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STATUS OF THE 45 GHz MARS-D ECRIS*

D. Z. Xie†, J. Y. Benitez, M. Kireeff Covo, A. Hodgkinson, M. Juchno, L. Phair, D. Todd, L. Wang
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

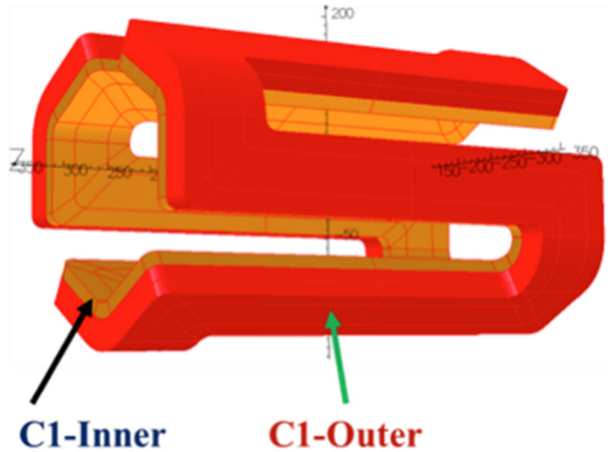
Development of MARS-D, a 45 GHz next-generation Electron Cyclotron Resonance ion source (ECRIS) using a NbTi MARS-magnet, continues to move forward at LBNL. All of the key components of MARS-D have been nearly finalized, with recent completion of the magnet stress analyses. This article presents and discusses the status of this new 45 GHz ECRIS, such as the latest design features and the component fabrication plans likely taking place in the near future.

INTRODUCTION

The next generation of ECRIS will operate at substantially higher magnetic fields and microwave frequencies, therefore source development will require addressing a number of challenges. The most critical challenge is constructing a superconducting magnet system capable of producing the needed high-magnetic fields. Compared to the two existing superconducting ECRIS magnet geometries: Sext-In-Sol and Sol-In-Sext, the Mixed Axial and Radial field System (MARS) presents many advantages [1]. The key advantage is the efficiency with which MARS can generate minimum-B fields capable of extending the NbTi conductor to the next generation of ECRIS operating at 45 GHz, whereas using one of the two existing geometries will require higher-current superconductors, such as Nb_3Sn or HTS. To validate and demonstrate the MARS magnet geometry as the superior ECRIS magnet scheme, MARS-D, a demonstrative ECRIS operating at 45 GHz, was proposed and conceptual design of the source system was initiated in 2015 [2]. A NbTi MARS-magnet will be used to produce a minimum-B configuration of field maxima of 5.6 T axially and 3.2 T radially needed for the 45 GHz MARS-D. Over the subsequent years, efforts to further optimize the design of MARS-D have been continuing. In the following sections, the optimized mechanical layout and main features of MARS-D will be presented and briefly discussed, such as the updated magnet dimensions, the coil stress analyses, multiple-frequency plasma heating, preliminary design of the plasma chamber, and plans for the conventional ion source components.

MAGNET OPTIMIZATIONS

The initial magnet design of MARS-D reported in 2015 [2] incorporated a set of hexagonal solenoids to increase the axial mirror fields of the closed-loop-coil to achieve the required minimum-B field for ECRIS operations. Since that time a few changes have been made to optimize the magnet design. First, the closed-loop-coil has been slightly modified for better form aspect ratio and electrically divided into inner and outer subsections with different currents, as shown in Fig. 1a, to keep this coil operating further away from the NbTi critical current. To mitigate the hoop-stress and reduce magnet coil quenching, the hexagonal solenoids have been replaced with a set of round solenoids where some of them are either electrically divided or mechanically divided, as shown in Fig. 1b. Table 1 lists the updated inner and outer diameters, axial widths and locations, and the designed engineering current densities for all coil subsections for 45 GHz operation.



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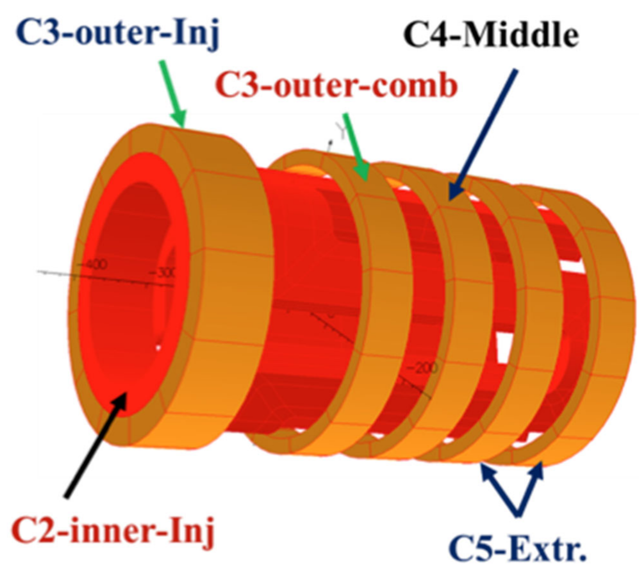

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Figure 1: **a** and **b** show the optimized layout of the NbTi MARS-based-magnet with electrical subdivisions for a 45 GHz next generation ECRIS: MARS-D.

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† zqxie@lbl.gov

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Table 1: Coil Mechanical Dimensions and Designed Current Densities of the Optimized MARS-D Magnet for Operations at 45 GHz

Coil Subsection	ID/OD/W (mm)*	Axial Z_1: Z_2 (mm)**	Des. J_{eng} (A/mm^2)
C1-Inner	220*/252/78	-270 : 270	140
C1-Outer	252*/316/78	-270 : 270	210
C2-in-Inj	250/320.5/90	-370 : -280	140
C3-out-Inj	320.5/391/90	-370 : -280	180
C3-out-comb	351/391/60	-150 : -90	180
C4-Middle	351/391/60	-30 : 30	-200
C5-Extr. (1 & 2)	351/391/60	80 : 140 200 : 260	180

* Minimum ID and OD of the hexagonal shape of the closed-loop-coil, W is the coil axial length.

** Axial coil location Zs are referenced in the center of the closed-loop-coil.

COIL SUPPORT AND STRESSES

Figure 2 shows a sectional view of the updated MARS-D magnet cold mass comprised of the NbTi coils and the support structure. After exploring the possible schemes for coil clamping, a shell-based technique of Bladder and Key [3], schematically illustrated in Fig. 3, developed by the BCMT (Berkeley Center for Magnet Technology) at LBNL has been chosen to radially clamp the MARS-D magnet coils. 2-D and 3-D stress analyses of the MARS-D magnet system have shown that the MARS-D magnet comes with substantially lower stress compared to either a NbTi or a Nb_3Sn magnet using the existing "Sext-In-Sol" magnet geometry for 28 and 45 GHz operations. Comparisons of the maximum coil stresses for the three high-field ECRIS magnets at designed excitations are tabulated in Table 2. The lower stresses on the NbTi coils of the MARS-D magnet will benefit the operation reliability. Row 4 of Table 2 shows that MARS-D at 45 GHz operation has the lowest stored energy of the three at 560 kJ. The substantially lower stored energy in MARS-D magnet system is a result of its smaller magnet volume since the system stored energy is linearly proportional to both the conductor wire length and wire current squared. A five-cooler wet-closed cryostat with a hexagonally shaped warm bore matching the MARS's closed-loop-coil shape has been planned and will be fabricated by a commercial company.

QUAD-FREQUENCY HEATING

As shown in Fig. 4, a minimum-B field configuration has many closed, nested ECR Heating (ECRH) surfaces, which can be used to energize plasma electrons by injecting appropriate microwave frequencies simultaneously. Double-frequency plasma heating was successfully demonstrated enhancing the ECRIS performance in the 1990's [4] and is commonly employed in high charge state ECRISs. Further benefits were demonstrated with the first use of triple-frequency heating in SECRAL-II [5]. One of the merits of multi-frequency plasma heating in ECRISs is that it can efficiently combine more wave power, from a number of low-power wave sources, through the nested ECRH surfaces into the plasma.

As a 45 GHz 20 kW microwave source is not yet available in the North America, we plan to commission MARS-D using a combination of four-frequencies, 22, 28, 35 and 45 GHz, with a total power of ≃ 4 kW as listed in Table 3, to establish a baseline performance before an eventual power upgrade to ~ 20 kW. Quad-frequency plasma heating should provide an opportunity to further study the effects of multi-frequency plasma heating in high charge state ECRISs, especially for the production of low-intensity ultra-high-charge-state ion beams.

The use of four-frequency heating will also allow investigations into the effects of power density in ECRISs and serve as a test of one of Geller's scaling laws stating that the microwave power P_μ dependence on the angular frequency ω, the optimum charge state q_{opt} and the ECRH volume V (volume enclosed by the ECRH surface), is summarized as [6]:

$$P_\mu/V \sim \omega^{1/2} q_{opt}^3 \quad (1)$$

The third generation sources have seen approximately a doubling of frequency from second generation (2nd: 14-18 GHz, 3rd: 24-28 GHz), while the heating volumes and injected microwave powers have increased a factor of 3-5. For example, P_μ and V in AECR-U (14 GHz) are 2.1 kW and ~ 300 cm^3, while in VENUS (28 GHz) are 10 kW and ~ 1300 cm^3. These parameters result in a P_μ/V ratio of ~ 7.0 W/cm^3 in AECR-U and about ~ 7.5 W/cm^3 in VENUS, i.e., about the same for the two generations of ECRIS. So far it is not clear what and how important a role the ECRH volume plays in the greatly enhanced VENUS performance over AECR-U which seems to contradict Geller's scaling mentioned above [6]. Thus an investigation into the effects of ECRH volume could yield a better understanding of the ECR plasma.

The ECRH volume for each planned frequency in MARS-D is computed and listed in column 4 of Table 3. For instance, the 45 GHz ECRH volume in MARS-D is about 2.3 – 2.5 liters, about a factor of 2-3 of the 28 GHz volume in MARS-D or VENUS. In the future, one could analyze the performance of the four ECRIS generations to explore the advantages and differences for a better understanding and revisit the wave power scaling in question if needed. The quad-frequency heating capability in MARS-D will also make it possible to study the effects of each of the four ECRH volumes in a more systematic and detailed manner.

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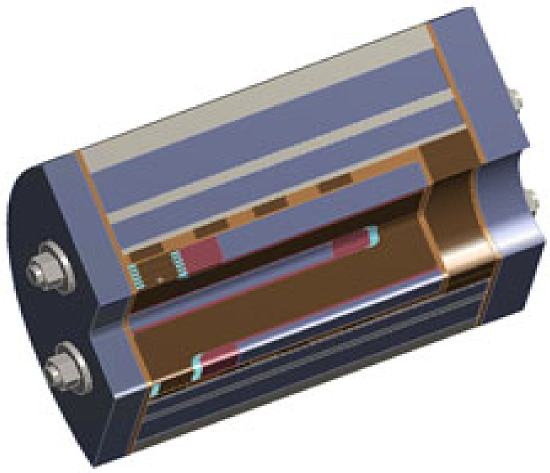
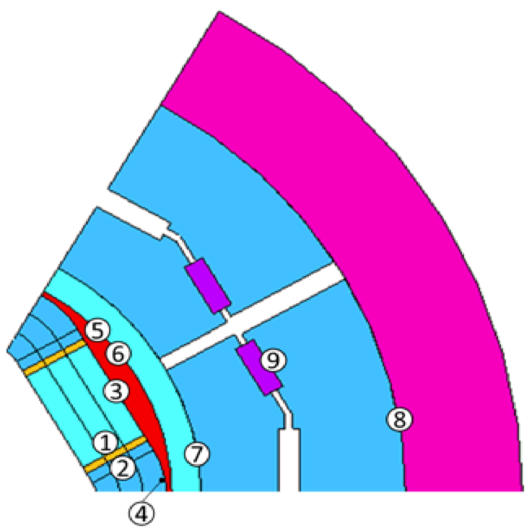


Figure 2: A sectional view of the optimized MARS-D NbTi magnet cold mass.



1. Coil to MoCu pole; **2.** MoCu to Iron pole; **3.** Coil/MoCu pole to Mandrel; **4.** Iron pole to Mandrel; **5.** Mandrel to Solenoid; **6.** Mandrel to Mandrel rib; **7.** Mandrel rib/Solenoid to Pad; **8.** Shell to Yoke; **9.** Yoke/pad to Key.

Figure 3: Interfaces between different cold mass materials are indicated. A Bladder and Key system will be used to radially pre-stress the coils of the MARS-D NbTi magnet.

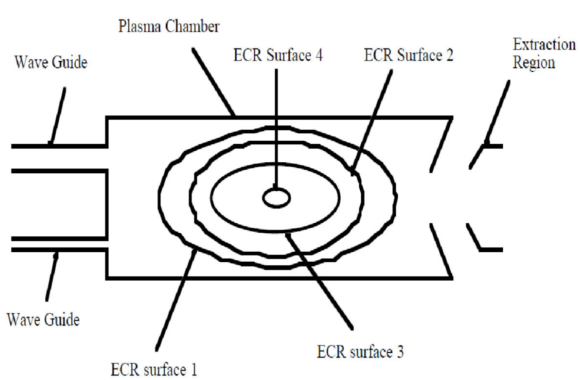


Figure 4. A schematic view of four nested ECR surfaces in a minimum-B field inside a plasma chamber of a high charge state ECRIS [4].

Table 2: Maximum Magnet Coil Stress of Three Magnet Systems for MARS-D, FRIB VENUS and IMP FECR

	FRIB VENUS[1]	**IMP FECR**[2]	**MARS-D**[3]
Frequency	28 GHz	45 GHz	**45 GHz**
Sextupole	140 MPa	144 MPa	**80 MPa**
Solenoids	90 MPa	100 MPa	**55 MPa**
Sys. stored Energy	720 kJ	1600 kJ	**560 kJ**
Geometry	Sext-In-Sol	Sext-In-Sol	**MARS**
Conductor	**NbTi**	**Nb_3Sn**	**NbTi**

[1] H. Felice, Report and Review on the FRIB VENUS magnet (Oct 2013) and (Sept 2014, unpublished).
[2] M. Juchno, Report on the IMP 45 GHz ECRIS magnet preliminary design review (Dec 2016, unpublished).
[3] M. Juchno, MARS-D NbTi Magnet Stress Analysis (June 2020, unpublished).

Table 3: Quad-frequency Heating Planned for Energizing the MARS-D Plasma

f (GHz)	**Max. Power (kW)**	**B_{ecr} (T)**	**ECRH V (Liter)**
22	1.5	0.79	0 – 0.4
28	1.0	1.00	0.5 – 0.9
35	1.0	1.25	1.1 – 1.5
45	0.5	1.61	2.3 – 2.5

Total power of 4 microwave sources ≃ 4.0 kW.

CONVENTIONAL SOURCE COMPONENTS AND BEAM OPTICS

A full superconducting ECRIS consists of three component categories: 1. The superconducting magnet; 2. The microwave sources; and 3. The conventional source components. Category 3 is the remainder as it is not addressed in the above Sections. To save engineering efforts and costs, most of the MARS-D conventional source components will be duplicated from the VENUS source system (e.g., beam optics, beam transport line, and ion beam analysis). Some of these duplications will involve minor revisions or simplifications, such as eliminating remote adjustment of the gap between the puller electrode and the extraction aperture, as VENUS is largely insensitive to the gap distance. The injection assembly will undergo somewhat larger changes, shortening it as much as possible to ease routine operations. The plasma chamber for MARS-D should meet a few requirements. First, it should be fabricated with a hexagonal shape matching the warm bore of the cryostat to maximize the utilization of the generated sextupole fields. Second, it should employ high x-ray attenuation in the

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plasma chamber to reduce the x-rays getting into the cryostat. Third, it should be able to sustain an anticipated 20 kW of wave power needed for intense ion beam production. A scheme, shown in Fig. 5, is being explored as a good candidate for the desired plasma chamber. A single rectangular water channel of ~ 21 mm^2 cross section is roughly equivalent to a single tube of 5-mm-diameter, and two of these channels near each plasma flute should be able to handle the anticipated maximum power deposition in the walls for ~ 20 kW operation.

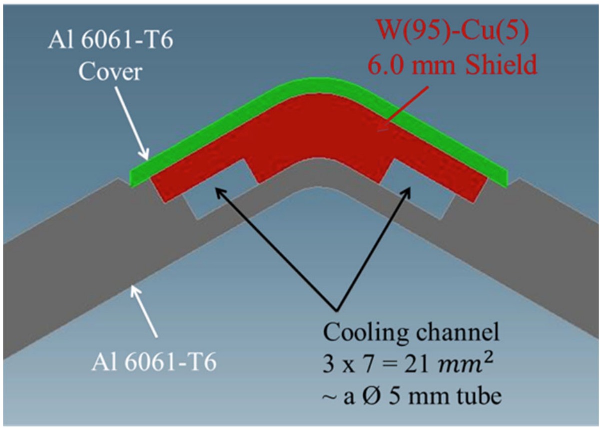

Figure 5. A cross-sectional view of a plasma flute in a hexagonal-shape plasma chamber with a W(95)/Cu(5) x-ray attenuator embedded inside the cooling channel.

For x-ray attenuation, tungsten will be used in place of tantalum as they have approximately the same atomic number, but tungsten is approximately 20% more dense and will attenuate more x-rays for the same thickness. Numerical computations indicate that a 6-mm-thick W(95)/Cu(5), planned for embedding in the MARS-D plasma flutes, will attenuate x-rays of energy ≤ 1 MeV by more than a factor of 2 compared to the 2 mm Ta shielding used in VENUS. This increased x-ray attenuation will help reduce the dynamic thermal load in the cryostat to keep the magnet functional at high frequency and power operation. The goal for the new W/Cu attenuator is to cope with at least the 4 kW power operation and a central field B_{min} of about 0.8 - 1.0 T during the commissioning which is substantially higher than in VENUS and could lead to very high yield of energetic x-rays [7]. The source commission with 4 kW should set up a baseline for future operations with higher power. Future solution is planned for the worst scenario by sacrificing more radial space to increase x-ray attenuation with thicker W/Cu slab and operating the source with as low B_{min} as possible to handle the operations with microwave power up to 20 kW.

DISCUSSION

The above presentation and discussion have shown that the MARS-D ECRIS is converging and nearly finalized on all the technical aspects. The optimized MARS magnet design and its lower coil stress are advantageous and should improve the operational reliability of the NbTi magnet for MARS-D. Once the NbTi MARS-magnet is constructed and tested, we will have passed the most difficult step, leaving only the fabrication of conventional source components and procurement of microwave sources. The utilization of quad-frequency plasma heating, even with limited power up to only 4 kW, will be a first for ECRISs. It could possibly lead to further enhancements of ECRIS performance, especially on the production of ultra-high charge state ion beams. In addition it will provide a new opportunity to study the merits of multiple-frequency plasma heating which will benefit the future ECRISs.

In summary the design of the 45 GHz MARS-D ECRIS has been optimized and source fabrication will begin once funding is available.

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