Completion of Sector Magnets for Superconducting Ring Cyclotron

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OVERVIEW: Development work on the SRC, which is the world's first ring cyclotron utilizing superconducting technology, for the heavy-ion accelerator RIBF being constructed by RIKEN has now been completed. The SRC is the final booster in the RIBF accelerator complex and is capable of accelerating even heavy ions such as uranium up to 350 MeV/nucleon. Based on its expertise and many years of experience in manufacturing large superconducting magnets, Hitachi, Ltd. was commissioned to develop and fabricate a total of six sector magnets, the most critical subsystem of the SRC. Constituent parts of the sector magnets were completed at the end of March 2003, and after delivery to the site and installation, all superconducting coils achieved their rated current without quenching in the fall of 2005, and the SRC delivered its first beam in December 2006.

INTRODUCTION

USE of particle beams in recent years is no longer confined to basic science, but they are used in a wide range of applications in biology, medicine, and a host of other areas. The pioneering work of atomic energy research by RIKEN has led to new insights affecting every element from hydrogen at one end of the spectrum to uranium at the other, and more breakthroughs will follow with the establishment of the heavy-ion accelerator, the RIBF (Radioactive Isotope Beam Factory). Construction of this next-generation facility that is far superior to any other similar facility around the world was begun in 1997, and is capable of producing particle beams including radioactive isotopes(1). RIBF is a heavy-ion beam accelerator complex in which beam are accelerated by a cascade operation of multiple cyclotrons and now the SRC (superconducting ring cyclotron) shown in Fig. 1, the final-stage accelerator in the cascade of ring cyclotrons, has been developed(2). Here we will give an overview of the key components of the sector magnets that Hitachi, Ltd. was commissioned to fabricate for RIKEN's SRC.

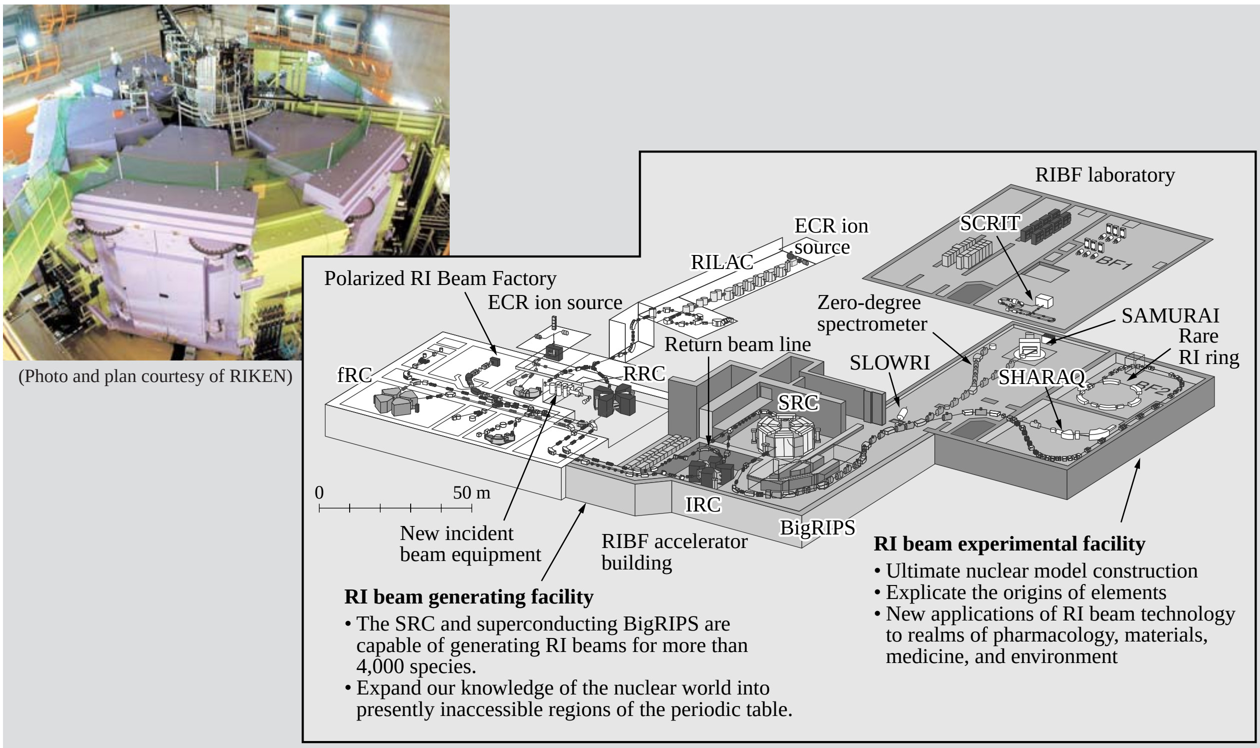
SRC SECTOR MAGNETS OVERVIEW

The world's first ring cyclotron implemented from superconducting coils, SRC, is the final booster in the cascade of ring cyclotrons at the RIBF accelerator complex, and generates magnetic fields powerful enough to accelerate heavy ions up to 350 MeV (mega electron volt)/nucleon. Table 1 shows the technical details of the SRC. The SRC has a maximum total stored energy of 240 MJ, and consists of six large superconducting sector magnet system. Extremely precise fabrication was required to use the SRC as an accelerator, and how to achieve this level of precision was the single greatest challenge.

Hitachi has considerable experience in manufacturing large superconducting magnets for fusion equipment and other projects, and relied on this experience in executing the present commission. Fig. 2 highlights Hitachi's main superconducting magnet commissions.

Fig. 3 shows cross-sectional and plan views of the sector magnet. The main components of the sector magnet are (1) a pair of main coils that generate a maximum sector field of 4 T, (2) four sets of SC (superconducting) trim coils that help generate isochronous fields with a maximum field of 1 T, and (3) a cryostat consisting of thermal insulation support links that support the cold mass (the main coils and superconducting trim coils) and a thermal radiation shield. The technical details for the main coils and superconducting trim coils are listed in Table 2.

To sustain a stable superconducting state under required constraints and specifications, the conductor must be maintained at liquid helium temperature (4.2 K). A composite superconducting cable (NbTi stranded cable covered with aluminum stabilizer) is used to achieve cryogenic stabilization based on pool



(Photo and plan courtesy of RIKEN)

RI beam experimental facility

- Ultimate nuclear model construction
- Explicate the origins of elements
- New applications of RI beam technology to realms of pharmacology, materials, medicine, and environment

RI beam generating facility

- The SRC and superconducting BigRIPS are capable of generating RI beams for more than 4,000 species.
- Expand our knowledge of the nuclear world into presently inaccessible regions of the periodic table.

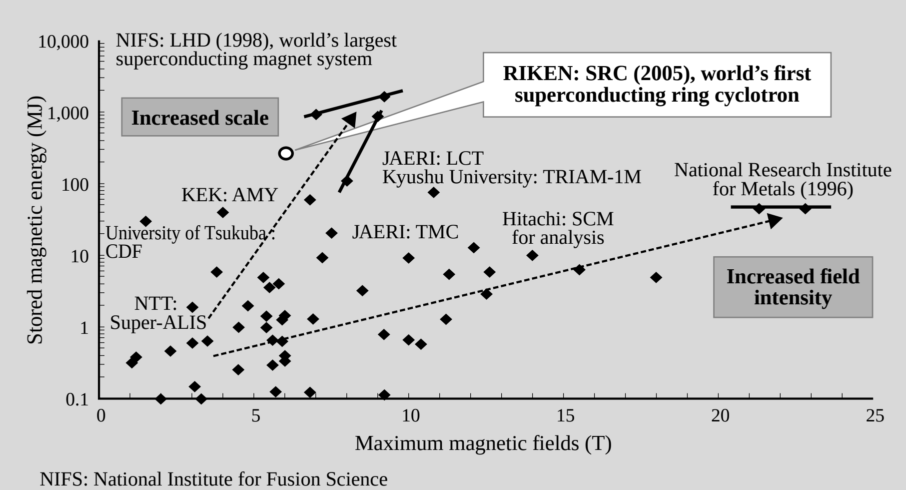
RI: radioactive isotope
SRC: superconducting ring cyclotron
RIBF: radioactive isotope beam factory
ECR: electron cyclotron resonance
RILAC: RIKEN heavy-ion linac
RRC: RIKEN ring cyclotron
fRC: fixed-frequency ring cyclotron

IRC: intermediate-stage ring cyclotron
BigRIPS: superconducting RI beam separator
SCRIT: self-confining radioactive ion target
SAMURAI: superconducting analyzer for multi-particle from radioactive isotope beam
SHARAQ: spectroscopy of hadronic systems with radioactive quantum beam
SLOWRI: radio frequency ion-guide for slow and trapped RI beam

Fig. 1—Overview of the SRC and Schematic Plan of the RIBF.
The SRC on the left is the final booster in the RIBF accelerator complex on the right that is now being constructed by the RIKEN. Installation and testing of the SRC have now been completed, and the first beam was successfully extracted. Currently, RIKEN is preparing the way to achieve world-class breakthroughs in advanced heavy-ion acceleration research at the RIBF.

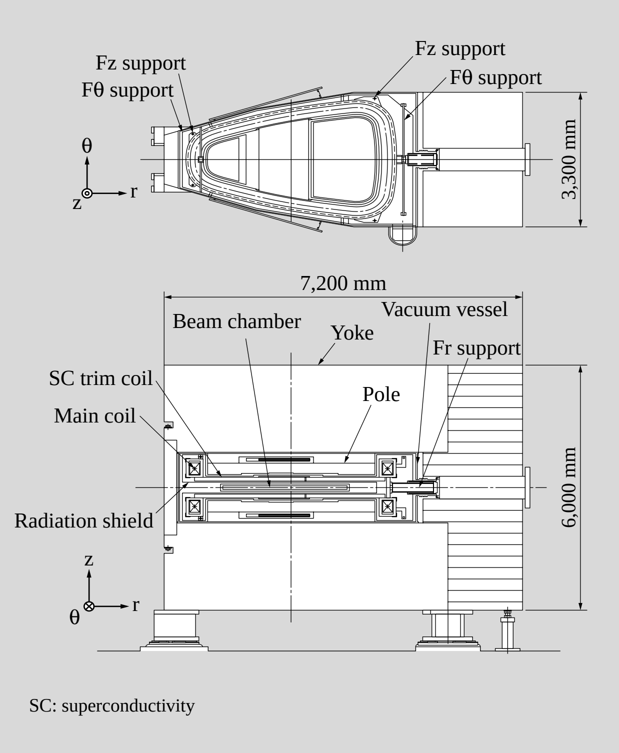
TABLE 1. SRC Technical Details
Key specifications required of the SRC are shown.

Item	Specification
K value	2,600 MeV
Maximum central magnetic field	3.8 T
Maximum magnetic energy	240 ML
Radio frequency	18 – 42 MHz
Injection radius	3.56 m
Extraction radius	5.36 m
Total mass	8,300 t



NIFS: National Institute for Fusion Science
KEK: High EnergyAccelerator Research Organization
JAERI: Japan Atomic Energy Research Institute

Fig. 2—Main Superconducting Magnet Commissions by Hitachi, Ltd.
Figure highlights Hitachi's main superconducting magnet commissions. Emphasis has been in two directions: increased scale and field intensity.



SC: superconductivity

Fig. 3—SRC Sector Magnet Equipment Configuration.
Configured from two kinds of superconducting coils, a cryostat, normal temperature pole, and yoke.

boiled cooling in the main coils and enhanced thermal conductivity based on conduction cooling of the SC trim coils.

FABRICATION OF THE SRC SECTOR MAGNETS

Main Coils

We were faced with three basic challenges in manufacturing large-scale noncircular coils using Al stabilizer superconductors such as shown in Fig. 4. Here we will examine those challenges and how we addressed them.

(1) A potential risk of short-circuits due to the conductor's low rigidity

The potential risk of short-circuits was greatly reduced by giving careful thought to the structure and work procedures, and virtually eliminated by implementing rigorous contaminant controls and continuous verification through electrical testing while the work was in progress.

(2) Securely anchoring the conductor to eliminate the possibility of quenching (abrupt catastrophic loss of superconductivity)

TABLE 2. Superconducting Coil Technical Details
Basic specifications for two types of superconducting coils are shown.

1. Main coil

Item	Specification
Magnetomotive force	4 MAT/sector
Rated current	5,000 A
Cooling method	Pool boiled cooling
Superconductor	Al stabilized NbTi stranded cable (dimensions: 8 × 15 mm)
Winding	Solenoid winding

2. SC trim coil

Item	Specification
Rated current	3,000 A
Cooling method	Indirect (conduction) cooling
Superconductor	Al stabilized NbTi stranded cable (dimensions: 8 × 15 mm)
Winding	Double pancake winding

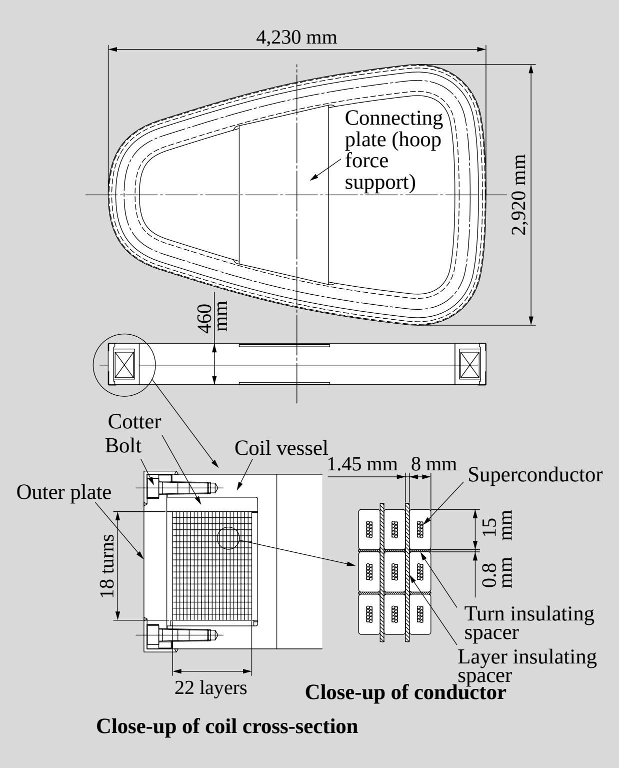


Fig. 4—Main Coil Configuration.
Overview of the main coil, the winding, and close-up of the superconductor is shown.

Uniform pressure is necessary to attach the conductor without deforming or damaging the aluminum stabilizer. This was not only achieved through the following three stages, but at the same time we also succeeded in assuring the winding precision (±0.6 mm) in the center of the coil.

(a) By applying tension on the conductor, we were able to attach it firmly radially around the winding.

(b) Pressure was applied on the conductor in the axial direction by inserting cotters between the coil and the vessel wall, so the conductors were secured.

(c) After the winding was complete, necessary pressure was uniformly applied to the outer surface of the coil, and the ratio of contact between the outer surface of the coil and inside of the outer plate was checked and adjusted using pressure measuring film. After verifying the contact surface, the outer plate is attached to the coil block and anchored with high-strength steel bolts. Fig. 5 shows a photo of the assembly.

(3) More reliable precise welding procedures for connecting the conductor

Fig. 5—Main Coil Winding.
Solenoid is wound as tension is applied to the superconductor, cotters are inserted between the coil and the inside wall of the vessel, and pressure is applied to the coil from above in the axial direction.

Conventional welding or soldering after copper plating was used to connect Al conductor in the past, but for this project we adopted FSW (friction-stir welding). FSW employed a rotating tool which is fed at a constant traverse rate into the joint line, and the frictional heat generated between the tool and workpieces causes plastic flow of the softened metal to produce a good quality weld. FSW produces excellent welds at far lower temperatures than conventional welding, and has a number of other significant advantages over conventional methods. FSW is capable of welding a seam up to 300 mm in length without affecting the superconducting performance, to produce a joint stronger than the base metal with a low resistance of 5 nΩ or less (at 5 K, 4 T).

SC Trim Coil

We faced two particular challenges in fabricating the SC trim coils shown schematically in Fig. 6, which are mounted in the narrow space between the main coil and the beam chamber and are instrumental in helping generate isochronous magnetic fields. Here we briefly describe how we addressed these challenges.

(1) Due to its super flattened configuration, there is not enough space above the trim coil to remove the helium gas bubbles that occur with pool boiled cooling. To solve the bubble removal problem, we switched from a pool boiled cooling approach to conduction cooling by two-phase flow cooling tubes. This raised new issues of how to cool the superconductor to liquid helium temperature, which we dealt with as follows.

(a) We improved the thermal conductivity using

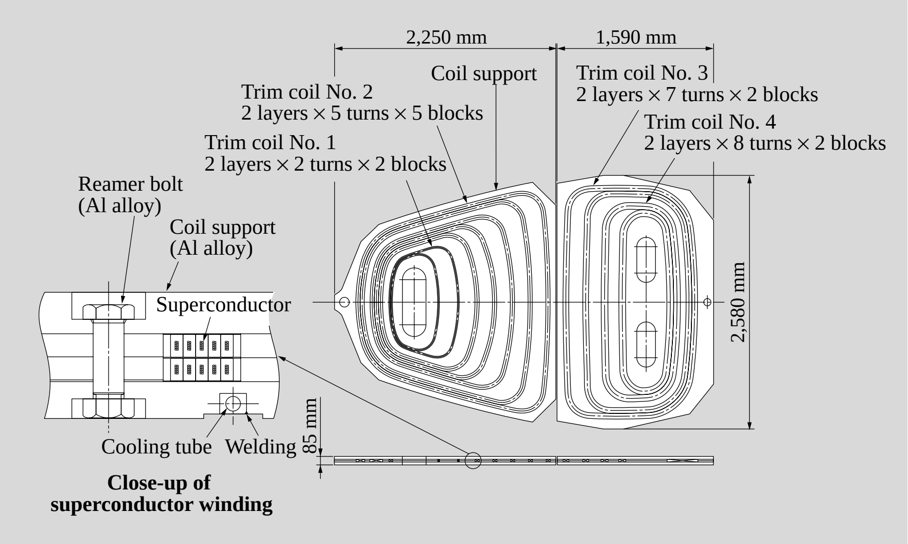


Fig. 6—SC Trim Coil.
Overview of the SC trim coil and close-up of the coil winding are shown. The SC trim coil consists of the four coils, with separate coil supports for the two-coil pairs.

Fig. 7—SC Trim Coil Winding.
The block construction Al alloy coil support assemblies and unique and double pancake windings are alternately assembled.

Fig. 8—Photo of Partially Assembled Equipment at the Plant.
To reduce the on-site installation work, completed sector magnet components were partially assembled at the plant before delivery to the site.

aluminum and aluminum alloy not only for the superconductor but for the structural elements and cooling tubes as well.

(b) The cooling tubes were continuously welded to the trim coil support base plates.

(c) We opted for this approach after conducting tests using prototype models to determine that sufficient thermal conductivity was achieved by bonding the base plates with embedded cooling tubes to the coils. We also conduced extensive tensile tests using various combinations of materials and work procedures to make sure the parts would not fall off when exposed to strong electromagnetic force. Essentially, we insulated the surface of the conductor with glass prepreg tape, applied strong adhesive epoxy resin, then cured the assembly applying strong spring force perpendicular to the coil. We then verified there was no separation at the bonded interface using ultrasonic flaw detection.

(2) Conductor discretely deployed radially

Coil supports are precisely machined out of aluminum alloy, and the shape of the windings must precisely match the supports. The split supports are successively assembled as the conductor is wound, and by using numerous cooling fit pins and reamer bolts, the finished winding shown in Fig. 7 has the required precision and mechanical strength to deal with the electromagnetic force.

Cryostat

Thermal insulating supports are installed in three directions from the normal temperature section — i.e. radial, vertical, and azimuthal directions — to anchor and support the cold mass. Eight titanium alloy rods designed for strength and to reduce the amount of heat penetration into the cold mass provide support against gravitational forces and seismic forces in the vertical direction (z) and seismic forces in the azimuthal direction (θ). Three cylinders made of stainless steel are connected in a turned-back three-layer cylinder that provides support against electromagnetic and seismic forces in the radial direction (r), and is designed to work within longitudinal space constraints, to ensure good mechanical strength, and to restrain heat from penetrating into the cold mass.

In addition, 80 K thermal radiation shields are supported from the cold mass due to assembly constraints, and FRP (fiber reinforced plastic) rod supports with sliding and plate spring deformation structure meet the two requirements of reducing heat penetration and alleviating thermal stress. Polyimide is adopted as multilayer insulation base material in areas subject to high dose of radiation.

CURRENT OPERATIONAL STATUS OF SRC

The sector magnet component systems were completed at the end of March 2003, partially assembled at the plant as shown in Fig. 8, then delivered and placed in position at the site. The SRC was completed in the fall of 2005. All superconducting coils achieved their rated currents in the first cooldown without quenching, and after some additional trials and fine-tuning, the SRC produced its first beam in December 2006. Now that the basic experimental equipment is finally in place, we are already beginning to see groundbreaking results through the generation of very short-lived new isotopes.

CONCLUSIONS

Here we highlighted some of the key final version technologies used in the development of the sector magnets for the SRC at RIKEN's RIBF. Development and technical insights gained in this work will certainly be applied and further extended in large-scale accelerator projects of the future.

ACKNOWLEDGMENTS

Finally we wish to express our appreciation to RIKEN scientists and other colleagues for their numerous helpful suggestions and cooperation.

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