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Authors

Xie, DZ

Benitez, JY

Hodgkinson, A

et al.

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Development status of a next generation ECRIS: MARS-D at LBNL^{a)}

D. Z. Xie,^{b)} J. Y. Benitez, A. Hodgkinson, T. Loew, C. M. Lyneis, L. Phair, P. Pipersky, B. Reynolds and D. S. Todd

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

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To demonstrate a Mixed Axial and Radial field System (MARS) as the best magnet scheme for future ECRISs, MARS-D, a demonstrative ECRIS using a NbTi MARS magnet is progressing at LBNL. An optimized MARS design can use either NbTi or Nb₃Sn coils with reduced engineering complexities to construct the needed high-field magnets. The optimized magnet design could enhance MARS-D to a next generation ECRIS by producing Minimum-B field maxima of 5.6 T axially and 3.2 T radially for operating frequencies up to 45 GHz. In-progress test winding has achieved a milestone demonstrating the fabrication feasibility of a MARS closed-loop coil.

I. INTRODUCTION

The performance of ECRISs following Geller's scaling law has greatly improved in the past decades and has led to high magnetic-field, high frequency ECRISs built with NbTi magnets.^{1,2,3} The next generation of ECRISs will operate at much higher Minimum-B fields and higher frequencies than current sources in order to meet the unprecedented requirements of ion beam intensity for next generation heavy ion accelerators and for upgrades to existing facilities. The substantially increased magnetic fields will require the use of Nb₃Sn magnets, which is a challenging technology.

A novel Mixed Axial and Radial field System (MARS), consisting of a hexagonally shaped closed-loop coil and a set of auxiliary solenoids combined with a hexagonal plasma chamber can efficiently generate the required higher strength Minimum-B fields.⁴ As shown in Figure 1, a MARS closed-loop coil combines six straight Ioffe⁵ bars and two tri-segmented solenoids into a single coil through continuous looping in which the current flows in the same azimuthal direction through the end turns (tri-segmented solenoids). By itself, the closed-loop coil generates a Minimum-B field. However for an ECR ion source the axial mirrors fields need to be enhanced by a set of auxiliary solenoids. With current flowing in the same direction, unlike the magnet designs employed in VENUS and SECRA,^{2,3} there are no repulsions between the solenoids and the closed-loop coil. This zero repulsion allows the auxiliary solenoids be located right inside, outside or next to the ends of the closed-loop coil which results in smaller superconducting magnets for ECRISs. The primary advantage of MARS is that, within the material constraints of a given superconducting wire, it has the potential to generate up to 50% higher fields than the

existing magnet designs and use only about one half as much of the superconducting wire. This primary advantage alone has the potential to make MARS the best magnet scheme for future ECRISs.

An ECRIS called MARS-D using a NbTi MARS magnet is under development at LBNL to validate the MARS magnet for applications in ECRISs. It was designed for operation frequencies of 18 and 28 GHz to enhance the capabilities of the 88-Inch Cyclotron.⁶ A test winding with copper wires is in progress to explore the fabrication of a closed-loop coil, the most critical component of the MARS magnet.

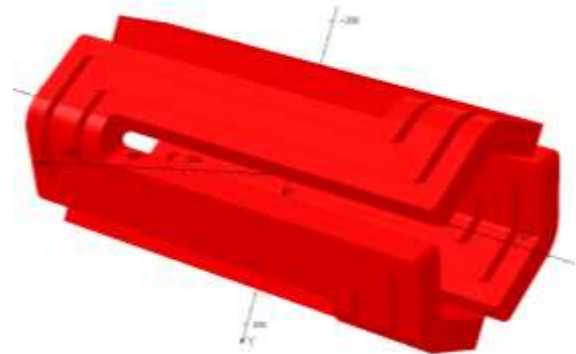


FIG. 1. A TOSCA-3d model of a MARS closed-loop coil that can generate a Minimum-B field by itself.

II. OPTIMIZED MAGNET DESIGN FOR MARS-D

The initial concept of MARS magnet for the next generation of ECRIS had a round solenoid located right inside one end of the closed-loop coil to produce a maximum axial field of ≥ 10.0 T. However this configuration would result in very complex and costly

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^{b)}Corresponding Author: D. Z. Xie, e-mail address: zxie@lbl.gov

fabrications. It would require a step-up transformation from a circular section to the hexagonal bore for both the cryostat and the ion source plasma chamber, which would be very inconvenient for source maintenance and services.⁴ To reduce the engineering complexity, the first magnet design for MARS-D used a set of three round auxiliary solenoids enclosing the closed-loop coil to eliminate the step-up transformation. TOSCA-3d calculations showed, within the NbTi conductor constraints, the magnet could generate a maximum axial field of only ~3.5 T, albeit the radial field reaching 3.2 T at the plasma chamber walls. These Minimum-B field strengths, similar to those of VENUS², are capable of supporting operation heating frequencies of 18 to 28 GHz.⁶

The configuration differences between the initial MARS magnet scheme and the first designed magnet for the MARS-D would lead to a rather complex and costly development, as it requires two sets of substantially different engineering designs. Thus it is very advantageous and preferable to have a magnet design that can be applied using either NbTi or Nb₃Sn coils with the same configuration, mechanical dimensions and at the same time further optimizing the magnetic field generation for MARS-D.

Figure 2 shows the coil configuration of the optimized MARS magnet design for MARS-D.

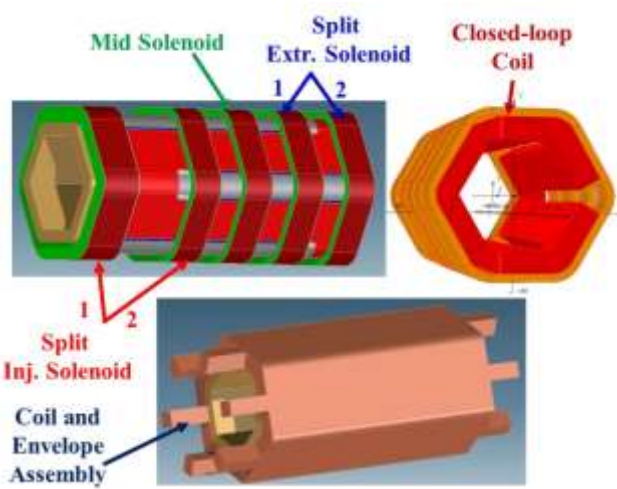


FIG. 2. Coil configuration of the optimized MARS magnet design for MARS-D (Creo-3d and OPERA-3d models). All the coils and a protective envelope will be vacuum epoxy impregnated together for easier magnet assembling and clamping.

This optimized MARS magnet design employs a few new features: 1. Hexagonally-shaped solenoids in combination with the closed-loop coil; 2. Split solenoids at injection and extraction to reduce the maximum field at the closed-loop coil so that it could operate at as high current as possible; 3. All coils and a protection envelope are to be vacuum epoxy impregnated together as a module, for easier magnet assembling and clamping, hoping to reduce the possible macroscopic coil movements due to the tremendous Lorentz interaction forces. Table I lists the major parameters of the coils and the designed fields for

MARS-D operating at 28 and 45 GHz, based on the ECRIS empirical design criteria.⁷ TOSCA-3d calculations show the optimized magnet design, with maximum fields of 7.95 T at the injection solenoid coil and 7.6 T at the closed-loop coil, could produce a Minimum-B field configuration with field maxima on axis of 5.6 T and 3.5 T with a separation of 520 mm. This field configuration can be combined with a hexagonal plasma chamber with a major radius of 82 mm along the plasma flutes where the maximum radial field will reach 3.2 T. The overall magnetic spatial volume inside the plasma chamber is about 9 liters, similar to that of VENUS.² The generation of similar Minimum-B fields in the plasma chamber for 28 GHz operation, as listed in Table I, results in a calculated magnet stored energy of only 212 kJ for MARS-D, substantially lower than the 715 kJ for VENUS. Even at the fields for MARS-D operating at 45 GHz, the calculated magnet stored energy of 387 kJ is just slightly over one half of that for VENUS operating at 28 GHz. The much lower magnet stored energy is a good manifestation and perspective of the advantages of the MARS magnet system.

TABLE I. Major parameters of the coils and calculated fields of the optimized magnet design for MARS-D for operations at 28 and 45 GHz.

Total magnet length (L = 642 mm)	CIC*	Injec. Solenoid (1/2)	Mid Solenoid	Extrac. Solenoid (1/2)
Axial center (mm)	0	-322/-120	0	120/240
Mini. ID (mm)	200	200/282	282	282/282
Thickness (mm)	41	56/15	15	15/15
Width (mm)	92	90/60	60	60/60
At eng. current density j_e (A/mm ²)				
28 GHz	135	115	-150	270
45 GHz	195	160	-60	210
B (T) radial[#]/axial				
28 GHz	2.2	4.1	0.7	3.0
45 GHz	3.2	5.6	1.1	3.5
B_{max} (T) at coil** (at designed j_e)				
28 GHz	5.8	5.9	4.2	5.6
45 GHz	7.6 (0.7)	7.95 (1.4)	4.9	5.9
Magnetic stored energy E (kJ) at designed j_e			In comparison:	
28 GHz	212	715 (VENUS@28GHz) ⁸		
45 GHz	387			

*: CIC = Closed-loop Coil

** : The fields quoted in the parentheses are the maximum fields contributed from other coils while the noted coil itself is at zero excitation.

: At major radii of 82 mm of the hexagonal plasma chamber.

Based on the designed engineering current densities j_e given in Table I, this Minimum-B field configuration could be produced by NbTi coils using the Oxford Instruments' 6867 NbTi wires (1.92 x 1.23 mm², Cu/Sc: 1.35), with somewhat aggressive assumptions of ~ 90% of wire packing and excitation of ~ 85% loading as indicated in Figure 3. With this optimized MARS magnet design, the NbTi magnet underdevelopment at LBNL has been revised with the aim of enhancing the MARS-D to a next generation ECRIS for operation frequency up to 45 GHz, instead of the previously planned 18/28 GHz. If the revised magnet for MARS-D is successfully developed, the

optimized MARS design will open a simpler and lower cost pathway for constructing magnets using NbTi coils for next generation of ECRIS for operation frequency up to about 45 GHz.

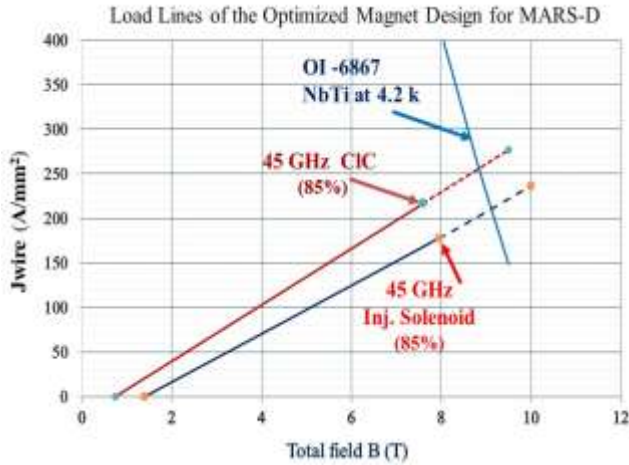


FIG. 3. The designed load lines of the closed-loop coil (CIC) and the injection solenoid of the magnet using the indicated OI NbTi wire for the ECRIS demonstrator: MARS-D, based on the optimized MARS magnet design and assumed 90% wire packing.

III. PROTOTYPING A MARS CLOSED-LOOP COIL

The most critical step in realizing the MARS magnet scheme is the fabrication of the closed-loop coil, in which the biggest challenge is keeping the tensioned wire in place. To develop the winding techniques and fixtures for fabricating the closed-loop coil, a test winding is underway at LBNL using copper wire of about the same size as the intended Oxford Instruments NbTi wire for the MARS-D's magnet. The size of the prototyped copper coil is about the same as the designed coil for MARS-D except the thickness is about 1/3 of the designed. So far 3 layers of the copper coil have been dry wound and the fixtures are being improved to speed up the winding. Figure 4 shows a fully wound layer of the coil winding in-progress. Based on the progress made so far in the test winding, we are confident the closed-loop coil can be fabricated. At the completion of the test winding, the prototyped copper coil will be vacuum epoxy impregnated to exam the fabrication quality, before commencing the NbTi magnet fabrication for MARS-D.

IV. CONCLUSIONS AND DISCUSSIONS

The development of an ECR ion source demonstrator, MARS-D, has been progressing in an exciting direction. An important milestone has been achieved in demonstrating the fabrication feasibility of a closed-loop coil, which is the most critical component of the MARS magnet scheme. Thorough structural 2d and 3d stress analyses are still needed to verify the MARS magnet design and are planned in the very near future.

If the magnet using the optimized MARS design succeeds, it will extend the usefulness of NbTi magnets to next generation of ECRIS, though the operation frequency will probably be limited to about 45 GHz. However a 45 GHz ECRIS built with a NbTi magnet will definitely result in substantial cost saving and relatively easier fabrications, compared to a Nb₃Sn magnet.

Once its applications have been validated in ECRISs, the optimized MARS magnet design could also be applied using Nb₃Sn coils for future ECRISs. TOSCA calculations have shown that the optimized MARS magnet scheme could likely generate field maxima of ~ 10.5 T axially and ~ 6 T radially within the Nb₃Sn conductor constraints. Such a high strength Minimum-B field is capable of supporting ECRIS operations with heating frequency up to 84 GHz. However constructing a Nb₃Sn MARS magnet will be more challenging as many issues need to be well addressed, such as the Nb₃Sn wire brittleness, less ductility and the afterwards heat-react treatments.

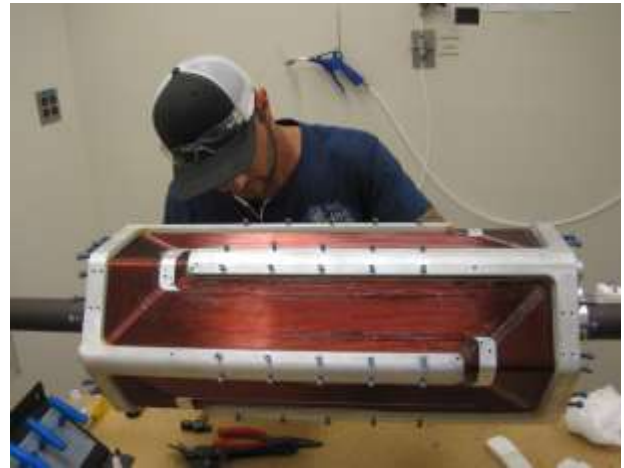


FIG. 4. A test winding using copper wires to explore the fabrication of the MARS closed-loop coil is progressing along. Shown is one fully wound layer of the copper coil demonstrating the fabrication feasibility of the exotic shaped coil.

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