STATUS OF HIGH PERFORMANCE ECR ION SOURCES: ACHIEVEMENTS AND PERSPECTIVES

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Abstract

The demand for high-intensity (0.5–1.0 emA) highly charged heavy ion beams continues to grow among next-generation heavy ion accelerator facilities worldwide, yet their production remains a significant challenge in the field. Electron Cyclotron Resonance (ECR) ion sources, recognized as the most powerful technology for generating such beams, have been widely adopted by major heavy ion accelerator facilities globally, driving continuous advancements in this domain. Despite more than five decades of development since the first ECR ion source prototype was introduced, these sources remain at the forefront of high-charge-state and high-intensity ion beam production. This paper reviews the latest advancements in high-performance ECR ion sources, focusing on four key areas: (1) the development of new ion source designs, (2) high-performance operational achievements, (3) emerging technologies in the field, and (4) future prospects for delivering high-intensity beams for heavy ion accelerators.

INTRODUCTION

Heavy ion science plays an indispensable role in both fundamental research and societal applications. Heavy ion beams have served as essential tools for advancing our understanding of nuclear structure, synthesizing over a thousand new isotopes, and discovering dozens of new elements. Beyond fundamental science, heavy ion technology has significantly impacted industry and medicine. For instance, heavy-ion therapy systems worldwide have demonstrated remarkable efficacy in treating cancer, while nuclear track membrane [1] production—a rapidly growing industry—relies heavily on heavy ion accelerators. Additionally, single-event effect (SEE) studies enable critical advancements in space exploration [2]. To generate energetic heavy ion beams, heavy ion accelerators have undergone continuous development over the past 80 years. Among the key requirements for efficient acceleration is the production of highly charged ion beams. This demand has driven the invention of various ion sources, including Electron Cyclotron Resonance (ECR) ion sources, Electron Beam Ion Sources (EBIS), and Laser Ion Sources (LIS). Notably, ECR ion sources have proven unparalleled in delivering high-current, high-charge-state ion beams, solidifying their dominance in the field.

The ECR ion source was first proposed and prototyped by Richard Geller in the 1970s [3]. Over the past five decades, hundreds of such devices have been deployed worldwide, serving both scientific facilities and practical applications. The growing demand for high-performance heavy ion beams—particularly in power frontier projects like superconducting radiofrequency (SRF) linacs (e.g., FRIB) and intensity frontier programs such as synchrotrons (e.g., HIAF)—has driven the need for more advanced ECR ion sources. An ECR ion source operates by generating plasma through microwave heating within a min-B magnetic confinement structure. The interaction between microwave radiation and the magnetic field configuration critically determines the source's performance. Over the years, empirical scaling laws have been established to summarize the fundamental principles governing ECR ion sources, providing essential guidance for their continued development.

Guided by scaling laws, achieving high-performance ECR ion sources necessitates operation in high magnetic field (high-B) and high microwave frequency regimes. Superconducting ECR ion sources, which leverage the strong magnetic fields generated by highly excited superconducting coils, have emerged as the most promising solution for producing high-performance, highly charged ion beams. The first prototype of such a system, the SERSE ion source [4], was jointly developed by LNS-INFN and CEA-Grenoble in the late 1990s. Subsequently, modern high-performance superconducting ECR ion sources optimized for 24–28 GHz microwave frequencies were pioneered—most notably by the VENUS source (LBNL, 2002) [5], and the SECRAL source (IMP, 2005) that introduced a novel reserved magnetic configuration [6]. Further advancements were achieved with the SuSI source (MSU) [7] and the SCECRIS source (RIKEN) [8], diversifying the landscape of high-performance ECR ion sources. Despite these successes, challenges persist in extending ECR ion sources to high-power, high-current heavy-ion beam applications. This paper reports recent progress in addressing these challenges and discusses future perspectives for ECR ion source development.

NEW HIGH PERFORMANCE ECR ION SOURCES

In recent years, numerous high-performance ECR ion sources have been proposed, developed, or commissioned for routine operation. These ion sources—primarily designed for new heavy-ion accelerator facilities or upgrades of existing accelerator systems —are universally optimized to deliver high-charge-state heavy-ion beams with exceptional intensity. Their development has become critical to

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advancing the capabilities of modern accelerator facilities, where they serve as indispensable workhorses for beam production.

The HPECR (High-Power Electron Cyclotron Resonance) ion source [9] for the FRIB was commissioned to deliver highly charged heavy-ion beams for the SRF linac. Based on the VENUS ion source design, the HPECR is also a superconducting ECR ion source optimized for operation at 28 GHz. Installed at the FRIB front end in 2023, this ion source, when integrated with an inductive heating oven, has demonstrated the capability to produce ~100 eμA of U^{35+} beam current, with 30 eμA routinely delivered for stable operation. This performance enabled FRIB's recent world record in uranium beam acceleration, achieving 20 kW beam power. The synthesis of superheavy elements (SHE) —particularly new elements in the 8th period of the periodic table —has become a major focus in nuclear physics, with leading laboratories such as RIKEN (Japan), IMP (China), LBNL (USA), and FLNR (Russia) engaged in a highly competitive research effort. RIKEN has successfully deployed a 28 GHz superconducting ECR ion source (SCECRIS), a duplicate of their existing system, which now operates routinely, delivering over 150 eμA of $^{51}V^{13+}$ for SHE experiments [10]. Similarly, at IMP, SECRAL-III—a successor to SECRAL-II—has recently been installed for the CAFE2 SHE facility [11]. Additionally, FLNR is developing a 28 GHz superconducting ECR ion source for the DC-280 cyclotron upgrade, intended to serve as a second injector for uranium beam acceleration. In parallel, the NEWGAIN project [12] at GANIL aims to enhance SPIRAL2's capability in accelerating heavy-ion beams up to uranium. A key component of this initiative is the ASTERICS ion source, currently under development. Designed with a 180-mm-diameter plasma chamber and optimized for high magnetic fields, ASTERICS is expected to support routine 28 GHz operation [13], further advancing SPIRAL2 heavy-ion beam performance.

At JYFL, an 18 GHz ECR ion source HIISI [14] has been developed, utilizing high mirror fields and strong radial fields, demonstrating the capability to deliver >10 enA of Xe^{44+} for the K130 cyclotron. Owing to its high magnetic fields, large-diameter (Ø100 mm) plasma chamber, and multi-frequency microwave heating, this source achieves performance comparable to state-of-the-art superconducting ECR ion sources operating at the same frequency. The hybrid superconducting ECR ion sources, which combine superconducting mirror coils and a permanent magnet hexapole, represent an advanced approach to generating high magnetic fields. Recent implementations of this technology include the AISHa source at INFN-LNS [15] and HECRAL-C at IMP. Both sources employ an LHe-free superconducting magnet design, enhancing their practicality for long-term operation. HECRAL-C, recently commissioned as a linac injector for a heavy-ion therapy facility, has demonstrated stable performance, delivering >1.3 emA of dc C^{4+} ion beams for medical applications.

RESEARCH TOWARDS CHALLENGES

When operating at higher frequencies, ECR ion sources require stronger magnetic fields, increased microwave power, and larger plasma chamber volumes to achieve high-density, stable plasma and superior beam performance. However, these advancements introduce new technical challenges, as highlighted in the review talk at HIAT25 [16]. A decade later, many of these challenges remain unresolved. Nevertheless, the most critical issues have made good progresses that include:

- Efficient microwave heating
- Localized overheating of the plasma chamber due to plasma losses under high microwave power.
- The production of ion beams from refractory metals, such as uranium, which presents significant material and operational difficulties.

Microwave Heating Study

The issue of microwave heating efficiency was first highlighted by D. Hitz in 2006 when comparing the O^{6+} beam current dependence on microwave power injection at 18 GHz and 28 GHz [17]. This question remained unresolved until 2013, when C. Lyneis conducted an experiment using a snake-mode converter for HE_{11}-mode microwave injection, evaluating its effectiveness against the conventional over-sized TE_{01} mode. However, this study did not yield conclusive results [18]. A year later, a similar experiment was performed at IMP using a tapered waveguide. Initial findings demonstrated that the method of microwave introduction into the plasma chamber significantly influences plasma behaviour, particularly in high-power ECR plasma heating [19]. This discovery led to the development of the Vlasov microwave launcher for ECR ion sources [20]. Although the first Vlasov launcher lacks axial position adjustability, it exhibits a clear impact on highly charged ion production. Subsequent validation with an online movable Vlasov launcher confirmed that microwave heating efficiency strongly depends on the launching scheme, and optimized highly charged ion yields can be achieved through adjustable launcher positioning [21].

These results provide new insights into the plasma heating mechanisms in highly charged ECR ion sources potentially guiding future research directions.

High Power Plasma Chamber

In a traditional ECR ion source plasma chamber, the primary concern is to manage the heat transferred from the plasma to the inner wall. This is crucial to prevent the demagnetization of the permanent magnet (in 2nd ECR ion sources) or to avoid strong instability and outgassing caused by temperature rise. Before the 3rd generation ion source reached its performance limit, the typical microwave power during routine operation was around 3-5 kW. As a result, there were very few reports of plasma chamber damage caused by hot plasma. In an ECR ion source, the hot electrons in the plasma are strongly magnetized and confined. The mechanism of ECR plasma confinement and the min - B structure of the three - dimensional magnetic field can lead to localized overheating on the plasma chamber surface [22]. Once the plasma conditions exceed a certain threshold, this overheating can cause a tiny hole and subsequent water leakage. In practice, the six sextupole coils are not perfectly aligned, and there are obvious concentricity errors between the plasma chamber and the sextupole fields, which exacerbate the situation. Localized overheating can boil the cooling water flowing through the plasma chamber. When stationary bubbles form, the wall dries out, and the heat - exchange coefficient decreases (since there is no direct cooling from the water). This causes the wall temperature to rise rapidly, potentially leading to melting. Subsequently, under the high pressure of the cooling water, a hole can form. A rough estimate shows that for a third - generation ECR ion source, the localized heat flux onto the chamber surface can reach 1 MW/m^2 per kW of microwave heating. The damage to the plasma chamber due to localized overheating is not a long - term process but occurs almost instantaneously.

Recently, a novel plasma chamber has been designed, fabricated, and used in routine high - power operations. Based on the concept of a micro - channel structure, by optimizing the local structure where a burnt hole is likely to occur, a good balance is achieved among the water flow rate, heat - exchange efficiency, and water flow distribution. This has enabled the SECRAL-II ion source to operate safely at a peak microwave power of 12 kW during performance tests and routinely at 8 kW for the production of intense highly charged ion beams for accelerators. With this issue resolved, the third - generation ECR ion source can be safely operated at power levels up to 10 kW, which is sufficient for most applications.

High Temperature Oven

The production of intense ion beams using an ECR ion source requires a reliable and stable gas-feeding system. Since most elements in nature exist in solid states, it is essential to evaporate the material and introduce it into the plasma. Traditionally, resistor ovens, sputtering, and MIVOC methods are commonly employed for the production of metallic ion beams. However, for refractory materials, especially those required for SHE research or large-scale facilities, such as vanadium, titanium, chromium, and uranium, high - temperature ovens are needed. These ovens must be durable at operating temperatures up to 2000°C. Given that the oven is exposed to complex operating conditions involving high magnetic fields, high operating temperatures, and high electrical currents, traditional resistor ovens are often damaged by strong Lorentz forces.

At IMP, a high-temperature oven based on the inductive heating concept has been developed and is now in routine operation for producing refractory metallic ion beams. Since its validation in 2019 [23], the total operating time of these inductive heating ovens at IMP may have exceeded 20,000 beam hours. This technology has proven to be reliable and easy to handle when used with the 3rd generation ECR ion source for the production of intense refractory ion beams. Recently, a similar oven design has been adopted for the routine operation of the HPECR ion source to produce intense U^{35+} beam. This has enabled the high-power acceleration of uranium beams in FRIB SRF linac. At LBNL, a vertically-positioned susceptor inductive heating oven has also been successfully developed [24]. Its long - term operation to deliver a >100 eμA ^{50}Ti^{12+} beam for SHE exploration using the 88-inch cyclotron has verified its durability. At RIKEN, through careful structural design and refinement of the oven's structural materials, an oven based on the traditional resistor heating design has also been shown to be durable for high - temperature operation [25]. This oven design has been routinely used with RIKEN's ion sources to deliver >110 eμA U^{35+} and ~150 eμA ^{51}V^{13+} beams for their heavy-ion beam accelerators.

In general, the challenge of producing intense refractory ion beams using the third-generation ECR ion source is no longer pressing today. The ECR ion source community has found solutions to produce 500 eμA U^{35+} beams.

4TH GENERATION ECR ION SOURCE

In the development of (ECR) ion sources, the frequency-scaling principle remains applicable. To develop high-performance ECR ion sources that outperform the current state-of-the-art high-charge-state machines, the development of next-generation machines is imperative. 3rd generation ECR ion sources typically operate at frequencies ranging from 18 to 28 GHz. Consequently, the 4th generation ECR ion sources are anticipated to operate at frequencies approximately twice that of the existing ones, specifically in the range of 40 to 56 GHz. Correspondingly, the peak magnetic fields inside the plasma chamber should reach as high as B$_{inj}$>5.0 T and B$_r$>2.8 T. These field strengths are unattainable with the conventional magnets used in 3rd generation ECR ion sources. There are two viable approaches (Fig. 1) for designing the magnets of the fourth - generation ECR ion sources. One is the conventional structure with solenoids on the outside and a sextupole on the inside, which employs Nb$_3$Sn superconductors. The other is an unconventional structure using NbTi superconductors that can fully utilize the generated magnetic flux. In this non-conventional design, the sextupole coil generates a solenoid moment inside the plasma chamber.

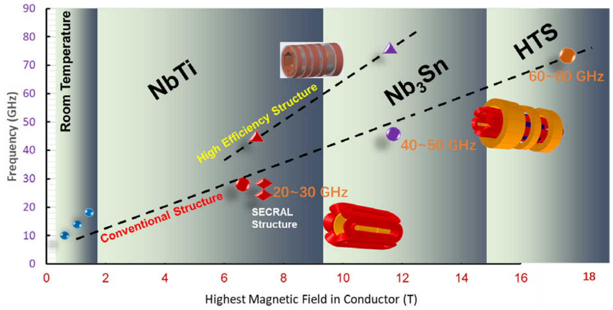

Figure 1: The viable approaches towards next generation ECR ion source magnet.

At IMP, the prototype ion source FECR has recently been developed [26]. It is equipped with a NbTi sextupole and four Nb3Sn solenoids, achieving a B$_{inj}$ of approximately 4.5 T and a B$_r$ of approximately 2.7 T. The first

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEX01

plasma, heated by 28+45 GHz microwaves, has successfully produced intense ion beams, such as 360 eμA of Bi^{35+}. The development of a full Nb_3Sn magnet is still in progress. As a backup ion source for FRIB, a hybrid superconducting ECR ion source magnet using a Nb_3Sn sextupole and NbTi solenoids is under development at LBNL [27]. Meanwhile, LBNL is fabricating a novel-structured magnet that uses only NbTi superconductors to reach the magnetic fields required for 45 GHz operation of an ion source called MARS-D [28]

We can anticipate that there will be at least two 4th generation ECR ion sources available in the laboratory for the production of highly charged ion beams in 5 years. However, more challenges may be encountered during the performance optimization process.

PERSPECTIVES

In recent years, with the advancement of research on ECR ion sources, researchers have gained new insights and made novel discoveries. These aspects were either not addressed or overlooked during low-power operation previously.

Quench Protection and Operation Safety

The existing high-performance ECR ion sources predominantly employ high - field superconducting magnets. The typical stored energy of the cold mass ranges from 0.6 to 0.9 MJ, presenting relatively few challenges in quench protection. However, the next-generation ECR ion sources utilizing Nb_3Sn magnets face severe challenges in quench protection. One crucial issue is the high stored energy. For example, the 45 GHz FECR has a total stored energy of 1.6 MJ. Moreover, the quench propagation speed of the Nb_3Sn superconductor is ten times slower than that of the NbTi superconductor. This slow propagation speed makes it extremely challenging to mitigate the risk of excessively high temperatures at the quench point. Furthermore, the intense flux jump observed in the FECR magnet indicates that this problem may occur throughout the entire magnet energizing process [29]. It can interfere with the quench detection system and may trigger either false or real quenches during the ion source tuning process aimed at performance optimization.

Transient Instability with Intense Beams

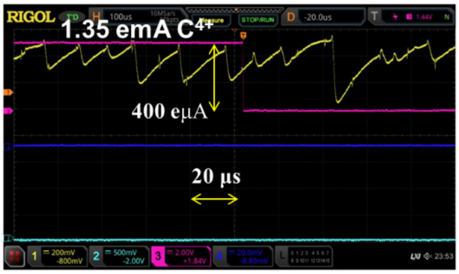

Figure 2: Transient instability with ECR ion source.

Intense heavy-ion beams are predominantly generated for injection into high - current linacs or synchrotron ring accelerators. We have detected strong transient instability in the delivered high - intensity ion beams. The typical duration of this instability ranges from 10 to 100 μs, which lies outside the well-known kinetic instability domain. This type of instability shows no obvious periodic characteristics (Fig. 2). However, we have observed a maximum transient drop of up to 50% in the beam intensity, followed by a recovery within a time frame of 10 to 100 μs. This phenomenon may have an impact on the operating current load effect of the linac and the bunch - to - bunch stability of the synchrotron. Further investigation is still required to fully understand this instability.

Beam Quality of Intense Beams

Accelerating a CW heavy-ion beam of high charge states at the 1 emA level remains a global challenge. The ion source must be able to generate a high-intensity heavy-ion beam reaching several emA, and the beam quality must be precisely controlled for injection into downstream accelerators. In recent high-intensity acceleration experiments using LEAF [30] and the warm front-end of HIAF, we discovered that the transmission efficiency of a high-intensity O^{6+} beam drops rapidly when the current exceeds 500 eμA. This decline is attributed to the space-charge effect and the degradation of beam quality during transmission. The acceleration of a CW proton beam up to 10 emA has already been achieved. However, the injected proton beam is carefully controlled to ensure excellent beam quality. In contrast, for heavy-ion beams produced by ECR ion sources, the ion distribution in the phase space is dispersed. This makes it difficult to achieve a good match for downstream acceleration and transmission, necessitating novel concepts and innovative solutions.

Before this issue can be resolved, to achieve the acceleration of a 1 emA U^{35+} beam, the ion source is expected to produce approximately 2.0 emA of U^{35+}. To meet the 400 kW power goal of FRIB, the ion source may need to extract more than 600 eμA, or even up to 1 emA, of a CW U^{35+} beam.

New Techniques for ECR Ion Sources

It should be noted that, considering the existing techniques associated with 3rd generation ECR ion sources, there remains room for further performance enhancement. However, this will require innovative concepts and novel techniques. With a deeper understanding of ECR plasma sustained by microwave heating, breakthroughs may be achieved in the fine-tuning or manipulation of the interaction between microwaves and the plasma. These breakthroughs could lead to the optimization of the control of the Electron Energy Distribution Function (EEDF) to generate a greater quantity of the desired ions.

In recent years, AI for science has been advancing at a rapid pace. ECR researchers are leveraging machine learning to enable ECR ion sources to operate more intelligently [31, 32]. Although it will take some time for exploration before it can be put into practical operation, it is certain that this approach will enhance the online operation efficiency and quality for heavy ion accelerators. Nevertheless, a long-term development plan needs to be formulated.

CONCLUSION

This paper offers a concise overview of the recent advancements in ECR ion sources, specifically focusing on their high-performance operation for accelerators. It encompasses the development of new ion sources, as well as novel technologies and discoveries. However, it should be noted that some significant progress, particularly in the areas of ion source experiments and theoretical studies, has not been covered in this paper. In recent years, the ECR ion source community has made remarkable headway in the field of high-performance ECR ion sources. Their contributions have been fundamental to the progress of heavy-ion accelerator science and the associated physics research. These achievements not only lay a solid foundation for future research but also open up new possibilities for the development of more advanced accelerator technologies and applications. Overall, while this paper provides a useful starting point for understanding the current state of ECR ion sources, further in-depth research and exploration are needed to fully exploit the potential of these sources in the context of accelerator-based applications.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Founda tion of China (Grant Nos. 11427904, 12025506), and the Scientific Instrument Developing Project of the Chinese Academy of Sciences, Grant No. GJJSTD20210007.

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