14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPA123

ECR ION SOURCE WITH HIGH TEMPERATURE SUPERCONDUCTING REBCO COILS

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Abstract

High temperature superconductor REBCO has the property of maintaining a high critical current density under strong external magnetic field, which makes it a promising material for electromagnets in cyclotron and ECR ion source. Therefore, an ECR ion source using iron-less REBCO coils as electromagnet is under development in Research Center for Nuclear Physics (RCNP), Osaka University. A coil system with 4 circular solenoid coils and 6 racetrack sextupole coils was fabricated, and low-temperature performance tests in 77 K were carried out. The test results upon the stability and capability of magnet field induction will be presented in this work. The design of the ion source will also be discussed. Results yielded in this research will also be made the best use of the development of a skeleton cyclotron, a compact air-core cyclotron being developed in RCNP, which is also planned to use REBCO coils as electromagnets.

NON-INSULATION COILS WITH SUPER CONDUCTING REBCO TAPE

High temperature superconducting ECR ion source (HTS-ECR) uses non-insulation REBCO coil as electromagnets. REBCO tape ($REBa_2Cu_3O_{7-x}$, RE = rare earth), is a second generation superconductor, which has critical temperature T_c larger than 90 K. Also, it has the property of maintaining high critical current denisty under strong external magnetic field, as REBCO tape has critical current density J_c larger than 400 A/mm^2 under 20 T of external perpendicular magnetic field component [1].

Moreover, high critical temperature allows REBCO coil to be wound in Non-insulation fashion [2], accomplishing high current density and high thermal stability at the same time [3]. The comparion between non-insulation and insulation coil is shown in Fig. 1. Since non-insulation has no insulation layer, it has the advantage of higher current density and lower production cost. At the same time, with high critical temperature, current inside non-insulation REBCO coil can by-pass through stabilizer to avoid loacl hotspot without causing normal conducting state transition. This grants high thermal stability to non-insulation coils. With these advantages, non-insulation REBCO coils are expected to be ideal candidates as electromagnet for ECR ion source and cyclotron. HTS-ECR also use them as electromagnets.

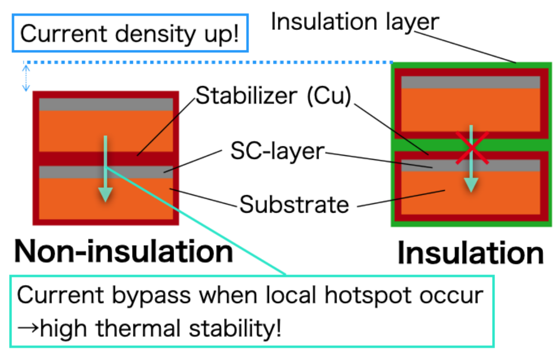

Figure 1: Comparison between non-insulation and insulation coil. Non-insulation winding allows coils to have high current density and thermal stability in the same time.

COIL ASSEMBLY OF HTS-ECR

HTS-ECR is an ion source with magnetic field inducted only by iron-less non-insulation REBCO coils. The coil assembly consisted of 6 racetrack sextupole coils and 4 circular solenoids, which are shown in Fig. 2.

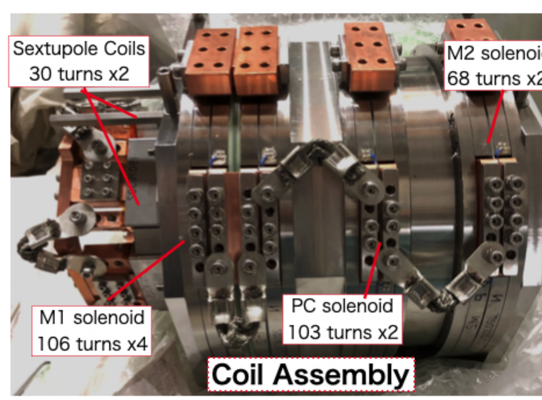

Figure 2: Coil assembly of HTS-ECR. Consisnted of 6 racetrack sextupole coils and 4 circular solenoids.

HTS-ECR will produce p$^+$, d$^+$ and He^{2+} beam, for the application of RI production, BNCT and targeted alpha-particle therapy. In order to accomplish larger thermal margin for stable operation, the operation temperature will be seted to 20 to 30 K, cooled by GM cryocooler. There will be two operation frequencies, which is 2.45 GHz for the produciton of p$^+$ and d$^+$, and 10 GHz for He^{2+}. Since HTS-ECR is

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also a key techonology development of an multi-function iron-less cyclotron, the multiple frequency feature can also examine the linear-adjustability of magnetic field induced by iron-less REBCO coils.

77 K PERFORMANCE TEST RESULT

Perfromances tests in 77 K has been carried out in order to examine the stable operation capability of the REBCO coils. In the performacne test, REBCO coil assembly is putted inside liquid Nitrogen (77 K), while the 4 solenoids and 6 sextupole coils are connected in two series respectively. When current is applied, the coils will suffer external magnetic field due to the other coils. The I-V characteristics of each sextupole coils is measured under different applied solenoid current, in order to examine their stability under different external magnetic field.

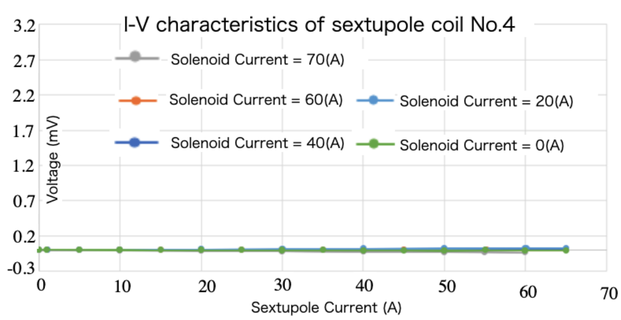

Figure 3: Low temperature test result of No.4 sextupole coil.

Figure 3 shows the the test result of the No.4 sextupole coil. The I-V characteristics of No.4 sextupole coil, under external magnetic field induced by solenoids with 0 A, 20 A, 40 A, 60 A and 70 A applied current, are shown in the figure. All the I-V characteristicc overlap with each other, implying that the external magnetic field, induced by current in solenoids up to 70 A, does not affect the electromagneitc characteristic of the sextupole coils. Also, there was no degeneration after multiple times of magnetic field induction. Simular result is obtained from other sextupole coils.

The voltage of the sextupole remains lower than 0.1 mV in the whole test. Since the criterion of normal conducting state transition is 10 V/cm, the criterion for the sextupole is 32 mV. Which means the induced voltage in the coil is lower than 1% of the criterion, under field of 70 A solenoid current. Conciderning that the lift factor of the used REBCO tape, $I_{c(20K,1T)}/I_{c(77K,\text{self field})}$, is approximately 5, the critical current of the sextupole coil is expected to be larger than 300 A in 20 K, under 1 T of external field. Critical current of 300 A is larger than the current required in practical operation. Therefore we conclude that the sextupole is capable of stable operation as an electromagnet of ECR ion source.

DESIGN OF HTS-ECR

Magnetic Field Design

The designed axial magnetic field of HTS-ECR is shown in Fig. 4. The green line is the field for 10 GHz operation mode, the blue line is the field for 2.45 GHz mode, and the dashed line is the ECR field of each frequency. Min-B configuration is used for both operation mode. The corresponding current for this magnetic field configuration in M1, PC, M2 solenoid and sextupole coil is 500 A, -420 A, 550 A and 250 A for 10 GHz operation, and 101.8 A, -66.6 A, 103 A and 250 A for 2.45 GHz operation, respectively.

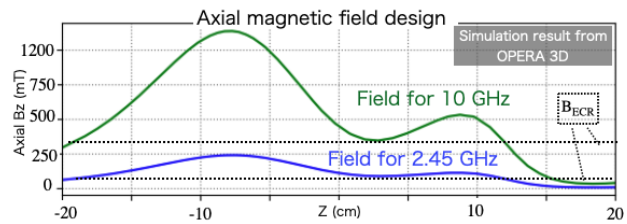

Figure 4: Axial magnetic field designed for HTS-ECR. Min-B configuration is used for both frequency mode.

We designed high magnetic field peak in the injection end in order to avoid R-wave cut-off [4]. R-wave, the principle wave of microwave inside magnetized plasma which corresponds to the ECR effect, have a cut-off criterion as shown in Eq. (1).

$$\omega = \frac{(\omega_{ce} + \sqrt{\omega_{ce}^2 + 4\omega_{pe}^2})}{2} \tag{1}$$

In Eq. (1), ω is the frequency of the input microwave, ω_{ce} is the electron cyclotron frequency, and ω_{pe} is the plasma frequency. By keeping magnetic field B always larger than B_{ECR} at the injection end, the R-wave cut-off criterion will never be met, therefore ionization can occur effectively. Furthermoer, by putting ECR zone at the bottom part of the field configuration, maximum energy gain of electron can be expected [5].

Extraction Electrode Design

The design of extraction electrode is done by using simulation code IGUN. The simulation result is shown in Fig. 5.

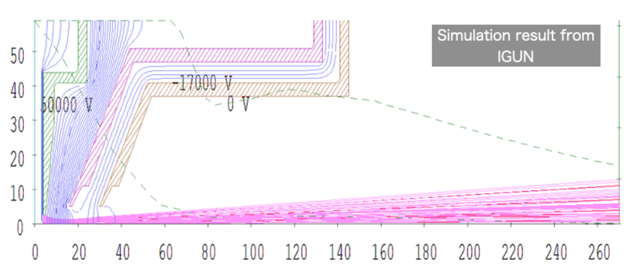

Figure 5: Beam extraction simulation result using IGUN. 40 mA of Helium beam can be extracted with efficiency of 100%.

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The designed electrode has a accel-decel arrangement, with 3 electrodes having voltage of 50 kV, -17 kV and 0 V respectively. By assuming 40 mA of Helium beam from plasma electrode, which is one of the highest Helium beam intensity that can be expected from an ECR ion source [6], the beam can be extracted with efficiency up to 100%, with RMS emittance being 20 mm mrad. By assuming 20% of the Helium beam being He^{2+}, 8 mA of He^{2+} beam can be extracted by using this electrode design. This current density will fulfil our goal of producing high density He^{2+} beam for the application of targeted alpha-particle therapy. Also, the maximum electric field on the electrode is 100 kV/cm, which is an amount that will not cause discharge on the electrode.

CONCLUSION

An ECR ion source, with high temperature superconducting non-insulation REBCO coil, is under development in RCNP, Osaka University. By using REBCO coil, the electromagnet is expected to have high critical current density under high external magnetic field. Also, non-insulation winding techgnique allow REBCO coil to have high current density and high thermal stability in the same time.

Coil assembly consisted of non-insulation REBCO coils has been manifatured, and performance test at 77 K on the coil assembly has been carried out. The test result shows that the I-V characteristics of the coils remain the same under external magnetic field, and the induced voltage is lower than 1% of the normal conducting state criterion. Therefore we concluded that the coil assembly is capable of stable operation.

Magnetic field configuration and extraction electrode for HTS-ECR are also designed. The magnetic field maximize the electron energy gain from microwave, while the electrode shown 100% extraction efficiency of 40 mA Helium beam in the IGUN simulation. Therefore we expect that high intensity beam can be produced by HTS-ECR with these design.

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