ECR ION SOURCES : A BRIEF HISTORY AND LOOK INTO THE NEXT GENERATION

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Abstract

In the last three decade, the performance of the electron cyclotron resonance ion sources (ECRIS) has dramatically improved. It is mainly due to the progress of understanding of the ECR plasma and technology of super-conducting and permanent magnet. Especially, the effect of key components of ECRIS (magnetic field configuration, gas pressure, microwave frequency etc) on the beam intensity and ECR plasma was gradually revealed in the last decade. Recently, the radio isotope beam (RIB) opened up the new field in the nuclear physics. Required beam intensity for next generation RIB factory and beta beam project is higher than those produced form present high performance ECR ion sources. Such requirement gives us the new motivation to improve the performance and to construct the new ECR ion sources. In this paper, the physics and technology of ECR ion sources will describe. Based on these results, we try to look into the next generation.

INTRODUCTION

ECR ion sources (ECRIS) are widely used for production of multiply charged heavy ion beams for accelerators, industrial applications. The development over last 30 years has provided remarkable improvement of the performance. For example, the beam intensity of Ar^{8+} increased from few ten μA to 2mA[1]. For long plasma confinement time, the ion source needs so called "minimum B" configuration, which consists of axial mirror magnetic field and radial multi-pole magnetic field, against plasma instabilities. The first ECRIS to produce multi-charged heavy ion beams were reported in early 1970's by Geller[2] and Wiesemann [3]. The structure of the present high performance ECRIS essentially same as the ion source built in 1970's. The improvement of the ion source performance on last three decades was mainly due to the understanding of the ECR plasma and use of modern technology (i.e., superconducting magnet, permanent magnet technology). Especially, in the last decade, we gradually revealed the effect of key components of the ECRIS (magnetic field configuration, gas pressure, chamber size) on the beam intensity and ECR plasma.

The interest in the radio isotope beam lead us to increase the beam intensity of highly charged heavy ions from ECR ion source for injecting into heavy ion driver accelerators. Such requirements give us the motivation to improve the performance and construct new generation ECRIS.

In this paper, we describe the physics and technology of the ECRIS at present stage. Based on these results, we try to look into the next generation.

PHYSICS OF ECR PLASMA

The ion confinement time, electron density and temperature are critical parameters in the ECRIS to produce intense beam of highly charged heavy ions. In ECR plasma, the main ionization process is the electron impact ionization, therefore it is necessary that the electron energy should be high enough to ionize the atoms to the desired charge state.(Electron temperature T_e). As step-by-step ionization is most efficient process for producing the highly charged heavy ions, it is necessary to keep the ions in the plasma for the time sufficient to reach the required charge state. (ion confinement time τ_c). To produce intense beam, it is important to obtain high density(electron density n_e). Figure 1 shows so called Golovanisvsky's Diagram.[4] For example, to produce Xe^{20+}, we need $n_e\tau_c$ ~10^9(cm^{-3}sec). However to produce higher charge state Xe ions, e.g. Xe^{27+}, $n_e\tau_c$ should be 10^{10}, which is one order magnitude higher than that of Xe^{20+}.

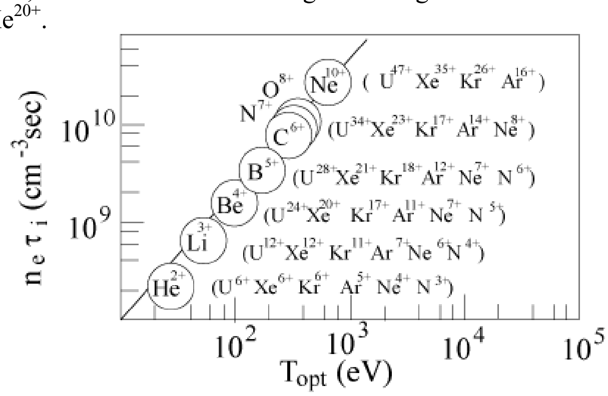

Figure: 1. Golvanisvsky diagram on ($n_e\tau_c$)T_e craiteria.

On the other hand, the beam intensity can be written as $I_q=(n_q qV/\tau_c)f_{ext.}$ (f_{ext}: efficiency of the beam extraction from the plasma at the extraction hole of the ion source). To maximize the beam intensity, we have to minimize τ_c, while keeping the $n_e\tau_c$=constant. Additionally, we have to maximize the f_{ext}. To make this condition, we have to control the ECR plasma by changing several key components of ECRIS.

The confinement criterion is satisfied by use of magnetic mirror confinement techniques. It is well known that the magnetic field strength and shape at the beam extraction side (B_{ext}) and injection side (B_{inj}) strongly influence the charge distribution and beam intensity. Figure 2 shows the beam intensities as a function of B_{inj} and B_{ext}. It is clearly seen that the beam intensity increases with increasing B_{inj} and B_{ext} and then saturated above certain values (B_{inj}>4B_{ecr}, B_{ext}>2B_{ecr}) (High B-mode operation) [5] Furthermore it is natural to think that minimum strength of mirror magnetic field (B_{min}) should influence to the beam intensity of heavy ions. Because the magnetic field configuration (or gradient of magnetic field) affects the plasma confinement and the effectiveness of the electron heating at resonance zone. Figure 3 shows the optimum $B_{min}((B_{min})_{opt})$ for maximizing the beam intensity for various heavy ions at the moderate RF power (~500W/L). It is clearly seen that the $(B_{min})_{opt}$ is almost constant and same as 0.7~0.8B_{min} [6]

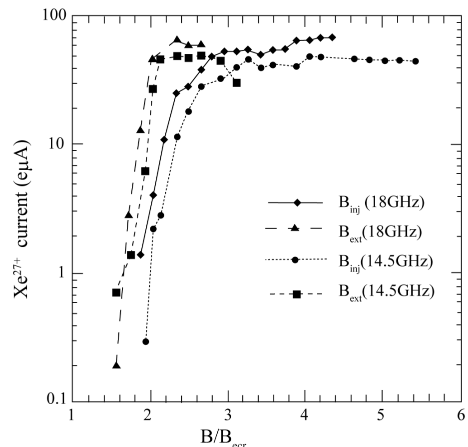

Figure: 2 Beam intensity of Xe^{27+} ion from SERSE as a function of B_{ext} and B_{inj}.

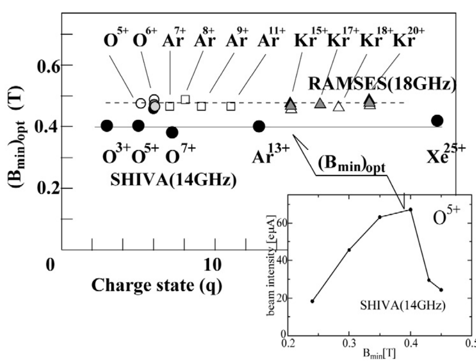

Figure 3: Optimum value for B_{min} for various heavy ions.

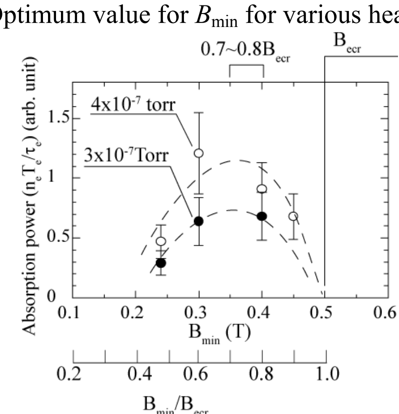

Figure 4: Plasma absorption power as a function of B_{min}.

Recently, the experiment by the injection of fluxes of metal atoms by laser ablation has been applied for the plasma diagnostics in ECRIS.[7]. Using laser ablation technique, one can obtain n_e, T_e, and τ_c simultaneously.[8] Figure 4 shows the absorption power (n_eT_e/τ_e) as a function of B_{min} for 14GHz ECRIS. In this calculation, we assumed that τ_e(electron confinement time) is equal to τ_c. The absorption power becomes maximum around B_{min}~0.7~ 0.8B_{ecr}. This is one of the reasons that the beam intensity of highly charged heavy ions became maximum at B_{min}~0.8B_{ecr}.

Figure 5 shows the $n_e\tau_c$ vs. T_e for various key parameters for 14 GHz ECRIS. In this figures, $n_e\tau_c$ and T_e increases with increasing B_{inj} and B_{ext}. It is mainly due to the plasma confinement by high magnetic mirror. It means that the change state of heavy ions in plasma increases with increasing B_{inj} and B_{ext}. On the other hand, Both $n_e\tau_c$ and T_e decrease with increasing the gas pressure. Simultaneously, we measured the beam intensity of $O^{3+,5+}$ (see fig.5 d). In this figure, dashed line is the calculated results of O^{3+} beam intensity by simple rate equations using the plasma parameters obtained in the laser ablation experiment. It is clearly seen in these figures that we need good vacuum to produce highly charged heavy ions. It is mainly due to the low $n_e\tau_c$ and T_e at high gas pressure.

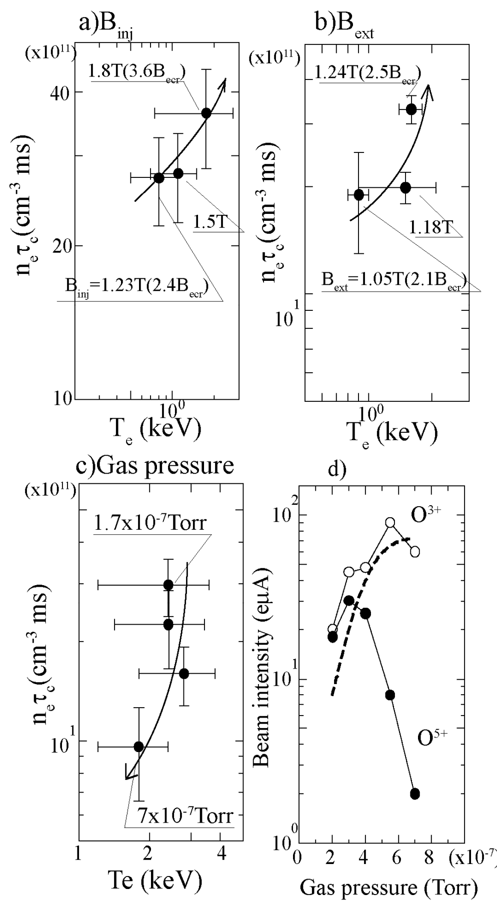

Figure 5: ($n_e\tau_c$) vs. T_e for several key parameters of ion source.

From these results, unfortunately, it is clear that we can not control the main plasma parameters, independently.

However, on the other hand, we have several key components to control these parameters as shown previously.

It was demonstrated that the ion confinement time linearly increases with increasing the charge state.[9] Therefore, we may conclude that the ambipolar diffusion is most probable mechanisms for ion transportation mechanisms. In this case, the ion confinement time increases with increasing the chamber size. For this reason, ECRISs which have bigger size plasma chamber can produce higher charge state of heavy ions.

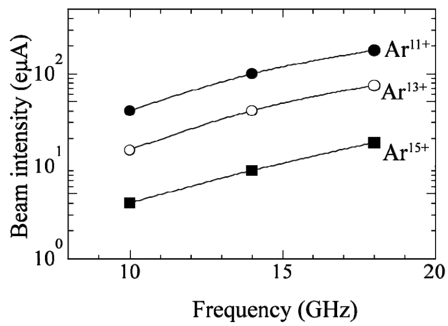

Figure 6: Effect of frequency on the beam intensity of multi-charged Ar ions.

Effect of the microwave frequency reported by several laboratories [10] and predicted by model calculation with Fokker-Planck equation[11]. The beam intensity increases with increasing the frequency, which is mainly due to the exposure time of electrons in ECR zone. Figure 6 shows the beam intensity of multi-charged Ar ions calculated by Fokker-Planck equation as a function of microwave frequency. [12]

TECHNOLOGY OF ION SOURCES

Figure 7 shows the optimum magnetic field strength of B_{inj}, B_{ext} and B_{min} as a function of microwave frequency and several high performance ECRISs. In this figure the bold faces indicated the ECRIS with fully superconducting magnet. The magnetic field of ECR ion source with 6~10GHz microwave frequency was supplied with room temperature solenoid coils and paramagnet hexapole magnet (Sm-Co) (Hybrid type ECRIS). The almost all ECRISs with microwave frequency higher than 14GHz consist with room temperature solenoid coils and stronger hexapole magnet made of Nd-B-Fe. Main progress in this frequency region is due to the progress of permanent magnet technology. The strongest permanent magnet hexapoles (Nd-B-Fe) has about 1.5T at the pole surface. At inner wall plasma chamber, the strength is ~1.2T. For this reason, the limited frequency for this type ECRIS is ~18GHz. To minimize the electric power consumption, superconducting solenoid coils with small G-M refrigerator was used instead of room temperature solenoid coils in several laboratories. (so-called Liquid He-free SC-ECRIS)[13]

The all permanent magnet ECRISs have low electric power consumption. The performance is strongly dependent on the permanent magnet technology. Figure 8 shows the beam intensity as a function of maximum magnetic field strength. The performance is limited by the axial magnetic field strength. Because we need large size of permanent magnet to obtain high axial field. The most advanced all-permanent ECRIS has same performance as the hybrid type ECRIS with 14 GHz.[14]

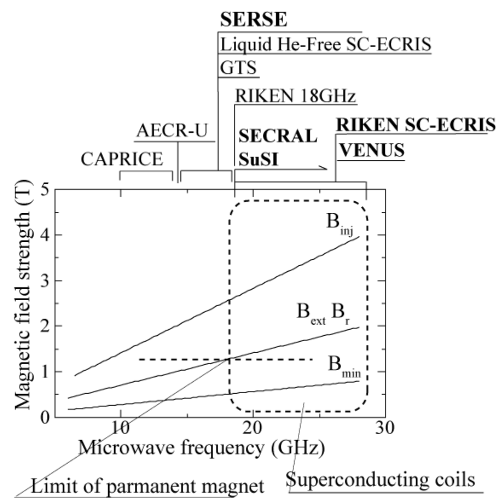

Figure 7: Optimum magnetic field strength as a function of frequency.

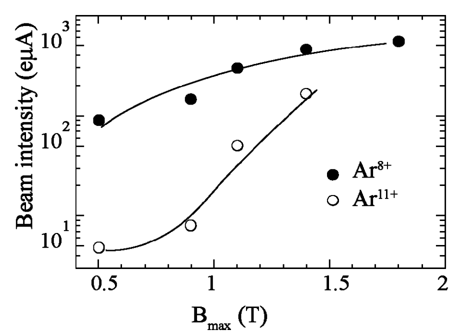

Figure 8: Beam intensity of all permanent magnet ECRISs as a function of maximum magnetic field.

Above 18GHz, it is difficult to provide optimum magnetic field strength with room temperature solenoid coils and permanent magnet as shown in Fig. 8. This limitation leads us to use superconducting magnet technology. In this frequency region, the most advanced ECR ion sources at present are VENUS [15] at LBL and SECRAL [16] at Lanzhou. The VENUS serves as a prototype ion source for FRIB front end. The axial magnetic fields are 4T at injection and 3T at extraction. Radial magnetic field strength is 2T at inner surface of plasma chamber. Figure 9 shows the beam intensity of U ion beam for several high performance ECRISs. It is clearly seen that the beam intensity is drastically increased with increasing the microwave frequency from

10 GHz to 28GHz. The beam intensity of highly charged U ion form AECR-U[17] is much higher than that from Caprice 14.5GHz [9]. It may be du to the magnetic field strength and plasma chamber size. The VENUS is the first ECR ion source to operate with optimum magnetic field strength for 28GHz. It can produce 220~170eμA of $U^{33+\sim35+}$, which is required beam intensity of FRIB.

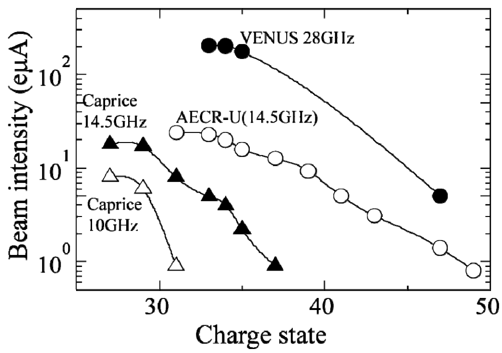

Figure 9: Beam intensity of multi-charged U ions from several high performance ECRIS.

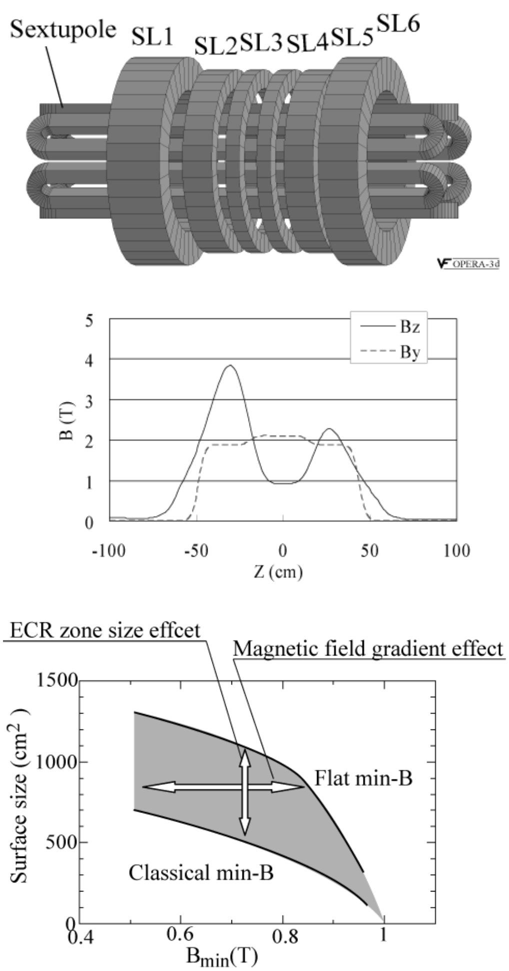

Figure 10: Coil arrangement of RIKEN SC-ECRIS, magnetic field strength, and ECR zone size vs. B_{min}.

For RIBF in RIKEN, new SC-ECRIS has been constructed.[18] It has a six solenoid coils for producing mirror magnetic field at axial direction. Inserting several middle coils is advantageous as it can give the flexible magnetic field to change the field gradient at resonance zone and increase the ECR zone size. The coil configuration is shown in Fig. 9. B_{inj}, B_{ext}, B_r are 3.8, 2.2 and 2.2 T respectively. Figure 10 shows the resonance zone size vs. B_{min}. Using this magnet arrangement, we can change field gradient and resonance zone size, independently.

In the last decade, small size gyrotron have become available for producing 20~28GHz microwaves. Beginning of 2000's, SERSE in Catania was tested with 28GHz gyrotron [19]. The same one was used for PHENIX in Grenoble under pulsed mode operation.[20] In 2006, VENUS successfully produced intense beam of highly charged heavy ions with 28GHz microwave.

NEXT GENERATION

In the last decade, the almost all the new ECRISs with higher microwave frequency (>18GHz) have been construct for the heavy ion driver accelerators of RIBF. These projects need more intensity of highly charged heavy ions than that produced from present high performance ECR ion sources. For example, the goal of RIKEN RIBF is to produce more than 15pμA of U^{35+} from ECRIS for production of 1pμA U ion beam on target at 345 MeV/u. Such requirement leads us to construct new ECRISs.

To increase the beam intensity of highly charged heavy ions, the straightforward way is to increase the microwave frequency as clearly shown in the previous section. To use higher frequency, we also have to increase the magnetic field strength. For example, it is needed that the maximum magnetic field at axial and radial direction for 36GHz are 5.2 and 2.6T, respectively. In this case, one of the most critical requirements is to develop the superconducting magnet system in high magnetic field. To avoid quenching, the magnet design must keep the superconducting wire current below the critical current (Ic). It is strongly dependent on the type of the superconducting wire. Figure 5 shows the Ic performance of the conductor with a rectangular shape(0.85mm x 1.15mm, Cu/NbTi ratio is 1.3) and the load points for the solenoid SL1 and the hexapole for RIKEN SC-ECRIS. Although the maximum field on the hexapole coil windings is 7.4 T, the component perpendicular to the current direction is 6.5 T. For 36GHz operation, the load point for the hexapole magnet exceeds the critical current of the wire as shown in Fig. 10. To solve this problem, we have to use new material (Nb_3Sn) instead of NbTi or NbTi wire at lower temperature (<4.2K) to increase the critical current.

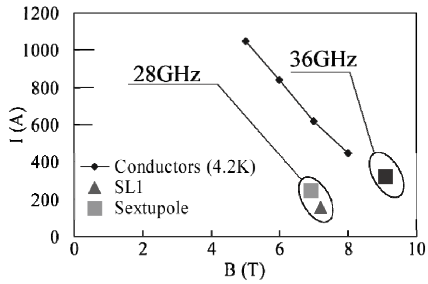

Figure 11: Ic performance of the super-conducting wire and load points for solenoid coil (SL1) and hexapole magnet.

Recently, x-ray emission from the ECR plasma of VENUS was measured under the various conditions. [21] It was reported that the energy of x-ray increased with increasing the microwave frequency.[21] The high energetic x-ray (> several 100 keV) can penetrate easily through plasma chamber wall and wall of cryostat. For example, even 2mm thick Ta sheet was inserted between plasma chamber and cryostat, Heat load from x-ray was about 1W/kW at 4.2K when a B_{min}/B_{ecr} ratio of 0.7 was used. It means that the heat load will be 10W at 10kW power injection. The new RIKEN SC-ECRIS will have two 5W JT-GM refrigerators to cool the coils against the heat load. However, it is obvious that the higher frequency microwave gives higher heat load. For this reason, solving the heat load problems is one of the key issue to construct next generation ECRIS.

While one of the straightforward ways is to increase the frequency and magnetic field strength, we have possibilities with the other approaches.

We still have the open question for the limitation of injecting microwave power into the plasma chamber. ECR heating is well suited for confinement of high energy electron population. As perpendicular energy is given to the electrons, the heated electrons are kept in the plasma by magnetic mirror. The collisions with ions sometimes give the large parallel velocity to the electrons and losses of electrons into the loss cone. Therefore, the high neutral gas pressure gives short electron confinement. However, at high energy, the electric field by microwaves push electrons into the loss cone and enhancing the electron loss. This mechanism limits the maximum energy of electron in the plasma. The model calculation with Fokker-Planck equation predicts such limitation.[22] Experimentally, the limitation of the injected microwave power is not clear yet. For example, the beam intensity from AECR-U was not saturated when injecting the power of 2.5kW/L. Most advanced SC-ECRISs(VENUS, SECRAL, RIKEN SC-ECRIS) have large chamber volume (5~10L). Even if we inject 10kW microwave power into these ECRISs, the power density is 1~2kW/L, which is lower than that for AECR-U. Actually, it was reported that the beam intensity of VENUS was not saturated at the 9kW (1kW/L). It means that we may have possibility to increase the beam intensity with present ECRIS to meet the requirements. All models are based on the stable plasma without including the plasma instability. However, the actual plasma in ECRIS has some instability as reported in ref. [23]. It may be the additional limitation to increase the beam intensity. To minimizing the construction cost of ECRIS, it is important to clarify these limitations. ECRIS performance is still improving. A part of the mechanisms for production of heavy ions from ECRIS was understood. The important points to be solved for improving the performance (limitation of injected RF power etc) are still remained. 28GHz ECRIS with fully superconducting magnet is now available. However, performance next generation ECRIS is strongly dependent on the development of sophisticated technology, such as superconductivity and cryogenics. ECRISs remain an interesting subject for ion source engineers and scientists and we still have room for innovation.

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