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Electrical Probe Measurements of an ECR Plasma Produced in a Cusp Magnetic Field
カスプ磁場中で生成した ECR プラズマの静電プローブ計測

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The electron cyclotron resonance (ECR) discharge in a cusp magnetic field has a better electron confinement compared to the conventional ECR discharge in a diverging or converging magnetic field, and the plasma has high electron density and degree of ionization. In this study, we measure the spatial distribution of the plasma potential and anisotropy in the electron energy distribution function (EEDF) using a single probe and a directional probe, respectively. From the evaluated EEDFs, we have found that the average electron kinetic energies in directions parallel and perpendicular to the magnetic field are about 3-4 and 8-10 eV, respectively.

1. Introduction

The magnetic field strength of a cusp magnetic field increases from the center toward the outward and its isomagnetic surfaces are concentric ellipsoids. In an ECR plasma produced in this field, electrons are confined by the magnetic mirror effect, and electron velocity perpendicular to the magnetic field increases by ECR heating on the closed the ECR surface. The end-loss of electrons through the loss-cone is then decreased [1]. The improved electron confinement could also result in the confinement improvement of ions by formation of an electric field around the ECR surface [2]. Based on these mechanism, the ECR discharge in a cusp magnetic field is expected to produce a plasma with high electron density and degree of ionization.

In this study, we measure the spatial distribution of the plasma potential and anisotropy in the EEDF using a single probe and a directional probe, respectively, in order to experimentally confirm the improvement of the electron confinement.

2. Methods

In a magnetized plasma, interpretation of the probe current-voltage (*I*-*V*) characteristics is not a trivial issue. However, from practical point of view, it is reported that T_e and n_e evaluated by using the un-magnetized probe theory empirically agree with other methods within a factor of 2, where T_e and n_e are the electron temperature and density, respectively. In particular when the probe biasing voltage is below the floating potential, the error becomes smaller [3]. Based on this fact, we measure the spatial distribution of the plasma potential and EEDF from the *I*-*V* characteristics.

We assume that the electron velocity distributions (EVDFs) in the directions parallel and perpendicular to the magnetic field are independent, and apply the one- and two-dimensional Druyvesteyn methods to the probe currents measured in directions parallel and perpendicular to the magnetic field, respectively [4]. When the probe normal is parallel to the magnetic field, the parallel component of the EEDF $f_{\parallel}(\epsilon)$ is obtained from the first derivative of the electron current I_e as

$$f_{\parallel}(-eV) = \frac{\sqrt{2m_e}}{e^2 n_e S}\frac{1}{\sqrt{-eV}}\frac{dI_e}{dV}, \qquad (1)$$

where e, m_e, S, and V are the elementary electric charge, electron mass, area of the probe, and probe voltage measured from the space potential, respectively. When the probe normal is perpendicular to the magnetic field, the perpendicular component of the EEDF $f_{\perp}(\epsilon)$ is obtained as

$$f_{\perp}(-eV) = \frac{2\sqrt{2m_e}}{e^3 n_e S}\frac{d}{dV}\int_{-eV}^{\infty}\frac{I'_e}{\sqrt{x+eV}}dx, \qquad (2)$$

where I'_e is a derivative of I_e with respect to V.

3. Experiments

3.1. ECR plasma in a cusp magnetic field

Experiments were carried out using an ECR plasma produced in a cusp magnetic field (Fig. 1 (a)). A helium plasma was produced by 2.45 GHz microwave under a pressure of 1.7 mPa.

We have developed a probe scanning system (Fig.2) ; the linear motion is operated through a linear bushing and the rotation around its axis is controlled by a stepping motor (Plexmotion, SSA-TR-56D1SD) with an angular resolution of 1°. The rotational motion of the probe is monitored by a rotary encoder (MUTOH, NS-360) connected to a digital input module (National Instruments, NI 9401).

3.2 Directional Langmuir probe

We used a directional Langmuir probe (DLP) which consists of a stainless steel (SUS304) planer electrode with a dimension of 5×5×0.1 mm^3 and a cylindrical alumina insulator with an outer diameter of 8 mm (Fig.1 (b)). The probe head was located at z = 10 and r = 102 mm, where the $\{r\theta z\}$ coordinate system is defined as shown in Fig.1 (a). The probe was rotated around its axis by 10^o at every discharge, and angle-resolved current-voltage characteristics were measured with a voltage sweeping frequency of 10 Hz while the plasma was steady-state. The current and the voltage were recorded using a digitizer (National Instruments, NI9205) with a sampling frequency of 60 kHz and a resolution of 16 bit.

3.3 Single Langmuir probe

A single Langmuir probe which consists of a tungsten cylindrical electrode and an alumina insulator tube (Fig.1 (c)) will be installed. The alumina insulator has an outer diameter of 3.0 mm. The diameter and length of the electrode are 0.5 and 3.0 mm, respectively. The probe has L-shape and its z- and r-positions are movable.

4. Results

The EEDF was obtained from the current-voltage characteristics measured by the DLP after averaging 10 data and applying binomial smoothing for 100 times. Fig.3 shows the evaluated EEDFs in the directions parallel to the magnetic field $\sqrt{\epsilon}f_{\parallel}(\boldsymbol{\epsilon})$ (α = 0^o and 180^o) and perpendicular to the magnetic field $f_{\perp}(\epsilon)$ (α = 90^o and 270^o), where α is the angle between the mid-plane cross-section of the ECR plasma device and the normal of the DLP. 0^o is the case when the probe normal is parallel to the magnetic field and oriented toward the magnetic upstream. The average electron kinetic energies $K_e = \frac{2}{3}\int_0^{\infty} \epsilon f(\epsilon) d\epsilon$ are in Table I. The results confirm the anisotropy in the EEDF due to the ECR heating.

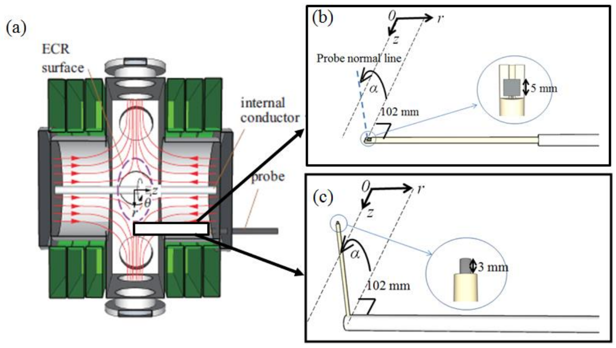

Fig.1. (a) A diagram of the mid-plane cross-section of the ECR plasma device. The lines with the arrows show the magnetic field. The ellipse with the broken line shows the ECR surface (87.5 mT). (b) A directional probe. (c) A single probe.

Fig.2. A probe scanning system.

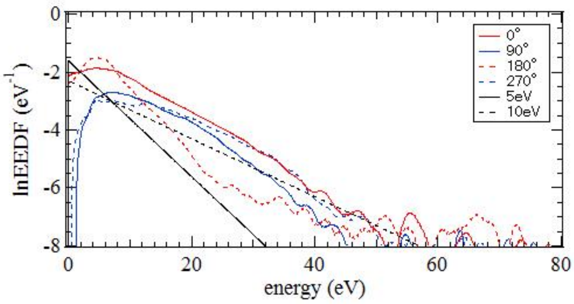

Fig.3. Evaluated EEDFs (0°, 90^o, 180°, and 270^o). The straight lines show the EEDFs of the Maxwellian distributions with the temperature 5 and 10 eV.

Table I. Average kinetic energy

Degrees	0	90	180	270
K_e (eV)	4.32	8.65	3.19	10.0

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