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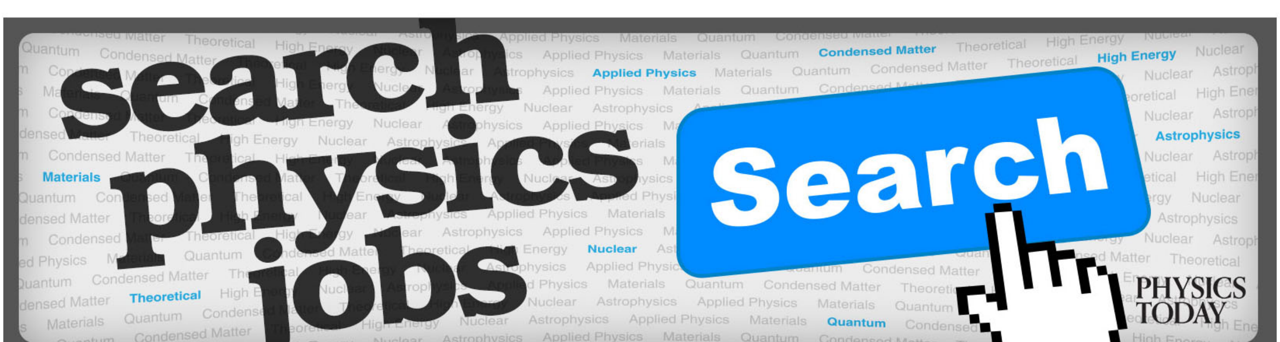

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 02A707 (2016)

Advancement of highly charged ion beam production by superconducting ECR ion source SECRAL (invited)

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At Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS), the superconducting Electron Cyclotron Resonance (ECR) ion source SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) has been put into operation for about 10 years now. It has been the main working horse to deliver intense highly charged heavy ion beams for the accelerators. Since its first plasma at 18 GHz, R&D work towards more intense highly charged ion beam production as well as the beam quality investigation has never been stopped. When SECRAL was upgraded to its typical operation frequency 24 GHz, it had already showed its promising capacity of very intense highly charged ion beam production. And it has also provided the strong experimental support for the so called scaling laws of microwave frequency effect. However, compared to the microwave power heating efficiency at 18 GHz, 24 GHz microwave heating does not show the ω^2 scale at the same power level, which indicates that microwave power coupling at gyrotron frequency needs better understanding. In this paper, after a review of the operation status of SECRAL with regard to the beam availability and stability, the recent study of the extracted ion beam transverse coupling issues will be discussed, and the test results of the both TE_{01} and HE_{11} modes will be presented. A general comparison of the performance working with the two injection modes will be given, and a preliminary analysis will be introduced. The latest results of the production of very intense highly charged ion beams, such as 1.42 emA Ar^{12+}, 0.92 emA Xe^{27+}, and so on, will be presented. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4933123]

I. INTRODUCTION

It has been about two decades since the first time the term of the 3rd G. (generation) ECR Ion Source (ECRIS) came into the ECRIS community.[1] And since then, it has been a global interest on the machine development, key technology study, and physics research. Just about 5 years later, the ECRIS development got really stepped into the era of the 3rd G. when the LBNL (Lawrence Berkeley National Laboratory) colleagues got the 1st beam with VENUS at 18 GHz.[2] The subsequent years of ion source experience with the 3rd G. ECRIS are full of surprises, challenges, and confusions. But no doubt, the 3rd G. sources are the most powerful ECR ion sources that the community has ever built so far, with regards to the extractable high charge state ion beam intensities and the achievable heavy ion charge states. Compared to the 2nd G. ECRISs, typical performances have been at least doubled, such as 350 eμA Xe^{30+} (6 times), 400 eμA U^{34+} (20 times), and 10.7 eμA Bi^{50+} (71 times).[3,4] Therefore, 3rd G. ECRIS has been dispensable intense highly charge ion beams injector for many heavy ion facilities or become the pre-injector baseline design for several newly funded heavy ion accelerator complexes. Nevertheless, there are still some puzzles about the ion sources working at gyrotron frequencies, typically 24 or 28 GHz, and the highlighted one is the efficiency of the gyrotron microwave power fed into a 3rd G. ECRIS. At the same microwave power level, a 24 or 28 GHz ECRIS has not produced the beam intensities as expected, which is an open question for the ECR community to work on.

SECRAL is the second 3rd G. ECRIS put into operation after VENUS. It was available at IMP in 2005.[5] The maximum mirror field at source injection is 3.7 T and the field at source extraction is 2.2 T. A 2.0 T radial field is measured at the Ø126 mm ID (Inner Diameter) plasma chamber inner wall surface. To shield the bremsstrahlung radiation hazard to the main HV (High Voltage) insulator material, a 2 mm thickness Ta jacket was inserted between the plasma chamber and the main insulator column. Therefore, after the modification of the structure, the aluminum plasma chamber inner wall diameter was decreased down to Ø116 mm that means a much lower maximum radial field for operation, i.e., $(116/126)^{2}*2 \sim 1.7$ T, which barely meets the optimum field for 24 GHz. The effective plasma chamber volume is typically 4.4 l. SECRAL delivered the first heavy ion beams to HIRFL (Heavy Ion Research Facility in Lanzhou) in 2007. Since then, SECRAL has become the main working horse to provide intense highly

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charged ion beams for the accelerators. Although most of the beam time of SECRAL has been occupied by the accelerator routine operation, the research with this powerful source has never been ceased. This paper will report the recent progresses toward more efficient gyrotron microwave coupling and very intense ion beam production.

II. STATUS OF SECRAL OPERATION

A. Operation beam time

SECRAL is capable of delivering intense high quality highly charged heavy ion beams for the accelerators; therefore, we have seen the increasing on-line beam time over the years. As of July 2015, the total beam time is about 20 700 h. Two kinds of heavy ion beam operation schemes would not be possible without SECRAL as the primary heavy ion beam injector source, i.e., high energy operation scheme or high power operation scheme. For the first scheme, SECRAL is used to produce intense highly charged heavy ion beams, such as Kr^{17+}, Xe^{27+}, and Bi^{31+}, and for the second scheme, highly charged heavy ion beams with reasonable beam intensities are delivered, for instance, Ar^{15+}, Ni^{19+}, and Bi^{36+}. The successful operation of SECRAL for HIRFL accelerator facility has fundamental impact to the performance of this national heavy ion research facility and the contribution to the sciences. Fig. 1 shows the typical ion beam species delivered by the different generations of ECR ion sources at IMP and the associated physics researches. Obviously, ECR ion sources are the dispensable machines for the heavy ion research facility, and the development of SECRAL source has a dominant contribution to the capacity of HIRFL and the recent physics advancement.

B. Metallic beam development and operation

As discussed in Sec. II A, in the beam list for routine operation, metallic ion beams are highly demanded by the user community. As presented in Ref. 6, alternative solutions have been developed at IMP to get intense highly charged metallic ion beams, and the most reliable and durable one is still the electrical heating oven. Especially, the recently developed cartridge heater type oven, which is a borrowed technique from LBNL, has contributed enormously to intense metallic ion

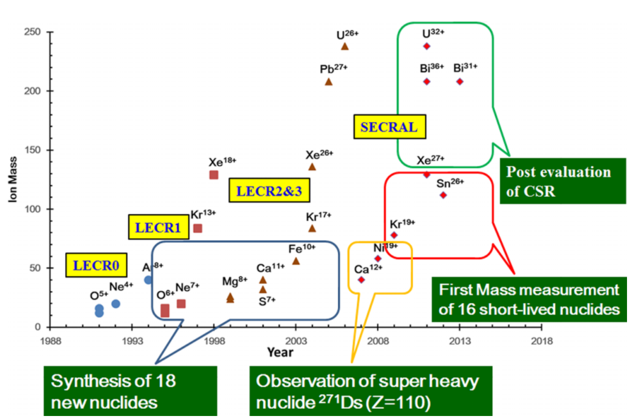

FIG. 1. Contributions of ECRISs at IMP to the sciences.

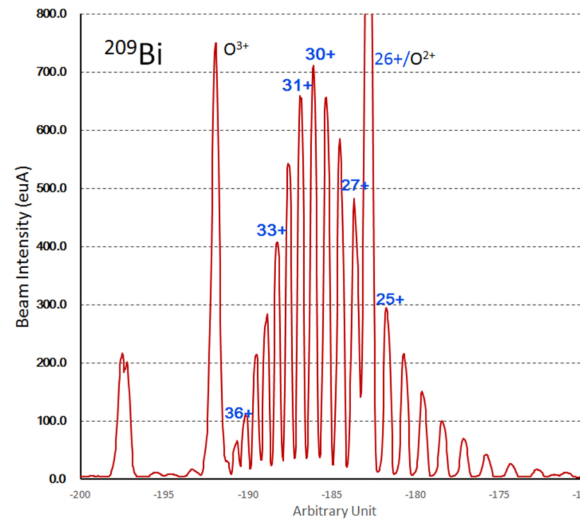

FIG. 2. Spectrum for 680 eμA Bi^{31+} beam production.

beam development. Compared to traditional resister heating oven, cartridge heater oven has more precise control on the oven temperature and enables a much larger loading capacity of metal material that is essential for a durable long-term continuous operation. For the IMP design, the maximum loading could be around 2 g bismuth powder, which enables a one-week operation with an average consumption rate of 11 mg/h with SECRAL for 400 eμA Bi^{31+}. Large volume oven is also very helpful in very high intensity low melting point metallic ion beam development, so as to further explore the potentials of a 3rd G. ECRIS. We reported in 2013 about the 400 eμA Bi^{31+} beam production with SECRAL at 24 GHz.[6] With a refined structure, the new oven can safely be operated around 600 °C and deliver sufficient metal vapor to the plasma. With this technical improvement, SECRAL had produced 710 eμA Bi^{30+} and 680 eμA Bi^{31+} at a 5 kW 24 GHz microwave power (Fig. 2). This is very favorable to the exploration of very heavy ion beams production capacity with a 3rd G. ECR ion source after the successful production of 400 eμA U^{34+} with VENUS in 2011.[7] The beam intensity limits for most metallic ions production with a high performance ECRIS are not by the ion source performance, but to the large extend by the factor how well the oven can work for the purpose. With the help of the same oven, it is easy to produce lighter metallic ion beams such as Ca^{11+} and Ca^{12+}. At 2.4 kW 24 GHz plus some 18 GHz power, SECRAL has demonstrated the performance of 710 eμA Ca^{11+}, 670 eμA Ca^{12+}, and 480 eμA Ca^{13+}.

The purpose of intense ion beams development is ultimately for the purpose of high quality on-line operation. The present operation status of SECRAL is a strong evidence of such a fact. However, we found that there is much more to do other than just high intensity ion beam extraction. A recent study on the delivered ion beams' long-term stability tells us that although the ion source was operated at even ~1/10 of its best performance, the stability, especially of metallic ion beams, needs to be improved. Fig. 3 gives the normalized stability over the operation time. Obviously, metallic beam stability is much worse than that of gaseous beam. Two reasons may account for that, i.e., oven conditioning is still going on during operation time and with the elapse of the operation

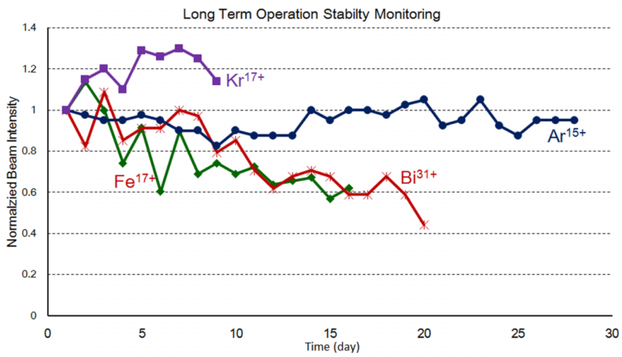

FIG. 3. Operation stability of different ion beams.

time, the load of the oven or the heated material is getting less which has influence on the vapor yield. An effective feedback loop is very necessary to improve this performance. Material consumption rate is one essential factor for metallic ion beam production, especially when very rare isotope material is used. Frequent tuning has been observed significantly increasing the consumption rate, for instance, a frequently interrupted operation resulted in a 6 mg/h bismuth consumption rate, while a steady operation can lower the consumption rate to 2.3 mg/h with the similar beam intensity output.

C. Beam characteristic study

What accelerators virtually need are not just high beam intensities, the brightness is also essential. Therefore, it is worth studying the behavior of intense beam extraction from an ECRIS. It is said that with the increasing of the extracted beam currents, space charge will dominate the beam extraction and transmission at the low energy section. SECRAL is capable of producing several hundred eμA Bi^{3x+} beams. As illustrated in Fig. 4, the emittance of Bi^{31+} from SECRAL was measured to be increasing but not linearly as predicated. Error bars are not given here, which should be in the range of $\pm 10\%$. And it is noticed that ion source tuning could have obvious influence on beam projection emittance. When more intense beam is extracted, the successive transmission system is also optimized which also has significant effects. This means that the projection emittances could be optimized to minimize the deterioration. But generally, the emittances get larger as more intense beams are extracted.

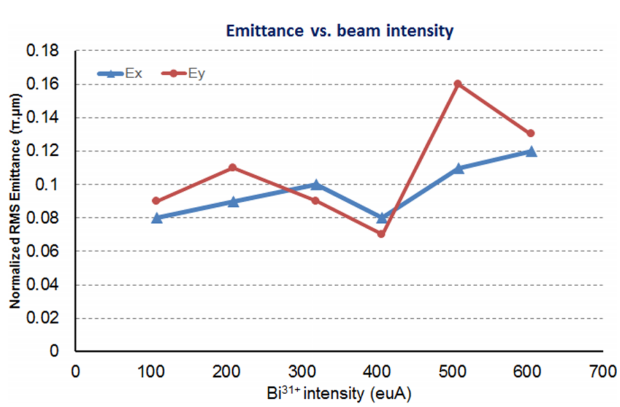

FIG. 4. Bi^{31+} emittances evolution with the intensity.

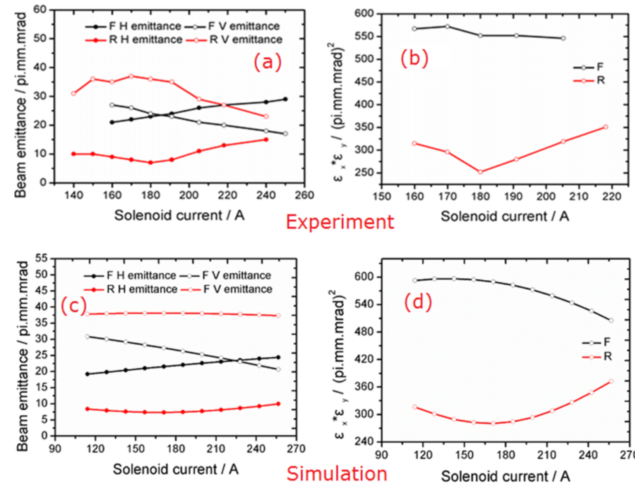

FIG. 5. Simulation ((c) and (d)) and experimental ((a) and (b)) study of beam coupling characteristics after ECRIS. RMS emittances of Xe^{29+} @25 keV/q are given in the plots.

Fig. 4 also indicates that the emittances in the horizontal and vertical planes are exchanging with the variation of the beam transmission conditions. Actually, theoretical derivation has already predicted that the extracted beam from an ECRIS is transversely coupled. To have a better interpretation of this characteristic of an ECRIS, extracted beam from SECRAL is investigated.[8] Fig. 5 shows the experiment and simulation results done with SECRAL transmission beam line. For modern high intensity heavy ion facilities, linac accelerators are common choice for the injector design, which normally has symmetric transverse acceptance. If the beam coupling dominates the beam quality deterioration, emittances at horizontal and vertical directions will be quite different, and high beam loss will be seen at the injection region. Some decoupling solutions should be adopted for the application.

III. GYROTRON FREQUENCY MICROWAVE COUPLING STUDY

A. ECR Heating (ECRH) with different RF modes

Gyrotron microwave power was first incorporated into an ECR ion source in INFN/Catania during the commissioning of SERSE source,[9] and it has become a standard ancillary hardware when ECRIS evolves into 3rd G. machines. As a conventional technique, the existing 3rd G. ECRISs are all using TE_{01} mode as the gyrotron microwave power coupling scheme, which is actually a directly borrowed technique from fusion community. RF electric field of TE_{01} mode is unpolarized and circular, which has a hollow power density distribution inside. Reference 10 has more detailed description on TE_{01} mode. Ion sources working at gyrotron frequency have been tested and the capacity to produce more intense highly charged ion beams with sufficient magnetic confinement has been verified as had been predicted by the frequency scaling laws. However, at the same microwave power level or same power density level, gyrotron frequency heating is not doing as well as predicted. In most occasions, compared to 18 GHz, it is behaving just like a linear extrapolation of power effect to get more intense highly charged ion beams.

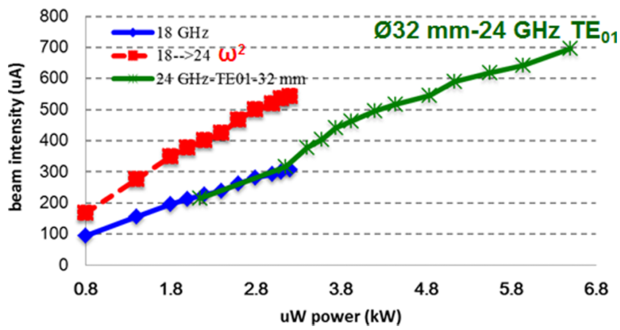

FIG. 6. Xe^{27+} beam intensity with an Ø32 mm waveguide TE_{01} mode microwave coupling.

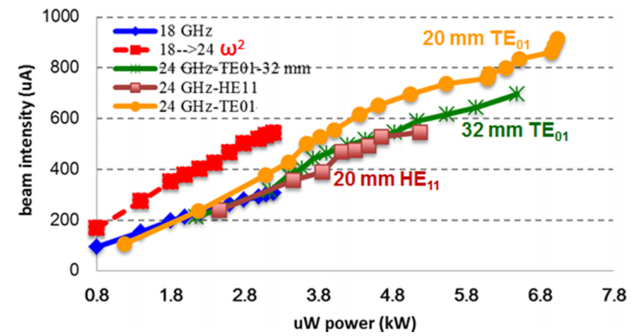

FIG. 8. Xe^{27+} beam intensity evolution with microwave power coupled at different schemes.

Fig. 6 gives the recent Xe^{27+} beam results with SECRAL. At 24 GHz, SECRAL can produce the beam intensity of the ω^2 scaling, but at much higher microwave power level compared to that at 18 GHz. Similar results have also been observed with SuSI.[11] This raised the question about the coupling efficiency of gyrotron microwave power into ECR ion source plasma. Already in 2006, Hitz proposed to use HE_{11} instead of TE_{01} for a gyrotron frequency ECRIS microwave feeding scheme in order to improve the efficiency as discussed above.[12] It was until 2013 Lyneis from LBNL designed and built a TE_{01}—HE_{11} mode convertor and tested it with VENUS ion source, which came out with the conclusion that HE_{11} mode worked well and at least its results were no worse than those of TE_{01} at the same power level.[10] HE_{11} mode can provide a linearly polarized microwave of Gaussian power distribution, which was expected to have better ECR heating effect and coupling efficiency to the ECR zone so as to achieve more intense beam production (more discussion was made in Ref. 10). The lack of gain in beam intensity with the HE_{11} mode means the physics inside plasma chamber is not what has been predicted.

The same experimental research activity was started at IMP since 2012. But due to lack of the experience in mode convertor design, the study did not progress until 2013. With the help of the colleagues from Frankfurt University, a prototype convertor design was made which consists of a snake waveguide and a corrugated waveguide, identical to the design by Lyneis. However, due to the size of the convertor and the smaller SECRAL plasma chamber diameter (Ø116 mm) compared to VENUS' (Ø144 mm), there is not enough space to fit in a large convertor in. Therefore, we had to look into alternative solution. By tapering down the Ø32 mm oversized waveguide to Ø20 mm, the resulting convertor could be more compact both in length and diameter (Fig. 7). However, the test of HE_{11} mode will be an Ø20 mm opening waveguide case, and to make an equivalent comparison, an Ø20 mm TE_{01} mode oversized waveguide was also fabricated and tested (see Ref. 13 for details). After a series of off-line burn mark checks with different waveguides and microwave modes, preliminary experimental tests with SECRAL were made at 24 GHz with 18 GHz as the supplemental heating frequency.

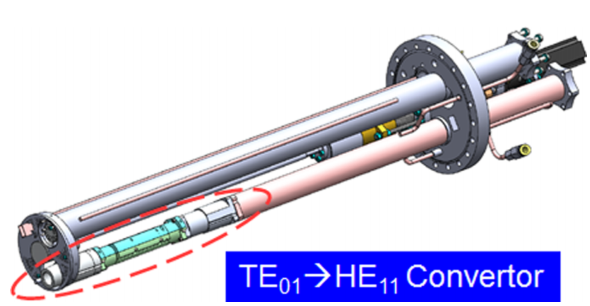

FIG. 7. $TE_{01} \rightarrow HE_{11}$ mode convertor developed at IMP.

As shown in Fig. 8, the ECRH effect of HE_{11} mode is almost the same as that with the Ø32 mm TE_{01} mode. Increasing the heating microwave power produced more beam, but that tendency was starting to change to saturate at the power density around 1 kW/l. The plasma became less stable and hard to tune for a better output. When the Ø20 mm TE_{01} mode oversized waveguide was installed, a significantly different microwave coupling behavior was observed. As shown in Fig. 8, the output of the ion source responded to the incident 24 GHz microwave very linearly. No saturation was found even at the power limit of this 24 GHz generation, i.e., 7.0 kW, which was corresponding to a power density of ∼1.6 kW/l. What is more important is that the production efficiency at the same RF power level for the case of Ø20 mm TE_{01} mode microwave is at least 30% higher than that of the Ø32 mm TE_{01} mode or the Ø20 mm HE_{11} mode.

B. Production of very intense beams

Obviously, the TE_{01} mode with Ø20 mm waveguide helps to make more beam out of the ion source compared to the conventional solution. It is then worth checking the potential capacity of highly charged ion beams production with the new scheme. Table I gives the typical results obtained with the 24 GHz microwave power level around 7 kW. The preliminary test with the new scheme at high RF power only continued for a week. Strong outgassing was very evident at that power level, which means better results could be possible provided sufficient time for source conditioning. It is very important that Ar^{12+} beam intensity for the first exceeded the threshold of

TABLE I. Typical results with SECRAL achieved at new ECRH scheme.

Ar	Q	11	12	13	14	16	17
	I (eμA)	1620	1420	930	846	350	50
Xe	Q	26	27	30	34		
	I (eμA)	1100	920	322	90		

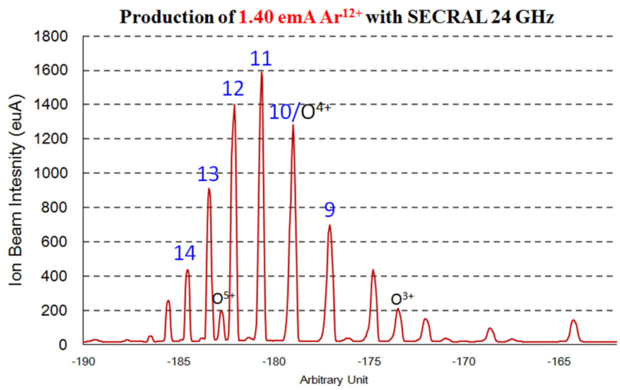

FIG. 9. Spectrum obtained with 1.4 emA Ar^{12+} production.

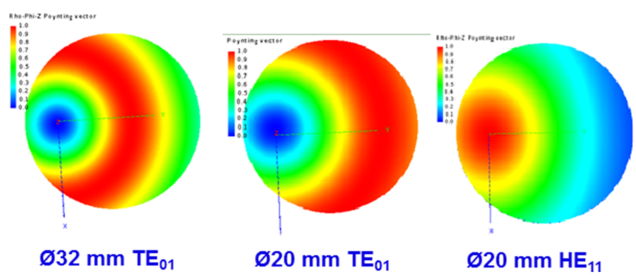

FIG. 10. Power distribution at the 1st ECR location with difference microwave feeding scheme.

1 emA, which had been granted as a barrier to the ECR ion source community for many years. Fig. 9 is the spectrum when 1.4 emA Ar^{12+} was tuned.

C. An attempt to interpret the new scheme

As is well known, for a high charge state ECR ion source, the plasma operates at a low plasma density, and therefore, the plasma chamber can be regarded as a multimode cavity.[14] For a 3rd G. ECRIS, the plasma chamber diameter is typically at the dimension of >Ø100 mm, which is much larger than that of the incident gyrotron frequency RF wavelength. For this reason, the ECRH may not be sensitive to the change of incident microwave modes. However, the microwave power coupling has consequences on how the microwave power is fed into the chamber, especially the free space power distribution within the plasma chamber dimension. As shown in Fig. 10, compared to other microwave coupling scheme, the Ø20 mm oversized TE_{01} scheme indicates a better microwave homogeneity inside the plasma chamber at the 1st ECR location, which might represent a more homogeneous heating of the plasma and therefore a more steady and gentle gradient plasma condition that is essential for longer ion confinement and more high charge state ion yield. This is just a tentative explanation of the new scheme. Additional work needs to be done to understand better microwave coupling to ECRH in an ECRIS, especially at gyrotron frequencies. Last but not least, for a conventional 18 GHz microwave power feeding with a WR62 waveguide, the incident power diverges very fast at the waveguide exit and induces a very homogeneous power distribution at the 1st ECR location if we assume that the microwave power is fed into an open space.

IV. CONCLUSION

This paper reviews the recent operation status of SECRAL. The development of intense metallic ion beams and its on-line features have been discussed, especially the material consumption rate and long-term stability issues. A recent approach for more efficient ECRH mode research at IMP with SECRAL revealed a new microwave heating scheme at gyrotron frequency, which can obviously improve the ion source yield by a factor of 30%–100%; typically, 1.42 emA Ar^{12+} and 1.1 emA Xe^{26+} have been produced with SECRAL at a 24 GHz power level of 7 kW. Ø20 mm oversized TE_{01} scheme might not be the optimum one for SECRAL which needs more investigation in the future. For the other 3rd G. ECRISs, the optimum scheme should be optimized accordingly to their plasma chamber geometries.

ACKNOWLEDGMENTS

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