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ECR multi-charged ion source directly excited in a circular TE_{01} mode cavity resonator

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Abstract

A new concept is proposed for enhancing the efficiency of an electron cyclotron resonance (ECR) plasma for production of multi-charged ions (TAIKOII). The plasma chamber is a circular cavity resonator with two metal plates. A fixed plate is installed at the tip of the ion extractor. The distance between the fixed plate and the antenna installed at the side wall is equal to a quarter of the guided wavelength λ_g for the circular TE_{01} mode microwave. A mobile plate is inserted from the opposite side along the geometrical axis to tune the microwave. Excitation of single TE_{01} mode has been confirmed. The electric field has only a circumferential component and is axially symmetric in the same direction as electron cyclotron motion. The peak value of the electric field is located at the ECR zone. Multi-charged ions are extracted by a voltage of 10 kV and the charge state distribution (CSD) of their ion currents are measured by using the sector magnet and the faraday cap. The extracted Ar^{4+} ion current changes periodically when the mobile plate moves in the plasma and the interval of the mobile and the fixed plates is several times $\lambda_g/2$ in the TE_{01} mode microwaves. We present and discuss production of multi-charged ions by applying the TE_{01} mode microwave in order to enhance efficiency of the ECR in the optimized magnetic field.

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Keywords: ECR source; Multi-charged ion; Microwave; Cavity resonator; Circular TE_{01} mode

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1. Introduction

Electron cyclotron resonance (ECR) ion sources have been widely used for production of high-intensity multi-charged ion beams for accelerators, atomic physics experiments and industrial applications as well as for cancer therapy. The design of these sources matured. Methods of fabricating ECR sources seem to be well understood. In contrast, the physical phenomena underlying the source performance and several empirical methods such as the biased disk, wall coating, low-Z gas mixing, pulse-modulated microwave and so on, are poorly understood.

To investigate the production mechanism of multi-charged ions, we have measured profiles of electron temperature, density and plasma potential by using the Langmuir probes [1]. The behavior of hot electrons has been examined using pulse height analysis of Bremsstrahlung [2]. On the basis of these results, we conducted experiments to enhance production of multi-charged ions by pulse-modulating the microwave to continuously add the afterglow phase [3]. We have also investigated both experimentally and theoretically the optimized shape of the ECR zone [4].

We propose a new concept for enhanced efficiency of the ECR plasma for production of multi-charged ions by constructing microwave cavity, and then making the maximum electric field correspond to the ECR zone. The excitation of microwave modes is a well-studied field. The most common 2.45 GHz ECR ion sources use rectangular or circular waveguides, operated preferentially in the fundamental mode, i.e. TE_{10} mode for rectangular waveguides and TE_{11} for circular waveguides [5]. In this article the experimental study concentrates on production of multi-charged ions with respect to a microwave mode, especially, a circular TE_{01} mode. The electric field of the circular TE_{01} mode has only a circumferential component in the same direction as electron cyclotron motion in the magnetic mirror field. We can position the peak of the electric field of the standing waves in the ECR zone of the cavity resonator, i.e. the vacuum chamber. We conducted simulated experiments and determined that the excitation was circular TE_{01} single mode. Guided by the simulated experiments, we constructed the ECR source (TAIKO II), and investigated the features of the plasma source in the cavity resonator of the circular TE_{01} mode.

2. Theoretical design aspects and experimental apparatus

On the basis of the theory, there are functional relationships between the free-space wavelength λ and the guided wavelength λ_g at the radius a of the resonator on the frequency, as the following:

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_g^2} + \frac{1}{\lambda_c^2}, \tag{1}$$

where λ_c is the cut-off wavelength and is given by $\lambda_c = 2\pi a/\chi$. χ indicates the n-th eigen mode value of the differential m-th Bessel function for the circular transverse electric TE_{mn} and one of the m-th Bessel function for the transverse magnetic TM_{mn} modes microwaves. This relationship dose not depend on frequencies of the microwaves, so the ECR plasma is not only suitable for multi-charged ions, but also for a ion/plasma source aimed at future material-processing at microwave frequencies [6]. Fig. 1 shows the λ_g of various available modes as a function of the radius a of the circular cavity resonator for various frequencies. The TE_{11} mode, i.e. primary mode has the minimum length of the λ_g Each mode has an asymptotic line at the radius a which the λ_c value is corresponding to the λ. The diameter of the previous experimental apparatus (TAIKO I) was about 146 mm (a = 73 mm) and TE_{01} mode did not exist. Now TAIKO II has a diameter of about 160 mm. The λ_g has the steep dependence around its value.

The TE_{01} mode is excited only by the circumferential currents on the cavity walls. Therefore disconnection of the end walls from the sidewall does not disturb the excitation of this mode differently from others. The experimental procedure was as follows: The radius a of the vacuum chamber was chosen as the λ_g for the circular TE_{01} mode had steep dependence on the value of a. The semi-dipole antenna was at the sidewall to directly excite the circumferential electric field. The shape and position of the antenna was optimized by