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Author(s)	Okazaki, Ryota; Sugawara, Hirotake
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Analysis of electron heating due to partial resonance in an inductively coupled plasma under confronting divergent magnetic fields

Ryota OKAZAKI and Hirotake SUGAWARA*

Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan

We investigate the partial resonance as one of the mechanisms of the electron heating to sustain inductively coupled plasmas driven under confronting divergent magnetic fields having an electron confinement function. Dependence of the partial resonance on operating conditions are observed. The electron energy gain (EEG), defined as a measure for evaluation of the partial resonance, was calculated by a Monte Carlo method under various magnetic field strengths and the RF antenna positions. It is confirmed that the partial resonance is observed in the resonant region even in low electric field and strong magnetic field. As an attempt to utilize the partial resonance, we demonstrate enhancement of the EEG and resulting ionization in the resonant region by placing the RF antenna near a region where the magnetic field lines running through the resonant region reach.

1. Introduction

Plasma sustainment at low gas pressures is one of the technical demands in material processing for fine fabrication of integrated circuits and microelectromechanical systems by anisotropic dry etching. Application of magnetic fields to plasmas is an effective way to keep the plasma density high even at low pressures. For example, the magnetic neutral loop discharge (NLD) plasma¹⁻⁸⁾ for etching is a high-density inductively coupled plasma (ICP) generated under a quadrupole magnetic field (QMF). As well, the X-point plasma,^{9,10)} which is an ICP proposed originally as a negative ion source, is driven under confronting divergent magnetic fields (CDMFs), and functions of the CDMFs have been discussed for their use as a magnetic shutter or filter¹¹⁾ for plasma confinement and modulation to reduce the damage of materials processed.

On the other hand, it has been pointed out that electrons under non-uniform magnetic fields obtain energy efficiently from AC (typically RF) electric field by the partial Larmor rotation²⁾ or the partial resonance⁶⁾ around the regions of the resonant magnetic field strength B_{ECR} . Here, B_{ECR} is such a magnetic field strength that the electron Larmor frequency is equal to the AC electric field frequency and that the electron cyclotron resonance (ECR) would occur when AC electric and DC magnetic fields are uniform. The QMF has a tubular B_{ECR} region around and along the ring-shaped null magnetic field region so-called the neutral loop, along which the NLD plasma is generated.^{12,13)} It was observed that the electron temperature has a peak near the B_{ECR} region in a QMF.¹⁴⁾ The CDMFs, under which the X-point plasma is driven, typically have a spheroid-like B_{ECR} region surrounding the magnetic null point so-called the X point. Here, the X point in the present geometry is an isolated singular point, while an X point refers to the intersection of a magnetic null line with a poloidal cross section in tokamak plasmas¹⁵⁾ or that with a transverse cross section in linear plasma devices.¹⁶⁾ It was reported that electrons under the CDMFs obtain energy near the B_{ECR} region via a stochastic process.^{11,17-19)} A notable feature is that the partial resonance may occur even in the region distant from the RF antenna. Although it is considered in general that magnetic field induces the magnetic cooling of the elec-

tron temperature by binding the electron motion, the partial resonance is an interesting phenomenon as a mechanism of energy supply to electrons, and it may assist the sustainment of the magnetized ICPs. Because it is expected that the B_{ECR} region can be designed and controlled by the current flowing in the DC magnetic coils and their positions, analysis of fundamental dependence of the partial resonance on the reactor arrangement and the plasma driving conditions is desired to obtain a guide to preferable plasma operation for utilizing the functions of the characteristic magnetic fields.

In this paper, an ICP driven by RF electric field at 13.56 MHz is adopted as the analysis model. The energy that an electron gains per unit time is quantified as the electron energy gain (EEG), and the spatial distribution of the EEG is evaluated. The EEG is calculated by a Monte Carlo method in a region of certain magnetic field strength range, which is defined as the 'resonant region'. The following three points are investigated; (a) the dependence of the EEG on the RF antenna position moved along the chamber ceiling or sidewall, (b) the dependence of the EEG on the magnetic field strength, and (c) the aspects of the EEG dependent on the path of magnetic field lines relative to the resonant region. Point (a) is for the design of the reactor; whether the RF antenna is placed over the chamber ceiling or around the sidewall. This can also be for a dynamic control if multiple RF antennas are switchable. Point (b) is to confirm the occurrence of partial resonance under strong magnetic fields. Point (c), which is of a new effort to utilize the features presented in recent reports,^{20,21)} intends an efficient supply of high-energy electrons to the resonant region along magnetic field lines connecting between the resonant region and the near-antenna region. We discuss the possibility of the partial resonance in functional use of magnetic fields for plasma operations.

2. Simulation model and conditions

In order to focus the present analysis on confirming fundamental dependence of the EEG on the arrangement of the electric and magnetic fields, we adopt a simple simulation model to track the electron motion and the simulations are limited to be of a relatively short time scale as explained in the following sections. Although plasma modelling techniques progress remarkably for practical and realistic simula-

*E-mail: sugawara@ist.hokudai.ac.jp

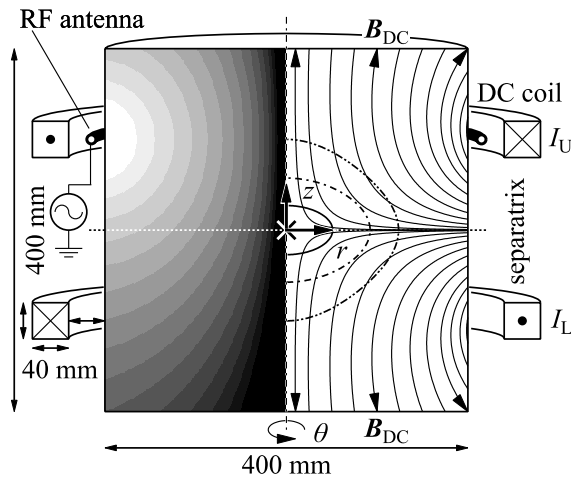


Fig. 1. Model reactor assumed in the present work. The left part shows an example of the amplitude distribution of RF electric field $\mathbf{E}_{\text{RF}}(t)$ (in logarithmic scale). Its values at some representative positions on the sidewall are about 479 V/m (maximum) near the RF antenna and 160 V/m at $z = 0$, and the amplitude of $\mathbf{E}_{\text{RF}}(t)$ decays inward to zero at $r = 0$. The right part shows magnetic field $\mathbf{B}_{\text{DC}}$ at $I_{\text{DC}} = 600$ AT; —, $|\mathbf{B}_{\text{DC}}| = 0.5B_{\text{ECR}}$; — · —, $1.0B_{\text{ECR}}$; and — · · —, $1.5B_{\text{ECR}}$, where $B_{\text{ECR}} = 0.4844$ mT at $f_{\text{RF}} = 13.56$ MHz.

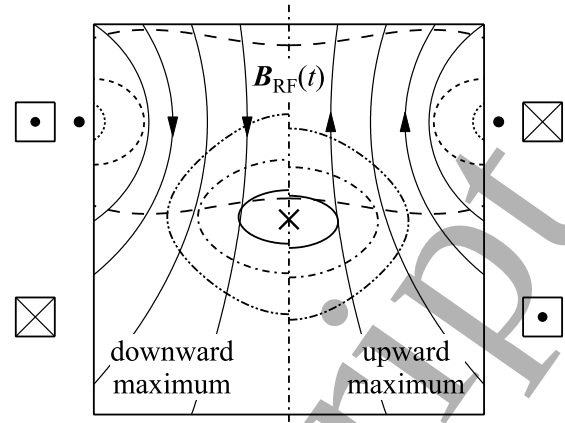


Fig. 2. RF magnetic field $\mathbf{B}_{\text{RF}}(t)$ induced by the RF antenna current at the phases of downward maximum (left) and upward maximum (right). The contours around the X point represent $|\mathbf{B}_{\text{DC}} + \mathbf{B}_{\text{RF}}(t)| = 0.5B_{\text{ECR}}$ (—), $1.0B_{\text{ECR}}$ (— · —), and $1.5B_{\text{ECR}}$ (— · · —) at $I_{\text{DC}} = 600$ AT, where $B_{\text{ECR}} = 0.4844$ mT at $f_{\text{RF}} = 13.56$ MHz. The maximum of $|\mathbf{B}_{\text{RF}}(t)|$ is about $0.3B_{\text{ECR}}$ at the position on the sidewall closest to the RF antenna. The broken curves represent the positions of $|\mathbf{B}_{\text{RF}}(t)| = 0.2B_{\text{ECR}}$, $0.1B_{\text{ECR}}$, and $0.05B_{\text{ECR}}$ in order from the closest to the RF antenna.

tions taking account of various plasma responses, that of magnetized plasmas is still under development for complicated behavior of electrons under magnetic field. In general, a particle model requires a heavy computational load, but Monte Carlo simulations are indispensable for the present purpose to evaluate the EEG by tracking microscopic electron behavior. From this point of view, a simple and less-loading model is preferable as long as the primary factors to reproduce the partial resonance can be considered relevantly, and such a model would at the same time free the analysis from the effects that make the essential mechanism of the focused phenomenon unclear.

2.1 Chamber dimensions and coordinates

Figure 1 shows the reactor assumed in the present work. The chamber is a cylinder with a 40.0-cm inner diameter and a 40.0-cm height as assumed in previous work.^{11,17,19} The origin of position (x, y, z) in a Cartesian coordinate or (r, θ, z) in a cylindrical coordinate is the center of the chamber. Here, r is the radial position, z is the axial position, and θ is the azimuthal angle. They are in relations of $x = r \cos \theta$, $y = r \sin \theta$, and $r^2 = x^2 + y^2$. The chamber radius is $R_C = 20.0$ cm, and the z positions of the chamber top and bottom are $Z_T = +20.0$ cm and $Z_B = -20.0$ cm, respectively.

The reactor has two DC coils to apply magnetic field $\mathbf{B}_{\text{DC}}$ and a one-turn RF antenna to induce RF electric field $\mathbf{E}_{\text{RF}}(t)$. Example distributions of the electric and magnetic fields are presented in Figs. 1–3; Fig. 1 shows those of $\mathbf{B}_{\text{DC}}$ and the amplitude of $\mathbf{E}_{\text{RF}}(t)$, Fig. 2 shows the RF magnetic fields $\mathbf{B}_{\text{RF}}(t)$ induced by the RF antenna current, and Fig. 3 shows variations of $\mathbf{B}_{\text{DC}}$. In order to examine the three discussion points mentioned in Sect. 1, the RF antenna position and the magnetic field strength are varied (Figs. 3(a) and 3(b)). Furthermore, the antenna position is varied also for an attempt to enhance the EEG by the partial resonance in the resonant region focusing on the path of magnetic field lines (Fig. 3(c)). They are detailed in the following sections.

2.2 DC coils and magnetic fields

The CDMFs are applied by two 36-turn coaxial circular DC magnetic coils, the upper and lower coils, with a thickness of $4.0 \text{ cm} \times 4.0 \text{ cm}$. The z positions of their centers are $Z_U = +10.0$ cm and $Z_L = -10.0$ cm. Their inner and outer radii are 24.0 and 28.0 cm, respectively. The separation between the coils is set narrower than in previous work to allow a wider resonant region to be defined later.

It is assumed that the currents of the upper and lower coils are commonly I_{DC} but opposite as $I_U = +I_{\text{DC}}$ and $I_L = -I_{\text{DC}}$. We set $I_{\text{DC}} = 13.3, 16.7$, and 20.0 A. These values correspond to 480, 600, and 720 ampere-turns (AT), respectively. We represent the strength of the CDMFs in AT hereafter.

Figure 1 shows typical CDMFs calculated on the basis of the Biot–Savart law at 600 AT. $\mathbf{B}_{\text{DC}}$ has only the radial and axial components, $B_{\text{DC},r}$ and $B_{\text{DC},z}$, respectively. $|\mathbf{B}_{\text{DC}}| = B_{\text{DC}} = 0$ at the X point at $(0, 0, 0)$. The separatrix of the CDMFs formed at $z = 0$ separating the upper and lower regions has a function of electron confinement as it prevents straightforward electron passage from one region to the other. B_{DC} increases outward from the X point, and the X point is surrounded by a spheroid-like region of $B_{\text{DC}} = B_{\text{ECR}}$ under a strong magnetic field. Here, the resonant magnetic field strength B_{ECR} satisfies $B_{\text{ECR}} = 2\pi(m/e)f_{\text{AC}}$, where f_{AC} is the frequency of the applied AC electric field. Especially, $B_{\text{ECR}} = 0.4844$ mT at a specific value $f_{\text{AC}} = f_{\text{RF}} = 13.56$ MHz as defined later. The broken curve, one-dotted chain, and two-dotted chain in Fig. 1 represent the equi-strength contours for $B_{\text{DC}} = 0.5B_{\text{ECR}}, 1.0B_{\text{ECR}}$, and $1.5B_{\text{ECR}}$, respectively.

In this analysis, we define the ‘resonant region’, which is focused on to evaluate the partial resonance, as the region of $0.5B_{\text{ECR}} \leq B_{\text{DC}} \leq 1.5B_{\text{ECR}}$. There is no established or commonly accepted definition for the magnetic field strength range of the resonant region, while B_{ECR} itself is well-defined. In preceding work dealing with the QMF or the CDMFs, the equi-strength contours of $B_{\text{DC}} = 1B_{\text{ECR}}$ and $2B_{\text{ECR}}$ have often

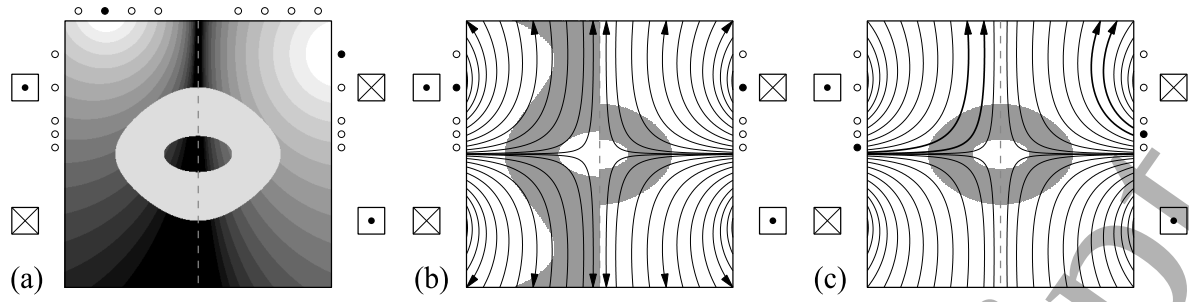


Fig. 3. Arrangements of RF antenna and DC magnetic coils to examine the dependence of the EEG on (a) electric field distribution, (b) magnetic field strength, and (c) path of near-antenna magnetic field lines. The full and open circles beside the chamber ceiling and sidewalls represent RF antenna positions (the full circles represent operative ones). The amplitude of $E_{RF}(t)$ at some representative positions in (a) is about 396 V/m (maximum) near the RF antenna and 35 V/m at $(r = R_C, z = 0)$ (left); and about 479 V/m near the RF antenna and 106 V/m at $(r = R_C, z = 0)$ (right). It decays inward to zero at $r = 0$. Its scale is logarithmic scale. The dots and crosses in the squares indicate the directions of the DC currents flowing through the magnetic coils. Arrows and curves are magnetic field lines. The resonant regions of $0.5B_{ECR} \leq |B_{DC}| \leq 1.5B_{ECR}$ are indicated by the shaded areas, where $B_{ECR} = 0.4844$ mT at $f_{RF} = 13.56$ MHz. The magnetic field strength is 600 AT for (a), 480 and 720 AT for (b), and 720 AT for (c).

been shown as a measure. Such contours have been referred to in demonstrations of the partial resonance and the resulting EEG in relation to the ECR,^{11,18,22–24} or to indicate the electron confinement region²⁵ and a rough boundary around which the electron motion changes from meandering to gyration.^{2,26–28} The present resonant region is set with widths of $\pm 0.5B_{ECR}$ for the both sides of $B_{DC} = B_{ECR}$.

The RF magnetic field $B_{RF}(t)$ induced by the RF antenna current is superposed to B_{DC} to obtain $B(t) = B_{DC} + B_{RF}(t)$ (see Fig. 2). The amplitude of $B_{RF}(t)$ at the X point is at most a few percent of B_{ECR} in the present conditions as specified in the following section. $B_{RF}(t)$ is set to lead $E_{RF}(t)$ by 90° as assumed in electron swarm analyses for ICPs.^{29–32} Nonetheless, this treatment did not cause substantial difference in the results of the EEG qualitatively within the present conditions. Here, the resonant region defined above on the basis of B_{DC} is time-invariant.

2.3 RF antenna and electric fields

$E_{RF}(t)$ is applied by a one-turn RF antenna equipped on the top or the side of the chamber. Let us call these arrangements the ceiling and sidewall arrangements, respectively. The antenna is placed in the region of $z > 0$, i.e. above the separatrix, in order to examine the EEG under conditions that the plasma confinement is operative. The antenna position is varied as follows. For the ceiling arrangement, which is a conventional arrangement, the effective antenna height Z_A is set at 21.5 cm and the effective antenna radius R_A is varied to be 6.0, 10.0, 14.0, 18.0 cm. For the sidewall arrangement, $R_A = 21.5$ cm and $Z_A = 1.0, 3.0, 5.0, 10.0, 15.0$ cm. This antenna height range has been extended from that examined in the preceding work.²¹ The tendency of the partial resonance is observed both for the ceiling and sidewall arrangements in the present paper. The amplitude of the AC antenna current is $I_A = 10.0$ A, and its frequency is $f_{RF} = 13.56$ MHz. This AC current induces $B_{RF}(t)$. We newly considered the action of $B_{RF}(t)$ on the electron motion, extending the conventional simulation model,^{20,21} but its influence on the EEG in the resonant region was small.

$E_{RF}(t)$ is assumed to have only the azimuthal component $E_\theta(r, z, t)$, which is sinusoidal as

$$E_\theta(r, z, t) = E_{\max}(r, z) \sin 2\pi f_{RF} t. \quad (1)$$

Here, the amplitude $E_{\max}(r, z) \geq 0$ is given as a two-variable function under the cylindrical symmetry of the system. The instantaneous values of the components of $E_{RF}(t)$ at (r, θ, z) are given as

$$E_{RF}(t) = (E_{RF,x}(t), E_{RF,y}(t), E_{RF,z}(t)) \quad (2)$$

$$= (-E_\theta(r, z, t) \sin \theta, +E_\theta(r, z, t) \cos \theta, 0). \quad (3)$$

It has been reported that a plasma sheath near the sidewall enhances the EEG.³³ Then, we adopt a simplified sheath model assuming a time-invariant sheath electric field E_S with a constant sheath thickness d_s and a constant voltage drop V_S . This model represents the electrical neutrality of the plasma bulk and a situation that the charged particles have formed a kind of steady-state distribution. Reports on the sheath of magnetized ICPs are rare, however, we assume $d_s = 0.5$ cm and $V_S = 40.0$ V considering measurements of sheath electric fields of ICPs.^{34,35} Comparable order of potential is observed also in a result of fluid-model ICP simulation.³⁶ $E_{RF}(t)$ is superposed to E_S as $E(t) = E_{RF}(t) + E_S$. Nonetheless, in preliminary simulations, the sheath field did not cause substantial change in the fundamental profile of the EEG in the resonant region, perhaps because the resonant region is formed mainly in an inner region distant from the sheath.²⁰ Qualitative profiles of the EEG seen in early models not considering the sheath would be still valid to some extent.

2.4 Tracking of electrons

The initial electrons were supplied at $t = 0$ from the chamber ceiling or the sidewall near the RF antenna with initial velocities chosen at random from a Maxwellian distribution with a mean energy of 1.0 eV. Their start position was assumed to be uniform for the area on the ceiling or the sidewall in a range between $r = R_A \pm \frac{1}{2}W$ on the ceiling and $z = Z_A \pm \frac{1}{2}W$ on the sidewall, where $W = 1.0$ cm.

The electron trajectory was calculated by solving the following electron motion equations using the Runge–Kutta method for every time step Δt :

$$\frac{d\mathbf{v}}{dt} = -\frac{e}{m} [\mathbf{E}(t) + \mathbf{v} \times \mathbf{B}(t)], \quad (4)$$

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}, \quad (5)$$

where $\mathbf{r} = (x, y, z)$ and $\mathbf{v} = (v_x, v_y, v_z)$ are the position and velocity of an electron, and e and m are the electronic charge and mass, respectively. Δt was chosen to be 3.7 ps, which is $1/24\,000$ of the RF period $T_{\text{RF}} = 1/f_{\text{RF}} = 73.7$ ns and sufficiently fine to draw an electron gyration locus.

Electrons were tracked until $t = 100T_{\text{RF}}$, by which the initial electrons diffused over the chamber and electron swarm parameters such as the mean electron energy reached their periodic steady-state values. The electrons were sampled during $80T_{\text{RF}} \leq t \leq 100T_{\text{RF}}$ to exclude the profile of the electron distribution under the influence of the initial relaxation phase. The number of electrons was 10^6 or more at the end of the simulation, which has been increased tenfold from that in the preceding calculation²⁰⁾ to reduce statistical fluctuation.

The gas was assumed to be Ar at 0.67 Pa at 300 K. The occurrence of the collisional events was judged by a time-saving scheme³⁷⁾ using random numbers on the basis of the collision probability. The set of electron collision cross sections of Ar³⁸⁾ referred to for the collision probability in the present simulations includes processes of elastic collision, excitation, and ionization. Perfect elastic reflection was assumed at the chamber wall.

2.5 Sampling sections

The chamber space (r, θ, z) is mapped onto two-variable space (r, z) under the assumption of cylindrical symmetry, and the rz -space is partitioned into sections for every Δr and Δz for electron sampling. The (i, j) th sampling section $S_{i,j}$ is defined as the region of $(i-1)\Delta r \leq r < i\Delta r$ and $(j-1)\Delta z + Z_B \leq z < j\Delta z + Z_B$. The resolution was set as $\Delta r = \Delta z = 0.5$ cm, thus i and j range $1 \leq i \leq 40 = R_C/\Delta r$ and $1 \leq j \leq 80 = (Z_T - Z_B)/\Delta z$, respectively.

2.6 Electron energy gain

We define the EEG, G , as the energy gained by an electron per unit time in a sampling section. The G value is represented using ‘the EEG unit’ in this paper. This unit is $\text{eV} \cdot (\text{RF period})^{-1} \cdot (\text{electron})^{-1}$, and 1 EEG unit is converted as $G = e \times (1 \text{ V})/T_{\text{RF}} = 2.17 \times 10^{-12}$ W per electron. G is such a quantity that $n_e G$ gives the power absorption density by electrons, where n_e is the electron number density, and we may estimate the total deposited power to the plasma by integrating $n_e G$ over the space in the chamber.

The sampling for the EEG in $S_{i,j}$ was done as follows with the k th electron:

$$G(S_{i,j}, t) = \left(\sum_{r_k \in S_{i,j}} \Delta \varepsilon_k(t) / \Delta t \right) / \left(\sum_{r_k \in S_{i,j}} 1 \right), \quad (6)$$

$$\Delta \varepsilon_k(t) = \varepsilon_k(t) - \varepsilon_k(t - \Delta t), \quad (7)$$

$$\varepsilon_k(t) = \frac{1}{2} m \{ [v_{x,k}(t)]^2 + [v_{y,k}(t)]^2 + [v_{z,k}(t)]^2 \}. \quad (8)$$

The electron energy loss by the inelastic collisions was sampled separately. In addition, the G value in a sampling section does not include neither the decrease of energy brought out by the electron flying out of the section to another nor the increase of energy brought in by the electron flying into the section from another. This is in order that the EEG represents only the energy increase or decrease during the flight in the sampling section. Otherwise, G becomes undesirably zero when an electron passes through a sampling section without

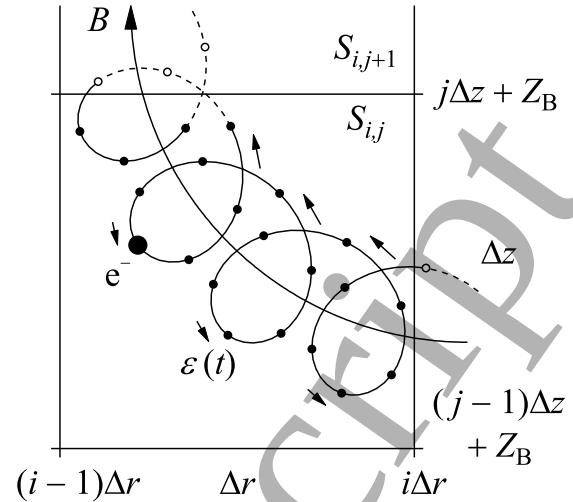


Fig. 4. Schematic of EEG sampling. The full circles on the electron locus represent the EEG sampling positions that $\Delta \varepsilon(t)$ is added to G of $S_{i,j}$.

collision even though it obtains energy in the section.

3. Results and discussion

3.1 Dependence of EEG on electric field distribution

Figure 5 shows the EEG in $B(t)$ with B_{DC} at 600 AT. $Z_A = 21.5$ cm, and $R_A = 6.0, 10.0, 14.0, 18.0$ cm in the ceiling arrangement. The high EEG near the RF antenna is due to high electric field. On the high EEG near the sidewall, it has been reported that the directionality of the azimuthal electron drift caused by the electron reflection at the sidewall contributes to the EEG stochastically,¹⁸⁾ and the EEG is enhanced in the presence of the sheath electric field.³³⁾ As R_A increases, the amount of energy supplied to electrons in the chamber increases, the region of high EEG becomes wider, and the EEG in the resonant region tends to increase.

Figure 6 shows the EEG in $B(t)$ with B_{DC} at 600 AT. $R_A = 21.5$ cm, and Z_A is varied to be 5.0, 10.0, and 15.0 cm in the sidewall arrangement. The EEG tends to be higher in the resonant region, even when the antenna becomes far away from the resonant region and the electric field strength becomes weaker there.

3.2 Dependence of EEG on magnetic field strength

Figure 7 shows the EEG in $B(t)$ with B_{DC} at 480, 600, and 720 AT. $Z_A = 10.0$ cm and $R_A = 21.5$ cm in the sidewall arrangement. The EEG tends to be higher in the resonant region as well as near the RF antenna and sidewall commonly at different I_{DC} values. This tendency is similar to the result mentioned in the previous section. With increasing I_{DC} , the EEG tends to lower and the resonant region becomes narrower. However, the EEG is still locally high in the resonant region. This feature would be beneficial for sustainment of those plasmas which are controlled by magnetic field, because it has a possibility to lead to a technique of position-selected energy deposition to electrons.

3.3 EEG results in chosen cases for enhancement of the partial resonance

Figure 8 shows the EEG in $B(t)$ with B_{DC} at 720 AT. $R_A = 21.5$ cm, and Z_A is varied to be 1.0, 5.0, 10.0, and 15.0 cm in

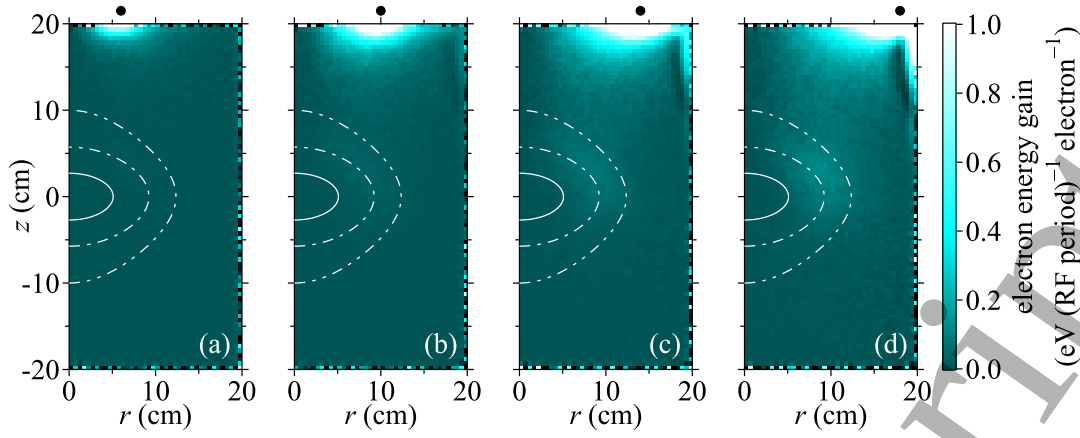


Fig. 5. EEG at various radii (a) $R_A = 6.0$ cm, (b) 10.0 cm, (c) 14.0 cm, and (d) 18.0 cm in $B(t)$ with B_{DC} at 600 AT in the ceiling arrangement. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

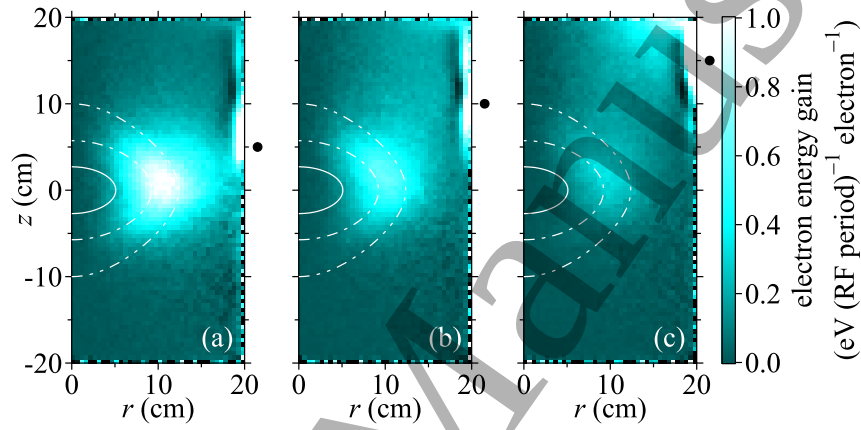


Fig. 6. EEG at various heights (a) $Z_A = 5.0$ cm, (b) 10.0 cm, and (c) 15.0 cm in $B(t)$ with B_{DC} at 600 AT in the sidewall arrangement. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

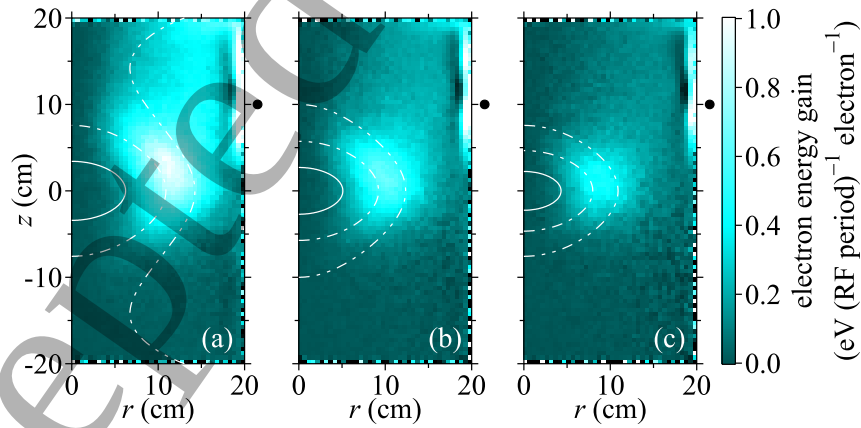


Fig. 7. EEG in various $B(t)$ with B_{DC} at (a) 480 AT, (b) 600 AT, and (c) 720 AT at $Z_A = 10.0$ cm in the sidewall arrangement. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

the sidewall arrangement. As the RF antenna becomes closer to the separatrix, the path of magnetic field lines starting from the near-antenna region approaches the resonant region (see Fig. 3(c)), and the EEG is more enhanced.

Figures 9 and 10 show distributions of electron number

density $n_e(r, z)$ and mean electron energy $\langle \epsilon \rangle(r, z)$, respectively. The conditions for Figs. 9 and 10 are the same as for Fig. 8.

In Fig. 9(a) at $Z_A = 1.0$ cm, it is observed that n_e is high along the magnetic field lines starting from the near-

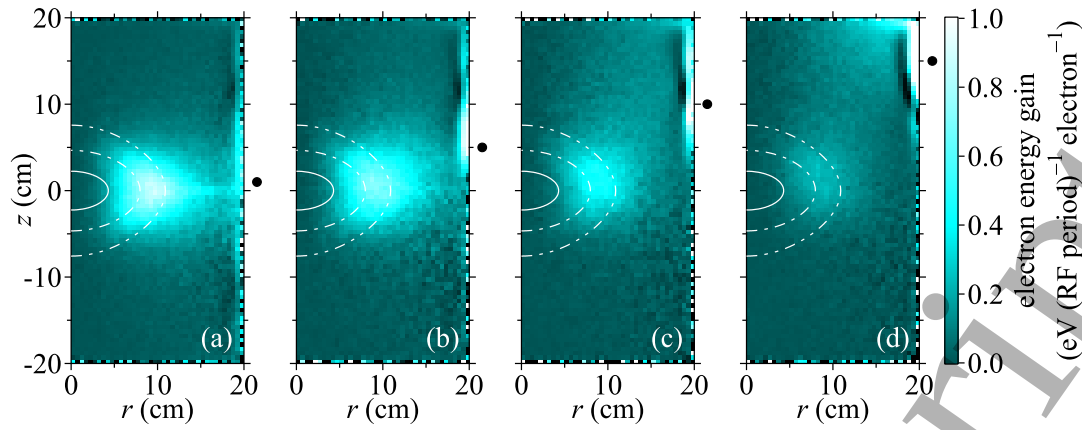


Fig. 8. EEG at various antenna heights (a) $Z_A = 1.0$ cm, (b) 5.0 cm (c) 10.0 cm, and (d) 15.0 cm in **B** at 720 AT in the sidewall arrangement. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

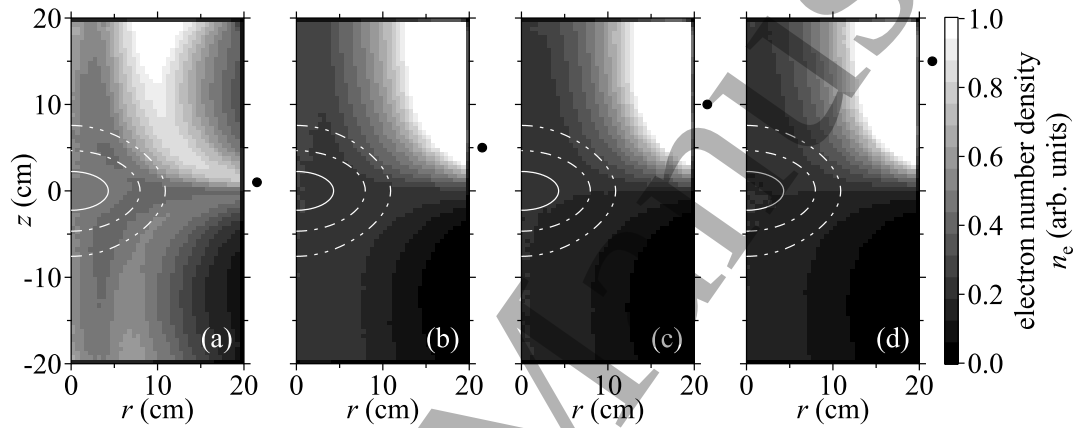


Fig. 9. Electron number density n_e at various antenna heights (a) $Z_A = 1.0$ cm, (b) 5.0 cm (c) 10.0 cm, and (d) 15.0 cm in **B** at 720 AT in the sidewall arrangement. n_e has been converted to such values that the total electron population in the chamber is the same among (a)–(d) and they can be depicted in a common scale. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

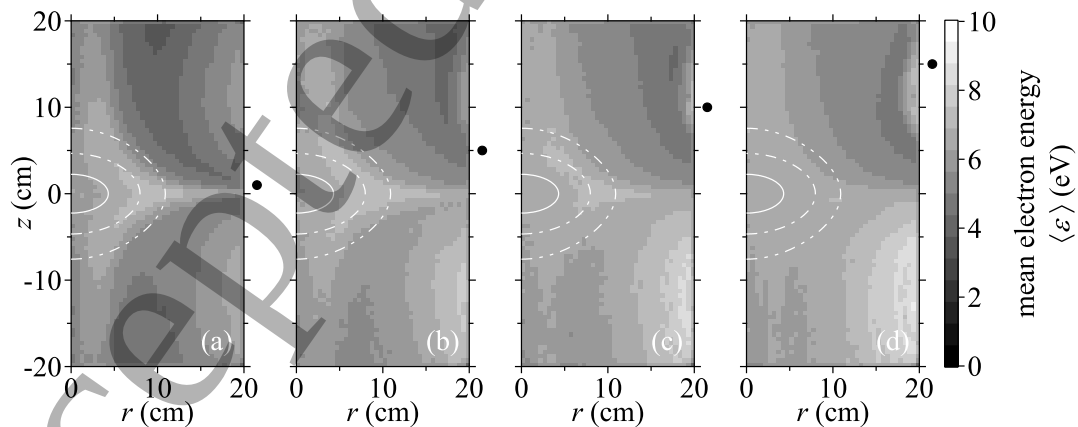


Fig. 10. Mean electron energy $\langle \epsilon \rangle$ at various antenna heights (a) $Z_A = 1.0$ cm, (b) 5.0 cm (c) 10.0 cm, and (d) 15.0 cm in **B** at 720 AT in the sidewall arrangement. The full circles indicate the RF antenna positions. The contours represent B_{DC} ; —, $0.5B_{ECR}$; — · —, $1.0B_{ECR}$; and — · · —, $1.5B_{ECR}$.

antenna region. The magnetic field binds electrons and prevents them diffusing across the magnetic field lines. Similarly, in Figs 9(b)–(d) at $Z_A = 5.0$ –15.0 cm, electrons are trapped

near the upper DC coil by its strong magnetic field.

In Fig. 10, $\langle \epsilon \rangle$ is high around the resonant region. Especially in Figs. 10(a) and 10(b) at $Z_A = 1.0$ and 5.0 cm, respec-

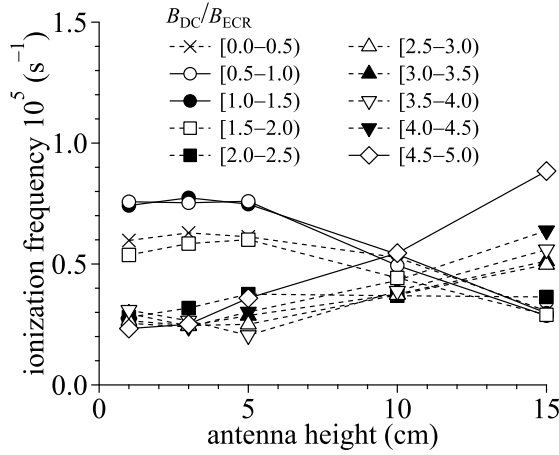


Fig. 11. Ionization frequency ν_{ion} in regions resolved according to B_{DC} at 720 AT at various antenna heights Z_A in the sidewall arrangement.

tively, high $\langle \epsilon \rangle$ values are clearly observed along the magnetic field lines that pass through the resonant region. This feature is similar to an experimental result,³⁹⁾ where high electron temperature regions are observed along magnetic field lines passing near the RF antenna, although the setup is different. Here, ridges of n_e in Fig. 9(a) and $\langle \epsilon \rangle$ in Fig. 10(a) do not overlap. Similar results are seen in reports on simulations of NLD plasmas.^{23,40)} The high $\langle \epsilon \rangle$ values observed near the lower DC coil under the separatrix (Fig. 10) represent that only high-energy electrons can escape the confinement of the CDMFs, but such electrons are rare as seen in the n_e profile in Fig. 9.

Next, we examine the possibility of the enhancement of the EEG by placing the RF antenna near the magnetic field lines that pass through the resonant region. For the evaluation of the EEG enhancement, ionization frequency ν_{ion} is calculated in regions sectioned on the basis of the B_{DC} value. The regions were set in a range of $0 \leq B_{\text{DC}} \leq 5.0B_{\text{ECR}}$ in steps of $0.5B_{\text{ECR}}$, which is finer than in the preceding work.²⁰⁾ The EEG enhancement due to the partial resonance would be identified clearly by this new treatment. Here, note that the high EEG region does not show directly the ionization position. High-energy electrons accelerated near the antenna advect along the magnetic field lines, around some of them undergo ionization. The present effort aims to combine the electron acceleration under high electric fields and the partial resonance in the resonant region by utilizing the electron transport along the magnetic field lines connecting the two regions.

Figure 11 shows ν_{ion} values in the regions resolved according to B_{DC} for every $0.5B_{\text{ECR}}$ at 720 AT. ν_{ion} in the resonant region (plotted with 'o' for the region of $0.5B_{\text{ECR}} \leq B_{\text{DC}} < 1.0B_{\text{ECR}}$ and '•' for the region of $1.0B_{\text{ECR}} \leq B_{\text{DC}} < 1.5B_{\text{ECR}}$) tends to be high similarly to the EEG, when the antenna is placed near the separatrix. ν_{ion} in the resonant region increases as the antenna becomes closer to the separatrix because electrons may advect mutually between the resonant region and the near-antenna region along the magnetic field lines and they may obtain energy both by the partial resonance in the resonant region and from high electric fields of the near-antenna region. The enhancement of ν_{ion} in the resonant region indicates a synergy effect between the partial resonance and the high electric fields near the antenna.

On the other hand, ν_{ion} at high antenna positions is high also in the strong magnetic field region of $4.5B_{\text{ECR}} \leq B_{\text{DC}} \leq 5.0B_{\text{ECR}}$ in Fig. 11. It is suggested that this tendency becomes more significant under stronger magnetic field up to $6.0B_{\text{ECR}}$ by the present calculation although it is not shown for statistical instability. In such a region, near the antenna and upper DC coil, where both n_e and $\langle \epsilon \rangle$ are high, the both ends of magnetic field lines inside the chamber are on the sidewall. Electrons reflect at the sidewall and reciprocate along such magnetic field lines. Those electrons which cannot escape from the strong magnetic field region are accelerated for a long period by the high electric fields near the antenna. This effect is different from the partial resonance; however, this would be applicable to energy deposition to electrons in addition to the partial resonance.

4. Conclusion

The microscopic behavior of the electrons in a low-pressure ICP under CDMFs is analyzed by a Monte Carlo method. The EEG and ionization frequency ν_{ion} were observed at various antenna positions and magnetic field strengths, and the dependence of the EEG on the conditions was investigated. The results are summarized as follows.

- EEG dependence on electric field distribution (dependence on R_A and Z_A). In the ceiling arrangement, the EEG is higher when the effective antenna radius R_A becomes larger. In the sidewall arrangement, the EEG in the resonant region tends to be lower when the antenna position becomes far away from the resonant region. However, the EEG there is locally higher than in its surround region. This indicates that the partial resonance remains even under lower electric fields.
- EEG dependence on magnetic field strength (dependence on I_{DC}). The EEG in the resonant region lowers when magnetic field becomes stronger. However, the EEG in the resonant region is locally high even under strong magnetic field as is observed in (a).
- EEG results in chosen cases for enhancement of the partial resonance. Promotion of ionization utilizing the partial resonance in the resonant region was demonstrated by appropriate choice of the antenna position. The antenna was placed near the magnetic field lines passing through the resonant region, along which high n_e and $\langle \epsilon \rangle$ are observed. The electrons accelerated under high electric fields near the antenna are guided efficiently by the magnetic field lines mentioned above to the resonant region, and they have further opportunity of energy gain there by the partial resonance. As the result, the ionization in the resonant region increases. Thus, by designing magnetic field, we can expect collaboration between the partial resonance in the resonant region and electron acceleration under high electric fields near the antenna.

On the other hand, as another mechanism of energy deposition to electrons, high ν_{ion} in strong magnetic field was observed at a specific case that the antenna is placed near the upper DC coil. At that time, the both ends of magnetic field lines inside the chamber are on the sidewall, and electron heating continues for a long period because the electrons can hardly escape from the binding by the magnetic field lines. This effect would also have a possibility to contribute to the plasma sustainment.

It was confirmed that the partial resonance occurs even in low electric fields and in strong magnetic fields. The enhancement of ionization utilizing the partial resonance would be applicable to the plasma sustainment at low pressures. The present analysis is of a short time scale in which only electrons move. Simulations for more realistic plasma operation with consideration of phenomena proceeding with a longer time scale, such as ion transport and accumulation of excited species, would be performed as succeeding work utilizing the findings and outcome data by the present model. Essential features observed in the present work would be informative for establishing the guidelines for the design and control of plasma reactors to be developed in the future.

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