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Electron Distribution in a Quadrupole Magnetic Field to Drive Magnetic Neutral Loop Discharge Plasma

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***Abstract* – We simulated the electron motion in a quadrupole magnetic field that drives a neutral loop discharge (NLD) plasma, using a Monte Carlo method. The structure of the electron distribution in the NLD plasma was observed. Electrons underwent reciprocating motion between reflecting boundaries as they gyrated along magnetic field lines. During this motion, they deviated from the neutral loop and concentrated beside the separatrices of the quadrupole magnetic field.**

***Index Terms* – Electron number density, Monte Carlo method, neutral loop (NL) discharge (NLD) plasma, quadrupole magnetic field, separatrix.**

MAGNETIC neutral loop (NL) discharge (NLD) plasma, used for dry etching, is a type of inductively coupled plasma. It can operate at low gas pressures (~ 1 mTorr) and high plasma densities (10^{10}–10^{11} cm^{-3}) [1], [2]. A typical NLD plasma reactor has three coaxial coils surrounding a cylindrical vessel [Fig. 1]. The magnetic field induced by the coil currents is quadrupole, and a ring of zero magnetic field, i.e., the so-called NL, is formed in the vessel. A ring-shaped plasma, i.e., the NLD plasma, is generated along the NL by the electric power from an RF antenna [3]. The radius and position of the NLD plasma are controllable via the coil currents. A dynamic control utilizing this feature for uniform wide-area etching has been proposed [4]. To understand the structure of the NLD plasma, the electron motion in the quadrupole magnetic field was simulated by a Monte Carlo method. In this work, we observed the three-dimensional structure of the electron distribution in the NLD plasma.

The diameter and height of the vessel were both 40 cm. Currents I_1, I_2, and I_3 of the top, middle, and bottom coils (60-turn coils) were set at +47.8, −55.75, and +47.8 A, respectively. The radius of the NL formed was 11 cm, and the gradient of the magnetic field was approximately 0.17 mT/cm near the NL. An RF (13.56 MHz) electric field with a sinusoidal waveform was induced by the one-turn RF antenna. Its amplitude at the NL was approximately 4.0 V/cm.

The gas medium was assumed to be CF_4 at 5 mTorr.

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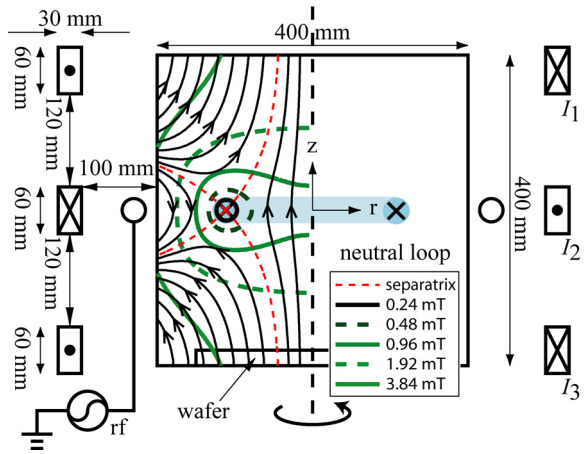

Fig. 1. Schematic of the NLD plasma reactor and quadrupole magnetic field. X denotes the NL of the zero magnetic field.

The electron collision cross sections of CF_4 were taken from [5]. The initial electrons were released in the NL region, which is the region where the magnetic field is weaker than the 0.48-mT strength of the RF-resonant magnetic field and the electric power is deposited into the plasma. The electrons were traced for 200 RF periods and sampled in the last 50 to obtain the time-averaged electron distribution after the initial relaxation process. We assumed a high electron reflectivity of 0.99 at the sidewall, ceiling, and bottom of the vessel, regarding it as the sum of the surface reactions such as electron absorption and emission of the secondary electrons [6].

Fig. 2 shows the electron number density n_e. The high-density region in which n_e is higher than 20% of its peak value is extracted. n_e is low near the separatrices of the quadrupole magnetic field, and electrons concentrate beside the separatrices. Electrons deviate from the separatrices, but further diffusion hardly proceeds. This is explained in the following manner. In the NL region, electrons do not gyrate because the magnetic field is weak. They meander and eventually deviate from the NL region. This leads to low n_e values along the separatrices as well since electrons near the separatrices are from the NL region. Electrons out of the NL region are captured by the magnetic field and gyrate. They move along their guiding magnetic field lines. For the electron reflection at the boundary, electrons undergo reciprocating motions between two boundaries at which the guiding magnetic field lines cross the vessel walls. This reciprocating motion is likely to be maintained at the present low gas pressure. The reciprocating motion along the separatrices is probably aborted in the NL region. In contrast, that

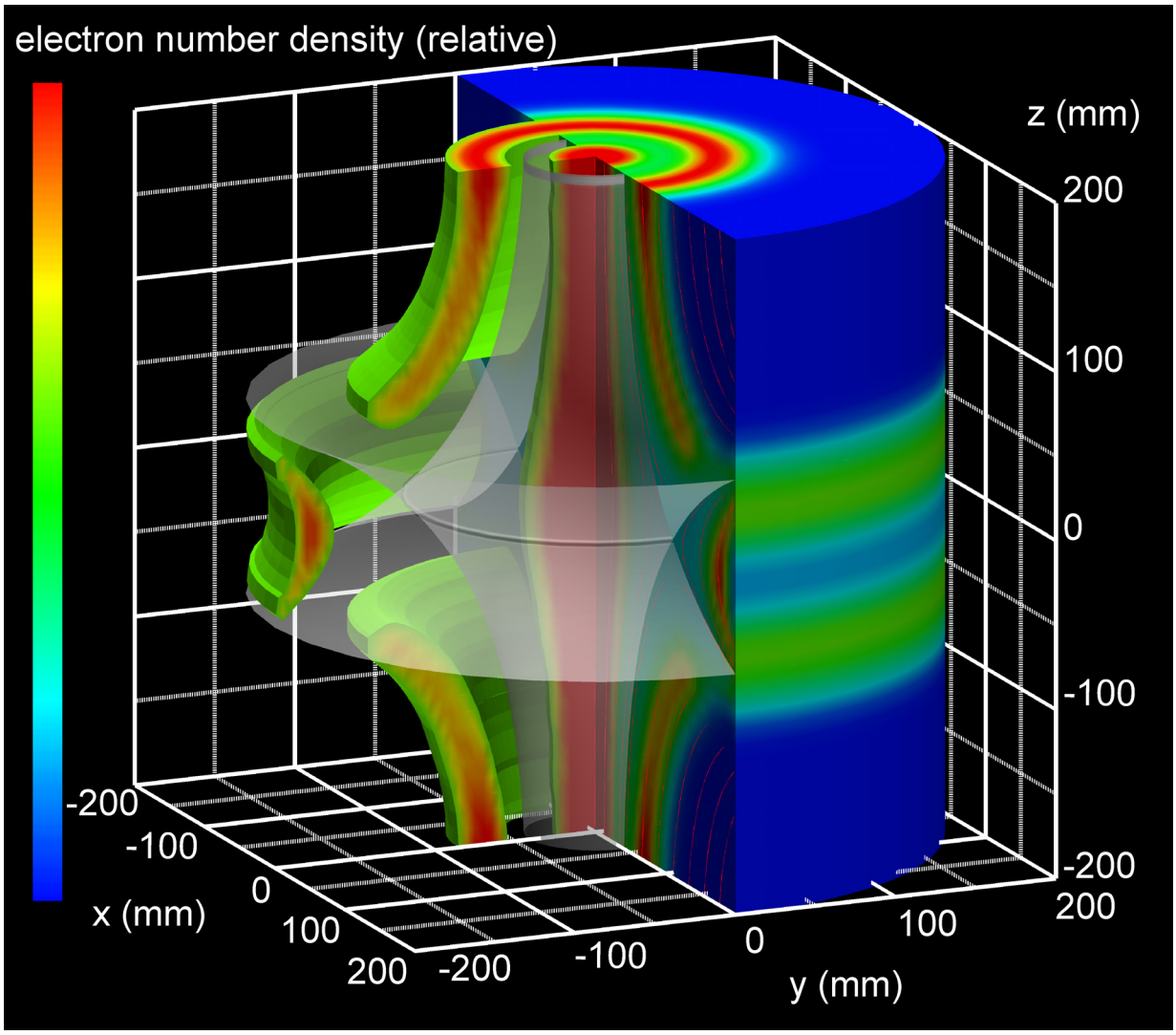

Fig. 2. Electron distribution n_e around the separatrices of the quadrupole magnetic field in the NLD plasma.

beside the separatrices is maintained. As a result, the peaks of n_e appear beside the separatrices.

The detailed electron motion in the NLD plasma is described in relation with the NL and separatrices of the quadrupole magnetic field. While the NL is often considered as the main factor governing the characteristics of the NLD plasma in conventional analyses, the separatrices also play a key role in determining the structure of the NLD plasma.

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