# Plasma Production in a Toroidal Heliac by Helicon Waves

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rf power in the lower-hybrid-frequency range is shown to produce plasma of density in the $10^{13}$-cm$^{-3}$ range in the small toroidal heliac SHEILA by launching helicon waves. Measurements of wave dispersion and mode structure confirm that an $m=1$ helicon mode is launched inside the highly asymmetric plasma confined in the device. The suggestion that the main energy-transfer mechanism is by Landau damping is strongly supported by the experimental data.

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There has been considerable recent interest in the use of radio-frequency-generated helicon waves to produce plasma in a wide variety of experimental situations, ranging from magnetically confined toroidal systems to plasma processing reactors. While their successful application to open-field geometries (e.g., etching reactors, linear plasma columns) is now fairly well documented [1-5] (argon plasma densities $\sim 10^{14}$ cm$^{-3}$ have been achieved using, typically, a few kW at 7 MHz), we report here what is believed to be its first use in a closed toroidal system where the evidence of helicon wave involvement is unambiguous. Helicon waves are bounded electromagnetic waves which propagate in the lower-hybrid-frequency range ($\omega_{ci} \ll \omega \ll \omega_{ce}$), and lie in the low-frequency whistler region of the fast-wave branch of the cold-plasma dispersion relation. Landau damping of fast waves was first discussed by Yoshikawa and Yamato [6]. A recent paper by Chen [7] discusses helicon waves in detail, elaborates on their partially electrostatic nature, and makes estimates on their Landau damping rates.

In this Letter we report detailed measurements made in a toroidal heliac (helical axis stellarator) in which helicon waves are launched by a simple antenna [5] and produce plasma remarkably efficiently. The wave fields and propagation will be shown to be entirely consistent with the predictions of a simple dispersion theory (modified to suit the plasma geometry), the measured damping lengths agreeing with the estimates of Chen [7], and direct evidence of strong wave-particle interaction will be presented.

The prototype heliac SHEILA ($R=19$ cm, $\bar{a} \leq 3.5$ cm, $B_0 \leq 2$ kG), described in detail elsewhere [8], forms closed toroidal flux surfaces with highly indented cross sections inside a set of toroidal coils whose centers lie on a three-turn toroidal helix which rotates around a central ring conductor (see Fig. 1, inset). The plasma is produced by coupling oscillating fields at (typically) 7 MHz from an rf power source (5 kW maximum) in pulses up to 20 ms during each magnetic field pulse (50 ms). The antenna consists essentially of a pair of current loops placed on either side of the elongated plasma column, the planes of the loops being both twisted so as to follow the helical axis of the plasma, and curved to conform with its bean-shaped cross section. The double-loop arrangement is connected so as to produce an oscillating magnetic field perpendicular to the plasma axis and thus couple to the $m=1$ mode of a helicon wave. At typical operating conditions, $P=3.5$ kW, $B_0=1.5$ kG, and Ar pressure of 5 mTorr, plasma is produced with $\bar{n}_e \simeq 2\times10^{13}$ cm$^{-3}$, $T_e \sim 5$ eV.

Local magnetic measurements of the wave field are made with resolution $\pm 2$ mm using magnetic probes with ten-turn, 1-mm-diam pickup coils. Two single Langmuir probes located at toroidal positions 10° and 140° from the antenna measure ion density (relative) and the electron energy distribution. A 2-mm microwave interferometer at 10° measures the electron density independently and is used to calibrate the probe data.

The basic structure and behavior of low-order helicon waves can be obtained from a simple, zero-resistivity model assuming a straight, cylindrical, uniform density plasma of radius $r=a$. The results presented here are restricted to azimuthal mode $m=1$ and the lowest radial

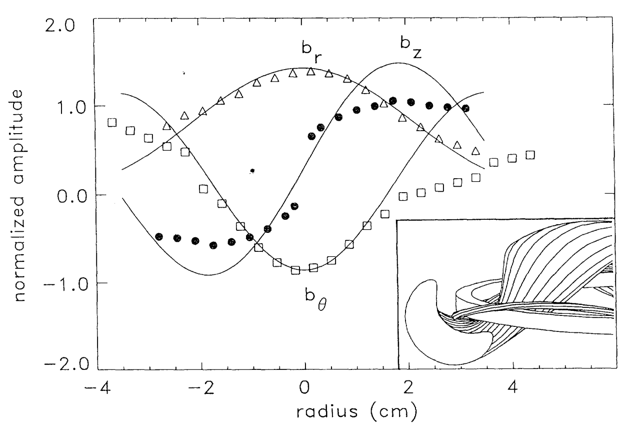


FIG. 1. Experimental wave field measurements of $b_z$ (●), $b_\theta$ (□), and $b_r$ (△) normalized to the corresponding theoretical components (conserving relative amplitudes). Inset: An example of the SHEILA geometry, including a typical plasma cross section.

mode, the mode most likely to be excited by this antenna. The wave field components then take the form

$$b_r = iA\left\{(q-k_\parallel)\frac{J_1(k_\perp r)}{k_\perp r} + k_\parallel J_0(k_\perp r)\right\},$$

$$b_\theta = A\left\{(q-k_\parallel)\frac{J_1(k_\perp r)}{k_\perp r} - qJ_0(k_\perp r)\right\},$$

$$b_z = Ak_\perp J_1(k_\perp r).$$

Here $A$ represents the wave amplitude, $k_\parallel$ and $k_\perp$ are the parallel and perpendicular wave numbers, respectively, $J_m$ is a Bessel function of the first kind, $r$ is the radial distance from the center of the plasma, and the dispersion relation is $q = 4\pi en_0\omega/k_\parallel cB_0$ (where $q^2 \equiv k_\perp^2 + k_\parallel^2$). Figure 1 shows how these fields compare with wave field components measured at $B_0 = 1.4$ kG. Here we have used a "circularized" flux-surface radius for the experimental data, with the plasma boundary taken as $r = \bar{a} = 3.5$ cm. (In earlier work it was shown that a transformation from straight-field-line flux coordinates to a periodic circular cylindrical model allowed experimental comparison with simple dispersion theory in the case of drift waves [9].) The results show that the measured radial variation in the field follows the simple cylindrical model remarkably well, except in the outer plasma regions. This discrepancy is almost certainly due to the inappropriate assumption of uniform plasma density in the theory. The good agreement with cylindrical theory indicates that the toroidal geometry of the experiment may be unimportant, although the periodic nature of the plasma may constrain $k_\parallel$.

As further evidence of helicon wave involvement, we examine the dependence of resultant electron density on $B_0$ for otherwise constant conditions. We find that in weak fields the plasma profile is flat, and becomes centrally peaked at the magnetic axis when $B_0 \gtrsim 0.8$ kG. Figure 2(a) shows the experimental dependence together with that from the dispersion relation

$$\frac{n_e}{B_0} = \frac{c}{4\pi e\omega}(k_\perp^2 k_\parallel^2 + k_\parallel^4)^{1/2}, \tag{1}$$

where we use the measured value $k_\parallel = 0.1$ cm$^{-1}$ (approximately constant for $B_0 \gtrsim 1$ kG) and put $k_\perp = 1.0$ cm$^{-1}$ from the boundary conditions. The uncertainty in $k_\parallel$ is estimated to be about 20% from variation in the data. The agreement is quite good at the higher fields ($B_0 > 1$ kG) where the plasma is well established.

Experimentally it is found that helicon waves ionize with much greater efficiency than nonresonant rf discharges and that the energy transfer cannot be explained by collisional dissipation [2–5]. Thus we examine the evidence for Landau damping, noting that its involvement has been suggested in some linear-plasma-column experiments [3,4], most directly by Komori *et al.* [2].

Landau damping occurs strongly when $v_\phi = \omega/k_\parallel \sim v_{\rm th}$

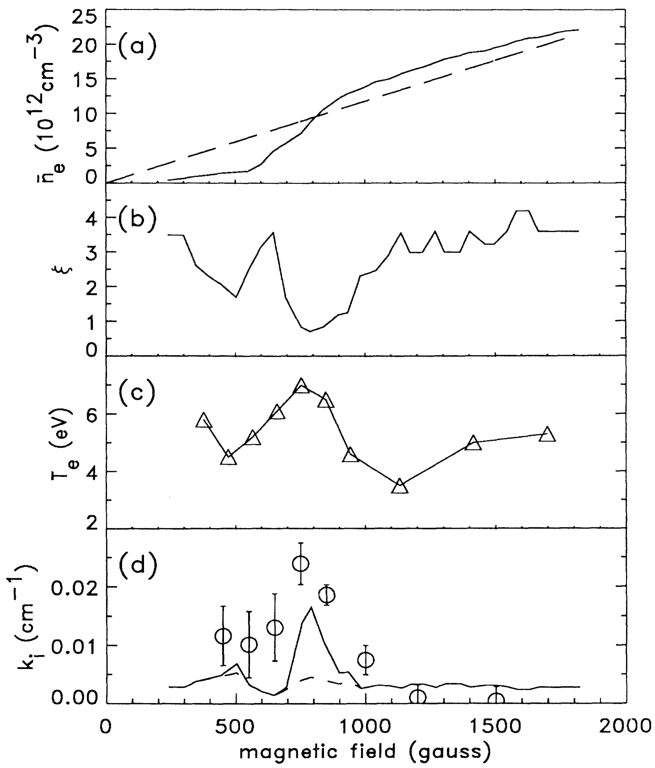


FIG. 2. Dependence on $B_0$ of (a) line averaged density, experimental (——) and estimated from Eq. (1) (---); (b) $\xi = v_\phi/v_{\rm th}$; (c) $T_e$; and (d) measured (○), estimated collisional (---), and total [collisional+Landau (——)] damping.

$= (2kT_e/m_e)^{1/2}$. Figure 2(b) shows how the ratio $\xi = v_\phi/v_{\rm th}$ (as measured) depends on $B_0$. The most rapid increase in $n_e$ and the highest electron temperature $T_e$ [Fig. 2(c)] both occur around $B_0 = 800$ G when $\xi \approx 1$, consistent with strong Landau damping.

This is shown most clearly in Fig. 2(d), which compares the experimentally measured spatial damping rate $k_i$ with the theoretical estimate [7] of the total damping given by

$$k_i = \frac{\nu k_\parallel}{\omega}\left(\frac{cq}{\omega_p}\right)^2 \Bigg/ \left(1 + \frac{k_\parallel^2}{q^2}\right),$$

where $\nu = \nu_{ei} + \nu_{\rm LD}$, $\nu_{ei}$ is the electron-ion collision rate, and

$$\nu_{\rm LD} = \frac{\omega}{\xi^2}{\rm Re}\left(\frac{1}{iZ'(\xi)}\right),$$

where $Z$ is the plasma dispersion function. The error bars shown in Fig. 2(d) represent uncertainties in the wave amplitude only, and neglect any effects of nonuniform density. The damping agrees reasonably well with the theoretically expected values, and has the predicted variation with $\xi$. Note that when $\xi \sim 1$, the observed

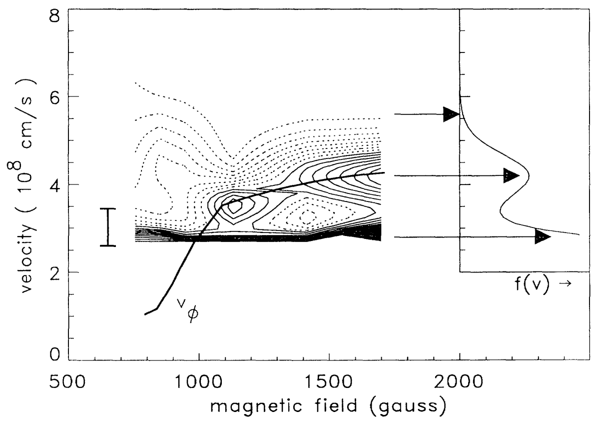


FIG. 3. Average measured $v_\phi$ superimposed upon contours of constant $f$ for a high-energy tail [$f/f(0) = 1.1\times10^{-4}$]. Dashed lines in the contour lie below $f/f(0) = 4.2\times10^{-5}$, solid lines above this value. The error bar indicates the uncertainties in both plasma potential and $v_\phi$. Inset: Example of a distribution function $f$ at $B_0 \approx 1.7$ kG.

damping is significantly greater than the estimated rate due to collisions.

Finally, we examine the effects of the wave on the electron velocity distribution function $f(v)$, which we obtain at different magnetic fields by differentiating the Langmuir probe characteristics. (Numerical simulations following the analysis of Hershkowitz *et al.* [10] show that the non-Maxwellian features obtained are unlikely to be artifacts caused by rf field effects.) A contour plot of the high-energy tail of the distribution function is shown in Fig. 3 along with $v_\phi$, both as a function of $B_0$. In the region where $v_\phi$ lies in the bulk of the distribution (i.e., $v_\phi < 2v_{th}$) there is little departure from Maxwellian, and, as noted, the plasma bulk temperature rises. As $b_0$ is increased, $v_\phi$ increases and Landau damping weakens. For $B_0 \geq 1$ kG a bump appears in the tail of the distribution function around $v = v_\phi$, that is, the population of electrons in this part of the distribution is enhanced above its thermal level. As shown in Fig. 3 the peak of this "bump on tail" follows $v_\phi$ as it increases with increasing $B_0$. Assuming this population to be unidirectional, it would correspond to a current $\sim 5$ A. This is of roughly similar current density to that observed by Goree *et al.* [11] in an experiment to test the principle of fast-wave current drive.

We note that hydrogen plasma of density $\bar{n}_e \approx 5\times10^{12}$ cm$^{-3}$ has been produced with 1.5 MW at 40 MHz in the CHS stellarator [12] using an antenna oriented to launch low-frequency whistler waves, although no investigation of wave structure or energy-transfer mechanism has been presented.

In summary, it has been shown that a low-order ($m = 1$) helicon wave can be excited in a complicated toroidal magnetic structure and can produce relatively dense plasma. The prediction that the high coupling efficiency of the helicon wave is caused by Landau damping is strongly supported by the experimental data. An enhancement above normal thermal levels of a population of electrons with $v \approx v_\phi$ was found, implying some form of wave-particle interaction.

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