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High density conics in a magnetically expanding helicon plasma

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A two-dimensional mapping of ion density and plasma potential in a diverging magnetized low pressure (0.4 mTorr) carbon dioxide helicon plasma containing a double layer reveals the presence of high density conics ($\sim 7\times 10^9$ cm^{-3}) along the most diverging magnetic field lines exiting the helicon source and connecting with the grounded expansion chamber. The density in the conic is about 30% greater than the density at the double layer and this results from local ionization associated with the presence of a high energy tail in the electron energy probability function. The plasma potential along the conic is constant at about 30 V. © *2010 American Institute of Physics*. [doi:10.1063/1.3309668]

Expansion of a low-pressure high-density magnetized or nonmagnetized plasma into vacuum or a low-density background plasma leads to ion acceleration.[1] The generic process of plasma expansion is applicable to a number of active research fields such as space plasma physics (solar corona, aurora), electric propulsion (plasma plume and detachment), and plasma processing of materials for various applications (microelectronics, hydrogen fuel cells).[2] Radiofrequency (rf) plasmas can be generated by rf power applied to electrodes or antennae, which are placed outside the plasma and are separated from it by an insulator which is generally part of the vacuum chamber. The insulator plays the role of a capacitor and is in contact with the plasma. This type of source is often attached to a contiguous metallic processing chamber where the plasma expands and interacts with a surface (chamber side and end walls or wafer).[3]

It has been recently shown that radiofrequency helicon sources operating with a divergent magnetic field along the axis of expansion can generate an electric double layer (DL) near the source exit when operating at low pressure, typically below a few millitorr.[2,4,5] Although the role of the expanding magnetic field in double layer formation has clearly been identified,[6] the details are still largely unknown partially due to the lack of spatial mapping of plasma parameters in the expansion region. Recent experimental studies have demonstrated the presence of various particle populations upstream and downstream of the double layer (e.g., trapped and free electrons upstream and thermal and accelerated ions downstream).[2] Two-dimensional (2D) mapping of the accelerated ion beam current[7] and radial measurements of the electron energy probability function (EEPF) in the source and in the expansion region[8,9] have shown the presence of distinct subregions within the plasma source and expansion chamber which result from the geometry of the double saddle field rf antenna and plasma cavity and from the magnetic field structure.

Here we carry out a 2D mapping of plasma potential and ion density in a double layer containing expanding plasma and identify a region of high plasma density shaped as a "conic" which extends from the radial edge of the source exit along the most diverging magnetic field line to the grounded expansion chamber. The symmetry axis along the conic follows a measured plasma potential contour.

Experiments are carried out in the CHI KUNG expanding plasma apparatus of Fig. 1 for conditions where a double layer spontaneously forms in the expansion region. The plasma source consists of a 15 cm diameter and 31 cm long pyrex tube surrounded by a helicon antenna ($z=3-21$ cm) and two axial solenoids ($z=1.5$ and 21 cm) and is mounted on a 30 cm long and 32 cm diameter earthed aluminum diffusion chamber.[2] A glass plate at the closed end of the source tube ensures that the plasma cavity has insulating walls only and that the electric double layer in the system is current-free. The system is pumped down to a base pressure of $\sim 2\times 10^{-6}$ Torr. The molecular gas CO_2 is the working gas of choice as it generates the double layer outside the source tube (Fig. 1) and allows for a more detailed 2D mapping of the expansion region.[10] The parameter space (pressure, rf power, and magnetic field) for obtaining the CO_2 DL is similar to that previously measured with argon.[2] A divergent magnetic field (field lines shown on Fig. 1), decreasing from a maximum of about 0.0142 T in the source ($z=20$ cm) to about 0.001 T in the middle of the diffusion vessel ($z=45$ cm), is used.[2] The laboratory probes consist of a grounded retarding field energy analyzer (RFEA) with a

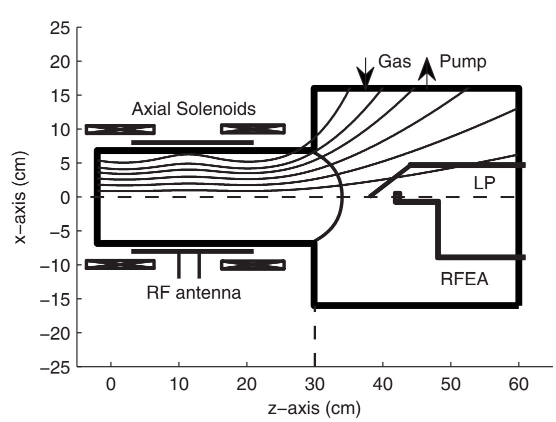

FIG. 1. Schematic of the CHI KUNG expanding plasma apparatus (with diverging magnetic field lines) which hosts the RFEA and rf compensated LP. The parabola shown by a solid line near the exit of the plasma source is the low potential edge of the double layer.

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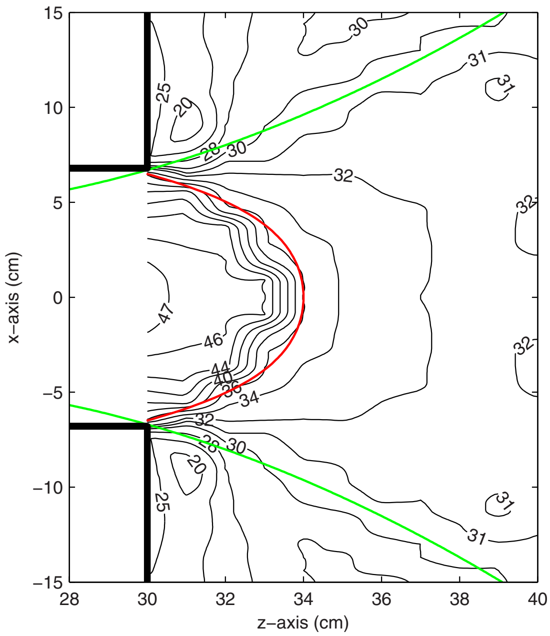

FIG. 2. (Color online) 2D equipotential contours measured with the RFEA for 250 W and 0.053 Pa (0.4 mTorr). The double layer extends between the 36 and 46 V contours. The solid parabolic line represents a fit of the 36 V contour which is the low potential edge of the U-shaped current-free double layer. The solid diverging line shows the most diverging magnetic field line exiting the source at $(x,z)=(6.7,30)$ cm.

2 mm diameter aperture hole to simultaneously measure the plasma potential and total ion density and a 3 mm long and 1 mm diameter rf compensated Langmuir probe (LP) to measure the EEPF.

Mapping is obtained with the RFEA rotating on its support tube axis every 5° ($x=-14-0$ cm) for each value of z ($z=30-49$ cm every centimeter). The data acquisition time is minimized to prevent the RFEA from overheating and failing from grid damage and the whole space is obtained by mirroring the data since the radial symmetry has been verified by earlier experiments.[10] The 2D mapping of the expansion region is carried out for operating rf power and gas pressure conditions of 250 W and 0.053 Pa (0.4 mTorr), respectively: these conditions lead to the formation of a U-shaped potential structure (solid parabola on Fig. 1) or "oblique" current-free electric double layer. The detailed analysis of the upper and lower edges of the double layer and of the downstream accelerated ion beam has been previously discussed[10] and here the aim is to investigate the region radially diverging from the double layer. This region "surrounds" the most diverging magnetic field lines exiting the source tube.

Figure 2 shows the measured plasma equipotential contours in the region of interest ($z=30-40$ cm). The 36 V potential contour is the low potential edge of the DL and is fitted by a parabola (solid parabolic line on Fig. 2 and Fig. 1) which corresponds to $z=34$ cm on the central axis ($x=0$ cm). The 46 V potential contour is the high potential edge of the DL. All equipotentials upstream ($V_p\geq 46$ V), within ($36\leq V_p\leq 46$ V) and downstream of the double layer ($36\geq V_p\geq 32$ V) exhibit a convex shape. There is no measurement within the DL and the contours result from the interpolation. The small irregularities in the contour results from a lack of spatial and energy resolution and have no physical meaning. The potential drop of the double layer is about 10 V for the present operating conditions. Since the electron temperature T_e measured downstream of the DL at $(x,z)=(9,37)$ cm is about 4.5 eV,[10] the strength of the DL is about 2.2 T_e and the plasma density near the DL is about 7×10^9 cm^{-3}.[10]

For x values near or greater than the source tube inner radius of 6.85 cm or equivalently for plasma potentials less than 32 V, the equipotential contours strongly differ from the convex shape and instead diverge from the tube radial edge at $z=30$ cm to a region near the chamber walls at $z=39$ cm (e.g., contours at 31 and 30 V on Fig. 2). Potentials smaller than 28 V define a "corner" region of triangular shape ($x\geq 8$ cm and $30\leq z\leq 32$ cm) with no "magnetic connection" with the source plasma.

For $0\leq z\leq 30$ cm, i.e., inside the source tube, most magnetic field lines near the inner wall ($x\geq 5$ cm) terminate on the walls (Fig. 1). The line passing through the $(x,z)=(6.7,30)$ cm coordinates (solid diverging line on Fig. 2) can be defined as the most diverging field line exiting the source tube (or "first open" field line) and traces back to the $(x,z)=(4.1,0)$ cm coordinates (Fig. 1). Interestingly this first open field line very closely follows the measured plasma potential contour at 30 V (Fig. 2). The type of plasma boundaries (insulating wall, earthed wall, conducting wall not earthed) is a parameter which will affect the final plasma equilibrium[3] and an important principle is that potentials are always defined with respect to some reference location. Experimentally, this is often chosen to be an earthed surface, which can be considered to be a nearby large area equipotential surface (in this experiment the grounded diffusion chamber) capable of absorbing a finite charge without changing its potential with respect to "infinity." The 30 V contour (measured with the grounded RFEA) indicates that the plasma generated in the source tube "finds" or "connects to" the earthed chamber at about $z=39$ cm (Fig. 2).

The total ion density measured by the RFEA (using a simple calibration of the RFEA ion current with the density measured with a Langmuir probe biased at −70 V) and simultaneously mapped with the plasma potential of Fig. 2 is shown in Fig. 3. Two ramifications presently defined as high density "conics" and originating from an annulus near the inner radial edge of the tube are observed. Assuming cylindrical geometry these two conics in the horizontal plane correspond to a hollow cone in three-dimensional. The density in the conic ($\sim 7\times 10^9$ cm^{-3}) is about 30% greater than the axial density at the double layer ($\sim 5\times 10^9$ cm^{-3}). The corner region of low plasma potential (less than 28 V on Fig. 2) corresponds to a low ion density region ($\leq 3\times 10^9$ cm^{-3} on Fig. 3). Measurement of the EEPF at $(x,z)=(12,32)$ cm shows a cold Mawellian electron population with a temperature of 3.5 eV in agreement with previous measurement in argon.[9] Previous measurements in argon of the radial profile of the total ion current at $z=37$ cm had shown a local maximum near $x=10$ cm (Ref. 11) which has been recently correlated with a high energy tail in the measured EEPF at that location and attributed to energetic electrons originating from the source and traveling downstream.[9] Here the EEPF measured in the conic at $(x,z)=(9,32)$ cm (black circle on Fig. 3) also shows the presence of the high energy tail with a temperature of 8.8 eV above a break energy[8,9] of about 18 eV and a bulk electron temperature of 4.4 eV (Fig. 4). The

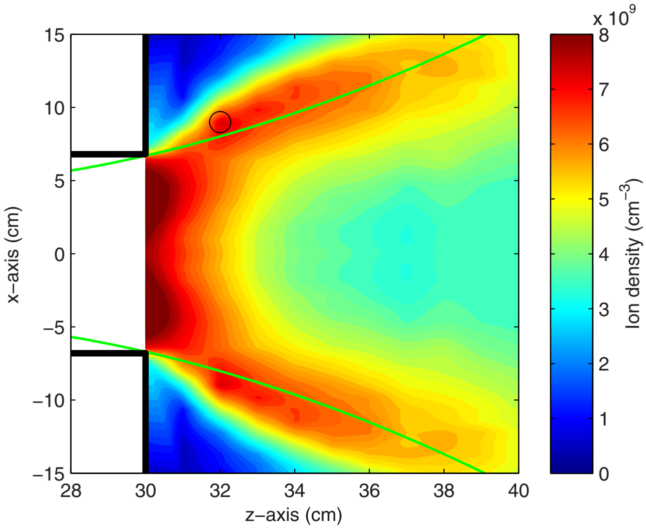

FIG. 3. (Color online) 2D contours of the ion density measured with the RFEA for 250 W and 0.053 Pa (0.4 mTorr). The solid diverging line shows the most diverging magnetic field line exiting the source at $(x,z)=(6.7,30)$ cm. The black circle at $(x,z)=(9,32)$ cm corresponds to the location of the LP for the EEPF measurement shown in Fig. 4; the density has been calculated from the total ion current from the RFEA and hence is only about ±20% accurate.

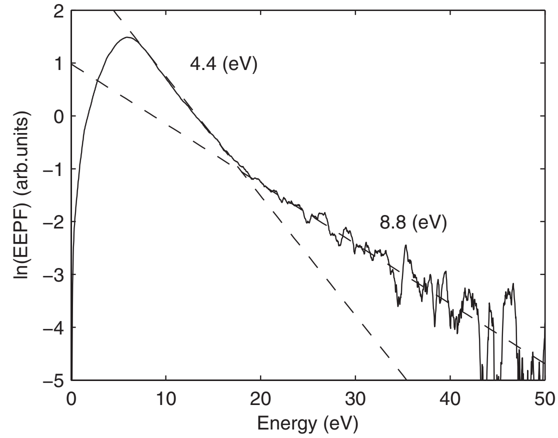

FIG. 4. EEPF measured in the high density conic at $(x,z)=(9,32)$ cm (black circle on Fig. 3) for 250 W and 0.053 Pa (0.4 mTorr).

break energy corresponds to the difference between the local plasma potential of about 30 V at $(x,z)=(9,32)$ cm and the plasma potential where the energetic electrons originate from $(30+18=48\ \text{V})$. Though not measured, the region with a plasma potential greater than 48 V is located in the source (Fig. 2). Since the ionization energy in CO_2 is 14 eV,[10,12] the 8.8 eV electrons heated in the source for x close to 4 cm and traveling along the peripheral open field lines are likely the source of additional ionization leading to the high density conic formation. The width of the conic results from effects of the Larmor radius, probe tip size, and sheath length.[9] The symmetry axis along the conic reveals an equipotential contour which "connects" the plasma to ground.

In summary high density ion conics in a magnetically expanding helicon plasma have been evidenced by 2D mapping using an energy analyzer and correlated with the first "open" field line originating from the helicon source and an equipotential contour giving a connection path from the source to the grounded chamber. This effect is likely to occur in any low pressure helicon plasma with a diverging magnetic field (with or without DL formation).

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