POSSIBLE OPTIMIZATIONS OF EXISTING MAGNET STRUCTURES FOR THE NEXT GENERATION OF ECRIS

D. Z. Xie†, W. Lu[1], G. Sabbi, D. S. Todd
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[1]also at Institute of Modern Physics, Lanzhou 730000, China

Abstract

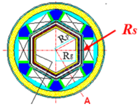
The next generation of Electron Cyclotron Resonance Ion Sources (ECRISs) will operate with higher magnetic fields and higher heating frequencies than those currently in use. Constructing a min-B configuration with higher confining fields is the prerequisite for this next generation of sources. There are three leading candidates for superconducting magnet structures in future ECRISs: a Mixed Axial and Radial field System (MARS) that merges the sextupole racetrack coils and segmented end-solenoids into an exotic closed-loop-coil; a classical structure of Sextupole-In-Solenoids; and a non-classical structure of Solenoids-In-Sextupole. Focusing on efficient magnetic field generation, this article briefly reviews the advantages and disadvantages of each of these magnet structures. Though Sext-In-Sol and Sol-In-Sext magnetic structures using NbTi conductor have been proven in current ECRISs, there are still rooms for improvements of these magnet structures. Potential optimizations to these existing magnet structures, such as using a non-conventional sextupole magnet consisting of either V-bend or skew coils, are discussed. The development status of a MARS NbTi magnet for a new ECRIS at LBNL will be also presented.

INTRODUCTION

Geller's scaling laws [1] predict that ECRIS performance will improve with magnetic fields and heating frequencies. This is the most effective path as demonstrated by the successful ECRIS developments in the past decades, especially the great achievements of the 3rd generation NbTi-magnet-based ECRISs [2-7]. Future operations with even higher magnetic fields require superconducting magnet systems capable of generating higher strength min-B fields ($B > 4$ T) for operations at frequency $f > 28$ GHz. Presently there is a novel magnet system under development at LBNL, MARS (Mixed Axial and Radial field System), which merges a sextupole and two segmented end solenoids into a closed-loop-coil to efficiently generate a high strength min-B configuration. This structure is unique in that its closed-loop-coil generates not only the high radial field but also contributes substantially to the axial field. Once the MARS magnet structure has been successfully developed, it will play an important role in constructing future high-field ECRISs utilizing either NbTi or Nb_3Sn magnets [8, 9]. This new magnet structure, along with the existing classical Sextupole-In-Solenoids (Sext-In-Sol) and the non-classical structure of Solenoids-In-Sextupole (Sol-In-Sext), shown in Fig. 1, will provide three base magnet systems for constructing future ECRISs. Table 1 lists the advantages and disadvantages of each of these structures. MARS' closed-loop-coil with its minimized forces on coils stands out as the magnet choice that harnesses the advantages but avoids the disadvantages of the two existing magnet structures. However, a price is paid in increased complexity in coil winding and the magnet cryostat, in which hexagonally-shaped warm bore and inner thermal shield are required to match the MARS cold mass [9].

Table 1: Comparison of the Three Potential Magnet Systems for Future ECRISs

System	Advantages	Disadvantages
a) **Sext-In-Sol**	Better utilization of the radial field **(~ 50%)***	Bulkier magnet and cryostat, higher and complex interaction forces
b) **Sext-In-Sol**	Lower and simpler interaction forces, smaller magnet and cryostat, simpler fabrication, lower cost.	Inefficient utilization of the radial field **(~ 34%)***
c) **MARS**	Least and simplest interaction forces, uses substantially less conductor, smallest magnet and cryostat, Best utilization of the radial field **(~ 67%)***	Complex fabrication of the closed-loop coil, slightly complex cryostat.



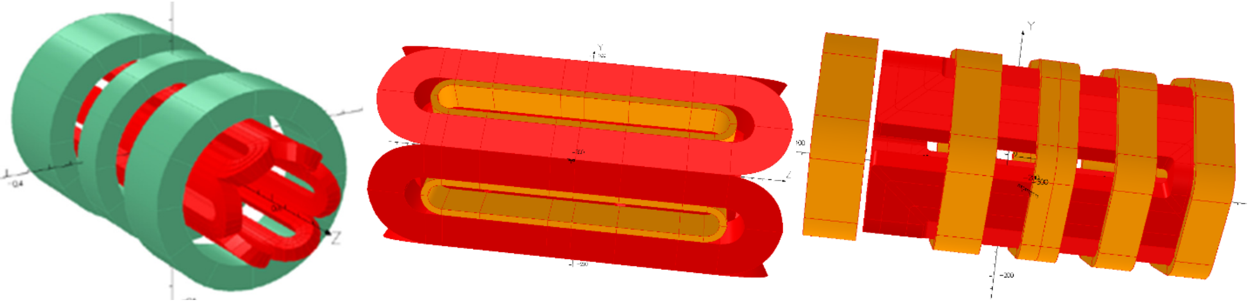
*: *Defined as square of the ratio of the plasma chamber inner radius Rc over the smallest inner radius Rs of the sextupole coil:* $(Rc/Rs)^2$.

The shortcoming of existing designs comes when looking toward the future with ECRIS operation at or above 45 GHz. For conventional operation of these sources at 45 GHz frequency, the required axial fields (6.5 and 3.3 T for injection and extraction) and radial fields (3.3 T at the wall) are shown in Figs. 2(a) and 2(b), respectively. The question arises as to whether there is any room to increase the magnetic field generation efficiency, where better efficiency would mean achieving the required fields with the lower total coil excitations CE = LI (wire length x current). A reduced coil excitation should lead to lower magnetic forces, system stored energy, conductor loading and smaller superconductor volume resulting in reduction of overall magnet size. Field calculations with TOSCA indicate that there are optimizations that can be made to the current structures, and they are presented below.

---

†email address: zqxie@lbl.gov

ISBN 978-3-95450-186-1



a) Sext-In-Sol b) Sol-In-Sext c) MARS

Figure 1: Schematic layout of the three possible magnet systems for future higher-field ECRISs.

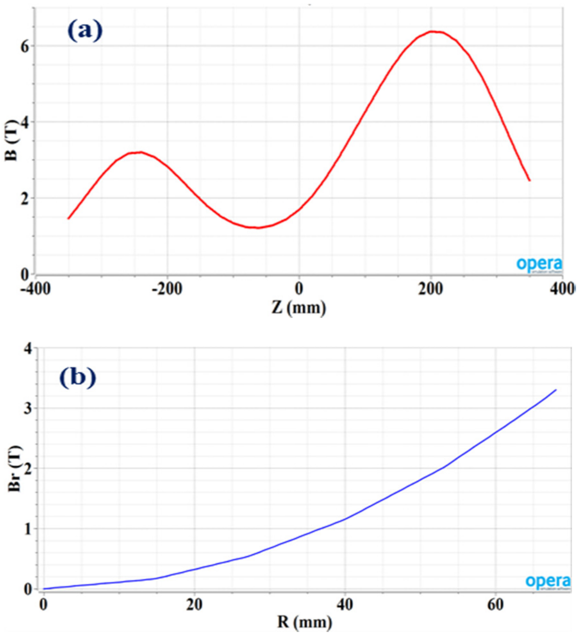


Figure 2: The axial (a) and radial (b) field profiles needed for an ECRIS to operate up to 45 GHz.

A SOL-IN-SEXT MAGNET WITH A SKEWED SEXTUPOLE

SECRAL, the first ECR ion source built with a Sol-In-Sext NbTi magnet, operates up to 24 GHz and has produced a number of CW beam records, validating the Sol-In-Sext magnet structure [10]. In order to generate the magnetic fields needed for operations up to 45 GHz, a straightforward path would be to simply replace the NbTi conductors by Nb_3Sn. Calculations show that this simple replacement would lead to maximum fields of 12.4 T on both the symmetric sextupole and the injection coils. Such high fields on the conductors are acceptable with the use of the very high J_c Nb_3Sn conductors, such as the Oxford Instruments Rod Restack Process (RRP) and the Brucker Powder in Tube (PIT). However the magnet performance can be significantly improved with a number of modifications to this magnet structure.

As schematically shown in Fig. 3, a magnetic structure here-to-fore referred to as a Skewed Sol-In-Sext design, would reduce magnetic fields on coils through the following modifications relative to the SECRAL parameters:

- Center section of the sextuple magnet skewed to lower the maximum field on the solenoids;
- Length of the magnet increased from 725 to 750 mm;
- Thickness of the sextupole reduced from 72 to 52 mm;
- Inner radii of the injection and extraction solenoids increased 3 mm, from 90 to 93 mm;
- Injection solenoid divided into two coils (1 and 2) to lower the loading;
- Plasma chamber radius R increased from 63 to 68 mm by slightly optimizing the cryostat to gain a 2 mm radial extra spacing;
- Sextupole, injection and extraction coils operate at higher current densities.

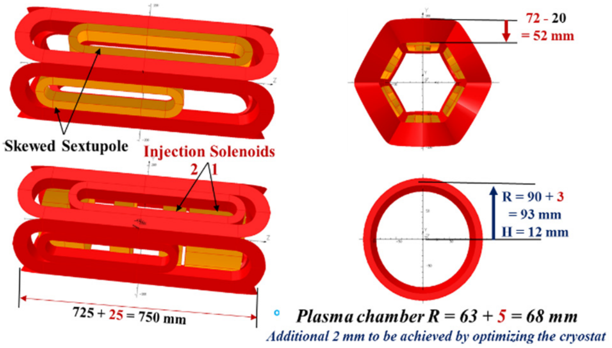


Figure 3: Layout of a Skewed Sol-In-Sext magnet constructed with an asymmetric sextupole and injection solenoid mechanically split (1 and 2) for reducing the maximum fields on the coil conductors.

Table 2 summarizes and compares the main parameters of the two magnet structures for generating the same min-B field for 45 GHz operations. The advantages of the Skewed Sol-In-Sext magnet can be easily seen and are listed below:

- Lower maximum fields on the coil conductors lead to thinner/smaller coils operating at higher currents for about the same and lower loading;
- Substantially lower system stored energy could help mitigating the quench heating somewhat in the cold mass with less LHe consumption;

ISBN 978-3-95450-186-1

- Greatly reduced the superconducting wire cost. If built with the same conductor wire the Skewed Sol-In-Sext uses only about ~ 60% of that would be needed for a conventional Sol-In-Sext magnet.

The primary drawback of the Skewed Sol-In-Sext is the requirement of two set of winding fixtures for the asymmetric sextupole coils instead of one set for the symmetric sextupole coils. Nevertheless, such an optimization to the Sol-In-Sext magnet would provide an option to a next generation ECRIS to be built with the Sol-In-Sext magnet structure.

Table 2: Sole-In-Sext Magnet System Variations

	Skewed Sol-In-Sext	**SECRAL Sol-In-Sext**
Magnet Length (mm)	750	725
Thickness (mm) of the sextupole coil	52	72
Designed plasma chamber ID R (mm)	136	126
ID/OD (mm) of the Injection Solenoid	186/210	180/210
Designed engineer current density $\mathbf{j}_e$ (A/mm^2) in Sext & Injection 1/2 coils	285/600/500	250/450
Peak fields on conductor: Sext & Injection 1/2 coils (T)	11.8/9.2/10.0	12.4/12.4
Loading Factor (%) on OST M grade conductor Sext & Injection 1/2 coils*	75/75/75	76/85
System Stored E (MJ)	1.0	1.7

*: 70% of bare wire packing assumed.

A SEXT-IN-SOL MAGNET WITH A V-BEND SEXTUPOLE

The Sext-In-Sol magnet structure was the first superconducting magnet structure used in an ECRIS and remains the most commonly used in the most recent (3rd) generation sources. It is built with a sextupole consisting of six coils assembled into an arched circle which, in conjunction with a circular plasma chamber, leads to ~ 50% utilization of the generated radial field in most of the sources. The disadvantage of this well-proven structure is the very complex and strong interaction forces require a fairly bulky magnet footprint and cryostat. Like the Sol-In-Sext structure there is room for further improvement.

A Sext-In-Sol structure using Nb_3Sn coils along with an arched sextupole to generate a min-B field for operations up to 45 GHz, named FECRAL, is under a joint engineering study at LBNL and IMP/CAS, China. The magnet structure of FECRAL is a slight variation of that designed for a 4th generation ECRIS for operations up to 56 GHz [11]. A possible optimization to this classical magnet system is to replace the arched sextupole with a hexagonally-shaped sextupole consisting of six “V-bend” coils. Figure 4 shows a V-bend Sext-In-Sol magnet constructed with a sextupole consists of six azimuthally V-shaped track coils and a mechanically split injection solenoid for slightly reduced maximum fields on the coil conductors. Using a hexagonal plasma chamber to match the sextupole shape, radial field utilization could equal that of MARS (~ 65%) with its hexagonal chamber. However, a distinct difference between this structure and MARS is the V-bend sextupole contributes nothing to the axial field which requires more of the solenoids for this structure.

Table 3 summarizes and compares the main parameters of the V-bend and the preliminarily designed (FECRAL) arched Sext-In-Sol magnets. With generation of the needed maximum radial field ≥ 3.2 T at the chamber inner surface, the major radius of 82 mm of the hexagonal plasma chamber is about 10% larger than the designed 75 mm for the arched sextupole, though the excitation of the V-bend sextupole is only ~ 85% of the arched sextupole. The overall footprints of the V-bend and arched magnets are essentially the same, but the V-bend sextupole operates at substantial lower current leading to lower maximum fields on the sextupole coils and greatly reduced conductor loading: a very preferable merit for magnetic field generation. The relatively low coil loading factors when using bronze (< 80%) given in Table 3 for both the sextupole and injection solenoid coils indicate that a V-bend magnet could be built with this wire, while the arched magnet would need to be built with Oxford Instruments’ M-grade or higher grades of wires.

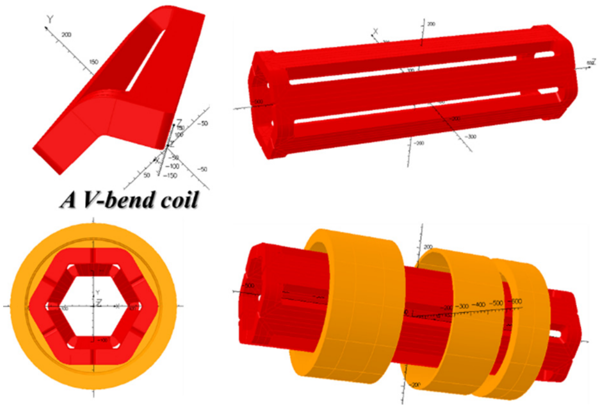


Figure 4: Schematic assembly of a V-Bend Sext-In-Sol magnet in which the sextupole constructed with six azimuthally V-shaped coils reduce the maximum fields on the coils. A hexagonal plasma chamber is to be used to match the shape of sextupole for better radial field utilization efficiency.

The fabrication complexity of a V-bend and an arched sextupole coil may vary slightly, but the coil clamping will differ substantially due to the geometric variation of the sextupoles. The issues of different coil clamping schemes need be addressed by stress analyses to come up better solutions in the actual developments.

Table 3: Sext-In-Sol Magnet Variations

	V-bend	**Arched* (FECRAL)**
Total Magnet Length (mm)	940	947
Thickness (mm) of the sextupole coil	35	26
Designed max. plasma chamber radius R (mm)	82	75
ID/OD (mm) of the Injection Solenoid	340/410	310/372
Designed engineer current density j_e (A/mm^2) in Sext/Injection coils	230/290	440/320
Peak fields on conductor Sext/Injection coils (T)	9.4/9.5	10.8/9.5
Loading Factor (%) Sext/Injection coils** on Bronze conductor or OST M-grade conductor	72/77 60/63	98/80 78/65
System Stored Energy (MJ)	1.17	1.15

*: Based on its preliminary design layout.
**: 70% of bare wire packing assumed.

STATUS OF MARS COIL PROTOTYPING

To develop the winding techniques and fixtures for fabricating the MARS 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 [9]. The dimensions of the prototyped copper coil are about the same except the thickness is ~ 1/3 of the designed coil. Figure 5 shows the completed prototype copper coil with 396 turns wound while 420 turns were expected for a perfect winding. To get a feel of the agreement of the field strength and profile of the fabricated coil to the designed, a field mapping was conducted by energizing the copper coil with current of 1.00 A. Figure 6a and 6b show the measured axial and radial field profiles in comparison to the TOSCA calculations. Because of the complexity to completely simulate the coil-end winding layers that alternatively spread over a 112 mm width compared to the 92 mm width of the straight bars, the simulated coil end is simplified to three sections with two air gaps of 1.0 cm each in between. It is convincible that this simplified simulation has under estimated ~ 2% of the axial peak fields and overestimated ~ 3-4% of the center field, respectively as shown in Fig. 6a. In the radial field profile the discrepancy of the average measured Br peak field is merely $\leqslant$ 1.0 % to the calculation. It is reasonable to say that the overall measurement agrees very well with the calculation and has demonstrated the field tomography of the MARS closed-loop-coil.

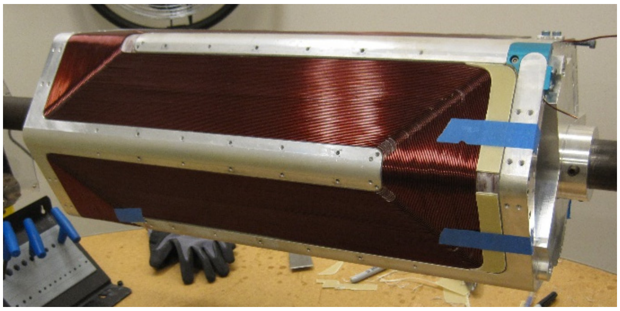


Figure 5: The wound prototype closed-loop copper coil in its winding fixture prior to field mapping.

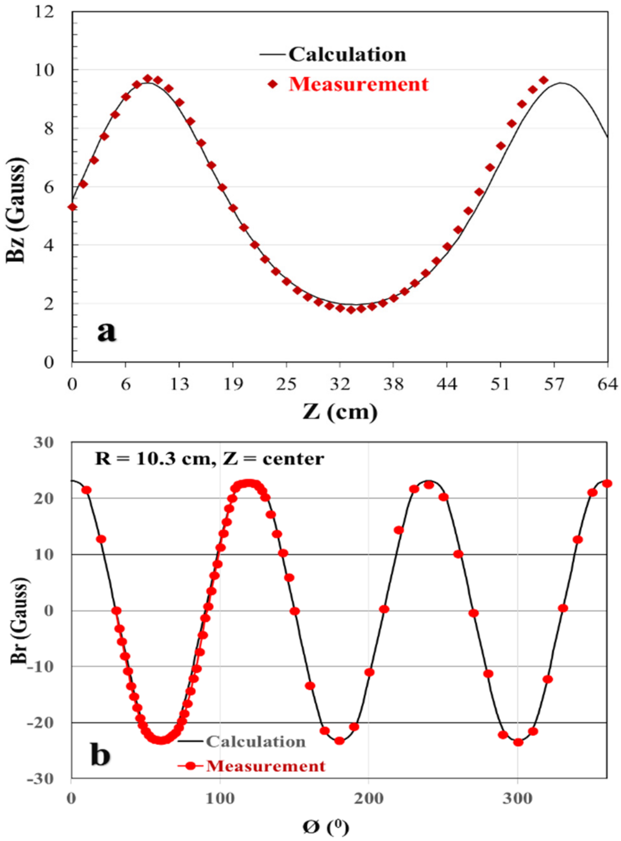


Figure 6: **a**. The measured axial field profile (red diamonds) of the prototype copper coil in comparison to the TOSCA calculation; **b**. The measured central radial field profile (red dots) at R = 10.3 cm in comparison to the calculation.

SUMMARY

The possible optimizations of magnet coil layout presented above, which can be further refined, have shown that there is still room for further improving the magnet design for ECRISs. The key enhancement comes essentially from converting the generated radial fields into the effective fields inside the ECRIS plasma chamber, i.e. increasing the utilization efficiency of the generated magnetic fields. For a given min-B configuration, the enhanced utilization of the generated fields leads to lower the maximum fields on the superconductors and loading, very preferable features for constructing a high field superconducting magnet system.

The field mapping of the prototype copper coil has demonstrated excellent agreement with the designed field profiles and the completion of the coil winding has demonstrated the techniques needed for fabricating an exotic-shape coil for a MARS magnet system. These accomplishments have further demonstrated the feasibility of a NbTi MARS-magnet-based 3rd generation ECRIS: MARS-D [9].

REFERENCES

[1] R. Geller *et al.*, "The Grenoble ECRIS Status 1987 and Proposals for ECRIS Scalings," in *Proc. of the 8th ECR Workshop*, NSCL Report: MSUCP-47 (unpublished), E. Lansing, MI, USA, 1987, p1.

[2] S. Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, and G. Melin, *Rev. Sci. Instrum*. **72**, 4090 (2001).

[3] C. M. Lyneis and Z. Q. Xie, "Concept for a third generation ECR source at LBL," in *Proc of the 12th International Workshop on ECR Ion Sources*, RIKEN, Japan, 1995, p. 119, (unpublished).

[4] H. W. Zhao *et al*., *Rev. Sci. Instrum*. **77**, 03A333 (2006).

[5] P. A. Zavodszky *et al*., *AIP Conf. Proc*. 749, 131 (2005).

[6] T. Nakagawa *et al*., *Rev. Sci. Instrum*. **81**, 02A320 (2010).

[7] B. S. Lee, S. Choi, J. H. Yoon, J. Y. Park, and M. S. Won, *Rev. Sci. Instrum*. **83**, 02A347 (2012).

[8] D. Z. Xie, *Rev. Sci. Instrum*. **83** 02A302 (2012).

[9] D. Z. Xie, J. Y. Benitez, A. Hodgkinson, T. Loew, C. M. Lyneis, L. Phair, P. Pipersky, B. Reynolds, D. S. Todd, *Rev. Sci. Instrum*. **87**, 02A702 (2016).

[10] L. Sun *et al*., *Rev. Sci. Instrum*. **87**, 02A707 (2016)

[11] C. Lyneis, P. Ferracin, S. Caspi, A. Hodgkison and G.L. Sabbi, *Rev. Sci. Instrum*. **83** 02A301 (2012).