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Fabrication of a Nb-Ti Superconducting Closed-loop Coil for the Next-generation 45 GHz ECR Ion Source MARS-D

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[1] ***Abstract*—Electron Cyclotron Resonance Ion Sources (ECRISs) that utilize Nb-Ti superconducting coils for 28 GHz frequencies have been operating effectively for over twenty years. However, transitioning to higher frequencies demands stronger magnetic fields, and the conventional racetrack-and-solenoid ECRIS structures have reached their maximum capability with Nb-Ti. To address this, a Mixed Axial and Radial field System Demonstrator (MARS-D) is being developed at Lawrence Berkeley National Laboratory (LBNL). This system features an innovative Closed-Loop Coil (CLC) design that optimizes the use of the conductor fields, enabling the application of Nb-Ti in the next-generation 45 GHz ECRISs. The fabrication of the hexagonal CLC is particularly challenging due to its complex winding path and shape, the stiffness of the Nb-Ti superconducting wire, and the small bending radius. To address these challenges, a series of unique fixtures and tools, as well as a pre-over-bending method, were developed for winding the CLC. To validate the winding fixtures, tools, procedures, and materials used in the coil assembly, a 4-layer practice CLC was wound, epoxy-impregnated, and then cold-tested using liquid nitrogen. The full-size MARS-D CLC is in the process of winding. This paper presents the structure of the MARS-D CLC, the winding fixtures and tools, the winding procedures, the quality control, the impregnation, the test results, and the potential future improvements.**

***Index Terms* — ECR ion sources, magnet structure, superconducting magnets.**

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I. INTRODUCTION

The current Electron Cyclotron Resonance Ion Sources (ECRISs), constructed with Nb-Ti wires, have achieved an axial magnetic field of 4.0 T and a radial field of 2.0 T, supporting operating frequencies up to 28 GHz and utilized approximately 90% of the critical current of the Nb-Ti wire [1-7]. The next generation of ECRISs will be designed to function at significantly higher minimum-B fields and frequencies to meet the demanding ion beam intensity requirements for future heavy ion accelerators and upgrades to existing facilities. Using Nb_3Sn wires is an option to achieve higher magnetic fields. However, Nb_3Sn wires introduce several challenges due to the strong interaction forces affecting the critical current of Nb_3Sn, the brittleness of the wire, and the complex reaction process in fabrication [8-11]. A novel Mixed Axial and Radial field System (MARS) consisting of a hexagonal Closed-Loop Coil (CLC) and a set of solenoids combined with a hexagonal plasma chamber is highly effective at generating the required higher minimum-B fields, as shown in Fig. 1. The primary advantage of MARS is its ability to produce up to 50% higher magnetic fields than current magnet designs within the material limitations of the superconducting wire being used, while requiring only about half the amount of superconducting wire. This significant advantage makes MARS a promising magnet design for future ECRISs. To demonstrate the suitability of the MARS magnet for use in ECRISs, a system named MARS-D, featuring a Nb-Ti MARS magnet, is currently under development at Lawrence Berkeley National Laboratory (LBNL). The optimized design of this magnet is expected to achieve minimum-B field strengths of 5.7 T axially and 3.1 T radially, supporting operation at frequencies up to 45 GHz, as shown in Fig. 2 and Table I [12-14]. However, the hexagonal CLC's fabrication is tricky due to its complicated winding geometry, the high rigidity of the Nb-Ti superconducting wire, and the required small bending radius. To overcome these issues, a series of unique fixtures and tools, as well as a pre-over-bending technique, were developed for winding the CLC. A 4-layer practice CLC was produced, epoxy-impregnated, and cold-tested with liquid nitrogen to validate the winding and assembly process. Certain fixtures, tools, and methods were optimized throughout the practice coil fabrication to improve the winding quality. The results of the impregnation and test, along with the ongoing full-scale MARS-D CLC winding, confirm the effectiveness of the removable mandrel, winding fixtures and tools, winding procedures, quality control measures, and impregnation materials and process. Most of the challenges in MARS CLC fabrication have been successfully addressed.

II. MARS-D CLC STRUCTURE

The MARS-D CLC has 24 wire layers, each with 64 turns of Nb-Ti superconducting wire, for a total of 1536 turns and 27648 bending corners. For the convenience of winding, the CLC is divided into 3 coil layers, each with 8 wire layers and a pair of current leads, which are directly connected to the power leads or quench protection and can carry different operation currents, as shown in Fig. 3.

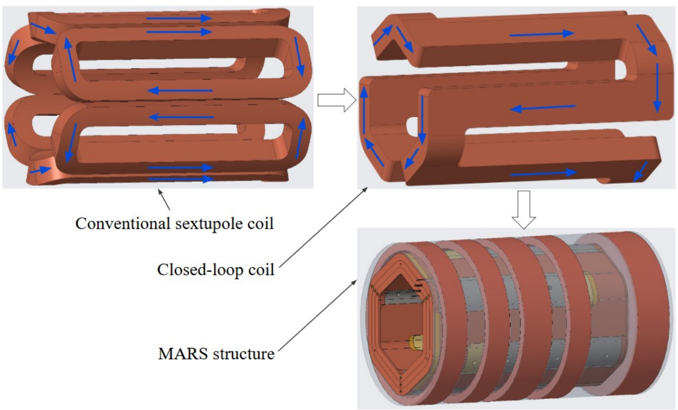


Fig. 1. MARS structure

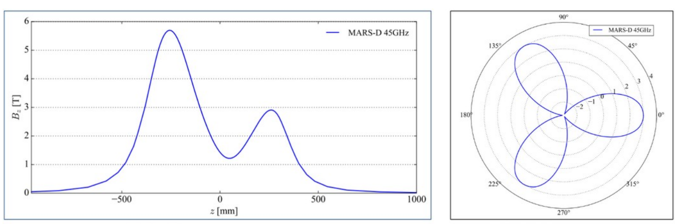


Fig. 2. Optimized MARS-D magnetic field

TABLE I
OPTIMIZED MARS-D MAGNET PARAMETERS

Item	Unit	Value
Microwave frequency f_{rf}	GHz	45
Resonant heating field B_{ECR}	T	1.6
Injection confinement field B_{inj}	T	5.7
Extraction confinement field B_{extr}	T	2.9
Radial confinement field B_{rad}	T	3.1
Stored energy E	kJ	560

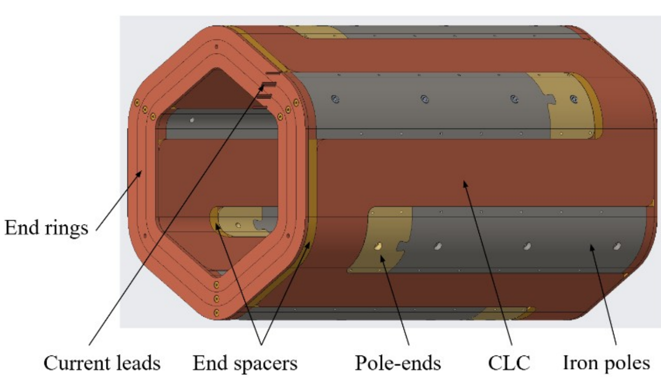


Fig. 3. MARS-D CLC structure

III. CHALLENGES OF CLC WINDING

As shown in Fig. 4, compared to conventional racetrack coil winding, the CLC winding is the most challenging due to the following factors.

- The most complicated hexagonal winding path and shape, 3D winding without wrapping force
- The stiffest rectangular (1.88 mm x 1.20 mm) Nb-Ti superconducting wire with a Cu/SC ratio of 1.3
- The smallest bending radius, R12.5 mm 90° bending at the easy way and R20 mm 120° bending at the hard way
- The shortest bending distance, two R12.5 mm 90° bending and one R20 mm 120° bending within 63 mm wire length

To ensure successful coil winding, a series of unique fixtures and tools, as well as a pre-over-bending method, were developed. The bending-etching test results showed that pre-over-bending did not damage Nb-Ti filaments, as shown in Fig. 5.

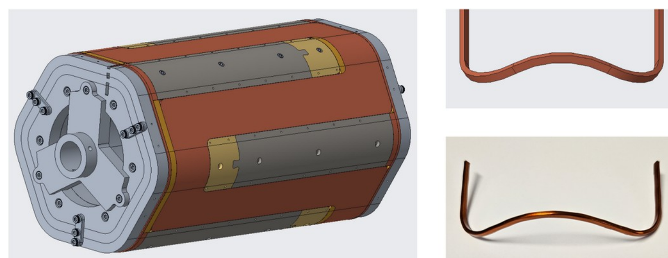
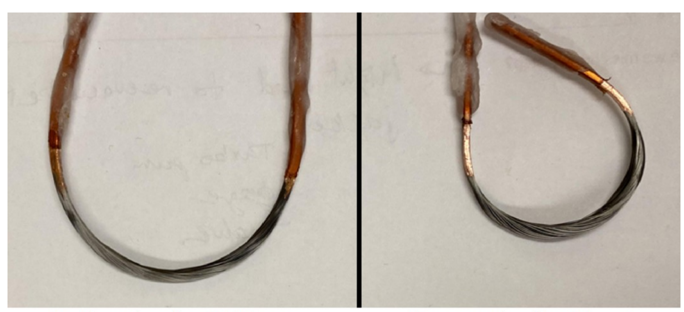


Fig. 4. Winding setup and conductor bending



(Hard way bending R12.5 mm) (Easy way bending R8 mm)

Fig. 5. Bending-etching test results

IV. REMOVABLE MANDREL STRUCTURE

After impregnation and assembly, the CLC mandrel have to be removed to maximize the use of the radial magnetic field at the chamber's inner surfaces. A removable mandrel structure was developed, as shown in Fig. 6. It consists of three fixed parts and three T-shaped filling parts with a draft angle. After removing the filled parts, the fixed parts can be easily removed. Room-Temperature Vulcanizing (RTV) silicone is used to seal the seams and around the screws. Mold release agent is applied on the surfaces that will contact the epoxy to facilitate demolding.

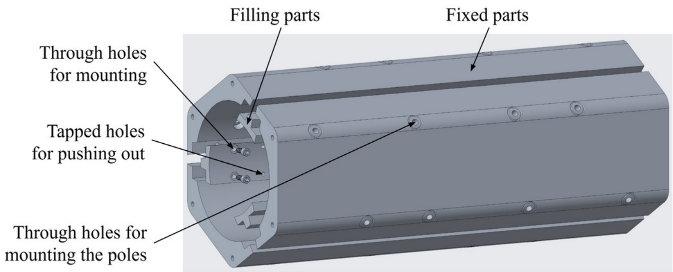


Fig. 6. Removable mandrel structure

V. WINDING FIXTURES AND TOOLS

As shown in Fig. 7, all fixtures are designed to be adjustable, enabling precise control between turns and layers during the winding process. Adjustable bending arms and blocks accurately position and hold the wire. Adjustable pressing arms and blocks press the wires. Adjustable quick-connect pressing bridges are used to secure the current layer and previous layers. Before placing the wire in the correct position, the wire is over-bent with a small radius and angle using pre-over-bending pliers to avoid spring-back of the stiff superconducting wire.

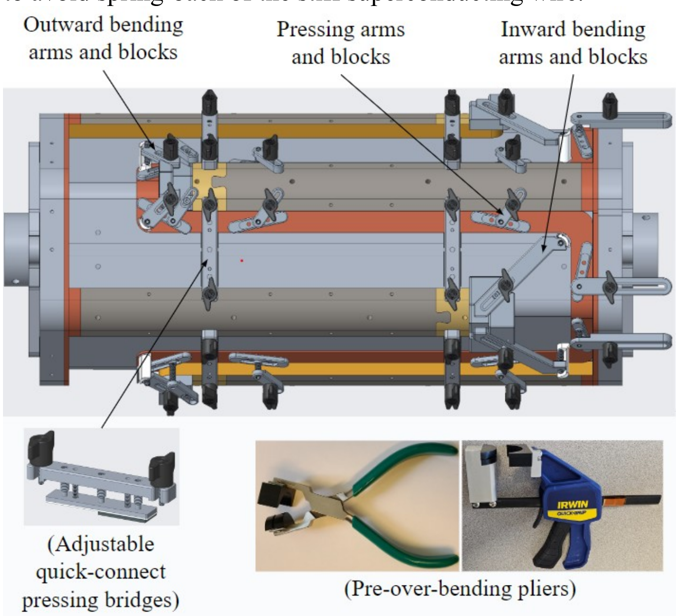


Fig. 7. Winding fixtures and tools

VI. CLC WINDING PROCEDURES

A. Pre-marking of Bending Positions

The pre-bending of superconducting wires requires marking the bending positions on the wires in advance based on the design dimensions, and the distance between each position is listed in a spreadsheet. A marking machine was developed to make manual marking easier and more accurate, as shown in Fig. 8.

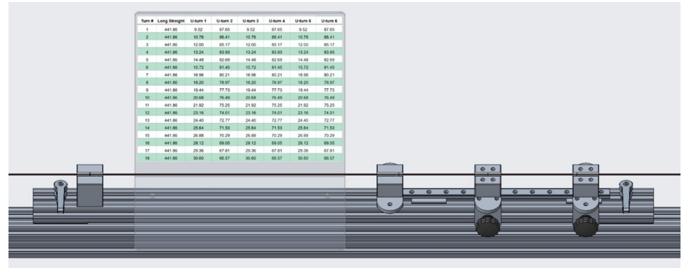


Fig. 8. Marking machine

B. Winding Procedures

The winding procedures are illustrated in Fig. 9. The inward and outward winding procedures are similar and are conducted alternately. A single-turn winding consists of six U-turns. A 4-meter-long marking machine guide rail is only suitable for a single-turn marking. Therefore, a single-turn winding and a single-turn marking must be performed alternately until one layer (64 turns) of winding is completed. One layer of 0.1 mm fiberglass fabric is added when transitioning to the next winding layer.

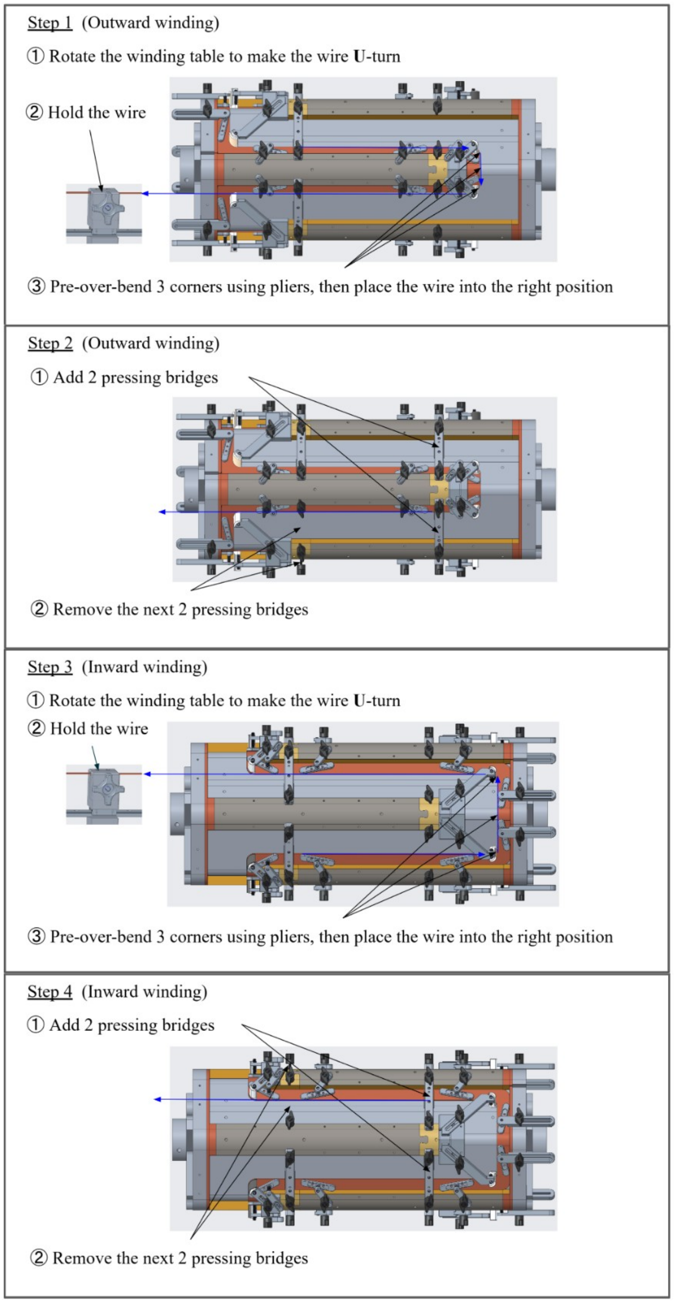


Fig. 9. CLC winding procedures

VII. QUALITY CONTROL

During the practice coil winding, the winding fixtures and procedures were optimized to improve the winding quality. A series of standard pressing blocks and fixtures were developed to ensure that the thickness increment between layers is within the design range. Room-temperature curing epoxy and chopped fiberglass were used to fill the gaps at the 90° bending corners and to secure the wiring layer, ensuring all the fixtures can be removed when transitioning to the next winding layer. Winding checklists and log sheets were developed for quality control documentation.

A milliohm meter was used to test the resistance of the wound conductor at each layer transition or wherever necessary to ensure there were no electrical shorts between turns or to ground. Ideally, the length of each turn of the conductor in the first wire layer is 3.375 m and increases by 0.0133 m layer by layer. The resistance of one meter of conductor is 15 mΩ. Therefore, the theoretical resistance of each turn, wire layer, and coil layer can be easily calculated. When testing, one probe is connected to the start of the conductor and the other probe is connected to a sharp needle that can penetrate the insulation at any point. Comparing the test results with the calculation results, any electrical shorts can be detected and the number of turns can be verified.

The full-size MARS-D CLC winding is underway, with 8 layers already completed. The winding quality is superior to the practice coil, and the coil size is within the design range, as shown in Fig. 10.

Fig. 10. The 8th layer of the full-size MARS-D CLC

VIII. IMPREGNATION AND TEST RESULTS

The 4-layer practice CLC was impregnated with CTD-101K epoxy in a vacuum chamber vertically and cured at 135°C. The epoxy flow paths are shown in Fig. 11 (left). After impregnation, the enclosures and the removable mandrel were removed easily, and the appearance of the impregnated CLC was inspected. The sealing RTV silicone and mold release agents performed effectively. The appearance of the impregnated CLC is excellent, as shown in Fig. 11 (right).

The impregnated 4-layer practice CLC was cross-cut to inspect the details of winding and impregnation. The array of straight sections is excellent, with tiny inter-turn gaps and small inter-layer gaps filled with 0.1 mm fiberglass fabric. The gaps at the 90° bending corners are larger due to the identical bending radius, and these gaps, are filled with chopped fiberglass. Microscope images show the high-quality epoxy filling, indicating that the application of fiberglass and epoxy, the epoxy flow route, and the impregnation process are reasonable, as shown in Fig. 11 (right).

One section of the impregnated 4-layer practice CLC was cold-tested using liquid nitrogen. After two cooling cycles, the epoxy filling remains in excellent condition. The properties of the super glue changed after impregnation and cooling, indicating that its use should be minimized or avoided.

For the full-size MARS-D CLC, the removable mandrel will be reinstalled into the coil once the impregnation appearance has been inspected. It will be a lifting aid and protection for the coil until the cold mass installation is completed.

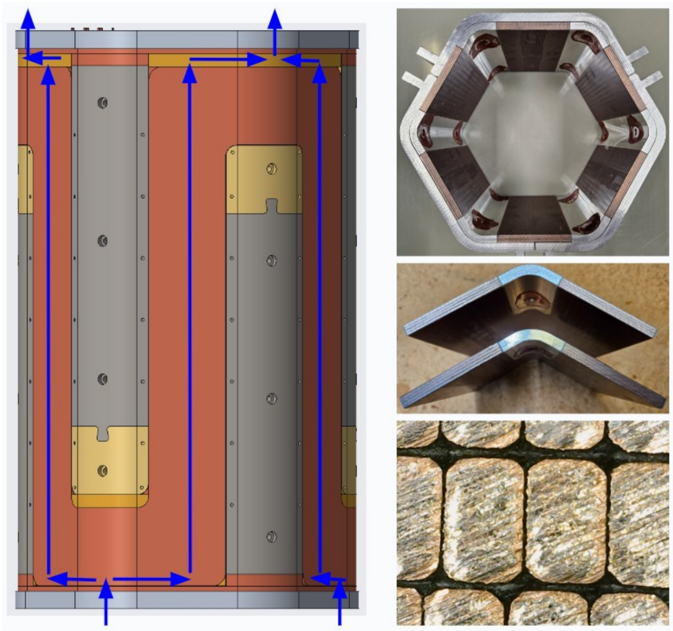


Fig. 11. Impregnation and test results

IX. Future Improvements

After the MARS-D CLC impregnation is completed, it will be installed into a cold mass with the solenoid coils. The cold mass will undergo comprehensive testing in a liquid helium cryostat. If it meets the design specifications, it will be integrated into the 4th generation ECRIS for the 88-inch cyclotron at LBNL.

In the near future, efforts will focus on increasing coil winding speed while maintaining high winding quality. A program-controlled marking robot is currently under development. It will replace manual labor to pre-mark the bending positions on the superconducting wire based on the design specifications. This advancement is expected to significantly increase winding speed and minimize human error.

Future efforts will also involve improving the fabrication process to utilize HTS superconducting wires for MARS magnets in the future generations of ECRISs, enabling the operation at increasingly higher fields and frequencies.

X. Conclusion

The successful completion of the 4-layer practice CLC winding, impregnation, testing, and the ongoing full-size MARS-D CLC winding demonstrates that the removable mandrel, winding fixtures and tools, winding procedures, quality control measures, and impregnation materials and processes are effective. Most challenges in MARS CLC fabrication have been resolved, although winding speed remains relatively slow. Given the benefits of the MARS magnet structure, it is anticipated to be a promising and feasible option for future ECRISs.

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