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# Magnetic Field Configuration Effect and New ECRISs for RIKEN RIBF Project

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**Abstract** We measured the main plasma parameters (density of electron, temperature of electron and ion confinement time) and beam intensity of various heavy ions as a function of $B_{\min}$. The $B_{\min}$ strongly affects the field gradient at the resonance zone, consequently the plasma parameters and beam intensity are changed. Based on these experimental results, we started to construct new 18GHz ECRIS and make a detailed design of the 28GHz SC-ECRIS for RIKEN RI beam factory project.

**Key words** magnetic field configuration, $B_{\min}$, superconducting ECRIS

## 1 Introduction

ECRISs became one of the key devices for production of radioisotope beam (RI beam). Since middle of 1990s, RIKEN has undertaken construction of new accelerator facility so-called RI Beam Factory[1]. In this project, the production of intense heavy ion beams is an important task to produce the intense RI beam using projectile like fragmentation. For this reason, at RIKEN, several high performance ECRISs have been constructed and improved (RIKEN 10GHz ECRIS[2], 18GHz ECRIS[3] and liquid He-free Super conducting ECRISs[4]) in the last decade. During the improvement, we have recognized that for increasing the beam intensity it is important not only to increase the magnetic field strength, but also to optimize magnetic field configuration[5]. Applying these methods, the beam intensities from RIKEN ECRISs have been dramatically increased[2].

To meet the requirement of the RIBF (primary beam intensity of 1pμA on target), we still need to increase the beam intensity of the heavy ions. For this reason, we are constructing new room temperature 18GHz ECRIS and make the detailed design of the new superconducting ECR ion source which has an operational frequency of 28GHz.

In this paper, we report the effect of magnetic field configuration on the bema intensity and progress of the new RIKEN ECRISs.

## 2 Magnetic field configuration

Last several years, we intensively studied the effect of magnetic field configuration on the plasma and beam intensity of highly charged heavy ions. In these studies, it is revealed that $B_{\min}$ plays important role to increase the beam intensity. In the systematic study of the effect of $B_{\min}$ on the beam intensity, we observed that the optimum $B_{\min}$ ($(B_{\min})_{\text{opt}}$) exists to maximize the beam intensity and it is almost constant ($0.7\sim0.9B_{\text{ecr}}$), which is independent on the ion spices and charge state at moderate RF power (several 100W)[5].

To investigate its mechanism, we applied so-called laser ablation technique to obtain important plasma parameters (density of electron, temperature of electron and ion confinement time)[6]. In these studies, we observed that the $B_{\min}$ strongly affect the density

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and temperature of electrons. In the laser ablation experiment, the main plasma parameters are obtained by using the data of the multicharged heavy ions and a least square method. Using this method, obtained density and temperature are not the “real” one, but the effective electron temperature and density for ionizing the multi-charged heavy ions, because very low and high temperature electrons can not affect the ionization of multi-charged heavy ions. Using these results, one can obtain the “effective” absorption power. Fig. 1 shows the effective absorption power of liquid He-free SC-ECRIS SHIVA (operational RF frequency of 14 GHz) as a function of $B_{\rm min}$. The effective absorption power increases with increasing $B_{\rm min}$ up to ∼0.4T and then gradually decreases. At resonance zone, the average energy gain per pass is written as follows

$$\Delta W \sim \frac{\pi e^2 |\boldsymbol{E}|^2}{m_{\rm e}\nu\omega\dfrac{1}{B_{\rm res}}\left(\dfrac{{\rm d}B}{{\rm d}Z}\right)_{\rm res}}\ , \tag{1}$$

where, $E$ and ${\rm d}B/{\rm d}Z$ are the electric and magnetic field gradient at the resonance zone. If we assume that the electron temperature is proportional to $\Delta W$, the electron temperature increases with increasing the $B_{\rm min}$ and “effective” electron density (for ionizing the multicharged heavy ions) may also increases. However, the size of the resonance zone decreases with increasing the $B_{\rm min}$. The effective absorption power may decreases above certain $B_{\rm min}$ by the resonance size effecet. This may be one of the reasons why “effective” absorption power becomes maximum at $B_{\rm min}$ ∼0.4T in case of the SHIVA

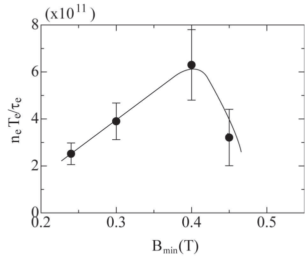

Fig. 1. Effective absorption power as a function of $B_{\rm min}$.

Figure 2 shows the drain current (closed circles) and vacuum (open circles) of the RF injection side of the liquid He-free SC-ECRIS RAMSES[7] (operational RF frequency of 18GHz) at fixed neutral gas flow. The neutral gas pressure at the RF power of 0W was $4.5\times10^{-7}$ Torr. The ion pumping effect and drain current became maximum at the optimum value for $B_{\rm min}$. These phenomena indicate that the ionization efficiency is strongly dependent on the $B_{\rm min}$. The higher electron density leads us to increase the ionization efficiency. This experimental result is consistent in the experimental results with laser ablation method.

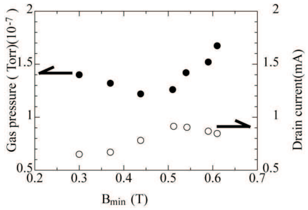

Fig. 2. Gas pressure and drain current as a function of $B_{\rm min}$.

According to the Eq. (1), we may need gentle field gradient to obtain high enough electron temperature at low electric field gradient (low input RF power). To investigate this effect, we measured the $(B_{\rm min})_{\rm opt}$ as a function of RF power. Fig. 3 shows the beam intensity of $\rm Ar^{9+}$ ions produced by RAMSES as a function of $B_{\rm min}$ at the RF power of 100 and 280W.

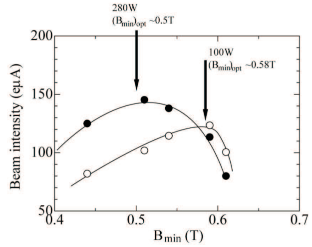

Fig. 3. Beam intensity of $\rm Ar^{9+}$ as a function of $B_{\rm min}$ at the RF power of 100 and 280W.

The gas pressure was tuned to maximize the beam intensity. The optimum value for $B_{\rm min}$ was 0.58T at the RF power of 100W, which was higher than that ($B_{\rm min}$ ∼0.48T) at higher RF power. To see this tendency more clearly, we measured the optimum value for $B_{\rm min}$ as a function of RF power. (see Fig. 4) The optimum value for $B_{\rm min}$ gradually increased with decreasing the RF power. For example, when we set the $B_{\rm min}$ ∼0.48T for production of $\rm Ar^{8+}$ at RF power lower than 250W, the magnetic field gradient may be too steep to give the enough kinetic energy to the electrons, because the electric field gradient is too low at lower RF power. In this case, $B_{\min}$ has to be higher to obtain gentler magnetic field. This is one of the reasons why we obtain higher optimum value for $B_{\min}$ for maximizing the beam intensity of multi-charged heavy ions at lower RF powers. To understand these phenomena, we need further investigations.

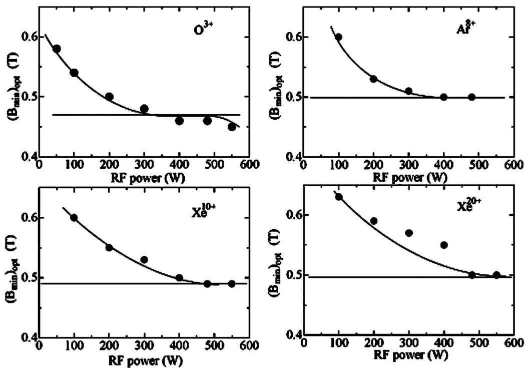

Fig. 4. Optimum value for $B_{\min}$ as a function of RF power for highly charged heavy ions.

Very recently, the beam intensity of highly charged Xe ion measured as a function of $B_{\min}$ with VENUS[8]. In this experiment, the optimum value for $B_{\min}$ was ~80% of $B_{\mathrm{ecr}}$. However the beam intensity was not so strongly influenced by changing the $B_{\min}$, which is different from our results, as shown in Fig. 5. One of the main differences between VENUS and RAMSES is the plasma chamber size (plasma chamber diameter of NVENUS is 150mm and RAMSES is 75mm). Fig. 6 shows the magnetic field gradient at the resonance zone as a function of $B_{\min}$. The field gradient for ion source which has a large plasma chamber diameter is very gentle and it is not influenced by changing $B_{\min}$. It may be the reason why the beam intensity produced by VENUS is not influenced by changing $B_{\min}$.

The beam intensity of $\mathrm{Xe}^{20+}$ produced by RIKEN 18GHz ECRIS, VENUS and SECRAL at the operational microwave frequency of 18GHz were 300, 167[9] and 470eμA[10], respectively. The plasma chamber volume (~10L) of VENUS is larger than those of the other ion sources (RIKEN 18GHz (~1L), SECRAL (~5L)). Fig. 7 shows the beam intensity of $\mathrm{Xe}^{20+}$ as a function of average energy gain. The average energy gain is defined as bellow

$$\Delta W \sim \frac{W_{\mathrm{RF}}}{\left(\dfrac{\mathrm{d}B}{\mathrm{d}Z}\right)_{\mathrm{res}} V_{\mathrm{chamber}}}\,, \tag{2}$$

where $W_{\mathrm{RF}}$, $(\mathrm{d}B/\mathrm{d}Z)_{\mathrm{res}}$, and $V_{\mathrm{chamber}}$ are the input RF power, magnetic field gradient at resonance zone and plasma chamber volume, respectively.

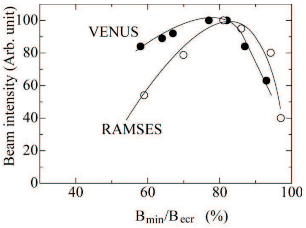

Fig. 5. Beam intensity of Xe ions produced by VENUS and RAMSES as a function of $B_{\min}$.

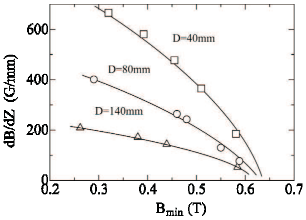

Fig. 6. Magnetic field gradient as a function of $B_{\min}$ for various plasma chamber diameters.

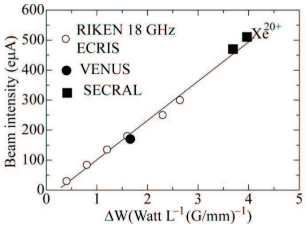

Fig. 7. Beam intensity produced by RIKEN 18GHz ECRIS, VENUS and SECRAL as a function of average energy gain at resonance zone.

## 3 RIKEN new ECRISs

Based on these experimental results, we are constructing new room temperature 18GHz ECRIS and making the detailed design of the 28GHz Sc-ECRIS to produce primary ion beams of 1pμA on target.

The new 18GHz ECRIS has an additional solenoid coils between two solenoid coils. Using this coil arrangement, we can change the $B_{\min}$ $B_{\mathrm{ext}}$ and $B_{\mathrm{inj}}$ independently to optimize the magnetic field gradient at the resonance zone. The maximum magnetic field strength of mirror field will be 1.4T. The radial magnetic field strength will be produced by hexapole magnet which consists of 36 segments of permanent magnets. The maximum magnetic field strength at the plasma chamber surface will be 1.2T. The chamber diameter is 80mm.

Figure 8 shows the schematic drawing and magnetic field strength of the superconducting ECR ion source which has an operational frequency of 28GHz. To obtain a larger resonance surface, we use a special geometrical arrangement of the solenoid coils (Flat $B_{\min}$ configuration) as shown in Fig. 8. Using this arrangement, we obtain the volume 3∼4 times larger than that for classical magnetic field configuration. A sextupole field is generated by six racetrack coils wounded around a pole piece. To obtain a good plasma confinement at 28GHz, we need a maximum mirror magnetic field strength of 4T and a radial field strength of 2T. Calculations using the three dimensional codes TOSCA were used to develop the superconducting magnet structure. The inner and outer diameters of solenoid coil 1 were 290 and 450mm, respectively. The estimated total stored energy was 300kJ under this condition. Using this coil arrangement as shown in Fig. 1, we can change $B_{\min}$ without changing maximum magnetic field ($B_{\text{ext}}$ and $B_{\text{inj}}$) independently to optimize the magnetic field gradient at the resonance zone.

The inner diameter and length of the plasma chamber are 15 and 50cm, respectively. The plasma chamber wall is made of Al to donate cold electrons to the plasma to decrease plasma potential. Note that Al is very resistant to plasma etching. This reduces contamination in the plasma of the ions from the wall. A biased electrode is installed to obtain the same effect as that of the Al chamber wall. The cooling of all surfaces in contact with the plasma using water minimizes the temperature effects caused by plasma and microwave heating at high microwave power. Detailed design is described in Ref. [11].

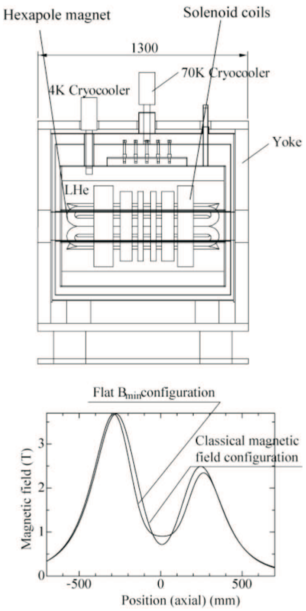

Fig. 8. Schematic drawing of the 28GHz SC-ECRIS (upper figure) and magnetic field strength at axial direction(lower figure).

The expected total current from the ion source is higher than 10mA. In this case, the normalized emittance of highly charged heavy ions is estimated to be 1$\pi$mm·mrad, which is mainly caused by the space charge effect[12]. Under this condition, we have to supply a very high extraction voltage (higher than 60kV) to obtain a good emittance (unnormarized emittance of ∼150$\pi$mm·mrad) for matching the acceptance of the RFQ linac. The ion source will be equipped with a movable accel-decel extraction system not only to improve the extraction conditions, but also to compensate for the space charge effect.

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