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HTS MAGNET TECHNOLOGY AS PATH TO FOURTH AND FIFTH GENERATION ECR ION SOURCES

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Abstract

Novel superconducting magnet systems for ECR ion sources (ECRIS) operating at frequencies above 28 GHz is a core technology to be developed. Current state-of-the-art magnet systems are based on the Nb-Ti technology at 4.2 K and are the new standard injectors for next generation heavy ion beam facilities. However, increasing the frequency beyond 28 GHz will further advance the performance of high charge state ECR ion sources. Nb_3Sn provides an immediate option for reaching higher frequencies, but Nb_3Sn designs would ultimately be limited to about 56 GHz. A versatile longer-term option is the high-temperature superconducting magnet technologies, which can enable operations of high field ECRIS magnets at $T \geq 20$ K. The ultimate operating frequency of HTS magnet systems is not limited to 56 GHz but in principle could even attain 84 GHz, due to the critical field and current density limits that can be achieved at high fields. The paper will first discuss the ECR ion source parameters driving the design of the Next Generation Superconducting ECR magnets, and will then focus on HTS magnet technology and its potential to further increase the performance of ECR ion sources.

ECR ION SOURCE PHYSICS PARAMETERS

ECR Ion Source Confinement

ECR ion sources use magnetic confinement and electron cyclotron resonance heating to produce a plasma consisting of energetic electrons (up to hundreds of keV) and relatively cold ions (a few eV). High charge state ions are primarily produced by sequential impact ionization. Therefore, the ions must remain in the plasma long enough (tens of ms) to reach high charge states and the main parameter determining the performance of an ECR ion source is the product of the plasma density and ion confinement time: $(n_e \cdot \tau_i)$. Together with the neutral gas density in the plasma this product determines both the peak of the charge state distribution and the highest charge state that can be produced in the plasma. Following the semi-empirical scaling laws first proposed by Geller [1], the plasma density scales with the square of the frequency $n_e \propto \omega_{rf}^2$. As the frequency increases, the magnetic fields have to be scaled accordingly to fulfill the resonant heating condition for the plasma electrons. As a consequence the plasma confinement time (τ_i) in the trap improves since it is proportional to the average field strength and the axial and radial magnetic mirror ratios B_{inj}/B_{min}, B_{ext}/B_{min}, B_{rad}/B_{min} of the magnetic trap [1].

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Following these fundamental principles, the trend for new ECR ion source constructions has been to design for both the highest confinement fields and highest heating frequency resulting in a number of high performance ECR ion sources developed over the last few decades. Compiling results from these high performing devices, guidelines for the design of an optimized magnetic confinement field configurations were established applicable to any heating frequency of an ion source [2]. These established field ratios are listed below with F_{rf} being the chosen operating microwave frequency for the new ECR ion source, with B_{inj}, B_{ext}, B_{min}, the maxima and minimum fields of the magnetic mirror, and B_{rad} the radial field strength on the plasma chamber wall.

- $B_{ECR} = F_{rf}(GHz)/28(GHz) \cdot T$
- $B_{inj}/B_{ECR} = 4$
- $B_{rad}/B_{ECR} = 2$
- $B_{ext} \approx 0.9 B_{rad}$

For the minimum B-field of the trap one can find [2, 3]

- $B_{min} \approx 0.4 B_{rad}$ and
- $0.4 < B_{min}/B_{ECR} < 0.8$

Another important parameter for establishing the overall plasma confinement is the electron energy distribution in the ECR plasma, which can be characterized by three components: a cold population (20 eV) - important for the overall plasma density and confinement time; a warm population (up to 100 kev) - responsible for the ionization process, and a hot population with a high energy tail reaching up to several hundreds of keV, which is highly confined in the core of the plasma and quasi collissionless. While the hot electron population does not contribute to the ionization process, these hot electrons are nevertheless crucial to establish the electrostatic confinement for the ions in the trap. Therefore, their presence is a necessary condition for the creation of high charge state ions [3]. However, one undesired consequence of this hot electron population is the creation of high energy x-rays that penetrate the plasma chamber and, in the case of a superconducting ECR ion source, add a substantial heat load to the cryostat. It would be desirable to optimize this temperature while minimizing the x-ray production and maintaining a strong electrostatic confinement. Results from recent x-ray studies suggest that this could be possible [4, 5].

Key results from experimental studies to understand the role of the hot energy tail ECR plasma are summarized below:

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- The high temperature tail of the electron energy spectrum (with energies above 200 keV) is key to establishing the electrostatic confinement necessary for the creation of high charge state ions.
- The hot electron temperature neither depends on the magnetic field gradient at the ECR zone as previously believed [6] nor on the heating frequency. The temperature mainly depends on the absolute value of the minimum B-field [4,5].
- For a given minimum B-field higher heating frequencies will result in higher plasma densities (frequency scaling law still applies) [5]
- Lower gradients at the ECR zone improve the microwave heating efficiency [6].
- The plasma density increases linearly with power until a threshold density is reached where non-linear phenomena occur [1]. Therefore, for a given confinement configuration the x-ray heat load depends linearly on the microwave power. The threshold density is proportional to the square of the microwave frequency [4–7].

Tuning Considerations

These results have important consequences for the operation of high field, high frequency superconducting ECR ion sources. Since the electron temperature is nearly independent from the heating frequency, the minimum B-field allows to control the hot electron temperature and therefore the x-ray loading into cryostat at the expense of power efficiency. Consequently, next generation ECR ion sources are typically operated at lower minimum B-fields; high performance superconducting 28 GHz ECR ion sources typically operate with a B_{min}/B_{ECR} between 0.4 to 0.6, while conventional magnet ECR ion sources (6 −18 GHz) can operate at a ratio of B_{min}/B_{ECR} between 0.6 and 0.8 to optimize the electrostatic confinement conditions and microwave heating efficiency in the trap. However, as mentioned above, the magnetic field gradient at the ECR zone improves the heating efficiency and allows to reach higher plasma density at a lower power density. Fig. 1 from [6] illustrates this dependence. While the same charge state distribution and currents can be achieved with both field configurations, the higher minimum B-field (shallower magnetic field gradient at the ECR heating zone) requires only 2/3 of the power to reach the same performance (see Fig. 1 from [6]). As demonstrated in [6], the charge state distributions and the warm electron densities are nearly identical in both cases.

Most superconducting ECR ion sources utilize 4 K cryostats using cryocoolers that typically provide less than 10 W of cooling power. This limitation forces the ECR operator to restrict the tuning range to minimum B-fields B_{min} that balance the available cooling power with the x-ray heat load from the plasma. Since the the absorption coefficient decreases logarithmically with x-ray energy while the x-ray energy increases linearly with B_{min}, the x-ray heatload increases exponentially with the B_{min} value. On the other

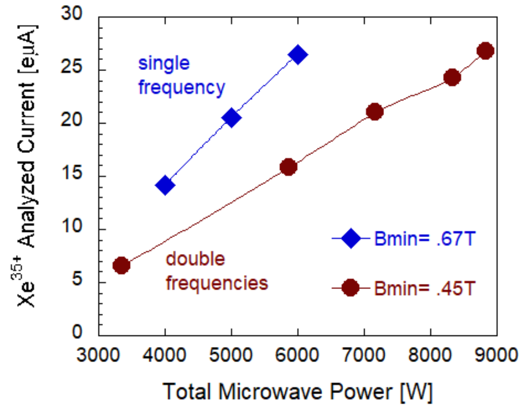

Figure 1: Power dependence of Xe^{35+} production for a B_{min} of 0.67 T using 28 GHz single frequency heating to a B_{min} of 0.45 T using 18 +28 GHz double frequency heating. [6]

hand, for a constant B_{min} field configuration, the x-ray load (plasma density) increases only linearly with power. Consequently, it is often more beneficial to operate at lower B_{min} and compensating the reduced heating efficiency with higher microwave power. This tuning restriction is one of the reasons, why none of the 3rd generation superconducting ECR ion sources have reached their performance limits with microwave power yet.

Status of the field - High Field Superconducting ECR Ion Sources

In the last two decades, Nb-Ti Superconducting ECR ion sources have been established as state of the art injectors for heavy ion facilities. Pioneered by the VENUS ECR ion source [8], which was the first superconducting ECR ion source with a magnetic confinement field optimized for operation at 28 GHz, several ECR ion sources were built for frequencies of 24 GHz to 28 GHz with similar confinement fields using either the same geometry as VENUS (Sextupole magnets are placed inside the solenoids) [9–11], or in case of SECRAL [12], a converted geometry (solenoids are placed inside the sextupole). All of these sources have fulfilled or exceeded their expected performance and continue to improve as more power is coupled efficiently into the plasma [12,13]. The magnetic field ratios as described in the previous section are utilized for all these source designs. To reach these values inside the plasma chamber, the maximum field on the sextupole conductor reaches 6 to 7 T, which is at the limit of what is feasible to achieve using Nb-Ti technology at 4.2 K. In order to further extend ECR ion source designs to frequencies well above 28 GHz, new superconductor magnet technology will be needed for the 4th and 5th Generation ECR ion sources. Presently, Nb_3Sn conductors, for which the upper critical field limit increases to about 20 T at 4.2 K [14], will most likely lead the way to develop 4th generation ECR ion sources with an operational range of 40 to 50 GHz. An ambitious project is currently underway at the Institute for Modern Physics (IMP) in Lanzhou to build the first Nb_3Sn ECR ion source optimized for operation at 45 GHz [12,15].

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The design was developed as a collaboration between IMP and the Lawrence Berkeley National Laboratory. The cold mass is currently under construction [15]. Thinking beyond this frequency range, the use of high temperature superconducting (HTS) cuprate conductors will need to be developed and applied to ECR ion source technologies. A fully high temperature high field superconducting magnet would offer advantages over the conventional 4 K conductors, in particular in terms of robustness of handling the x-ray load and the ultimate fields that can be reached. Operating at 20 K would allow to explore the ECR source performance without the limit of the cryostat cooling power limits that are present at 4 K or 2 K systems. In the next sections we explore the state of the art high temperature superconducting magnet and its potential to develop ECR ion source structures.

STATUS OF THE FIELD - HTS MAGNETS

The superconductor and magnet communities have long been seeking to broaden the application scope to higher fields at low temperatures (4.2 –20 K) or higher temperatures (20 –77 K) using HTS conductors. Arduous conductor development efforts over the past three decades have resulted in commercially produced HTS conductors including Bi-2212, Bi-2223, and $REBa_2Cu_3O_x$ (REBCO). They are produced in practical forms of metal/superconductor composite conductors and available in lengths suitable for making magnets. Their upper critical magnetic fields (see Fig. 2) exceed 50 T at 4.2 K which is well above Nb-Ti (≈ 14 T at 1.8 K) and Nb_3Sn (≈ 26 – 27 T at 1.8 K), making them potentially useful for making high-field magnets, such as 30 T superconducting solenoids needed for 1.3 GHz NMR spectrometers, 20 T accelerator dipoles for a potential high-energy upgrade of the LHC, and > 28 GHz ECRIS magnets. The whole wire engineering critical current densities of these high performance conductors in comparison with Nb-Ti and Nb_3Sn conductors are plotted in Fig. 2. While Nb-based superconducting materials have reached their peak performance, the engineering critical current density of HTS wires continue to rise [16, 17].

At the front of HTS magnet technology research, significant progress has been made, particularly in small-bore solenoids made of REBCO, enabling the successful realization of a 32 T user solenoid constructed at the National High Magnetic Field Laboratory [18, 19]. However, this record magnetic field was realized in a small bore (40 mm) using only short conductor piece lengths (<100 m). The magnet also has a relatively low total stored energy of 1.3 MJ. Even for this solenoid magnet system, a key challenge is protection against quenches when the winding loses superconductivity locally, creating local hot spots with temperature and thermal-induced stress that may, without suitable protection, lead to degradation. The 32 T HTS magnet is protected with a battery bank that provides an energy input of 130 kJ at 400 V to a set of heaters embedded into HTS coils, a system that is inconvenient to implement for a user magnet. Several other HTS magnets systems, however, have been de-

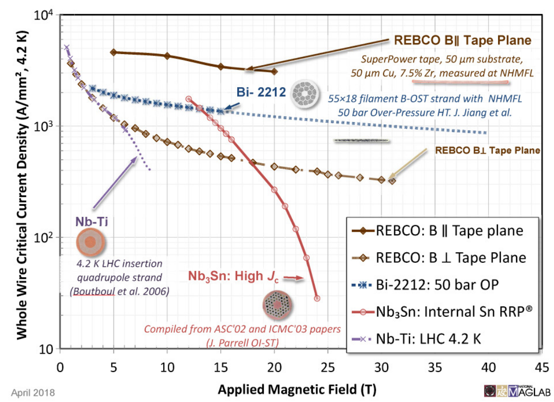

Figure 2: Critical current density (J_e) of different HTS and LTS technologies at 4.2 K [14]

graded during quench [20–22]. Extending this technology to ECR magnets is challenging and will require long and focused industrial conductor R&D. The magnet system for ECRIS is unique and much more complex than the small solenoids currently being built and tested. The sheer size of the magnet system and a combination of coils present unique challenges for HTS conductor and magnet technologies, and it would represent one of the most complex HTS magnet system ever engineered and fabricated. A potential solution to the quench protection problem of REBCO magnets is to build REBCO coils with metallic insulation such as stainless steel or without any insulation between turns ((NI)-REBCO conductors) [18, 24, 25], allowing adjacent turns to share electric current during a quench or allow to bypass a hot spot and flow into the adjacent turns preventing quenches. Both options are of great interest for high field ECR magnet structures. Particularly, the (NI)-REBCO conductors can use REBCO-tapes with only 10 µm thick Cu or less and therefore has a much improved yield stress of≈1100 MPa.

The disadvantage of this technique is the slow charging and discharging time of these structures in the order of T/hour [18, 26]. Therefore, this technique would only be useful for a quasi static magnet such as the sextupole, where field changes would only be done occasionally. On the other hand the solenoids can be either constructed from REBCO tape insulated with metallic insulation (as proposed in the conceptual magnetic design in the next section) or possibly as a hybrid magnet combining (NI)-REBCO coil insert with a low current density trim coil to enable faster tuning time within a small range.

Using tuning parameters from the last several years of the LBNL VENUS source [27] as an example, the source tuning is typically restricted to a narrow range. The injection solenoid is typically tuned within about ±5%, the extraction solenoid is typically tuned within ±5 – 10% of the sextupole field. The middle field solenoid has the largest tuning range of ±30%. However, the fast tuning range (for a particular

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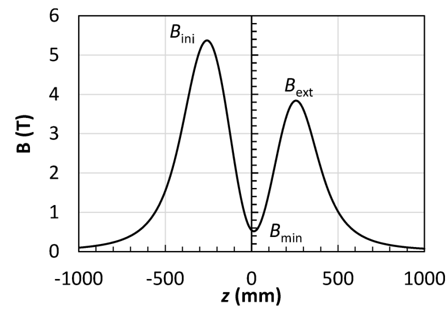
optimization or study) could be restricted to ±5% for a given field configuration.

Extending the conductor properties to the highest conceivable ECR magnet structure one can make a first cut - envelope concept for an ECR ion source working even at at 80 GHz. Similarly to Nb-Ti and Nb_3Sn magnets, the coupling between the coils driven by multiple power supplies, protecting against quenches induced through external noise (such as high voltage sparks in operations) is a major issue for these magnet systems. In addition, the shear conductor lengths required for ECR magnets makes this structure very challenging. Before one can think of constructing a structure that pushes all limits of this technology, smaller scale coupled coil prototype HTS magnet system should be pursued to better understand the engineering issues associated with ECR structures. The magnet system case study below describes a 37.5 GHz ECR magnet structure for which we propose using stainless steel insulated coils for the solenoid system and (NI)-REBCO for the sextupole system. While challenging, this design is well within the magnetic margins of the HTS technology and would be a goal that could be realized within the next decade.

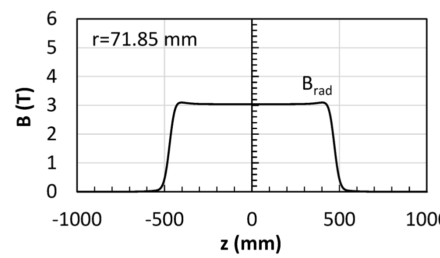
MAGNETIC FIELD PROFILES FOR A 37.5 GHZ ECRIS

Fig 3 presents preliminary field profiles of an HTS (REBCO) magnet that meets performance requirements of a 37.5 GHz ECRIS, whose key parameters are listed in Table 1. The sextupole coils are assembled from six flat racetrack coils, a geometry that is favorable for fabricating magnets using REBCO tapes, whereas solenoids are stacked from double-pancake coils, also wound with REBCO tapes. A clear difficulty for building such magnet system is the quench protection. The sextupole coils are designed to be built with the (NI)-REBCO magnet technology; they are compact, working at a high overall coil current density of 800 A/mm^2 [25]. The metallic-insulation REBCO magnet technology for the three solenoids is selected to provide a ramp rate dI/dt required for tuning the magnetic mirror fields. A concern of the design is the stress management with increasing magnetic fields. A simple BJR hoop stress calculation results in stress values greater than 470 MPa in the injection solenoid which is well within the performance of the conductor specified in the table 1 (30 µm thick Hastelloy substrate, 3.6 µm Ag, 15 µm Cu, and a yielding stress of 800 MPa). As comparison 470 MPa would exceed the yielding strength of the RRP (Restack Rod Process) Nb_3Sn conductor (50% Cu and a yielding stress of 250 MPa). Due to the expected high stress, the overall coil current density of the injector solenoid is reduced to 310 A/mm^2 in order to provide some engineering margin to the design.

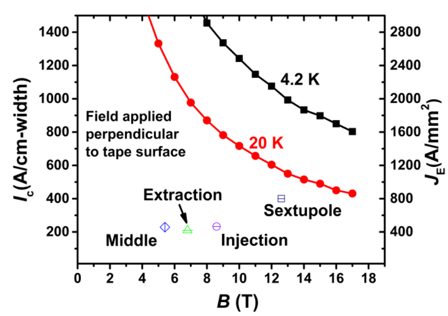
The piece lengths required for each double pancake coil is about 3 km for each sextupole coil (19 110 m total) and 1 km for the solenoids (28 021 m total), respectively (Table 1). Using a market average price of \$60/m (8 mm wide tape) the conductor costs result in \$1.1 million for the six sextupole



(a) Nominal magnetic field density along the main axis of the ECRIS (at r = 0 mm).



(b) Sextupole (only) field density (at r = 71.85 mm)



(c) Working point of the injection, middle, extraction solenoids, and the sextupole. Critical surface of the REBCO tape at 20K and 4.2K with the field applied perpendicular to the tape's wide surface.

Figure 3: Key magnetic parameters of the 37.5 GHz ECRIS

coils, and \$1.5 million for solenoid coils. At present, the REBCO industry is, though barely, capable of delivering conductors with such lengths with the caveat that there may be non-uniformities in the conductor with occasional I_c drop by 10% or higher [28]. There is a report indicating that such I_c drops along the length of conductor can be tolerated for (NI)-REBCO coils [23].

CONCLUSION

Over the last several decades, ECR ion source performance has been pushed forward by increasing the magnetic field and the operating frequency. With the current state of the art 28 GHz ECRIS, a limit of what is feasible with established superconducting magnet technology has been reached. Nb_3Sn is the logical next choice for higher frequency sources [12] and will dominate the 4th Generation ECR ion sources developed over the next decades. In this

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Table 1: Key parameters of the solenoids and sextupole coils for a conceptual 37.5 GHz ECRIS REBCO magnet working at 20 K. The solenoids are based on a partial-insulated REBCO magnet technology. The sextupole coils are based on a (NI)-REBCO magnet technology, and working at a high coil current density of 800 A/mm^2.

Solenoid Coils	**Injection**	**Middle**	**Extraction**	**Sextupole Coils**	
Fabrication Method	Stack of Double Pancakes (DP)			2-layer flat racetrack coils DP technology	
Mirror Length (mm)	500			Plasma Chamber Radius	70
B_0 (T)	5.4	0.5- 1.0	3.8	Field at Plasma Chamber Wall	3
B_{peak} (T)	8.6	5.4	6.8		12.6
Inner Diameter (mm)	352	352	352	Bore Diameter	200
				Inner Winding Radius (mm)	15
				Coil Width (mm)	16
Thickness (mm)	32	32	32		36
Length (mm)	194.4	64.8	145.8		1000
Operating Current (A)	186	183	168		320
J_{coil} (A/mm^2)	310	305	280		800
Peak Hoop Stress	469	290	335		
	REBCO Tape				
Thickness (mm)	0.05	0.05	0.05		0.05
Width (mm)	8	8	8		8
Insulation	Stainless steel 25 μm in thickness			none between turns	
Number of Double Pancakes (DP)	12	4	9		2
Tape Piece Length/DP (m)	1040	1040	1040	per sextupole coil (m)	3185
Total Tape Length (m)	12480	4160	9360	Total (m)	26000

paper we proposed to pursue HTS technology, which might lead the path to the 5th Generation ECR ion sources. While magnetic fields for frequencies up to 80 GHz are in principle within the reach of this technology, we presented the design of a much more modest system operating at 37.5 GHz that will allow to better understand and solve the key technology issues associated with emerging conductor materials.

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