Fast-Wave Current Drive in a Toroidal Plasma

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Fast-wave current drive is demonstrated in the Princeton ACT-I toroidal device. The fast Alfvén wave, in the range of high ion-cyclotron harmonics, produced 40 A of current from 1 kW of rf power coupled into a plasma by a fast-wave loop antenna. This wave excites a steady current by damping on the energetic tail of the electron distribution function in the same way as lower-hybrid current drive, except that fast-wave current drive is appropriate for higher plasma densities.

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Radio-frequency current drive has become a familiar feature of toroidal plasma experiments,[1] beginning in 1966 with the observation of a steady current excited by the ion-cyclotron wave in the C-Stellarator[2] and more recently with the demonstration of lower-hybrid current drive (LHCD) in 1980 in the Princeton Advanced Concepts Torus (ACT-I) toroidal device.[3] Recently, large currents made by electron Landau damping of the lower-hybrid wave have been sustained, and even started up, in tokamaks.[4–7] For tokamak reactor operation, LHCD shows promise, but there remain problems such as a density limit[8] and scattering by density fluctuations[9,10] that might be overcome by use of other rf waves. The fast Alfvén wave can interact with the superthermal tail of the electron distribution function to maintain a current in much the same way as LHCD.

Since the fast wave propagates at higher densities and has a longer wavelength perpendicular to the magnetic field, it may serve better than the lower-hybrid wave in a tokamak reactor. The lower-hybrid wave is ultimately limited to plasmas less dense than the lower-hybrid resonance density (see Fig. 1). Its short wavelength makes wave penetration more sensitive to the qualities of the plasma edge. This Letter reports for the first time an observation of toroidal fast-wave current drive (FWCD). In this experiment, a wave is launched that travels in both toroidal directions, and the direction of the driven current is determined by the slope of the target electron distribution function.

The experiment was run on the ACT-I device, a torus with the following parameters: major radius 59 cm, minor radius $a = 7.6$–8.6 cm, toroidal field $B_0 = 4.5$ kG, electron temperature ≤ 17 eV, and density $\bar{n}_e \simeq 3\times10^{12}$ cm^{-3}. Unlike a tokamak, this machine has a magnetic field with no poloidal component, and there is no toroidal electric field. Lines of force have a slight vertical pitch. As they circle toroidally around the device, they make spirals that form vertical cylindrical surfaces. The lines are not closed; therefore, collisionless electron orbits are not confined indefinitely. A tokamak geometry confines electrons much better, which is an important distinction in considering rf current-drive experiments in the two types of devices.

An intense 40-A, 400-eV unidirectional pulsed electron beam, injected into the plasma along the field, makes a fast electron tail and ionizes the plasma as well. A lanthanum-hexaboride cathode inserted into the bottom of the torus produces the beam, with the plasma serving as the anode. Numerical simulations by Okuda *et al.*[11] indicate that a beam's contribution to the velocity distribution function takes a smooth negative slope, $f_0'(v_\parallel) < 0$, and that this distribution extends to velocities much higher than the velocity of the electrons injected by the cathode. In the central portion of the plasma, the beam contains 1% or more of the electron density. Such a prominent feature in

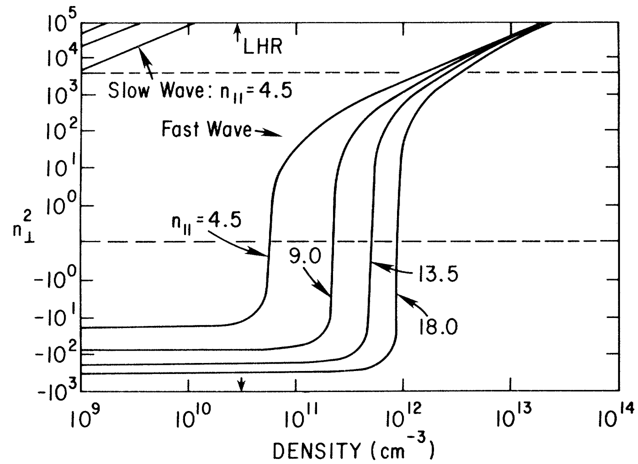

FIG. 1. Dispersion relation of the fast and slow waves. The unbounded cold-plasma dispersion-relation solutions are shown for $B_0 = 4.47$ kG, $f = 18$ MHz, and $m_i = 4$ amu. This plot is made of two log-log plots joined together: one for positive, i.e., propagating, values of $k_\perp^2$, and one for negative values. The upper horizontal dashed line gives an estimate of the density required to fit a half wavelength across the diameter of the ACT-I vessel. (The density actually required is less because rounded density profiles allow certain eigenmodes to propagate with less density.) The lower-hybrid resonance density is indicated by arrows.

$f_0(v_\parallel)$ is expected to be an ideal target for unidirectional damping of an rf wave and for the production of a unidirectional rf-driven current. In fact, a single-element waveguide launcher was previously used for successful LHCD with this discharge.[12]

For the present FWCD experiment, a single 140°-turn loop antenna excited the fast wave. This antenna is of the same type as those commonly used for fast-wave ion-cyclotron heating in tokamaks. It is covered with Faraday shields to suppress electrostatic interaction with the plasma. A number of rf diagnostics (magnetic loop probes, Langmuir probes, and far-infrared laser scattering[13]) were used to detect the rf power in the plasma, thereby identifying the fast wave and confirming that this mode was present everywhere in the torus. The dispersion relation indicates that propagation requires a sufficiently high wave frequency ω, mass density $n_i m_i$, B^{-1}, and a. We therefore used a He^+ plasma, for its ion mass, making it possible to fit an eigenmode into the small ACT-I cavity. The frequency was $\omega = O(10\Omega_{ci})$.

Fast-wave current drive was observed by monitoring of the signal from a Rogowski loop while the rf power was pulsed on. The circulating current increased by 40 A when 1 kW of rf power coupled into the plasma, as shown in Fig. 2. The following issues are examined to

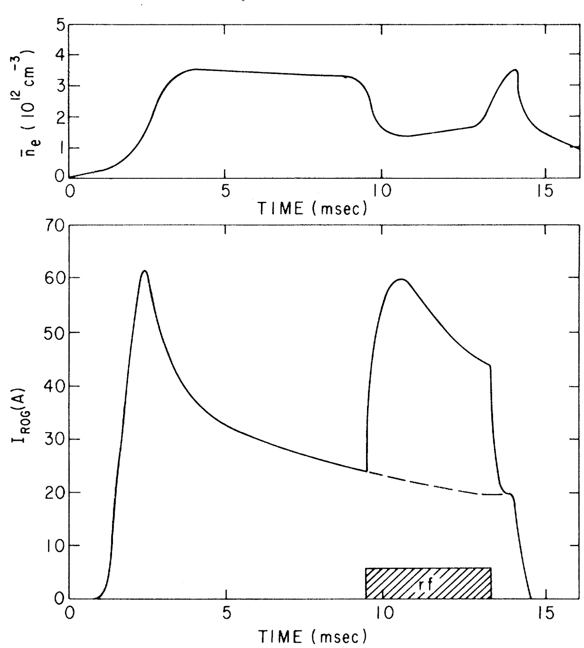

FIG. 2. Circulating current $I_{\rm rog}$, and density $\bar{n}_e$, during the main discharge. The 18-MHz rf power is on for a duration of 5 msec in alternate discharges. The discharge without rf is indicated by the dashed curve. The injected electron beam produces the current that circulates normally, and FWCD augments that current when rf power is applied. The discharges are highly repeatable.

ascertain that the current increase is caused by true FWCD.

The bulk electron density declines during the application of rf power, but that does not by itself promote a change in the total circulating current. As the density drops, the injected beam becomes less collisional; therefore, it circulates more times around the torus before its momentum expires in collisions. Meanwhile, the current leaving the cathode decreases, as required by the sheath condition. (It is the bulk electron density that determines the sheath condition; heating of the beam electrons by rf power is not a factor in the sheath condition.) If we take these two effects into consideration, the total circulating current of the beam is proportional to the injected current divided by the collisional drag, and that ratio remains constant as the density changes.

Only rf-induced velocity-space diffusion, i.e., true rf current drive, can shift the beam's distribution function to have more density at higher velocities and thereby augment the circulating current. Heating of the electrons lowers the plasma resistivity and would raise the Ohmically driven current if there were any, but we operated the plasma without a toroidal electric field to avoid this complication. Without a change in the shape of the electron distribution function, a change in the beam cannot account for the observed increase in circulating current.

Modification of the plasma edge by the rf does not make the current increase. By sustaining a steady current for a long period of time, we checked that the current increase is not produced by a momentary imbalance in particle fluxes when the rf is turned on. As another test, we pushed the outboard-side limiter in from its usual radius of 7.6 cm, which matches the depth of the antenna, to a radius of 4.5 cm; this caused little change in either the current increase or the antenna loading.

The fast-wave cutoff coincides with a threshold of the driven current. The threshold is seen when the plasma density is gradually lowered while all other parameters are held steady; the extra current during rf becomes smaller and vanishes. The wave cutoff is determined from the magnitude of signals from magnetic loop probes located far from the antenna. As the density is lowered, first there are a few broad peaks in the amplitude, suggesting the presence of various eigenmodes, and then the amplitude disappears. The densities at which the driven current and the probe signals begin to vanish are plotted in Fig. 3 as a function of wave frequency. From the fast wave's dispersion relation, it is expected that the relationship of the inverse frequency of the wave cutoff with density is linear. That dependence is seen in the wave data, and the driven-current data coincide with it. From all these tests, we conclude that FWCD has been ob-

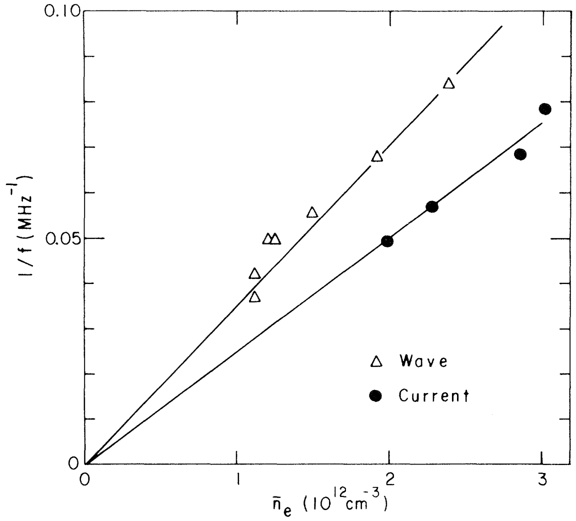

FIG. 3. Fast-wave cutoff and FWCD threshold densities. Their coincidence, and their identical scaling with frequency, show an interrelation of fast-wave propagation and the current increase illustrated in Fig. 2. A point between the two lowest identifiable peaks in a magnetic probe's amplitude is used for the wave cutoff, and the half-maximum level of the current increase is used for the FWCD threshold. The difference in slopes is not physically meaningful. Adjusting slightly the criteria for the cutoff or threshold could give the lines identical slopes. The neutral pressure was held constant for this measurement.

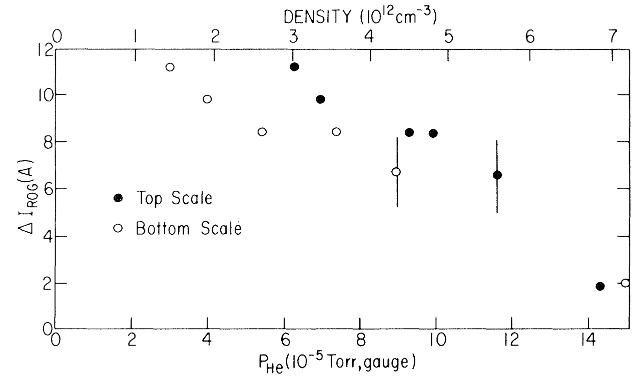

FIG. 4. Current-drive scaling with neutral pressure. The increase in circulating current diminishes as the neutral pressure (and consequently the neutral density) increases, as shown by the open circles. The electron density follows the neutral density, as indicated by the top scale and the solid circles. The parameters were $f = 18$ MHz, $B_0 = 4.6$ kG, and a larger vertical pitch was applied to the field lines than for Fig. 2.

served.

The current increase diminishes with neutral density in the partially ($\simeq 50\%$) ionized ACT-I plasma. Figure 4 demonstrates this with the results of a neutral pressure scan. The electron density $\bar{n}_e$ was allowed to increase with the neutral pressure, while all other parameters were held constant. Provided that the electron density is high enough to allow eigenmodes with the appropriate $k_\parallel$ into the plasma, current drive is expected to be less at higher neutral densities and higher bulk electron densities, since fast electrons are collisional with the bulk electrons and neutrals.

In this experiment and in the LHCD experiment performed in the same discharge,[12] the driven current was found to vary with the vertical field, and was largest for vertical fields that most nearly canceled the vertical guiding-center drifts of fast electrons. This behavior of current drive in a toroidal device without confined orbits was explained earlier by Wong.[3]

An asymmetry is required to attain unidirectional current generation and not merely heating. In a tokamak, the favored way is the use of a phased array of antenna structures that excites waves with a single direction of parallel phase velocity. All reported demonstrations of high-power LHCD in tokamaks have used this method, as will future FWCD experiments. The original stellarator rf current drive[2] occurred because of a structural asymmetry in the device; it had a magnetic beach (to heat ions) in one direction. Waves were launched equally into the opposite direction, where only electrons could damp the wave. In the present experiment, the unidirectional electron beam promotes the damping and velocity-space diffusion required for rf current generation; the directionality in the target distribution function is responsible for the unidirectional current. This is to be contrasted with current drive in a tokamak, where the slope of the electron distribution will be determined solely by the incident wave.

In a comparison of our experiment to LHCD in the same ACT-I device,[12] the efficiencies of FWCD and LHCD are comparable. We believe that a detailed comparison of FWCD and LHCD efficiencies will be of interest in future tokamak experiments. Our experiment demonstrates that FWCD is physically possible, but the efficiency cannot be extrapolated directly to a tokamak.

Performance of FWCD and LHCD in the same tokamak promises to be an exciting future experiment. An outstanding problem of explaining the success of LHCD is the question of how waves of high parallel phase velocity can excite a large current when there are virtually no electrons in the velocity gap between the antenna's spectrum of $\omega/k_\parallel$ and the thermal bulk. Having current-drive data for two different waves, one might separate the effects of wave propagation and electron kinetics. The fast wave also offers a chance to exceed the LHCD density limit. This Letter reports a step in this direction in the development of steady-state current drive for tokamaks.

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