SPATIAL STRUCTURE OF K-FULLERENE PLASMA

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Abstract

Huge negative ions are observed to be dominated by a strong diffusion across magnetic-field lines, which results in a broad redistribution of positive ions in marked contrast with well-confined electrons, in a K-fullerene plasma mainly consisting of C_{60} negative ions and potassium positive ions. The C_{60}^- radial profile is effectively controlled by changing the magnetic-field strength.

1. Introduction

Plasmas including dust or fine particles have been the recent subject of intensive study in various fields of physics and engineering such as space-astrophysics, plasma-aided manufacturing, and fusion technology. We have successfully produced a K-fullerene plasma consisting of positive potassium ions (K^+), large negative fullerene ions (C_{60}^-), and residual electrons by locally introducing fullerene ultrafine-particles into a low-temperature ($\simeq$ 0.2 eV) potassium plasma column in an axial magnetic field [1]. The K-fullerene plasma is useful for not only investigating physics of plasma collective phenomena such as plasma-wave propagation and instability in fine-particle plasmas but also producing fullerene-based materials with unique functions such as alkali fullerides and endohedral metallofullerenes [2].

In order to efficiently evolve such researches it is necessary not only to understand dependence of C_{60}^- production on parameters such as quantity of the fullerene particles introduced and magnetic-field strength but also to control radial and axial profiles of K^+, C_{60}^-, and electrons in the K-fullerene plasma. Here we clarify a spatial structure of the K-fullerene plasma on the basis of measurements of negative ion profile with an electrostatic ion-sensitive probe and ion-acoustic wave propagation.

2. Experimental apparatus and methods

The experiment is carried out in a single-ended Q machine with a vacuum chamber of 10 cm in diameter and 132 cm length [3]. A plasma consisting of electrons and potassium ions K^+ is produced by contact ionization of K atoms on a hot tungsten plate (2 cm in diameter) under the electron-rich condition. The background gas pressure is $(1 \sim 2)\times 10^{-4}$ Pa. The plasma of density $0.5 \sim 1\times 10^{10}\ cm^{-3}$ and electron temperature $T_e \simeq$ 0.2 eV $\gtrsim T_p$ (positive ion temperature) is radially confined by a strong magnetic field ($0.2 \leq B \leq 0.7$ T). The plasma flowing along the magnetic field passes through the heated cylinder (diameter: 6 cm, length: 17 cm, 450 $\sim$ 500℃) with a oven for fullerene sublimation, the center of which is set at 17 cm from the hot plate surface. The fullerene quantity introduced is controlled by this C_{60}-oven temperature T_o (200 $\sim$

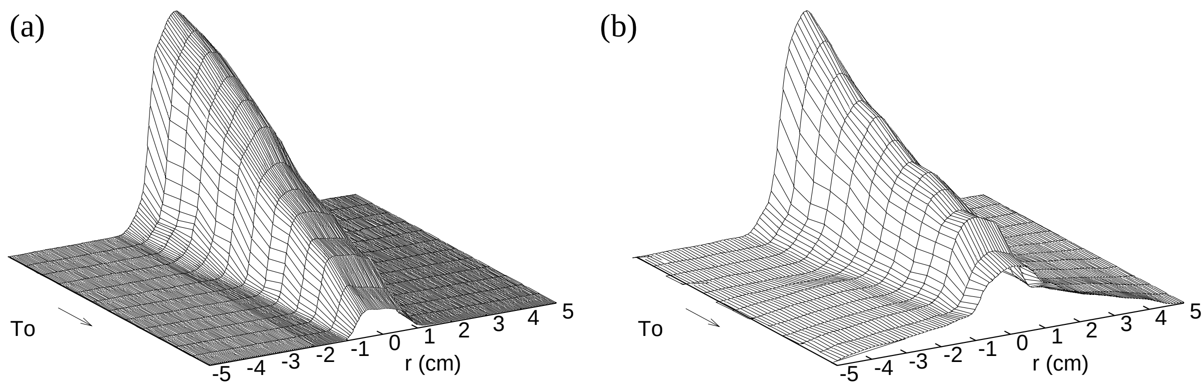

Figure 1. Radial profiles of the Langmuir probe (a) I_{s-} and (b) I_{s+} vs the C_{60} oven temperature. $z = 16$ cm, $B = 0.3$ T, and $T_o = 200 - 500^{o}$C.

500℃) which covers the range of the C_{60}-sublimation temperature (300 $\sim$ 400℃). C_{60} particles with relatively-large electron affinity ($\simeq 2.65$ eV) become negative ions (C_{60}+ e $\rightarrow$ C_{60}^{-}) as a result of attachment of low-energy electrons.

Most of plasma parameters are measured by movable Langmuir probes while negative ions are measured by ion sensitive probes [4]. The ion sensitive probe can pick up only negative ions due to Larmor-radius difference between negative ions and electrons. A ratio of negative (n_-) to positive ion (n_+) densities is estimated by measurements of ion-acoustic wave propagation and current I_p−voltage V_p characteristics of the probes.

3. Experimental results and discussions

When the oven temperature T_o is gradually increased, C_{60} negative ions start to be produced above 200℃ and the ratio $\varepsilon(= n_-/n_+)$ continuously increases, i.e., the electron fraction $1 - \varepsilon(= n_e/n_+,\ n_e$: electron density) decreases as shown in Fig. 1(a), where radial profiles of the negative-saturation current I_{s-} of the Langmuir probe are measured at $z = 16$ cm (z: distance from the downstream edge of the heated cylinder) as a function of T_o ($= 200 - 500$℃). Radial profiles of the positive-saturation current I_{s+} of the probe in Fig. 1(b), on the other hand, indicate that positive ions radially diffuse further beyond ($|\ r\ | > 1$ cm) the core plasma region, where electrons are well confined [$|\ r\ | < 1$ cm, see Fig. 1(a)] in marked contrast with the positive ions. Figure 2 gives radial profiles of space and floating potentials in the K-fullerene plasma ($T_o = 480$℃), where the space potential is determined from the potential at $d^2I_p/dV_p^2 = 0$ of the Langmuir-probe characteristic. The floating potential is higher than the space potential all

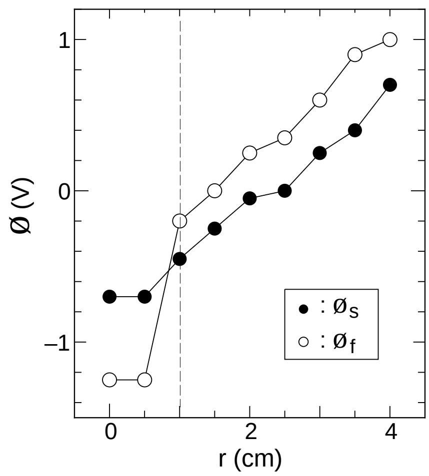

Figure 2. Radial profiles of space potential ϕ_s and floating potential ϕ_f in the K-fullerene plasma. $T_o = 480^{o}$C.

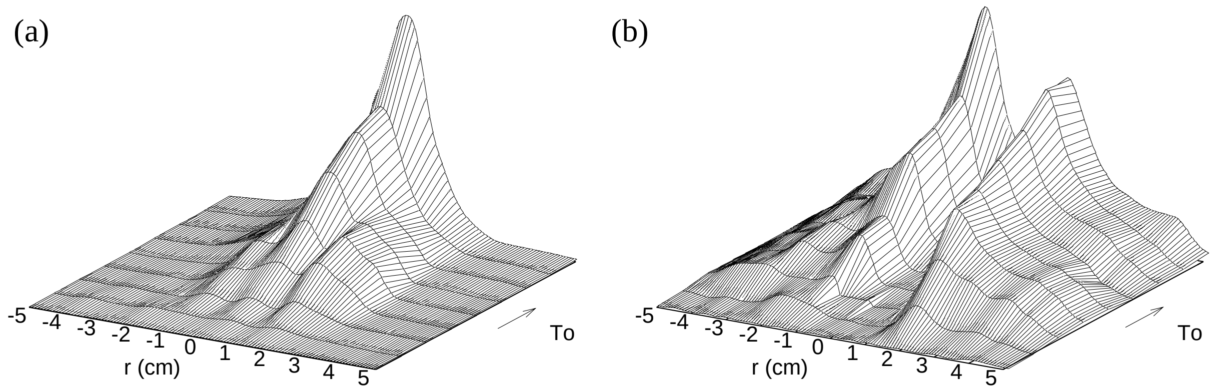

Figure 3. Radial profiles of the ion-sensitive probe I^i_{s-} due to negative ions vs the C_{60} oven temperature in the cases of (a) B = 0.7 T and (b) B = 0.3 T.

over the periphery region of the plasma column ($|\ r\ |\ \gtrsim 1$ cm) while the former is lower than the latter in the core plasma region ($|\ r\ |< 1$ cm) as in the case of the usual (electron/positive-ion) plasma. It is to be noted that positive and negative ion sheaths are formed in the core and periphery regions, respectively, when the Langmuir probe is immersed in the plasma for the purpose of estimating ε [5]. The results in Figs.1 and 2 are confirmed to be relatively insensitive to the magnetic-field strength in the range $B = 0.2 - 0.7$ T.

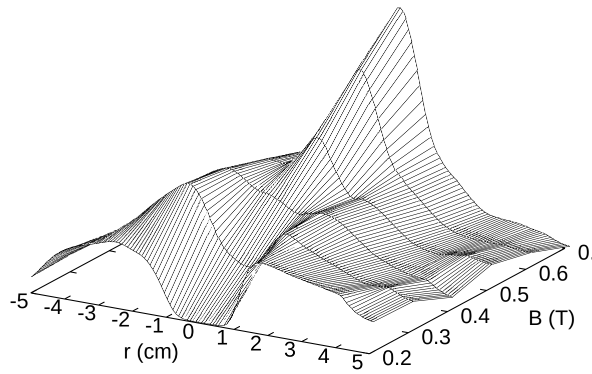

Figure 4. Dependence of the ion-sensitive probe $I^i_{s-}(r)$ due to negative ions on magnetic-field strength at $z = 16$ cm. $T_o = 480^{\rm o}$C.

In order to measure radial profiles of negative ions C^-_{60}, bias voltages applied to electrodes of the ion sensitive probe are carefully adjusted so as to prevent the electrons from flowing into the collector. Figure 3 presents dependence of the radial profile of its negative saturation current I^i_{s-} on T_o for typical magnetic-field strengths. The negative ions are observed to concentrate on the core plasma region as the C^-_{60}-production quantity is increased under the strong magnetic field ($B = 0.7$ T). In the case of weaker magnetic field ($B = 0.3$ T), however, they tend to be preferentially distributed beyond the core region, and the pronounced peaks in the radial profile appear in the periphery region ($|\ r\ |> 1$ cm) as T_o is increased. Here the radial profile of I^i_{s-} is measured as a function of the magnetic field at this axial position ($z = 16$ cm) for the K-fullerene plasma ($T_o = 480^{\rm o}$C). As shown in Fig. 4, it is clearly observed that the negative-ion density profile changes from a hill type to a hollow type when the magnetic field is decreased.

According to two-dimensional ($r - z$) measurements of I^i_{s-}, the radial density profile of C^-_{60} shows a prominent peak around the center of the plasma column in the upstream region

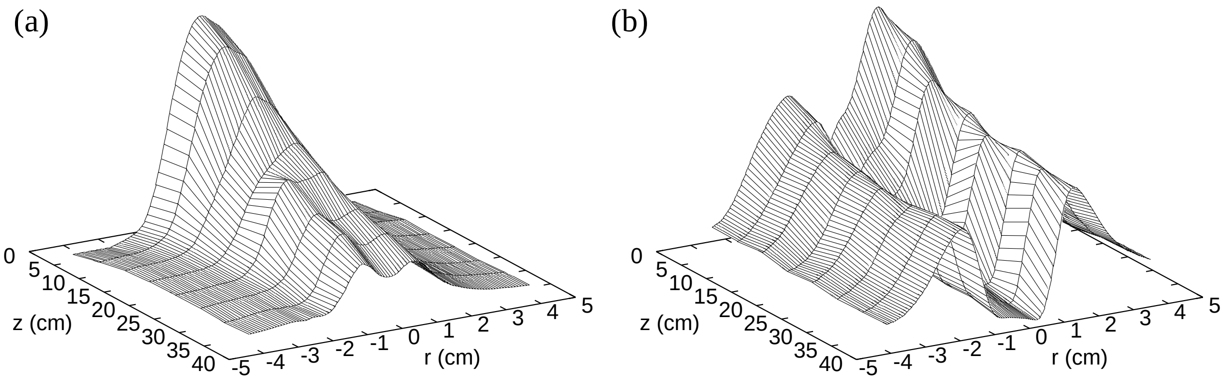

Figure 5. Two-dimensional profiles of the ion-sensitive probe I^i_{s-} due to negative ions in the cases of (a) B = 0.7 T (b) B = 0.3 T. $T_o = 480^o$C.

under the strong magnetic field, but gradually changes to a apparently-diffused trace as the plasma flows downstream along the magnetic-field lines, as shown in Fig. 5(a). The hollow radial profile with pronounced peaks in the periphery region is obtained in the case of weaker magnetic field over the whole plasma column downstream from the C_{60}^- production region [see Fig. 5(b)]. The result indicates that there exists a physical mechanism leading to the anomalous diffusion of the huge negative ions in the K-fullerene plasma.

Finally in order to quantitatively estimate the radial variation of ε, ion-acoustic wave propagations along the magnetic field lines are measured [1] as a function of radial position. After making a comparison with the Langmuir-probe measurements [5] it is confirmed that the electron-free K-fullerene plasma ($\varepsilon > 0.9999$) is realized in the periphery region ($1 < r \lesssim 5$ cm) and the electron fraction in the core region decreases with an increase in the magnetic-field strength ($\varepsilon \gtrsim 0.98$).

4. Conclusions

The spatial structure of the K-fullerene plasma is experimentally clarified by using Langmuir, ion-sensitive probes, and ion-acoustic wave propagation. Since there intrinsically exists an enhanced cross-field diffusion of C_{60} negative ions, the variation of magnetic-field strength enables the C_{60}^- radial profile to be controlled. The results could be useful for producing fullerene-based materials in the K-fullerene plasma.

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