

Enhanced plasma production by ambipolar electric fields in convergent magnetic fields

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Controlled unidirectional remote plasma production in a radio-frequency (rf) plasma source is demonstrated by placing magnetic nozzle throat several tens of centimeters away from the rf antenna, where a local density peak forms near the throat. The experiment indicates that the dominant electron energization mechanism responsible for the density peak in the magnetic nozzle throat is electrostatic electron acceleration driven by a spontaneously formed ambipolar electric field, yielding an energy gain of approximately 5 eV and enhanced remote ionization. These results establish plasma sources driven by spontaneous electrostatic electron acceleration.

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I. INTRODUCTION

Energization of electrons is essential for plasma generation in both laboratory and natural environments, as it gives rise to a variety of natural phenomena and plasma sources. In Earth's magnetosphere, electrons are accelerated via wave-particle interactions with whistler-mode chorus waves [1,2]. In the ionosphere, satellite observations have revealed electrostatic electron acceleration by quasi-steady-state electric fields near the Earth poles, leading to auroral emissions [3,4]. In laboratory plasmas, radio-frequency (rf) heating in the megahertz range has been widely employed in industrial plasma processes, particularly in micro- and nanoelectronics [5]. rf plasma sources are commonly classified according to their energy coupling mechanisms into capacitive, inductive, and wave coupling sources [6]. Under a static magnetic field, a helicon wave, which is the whistler mode in bounded plasmas, can propagate in magnetized plasmas and transfer its energy to electrons [7], providing a high plasma density exceeding 10^{18} – 10^{19} m⁻³ with only a few kilowatts of rf power.

Recent experiments have reported the formation of a high-density plasma at an axial position far from the rf antenna in nonuniform magnetic field configurations, where the density peak appears near the throat of a convergent-divergent magnetic field structure known as a magnetic nozzle (MN) [8–10]. This density peak has been observed even in the absence of helicon-wave propagation [8] or under the condition that the energy transfer by a helicon wave is not effective [11,12]. Although the nonlocal transport of electrons heated by the antenna field has been discussed [13], the mechanism of electron

energization responsible for the density peak away from the antenna has remained an unresolved issue.

In this article, we show that an axial ambipolar electric field is formed along the convergent magnetic field, accelerating electrons from the source toward the MN throat with an energy gain of 5 eV. This acceleration enhances ionization near the throat through an increase in the ionization rate constant. It is further demonstrated that this mechanism enables controlled unidirectional remote plasma production by locating the MN throat on either side of the rf source.

II. EXPERIMENTAL SETUP

Experiments are conducted using a 6.5-cm-inner-diameter and 35-cm-long pyrex glass source tube an external double-turn rf antenna at the center (defined as $z = 0$, as in Fig. 1). Both open ends of the source tube are connected contiguously to 13.5-cm-inner-diameter and 50-cm-long pyrex glass chambers. These chambers are further connected to grounded stainless steel vacuum chambers evacuated by turbomolecular pumps to a base pressure below 10^{-4} Pa. Argon gas is introduced through gas inlets at the stainless steel chambers and regulated by mass flow controllers. The flow rates at the left and right sides are each maintained at 20 sccm, providing a pressure of 0.2 mPa. Ionization gauge measurements confirm that the pressures on both sides are equal. Fourteen solenoids are arranged around the source tube, the pyrex chambers, and the stainless steel chambers, which are labeled as “L1–L7” and “R1–R7” for the left and right sides, respectively. In the present experiments, only the solenoids L3–L5 and R3–R5 are powered to place the MN throat several tens of centimeters away from the antenna. The antenna is powered by a 13.56 MHz rf generator through an impedance matching box consisting of two variable capacitors. A plasma brighter than that near the antenna is visually confirmed near the MN throat, and a blue discharge of strong optical emissions from argon ions is confirmed for rf powers above several hundred watts.

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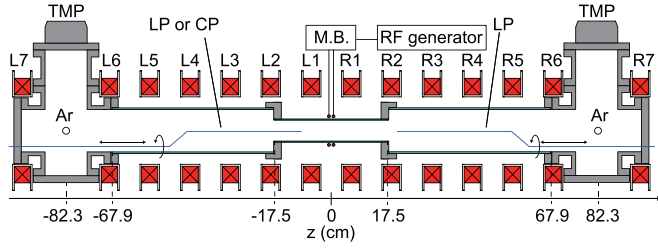


FIG. 1. Schematic of the experimental setup.

Radially facing, 3-mm-diameter planar Langmuir probes (LPs) are inserted through vacuum ports on the end flanges, as shown in Fig. 1, to measure the ion saturation current I_{is} , which serves as a qualitative indicator of plasma density. The probe shafts are mounted on axially movable stages, allowing both axial and approximately radial scans. Because the I - V characteristic of the LP is known to be distorted by rf potential oscillations, an rf-compensated Langmuir probe (CP) [14] is installed on the left-hand side when measuring the electron energy probability function $g_p(\varepsilon)$ (EEPF) as a function of electron energy ε . The CP has a 0.15-mm-radius and 3-mm-long cylindrical tungsten tip, oriented perpendicular to the z axis. The tip radius is smaller than the electron gyroradius calculated using the electron thermal velocity ($\sim 1.6 \times 10^6$ m/s) and the maximum magnetic field (~ 465 G). The EEPF is obtained from the second derivative of the I - V curve using a classical analog differentiation technique [15]. It is noted that the Druyvesteyn method has been validated in the energy range where the electron gyroradius is larger than the probe radius, corresponding to energy level above 5 eV even at the maximum field strength [16]. The effective electron temperature T_{eff} , being equivalent to a mean energy of electrons, is calculated from the measured EEPF $g_p(\varepsilon)$ by $T_{eff} = 2/3(\int \varepsilon \sqrt{\varepsilon} g_p(\varepsilon) d\varepsilon) / (\int \sqrt{\varepsilon} g_p(\varepsilon) d\varepsilon)$, and the local plasma potential V_p is determined from the zero-crossing point of the second derivative.

III. EXPERIMENTAL RESULTS

Four types of magnetic field configurations [labeled as B_{L23} and B_{L34} in Fig. 2(a), and B_{R23} and B_{R34} in Fig. 2(b)] are tested and their axial profiles are shown in Fig. 2. In each configuration, a solenoid current of 30 A is supplied to the solenoids indicated by the subscripts; e.g., the solenoids (L2, L3) and (R2, R3) are powered for B_{L23} and B_{R23} , respectively. Axial profiles of I_{is} of the LPs at an rf power of 500 W are plotted by filled and open circles in Figs. 2(a) and 2(b), together with the corresponding magnetic field strengths. In all cases, a density peak clearly appears near the MN throat, i.e., at the axial position where the magnetic field reaches its maximum. Comparisons between B_{L23} and B_{L34} , and between B_{R23} and B_{R34} , show that the axial position of the density peak shifts together with the MN throat, consistent with previous observations [8]. By placing the MN throat on either the left or right side, controlled unidirectional plasma production is achieved, showing the contribution of convergent magnetic field lines on the density peak formation. It is also confirmed that the rf power has no significant influence on the formation of the density peak at the MN throat (data not shown).

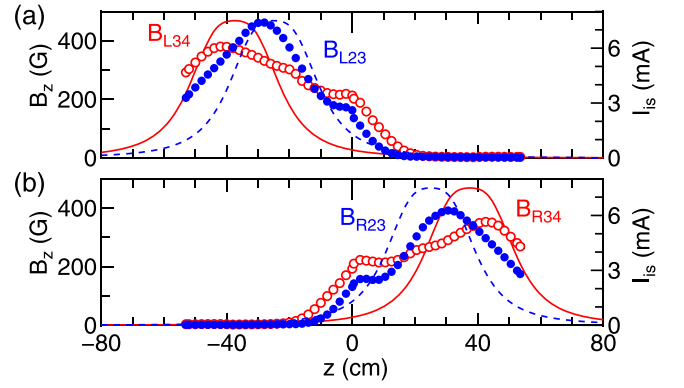


FIG. 2. Axial profiles of the ion saturation current I_{is} (filled and open circles) and magnetic field strength (dotted and solid lines) for the configurations of (a) B_{L23} (blue) and B_{L34} (red), and (b) B_{R23} (blue) and B_{R34} (red).

To further clarify the spatial structure, two-dimensional maps of I_{is} of the LPs are taken for the configurations B_{L34} and B_{R34} as shown in Figs. 3(a) and 3(b), respectively, together with the calculated magnetic field lines (white lines). The values of I_{is} at the MN throat are found to be larger than that near the antenna over the entire radial region of the measurement. This observation indicates that the high-density plasma at the throat is not simply formed by focusing plasma from the source along the convergent magnetic field lines. Instead, the density peak seems to result from ionization occurring at the throat, which is located several tens of centimeters away from the antenna.

Figures 4(a)–4(c) show the two-dimensional maps of I_{is} , T_{eff} , and V_p measured with the CP inserted from the left side for the configuration B_{L23} , together with the magnetic field lines (white lines), where the rf power is reduced to 300 W to prevent thermal damage to the CP. The maximum plasma density estimated from I_{is} and T_{eff} is about $2.5 \times 10^{18} \text{ m}^{-3}$. Figure 4(d) shows the measured typical EEPFs on the z axis at various axial positions. A high electron temperature region

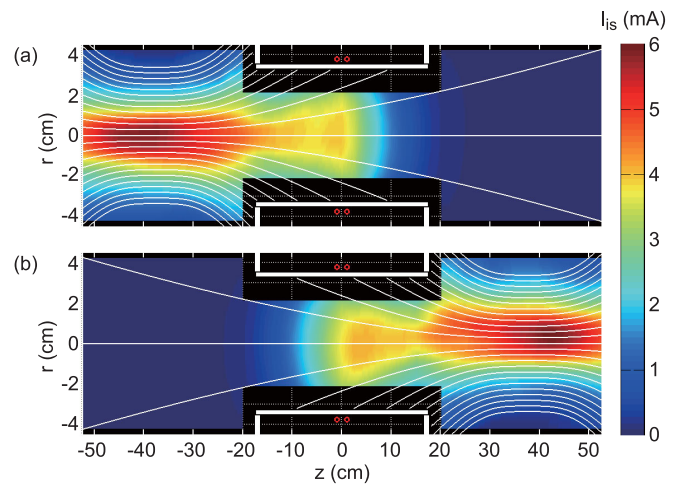


FIG. 3. Two-dimensional maps of the ion saturation current I_{is} for the configurations (a) B_{L34} , (b) B_{R34} , and (c) B_{LR34} . White lines show the calculated magnetic field lines.

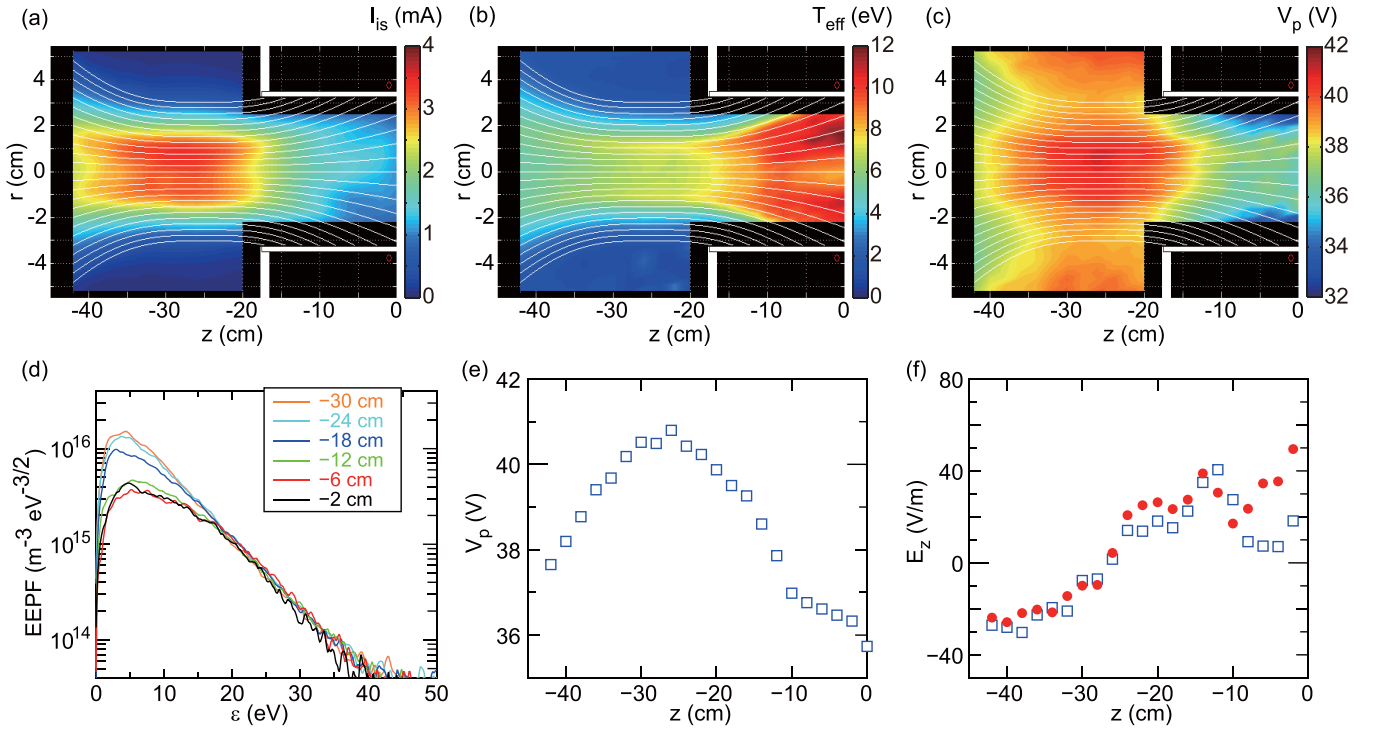


FIG. 4. Two-dimensional maps of (a) the ion saturation current I_{is} , (b) the effective electron temperature T_{eff} , and (c) the local plasma potential V_p measured by the CP on the left side, together with the magnetic field lines (white lines). (d) Representative EEPFs on the z axis at various axial position z . (e) On-axis profile of V_p . (f) Ambipolar electric field estimated from the on-axis data of I_{is} and T_{eff} (red filled circles), together with the actual electric field obtained from the data in panel (e).

is formed near the antenna ($z \sim 0$) and follows the convergent magnetic field lines, and the electron temperature decreases at the left side ($z < -20$ cm) as seen in Fig. 4(b). The decrease in the temperature is found to be accompanied by an increase in I_{is} , i.e., the plasma density. Figure 4(d) shows an unchanged slope and magnitude in the EEPFs at energies above 20 eV, while low-energy electrons appear in the MN throat region ($z < -18$ cm). The larger amplitude of the EEPF curves in the low-energy range observed farther away from the antenna reflects the increases in the number of low-energy electrons and in the resultant local plasma density, being consistent with the density peak near the throat. These low-energy electrons are considered to result from local ionization in the throat region and lead to a decrease in the mean electron energy T_{eff} . Since this cooling process results from the energy transfer via ionization, it is different from the previously observed electron cooling in divergent magnetic fields, where electrons do work on the divergent magnetic field structure [17]. Although the detection of low-energy electrons could be reduced by a high magnetic field strength [16], the data show the increase in the magnitude of the EEPF for low-energy electrons in the high-field region. Therefore, the magnetic field effect on the EEPF measurement is unlikely to affect the interpretation of the EEPFs. Ionization processes are expected to contribute to isotropizing the EEPF, and the measured EEPF should therefore provide a reasonable approximation of the electron energy distribution.

Figure 4(e) shows the on-axis profile of V_p , indicating values of $V_p \sim 41$ V and $V_p \sim 36$ V near the throat and the antenna, respectively. It is considered that the plasma

is accumulated along the convergent field lines, causing the high plasma potential near the throat. Under the present low-pressure condition, where the spatial scale of the potential structure is shorter than collisional mean free path, this potential structure allows the electrons to be accelerated from the source toward the MN throat with an energy gain of approximately 5 eV, thereby enhancing the local ionization near the throat, as demonstrated later. Furthermore, the high potential in the MN would axially confine the low-energy electrons and sustain the high plasma density in the MN throat. It is noted that the EEPFs between the antenna and the throat would consist of a superimposition of the electrons accelerated from the antenna side toward the throat and the electrons traveling from the throat toward the antenna side by overcoming the potential drop. Since the electron density near the throat is enhanced by ionization, it would be difficult to clearly identify the accelerated electron component solely from the EEPF measurement.

To understand the formation of the axial electric field that accelerates electrons, a steady-state one-dimensional electron force balance neglecting the electron inertia term is considered. The on-axis electric field E_z , known as an ambipolar electric field, can be expressed as $en_p E_z = -dp_e/dz$, where e , n_p , and $p_e = en_p T_e$ are the elementary charge, the plasma density, and the electron pressure defined by the plasma density n_p and the electron temperature T_e in the unit of eV, respectively. The ion saturation current is generally given by $I_{is} = 0.61en_p u_B S$, where $u_B = \sqrt{eT_e/M}$ is the Bohm velocity, S is the collecting area of the Langmuir probe, and M is the ion mass. By combining these two equations for E_z and I_{is} , the

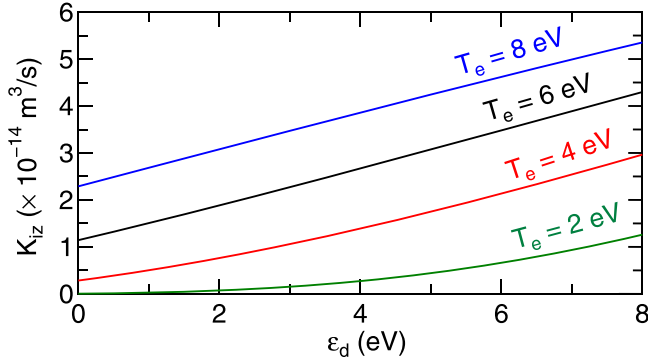


FIG. 5. Calculated ionization rate constant K_{iz} as a function of accelerated drift energy ϵ_d for various electron temperature, assuming a Maxwellian EEPF.

ambipolar electric fields can be expressed as

$$E_z = -\frac{\sqrt{T_e}}{I_{is}} \frac{d}{dz} (I_{is} \sqrt{T_e}). \quad (1)$$

The ambipolar electric field estimated from the on-axis data [Figs. 4(a) and 4(b)] using Eq. (1) is plotted in Fig. 4(f) (red filled circles), together with the actual electric field (blue open squares) determined from the measured plasma potential [Fig. 4(e)] using $E_z = -dV_p/dz$. The good agreement between the two calculations indicates the formation of an ambipolar electric field resulting from the density and temperature profiles. The ensuing potential hill at the throat accelerates electron toward the throat with an energy gain of ~ 5 eV.

The contribution of the ~ 5 eV acceleration to the ionization is discussed here by calculating the ionization rate constant K_{iz} for shifted Maxwellian EEPFs, where the shifted Maxwellian velocity distribution function $f(v)$ having a drift velocity u_d (a drift energy of $e\epsilon_d = mu_d^2/2$) in the z direction is written as

$$f(v) = \left(\frac{m}{2\pi k_B T} \right)^{3/2} \exp \left(-\frac{m}{2k_B T} [v_x^2 + v_y^2 + (v_z - u_d)^2] \right). \quad (2)$$

Here m , k_B , and T are the electron mass, the Boltzmann constant, and the electron temperature in kelvin, respectively. The ionization rate constant K_{iz} can be described with the ionization cross section $\sigma_{iz}(v)$ by

$$K_{iz} = \int_0^\infty \sigma_{iz} v f(v) d^3v, \quad (3)$$

where $v = \sqrt{v_x^2 + v_y^2 + v_z^2}$. By performing the velocity-space integration of Eq. (3) in spherical coordinates and using the electron temperature T_e in the unit of eV, K_{iz} can be written as

$$K_{iz} = \sqrt{\frac{2e}{\pi m \epsilon_d T_e}} \exp \left(-\frac{\epsilon_d}{T_e} \right) \int_0^\infty \sigma_{iz} \exp \left(-\frac{\epsilon}{T_e} \right) \times \sinh \left(\frac{2\sqrt{\epsilon_d \epsilon}}{T_e} \right) \sqrt{\epsilon_d \epsilon} d\epsilon. \quad (4)$$

The ionization cross section is assumed to be given by the Thomson cross section $\sigma_{iz}(\epsilon) = \alpha \pi (e/4\pi\epsilon_0)^2 (1/\epsilon)(1/\epsilon_{iz} - 1/\epsilon)$, where ϵ_0 and ϵ_{iz} are the vacuum permittivity and the ionization energy, respectively, and $\alpha = 6$, which is a coefficient to fit the approximate cross section with the actual one, is used here [18].

K_{iz} calculated from Eq. (4) are drawn by solid lines in Fig. 5 as a function of the drift energy ϵ_d for various values of T_e , indicating the increase in K_{iz} with increases in both T_e and ϵ_d . For typical electron temperature of $T_e = 8$ eV, the electron acceleration of $\epsilon_d = 5$ eV is found to yield an approximately double ionization rate constant compared with that for $\epsilon_d = 0$. This calculation qualitatively explains the enhanced ionization accompanying the electron acceleration of about 5 eV, which is induced by the spontaneously formed ambipolar electric field shown in Fig. 4. This energization mechanism seems to mimic the electron acceleration related with auroral emissions and proposes a distinct category of efficient plasma sources utilizing this spontaneous acceleration process in convergent magnetic fields.

IV. CONCLUSION

In summary, the controlled unidirectional remote plasma production in the rf plasma source is achieved by placing the MN throat several tens of centimeters away from the antenna. The plasma is considered to be accumulated along the convergent magnetic fields, causing the potential hill near the throat. Measurements indicate that the dominant electron energization mechanism responsible for the enhancement of ionization in the MN throat is the electrostatic electron acceleration driven by the spontaneously formed ambipolar electric field in the convergent magnetic field, where the measured results show the steady-state structure balancing the electron pressure and the axial electric fields. The resulting energy gain is approximately 5 eV, which enhances ionization as demonstrated by the analysis of the ionization rate constant considering the shifted velocity distribution function. The rf plasma source operated under convergent magnetic field can thus be regarded as a distinct category of plasma source in terms of its electron energization mechanism.

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DATA AVAILABILITY

The data that support the figures within this paper are available from corresponding author upon reasonable request.

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