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Time development of a current-free double-layer

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The time development of a supersonic ($\sim 2.3c_s$) argon ion beam generated by a current-free double-layer (DL) is obtained by pulsing a “helicon” discharge (13.56 MHz) and measuring the total ion current and the ion beam current during the first few milliseconds using a retarding field energy analyzer. The ion beam current is detected during the plasma breakdown phase (60–250 μ s) and is stable thereafter (≥ 250 μ s). Temporal measurements of the floating potential upstream and downstream of the DL show evidence of wall charging in the plasma source during the first 250 μ s of the discharge which appear to be related to the appearance of the double-layer. A comparison between the DL case and a somewhat higher pressure “non DL” case suggests that the double-layer is formed at ~ 100 μ s. © 2004 American Institute of Physics. [DOI: 10.1063/1.1764829]

I. INTRODUCTION

An electric double-layer (DL) is a localized region within a plasma which can sustain a potential difference and cause electron and ion acceleration. DLs are of great interest in astrophysics¹ as they occur naturally in a variety of space plasmas (aurora,² solar corona,³ extragalactic jets,⁴...). In the laboratory, they are often generated using various types of current-driven discharges (filament discharges,⁵ cylindrical “Q” machines⁶) but plasma expansion in a magnetic field may also lead to the formation of magnetic field aligned current-free double-layers.^{7,8} In many experimental systems, the DL propagates away from the plasma source before reaching steady state on a time scale greater than the thermal ion transit time across the system, typically a few hundreds of microseconds.^{7,9}

Recently, we have measured a supersonic ion beam generated while traversing a current-free double-layer in a helicon radio-frequency plasma.¹⁰ To date there is no satisfactory theoretical analysis of this DL but its characteristics are somewhat similar to the current-free DL observed in a collisionless plasma⁷ although the DL was moving and existed only after $t \geq 200$ μ s.

In this paper, we present experimental evidence of the formation of a current-free helicon DL during the first 100 μ s of plasma breakdown and on its subsequent temporal stability. The time dependence of the supersonic ion beam is measured while pulsing the helicon plasma. Measurements of the floating potential upstream and downstream of the DL suggest that its formation time scale is also related to wall charging in the plasma source.

II. EXPERIMENTAL SETUP

A horizontal helicon system consisting of a 15-cm-diameter helicon source (32-cm-long cylindrical glass tube

terminated with a 1-cm-thick glass plate and surrounded by a 20-cm-long double-saddle antenna) is attached contiguously to a 30-cm-long 32-cm-diameter earthed aluminum diffusion chamber (Fig. 1). The antenna is fed from a radio-frequency (rf) matching network/generator system operating at 13.56 MHz which can be pulsed using a pulse generator and a 30 dB coupler to monitor the forward and reflected powers. The argon feed gas is introduced on the side of the chamber, and a turbomolecular/rotary pumping system is connected to the sidewall of the chamber. The base pressure is 2×10^{-6} Torr, the pressure being measured with an ion gauge and a baratron gauge. Two solenoids situated around the source are used to create an expanding magnetic field of about 250 G in the source center decreasing to a few tens of Gauss in the diffusion chamber (solid line on Fig. 2). We have previously shown the presence of a current-free DL at $z = 25$ cm for an argon discharge.⁸ More recently both an Ar^+ ion beam and evidence of an electron beam have been detected arising from the DL.¹¹ The same magnetic field configuration is used for the present experiments and the operating pressure and rf power are 0.3 mTorr and 800 W, respectively. The results on the pulsed DL case are compared to a “non DL” case which is similar to previous breakdown studies and which corresponds to a higher pressure of 1.3 mTorr, a lower rf power of 250 W, and a lower magnetic field decreasing from about 80 G in the source center to a few Gauss in the diffusion chamber (dotted line on Fig. 2).

A movable retarding field energy analyzer (RFEA) is inserted radially through a port at $z = 37$ cm on the chamber sidewall. By rotating the RFEA on its support tube axis, measurements of the positive ions are made with the entrance orifice facing axially or radially; a detailed description and optimization of the analyzer have been previously reported and showed that the energy resolution is expected to be less than 1 eV and no peak separation due to rf oscillation of the sheath is expected.¹² The derivative of the collector current versus discriminator voltage $I(V_d)$ characteristics is called the ion energy distribution function (IEDF) although we are not measuring the actual ion energy distribution func-

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FIG. 1. Schematic of “Chi Kung,” a horizontal helicon system.

tion but rather the energy of the ions falling through the potential drop (DL/sheath) in front of the earthed analyzer. Two Langmuir probes are placed on the z axis to monitor the time dependence of the floating potential upstream ($z = 7$ cm) and downstream ($z = 57$ cm) of the DL (Fig. 1).

III. EXPERIMENTAL RESULTS

The current measured by a gridded RFEA can be written as

$$I(v_0) = eAT^4 \int_{v_0}^{+\infty} v f(v) dv, \quad (1)$$

with

$$\frac{1}{2} m_i v_0^2 = e V_d \quad (2)$$

where e is the electronic charge, A is the area of the analyzer aperture, T is the grid transmission factor (four grids in this case), v is the component of the ion velocity parallel to the axis of the analyzer, $f(v)$ is the velocity distribution at the entrance of the analyzer, and m_i is the ion mass.

Figures 3(a) and 3(b) show the normalized radial (dotted lines) and axial (solid lines) IEDFs measured with continuous (CW) rf excitation for the DL case (0.3 mTorr and 800 W) and for the non DL case (1.3 mTorr and 250 W), respectively. The RFEA measurements are made in a continuous run. As discussed in our previous paper,¹¹ the DL distribution

FIG. 2. Magnetic field on axis for the DL case (solid line) and the “non DL” case (dotted line).

FIG. 3. Normalized axial (solid line: axial measurement with RFEA facing the DL) and radial (dotted line: radial measurements with RFEA facing the chamber sidewalls) IEDFs obtained with the RFEA located on axis at $z = 37$ cm for the (a) DL case (pressure of 0.3 mTorr and rf power of 800 W) and (b) “non DL” case (pressure of 1.3 mTorr and rf power of 250 W).

measured with the analyzer facing radially exhibits a single peak at the local plasma potential ($V_p \sim 25$ V). In addition to this low energy peak around V_p the distribution measured with the analyzer facing axially toward the plasma source (and DL) exhibits an additional peak at 43 V corresponding to a beam velocity v_{beam} of 2.3 the sound speed c_s [Fig. 3(a)]. The non DL distributions exhibit a single peak around 20 V when the RFEA is facing the source and is facing the walls, with no detection of high energy ions [Fig. 3(b)].

The RFEA results for continuous excitation correspond to a time-average measurement which could mask any spatial or temporal stability of the DL. To get some insight into the DL formation, the plasma was pulsed with a 2 ms “on” period and a 10 ms “off” period, allowing extinction of the plasma between pulses. The tuning was initially set for CW mode and only slightly adjusted for minimum reflected power at the end of the 2 ms pulse. The rise time of the rf generator measured using the forward power on the coupler

FIG. 4. Ion current measurements versus time in the pulse (2 ms “on”/10 ms “off”) obtained with the RFEA located on axis at $z=37$ cm for the (a) DL case (pressure of 0.3 mTorr and rf power of 800 W) and (b) “non DL” case (pressure of 1.3 mTorr and rf power of 250 W): $I_{axial}(0 V)$ (dashed line), $I_{axial}(43 V)$ (solid line), and $I_{radial}(43 V)$ (dotted line) are derived from Eq. (1).

is 50 μs and the results are averaged over many pulses. From the results in Fig. 3(a), we select two discriminator voltages for the temporal study of the DL, $V_d=0 V$ ($v_0=0$) where ions of all energies are collected and $V_d=43 V$ ($v_0=v_{beam}$) where only ions with energies greater than 43 V are collected [Eq. (1)]: Figures 4(a) and 4(b) show the results obtained for the DL case and for the non DL case, respectively.

The axial measurement of the total ion current $I_{axial}(0 V)$ [dashed line on Fig. 4(a)] shows typical breakdown characteristics. In plasma breakdown,^{13–15} electrons are accelerated to many hundreds of volts by the rf fields of the antenna. These electrons ionize the background gas and after about 1 μs the Debye length enters the system shielding the plasma from the rf fields. At this stage the plasma potential is also very high (hundreds of volts) and ions are accelerated out of the plasma at high energy and in all directions. Ionization proceeds increasing the density of the plasma while the electron energy and the plasma potential decrease

on a time scale of a few tens of microsecond, reaching equilibrium after about 250 μs .

Evidence of the high energy electrons before the Debye length enters the system, followed by the high energy ions streaming out when the plasma potential is large is clearly shown by the initial small “negative” and subsequent “positive” excursions in the measurement of $I_{radial}(43 V)$ in the pulse [dotted line on Fig. 4(a)]. $I_{radial}(43 V)$ corresponds to the collection with the RFEA facing the walls of ions with energies greater than 43 V. The first negative excursion in $I_{radial}(43 V)$ [also present in $I_{axial}(0 V)$] is due to these high energy electrons. This excursion is not as prominent as that measured in previous work¹⁶ due to the presence of the repeller grid just behind the grounded orifice plate in the RFEA which is biased at $-80 V$ since we are using the RFEA in positive ion collection mode. Following the first electron bump, the second bump in $I_{radial}(43 V)$ [also seen in $I_{axial}(0 V)$] corresponds to the high energy ions escaping the plasma in all directions when the plasma potential is very large. Following breakdown, $I_{radial}(43 V)$ is zero, in agreement with the CW results on Fig. 3(a) [dotted line] where no high energy ions are detected when the RFEA is not facing the DL.

It is interesting to compare these results with those obtained at a somewhat higher pressure where it was not possible to create the DL: Fig. 4(b) shows the temporal evolution of the ion current collected at 0 V (dashed line) and 43 V (dotted line) for the “non DL case” (1.3 mTorr, 250 W, and lower magnetic field). As mentioned previously [Fig. 3(b)], there is no major difference between the axial and radial orientation so only the axial current is shown. At this higher pressure it is difficult to detect the electron excursion at the beginning of the pulse but there are clear similarities and differences between the DL and the non DL cases. The axial current $I_{axial}(43 V)$ in Fig. 4(b) is very similar to the radial current $I_{radial}(43 V)$ in Fig. 4(a), showing the same evolution of the high plasma potential at the beginning of the pulse. Looking at $I_{axial}(0 V)$, for both conditions the ion current (plasma density) increase follows a similar time scale of about 250 μs to achieve equilibrium. However, for the DL case, there is a quite distinct decrease in the ion beam current $I_{axial}(43 V)$ at 200 μs suggesting that the total ion current measured downstream of the DL is significantly affected by its presence.

The time development of the ion beam can be further analyzed by comparing the $I_{axial}(43 V)$ shown in Figs. 4(a) and 4(b). In the low pressure DL case, the evolution of the ion beam follows the general development of the total ion current and in the higher pressure non DL case there is zero ion current. Hence we need to investigate the temporal evolution of the plasma potentials in the first few tens of microseconds of the breakdown. However, at low pressures, time resolved measurements of plasma potentials using RFEAs or Langmuir probes are quite challenging. Consequently we have made temporal measurements of the floating potential with a Langmuir probe connected to a 1 M Ω oscilloscope which is a much simpler measurement. That said, it should be noted that the floating potential should be regarded as a guide as the presence of non-Maxwellian distributions and

FIG. 5. Floating potential vs time in the pulse (2 ms “on”/10 ms “off”) obtained with the Langmuir probes upstream at $z=7$ cm (positive curves), and downstream at $z=57$ cm (negative curves) of the double-layer for the DL case (solid lines) and for the “non DL” case (dotted lines), respectively. The values measured for CW mode are 14.3 V, -3.8 V for the DL case and 4 V and -2 V for the “non DL” case, respectively.

electron and ion beams can significantly distort the I - V characteristic of the Langmuir probe. Nevertheless, under these circumstances, there are no other options open to us in the present experiment.

The floating potential measured upstream ($z=7$ cm) and downstream ($z=57$ cm) of the double layer are shown as a function of time in Fig. 5, for the DL case (solid lines) and for the somewhat higher pressure non DL case (dotted lines). The difference between the two regions separated by the DL is very clear and present: the upstream region has positive floating potentials and the downstream region negative floating potentials. For the DL case, the floating potential in the source has a temporal evolution similar to that of the total ion current $I_{axial}(0$ V) [Fig. 4(a)]. The difference between the DL case and the non DL case in the source appears to imply wall charging of the source tube and end glass plate (Fig. 1). Wall charging effects have been often reported in these plasma sources^{17,18} and the high value of the floating potential (~ 15 V) in the source seems to be a key indicator for the DL formation.

IV. DISCUSSION

To recap a few results from our previous experiments:^{8,10,11} the DL forms for gas pressures below 1 mTorr, at least in argon and hydrogen. The potential drop is typically $3kT_e$ (where T_e is the electron temperature) which is less than the potential drop (for these gasses) created by a wall sheath to ensure current equality. Hence, there is a flow of electrons over the DL which can easily neutralize the ion beam created by the DL, and, in the experimental case here, also create plasma downstream. The present results strongly suggest that the DL is formed in the first 100 μ s or so of the discharge. Since the upstream and downstream regions of the plasma must have very different potentials to support the DL it is interesting to investigate results presented in Fig. 5 in

some more detail. First, we need to be sure that the pulsed experiments have some link with the continuous experiments as the tuning of the rf matching network can produce major changes in plasma parameters in helicon discharges. For this reason, the values of the floating potential obtained in CW mode is also shown in the caption of Fig. 5 and can be seen to be very close to the values obtained in the pulsed discharge (after 800 μ s). From both Figs. 4 and 5 it seems that the double-layer forms at around 100 μ s where the floating potential for the non DL case (dotted line) starts to decrease but the floating potential in the DL case (solid line) continues to increase. There is also an appreciably lower floating potential in the downstream plasma for the DL case. From these results it seems clear that the double-layer forms during the first 100 μ s of the discharge, well before the plasma has come to equilibrium. A possible scenario, which can be gleaned from the results presented here, is that the high plasma potential developed during the breakdown evolves as the positive ions are accelerated out of the discharge to the walls. This loss of positive ions decreases the positive plasma potential to a value eventually determined by the condition for equal ion and electron currents to the walls. If the walls were conducting then eventually the system would settle down to a condition where the floating potential were zero (to match that of the conducting walls). However, in the present experiment we have an expanding plasma and the Boltzmann relation defines that a potential difference is set up to balance the pressure gradient caused by the expansion $n=n_0 \exp(e\phi/kT_e)$, assuming the electron temperature T_e is constant. If we take the present case where the density drop⁸ without the double-layer is about a factor of 100 ($1 \leq p \leq 3$ mTorr) then the Boltzmann relation would predict a potential difference between the maximum and minimum densities of at least 25 V ($T_e \sim 5$ eV) which exists internally in the plasma. Now we turn our attention to the current equality at the walls, assuming the electron temperature is constant (which we did for the simplification of the Boltzmann relation). At the top and bottom of the source, the plasma potential must be about five times the wall potential (at least for argon) and (for example) for an electron temperature of 5 eV, this would lead to a potential difference of 25 V between the wall and the plasma potential.¹⁹ Here lies the crux of the matter, the nub as it were. If the wall at the end of the source is at earth potential and is electrically connected to the wall at the end of the diffusion chamber, then the plasma potential at each extremity must be 25 V higher than the walls. Unfortunately, the Boltzmann relation demands that a potential difference of 25 V exist in the plasma which is inconsistent with the extremely low electrical resistivity of the plasma. In the case of a plasma totally surrounded by an electrically conducting wall it is possible to invoke a sort of “Simon effect” where currents flow in the external earth circuit and allow these potentials to exist. This is not the case for the present experiment where the whole of the source volume is insulating (Fig. 1) and currents cannot flow to other parts of the system. It would seem then, that in order to satisfy the basic Boltzmann relation and the equality of currents at each end of the expanding plasma, the source walls must charge up to allow the potential drop to occur in the plasma. It is,

perhaps, for this reason, that current-free double-layers have not been previously measured in expanding plasmas, though titillating evidence of their existence has been previously reported.²⁰

In summary, ion measurements using an energy analyzer and floating potential measurements using two Langmuir probes have been performed in a helicon plasma reactor for continuous and pulsed excitation with and without the presence of a double-layer. The results show that the current-free double-layer appears during plasma breakdown at about 100 μ s and is stable thereafter.

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