Observation of a Plasma Current Driven by rf Waves at the Electron Cyclotron Resonance in the Culham Levitron

D. F. H. Start, N. R. Ainsworth, J. G. Cordey, T. Edlington, W. H. W. Fletcher, M. F. Payne, and T. N. Todd
Euratom–United Kingdom Atomic Energy Authority Fusion Association, Culham Laboratory, Abingdon, Oxon OX14 3DB, United Kingdom
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The observation of a plasma current generated by the absorption of rf waves at the electron cyclotron resonance is reported. The current flows in opposite directions on opposite sides of the electron-cyclotron-resonance position, confirming that the current is driven by asymmetric heating of the electron distribution function. The current (~ 30 mA/W) varies linearly with microwave power and electron temperature and inversely with electron density.

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During the last few years there has been a growing interest in the possibility of driving the plasma current in a tokamak reactor by continuously using rf waves. Recently Fisch and Boozer[1] have proposed a scheme which relies on creating an asymmetric plasma resistivity. In this scheme an electron cyclotron wave is used to increase the perpendicular energy of resonant electrons moving in a particular direction along the field lines. Since these electrons are less collisional than those moving in the opposite direction, a net transfer of parallel momentum between ions and electrons occurs and a plasma current flows. The present paper reports the first observation of such a current which was driven by electron-cyclotron-resonant heating (ECRH) in the Culham Levitron.[2]

The magnitude of the current can be estimated using the linear Fokker-Planck theory given by Cordey, Edlington, and Start[3] which includes a full treatment of electron-electron collisions. The ECRH-driven current, I, flowing parallel to the magnetic field divided by the power, P_{ab}, absorbed by the electrons is given by

$$\frac{I\ (\mathrm{A})}{P_{ab}\ (\mathrm{W})} = -\frac{0.122 T_e\ (\mathrm{keV})}{a(m) n_{20} \ln\lambda} \frac{u}{|u|} G(u), \qquad (1)$$

where $u = [\omega - \Omega(r)]/k_{\parallel} v_e$, T_e is the electron temperature, a is the minor radius for the Levitron geometry, n_{20} is the density in units of $10^{20}\ \mathrm{m}^{-3}$, $\ln\lambda$ is the Coulomb logarithm, Ω is the electron gyrofrequency, ω and $k_{\parallel}$ are the wave frequency and parallel wave vector, respectively, and v_e is the electron thermal velocity. Reference 3 gives values of $G(u)$, which has the form $G(u) \cong 1.8u$ for $u < 0.5$ and $G(u) \cong 0.5u^2$ for $u > 4$. The power, P_{ab}, absorbed by the electrons is now obtained in terms of the injected microwave power, P, by a quantitative analysis of the wave absorption process proposed by Riviere, Alcock, and Todd.[4]

In the present experiment the incident radiation is predominantly in the extraordinary mode and is injected from the low-field side of the machine (see Fig. 1). Approximately half of the injected radiation encounters the low-density cutoff where tunneling takes place through the evanescent region to the upper hybrid resonance (UHR). At the UHR the wave is partially converted to a Bernstein wave which then propagates inwards and is completely absorbed close to the electron cyclotron resonance (ECR). Between the cutoff and UHR the wave is described by Budden's equation.[5] For simplicity, only perpendicular propagation of the X mode near the UHR is considered and

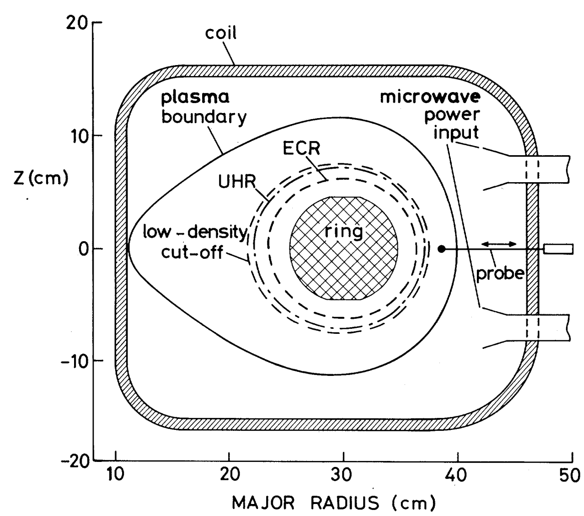

FIG. 1. Cross section of the Levitron showing the rf injection geometry, the detection coil, and the upper hybrid and electron cyclotron resonances.

Budden's equation becomes[6]

$$\frac{d^2\varphi}{dx^2}+\frac{\Omega^2 L}{c^2}\left(\frac{1}{x}+\frac{1}{X}\right)\varphi=0, \tag{2}$$

where $L^{-1}=\omega_p^{-2}d(\omega_p^2+\Omega^2)/dr$, X is the distance between the cutoff and UHR, and ω_p is the electron plasma frequency. From Budden's analysis[5] the power converted to the Bernstein wave is $\xi(1-\xi)P/2$ and the power transmitted is $\xi P/2$, where $\xi=\exp[-\pi(\Omega^2 XL/c^2)^{1/2}]$. With the assumption that the transmitted power reaches the UHR from the high-field side, a fraction $1-\xi$ also becomes a Bernstein wave. Thus the total power converted to the Bernstein wave and then absorbed by the electrons, P_{ab}, is given by $P_{ab}=\xi(1-\xi)P$.

Typical parameters used in the present work are $T_e=7.5$ eV, $n_e=3\times10^{17}$ m^{-3}, $a=6.2$ cm, $X=3.5$ mm, and $L=5$ mm. The effective value of u is expected to be close to unity since the absorbed power for current drive scales[3] as $\exp(-u^2)$. These values together with $G(1)=1.5$ give a current-drive efficiency of $I/P=50$ mA/W for single-pass absorption. Multiple reflection of the rf is assumed to produce a symmetric $k_\parallel$ spectrum giving no additional net current.

From Eq. (1) it can be seen that the current changes sign as $\omega-\Omega$ changes sign. Hence the current is expected to flow in opposite directions on opposite sides of the ECR. The radial separation of these two current channels is estimated to be ~1 mm using $u=1$ and $k_\parallel=2.5$ cm^{-1} for the Bernstein wave, the latter value being obtained from a ray-tracing code.

In the present experiments, the Levitron ring current was 120 kA and the poloidal field exceeded the toroidal field by about an order of magnitude at the ECR. The helium plasma was formed by ECRH using 10-GHz microwave radiation which could be injected either above or below the ring (see Fig. 1), to align the wave vector parallel or antiparallel to the poloidal field. The incident radiation was polarized with the electric field vertical.

Microwave power levels of up to 120 W gave temperatures and densities in the range 3 eV $<T_e<$ 18 eV and 1×10^{17} m$^{-3}<n_e<3\times10^{17}$ m^{-3}. Profiles of T_e and n_e were measured using a swept double Langmuir probe. The rf power was 100% square-wave modulated at 2.88 kHz and the total oscillating plasma current was detected through the voltage induced in a 40-turn coil which looped the plasma in the poloidal direction. The 2.88-kHz component of the signal was obtained by Fourier analysis. The coil signal consisted of a component due to the wave-driven current flowing parallel to the field lines and a component arising from the modulation of the perpendicular diamagnetic current due to modulation of n_e and T_e. The diamagnetic component (typically 15% of the parallel component) was eliminated by averaging the results obtained with "normal" and "reversed" toroidal fields. Signals from the coil (inset in Fig. 2) show that the current rises in about 15 μs after the microwave power is switched on. This fast rise time eliminates the possibility that the current is carried by runaway electrons and is consistent with the calculated skin time of the plasma. The inset coil signals also show the reversal of the current when the poloidal direction of the incident radiation is reversed as predicted by Eq. (1). Rotation of the plane of polarization of the rf through 90° affected the current by less than 30% as expected since, in either orientation, most of the power was in the extraordinary mode.

The radial position of the current was located by recording the coil signal as a floating probe was inserted into the plasma to inhibit the current. (The probe adjusts its floating potential to draw an essentially randomly directed current from the plasma to cancel the intercepted wave-driven current). The probe measured 3 mm in minor radius, 3 mm poloidally, and 5 cm toroidally and was mounted on a thin, radially aligned ceramic support. The radial position of the probe was checked against that of the T_e probe using the beam from an electron gun. Figure 2 shows the variation of the 2.88-kHz component of the coil signal as the floating probe moves through the

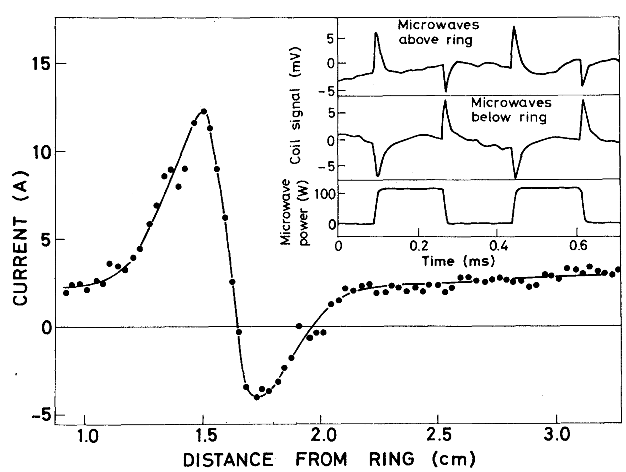

FIG. 2. Current vs probe position. Inset: coil signals for rf input above and below the ring.

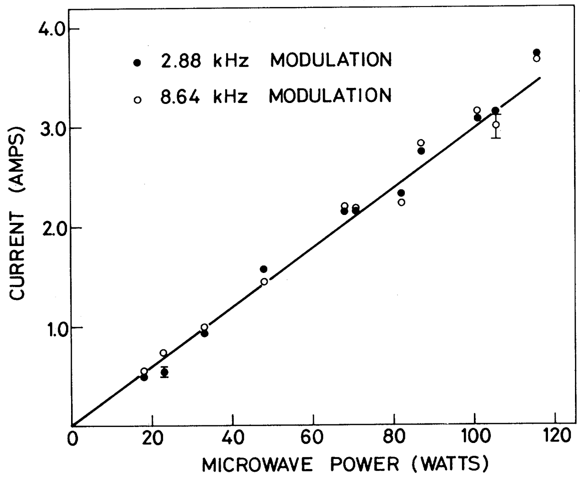

FIG. 3. Current vs microwave power.

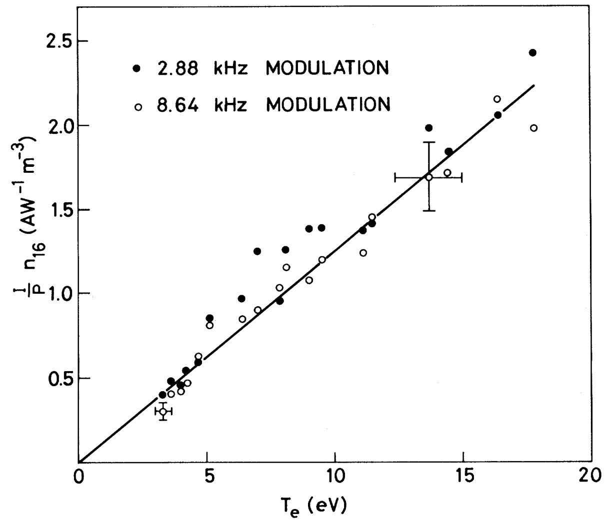

FIG. 4. Current per unit power times density (in units of 10^{16} m^{-3}) vs electron temperature.

plasma. The ECR is 1.55 ± 0.05 cm from the ring. As the probe moves inwards the current sensed by the coil is unaffected until the ECR region is approached. At 2 cm the net current begins to fall and then reverses sign until the resonance is reached. The net current then swings positive again as the probe moves closer to the ring. Although the probe produces a large perturbation of n_e and T_e as it passes through the resonance region the results shown in Fig. 2 clearly demonstrate that the current flows close to the ECR and in opposite directions on either side of it.

It is also clear from Fig. 2 that the current outside the ECR makes the larger contribution to the coil signal except when inhibited by the probe. This is expected since (a) the Bernstein wave is mainly absorbed in this region and (b) the coil is most sensitive to currents flowing at large radii. The direction of this outer current can be deduced from the polarity of the coil signal. When the microwaves were injected above the ring the net poloidal current flowed in a clockwise direction with reference to the cross section shown in Fig. 1 and this agrees with Eq. (1) for $\omega > \Omega$.

The current was found to vary linearly with the injected rf power as shown in Fig. 3 where data obtained from the first and third harmonic of the modulation frequency are plotted. In obtaining the current from the coil signals, inductive corrections for plasma skin-time effects of typically 4% and 30% were made for the 2.88- and 8.64-kHz data, respectively. In these experiments a target plasma was formed using 63 W of unmodulated 10-GHz microwave power in order to keep T_e (7.5 eV) and n_e (2.9×10^{17} m^{-3}) constant as the modulated power was increased. The solid line in Fig. 3 is a least-squares fit of a straight line to the data giving a net current-drive efficiency of 30 mA per watt of modulated power. This is somewhat less than the model estimate of 50 mA/W but the latter does neglect the canceling effect of the current channel on the inside of the ECR.

The dependence of the current on plasma density and temperature is shown in Fig. 4 where the product of n_e and the current, I, is plotted against T_e. The values of T_e and n_e are those at the ECR surface. The observed linear dependence of I/P on the ratio T_e/n_e is universally predicted by wave-driven current theory provided the value of u is constant [see Eq. (1)].

In summary, a net plasma current of 30 mA/W has been driven by rf waves close to the ECR. The current flows in opposite directions on opposite sides of the ECR, consistent with it being driven by asymmetric heating of the electrons. The magnitude of the current agrees well with a model in which a fraction of the incident electromagnetic wave is converted at the upper hybrid layer to a Bernstein wave which is then absorbed at the ECR. The current varies linearly both with microwave power and T_e/n_e in agreement with theory for a constant, normalized wave phase velocity.

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Classical Diffusion on a Random Chain

B. Derrida and Y. Pomeau
Service de Physique Théorique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette, France
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A simple model of classical diffusion on a random chain is studied. The velocities to the right and to the left are calculated. When one changes continuously the probability distribution ρ of the hopping rates, a whole region is found where these two velocities vanish. In this region, the distance R covered by a particle during the time t behaves like $R \sim t^x$, where x depends continuously on ρ. The exponent x is calculated for a simple example.

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Recently, the problem of classical diffusion in a random medium has attracted a lot of interest.[1-4] In these works, the problem was studied on a lattice with random nearest-neighbor transfer rates which are symmetric: The probability of hopping from site i to site j was equal to the probability of hopping from site j to site i. Several interesting results were derived depending on the distribution of these random transfer rates.[2] A list of physical situations (the hopping conduction, magnetic models, etc.) leading to this problem can be found in Ref. 2.

Even more interesting seems to be the nonsymmetric case. In a discrete-time version, one can formulate the problem as follows. One considers a particle on a one-dimensional lattice. If the particle is on site i at time t, it will be at time $t+1$ either on site $i+1$ with probability p_i or on site $i-1$ with probability $q_i = 1 - p_i$. The problem is obvious if all the p_i are equal. However, if the p_i are randomly chosen with some probability distribution $\rho(p_i)$, one can observe very unexpected behaviors. One of the most striking results was obtained by Sinai[5] who has studied a case where the distribution $\rho(p_i)$ satisfies

$$\langle \ln[p_i/(1-p_i)] \rangle = \int \rho(p_i) dp_i \ln[p_i/(1-p_i)] = 0. \tag{1}$$

He finds that if a particle is on site 0 at time 0, then with probability 1 it will be at a distance $R \sim \ln^2 t$ at time t. This behavior differs completely from the usual diffusion (all the $p_i = \frac{1}{2}$) where $R \sim t^{1/2}$.

The purpose of this Letter is to show that other unexpected behaviors occur even when the constraint (1) is not present. We first show that there exists a finite velocity to the right (to the left) only if $\langle (1-p_i)/p_i \rangle < 1$ $[\langle p_i/(1-p_i) \rangle < 1]$. If these two inequalities are both unsatisfied, the distance R covered by the particle during the time t behaves like $R \sim t^x$, where x is an exponent depending continuously on the distribution ρ. For a simple distribution ρ, we give the expression of x as a function of the parameters which define ρ.

For this problem of diffusion, the first equation that one can write is an equation for $P_n(t)$ which is the probability for the particle to be on site n at time t. It is clear that $P_n(t)$ verifies

$$P_n(t+1) = q_{n+1} P_{n+1}(t) + p_{n-1} P_{n-1}(t). \tag{2}$$

To calculate the velocity V, it is easier to consider a lattice of N sites with periodic boundary conditions (site $N+n$ is identified with site n). After a very long time, the probability distribution $P_n(t)$ converges to an equilibrium probability distribution Q_n which satisfies

$$Q_n = q_{n+1} Q_{n+1} + p_{n-1} Q_{n-1}. \tag{3}$$