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Magnetic steering of a helicon double layer thruster

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The ion beam generated by a helicon double layer has been electrically steered up to 20° off axis by using a solenoid placed normal to the two axial solenoids of the helicon plasma source without significantly changing the beam exhaust velocity. © *2008 American Institute of Physics.*
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Over the past few years, there has been an increasing interest in the experimental[1–5] and analytical[6–8] investigations of double layer (DL) formation in low pressure expanding magnetized plasmas. Although the details are not fully understood, it has been experimentally shown that the shape and strength of the magnetic field play an important role in the DL formation[9–12] and that ion beam detachment occurs downstream of the DL.[12–14] Experimental investigation of DL formation in more complex magnetic structures is directly relevant to the field of space plasmas (such as the solar corona[15]) and electric propulsion [such as the helicon double layer thruster (HDLT) (Refs. 16 and 17)]. Although the magnetic field configuration plays a critical role in both the HDLT[18,19] and in Hall thrusters,[20,21] the basic role and physics behind the two concepts strongly differ. In Hall thrusters, the magnetic field lines are perpendicular to the thrust axis while they are aligned with the thrust axis in the HDLT. In the latter, a magnetic-field-induced transition from a plasma expanding along the magnetic and geometric axis to one supporting a DL has been reported.[10] Here we present the first experimental evidence of DL formation and controlled ion beam deflection by using an additional "transverse" solenoid.

The HDLT configuration used as a reference, and reported upon previously,[17] consists of a 15-cm-diameter 31 cm long pyrex source tube surrounded by two axial solenoids positioned at $z=1.5$ and 21 cm and is shown in Fig. 1. The "magnetically steerable" helicon double layer thruster (MS-HDLT) configuration comprises three solenoids in a horizontal plane: the two axial solenoids ($z=1.5$ and 21 cm) of the reference HDLT and a third perpendicularly oriented transverse solenoid, TS ($z=10.5$ cm and $x=-16.2$ cm), as shown in Fig. 2. For both the HDLT and MS-HDLT, the source tube is attached to CHI KUNG's 30-cm-long 32-cm-diameter earthed aluminum diffusion chamber described previously,[22] which is pumped down to a base pressure of $\sim 2\times 10^{-6}$ Torr using a 150 l s^{-1} turbo-molecular/rotary pumping system connected to the side of the diffusion chamber. Argon gas is injected via a chamber side port and the operating pressure measured in the chamber using a baratron gauge is maintained at about 0.3 mTorr. The 18 cm long double-saddle field antenna (not shown for clarity in Figs. 1 and 2) that surrounds the pyrex tube has been flipped horizontally and rotated by 90° compared to the initial DL experiment in Ref. 22 to allow the three solenoids to be centered in the horizontal plane. A constant rf power of 250 W is fed from a rf matching network/generator system operating at 13.56 MHz.

The previously described[10] standard DL operating conditions correspond to a divergent magnetic field decreasing from a maximum of about 140 G in the source to about 10 G in the middle of the chamber. In this study, the parameter is the current I_{TS} in the transverse solenoid ($I_{TS}=0$ to 6 A corresponding linearly to a magnetic field of $B_{TS}\sim 3$ to 246 G inside the transverse solenoid, respectively) with north pointing radially outward from the pyrex tube. The magnetic field lines and the magnetic field magnitude are shown in Figs. 1 and 2 for $I_{TS}=0$ A and $I_{TS}=4$ A ($B_{TS}=165$ G), respectively. The source/chamber interface is defined at $z=30$ cm.

In contrast to other propulsion techniques, visual inspection is insufficient to identify the steering of the HDLT ion beam nor characterize its potency. A retarding field energy analyzer (RFEA) (Ref. 22) with the aperture hole facing the plasma source, positioned at $z=36$ cm (Fig. 1) and free to move from wall to wall along the x-axis of the chamber, is used to measure the current versus discriminator voltage $I(V_d)$ characteristic. Its derivative, the ion energy distribution function (IEDF),[22] was measured for seven values of I_{TS} (0, 1, 2, 3, 4, 5, and 6 A). The IEDFs obtained across the cham-

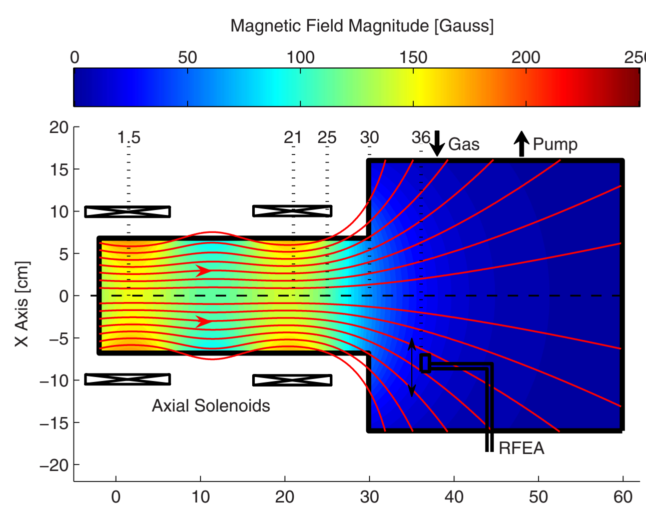

FIG. 1. (Color online) Top down schematic of the reference HDLT attached to the CHI KUNG diffusion chamber showing the RFEA and the two axial solenoids with the corresponding calculated magnetic field lines (red solid lines) and amplitude (color bar).

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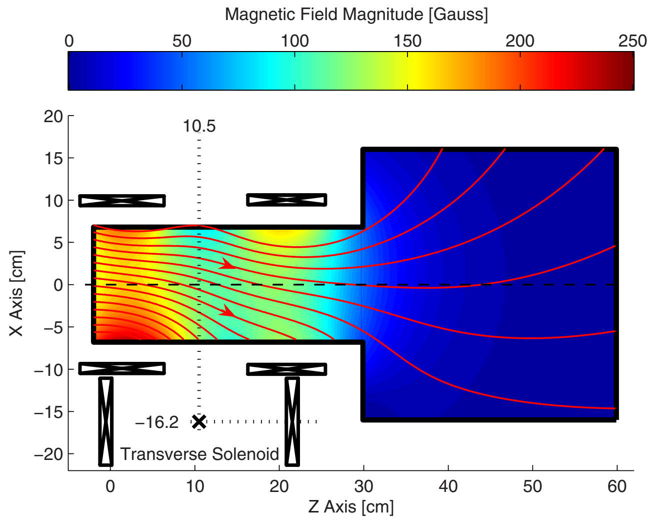

FIG. 2. (Color online) Top down schematic of the MS-HDLT showing the two axial and one transverse ($I_{TS}=4$ A) solenoids. The north of the transverse solenoid field is pointing outward from the source tube.

ber ($x=-13$ to 13 cm, $z=36$ cm) for $I_{TS}=4$ A are shown in Fig. 3. The local plasma ($V_p \sim 38$ V) and ion beam ($V_{beam} \sim 44$ to 52 V) populations can be fitted by two separate Gaussians with central positions marked by the black and red crosses, respectively. A first inspection of the results in Fig. 3 shows that the ion beam profile appears asymmetric about the z-axis. The maximum at about $x=8$ cm in the local plasma band (red region at about 8×10^{-3} in the color bar) is not well understood at present and will be reported upon in a later publication. The reference IEDFs ($I_{TS}=0$ A) are similar to previously published data in argon[12,22,23] and xenon[16,18] and exhibit a symmetry of both low and high energy bands about the z-axis.

The ion beam current profile is shown in Fig. 3 and is distinct from the IEDF magnitude profile at the ion beam voltages (red crosses). Identification and characterization of ion beam steering require an analysis of the current measured

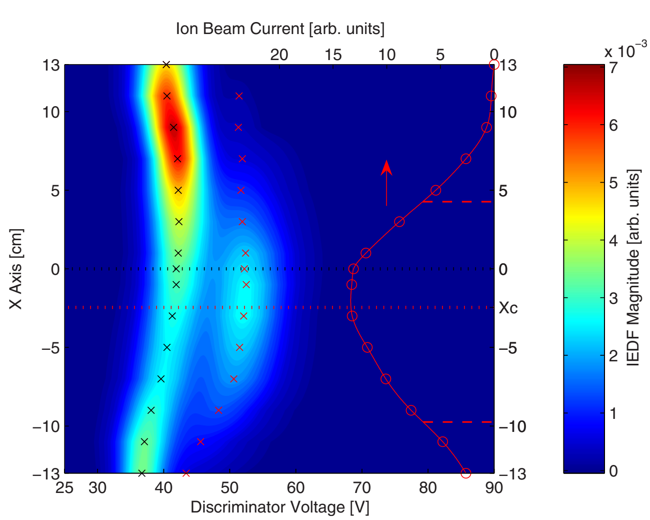

FIG. 3. (Color online) X-axial profile of the IEDFs measured in the chamber using the RFEA ($x=-13$ to $+13$ cm, $z=36$ cm); operating conditions are 250 W rf power, 0.3 mTorr argon pressure, and the magnetic field configuration of Fig. 2. The black and red crosses correspond to the local plasma and ion beam potentials, respectively. The ion beam current profile is shown by the red circles. The location of the beam center x_c defines the beam center line (dotted red line).

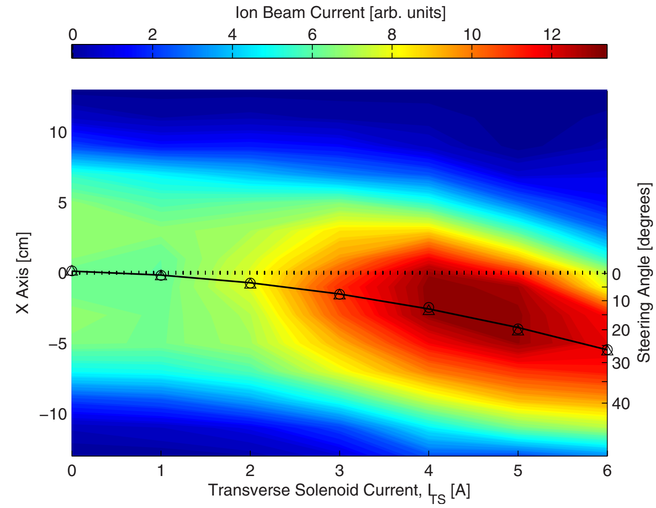

FIG. 4. (Color online) X-axial profile of the ion beam current measured in the chamber using the RFEA ($x=-13$ to $+13$ cm, $z=36$ cm) as a function of I_{TS} for 250 W rf power and 0.3 mTorr pressure conditions. The triangles correspond to the midpoint between the FWHM x-axial positions (dashed lines in Fig. 3) of the ion beam current profiles and the circles show the half integral beam center position x_c. The solid line is the quadratic line of best fit ($x_c=-0.13\times I_{TS}^2-0.15\times I_{TS}+0.12$) through these circles. The right vertical axis shows the steering angle and is a nonlinear scale given by Eq. (1), such that the positions of the triangles and circles also correspond to the steering angle axis.

by the RFEA at the beam voltage and the resulting asymmetry in the ion beam current profile. The IEDF magnitude profile is insufficient for this purpose as it is only a measure of the $I(V_d)$ characteristic gradient, and consequently a large value in the IEDF magnitude does not signify a large measurement of beam ions. Evaluation of the effect of the transverse solenoid on steering the ion beam requires identification of the center of the beam in order to estimate the degree of its deflection. Two methods are considered in the identification of the ion beam center. The first method involves considering the two x-axial points on the ion beam current profile corresponding to the full width at half maximum (FWHM) (dashed red lines). The midpoint between these two x-axial positions is defined as the FWHM beam center. An alternative definition is obtained by integrating the ion beam current profile between the two FWHM x-axial positions. Incrementally repeating this integration until half of the total integral is reached generates the (integrated) beam center x_c at the interface between the equal areas under the ion beam current profile. For $I_{TS}=4$ A, $x_c=-2.45$ cm and is within 5% of the FWHM midpoint, indicating a relatively symmetric ion beam current profile. For the present analysis we define $(V_{beam})_{bc}=52.3$ V and $(V_p)_{bc}=41$ V as the values on the beam center line (Fig. 3).

The steering angle θ_{st} (defined as the angle between the beam center line and the z-axis) calculated using the previously measured DL position[1] ($z_{DL}\sim 25$ cm) can be estimated as follows:

$$\tan\theta_{st} = \frac{|x_c|}{z_{RFEA}-z_{DL}}, \quad (1)$$

where z_{RFEA} is the axial position of the analyzer. θ_{st} is found to be about 12.6° for $I_{TS}=4$ A. The ion beam current profile and the steering angle are plotted in Fig. 4 for all values of I_{TS}. The steering angle increases quadratically from 0.4° to

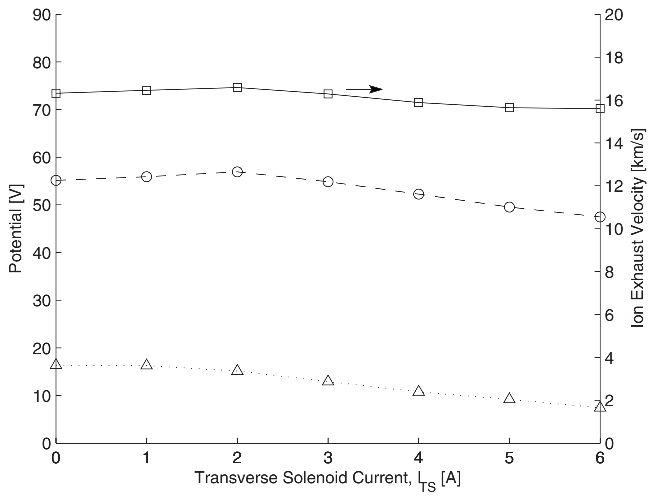

FIG. 5. $(V_{beam})_{bc}$ (open circles), $(V_{beam}\text{-}V_p)_{bc}$ (open triangles), and $(v_{exhaust})_{bc}$ (open squares) as a function of I_{TS} for 250 W rf power and 0.3 mTorr pressure conditions.

about 27.2° when the transverse solenoid current is increased from 0 to 6 A, compared to the maximum magnetic field deflection over this region of less than 5°. For $I_{TS}=4$ A, the ion beam current maximum is about 1.8 times higher than for the reference case ($I_{TS}=0$ A). For I_{TS} greater than 5 A, the ion beam has become degraded and a further increase in the TS current is likely to result in destruction of the ion beam.

The corresponding values of $(V_{beam})_{bc}$, $(V_{beam}\text{-}V_p)_{bc}$, and $(v_{exhaust})_{bc}$ are plotted in Fig. 5 for all values of I_{TS}, where $(v_{exhaust})_{bc}$ is the ion exhaust velocity,[18]

$$(v_{exhaust})_{bc} = \sqrt{\frac{2e(V_{beam})_{bc}}{M}}, \quad (2)$$

where e is the electronic charge and M is the argon ion mass. The corresponding exhaust beam velocity is presently about 16×10^3 m s^{-1} and does not vary much. $(V_{beam}\text{-}V_p)_{bc}$ gives an indication of the strength of the DL and decreases with increasing I_{TS}.

Although the magnetic steering is confirmed for a large range of transverse solenoid currents, direct spatial measurements of plasma density and potentials in the plasma source will need to be carried out for a clearer understanding of the physics behind the steering. These results show that the heavy gimbals currently in use for satellite steering could be replaced by additional solenoids to induce a local perturbation of the magnetic field structure, which results in an asymmetric exhaust. Although not yet demonstrated, the results suggest that steering in the y-z plane could be obtained by a second transverse solenoid placed at 90° with respect to the present transverse configuration, i.e., below the source tube. This would result in full thruster magnetic steering capability.

In summary, it has been demonstrated that the addition of a transverse solenoid to the HDLT leads to magnetic steering in the plane of the three solenoids of the ion beam generated by acceleration in the field of the electric DL. The inclusion of the transverse solenoid is shown to have a negligible effect on the ion exhaust velocity.

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