CONSTRUCTION AND TEST OF THE SUPERCONDUCTING COILS FOR RIKEN SC-ECR ION SOURCE

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Abstract

A superconducting coil assembly for a new SC-ECR ion source at the RIKEN RI beam factory was constructed and its excitation tests were carried out. The coil assembly consists of a set of sextupole coils and six solenoids to generate a confinement magnetic field. All the coils use a NbTi conductor and are bath-cooled in liquid helium. The maximum magnetic field on the coils is 7.4 T. The characteristic feature of this coil system is that the six solenoids can generate a flat region in the axial confinement magnetic field. A large radial magnetic field due to this solenoid configuration is accordingly provided on the sextupole coils, and an inhomogeneous, strong expansion force is generated on the sextupole coils; this makes the design and fabrication of the sextupole coil assembly difficult. The construction began at a factory of Mitsubishi Electric Corporation in October 2007. After all the coils were wound and assembled, the excitation tests were performed in June 2008.

INTRODUCTION

The accelerator complex of the RIKEN RI beam factory (RIBF) consists of a heavy-ion linac and four ring cyclotrons, and can accelerate all kinds of ions from hydrogen to uranium up to an energy of 345 MeV/nucleon [1]. Three newly constructed ring cyclotrons were commissioned in 2006 and the acceleration of uranium beams succeeded in 2007 [2]. An 18 GHz ECR ion source is now used for the production of uranium ions. The beam intensity from it, however, is so low as to achieve the design goal of 1 pμA of 345 MeV/nucleon uranium ion beam. In this situation, we decided to make a new superconducting ECR ion source of a frequency of 28 GHz [3], which is expected to enable us to increase a beam current of uranium ions remarkably [4].

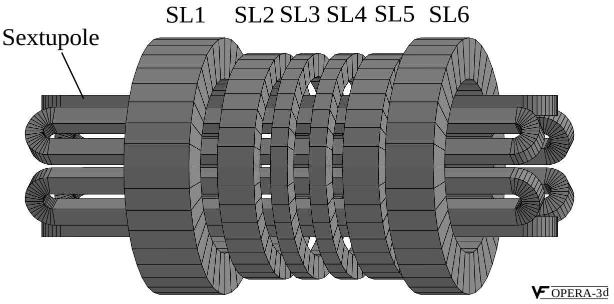

Figure 1: Arrangement of the superconducting solenoid and sextupole coils.

COIL CONFIGURATION AND PARAMETERS

A schematic of the superconducting coil system for the newly designed ECR ion source is shown in Fig. 1 [5]. It consists of six solenoids SL1~SL6 and a set of sextupole coils to make a confinement magnetic field. Figure 2 shows the axial and the sextupole magnetic field distributions along the beam axis. The maximum axial

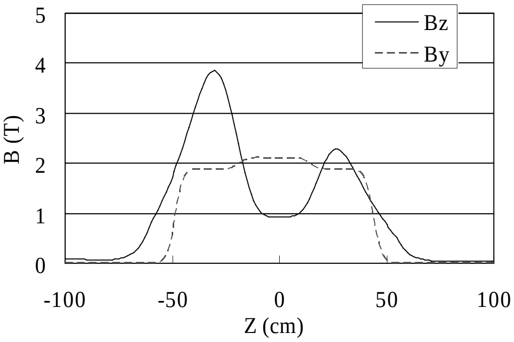

Figure 2: Axial and sextupole magnetic field distributions: Bz indicates the solenoid field along the beam axis and By sextupole field on the surface of the plasma chamber (r = 75mm).

Table 1. Parameters of the supeconducting coils

	SL 1	SL 2	SL 3	SL 4	SL 5	SL 6	Sextupole
Inner radius (mm)	170	175	175	175	175	170	102
Outer radius (mm)	250	220	220	220	220	250	142
Length (mm)	135	75	35	35	75	100	1073
Conductor size (mm)	0.82 x 1.15	0.82 x 1.15	ϕ1.09	ϕ1.09	0.82 x 1.15	0.82 x 1.15	0.82 x 1.15
Cu/NbTi ratio	1.3	1.3	6.5	6.5	1.3	1.3	1.3
No. turns	9124	2778	1305	1305	2778	6830	1216
Current (A)	162	182	109	109	155	132	271
Bmax (T)	7.2	5.2	3.1	3.0	4.8	5.4	7.4 (6.5)
Ic (A)	203	298	229	233	278	223	349
Iop/Ic	0.80	0.61	0.47	0.47	0.56	0.59	0.78
Inductance (H)	34.0	4.0	1.0	1.0	4.0	20.0	6.9

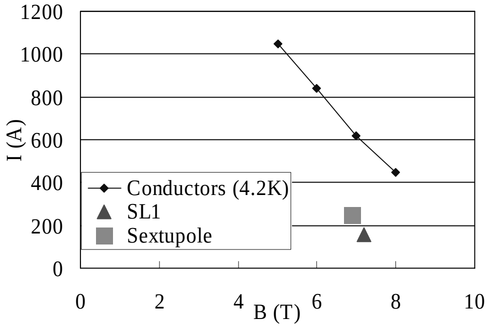

Figure 3: Ic performance of the conductor and the load points for the SL1 and the sextupole.

magnetic fields are 3.8 T at the RF injection side and 2.2 T at the beam extraction side. Four coils from SL2 to SL5 are used for introducing a flat magnetic field region between the mirrors. The sextupole magnetic field is 2 T on the inner surface of the plasma chamber (r = 75 mm). The sextupole field in the central confinement region is increased by using iron poles.

The coils use a NbTi-copper conductor and are bath-cooled in liquid helium. Parameters of the coils are shown in Table 1. The SL3 and SL4 use a conductor with a round shape of ϕ1.09 mm and a NbTi/Copper ratio of 6.5, while the other solenoids and the sextupole use a conductor with a rectangular shape of 0.82 mm x 1.15 mm and a NbTi/copper ratio of 1.3. A saddle form, which was adopted for each sextupole coil in the original design so as to fit a bore cylinder, has been changed to a flat shape to make the coil winding easy. Because this change decreases the sextupole magnetic field, the inscribed radius of the coils was reduced to 98.5 mm from 102 mm at the expense of the thickness of the vacuum insulation of the cryostat. Figure 3 shows the Ic performance of the conductor with a rectangular shape and the load points for the solenoid SL1 and the sextupole. Although the maximum field on the sextupole coil windings is 7.4 T, the component perpendicular to the current direction is 6.5 T.

SUPPORT STRUCTURE FOR SEXTUPOLE COIL

The sextupole coils are very difficult to design and fabricate because of the following reasons: the magnetic field on their windings is high, the magnetic force on them is strong and inhomogeneous, they are assembled from six long racetrack coils, and the inside space limited by a warm bore is narrow. The longitudinal distributions of the magnetic force acting on the straight region of the sextupole coils are shown in Fig. 4. Because the expansion magnetic force in the azimuth direction is generated by their self-field as well as the radial magnetic field of the solenoids, its magnitude changes according to the longitudinal position and the polarity of the sextupole coil. Especially, this magnetic force is strong in the region between the SL1 and the SL2 because these coils are excited with opposite polarities to each other and generate a strong magnetic field in the radial direction.

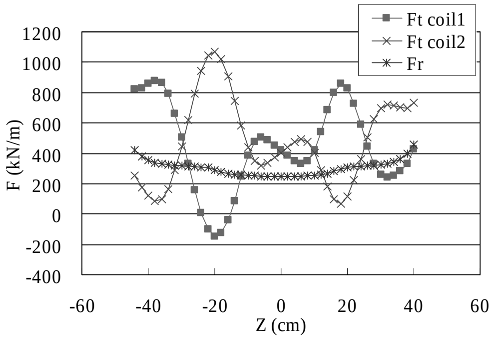

Figure 4: Magnetic forces acting on the sextupole coils. Fr and Ft indicate the force in the radial direction and the expansion force of a coil in azimuth direction. Coil1 and coil2 differ in terms of the polarity.

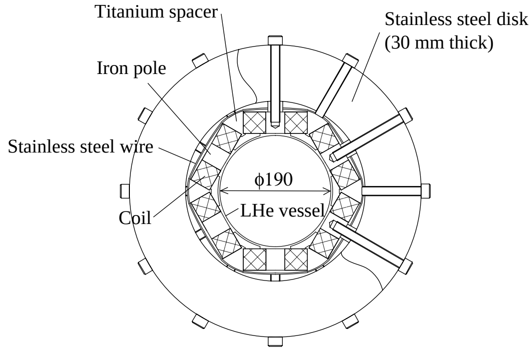

Figure 5: Cross section of the straight part of the sextupole coils. A 30 mm thick stainless steel disk is inserted between the SL1 and the SL2.

Figure 5 shows a cross section of the straight part of the sextupole (the part between the SL1 and SL2). The six sextupole coils are assembled using titanium spacers with a triangle cross section and fixed with four layers of ϕ0.65 mm stainless steel wires wound with very high tension of about 580 MPa. An iron pole of 330 mm in length is inserted in the central region of each coil to increase the sextupole field. A stainless steel disk with outer diameter of 250mm and a thickness of 30 mm are inserted between the SL1 and the SL2 to fix the sextupole coils more tightly because the magnetic force in the azimuth direction is strongest there. 3D calculations of the deformation of the coil assembly were performed with ANSYS [6]. The coils were treated as orthotropic material where the elastic coefficients are 97 GPa in the direction of conductors and 16 GPa in the orthogonal. Assuming that a shrinkage factor of the coils is 0.5% in the cooling down to the LHe temperature, the tension of the binding wire was calculated to decrease by 25% and the coils to shift inward by 0.16 mm at the maximum due to the remaining compressive force. When the magnetic force was given on the coils, the deformation and shear stress of

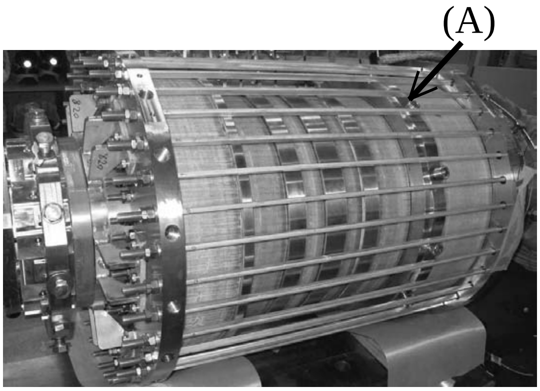

Figure 6: Photograph of the coil assembly. (A) is a 30 mm thick stainless steel disk inserted between the SL1 and the SL2.

the coils were calculated to be 0.03 mm and 7 MPa at the maximum, respectively, which are tolerable.

COIL CONSTRUCTION

Each of the six sextupole coils was dry-wound to work for turn transitions and was vacuum impregnated with epoxy. The percolation of the epoxy into the inside of the windings was inspected to be successful by cutting a trial winding. On the other hand, each solenoid coil was wet-wound with warm epoxy and cured. Figure 6 shows the final assembly of the sextupole coils and six solenoids. The ends of the sextupole coils are fixed with a stainless steel ring to support the large radial magnetic force acting on the current return sections. The six solenoids were assembled with stainless steel spacers and tightened with sixty-four long aluminium-alloy bolts that support a repulsive force of approximately 800 kN at the maximum among them.

Table 2. Coil currents (A) when the sextupole quenched.

run #	sextupole	SL1	SL2	SL5	SL6
design	272	162	182	155	132
1	189				
2	255				
3	90	136	183		
4	65	136	183		
5	73	136	183		
6	114	136	183		
7	70	136	183		
8	77	136			
9	109				132
10	220				92
11	204			155	132
12	230			132	112
13(NQ)	272				
14	258	146	164		
15	234			135	114
16	238			136	116
17	235	127	143		
18	256	137	154		

EXCITATION TEST

After the solenoid and sextupole coils were assembled into a final structure, the excitation tests were performed in a commonly used cryostat. Both ends of all coils of the solenoids and the sextupole were connected with clamp diodes placed in liquid helium for the quench protection.

First, all the solenoids were excited and tested one by one. Each coil achieved its design current without a quench. Next, the sextupole was tested. Table 2 shows the currents when a quench occurred in the sextupole. The sextupole also achieved the design current (271A) after two quenches (189A, 255A) when no solenoids were excited. In the combination tests in which the sextupole and one or two of the solenoids were excited at the same time, the sextupole quenched in all cases. The sextupole quenched at low currents ranging from 65 A (24%) to 115 A (42%) when the SL1 and the SL2 were excited at their design currents in advance (run #3~#7). The sextupole also quenched similarly when the SL6 was excited in advance (run #9, #11). A cause of these quenches was presumed to be a coil motion at the ends of the sextupole from the voltage signals observed in some of these runs. In run #10, the SL6 was ramped after the sextupole was excited at 220 A. In run #12 and #14~#17, the solenoids and the sextupole were excited simultaneously keeping a ratio of the currents so that the direction of the force acting on the sextupole coils did not change during the excitation. The quench current of the sextupole increased to more than 85% of the design value in this way. It, however, was difficult to reach the design current. We have thus concluded that it is necessary to reinforce the structure at the coil ends of the sextupole.

CONCLUSION

The superconducting coil assembly for the RIKEN SC-ECR ion source was constructed and the excitation test was performed. In the combination tests with the solenoids and sextupole, it was found that a quench occurred at approximately 85% of the design current. Causes for this are under investigation. After the improvement of the coil performance, the assembling of the cryostat for these superconducting coils will be started. A target date of the completion of the magnet system for the superconducting ECR ion source is October 2008.

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