| | |
|---|---|
| Title | Test of High Temperature Superconducting REBCO Coil Assembly for a Multi-Frequency ECR Ion Source |
| Author(s) | Chong, Tsun Him; Fukuda, Mitsuhiro; Yorita, Tetsuhiko et al. |
| Citation | IEEE Transactions on Applied Superconductivity. 2024, 34(5) |
| Version Type | AM |
| URL | https://hdl.handle.net/11094/96481 |
| rights | © 2024 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. |
| Note | |

# Test of High Temperature Superconducting REBCO Coil Assembly for a Multi-Frequency ECR Ion Source

Tsun Him Chong, Mitsuhiro Fukuda, Tetsuhiko Yorita, Hiroki Kanda, Shigeo Nagaya, Atsushi Ishiyama, So Noguchi, Hiroshi Ueda, Satoshi Fukui, Tomonori Watanabe, Jun Yoshida, Takashi Hirayama, Yukio Mikami, Yuji Matsubara and Takashi Kitamura

Abstract—High temperature superconducting REBCO tape has the characteristic of maintaining high critical current density under strong external magnetic field, which makes it an ideal material for the construction of air-core electromagnets of accelerator and electron cyclotron resonance (ECR) ion source. In Research Center for Nuclear Physics, Osaka University, a non-insulated air-cored REBCO coil assembly has been constructed. This coil assebmly consists of three circular REBCO solenoid and six racetrack REBCO coil. This coil assembly will be used as an electromagnet of a multi-frequency ECR ion source, and is also developed as a key technology development of an air-core cyclotron. The magnetic field of this ion source are designed, and 77K performance tests of the assembly are carried out in order to examine the capability of REBCO coils of inducing magnetic field under external field. In this work, the test results and the magnetic field designed for the ECR ion source will be presented and discussed.

Index Terms—HTS-magnet, REBCO, Ion Source.

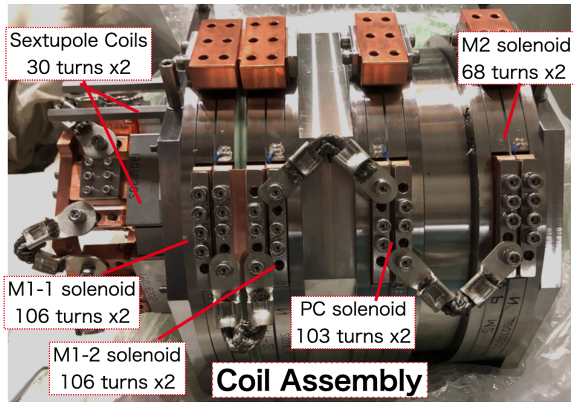

Fig. 1. Coil assembly of HTS-ECR.

## I. Introduction

MAGNETIC field and RF wave is required for ECR ion source to confine electron and produce high charge ion beam. With stronger magnetic field, ECR ion source are expected to be capable of producing higher charge and higher intensity ion beam [1]. While there is project that use low temperature superconducting (LTS) magnet for the next generation ECR ion source [2], non-insulated REBCO magnet can also be a promising candidate to provide strong magnetic field. With its high heat stability [3] and high critical current density under strong external magnetic field [4], stable-operation high intensity ECR ion source can be achieved. However, the fabrication technique of non-insulated REBCO magnet is not mature yet, and further study of its electro-magneitc characteristics and stability is necessary. Therefore, a High Temperature Superconducting ECR ion source (HTS-ECR) is under development in Research Center for Nuclear Physics(RCNP), Osaka University. HTS-ECR uses a non-insulated air-cored REBCO coil assembly as electromagnet, which consists of 3 solenoids and 6 racetrack sextupole coils. HTS-ECR is also an key technology development for skeleton cyclotron [5], an air-cored cyclotron which is also under development at RCNP. In the development of HTS-ECR, the non-insulation air-cored REBCO coils' performance under complicated configuration external field are investigated.

## II. Design and coil configuration of HTS-ECR

HTS-ECR uses three REBCO solenoids and six racetrack sextupole REBCO coils as electromagnet. Both solenoids and racetrack coils are non-insulated, and have double pancake structure. The fabricated and assemblied coils are shown in Fig. 1. From the injection end, the 3 solenoids are called M1-1, M1-2, PC and M2 solenoid. The turn numbers of each coil are also specified in the figure. The three solenoids will induce magnetic filed for electron confinement in axial direction, and the 6 sextupole coils will induce magnetic field for radial direction electron confinement.

The specification of HTS-ECR is shown in Table. I. The solenoids have bore diameter of 190 mm and outer

T. H. Chong, M. Fukuda, T. Yorita, H. Kanda and S. Nagaya are with the Research Center for Nuclear Center, Osaka University, Osaka 567-0047, Japan(email:oscar@rcnp.osaka-u.ac.jp).

A. Ishiyama is with the Department of Electrical Engineering and Bioscience, Waseda University, Tokyo 169-8555, Japan.

S. Noguchi is with the Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan.

H. Ueda is with the Okayama Universty, Okayama 700-8530 Japan, Japan.

S. Fukui is with the Niigata University, Niigata 950-2181, Japan.

T. Watanabe is with the Chubu Electric Power Co., Inc., Aichi 461-8680, Japan.

J. Yoshida, T. Hirayama, Y. Mikami and Y. Matsubara are with the Sumitomo Heavy Industries Ltd., Kanagawa 237-8555, Japan.

T. Kitamura is with the Hagoromo Electric Inc., Osaka 593-8327, Japan.

TABLE I
Specification of HTS-ECR

| | |
|---|---|
| Solenoid bore diameter | ∼ 190 mm |
| Solenoid outer diameter | ∼ 220 mm |
| Racetrack coil length | ∼ 240 mm |
| Racetrack coil bend radius | ∼ 25 mm |
| Particle type | $H^+$, $D^+$ and $He^{2+}$ |
| Operation Temperature | 20 ∼30 K |
| Cooling | GM cryocooler |
| RF frequency | 2.45 GHz and 10 GHz |

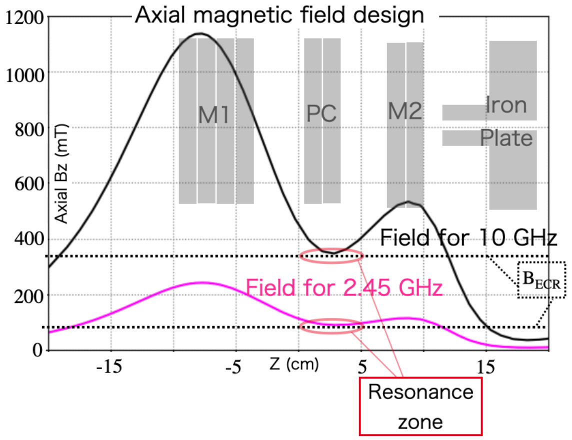

Fig. 2. Designed axial magnetic field for HTS-ECR.

TABLE II
Required current of each coil for magnetic field induction.

| | 10 GHz mode | 2.45 GHz mode |
|---|---|---|
| M1 solenoid | 500 A | 101.8 A |
| PC solenoid | -420 A | -66.6 A |
| M2 solenoid | 550 A | 103 A |
| Sextupole coil | 250 A | 250 A |

diameter of 220 mm. The racetrack coils have length of 240 mm in the axial direction, and bend radius of 25 mm in both end. The particle type of the beam is designed to be $H^+$, $D^+$ and $He^{2+}$, for the application of medical RI production. In order to examine the REBCO coils' capability of inducing varient magnetic field configuration, HTS-ECR will have two RF operation frequency as 2.45 GHz and 10 GHz.

## III. Magnetic Field of HTS-ECR

### A. Designed Magnetic Field

Magnetic field for HTS-ECR is designed and shown in Fig. 2. The required current of each coil are shown in Table. II.

In Fig. 2, pink line is the axial field for 2.45 GHz operation, black line is the field for 10 GHz operation mode. Dashed line is the resonance field $B_{\mathrm{ECR}}$ for each mode. ECR effect is expected to occur where magnetic field met the resonance field, and electron would gain energy from the inputed RF wave. This region is shown as resonance zone in Fig. 2. Mini-B configuration will be used for both 2.45 GHz and 10 GHz operation mode [6]. M1 and M2 solenoid will produce strong field on the injection and extraction end, where PC solenoid will be used to adjust the minimum field at the center. An iron plate is placed at the extraction end to decrease the magnetic field magnitude on the down stream, in order to maintain a low beam emittance. In Fig.2, the ECR zone is placed at the bottom part of the magnetic field, in order to maximize the electron energy gain [7]. Also, in a magnetized plasma, including ECR ion source, input RF wave may be cut off due to its dispersion relation inside the plasma. In order to deliver sufficient energy to the resonance zone and produce high intensity beam, it is critical to avoid RF wave cut-off in ECR ion source. Especially for the R-wave, which is the principle wave corresponding to the ECR effect. [8] The R-wave cut-off criterion is given as below.

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

In Eq. 1, $\omega$ is the angular frequency of the inputed RF, which is proportional to the resonance field $B_{\mathrm{ECR}}$. $\omega_{\mathrm{ce}}$ is the electron cyclotron frequency, which is proportional to the magnetic field $B$. $\omega_{\mathrm{pe}}$ is the plasma frequency, which is porportional to the electron density. The designed field in Fig. 2 has magnetic filed $B$ larger than $B_{\mathrm{ECR}}$ everywhere inside the plasma chamber, which makes $\omega_{\mathrm{ce}}$ always larger than $\omega$. Therefore R-wave cut-off criterion will never be met, and HTS-ECR is expected to be capable of high intensity beam production.

### B. Magnetic Field on REBCO coils.

In order to induced the designed magnetic field, REBCO coils in HTS-ECR need to be applied with high current density under strong external magnetic field. Magnetic field, especially field component that is perpendicular to the HTS tape surface, will limit the critical current density of the coil [9]. Therefore, magnetic field amplitude on the coil surface is investigated in order to ensure that the REBCO coils are capable of producing the designed field. The analysis is done by using OPERA-3D, a simulation software with finite element method. In the simulation, an iron plate is placed at the down stream of the coil assembly, and the coil assembly is set to be surrounded by vacuum.

The magnetic field on coil surface in 10 GHz operation mode is shown in Fig. 3. In Fig. 3, the iron plate has the highest magnetic field magnitude on its surface. Among the coils, M1 solenoid has the highest surface magnetic field with $|B_{\mathrm{max}}| \sim 3000$ mT. This is due to the magnetic field peak at the injection end.

The magneitc field on M1 solenoid and sextupole are further investigated. The result is shown in Fig. 4.

In Fig. 4, the magnitude of the magnetic field is shown. Also, magnitudes of the perpendicular field component $B_\perp$ on some characteristic spot of the coil are also shwon in number. For M1 solenoid, the inner side of the coil has the strongest $|B|$. However, for perpendicular magnetic field component, the edge of the outter side of the coil

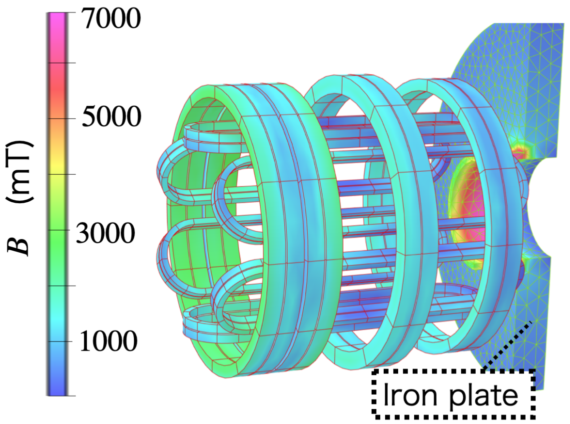

Fig. 3. Magnetic field magnitude on coils and the iron plate in 10 GHz operation mode.

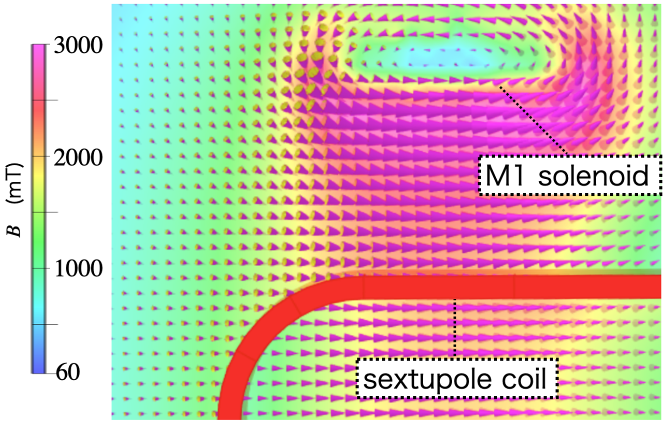

Fig. 5. Magnetic field vector around M1 solenoid and sextupole.

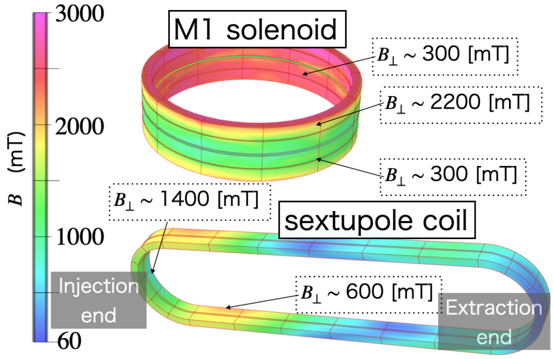

Fig. 4. Magnetic field magnitude on M1 solenoid and sextupole coil in 10 GHz operation mode. Magnitude of magnetic field component that is perpendicular to the tape surface is also shown in number.

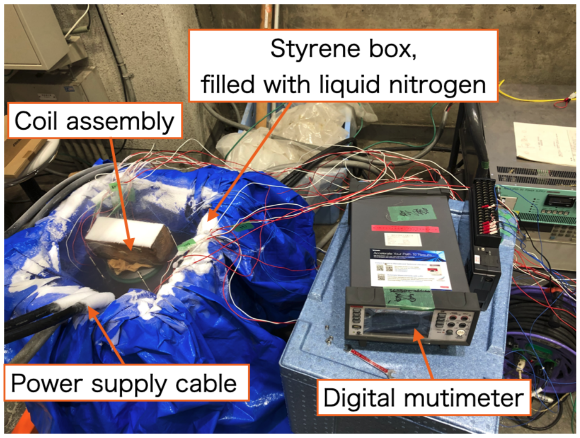

Fig. 6. Setup of performance test in 77 K. The coil assembly is put inside a styrene box and submerged in liquid nitrogen.

suffers the strongest $B_\perp$. The maximum $B_\perp$ is about 2200 mT. For sextupole coil, the injection side suffer strongder external magnetic field. The $B_\perp$ on the straight part of the racetrack coil is around 600 mT, while the strongest $B_\perp$ is on the curved part, which is around 1400 mT.

The magnetic field around M1 solenoid and sextupole coil is shown in vector form in Fig. 5. Figure 5 shows that the magnetic field which sextupole coils are suffering, is mostly induced by M1 solenoid. In the meantime, field that M1 solenoid suffers is mostly due to its self field. Therefore, we conclude that the critical current of the sextupole coils are limited by the peak field at the injection. In other words, the radial direction magnetic field in HTS-ECR is limited by the axial peak filed on the axial direction.

## IV. Performance Test in 77 K

Performance tests were done in order to investigate the coils' critical current under external magnetic field. The setup of the performance test is shown in Fig. 6. In the test, the coil assembly is put inside a styrene box and submerged in liquid nitrogen, in order to create a 77 K enviroment. Two power supply is used in the test. One is used to apply current to one of the sextupole coil (SC6). Another power supply is used to apply current to M1-2, PC and M2 solenoid in series. Digital multimeter (Keithley, DMM6500) is connected to the two end of each coil in order to measure the induced voltage. During the test, current is applied to M1-2, PC and M2 coil as back ground, so that SC6 would suffer magnetic field induced by the solenoids. With this set up, current is applied to SC6, and its I-V characterstics under external magnetic field was measured.

The test result is shown in Fig. 7. Figure 7 shows the I-V characteristics of SC6 while solenoids are applied with current of 0 A, 30 A, 60 A, 90 A and 120 A. The external magnetic field dependency can be seen in the result, where under a stronger external field the coil voltage increase with lower applied current. The magnetic field on SC6 in each case is also calculated. When 75 A of current is applied to SC6, with current of 0 A, 30 A, 60 A, 90 A and 120 A in solenoids, the maximum $B_\perp$ on SC6 was about 100 mT, 115 mT, 130 mT, 150 mT and 160 mT respectively.

The $n$ value of the coil is also shown in Fig. 7. With solenoids current of 0 A and 120 A, the $n$ value was about 21.4 and 24.4 respectively. With the phase transition criterion as 10 $\mu$V/cm, the criterion for SC6 is 32 mV.

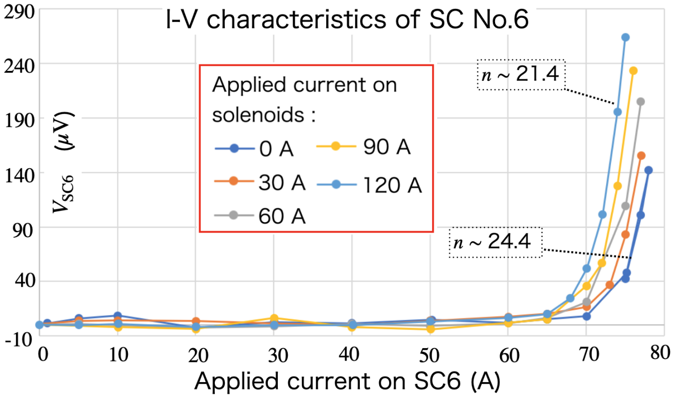

Fig. 7. I-V characteristic of sextupole coil No. 6. Different color line stands for result with different current applied on M1-2, PC, M2 solenoid.

Evaluated from the $n$ value, with 0 A and 120 A current in solenoids, the critical current of SC6 is 97.5 A and 94.5 A, respectively.

Since the tape used in the coil has a lift factor = 4 (20 K, 2.5 T/ 77K, s.f.) [10], the critical current for SC6 in 20 K operation is around 390 A, which is higher than the required current 250 A for the designed field. Therefore, we concluded that the sexdtupole coil we fabricated is capable of inducing the field for a high performance ECR ion soruce.

Performance test result of disassembled coil can be found in the refernce [11].

## V. Summary

Non-insulated air-cored REBCO coils were fabricated and assembled as an electromagnet for HTS-ECR. It consists of 3 solenoids and 6 racetrack sextupole coils. The coil assembly will produce magnetic field for 2.45 GHz and 10 GHz ECR ion source operation. Magnetic field was designed for the ion source, and the solenoids and sextupole coils are expected to suffer maximum $B_\perp$ of 2200 mT and 1400 mT in 10 GHz operation mode.

In the performance, the I-V characteristics of sextupole coil No.6 under external field was measured. From the test result, the critical current of the sextupole coil in 77 K is evaulated as 97.5 A in self field, and 94.5 A in maximum 160 mT of $B_\perp$. With the lift factor of the tape, the sextupole coil is expected to have a critical current higher than the required current for HTS-ECR in 20 K, 2.5 T enviroment.

In the future, coil assembly performance test in 20 K enviroment will be done. The magnetic field induced by the coil assembly will also be measured, in order to investigate the magnetic field stability and accuracy.

## References

[1] S. Gammino and G. Ciavola,"The role of microwave frequency on the high charge states buildup in the ECR ion sources". Plasma Sources Sci. Technol. 5, 1927 (1996). DOI:10.1088/0963-0252/5/1/002.

[2] T. Thuillier el at,"Prospect for a 60 GHz multicharged ECR ion source". Rev. Sci. Instrum. 89, 052302, (2018). DOI:10.1063/1.5017113.

[3] T. Wang el at,"Analyses of Transient Behaviors of No-Insulation REBCO Pancake Coils During Sudden Discharging and Overcurrent". IEEE Transactions on Applied Superconductivity, 25, no. 3, pp. 1-9, 4603409 (2015). DOI: 10.1109/TASC.2015.2393058.

[4] V. Bracciniel at "Properties of recent IBAD–MOCVD coated conductors relevant to their high field, low temperature magnet use." Supercond. Sci. Technol. 24 035001 (2011). DOI: 10.1088/0953-2048/24/3/035001.

[5] H. Ueda el at,"Conceptual Design of Next Generation HTS Cyclotron". IEEE Transactions on Applied Superconductivity, 23, no. 3, pp. 4100205-4100205, 4100205 (2013). DOI: 10.1109/TASC.2012.2232955.

[6] Ian G. Brown, The Physics and Techonology of Ion Sources. Wiley-VCH Verlag GmbH & Co. KGaA, 2004.

[7] R. Geller, Electron Cycloyton Resonance Ion Sources and ECR plasmas. Institute of Physics Publishing, 1996.

[8] M. A. Liberman and A. J. Lichtenberg, Priciples of Plasma Discharges and Materials Processing. Wiley Interscience, 2005.

[9] T. Benkel, Y. Miyoshi, X. Chaud, A. Badel and P. Tixador. . "REBCO tape performance under high magnetic field". The European Physical Journal Applied Physics. Vol. 79, 2017. DOI: 10.1051/epjap/2017160430.

[10] Faraday Factor product data: https://www.faraday-group.com/en/product/

[11] T. H. Chong, el at,"Development of ECR ion source with high-temperature superconducting REBCO coils". J. Phys.: Conf. Ser. 2244, 012108. DOI:10.1088/1742-6596/2244/1/012108.