Three-Dimensional Mapping of Ion Density in a Double-Layer Helicon Plasma

Wes Cox, Rhys Hawkins, Christine Charles, and Rod Boswell

***Abstract*—An investigation of the ion density produced inside the Chi Kung reactor at 250 W and 0.30 mtorr was performed through Langmuir probe measurements. Three-dimensional interpolation combined these data to produce a 3-D density volume. The resulting image was used to identify three distinct regions of differing density: power deposition, acceleration, and expansion. The ion density over these regions was found to vary from $\sim 1.3 \times 10^{10}$ to $\sim 2.7 \times 10^{11}$ cm^{-3}.**

***Index Terms*—Electric propulsion, ion beam, ion density measurements, plasma diagnostics, plasma propulsion.**

ELECTRICAL methods of space propulsion provide higher exhaust velocities than their chemical counterparts, increasing fuel efficiency and mission duration [1]. Current-free double layers accelerate ions in the absence of electric grids, eliminating electrode erosion issues which limit the lifetime of conventional electric propulsion techniques [2, and references within]. An important thing in developing a thruster based on the double-layer phenomenon is a study of the plasma density cartography and the corresponding identification of the various regions within.

The Chi Kung geometry has been detailed previously [3], and it consists of a 31-cm-long 15-cm-diameter cylindrical Pyrex source tube attached contiguously to a 29.4-cm-long 32-cm-diameter Al diffusion chamber. This source tube/diffusion chamber interface (the flange) is defined as $z = 30$ cm such that the top of the source tube is $z = -1$ cm and the backplate of the diffusion chamber is at $z = 59.4$ cm. The Ar gas (at a pressure of 0.30 mtorr) is ionized by 250 W of RF power supplied via a π-matching network/generator system through the helicon antenna surrounding the source tube. Two solenoids produce a magnetic field maximum of ∼130 G in the source and a few tens of gauss in the diffusion chamber [4]. The measurements of the plasma ion density using a Langmuir probe were taken inside the Chi Kung reactor (the basis for the helicon double-layer thruster). The Langmuir probe consists of a 1-mm-diameter circular nickel disk attached to a quarter inch RF shielded tube inserted into the chamber through a port that is offset by 57 mm from the center axis of the reactor. The probe tube enters through the backplate of the diffusion chamber, and the end 10-cm is bent at an angle to allow measurement of the points that are 54.5 mm from the center of the probe post.

The measurement of the ion density involves the rotation of the Langmuir probe in 10° intervals through an arc to and from each wall inside the source tube and through a full rotation in the diffusion chamber. This is repeated in 2-cm intervals from $z = 5$ cm (in the source) to $z = 47$ cm (diffusion chamber). Furthermore, by then rotating the backplate of the diffusion chamber (through which the probe is inserted) through a full rotation in 30° intervals, we can sweep out a full 3-D volume of Chi Kung in the corresponding region.

The ion density (error of $< 15\%$) shown in Fig. 1 is derived from the ion saturation current measured with the Langmuir probe that is negatively biased at -70 V [4], [5]. The Bohm velocity is calculated by using a constant electron temperature of 8 eV throughout the volume; however, this is only true for regions that are upstream of the double layer [6]. This results in an underestimation by less than 21% downstream, which is small compared to the factor of eight contrast in plasma density between up- and downstream.

Near the walls, the floating potential can become strongly negative, which will prevent the probe from operating in the ion saturation mode [7]. This can cause the collection of fast moving electrons, decreasing the current measured by the probe and reducing the inferred ion density. The accurate ion density measurements in these regions require the compensation for high energy electrons through applying a stronger bias. The measurements described in this paper and shown in Fig. 1 do not incorporate this compensation. Consequently, the ion density near the walls is underestimated, quite dramatically in regions where the floating potential approaches the probe bias. Some negative values for the ion density were obtained as a result of high energy electrons; however, these have been zeroed out in Fig. 1. The floating potential away from the walls varies between ∼1 V downstream to ∼25 V upstream, and the effect on the measured density is less than 20%, although the influence of floating potential on measured density will be studied in greater detail in future work.

Fig. 1 is obtained by interpolating the Langmuir probe data into a 3-D volume, scaling ion density as a function of color. In order to emphasize the low-density core ($\sim 1.5 \times 10^{10}$ cm^{-3})

Manuscript received November 30, 2007; revised April 5, 2008.

W. Cox, C. Charles, and R. Boswell are with the SP3 Group, Plasma Research Laboratory, RSPhysSE, The Australian National University, Canberra ACT 0200, Australia (e-mail: wes.cox@anu.edu.au).

R. Hawkins is with the SP3 Group, Plasma Research Laboratory, RSPhysSE and the Vizlab, The Australian National University (ANU) Supercomputing Facility, ANU, Canberra ACT 0200, Australia.

Digital Object Identifier 10.1109/TPS.2008.924429

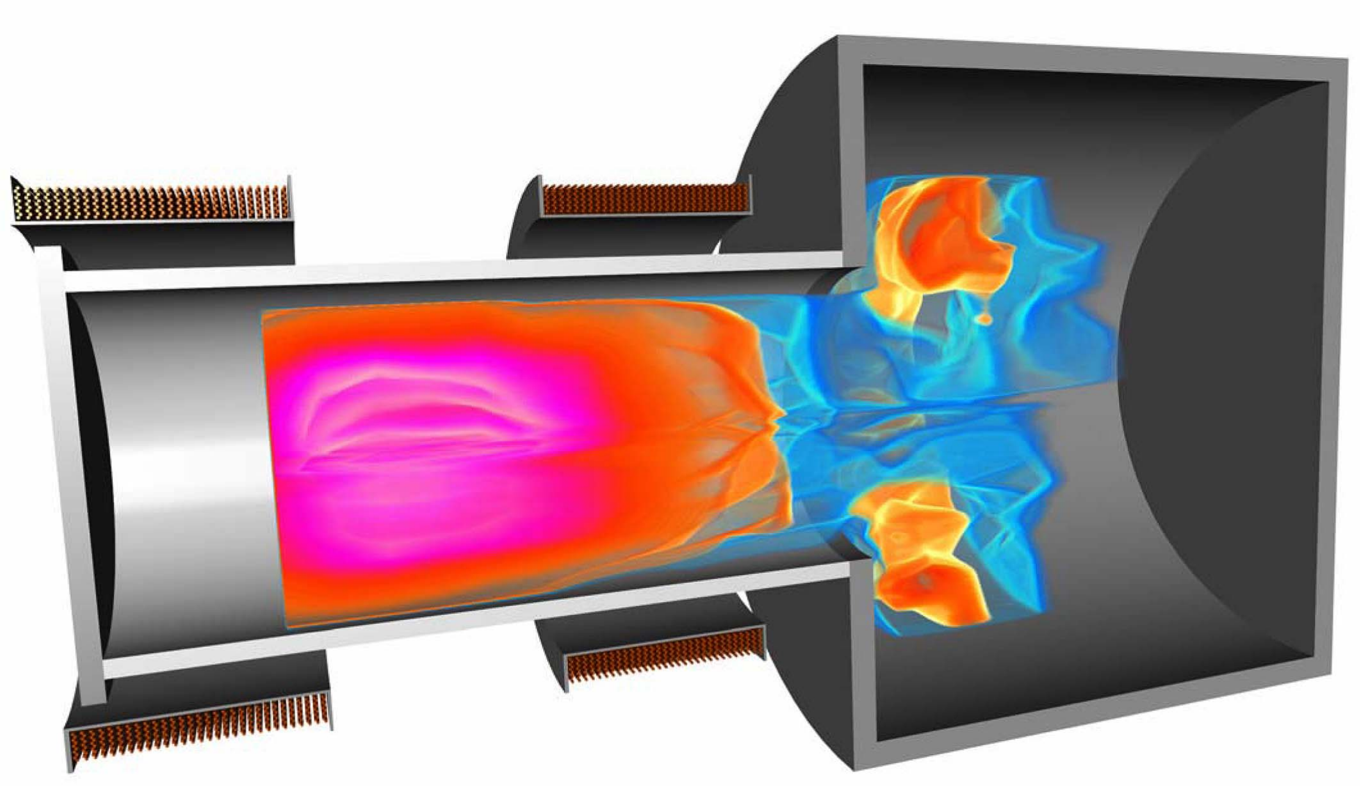

Fig. 1. Three-dimensional image of the plasma density measured inside Chi Kung (a horizontal helicon plasma system), using a Langmuir probe, where the color scale represents the following: 2.7×10^{11}–5.3×10^{10} cm^{-3} as white to red, 3.1×10^{10}–2.6×10^{10} cm^{-3} as dark to bright orange, and 1.6×10^{10}–1.3×10^{10} cm^{-3} as light to dark blue, respectively. The plasma is ionized in the smaller diameter source tube region, and it expands into the larger diameter diffusion chamber. The measured region of plasma shown in the image is between (left) $z = 5$ cm and (right) $z = 47$ cm, where $z = 30$ cm is defined as the interface between the source tube and diffusion chamber. The radius of the plasma density shown in the source tube is ∼6 cm (the source tube internal radius is $r = 6.85$ cm). In the diffusion chamber, the maximum radius reached by the probe is 11.2 cm, which is ∼5 cm from the chamber wall. The diffusion chamber is 29.4 cm long, and as such, there is 12.4 cm of plasma exhaust plume, which is not measured but still exists in the diffusion chamber.

surrounded by the medium density ring ($\sim 2.7 \times 10^{10}$ cm^{-3}) in the diffusion chamber, the regions of plasma outside this density range have been suppressed. The volume containing the low-density core corresponds to the region where the ion beam has been previously measured [3]. The acceleration region ($z =$ 21 to 29 cm) exists at the interface between the pink upstream power deposition region ($\sim 2.7 \times 10^{11}$ cm^{-3} maximum) and the blue downstream low-density plasma in the diffusion chamber. This region contains the double layer ($z_{\mathrm{DL}} \approx 25$ cm [3]); the ion beam detected downstream ($z \geq 25$ cm), using an energy analyzer [3], cannot be clearly identified in the Langmuir probe ion saturation data (Fig. 1). Unlike the bell-shaped profile further upstream, the profile in the acceleration region is flat, possibly suggesting some local modification of the radial cross-field diffusion [8].

In conclusion, the results are consistent with the literature [2], also providing clear evidence of the presence of the medium density ring in the diffusion chamber, which could only be investigated due to this spatial study.

REFERENCES

[1] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*, 7th ed. New York: Wiley-Interscience, 2001, ch. 2.

[2] C. Charles, “A review of recent laboratory double layer experiments,” *Plasma Sources Sci. Technol.*, vol. 16, no. 4, pp. R1–R25, Nov. 2007.

[3] C. Charles and R. W. Boswell, “Laboratory evidence of a supersonic ion beam generated by a current-free “helicon” double-layer,” *Phys. Plasmas*, vol. 11, no. 4, pp. 1706–1714, Apr. 2004.

[4] C. Charles and R. W. Boswell, “The magnetic-field-induced transition from an expanding plasma to a double layer containing expanding plasma,” *Appl. Phys. Lett.*, vol. 91, no. 20, pp. 201 505–201 507, Nov. 2007.

[5] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed. New York: Wiley-Interscience, 2005, ch. 6.

[6] K. Takahashi, C. Charles, R. W. Boswell, T. Kaneko, and R. Hatakeyama, “Measurement of the energy distribution of trapped and free electrons in a current-free double layer,” *Phys. Plasmas*, vol. 14, no. 11, pp. 114 503–114 506, Nov. 2007.

[7] C. Charles, R. W. Boswell, and M. A. Lieberman, “Energy balance in a low pressure capacitive discharge driven by a double-saddle antenna,” *Phys. Plasmas*, vol. 10, no. 3, pp. 891–899, Mar. 2003.

[8] C. Charles, R. W. Boswell, and M. A. Lieberman, “Xenon ion beam characterization in a helicon double layer thruster,” *Appl. Phys. Lett.*, vol. 89, no. 26, pp. 261 503–261 506, Dec. 2006.