

## Fast-Wave Current Drive in the Irvine Torus

R. McWilliams and R. C. Platt

*Department of Physics, University of California, Irvine, California 92717*

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Steady-state electron currents were driven by fast waves with  $\omega_{ci} \ll \omega \ll \omega_{ce}$  in an initially current-free plasma in the Irvine Torus. Current direction was controlled by the fast-wave phased-array antenna. Low-power experiments ( $< 25$  W) generated up to 1.3 A of electron current with a peak efficiency of  $\eta = InR/P \approx (6 \times 10^{-2} \text{ A/W})(10^{13} \text{ cm}^{-3})\text{m}$ . Up to 14% of the wave energy was converted to poloidal magnetic field energy.

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Prospects for steady-state tokamak operation have been greatly enhanced by the successes of lower-hybrid current drive.<sup>1-4</sup> Plasma discharges have achieved over 100-kA currents<sup>4</sup> without the use of Ohmic transformers. Discharge durations seconds long have been produced,<sup>3</sup> apparently limited only by heating in the rf power supplies. A limitation encountered by lower-hybrid current drive is the so-called "density limit," whereby current-drive efficiency is seen to drop dramatically for plasma densities bringing the wave frequency within a factor of 2 of the lower-hybrid frequency. There is also concern about the role of scattering by density fluctuations.<sup>5</sup>

In this Letter we report observations of steady-state electron currents driven in a plasma by a phased-array fast-wave antenna. Toroidal currents were driven with controllable direction in an initially current-free plasma. Current-drive efficiencies compare favorably with slow-wave current-drive results. The experiment was performed at a density above the "density limit" encountered by lower-hybrid current drive.

In the frequency regime  $\omega_{ci} \ll \omega \ll \omega_{ce}$ , the fast wave should propagate to high densities, without suffering from encounter with the resonance layer met by the slow electrostatic lower-hybrid wave. Also, since the fast wave does not propagate in resonance cones, parametric decay should not present an energy-loss channel until very high power levels are reached.

For three reasons most previous current-drive work has concentrated on use of the slow wave. Earlier radio-frequency studies tended to concentrate on ion heating, for which it was thought that the slow wave is better suited than the fast wave, and hence more understanding of the slow wave was obtained. Secondly, cutoff conditions were met more easily for slow-wave experiments. Lastly, the antennas for slow waves are easier to build than fast-wave antennas. However, with the results discovered in slow-wave current-drive experiments, it is apparent now that fast-wave current drive deserves serious examination. Recently, experimental results of fast-wave current rampup via toroidal eigenmode excitation ( $\omega \sim 10\omega_{ci}$ ) were reported.<sup>6</sup>

For both the slow and the fast waves there is an accessibility criterion which places an upper limit on the density to which the waves will propagate and a cutoff condition which places a lower limit on the density. Golant<sup>7</sup> has examined the cold-plasma dispersion relation equations for the slow and fast waves. Theilhaber and Bers<sup>8</sup> and McWilliams and Mok<sup>9</sup> have discussed the coupling to the fast wave in more detail. Experimental measurements of the coupling to the fast wave via a phased waveguide array have been reported.<sup>10</sup> The cutoff density for the fast wave is given approximately by

$$\begin{aligned} \omega_{pe}^2(\text{cutoff}) \\ \approx \omega \omega_{ce} (n_z^2 + n_\theta^2 - 1)^{1/2} (n_z^2 - 1)^{1/2}. \end{aligned} \quad (1)$$

For  $n_\theta \neq 0$ , the cutoff density may rise or fall somewhat from Eq. (1), depending on whether  $k_\theta dn/dx$  is greater or less than zero, respectively. The dispersion relation for the fast wave is given approximately by

$$n_x^2 \approx \left( \frac{\omega_{pe}^2}{\omega \omega_{ce}} \right)^2 \frac{1}{n_z^2 - 1}. \quad (2)$$

Fast-wave coupling efficiency may be estimated by theory and compared with experiment by calculation of the impedance mismatch from the antenna to the plasma. The plasma impedance is

$$Z \approx \frac{n_z^2 + n_\theta^2 - 1}{(n_z^2 - 1)^{1/2}} \frac{\omega \omega_{ce}}{\omega_{pe}^2}, \quad (3)$$

where we assume  $\omega_{pe}^2/\omega^2 \gg 1$  and  $\omega_{pe}/\omega_{ce} \sim 1$ . Reflection coefficients as low as 1% have been observed.<sup>10</sup>

The experiments reported here were performed on the Irvine Torus (see Fig. 1), a steady-state toroidal device with major radius 56 cm, minor radius limiters set at 3.5 cm,  $T_e \leq 15$  eV (but with a substantial high-energy electron tail, as mentioned below), and  $n_e \leq 3 \times 10^{13} \text{ cm}^{-3}$ . The density was typically  $n_e \approx 4 \times 10^{12} \text{ cm}^{-3}$  for these experiments. The toroidal field was set equal to  $B_\phi = 1$  kG to ensure being above cutoff for the fast wave ( $6 \times 10^{11} \text{ cm}^{-3}$  here). Vertical

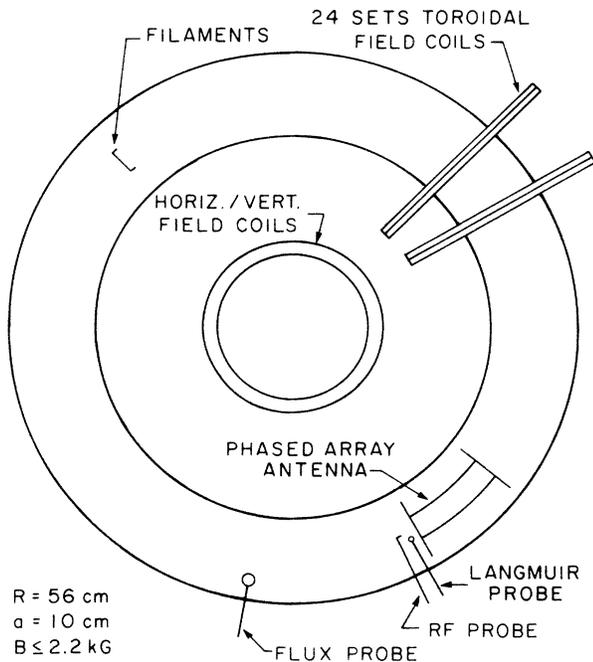


FIG. 1. Top view diagram of the Irvine Torus.

and horizontal magnetic fields are available for plasma control. There is no Ohmic pulse and hence no toroidal dc electric field. The plasma was formed by thermionic emission from filaments at the bottom of the vacuum vessel. These electrons form 75-mA, 350-V high-energy electron-tail beams circulating in both directions in the torus when no vertical field is applied, as was the case for these experiments. The circulating beam produces plasma by ionization of argon gas bled into the chamber. Argon pressure was  $8.8 \times 10^{-5}$  Torr for the results presented here and hence the plasma region is almost completely ionized. The toroidal plasma thus formed has no toroidal current without introduction of the fast waves.

Plasma density and electron temperature were inferred from Langmuir-probe measurements. Currents generated by the waves were measured by means of small-area, single-turn dual magnetic pickup loops built so as to discriminate against electrostatic pickup. These probes are movable radially inside and outside of the plasma column. The fast waves were excited by application of a 94-MHz signal to a sixteen-element phased-array antenna, as shown schematically in Fig. 2. This array was built following techniques similar (but suitably modified to excite the fast-wave fields) to those devised for slow-wave excitation.<sup>11</sup> The array was one wavelength long in the  $Z$  and  $\theta$  directions and excites primarily the  $E_\theta$  required for fast-wave launching (as opposed to  $E_z$  for the slow wave). The principal indices of refraction excited are  $n_\theta = 14.5$ ,

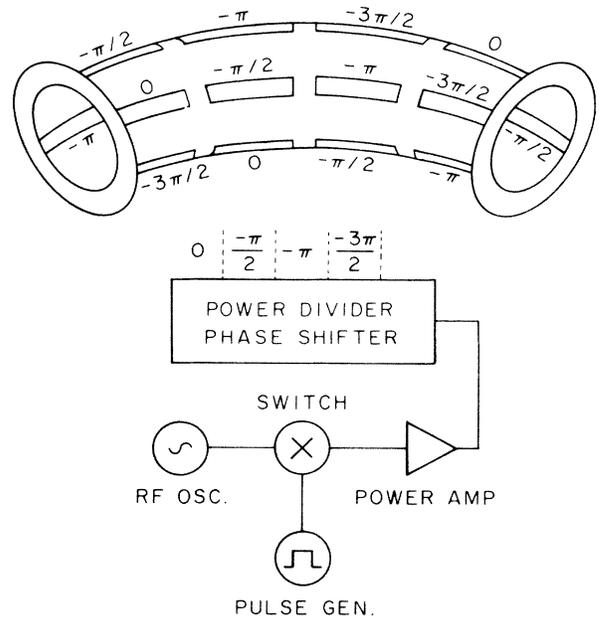


FIG. 2. Schematic diagram of fast-wave antenna structure.

$n_z = 10.6$ .

The direction of fast-wave propagation around the torus was controlled by selection of the phasing to each element of the array. For current drive it is desirable to launch the wave in one toroidal direction only. Indeed, when symmetric phasing was used, no current was detected. The phase difference between adjacent elements used to produce current drive was  $\pm 90^\circ$  depending on the direction desired. The current produced was slightly, but not significantly, larger for one phasing, compared to the other. The direction of the electron flow induced was in the direction of the axially imposed phase velocity of the fast wave, i.e., launching the wave clockwise around the torus induced clockwise electron flow and counterclockwise phasing induced counterclockwise electron flow.

Current generation via waves should occur only for densities above the wave cutoff density. For this experiment the fast-wave cutoff density was about  $6 \times 10^{11} \text{ cm}^{-3}$  while the slow-wave cutoff is near  $10^8 \text{ cm}^{-3}$ . Figure 3 shows wave-driven current as a function of density, with the radio-frequency power delivered to the antenna held constant. When the density was lowered below about  $6 \times 10^{11} \text{ cm}^{-3}$  no current generation was observed. Hence, slow waves did not play a significant role in the current generation reported here. At  $n_e = 4 \times 10^{12} \text{ cm}^{-3}$  the experiment was  $\omega/\omega_{pi} = 1.4$ . Hence, the results of fast-wave current drive reported here occur for densities higher than the "density limit" ( $\omega/\omega_{pi} \sim 2$ ) found during lower-hybrid current-drive experiments.

The estimated  $L/R$  response time required by the

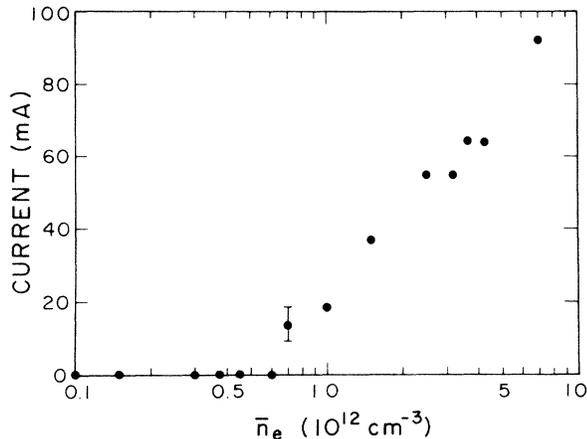


FIG. 3. Driven current vs plasma density, with rf power to antenna held constant.

plasma to build a poloidal magnetic field was 200 nsec. The observed rise time of the current was 280 nsec. Upon wave turnoff the current dissipated to zero in 600–800 nsec, consistent with the measured time for a 1-keV electron to drift out of the torus. After initiation the current remained constant until the wave power was terminated, regardless of wave pulse duration.

Figure 4 shows dependence of current on wave power. The maximum current of 1.34 A was driven by 20.5 W of power coupled into the wave. Reversal of antenna phasing drove similar currents in the opposite direction around the torus. For the maximum current, 14% of the wave energy was converted to poloidal magnetic field energy. Also of interest from this graph is the efficiency of the fast-wave current drive. From the graph the central data points yield

$$\eta = InR/P \approx (6 \times 10^{-2} \text{ A/W})(10^{13} \text{ cm}^{-3})\text{m}.$$

For lower-hybrid current drive  $\eta$  has steadily increased as experiments have gone to larger devices with improved confinement. We note that  $\eta$  for fast-wave current drive on the Irvine Torus compares very favorably with typical figures for slow-wave current drive for similar experiments.

In conclusion, an antenna designed to couple to the fast wave in the regime  $\omega_{ci} \ll \omega \ll \omega_{ce}$  has driven over 1 A in the Irvine Torus with efficiencies up to

$$\eta = (6 \times 10^{-2} \text{ A/W})(10^{13} \text{ cm}^{-3})\text{m}.$$

The electron current response to the fast wave was in the direction of axial propagation of the fast wave (reversing direction when the wave phasing was re-

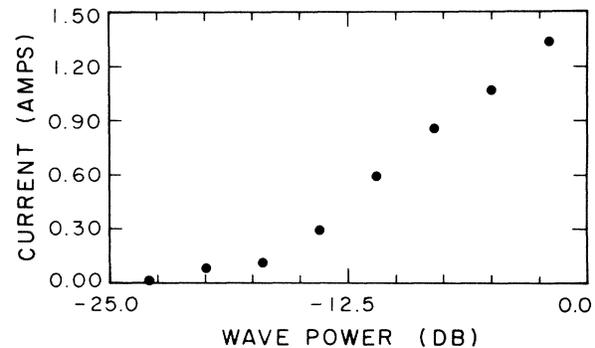


FIG. 4. Fast-wave current vs log(power in the waves). 0 dB=32.5-W fast-wave power. Wave frequency 94 MHz, principal parallel index of refraction 10.6.

versed). At the maximum current, 14% of the wave energy was converted to poloidal magnetic field energy. The current started from a zero-current toroidal plasma and was maintained for the duration of the fast-wave pulse. The experiments were performed at a density above the “density limit” observed in slow-wave current drive experiments. In addition to fusion application, the ability of fast electromagnetic waves to drive steady-state electron currents is of interest in astrophysical problems and in magnetospheric physics where such interaction is thought to occur.

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