Observation of Beam-Induced Currents in a Toroidal Plasma

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We report the observation of a reverse electron current excited when fast ions are trapped in a toroidal plasma. The induced electron current was measured in the Culham superconducting Levitron as a function of electron temperature and found to be larger than that predicted assuming a shifted Maxwellian electron distribution.

It was first suggested by Ohkawa[1] that the plasma current in a toroidal fusion device could be continuously maintained by the injection of a fast-ion beam which would exert frictional drag on the plasma electrons and ions through Coulomb collisions. In this way, present-day pulsed devices such as the tokamak and reversed-field pinch might be given the technological and economic advantages of steady-state operation. On the other hand, induced plasma currents may reduce the probability of achieving field reversal in a mirror machine by fast-ion injection. Clearly it is important to establish experimentally the existence and magnitude of such currents. In this Letter we report the observation of a reverse electron current induced by fast-ion injection into the plasma of the Culham Levitron. The experimental method was based on the fact that the electron current is sensitive to the electron temperature when the fast-ion and electron thermal velocities are comparable.

When fast ions are injected into a toroidally confined plasma, the current, I_b, injected parallel to the magnetic field is multiplied many times by the overlapping of successive ions transits around the device.[2] The circulating fast-ion current, I_f, satisfies the equation

$$dI_f/dt = I_b/\tau_c - I_f/\tau_L, \qquad (1)$$

where τ_c is the circulation time and τ_L is given by $\tau_L^{-1} = \tau_f^{-1} + \tau_{\text{cx}}^{-1}$ in which τ_f is the time for the ions to slow down by Coulomb collisions with the electrons[1] and τ_{cx} is the charge-exchange time. The slowing-down time, which depends on both the fast-ion velocity, v_f, and the electron thermal velocity, v_e, is given by Spitzer[3]: $\tau_f = v_f v_e^2/(1 + m_f/m_e)A_f G(v_f/v_e)$ with $A_f = 8\pi Z_f^2 e^4 n_e \ln\Lambda/m_f^2$ where Z_f is the fast-ion charge, $\ln\Lambda$ is the Coulomb logarithm, and m_f and m_e are the fast-ion and electron masses, respectively. In the limit $v_f/v_e = 0$, the slowing-down time becomes $\tau_f(0) = 3\pi^{1/2} m_e v_e^3/2A_f m_f$, if m_e is neglected in comparison with m_f. The charge-exchange time is given by $\tau_{\text{cx}} = (n_0 \sigma_{\text{cx}} v_f)^{-1}$ where n_0 is the neutral-gas density and σ_{cx} the charge-exchange cross section.

The momentum gained by the electrons as the fast ions slow down is lost by Coulomb collisions with the plasma ions. These in turn slow down by collisions with the gas molecules or escape from the confinement system. Thus, both the plasma ions and electrons gain a net drift in the direction of the fast ions and we assume that they can be represented by Maxwellian distributions shifted by $\bar{v}_i$ and $\bar{v}_e$, respectively. The total circulating current in the plasma can be obtained from the force balance equation for the electrons,

$$\frac{n_e m_e dv_e}{dt} = \frac{n_f m_f (v_f - \bar{v}_e)}{\tau_f} + \frac{n_i m_i (\bar{v}_i - \bar{v}_e)}{\tau_i}, \qquad (2)$$

where n_f, n_e, and n_i are the densities of the fast ions, electrons, and plasma ions, respectively; and m_i is the mass of the plasma ions. In writing down Eq. (2) we have assumed there is no significant spread in the fast-ion velocity since $\tau_f > 10\tau_{\text{cx}}$ in the present experiment. For the Levitron plasmas, $v_e \gg v_i$ so that the time for momentum transfer between plasma ions and electrons is given by $\tau_i = 3\pi^{1/2} m_e v_e^3/2A_i m_i = \tau_f(0) m_i Z_f^2/m_f Z_i^2$. Expressing Eq. (2) in terms of the fast-ion and plasma currents, and noting that $n_f/n_e \ll 10^{-3}$ for the present experiments, we find the net current to be

$$I_T = I_f[1 - Z_f \tau_f(0)/Z_i \tau_f], \qquad (3)$$

for a slowly varying beam current. Thus the electron current cancels both the plasma ion current and a fraction $Z_f \tau_f(0)/Z_i \tau_f$ of the fast-ion current. In the regime $v_e \gg v_f$, the ratio $\tau_f(0)/\tau_f$ tends to unity and so no net current flows for equal fast-ion and plasma-ion charges, as was found by Ohkawa.[1] However, as the electron temperature is reduced, the electron current decreases until, in the limit $v_e/v_f = 0$, the net current equals the circulating fast-ion current.

The experiments were performed by injecting an atomic hydrogen beam of 0.2-A mean equivalent intensity into a hydrogen target plasma produced by electron–cyclotron-resonance heating. The beam current was 100% modulated at 2.88 kHz using the method of Hammond *et al.*[4] and comprised of 5-keV (38%), 7.5-keV (36%), and 15-keV (26%) atoms. The beam trajectory through the plasma is shown schematically in Fig. 1, which is a top view of the apparatus. The angle of the trajectory to the horizontal is 37.5°. Approximately 3% of the fast atoms were captured by charge exchange with the plasma protons at a density of 10^{12} cm^{-3}.

The current in the superconducting ring was 180 kA and the center-column current, I_z, was set at values between +288 and −252 kA, where current flowing up the center column is defined to be positive. The target plasma was produced using a source of 16-GHz microwaves operated at selected power levels between 35 and 500 W. The microwaves were pulsed on for 3.5 sec and the beam was injected into both the main discharge and afterglow plasma for a total duration of 1.5 sec. The plasma conditions were 2×10^{11} cm^{-3} $\leq \bar{n}_e \leq 1.5\times10^{12}$ cm^{-3} and 1 eV $\leq \bar{T}_e \leq 4.7$ eV. For each set of conditions, the electron density and temperature profiles were measured using a swept double probe.[5] Fast ions lost by charge exchange were detected using a Faraday cup covered with a 3-μg/cm^2 carbon stripping foil. The hydrogen gas pressure was typically 8×10^{-6} Torr.

The total oscillating current flowing in the plasma was detected through the voltage induced in a 40-turn coil which looped the plasma in the poloidal direction. After amplification, the coil signal was recorded digitally for 105 msec at a sampling rate of 9.8 kHz. The signals from the neutral-particle detector and the secondary-emission detector which monitored the beam transmitted by the plasma were recorded in the same way. The signals were then Fourier transformed to obtain the amplitudes and phases of the 2.88-kHz components. The final signal-to-noise amplitude ratio was typically 10:1.

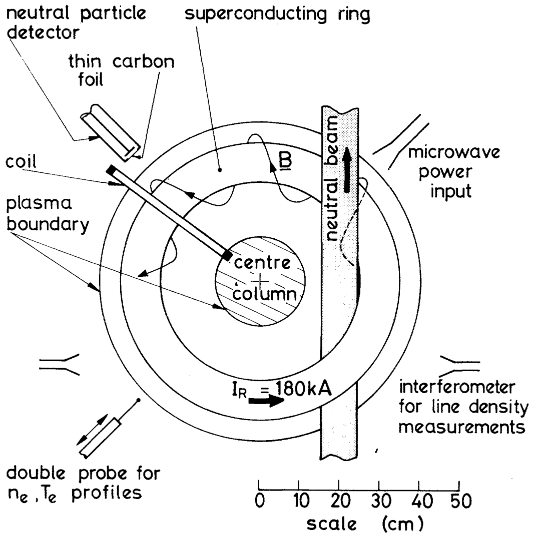

FIG. 1. Schematic of experimental apparatus.

The observed signal consisted of a component, $V_\parallel$, due to the net current flowing parallel to the field lines and a component, $V_\perp$, arising from the diamagnetic current of the fast ions. In order to separate these components, the coil signal was measured as a function of the toroidal field current I_z. This procedure was repeated at different values of $\bar{T}_e$ to determine the temperature dependence of $V_\parallel$.

Theoretical values of $V_\parallel$, as a function of both I_z and $\bar{T}_e$, were obtained from a numerical calculation. For an input neutral beam of equivalent current $I_n = I_0(1+\cos\omega t)$ and of cross-sectional area A, the fast-ion current captured from a volume dV of the beam trajectory is given by $dI_b = I_n A^{-1} n_e \sigma_{cx} dV$. The corresponding current in the plasma is found from Eqs. (1) and (3) and leads to the expression

$$V_\parallel = \int I_0 A^{-1} n_e \sigma_{cx} (\bar{v}_\theta / v_f)(\tau_L/\tau_c)[1-\tau_f(0)/\tau_f]\Phi\,\omega(1+\omega^2\tau_L^2)^{-1/2}\sin(\omega t - \tan^{-1}\omega\tau_L)\,dV \tag{4}$$

for the voltage per turn induced in the coil by the total parallel current. The average fast-ion velocity around the minor azimuth is denoted by $\bar{v}_\theta$ and the ratio $\bar{v}_\theta/v_f$ is a geometrical factor which, in the general case, accounts for the finite angle of injection to the field lines and the fact that the coil senses only the poloidal current. The quantity Φ is the flux through the coil due to unit poloidal current of ions captured in dV and takes into account the fact that at 2.88 kHz the flux is totally excluded from the superconducting ring. Values of τ_c and $\bar{v}_\theta$ were obtained from an orbit-following code. The loss time τ_L was taken to be 37 μsec from the experimental phase shift: This agreed well with both the value of 36 μsec obtained from the phase of the neutral-particle-detector signal and the charge-exchange time of 32 μsec calculated from the gas pressure of 8×10^{-6} Torr. This agreement confirmed the theoretical expectation that plasma-skin-time effects were unimportant and inductive corrections are not required. The momentum loss times were those given by Spitzer and take no account of the dependence of $\ln\Lambda$ on the test-particle velocity. However, the corrections given by Itikawa and Aono[6] for the energy-loss time indicate that this velocity dependence would not affect the value of $1-\tau_f(0)/\tau_f$ by more than 5%. Values of n_e and T_e were taken from the measured profiles.

The signal calculated from this expression is a maximum when the toroidal field is orientated along the beam trajectory ($I_z=+300$ kA). As I_z is reduced, $V_{\parallel}$ falls monotonically and passes through zero for mainly perpendicular injection ($I_z=-280$ kA). The predicted signal is closely approximated by $V_{\parallel}(\overline{T}_e)=[1-\tau_f(0)/\tau_f]V_{\parallel}(0)$, where $\tau_f(0)/\tau_f$ is evaluated with use of the average electron temperature and an average beam energy of 8.5 keV.

The diamagnetic signal, $V_{\perp}$, was calculated using the code of Laing and Tan[7] to give the fast-ion density distribution. This signal vanishes at $I_z=0$ (since the diamagnetic current is then in the toroidal direction) and is an approximately antisymmetric function of I_z over the range of interest.

The coil signal amplitude per turn at 2.88 kHz obtained from the Fourier analysis and divided by both the beam amplitude, I_0, and the line density, $\overline{n}_e$, is plotted as a function of I_z in Fig. 2. Data are shown for three values of the mean electron temperature. At $\overline{T}_e=1.1$ eV the signal is large and decreases as I_z is reduced, as expected for parallel current. As $\overline{T}_e$ is raised to 4.7 eV the parallel current is so diminished that the diamagnetic current dominates and causes the signal to change sign on reversal of I_z.

The variation of $V_{\parallel}$ with $\overline{T}_e$ is determined by the intercept with the $I_z=0$ axis, since $V_{\perp}=0$ at this point. Each intercept was obtained from a least-squares fit to the data using the expression $V_{\text{coil}}=V_{\parallel}+V_{\perp}$. The amplitudes of $V_{\parallel}$ and $V_{\perp}$ were the variables and the results are shown by the solid curves in Fig. 2. For illustration, the parallel and diamagnetic components of the fit to the data at 1.1 eV are shown by the dashed curves.

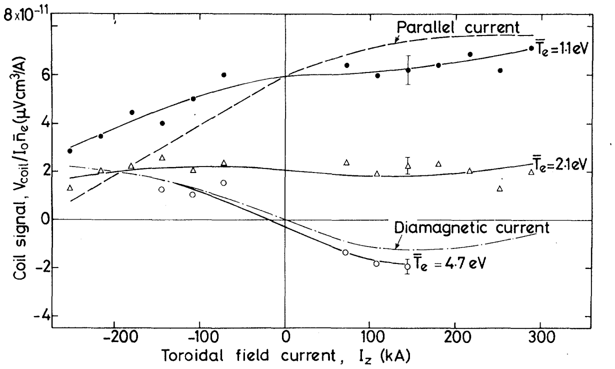

FIG. 2. Coil signal vs toroidal-field current.

The values of $V_{\parallel}$ at zero toroidal field obtained by this analysis are plotted as a function of $\overline{T}_e$ in Fig. 3. The solid line is the theoretical curve obtained from Eq. (4) with no fitting parameters. As stated above, this curve is closely approximated by the expression $V_{\parallel}(\overline{T}_e)=[1-\tau_f(0)/\tau_f]v_{\parallel}(0)$, which is shown by the dashed line in Fig. 3 for comparison. The similarity between these curves reflects the insensitivity of the predictions to plasma profile changes.

At low temperature we observe a current close to the full parallel fast-ion current. As the temperature is raised, the net parallel current is reduced by the increase in the backward electron current, in qualitative agreement with theory. Complete cancellation of the forward current occurs at $\overline{T}_e=4.7$ eV, which gives a more rapid increase in the electron current than predicted theoretically. Thus the effective ratio of the rates of momentum transfer from the fast ions to the electrons and from the electrons to the cold ions [i.e., $\tau_f(0)/\tau_f$] appears to be higher than that predicted by classical theory for this temperature range. Indeed, a good fit to the data is obtained if this ratio is increased twofold (dot-dashed curve in Fig. 3). This is in the wrong direction

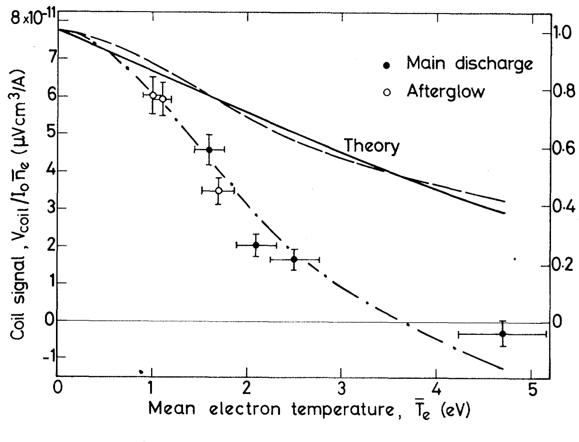

FIG. 3. Coil signal at $I_z=0$ vs mean electron temperature. Values of $1-\tau_f(0)/\tau_f$ representing the ratio to full parallel fast-ion current are shown on the right. The dot-dashed curve is $1-2\tau_f(0)/\tau_f$.

to be explained by trapped electrons or an increase in the Z_{eff}. Enhanced slowing-down of ions has been observed to result from beam-plasma instabilities[8] but the threshold fast-ion density ($n_f/n_e \gtrsim 10^{-3}$) appears to be somewhat higher than in the present experiment ($n_f/n_e \approx 5 \times 10^{-4}$). A more likely explanation might be the distortion of the electron distribution from that of a shifted Maxwellian. There is evidence from the work of Fomenko[9] that such a distortion increases the backward electron current for $T_e \gg 5$ eV and so a full Fokker-Planck treatment for the present regime might bring theory into better agreement with experiment. For small distortions, such a theory would still reproduce the energy loss rates obtained with a Maxwellian distribution and would not conflict with the classical energy loss rates observed by Klavan *et al.*[10]

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Stabilization of the Linear Drift Tearing Mode by Coupling with the Ion Sound Wave

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The resistive drift tearing mode is shown to be stabilized by the ion motion along magnetic field lines. The effects of an electron temperature gradient are included in the discussion of the results.

The tearing mode[1] is important in the theory of plasma confinement in tokamaks because of the increased radial transport in the resulting "island structure" and the probable involvement of this mode in the internal[2,3] and external[4,5] disruptions. In this Letter we consider again the stability of the "drift collisional" tearing mode $l \geq 2$. Experimentally,[6] during a "typical good plasma discharge," the mode $l = 2$ is observed to be oscillating and stable or saturated to a very small amplitude (which corresponds to a magnetic island of some millimeters). At the end of the discharge the mode may become strongly unstable just before the external disruption. Different