Observations of Ion-Beam Formation in a Current-Free Double Layer

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With nonperturbative laser-induced fluorescence measurements of ion flow, we confirm numerical simulations of spontaneous electric double-layer (DL) formation in a current-free expanding plasma. Measurements in two different experiments confirm that the DL is localized to the region of rapidly diverging magnetic field. The measurements indicate that the trapped ion population is a single Maxwellian, that the spatial gradient of the energy of ions accelerated through the DL matches the magnetic field gradient, and that DL formation is triggered when the ion-neutral collisional mean-free path exceeds the magnetic field gradient scale length.

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Recent experiments have demonstrated that electric double layers (DLs) can form spontaneously in a current-free plasma expanding in a diverging magnetic field [1–5]. DLs are narrow, local regions of electric potential gradient isolated from plasma boundaries. Alfvén suggested that the aurora resulted from energetic electrons precipitating onto the upper atmosphere and that the electrons in space could be accelerated by DL electric fields [6]. Later observations provided strong experimental evidence in support of Alfvén's hypothesis [7]. Since then, DLs have been invoked in discussions of solar flare phenomena [8], high-power gas lasers [9], and laser-ablated plasmas [10]. Previous observations of DLs in space [7], in laboratory experiments [11,12] and simulations [13,14] have occurred in systems driven by electric current, externally imposed potential differences, or the merging of two plasmas with initially different electron temperatures.

That DLs can form in a current-free plasma expanding in a divergent magnetic field was predicted in an analytical study by Perkins in 1981 [15]. Although experimental observations of ion acceleration in expanding current-free plasmas soon followed [16–18], no clear evidence of DL formation was obtained in those experiments. Unambiguous observations of DL formation in current-driven plasmas expanding in a diverging magnetic field suggested that divergent magnetic fields themselves could play an important role in initiating DL formation [19].

Current-free plasma expansion in a divergent magnetic field is surprisingly common and is found on a variety of spatial scales and in a variety of applications. Plasma expansion is essentially equivalent to a pressure gradient arising from a change in the plasma density. The density gradient can give rise to a potential gradient that retards motion of the lighter plasma electrons but accelerates the more massive ions downstream. Solar wind expansion and the corresponding creation of the interplanetary electric field is a classic example of this process [20]. Under isothermal, collisional conditions, the electron density depends on the plasma potential through the classic Boltzmann equation. However, in collisionless plasmas, the mean-free path for ion collisions (such as elastic and charge-exchange collisions) can be much longer than the scale length of the plasma expansion and/or the magnetic field gradient. Under these conditions electric DLs can arise. For DLs that are essentially ion acoustic solitons, the strength of the DL, i.e., the voltage drop across the DL, can be low, a few times the electron thermal energy ($\sim 2kT_e/e$) [21]. Stronger DLs can be many times the electron temperature, e.g., many hundreds, if not thousands, of times the electron thermal energy [22].

A recent one-dimensional, unmagnetized, hybrid simulation (particle ions and fluid electrons) that modeled plasma expansion in a diverging magnetic field with a position dependent particle loss rate [see Fig. 1(a) for the experimental geometry and Fig. 1(b) for the loss rate model] provided further evidence that a DL can form in a current-free plasma [23]. In that simulation, a DL formed at the location of rapid plasma expansion. Throughout the simulation volume, a low energy population of ions created by ionization and by charge-exchange collisions was observed. Downstream of the DL, a high-energy ion population accelerated through the DL was observed. The roughly 14 eV potential drop across a DL with a width of a few tens of Debye lengths was obtained in the simulation for an argon plasma at a pressure of 0.5 mTorr, an electron density of 6.5×10^8 cm^{-3} and an electron temperature of 7.2 eV. The total ion acceleration occurred over roughly an ion mean-free path.

The hybrid simulation results were consistent with retarding field energy analyzer (RFEA) probe measurements in the Chi-Kung helicon plasma source [24] that indicated a sharp discontinuity in the plasma potential at the location of rapid plasma expansion [1] (current-free DL of strength $\sim 3kT_e/e$) and the existence of an energetic ion beam downstream of the expansion point ($v_{\rm beam} \sim 2v_{\rm sound}$) with a density of $\sim 10^9$ cm^{-3} at low neutral pressures in

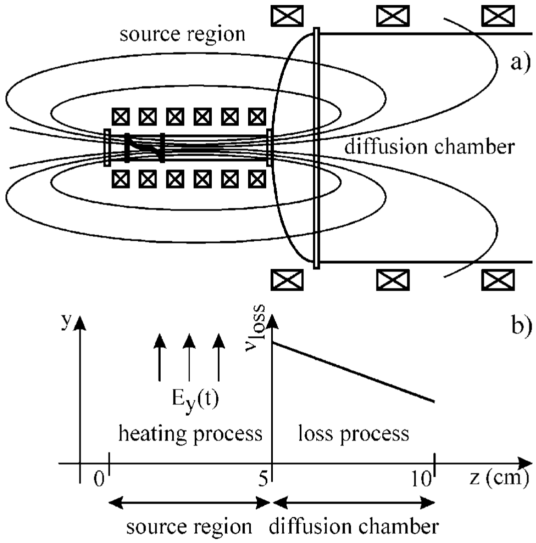

FIG. 1. (a) Geometry of all three helicon source experiments referred to in this work with a range of magnetic field strengths (70 to 1000 G) and a larger diameter, coaxial, expansion chamber with (or without) additional magnetic field coils. Divergent region of magnetic field is near the junction of the two chambers. (b) Spatial dependence of electron heating and loss rate used in PIC model of plasma expansion.

the source [3]. Independent experiments in the Magnetic Nozzle Experiment (MNX) reported similar plasma behavior: formation of an energetic, supersonic ion beam below a threshold neutral pressure for a helicon plasma expanding in a divergent magnetic field [4].

In this Letter, we report direct measurements, via laser-induced fluorescence (LIF), of the ion phase-space density upstream, inside, and downstream of a DL. The experiments were conducted in two different helicon plasma sources: Chi-Kung [24] and HELIX [25]. The observations of ion-beam formation confirm predictions of an improved computational model of a current-free, expanding plasma in remarkable detail.

In Chi-Kung, the plasma is produced in a 15 cm diameter glass cylinder centered in the axial magnetic field created by a Helmholtz coil pair. A larger diameter chamber placed at the end of the glass chamber serves as an expansion chamber [Fig. 1(a)]. The trigger for formation of the DL and ion beam was determined to be the neutral pressure in the plasma source [1]. Below a threshold pressure of 1–2 mTorr, the ion beam (identified through RFEA measurements) appeared downstream of the location of the start of the divergent portion of the magnetic field. No DL was experimentally observed in Chi-Kung in the absence of a magnetic field. For a constant field in the source (same current in 2 coils) a minimum field of about 60 G in the source is necessary to obtain a DL.

The argon ion velocity distribution function (ivdf) for ions flowing along the Chi-Kung axis was nonperturbatively measured with a portable, tunable diode laser, LIF diagnostic [26]. By scanning the LIF collection optics along the injected laser beam, the ivdf as a function of axial position (the ion phase-space density) was measured. Absolute flow velocities were determined for each ivdf measurement by simultaneous measurements of the fluorescence spectrum from a heated iodine cell [27]. The log of LIF signal versus parallel ion flow speed and axial position in Chi-Kung for a neutral pressure of 1.3 mTorr and a magnetic field strength of 70 G is shown in Fig. 2(a). Based on the appearance of strong ion acceleration in the LIF data (from $z = 25$ to $z = 28$ cm) the DL occurs at about $z = 28$ cm along the axis, slightly further downstream than the $z = 25$ cm DL location determined from RFEA measurements for higher magnetic field strengths ($\sim$140 G) and lower neutral pressures ($\sim$0.2 mTorr). Downstream of the DL, the trapped ion population and its acceleration through the sheath to the grounded end wall are also clearly visible. Measurements at a variety of neutral pressures suggest that DL develops closer to the source and with increasing strength along the rapidly divergent magnetic field as the neutral pressure decreases.

For all accessible neutral pressures in Chi-Kung, the ion beam is not detectable by LIF beyond the acceleration

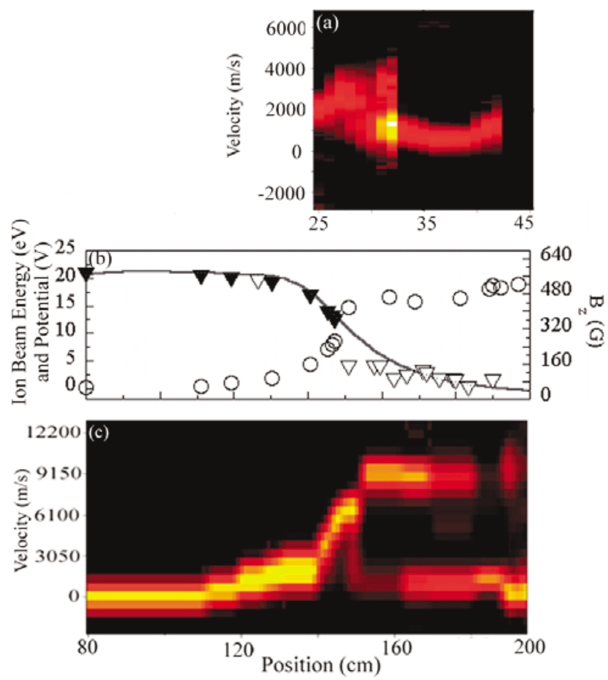

FIG. 2 (color). (a) Logarithm of amplitude of parallel ivdf (color bar) versus parallel velocity and axial position as measured by LIF in the Chi-Kung experiment. (b) DL potential difference (plasma potential - 9.8 V) versus axial position as measured with a rf-compensated, planar Langmuir probe in HELIX (open triangles), ion-beam energy as measured with LIF (open circles), predicted upstream potential difference based on ion-beam data (solid triangles), and axial magnetic field strength (solid line). (c) Logarithm of amplitude of parallel ivdf (color bar) versus parallel velocity and axial position in HELIX. Figure components (a), (b), and (c) have been aligned by location of the beginning of rapidly expanding magnetic field.

region. At a pressure of 1.3 mTorr (higher than in the Fig. 1(b) simulation), RFEA measurements confirm the presence of a few eV ion beam (consistent with the LIF measurements) with a beam density of only a few 10^9 cm^{-3} at $z = 37$ cm. Previous measurements in MNX indicated that such low density ion beams become undetectable within a few (~ 5) cm of the DL by low-power ($\sim$15 mW) LIF because of metastable quenching; i.e., the density of the metastable ion state probed decreases exponentially in the expansion region as collisions depopulate the metastable state [4]. As the neutral pressure is lowered to 0.55 mTorr, the ion beam is observed to accelerate up to roughly 15 eV at the DL, consistent with the predictions of the hybrid simulation.

The lack of an unambiguous LIF measurement of the ion beam through the DL and into the downstream region prevented us from estimating the thickness of the DL and the total potential difference across the DL solely from the LIF measurements in Chi-Kung. Therefore, LIF measurements of DL formation in the higher density, larger diameter, HELIX helicon source were undertaken using a higher power ($\sim$ 50 mW), tunable dye laser, LIF diagnostic. For a neutral pressure of 1.3 mTorr, we obtained the plasma potential profile (with a rf-compensated, planar Langmuir probe) and LIF measurements of the parallel ivdf shown in Figs. 2(b) and 2(c). The end of the HELIX source is located at $z = 150$ cm, at nearly the same spot as the DL evident in the plasma potential and LIF data. The ions accelerate through the presheath upstream of the DL and reach a peak energy of approximately 18 eV. Each ivdf measurement used to create Fig. 2(c) has been corrected for the changing Zeeman shift as the ions move along the weakening axial magnetic field. The ivdf is well fit by a single Maxwellian distribution. Since the downstream plasma electron temperature is 5.0 eV, the ion beam is supersonic with a Mach number of roughly 2.0. The LIF measurements indicate that the total ion acceleration occurs over approximately 20 cm (with strong ion acceleration occurring over a much narrower region, $\sim$5 cm, located at the maximum of the magnetic field strength gradient). Consistent with the LIF-determined peak ion-beam energy, the measured jump in the plasma potential across the DL in the plasma potential was 18 V [Fig. 2(b)]. Also shown in Fig. 2(b) as solid triangles are the predicted potential difference (plasma potential minus 9.8 V) upstream of the DL based on the measured gain in ion-beam kinetic energy (the planar Langmuir probe could not access much of the region upstream of the DL). The solid line in Fig. 2(b) is the magnitude of the axial magnetic field strength. It is notable that the relative changes in the plasma potential, and therefore the ion-beam energy, clearly track the axial magnetic field strength, i.e., the ion-beam energy and magnetic field strength axial gradients are nearly identical. A similar correlation between ion-beam energy and magnetic field gradient was previously reported in Ref. [19] for an electron cyclotron resonance plasma. These LIF measurements confirm the hybrid model predictions of the location and general features (ion-beam energy and trapped ion population distribution) of a magnetic field strength gradient induced DL in a current-free plasma.

Because the hybrid model used previously to examine DL formation due to rapid plasma expansion assumed a uniform Maxwell-Boltzmann distribution for the electrons, a one-dimensional Monte Carlo collision particle-in-cell (MCC-PIC) code with a self-consistent electron distribution was developed to investigate electron transport through the DL and to confirm the current-free nature of the DL [28]. The PIC simulation consists of a bounded plasma with a floating left wall and a grounded right wall. The system is separated into two regions: the source region and the diffusion chamber [Fig. 1(a)]. In the source region, the electrons are heated by a uniform rf electric field of 10 MHz perpendicular to the axis of the simulation. In the diffusion chamber, the expansion of the plasma in the diverging magnetic field is again modeled with a spatially dependent loss mechanism [Fig. 1(b)]. Figure 3(a) shows the density and potential profiles for the current-free DL obtained with a loss frequency slightly greater than the creation frequency (i.e., ionization frequency) for a neutral pressure of 1 mTorr and a plasma density of 7×10^8 cm^{-3}. The potential drop across the DL is approximately 12 V over a thickness of less than 20 Debye lengths and it is associated with a charging of the source (left wall) up to 10 V. The evolution of the DL as a function of the expansion rate (proportional to the magnetic field gradient) was studied for different pressures and we found that the expansion rate compared to the particle creation frequency (ionization frequency) was the critical parameter that de-

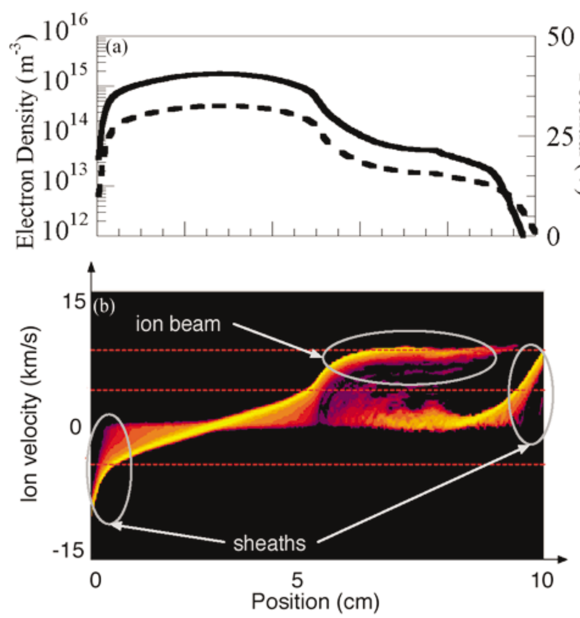

FIG. 3 (color). (a) Plasma density (solid line) and plasma potential (dotted line) along axis obtained from simulation. (b) Parallel ivdf along simulation axis.

termines the existence of the DL. We also found that the DL was completely current-free as long as the source is allowed to charge up and that the resultant electron energy distribution is uniformly Maxwellian and in Boltzmann equilibrium (explaining why the simpler hybrid model yielded similar DL structure). Another important result of the PIC simulation is that no electron beam is observed upstream of the DL in the simulation. One possibility under investigation is that instabilities generated in the DL region scatter electrons as they accelerate in the DL and prevent formation of an electron beam. What is clear, however, is that DLs arising from rapid plasma expansion appear to be distinctly different from those that are generally simulated or those believed to be responsible for electron acceleration in the aurora [13,14].

The magnitude of the ivdf in phase-space predicted by the PIC code is shown in Fig. 3(b). Throughout the simulation length, a low energy population of ions is observed which corresponds to the ions that are created by ionization and charge-exchange collisions. Downstream of the DL a high-energy population can be seen which corresponds to the ions accelerated while traversing the potential drop of the DL. Note that the acceleration of the ions occurs over many centimeters in the simulation (in the presheath and the sheath) while the actual DL is much narrower and appears in the ion phase-space plot as a narrow region of strong ion acceleration. The acceleration of the background ion population to the floating and grounded boundaries of the simulation volume as the ions fall through the sheath is also evident at the sides of Fig. 3(b). The spatial structure, beam energy, character of the ion acceleration region, and ion heating in the presheath in the simulation are all consistent with the LIF measurements shown in Figs. 2(a) and 2(c). The plasma potential measurements [Fig. 2(b)] are also consistent in both magnitude and spatial structure as the predicted plasma potential axial profile [Fig. 3(a)]. Therefore, the measurements confirm the simulation predictions of DL formation in current-free, expanding plasmas.

In the HELIX experiments, the strength of the DL was about $3kT_e/e$, comparable to the DL formed in the free expansion Chi-Kung experiments and slightly weaker than the DL formed in the MNX experiments with a strong magnetic nozzle field. In all three helicon plasma experiments, the DLs appear in the expansion region for neutral pressures below some critical value. A recent experiment by *Plihon et al.* demonstrated DL formation in an axially uniform plasma with a uniform magnetic field by puffing SF_6 gas into the plasma at a single axial location [29]. The SF_6 gas, which is highly electronegative, induces a strong electron density gradient along the plasma axis by substantially reducing the electron density, thereby simulating rapid plasma expansion without a divergent magnetic field. If the ion-neutral mean-free path is comparable to or larger than the scale length of the density gradient (equivalent to the scale length of the magnetic field gradient in HELIX and Chi-Kung), DL formation was observed.

In summary, the LIF measured DL potential structure and ion-beam energies are consistent with the MCC-PIC computer simulation for a current-free, expanding helicon plasma. In the expansion region, the magnetic field gradient scale length ($B/\nabla B$), and therefore the probable density gradient scale length, is approximately 20 cm. In these experiments, the DL appeared at neutrals pressures such that the ion-neutral collision length was comparable to the gradient scale length.

[1] C. Charles and R. W. Boswell, Appl. Phys. Lett. **82**, 1356 (2003).
[2] C. Charles, Appl. Phys. Lett. **84**, 332 (2004).
[3] C. Charles and R. W. Boswell, Phys. Plasmas **11**, 3808 (2004).
[4] S. A. Cohen *et al.*, Phys. Plasmas **10**, 2593 (2003).
[5] X. Sun, C. Biloiu, R. Hardin, and E. Scime, Plasma Sources Sci. Technol. **13**, 359 (2004).
[6] H. Alfven, Tellus **10**, 104 (1958).
[7] R.D. Albert and P.J. Lindstrom, Science **170**, 1398 (1970).
[8] P. Carlqvist, in *Proceedings of the Second Symposium on Plasma Double-layers and Related Topics*, edited by R. Schrittweiser and G. Eder (Institute for Theoretical Physics, Innsbruck, Austria, 1984), p. 340.
[9] W. B. Bridges *et al.*, Proc. IEEE **59**, 724 (1971).
[10] H. Hora, P. Lalousis, and S. Eliezer, Phys. Rev. Lett. **53**, 1650 (1984).
[11] P. Coakley and N. Hershkowitz, Phys. Fluids **22**, 1171 (1979).
[12] B. H. Quon and A. Y. Wong, Phys. Rev. Lett. **37**, 1393 (1976).
[13] C. K. Goertz and G. Joyce, Astrophys. Space Sci. **32**, 165 (1975).
[14] D. L. Newman *et al.*, Phys. Rev. Lett. **87**, 255001 (2001).
[15] F. W. Perkins and Y. C. Sun, Phys. Rev. Lett. **46**, 115 (1981).
[16] D. J. Trevor *et al.*, Appl. Phys. Lett. **57**, 1188 (1990).
[17] N. Sadeghi *et al.*, J. Appl. Phys. **70**, 2552 (1991).
[18] C. Charles *et al.*, J. Vac. Sci. Technol. A **9**, 661 (1991).
[19] R. Schrittwieser *et al.*, IEEE Trans. Plasma Sci. **20**, 607 (1992).
[20] E. N. Parker, J. Geophys. Res. **62**, 509 (1957).
[21] C. Chan, M. H. Cho, N. Hershkowitz, and T. Intrator, Phys. Rev. Lett. **52**, 1782 (1984).
[22] Y. Takeda and K. Yamagiwa, Phys. Rev. Lett. **55**, 711 (1985).
[23] A. Meige *et al.*, IEEE Trans. Plasma Sci. **33**, 334 (2005).
[24] C. Charles *et al.*, Phys. Plasmas **7**, 5232 (2000).
[25] J. L. Kline *et al.*, Phys. Plasmas **10**, 2127 (2003).
[26] R. F. Boivin and E. E. Scime, Rev. Sci. Instrum. **74**, 4352 (2003).
[27] A. M. Keesee, R. Boivin, and E. Scime, Rev. Sci. Instrum. **75**, 4091 (2004).
[28] A. Meige, R. W. Boswell, C. Charles, and M. Turner, Phys. Plasmas **12**, 052317 (2005).
[29] N. Plihon, C. S. Corr, and P. Chabert, Appl. Phys. Lett. **86**, 091501 (2005).