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Laboratory evidence of a supersonic ion beam generated by a current-free “helicon” double-layer

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An electric double-layer is generated near the open end of a high-density low pressure helicon sustained radio frequency (13.56 MHz) plasma source which expands into a diffusion chamber. Ion energy distribution functions measured with a retarding field energy analyzer placed in the diffusion chamber with its aperture facing the double-layer show the presence of a low energy peak (~29 V) around the local plasma potential and a high energy peak (~47 V) corresponding to a supersonic ion beam (~2.1c_s). At an axial distance 12 cm downstream of the double-layer, the beam density is 14% of the local density at that position and the ion energy gain is approximately 70% of the potential drop of the double-layer. The ion beam is observed from the center out to a radius corresponding to that of the plasma source tube (~6.8 cm≤r≤+6.8 cm) and is not greatly affected by the expanding magnetic field. A depression in the total ion flux just downstream of the double-layer—previously measured on the main z-axis of the reactor—is also present across the chamber diameter. Evidence of an electron beam near the closed end of the source tube, generated via “backwards” acceleration through the double-layer, has been observed on a Langmuir probe trace. © 2004 American Institute of Physics. [DOI: 10.1063/1.1652058]

I. INTRODUCTION

The process of plasma expansion and subsequent ion acceleration has been studied experimentally, theoretically and by computer simulation since the 1930s.1 In the simple case, the pressure gradient created by the change in the plasma density gives rise to a potential gradient which can be thought of as retarding the plasma electrons but accelerating the ions. Plasma expansion offers applications in many active research fields (space and solar sciences,2 plasma thrusters,3 material processing,4 microelectronics,5 etc.) since it allows some control of the positive ion fluxes.

For pressures above a few mTorr in typical laboratory experiments, the mean free path for ion collisions (elastic and charge exchange) is less than a cm, i.e., much smaller than the scale length of the expansion of the plasma and/or the axial magnetic field. The ion distribution may heat up but it remains essentially isotropic and the electron temperature T_e is fairly constant along the expansion axis. Under these isothermal, collisional conditions, the relationship between the density gradient (n−n_0) and the potential drop φ measured with a retarding field energy analyzer (RFEA) in a magnetic field free experiment agrees well with the simplified Boltzmann equation:6 n=n_0 exp(eφ/kT_e). Experiments in an electron cyclotron resonance (ECR) system with a maximum field of 1000 G showed the existence of accelerated metastable ions, measured with laser induced fluorescence (LIF).7 Theoretical work has also been carried out in the recent past to model some of the behavior of the ions in low pressure expanding plasmas.8–10

At very low pressures, typically below 1 mTorr, the mean free path for ion collisions often becomes of the order of, or larger than, the dimensions of the experimental device and a non-negligible fraction of ions may acquire supersonic velocities. Under these conditions the plasma is fairly collisionless and an electric double-layer (DL), a narrow, isolated region of rapid potential change, can form. Steady-state DLs have been experimentally generated in various types of discharges [filament discharges,11 cylindrical Q machines,12,13 helicon radio frequency (rf) plasmas,14 etc.] and the correlation between ion beam generation and the double-layer has been demonstrated in high-current gas discharges.15 We have previously described a new phenomenon of a current-free double-layer in an expanding helicon plasma14 but there has been no experimental evidence of ion beam creation in the potential drop φ_DL.

Here we report the first direct observation of a highly supersonic ion beam on the low potential side of a current-free double layer generated in an expanding radio frequency helicon plasma. Spatial characterization of the beam shows its presence over the entire plasma source diameter. An electron beam is experimentally observed on the high potential side of the DL. Electric DLs really started being investigated in space science,16,17 as it has long been believed that they are intimately involved with the creation of the aurorae.18 It seems that a possible scenario is that during a period of enhanced magnetic activity in the magnetosphere of the earth, the tail magnetic field is “stretched” and extended until it “breaks” causing a reconnection event and the generation of an earth moving slow period Alfvén wave carrying a lot of...
energy. This can be the energy source for certain types of aurora and could provide the power necessary to maintain an electric DL at an altitude of about 6000 km about the auroral region. Satellite measurements\textsuperscript{20,21} show that there can be double-layers which accelerate electrons down toward the earth, as in the visible aurora and upwards, perhaps serving as a current closure for the auroral/magnetosphere current system. The strength of these DLs can be low, a few volts, or large single structures of many hundreds of volts. The DLs can be low, a few volts, or large single structures of many hundreds of volts. The strength of these DLs can be low, a few volts, or large single structures of many hundreds of volts. The strength of these DLs can be low, a few volts, or large single structures of many hundreds of volts. The strength of these DLs can be low, a few volts, or large single structures of many hundreds of volts. The strength of these DLs can be low, a few volts, or large single structures of many hundreds of volts. This configuration leads to a magnetic-field aligned electric field similar to that of the auroral plasma.\textsuperscript{20} The plasma density profile ($n_o$) previously measured upstream and downstream of the double-layer\textsuperscript{14} using the RFEA is shown in Fig. 3 and the electron “bulk” temperature $T_e$ measured upstream and downstream of the DL is about 10 and 8 eV, respectively.\textsuperscript{14}

To get some insight into ion beam created by the potential drop $\phi_{DL}$ of the double-layer, a small RFEA is mounted on the diffusion chamber sidewall using the chamber side-wall or on the high potential side of the DL.\textsuperscript{23} For the experiments to get some insight into ion beam created by the potential drop $\phi_{DL}$ of the double-layer, a small RFEA is mounted on the diffusion chamber sidewall using the chamber side-wall or on the high potential side of the DL.\textsuperscript{23} For the experiments

\section{II. EXPERIMENTAL SETUP}

\subsection{A. Chi-Kung with diagnostics}

A horizontal helicon system consisting of a 15-cm-diam 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-diam earthed aluminum diffusion chamber (Fig. 1). The antenna is fed from a rf matching network/generator system operating at 13.56 MHz. The argon feed gas and the turbo-molecular/rotary pumping system are connected to the sidewall of the chamber. The base pressure is $2 \times 10^{-6}$ Torr, the pressure being measured with an ion gauge and a baratron gauge, both attached to the diffusion chamber. 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 Gauss in the diffusion chamber (Fig. 2). With this field configuration, a current-free, electric double-layer with $e\phi_{DL}/kT_e \sim 3$ and a thickness of less than 50 D lengths is generated near the open end of the helicon source ($z = 25$ cm) for pressures less than 1 mTorr and rf powers up to a few kW (Fig. 1). This configuration leads to a magnetic-field aligned electric field similar to that of the auroral plasma.\textsuperscript{20} The plasma density profile ($n_o$) previously measured upstream and downstream of the double-layer\textsuperscript{14} using the RFEA is shown in Fig. 3 and the electron “bulk” temperature $T_e$ measured upstream and downstream of the DL is about 10 and 8 eV, respectively.\textsuperscript{14}

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\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{fig1}
  \caption{Schematic of “Chi-Kung,” a horizontal helicon system, showing major components and the axial location of the double-layer.}
  \label{fig:chi-kung-schematic}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{fig2}
  \caption{$B_z$ component of the dc magnetic field along axis.}
  \label{fig:magnetic-field}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{fig3}
  \caption{Plasma density $n_o$ [Eqs. (1) and (4)] measured with the RFEA [radial measurement (Ref. 14)] for a pressure of 0.2 mTorr, a rf power of 250 W, and a magnetic field $B_z$ decreasing from about 250 G at $z = 25$ cm to about 50 G at $z = 37$ cm (Fig. 2).}
  \label{fig:plasma-density}
\end{figure}
represents here, a constant rf power of 250 W, a pressure of 0.35 mTorr, and the magnetic field configuration shown in Fig. 2 is used, and the main variable parameters are the collection angle \( \alpha \) and the radial position \( r \) of the RFEA (Fig. 1).

**B. Broadening mechanisms of the IEDF**

For a planar probe sufficiently negatively biased to collect only the positive ions, the collected current in an argon plasma is:

\[
I_p = e A p n_s c_s = 0.6e A p n_o c_s ,
\]

where \( e \) is the electronic charge, \( A_p \) is the probe collection area, \( c_s \) is the sound speed, \( n_s \) is the density at the sheath edge, and \( n_o \) is the density in the probe neighborhood. In the general case, the ion current versus discriminator voltage \( V_d \) with entrance of the analyser, and \( m_i \) is the ion mass. The total ion flux \( I(0) \) corresponds to the integration over the whole ion velocity range \( (v_0 = 0) \) and is obtained from the measurement at zero discriminator voltage \( (V_d = 0 \text{ V}) \). With the assumption of all ions entering the sheath in front of the RFEA at the sound speed, \( I(0) \) is reduced to Eq. (1),

\[
I(0) = e A T^4 \int_0^{+\infty} c_s f(v) dv = e A T^4 n_s c_s ,
\]

where \( V_{dc} \) and \( V_{rf} \) are the constant (dc) and oscillating (rf) components of the potential \( (V_{df} = \text{peak rf amplitude}) \) and \( \omega = 2 \pi f = 85.2 \times 10^6 \text{ rad s}^{-1} \) is the radiant frequency. We have previously shown that the peak broadening or splitting in the IEDF from rf oscillation of the sheath can be approximated by

\[
\Delta E = \frac{2e V_{rf}}{\sqrt{1 + (\omega \tau_{av})^2}}
\]

where \( \tau_{av} \) is the average ion transit time in the sheath in front of the RFEA,

\[
\tau_{av} \sim 1.2 \sqrt{\frac{e_0 m_i}{n_0 e_0^2 \frac{1}{kT_e}}}
\]

and \( e_0 \) is the free space permittivity, \( k \) is the Boltzmann's constant, \( n \) is the plasma density, and \( T_e \) is the electron temperature.

Using the previously measured parameters of 1 \( \times 10^{10} \text{ cm}^{-3} \), 30 V and 8 eV for the plasma density \( n \), the average plasma potential \( V_{dc} \) and the electron temperature \( T_e \) at about \( z = 37 \text{ cm} \), respectively, we estimate a \( \Delta E/2e V_{rf} \) ratio of about 0.25 [Eq. (6)]:

A peak rf amplitude \( V_{rf} \) of say 4 V would result in a peak broadening \( \Delta E \) of 2 V. Hence, for a plasma in the diffusion chamber, we would expect a single peaked IEDF around the plasma potential \( V_p \) with a width of around 5 V including all broadening effects mentioned above. At these low densities \( (\leq 1 \times 10^{10} \text{ cm}^{-3}) \) no peak separation due to rf oscillation of the sheath is expected. Hence the measured two peak distribution presented in the next sections is due to the local plasma potential and ion beam and not to rf splitting of the peak corresponding to the plasma potential.

**III. EXPERIMENTAL RESULTS**

**A. Ion beam velocity**

With the analyzer positioned at \( z = 37 \text{ cm} \) (12 cm downstream of the DL) and \( r = 0 \text{ cm} \), a continuous argon plasma operating at 250 W rf power and 0.35 m Torr pressure conditions is initially coupled and four measurements are made in one continuous run by gradually rotating the RFEA from a position facing the diffusion chamber, we would expect a single peaked IEDF around the plasma potential \( V_p \) with a width of around 5 V including all broadening effects mentioned above. At these low densities \( (\leq 1 \times 10^{10} \text{ cm}^{-3}) \) no peak separation due to rf oscillation of the sheath is expected. Hence the measured two peak distribution presented in the next sections is due to the local plasma potential and ion beam and not to rf splitting of the peak corresponding to the plasma potential.
eV ions. Hence with a potential drop \(f_{DL}\) of the DL of about 25 V, we would expect a large proportion of ions to be accelerated to about 25 eV which is highly supersonic. The ion beam disappears from the IEDF for angles larger than 45° in good agreement with the geometric angle of acceptance of this RFEA (~40°).

A simple model for estimating the ion beam energy and density can be developed. The Bohm velocity or ion sound speed is

\[ c_s = \sqrt{\frac{kT_e}{m_i}}. \]  

(8)

The electron temperature measured downstream of the double-layer is about 8 eV. The axial IEDF measurement 12 cm downstream of the DL shows that a good proportion of the potential drop of the double-layer \( (\phi_{DL}\sim 25 \text{ V})\) is transferred into the beam formation

\[ V_{beam} - V_p \sim 18 \text{ V} \sim 2.25 T_e \sim 0.7 e\phi_{DL}. \]  

(9)

The energy gain of \(\sim 0.7 e\phi_{DL}\) by ions across the DL compares well with the energy gain by electrons \((0.7 e\phi_{DL} \approx E_{beam} \approx 0.9 e\phi_{DL})\) measured in current driven DLs. The beam average velocity can be written as

\[ v_{beam} = \sqrt{\frac{2e(V_{beam} - V_p)}{m_i}} \sim \sqrt{\frac{4.5kT_e}{m_i}} \sim 2.1c_s. \]  

(10)

which is supersonic. Supersonic ions have already been measured using RFEA’s or LIF techniques in low pressure magnetic field free helicon plasmas and in low pressure ECR plasmas with a strong magnetic field gradient. These previous experiments were characterized by IEDFs resulting from a balance between acceleration in a slowly decreasing potential and deceleration or change of momentum via charge exchange or elastic collisions with the background neutral gas. In some cases, authors have suggested that strong acceleration over short distances (~1 cm) typical of ion acceleration in a double-layer would be consistent with their experimental results. We have previously shown

\[ \text{FIG. 4. (a) } I(V_d) \text{ characteristics and (b) normalized IEDFs obtained with the RFEA located at } z = 37 \text{ cm and } r = 0 \text{ cm for various collection angles: (solid line) } a = 0^\circ \text{ (axial measurement with RFEA facing the DL), (dotted-dashed line) } a = 90^\circ \text{ (radial measurements with RFEA facing the chamber sidewalls), (dotted line) } a = 22^\circ \text{, and (dashed line) } a = 45^\circ \text{; operating conditions correspond to a pressure of } 0.35 \text{ mTorr, a rf power of } 250 \text{ W, and a magnetic field } B_z \text{ decreasing from about } 250 \text{ G at } z = 25 \text{ cm to about } 50 \text{ G at } z = 37 \text{ cm (Fig. 2).} \]

\[ \text{FIG. 5. (a) Axial (} a = 0^\circ, \text{ facing the DL) } I(V_d) \text{ characteristics and (b) normalized IEDFs obtained with the RFEA located at } z = 37 \text{ cm for various positions on the chamber radius: (solid line) } r = 0 \text{ cm (RFEA on the } z\text{-axis facing the DL), (dotted line) } r = -5.5 \text{ cm (RFEA facing the inner edge of the source tube), (dashed line), } r = -7.5 \text{ cm (RFEA facing the outer edge of the source tube), and (dotted-dashed line) } r = -13.5 \text{ cm (RFEA facing the plate connecting the tube and chamber); same operating conditions as Fig. 4. The internal tube radius is } 6.8 \text{ cm.} \]

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that it is possible to create a current-free DL in a helicon plasma system\textsuperscript{14} and the results shown in Fig. 4 confirm that acceleration of the ions through the DL potential drop leads to the formation of a supersonic ion beam in the low potential side of the DL.

**B. Ion beam density**

Although interpretation of the IEDF is difficult in the case of a flowing plasma, there is good agreement between $V_p$ measured in radial and axial collection modes, respectively (low energy peak at 29 V on Fig. 4), and the experimental data can be used to estimate the beam density. As it would seem that the length of the presheath is related to the mean free path for charge exchange collisions,\textsuperscript{34} the presheath in our system is longer than any typical dimensions that we are studying. Hence, although this does not directly affect our final result, we will not use the factor of 0.6 [Eq. (1)] in calculating the density from a flux measurement by an electric probe but rather refer simply to the density at the sheath edge $n_s$ in front of the RFEA.

Figure 4 shows that the radially oriented RFEA underestimates the plasma density by about 20% ($I_{\text{radial}}(0)/I_{\text{axial}}(0) \approx 1.4 \times 10^{-3}/1.8 \times 10^{-3}$) since it does not collect the fast ions accelerated by the potential drop of the DL. The radial measurement corresponds to the collection of one population of ions only, that of the local ions at the edge of the sheath (i.e., at the sound speed $c_s$) in front of the analyzer [Eq. (4)]:

$$ I_{\text{axial}} = I_{\text{axial}}(0) = eAT^4n_sc_s .$$  \hfill (11)

We can reasonably make the assumption that the axial measurement corresponds to the collection of two distinct populations of ions, a first population of local ions (of density $n_s$ and average velocity $c_s$) falling through the sheath of the earthed analyzer and a second population of ions (of density $n_{\text{beam}}$ and average velocity $v_{\text{beam}}$) accelerated into a beam through the DL and subsequently falling through the sheath of the earthed analyzer.

$$ I_{\text{axial}}(0) = eAT^4(n_s + v_{\text{beam}}) .$$  \hfill (12)

An estimation of the beam density is obtained from the two measurements:

$$ \frac{n_{\text{beam}}}{n_s} \approx \left( \frac{I_{\text{axial}}}{I_{\text{radial}}} - 1 \right) \frac{c_s}{v_{\text{beam}}} \approx 0.14 \pm 0.03 \text{  (13)}$$

which is quite large since we are 12 cm away from the DL.

The density ratio can also be derived by using the axial distribution only:

$$ \frac{n_{\text{beam}}}{n_s} \approx \left( \frac{I_{\text{axial}}(V_{\text{beam}})}{I_{\text{axial}}(V_{\text{beam}})} \right) \frac{c_s}{v_{\text{beam}}} \approx 0.14 \pm 0.03 , \text{  (14)}$$

where

$$ I_{\text{axial}}(V_{\text{beam}}) = eAT^4n_{\text{beam}}v_{\text{beam}} .$$  \hfill (15)

The density ratios calculated using Eqs. (13) and (15) are in quite good agreement. The density $n_s$ of the background plasma is about $1 \times 10^{10}$ cm$^{-3}$ at the RFEA position and the estimated ion beam density is $\approx 1.4 \times 10^9$ cm$^{-3}$. 

**FIG. 6.** $I(V) = 0$ V (crosses), $I(V) = 47$ V (open squares) across the chamber radius obtained with the RFEA located at $z = 37$ cm and facing the DL ($\alpha = 0^\circ$). The open diamonds correspond to additional measurements of $I(V) = 0$ V with the RFEA located at $z = 50$ cm; same operating conditions as Fig. 4. The internal tube radius is 6.8 cm.

**FIG. 7.** (a) Typical $I(V)$ characteristic (solid line) with data fit (dotted line) and (b) normalized IEDFs with three Gaussian deconvolutions. This reference data set corresponds to the solid line in Figs. 4(a), 5(a), and 10(a).
C. Ion beam shape (or radial uniformity)

There is no established theory or computer simulation of current-free double-layers in expanding plasmas available in the literature yet, although Perkins et al. have suggested that the current-driven theories could be applied to current-free DLs in some cases.\(^\text{16}\) Hence acquiring any spatial information on the DL is of importance. Measurements along the chamber diameter \((r\text{-axis})\) are made with the entrance orifice of the analyzer facing axially, i.e., facing the DL. The measurements are performed in a continuous run from \(r = +0.5\) to \(-13.5\) cm followed by \(r = 0-10.5\) cm. The IEDF is shown in Fig. 5 for four values of \(r\) \((0, -5.5, -7.5,\) and \(-13.5\) cm), corresponding to the middle of the source tube (solid line), the inner (dotted line) and outer (dashed line) tube edges and the outside ring (dotted–dashed line), respectively. The results show that the ion beam is present across the source tube radius \((r = 6.8\) cm\) but not in the outside region of the diffusion chamber, suggesting that the ion beam is not particularly affected by the expanding magnetic field. Figure 5 shows that the ion fluxes vary with \(r\) and that the plasma potential and beam energy decrease with increasing \(r\).

The total ion flux \(I(0)\) and the ion flux measured at the beam energy \((\sim 47\) V\) \(I(47)\) are shown across the chamber diameter in Fig. 6. A depression in the total ion flux (crosses) and an increase in the ion beam flux (open squares) are observed in the central region of the diffusion chamber for radii corresponding to the source tube. Such a radial profile for \(I(0)\) suggests the presence of a strongly nonlinear system very different to an ambipolar or free fall radial diffusion—previously measured and modelled in a similar system with no magnetic field\(^\text{35}\)—where the total ion flux would monotonically decrease from the center to the walls. An additional set of data corresponding to \(I(0)\) at \(z = 37\) cm and \(r = 0\) cm \((25\) cm downstream of the DL\) is shown by open diamonds. The depression in the total flux is still observed although largely attenuated by the effect of elastic and charge exchange ion–neutral collisions. This weak density depression has been found in simulations of current driven DLs.\(^\text{36,37}\)

Analysis of the complete set of data is performed as follows: the IEDF corresponding to the term \(v f(v)\) in Eq. (2) is modelled by a sum of one to three Gaussians (depending on the radius) and subsequently integrated from \(V_d\) to \(+\infty\) to fit the experimental data. This is illustrated by solid (measurement) and dotted lines (fit) in Figs. 7(a) and 7(b). The slight discrepancy between the data fit and the measured \(I(V_d)\) characteristic just below the plasma potential is related to secondary electron emission within the RFEA \((\leq 5\%)\). The data fit gives access to the radial profiles of the local plasma potential \(V_p\) (crosses), the beam energy \(V_{\text{beam}}\) (open squares), and of the velocity ratio \(v_{\text{beam}}/c_s\) derived from Eq. (10) (open diamonds), shown in Figs. 8(a) and 8(b), respectively. Both \(V_p\) and \(V_{\text{beam}}\) decrease with increasing radius but the ion velocity ratio is constant \((-2)\) across the source tube suggesting a uniform potential drop \(\phi_{\text{DL}}\) across the source. The ion current measurement at \(V_{\text{beam}}\) is inserted into Eq. (14) to estimate the density ratio \(n_{\text{beam}}/n_s\) along \(r\) shown by open diamonds in Fig. 9: it varies from about \(6\%\) at the source tube edge to about \(15\%\) on the \(z\)-axis. The small triangles in Fig. 9 correspond to the upper limit for the beam density ratio derived from the Gaussian fits of the IEDFs:
This calculation includes all broadening/resolution effects mentioned previously and only serves as a visual guide. The data fits show that, outside the tube radius, no high energy Gaussian is present which probably would make it difficult for instability growth where there would be no background gas.38 Figure 10 shows the axial measurement for \( z = 50 \text{ cm} \) (dotted line), i.e., 25 cm downstream of the DL. The reference measurement (solid line in Figs. 4 and 5) at \( z = 37 \text{ cm} \) is shown as a solid line in Fig. 10. A few mean free paths away from the DL, the beam is not detected anymore (although a tail is present) and the energy has been spread into heating the background gas. This effect would be different in a space situation. As previously detailed,9 the final shape of the IEDF results from the balance between ion acceleration in the field of the double-layer and the effect of ion neutral collisions (charge exchange and elastic scattering). The IEDF deconvolution previously shown in Fig. 7(b) shows that a medium energy Gaussian is present which probably results from some collisional effects between the DL and the collection position 12 cm downstream of the DL.

**D. Electron beam in the source**

Preliminary results obtained from a LP characteristic situated near the closed end of the source tube (\( z = 3 \text{ cm} \)) are shown in Fig. 11: the measured floating potential is about 16 V which is consistent with some wall charging9 in the source and with the presence of the glass plate on the closed end of the source. It appears that there is an electron beam at about 17 V below the floating potential. This is taken simply by subtracting the inflection point from the floating potential and is qualitative.25 We present these data because the apparent velocity of the electron beam correlates well with the height of the double-layer (\( \phi_{DL} \sim 25 \text{ V} \)) and the measured ion beam energy gain (\( \sim 0.7 e \phi_{DL} \sim 18 \text{ V} \)), although the exact analysis is quite difficult. It is found that a calculated characteristic for a plasma that includes an electron beam can fit the measured probe characteristic quite well.30,41 The electron beam probe current written as

\[
I_{beam} = a \exp \left( -\frac{(x+b)^2}{c} \right) \tag{17}
\]
(where $x$ is the probe voltage referenced to $-60$ V) is added to a Maxwellian electron current written as

$$I_e = a \exp\left(-\frac{(x-b')}{c}\right).$$  \hspace{1cm} (18)

An ion current in the form of a constant $d$ is added for the final fit of the characteristic over the selected probe voltage range (Fig. 11). Hershkowitz\(^{43}\) has shown that the ratio between the two electron currents terms can be written as

$$\frac{I_{beam}}{I_e} = \frac{n_{beam}}{n_e} \sqrt{\frac{T_{beam}}{T_e}}.$$ \hspace{1cm} (19)

where $T_{beam}$ is the beam thermal spread:

$$T_{beam} \approx \Delta E_b \left(\frac{\Delta E_b}{4E_b}\right)^{1/2}$$ \hspace{1cm} (20)

with $\Delta E_b$ the spread in the beam energy that corresponds to the half-width of the beam distribution at the $e^{-1}$ point. The current ratio derived from the fitted characteristic gives a value of 0.12. Using the Gaussian’s parameters leads to a $T_{beam}$ value of a few volts and to $\sqrt{T_{beam}/T_e}$ in the 0.35–1 range, suggesting that our value of 0.12 is a lower limit. Similar backwards acceleration of electrons from the downstream side of the DL has often been measured in other laboratory experiments with DL (Refs. 25, 42) and in the downward region of the aurora.\(^{45}\) This effect would be consistent with the ion beam energy gain measured in the downward region of the double-layer and with the beam/local density ratio of $-0.14 \pm 0.03$ obtained from Eqs. (13) and (14). However, these numbers must be regarded as preliminary estimates. The experimental data also show that for probe voltage below $-20$ V, perturbation of the DL is induced by the probe itself, suggesting that a more detailed experimental analysis should be carried out to get some insight into the high potential side of the DL.

**IV. DISCUSSION**

In this paper, we have presented experimental results on the formation of a supersonic $Ar^+$ ion beam generated by a current-free “helicon” double-layer ($v_{beam} \approx 2.1c_e$). Recently, we have shown that similar results can be obtained in a hydrogen discharge\(^{44}\) suggesting that it is the electron dynamics which are determining the existence conditions for the DL. It also suggests that applying this laboratory phenomenon to space and astrophysical phenomena might be possible. Raadu\(^{45}\) has described in great detail the various theoretical and experimental (laboratory and space measurements, computer simulations) works associated with the physics of double-layers and their role in astrophysics. At this stage, no defined theoretical interpretation can be directly applied to our results. In this particular experiment, we seem to have two plasmas, the high potential plasma generated in the source and a lower density plasma in the diffusion chamber probably created by electrons escaping over the top of the DL and a contribution from cold ions resulting from charge exchange of the beam ions accelerated by the DL. The plasma in the diffusion chamber (the downstream plasma) can be reasonably dense and the ratio of the measured ion beam to background plasma reflects these downstream ionization processes. Hence, although all the ions just upstream would be accelerated by the DL, their density decreases due to their increase in velocity and the density ratio $n_{beam}/n_e$ deduced from the experimental data reflects this decrease in the density of the accelerated ions and the ions created downstream. We have not worked on the details of this ionization mechanism as it would probably not be present in a space plasma where the neutral density is much lower than in the laboratory.

It would seem that we are working in a fairly defined window where the ions need to be accelerated to above the sound speed between charge exchange collisions in the upstream plasma before the DL forms. This speculation lends weight to the possibility that the DL is a form of collisionless shock propagating upstream in the accelerated upstream ions. One could also speculate as to why a DL forms under these circumstances and we are working on some models which may shed light on this complicated and curious phenomenon. For pressures higher than 1 mTorr the plasma expands “normally” and there is a self-consistent field set up by the pressure gradient, which, in this essentially isothermal (at least for the electrons) plasma, is due to the gradient in the plasma density.\(^{14}\) In this case the downstream plasma density seems to be dominated by diffusion from the plasma in the source. However, for the lower pressures where the DL is observed, the mean free path for the electrons is much longer than the system length and simple ideas of diffusion must be used with considerable caution. In addition, the DL is definitely collisionless so it is difficult to compare it with traditional shock waves and Laval nozzles.\(^{45}\)

**V. CONCLUSION**

Ion acceleration through the potential drop of a current-free double-layer resulting in the formation of a supersonic ion beam has been demonstrated using an energy analyzer. The ion beam density and radial profile across the diffusion chamber have been measured and have shown the presence of a uniform beam across the entire source diameter, with no detrimental divergence effect from the expanding magnetic field. An electron beam has also been detected upstream of the DL.

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