Stochastic scattering process to induce inward electron flow in electron conduction path between antiparallel gradient magnetic fields

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Electron motion in antiparallel gradient magnetic field was simulated in order to investigate properties of the electron conduction forming a loop current in a magnetic neutral loop discharge plasma. The lateral electron distribution across the conduction path decays outward. Its shape is determined under the balance between the outward and inward electron flows. The former is caused by the diffusion due to the density gradient of the lateral electron distribution. The latter, which has been unexplained, is considered to be due to a stochastic scattering process that induces an inward shift of the electron gyration range. Simulation data to explain this mechanism were presented.

Antiparallel gradient magnetic fields are a component of a quadrupole magnetic field to drive magnetic neutral loop discharge (NLD) plasmas. The NLD plasma, which is a low-pressure high-density inductively coupled plasma used for dry etching, is generated along a loop of zero magnetic field (neutral loop: NL) formed by superposing the magnetic fields induced by three coaxial coils surrounding a plasma chamber [1,2] (Fig. 1). Electrons are accelerated by the radio-frequency (rf) electric field induced by an rf antenna, mainly under the weaker magnetic field near the NL, that makes the plasma ring-shaped. The electron conduction along the NL plays a key role in the power deposition from the rf antenna to the plasma for sustainment of the NLD plasma.

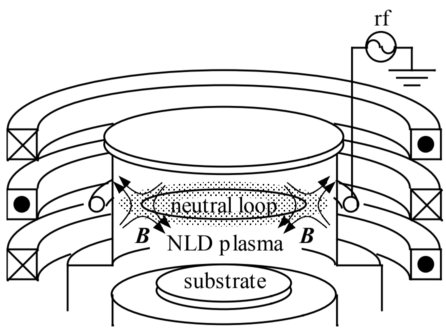

Fig. 1: Schematic of a neutral loop discharge (NLD) plasma reactor.

The magnetic field around the NL has a quadrupole structure. Fig. 2 shows a simplified model quadrupole magnetic field consisting of two pairs of antiparallel magnetic fields. Fundamental electron motion in NLD plasmas has often been analyzed in antiparallel magnetic fields [3]. After the preceding work, let us assume a model magnetic field as $\boldsymbol{B} = (B_x, B_y, B_z) = (0, 0, \beta x)$, where $\beta = \mathrm{d}B_z/\mathrm{d}x$ is a constant. Electrons undergo meandering in the weaker magnetic field near $x = 0$ and gyration in the stronger magnetic field apart from $x = 0$. Then, the electron conduction path is formed along the y-axis, and it was reported that the conduction path has a structure consisting of directional lanes [3]. The lateral electron distribution $n(x)$ across the path decays outward and has a breadth proportional to $\beta^{-1/2}$. It is considered that the shape of $n(x)$ is determined under a balance between outward and inward electron flows. The former is the electron diffusion due to the gradient of $n(x)$. On the other hand, the latter has been unexplained. Unlike electric field, in which electron motion is limited under the energy conservation law, the mechanism that the antiparallel magnetic fields attract the electrons inward is not of the potential energy. In this report, an explanation for the mechanism to induce the inward electron flow is presented with some simulation data indicating a stochastic scattering process.

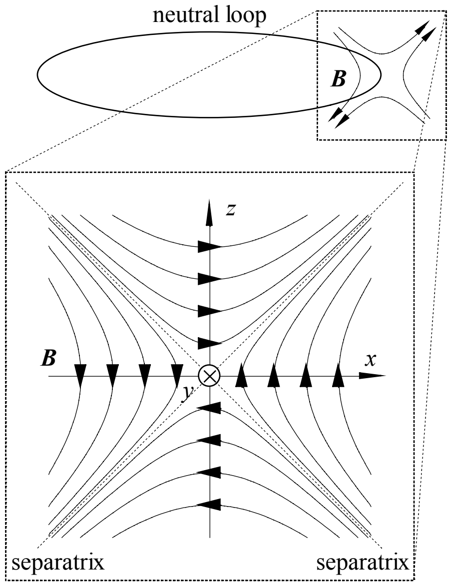

Fig. 2: Model of quadrupole magnetic field around the neutral loop.

A Monte Carlo simulation of the electron motion in the $\boldsymbol{B}$ field defined above was carried out. The value of β was set at 1.0 mT/cm. The rf electric field was assumed to be $\boldsymbol{E} = (E_x, E_y, E_z) = (0, E_0 \sin 2\pi f t, 0)$, where $f = 13.56$ MHz and $E_0 = -10.0$ V/cm. The ambient gas was 5-mTorr CF_4. The set of electron collision cross sections of CF_4 was taken from Ref. [4].

Fig. 3 shows a typical electron locus in the antiparallel magnetic fields. It is observed that the gyroradius is longer in the inner part of the locus relative to the gyrocenter because of the weaker magnetic field, and is shorter in the outer part in the stronger field. The gyration does not occur near $x = 0$ because the magnetic field is not strong enough there to make the electron locus circular. Simulation data indicated that the period during which an electron is in the inner part of its locus is longer than that in the outer part. Because the number of electron–molecule collisions is roughly proportional to the electron flight time, the electron collisions in the inner part would be more than those in the outer part.

The gyroradius temporally varies under the acceleration of the rf electric field. However, it is observed that the gyration is within a limited x range during a free flight between two successive collisions. Let us define this range as $x_{\min} \le x \le x_{\max}$ for an electron gyrating in the region of $x > 0$. The above discussion on collisions argues that electron collision in a range of $x < x_{\mathrm{mid}} = (x_{\min} + x_{\max})/2$ is more frequent than in $x > x_{\mathrm{mid}}$.

Fig. 4 shows the ratio R_b of the backward flight time T_b, during which an electron moves toward the $-y$ direction, in its gyration, plotted against x_{mid}. Here, $R_b = T_b/(T_b + T_f)$ and T_f is the forward flight time. The simulation was performed in a collisionless condition for 10^4 electrons released at x chosen at random, and their flights were traced for 100 rf periods to obtain the average of R_b. T_b is an approximate translation of the period of $x < x_{\mathrm{mid}}$, because the electron gyration is anticlockwise in the region of $x > 0$. The result that $R_b > 1/2 > R_f$ $(= 1 - R_b)$ except for a few cases suggests that electrons tend to collide in the inner part of their gyration ranges.

After an electron collides with a gas molecule and is scattered, the electron would start its succeeding gyration with a new locus. The new gyration range tended to shift inward from the scattering position. Fig. 5 shows that most of x_{mid} of electrons after isotropic scattering are inside of the scattering position x_{scat}; i.e. $x_{\mathrm{mid}} < x_{\mathrm{scat}}$. This is also because the gyroradius is longer in the weaker magnetic field near $x = 0$ and is shorter in the stronger magnetic field.

The mechanism of antiparallel magnetic fields to attract the electrons inward, by which the lateral electron distribution $n(x)$ across the electron conduction path concentrates near $x = 0$, is considered to be based on the following tendencies:

(i) electrons tend to collide in the inner parts of their gyration ranges, and

(ii) the electron gyration range after collision tends to shift inward on average.

The inward electron flow appears by this stochastic process.

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References

[1] T. Uchida, *Japan. J. Appl. Phys.* **33** (1994) L43–L44.

[2] T. Uchida and S. Hamaguchi, *J. Phys. D: Appl. Phys.* **41** (2008) 083001-1–083001-21.

[3] H. Sugawara, T. Osaga and M. Yamamoto, *Plasma Sources Sci. Technol.* **20** (2011) 065003-1–065003-7.

[4] M. Kurihara, Z. Lj. Petrović, and T. Makabe, *J. Phys. D: Appl. Phys.* **33** (2000) 2146–2153.

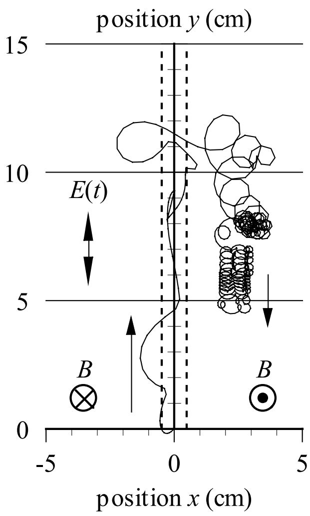

Fig. 3: Typical electron locus in the antiparallel magnetic field $\boldsymbol{B} = (B_x, B_y, B_z) = (0, 0, \beta x)$, where $\beta = \mathrm{d}B_z/\mathrm{d}x = 1.0$ mT/cm. The broken lines indicate the positions of rf-resonant magnetic field $|\boldsymbol{B}| = 0.48$ mT at 13.56 MHz.

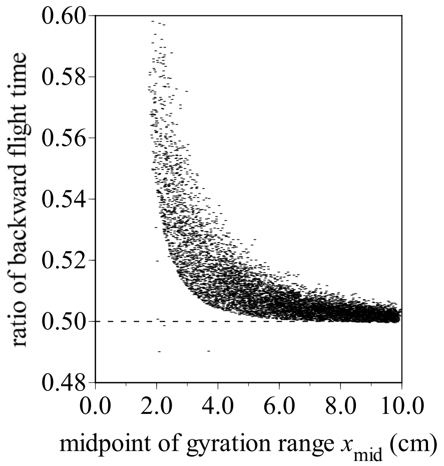

Fig. 4: Ratio of backward flight time versus midpoint of gyration range.

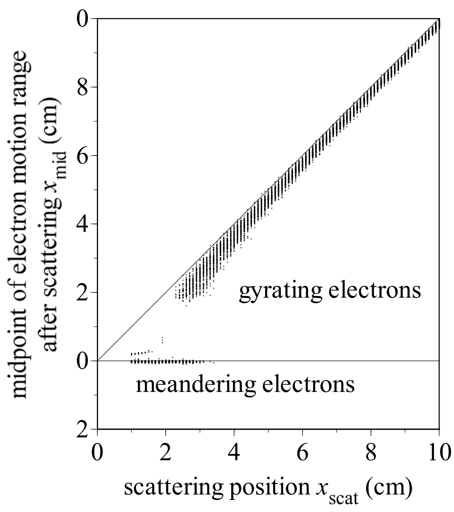

Fig. 5: Distribution of midpoints of electron motion ranges after scattering.