ECRIS DEVELOPMENTS TOWARDS INTENSE HIGH BRIGHTNESS HIGHLY-CHARGED ION BEAMS *

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Abstract

To meet the increasing needs of modern heavy ion accelerators, ECR ion source must be developed to deliver high intensity high brightness high charge state ion beams, in terms of accelerator output power and beam transmission efficiency. With the success in several laboratories on fully superconducting ECR ion source development, the performance of highly charged heavy ion beams have been greatly enhanced. For instance, U^{33+} intensity had been doubled in 2011 by VENUS source at LBNL. This paper will present the development work at IMP towards high performance ECR ion source. Recent high intensity bismuth results will be given, such as 710 eμA Bi^{30+} with SECRAL source. The first room temperature ECR ion source using evaporative cooling technique will also be reviewed. And the discussion of ECRIS beam extraction and the transmission beam line elements on ion beam quality will also be presented in this paper.

INTRODUCTION

Since been used as preinjectors for heavy ion accelerators about 30 years ago, Electron Cyclotron Resonance (ECR) ion source has been an indispensable machine to provide intense CW or long pulse (~ms) highly charged ion beams. The development of nuclear research strongly demands the modern heavy ion accelerators to be constructed or under construction to be capable of delivering high power heavy ion beams on the targets. To make the accelerators cost efficient, and achieve the design goal, intense highly charged heavy ion beams must be provided in the front end section. The FRIB project under construction at MSU campus needs 13 pμA $U^{33+\,\&34+}$ beam from the ion source and a dedicated achromatic transmission line and the successive matching beam line for downstream RFQ [1]. The SPIRAL 2 project going on at GANIL laboratory, eventually 1 emA Ar^{12+} is expected to be delivered from the ion source to reach the goal of 1 emA heavy ion beam with the M/Q =3 for M⩽36 [2]. And the RIKEN RIBF project also demands 15 pμA U^{35+} eventually [3]. For the upgrade programme at IMP, the HIRFL facility needs the ion source being capable of producing very high charge state heavy ion beams with sufficient beam intensities, such as 100 eμA Xe^{31+} and U^{41+}. All these facilities have made ECR ion sources in the baseline design to reach the desired parameters, due to the features of its high capacity of intense high charge state heavy ion beam production. Fundamentally, the front end beam properties are determined by the ion source performance and the successive low energy beam transmission (LEBT) line design. The intrinsic properties have big impact on its output beam quality, which should be taken care of during the ion source and its LEBT design. A high performance ECR ion source injector front end should be an optimum design of both the ion source and the matching LEBT line, which enables the front end section to be capable of providing high brightness ion beam with sufficient beam intensity. In the following contents, the production of intense heavy ion beams with an ECR ion source will be generally reviewed, and the features of the ECR ion source LEBT line will also be discussed in terms of beam quality.

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INTENSE BEAM PRODUCTION WITH MODERN ECR ION SOURCES

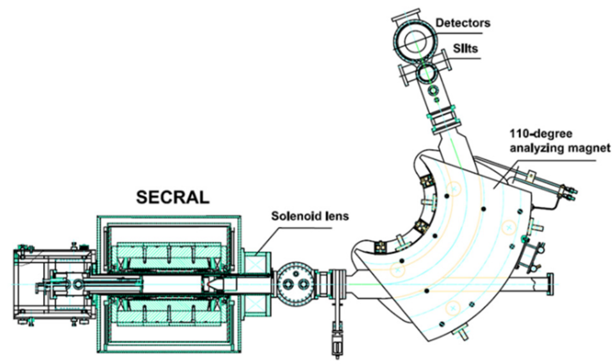

Figure 1: SECRAL ion source and LEBT layout.

ECR ion source is a kind of magnetic confined plasma machine, which was actually developed based on plasma fusion device [4]. Plasma electrons are heated through ECR heating to high energy by coupled microwave power with the frequency in the range of 2.45 GHz to 28 GHz. The plasma is confined by a strong nested so-called mini-B magnetic field configuration, which is the superposition of an axial mirror field and a radial multiple field (normally a hexapole field). Hot electrons are confined at the centre of the nested field and the HCIs, which are produced by stepwise ionization while they are confined in the plasma, are trapped by the space charge established by the electrons inside the plasma. The lost ions that enter the extraction region will be accelerated by the applied HV potential to form intense mixed ion beams. HCI beams in the extracted mixing beam can be separated with an analyser dipole magnet. Normally, a solenoid is used to focus the extracted intense beams to match the downstream elements. Fig. 1

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gives the LEBT line layout of SECRAL source. Electrostatic lens is an alternative option for the purpose of beam focusing, such as the LEBT line of SuSI at MSU [5].

Ion Source Development

As ECR ion source is a magnet confined microwave heating plasma machine, its features could be generally described with the knowledge of under dense plasma. ECR source researchers have summarized the machine's performance with semi-empirical laws, i.e. extracted ion beam with charge state of q is determined by

$$I_i^q = \frac{1}{2}\frac{n_i^q qeV_{ex}}{\tau_i^q},$$

where n_i^q is the incident ion density, V_{ex} is the effective volume of the ion with charge state q, τ_i^q is the average confinement time of the ion with charge state q, and the factor *1/2* means that the magnetic configuration of an ECRIS has two symmetrical ends while the ion beam is extracted on one side only. From the formula above, it is easy to see that high charge state ion beam production in an ECR ion source is a compromise of ion creation and loss. Therefore, the source parameters need to be optimized for best performance during operation. The most efficient way to increase the beam output is to increase the ion density and enhance the efficient plasma volume. According to the knowledge of microwave heating plasma, the higher the incident microwave frequency ω_{ecr}, the more beam could be achieved, i.e. $I_i^q \propto \omega_{ecr}^2$. For this reason, modern ECR ion sources are mostly working in the frequency range of 14~28 GHz. Since sufficient magnetic confinement is essential for the production of highly charge ions, the higher the frequency adopted, the stronger the magnetic fields are required. Therefore, when coming to the gyrotron frequency (f > 20 GHz), superconducting technique is incorporated.

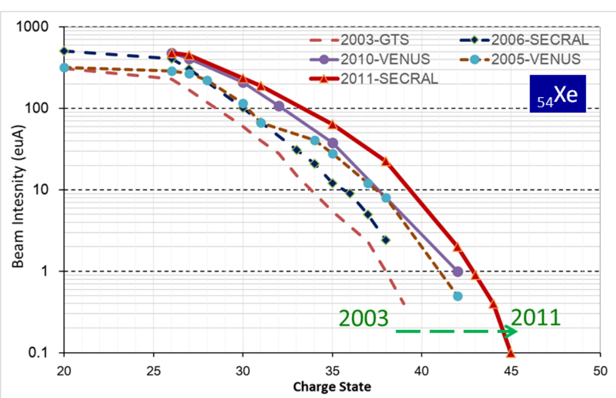

Figure 2: Xenon ion beam intensities evolution from 2003 to 2011 with the contribution of advanced sources.

Two kinds of configurations are utilized in the magnet design of fully superconducting ECR ion sources, i.e. the conventional structure, such as VENUS/LBNL [6], SERSE/INFN [7], SuSI/MSU [5] and SCECRIS/RIKEN [3], and the one with the unique reversed structure, or SECRAL design [8]. There are many pros and cons in the design of each technical solution, however either of them can provide good enough magnetic confinement to the plasma created therein, which guarantees sufficiently good source performance. With the contributions from the modern ECR ion sources, especially those from fully superconducting ECR ion sources, beam results are enhanced obviously. Fig. 2 provides xenon beam results evolution between 2003 and 2011. Apparently, either the beam intensities or the beam charge states have been boosted enormously over the time. And the evolution is still going on with the ECR ion source technology advancement.

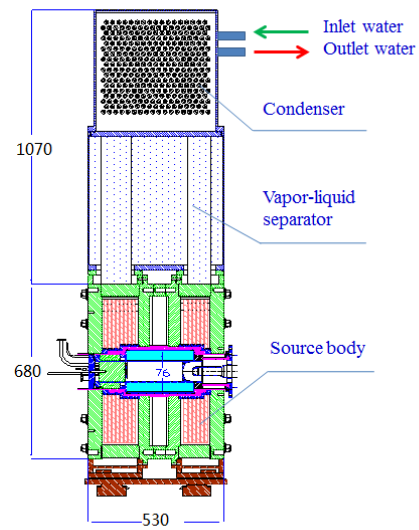

Figure 3: Schematic plot of LECR4 ion source.

Since superconducting technology is costly, challengeable and time consuming solution towards intense high charge state ion beam production, we are investigating into alternative technical solution of magnet design for an ECRIS to achieve similar beam performance that a superconducting ECR ion source can make at 18 GHz. Evaporative cooling technology has been applied in many high-power, high current density devices, such as Three Gorges Power Station in China. Evaporative cooling technology is a new efficient heat transfer method, which utilizes phase-change heat transfer mode to achieve the cooling for heating equipment. The coolant absorbs the latent heat of vaporization to cool the heating parts. The coolant can generally keep under a boiling point of 40-60℃, and the temperature of heating parts can be controlled under an ideal situation. On the other hand, the insulation of coolant can surely lead to a direct contact between electrified parts and evaporative coolant, therefore the coils can be immersed in the liquid coolant [9]. The heat transfer is very efficient and reliable. The typical adventures of such a technology to be utilized in an ECR ion source are (in comparison with traditional room temperature ECR ion source using deionized water cooled pancake coils):

- High pressure (in the range of 20 kg/cm^2) deionized water free.
- Higher current density in the coils.
- Sufficiently high axial field confinement for 18 GHz operation.

Based on this concept, the first ECR ion source named

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LECR4 (Sectional plot shown in Fig. 3) has been successfully constructed at IMP [10], which can produce the best results in comparison with other high performance room temperature ECR ion sources such as GTS/Grenoble [11], and even close to the best results that an superconducting ECR ion source optimized to 18 GHz (as indicated in Table 1). This new results provide an alternative option for the development of an ECR ion source that has the similar performance of a fully superconducting ECR ion source working at 18 GHz.

Table 1: First Beam Results of LECR4 at 18 GHz

f (GHz)		SECRAL *18*	GTS *18*	LECR4 18
^{16}O	6^+	2300	1950	1970
	7^+	810		438
^{40}Ar	8+		1100	1717
	9^+	1100	920	1075
	11+	810	510	503
^{129}Xe	20+	505	310	293
	23+			143
^{209}Bi	28+	214		118
	30+	191		78
	32+			51.5

Intense Beam Production

As shown in Fig. 2, a state of the art ECR ion source has already produced very intense highly charged gaseous ion beams. But practically, most of the ion beams that the experimenters demand are from solid elements. For the case of solid material or metallic ion beam production, special instrument is needed to produce sufficient vapor of incident material that could be delivered and ionized by the hot ECR plasma. Typical techniques such as plasma insertion, plasma sputtering, MIVOC and micro-oven have been used, however with regard to long term service with intense highly charged ion beams, for instance >10 pμA U^{34+}, micro-oven is the only workable solution. 4 types of micro-ovens have been designed and tested in ECR ion source laboratories, i.e. resistor oven with the highest operating temperature of 1600° C but moderate material loading capacity, low temperature oven incorporating cartridge heaters with the highest operating temperature of 800° C and much larger material loading capacity, high temperature resister oven that could reach the temperature of 2000° C mainly designed for refractory material ion beam production and the inductive heating oven that could also reach the temperature up to 2000° C but with a much complicated auxiliary power system.

Traditional resister heating oven has been widely adopted in ECR ion source laboratories for many years. It is a quite matured technique to serve tens of eμA ion beams production from moderate melting temperature solids. For very refractory ion beam production, such as uranium, traditional oven is not suitable for the application. A high electrical current driven resister heating oven has been developed in LBNL [12], which utilizes resistively-heated refractory metal enclosures, normally of the material of Re, Mo, W or Ta. The nominal excitation current is up to 400 A. The off-line test of this kind of oven has reached a temperature up to 2300℃. However, during operation, the oven is located off-axis near the ion source injection field peak, where exists a very strong magnetic field up to 4 T (for VENUS) contributed from both the solenoids and the sextupole magnet. Therefore, Lorentz forces from different directions act upon the oven during operation. When very high temperature needed, high electrical current is energized in the oven, which makes the Lorentz forces even stronger. As most of the metals will soften at high temperature, the high Lorentz force will twist the oven and eventually destroy the oven. After years' research and upgrade, the LBNL researchers have developed a more durable oven that can work under high field with sufficiently high temperature for about one week or even longer. With this oven, recorded uranium beam intensities were made with VENUS in 2011, as shown in Fig. 4. Based on the same design, a high temperature oven has also been recently developed in RIKEN and been used for routine operation [13].

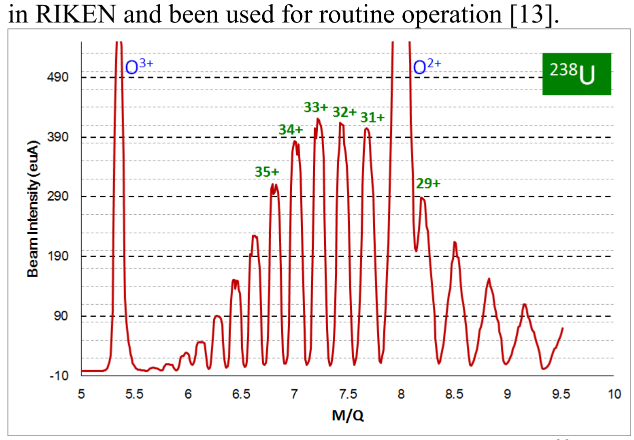

Figure 4: Spectrum from VENUS when 440 eμA U^{33+} produced at 28 GHz.

A DC current driven high temperature oven as discussed above can't avoid the strong Lorentz forces when used for operation in an ECR ion source. As for the 4th generation ECR ion source working at the frequency higher than 40 GHz, the field at the oven location is even higher (proportional to the working frequency), which indicates that much stronger Lorentz force will be applied to the oven. For this reason this type of high temperature oven might not be applicable to the future needs. An alternative solution is based on the traditional inductive heating technique that has been widely used in industrial processing of metal materials. At NSCL/MSU, a micro-oven based on inductive heating technique has been developed and used in routine operation for refractory ion beam production (Fig. 5). This oven technique can definitely avoid the Lorentz forces problem. But it utilizes 1~2 kW RF power in the frequency range of ~100 kHz, the power coupling between the RF generator and the oven susceptor needs professional design and fabrication. Additionally, working at the temperature below 2000℃, the oven is reliable and stable, but at higher

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temperature the furnace heat insulator degrades very quickly and the oven can't hold the temperature thereafter. Nevertheless, with new furnace heat insulator materials utilized, this type oven may sustain the long term operation at the temperature up to 2300℃.

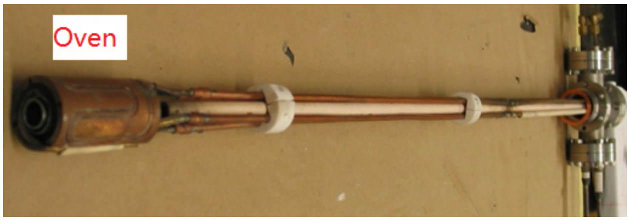

Figure 5: Picture of an inductive heating oven developed at NSCL/MSU.

For very intense solid material ion beam production, a vapour pressure up to 10^{-1} mbar is needed from the oven. To sustain such a working condition for a very long time, the oven loading capacity must be high enough. For this reason, a kind of oven utilizing cartridge heaters has been designed and fabricated at IMP based on the LBNL concept. Another advantage of this type of oven is the precise control of the temperature rise, since the temperature control of the oven is realized through cartridge power control, and the temperature rise is quite slow. For the solid material that needs the temperature below 700℃, such as Ca, Bi, Pb and etc., this oven is a very applicable technical approach. With this type of oven installed, recorded bismuth beam intensities have been produced in 2014. Working at 4.74 kW@24 GHz + 1.4 kW@18 GHz, 710 eμA Bi^{30+} and 680 eμA Bi^{31+} have been obtained at the faraday cup [14]. Fig. 6 gives the spectrum when 710 eμA Bi^{30+} produced. The present results seems to be still limited by oven output of Bi vapour and ion source conditioning at high power.

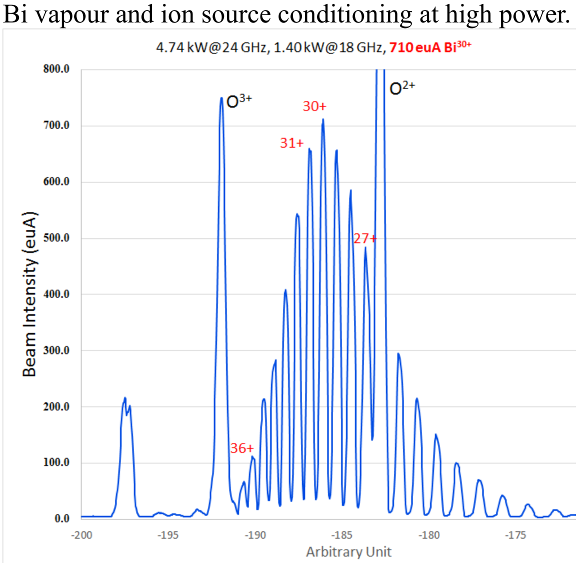

Figure 6: Spectrum optimized for 710 eμA Bi^{30+}.

Intense Beam Emittance

In general, two issues are essential for ion beams injected to an accelerator, i.e. beam intensity and beam brightness. High power accelerators need very intense ion beams, while optimal brightness can guarantee the transmission of ion beam with less losses. With the increase of ion beam extracted from an ECR ion source, beam quality will deteriorate as a cause of more severe space charge effect. It is worth checking the beam emittance evolution with the increase of beam intensity. With SECRAL source, the beam emittance was measured with Alison type scanners. Fig. 7 shows the horizontal and vertical normalized rms emittances measured for Bi^{31+} intensity from 100 eμA to 600 eμA. Error bars are not given here, which should be in the range of ±10% [15]. According to the study, the emittances do not deteriorate dramatically with the beam intensity increase.

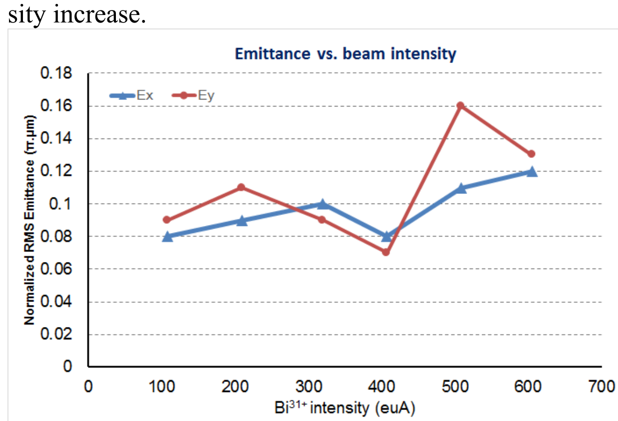

Figure 7: Bi^{31+} beam emittance variation with the increase of beam intensity.

ECR LEBT AND BEAM QUALITY

Ion Beam from an ECR Ion Source

In an ECR ion source, the ions are produced in a superimposed field of axial mirror field and radial sextupole field, which makes the ions have inhomogeneous spacial distribution at the ion source extraction that is reflected by the triangle tracks at the both ends of the ion source. Fig. 8 provides the triangle image created at SECRAL plasma electrode.

Ion Source Extraction Field

As shown in Fig. 9, when ion beam extracted, it will experience a hemi-solenoidal field. Provided that the extracted beam is a symmetrical one, we have the initial σ matrix:

$$\sigma_0 = \varepsilon\begin{pmatrix} \beta & -\alpha & 0 & 0 \\ -\alpha & \gamma & 0 & 0 \\ 0 & 0 & \beta & -\alpha \\ 0 & 0 & -\alpha & \gamma \end{pmatrix},$$

and the hemi solenoid transport matrix assumed to be:

$$R_{exit} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ -k & 0 & 0 & 1 \end{pmatrix},$$

Therefore, the extracted beam final σ matrix will be:

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$$\sigma_s = R_{exit}\sigma_0 R_{exit}^T = \varepsilon\begin{pmatrix} \beta & -\alpha & 0 & k\beta \\ -\alpha & k^2\beta+\gamma & -k\beta & 0 \\ 0 & -k\beta & \beta & -\alpha \\ k\beta & 0 & -\alpha & k^2\beta+\gamma \end{pmatrix}$$

where α, β and γ are beam Twiss parameters, ε is the beam initial emittance, $k=B_s/B\rho$, B_s is the extraction field, and $B\rho$ is the ion rigidity. Obviously, the hemi solenoid field introduces a coupling between the horizontal and vertical coordinates, and causes beam emittance growth. As discussed above, the extracted beam is actually asymmetric which will induce more severe coupling and beam emittance deterioration.

Figure 8: Plasma bombardment images on plasma electrode.

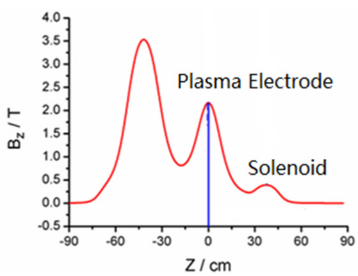

Figure 9: SECRAL axial field distribution, and ion beam extraction started from plasma electrode.

Solenoid lens can provide very efficient pre-focusing of the beam extracted from an ECR ion source in a short transmission length. Compared with an electrostatic lens, it will not destroy the space compensation in the source extraction region. The matrix operations of a solenoid in beam optics tell us that for an axisymmetric and un-coupled beam, a solenoid will only have focusing effect, without any additional transverse coupling. However, if a coupled beam transmits through a solenoid, the coupling effect will become more severe, transverse emittance will transfer between the horizontal and vertical directions, and the polarity of the solenoid field will have obvious impact on the beam quality. Fig. 10 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 purpose.

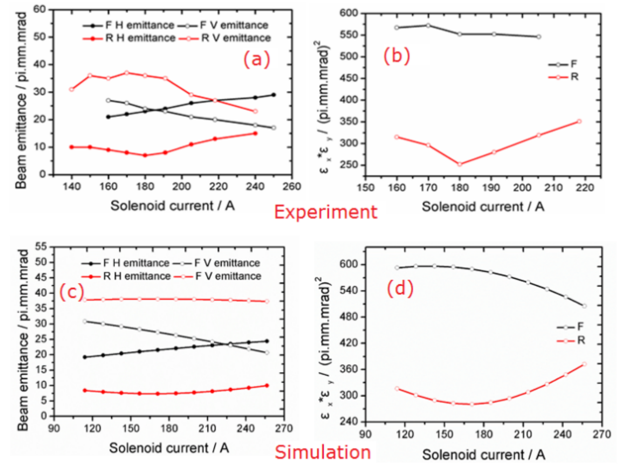

Figure 10: Experiment (a, b) and simulation (c, d) results to understand the beam coupling with SECRAL ion source and LEBT.

Dipole Magnet Design

Dipole magnet is an essential part in the LEBT design for an ECR ion source system. It will determine the downstream beam quality and quantity. Most of the analyser magnet has double focusing structure to have beam focusing in both vertical and horizontal directions. As the design of SECRAL LEBT line, one solenoid lens is used in the ECR beam line which can't control the beam envelope and divergence simultaneously at the entrance of the dipole magnet. Therefore, a large magnet gap is favoured to provide the highest beam acceptance, and it also can minimize the high order aberration induced to the large envelope beams. And essentially, the mass resolution should be high enough, especially when very highly charged heavy ion beams are desired, and normally a $\Delta m/m = 1/100$ resolution is desired.

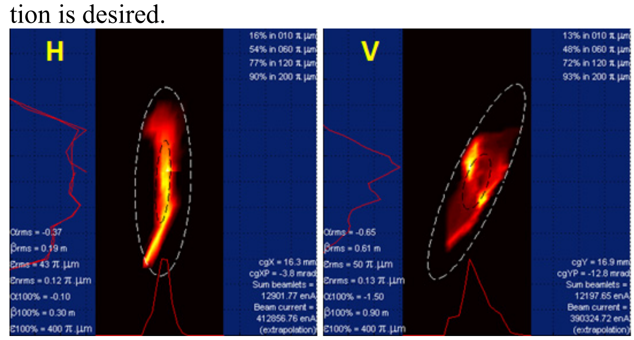

Figure 11: Beam emittances in Horizontal (left) and Vetical (right) directions: $\varepsilon_{h.rms}$=0.12 π.µm, $\varepsilon_{v.rms}$=0.13 π.µm. $\alpha_{h.rms}$= -0.37, $\alpha_{v.rms}$= -0.65.

A normal dipole design 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. Fig. 11 is the beam emittance plot from SECRAL source. Since sextupole component field increases quadratically from the center beam trace, the larger envelop beams may see stronger sextupole components, and therefore more severe aberration. Two applicable technical solutions can solve the problem,

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i.e. a well-trimmed dipole magnet, or external compensation with sextupole magnet. The first option is a very straightforward method. By accurate calculation and simulation, the magnet can be designed to correct the sextupole components in both vertical and horizontal planes. Technically, the magnet edges need to be carefully shaped, and the pole surfaces need to be trimmed to have smoothly varying shape to produce a desired quadratic terms. This technical approach is very time consuming and expensive. The VENUS [16] and SuSI [17] analyser magnets are using this concept. An alternative and cheap solution is to add an external sextupole magnet to generate a reversed sextupole field against the one induced by the dipole magnet so as to cancel the sextupole magnet negative effect and reduce the aberration. Recently a sextupole magnet has been built and installed to the SECRAL LEBT dipole magnet exit to investigate the feasibility. Meanwhile the code simulation already indicates that the design is very effective to reduce the aberration and improve the beam quality [18].

Space Charge

Space charge has been discussed in many presentations about the negative effect induced. For most of the ECR ion sources in operation, the total extracted ion beam is no more than 4 emA, which will not give much space charge influence. While for the very intense beam production, for example, when more than 400 eμA U^{33+} produced with VENUS and 700 eμA Bi^{30+} produced with SECRAL, the total extraction beam was over 10 emA, and the space charge effect will dominate the beam quality issues. According the recent research results from NSCL/MSU with a space charge detector, the space charge compensation ratio at the source extraction region is about 70% [19]. Thus, for a 10 emA total beam extraction, 3 emA space charge will have influence on incident ion beam quality. There're several negative effects the space charge will affect the beam transmission, i.e. beam aberration and emittance growth, decrease of momentum resolution of the Q/A selector system which is discussed in Ref. 20 in details.

CONCLUSION

To meet the needs of future heavy ion accelerators, ECR ion sources have been developed to produce very intense highly charged ion beams, such as 400 eμA U^{33+} and 700 eμA Bi^{30+}, but the beam quality is another issue which needs a systematic consideration of the design from the ion source to the downstream LEBT line, so as to minimize the emittance growth and beam quality degradation, therefore to guarantee injection to the post accelerator with high enough beam intensity and brightness. In terms of the several high intensity projects under construction and to be started in next 5 years, such as FRIB, SPIRAL 2, and HIAF (50 pμA U^{34+} needed) and etc., intense beam extraction and transmission is very critical and challengeable research topic for the ECR ion source researchers to take on, other than the high performance ECR ion source development. Higher frequency next generation ECR ion source could be built in 10 years, however, to produce very intense highly charged beams from solid materials especially those from refractory ones, oven is a real challenge as a supporting technology.

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