

## CHALLENGES FOR THE NEXT GENERATION ECRIS

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### Abstract

As an indispensable device to produce intense highly charged ion beams, ECR ion source has evolved into the 4<sup>th</sup> generation or the next generation. Knowledge from the development of the 3<sup>rd</sup> generation ECR ion sources could provide valuable reference for the next generation machine design and fabrication, however there are still many challenges with regards to several key technical issues and physics approaches. This paper will review what we have learned from the state of the art ECR ion sources, and then critical aspects concerning the higher performance next generation ECR ion sources development will be discussed.

### INTRODUCTION

For existing facilities, or projects to be done, such as FRIB project, SPIRAL2 project, HIRFL facility, RIBF project, RHIC, LHC, FAIR and etc., the preinjectors are essentially important. Higher Q/M or charge state Q from an ion source makes the downstream accelerators more compact and less costly. High Charge state Ion (or HCI) beam at the preinjector is delivered from a HCI source. But because of the capacity and characteristics of an ion source is inherent, the choice of ion beam charge state is a tradeoff between ion beam intensity and charge state. Therefore, the choice of the ion source is also strongly depending on the accelerator needs, for instance, EBIS is the ion source solution to RHIC preinjector [1], and ECRIS is the must-have choice for FRIB project [2]. For high charge state intense CW or long pulse (~ms) ion beams solution, ECR in source is still the dispensable one. HIAF or High Intensity heavy ion Accelerator Facility project to be launched in China, 50  $\mu\text{A}$  of  $\text{U}^{34+}$  beam production performance should be demonstrated by the injector ion source so as to ensure the possibility to operate the ion source routinely with an intensity of 40  $\mu\text{A}$ . The state of the art high performance ECR ion source such as VENUS can produce a beam intensity of  $\sim 11.7 \mu\text{A}$   $\text{U}^{34+}$  [3] which is barely 1/4 of the desired beam intensity. Thanks to the recent intense development with SECRA, 22  $\mu\text{A}$   $\text{Bi}^{31+}$  has been obtained, which is an indication that with a proper oven that gives sufficient uranium vapour, ECR ion source of 3<sup>rd</sup> G. can also produce an equivalent beam intensity of  $\text{U}^{34+}$ . However, this value still needs to be multiplied by a factor of 2.3 to get the HIAF goal.

ECRIS development stepped into the era of the 3<sup>rd</sup> G. when the LBNL colleagues got the 1<sup>st</sup> beam with VENUS at 18 GHz in 2002[4]. Together with the following-up development of superconducting ECR ion sources in IMP, MSU and RIKEN, it have been evidenced that the 3<sup>rd</sup> G. ECR ion source is virtually a very powerful machine in terms of intense highly charged ion beam production. The

empirical frequency scaling laws still works well with a 3<sup>rd</sup> G. ECRIS. According to the scaling laws, one must build a min-B device with high enough magnetic field to confine the much denser plasma that are induced by higher frequency microwave heating, so as to produce intense HCI beams since  $\Sigma n_q = n_e$  and  $n_e \propto \omega^2$ , where  $n_q$  is the ion density of charge state  $q$  and  $\omega$  is the microwave frequency. Therefore, to produce highly charged ion beam intensities beyond the 3<sup>rd</sup> G. ECRIS capacity, a 4<sup>th</sup> G. ECRIS is very likely the only economical solution. Learned from experience during the development of a 3<sup>rd</sup> G. ECRIS, there are many technical and physics challenges that need long-term R&D and probably some big break-through. In this paper, we will review and discuss the challenges and difficulties that we could envision during the development of a 4<sup>th</sup> G. ECRIS.

### DEVELOPMENT OF 3<sup>RD</sup> G. ECRIS

3<sup>rd</sup> G. ECRISs have shown obvious performance enhancement over the 2<sup>nd</sup> G. ones, however there are many technical and physics challenges during the ion source development that makes the device more complicated and expensive. In this section, a general review of the typical issues that the ECRIS community have learned during a high performance superconducting ECR ion source development. Figure 1 gives the layout of a typical ECR ion source and the analysing beam line system which.

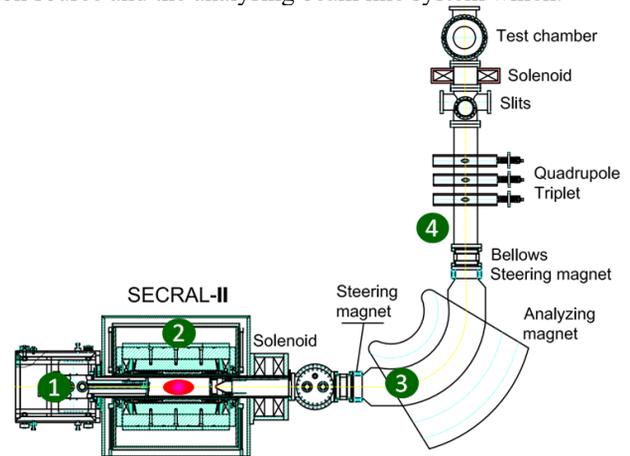


Figure 1: Layout of a typical ECRIS test bench, 1-Ion source injection part; 2-Ion source magnet; 3-ECR beam line; 4-Analysing beam line and beam diagnostics.

### Superconducting Magnet

One typical feature of the 3<sup>rd</sup> G. ECRIS is that they are all incorporated with NbTi superconducting magnet technique so as to provide sufficient magnetic field confinement for the optimum operation at 24~28 GHz. Superconducting magnet design and construction is of the

highest challenge in a 3<sup>rd</sup> G. ECRIS development. ECR ion source magnet has a sophisticated structure which has a superimposed configuration of axial solenoids and radial sextupole magnet. For superconducting ECRIS magnet, because of the very high field produced and the high currents in the coils, strong Lorentz forces are induced in the coils. Therefore, it is essential to do sufficient clamping to all of the superconducting coils to prevent any slight movement during the magnet coil ramping and operation. Insufficient coil clamping will most likely cause quenches and probably magnet failure. The most critical forces in a superconducting ECRIS magnet are the EM forces at the sextupole coils ends, where the sextupole coil currents in the return ends see the magnetic field components from the axial solenoids, and consequently strong Lorentz forces created at the sextupole coil ends. To reduce the strong forces, design with conventional structure has to extend the ends to a certain distance from the axial solenoids so as to lower the forces to safe values for operation, which makes the conventional structure magnet more bulky and engineering complicated. An alternative and also very effective solution to this issue is to place the sextupole coils external to the solenoids. With this design, the sextupole coils see much lower axial fields and therefore, the sextupole magnet could be designed with a short length that makes the whole magnet very compact. The schematic structure of the conventional one (adopted by VENUS, SuSI and Riken SCECRIS, an etc.) and the alternative one (SECRAL) are shown in Fig.2. Nevertheless, with either design configuration, magnet clamping and coil pre-stress is very critical. VENUS source magnet incorporated a very innovative pre-stress technique by using liquid metal bladder [5]. The similar technical approach was also employed during the fabrication of SuSI ion source [6]. For SECRAL magnet, massive cold iron had been used in the design so as to boost the radial field and also to shield the stray field. The cold iron sections together with the coils are efficiently clamped by big aluminium rings installed through hot jacket fit. Besides proper pre-stress or clamping, precise calculation and mechanical design taking into account of the thermal contraction from room temperature to 4.2 K are required essentially.

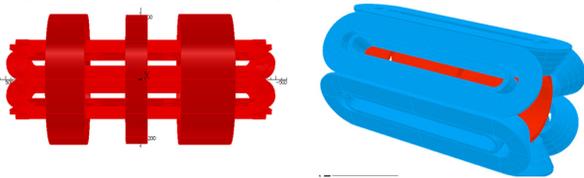


Figure 2: Conventional superconducting ECRIS magnet structure (left) vs. SECRAL type magnet structure (right).

### Cryogenic System

For most of the superconducting ECR ion sources in operation now, the cold mass is immersed in 4.2 K LHe atmosphere, therefore sufficient LHe level must be kept to guarantee their continuous operation. Two feasible approaches have been adopted in different labs, i.e. the

LHe supply tube is connected to the cryogenic circulation loop of a cryo-plant, such as SuSI in NSCL, or by using cryo-coolers to recirculate the evaporated He from the LHe reservoir, such as VENUS in LBNL. Since the second option is more flexible and convenient for operation, it is the most recommendable and widely adopted one. However, unlike the other cryogenic system, ECRIS cryogenic system has strong subsequent influence of the plasma condition. When ECR plasma is heated with high microwave power, strong bremsstrahlung radiation is created which induces dynamics radiation heat load to the 4.2 K region. This plasma radiation dynamic heat load dominates the heat load to the 4.2 K when the ion source is working at higher frequency. For instance, the static heat load at 4.2 K of SECRAL magnet is about 1.0 W, but when operated at 24 GHz, typically 1.0W/kW dynamics heat load has been observed. When higher  $B_{min}$  is tuned for the highly charged ion production, this rate becomes much higher. More cryo-coolers or high cooling capacity coolers on the service turret could be a straight-forward solution. For example, SCECRIS in Riken has utilized 2 GM-JT coolers and 1 GM cooler to solve the problem, and have enough redundancy for high power operation at 28 GHz (Fig. 3) [7]. However, for the successful operation of the ion source at 10 kW/28 GHz, a  $\geq 10$  W dynamics heat load could be induced, which is still a big challenge for all the 3<sup>rd</sup> G. ECRISs.

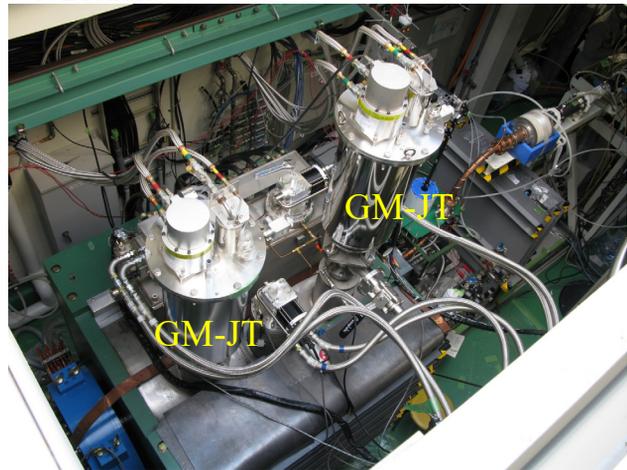


Figure 3: Service turret of Riken SCECRIS ion source.

### Conventional Parts

A high performance 3<sup>rd</sup> G. ECRIS will deal with maximum 10 kW microwave power heating inside the plasma chamber. This is a challenge for the conventional parts' cooling design, especially those sections facing the plasma directly, i.e. biased disk, plasma chamber, and plasma electrode. Different labs have alternative approaches to a successful design. But long-term reliable operation at high power is still a big issue. Additionally, strong bremsstrahlung radiation will cause insulation performance degradation of the high voltage insulator housing the plasma chamber, and ultimately result in high voltage insulation failure. Presently, insertion of a 1.5~2 mm tantalum sheet between the plasma chamber and HV

insulator column seems to be an applicable solution (Fig.4), but after certain long operation period at high microwave power, degradation is still witnessed inside the insulator.

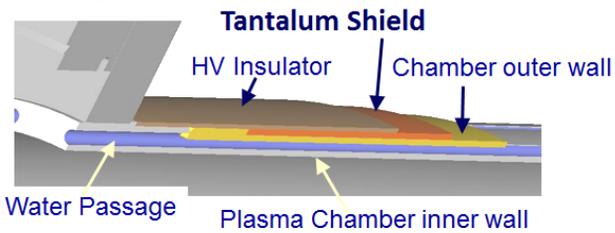


Figure 4: Ta shielding design for a 3<sup>rd</sup> G. ECR ion source.

### Intense Beam Transmission

When operated for intense highly charged ion beam production, a 3<sup>rd</sup> G. ECRIS typically extracts 10~15 emA total current from the plasma with a maximum energy of 25~30 keV/q. Space charge is very severe during such an intense beam transmission with low energy. Thanks to the space charge compensation in the ECR beam line, typically ~70% space charge has been compensated [8]. However, severe beam divergence is still obvious at the entrance of the analyser magnet. The ECR beam line is intentionally designed very short for high transmission efficiency, therefore, no extra space is left for additional beam focusing elements. When large envelope beam passing through the dipole, it might be exposed to the high order component therein, which causes high order aberration to the analysed beams. Larger gap magnet with proper pole surface trimming will be very helpful to improve the beam quality (Fig. 5) [9]. An alternative solution might be a sextupole magnet corrector installed either upstream or downstream of the dipole magnet. However, it is not easy to make a high quality beam for the downstream accelerators. The ion beam condition at the ECR beam line is far from been better understood, as a cause of insufficient diagnostic, which makes the downstream beam matching challengeable. Besides, the ion beam extracted from an ECR ion source is inhomogeneous and highly coupled in transverse space [10].

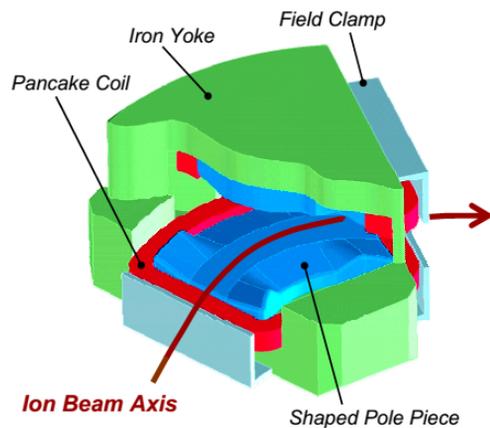


Figure 5: Batman analyser dipole magnet design for VENUS ion source beam line.

### TOWARDS A 4<sup>TH</sup> G. ECRIS

A 4<sup>th</sup> G. ECRIS is expected to be operated at the frequency of 40 GHz or higher. Compared to a 3<sup>rd</sup> G. ECRIS, the challenges to build a 4<sup>th</sup> G. ECRIS will be more or less similar. But since the next generation ion source will be operated at higher frequency, higher microwave power under the condition of higher magnetic field confinement to the plasma, the challenges existing with a 3<sup>rd</sup> G. ECRIS will become more severe that makes the development of a 4<sup>th</sup> G. ECRIS more difficult.

### *Nb<sub>3</sub>Sn Superconducting Magnet*

As discussed in the former section, to meet the highly charged ion beam intensity needs of a next generation heavy ion accelerator, such as HIAF, an intensity gain by a factor of ~2.3 should be made. According to  $\omega_{\text{ecr}}^2$  scaling, the next generation ECRIS is desired to be operated at  $\omega_{\text{ecr}} = (2.3)^{0.5} * 28 \sim 43$  GHz. At IMP, a 45 GHz ECRIS is under construction with this guiding rule.

To make an ECRIS optimum for operation at the frequency of 45 GHz, magnetic fields of two mirror maxima 6.5 T and 3.5 T at source injection and extraction sides respectively, 3.4 T at the ion source plasma chamber wall are desired. For this purpose, approximately 1400 A/mm<sup>2</sup>@12 T will be seen inside the superconductor. Obviously, this parameter is far beyond the NbTi superconducting technology. The state of the art Nb<sub>3</sub>Sn technology is therefore the feasible solution to the 4<sup>th</sup> G. ECRIS magnet. Unlike NbTi, which is ductile and can withstand high compressive force, Nb<sub>3</sub>Sn is brittle and strain sensitive. As a result, the current carrying capability of Nb<sub>3</sub>Sn coils is affected by mechanical stresses in the windings. The actual behaviour depends on several factors, such as the wire design and the fabrication process. However, reversible degradation is generally observed above 150 MPa with severe and permanent degradation occurring above 200 MPa [11].

When designing a 4<sup>th</sup> G. ECRIS magnet, there several choices must be made first with series of comparison of pros and cons. As shown in Fig. 6, Nb<sub>3</sub>Sn wire with Bronze method can barely meet the requirement of a 45 GHz ECRIS magnet, therefore it is better to go with the selection of Internal Tin method, typically the rod-restack processed or RRP Nb<sub>3</sub>Sn. To have a 15~20% operation safety margin, it is better to go with M-grade RRP wire as shown in the picture. However, as mentioned in the former paragraph, Nb<sub>3</sub>Sn is brittle and non-ductile, winding of the coils with one single strand will have high risk of magnet break-down if one of the strand could be broken for any reasons. The scheme with Nb<sub>3</sub>Sn cable winding will be a more robust one, but it also has many subsequent issues. Cable solution means that the magnet coils will be excited with currents up to 10 kA for our application. More expensive power supplies and current leads will be used. Since for >1000 A excitation currents, HTS leads are no longer applicable, heat load to the 4.2 K region will be high, therefore traditional solution with cryocoolers will not be applicable. Two technical approaches are recommended, i.e.

connection the LHe feeding port to the main cryogenic system of the accelerator, or place a dedicated LHe liquefier system (such as Linde L70 liquefier) adjacent to the ion source magnet. But most of the high performance ECR ion source as an injector ion source will be placed on a high voltage platform, for instance ECRIS for HIAF is going to be floated to 100 kV or higher. The solution of LHe lines connected to the main cryogenic pipes at ground potential will be very technically challengeable in terms of the HV insulation. The solution with a LHe liquefier placed on the high voltage platform will increase enormously the footprint and electricity capacity needs of the high voltage platform, and of course a much higher budget tolerance must be made as well.

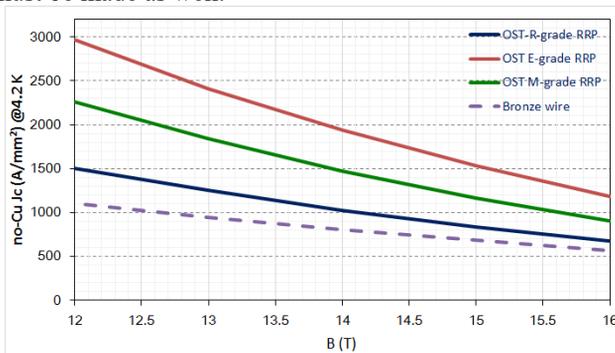


Figure 6: Typical performances of Internal tin Nb<sub>3</sub>Sn wires vs. Bronze Nb<sub>3</sub>Sn wire.

Economical Nb<sub>3</sub>Sn strand is commercially available within the length of 1 km for the diameter control of Ø0.8 mm to Ø1.8 mm. For the 4<sup>th</sup> G. ECRIS magnet coils, if wound with single strand, maximum wire length of 4.0 km might be necessary, which means superconducting wire joints must be made for the incident coils. This is very a challengeable technique, especially when many joints should be made inside such a high field magnet. Winding with Nb<sub>3</sub>Sn cable can avoid such a trouble, but with the other problems as discussed above.

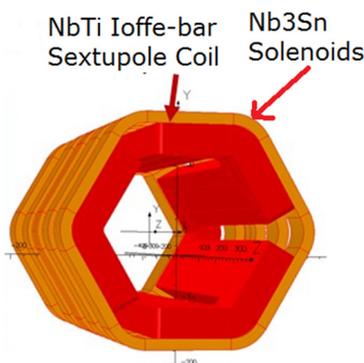


Figure 7: Ioffe-bar sketch for a 45 GHz ECRIS.

Besides the superconductor issue, the choice of the magnet configuration is another very critical aspect in the 4<sup>th</sup> G. ECRIS development. As for the moment, three magnetic configurations are available for choice, i.e. the

conventional type, SECRAL type, and the latest proposed Ioffe-bar type (Fig. 7). Each of these configurations has its specific features and advantages. Both SECRAL and conventional configuration ECRIS magnets have been practically tested with the 3<sup>rd</sup> G. ECRISs. Ioffe-bar configuration has the biggest advantage by using NbTi wire to get the radial fields for the optimum operation of an ECRIS at 45 GHz, which can avoid the risk of complicated Nb<sub>3</sub>Sn sextupole coil fabrication and also make the magnet more cost efficient [12]. However, this innovative idea needs further proof of principle test to demonstrate the feasibility.

### Cryogenic System

Several issues concerning the cryogenic system have already been discussed in the former section. In the Nb<sub>3</sub>Sn cable scheme, either support with the cryogenic plant or a dedicated LHe liquefier could be the solution with sufficient 4.2 K heat load tolerance. While winding with a single Nb<sub>3</sub>Sn strand, it is more preferable to utilize GM-JT coolers. Two GM-JT coolers could provide maximum 9.0 W (50 Hz) cooling capacity at 4.2 K, which might not be enough for a 45 GHz microwave power heating ECR plasma operation at ≥10 kW. A dynamic heat load of >1.5 W/kW is predicated according to the operation experience with a 3<sup>rd</sup> G. ECRIS. How to get sufficient 4.2 K cooling capacity is one challengeable issue for the development of a next generation ECRIS. Alternative approach other than providing higher 4.2 K cooling capacity, effective X-ray shielding in the warmbore or 70 K shield might help to lower the 4.2 K dynamic heat load.

Quench protection is another critical issue needs to be considered. As a 4<sup>th</sup> G. ECRIS operated at 45 GHz has a stored energy up to 1.8 MJ, to dump such a high energy in a short time without any potential damage to the superconductor when magnet quenches needs a robust quench protection scheme. The winding scheme with Nb<sub>3</sub>Sn cable allows high operation currents and much less coil turns that indicates much lower inductance and mutual inductance in the coils. Provided with a limit on the maximum voltage inside the quench protection loop (typically 1000 V), the maximum temperature rise will be much lower and within the safe operation margin which does not need a specific design on the quench protection loop. While for the single strand winding scheme, higher inductance and mutual inductance will be created, which could be problematic for the quench protection system design. Sectional protection loop for each coil could be a feasible approach.

### Microwave Coupling and Heating

Gyrotron frequency microwave was incorporated into ECR ion source firstly in INFN/Catania during the commissioning of SERSE source [13]. And it becomes a standard ancillary hardware when ECRIS evolves into 3<sup>rd</sup> G. machines. As a conventional technique, the existing 3<sup>rd</sup> G. ECRISs are all using TE<sub>01</sub> mode as the gyrotron microwave power coupling scheme, which is actually a directly borrowed technique from fusion community. Ion

sources working at gyrotron frequency have been tested and verified having the capacity to produce more intense highly charged ion beams with sufficient magnetic confinement, which has 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 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. Figure 8 gives the recent Xe<sup>27+</sup> beam results with SECRAL. At 24 GHz, SECRAL can produce the beam intensity of the  $\omega^2$  scaling, but at much higher microwave power level compared to that at 18 GHz. Similar results have also been observed with SuSI [14]. This raised the question about the coupling efficiency of gyrotron microwave power into ECR ion source plasma. This question remains a very puzzling one for the ECRIS community in the 3<sup>rd</sup> G. ECRIS development. Without any progress, this would become a severe problem for a 4<sup>th</sup> G. ECRIS development, i.e. one can't achieve the desired performance with a 4<sup>th</sup> G. ECRIS. Technically and physically understanding and improving the microwave coupling and heating efficiency of a gyrotron frequency microwave is one of the critical topics in ECRIS source development and very essential for the 4<sup>th</sup> G. ECRIS development.

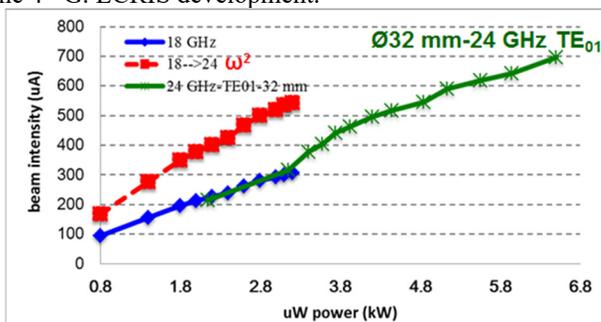


Figure 8: Recent Xe<sup>27+</sup> results with SECRAL ion source at 24 GHz in comparison with the results at 18 GHz and the extrapolated results from 18 GHz to 24 GHz.

Since the wavelength of 45 GHz microwave is  $\sim 6.67$  mm, quasi-optical transmission scheme is routinely utilized for high power transmission. This scheme has already been widely utilized in the fusion machines, but to accommodate with an ECRIS, the outcome is not evidenced yet. Many technical details and modifications will be made accordingly.

### Intense Beam Extraction and Transmission

While the typical highest extracted beam currents from a 3<sup>rd</sup> G. ECRIS for the production of intense highly charged ion beams are of 10~15 emA, the extractable beam intensity from a 4<sup>th</sup> G. ECRIS might exceed 20 emA. How to realize the efficient extraction of very intense ion beam from the much denser ECR plasma needs further investigation. Higher extraction HV might be helpful, for instance 35~40 kV, but the operation stability at strong stray magnetic field needs to be investigated.

Transmission of intense ion beam in the ECR beam line remains a problem for the 4<sup>th</sup> G. ECRIS. As the intensity gets higher, much stronger space charge will be observed in the beam line. For the analysing beam line (or ECR beam line), stronger space charge will weaken the focusing force of the Glaser lens at source extraction and deteriorate the mass separation resolution at the image point of the analyser magnet, and under the worst case, it is impossible to separate two adjacent heavy ion charge states at the faraday cup, such as U<sup>33+</sup> and U<sup>34+</sup>. It is mandatory to take into account of the worst case of very intense beam extraction and transmission in the beam dynamics simulation. A 110° large gap analyser magnet is an applicable solution [15].

### Miscellaneous Aspects

Strong bremsstrahlung radiation remains a very severe problem for a 4<sup>th</sup> G. ECRIS development. Besides the cryogenic issues discussed above, the potential damage to the magnet coil impregnation epoxy is still not very clear. Strong X-ray radiation will also induce photoelectric effect in metals, which might cause malfunction of electronic units. Sufficient lead shielding is desired, but the utility will be very bulky and costly. One ultimate goal of the 4<sup>th</sup> G. ECRIS is to produce very intense highly charged uranium ion beams. The obvious barrier so far the ECRIS community can foresee is the capacity of the high temperature oven. To produce 50  $\mu$ A U<sup>34+</sup> beam, the oven must be very reliable at high temperature up to 2100 °C and have a large loading capacity. Uranium beam is just one example. How to produce enough metal vapour to the ECR plasma is one of the biggest challenges to the next generation ion source development. Last but not least, the routine operation of an ECRIS with  $\sim 1$  emA highly charged ion beam has never been evidenced. The long-term stability and reliability really concerns the operation of next generation heavy ion accelerators.

## CONCLUSION

By reviewing the problems and challenges existing with the development of a 3<sup>rd</sup> G. ECRIS operated at 24 or 28 GHz, we could envision the possible challenges we might have for the next generation ECR ion source development, which is most likely to be operated at 45 GHz. Even after more than 10 years after the first plasma at 28 GHz with a 3<sup>rd</sup> G. ECRIS, promising improvement has been made annually among the ECR community, which also gives strong support to the successful development of a 4<sup>th</sup> G. ECRIS which is under design at IMP. And also with the rapid improvement of accelerator technologies, many challenges to the 4<sup>th</sup> G. ECRIS development will be properly handled.

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