NEW DUAL-TYPE ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR A UNIVERSAL SOURCE OF SYNTHESIZED ION BEAMS*

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Abstract

A new dual-type source has been constructing on the basis of electron cyclotron resonance (ECR) plasma for producing synthesized ion beams in Osaka Univ. Magnetic field in the 1st stage consists of all permanent magnets, *i.e.*, cylindrically comb shaped one, and that of the 2nd stage consists of a pair of mirror coil, a supplemental coil and the octupole magnets. Both stage plasmas can be individually operated, and produced ions which energy controlled by large bore extractor also can be transported from the 1st to the 2nd stage. Fundamental operations and effects of this source, and analysis of ion beams and investigation of plasma parameters are conducted on produced plasmas in dual plasmas operation as well as each single operation.

INTRODUCTION

A new concept on magnetic field of plasma production and confinement has been proposed to enhance efficiency of an electron cyclotron resonance (ECR) plasma for broad and dense ion beam source under the low pressure [1]. We make this source a part of new dual-type ion source for the 1st stage. We are also constructing the large bore 2nd stage for synthesizing ions, extraction and beam analysis [2]. We investigate feasibility and hope to realize the device which has wide range operation window in a single device to produce many kinds of ion beams, *e.g.*, from multiply charged, to molecular, cluster ions, nanotube, fullerenes, including impurities trapped as iron-endohedral fullerene, *etc.*, as like to universal source based on ECR ion source (ECRIS). We consider to being necessary to device that is available to individual operations with different plasma parameters, and then obtain concept of dual ECRIS from relevant previous works.

EXPERIMENTAL APPARATUS

The top view of the dual-type ECRIS and the beam line for the ion extraction and the analysis are shown in Fig.1. The 1st stage of the device is large-bore one using cylindrically comb-shaped permanent magnets, *i.e.* octupole magnets with a pair of ring magnets whose polarity is opposite each other [3-5]. Two frequencies microwaves are supplied to the plasma chamber (200mm in diameter and 320mm in length) [6]. Incident and reflected microwaves are tuned by the stainless steel/aluminum plate tuner. We are investigating positional dependence of this tuner to ion beam currents and plasma parameters in detail [7].

Ion produced in the 1st stage is extracted and transferred to the 2nd stage by the large bore extractor consisted of three electrode plates CE1-3 (V_{CE1-3}) with multi-holes (200 holes of 8mm in diameter) and the effective diameter 154mm, and the ion beam current $I_{FCx,y}$ is measured by two faraday cups. The typical extraction voltages range within about 1.0kV.

The magnetic configuration of the 2nd stage is mirror field formed by the coil A, B, and C, and superimposed the octupole magnetic field by permanent magnets [8]. The ECRIS performance is very sensitive to shape, intensity, and gradient nearby the ECR zone around bottom of mirror field, and we are available to control them precisely by the coil C [8]. The plasma chamber of the 2nd stage is about 160mm in diameter and 1000mm in length. 2.45 GHz microwaves are launched by the Ti rod antenna from the side wall. The single aperture extractor assembly is set at the mirror end plate with the aluminium plate for the microwave mode. The extractor consists of three electrodes, *i.e.*, the plasma electrode PE, the mid-electrode E1, and the extractor electrode E2. The typical extraction voltage (V_{PE}) and the extractor voltage (V_{E2}) are usually 10kV and the ground, respectively. The mid-electrode voltage (V_{E1}) is used on optimizing extraction of each ion species. We also install the ion-beam irradiation system (IBIS) in the downstream beam line for beam profiles, emittance measurements, and various beam-material applications.

In the both stages, plasma parameters and pressures are measured by Langmuir probe and Bayard-Alpert (B-A) gauges. The electron density n_e and the temperature T_e are measured from the probe current I_p and voltage V_p characteristics. We have also estimated electron energy distribution function (EEDF) from these probe data [9].

We confirmed that the ion beam is flowed from the 1st to the 2nd stage. From the result, we can become possible to conduct experiment at least on the dual-type ECRIS.

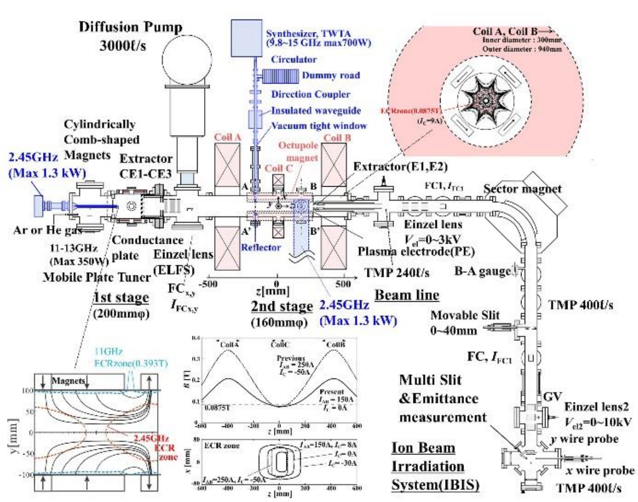

Figure 1: Schematic drawing of the top view of the new dual-type ECRIS (Osaka Univ.).

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EXPERIMENTAL RESULTS AND DISCUSSIONS

Typical Experimental Results on the 1st Stage

Beam current profile control by multi-frequency microwaves We have investigated the effect of launching multi-frequencies microwaves to ECRIS plasma on constructing ion beams. In the 1st stage, 2.45 GHz and 11–13 GHz microwaves can be supplied to plasma chamber individually and simultaneously. The resonance zones of 2.45 GHz and 11–13 GHz microwaves are located at the center and the peripheral regions of the chamber, respectively. It has been found that controlling beam profiles is available by feeding multi-frequencies microwaves and adjusting their powers to the ECRIS [6].

Beam current optimization with mobile plate tuner position The $I_{FCx,y}$ from the 1st stage and ion saturation current I_{is} in the 1st stage plasma oscillate with respect to the position of the mobile plate tuner. It is clear that the $I_{FCx,y}$ coincides reproducibly with the I_{is} in both cases of multi-frequency and each single frequency. The variation level and the number of peaks in 11 GHz are larger than those of 2.45 GHz [7].

Selective microwave modes excitation for efficient ECR It is known the beam current is affected by the position of the mobile plate tuner in the vacuum chamber as like a circular cavity resonator. The $I_{FCx,y}$ and the I_{is} change periodically in moving the position of the mobile plate tuner. For each microwave mode TE_{nm}, we analyse the electric field distribution and the microwave power absorbed by electrons per unit area S_{nm}. We obtain that a new guiding principle for the number of efficient microwave mode is selected to fit to that of the multipole number of the comb-shaped magnet for 11 and 2.45 GHz We made a new mobile plate tuner from the theoretical analysis. We measured the $I_{FCx,y}$ and the I_{is} in using it, and we obtained excitation of selective microwave modes to enhance ECR efficiency [10].

Typical CSDs of beams from the 1st stage We investigate the CSDs of the 1st stage plasma on the dual-type ECRIS for first time. We conduct measurement of them by extracting ion beam from the 2nd stage where there is no plasma but exits magnetic mirror fields. We can observe the Ar charge state up to q=4, despite all magnets and large bore source. The values of the beam currents increase significantly by $V_{EC1,2}$. In addition to increase of the ion beam current, sifts of the CSD spectrum by extracting from the 1st to the 2nd stage (<1kV) are observed on the basis of the V_{PE}, usually about 10kV. Ion beam currents is loosely proportional to the $V_{EC1,2}$, but each fraction is almost constant at their various values [11].

Typical plasma parameters in the 1st stage We measure the profiles of the n_e and the T_e in the 1st stage plasma corresponding to mobile plate positions. The n_e at the peak position is much larger than one at the minimum positions, while the T_e is almost same value. It is considered enhancement of the ion beam currents $I_{FCx,y}$ by excitation of selective microwave mode is caused by increase of the n_e, not rather one of the T_e as similar results in the cases of 11-GHz frequency microwaves [7]. On basis of plasma theory, I_{is} is proportional to n_e and $T_e^{1/2}$. Therefore increments of the $I_{FCx,y}$ are strongly due to the n_e inside the ECRIS plasma, and selective mode excitation of microwaves is useful to enhance n_e values and the $I_{FCx,y}$.

Typical Experimental Results on the 2nd Stage

Beam currents affected by shape of ECR zones The total ion beam currents I_{FC1} extracted from the 2nd stage are measured at just downstream of extractor assembly and einzel lens against various Coil C currents I_c, *i.e.* various shapes of ECR zone. According to the typical dependence, the maximum current is usually obtained around I_c = 10A, where the minimum ECR zone is constructed around the mirror bottom with the mirror coil A, B currents $I_{A,B}$=150A. The I_{FC1} decreases, as the I_c decreases. But the 2nd peak is recognized again around I_c~-30A. Now we are paying attention to this phenomenon as a new heating mechanism as we will discuss later.

Typical CSDs of beams from the 2nd stage We investigated the CSD of the extracted ion beams I_{FC} from the 2nd stage and their dependence on the intensity of the I_C corresponding to the above mentioned results. The $Ar^{3+\sim8+}$ beam currents attain their peak values at the minimum ECR zone constructing around the mirror bottom at I_C~5A in the case of I_{AB}=150A and I_c~0A in that of I_{AB}=170A, respectively. In the case of I_{AB}=150A, the 2nd peak of the I_{FC1} around I_C~-30A is found to be corresponding to the 2nd peak of Ar^+ and Ar^{2+}. These experimental results will be recalled in the consideration of the accessibility condition.

ECR efficiency by microwave mode analysis We have already proposed a concept for enhanced efficiency of the ECR plasma for production of multicharged ions by constructing a microwave cavity, and then making the maximum electric field correspond to the ECR zone [12]. We investigate available microwave modes in circular cavity resonator. Microwave modes existing are mainly several transvers electric modes, *i.e.* TE_{01}, TE_{11}, and TE_{21}. It is found that the 1st peak of the I_{FC1} against the I_C coincides to the each peak position of the S_{nm} for each TE_{nm} mode, except for the decreasing behaviours. But the 2nd peak cannot be explained by discussion of microwave modes including the 2nd harmonics ECR.

Typical plasma parameters in the 2nd stage After preparation of the electricity and cooling system for mirror coils to some extent 60% for the maximum in the 2nd stage, we are available to sustain discharge in low pressures ($10^{-4\sim-5}$Pa). First beam have been successfully extracted at November 2013. We can measure and observe the ECR plasma continuously on various intensities of the magnetic field. The n_e is over the cut-off density ($7.4\text{x}10^{16}\text{m}^{-3}$) for 2.45GHz microwave, and then it suggests propagation of whistler modes. Because the measured n_e is no longer over cut-off density of launched microwave frequency, we must consider dispersion relations and propagation of waves in the magnetized plasma, *i.e.* accessibility condition of electromagnetic and electrostatic waves in the ECR plasma.

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We use these data for estimating accessibility condition of wave propagation in the ECR plasma in changing various magnetic fields.

Accessibility condition of microwaves in ECR plasma and additional heating possibility We investigate the accessibility condition of waves in the ECR plasma by using profiles of the magnetic field and the n_e in the 2nd stage of the dual-type ECRIS at various I_C values. We estimate ray traces of propagating microwaves launched from the antenna with various direction in real spaces in the 2nd stage chamber and in the space of Clemmow-Mullaly-Allis (CMA) diagram corresponding to the former trace [13]. There exists four principle modes, *i.e*., the ordinary (O-made), the extraordinary (X-mode), the right hand polarization (R-mode), and the left hand polarization (L-mode) waves, of waves propagations in the magnetized plasma [13]. It is found that the 2nd peak of the I_{FC1} and their behaviour coincides the appearance of the upper hybrid resonance (UHR) and their development and decrease of the ECR efficiency. The UHR may be strong candidate for explanation of the experimental results. It is suggested that there are some room for additional enhancing efficiency of the electron heating on ECR, and then moreover enhance production of multicharged ions.

Preliminary Experimental Results on Effects of Dual Operation and Each Single Operation

We investigated the CSD in the case of both stages and each single plasma operations. We have been conducting preliminary experiments on investigating effects of dual operation and each single operation. Produced ions in the 1st stage can be transported to the 2nd stage with imparted energy (<1kV) by the large bore extractor. It is found that drastic changes in the CSD's of the 2nd stage plasma with or without the flow from the 1st stage plasma at the extreme low microwave power in the 2nd stage. As the extraction energies from the 1st stage increase gradually, the I_{FC} increase, and we use to observe the splitting spectrum for each Ar^{q+} beams as already mentioned [11].

New Applications on the Dual-Type ECRIS, Future Planning, and Perspective

We will investigate both stage plasmas' characteristics and the effects of the dual-type ECRIS. We will also investigate new wave heating/cooling methods in the device as also a universal theme in ECRIS in near future.

It is also found that the more pressure difference between the 1st and the 2nd stage are needed for applications.

We have been developing the pure vapour sources for fullerene and iron. We have succeeded in producing iron ion beam from the 1st stage and multi-charged fullerene beams from the 2nd stage. We will try to synthesize iron-endohedral fullerene by using this dual-type ECRIS in near future. Furthermore we are planning to implant many kind ion beams to materials having potential and new functionality, *e.g.*, visible reaction of photocatalytic titanium dioxide and strontium titanate, *etc.*, in future material beam-processing.

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