INTENSE BEAM PRODUCTION OF HIGHLY CHARGED IONS BY THE SUPERCONDUCTING ECR ION SOURCE SECRAL FOR HEAVY ION LINACS*

L. Sun#, H. W. Zhao, W. Lu, J. W. Guo, Y .C. Feng, W. H. Zhang, X. Z. Zhang, Y. Yang, C. Qian, X. Fang, Z. Shen, W. Wu, L. Zhu, L. Z. Ma
IMP/CAS, Lanzhou, 730000, China

Abstract

Superconducting ECR ion source (SC-ECRIS) represents the state of the art technologies of ECR ion sources. Existing SC-ECRISs developed in different labs have contributed significantly for ECRIS technology advancement in the last 15 years. Recently the superconducting ECR ion source SECRAL operated at 24 GHz at IMP has produced many new world recorded beam intensities of highly charged ions due to new technologies applied, such as a new microwave coupling scheme. At the meantime, the world first 4th generation ECR ion source operated at 45 GHz is being developed at IMP. All these developments on intense beam production of highly charged ions with superconducting ECR ion source may play significant roles for the next generation heavy ion linacs such as FRIB and iLinac of HIAF project. This paper will report the recent developments of intense highly charged heavy ion beams at IMP and the discussion on perspectives of next generation ECRIS for the future heavy ion liancs.

INTRODUCTION

Highly charged ion sources have been widely used as preinjectors of highly stripped heavy ion beams for accelerators. EBIS (Electron Beam Ion Source) and ECRIS (ECR Ion Source) are the two types of highly recognized high charge state ion sources used in worldwide heavy ion accelerator labs. EBIS is capable of producing low duty factor very high charge state high peak current ion beams, for instance the powerful RHIC-EBIS at BNL, for the RHIC heavy ion program, 1.7 emA Au^{32+} with the pulse length of ~10 μs is required from the ion source in order to deliver 3×10^9 ions/pulse to the Booster at a repetition rate of 5 Hz [1]. As for the production of high repetition rate or CW highly charged ion beams of high intensity, ECRIS is an indispensable machine. Yves Jongen firstly put ECRIS in accelerator injection more than 35 years ago [2]. With this success, ECRISs have been widely used in worldwide laboratories as HCI (Highly Charged Ion) injectors. They have firstly proven the success in the field of cyclotrons, and later on in the field of linear accelerators. Nowadays, high power and high energy Linacs could not be possible without the contribution of high performance HCI ECRISs, such as FRIB at MSU, ROAN in South Korea, SPIRAL 2 project in GANIL, and etc. And the increasing needs from accelerator community, especially the recent fast advancement of high current high power Linacs has greatly stimulated the development of HCI ECRISs.

ECR ion sources have been used in IMP as the heavy ion injectors for over 20 years. Absolutely, the incorporation of ECR ion source to the heavy ion accelerator complex has already improved the machines' performance. The existing facility HIRFL (Heavy Ion Research Facility in Lanzhou), is mainly composed of one K69 cyclotron SFC, one K450 cyclotron SSC, RIBLL1 for radioactive beam production, cooler storage rings CSRm and CSRe, and the radioactive beam line RIBLL2 to connect the two rings [3, 4]. Linac injector systems have also been designed and under construction at IMP, as an upgrade program to boost the performance of the SSC cyclotron and also the storage ring. In phase 1 of the upgrade program, a project proposal has been issued to build a dedicated injection linac injector for SSC with ~ 1 MeV/u U^{34+} beam (Fig.1). The most interested ion beam for the design is several puA of U^{34+}, however the more preferred one is U^{37+}. Fundamentally, only with a SECRAL type 3rd generation ECR ion source, the goal could be achieved. Therefore, it is essential to use the existing SECRAL ion source to produce intense HCI beams to demonstrate the performance desired, and at the meantime, a high performance ECRIS for SSC-linac is under development.

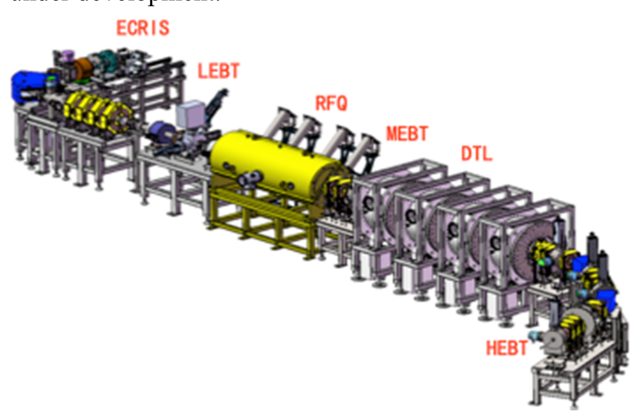

Figure 1: Layout of SSC-Linac.

SECRAL was connected to the injection line of HIRFL complex in 2007 and as of early 2016, more than 25,000 hours' beam time has been accomplished. It has been proved to be a very reliable and high performance ECR ion source. Especially, the recent progress with high intensity Ar and Xe beams, such as 1.42 emA Ar^{12+}, 1.1 emA Xe^{26+}, 0.67 emA Ca^{12+}, 0.68 emA Bi^{31+} and etc., has demonstrated its performance and capacity [5].

*Work supported by NSF (contract No. 11375244), NSF (contract No. 11427904) and MOST (contract No. 2014CB845500).
#sunlt@impcas.ac.cn

INTENSE HCI BEAMS PRODUCTION WITH SECRAL

SECRAL is the second 3rd G. ECRIS put into operation after VENUS. It was available at IMP in 2005. 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 plasma chamber inner wall surface. To shield the bremsstrahlung radiation hazard to the main HV 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 Ø 116 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 liters. SECRAL delivered the first heavy ion beams to HIRFL in 2007. Since then, SECRAL has become the main working horse to provide intense highly charged ion beams for the accelerators.

High Intensity HCI Production

High intensity HCI beam production needs very much physics understanding of a high performance machine and also inquires remarkable technical advancement. SECRAL produced the first HCI beams in 2005. With two 18 GHz klystron amplifiers, SECRAL was able to produce many world recorded HCI beam intensities in 2006 [6]. SECRAL was designed to be able to operate at 24 or 28 GHz, at which condition the ion source can reach its best performance. A 24 GHz gyrotron amplifier was connected to SECRAL in 2009, and significant enhancement of HCI beam intensities had been observed [7], which is in agreement with the scaling of frequency effect. But the efficiency of 24 GHz microwave heating to produce HCI beams has been questioned, since the euA/kW results are still quite low compared to the extrapolation with ω^2_{rf} scale. 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. Many ECR researchers believed that with a Gaussian distribution microwave power mode, it might be able to enhance the ion source performance. First test with HE_{11} mode with VENUS at LBNL did not give any expected results [8]. The similar test with SECRAL also indicated that there is no much difference of ECR heating with regards to HCI production between TE_{01} and HE_{11}. However, a later test with a Ø20 mm tapered TE_{01} waveguide has given surprisingly high yield of HCI beams as shown in Fig. 2 [5]. Recently, HCI beam production test with a Ø20 mm tapered waveguide also helped boosted the performance of 28 GHz VENUS at LBNL [9]. The physics behind this technical improvement is still unknown, but the impact is enormous. Table 1 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 1 emA, which had been granted as a barrier to the ECR ion source community for many years. Figure 3 summarizes the performance enhancement with SECRAL since its first Ar beam production in 2005. After 10 years' continuous development, the typical HCI intensities have at least been increased by a factor of 2~3.

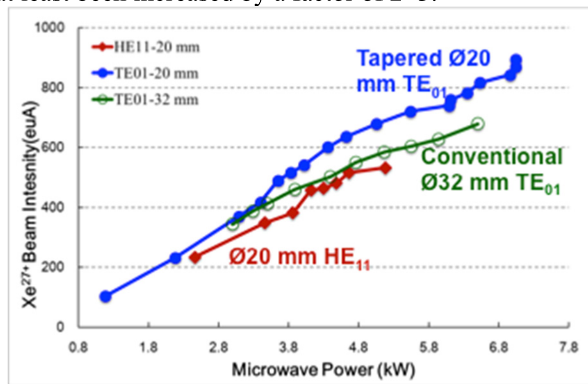

Figure 2: Xe^{27+} production with different μW coupling.

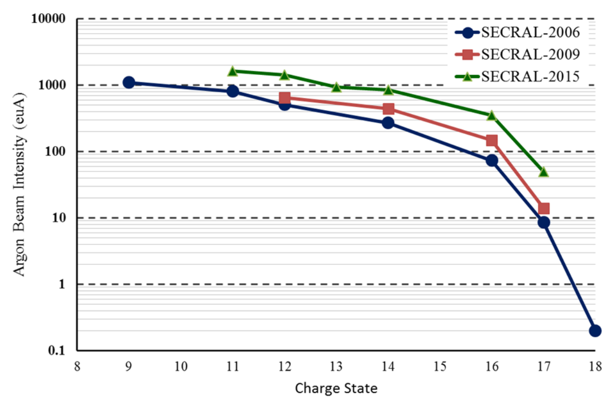

Figure 3: Ar beam development with SECRAL.

Table 1: 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		

Intense Metallic Ion Beam Production

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/hr 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 [10]. With a refined structure, the new oven can safely be operated around 600 °C and deliver sufficient metal vapour 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. 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 good 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+}, Ca^{12+}, and etc. 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+}, 480 eμA Ca^{13+}. For Linac application, ECRIS is expected to deliver HCI beams of several hundred euA. Short time test of beam stability gave quite reasonable results, for instance for the production of 350 euA Bi^{31+}, the beam intensity variation is about ±3% within several hours, while for long term operation, the stability is much worse as shown in Fig.4. Obviously, compared to gaseous ion beams, metallic beam stability is much worse. Two reasons may account for that, i.e. oven conditioning is still going on during operation time and with the elapse of the operation time, the load of the oven or the heated material is getting less which has influence on the vapour 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/hr bismuth consumption rate, while a steady operation can lower the consumption rate to 2.3 mg/hr with the similar beam intensity output.

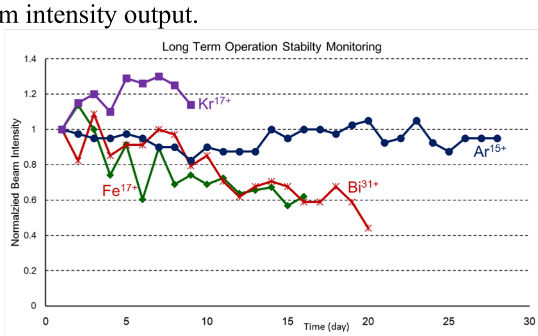

Figure 4: Long term beam stability of various ions.

Beam Quality 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. 5, the emittance of Bi^{31+} from SECRAL was measured to be increasing but not linearly as predicated. Based on the tendency of the curves, we can bravely deduce that for a 1 emA Bi^{31+} beam, the normalized rms emittance could be around 0.2 πmm.mrad.

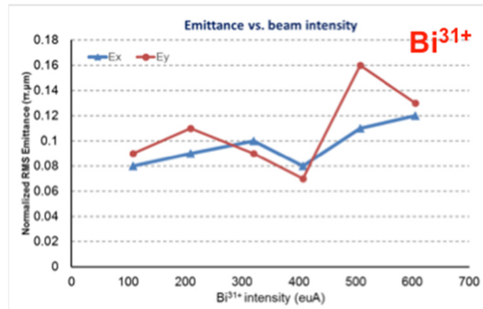

Figure 5: Bi^{31+} beam emittance vs. beam intensity.

Transverse beam coupling issues have been both theoretically and experimentally studied with SECRAL. It has been detailed in former presentation [11]. Another important topic in the ECRIS LEBT design is the high order aberration. Dipole magnet is an essential part in the LEBT design for an ECR ion source system. A typical dipole will have sextupole field component in the vertical plane at the magnet entrance and exit, and in the horizontal plane along the beam trace. The sextupole component causes obvious beam aberration, and consequently beam emittance increase. It has been widely considered that the high order aberration of the analysed ion beam from an ECRIS stems from the sextupole field component of the dipole. Recently a sextupole magnet has been built and installed to the SECRAL LEBT dipole magnet exit to investigate the possibility to correct the aberration. However, the experimental results showed that when the sextupole magnet is polarized in accord with the design current to cancel the sextupole filed from the dipole, the aberration becomes worse. A reversed current can obviously improve the beam quality as shown in Fig. 6. Under such a condition, the polarization of the sextupole field is reverse to the stray field from SECRAL sextupole magnet. Later simulation indicates that the stray field strength at the source extraction region is much higher than that of the dipole. Therefore, higher order aberration in the HCI beams extracted from an ECRIS is mostly from the ion source sextupole stray field. The dipole magnet high order component plays less significant roles in the aberration formation.

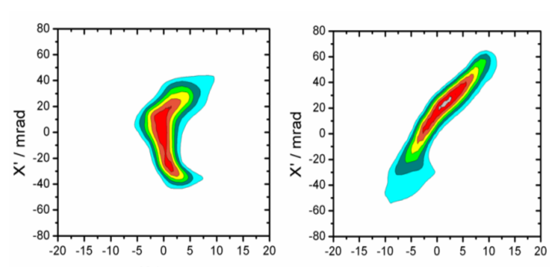

Figure 6: O^{3+} beam phase space distribution before (left) and after (right) sextupole correction.

SECRAL II ION SOURCE DEVELOPMENT

The SECRAL II cold mass is nearly a duplicated one of SECRAL. Since SECRAL was designed and built without He recondensation system, the operation efficiency has been greatly affected, especially at high power. Therefore, SECRAL II should be designed with integrated LHe recondensation cryogenic system so as to be able to tolerate large dynamic heat load under high microwave power heating conditions. The main design parameters are given in Table 2 in comparison with SECRAL.

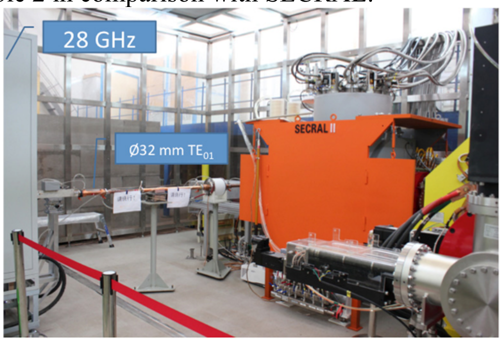

Figure 7: SECRAL II test bench.

Table 2: Main Design Parameters of SECRAL II

	SECRAL	SECRAL II
ω_{ecr}	24 GHz	28 GHz
B_{inj}	3.7 T	3.7 T
B_{ext}	2.2 T	2.2 T
Mirror Length	420 mm	420 mm
B_r	~1.8 T	~2.0 T
Warmbore ID	Ø140 mm	Ø142 mm
Dynamic cooling capacity@4.2 K	-	> 5 W

The magnet was ready at IMP in October 2015. User's site test had been completed in that December after about one month's preparation. The magnet was eventually energized to ~100% design currents after 9 quenches, which announced the success of this magnet fabrication. SECRAL II magnet indicates more robust coil clamping as it reaches 95% of the design currents via 3 quenches. But it has to overcome the preloading while releasing the stress caused by slight movement during ramping to higher currents, which might be a stepwise process if the preloading is high. The cryogenics system was tested during the system cooling down and static condition at 4.2 K. According to the test with embedded heaters at 4.2 K region, a dynamic heat load capacity of ~6.0 W is estimated.

SECRAL II has been mainly commissioned at 28 GHz with O and Xe plasma on the test bench (Fig. 7). The 1st plasma with beam extraction at 18 GHz has produced 1.75 emA O^{6+}. At 28 GHz, with even 1 kW, about 2.2 emA O^{6+} has been extracted, which is obviously a strong frequency effect against that of 18 GHz. The plasma responds linearly to microwave power input. At 4.5 kW, 5.4 emA O^{6+} has been obtained at the source potential of 25 kV. The typical oxygen spectrum is given Fig. 8 when O^{6+} is optimized with He as support gas. At 3.5 kW, a 1.57 emA O^{7+} beam has also been extracted. A 20 emA total drain is detected when 5.4 emA O^{6+} created. For Xe^{27+} production, 3.5 kW has been used to give a result of 510 euA beam intensity. Given more microwave power, this intensity could be further increased according to the beam tuning. Thanks to the high beam acceptance provided by the 18 cm gap dipole. For 7.0 emA Xe+O ion beams, a transmission efficiency of 86% was also achieved.

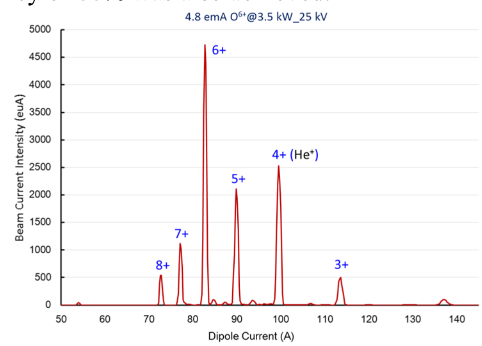

Figure 8: Typical Spectrum optimized for 4.8 emA O^{6+} beam production.

DEVELOPMENT OF 4TH G. ECRIS

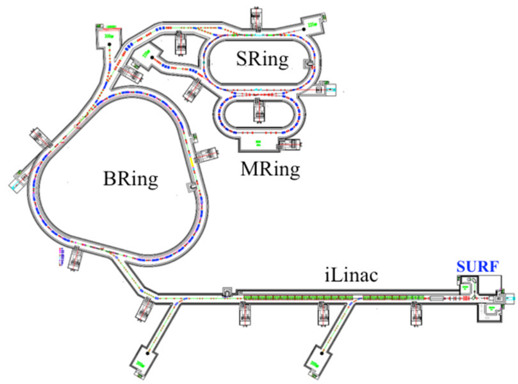

Figure 9: Layout of HIAF project.

HIAF or High Intensity heavy ion Accelerator Facility project has got official approval at the end of 2015. This national project is aiming to provide unique experimental conditions for nuclear physics research. In Phase I strategy, the project includes a high performance HCI ECRIS, an high current injector SC-Linac (iLinac) that can accelerator U^{35+} to 17 MeV/u, a booster ring (Bring) that can accelerate U^{35+} to 0.8 GeV/u with an ion accumulation intensity up to 1.5×10^{11} ppp, a spectrometer ring (SRing), and an ion-ion merging ring (MRing) . The schematic layout of HIAF facility is given in Fig. 9. To make the accelerator meet the design goal, the ion source needs to provide HCI beam intensities several times of the recorded beam intensities, such as 20 puA CW and 40 puA pulsed (400 us/2~5 Hz) U^{35+} beam. According to the guiding role of ECRIS development, a high performance 4th G. ECRIS will be capable of producing 2~3 times the beam intensities that have been demonstrated with existing 3rd G. ECRIS, such as SECRAL and VENUS. For instance, VENUS can produce about 320 euA U^{35+} CW beam at 28 GHz [12].

According to microwave frequency effect, at 45 GHz, a beam intensity of ~800 euA U^{35+} should be expected, which can well meet the project goal of HIAF with 20 puA. Therefore, the ion source group at IMP is now doing the prototyping 4th G. ECRIS optimized for 45 GHz microwave heating with the support of LEAF (Low Energy Accelerator Facility) project. The design parameters of this 45 GHz ECRIS is given in Table 3. Figure 10 is the schematic design of the ion source. Based on the experience with 3rd G. ECRIS development, the ECRIS community has already envisioned the great challenges for a 4th G ECRIS development, such as:

- ✧ Construction of a fully superconducting "min-B" configuration magnet based on Nb3Sn technique.
- ✧ 45 GHz/20 kW microwave power transmission and coupling to ECR plasma for high yield of HCIs.
- ✧ Severe bremsstrahlung radiation protection and the resulted 4.2 K dynamic heat load mitigation.
- ✧ 20~40 emA HCI beam extraction and high quality transmission.
- ✧ Intense refractory metallic ion beams production and beam stability.

Without the above challenges being properly handled, it would not be possible to build a successful 4th G. ECRIS. Nevertheless, a next generation HCI ECRIS will provide Linac accelerators with the intensities of high quality HCI ion beams never been made before, which will pave the way to build high current high power next generation Linacs.

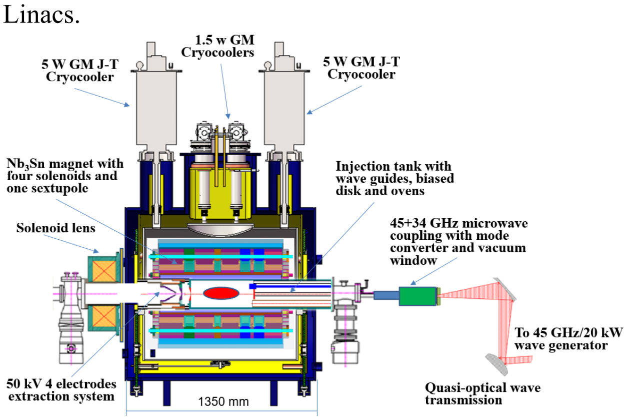

Figure 10: Schematic plot of the 45 GHz ECRIS.

Table 3: General Parameters of the 45 GHz ECRIS

Parameters	Unit	State of the art	45 GHz ECRIS
Frequency	GHz	24-28	45
B_{ecr}	T	0.86-1.0	1.6
B_{rad}	T	2	>3.2
B_{inj}	T	3.6~4	>6.4
B_{ext}	T	2~2.5	3.4~4.0
Chamber ID	mm	100~150	150
Warmbore ID	mm	140~180	170
L_{mirror}	mm	400~500	500

SUMMARY

Two high performance superconducting ECRISs have been successively developed at IMP. More than 10 years' continuous physics and technology advancement with the sources has made remarkable achievements with many world record beam intensities of HCIs, such as 1.4 emA Ar^{12+}, 1.1 emA Xe^{26+} and 0.68 emA Bi^{31+} and etc. Those could a fundamental baseline for high current high power heavy ion Linac development. But for the next generation heavy ion Linac such as iLinac of HIAF project, the state of the art ECRISs are still far from meeting the beam intensity needs. Therefore the development of a 4th G. ECRIS has been proposed. In this project, there are many very challengeable physics and technology problems to be solved in the development a 45 GHz ECR ion source.

REFERENCES

[1] E. N. Beebe, J. Alessi, A. Pikin, "Electron Beam Ion Sources, Traps, and Strings: Versatile Devices to Meet the High Charge State Ion Needs of Modern Facilities", in *Proc. HIAT'12*, Chicago, June 2012, WEB01, p. 164. `http://www.JACoW.org`

[2] Y. Jongen, C. Pirart, G. Ryckewaert, IEEE Transactions on Nuclear Science 28(3): 2696 – 2698 (July 1981).

[3] J. W. Xia *et al.*, "HIRFL Status and HIRFL-CSR Project in Lanzhou", in *Proc. APAC'98*, Tsukuba, Japan, March 1998, p. 342 `http://www.JACoW.org`

[4] Y. J. Yuan et al., Nucl. Instr. Meth. B 317, 217 (2013).

[5] L. Sun *et al.*, Rev. Sci. Instrum. 87, 02A707 (2016);

[6] L. Sun et al., Journal of Physics: Conference Series 58 (2007) 435–438.

[7] H. W. Zhao *et al.*, Rev. Sci. Instrum. 81, 02A202 (2010).

[8] C. Lyneis, J. Benitez, A. Hodgkinson, B. Plaum, M. Strohmeier, T. Thuillier and D. Todd, Rev. Sci. Instrum. 85, 02A932 (2014).

[9] D. Xie, "Recent production of intense high charge ion beams with VENUS", Presented at ECRIS'16, Busan, South Korea, Aug. 2016, (unpublished), `http://www.JACoW.org`

[10] L. Sun, *et al.*, Rev. Sci. Instrum. 85, 02A942 (2014) ;

[11] L. Sun, *et al.*, "ECRIS Developments towards intense high brightness highly-charged ion beams", in *Proc. HB'14*, East Lansing, USA, Nov. 2014, p. 363 (2014); `http://www.JACoW.org`

[12] J. Benitez, K. Y. Franzen, C. Lyneis, L. Phair, M. Strohmeier, G. Machicoane, L. T. Sun, "Current Development of the VENUS Ion Source in Research and Operations", in *Proc. ECRIS'12*, Sydney, Australia, 25-28 Sept. 2012, p. 153 (2012). `http://www.jacow.org`

ISBN 978-3-95450-169-4