM assembled with the control Dewar is shown in Figure 4.3.5.

Cryogenic cooling system

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 the current leads. Gas helium for the thermal shield and 4.5 K liquid helium for the coil cooling are supplied to the SBM cryostat by the big refrigeration system of the sector magnets. The current leads are installed in the He reservoir 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 liquid He Dewar.

Coil protection

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. The 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 the ground in the middle of it.

Cool-down and excitation test

The cool-down test of the SBM was carried out in stand-alone immediately after it was completed in August 2003. Figure 4.3.6 shows the trend of the coil temperature during the test. It took about 100 hours to cool the cold mass of about 3 t down from the room temperature to 4.3 K. The coolant was changed from liquid nitrogen to gas helium at about 110 K in order to prevent liquid nitrogen from remaining in the coil vessels. Figure 4.3.7 shows the excitation curve obtained together with the history of quenches. The magnet reached the designed field after the first quench, which occurred at 315 A. Training effects were clearly observed.

Magnetic fields along the beam trajectory were also measured to get effective lengths and field uniformity at various excitation levels. The measured effective length agrees with the designed value, though it differs by about 1.6 % for some excitation levels.

Table 4.3.1. Main parameters of the SBM.

Item	Value
Type	Flat coil, Iron pole Iron Yoke (Cold and Warm)
Required field	3.8 T@ 363 A
Maximum field in the coil	4.2 T
Stored Energy	0.56 MJ
Homogeneity	few x 10^{-3}
Beam bore	40 (H) x 30 (V) mm^2
Radius	1208.4 mm (Room temperature)
Angle	75.72 degree
Coil cross section	55 x 58 mm^2

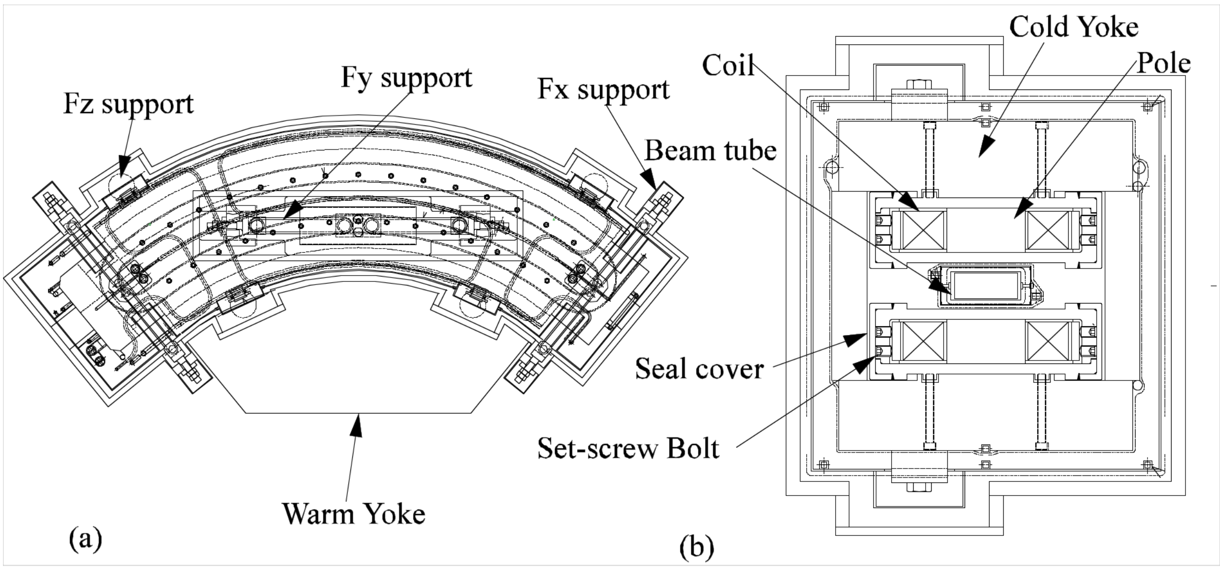

Figure 4.3.1. Plan view (a) and cross sectional view (b) of the SBM.

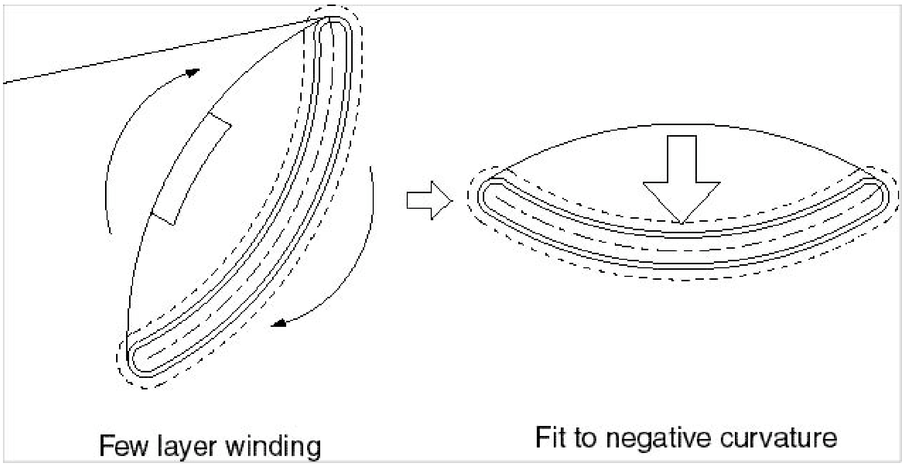

Figure 4.3.2. Concept of the coil winding.

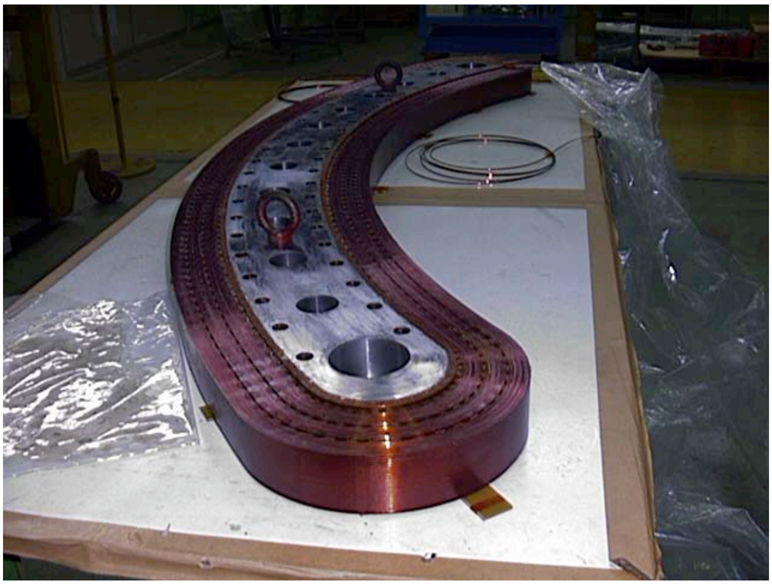

Figure 4.3.3. Photograph of the completed coil.

Figure 4.3.4. Assembling of the cold mass.

Figure 4.3.5. Photograph of the completed SBM.

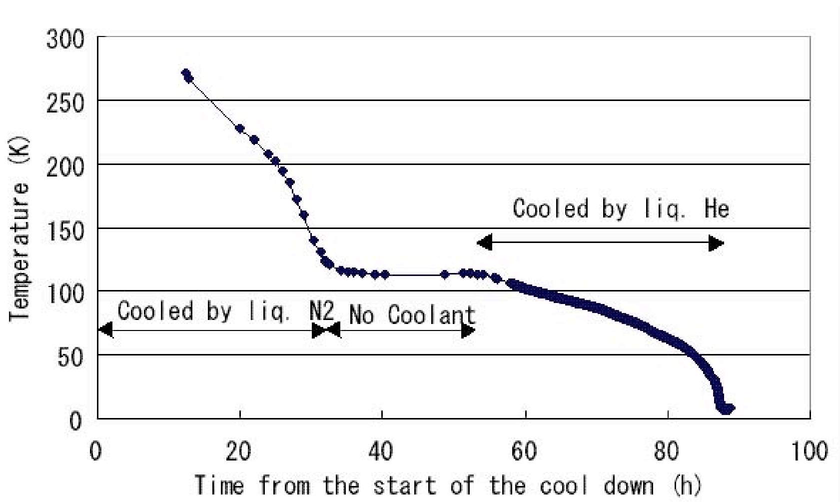

Figure 4.3.6. Trend graph of the coil temperature during the col-down.

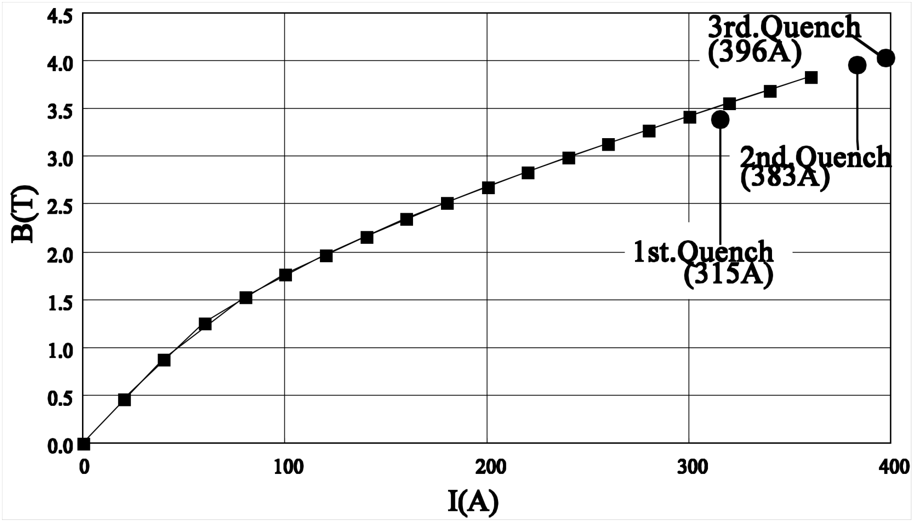

Figure 4.3.7. Excitation curve obtained together with the history of quenches.