

LARGE BORE ECR ION SOURCE WITH CYLINDRICALLY COMB-SHAPED MAGNETIC FIELDS CONFIGURATION

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Abstract

Electron Cyclotron Resonance Ion Sources (ECRIS) have been developed for long time and performances are still extended at present. Recently, they are not only used in producing multi-charged ions, but also molecules and cluster ions. A new type of ion source with a wide operation window is expected for various uses. We developed a novel magnetic field configuration ECRIS. The magnetic field configuration is constructed by a pair of comb-shaped magnetic field by all permanent magnets and has opposite polarity each other with ring-magnets. This magnetic configuration suppresses the loss due to $E \times B$ drift, and then plasma confinement is enhanced. We conduct preliminary extracting and forming large bore ion beam from this source. We will make this source a part of tandem type ion source for the first stage. Broad ion beams extracted from the first stage are transferred like a shower to the plasma generated by the second stage. We hope to realize a device which has a very wide range operation window in a single device to produce many kinds of ion beams. We try to control plasma parameters by multiply frequency microwaves for broad ion beam extraction. It is found that plasma and beam can be controllable on spatial profiles beyond wide operation window of plasma parameters. We investigated feasibility of the device which has wide range operation window in a single device to produce many kinds of ion beams as like universal source based on ECRIS.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) have developed with time [1, 2]. Nowadays the ECRIS is used not only in atomic physics and semi-conductors but also with a wide variety of applications. For example, they are applied to heavy ion cancer therapy [3], investigation for discovery of new elements, and super-heavy nucleus science [4], and so on. Recently, the ion sources are not only used in producing multi-charged ions, but also cluster ions, iron encapsulated fullerenes which are important in the field of bio-nano technology [5]. A new type of ion source with a wide operation window is expected for various uses. We are planning to build the device which gives these required performance features in a single apparatus.

We developed a novel magnetic field configuration ECRIS. The magnetic field configuration is constructed by a pair of comb-shaped magnetic field by all permanent magnets and has opposite polarity each other with ring-magnets. The comb-shaped magnet cylindrically

surrounds the plasma chamber. This magnetic configuration suppresses the loss due to $E \times B$ drift, and then plasma confinement is enhanced. We tried many experiments by this ECRIS [6-8]. We will make this source a part of tandem type ion source for the first stage. We conduct preliminary extracting and forming large bore ion beam from this source [9]. Extraction broad-ion-beam from the first stage plasma are transferred like a shower to the plasma generated by second stage ECRIS. We hope to realize a device which has a very wide range operation window in a single device to produce many kind of ion beams, *e.g.*, from multi-charged ion to cluster ion, nano-tube, fullerenes, including impurities trapping, etc, as a universal source.

In this paper, we try to control plasma parameters and their profiles in an unused way, *i.e.*, by feeding simultaneously 2.45 GHz and 11 to 13 GHz frequency microwaves for broad ion beam from the first stage.

EXPERIMENTAL DEVICE

Outline of Experimental Device

The top view and the side view of the large bore ECRIS as the first stage of tandem ECRIS is shown in Fig. 1. The base pressure is about 10^{-5} Pa. Two frequencies microwaves are supplied to the plasma chamber (200 mm in diameter and 320 mm in length) with the cylindrically comb-shaped magnetic fields. 2.45 GHz microwaves generated by magnetron (max. power: 1.3 kW) are transformed from the waveguide mode to the coaxial mode, and launched to the chamber along z -axis by L-shaped semi-dipole antenna. 11 to 13 GHz microwaves amplified by travelling-wave transformer amplifier (TWTA, max. power: 350 W) from the synthesizer are directly fed to the chamber beyond a quartz window along to z -axis. Incident and reflected microwaves are tuned by the stainless steel meshed plate for the 11 to 13 GHz microwaves. The 2.45 GHz microwaves are tuned by the three stub tuner. The operating pressure is about $10^{-1 \sim -3}$ Pa. The plasma parameters are measured by a Langmuir probe. The measurement position ranges vertically from the chamber wall ($y=100$ mm) to the center of the chamber ($y=0$ mm). Ion beam is preliminarily extracted from this source by the large bore extractor consisting of three electrode plates with multiple holes, and measured by the Faraday cup (20 mm in diameter and 37 mm in length) located at $z=360$ mm, 263 mm apart from the electrode. The position and gap length of these electrodes are not yet optimized, and are now under investigation [9].

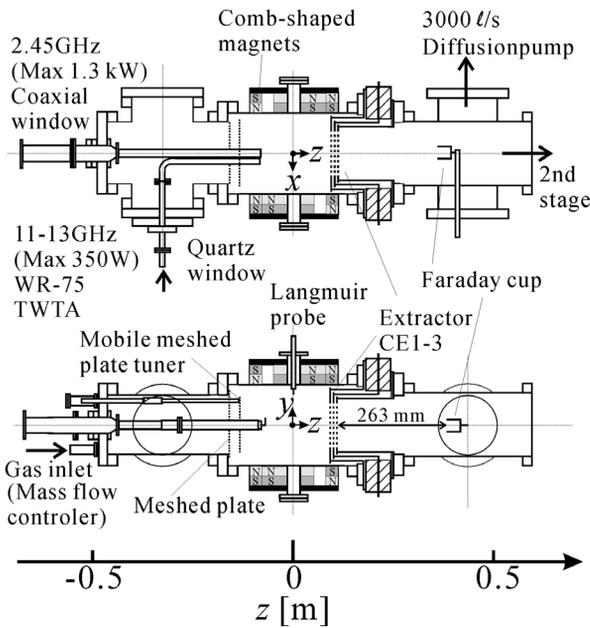


Figure 1: Top and side views of the large bore ECRIS as the first stage of tandem ECRIS.

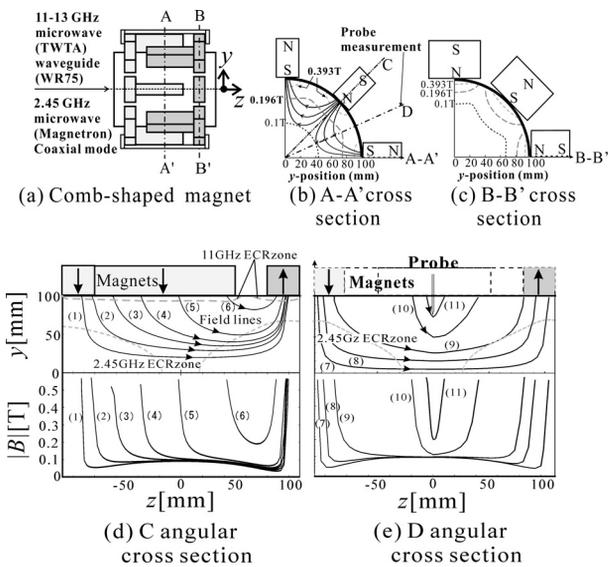


Figure 2: Side view of cylindrically comb-shaped magnets (a). Contour plots of field strength and field lines in A-A' (b) and B-B' cross sections (c), respectively; those in radial-z direction at C (d) and D angular (e).

Configuration of Magnetic Field

Fig. 2 (a) shows side view of the cylindrically comb-shaped magnets surrounding the chamber, *i.e.* octupole magnets with a pair of ring magnets with opposite polarity. Fig. 2 (b) and (c) show contour plot and line forces in the cross section A-A' and B-B' indicated in Fig. 2 (a). The upper figures of Fig. 2 (d) and (e) depict contour plots and field lines in the radial and z direction cross section at the positions indicated by C and D angular cross section in Fig. 2 (b). The field lines in Fig. 2 (e) indicate their projections to the plane. The lower

figures denotes field strength along the field line labelled by (1)~(11) corresponding to the upper field lines. The positions of resonance zones for 11 GHz microwaves are formed around peripheral region nearby the chamber wall. Those for 2.45 GHz are formed around the center of the chamber, but vanish at the center cross section. The probe measurement conducted along D angular cross section is indicated in Fig. 2 (b).

EXPERIMENTAL RESULTS AND DISCUSSION

By using 2.45 and 11 to 13 GHz microwaves individually, we can conduct experiments for production of ECR plasma and extraction of ion beams. First of all we investigate profiles of plasma parameters and characteristics in feeding each single frequency microwave to the ECRIS. Then we introduce simultaneously two frequency microwaves, measure the profiles, survey the experimental conditions, and confirm the effect of feeding multi-frequencies microwaves on the ECRIS plasma. We conduct preliminary ion beam extraction.

ECR Ion Source Plasma Characteristics in Single Frequency Microwave (11 to 13 GHz)

Fig. 3 shows the experimental results obtained by 11 GHz frequency microwaves. The upper and lower figures depict profiles of the electron density n_e and the electron temperature T_e . The left and right side figures are the cases of microwave power 100 W at 0.03 Pa and 0.016 Pa, and those of pressure 0.03 Pa at microwave powers 100 and 200 W, respectively. Each horizontal axis indicates y directions, where $y=0$ and $y=100$ mm means the center and the inner wall of the chamber. The peak positions of n_e and T_e are observed around the second harmonics resonance zone at $y=80$ mm [8]. These tendencies, *i.e.* peaking in peripheral regions, are caused from the peripheral formations of the fundamental and the second harmonic resonance zones, and are largely-unaltered by variation of microwave powers and pressures.

ECR Ion Source Plasma Characteristics in Single Frequency Microwave (2.45 GHz)

The experimental results obtained by 2.45 GHz frequency microwaves are shown in Fig. 4. The upper and lower figures depict profiles of n_e and T_e . The left and right side figures are the cases of microwave power 200 W at 0.03 Pa and 0.016 Pa, and those of pressure 0.03 Pa at microwave powers 200 and 300 W, respectively. Horizontal axes are the same of Fig. 3. It is found that n_e attains and crosses the cut-off density depicted by dotted lines in Fig. 4 for 2.45 GHz under low microwave powers. The peak positions are observed around the center at $y=0$ mm in contradiction to the case of 11 GHz microwaves. While these facts are the result of the construction of the ECR zone for 2.45 GHz frequency microwaves around the center, these tendencies are also largely unaltered by variation of microwave powers and pressures. It is

considered that the profile controlled by single microwave frequency in fixed magnetic field consisting only of permanent magnets is limited within operating pressure and microwave powers.

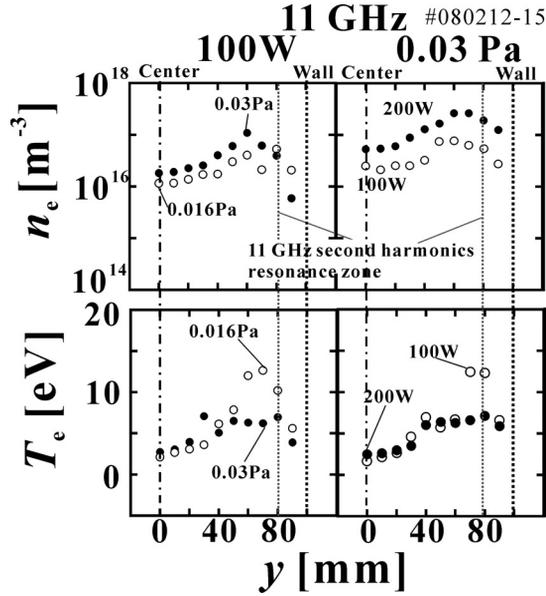


Figure 3: Profiles of n_e and T_e at the center in the cylindrically comb-shaped magnetic field ECRIS in the case of microwave frequency 11 to 13 GHz.

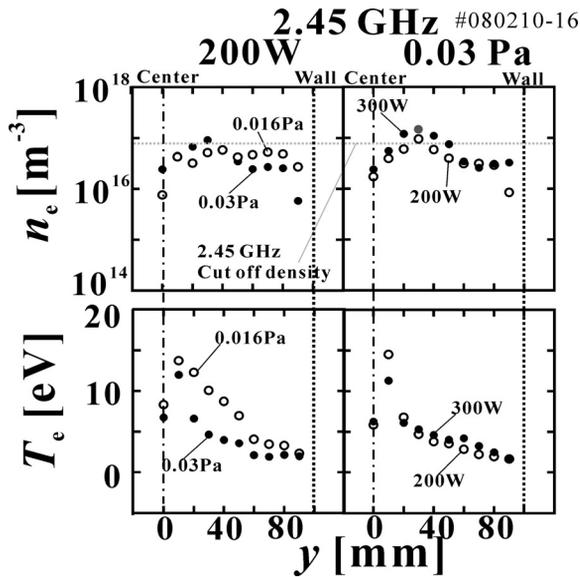


Figure 4: Profiles of n_e and T_e at the center in the cylindrically comb-shaped magnetic field ECRIS in the case of microwave frequency 2.45 GHz.

Efficiency of Comb-Shaped Magnets and Dependence of n_e on Microwave Power

In our experimental procedures, first of all we produced ECR plasma by using simple multipole (octupole) magnets, and measured its plasma parameters briefly. After then we reconstructed them to comb-shaped

magnets and produced ECR plasma in the same experimental conditions except them [6]. We measured the n_e around their peak position ($r=60$ mm) in the case of 11-13 GHz frequency microwaves, and measured the dependences of the n_e on microwave power and frequency at high pressure (0.3 Pa).

Fig. 5 shows dependence of electron density on microwave powers. Solid lines and dotted lines indicate the case of comb-shaped and that of the simple multipole magnets. It is found clearly that n_e increased in the case of comb-shaped magnets with respect to that in the simple multipole magnets, and that the confinement was improved by constructing comb-shaped magnets. Under the maximum power of the TWTA, the saturation of n_e does not appear yet. When the frequency increased, n_e increased. Furthermore we obtained a 10^{18} m^{-3} density by using 13 GHz frequency microwaves at high pressure (1 Pa) at rather low microwave powers (350 W).

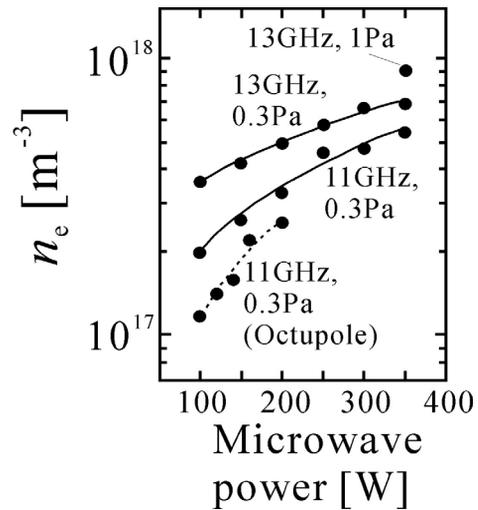


Figure 5: Dependence of n_e on microwave powers, and comparison between simple multipole and comb-shaped magnets.

Profile Controlling by Multi-Frequencies Microwaves

Next we tried to control the n_e and the T_e profiles by feeding simultaneously three microwave frequencies, *i.e.* 11 to 13 GHz and 2.45 GHz. Our experimental procedure is the following: we launch the 2.45 GHz microwaves into the chamber flowing Ar operating gas, ignite, and then sustain the ECR discharge. We superimpose 11 to 13 GHz microwaves to this initial ECR plasma, *i.e.* simultaneous two frequencies microwaves operations. The appearance from the viewing port obviously changes to be more luminous in contrast to the case of single 2.45 GHz frequency microwaves. Finally we turn off 2.45 GHz microwave and hold the ECR plasma by only 11 to 13 GHz microwaves. We recognized the difference in plasma emissions in each case of single 2.45 GHz and 11 to 13 GHz. We conducted measurements of the n_e and the T_e profiles in these steps.

Fig. 6 shows the typical n_e and T_e profiles obtained by these experimental results. The operating pressure is 0.03 Pa. The microwave powers are 200 W and 100 W for 2.45 GHz and 11 GHz, respectively. Fig. 6 (a) shows the peaking profiles around the center and periphery regions for the 2.45 GHz (open circles) and the 11 GHz (open squares) lined by gray lines, respectively. On the other hand, we obtain the flat profiles by launching simultaneous multi-frequencies microwaves as shown by closed circles and solid lines in Fig. 6 (a). The n_e profile can be controlled by varying each frequency microwave power. Fig. 6 (b) shows the T_e profiles corresponding to the n_e profiles as shown in Fig. 6 (a). The T_e profiles has basically the similar tendency to the case of the n_e , but flattening the T_e peaking is a little harder than that of the n_e at the low pressure. The T_e profile can be also controlled by varying each frequency microwave power.

The cylindrically comb-shaped magnetic field configurations are easy to scale up to larger size by selecting the number of multipole and the strength of the ring-like magnets. The disadvantages of fixed magnetic configuration of ECR zone, operation and controllability of the profiles are redeemed by frequency-controllable TWTA, and moreover simultaneously feeding largely different frequency microwaves, as in our experimental results.

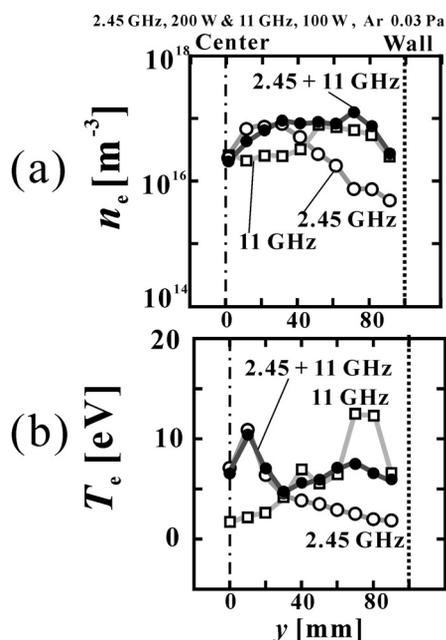


Figure 6: n_e and T_e profiles in the cases of each single and multi-frequencies microwaves.

Preliminary Ion Beam Extractions from ECRIS with Comb-Shaped Magnetic Field

We conduct preliminary ion beam extraction from the cylindrically comb-shaped magnetic field configuration ECR ion source [9]. At present, we are optimizing extraction conditions of ion beams, *i.e.* the position, the gap length, the shape of multi-holes extractor. We are

investigating the effect of multi-frequencies of microwaves to the ion beams. At present we obtain also different profile ion beams and find a way to control spatial profiles of broad ion beams by these multi-frequencies microwaves; moreover, we are optimizing the ion beam extraction.

FUTURE PLANNING

Construction of Tandem Type ECRIS

We will make this ECRIS consisting of all comb-shaped magnets a part of tandem type ion source for the first stage. Large bore extractor set at the end of this source and extracted broad ion beams under low voltages to the second stage, like shower of ions, are needed. The second stage will also be large bore and ECRIS with long length along the z axis, individually operated by 2.45 GHz microwaves. The magnetic field configuration consists of octupole magnets and a mirror field made of 2 coils and a supplemental coil. At the end plate of the second stage we set the single hole extractor, and set beam lines for handling and analysis of ion charges state distributions.

We investigated feasibility and hope to realize the device which has a wide range operation window in a single device with tandem-type ion source based on ECR to produce many kinds of ion beams from multiply charged, to molecular, cluster ions, nano-tube, fullerenes, including impurities trapping, etc, aiming at a universal source based on ECRIS.

This tandem type ion source and ancillary equipments are now in construction. In the second stage, preliminary plasma production and the extraction have already been conducted under the limited low magnetic mirror field.

Large Bore Ion Extractions

Large bore extractor consisting of three electrodes is set at the opposite side against the microwaves feeds between the first stage and the second stage of the tandem-type ECRIS. We need to optimize the extractor position, the gap length and the shape of electrodes. The profiles of the extracted ion beams are measured by a Faraday cup downstream the extractor.

We will conduct the profile control of these broad ion beams by multiplex frequencies microwaves, and will investigate effects of ion streams from the first stage to the second stage plasma and the ion beams and the charges state distributions from the second stage.

Further Enlarged Operation Window by Pulse Modulated Microwave Feeding

Effects of after glow mode were well-known on conventional ECRIS's for production of multicharged ions and have been conducted in almost all ECRIS's in the world [10-12]. In a first stage, we tried to feed pulse-modulated microwaves to the ECRIS in order to enlarge operation windows for ECR plasma production, and then also to enhance ion beam current adding the after glow mode. Under the constraint of the same time-average

incident microwave, typical duration of pulse mode microwave operations and duty ratios are 50-500 μs and 30-80%, respectively. The maximum currents are obtained in the cases of 100-200 μs duration at 50% duty ratio. It is found that the total beam currents are enlarged by pulse mode operations.

The profiles of n_e and T_e are measured in both cases of CW and pulse mode. It is found that differences of their profiles also appear similar to ion beam profiles. It is found that the peak value of n_e in the pulse mode is larger than that in the CW mode, and that T_e in the pulse mode has tendency to be lower than that in the CW mode operations. These indirect evidences cause to enhance ion beams in the pulse mode operation, and then suggest a spread of operation windows for plasma parameters suitable to production of molecular or cluster ions. At present we are measuring time-dependent behaviors of the n_e and the T_e .

The pulse-modulated microwave operation is one of the powerful candidates to enlarge the operation window of the ECRIS, as well as availability of controlling microwave frequencies by TWTA on magnetic configurations fixed by all magnets.

We will be able to operate also 2.45 GHz frequency microwaves in the second stage by similar pulse-mode launching.

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