

Xenon ion beam characterization in a helicon double layer thruster

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A current-free electric double layer is created in a helicon double layer thruster operating with xenon and compared to a recently developed theory. The Xe^+ ion beam formed by acceleration through the potential drop of the double layer is characterized radially using an electrostatic ion energy analyzer. For operating conditions of 500 W rf power, 0.07 mTorr gas pressure, and a maximum magnetic field of 125 G, the measured beam velocity is about 6 km s^{-1} , the beam area is about 150 cm^2 , and the measured beam divergence is less than 6° . © 2006 American Institute of Physics.

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Magnetic-field-aligned electric fields called electric double layers (DL's) occurring naturally in space plasmas are known to be the source of particle acceleration.¹ Recently, a current-free electric DL has been found in low pressure laboratory plasmas expanding in a divergent magnetic field.²⁻⁴ Experimental evidence of a large area supersonic ion beam downstream of the DL has been shown and the results have been correlated with results from particle-in-cell simulations.^{4,5} The strength of the DL is a few times the electron temperature T_e and may be a candidate for particle acceleration in space plasmas⁶ or for electric propulsion.^{2,7,8}

The spontaneous formation of the DL requires no applied current or potential on electrodes immersed in the plasma and hence avoids detrimental electrode erosion. The ion beam is neutralized by electrons overcoming the potential of the DL, and no additional neutralizer is needed. This differs from the ion gridded engines or Hall thrusters which have been developed for the past few decades.⁹ In the latter, minimizing beam divergence for extended ranges of operating parameters remains a challenge, as the radial and axial plasma potential profiles are strongly correlated with the magnetic field distribution.¹⁰⁻¹³

We refer to the present magnetoplasma thruster with anticipated long life characteristics as the helicon double layer thruster (HDLT). The purpose of this letter is to show the experimental and theoretical validities of the HDLT operating in xenon, the inertial gas preferred for actual plasma thrusters due to its large ion mass, and to present the characterization of the Xe^+ ion beam.

The helicon double layer thruster is mounted on Chi Kung's 30-cm-long, 32-cm-diameter earthed aluminum diffusion chamber described previously.¹⁴ The HDLT consists of a 15-cm-diameter Pyrex tube with a middle section defining a plasma cavity length of 31 cm. Xenon gas is injected using nylon tubing on the closed end of the helicon source cavity via a hole in the middle section of the Pyrex tube. Hence, the entire thruster walls are insulating. The 18-cm-long double-saddle field antenna that surrounds the Pyrex tube is fed from a rf matching network/generator system operating at 13.56 MHz, and the rf power is maintained at 500 W. Two solenoids surrounding the HDLT generate a

divergent magnetic field, decreasing from a maximum of about 125 G in the source to about 10 G in the middle of the pumping vessel.

Chi Kung's vacuum chamber is pumped down to a base pressure of $\sim 2 \times 10^{-7}$ Torr using a 2000 l s^{-1} turbomolecular/rotary pumping system connected to the closed end of the diffusion chamber and facing the HDLT. The effective pumping speed measured for Xe is about 700 l s^{-1} . The pressure is measured using a baratron gauge and an ion gauge attached to a side port of the chamber. Previous experiments in similar geometry and with an effective pumping speed 15 times lower and a somewhat higher pressure have shown the presence of a current-free DL at $z=25 \text{ cm}$ for an argon discharge,² where $z=0 \text{ cm}$ is defined at the closed end of the thruster. The DL has been correlated with the presence of an Ar^+ ion beam detected using a retarding field energy analyzer¹⁴ (RFEA).

In this study, the RFEA is initially placed on the main axis at $z=37 \text{ cm}$ and $r=0 \text{ cm}$ (r is the chamber radius) using a side port on the diffusion chamber.¹⁴ The analyzer is facing the HDLT and can be moved radially across the chamber. The energy resolution is about 1 eV. The ion energy distribution function (IEDF) corresponds to the derivative of the measured current-voltage characteristic and is analyzed using a deconvolution method previously described¹⁴ to determine the ion beam energy V_{beam} (which corresponds to the plasma potential inside the thruster just upstream of the DL), the local plasma potential V_{chamber} at the probe position, the DL potential drop $V_{\text{DL}} \sim (V_{\text{beam}} - V_{\text{chamber}})$, the beam velocity v_{beam} , and the ion beam density n_{beam} .

The IEDF obtained at $r=0 \text{ cm}$ ($z=37 \text{ cm}$) for a pressure of 0.07 mTorr is shown in Fig. 1. It shows the presence of two peaks, a low energy peak which corresponds to a population of cold ions near the probe ($V_{\text{chamber}}=31 \text{ V}$) and a high energy peak which corresponds to the Xe^+ ion beam ($V_{\text{beam}}=49.5 \text{ V}$). The corresponding DL potential drop is $V_{\text{DL}} \sim 18.5 \text{ V}$ at 0.07 mTorr, i.e., lower than the pressure cutoff previously seen in argon.^{15,16} The ions generated in the helicon source and accelerated through the potential drop V_{DL} form a well defined beam, whose velocity can be calculated using

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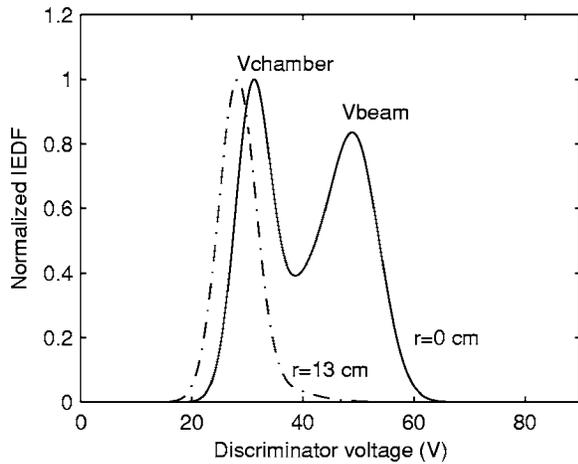


FIG. 1. Normalized IEDF in xenon measured with the RFEA placed at $r=0$ cm (solid line) and $r=13$ cm (dashed line).

$$v_{\text{beam}} = \sqrt{\frac{2e(V_{\text{beam}} - V_{\text{chamber}})}{M}} = \sqrt{\frac{2eV_{\text{DL}}}{M}} \sim 6 \text{ km s}^{-1}, \quad (1)$$

where e is the electron charge and M is the xenon ion mass. A study of V_{DL} versus pressure is carried out experimentally by measuring the IEDF at $r=0$ cm and theoretically by using xenon cross sections¹⁷ in a recently developed model,^{15,16} and the results are shown in Fig. 2. A comparison between xenon and argon shows that the cutoff exists at a lower pressure in xenon. The results agree quite well and demonstrate experimental evidence of the generation of a current-free double layer in xenon and a further validation of the theory.

Maintaining the pressure at 0.07 mTorr, the beam is subsequently spatially characterized by moving the RFEA from the central axis ($r=0$ cm) to the chamber walls ($r=16$ cm) with the measurements taken along one radius only ($0 \text{ cm} \leq r \leq +13 \text{ cm}$). The radial profiles of V_{beam} , V_{chamber} and the derived V_{DL} are shown in Fig. 3. V_{beam} reflects the plasma potential just upstream of the DL, i.e., inside the HDLT at about $z=23$ cm. It is maximum in the center (~ 50 V) and slightly decreases towards the edge. V_{chamber} is very uniform (28 ± 3 V). Consequently, the DL potential drop is radially uniform (~ 17 V) and the beam velocity is radially uniform

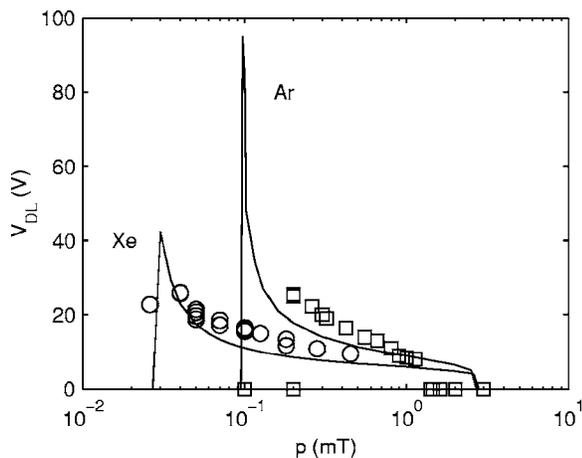


FIG. 2. Double layer strength V_{DL} vs pressure: theoretical (solid line) and experimental (open circles) results for xenon; results for argon (solid line and open squares) are from Refs. 15 and 16.

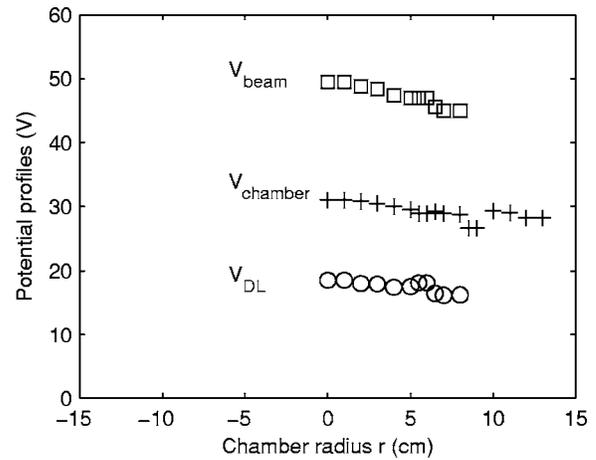


FIG. 3. Potential profiles in xenon.

($6 \pm 0.5 \text{ km s}^{-1}$). The IEDF measured at $r=13$ cm is shown in Fig. 1 and only exhibits the low energy peak at about 28 V.

The ion beam flux measured by the RFEA can be written as

$$I(v_{\text{beam}}) = eAT^4 \int_{v_{\text{beam}}}^{+\infty} v f(v) dv \sim eAT^4 n_{\text{beam}} v_{\text{beam}}, \quad (2)$$

where A is the analyzer aperture area, T is the grid transmission coefficient (four grids), and n_{beam} is the beam density at the position of the probe. In the laboratory, the beam density decreases exponentially along the z axis as a result of charge exchange collisions between ions and neutrals in the pumping chamber.¹⁴ The normalized ion beam density n_{beam} profile derived using Eqs. (1) and (2) is shown in Fig. 4. The profile exhibits a peak at $r=4$ cm. Since the beam velocity is constant for $r=0-8$ cm (Fig. 3), this peak results from the radial density profile upstream of the DL, hence from the helicon coupling mechanism. Assuming geometrical symmetry for $-13 \text{ cm} \leq r \leq 0$ cm leads to a “double hump” density profile which has been previously measured and is a common feature of a high density plasma coupling mode.^{18,19} An estimation of the plasma density upstream of the double layer gives a few 10^{11} cm^{-3} .

The largest value of r where a beam is detected is 8 cm, and no beam is measured for r greater than 8.5 cm (Fig 4).

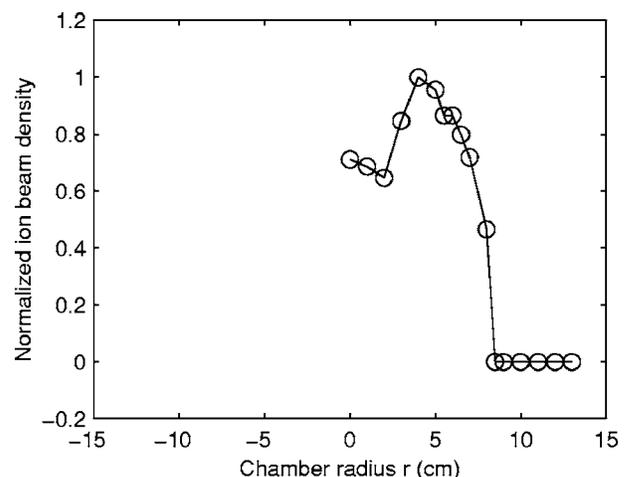


FIG. 4. Xe^+ ion beam density profile.

Using $r_{\text{edge}}=8$ cm as the beam edge, we can estimate the beam divergence angle α using

$$\tan \alpha = \frac{r_{\text{edge}} - r_{\text{tube}}}{z_{\text{RFEA}} - z_{\text{DL}}}, \quad (3)$$

where r_{tube} is the internal radius of the HDLT (6.8 cm) and z_{RFEA} and z_{DL} are the position in the magnetic nozzle of the RFEA and of the DL, respectively. The calculated Xe^+ ion beam divergence is $\alpha=5.7^\circ$. The beam area calculated at the position of the DL is about 145 cm^2 . Hence a large area ion beam with low divergence is obtained in the magnetic nozzle of the HDLT. The low divergence suggests that the beam profile is mostly determined by the DL and is not strongly affected by the divergent magnetic field, in good agreement with simulation work.⁷ Such a low divergence is also in good agreement with the uniform plasma potential profile upstream of the DL (Fig. 3).

In summary we have shown experimental evidence of a current-free electric double layer self-consistently generated at the exit of a helicon double layer thruster operating in xenon, at 500 W, with a magnetic field of 125 G and with a pumping speed of 700 l s^{-1} . Both the experiment and theory show that the operating range of the HDLT in xenon extends to lower pressure than for argon. The ion beam velocity does not vary much radially and the beam divergence is less than 6° . The beam density profile has the double hump shape typical of high density coupling modes, suggesting the possibility of further improvement of the HDLT in terms of high power scalability.

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