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By

W. Hooke et al.

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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W. Hooke, S. Bernabei, D. Boyd, A. Cavallo, T.K. Chu
S. Cohen, P. Colestock, C. Daughney, S. Davis,
D. Dimock, P. Efthimion, D. Herndon, H. Furth,
J. Hosea, J. Hovey, F. Jobes, R. Kaita,
A. Martin, E. Mazzucato, D. McNeill, E. Meservey,
R. Motley, D. Ruzic, R. Schwartz, J. Stevens,
J. Strachan, S. Suckewer, G. Taylor, J. Timberlake,
E. Valeo, R. Wilson, S. von Goeler

Plasma Physics Laboratory
Princeton University
Princeton, New Jersey 08544

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ABSTRACT

Steady currents up to 165 kA for 3.5 seconds and 420 kA for 0.3 seconds have been maintained by 800 MHz lower hybrid waves. For line-averaged densities up to $7 \times 10^{12} \text{ cm}^{-3}$ the current is maintained with no input power from the ohmic heating transformer. The waves are launched with an array of six waveguides. Measurements of x rays and electron cyclotron radiation show that the rf power produces and maintains a suprathermal tail of electrons apparently independent of the number of fast electrons in the plasma prior to turning on the rf power. Measurements of current-drive efficiency and the electron tail provide direct evidence for a resonant wave-particle interaction. The radial profile of the rf-sustained current inferred from x-ray measurements is peaked in the center of the plasma and appears to obey the same q-value restraints as the inductively driven ohmic heating current. Current drive is observed to be accompanied always by radiation at frequencies $\geq \omega_{ce}$ and $\leq \omega_{pe}$. The connection between this radiation and the current-drive mechanism is under study. We characterize the current-drive efficiency by the figure of merit $I n_e / P_{RF} = 0.8 \times 10^{13} \text{ A cm}^{-3} / \text{W}$ for waves with $n_{||} = 1.5$ – 2.0 , the efficiency for larger values of $n_{||}$ being significantly lower. Above $n_e = 7 \times 10^{12} \text{ cm}^{-3}$ the efficiency drops to zero, although, in certain circumstances, current drive effects have been seen up to $n_e = 1.2 \times 10^{13} \text{ cm}^{-3}$. A comparison in H^+ and D^+ plasmas suggests that this density limit would be higher at higher frequencies.

EXPERIMENTAL RESULTS

We report here current-drive experiments with an 800 MHz system operating typically up to power levels of 400 kW and pulse lengths of several seconds. Waves are coupled to the plasma with an array of six waveguides, each waveguide being driven by a klystron with independent adjustment for power and phase. This phase control allows us to determine the direction and the phase velocity ($1 < n_{||} \leq 4.5$) of the waves parallel to the confining magnetic field.

Coupling measurements show excellent transmission ($\geq 85\%$) of the power in good agreement with theory. Initial attempts to operate above 170 kW led to a sharp increase in reflection resulting, apparently, from plasma formation within and just outside the mouth of the waveguide. Recent improvements including carbon coating of the waveguides to reduce secondary

electron emission, removal of the limiters from the coupler port location and relocation of the gas injection valve have permitted operation up to the 630 kW level with four waveguides, corresponding to power densities somewhat above 2 kW/cm². Operation at higher power levels is limited by circuit components in the rf source and not by ionization of gas in the coupler.

At 800 MHz lower-hybrid wave interaction with plasma ions should take place roughly at densities above $\sim 10^{13}$ cm⁻³ with the electron interaction increasing as the density is lowered. The major emphasis in this study has been on the lower-density region and the wave-ion interaction or "conventional" lower hybrid heating has not been thoroughly studied. However, effective collisional heating has been observed in the current-drive experiments in that plasmas with $T_{e0} = 1$ keV and $T_{i0} = 400$ eV have been obtained with no external source of power other than the 800 MHz rf. An effort has been made in this work to use long rf pulses in order to reduce the effect of transient fields. By simultaneously working with long pulses, keeping $di_p/dt = 0$, and turning off the ohmic heating input (i.e., keeping the current in the OH primary constant) we minimize the electric fields in the plasma in an effort to allow the rf fields to dominate the electron dynamics. Figure 1 shows a case where a 160 kA current was driven for 3.5 s. Currents up to 420 kA have been driven for 0.3 s with the limitation on pulse length determined by the rf generator.

In general, but with exceptions, the current driven by the rf increases with power and decreases with density. We choose, therefore, to characterize the current-drive effectiveness with a figure of merit, C , which is normalized with respect to density and is expressed in units of amperes per watt times density measured in units of 10^{13} cm⁻³. Here the current is that which the rf will maintain constant with no power input from the ohmic heating circuit. Figure 2 shows the variation of C with density for three different waveguide phase settings. Analysis of the dependence of C on waveguide phase shows that the efficiency of current-drive increases as the wave velocity parallel to B is increased. At low levels of current (≤ 150 kA) we see a decrease in C by a factor of 2 to 3. At higher densities ($\sim 7 \times 10^{12}$ cm⁻³) the rf current cannot be kept constant with the available power. To date the highest density at which we have seen current-drive effects at 800 MHz is 1.2×10^{13} cm⁻³. A ~30% decrease in the density limit in changing from D⁺ to H⁺ plasmas, and an inverse correlation between current-drive and neutron production as $\omega/\omega_{LH} \rightarrow 1$ suggest that the density limit may increase with frequency.

The x-ray emission during the rf current-drive reveals that a suprathermal 50 - 150 keV electron tail is formed within 20 to 50 ms after the start of the rf power. Radial profiles of soft x-ray emission ($E \leq 25$ keV) indicate that the tail formation peaks in the center of the discharge. This x-ray profile broadens (Fig. 3) if the current is increased or the toroidal field is decreased. The rf driven current profile can be estimated from the x-ray profile. The resulting q-profiles show that q approaches unity on axis.

Measurements of the hard x-ray emission from the center of the plasma, Fig. 4, show that the "target" plasma need not have a significant suprathermal tail population before the rf is turned on. The rf power, directly or indirectly, creates the tail as well as maintains it. Figure 4 also shows that the slope of the tail is affected by the phase velocity of waves launched at the plasma surface; faster waves produce faster electrons, as one would expect in a resonant wave-particle interaction.

Radiation in the frequency ranges $\omega_{ce} \leq \omega < 10 \omega_{ce}$ and $\omega < \omega_{pe}$ is observed to increase rapidly (by a factor of at least 10) as the switch-over from inductive to rf current-drive occurs. The synchrotron radiation intensity rises to a steady state in about 50-100 msec. However, if the current-drive is weak (i.e., $I < 0$) we see relaxation oscillations in these radiation signals. The ordinary-mode emission near $\omega = \omega_{ce}$ oscillates in phase with the plasma frequency emission and both are out of phase with the extraordinary emission near $\omega = n\omega_{ce}$ where $n > 2$. A similar instability was predicted¹ and observed² in low-density TM-3 discharges, and may play a role in RF current drive.³ Figure 5 shows the dependence of the intensity of $\omega < \omega_{pe}$ radiation as a function of time for three waveguide phase settings.

The magnitude of the current drive (~ 0.8 A cm⁻³/W) and its dependence on density (for $\bar{n}_e < 0.7 \times 10^{12}$ cm⁻³) are consistent with theoretical calculations⁴ assuming collisional transfer of energy from a suprathermal tail to the warm background electrons.

Many of the future tokamak scenarios planned today involve combinations of rf and inductive current-drive. In these cases one encounters a practical engineering question: to what extent can one reverse the sense of the flux change in the ohmic transformer while maintaining the current-drive? Alternatively, this question becomes: what happens to an energetic electron when it is being pushed in one direction by the rf and in the opposite direction by a steady electric field? Some very preliminary measurements related to these questions are shown in Fig. 6. Both the primary and secondary (plasma) current in the ohmic heating transformer are shown with reversed electric field and no rf power (Fig. 6a); with rf power alone (Fig. 6c), and with rf and reversed inductive drive combined (Fig. 6b).

Although the plasma current drops somewhat in Fig. 6b, the reversed electric field (≈ -0.2 V) produced no change in the intensity of radiation from the suprathermal electrons. It appears likely that the rf power can maintain the electron tail, but that a reversed ohmic current arises in the bulk electrons.

SUMMARY

Current-drive efficiency has been measured under circumstances where the effects of electric fields are negligible. The maximum observed efficiency is 0.8×10^{13} A/W cm⁻³ with a waveguide phasing of 60°. X-ray emission shows that the rf-driven suprathermals are located in the center of the plasma, and the presence of large numbers of suprathermal particles in the target plasma is not necessary for effective current-drive. Relatively intense radiation at frequencies below ω_{pe} and above ω_{ce} indicate that waves other than the launched 800 MHz lower hybrid waves may play a role in the current-drive mechanism. Preliminary results indicate that current-drive may be effective even if the primary of the ohmic heating is "recharged," driving an electric field opposing the direction of the plasma current.

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FIGURE CAPTIONS

- FIG. 1. Plasma current and density vs time: a) with no rf power; b) with rf power. The rf was on at 0.4 sec and off at 3.9 sec. RF power = 70 kW, $\Delta\phi = 90^\circ$, $B_t = 23$ kG.
- FIG. 2. Current-drive efficiency vs density for three different phase settings for the waveguide coupler. Only those points for which the current could be held constant are plotted.
- FIG. 3. Radial variation of x-ray intensity at 14 keV from a moveable silicon detector, after Abel inversion, $\bar{n}_e = 5 \times 10^{12} \text{ cm}^{-3}$. A: $P_{RF} = 200$ kW, $I_p = 200$ kA, $B_t = 31$ kG; B: $P_{RF} = 250$ kW, $I_p = 210$ kA, $B_t = 15$ kG; C: $P_{RF} = 320$ kW, $I_p = 290$ kA, $B_t = 15$ kG.
- FIG. 4. Plasma x-ray spectrum with and without rf for three phase settings, (from NaI detector); $B_t = 31$ kG, $I_p = 200$ kA, $\bar{n}_e = 3 \times 10^{12} \text{ cm}^{-3}$.
- FIG. 5. Intensity of 16 GHz radiation vs time for three waveguide phase settings. When the rf is turned off, the plasma loop voltage becomes positive, and the radiation increases further.
- FIG. 6. Ohmic heating primary current I_{OH} (dashed line), and plasma current I_p , vs time. In Fig. 6a the decreasing primary current induces an electric field opposing the rapid drop in plasma current. In Fig. 6b, the rf power is turned on and the decline in current is significantly reduced. In Fig. 6c, the primary current is held constant and the rf is left on.

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Fig. 1

Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

Fig. 6