DESIGN STUDY OF A HIGHER-MAGNETIC-FIELD SC ECRIS AT IMP

D. Z. Xie*, W. Lu#, X. Z. Zhang and H. W. Zhao
Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS), Lanzhou 730000
People's Republic of China

Abstract

Development of ECR ion source has demonstrated that, as the empirical scaling laws summarized, higher magnetic field with higher operation frequency will greatly improve the source performance. Based on the great success of SECRAL at IMP, a higher-magnetic-field SC ECRIS is planned to meet the new accelerator demands. However, there are many practical issues in the design and construction of a higher-field SC ECRIS which need addressed. In this paper we will present and discuss the design features of the higher-field SC ECR with a maximum axial field of 7.0 T and a radial field of 3.5 T at the plasma chamber wall of ID 110 mm, and operating frequency up to 50 GHz.

INTRODUCTION

Performance of high-charge-state Electron Cyclotron Resonance Ion Source (ECRIS) has been greatly improving since its advent and especially in the past decade, thanks to the continuous increase of magnetic-field-strength and operating frequency. Although a full understanding of the detailed physics process involved in ECR plasma is still in the horizon, higher-magnetic-field combined with higher-operating-frequency remains nowadays the relatively easy and straightforward way to further the development of ECRIS. Based on the empirical scaling laws [1], there were a few fully superconducting (SC) ECRISs all built with NbTi magnets in the past decade. At safe current loadings (up to about 90% of its critical current), the highest field strength reaches 4 T on axis and 2 T at the plasma chamber wall of ID 100 to 140 mm for operating frequency up to 28 GHz. These SC ECRISs have significantly improved the ECRIS performance by a great factor in both the ion beam intensity and charge state. To further enhance the ECRIS performance to meet new demands, higher-field ECRISs have been proposed and are under design. The maximum field strengths are to reach 8 T on axis and 4 T at the plasma chamber wall by using the higher-critical-current Nb_3Sn wires to construct the SC magnets [2].

At the Institute of Modern Physics (IMP), the great success of SECRAL has demonstrated that further ECRIS performance is not only possible but also needed. The institute is planning a future facility of higher-energy and higher-beam-intensity for nuclear physics research. This new facility requires very intense ion beams, for example, at least 15 pμA of Bi^{31+} and about the same intensity of U^{33+} are to be extracted from the proposed accelerator. Such intense beam intensities require at least a new higher-field SC ECRIS that leads to this design study.

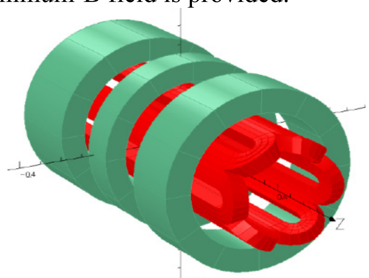
A BRIEF REVIEW OF THE SC MAGNET STRUCTURES FOR ECRISs

Presently there are two different types of magnet structures used in the SC ECRISs. Figure 1 shows the "classical" structure, the sextupole coils sit inside the solenoid coils, that is used so far in all ECRISs but one. Because of the very strong Lorenz interaction forces, especially the repulsing force, the sextupole coils have to be ended at a good distance away from the solenoid coils so that the interaction forces can be reduced. The lengthy end extension results in a bulky magnet structure and cryostat. Sometimes a set of liquid-metal-filled bladders that increases the complexity of magnet fabrication is used to harness the very strong forces [3]. So far the best embodiment of the classical magnet structure remains to be the LBNL VENUS, the first ECRIS that has been designed and reached 4 T on axis and 2 T at the plasma chamber wall of ID 140 mm [4]. Its magnet assembly is wound with NbTi wires of high Cu/Sc Ratios of 3.0 and 4.0 for better thermal stability. Since 2002 it has been commissioning at 18, 28 GHz and double-frequency heating at 18+28 GHz with wave power up to ~10 kW and has produced very great performance. A few example beams produced with VENUS are listed in Table 1 below.

The "non-classical" magnet structure is shown in Figure 2. A striking feature of this structure is that the sextupole coils not only sit outside the solenoid coils but also ended right next to the solenoid coils. A set of simple cold irons, no bladders, is used to clamp down the magnet coils and reduce the stray field right inside the cryostat. This non-classical magnet structure results in a smaller magnet assembly and simplifies somewhat the fabrication process. The IMP's SECRAL is the first SC ECRIS built with this non-classical magnet structure. All the SECRAL magnet coils are wound with the NbTi wires of low Cu/Sc Ratio of 1.35. The field maxima are 3.6 T on axis and ~2.0 T at the plasma chamber wall of diameter of 126 mm. SECRAL had begun its commissioning at 18 GHz with maximum microwave power of about 3.5 kW in 2005. Though operated at lower magnetic fields, lower frequency and wave power, SECRAL has produced very compatible results in comparison to VENUS at higher fields, higher frequency and wave power. So far SECRAL has reliably provided more than three-thousand hours of ion beams to the IMP accelerators and sometimes the operation lasted months without system failures. SECRAL has recently begun its commissioning operation at 24 GHz and already shown better performance than at

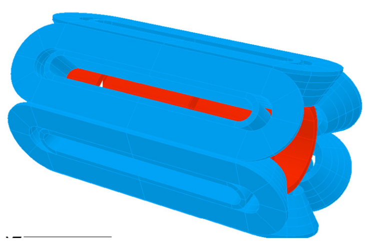
* Visiting Scientist
# Also of the Graduate School of CAS, Beijing 100049, P. R. China

18 GHz. Shown in Table 1 is a summary of a few example beams of SECRAL operating at 18 GHz and the preliminary results at 24 GHz [5], as well as VENUS performance for comparison. The great performances of SECRAL and VENUS have demonstrated that SC ECRIS is independent of the magnet structure, so long as a high-strength Minimum-B field is provided.



Sextupole-inside-solenoid

Figure 1: The classical magnet structure for ECRIS.



Solenoid-inside-sextupole

Figure 2: The non-classical magnet structure.

Table 1: Example Beams from SECRAL and VENUS

	Q	SECRAL 18 GHz <3.2 kW μA	SECRAL 24GHz 3-4 kW μA	VENUS 28 GHz 5-9kW μA
^{16}O	6+	2300		2860
	7+	810		850
^{40}Ar	12+	510	650	860
	16+	73	149	270
	17+	8.5	14	36
^{129}Xe	27+	306	455	270
	35+	16	45	28
	42+	1.5	3	0.5
^{209}Bi	30+	191		240
	41+	22		15
	50+	1.5		0.5

DESIGN OF A NEW HIGHER-FIELD SUPERCONDUCTING ECRIS

The studied SC ECRIS reported here is essentially a scaled-up version of SECRAL using Nb_3Sn wires to construct the magnets. The great success of SECRAL has demonstrated the advantages of the non-classical magnet structure in many ways, such as the performance, smaller magnet size and cost effectiveness. Therefore it is very natural to follow a good source as the first step to design a higher-field ECRIS, though it may not necessarily guarantee the best results. Figures 3 and 4 show the axial field and radial field profiles in which the peak axial field reaches 7 T at the injection region and the maximum radial field reaching 3.5 T at the plasma chamber wall of ID 110 mm, hoping a slightly smaller chamber could increase the wave power density and perform as well as a larger chamber. Figure 5 shows a histogram along a pole line at the maximum designed currents. As a norm, a maximum loading of about 90% of the critical current is assumed in this design. Table 2 lists a few key parameters of the new magnet assembly and of SECRAL for comparison.

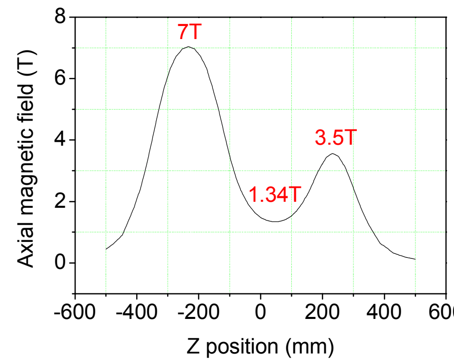


Figure 3: The axial field profile of the SC ECRIS under study. The maximum axial fields reach 7 T at the injection and 3.5 T at the extraction, respectively.

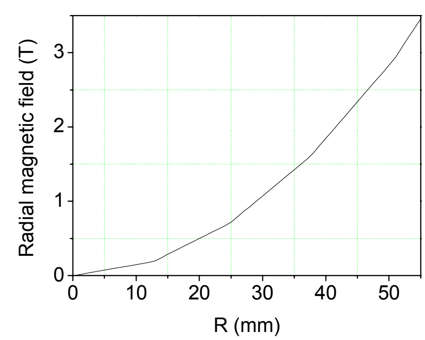


Figure 4: The radial field profile of the SC ECRIS under study which reaches 3.5 T at the plasma chamber of ID 110 mm.

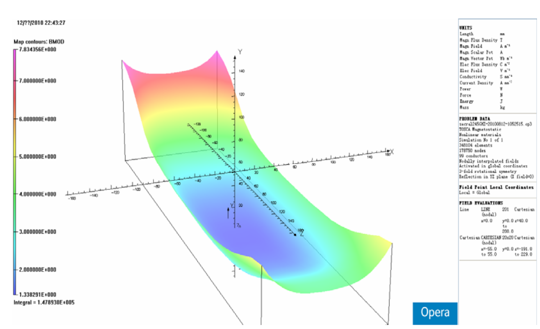


Figure 5: The histogram of the total field inside the plasma chamber that yields a maximum closed contour of 3.6 T inside the chamber at the designed electrode orifice.

Table 2: A Few Key Parameters and Comparison

	New ECRIS <50 GHz	SECRAL 24 GHz
Superconducting Wire	Nb_3Sn*	NbTi (F54)
Critical Jc	400 A /14 T	197 A /9 T
Sextupole Coil (Ampere-Turns)	1,167,000	627,000
Injection Coil (Ampere-Turns)	1,540,000	689,000
Middle Coil (Ampere-Turns)	36,000	162,000
Extraction Coil (Ampere-Turns)	551,000	272,000
Magnet Length (mm)	822	724
Max. Torque (N/M) (a Racetrack Coil)	69.7 E6	8.9 E6
Magnetic Peak Axial Field (T)	7	3.6
Magnetic Radial Wall Field (T)	3.5	1.8
Plasma Chamber ID/Volume (mm/L)	110/4	126/5

*: BRUKER NST 11000 A23 Ø1.0 mm Nb_3Sn wire was used in the design and F54 Ø1.0 mm NbTi wire was used in SECRAL.

DISCUSSIONS

With maxima of 7 T on axis and of 3.5 T at the plasma chamber wall, this magnetic configuration is strong enough, based on the High-B mode [6], to support an operating frequency up to about 50 GHz and it could further significantly enhance the ECRIS' performance. However before it can become a reality, there are a few important issues that must be well addressed. The first is the interaction force among the solenoid coils and the sextupole coils and its resulting torque that has been much more than quadrupled in comparison to the SECRAL. This much higher torque no doubt will pose a dilemma for the magnet clamping. A strong and possibly very deliberate clamping scheme may be required. Secondly, how do the strong interaction force and the huge torque experienced by the individual sextupole racetrack coil affect the Nb3Sn critical current have to be addressed. Though there have been successful high-field coils built with Nb_3Sn wires for non-ECRIS magnets [7], the ECRIS' magnet structure, a mixture of solenoids and a multipole, is more complicated than those simple solenoids or multipole only. Thirdly, unlike the NbTi wire, the Nb_3Sn wire has a pretty poor ductility and it requires a tedious after-coil-winding heat treatment that typically lasts at least one to two weeks at about 700 °C in order to reach its superior critical current. This third issue could lead to a very complex Nb_3Sn magnet fabrication process.

On the other hand, the NbTi magnet has fully demonstrated its workability with exercitation current very close to its critical limit in the built SC ECRISs with either the classical or the non-classical magnet structure. This is why the higher-critical-current Nb_3Sn wires are used in the design of the higher-field ECRIS magnets. However, using NbTi wire has a number of advantages over the uncertain Nb_3Sn wire. Will there be any other NbTi magnet structures that could produce about the same fields discussed above? We have recently begun a magnet structure exploration and the preliminary result is very encouraging and promising. At about the same 90% loading, a novel NbTi magnet structure may be able to produce a minimum-B filed of maximum fields of 6-6.5 T on axis and 3.5-4 T at the plasma chamber wall of IDs 160-180 mm. Somewhat higher radial fields could also be possible at the price of more deliberate structure designs. Furthermore, if this new magnet structure can be fabricated with the Nb_3Sn wires, the maximum fields could reach at least 10 T on axis and 5.5-6 T at the plasma chamber wall of the same diameters, respectively. With maximum fields of 10 T on axis and 6 T at plasma chamber wall, a 70 GHz or higher frequency ECRIS could then be realized which would be a milestone of more than halfway of a 120 GHz ECRIS that Dr. Geller had envisioned decades ago [8]. Unfortunately, this novel magnet structure needs a thorough investigation and hopefully a sound magnetic field calculation and profile design can be reported soon.

Higher magnetic field and operating frequency is the relatively easy way to enhance the ECRIS performance but it comes costly and will run up to the limit of the present superconducting magnet technology in the foreseeable future. To further ECRIS, we should also spend more efforts to investigate other techniques, such as lower frequency heating with a much higher-B mode configuration and microwave heating efficiency [9], etc.

ACKNOWLEDGEMENT

The authors are very grateful to Dr. L. T. Sun for his fruitful inputs and great helps in this study.

REFERENCES

[1] R. Geller, "Electron Cyclotron Resonance Ion Source and ECR Plasma", Institute for Physics Publishing, Bristol, p. 395 (1996).

[2] S. Prestemon *et al*, "Design of a NB_3SN Magnet for a 4th Generation ECR Ion Source**",** IEEE Trans. on Applied Superconductivity, 19(3), p. 1336 (2009).

[3] C. E. Tayler *et al*, "Magnet System for an ECR Ion Source", IEEE Trans. on Applied Superconductivity, 10(1), p. 224 (2000).

[4] C. M. Lyneis, Z. Q. Xie and C. E. Taylor, RSI, 69(2), p. 682 (1998).

[5] H.W. Zhao *et al*, RSI, 81, 02A202 (2010).

[6] T. Antaya & S. Gammino, RSI, 65(5), p. 1723 (1994).

[7] G. Ambrosio *et al*, "Development and Coil Fabrication for the LARP 3.7-m Long Nb_3Sn Quadrupole", IEEE Trans. on Applied Superconductivity, 19(3), p. 1231 (2009).

[8] R. Geller, IEEE Trans NS-26, 1979.

[9] B. Jacquot, private communications.