Comment on "Upper Limit to Landau Damping in Helicon Discharges"

In a recent Letter, Chen and Blackwell (CB) concluded that the high densities produced by helicon discharges could not only be explained by thermal electrons [1], without invoking Landau-damped energetic electrons, but also that nonthermal electrons did not exist in their experiment. I would like to comment on the reasons for their null result, and show that measurements of energetic "surfing" or wave-trapped electrons (WTE) are not artifacts induced by radio frequency (rf) oscillations in the plasma potential, as they suggested.

Five factors contribute to the null measurement of WTE in the CB experiment. (1) CB used a magnetic field of 360 G, higher than in experiments that observed WTE:100 G [2] and 60–90 G [3]. Fields above 100 G reduced WTE in Ref. [3]. (2) CB operated at lower power, 1 kW, for the electron analyzer data. Reference [3] required 3.5 kW for the highest current of WTE. The WTE currents were ≥ 7 times lower between 3.5 kW and the helicon threshold of 1.3 kW. (3) The electron energy distribution is normally truncated below the plasma potential energy, with only WTE reaching higher energies where they become detectable; otherwise, energetic electrons would have always been observed in Ref. [3]. (4) CB operated in the far field, whereas Refs. [2,3] operated in the near field of the antenna. (5) The analyzer used by CB measured the bulk electron distribution: Consequently, a very large dynamic range would be required to measure a small population of energetic WTE; by their estimate, the noise level was 2.4×10^{-4} of the bulk density. I predict that limitation (2) alone gave CB an undetectable WTE fraction of $\leq 1.3 \times 10^{-4}$.

The energetic electron currents are not artifacts of thermal electrons expelled from the oscillating plasma potential (as suggested by CB), as I will show by both the phase and the magnitude of the floating potential (V_f). For a fixed electron distribution function, the floating and plasma potentials are separated by a constant offset. V_f oscillations were measured using a high impedance probe [4] ($12\ \mathrm{k}\Omega \gg R_{\mathrm{sheath}} \sim 1\ \mathrm{k}\Omega$) with a fast rise time ($5\ \mathrm{ns} \ll 1/13.56\ \mathrm{MHz} = 73.7\ \mathrm{ns}$). The probe was installed on the horizontal midplane at the same axial position but on the opposite side of the axis from the energy analyzer. I verified that magnetic probe B_z oscillations and energetic electron pulses were shifted in phase by 180° on either side of the axis, as was the ϕ_{B_z} data at 1.3 and 2.3 kW in Fig. 4 of Ref. [5]. Therefore, the oscillations in V_f are shifted by half the 73.7 ns period, to show the relative phase at the analyzer location (Fig. 1). The electron pulses closely follow the positive peaks (by ~10 ns), as expected for accelerated WTE. They are not centered on the negative peaks as would be the case for thermal electrons expelled by the oscillating potential. Trapped electrons in the positive peak of the plasma potential wave should shift it toward zero without affecting the negative peak. This is apparent in Fig. 2—the positive envelope of V_f decreases approximately inversely with the electron current for $B < 90$ G. Beyond 90 G, the decreases in V_f and in WTE may be due to longer rf wavelength coupling to fewer WTE [3] and lower rf power.

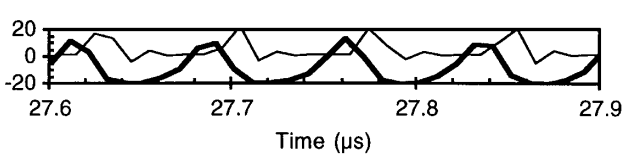

FIG. 1. V_f(V) [thick line] and energetic electron current (mA/cm^2) [thin line] vs time.

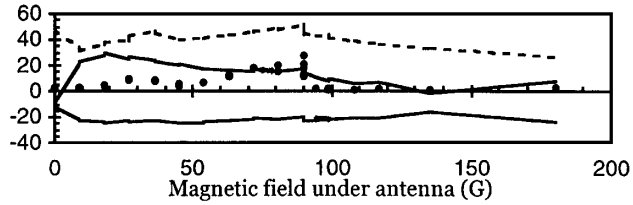

FIG. 2. rf power (0.1 kW) [dashed line], V_f envelope (V) [solid lines], energetic electron current (mA/cm^2) [points] vs magnetic field (G).

We do not dispute the conclusion of CB that the plasma density can be accounted for without energetic electrons. But, as I have shown, reliable evidence indicates the presence of energetic WTE in certain modes of helicon operation. The physics of trapping and accelerating those electrons may provide a low frequency analog to laser acceleration, and WTE can produce other effects, such as biasing the potential of surfaces exposed to the plasma and altering the plasma chemistry [6].

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