Upper Limit to Landau Damping in Helicon Discharges

Francis F. Chen and David D. Blackwell
Electrical Engineering Department, University of California, Los Angeles, California 90095-1594

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The uncommonly high rf absorption efficiency of helicon discharges has been thought to be caused by Landau damping of helicon waves and the concomitant acceleration of primary electrons. By constructing an energy analyzer that accounts for rf fluctuations in plasma potential, it is shown that Landau-accelerated electrons are too sparse to explain the ionization efficiency. Instead, rf absorption and ionization are found to be consistent with the mechanism of mode coupling to Trivelpiece-Gould modes at the plasma boundary. [S0031-9007(99)08827-4]

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Ever since Boswell [1] reported the high densities produced by helicon discharges, the reason for the efficiency of these discharges in converting rf power into plasma density has been a conundrum. In 1991, Chen [2] proposed the Landau damping hypothesis, in which electrons are accelerated by "surfing" on the helicon waves, which have the proper phase velocity to bring electrons to the peak of the ionization cross section. Since that time, numerous papers have appeared, including three Letters [3–5], purporting to have verified this hypothesis either by direct measurement of the fast electrons [3–12] or by inferring their existence from the wave phase velocity or other artifacts [13–19]. However, ten years of experimentation in our own laboratory have not yielded a single direct observation of non-Maxwellian electron distributions.

The grounds for dispute arise from the difficulty in eliminating the effects of fluctuations in plasma potential at the rf driving frequency, which are known [20] to distort probe characteristics and give spurious electron distribution functions $f(v)$. On the other hand, we have shown [21] that probes with good rf compensation [22] would be blind to rf-phased pulses of electrons, since the floating potential also shifts synchronously. Uncompensated probes can detect the presence and mean energy of fast electrons [5] but cannot accurately give their density or $f(v)$. A *few* fast electrons can be expected to be found in almost any rf discharge, if it is given the scrutiny accorded to helicon discharges; indeed, it has been pointed out [9] that these could arise during the initial stages of a pulsed discharge. The most convincing evidence of Landau acceleration was given by Ellingboe *et al.* [10] who observed the pulsed Ar^+ light excited by these electrons in synchronism with the rf phase. This diagnostic was insensitive to rf potential fluctuations even though it was used in the near field of the antenna. Linear Landau damping was too weak to explain the observed damping, and Ellingboe and co-workers [10,17,18] have attempted to explain the damping by a nonlinear trapping theory. However, the density of the fast electrons was not published. More quantitative measurements of phased fast electrons were made by Molvik *et al.* [4,11] with a gridded energy analyzer; this will be discussed below.

Proving that Landau damping is essential to rf absorption and ionization in helicon discharges requires two separate conditions: (1) A large enough number of phased fast electrons exists to account for most of the ionization, and (2) Landau damping accounts for most of the rf loading of the antenna. In this Letter, we disprove (1) with new experimental data and disprove (2) by interpreting old data in the light of new theory.

In contrast to all previous measurements of $f(v)$, which were time averaged, Molvik *et al.* [4,11] constructed a gridded analyzer with sufficient frequency response to resolve the rf phase to within 15° and measured the current of electrons with enough energy to overcome the sheath drop of ≈ 15 eV at the grounded first grid. This current was found to be modulated at the rf frequency, occurring during one-third of the rf cycle, and was interpreted as evidence of Landau acceleration. However, oscillations in plasma potential V_s could also lead to a modulated analyzer current, thus this diagnostic suffers from the same deficiency as a noncompensated Langmuir probe. The authors gave qualitative arguments that the V_s oscillations were unimportant, but no data were shown. Furthermore, the modulated current was found to have a sharp peak as the dc field B_0 was varied, a feature not reflected in the plasma density. The fraction of electrons in the 15–25 eV range in a 3 eV plasma at 1×10^{12} cm^{-3} density was given as 5×10^{-5}. Since the ratio of ionization probability at $KT_e = 20$ eV is only ≈ 20 times that at 3 eV, it is clear that the measured fast component does not contribute significantly to the total ionization.

An experiment was performed to account for V_s fluctuations, which cannot only modulate the analyzer current, but also couple capacitively to the measuring device. The discharge [Fig. 1(a)] was operated in a 10 cm diam Pyrex tube 108 cm long at ≈ 400 G in ≤ 2 mTorr of argon, driven by a 20-cm-long Nagoya type III antenna at 13.56 MHz with $P_{\mathrm{rf}} \leq 2$ kW. These conditions were above the threshold for helicon excitation, as verified by wave phase measurement with a magnetic probe. After careful optimization, an energy analyzer with only two electrodes [Fig. 1(b)] was chosen. The absence of a grounded front grid reduces the large dc sheath drop

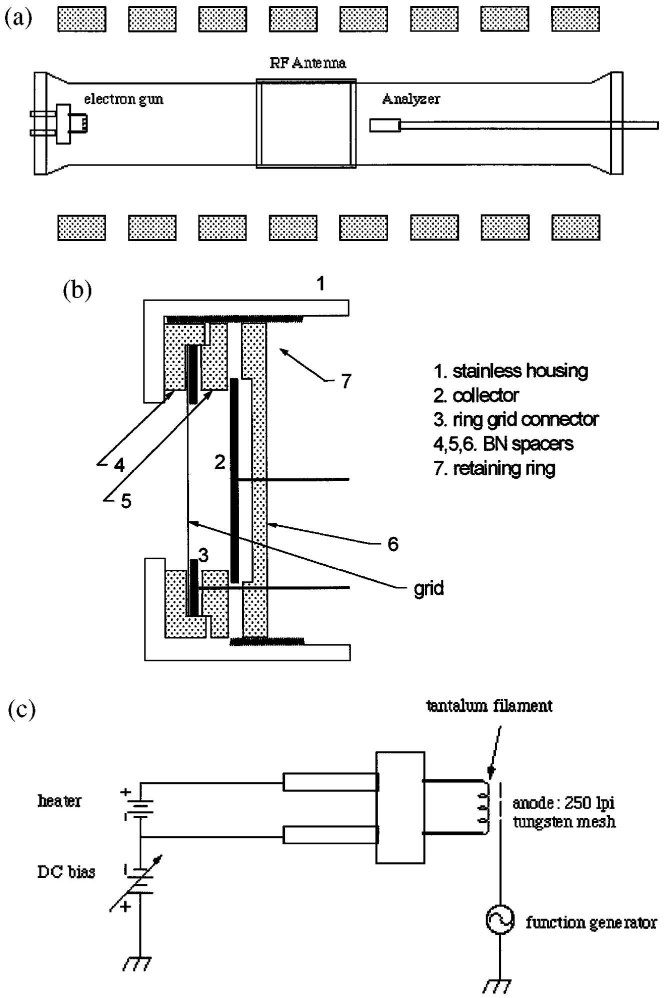

FIG. 1. Diagram of the apparatus: (a) discharge tube; (b) gridded analyzer; (c) electron gun.

and allows further probing into the bulk electron distribution, and no suppressor is necessary when collecting electrons. The 1.27 cm diam front grid (tungsten, 2000 lines per inch, 40% transparency) is the discriminator, henceforth called "grid," and the tantalum plate ("collector") 3 mm behind it is biased at $+300$ V to collect all electrons reaching it. The 2.54 cm housing is grounded, and the two electrodes are rf bypassed to ground to avoid coupling to oscillations in sheath capacitance. The electrodes are connected to a 10^9 samples/sec 250 MHz digital oscilloscope via cables whose lengths and grounding scheme were chosen to minimize pickup and maximize frequency response. To calibrate the latter, an electron gun ["gun," Fig. 1(c)] was used to produce a beam that could be rf modulated with a mesh anode ("anode"). With the grid floating dc-wise but grounded rf-wise, and with the anode modulated at 13.56 MHz under emission-limited gun operation, the electron current I_c at the collector appears as shown in Fig. 2(a) for a beam-created plasma of $\approx 10^{11}$ cm^{-3} density at 400 G. The nonlinear fluctuations in current are cased entirely by oscillations in V_s, which follow the anode potential. Thus, $f(\nu)$ is sampled by the oscillating sheath drop. To check the frequency response of the analyzer, an I-V characteristic is taken in vacuum, 5 cm away from the gun, as the dc grid voltage V_g is swept and I_c is recorded at various phases of the V_s oscillation by boxcar averaging. The thick curves in Fig. 2(b) are such I-V traces taken at the maximum ($V_{\max}$) and minimum ($V_{\min}$) of the V_s oscillation. The thinner curves are dc beam characteristics taken with the anode fixed at $V_{\max}$ and $V_{\min}$. The two sets of curves are found to agree quite well, showing a V_s fluctuation of about 20 V but no significant distortion of the curves taken under rf conditions. Similar agreement was obtained with a beam-generated plasma.

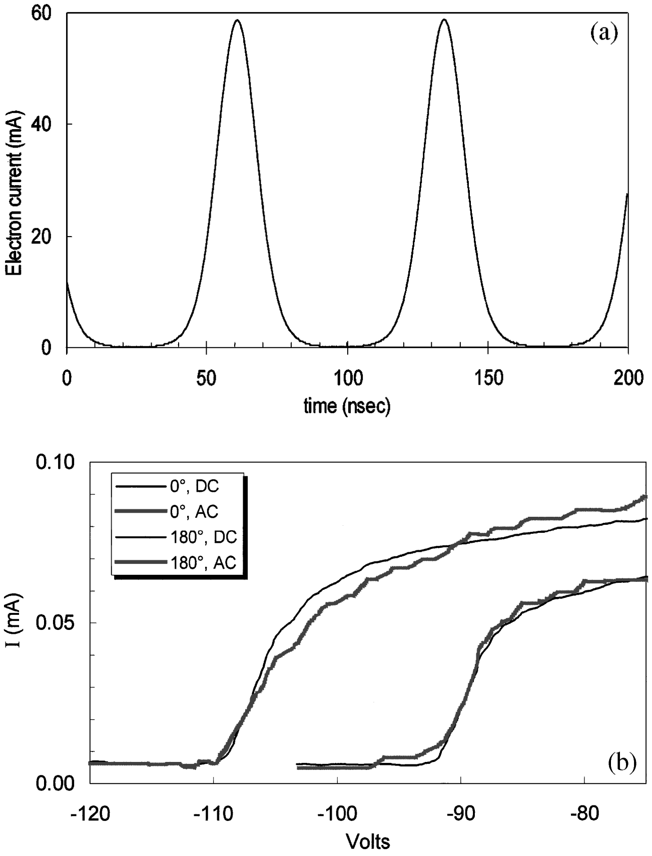

FIG. 2. (a) Modulation of analyzer current by rf fluctuations in plasma potential. (b) Analyzer I-V curves of rf modulated beam (thick curves) taken 180° apart in phase, and of dc beams (thin curves) with corresponding voltage difference.

A 1.2×10^{12} cm^{-3} density helicon discharge was then created in 2 mTorr of argon with $P_{\mathrm{rf}} = 1$ kW and $B_0 = 360$ G. With the electron gun off, phase-resolved analyzer I-V curves were taken 20 cm downstream from the antenna, as shown in Fig. 3(a) for rf phases 180° apart. After removing the digital noise, these curves are plotted logarithmically in Fig. 3(b) with one curve shifted horizontally to get both on the same graph. It is seen that $f(\nu)$ fits pure Maxwellians of 3 and 3.35 eV over about 2.5 orders of magnitude. The leveling off at low

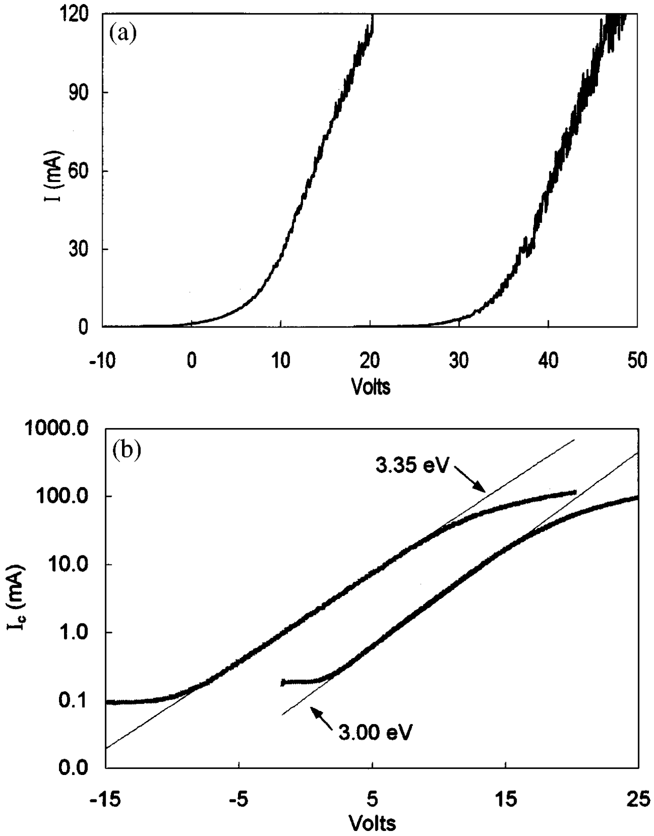

FIG. 3. (a) Time-resolved analyzer *I-V* curves taken at extremes of the plasma fluctuations. (b) The same curves on a log scale, compared with pure exponentials.

I_c indicates the detection limit; leveling off at high I_c is due to the depletion of Maxwellian electrons along the field lines intersecting the analyzer. Note that the phase is relative to the global fluctuation in plasma potential, not to the phase of the wave. Different wave phases can be sampled by moving the analyzer axially. No high energy tail was detected at any phase.

Even if a population of 50 eV electrons existed at the detection limit, its density would be only about $1/(10^3\sqrt{50/3}) = 2.4 \times 10^{-4}$ of the bulk density, an upper limit consistent with the estimate of Molvik *et al.* [11]. Though $\langle \sigma v_{\text{ion}} \rangle$ is 413 times larger at 50 eV than at 3 eV, the fast electrons would produce only 10% of the ionization. Thus, there are too few Landau electrons (if any) to account for the major part of the ionization.

The fact that Landau electrons are not needed for producing the observed densities was shown by Sudit and Chen [23]. By measuring $n(z)$ and $KT_e(z)$ in a long discharge and integrating over z to obtain the total rate of ionization by thermal electrons, they found that this exceeded the loss rate by an order of magnitude. To obtain agreement, they had to assume that the neutral gas was depleted during the discharge pulse. This effect has since been confirmed by direct measurement by Gilland *et al.* [24]. Thus, ionization by a purely Maxwellian distribution is more than enough to account for the observed densities.

Collisional damping of helicon waves is too weak to account for the resistive loading of the antenna [1,5], and we have no evidence of strong Landau damping. Fortunately, Shamrai and Taranov [25] suggested another mechanism: mode coupling to Trivelpiece-Gould (TG) waves at the radial boundary. Being nearly electrostatic and of short radial wavelength, these waves are strongly absorbed as they propagate inward. Helicon waves deposit their energy into the plasma by coupling their energy to TG waves, which are then rapidly absorbed. Figure 4 shows the plasma resistance R_p measured by Miljak and Chen [26] in a helicon discharge driven by a half-wavelength, right-helical, bifilar antenna as the phase between the two windings, separated by 90° in azimuth, is varied. The peak at 90° (R_{max}) results mainly from the excitation of $m = +1$ helicon waves and the circuit losses R_{vac}. The minimum R_p at $-90°$ represents loading by the $m < 0$ modes, as well as parasitic effects such as capacitive and nonresonant inductive coupling. The computational procedure of Arnush and Chen [27] can be used to compute the theoretical loading due to Shamrai's mechanism for the exact parameters of the experiment, including the radial density profile. The computed loading R_p (for the $m = +1$ mode alone) is also shown in Fig. 4. It is seen that the wave loading is about 2.8 Ω, in reasonable agreement with the measured value of $R_{\text{max}} - R_{\text{vac}} = 2.2\ \Omega$, considering the idealizations of the theory. Landau damping is not needed to explain the magnitude of the plasma loading.

It appears that both antenna loading and plasma ionization can be explained quantitatively with classical, collisional theory, in agreement with our negative result on fast electrons. We have shown that linear Landau damping in the downstream region plays a negligible role in helicon discharges, at least at densities above, say, 5×10^{12} cm^{-3}, at which the efficiency of helicon discharges is problematical. Fast electrons detected by others, we believe, are

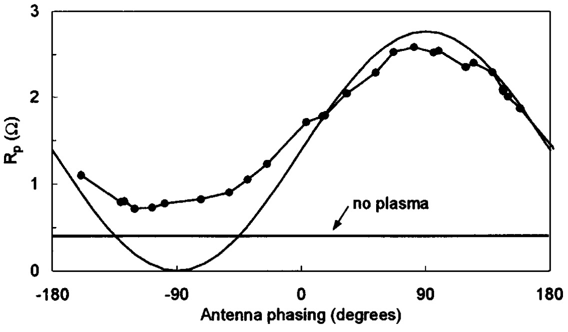

FIG. 4. Plasma loading resistance as measured (circles) and compute (curve) in a 2.5 cm radius discharge, 800 G, 1.8 kW at 27.12 MHz, 20 mTorr argon fill, 3×10^{13} cm^{-3} peak density, bifilar ($m = +1$), 10 cm long, half-helical antenna. The theory includes the $m = +1$ mode only and assumes a plasma-on pressure of 5 mTorr.

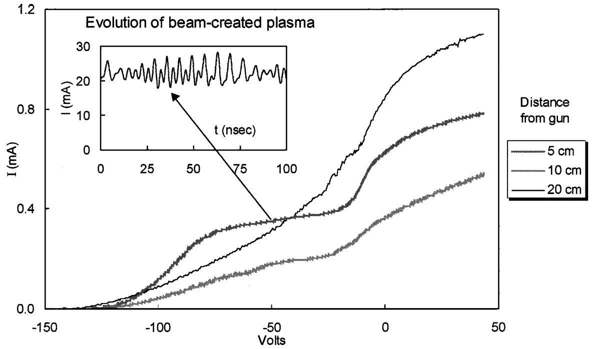

FIG. 5. Analyzer I-V curves in a beam-produced plasma. Inset: unstable oscillations.

incidental artifacts unrelated to the primary helicon ionization mechanism. We cannot, however, rule out the existence of nonlinear kinetic effects under and near the antenna at low densities, as advocated by Ellingboe and co-workers [10,17,18]. Indeed, fast electrons oscillating in standing waves under the antenna or injected into the plasma just past the antenna are subject to a beam-plasma instability and could be thermalized rapidly [28]. Data from the present experiment support this possibility. Figure 5 shows analyzer I-V curves at various distances from the electron gun in a plasma created by a 100 eV beam in 1 mTorr of argon at 360 G. At 5 cm, a clear beam is seen. By 20 cm, $f(v)$ has thermalized into a smooth curve with about 40 eV temperature; by 50 cm, the plasma cools to 9 eV, with a hot tail extending to 100 eV. The inset shows oscillations in the collector current at 5 cm. The 150 MHz signal is not understood (it corresponds to plasma frequency at only 3×10^8 cm^{-3}), but the 12 MHz modulation agrees with the ion plasma frequency, at which the growth rate of the ion-acoustic instability is near its maximum. No hot electron tail, however, is seen in helicon plasmas without an injected beam, suggesting that hot electron currents as large as 0.5 mA/cm^2 (Fig. 5) are not generated by the antenna. (Note that the beam-plasma instability growth rate varies only as the cube root of the beam/plasma density ratio.)

In any case, the hypothesis of Landau damping as originally proposed by Chen [2], involving a hyperthermal, downstream distribution of electrons moving at the phase velocity, is almost certainly incorrect and should now be discarded.

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[1] R. W. Boswell, Phys. Lett. **33A**, 457 (1970); Plasma Phys. Controlled Fusion **26**, 1147 (1984).

[2] F. F. Chen, Plasma Phys. Controlled Fusion **33**, 339 (1991).

[3] P. K. Loewenhardt, B. D. Blackwell, R. W. Boswell, G. D. Conway, and S. M. Hamberger, Phys. Rev. Lett. **67**, 2792 (1991).

[4] A. W. Molvik, A. R. Ellingboe, and T. D. Rognlien, Phys. Rev. Lett. **79**, 233 (1997).

[5] R. T. S. Chen and N. Hershkowitz, Phys. Rev. Lett. **80**, 4677 (1998).

[6] P. Zhu and R. W. Boswell, Phys. Fluids B **3**, 869 (1991).

[7] T. Shoji, T. Mieno, and K. Kadota, *Proceedings of the International Seminar on Reactive Plasmas, Nagoya, Japan* (Nagoya Industrial Science Research Inst., Nagoya, Japan, 1991), p. 377.

[8] T. Abe, S. Nakazawa, N. Koshikawa, Y. Sakawa, and T. Shoji, Proceedings of the 2nd International Conference on Reactive Plasmas, Yokohama, 1994 (to be published).

[9] R. W. Boswell and D. Vender, Plasma Sources Sci. Technol. **4**, 534 (1995).

[10] A. R. Ellingboe, R. W. Boswell, J. P. Booth, and N. Sadeghi, Phys. Plasmas **2**, 1807 (1995).

[11] A. W. Molvik, T. D. Rognlien, J. A. Byers, R. H. Cohen, A. R. Ellingboe, E. B. Hooper, H. S. McLean, B. W. Stallard, and P. A. Vitello, J. Vac. Sci. Technol. A **14**, 984 (1996).

[12] G. D. Conway, A. J. Perry, and R. W. Boswell, Plasma Sources Sci. Technol. **7**, 337 (1998).

[13] P. Zhu and R. W. Boswell, Phys. Rev. Lett. **63**, 2805 (1989).

[14] A. Komori, T. Shoji, K. Miyamoto, J. Kawai, and Y. Kawai, Phys. Fluids B **3**, 893 (1991).

[15] F. F. Chen and C. D. Decker, Plasma Phys. Controlled Fusion **34**, 635 (1992).

[16] A. R. Ellingboe and R. W. Boswell, Phys. Plasmas **3**, 2797 (1996).

[17] A. W. Degeling, C. O. Jung, R. W. Boswell, and A. R. Ellingboe, Phys. Plasmas **3**, 2788 (1996).

[18] A. W. Degeling and R. W. Boswell, Phys. Plasmas **4**, 2748 (1997).

[19] P. A. Keiter, E. E. Scime, and M. M. Balkey, Phys. Plasmas **4**, 2741 (1997).

[20] N. Hershkowitz, in *Plasma Diagnostics,* edited by O. Auciello and D. L. Flamm (Academic, New York, 1989), Vol. 1, Chap. 3.

[21] F. F. Chen, Plasma Phys. Controlled Fusion **39**, 1533 (1997).

[22] I. D. Sudit and F. F. Chen, Plasma Sources Sci. Technol. **3**, 162 (1994).

[23] I. D. Sudit and F. F. Chen, Plasma Sources Sci. Technol. **5**, 43 (1996).

[24] J. Gilland, R. Breun, and N. Hershkowitz, Plasma Sources Sci. Technol. **7**, 416 (1998).

[25] K. P. Shamrai and V. B. Taranov, Plasma Sources Sci. Technol. **5**, 474 (1996).

[26] D. G. Miljak and F. F. Chen, Plasma Sources Sci. Technol. **7**, 61 (1998).

[27] D. Arnush and F. F. Chen, Phys. Plasmas **5**, 1239 (1998).

[28] A. I. Akhiezer, V. S. Mikhailenko, and K. N. Stepanov, in *Proceedings of the 1998 International Congress on Plasma Physics* (Institute of Plasma Physics, Prague, 1998), Europhysics Conference Abstract No. 22C, p. 2825.