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Design of a New Superconducting Magnet System for High Strength Minimum-B Fields for ECRIS

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***Abstract*—A novel Mixed Axial and Radial field System (MARS) seeks to enhance the B fields inside the plasma chamber within the limits of a given conductor, thereby making it possible to raise the operating fields for Electron Cyclotron Resonance Ion Sources (ECRISs). The MARS concept consists of a hexagonally shaped closed-loop coil and a set of auxiliary solenoids. The application of MARS will be combined with a hexagonal plasma chamber to maximize the use of the radial fields at the chamber inner surfaces. Calculations using Opera's TOSCA-3D solver have shown that MARS can potentially generate up to 50% higher fields and use of only about one half of the same superconducting wire, compared to existing magnet designs in ECRISs. A MARS magnet system built with Nb_3Sn coils could generate a high strength Minimum-B field of maxima of ≥ 10 T on axis and ~ 6 T radially in an ECRIS plasma chamber. Following successful development, the MARS magnet system will be the best magnet scheme for the next generation of ECRISs. This article will present the MARS concept, magnet design, prototyping a copper closed-loop coil and discussions.**

***Index Terms*—Superconducting magnets, special coils, Minimum-B fields, ECR ion source.**

I. Introduction

PERFORMANCE of the Electron Cyclotron Resonance Ion Sources (ECRISs) following Geller's scaling law [1] has greatly improved in the past decades and has led to high B field, high frequency ECRISs built with NbTi magnets. Based on the existing magnet structures and within the NbTi conductor limits, field maxima of up to 4.0 T on axis and 2.2 T radially at the plasma chamber walls have been achieved and which have greatly enhanced the ECRIS performance [2], [3]. The next generation of ECRISs will operate at much higher B fields and higher frequencies than current sources in order to meet the ion beam intensities needed by future heavy ion accelerators and to upgrade existing facilities. These high magnetic fields, preferably as high strength as possible, will require the use of Nb_3Sn magnets. A straightforward extrapolation of a present 3rd generation ECRIS magnet structure indicates that magnetic fields of about 8 T on axis and 4 T radially could be achieved with Nb_3Sn coils [4]. However there may be room to further optimize the magnetic structure of the scaled design. A Mixed Axial and Radial field System (MARS) is a new magnetic structure designed to optimize the magnetic field generation and to reduce the very strong and complex Lorentz interactions in the superconducting magnets for ECRISs [5].

In this paper the concept and major characteristics of the MARS magnet system are presented and discussed. Section II briefly reviews the requirements of Minimum-B fields as well as the advantages and disadvantages of the presently used ECRIS magnet designs. Section III discusses the MARS concept, and magnet design. Section IV presents the development status of a MARS-based ECRIS at Lawrence Berkeley National Laboratory (LBNL). Section V discusses the overall merits and the potential of MARS for high field strength ECRISs.

II. Minimum-B Field and Existing Magnet Structures for ECRISs

A. Requirements of Minimum-B Field for ECRISs

A Minimum-B field, resulting from the superimposition of axial magnetic mirrors and radial multipole fields, is the key component of an ECRIS for confining the plasma with millisecond-lifetime needed for the production of highly-charged ions. It provides a closed electron resonance heating surface in which the local field strength satisfies the relation: $\boldsymbol{B_{ECR}} = \frac{2\pi f m_e}{e}$, where f, m_e and e are the incoming wave frequency, the electron mass and charge, respectively. Based on the empirical ECRIS design criteria [6], the field maxima of a Minimum-B should be proportional to $\boldsymbol{B_{ECR}}$ in the following manner:

$$B_{inj} \sim 3.5 - 4\,\boldsymbol{B_{ECR}} \text{ and } B_{ext} \approx B_{rad} \geq 2\,\boldsymbol{B_{ECR}} \qquad (1)$$

where B_{inj} and B_{ext} are the axial peak fields at the injection and extraction regions, B_{rad} is the maximum radial field at the inner surface of the cylindrical plasma chamber commonly used in ECRISs. For microwaves at 28 GHz correspond to a resonance field strength $\boldsymbol{B_{ECR}}$ of 1 T, and therefore the ECRIS design criteria indicate B_{inj} should be ~ 3.5 – 4 T while B_{ext} and B_{rad} should be at least 2 T. In the present superconducting ECRISs the radial field, B_{rad}, is generated by a sextupole magnet consisting of six racetrack or saddle coils as shown in Fig. 1. The end-current of such a sextupole magnet flows in opposite directions in adjacent coils yielding zero net axial field contribution, thus fairly large solenoids are used to provide all the needed axial fields of a high field ECRIS Minimum-B. Furthermore, the alternating end-currents interact with the injection and extraction solenoids which results in strong radial inward and outward forces on the sextupole coil ends [2]. This in turn requires an extended distance between the sextupole coil ends and the solenoids so the interaction forces can be managed.

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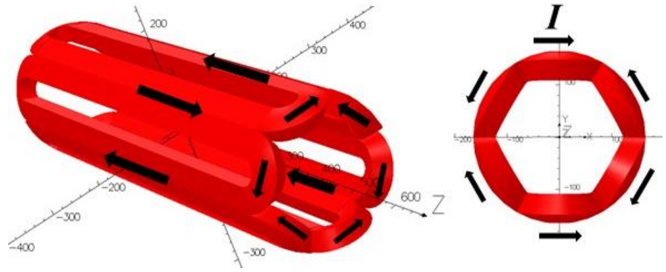

Fig. 1. A 3D model of a sextupole magnet consists of six racetrack coils commonly used in ECRISs, in which the coil end-current *I* (indicated by the black arrows) flows in opposite directions in adjacent coils yielding zero net axial field contribution to the Minimum-B field.

B. *Existing ECRIS Magnet Structures*

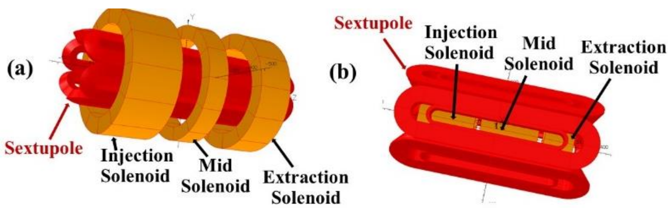

Fig. 2. 3D models of the two existing ECRIS magnet structures: (a) Sextupole-In-Solenoids and (b) Solenoids-In-Sextupole. Each of the magnet structures has its own advantages and disadvantages.

Fig. 2 shows the two superconducting magnet structures presently employed in ECRISs: (a) Sextupole-In-Solenoids and (b) Solenoids-In-Sextupole. Because of the very strong Lorentz forces, i.e, the attractions and the repulsions resulting from the interactions between the solenoids and the sextupole coil ends, the length of the sextupole magnet has to be extended in the Sextupole-In-Solenoids and in some cases a set of liquid-metal-filled bladders have been used to securely clamp the sextupole coils. The Solenoids-In-Sextupole reduces the interaction forces and the magnet fabrication complexities but it does not efficiently utilize the radial fields. Table I lists the advantages and disadvantages of these two existing magnets.

TABLE I
COMPARISON OF THE EXISTING MAGNETS

Structure	Sextupole-In-Solenoids	Solenoids-In-Sextupole
Advantages	Better utilization of the radial fields	Lower and simpler interaction forces, slightly smaller magnet and cryostat, simpler fabrication with lower cost
Disadvantages	Longer and bulkier magnet and cryostat; higher and complex interaction forces	Inefficient use of the radial fields.

Within the NbTi conductor limits and use of a cylindrical plasma chamber, the LBNL VENUS was built with a Sextupole-In-Solenoids magnet and become the first ECRIS to reach 4 T on axis and 2.2 T at the plasma chamber inner surface for operation at 28 GHz [2]. The IMP SECRAL, built with a Solenoids-In-Sextupole magnet, reached 3.6 T on axis and 2 T radially for operation at 24 GHz [3]. Both ion sources are the best performing and have produced many record ECRIS ion beams [7], [8] demonstrating that the ECR plasma is independent of the magnet structure, as long as a high strength Minimum-B is provided.

III. MARS CONCEPT AND ITS MAGNET DESIGN

Fig. 3 shows the key component of the MARS concept: a closed-loop coil constructed by combining six straight bars of rectangular cross-section and two tri-segmented-hexagon end solenoids into a single coil. In contrast to the zero axial field contributions of the conventional sextupole magnet, this closed-loop coil generates both radial and significant axial fields as its end currents all flow in the same direction resulting in a Minimum-B field. Fig. 4 (a), (b) and (c) show the axial, the radial, and the resulting Minimum-B fields generated by a closed-loop coil enclosed by a slightly asymmetric iron yoke (not shown in Fig. 3 and Fig. 6).

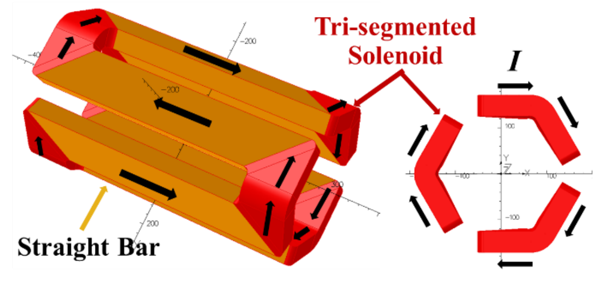

Fig. 3. A 3D model of a MARS closed-loop coil constructed by combining six straight bars with two tri-segmented-hexagon end-solenoids. All the end-currents (indicated by the black arrows) *I* flow in the same azimuthal direction.

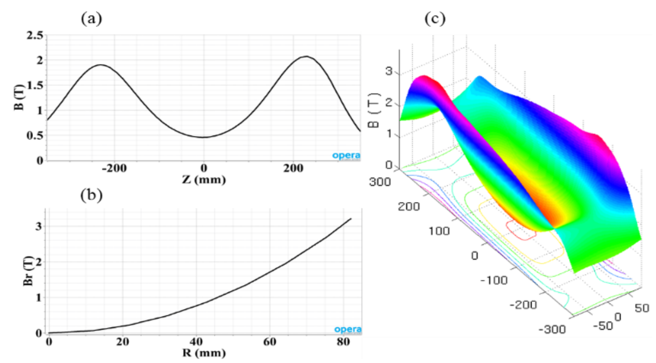

Fig. 4. TOSCA-3D magnetic field calculations of a MARS closed-loop coil: (a). Axial field profile in which the slight asymmetry is due to the asymmetric enclosing iron yoke; (b). Radial field profile for an inner chamber radius up to 82 mm; (c). Field contours of the resulted Minimum-B field.

Although the closed-loop coil generates a Minimum-B field, the axial field mirrors need enhanced for applications in ECRISs. This can be easily done by taking the advantage of the lack of repulsive forces between the external solenoids and the closed-loop coil ends. The solenoids can be located right inside, outside or next to the ends of the closed-loop coil and thus a set of auxiliary small solenoids completes MARS for ECRISs.

The sextupole field strength is proportional to the square of the radial distance *r* in ECRISs:

$$B_r(r) = B_{rm} \left(\frac{r}{R}\right)^2 \qquad (2)$$

where B_{rm} is the maximum pole field strength at the inner surface of the chamber of radius *R*. For optimum utilization of the radial fields generated by MARS, a hexagonal plasma chamber is to be used to match the pole field and the cryostat hexagonal warm-bore housing the closed-loop coil. As schematically shown in Fig. 5, utilizing a hexagonal chamber more effectively uses the generated radial pole fields, increasing the maximum radial field by a factor of $\chi = (R_{maj}/R_{min})^2 \approx 1.33$, where R_{maj} and R_{min} are the major and minor radii of a hexagonal chamber, and R_{min} is also the radius of a cylindrical chamber if used in the MARS magnet structure.

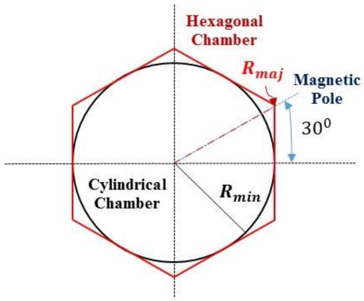

Fig. 5. A hexagonal plasma chamber matching the MARS closed-loop coil has a better geometric form factor than the existing cylindrical designs used in ECRISs. The effective use of the generated radial pole fields can increase the maximum radial field at least 30%.

A. Magnet Design

A demonstration ECRIS named MARS-D, based on the MARS magnet design and using NbTi coils, is under development at LBNL to validate the MARS magnet for applications in ECRISs and to enhance the capabilities of the 88-Inch Cyclotron [9]. Fig. 6 shows the designed MARS magnet configuration and the cold-mass assembly. It has been further optimized by employing a few new features:

- Hexagonally-shaped solenoids in combination with the closed-loop hexagon coil;
- 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;
- Coils and a protection envelope vacuum epoxy impregnated together as a module for easier magnet assembly and clamping to reduce the possible macroscopic coil movements due to the tremendous Lorentz interaction forces.

Fig. 7 (a) and (b) show the calculated maximum axial field and the resulting Minimum-B field, generated by the optimized MARS design shown in Fig. 6, in which the maximum radial field is the same as shown in Fig. 4 (b). Within the NbTi conductor limits, the designed magnet for MARS-D should be able to generate axial peak fields of 5.6 and 3.5 T separated axially 520 mm, and a maximum radial field of 3.2 T at the 82 mm major radius of a hexagonal plasma chamber having about the same chamber volume as in VENUS. These field strengths meet the design criteria for operations up to 45 GHz, i.e., a next generation ECRIS. Table II lists the major coil parameters for the designed MARS magnet and magnetic fields with various engineering current densities. To generate the field strengths stated above for MARS-D, the peak fields on the coils are 7.6 T and about 8 T, respectively, for the closed-loop coil and the injection solenoid. These maximum fields on the coils are feasible with the NbTi conductor and therefore a NbTi MARS magnet can likely be built for MARS-D.

In addition, the calculated magnet stored energies, a manifestation of the overall size and the excitations of a magnet system, clearly indicate the merits of the MARS magnet design. To generate the same fields for 28 GHz operations, the 212 kJ stored energy in MARS is just 30% of the stored energy in a Sextupole-In-Solenoids for VENUS. For the case of 56 GHz operations, this ratio is even lower at ~ 25%, clearly indicating the MARS' field-generation efficiency. As tabulated in Table II, MARS requires only 8.2 km of a rectangular NbTi wire (1.92 mm x 1.23 mm) to construct the magnet for operations to 45 GHz, while the VENUS' Sextupole-In-Solenoid magnet would need 18.5 km of the same wire and could operate to only 28 GHz. For operation frequency above 45 GHz, Nb_3Sn magnets would be needed. With the assumptions of 90% wire packing and ~ 85% of short sample wire loading as indicated in Fig. 8, Oxford Instruments' 6867 NbTi wires (1.92 mm x 1.23 mm, Cu/Sc: 1.35) could be used for constructing the magnet for MARS-D. If this magnet design could be built with the OI 2004 RRP Nb_3Sn wires it would generate a Minimum-B field of ~ 10.5 T on axis and ~ 6 T radially at the 82 mm major radius of a hexagonal plasma chamber for future ECRISs.

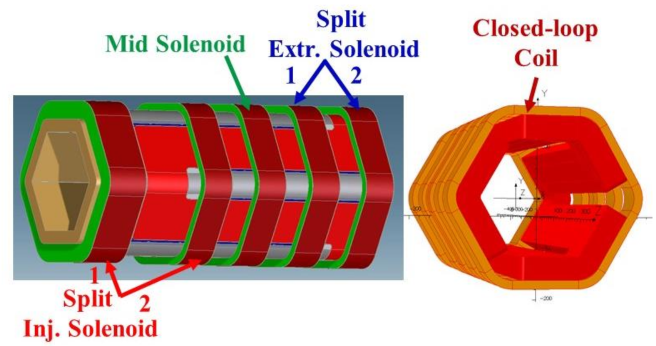

Fig. 6. Coil configuration of the optimized MARS magnet design for MARS-D. All the coils are to be epoxy impregnated together for easier magnet assembly and clamping.

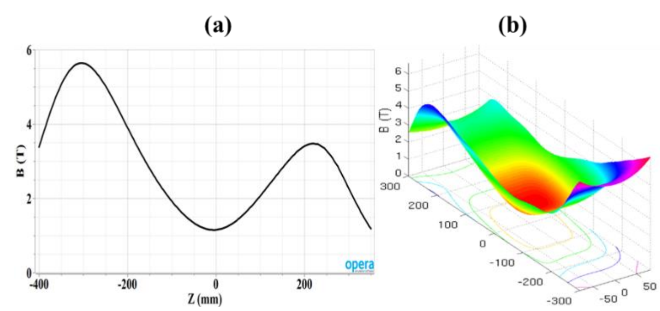

Fig. 7. (a): TOSCA calculated axial magnetic field profile for MARS-D. (b): Histogram of the resulting Minimum-B shows a field minimum at the center.

B. Prototyping a Copper Closed-loop Coil

Fabrication of a closed-loop superconducting coil is the most critical challenge in realizing the MARS scheme. The challenge is to keep the dry tensioned wire in place, thus a set of special winding fixtures and winding procedures need to be developed. To explore the feasibility of such a closed-loop coil, a test winding is in progress at LBNL using rectangular copper wire of about the same size as the Oxford Instruments 6867 NbTi wire. The copper closed-loop coil being prototyped is about the same size as the one designed for MARS-D, except the thickness is about 1/3 of the full design. So far more than 3 layers of the copper coil have been wound and the fixtures are being improved to speed up the winding. Fig. 9 shows a fully wound layer of the test coil. Based on the progress made so far, we are confident the MARS closed-loop coil can be fabricated.

TABLE II
MAJOR PARAMETERS OF THE MARS MAGNET AND EXTRAPOLATIONS

Total magnet length (L = 642 mm)	**ClC**[a]	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
56 GHz	255	240	-150	270
84 GHz	375	310	-150	370
B (T) radial[b]/axial				
28 GHz	2.2	4.1	0.7	3.0
45 GHz	3.2	5.6	1.1	3.5
56 GHz	4.1	8.0	1.3	4.4
84 GHz	5.9	10.5	2.1	6.2
B$_{max}$ (T) at coil[c] (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
56 GHz	10.0 (1.1)	11.5 (1.9)	6.7	7.7
84 GHz	14.3 (1.5)	14.7 (2.7)	8.8	10.5
Magnetic stored energy **E** (kJ) at designed **j$_e$**		In comparison:		
28 GHz	212	**715** (VENUS@28GHz, [10])		
45 GHz	387			
56 GHz	707	**2900** (VENUS56, [11])		
84 GHz	1346			
Total wire[d] usage (km)	8.2	**18.5** (VENUS@28GHz)		

[a]ClC = Closed-loop Coil.
[b]At major radii of 82 mm of the hexagonal plasma chamber.
[c]The fields quoted in the parentheses are the maximum fields contributed from other coils while the noted coil itself is at zero excitation.
[d]OI 6867 rectangular NbTi wire (1.92 mm x 1.23 mm) and 2.5 mm^2 assumed in winding.

IV. DISCUSSIONS

Among the MARS' advantages over the existing magnet designs for ECRISs, the primary one is that it has the potential to generate up to 50% higher fields while using only about one half as much of the same size superconducting wire, as tabulated in Table II. This primary advantage alone could make MARS the best magnet scheme for future ECRISs.

The development of a demonstration MARS-based ECRIS, MARS-D, has progressed with the demonstration of feasible fabrication of the closed-loop coil. If MARS-D succeeds, it will extend the usefulness of NbTi magnets to next generation ECRIS, up to about 45 GHz. A 45 GHz ECRIS built with a NbTi magnet should result in substantial cost saving and relatively easier fabrication compared to a Nb_3Sn magnet.

Constructing a MARS magnet with Nb_3Sn wires would be more challenging than a NbTi one and many issues need to be addressed, such as the Nb_3Sn wire brittleness, the poor ductility, the available length of monolithic wire and the post-heat-react treatments. It would significantly advance the ECRIS technology if a Nb_3Sn MARS magnet can be developed to generate field maxima of ~ 10.5 T on axis and ~ 6 T radially to support ECRIS operations up to 84 GHz.

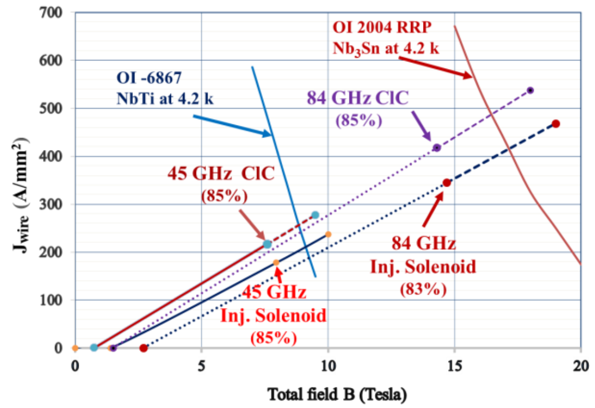

Fig. 8. Designed load lines of the closed-loop coil (ClC) and the injection solenoid of the MARS magnet with the indicated OI NbTi (for MARS-D) and Nb_3Sn wires (for future higher field ECRISs with operations up to ~ 84 GHz).

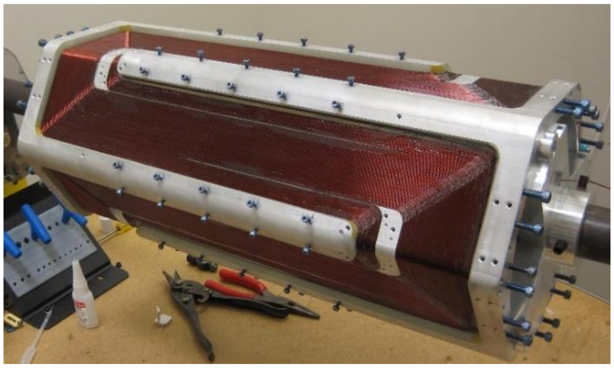

Fig. 9. A test dry-winding using copper wires to explore the fabrication of a MARS closed-loop coil is progressing along. Shown is one of the fully wound layers of the coil demonstrating the fabrication feasibility of the exotic shaped closed-loop coil.

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