LETTER

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Letter

Field-aligned Boltzmann electric triple layer in a low-pressure expanding plasma

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Abstract

A deep and narrow potential structure has been measured along the last magnetic field line to exit the source tube of an expanding plasma device. The potential structure is identified as an electric triple layer and features a potential dip with Full Width Half Maximum ~ 70 Debye lengths (16 mm), depth of ~ 25 V ($q\phi_{\text{drop}}/kT_e \sim 2$) and its width and magnitude are seen to decrease with increases in argon pressure. The triple layer acts as a potential barrier for field-aligned electron transport, decelerating hot electrons exiting the plasma source before reaccelerating into the expansion chamber those that are able to overcome the triple layer potential, explaining the topography of high density plasma conics published previously. Measurements of the electron energy probability function at locations upstream and downstream of the potential structure show two-temperature electron populations with break energies of 41.5 V and 22 V, respectively, values that are consistent with the plasma potential measurements along the field line. Under these experimental conditions, the dielectric wall of the source tube charges to significantly negative potentials and the proximity of the field line to this negatively charged wall appears to be the cause for the triple layer.

Keywords: double layer, triple layer, low pressure plasma, radiofrequency plasma, expanding plasma

Current-free double layers (DLs) created at colocated geometric and magnetic expansions in low-pressure (sub-millitorr) expanding plasma devices have been studied widely over the last two decades. Due to the relevance to electric propulsion [1–3] and astrophysics [4–6] communities, the previous work has centred around the characterisation of the plasma source and expanding plume. At sufficiently low pressures and high magnetic field strengths, the plume can be described as an axial ion beam accelerated by the DL [7] surrounded radially by a region of high plasma density, commonly referred to as high density conics or a hollow density profile [8–12]. The high density conics exist for the same experimental conditions as the ion beam and have been shown to be spatially isolated from the source plasma in argon discharges (density contour shown in figure 1) [13, 14].

Ionisation of the conics occurs locally due to electrons that have been heated near the radio-frequency (RF) antenna

and transported along the last magnetic field lines escaping the source tube outlet [15]. In the conics, the transported electron population can be detected as a hot tail in the electron energy probability function (EPPF) existing above some break energy ($\varepsilon \geq \varepsilon_{\text{break}}$) where ε is the kinetic energy of the electrons in the distribution [16]. Further, measurements of the EPPF in the plasma source region located on the magnetic field line connecting to the conics demonstrate a depleted tail, showing that the bulk electrons ($0 < \varepsilon < \varepsilon_{\text{break}}$) are hotter than the tail. At some point along the field line connecting these two regions the EPPF must transition between a hot bulk and a hot tail. This has been attributed to the DL on axis, however the measured break energies do not conform to the reported DL potential drop, as they do on axis. The previous results imply that an off-axis potential structure is influencing the electron transport from the region near the RF antenna to the conics. Understanding the nature of electron transport

Figure 1. Schematic of the Chi Kung reactor including the location of the gas input, RF antenna and solenoids. The diagnostic probes (CP/LP/EP) used in this study are labelled and shown approximately to scale. The first escaping magnetic field line is illustrated as a dashed-dotted line and the EP/LP measurement positions are shown with crosses. The location of the EEPF measurements in figure 3 are circled in red. The conics density profile from [14] is reproduced in the bottom half plane of the expansion region and corresponds to the low pressure case.

between these regions could be important as it has previously been shown to effect the axial beam characteristics [17]. In this study, we investigate the particle transport along the most radial field line escaping the source and show for the first time that the potential structure along it features a strongly Boltzmann triple layer (TL) structure, explaining a number of previously published measurements.

Measurements were conducted using the Chi Kung reactor [7] (figure 1) which consists of a 32 cm long, 13.6 cm inner diameter pyrex source tube contiguously attached to a 30 cm long, 30 cm inner diameter cylindrical, grounded aluminium expansion chamber. The plasma is created in the source tube ($z < 0$ cm) while the expansion chamber ($z > 0$ cm) provides a volume in which the plasma can expand. An 18 cm long double saddle antenna centred on $z = -18$ cm surrounds the source tube and is fed with 315 W of RF power at 13.56 MHz via an L-matching network. Surrounding the source tube are two solenoids in a Helmholtz pair configuration which create a maximum axial magnetic field of ~ 145 Gauss which rapidly decreases to a few tens of Gauss and diverges in the expansion chamber. The magnetic field strength along the most radial field line escaping the source is also shown in figure 2(b). The aluminium expansion chamber is fitted with a ‘vacuum slide’ at $z = 30$ cm, allowing for both axial and radial movement of *in situ* diagnostic probes.

The diagnostic probes used in this study are illustrated in figure 1 and consist of an RF-compensated Langmuir probe (CP), an uncompensated Langmuir probe (LP), and an emissive probe (EP). The CP follows a design published previously [18], consists of a 0.5 mm diameter, 5 mm long cylindrical tungsten tip aligned perpendicularly to the magnetic field lines and measures the EEPF through the implementation of two analog differentiator circuits [19, 20]. The EEPFs are averaged 500 times to ensure the statistical

Figure 2. Measurements of the local (a) plasma potential; and (b) plasma density along the most radial magnetic field line escaping the source at the positions shown as crosses in figure 1 for pressures of 0.3 and 2 mTorr. Also shown in (b) is the magnetic field strength along the field line escaping the source (dashed line). The thick solid (0.3 mTorr) and dotted (2 mTorr) red lines show the calculated potentials using equation (1). The thin black lines connecting markers are presented for visualisation purposes only. Regions up and downstream of the TL can trap electrons as indicated in (a).

significance of their features. The uncompensated LP consists of a one-sided 0.95 mm radius nickel disk which can be biased to -80 V to acquire the ion saturation current (I_{sat}) or allowed to float to measure the floating potential V_f . The local ion density (n_i) is found using the ion saturation current measurement and Sheridan’s method [21, 22]. The EP consists of a ~ 5 mm long thoriated tungsten coil and uses the floating potential method to measure the local plasma potential (V_p) [23].

To investigate the potential structures encountered by the electron population travelling along the first escaping magnetic field line, the EP and LP were positioned at locations marked with crosses in figure 1. Measurements of V_p and n_i at these locations are plotted in figure 2 against their z -axis locations for neutral pressures of 0.3 mTorr (squares) and 2 mTorr (triangles). Plotting the measurements as a function of z is approximately equal to plotting against the chord length along the magnetic field line in the source region where the field is approximately parallel to the axis. However, near the outlet the field line is at an angle of $\sim 30^\circ$ to the z -axis, meaning the distance along the field line is underestimated by a factor of $1/\cos(30^\circ) = 1.15$.

At 0.3 mTorr, a Boltzmann double layer-like plasma potential structure is known to exist on axis [14], whereas at 2 mTorr, the axial structure does not form [24]. As such, these pressures are tested here as low and high pressure cases, respectively. For the 0.3 mTorr case, figure 2(a) shows V_p decreasing with increasing z from a maximum value of ~ 50 V at $z = -25$ cm to 34 V at $z = -3.5$ cm, followed by a 6 cm wide (~ 250 Debye lengths, ~ 70 Debye lengths FWHM) sharp potential dip ($\phi_{\text{drop}} \sim 25$ V, $q\phi_{\text{drop}}/kT_e \sim 2$) at positions just upstream of the outlet at $z = 0$ cm. Here, q is the elementary charge, ϕ_{drop} is the magnitude of the plasma potential dip, k is the Boltzmann constant and T_e is the electron temperature. Calculations used a measured value of T_e for the bulk electrons upstream (11.5 eV for 0.3 mTorr). Downstream of the outlet, the plasma potential plateaus to a constant value in the conics region. At 2 mTorr, V_p in the source region is reasonably constant until a small decrease just prior to the outlet. A hint of the sharp potential structure seen in the 0.3 mTorr case is visible in the 2 mTorr case at the same location, however it is much less pronounced.

Figure 2(b) shows the calculated values of n_i from the measured LP data along the field line. For the 0.3 mTorr case, n_i decreases from $\sim 8 \times 10^{10} \text{ cm}^{-3}$ at $z = -25$ cm to $\sim 3 \times 10^9 \text{ cm}^{-3}$ at $z = 0$ cm before increasing to $\sim 2 \times 10^{10} \text{ cm}^{-3}$ in the conics. Again, the 2 mTorr case shows a similar but weaker trend near the outlet. The main differences between these profiles can be described by the behaviour close to and far away from the potential dip at $z = 0$ cm. Far from $z = 0$ cm, the density profiles differ in magnitude and the location of peak density moves closer to the outlet at higher pressure. These characteristics are consistent with those published previously and the locations of maximum density on the field line for each pressure correspond to the locations of maximum axial density [24]. Near $z = 0$ cm, the profiles in figure 2 show a far more significant dip in density and potential at lower pressures. This is addressed later when the effects of wall charging are discussed.

The increase in n_i along the field line found at the outlet is directly related to the potential structure and the plasma potential can be calculated using the Boltzmann equation:

$$V_p(z) = V_p(z_0) + T_e \ln\left(\frac{n_i(z)}{n_i(z_0)}\right). \quad (1)$$

Using $z_0 = -24$ cm and measured bulk T_e values of 5 eV and 11.5 eV for high (red dotted line) and low (red solid line) pressure cases, respectively, V_p can be calculated using equation (1) and the results are shown in figure 2(a). The Boltzmann approximation is in good agreement with the probe data for both high and low pressures, implying that the electron transport is strongly field-aligned in each case. However, it should be noted here that the Boltzmann equation inherently assumes a constant electron temperature, which is not the case in expanding plasma devices like Chi Kung [16].

The behaviour of the potential dip found at 0.3 mTorr is distinctly different from that of a DL (like that found on axis) because the defining feature of a DL is an ion sheath followed by an electron sheath which curves the potential down and then up. This means that ions are accelerated towards the DL

Figure 3. Measured EEPFs for the 0.3 mTorr condition (a) upstream ($z = -24$ cm, $r = 4.5$ cm); and (b) downstream ($z = 4.2$ cm, $r = 10$ cm) of the measured potential dip shown in figure 2(a).

from one direction while electrons are attracted from the other. Particles in a 1D system containing a DL fit into one of four categories (trapped or free ions or electrons) depending on their energy and which side of the DL they are on [25]. The dip measured along the most radial field line escaping the source of Chi Kung curves down, up and then down again which requires an ion sheath, an electron sheath and then an ion sheath again. This implies that the structure is in fact a TL. Such a structure attracts ions and allows for two separate regions of trapped electrons, one upstream (in the source region) and one downstream (in the conics).

The TL measured in this study also acts as an energy barrier for electrons travelling along the field line from source to conics. As electrons climb the potential hill of the TL's upstream ion sheath they lose energy resulting in less ion-neutral impact ionisation, explaining the depletion of n_i in this region. Electrons with high enough energy to overcome the potential barrier are reaccelerated at the downstream ion sheath, gaining energy useful for ionisation. As opposed to a monotonic field-aligned decrease in density from the source to the conics, the TL creates a region of decreased plasma density followed by an increase in the conics. Electrons can then be trapped in the regions between the TL and the upstream and downstream chamber walls (indicated in figure 2) thereby explaining the spatial isolation of the conics presented previously in [13, 14].

Given the magnitude of the potential dip, an electron travelling in the $+z$ direction on the field line at $z = -24$ cm would see a potential barrier of ~ 40 V. Similarly, an electron travelling from the source that overcomes the potential barrier would then be accelerated by ~ 22 V into the conics. EEPFs measured at these locations (red circles in figure 1) using the CP are shown in figure 3. The EEPFs demonstrate corresponding $\varepsilon_{\text{break}}$ values of 41.5 V and 22 V, respectively, showing very good agreement with the measurements of V_p and confirming that this field-aligned potential structure is affecting the electron transport as expected. The observation of the potential dip also explains where the shape of the EEPFs would transition from demonstrating a hot bulk ($0 < \varepsilon < \varepsilon_{\text{break}}$) of electrons to a hot tail ($\varepsilon \geq \varepsilon_{\text{break}}$). Hence, the TL acts as a high-pass energy filter on electrons travelling along this field line as those without energy high enough to

Figure 4. Measurements of the radial plasma potential profile at $z = -0.5$ cm for pressures of 0.3 and 2 mTorr. The solid (0.3 mTorr) and dotted (2 mTorr) red lines show the potentials calculated using equation (1) and LP data. The vertical solid line at $r = 6.8$ cm shows the location of the source tube wall.

overcome the potential barrier are not permitted to leave the source region while those that can leave the source are reaccelerated.

To determine the radial width of the potential structure, V_p and n_i were measured radially at $z = -0.5$ cm, the z -axis location of the bottom of the potential dip. Here, the measurements at $r = 6.5$ cm correspond to those taken at the bottom of the potential dip in figure 2(a). Figure 4 shows the measured V_p for the 0.3 mTorr (squares) and 2 mTorr (triangles) cases as well as the predicted potentials found using equation (1) and the LP measurements (solid and dashed red lines). The figure shows very different behaviour between the measured and calculated potentials, with a stark difference at 0.3 mTorr. The observed differences appear to be due to the radial measurements cutting across field lines. As such, it is predicted that each of the radial measurements would lie along their own field-aligned potential profiles conforming to the Boltzmann relation.

It is interesting to note that the width of the strongly decreasing section of the radial potential profile shown in figure 4 for the 0.3 mTorr case is localised to within about 1 cm of the source tube wall (vertical solid line in figure 4). Previous experiments have shown that the source tube wall near the outlet becomes significantly negatively charged (~ -40 V) under similar conditions [26]. As such, particles bound to the magnetic field line must pass by a region of built up negative charges as the field line approaches the wall. Because the electrons are more highly magnetised than ions, their transport along the field line is more affected by the negatively charged wall.

Wall charging in Chi Kung is thought to be due to a combination of self-biasing near the RF antenna [27] and charging due to the flux of fast electrons inherent to a hot electron population created on field lines that terminate on the wall. Indeed, radial profiles of T_e in the source region of

expanding plasma devices have previously shown that the electron temperature increases away from the central axis. This means that increasingly higher temperature electrons will be bound to field lines that intersect the dielectric source wall and cause it to charge negatively as per equation (2) [28].

$$V_f = \frac{kT_e}{2q} \ln\left(\frac{2\pi m}{M}\right). \quad (2)$$

In equation (2), V_f is the floating potential relative to the plasma potential, m is the electron mass and M is the ion mass. As $m \ll M$, V_f is always negative with respect to the plasma potential and the value of T_e determines the magnitude. Equation (2) can be evaluated for the 0.3 ($T_e = 11.5$ eV) and 2 mTorr ($T_e = 5$ eV) cases discussed in this study giving values of V_f of -53 V and -23 V, respectively. Measurements of V_f at the bottom of the TL (position closest to the source tube wall) can be found using absolute measurements of the floating (LP) and plasma potentials (EP). This analysis yields V_f values of -47 V and -28 V, respectively, which are in reasonable agreement with the values found using equation (2). This implies that the source wall charging at the outlet is consistent with the measured values of T_e . It is no surprise then that the field aligned V_p profile of the 2 mTorr case exhibits a less severe potential structure in figure 2 given that the temperature of electrons bound to field lines that terminate on the source wall is lower than the 0.3 mTorr case, resulting in less significant wall charging.

Figures 1 and 2 show that the potential structure is located near $z = 0$ cm, the intersection between the axial plasma source wall and the radial wall of the grounded expansion chamber. Given that the TL itself is characterised by a sharp decrease towards zero potential it seems possible that the potential structure arises to match the boundary conditions imposed by the grounded chamber wall. To ensure that this was not the case, a thin film of insulating tape was used to cover the first few centimetres of the grounded aluminium chamber wall adjacent to this intersection and the experiments repeated. The repeat experiments gave the same results, confirming that this phenomenon is in fact due to wall charging, not due to wall grounding.

In this study, measurements of an electric triple layer situated along the most radial field line escaping an expanding plasma device have been presented. Electron transport was found to be strongly field-aligned and the TL explains a number of previously published measurements. The TL appears to be caused by negative charging of the dielectric source tube by hot electron populations bound to magnetic field lines that terminate on the wall. Electrons travelling along the magnetic field are repelled by the build up of negative charge on the wall, forming a potential barrier for these electrons to escape the plasma source. Those electrons with sufficient energy to overcome the upstream ion sheath of the TL are then accelerated by the downstream ion sheath (~ 22 V) and ionise background neutral gas that is present in the conics region. It is possible that this structure has previously been overlooked in the Chi Kung reactor and other expanding plasma devices because the focus has been largely on the axial characteristics of these systems. The diagnostics

used in this study were also required to be less bulky in order to measure along the field line close to the chamber walls. It is for this reason that the study of the ion dynamics in the TL is difficult as typical ion energy analysers are quite large. Future studies with a specially designed energy analyser could investigate these effects. Further, while it is widely believed that wall charging effects play an important role in the creation of the axial current-free DL [29–31], how the field-aligned TL affects the creation of the axial DL is not obvious and future studies could attempt to make this clear. The present results are important to the electric propulsion community because the transport of electrons to the region where conics form has previously been linked to the exhaust beam velocity [17] and creation of the field-aligned TL is expected to occur in any expanding plasma device in which a magnetic field line passes nearby to a boundary, e.g. in those devices that have previously shown the formation of the conics [8–12] (and references therein). Studies focusing on how electrons interact with the measured TL could also be useful for the astrophysics community given that field aligned TLs have been previously measured in the magnetosphere [32, 33].

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