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Intense highly charged ion beam production and operation with a superconducting electron cyclotron resonance ion source

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The superconducting electron cyclotron resonance ion source with advanced design in Lanzhou (SECRAL) is a superconducting-magnet-based electron cyclotron resonance ion source (ECRIS) for the production of intense highly charged heavy ion beams. It is one of the best performing ECRISs worldwide and the first superconducting ECRIS built with an innovative magnet to generate a high strength minimum-B field for operation with heating microwaves up to 24–28 GHz. Since its commissioning in 2005, SECRAL has so far produced a good number of continuous wave intensity records of highly charged ion beams, in which recently the beam intensities of $^{40}\text{Ar}^{12+}$ and $^{129}\text{Xe}^{26+}$ have, for the first time, exceeded 1 emA produced by an ion source. Routine operations commenced in 2007 with the Heavy Ion accelerator Research Facility in Lanzhou (HIRFL), China. Up to June 2017, SECRAL has been providing more than 28,000 hours of highly charged heavy ion beams to the accelerator demonstrating its great capability and reliability. The great achievement of SECRAL is accumulation of numerous technical advancements, such as an innovative magnetic system and an efficient double-frequency (24 + 18 GHz) heating with improved plasma stability. This article reviews the development of SECRAL and production of intense highly charged ion beams by SECRAL focusing on its unique magnet design, source commissioning, performance studies and enhancements, beam quality and long-term operation. SECRAL development and its performance studies representatively reflect the achievements and status of the present ECR ion source, as well as the ECRIS impacts on HIRFL.

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I. INTRODUCTION

ECRIS (electron cyclotron resonance ion source) is a plasma device dedicated to the production of intense singly and highly charged ion beams [1]. Highly charged ion beams enable the accelerators to produce very energetic ions at substantially lower cost and much smaller machine footprints, as the energy gains from heavy ion accelerators are either proportional to the ion charge state Q or Q^2 . Since its advent, ECRIS has been playing a significant role in enhancing the capabilities of many cyclotrons, linacs, and synchrotrons with much greater variety of ion species, beam intensity and ion energy, and operation reliability [1–3]. The enhancements of accelerators from ECRIS have led to substantially greater research opportunities in nuclear physics, atomic physics, and other disciplines, as well as various industrial applications. It may be arguable to say

that without ECRIS it would be very difficult or unlikely to continue the syntheses of new superheavy elements or to construct a national facility of radioactive ion beams to further nuclear physics research, while heavy ion cancer therapy would likely remain a dream [1–3].

Since SUPERMAFIOS [1,4], the first of the first generation high charge state ECR ion source developed in Grenoble in the mid-1970s, the ECRIS performance on the ion charge state and beam intensity has been leaping forward greatly with each new generation source developed. The category of the “generation” in ECRIS is based on the operating frequency: first generation at 5–10 GHz; second generation at 14–18 GHz; third generation at 20–28 GHz and fourth generation at >28 GHz. To date, there are three “generations” of ECRIS developed and demands by heavy ion accelerators for more intense and higher charge state heavy ion beams have been driving the ongoing development of the fourth generation [3]. Many of the existing, under-construction and next generation accelerators require very intense highly charged heavy ion beams. One can cite, for instance, 1 emA of pulsed $^{208}\text{Pb}^{27+}$ for CERN LHC [5], 1 emA of pulsed $^{238}\text{U}^{28+}$ for the FAIR project [6], 0.4 emA of continuous wave (cw) mixed beam of $^{238}\text{U}^{33+}$ and $^{238}\text{U}^{34+}$ for the FRIB project [7], 1 emA of cw $^{36}\text{Ar}^{12+}$ for GANIL SPIRAL2 [8], 0.5 emA of cw $^{238}\text{U}^{35+}$ for RIKEN RIBF [9], 0.85 emA of cw $^{238}\text{U}^{35+}$ and

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1.7 emA of pulsed $^{238}\text{U}^{35+}$ for the IMP HIAF project [10]. Successful accelerations of these intense highly charged ion beams directly provided by an ion source will result in a relatively low cost accelerator, and definitely would lead to much higher beam power providing many new opportunities in physics research. However none of the existing ion sources could produce all of the required ion beam intensities, but ECRIS has the greatest potential to meet these requirements. Based on the demonstrated performance of the third generation ECRISs, a fourth generation ECRIS operating at higher heating microwave frequency and then at higher magnetic fields will be able to meet all of the aforementioned demands.

Developments have demonstrated that ECRIS operating at higher magnetic fields and higher heating microwave frequency is the most straightforward path to achieve higher source performance. Nonetheless, high magnetic fields would need to use superconducting magnets and one must cite the early pioneering developments of superconducting ECRISs which, however, were operated at rather low fields and frequencies. These trailblazers include ECREVIS [11–13], the first superconducting-magnet-based ECRIS developed in 1983 in Louvain-La-Neuve, Belgium; Jülich ICIS [14], commissioned in 1988 in Wilhelm-Johnen, Germany; MSU SCECR [15], a 6.4 GHz ECRIS commissioned in 1989 in East Lansing, USA, and INFN SERSE [16–17], developed in the early 1990s in Grenoble and Catania. These pioneers have addressed some of the challenges in building complex superconducting magnets for higher-field ECRISs, from which today's highest magnetic fields for the third generation of ECRIS are 4 T for the axial field, and 2.2 T for the radial field at the inner surface of the plasma chamber.

VENUS, a fully superconducting ECRIS built at LBNL and operating at 18–28 GHz, one of the best performing of the third generation ECRIS, had been commissioned successfully in the early 2000s [13,18–19]. Then, SECRAL, from IMP-Lanzhou operating at 18–24 GHz, was commissioned in 2005. This is the fully superconducting ECR source with the smallest footprint, thanks to its novel magnet structure. Following SECRAL came several more third generation performing ECRISs, such as SuSI at NSCL/MSU [20–21], RIKEN-SCECR [22], and KBSI-SCECR [23]. These third generation ECRISs have not only successfully enhanced by a factor 2–10 the ion beam current, but also delivered new high ion charge states.

However, the developments of the third generation ECRISs have continuously encountered technical challenges, such as the difficulties in fabricating a higher-field superconducting magnet system because of the very strong Lorentz force that is proportional to the square of the magnetic field strength B and the complex force patterns. Other issues encountered by the designers of these machines are high power microwave coupling, plasma chamber cooling, strong bremsstrahlung radiations from plasma leading to

the magnet cryostat heat load increase and to a fragility of the plasma chamber high voltage, extraction and transport of intense multiply charged ion beam.

The development of SECRAL is to provide intense highly charged ion beams to enhance the capability of the Heavy Ion Research Facility in Lanzhou-China (HIRFL), an accelerator complex based on heavy ion cyclotrons and cooling storage rings [24–26]. The commissioning of SECRAL took place in 2005 [27–28], and since 2007 this third generation ECRIS has been in routine operation for HIRFL [29–30]. Performance of the SECRAL source has been continuously improved in terms of beam intensity, charge states and beam stability, especially during the past years thanks to the use of new techniques or “tricks” [31–35]. Beam intensities of the highly charged heavy ions have been increased by a factor of 3–10, setting then many beam records produced by an ECRIS in cw mode. So far, SECRAL has strongly shifted the fateful 1 emA level given by an ECRIS as it delivers more than 1.4 emA of $^{40}\text{Ar}^{12+}$ and 1.1 emA of $^{129}\text{Xe}^{26+}$ [35]. Regarding high charge states, SECRAL can deliver 0.32 emA of $^{129}\text{Xe}^{30+}$, 0.68 emA of $^{209}\text{Bi}^{31+}$ and 10 μA of $^{209}\text{Bi}^{50+}$. This outstanding SECRAL performance has significantly contributed to HIRFL capability enhancement in ion beam energy, intensity and variety. For example, thanks to the highly charged ion beams exiting from SECRAL and HIRFL, such as $^{40}\text{Ca}^{11+}$, $^{58}\text{Ni}^{19+}$, $^{112}\text{Sn}^{26+}$, $^{209}\text{Bi}^{31+}$ and $^{238}\text{U}^{32+}$, nuclear physicists have synthesized, at IMP, many new isotopes and conducted high precision mass measurements of 35 short-lived nuclides for the first time [36]. To date the total beam delivery to HIRFL by SECRAL has reached more than 28,000 hours, a good demonstration of the SECRAL reliability and a record for a third generation ECRIS in operation with an accelerator.

The success of SECRAL and the achievements of other superconducting ECRISs, such as LNS SERSE [17], LBNL VENUS [13], RIKEN SCECR [22] and MSU SuSI [21], have embodied the third generation ECR ion sources in advancing the ECRIS technology. After a brief reminder of ECRIS principles, this article reviews the development of SECRAL mostly in terms of magnetic structure design and microwave coupling.

II. ECRIS GENERAL PRINCIPLE

ECRIS is a microwave-driven plasma device originated from fusion research [4]. Although it has been developing for more than four decades, the detailed physics processes involved in the ECR hot plasma remain poorly understood, due to the difficulties in decoupling the parameters. The detailed physics processes include the plasma magnetic confinement, ionization and atomic properties, interaction between electromagnetic waves and plasma (plasma heating), interaction between plasma and chamber surface of different materials, microwave coupling and multimode

resonator, beam formation, etc. There have been many studies on the ECRIS physics [37–55], especially in the recent years, resulting in a number of plausible and essential conclusions.

Generally speaking, ECR plasma is produced and energized by microwave power through electron cyclotron resonance heating, in which the electrons oscillate along the magnetic mirror lines in a minimum-B configuration absorbing the microwave energy when the electron gyro-frequency equals the incoming microwave frequency:

$$\omega_e = \frac{e \cdot B_{\text{ECR}}}{m} = \omega_{rf}, \quad (1)$$

where m is the mass and e the electric charge of the electron, B_{ECR} is the resonant magnetic field, ω_e and ω_{rf} are the electron gyrofrequency and the microwave frequency, respectively. The resulted energetic electrons ionize the atoms and lowly charged ions through sequential impact ionization so that the ions could reach as high charge state as possible provided a long ion lifetime. The ECR plasma is confined and stabilized by a “minimum-B” magnetic field produced by mirror coils superimposed with a radial field mostly generated by a sextupole magnet, as schematically shown in Fig. 1. In ECRIS plasma, the key parameters, determining the highly charged ion yield, are the electron density n_e , the ion confinement time τ_i , the electron temperature T_e and the neutral density n_0 . To achieve high throughput of highly charged ions, the product of $n_e \tau_i$ should be as high as possible so that there is a high enough number of electrons carrying out the ionizations and the ions can stay a long enough time to reach the desired charge state. The electron density n_e is related to the microwave frequency, the absorbed microwave power, the magnetic field and the neutral density in the plasma [40,56]. The loss of high charge state ions is determined by plasma ambipolar diffusion, charge exchange among the neutrals and low charge state ions. Therefore, low neutral pressure is preferable and needed inside the plasma to maximize the yields of the highly charged ions.

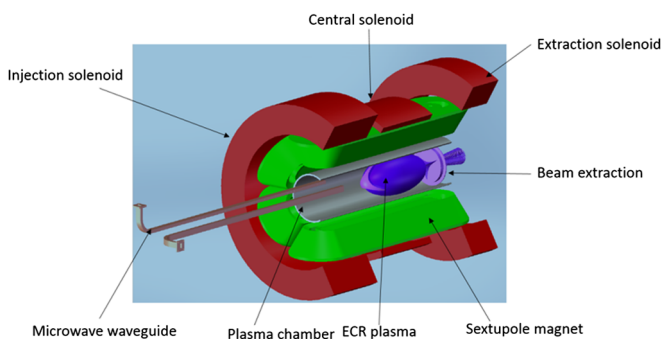


FIG. 1. Schematic view of the ECR ion source structure with minimum-B magnet configuration.

The highly charged ions are produced by stepwise electron-impact ionization in ECR plasma, and therefore the ions have to stay a quite long time in the plasma to reach the high charge states. In ECRIS the ions are relatively cold, having energy in the range of a few qeV (q being the ion charge), highly collisional and not magnetized.

The extracted ion current from an ECR ion source corresponds to the losses of the plasma confinement and can be written as [2,57]

$$I_i = (n_i q e V / \tau_i) \eta_p, \quad (2)$$

where I_i is the extracted ion beam current, q is the ion charge state, V is the plasma volume and η_p is the efficiency of the plasma flow from the main plasma to the extraction hole of the ECR ion source.

The performance of a highly charged ECR ion source strongly depends on optimization of the ECR plasma and then a good understanding of the physics processes is crucial. Since the advent of ECRIS, the knowledge of its plasma behavior is mostly semiempirical, with nevertheless several theoretical models. In 1987, Geller had suggested a few ECRIS scaling laws pointing out that the electron density and the intensity of highly charged ions are proportional to the square of the microwave frequency, while the ion confinement time is related to the magnetic mirror ratio [58–59]. The so-called high-B mode with higher magnetic fields for highly charged ECR ion source was proposed by Gammino [56,60–61]. Ten years later, a set of new empirical criteria for designing an ECRIS magnetic field configuration has been established based on experimental results from the SERSE superconducting ECR source [62]. Recently some scaling laws were proposed to illustrate the role of the microwave power as well as the axial minimum-magnetic-field B_{min} based upon experimental results from the LBL VENUS ECR ion source [63–65].

Based upon the basic ECR physics, scaling laws and the history of ECRIS development, it comes out that, to produce intense highly charged ion beams, one must use high microwave heating frequency to push the cutoff frequency to high values. This requires then strong magnetic fields and leads to high microwave power. As a consequence, for ECR ion sources operating at microwave frequency above 18 GHz, the magnetic bottle has to be made of superconducting magnets. Numerous technical challenges have been addressed and overcome during the development of the NbTi-magnet-based superconducting ECR ion sources, such as the LNS SERSE [17], LBNL VENUS [13], IMP SECAL [31], MSU SuSI [21], RIKEN SCECR [22] and other third generation ECRISs under development [23,66]. However, there are still many new technical challenges to be addressed for the construction of a future source based on Nb₃Sn magnet systems [67].

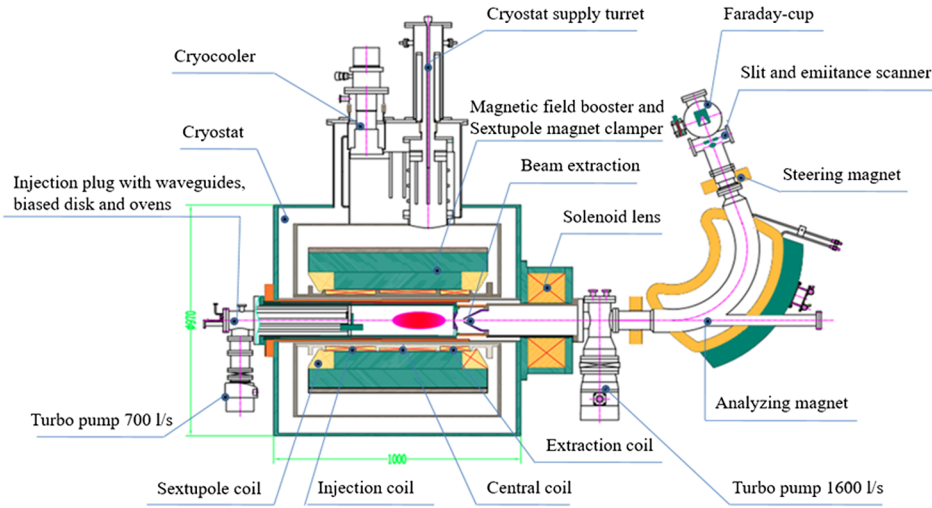


FIG. 2. Layout of the SECRAL ion source and its beam transport line.

III. THE DEVELOPMENT OF SECRAL

A. SECRAL overview

SECRAL is a third generation fully superconducting 24 GHz ECR ion source, with magnetic field maxima of 3.6 T on axis and 2.0 T radially at the plasma chamber inner wall. The goal of SECRAL is to enhance the production of highly charged heavy ion beams with reliable long-term stability needed for the HIRFL accelerator.

Figure 2 schematically shows the key footprints of SECRAL with its ion beam analysis and diagnostics.

SECRAL comprises an innovative compact superconducting magnet surrounding a plasma chamber with dimensions close to LNS-SERSE ($ID = 120\text{--}126\text{ mm}$), an injection system dedicated to microwave, gas and metals feeds and a beam extraction mechanism, as shown in Figs. 3 and 4. The double-wall plasma chamber is made of either stainless steel or aluminum with water cooling channels in between. In addition, the cooling water runs through the whole chamber up to the location of the extraction electrode to provide sufficient thermal conduction cooling. A 1.5 mm thick tantalum liner encloses the plasma chamber to strongly reduce the hard x-ray damage to the high voltage PEEK insulator and thermal load to the magnet cryostat [68]. A 700 l/s and a 1600 l/s turbomolecular pump is installed at the injection and the extraction region respectively to achieve the high vacuum needed for the production of highly charged ions. Ions are extracted at voltages ranging from 20 to 30 kV to match the accelerator requirement and minimize ion beam transport losses.

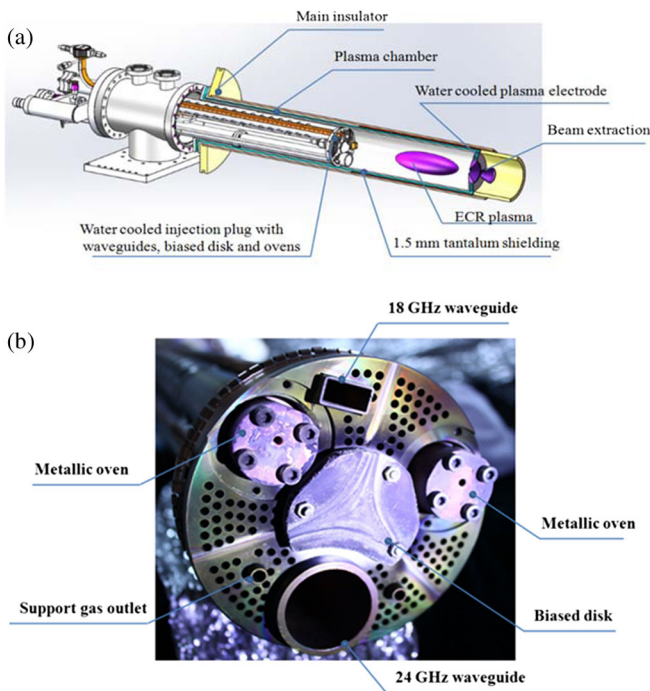


FIG. 3. Conventional components of the SECRAL source: (a) schematic view of the injection tank; (b) photo of the injection tank end.



FIG. 4. The SECRAL source with 24 GHz microwave coupling.

B. Novel superconducting magnet and magnetic field distribution

Typically, the magnetic structure of an ECRIS is made of axial solenoid coils surrounding the radial sextupole magnets (called Sext-in-Sol), whatever the materials, room temperature or superconducting wires. Such classical magnetic structure is shown in Fig. 5(a). The novel feature of the SECRAL superconducting magnet is to locate the axial solenoid coils inside the radial sextupole magnet (called Sol-In-Sext), as shown in Fig. 5(b).

Regarding the Sext-in-Sol structure, the sextupole is surrounded three or more solenoids to get the magnetic mirror profile. The sextupole is made of six curved race-track coils to generate a radial field proportional to the square of its radius. In such a classical magnet structure, the complex and very strong Lorentz interaction forces result in very challenging coil clamping, especially if the racetrack coil ends are close to the solenoids. At each side of the magnetic structure, i.e. injection and extraction, there are six sextupole ends in which the current flows oppositely to the adjacent end, as shown in Fig. 6. This alternating current interacts with the magnetic field produced by the solenoids resulting in forces outward and inward radially, and axially that push and pull the sextupole ends. As counteractions, there are strong axial repulsions and attractions on the solenoid coils. In addition there are

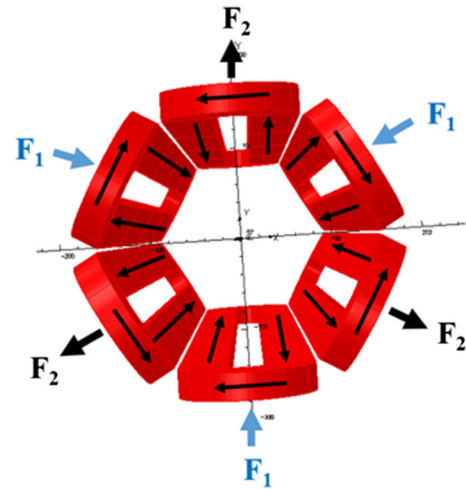


FIG. 6. View of sextupole-coil end in which the adjacent end electric-current flows oppositely. Interaction between the end currents and the axial fields results in strong radially inward force F_1 and outward force F_2 .

strong azimuthally positive/negative forces on the straight sections of the sextupole coils as well, due to the interaction with the radial fields produced by the solenoids. Measures have been taken to mitigate these strong Lorentz forces: (1) extension of the sextupole length to place the racetrack ends far away from the axial coils and then to reduce the interactions between sextupole end and solenoids leading then to lengthy magnet and cryostat; (2) insertion of liquid metal bladders axially in between the straight sections of the sextupole to avoid any azimuthal deformation [69–70]. With these successful techniques, the air-cored classical Sext-In-Sol magnet is commonly used in the existing or under development high-field superconducting ECR ion sources, such as LNS SERSE [17], LBNL VENUS [13], RIKEN SCECR [22] and MSU SUSI [21].

To simplify the complex and lower the strong Lorentz interactions for easier magnet coil clamping, SECRAL uses a Sol-In-Sext magnet by reversing the positions of the solenoids and sextupole, in conjunction with a six segments cold-iron shell to concentrate the magnetic fields and minimize the stray fields outside the magnet assembly. The axial field strength generated by the solenoids is proportionally reciprocal to the average radius R of the solenoids. Thus placing the solenoids inside the sextupole substantially reduces the average radius of the solenoids and the needed Ampere/Turns for the production of the same field strength on axis. This reduction is also beneficial as it gives lower fields outside the solenoids where the sextupole is located, leading then to weaker Lorentz interactions. This magnetic configuration allows then to build compact sextupole and cryostat. In addition, each of the six sextupole coils is bolted to one of the six iron segments for better mechanical support. Moreover, the iron can also play a role in attracting the sextupole coils toward

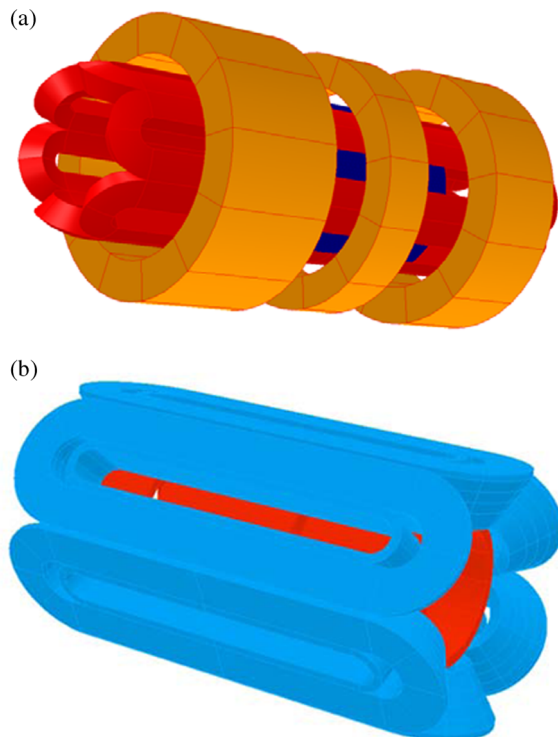


FIG. 5. Magnet coil configuration of the highly charged ECRIS. Classical ECRIS magnet coil configuration of Sext-In-Sol. The SECRAL superconducting magnet coil configuration of Sol-In-Sext.

the iron segment which results in a net outward force on all of the SECRAL's NbTi sextupole end, instead of alternately "in" and "out" in the case of a classical structure. Thanks to this Sol-in-Sext configuration that SECRAL is the most compact fully superconducting ECR ion source with no more than 1 m in both length and diameter of the cryostat. However, the main disadvantage of a Sol-In-Sext magnet is the inefficient utilization of the generated radial field. In addition, as the solenoids are located inside the hexapole, they experience high strength radial field leading to high stresses within the solenoid coils. However, these stresses can be easily overcome. To compensate for the radial field inefficiency in the Sol-In-Sext magnet, a high sextupole field is needed and the plasma chamber is slightly smaller than in the standard configuration. The warm bore of the SECRAL cryostat is slightly smaller than VENUS (14 cm for SECRAL and 17 cm for VENUS), while the sextupole magnet length is much shorter for SECRAL (73 cm for SECRAL and 92 cm for VENUS) [70]. Another unique feature of the Sol-In-Sext magnet structure is the use of a cold-iron shell to enhance the radial field and also to minimize the stray field outside the magnet assembly which can easily reach less than 50 G. Such a low stray field leads to a small interaction between the magnets and the outer iron yoke of the cryostat, which is benefiting for the magnet suspension and for installations of the cryocoolers and high Tc current leads inside the cryostat.

In addition to all features mentioned above, the clamping of the SECRAL magnet is rather simplified thanks to rather weak Lorentz forces. Unlike the classical magnet fabrication, in which complex bladders and formers between the sextupole and solenoids have to be used, the clamping used in the Sol-In-Sext magnet is simply a four-aluminum-sleeve enclosing the segmented iron shell to provide the needed prestress by their different thermal contractions after the system cooled down. When SECRAL is energized, the magnetic forces experienced by the six iron segments will add additional self-clamping force to the magnet assembly resulting in a rugged superconducting magnet, as shown in Fig. 7. Each of the six superconducting racetrack coils is wound around a piece of iron pole in the center to boost the pole field by more than 2 kG. Stainless steel wedges are axially inserted in between the adjacent sextupole coils to make them more rigid. Each of the sextupole coils is bolted to one of the six iron segments of the outer shell which covers the iron pole and the sextupole coil for easier magnet clamping and field concentration. The three axial solenoid coils are wound onto a stainless steel bobbin to prevent excessive deformation of the sextupole assembly under large magnetic force. Figure 8 shows the fabricated magnet assembly with the detailed coil structure.

The mirror magnetic field of SECRAL is designed according to the high mirror ratio magnetic profiles determined by the so-called high-B mode proposed by Gammino [56,60–61] and the magnetic field scaling laws

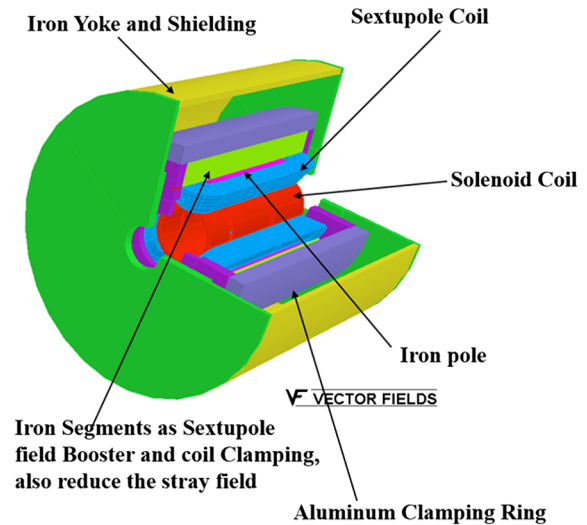


FIG. 7. SECRAL magnet structure and superconducting coil configuration.

[62]. It is now able to generate maximum axial fields of about 3.6 T at injection (B_{inj}) and 2.0 T at extraction (B_{ext}) with a mirror field peak distance of 420 mm, and a maximum sextupole radial field of 2.0 T (B_{rad}) at the plasma chamber inner wall, to run this ECRIS at 24 and/or 28 GHz. The SECRAL magnetic profile agrees with today's scaling laws determined for a single frequency

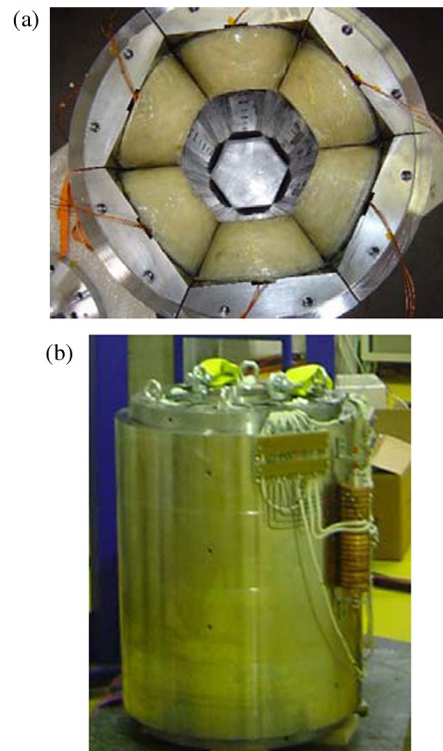


FIG. 8. Fabricated SECRAL magnet assembly and its detailed coil structure.

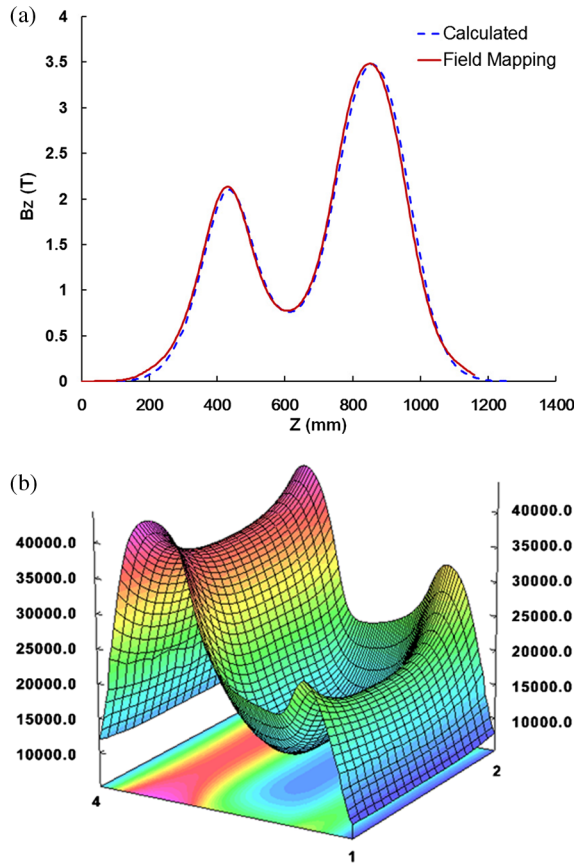


FIG. 9. SECRAL axial magnetic field distribution. (a) Designed axial mirror magnetic field (B_z) distribution on the axis for SECRAL 24–28 GHz operation. (b) 3D field distribution at the x-z plane in the plasma chamber.

heating. The designed and measured axial field profile, and the total field distribution calculated by Opera-3D, at a plane cutting along the central line between two poles through the plasma chamber are shown in Fig. 9. As the axial minimum-B value (B_{min}) can vary from 0.5 T up to 0.8 T, SECRAL could be run at a frequency ranging from 18 GHz up to 28 GHz and can advantageously use the double frequency heating technique. The resonance length on axis is about 120–130 mm for SECRAL for 24–28 GHz operation. On the other hand, the minimum-B position (B_{min}) is not located at the center of the plasma chamber, but at several centimeters closer to the plasma electrode in order to achieve an efficient extraction of highly charged ion beams. A detailed distribution analysis of the three-dimensional magnetic field does not show any so-called “magnetic holes” along the plasma chamber walls, which could lead to severe concentration of hot electron dumping and to a high level of x-ray radiation in a small location damaging the chamber and the high voltage insulator. The distance between the magnetic field peak at the extraction B_{extr} and the first focusing solenoid lens is designed as short as possible so that extracted beam could be focused as soon as possible to avoid beam blowup.

The SECRAL magnet assembly is immersed and cooled down in a liquid helium bath. The precooling to 30–50 K is achieved by the use of one stage cryocooler at the thermal radiation shields surrounding the liquid helium reservoir. Five high Tc current leads serve both as thermal insulators and electric continuity to the 4.2 K cold mass. They are mounted within the cryostat service turret and their high temperature ends are thermally linked to the cryocooler through a 30–50 K termination. The total heat load on the liquid helium reservoir is less than 1 W at 4.2 K and the liquid helium consumption rate measurement is less than 1.5 l/h. The magnet had finally reached 100% of the design fields after 13 quenches at ACCEL company and five quenches at IMP during the user’ site test.

C. Microwave coupling

It is crucial for any high performance ECR ion source to efficiently couple microwave power into the plasma. To do so, SECRAL is designed with the possibility to use the commonly adopted of double-frequency heating. In the case of a single frequency heating at 18 GHz, like the wave launching scheme commonly used in ECR ion sources [17,25,69–72], traditional off-axis rectangular waveguides (WR62) are used to launch the microwaves into the plasma. However, as the commercial klystron amplifier is limited to 2 kW, two separate microwave generators and waveguides are used in SECRAL, as shown in Fig. 10. This parallel 18 GHz microwave launching scheme should be more efficient than one line since the plasma itself could combine and absorb the microwave power effectively in such a case [30].

On the other hand, even if SECRAL can efficiently run at 18 GHz, a 24 GHz heating is more suitable for this machine, according to its magnetic field profile. In the past, 28 GHz microwave coupling to an ECR ion source has been successfully demonstrated with SERSE [17].

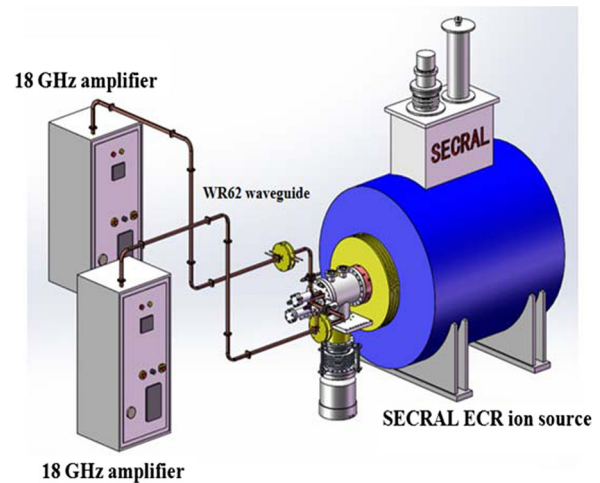


FIG. 10. SECRAL double waveguides coupling system both at 18 GHz.

This success has established a base for coupling 28 GHz microwaves into the high field superconducting ECR ion sources. Several years later, through the development of LBL-VENUS, a great number of technical challenges have been overcome to safely launch rf power larger than 6 kW [13]. For SECRAL, the 24 GHz launching is similar to that designed for SERSE and VENUS at 28 GHz: an oversized circular waveguide is capable of transmitting 7 kW from the gyrotron to the plasma. Figure 11 shows the scheme for double-frequency (24 + 18 GHz) heating wave launching into SECRAL.

The 24 GHz gyrotron system, built by GYCOM, Russia, is capable of transmitting the maximum power of the gyrotron, up to 7 kW in TE₁₂ mode [73]. Similarly to the previous 28 GHz lines, an arc detector is installed on the microwave transport line to detect any spark on the microwave window, and a bidirectional coupler measures both forward and reflected power. A mode converter converts the TE₁₂ waves from the gyrotron into TE₀₁ waves before being launched into the plasma chamber. A mode filter in the transport line based on selective power absorption of nonsymmetrical modes prevents the gyrotron from any reflected waves [73]. A 90° quasi-optical mirror bend is used to guide the microwave power by 90° from the microwave generator line to the ion source injection port. Two mechanical compensators are installed to compensate for any thermal expansion in the transmission line and to tolerate small errors of the waveguide alignment. A 30 kV dc break is placed between the mode convertor and the microwave window made of water-cooled boron-nitride separates the source vacuum from atmosphere pressure.

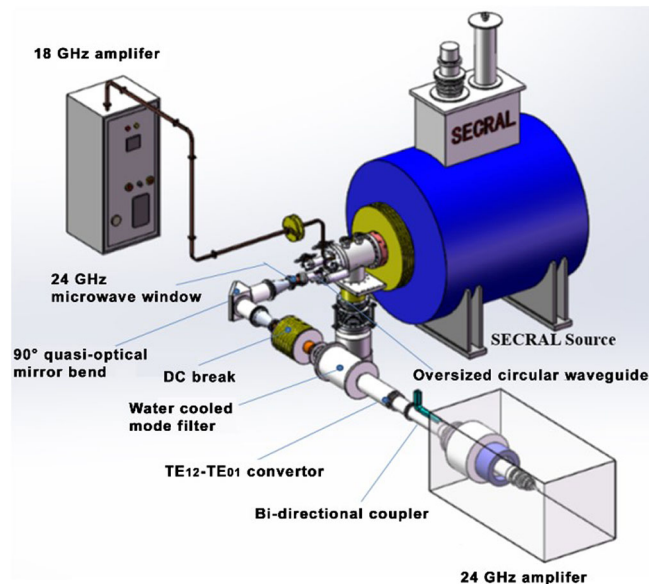


FIG. 11. SECRAL microwave coupling system with 24 + 18 GHz double frequency heating.

IV. COMMISSIONING AND PERFORMANCE STUDY

A. SECRAL milestones

SECRAL started its maiden voyage with plasma energized by microwaves of 18 GHz in August 2005 [27]. While many of these kinds of sources undergo 3–5 years of commissioning to optimize performance before serving the accelerators, SECRAL has been routinely delivering a great variety of highly charged heavy ion beams to the HIRFL accelerator facility since May 2007 [30]. SECRAL's performance, i.e. charge state, beam intensity and stability, has been continuously improved, especially more recently thanks to the use of new techniques [27–35].

Listed below are the milestones of the SECRAL development: (i) September 2000, the project was approved. (ii) April 2002, the magnet fabrication was contracted with ACCEL. (iii) August 2005, the first beam was produced at heating microwave of 18 GHz. (iv) 2005–2006, SECRAL was Commissioned at 18 GHz and achieved 505 eμA of ¹²⁹Xe²⁰⁺ and 101 eμA of ¹²⁹Xe³⁰⁺. (v) May 2007, the first beam was delivered to HIRFL accelerator. (vi) October 2008, SECRAL was tested with 18 + 14.5 GHz double frequency heating and aluminum chamber for highly charged ion beam production. (vii) August 2009, the first beam was produced at heating microwave of 24 GHz. (viii) December 2009, 3500 hours of beam was delivered to HIRFL accelerator. (ix) July 2011, SECRAL was tested with 3–5 kW microwave power at 24 GHz and achieved 236 eμA of ¹²⁹Xe³⁰⁺ and 242 eμA of ²⁰⁹Bi³¹⁺. (x) September 2011, ²³⁸U³²⁺ beam was firstly delivered to HIRFL accelerator. (xi) December 2011, 8000 hours of beam was delivered to HIRFL accelerator. (xii) March 2013, SECRAL was tested with 3–4 kW microwave power at 24 + 18 GHz double frequency heating and achieved 396 eμA of ²⁰⁹Bi³¹⁺ and 202 eμA of ²³⁸U³³⁺. (xiii) December 2013, 15000 hours of beam was delivered to HIRFL accelerator. (xiv) April 2014, SECRAL was tested with 5 kW microwave power at 24 + 18 GHz double frequency heating and achieved 680 eμA of ²⁰⁹Bi³¹⁺ and 10 eμA of ²⁰⁹Bi⁵⁰⁺. (xv) March 2015, SECRAL was tested with 8 kW microwave power at 24 + 18 GHz double frequency heating and achieved 1.4 emA of ⁴⁰Ar¹²⁺ and 1.1 emA of ¹²⁹Xe²⁶⁺. (xvi) July 2016, 25000 hours of beam was delivered to HIRFL accelerator. (xvii) June 2017, 28000 hours of beam was delivered to HIRFL accelerator.

B. Commissioning at 18 + 14.5 GHz double-frequency heating

In the initial commissioning the SECRAL plasma was energized by microwaves of 18 GHz with the production of a good number of gaseous and metallic ion beams, such as oxygen, argon, calcium, iron, nickel, krypton, xenon, lead, bismuth and uranium. Though the major focus of the commissioning was on gaseous ion beams since gases are

much easier to be introduced into the source, high charge state ion beams of Ar, Xe and Bi represent SECRAL's production capability on the light, intermediate and heavy elements, respectively.

Base vacuum (without plasma) achieved in SECRAL was 4.0×10^{-8} mbar at the source injection region, 3.0×10^{-8} mbar at the extraction region and 1.0×10^{-8} mbar at the beam line. During the commissioning, two different plasma chambers were tested, one made of stainless steel with $\emptyset 126$ mm inner diameter, while the other one was made of aluminum with $\emptyset 116$ mm inner diameter. As already mentioned, a 1.5 mm thick Ta shielding sleeve encloses the plasma chamber to reduce the x-ray irradiation damage to the high voltage insulator, following the experience of VENUS at LBNL [68].

During initial SECRAL commissioning at 18 GHz, the source was equipped with a stainless steel plasma chamber and one microwave generator with 1.7 kW power at maximum. Good performances were obtained and showed no beam current saturation with microwave power. This is understandable according to the plasma chamber volume. Then a second 18 GHz generator was connected to the ion source. It was noticed that better beam stability is obtained with two waveguides for the same total power. As there is a resonance point inside the waveguides, it is necessary to avoid any outgassing and then the lower power launched in a waveguide. To some extent, for a total microwave power of, say, 6 kW, it would be better to launch this power through four fundamental waveguides (WR62) or through one oversized waveguide (WR187). For the sake of simplicity, as this source is designed to run at a frequency higher than 18 GHz, we chose the multiple waveguides, as shown in Fig. 10. On the other hand, many tests with SECRAL show the total reflected power from two waveguides is less than that of a single waveguide at the same power level. Typically the total reflected power with two waveguides is less than 5%, while the maximum reflected power with a single waveguide can be 10%. With total input power ranging from 2.5 to 3.3 kW, SECRAL could deliver, at 25 kV, 810 μA of $^{16}\text{O}^{7+}$ and 505 μA of $^{129}\text{Xe}^{20+}$ [28]. For that, the optimum magnetic field profile was $B_{\text{inj}} = 2.2$ T, $B_{\text{min}} = 0.47$ T and $B_{\text{rad}} = 1.1\text{--}1.2$ T, $B_{\text{ext}} = 1.27\text{--}1.36$ T. Moreover, beam intensity increases linearly with the microwave power and showed no saturation indicating higher microwave power would lead to more intense beams. In spring of 2009, after more than 20 days of continuous $^{129}\text{Bi}^{31+}$ beam delivery to the HIRFL cyclotrons, an exploration was carried out for the production of very highly charged bismuth beams. Very impressive performance was obtained at 2.6 kW, like 150 μA of $^{209}\text{Bi}^{31+}$, 22 μA of $^{209}\text{Bi}^{41+}$ and 1.5 μA of $^{209}\text{Bi}^{50+}$ [32]. To do so, the production of such highly charged heavy ion beams requires substantially high magnetic fields: $B_{\text{inj}} = 2.5\text{--}2.6$ T, $B_{\text{min}} = 0.5$ T, $B_{\text{rad}} = 1.3$ T and $B_{\text{ext}} = 1.26\text{--}1.35$ T. Figure 12 shows the charge

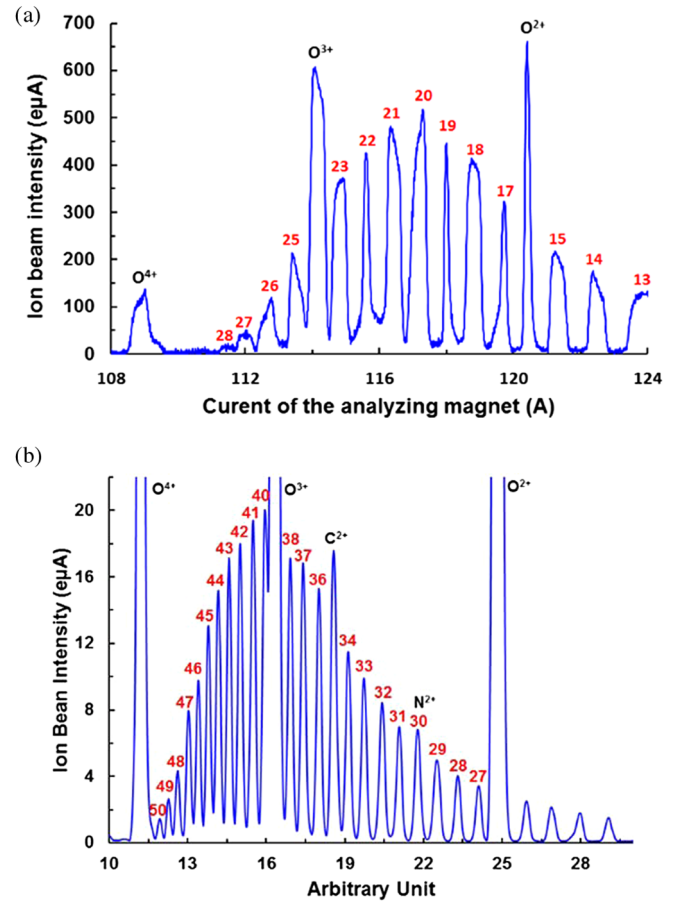


FIG. 12. CSD spectrum with the source optimized for $^{129}\text{Xe}^{20+}$ and $^{209}\text{Bi}^{50+}$. (a) Xenon CSD spectrum with the source optimized for $^{129}\text{Xe}^{20+}$ at 2.9 kW of 18 GHz microwave power and 25 kV extraction voltage. (b) Bismuth CSD spectrum with the source optimized for $^{209}\text{Bi}^{50+}$ at 2.6 kW of 18 GHz microwave power and 25 kV extraction voltage.

state distribution (CSD) with the source optimized for $^{129}\text{Xe}^{20+}$ and $^{209}\text{Bi}^{50+}$.

Later on, SECRAL was commissioned with both the stainless steel chamber and the aluminum chamber at 18 GHz as well as 18 + 14.5 GHz double frequency heating. As already noticed with another source, a stainless steel chamber gives better results in terms of beam intensity and stability than an aluminum chamber for medium charge states such as Ar^{14+} , Xe^{20+} and Xe^{27+} , even with 18 + 14.5 GHz double frequency heating. Figure 13(a) illustrates beam intensity evolution of $^{129}\text{Xe}^{27+}$ as a function of microwave power for two plasma chamber materials at 18 GHz, and at 18 + 14.5 GHz [32]. Here also, there is no saturation with rf power. However, the beam intensity enhancement with the aluminum chamber at 18 + 14.5 GHz double frequency heating for very high charge state of xenon beam is quite obvious and significant, as shown in Fig. 13(b) [32], where the beam intensity ratios were normalized to per kilowatt (I_q/P_{rf}) microwave

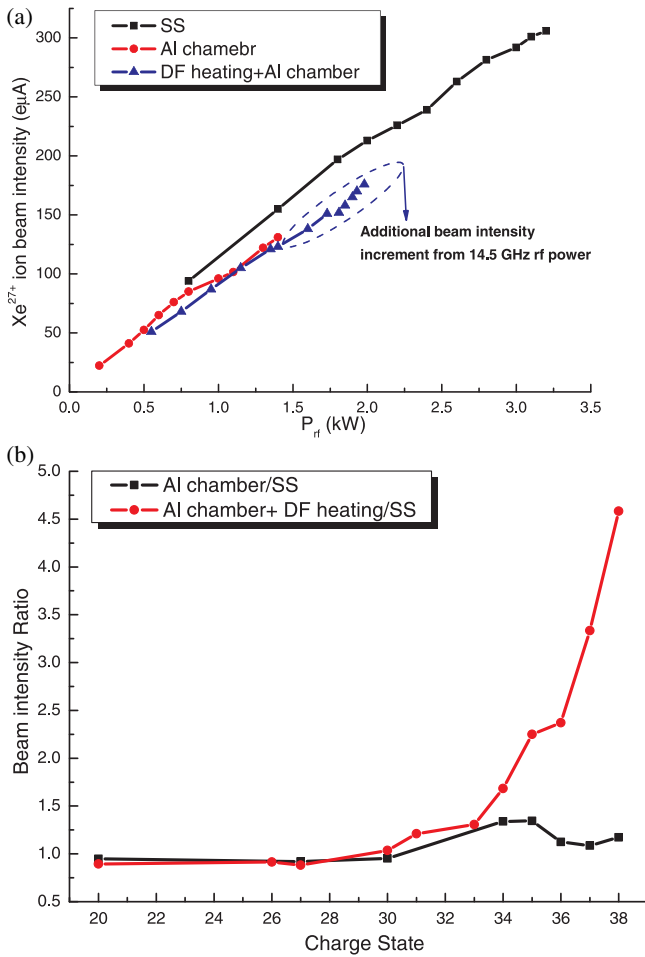


FIG. 13. Xenon beam intensity study with different chamber and microwave power. (a) $^{129}Xe^{27+}$ beam intensity evolution as a function of microwave power and comparison among stainless steel (SS) chamber at 18 GHz, aluminum (Al) chamber at 18 GHz, and aluminum chamber at 18 + 14.5 GHz. (b) Xenon beam intensity enhancement with aluminum chamber at 18 + 14.5 GHz double frequency heating.

power. It is worth pointing out that plasma and beam stability at 18 + 14.5 GHz double-frequency heating with the aluminum chamber is much more improved than the case of 18 GHz single frequency with an aluminum chamber, as demonstrated decades ago at LBL [74]. The reason for improvement of plasma and beam stability by the double frequency heating might be related to suppression of electron cyclotron instability suggested by Skalyga [51].

C. Bismuth and uranium beams with 24 + 18 GHz heating waves

In a third step of source commissioning, after the arrival of the 24 GHz gyrotron in August 2009, SECRAL has been operating at 24 + 18 GHz. Very extensive source tuning on bismuth beams was conducted at various conditions to study the SECRAL capability and to determine the

optimum parameters for the production of the very heavy ions. Bismuth was chosen because its mass is close to uranium, its vapor is easy to produce, it is chemically stable as compared to uranium and it is not radioactive.

Two different ovens are used to feed bismuth vapor [34]. The first one is an oven enclosed by resistive heating coil with maximum operation temperature of $1600^{\circ}C$ but with moderate material loading capacity. The second one is a low temperature oven constructed with a large load crucible for long term operations and a commercial 100 W “Watt-Flex Cartridge Heater” for maximum oven operating temperature of $700^{\circ}C$. This last low temperature oven is a duplicate of the LBNL one and is sufficient to create Bi vapor [75–76].

The experiment with bismuth beams was carried out in two stages at two different total microwave power, 3–4 and 4–6 kW.

Bismuth beam tests with microwave power of 3–4 kW focused on the production of ion beams of charge states from 30 to 55 with the use of the aluminum plasma chamber (ID = 116 mm) and the first oven. The maximum beam currents achieved were $242 e\mu A$ of $^{209}Bi^{31+}$ and $160 e\mu A$ of $^{209}Bi^{36+}$ at 2.5 kW power of 24 GHz plus 0.4 kW power of 18 GHz. In that case, the magnetic field configuration was $B_{rad} = 1.6$ T, $B_{inj} = 3.45$ T, $B_{min} = 0.60$ T, and $B_{ext} = 1.8$ T.

At higher microwave power (3.8 kW power of 24 GHz plus 1.3 kW of 18 GHz), a stainless steel chamber was used (ID = 120.5 mm) together with the Cartridge Heater oven. Higher intensities and charge states were obtained like $396 e\mu A$ of $^{209}Bi^{31+}$, $50 e\mu A$ of $^{209}Bi^{41+}$ and $4.3 e\mu A$ of $^{209}Bi^{50+}$. The magnetic field configuration was $B_{rad} = 1.71$ T, $B_{inj} = 3.41$ T, $B_{min} = 0.60$ T, and $B_{ext} = 1.7$ T [77]. The plasma stability was satisfactorily stable with the stainless steel chamber at microwave power of about 3 kW or lower, but it was difficult to keep the plasma stable at microwave power above 4 kW. The plasma instabilities are likely caused by the strong anisotropy of hot electrons in the velocity space, i.e. the transverse velocity is much larger than the longitudinal one with respect to the magnetic field lines [38].

In a next step, the aluminum plasma chamber was reinstalled in conjunction with an improved cooling of all source components (biased disk, waveguides and micro-oven) in order to run the source above 4 kW without instabilities. Thanks to the aluminum wall coating effect and the secondary electron emission of this material, no instabilities were seen up to 6 kW of total power. The beam currents of highly charged bismuth ion beams were then increased by at least a factor of 2 when the source was able to operate at the total wave power of 5–6 kW compared to the operations with power less than 4 kW, as shown in Fig. 14. A large number of record beam intensity of highly charged ions has been produced: $680 e\mu A$ of $^{209}Bi^{31+}$, $320 e\mu A$ of $^{209}Bi^{36+}$, $100 e\mu A$ of

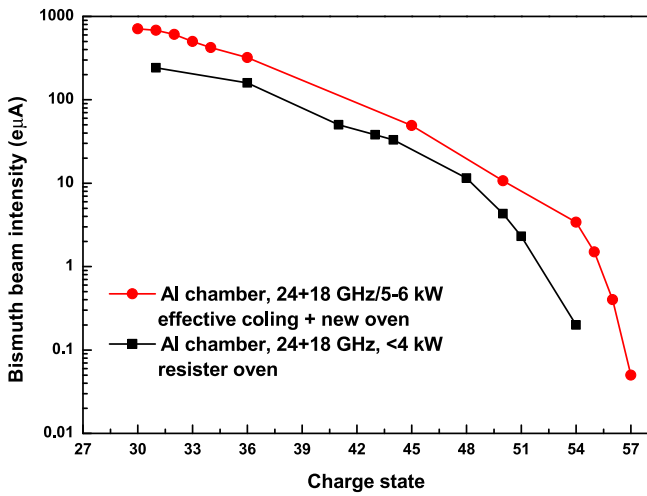


FIG. 14. Bismuth beam currents at the total microwave power 5–6 kW with a new oven and compared to those at the power less than 4 kW.

$^{209}\text{Bi}^{41+}$ (with 4.5 kW at 24 GHz plus 1.2 kW at 18 GHz), and 10 eμA of $^{209}\text{Bi}^{50+}$ (with 3.3 kW at 24 GHz plus 1.0 kW at 18 GHz). It should be pointed out that the temperature of the Cartridge Heater oven can be controlled accurately so that the evaporated bismuth vapor was stable during the beam tests.

Regarding the production of uranium beams with SECRAL, the sputtering method was used at 24 + 18 GHz double-frequency heating. Equipped with an aluminum chamber, SECRAL has produced 202 eμA $^{238}\text{U}^{33+}$ (with 3.8 kW at 24 GHz plus 1.0 kW at 18 GHz) [34]. Figure 15 shows the CSD spectra with the source tuned for $^{209}\text{Bi}^{31+}$, $^{209}\text{Bi}^{50+}$ and $^{238}\text{U}^{33+}$, respectively.

SECRAL’s production of bismuth and uranium beams with high power of 24 + 18 GHz has demonstrated that the production of intense very heavy ion beams is achievable with an ECRIS.

D. Production of record beam intensities by a new microwave coupling

In 2000, for the first time, 28 GHz microwaves were successfully launched into SERSE [17], a superconducting ECR ion source designed for operation at 18 GHz but having a rather sufficient magnetic configuration to be run at higher frequency. The 28 GHz microwaves generated by a gyrotron in TE₀₂ mode were then converted into TE₀₁ wave and transported in an oversize circular waveguide of conventional diameter of 32 mm before being launched into the ion source. All other 24–28 GHz ECR sources have utilized the similar microwave coupling system, like VENUS [13], SECRAL [31], RIKEN-SCECR [22], SuSI [21], and so on. TE₀₁ wave mode is used since losses along the waveguide are very low, theoretically zero. The electric field of the TE₀₁ wave is unpolarized and circular having

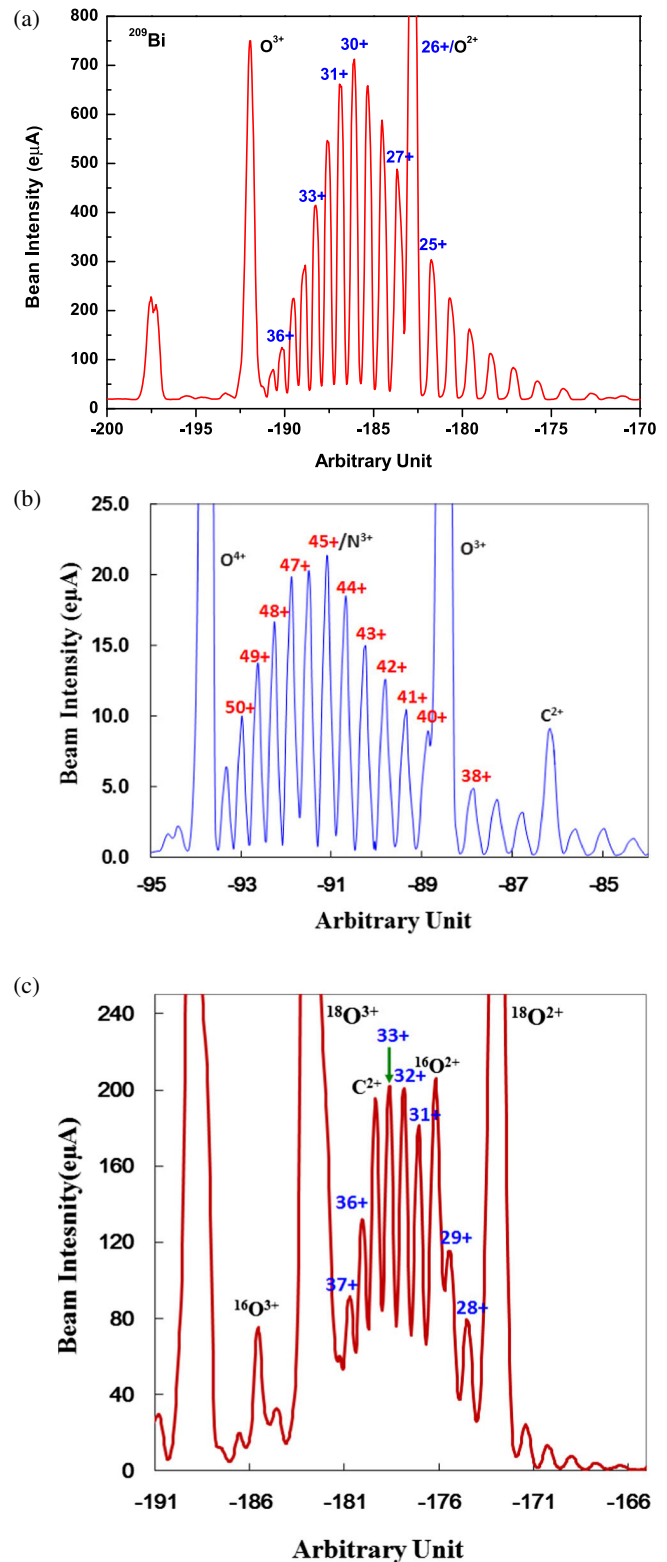


FIG. 15. CSD spectra with the source tuned for $^{209}\text{Bi}^{31+}$, $^{209}\text{Bi}^{50+}$ and $^{238}\text{U}^{33+}$. (a) Bismuth CSD spectrum with the source optimized for $^{209}\text{Bi}^{31+}$ at total microwave power 5.1 kW of 24 + 18 GHz. (b) Bismuth CSD spectrum with the source optimized for $^{209}\text{Bi}^{50+}$ at total microwave power 4.3 kW of 24 + 18 GHz. (c) Uranium CSD spectrum with the source optimized for $^{238}\text{U}^{33+}$ at total microwave power 3.7 kW of 24 + 18 GHz.

FIG. 16. Compact mode converter from TE_{01} to HE_{11} .

zero electric fields at the inner surface and axis of the waveguide, i.e. the power distribution at the waveguide center is also very low. To avoid this zero power on waveguide axis, Hitz proposed other launching TE_{11} and HE_{11} into ECR ion sources which could lead to more efficient coupling to the plasma [2]. The HE_{11} mode is polarized with a quasi-Gaussian power distribution being maximum at the center [78]. It is thought that the HE_{11} might be, like in fusion machines, more efficient for the ECR heating and would enhance the source performance. The TE_{01} — HE_{11} microwave coupling was not explored until 2013, when Lyneis had designed and built, at LBNL, a 28 GHz TE_{01} — HE_{11} mode converter and carried out tests with VENUS. However, no improvement was observed with this new coupling [78].

A similar launching wave mode has been tested with SECRAL at 24 GHz with a TE_{01} to HE_{11} mode converter and microwave coupling system made of a snake waveguide and a corrugated waveguide [35,79]. However, due to the size of the converter and the plasma chamber diameter (ID = 116 mm), there was not enough space to house such a large converter. Then, the original $\text{\O}32$ mm circular waveguide was tapered down to $\text{\O}20$ mm, before the TE_{01} to HE_{11} mode converter. This compact mode converter developed by IMP is shown in Fig. 16. To have a meaningful comparison, an $\text{\O}20$ mm TE_{01} mode circular waveguide was also fabricated and tested with SECRAL.

Tests were carried out with SECRAL focusing on the production of highly charged argon and xenon ion beams, with three different launchings: standard $\text{\O}32$ mm TE_{01} , $\text{\O}20$ mm TE_{01} and $\text{\O}20$ mm HE_{11} waves, with the double frequency heating at 24 + 18 GHz. To get a good comparison between these launchings, SECRAL source parameters were optimized but kept as close to each operating wave as possible. Figure 17 illustrates the efficiency of these three launchings for $^{129}\text{Xe}^{27+}$, $^{40}\text{Ar}^{12+}$ and $^{40}\text{Ar}^{14+}$ with the same extraction voltage set at 25 kV. Figure 17 also demonstrates that whatever the wave coupling scheme, the beam intensities for the ions $^{129}\text{Xe}^{27+}$, $^{40}\text{Ar}^{12+}$ and $^{40}\text{Ar}^{14+}$ keep increasing almost linearly with the input microwave power even up to 9 kW without saturation.

Table I compares the achieved ion beam intensity at similar wave power level for each of the launching schemes. The corresponding sextupole field at the chamber wall and the axial magnetic fields for the source tuning

are also listed in Table I. These results have demonstrated that though the HE_{11} waves can produce about the same highly charged ion beams as the TE_{01} waves, no performance enhancements were obtained, as for VENUS [78]. On the other hand, beam tuning with the HE_{11} waves at high power appeared to be more difficult to generate a stable ECR plasma.

In addition to the results with the HE_{11} waves, Fig. 17 and Table I show the very good efficiency of the $\text{\O}20$ mm TE_{01} wave coupling, even if the gain for the higher charge state ion beam like $^{129}\text{Xe}^{34+}$ is small. Moreover, beam tuning with the $\text{\O}20$ mm TE_{01} waveguide appears to be much easier than with the other launchings. Table I also

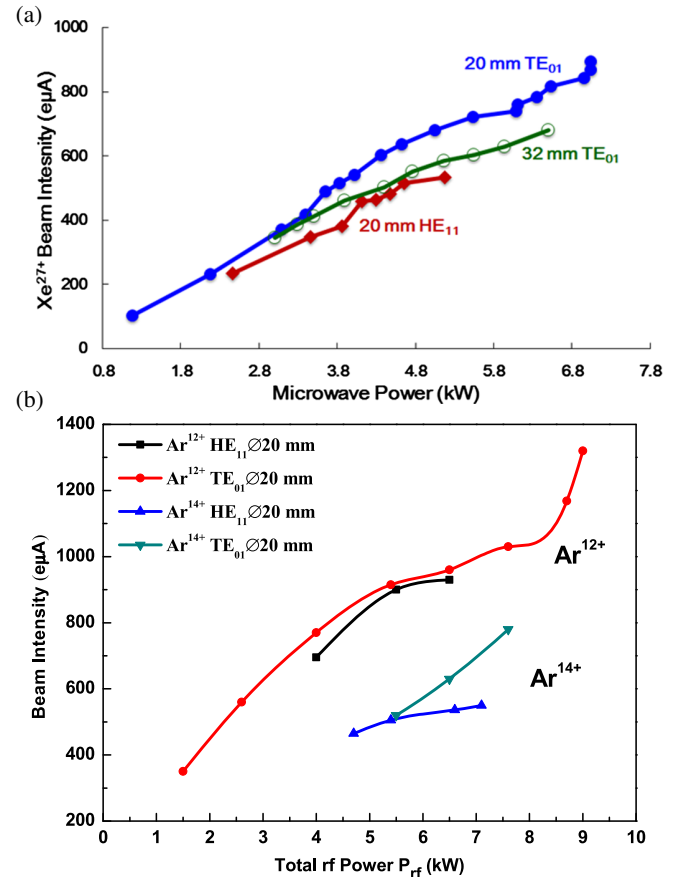
FIG. 17. Dependence of beam intensity on total microwave power at 24 + 18 GHz coupled at different microwave coupling schemes. (a) $^{129}\text{Xe}^{27+}$ beam; (b) $^{40}\text{Ar}^{12+}$ and $^{40}\text{Ar}^{14+}$ beam.

TABLE I. Comparison of typical beams and the beam intensities at the similar microwave power level by using different wave coupling schemes.

Ion	I (μA)	P_{rf} (kW) 24 + 18 GHz	$B_{rad}, B_{inj}, B_{min}, B_{ext}$ (T)	V_{extr} (kV)	rf coupling
$^{129}\text{Xe}^{27+}$	588	6 + 1.6	1.65, 3.45, 0.58, 1.66	25	$\text{TE}_{01}\varphi_{32}$
	738	6 + 1.6	1.61, 3.40, 0.58, 1.68		$\text{TE}_{01}\varphi_{20}$
	620	6 + 1.6	1.63, 3.31, 0.53, 1.62		$\text{HE}_{11}\varphi_{20}$
$^{129}\text{Xe}^{30+}$	265	7 + 1.2	1.66, 3.50, 0.60, 1.80	25	$\text{TE}_{01}\varphi_{32}$
	293	7 + 1.0	1.65, 3.49, 0.62, 1.94		$\text{TE}_{01}\varphi_{20}$
	235	7 + 1.7	1.65, 3.54, 0.56, 1.74		$\text{HE}_{11}\varphi_{20}$
$^{129}\text{Xe}^{34+}$	80	4.2 + 1.1	1.66, 3.43, 0.63, 1.81	25	$\text{TE}_{01}\varphi_{32}$
	90	7 + 1.4	1.65, 3.50, 0.60, 1.82		$\text{TE}_{01}\varphi_{20}$
	25	6 + 1.5	1.65, 3.60, 0.58, 1.70		$\text{HE}_{11}\varphi_{20}$
$^{40}\text{Ar}^{12+}$	1300	6 + 1.7	1.54, 3.23, 0.55, 1.52	26	$\text{TE}_{01}\varphi_{20}$
	1120	6 + 1.7	1.43, 3.30, 0.52, 1.60		$\text{HE}_{11}\varphi_{20}$
$^{40}\text{Ar}^{14+}$	630	5 + 1.5	1.58, 3.46, 0.56, 1.59	25	$\text{TE}_{01}\varphi_{20}$
	516	5 + 1.5	1.63, 3.52, 0.53, 1.59		$\text{HE}_{11}\varphi_{20}$
$^{40}\text{Ar}^{16+}$	310	6 + 1.5	1.65, 3.50, 0.60, 1.70	26	$\text{TE}_{01}\varphi_{20}$
	198	6 + 1.75	1.66, 3.46, 0.59, 1.70		$\text{HE}_{11}\varphi_{20}$

indicates that for all three types of launching, the magnetic field configuration is almost the same: $B_{rad} \sim 1.9B_{ecr}$, $B_{inj} \sim 4.0B_{ecr}$, $B_{min} \sim 0.67\text{--}0.73B_{ecr}$, and $B_{ext} \sim 1.9\text{--}2.1B_{ecr}$, where B_{ecr} is the electron resonance field for 24 GHz waves, i.e. 0.86 T. This is consistent with the scaling laws determined with SERSE for one frequency heating [17,62], as the second frequency mostly helps in plasma stabilization.

With the $\varnothing 20$ mm TE_{01} circular waveguide, SECRAL has produced again a large number of new record beams of highly charged ions, such as, 1420 μA of $^{40}\text{Ar}^{12+}$, 846 μA of $^{40}\text{Ar}^{14+}$, 1100 μA of $^{129}\text{Xe}^{26+}$, 920 μA of $^{129}\text{Xe}^{27+}$, 322 μA of $^{129}\text{Xe}^{30+}$ and 90 μA of $^{129}\text{Xe}^{34+}$.

Figure 18 shows the CSD spectra at total microwave power 8.5 kW of 24 GHz + 18 GHz double frequency heating with the $\varnothing 20$ mm TE_{01} circular waveguide when the source is optimized for $^{40}\text{Ar}^{12+}$ and $^{129}\text{Xe}^{30+}$. It is worth pointing out that for the first time for $^{40}\text{Ar}^{12+}$ and $^{129}\text{Xe}^{26+}$, the 1 eMA level has been reached and exceeded. The previous record beam intensities of $^{40}\text{Ar}^{12+}$ were 860 μA by LBNL VENUS in 2006 [80] and $^{129}\text{Xe}^{26+}$ was 480 μA by IMP SECRAL in 2009 [31].

The performance achieved recently with SECRAL has demonstrated that there is still potential in enhancing the performance of ECR ion sources by improving the microwave coupling. Speculative thought was that the HE_{11} waves with most of the energy concentrated on axis could benefit the ECR heating to improve the source performance, but surprisingly the tests in both SECRAL and VENUS reveal that it is not the case. The tests of the HE_{11} mode coupling with VENUS and SECRAL have once again raised the question: is the performance of an ECR ion source independent on the microwave mode? Further

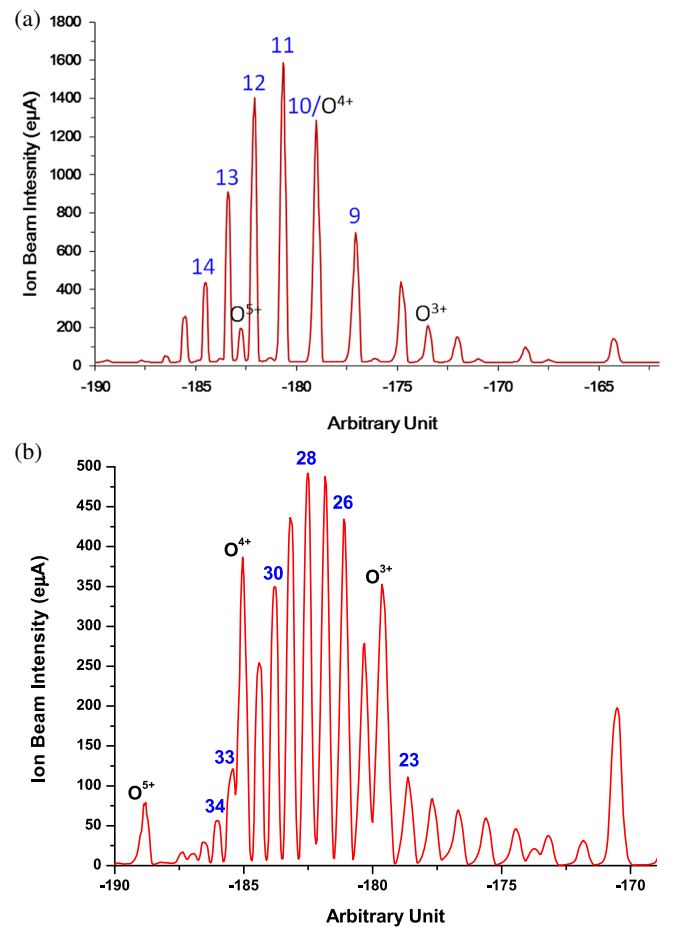


FIG. 18. CSD spectra at total microwave power 8.5–8.7 kW of 24 + 18 GHz double frequency heating with the $\varnothing 20$ mm TE_{01} circular waveguide. (a) The SECRAL source optimized for $^{40}\text{Ar}^{12+}$. (b) The SECRAL source optimized for $^{129}\text{Xe}^{30+}$.

theoretical and experimental studies should lead to a more definite conclusion.

SECRAL performance on the highly charged ion beams has been substantially improved by reducing the size of the TE_{01} waveguide down to $\varnothing 20$ [35,79]. Later on, similar experiments were conducted at 28 GHz LBNL VENUS in 2016 [65]; and strong intensity enhancements were noticed for highly charged oxygen, argon and krypton ion beams. The experiments with reduced size of the TE_{01} waveguide demonstrate that optimizing different ion beam production may require different launching size of the circular waveguide. The key reason might be related to absorption of the microwave power by the ECR plasma. Unfortunately the existing designed microwave coupling system is not able to measure the reflected power at 24–28 GHz with the oversize circular waveguide due to multimode transmission.

It is worth mentioning the explanation of Melin in the 12th ECRIS workshop [81] on the electron heating which may help with understanding of the experimental results. “It could be said that, the electron heating has to be perpendicular, with respect to the local magnetic field. The electron, moving back and forth along a magnetic field line, receives a kick in perpendicular velocity when crossing the resonance zone only if there is an electric field transversal with respect to the magnetic field. An electric field parallel to the magnetic field would cause the electron to fall in the loss-cone and to get lost rapidly. Nonetheless, as hot plasma is created close to the main axis, the direction is somewhat preferential and will be referred to below as the parallel direction. Thus it is preferable to have the rf wave launched parallel to this main axis, with an electric field perpendicular to this axis.”

This is the case for all three types of launching studied here; however, as the electrons spiral along the magnetic field lines, one may easily suppose that the chances to get positive kicks of energy are larger with TE_{01} than with HE_{11} . One also can imagine that chances are also better with smaller waveguide diameter, some further simulation and tests with SECRAL to study the microwave coupling are underway hoping to gain a better understanding.

E. Microwave frequency and power effect

The SECRAL data show one more time that performance of the highly charged ECR ion source is improved with microwave increase, provided that the magnetic confinement follows the well-established scaling laws for the main frequency heating. Geller’s scaling law predicts the beam intensity I_q of an ECR ion source is proportional to the square of the microwave frequency ω_{rf} , and then proportional to B_{ecr} , while the mean charge state $\langle q \rangle$ increases with the microwave frequency according to the formula $\langle q \rangle \propto \log \omega_{rf}^{3.5}$ [1,58–59,82].

Performance of high field and high frequency ECR ion sources, such as LNS SERSE [17], LBNL VENUS [13],

IMP SECRAL [31], NSCL SuSi [21] and RIKEN SCECR [22], have validated a perspective of the development of ECR ion sources in terms of the scaling law prediction by continuously increasing the beam intensities and charge states. However, do those third generation ECR sources, operating at 24–28 GHz with 5–10 kW high microwave power, still follow the scaling law prediction that the beam intensity is proportional to the square of the microwave frequency? Which parameter among the magnetic field, the microwave frequency and the microwave power, is more critical and dominant for the intense ion beam production of certain range of charge states? Effects of microwave frequency and power scaling at both 18 + 14.5 GHz and 24 + 18 GHz studied with SECRAL source are presented.

Figure 19 shows the best beam intensities of $^{129}\text{Xe}^{27+}$ achieved with SECRAL as a function of the injected power density for 18 + 14.5 GHz and 24 + 18 GHz. As the hot plasma volume is delimited by the resonance surface, it is more relevant to assume that most of the microwave power is absorbed in this volume and not spread in the entire plasma chamber. This plasma volume delimited by the main resonance zone is roughly 0.5 l at 24 GHz and 0.38 l at 18 GHz for the source conditions set to get the Xe^{27+} beam intensities presented in Fig. 19. Also shown in this figure is an extrapolation from 18 to 24 GHz with the frequency square. Above 7 W/cm^3 , there is a remarkable coincidence between this extrapolation from 18 GHz and the best 24 GHz rf coupling, i.e. TE_{01} - $\varnothing 20$ mm. This 7 W/cm^3 corresponds to 2.7 kW at 18 GHz and 3.5 kW at 24 GHz.

On the other hand, below 7 W/cm^3 , the situation at 24 GHz is very different as beam intensities are identical for both 18 and 24 GHz. This means that the input power is not entirely absorbed by the plasma and is either reflected to the microwave generator or spread inside the plasma chamber. The way that the microwave transmission line is designed

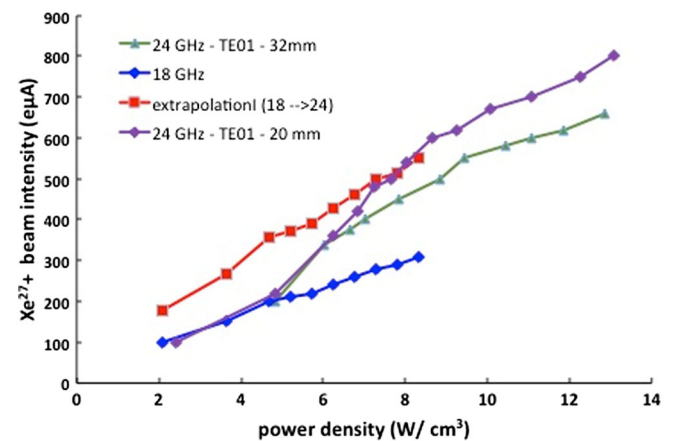


FIG. 19. Dependences of the best beam intensities of $^{129}\text{Xe}^{27+}$ on the total incident microwave power density at 24 + 18 GHz and 18 + 14.5 GHz.

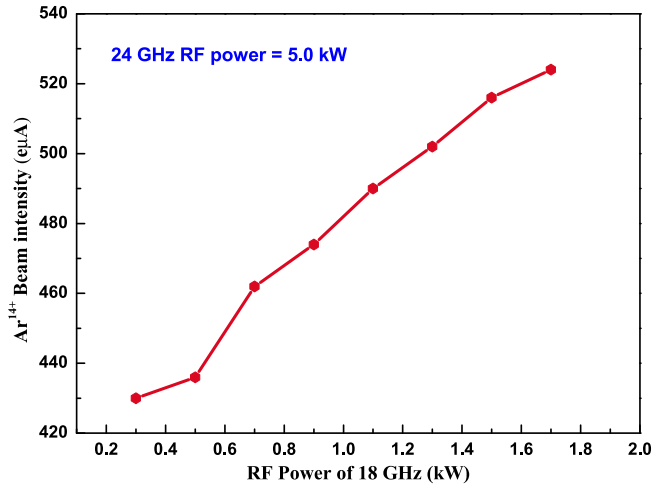


FIG. 20. $^{40}\text{Ar}^{14+}$ beam intensity dependence on microwave power of the second supplemental heating frequency 18 GHz when the main frequency 24 GHz power is fixed.

does not allow any measurement of the reflected power as the bidirectional coupler can only detect the TE_{02} mode. Nevertheless, from Fig. 19, one can notice that the 24 GHz is efficient above 3.5 kW. An explanation is given by Girard in the article [40] which shows that the absorbed power increases with the microwave wave electric field up to a maximum the plasma builds up, i.e. at low microwave power, the electron density is small and cannot absorb the total input power. Therefore, in the case of SECRAL, the buildup limit is about 7 W/cm^3 . Another explanation and understanding could be given by Ivanov in the article [83] which points out that with increasing the microwave power the electrons are heated more and more, resulting in an increase of the ionization coefficients; meanwhile, the confinement time of the plasma decreases due to ion heating and an increase of the turbulence enhanced plasma transport to the walls. At low power, the beneficial effect of electron heating dominates. Thus, increasing the admitted power improves the performance of an ion source. At a certain power level, the increase of plasma losses due to

transport balances the improvement due to electron heating, outweighing it when increasing the admitted power further [83]. Some significant studies on these issues were also conducted by Gammino, Mascali, Koivisto and Lyneis [43,84–87], which can be helpful for understanding the role of microwave coupling, effects of microwave frequency and power.

However, during some other experiments performed with argon, for the production of $^{40}\text{Ar}^{14+}$ ion beam with the $\emptyset 20 \text{ mm}$ HE_{11} mode at 24 GHz, the contribution of the second frequency, i.e. 18 GHz, enhances the ion beam intensity by 25%. Figure 20 shows the strong contribution of the second frequency heating, which does not only rely on plasma stability. This contribution to beam intensity enhancement probably leads to a better absorption of the 24 GHz or stronger electron density increase.

F. Magnetic field effect

The magnetic field configuration parametrized by B_{rad} , B_{inj} , B_{min} and B_{ext} has a significant impact on the performance of a highly charged ECR ion source for providing the electron heating and determining plasma confinement time. What is the best magnetic field configuration for the production of highly charged ion beams by ECR ion sources remains arguably a possibility for further enhancing source performance, which has been studied by many groups [19,29,43,62,88–94], even though the empirical magnetic-field design criteria work well. Magnetic field studies for $18 + 14.5$ and $24 + 18$ GHz double-frequency heating were carried out with SECRAL. Table II shows the key values of the magnetic fields $B_{\text{rad}}/B_{\text{ecr}}$, $B_{\text{inj}}/B_{\text{ecr}}$, $B_{\text{min}}/B_{\text{rad}}$, $B_{\text{ext}}/B_{\text{rad}}$ and $B_{\text{last}}/B_{\text{ecr}}$, which demonstrate a good agreement with the well-established scaling laws by Hitz [62]. Whatever the element and charge state, the magnetic parameters used with SECRAL even under the double frequency heating, they all the time are in agreement, except however for Ar^{16+} where the extraction field is somehow high. The minimum value of the axial mirror magnetic field (B_{min}) has a big impact on

TABLE II. Ratios of those key magnetic field values $B_{\text{rad}}/B_{\text{ecr}}$, $B_{\text{inj}}/B_{\text{ecr}}$, $B_{\text{min}}/B_{\text{rad}}$, $B_{\text{ext}}/B_{\text{rad}}$, $B_{\text{last}}/B_{\text{ecr}}$ at $18 + 14.5$ GHz and $24 + 18$ GHz double frequency heating to achieve the best beam intensities for SECRAL.

Ion beam	$B_{\text{rad}}/B_{\text{ecr}}$		$B_{\text{inj}}/B_{\text{ecr}}$		$B_{\text{min}}/B_{\text{rad}}$		$B_{\text{ext}}/B_{\text{rad}}$		$B_{\text{last}}/B_{\text{ecr}}$	
	24 + 18 GHz	18 + 14.5 GHz	24 + 18 GHz	18 + 14.5 GHz	24 + 18 GHz	18 + 14.5 GHz	24 + 18 GHz	18 + 14.5 GHz	24 + 18 GHz	18 + 14.5 GHz
$^{40}\text{Ar}^{12+}$	1.8	1.8	3.8	3.4	0.34	0.39	0.97	1.06	1.94	1.92
$^{40}\text{Ar}^{16+}$	1.9	2.3	4.1	4.1	0.36	0.37	1.05	1.43	2.02	2.44
$^{129}\text{Xe}^{27}$	1.91	2.0	4.1	3.9	0.37	0.41	1.10	1.10	2.04	2.16
$^{129}\text{Xe}^{34}$	1.92	2.0	4.1	3.9	0.36	0.40	1.09	1.05	2.05	2.14
$^9\text{Bi}^{31+}$	1.84	1.9	4.0	3.9	0.38	0.40	1.08	1.05	1.97	2.05
$^{209}\text{Bi}^{36+}$	1.84	2.0	4.0	4.1	0.38	0.39	1.08	1.00	1.97	2.14
$^{209}\text{Bi}^{50+}$	1.84	2.0	4.0	4.1	0.36	0.41	1.08	1.05	1.96	2.15

TABLE III. The optimum B_{\min} values and the corresponding beam intensities for optimizing different ion beam production at different microwave power level during SECRAL beam tests at 24 + 18 GHz.

Ion beam	I (μA)	P_{rf} (kW)	B_{\min} (T)
$^{40}\text{Ar}^{12+}$	850–1000	4–5	0.56
	1100–1250	6–7	0.55
	1250–1420	8–9	0.54
$^{40}\text{Ar}^{14+}$	360–520	4–5	0.56
	630–750	6–7	0.58
	750–846	8–9	0.59
$^{129}\text{Xe}^{27+}$	270–430	3–4	0.59
	480–630	5–6	0.58
	700–920	7–9	0.58
$^{129}\text{Xe}^{30+}$	150–190	3–4	0.60
	220–350	7–8	0.62
$^{209}\text{Bi}^{31+}$	242	2.8	0.60
	680	6.1	0.59

highly charged ion beam production of an ECR ion source because the magnetic field distribution affects the plasma confinement and the electron heating effect, which has been studied by a few groups [19,43,62,88–94]. Table III shows the optimum B_{\min} values and the corresponding beam intensities for optimizing different ion beam production at different microwave power level during SECRAL beam tests at 24 + 18 GHz.

It is interesting to notice that the magnetic field distribution for SECRAL operation at 24 + 18 GHz is very similar to those of VENUS and RIKEN-SCECR operating at 28 + 18 GHz as presented in Table IV [19,22,65,91,93–95]. Particularly, comparison of the axial mirror magnetic fields between SECRAL and VENUS for optimizing production of different highly charged ion beams such as Ar^{16+} , Xe^{27+} , Bi^{31+} , U^{34+} and Bi^{50+} could be interesting and the axial fields approximately are $B_{\text{inj}} \sim 3.5$ T, $B_{\min} \sim 0.45\text{--}0.60$ T and $B_{\text{ext}} \sim 1.7\text{--}2.2$ T for SECRAL and VENUS. The axial magnetic field profiles for SECRAL and VENUS achieving the maximum $^{209}\text{Bi}^{30+}$ intensity is shown in Fig. 21 [19,65,95], and the new axial magnetic field profile after a few technical modifications for VENUS is also shown in Fig. 21 for comparison [65]. Table IV and

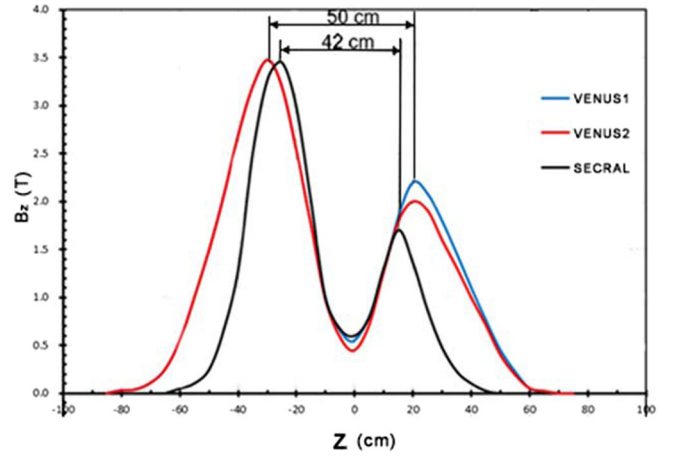


FIG. 21. Comparison of the axial magnetic field distribution between SECRAL and VENUS. (The blue line VENUS1 and the dark line SECRAL are the magnetic field distribution for optimizing high intensity $^{209}\text{Bi}^{30+}$ beam respectively. The red line VENUS2 is the new field distribution for VENUS after modifications.)

Fig. 21 demonstrate that the axial injection peak field B_{inj} for SECRAL and VENUS is almost the same, and the magnetic field gradient ∇B and the minimum-B field B_{\min} are quite similar or no significant difference. But the key differences of the field distributions for the two sources are located at the mirror space, the extraction peak field B_{ext} and the sextupole field at the plasma chamber inner wall B_{rad} . The B_{ext} for SECRAL is much lower than that of VENUS because the sextupole field B_{rad} at the plasma chamber wall for SECRAL is lower than that of VENUS, in which VENUS operated previously at higher B_{ext} is likely due to poor electrode cooling [65]. The extraction field for SECRAL are about 3 cm closer to the ECR zone compared to that of VENUS. The new axial magnetic field profile of VENUS (the red line in Fig. 21) with lower B_{\min} , lower B_{ext} , but higher B_{rad} , is likely due to higher microwave power operation (10 kW) and lower bremsstrahlung radiation [63–65].

The question arises why the optimum magnetic fields are so close for achieving the best intensities of those different ion beams such as Ar^{16+} , Xe^{30+} , Xe^{34+} , Bi^{36+} and Bi^{50+} ? The reason could be the value of the key parameters $n_e \tau_i$

TABLE IV. Comparison of the optimized magnetic fields among SECRAL, VENUS and RIKEN-SCECR.

ECR ion source	28(24) + 18 GHz $B_{\text{rad}}, B_{\text{inj}}, B_{\min}, B_{\text{ext}}$ (T)	18 + 14.5 GHz $B_{\text{rad}}, B_{\text{inj}}, B_{\min}, B_{\text{ext}}$ (T)	Ion beams to optimize
SECRAL	1.63, 3.43, 0.51–0.60, 1.71	1.28, 2.56, 0.49–0.55, 1.28	Ar^{16+} , Xe^{27+} , Xe^{34+} , Bi^{30+} , Bi^{36+} , Bi^{50+}
VENUS(1)	2.0, 3.5, 0.55–0.6, 2.0–2.2	1.28, 2.56, 0.51, 1.47	Xe^{27+} , Xe^{28+} , Bi^{30+}
VENUS(2)	2.2, 3.5, 0.45, 2.0		O^{7+} , Ar^{14+} , Ar^{16+}
RIKEN SCECR	1.88, 3.1, 0.65, 1.78	1.21, 2.30, 0.51, 1.21	$^{238}\text{U}^{35+}$

and T_e related to the confinement and electron heating are quite close or at the similar level if we look at Golovanivsky's diagram of the $(n_e \cdot \tau_i)T_e$ criteria [82,96]. Moreover, differences of the optimum values B_{\min} for those different ion beams and even for the different heating frequencies are minor or of no significant difference ranging from 0.45–0.65 T only, which may be due to the reason that production of those different highly charged ions requests the similar level of the hot electron energy T_e , and possibly T_e could be determined by B_{\min} , and T_e may be independent on the microwave heating frequency. This explanation is consistent with the recent bremsstrahlung measurements at VENUS demonstrating the spectra temperature T_s is linearly dependent on B_{\min} and independent on the microwave frequency [64].

Effects of the magnetic field configuration on the ECR electron heating and plasma confinement are very much sophisticated and remain arguable. Gammino [43] and Leitner [91] point out in terms of bremsstrahlung spectrum measurements at VENUS that the magnetic field gradient near the resonance zone ∇B plays a key role for the hot electron production and the source performance, which is also related to the axial minimum field B_{\min} . A gentler magnetic field gradient at the resonant zone will result in a more efficient heating process and will lead to the generation of a hot electron tail in the electron energy distribution, and this high energy tail is strongly affected by the ratio of B_{\min}/B_{ECR} and by the heating frequency [91], while the sextupole field under the high-B mode requirements and the improvement of the electron confinement due to the suppression of any MHD instability plays a major role in determining the plasma dynamics, and the sextupole field has a limited influence on the electron energy distribution function, but it affects the electron density [43]. Nakagawa has studied a lot on the magnetic field effect on performance of an ECR ion source [88–90, 94]. Nakagawa's studies stress that not only B_{inj} , B_{\min} , B_{rad} and ∇B , but also B_{ext} , are quite essential to the source performance on highly charged ion beam production, and optimum B_{\min} to maximize the beam intensity is dependent on the gas pressure and biased disk voltage [94]. Benitez [64] reported recently that bremsstrahlung spectrum measurements at VENUS have demonstrated the spectra temperature T_s is independent on the field gradient ∇B and the heating frequency, but T_s is dependent on B_{\min} [64]. However, B_{inj} , B_{\min} , B_{ext} and the magnetic field gradient ∇B are always quite difficult to be decoupled, and it is still an open question which parameter is the most dominant one and how these magnetic-field parameters impact on those key ECR-plasma parameters n_e , τ_i , τ_e and T_e , and then correspondingly how to impact on the performance of highly charged ECR source. These key issues are essential to intense beam production of very high charge state ions such as Xe^{48+} , Bi^{60+} and U^{60+} , and also very crucial to the design of the fourth generation ECR ion source.

G. Summary of the update performance of SECRAL

The present performance of SECRAL on the production of highly charged ion beams has been enhanced drastically since its first beam produced in 2005. Such enhancement is the accumulation of continuous exploration and component modifications as described previously. Particularly, efficient cooling of the injection system (biased disk, waveguide, etc.) and new 24 GHz microwave launching enabled SECRAL to operate stably at total microwave power up to 7–9 kW of 24 + 18 GHz. The great performance improvements lead to many intensity records of highly charged heavy ion beams from an ECR in source. Table V summarizes all beam intensity records presently produced by SECRAL in comparison to those produced by VENUS after modifications of the new microwave coupling and raising the microwave power up to 10 kW and the extraction voltage up to 28 kV [13,65,75–76].

Figures 22 illustrates beam intensity evolution of $^{209}\text{Bi}^{31+}$ and $^{129}\text{Xe}^{30+}$ with different technical developments from year 2006 to year 2015. $^{209}\text{Bi}^{31+}$ intensity has been increased by a factor of 10, while $^{129}\text{Xe}^{30+}$ beam intensity has been increased by a factor of 3.

On the other hand, one has to keep in mind that the frequency gap between 24 and 18 GHz for the double-frequency heating is smaller than that with 28 + 18 GHz, which may be beneficial to SECRAL operations. However, source tuning indicates that the SECRAL performance

TABLE V. The record beam intensities presently produced by SECRAL and comparison to those produced by VENUS*.

Ion beam	SECRAL I ($e\mu\text{A}$)	SECRAL I ($e\mu\text{A}$)	VENUS I ($e\mu\text{A}$)
	18 + 14.5 GHz 2–3.2 kW	24 + 18 GHz 4–9 kW	28 + 18 GHz 4–9 kW
Ar^{12+}	510	1420	1060
Ar^{14+}	270	846	840
Ar^{16+}	73	350	523
Ar^{17+}	8.5	50	115
Xe^{20+}	505		
Xe^{26+}	410	1100	
Xe^{27+}	306	920	
Xe^{30+}	101	322	211
Xe^{34+}	21	90	
Xe^{42+}	1.5	10	1
Bi^{30+}	191	710	
Bi^{31+}	150	680	300
Bi^{41+}	22	100	
Bi^{45+}	15	49	
Bi^{50+}	1.5	10	5.3
Bi^{55+}		1.5	
U^{32+}		200	450
U^{33+}		202	400

* Argon beam intensities produced by VENUS were published in 2016 [65] and the other beams produced by VENUS were published before 2013 [13,75–76].

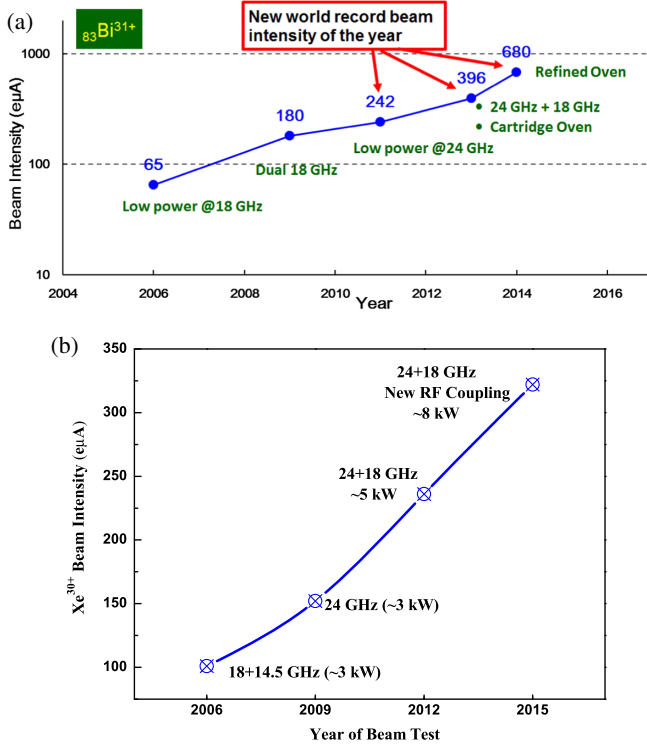


FIG. 22. $^{209}\text{Bi}^{31+}$ (a) and $^{129}\text{Xe}^{30+}$ (b) beam intensity evolution with different technical developments from the year 2006 to 2015.

would be further improved if the magnetic fields both for the sextupole and the axial mirror fields could reach higher values.

V. BEAM QUALITY AND LONG-TERM OPERATIONS

A. Beam emittance

Beam emittance ϵ is a key issue for an ECR ion source, particularly for application in accelerator. Accelerator physicists always require higher beam brightness defined by the square of the beam current I over the emittance, i.e. $\text{brightness} = I^2/\epsilon$, thus for the same beam current, the lower the emittance is the higher the brightness. Generally speaking, the ion beam intensities of the third generation ECR ion sources have been enhanced by a factor of 2–10 over the second generation ECR sources, achieved by increasing the magnetic fields and microwave power by a factor of 1.5–2. One of the main concerns is the beam quality for the third generation ECR ion source when microwave frequency, microwave power and magnetic fields are strongly increased. A beam emittance study has been conducted with SECAL at both 18 and 24 GHz by an Allison emittance scanner located just behind the focal point of the analyzing magnet. The challenge to a good beam emittance study of an ECR source is that it is sensitive to the source tuning, plasma

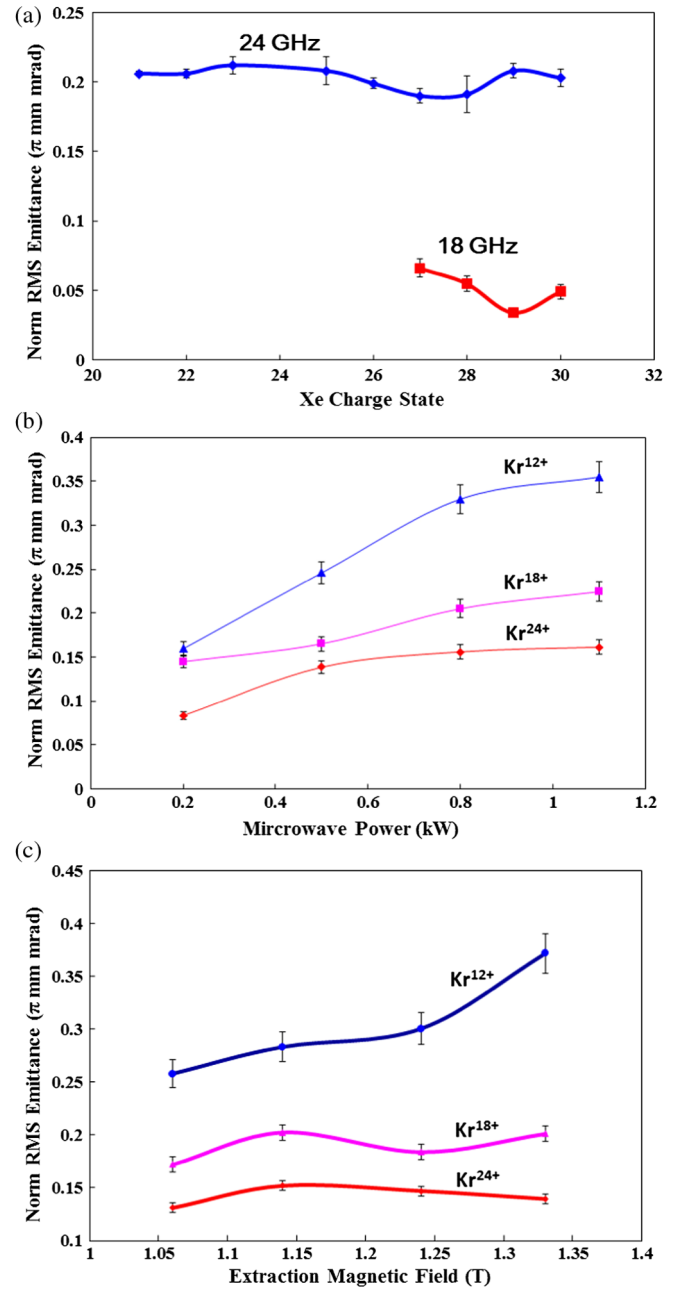


FIG. 23. SECAL beam emittance study. (a) Xenon beam emittance measured at low microwave power of 24 and 18 GHz. (b) Dependences of normalized rms emittance on 18 GHz microwave power measured at SECAL. (c) Dependences of normalized rms emittance on the extraction peak field at 18 GHz SECAL.

condition and quality of the beam transport line. Thus at roughly the same conditions the study can result in relative and statistical comparison of beam emittance.

Square root normalized rms emittance $\epsilon_{sr} = (\epsilon_{xn-rms}^2 + \epsilon_{yn-rms}^2)^{1/2}$ is typically a good quality depiction of an ion beam. Figure 23(a) shows the measurements of normalized rms emittance in the horizontal direction for high charge state xenon ion beams produced with SECAL

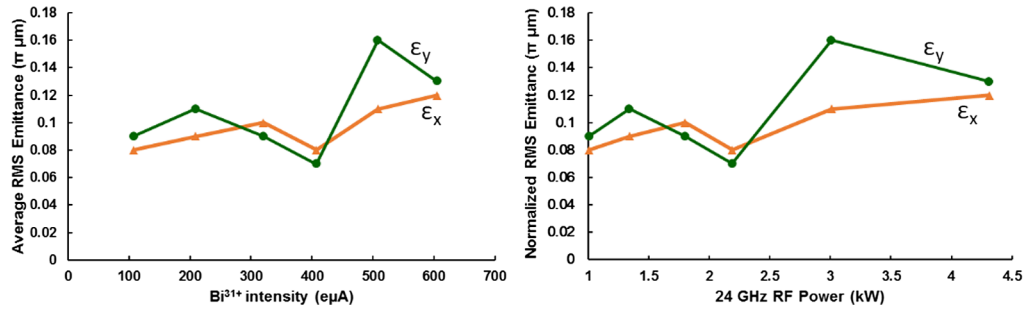


FIG. 24. Dependences of normalized rms emittance on the beam $^{209}\text{Bi}^{31+}$ intensity and the 24 GHz microwave power at SECRAL.

at low microwave power of 24 and 18 GHz (both less than 1 kW) at 15–20 kV extraction voltage. It indicates that emittance at 24 GHz operation, with low beam intensity and low microwave power, is larger than that at 18 GHz. Dependences of the normalized rms emittance on the operating 18 GHz microwave power and the extraction peak field for the ion beams $^{78}\text{Kr}^{24+}$, $^{78}\text{Kr}^{18+}$ and $^{78}\text{Kr}^{12+}$ beams were measured at SECRAL, as shown in Figs. 23(b) and 23(c), respectively. Figure 23(b) indicates beam emittance could increase slightly with the wave power and beam intensity although the measurements were conducted at lower power and low beam intensity. Figure 23(c) shows that increasing the extraction peak field may raise the beam emittance slightly and emittance variations of different charge state could be different. The emittance measurement errors shown in Fig. 23 are errors of mean square root calculated from many time measurements. Emittance studies with SECRAL in Fig. 23 were conducted with low beam current less than $100\text{ e}\mu\text{A}$ and low wave power less than 1.5 kW. Figure 24 illustrates dependence of normalized rms emittance on the beam intensity of $^{209}\text{Bi}^{31+}$ from $100\text{ e}\mu\text{A}$ to $600\text{ e}\mu\text{A}$ versus 24 GHz power from 1 to 4.5 kW [35]. Each beam emittance measurement in Fig. 24 was conducted by optimizing all other source parameters to reach the highest beam intensity of $^{209}\text{Bi}^{31+}$ at a fixed 24 GHz microwave power. The measurements shown in Fig. 24 indicate that the emittance of high charge state ion beam may increase with beam intensity and microwave power slightly, but even up to a few hundreds of $\text{e}\mu\text{A}$ and a few kilowatts of microwave power, there is no significant increase of beam emittance.

Comparing with data obtained at 18 GHz in Fig. 23, the beam emittance shown in Fig. 24 was measured when microwave frequency, power level, magnetic fields and beam intensity were strongly increased. Figure 25 shows beam emittance phase-space patterns and beam images for the ion beam $^{209}\text{Bi}^{31+}$ at $115\text{ e}\mu\text{A}$ with 1.0 kW of power at 24 GHz and $330\text{ e}\mu\text{A}$ with 3.4 kW of 24 GHz power, respectively. It is clearly demonstrated that the beam distribution in phase space is very much distorted, which could be caused by space charge effect, transversal coupling due to the solenoid lens, aberrations from the solenoid lens and the analyzing magnet.

However, the projection emittance shown in Fig. 25 for $330\text{ e}\mu\text{A}$ of $^{209}\text{Bi}^{31+}$ produced with 3.4 kW of 24 GHz power is quite large, i.e. $200\text{--}350\pi\text{ mm mrad}$ in the horizontal direction and $350\text{--}450\pi\text{ mm mrad}$ in the vertical direction with 90%–95% of the beam current. This horizontal emittance value is almost the same as that obtained with VENUS for $365\text{ e}\mu\text{A}$ of $^{238}\text{U}^{33+}$ produced with 6 kW of 28 GHz wave power [97], but the vertical emittance for SECRAL is larger than that of VENUS [97].

A beam quality study has demonstrated that beam emittance from SECRAL, operated at 24 GHz at high microwave power and high magnetic fields, is at a similar level as that of 18 GHz. Generally speaking, the normalized-rms emittance is around $0.05\text{--}0.2\pi\text{ mm mrad}$ or slightly higher, depending upon the source tuning, the plasma conditions and the solenoid lens setting.

Beam emittance of an ECR ion source operating at higher microwave frequency and power, and higher magnetic fields, could be slightly higher but not significantly than at lower microwave frequency and power, and lower magnetic fields. The normalized-rms emittances measured with SECRAL at both 18 and 24 GHz operations are

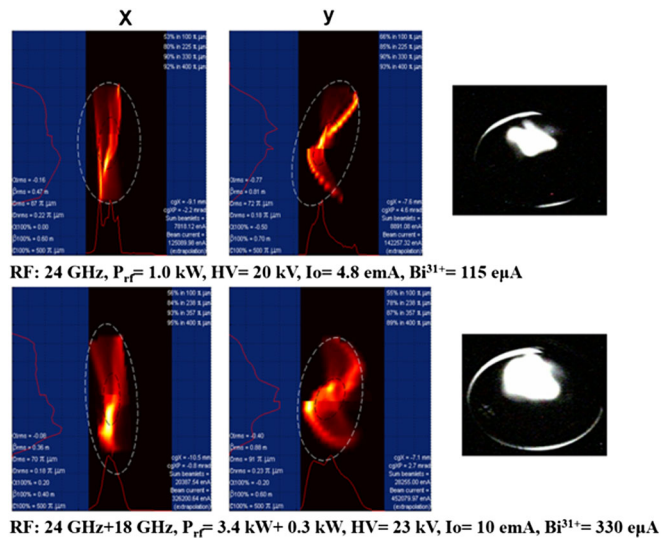


FIG. 25. Beam emittance phase-space patterns and beam images for the beam $^{209}\text{Bi}^{31+}$ at different conditions for SECRAL operating 24 GHz.

roughly the same as those measured with VENUS and RIKEN-SCECR [97–100].

B. Beam stability

Long-term beam stability is one of the most important qualities of an ion source. At low beam intensity, i.e. below $200 \text{ e}\mu\text{A}$, and below 2 kW of microwave power, long-term beam stability has been demonstrated by many ECR ion sources delivering beams to the heavy ion accelerators [89,101–105], but not yet for highly charged heavy ion beam intensity exceeding $300 \text{ e}\mu\text{A}$ produced with wave power above 5 kW.

The microscopic instability could be caused by kinetic plasma instabilities resulting in periodic beam intensity oscillations, which have been studied by Skalyga and Tarvainen [51,54–55,106] recently and also reported by Kitagawa [107] and Nakagawa [105].

The plasma instabilities due to electron cyclotron instabilities may arise from the strongly anisotropic distribution function of electrons in the velocity space, which fundamentally affects the plasma confinement and leads to a disruption of highly charged ion production [51,54–55]. The beam instabilities caused by the plasma instabilities could be partially mitigated by the two-frequency heating and optimized tuning of the magnetic field distribution, which were reported by many ECRIS labs [31,51,74,76,92,106–108].

Figure 26 shows suppression of beam instabilities by two-frequency heating (28 + 24 GHz) and three-frequency heating (28 + 24 + 18 GHz) conducted recently with SECRAL at 3 kW 28 GHz microwave power for $^{129}\text{Xe}^{27+}$ beam intensity around $550 \text{ e}\mu\text{A}$. Figure 26 illustrates that the role of the 18 GHz at 200 W is only to stabilize the plasma during the three-frequency heating (28 + 24 + 18 GHz); while the second frequency 24 GHz, even at 200 W, not only contributes to the beam intensity enhancement, but also to the suppression of the plasma instabilities. Nevertheless, contribution of 24 GHz frequency to suppress the plasma instabilities is less efficient than that of 18 GHz during the three-frequency heating (28 + 24 + 18 GHz). Experiments with SECRAL have

demonstrated that suppression of the plasma instabilities may not be effective with multifrequency heating if frequency gap is not large enough. (28 + 18 GHz), (24 + 18 GHz) and (28 + 24 + 18 GHz) could be a good option respectively if only considering suppression of the plasma instabilities.

The macroscopic instability could result from outgassing and/or discharge. Such macroscopic instability could be eliminated or mitigated with long time conditioning at high microwave power. Figure 27(a) shows beam intensity instability of $^{129}\text{Xe}^{27+}$ at $435 \text{ e}\mu\text{A}$ when SECRAL was tested at single frequency heating of 24 GHz at 3.5 kW without a long-term conditioning and optimized tuning. After long time conditioning at total microwave power about 4 kW, fine-tuning of the magnetic field distribution and two-frequency heating with 24 + 18 GHz, even higher charge state beam at high beam intensity could become quite stable as shown in Fig. 27(b) which shows the beam stability of $^{129}\text{Xe}^{30+}$ at $235 \text{ e}\mu\text{A}$ achieved by 24 + 18 GHz at 4.3 kW + 1.3 kW microwave power.

Figure 27(c) demonstrates beam intensity stability of $^{209}\text{Bi}^{31+}$ at $330 \text{ e}\mu\text{A}$ tested continuously during 2.5 hours by 24 + 18 GHz two-frequency heating at 3.4 kW + 0.3 kW microwave power [34], from which beam intensity oscillation at small scale magnitude can be observed.

Long-term stability of ECR source beam intensity is extremely important for accelerator operation. Mechanism of beam intensity instabilities caused by the plasma instabilities or other reasons should be studied in more detail through experiments and theoretical simulations. Long-term stability during days even weeks with SECRAL at high beam intensity level above $300 \text{ e}\mu\text{A}$ and at high microwave power level of 5 kW still needs to be further verified.

C. SECRAL operations enhancing capabilities of the HIRFL accelerator complex

The HIRFL accelerator complex is comprised of an injector cyclotron sector focus cyclotron (SFC), a main cyclotron separated sector cyclotron (SSC) and two cooling

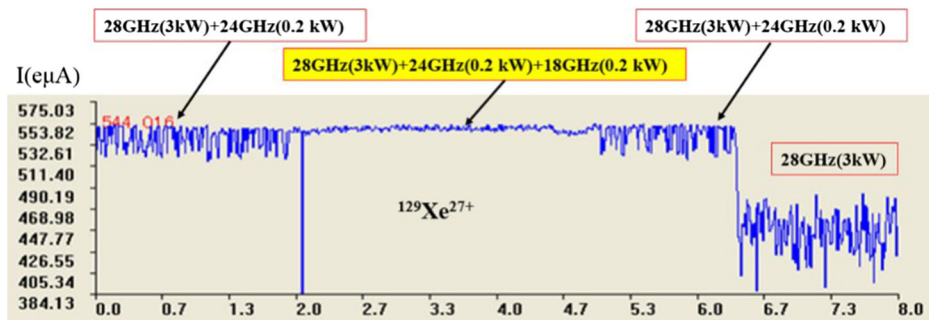


FIG. 26. Suppression effect of beam instabilities by two-frequency heating (28 + 24 GHz) and three-frequency heating (28 + 24 + 18 GHz).

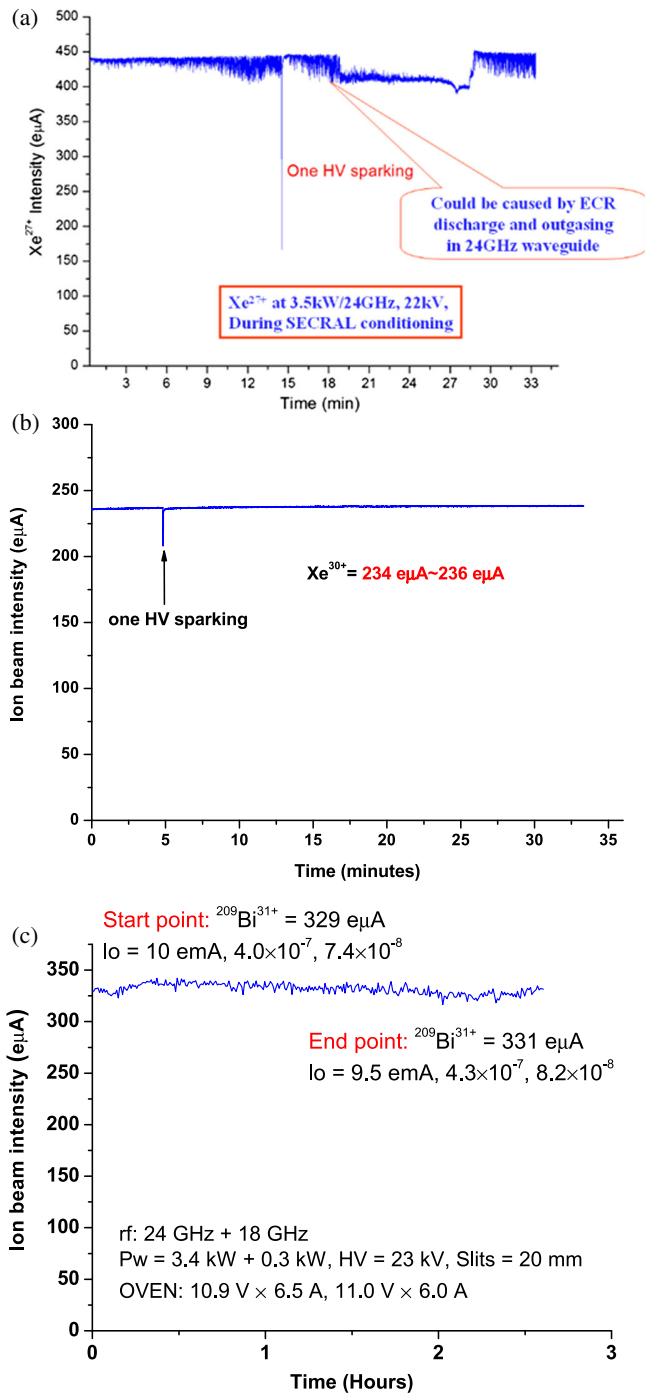


FIG. 27. SECRAL beam stability study. (a) Beam intensity instability of $^{129}Xe^{27+}$ at $435 e\mu A$ when SECRAL was tested with single frequency 24 GHz heating at 3.5 kW power. (b) $^{129}Xe^{30+}$ beam intensity stability at $235 e\mu A$ with 24 + 18 GHz. (c) $^{209}Bi^{31+}$ beam intensity stability at $330 e\mu A$ testing continuously during 2.5 hours.

storage rings (CSR) [24]. SECRAL, used as an external ion source, has been delivering highly charged heavy ion beams to the injector SFC cyclotron since May 2007 [30]. Depending upon the required ion beam and intensity,

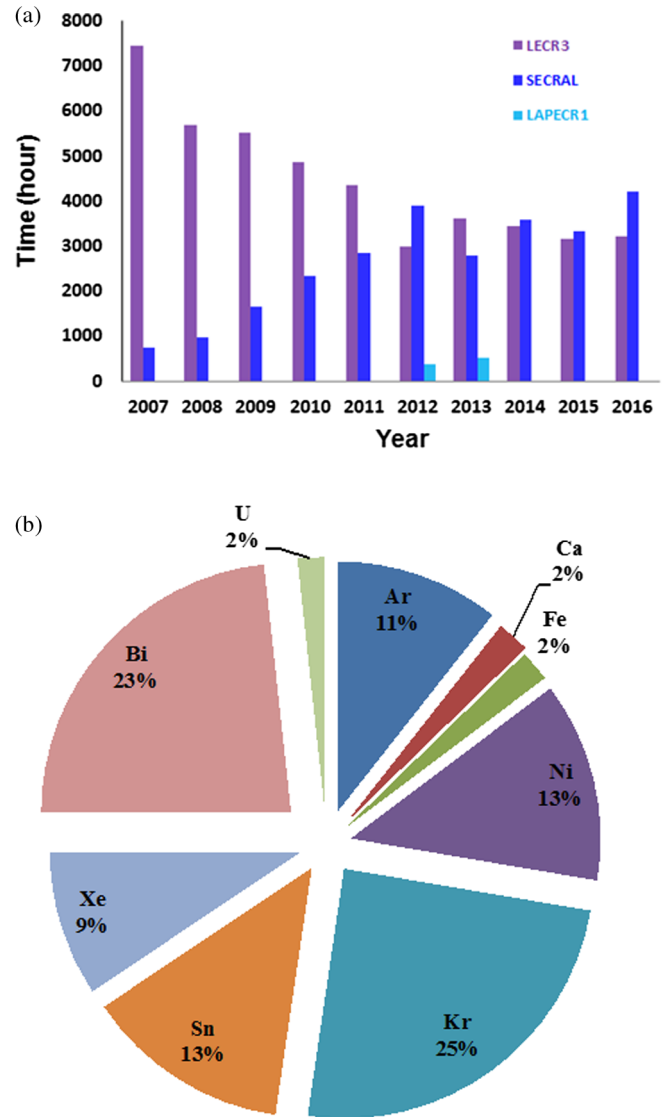


FIG. 28. SECRAL operation statistic data for the HIRFL accelerator. (a) Beam delivering time by SECRAL from May 2007 to December 2016 in comparison to LECR3. (b) Typical beams provided by SECRAL during operation for the HIRFL accelerator.

SECRAL can flexibly operate at 18 GHz only or 24 + 18 GHz to provide those ion beams unavailable from the room temperature ECR sources LECR2&3 [25]. Figure 28(a) shows the beam delivery by SECRAL from May 2007 to December 2016, starting with very limited time but increasing yearly to overtake the room temperature source LECR3 in a few years. SECRAL's heavy ion beam delivery accounts for more than 3500 annual hours during 2014–2016. The total beam delivery from SECRAL to the HIRFL accelerator so far is more than 28,000 hours by June 2017. The typical ion-beam percentage delivered are graphically shown in Fig. 28(b). SFC is a small cyclotron with energy constant $K = 69$ and its capability has been greatly enhanced with ECR ion sources, as shown in

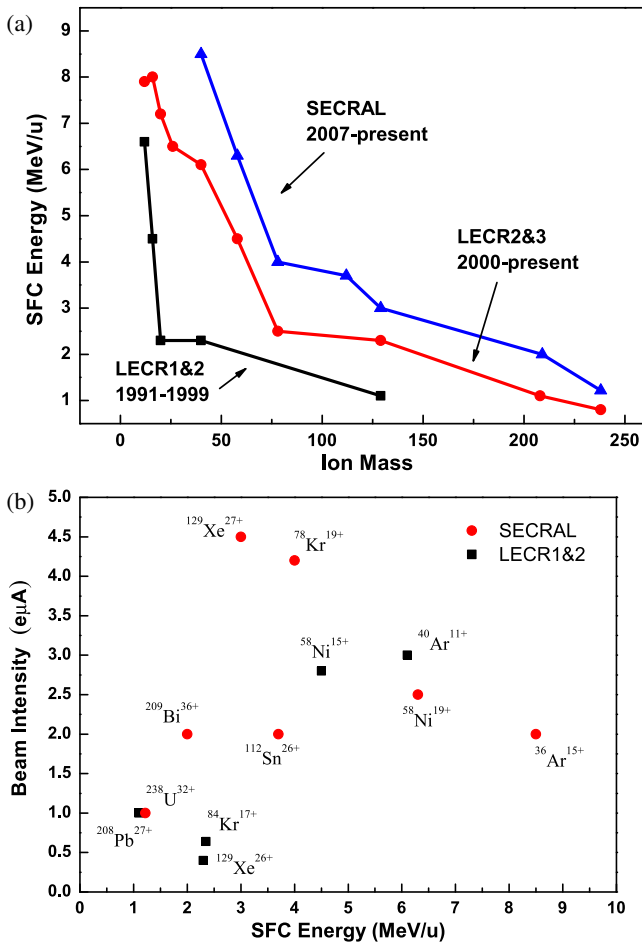


FIG. 29. Enhancement of SFC cyclotron beam energy and beam intensity due to SECRAL operation. (a) SFC beam energy improvement by SECRAL compared with the normal conducting ECR ion sources LECR0&1 and LECR2&3. (b) Enhancement of SFC beam intensity and energy by SECRAL compared with the normal conducting ECR ion sources LECR2&3.

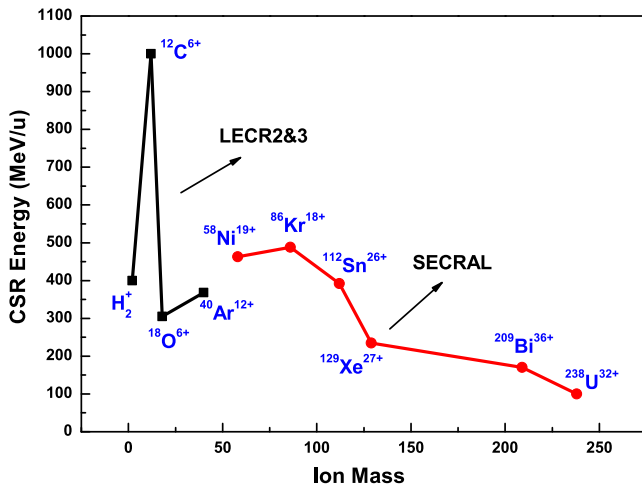


FIG. 30. CSR performance enhancement by SECRAL compared with the normal conducting ECR ion sources LECR2&3.

Fig. 29, especially with the beam delivery from SECRAL. For example, xenon beam intensities delivered by SFC and SSC were enhanced by a factor 10 and 50 respectively thanks to SECRAL. The cooling storage ring CSR of HIRFL is capable of routinely accelerating the very heavy ions, such as tin, xenon, bismuth and uranium, to hundreds of MeV/n, as shown in Fig. 30. However, it is only possible with the energy and beam intensities delivered by the combination of the SECRAL and the SFC, fitting the injection requirements of the CSR. The enhanced capability of the HIRFL accelerator complex leads new research opportunities, shown in Fig. 31 for instance, the first precise mass measurements of more than 35 short-lived nuclides were conducted with CSR by using primary beams $^{112}\text{Sn}^{26+}$, $^{58}\text{Ni}^{19+}$ and $^{78}\text{Kr}^{19+}$ delivered by SECRAL [36].

VI. UPGRADE AND FUTURE DEVELOPMENT

A new superconducting ECR ion source, SECRAL-II, has been built for a heavy ion linac injector for the SSC cyclotron at the HIRFL [77]. SECRAL-II is almost a duplicate of SECRAL except for the cryogenic system and a slightly higher radial field and a larger plasma chamber for operation at 28 GHz. The cryogenic system of SECRAL-II was designed to be operated with 5 GM cryocoolers that are capable of providing a dynamic cooling capacity of more than 5 W to the 4.2 K reservoir to mitigate the dynamic heat load due to the strong bremsstrahlung radiation. SECRAL-II is designed to be operated at maximum frequency of 28 GHz. The SECRAL-II superconducting magnet assembly, Sol-In-Sext configuration, shown in Fig. 32, was fabricated by WST in China and finally reached 100% designed fields [77]. This new source SECRAL-II is presently under commissioning with quite promising test results, such as $^{16}\text{O}^{6+}$ 6.5 mA produced by 5 kW 28 GHz microwave power [109].

The third generation of ECR ion source, like SECRAL, VENUS, RIKEN-SCECR and SuSI, has achieved remarkable advancement in the production of intense highly charged ion beams and efforts on further source performance are continuing.

However the beam intensity requirements of the very heavy ions, like lead and uranium, of future heavy ion accelerators are beyond the capability of the third generation ECR ion sources and demand the development of the next generation of ECR ion source [67,110]. To meet the demands, based on the scaling laws and what have been achieved by the third generation sources, the next generation one should operate at microwave frequency in the range of 40–60 GHz, even higher, hoping a factor of 2–5 gain in beam intensity. Such an increase implies the production of about 1.5 eμA of $^{238}\text{U}^{33+}$, 400 eμA of $^{238}\text{U}^{40+}$, 200 eμA of $^{238}\text{U}^{46+}$ and 50 eμA of $^{238}\text{U}^{50+}$ by the next generation ECR ion sources [67].

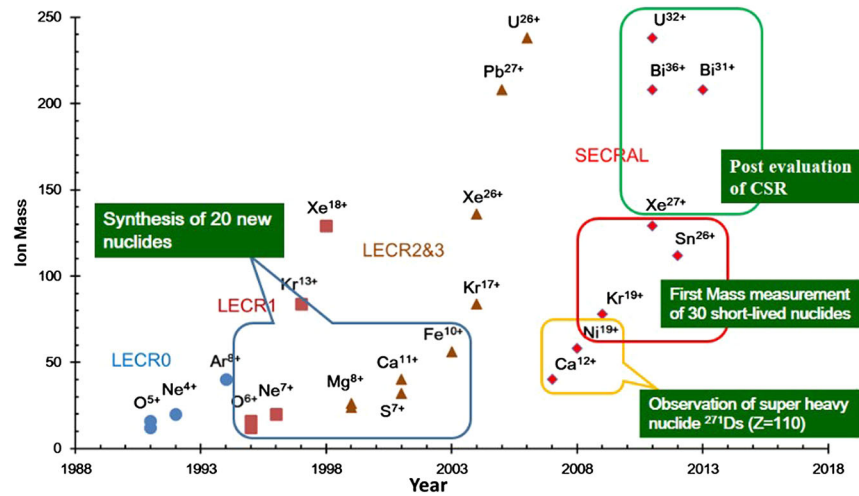


FIG. 31. Contributions of SECRAL and the normal conducting ECRIS at IMP to physics research based on the HIRFL accelerator.



FIG. 32. The SECRAL-II ECR ion source at beam commissioning.

However, there are many challenges to overcome for the development of the next generation [67]. The prerequisite is to successfully construct a superconducting magnet that can produce peak axial mirror fields of $B_{inj} = 6-8$ T and radial field $B_{rad} = 3-4$ T at the chamber wall to confine a higher density and hotter ECR plasma. In addition, cryogenic system, beam extraction, quality and transport and high power 40–60 GHz microwave coupling would be other key issues, which need carefully addressed with substantial R&D efforts.

VII. SUMMARY AND CONCLUSION

SECRAL is a superconducting-NbTi-magnet-based third generation ECR ion source for the production of intense multiply and highly charged ion beams. SECRAL is the first ECR ion source built with a novel magnet structure, which results in the smallest superconducting magnet for an ECR ion source, for operations at 24 GHz microwave

frequency. SECRAL combines a high strength minimum-B field generated by the novel magnet with high power of 18–24 GHz microwaves to energize the ECR plasma to produce the intense multiply and highly charged ion beams. During the decade development, from initial commissioning at 18 GHz to high power 24 GHz regular operation, beam intensities have been increased by a factor of 3 to 10 for those typical highly charged ion beams such as $^{129}\text{Xe}^{30+}$ and $^{209}\text{Bi}^{31+}$. A number of world record ECRIS cw beam intensities have been produced recently by SECRAL, such as $1420 \text{ e}\mu\text{A}$ of $^{40}\text{Ar}^{12+}$, $1100 \text{ e}\mu\text{A}$ of $^{129}\text{Xe}^{26+}$, $322 \text{ e}\mu\text{A}$ of $^{129}\text{Xe}^{30+}$, $680 \text{ e}\mu\text{A}$ of $^{209}\text{Bi}^{31+}$, and $10 \text{ e}\mu\text{A}$ of $^{209}\text{Bi}^{50+}$. This remarkable performance has been achieved due to several technical advancements and innovations like the innovative magnet structure and the effective double frequency heating (24 + 18 GHz), especially with the recent new microwave coupling scheme for high microwave power operation at 24 GHz plus 18 GHz. The achievement of a good number of ECRIS record intense beams and more than 28,000 hours of beam delivery to the HIRFL accelerator facility have demonstrated that SECRAL is one of the world's best-performing third generation ECR ion sources. With the greater variety of ion beams from SECRAL, the overall capability of the HIRFL accelerator complex has been dramatically enhanced with higher beam energy and intensity, which has opened up many new research opportunities at IMP. Based upon the demonstrated performance of the third generation of ECR ion source and its significant impact to heavy ion accelerators, it is reasonable to anticipate the next generation of ECR ion source will greatly advance the future heavy ion accelerator facility and physics research.

The following conclusions could be drawn from the development of SECRAL.

(1) To produce stable and intense beams of highly charged heavy ions, the third generation ECR ion source needs to operate at multifrequency heating (24 + 18 or

28 + 18 GHz) with total microwave power more than 5 kW and effective cooling to all components inside the plasma chamber.

(2) The new microwave coupling through a smaller circular waveguide of $\varnothing 20$ mm, instead of the original $\varnothing 32$ mm waveguide, to launch the TE_{01} microwaves into the plasma improves SECRAL performance significantly for the production of highly charged ion beams. This indicates that there will be an optimum for better wave coupling that will be very important for both the third generation and the next generation ECR ion source.

(3) For high power operations in the third generation ECR ion sources, optima should exist in the frequency gap of double-frequency heating and matched magnetic field configuration.

(4) The optimum magnetic fields for SECRAL to produce the highly charged ion beam typically are in the ranges of $B_{\text{rad}} = 2.0B_{\text{ecr}}$, $B_{\text{inj}} = 4.0B_{\text{ecr}}$, $B_{\text{min}} = 0.35 - 0.40B_{\text{rad}}$, and $B_{\text{ext}} = 1.0B_{\text{rad}}$ for operations with high power at 18–24 GHz wave frequency; The optimum magnetic fields are very similar for achieving the best intensities of those different ion beams such as Ar^{16+} , Xe^{30+} , Xe^{34+} , Bi^{36+} and Bi^{50+} . Differences of the optimum values B_{min} for those different ion beams and even for the different heating frequencies 18–28 GHz are minor or no significant difference ranging 0.45–0.60 T only.

(5) SECRAL beam emittance studies have demonstrated that beam emittance of the third generation ECR ion source operated at 24–28 GHz with higher microwave power and higher magnetic fields is roughly the same compared to that at 18 GHz, i.e. no significant emittance increase for ECRIS operating at higher fields and high frequencies.

(6) Long-term operating stability of beam intensity of days and weeks at high intensity of more than 300 $e\mu\text{A}$ and at high microwave power of >5 kW, still needs demonstration for the third generation ECR ion sources.

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