Experimental Observations of Steep Temperature Steps in Dense Magnetized Plasmas

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Quasi-steady-state steep temperature steps have been experimentally observed in dense ($>10^{19}$ m^{-3}) linear magnetized helium plasma columns submerged in a high-density (>100 mT) neutral-gas environment. The formation of such features is found to be favored by a high neutral gas density or a positive bias ($\geq V_{\mathrm{fl}}$) placed on the end plate. A rapid reduction in plasma density and electron temperature is observed to exist across the steps, as is a dramatic increase in neutral line radiation. Potential steps are inferred. Detailed Langmuir probe measurements have revealed three-dimensional structures. Possible mechanisms of formation are discussed.

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Double layers (DLs) are electrostatic structures sustaining significant net potential differences ϕ_{DL} which separate two quasineutral plasmas of differing space potentials ϕ_s [1]. At least two types of DLs have been identified. Monotonic DLs are found to be Bernstein-Greene-Kruskal [2] solutions of the Vlasov-Poisson equations, while ion-acoustic DLs are nonmonotonic structures with negative potential dips located on the low-potential side. The latter type has been observed in computer simulations [3] and in experiments [4] growing out of ion-acoustic fluctuations. DLs are formed in voltage-, current-, or beam-driven systems [5], or when different plasma sources are allowed to interact [6], or when a plasma encounters a geometrical constriction or expansion [7]. In addition, DLs have been predicted to form in the absence of relative electron-ion drift [8], and verified experimentally by Hairapetian and Stenzel [9] in a two-temperature collisionless plasma. Formerly in a high-density ($\approx 2 \times 10^{19}$ m^{-3}) [10] θ pinch moving and expanding pulsed (20–50 μs) plasma column, DLs were observed to propagate into the vacuum when the axial current exceeded a critical density. In this Letter we report on the first experimental evidence of double-layer-like phenomena arising from a single quasi-steady-state plasma source at high plasma densities ($>5 \times 10^{19}$ m^{-3}) in a collisional current-free setting.

Helium plasma was generated from a lower-hybrid-wave-heated source [11] enclosed at one end of a cylindrical 2 cm diameter tube. Of the available 1 kW microwave (2.45 GHz) power, 700 W was absorbed by the plasma in the source. An axial magnetic field of 0.35 T was used to enable wave heating of overdense plasmas and to confine the plasma radially. The plasma was allowed to emerge out of the tube and subsequently be terminated by a biasable graphite end plate. The typical diameter and length of the plasma column were 2 and 40 cm, respectively. The achieved plasma density and electron temperature at the exit of the tube were 7×10^{19} m^{-3} and 5 eV, respectively, resulting in a Debye length of $\lambda_D = 2 \times 10^{-6}$ m. Unless otherwise stated, the end plates were floating in the experiments so that no net current was drawn. This plasma column was bathed in and allowed to interact with surrounding helium neutral gas, at an operating pressure between 50 and 500 mT. A more detailed description of the system setup can be found in [12].

Axial and radial profiles of plasma density n, electron temperature T_e, and floating potential V_{fl} were measured with a single Langmuir probe, using one-temperature analysis [13], but noting effects due to plasma collisionality, magnetic fields, and hot electrons. The achieved spatial resolution was 10^{-3} m and the data are time averaged over ten $\sim$20 ms duration probe *I*-*V* scans. Plasma potential ϕ_s was calculated according to

$$\frac{e(V_{\mathrm{fl}} - \phi_s)}{T_e} = 0.5 \ln\left[\left(2\pi \frac{m_e}{m_i}\right)\left(1 + \frac{T_i}{T_e}\right)\right] + 0.5\,, \tag{1}$$

where the last term incorporated the presheath drop. Ion and neutral temperatures measured at $P_n \approx 90$ mT was 0.6 and 0.1 eV, respectively at $T_e = 5$ eV [14], and were assumed constant in the analysis. Radially integrated but axially resolved profiles of line emission were recorded by an optical multichannel analyzer (OMA). The axial spatial resolution was calculated to be about 2×10^{-3} m. Current and power fluxes impinging onto the end plate were measured, the latter by thermocouples placed on the plate.

Figure 1 shows the axial profiles of n, T_e, V_{fl}, and ϕ_s along the column axis at an ambient helium neutral pressure P_n of 130 mT. The length of the plasma column L was 40 cm, with the plasma source near $z = -15$ cm and the end plate at $z = 25$ cm ($z = 0$ cm denotes the exit of the tube).

The plasma was seen to experience an abrupt reduction in temperature from a nominal $\approx$3.5 to 0.5 eV within an axial distance of $\approx$2 cm, initiating from $z = 10$ cm. Consequently the calculated ϕ_s was found to sustain a potential drop of $\approx$9 V. This value exceeds by a factor of 40 that due to classical electron-neutral collisionality. Accordingly, we term these DL-like structures "steep temperature and electrostatic potential steps" (STEPS).

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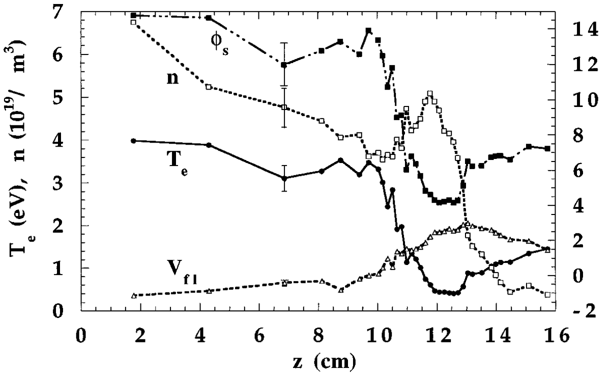

FIG. 1. Axial profiles of n, T_e, ϕ_s, and V_{f1} of helium plasma bathed in neutral gas of ambient pressure $P_n = 130$ mT, showing the formation of STEPS. The plasma source is located at $z = -15$ cm and the end plate is at $z = 25$ cm.

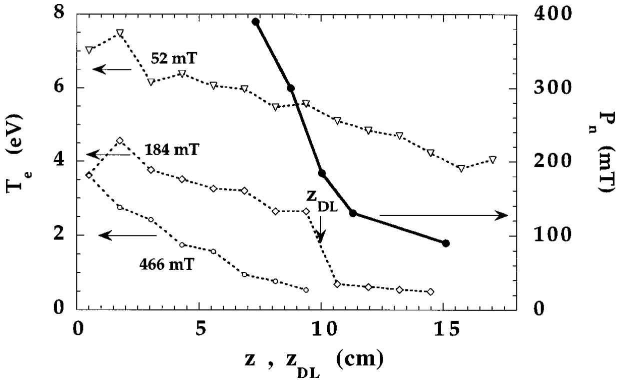

FIG. 2. Axial T_e profiles (open curves) at three P_n's. Also plotted (solid curve) is the location of the STEPS z_{SP} as a function of P_n. z_{SP} is positioned at the point of maximum rate of thermal collapse.

There also existed a temperature "hole" extending between $z = 12$ and 13 cm. The potential dip calculated was on the low-ϕ_s side. The STEPS were observed to be stationary in space and time throughout the duration of the plasma pulse of ≈250 ms. Previous studies [4] had found DLs evolving on the order of ion-acoustic time scale (≈10 μs in our case); these faster fluctuations would have been inherently filtered out by our diagnostics.

Simultaneously and within the region of this temperature collapse, density reversed a slow decrease at 3.5×10^{19} m^{-3} and began to rise, reaching a peak density of $\approx 5 \times 10^{19}$ m^{-3}, before falling precipitously below 0.5×10^{19} m^{-3}. The intermediate density increase was insufficient to maintain axial plasma pressure balance, as is commonly expected in a normal low- or high-recycling sheath [13]. The plasma (electron) pressure $P_e \equiv nT_e$ was calculated to fall monotonically by a large factor. We note, however, that P_n was enough to balance P_e at a sufficiently large axial distance from the plasma source.

The occurrence and location of the STEPS have been found to depend on the ambient neutral pressure P_n. Figure 2 plots three axial T_e profiles and location of the STEPS, z_{SP}, at different P_n's, with the plasma column length L set at 40 cm. At sufficiently high neutral pressures (≥60 mT), T_e's decreased slowly to ≈3.5 eV before the abrupt collapse to ≈0.5 eV. At still higher pressures (≥400 mT) when the initial T_e was below ≈3.5 eV, no sudden collapse was observed. The position of the STEPS is seen to move towards the plasma source with increasing P_n.

The dc bias placed on the end target plate V_p has also been varied and found to exert a profound effect on the formation of the STEPS. This can be seen from Fig. 3 where the axial T_e profiles are plotted for V_p from −30 to +12 V. At these potentials the net current collected at the end plate were +0.36 and −0.28 A, respectively. P_n was maintained at 300 mT and L at 40 cm. The nominal floating potential of the end plate V_{pf} was +5 V. Note that the positive biases were less than that of the ionization potential χ for helium (25.6 eV); hence ionization effects did not play a direct role in the formation of STEPS, in contrast to other previous experiments [15] where V_p exceeded χ. Ionization across the STEPS was probably also not significant as the potential difference ϕ was less than χ. Ohmic power from the applied bias was also small compared to the input microwave power.

Positive $V_p > V_{pf}$ (drawing negative current or electrons to the plate) favors the formation of STEPS while a negative V_p inhibits the temperature collapse. At a low bias of −30 V, the plasma operated in the uncollapsed low-recycling mode, where the sheath remained attached to the end plate. As V_p was raised, T_e decreased in a linear fashion, reaching below 1 eV when V_p was +3 V, although no abrupt collapse ensued. At still higher biases

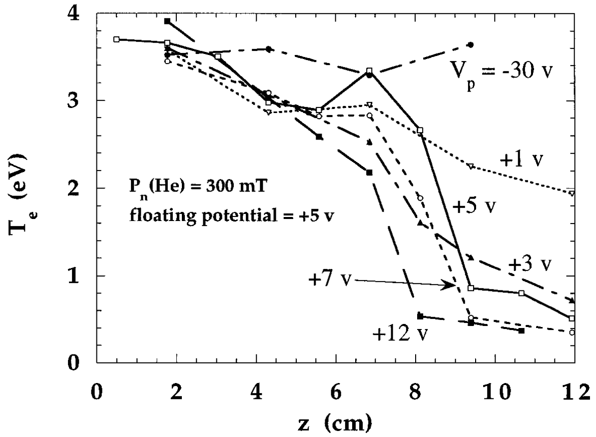

FIG. 3. Axial T_e profile as a function of the dc bias V_p placed on the end plate. P_n is kept at 300 mT. STEPS are formed for sufficiently positive V_p's.

equal or greater than V_{pf}, fully collapsed T_e profiles followed and STEPS were formed. The distance between the region of thermal collapse and the plasma source shortened with increasing V_p.

Radial profiles of these STEPS have also been obtained. A typical case at P_n of 300 mT is shown in Fig. 4, where the density and T_e profiles at successive axial positions from $z = 0.5$ to 13.2 cm are plotted. Note that there was little particle diffusive radial transport before STEPS are formed, as evidenced by the almost constant radial density scale lengths at each axial position. This was true for the entire neutral pressure range employed in the experiments, and represented a major divergence, possibly due to our higher operating B field and more quiescent source, compared to earlier gas target studies on other linear machines [16]. In general, density decreased with increasing axial distances at all radial positions until the formation of the STEPS, whereby an intermediate density increase ensued at the center. Thereafter, density decreased once again. The overall density decrease at the center can be as much as a factor of 20, in contrast to the nominal factor of 2 to 3 decrease for the uncollapsed low-recycling case.

T_e typically decreased at and around the center but remained high (≈ 5 eV) near the edges. Furthermore, the origin and rate of temperature decrease seemed to initiate and was greater in regions surrounding the center than at the center. Consequently, a relatively hot "tongue" was found to persist, narrowing as it traversed axially. This phenomenon was especially evident from Fig. 4 at $r = -0.25$ cm, extending from $z = 8.1$ cm until its eventual collapse at 10.7 cm. Finally, we have also observed relatively large temporal variations ($\leq 50\%$) in temperature on the low-T_e side of the STEPS. This may be a consequence of the extreme sensitivity of the probe fitting procedure at low T_e's, or due to instabilities and turbulences.

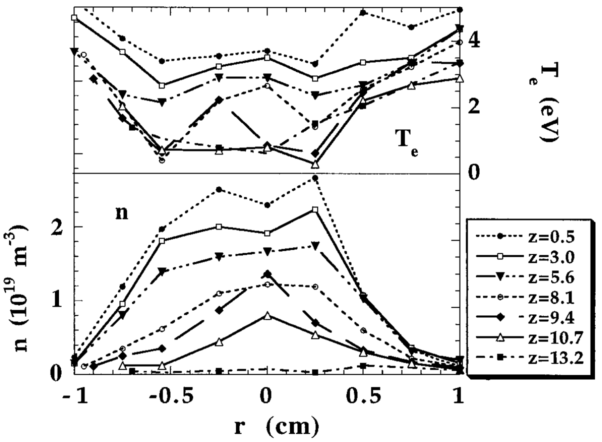

FIG. 4. Radial n and T_e profiles at successive axial positions $z = 0.5$, 3.0, 5.6, 8.1, 9.4, 10.7, and 13.2 cm.

Concomitant with the appearance of the STEPS was a large increase in neutral line radiation. Figure 5 superimposes the axial T_e profiles with the radially integrated emission profiles of the 5875.7 Å (He I $3d^3D$-$2p^3P$) transition, taken at $P_n = 90$ and 180 mT and $L = 27$ cm. Whereas the plasma emitted almost uniformly at lower P_n's (no STEPS are formed), a large increase in line intensity occurred at higher P_n's, within and beyond the region where STEPS were formed. The occurrence of increased intensity extended to all observed optical line radiation from 4000 to 7000 Å. We have measured line transitions of the type nd^3D-$2p^3P$ up to $n = 8$, and have found a similarly large increase in radiation intensity at and beyond the regions of the STEPS and thermal collapse. No resonance ($n = 2$ to 1) radiation has been detected, as expected from opacity estimates.

It has been suggested [17] that DLs are formed to limit both the current and power fluxes. We have found that the formation of STEPS limited the net current flow. The area-integrated current $I = \int J\,dA$ to the end plate was estimated assuming $J = nec_s$ (where c_s is the ion sound speed) using measured plasma n and T_e profiles. This was compared with the measured current (at $V_p = -10$ V) in both uncollapsed (no STEPS formed) and collapsed (STEPS formed) plasmas. The results yielded a ratio $I(P_n = 300\text{ mT, collapsed})/I(P_n = 53\text{ mT, uncollapsed})$ of 0.070 ± 0.020, whereas the measured current ratio was 0.025 ± 0.005.

As regards thermal fluxes, we estimated the calculated power Γ_E impinging on the end plate:

$$\Gamma_E = \int \frac{J}{e}(\delta_E T_e + \chi)\,dA\,, \tag{2}$$

where δ_E was the total energy sheath transmission factor [13], and χ the recombination energy as the plasma impinged on the end plate. Γ_E was compared

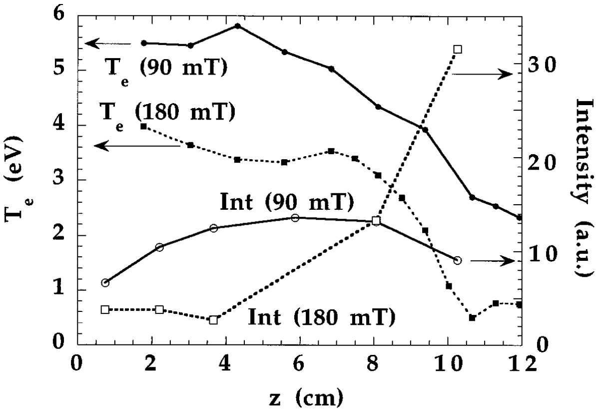

FIG. 5. Axial line (5875.7 Å) intensity profiles at $P_n = 90$ and 180 mT. The corresponding T_e profiles are also shown. The STEPS region is associated with an enhanced emission from states $n \geq 3$ to $n = 2$.

to the power measured experimentally by the thermocouples. The result yielded an expected ratio $\Gamma_E(P_n = 180\ \mathrm{mT, collapsed})/\Gamma_E(P_n = 60\ \mathrm{mT, uncollapsed})$ of 0.40 ± 0.14, whereas the measured ratio was 0.18 ± 0.05. Thus the formation of the STEPS was found to inhibit heat flow towards the plate, at least within the context of an assumed purely convective flow. Baker *et al.* [18] have attributed the distinction of warmer electrons on the high-ϕ side to the inhibition of thermal energy transport by the DL.

The inferred potential of the STEPS is fundamentally different from that of the usual ambipolar potential, where

$$n \propto n_0 \exp\left(\frac{\phi_s - \phi_{s0}}{T_e}\right), \tag{3}$$

with n_0 and ϕ_{s0} the unperturbed plasma density and potential, i.e., upstream from the STEPS. For instance, the intermediate density increase accompanying the collapse in T_e is incompatible with an ambipolar potential. We can nevertheless postulate that the STEPS are formed self-consistently in order to preserve charge neutrality in the hot and cold regions in the presence of intense plasma-neutral interactions. Because of disparate ion and electron speeds and collisional cross sections, the ion-neutral mean free path is nominally ≈ 5 times less than the electron-neutral mean free path, which is in turn of the order of 10% of the scale length of ϕ_s. Consequently, plasma-neutral collisions will impede ion momentum more so than electron flow, leading to ion-electron separation. STEPS are then formed self-consistently to decelerate the electrons and bring about ambipolar flow. This interpretation is consistent with the observed variations in P_n and V_p. Increasingly frequent plasma-neutral collisions at high P_n will precipitate the formation of STEPS closer to the source. Similarly, a positive bias will tend to preferentially accelerate electrons and curtail ion flow, further aiding STEPS to form.

The reduction of current and power flow to an end plate will be of great benefit in the design of the ITER (International Thermonuclear Experimental Reactor) divertor [19]. Important comparisons between the ultrahigh pressure gas target scheme of Petravic [20] and our experiments can be made. In his scheme the temperature in the scrape-off layer is allowed to be so small (<1 eV) that volumetric recombination becomes dominant, thus effectively "extinguishing" the plasma into high pressure (≈ 1 torr) neutral gas. Power is dissipated by radiation as well as thermal convection or conduction by neutral gas, which is distributed over a wide area and can alleviate the issue of intense thermal flux onto divertor plates. In our experiments the presence of high-pressure neutral gas leads to current and heat flow inhibition through the formation of STEPS. It is easily shown that T_e within and downstream of the STEPS region is too low to excite and account for the observed line emission. Recombinative radiation is a plausible candidate, as the estimated ion residence time (≈ 10 ms) is comparable to the recombination time (≈ 20 ms) [14] while self-absorptional and neutral density gradient effects are found to be small. Further modeling efforts, especially of the role of hydrogen atomic physics, are underway.

In conclusion, we have observed the formation of inherently three-dimensional STEPS in dense helium plasmas bathed in a high-pressure helium neutral gas environment. Plasma density and temperature are observed to undergo an abrupt collapse across the STEPS, and line emission is dramatically enhanced. Both current and thermal flux transport to the target plate are significantly reduced. The relevance to the ultrapressure gas target scheme utilizing volumetric recombination is apparent.

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