SC-ECRIS for RIKEN RI beam factory project

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To meet the required beam intensity of heavy ions (1 particle μA on target) for RIKEN RI beam factory project, we started to construct new RIKEN Superconducting ECR ion source which has an operational frequency of 28 GHz. In this contribution, we will present the conceptual design of the SC-ECRIS.

1 INTRODUCTION

To meet the required beam intensity of heavy ions (1 particle μA on target) for RIKEN RI beam factory project[1], we constructed several high performance 18 GHz ECR ion sources[2]. However, to achieve 1 particle μA of U ion beam at 350 MeV/u, higher than 15 particle μA of U^{35+} ion beam is required from an ion source, unless we use the first charge stripper. To produce such intense beam of U^{35+} ions, we have to use a higher magnetic mirror ratio and a higher microwave frequency (> 18 GHz) to increase the plasma density and the ion confinement time.

Last decade, we have intensively studied the effect of magnetic field configuration to increase the beam intensity. In this study, we 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[3].

Based on these studies, we designed the new SC-ECRIS which has an operational frequency of 28 GHz

In this paper, we report the effect of magnetic field configuration on the beam intensity and design of the new SC-ECRIS.

2 MAGNETIC FIELD CONFIGURATION

End of 1990's, we recognized that the high magnetic field strength gives us the intense beam of highly charged heavy ions (High-B mode operation). Based on it, many high performance ECR ion source was constructed and gave us the excellent results.

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} ($(B_{min})_{opt}$)exists to maximize the beam intensity and it is almost constant(0.7~0.9B_{ecr}), which is independent on the ion spices and charge state at moderate RF power (several 100 W). [3]

Figure 1 shows the beam intensity of O^{5+} ions produced form SHIVA, which has an operational frequency of 14 GHz, as a function of B_{min}. It is clearly seen that the beam intensity increased with increasing B_{min} and then gradually decreased.

Figure 2 shows the summary of $(B_{min})_{opt}$ for SHIVA (14GHz) and RAMSES(18GHz). As described previously, the value of $(B_{min})_{opt}$ was ~0.8B_{ecr}.

From these experimental results, we obtained the empirical formula for magnetic field strength of ECR ion source.

$$
\begin{aligned}
&B_{inj} \sim 4B_{ecr}\\
&B_{ext} < 2B_{ecr}\\
&B_r \sim 2B_{ecr}\\
&B_{min} \sim 0.8B_{ecr} \qquad (1)
\end{aligned}
$$

where B_{inj},B_{ext} and B_r are the maximum magnetic field strength of RF injection side, beam extraction side and maximum radial magnetic field strength. B_{min} is the minimum strength of mirror magnetic field.

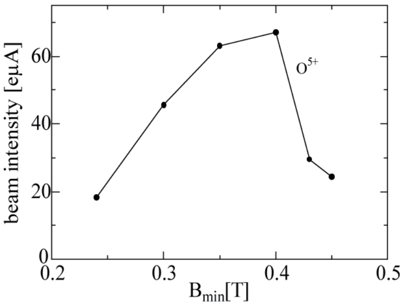

Fig.1 Beam intensity of O^{5+} as a function of B_{min}

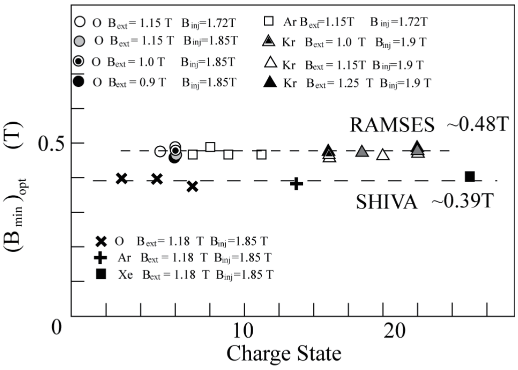

Figure 2. $(B_{min})_{opt}$ for various charge state heavy ions

To investigate the effect of B_{min}, we applied so-called laser ablation technique to obtain important plasma parameters (density of electron, temperature of electron and ion confinement time).[4] In these studies, we observed that the B_{min} strongly affect the density 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 these results, one can obtain the "effective" absorption power. Figure 1 shows the effective absorption power of liquid He-free SC-ECRIS SHIVA (operational RF frequency of 14 GHz) as a function of B_{min}. The effective absorption power increases with increasing B_{min} up to ~0.4T and then gradually decreases. At resonance zone, the average energy gain per pass is written as follows

$$\Delta W \sim \frac{\pi e^2 \left|\vec{E}\right|^2}{m_e v \omega \frac{1}{B_{res}} \left(\frac{dB}{dZ}\right)_{res}} \qquad (2)$$

where, E and dB/dZ are the electric and magnetic field gradient at the resonance zone. If we assume that the electron temperature is proportional to ΔW, the electron temperature increases with increasing the B_{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_{min}. The effective absorption power may decreases above certain B_{min} by the resonance size effect. This may be one of the reasons why "effective" absorption power becomes maximum at B_{min}~0.4T in case of the SHIVA

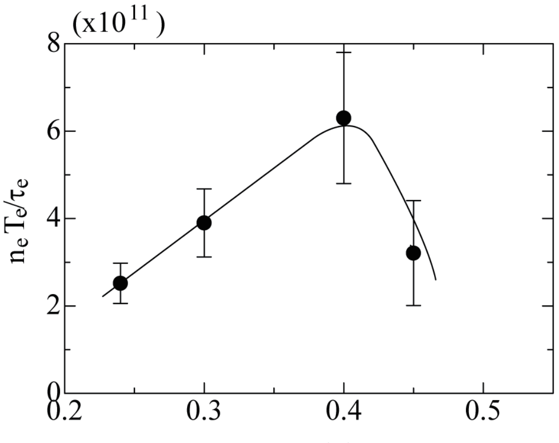

Fig.3. Effective absorption power as a function of B_{min}

The beam intensity of Xe^{20+} produced by RIKEN 18 GHz ECRIS[5], VENUS[6] and SECRAL[7] at the operational microwave frequency of 18 GHz were 300(RF power of 600W), 167(2000W) and 470eμA(3000W), respectively.

The plasma chamber volume (~10L) of VENUS is larger than those of the other ion sources (RIKEN 18 GHz (~1L), SECRAL (~5L)). Figure 4 shows the beam intensity of Xe^{20+} as a function of average energy gain defined by the eq.(1). From these experimental results, it is clearly seen that the power density of microwaves also plays important role to increase the beam intensity.

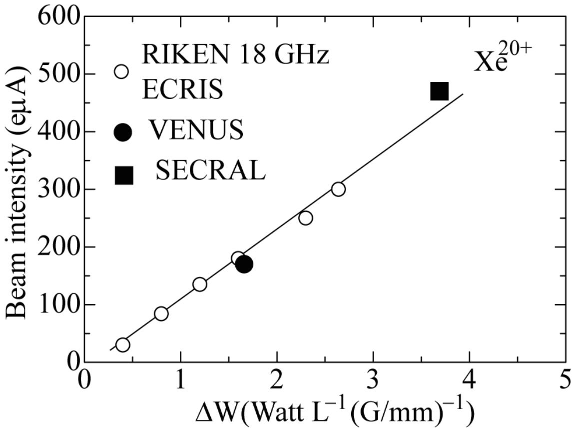

Fig.4 Beam intensity produced by RIKEN 18 GHz ECRIS, VENUS and SECRAL as a function of average energy gain at resonance zone.

According to this result, to increase the power density at the fixed input RF power, it is better to make a small plasma chamber. However, the ion confinement time is strongly dependent on the plasma chamber size(lager chamber gives longer confinement time) as shown in eq. (3)

$$\tau_q = 7.1x10^{-20} Lq \ln \Lambda \sqrt{A}\, \frac{n_e q_{eff}}{T_i^{3/2} E} \qquad (3)$$

, where L is the length of the plasma chamber. n_e,q_{eff}, T_{i} and E are the electron density, average charge state of heavy ions, ion temperature and electric field between plasma and plasma chamber, which is mainly due to the plasma potential. It means that we have to optimize the plasma chamber size and input RF power to maximize the beam intensity of U^{35+} ions

3. RIKEN NEW SC-ECRIS

Based on these experimental results, we made the detailed design of the 28 GHz Sc-ECRIS to produce primary ion beams of 1pμA on target.

Figure 5 shows the schematic drawing and magnetic field strength of the superconducting ECR ion source which has an operational frequency of 28 GHz. Detailed design of the super-conducting magnet is described in ref. 8. To obtain a larger resonance surface, we use a special geometrical arrangement of the solenoid coils (Flat B_{min} configuration) as shown in Fig.5. 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 28 GHz, 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 450 mm, respectively. The estimated total stored energy was 300 kJ under this condition. Using this coil arrangement as shown in Fig.1, we can change B_{min} without changing maximum magnetic field (B_{ext} and B_{inj}) independently to optimize the magnetic field gradient at the resonance zone.

As described in previous chapter, to produce highly charged heavy ions, we need lager plasma chamber volume. For this reason, we have chosen the inner diameter of 15 cm and length of the plasma chamber of 50 cm. The plasma chamber volume is 10 L, which is ten times lager than that of RIKEN 18 GHz ECRIS. To obtain high microwave power density, we will use 28GHz RF power supply which has maximum output power of 10 kW. Using this power supply, we can obtain the maximum power density of 1kW/L.

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.

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 πmm・mrad, which is mainly caused by the space charge effect.[9] Under this condition, we have to supply a very high extraction voltage (higher than 60 kV) to obtain a good emittance (unnormarized emittance of ~150πmm・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.

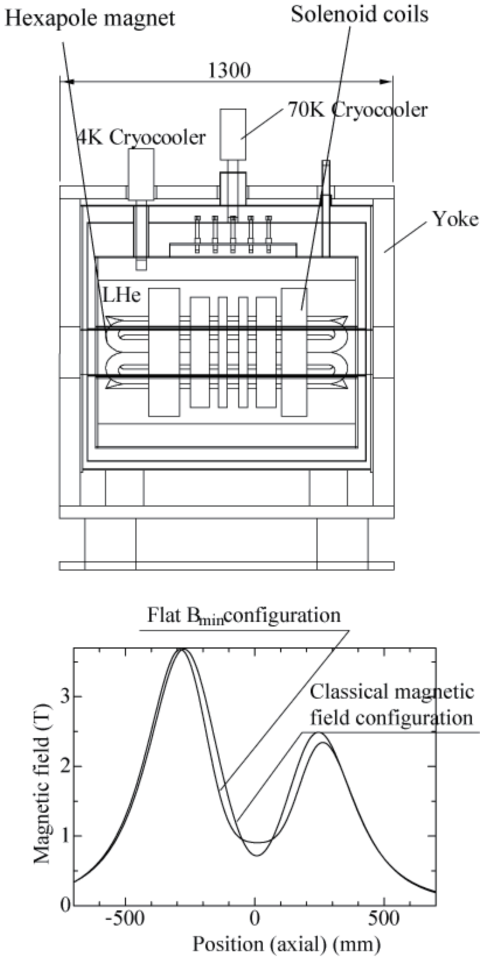

Fig.5 Schematic drawing of the 28GHz SC-ECRIS (upper figure) and magnetic field strength at axial direction(lower figure)

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