# DEVELOPMENT OF HIGH TEMPERATURE SUPERCONDUCTING ECR ION SOURCE USING REBCO COILS

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### *Abstract*

A High Temperature Superconducting ECR ion source (HTS-ECR) using REBCO coils is under development in Research Center for Nuclear Physics (RCNP), Osaka University. REBCO tapes are the second-generation high temperature superconductor, which maintains a high critical current even being placed in a strong external magnetic field. Using this REBCO coils as electromagnets, the HTS-ECR was designed to operate at microwave frequencies of 2.45 GHz and 10 GHz, for the purpose of propducing high intensity proton, deuteron and helium beams. In this work, the low-temperature perfromance test results of the REBCO coils will be presented. The coil system and plasma chamber designed for the HTS-ECR 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 which is under development in RCNP, Osaka University.

## REBCO COILS IN HTS-ECR

### *Electromagnet using REBCO Tape*

REBCO ($REBa_2Cu_3O_{7-x}$, RE=rare earth) is a second generation high temperature superconducting material, which has critical temperature $T_c$ higher than 90K. It also remain high critical current dendity even being placed in a strong external magnetic field. Under 20 $T$ of external perpendicular magnetic field component, REBCO's critical current density remain larger than 400 A/mm$^2$ [1].

For its capability to carry high current under strong external magnetic field, REBCO tape is a promising material to construct iron-less electromagnet for cyclotron and ion source. An iron-less electromagnet, which has no hysteresis property, will permit quick adjustment on the magnetic field configuration according to the objective of the operation. An High Temperature Superconducting ECR ion source (HTS-ECR), which use only REBCO coils to induce magnetic field, is under development at Research Center for Nuclear Physics (RCNP), Osaka University. Results yielded in this research will also be made the best use of the development of a skeleton cyclotron [2]. a compact air-core cyclotron which is also under development in RCNP.

### *HTS-ECR*

HTS-ECR has 4 circular REBCO solenoids and 6 racetrack sextupole coils to induce axial magnetic mirror field and sextupole field respectively. Figure 1 shows the coil assembel of HTS-ECR. Starting from the injection end, solenoid coils are called M1, PC and M2 solenoids, which has 106 turns two double pancakes, 103 turns double pancake and 68 turns double pancake configuration respectively.

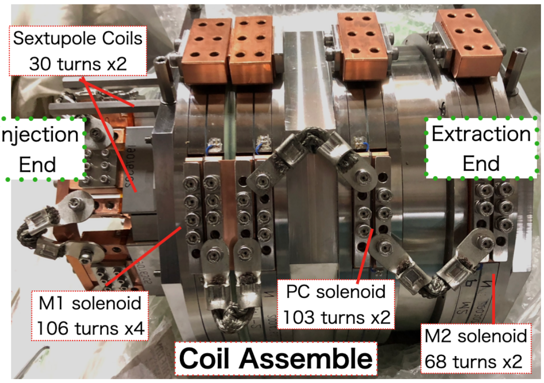

Figure 1: Coil assemble of HTS-ECR.

Specifications of HTS-ECR is shown in Table 1. HTS-ECR will provide high intensity proton, deuteron and He$^{2+}$ to applications like RI production, BNCT and Targeted Alpha-particle Therapy. Although REBCO has critical temperature higher than 90K, HTS-ECR are designed to operate in 20~30 K, with large thermal margin to pursue stable operation. Also, in order to examine the adjustability of magnetic field configuration induced by REBCO coils, HTS-ECR are designed to operate at frequency of 2.45 GHz and 10 GHz.

## LOW TEMPERATURE PERFORMANCE TEST ON REBCO COIL ASSEMBLE

The REBCO coils' capabilities of inducing magnetic field with high stability and reproducibilty in seperate operation

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Table 1: HTS-ECR Specifications

| **Paramter** | **Value** |
|---|---|
| Particle Type | $p^+$, $d^+$ and $He^2$+ |
| Cooling System | GM cryocooler |
| Operation Temperature | 20 ~ 30 K |
| Extraction Vlotage | 50 kV |
| Operation Frequency | 2.45 GHz and 10 GHz |

are reported in previous work [3]. However, external magnetic field tends to limit the critical current density and stability of superconducting coils. Therefore, low temperature performance test on the coil assemble are carried out. In this case, REBCO coils are subjected to the magnetic field produced by each other.

In the low temperature performance test, the coil assemble is putted into liquid Nitrogen (77K). 3 solenoid coils are arranged to be in one series, and 6 sextupole coils another series. Currents are applied to the solenoid and sextupole coil series independently, while voltage of coils were measured by digital multimeters(KEITHLEY, DMM6500). The test result of M2 solenoid and sextupole coil No.1~3 are shown in Figs. 2 and 3.

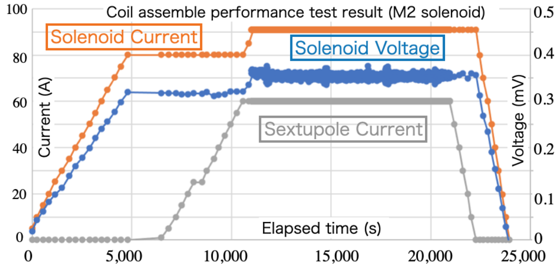

Figure 2: Voltage of M2 solenoid during 77 K coil assemble performance test.

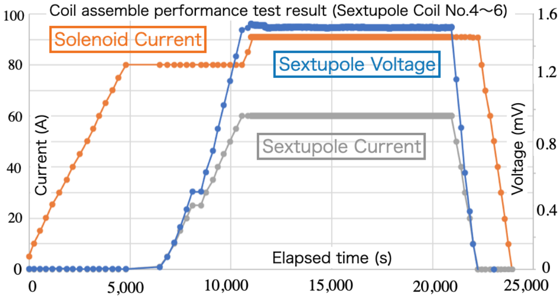

Figure 3: Voltage between sextupole No. 1~3 during 77 K coil assemble performance test.

In Fig. 2 and 3, applied current in solenoids was first increased from 0 A to 80 A, then current in sextupoles was increased from 0 A to 60 A, and current in solenoids was finally increased from 80 A to 90 A. Voltage of M2 solenoid increased proportional only to the current in the solenoids series,and sextupole coils voltage increased proportional only to the sextupole current. This result implys that the voltage increases is due to the normal conducting part in the coil assemble, and there was no normal conducting state transition in the whole process. There was no degeneration on the coil properties due to the external magnetic field.

Voltage in both coils remain the same at elapsed time from 11,000 s to 22,000 s, implying that both coils have good stability under external magnetic field. Similar results are also obtained from the other coils. Since the performance test lasted for 7 hours, the coil assemble proved its capability of hours long operation as an electromagnet.

## MAGNETIC FIELD CONFIGURATION DESIGN

### *Magnetic Field Configuration of HTS-ECR*

Magnetic field required for high-performance ion source are designed, and it will be provided by the REBCO coil assemble. Figure 4 shows the designed magnetic field configuration of HTS-ECR for 10 GHz and 2.45 GHz operation.

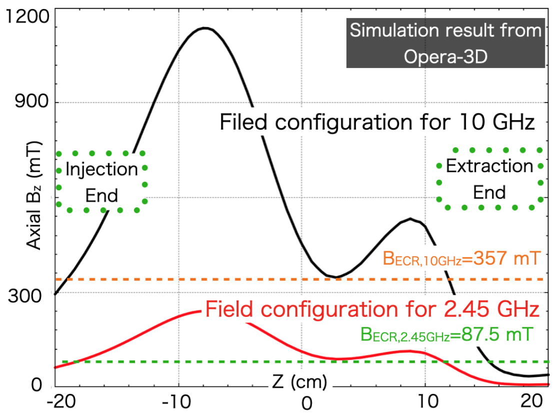

Figure 4: Magnetic field configuration of HTS-ECR.

Figure 4 shows the calculated axial magnetic field on the center of the coil assemble. Mirror field will be used in both 2.45 GHz and 10 GHz operation. In order to provied this configuration, for 10 GHz operation, currents in M1, PC, M2 and sextupole coils are 500 A, -580 A, 500 A and 250 A respectively. For 2.45 operation, it is 101 A, -66.6 A, 103 A and 250 A.

### *Design Concept*

There are two objective in the magnetic field design in Fig. 4. It is to avoid the microwave cut-off, and to maximize the electron energy gain from ECR effect.

**Avoiding R-wave Cut-off** Inside a magnetized plasma, microwave can be interpreted by four principle waves, which are R-wave, L-wave, O-wave and X-wave [4]. Only R-wave corresponds to the ECR effect, and it is critical to let R-wave propogate to the resonance zone. However, R-wave is cuted-off when the below creterion is met, and the ion source performance will be limited.

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

In Eq. (1), $\omega$ is the angular frequency of the input microwave, $\omega_{\mathrm{pe}}$ the plasma frequency, and $\omega_{\mathrm{ce}} = qB/m$ the electron cyclotron frequency. In order to avoid R-wave cut-off, $\omega_{\mathrm{ce}} > \omega$ must be satisfied everywhere inside the plasma chamber except for the resonance zone. Since $\omega_{\mathrm{ce}}$ is proportional to magnetic field magnitude $B$ and $\omega$ is proportional to the resonance field $B_{\mathrm{ECR}}$, the criterion to avoid R-wave cut-off can be written as $B > B_{\mathrm{ECR}}$. For this reason, magnetic field in Fig. 4 has magnetic field magnitude larger than the resonance field everywhere in the plasma chamber, in order to avoid R-wave cut-off and to maximize the ion source perfromance.

**Maximizing Electron Energy Gain** Inside an ECR ion source, electrons gain energy at the resonance zone, where $B = B_{\mathrm{ECR}}$. The energy gain is proportional to the square of the electric field magnitude, and the reverse of the gradient of the magnetic field. It can be writted as Eq. (2) [4].

$$W \propto E^2/(\Delta B/\Delta z) \tag{2}$$

In Eq. (2),$W$ is the electron energy gain, $E$ the electric field magnitude, and $(\Delta B/\Delta z)$ the gradient of the magnetic field. By putting the resonance zone at the bottom of the mirro field, as we do in Fig. 4, the gradient of magnetic field $\Delta B/\Delta z$ is almost zero. Therefore electron energy gain will be maximized.

## PLASMA CHAMBER DESIGN

### *Chamber Dimension*

A plasma chamber that can be used for both 10 GHz and 2.45 GHz operation is designed. In order to obtain large electromagnetic field magnitude, a standing wave is required inside a plasma chamber. The criterion of constructing a stangind wave inside a cylindrical chamber is shown below.

$$f_{mnp} = \frac{c_0}{2\pi}\sqrt{\left(\frac{j'_{mn}}{r}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \tag{3}$$

where $f_{mnp}$ is the frequency of the input microwave, $r$ is the radius of the chamber, $d$ is the length of the chamber, $j'_{mn}$ is the zeroes of the derivatives of Bessel function. $m, n, p$ is the index to distinguish the mode of the standing wave. When Eq. (3) is satisfied, a large magnitude of electromagnetic field can be obtained.

In order to change the operation mode between 10 GHz and 2.45 GHz without changing the plasma chamber, we decided to desgin a plasma chamber that create standind wave in both operation frequency. Through numerical analysis on Eq. (3), the required radius and length of a chamber is obtained. The result of the numerical analysis is shown in Fig. 5.

In Fig. 5, lines with different color represent dimensions of chamber that satisfy the standing wave criterion Eq. (3) with different operation frequency. The overlaps of two lines represent dimensions that are able to create standing wave in both 10 GHz and 2.45 GHz. Therefore, according to the result in Fig. 5, the plasma chamber of HTS-ECR is decided to be 38 mm in radius, 184.5 mm in length.

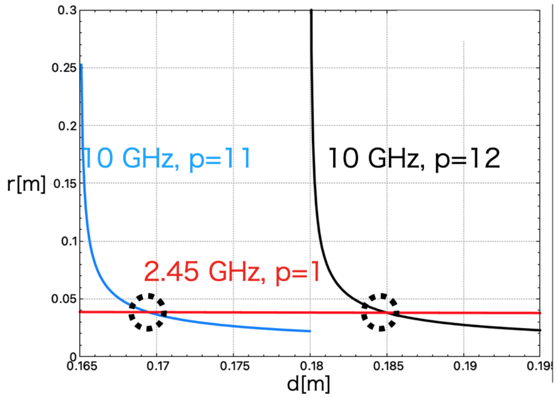

Figure 5: Numerical analysis result of Eq. (3). The overlaps of two lines imply a chamber dimension that can create standing wave in both 10 GHz and 2.45 GHz operation.

### *Energy Gain inside the Designed Plasma Chamber*

By using simulation software Ansys-HFSS, electromagnetic field that can be created inside the designed chamber are calculated. The results are shown in Figs. 6 and 7.

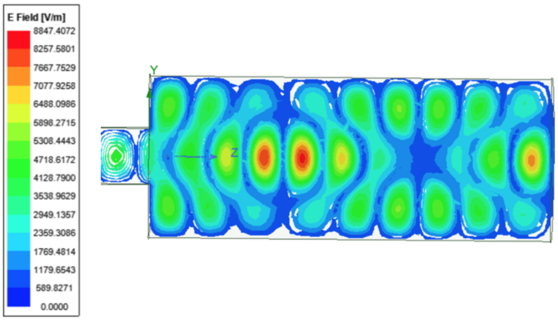

Figure 6: Magnitude of electric field that can be created inside the designed chmaber in 10 GHz operation, with 1 W input.

According to Cannobio's Theory [5], the maximum energy that electrons can gain can be written as below.

$$W_{\mathrm{max}} = 1.5 \times 10^9 \left(\frac{E(\mathrm{Vcm}^{-1}}{\omega}\right) \tag{4}$$

According to Eq. (4), with 18 W microwave input, the designed plasma chamber can provide electron with maximum energy of 12 keV for 10 GHz and 30 keV for 2.45 GHz operation. Since ionization energy of proton and $\mathrm{He}^{2+}$ is 14 eV and 54 eV, it is expected that the designed chamber can provide sufficiently strong electric field for effective ionization.

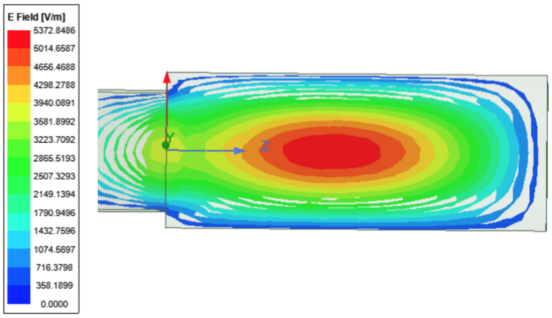

Figure 7: Magnitude of electric field that can be created inside the designed chmaber in 2.45 GHz operation, with 1 W input.

## CONCLUSION

An high temperature superconducting coil assemble for an ECR ion source is constructed. The magnetic field configuration and plasma chamber for the ECR ion soruce is also designed.

The coil assemble is made by iron-less REBCO solenoid and sextupole coils. It showed high stability in the 77 K performance test, and the capability of operating for 7 hours without degeneration occuring on the coil property. The magnetic field configuration is designed based on the mode theory of magnetized plasma, to avoid R-wave cut-off and maximize the electron energy gain. A plasma chamber that can be used in both 2.45 GHz and 10 GHz operation is also designed. The electromagetic field that can be constructed inside the chamber is sufficient for effective ionization.

As future work, performance test on the magnetic field inducing ability of the coil assemble will be done. Also, performance test at the operation temperature, 30 K, is also necessary. The cryostat for 30 K operation is under development, and is expected to be completed in the next year.

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