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OBSERVATION OF A PLASMA CURRENT DRIVEN BY RF WAVES AT THE ELECTRON CYCLOTRON RESONANCE IN THE CULHAM LEVITRON

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ABSTRACT

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) is directly proportional to both the microwave power and electron temperature and inversely proportional to the 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 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 Fokker-Planck theoretical treatment by Cordey et al[3]. The total current, $I_{\parallel}$, flowing parallel to the magnetic field divided by the power, P_{ab}, absorbed from the wave is given by

$$\frac{I_{\parallel}\text{ (amps)}}{P_{ab}\text{ (watts)}} = -\frac{0.122\ T_e(\text{keV})}{R(m)\,n_{20}\,\ell n\lambda} \cdot u(1.5 + 0.06|u|) \quad (1)$$

where $u = (\omega-\Omega(r))/k_{\parallel}v_e$, T_e is the electron temperature, R is the minor radius, n_{20} is the density in units of $10^{20}m^{-3}$, $\ell n\lambda$ 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. The power absorbed is calculated below using a detailed analysis of the wave absorption process proposed by Riviere et al[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 the injected radiation encounters the low density cut-off 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. The behaviour of the wave between the cut-off and UHR is described by Budden's equation[5]. From this equation the power P_{ab} in the Bernstein wave can be obtained in terms of the injected power P, namely[6] $P_{ab}/P = \xi(1-\xi)$ where $\xi=\exp\left(-\pi\sqrt{\Omega^2 XL/c^2}\right)$, $L^{-1} = \omega_p^{-2}\frac{d}{dr}(\omega_p^2 + \Omega^2)$, X is the distance between the cut-off and UHR and ω_p is the electron plasma frequency. The Bernstein wave propagates inwards and is completely absorbed in the region of the electron cyclotron resonance (ECR).

Typical parameters used in the present work are T_e = 7.5 eV, $n_e = 3 \times 10^{17} m^{-3}$, R = 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 give a current drive efficiency of I /P=50 mA/W.

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, a feature which is characteristic of current drive schemes based on asymmetric heating of the electron distribution function. The radial separation of these two current channels is estimated to be ∿ 1 mm using u= 1 and $k_{||}$ = 2.5 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 current through the centre column which provided the toroidal field was 65 kA. At the ECR the poloidal field exceeded the toroidal field by about an order of magnitude. 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 anti-parallel to the poloidal field. The incident radiation was polarised with the electric field vertical.

Microwave power levels of up to 120 watts were used to form helium plasmas with temperatures and densities in the range 3 eV < T_e < 18 eV and 1×10^{17} $m^{-3} < n_e < 3 \times 10^{17} m^{-3}$. For each set of conditions the profiles of T_e and n_e were measured using a swept double Langmuir probe. The microwave power was 100% square-wave modulated at 2.88 kHz and the tctal 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. The 2.88 kHz component of the signal was then extracted by Fourier analysis. The observed 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, displayed in the inset to Fig.1, 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 upper and lower coil signals show the reversal of the current when the poloidal direction of the incident radiation is reversed as predicted by eq(1). Rotating the plane of polarisation of the microwaves 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 using a floating probe which intercepted 3 mm of plasma in minor radius and 5 cm in the toroidal direction and which served 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 radial position of this probe was checked against that of the T_e probe using the beam from an electron gun. Figure 2 shows the 2.88 kHz component of the coil signal as a function of the probe distance from the ring. The ECR is 1.55 ± 0.05 cm from the ring.

As the probe moves inwards the current 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. At this point the net current 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. The separation of the current channels is about 2.5 mm which is somewhat larger than the estimated 1 mm.

It is also clear from Fig.2 that the current on the low field side of the ECR makes the larger contribution to the coil signal when the probe is out of the plasma. This is expected since (a) most of the power from the Bernstein wave is 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 and provides an additional test of the theory. 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.2 and this is in agreement with eq(1) for $\omega > \Omega$.

The current was found to vary linearly with the injected microwave 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 kHz and 8.64 kHz data respectively. In these experiments a target plasma was formed using 63 watts of unmodulated 10 GHz microwave power in order to keep T_e(7.5 eV) and n_e ($2.9 \times 10^{17} m^{-3}$) constant as the modulated power was increased. The solid line in Fig.3 is a least square fit of a straight line to the data giving a current drive efficiency of 30 mA per watt of modulated power which is in reasonable agreement with the value of 50 mA/W estimated above.

The functional dependence of the current on plasma density and temperature is shown in Fig.4 where the product of n_e and the current is plotted against T_e. The values of T_e and n_e are those at the ECR surface. The observed linear dependence of the current per unit power on the ratio T_e/n_e is universally predicted by wave-driven current theory provided the effective value of u is constant (see eq(1)).

In summary, plasma currents of a few tens of milliamps per watt have been driven by the absorption of 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. The latter result agrees with the general prediction of wave-driven current theory for a constant, normalised wave phase velocity.

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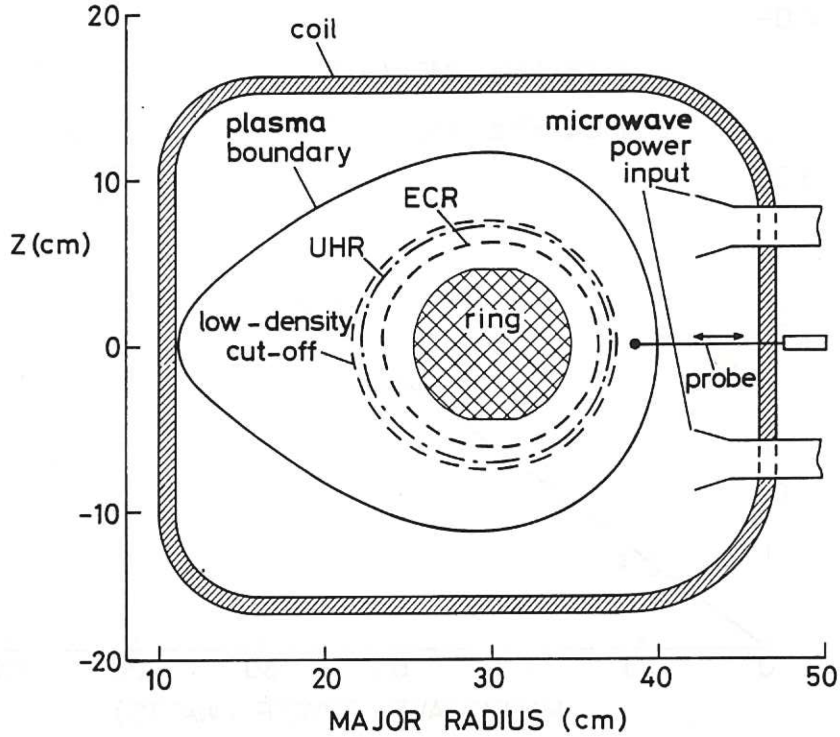

Fig.1 Cross-section of the Levitron device showing the microwave injection geometry, the detection coil and the positions of the upper hybrid (UHR) and electron cyclotron (ECR) resonances.

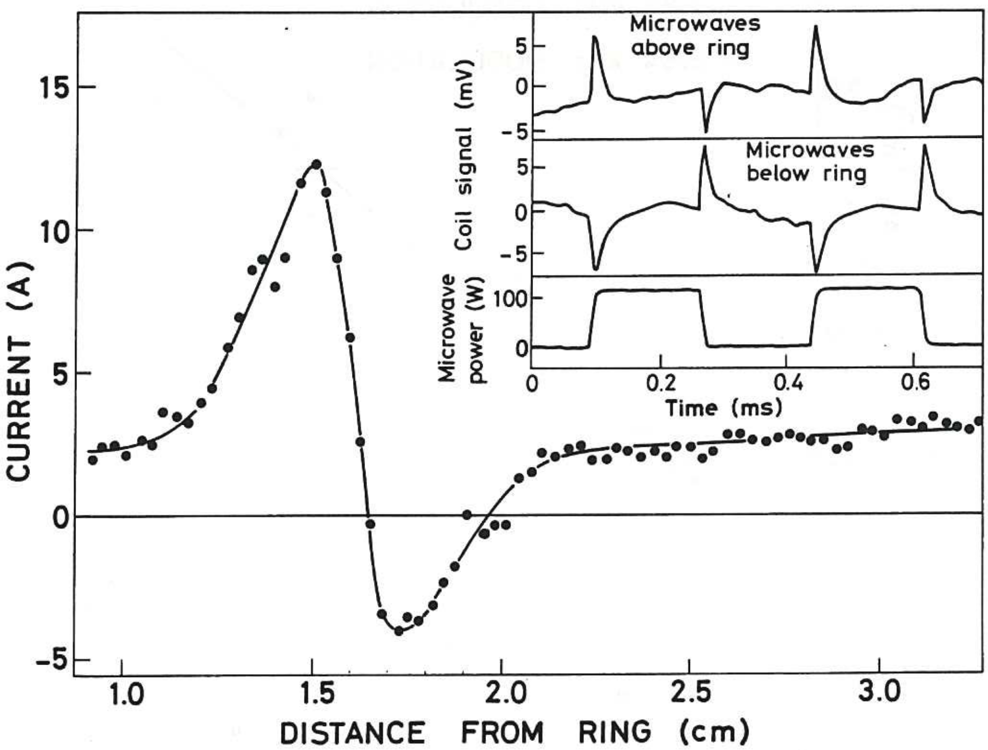

Fig.2 Current versus probe position. The inset shows the coil signal for microwave input above and below the ring.

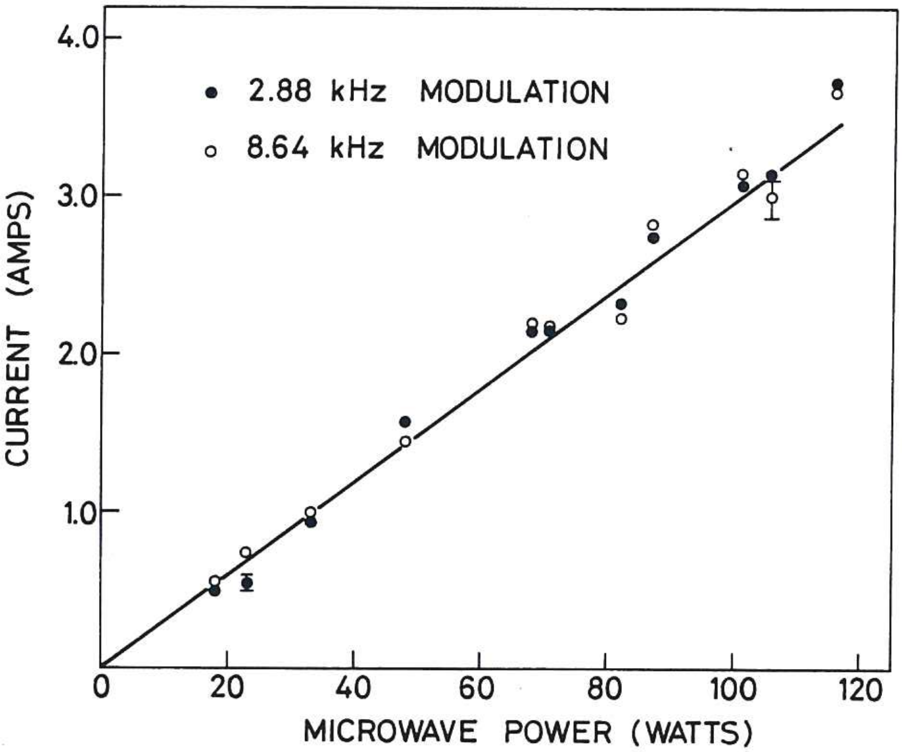

Fig.3 Current versus microwave power.

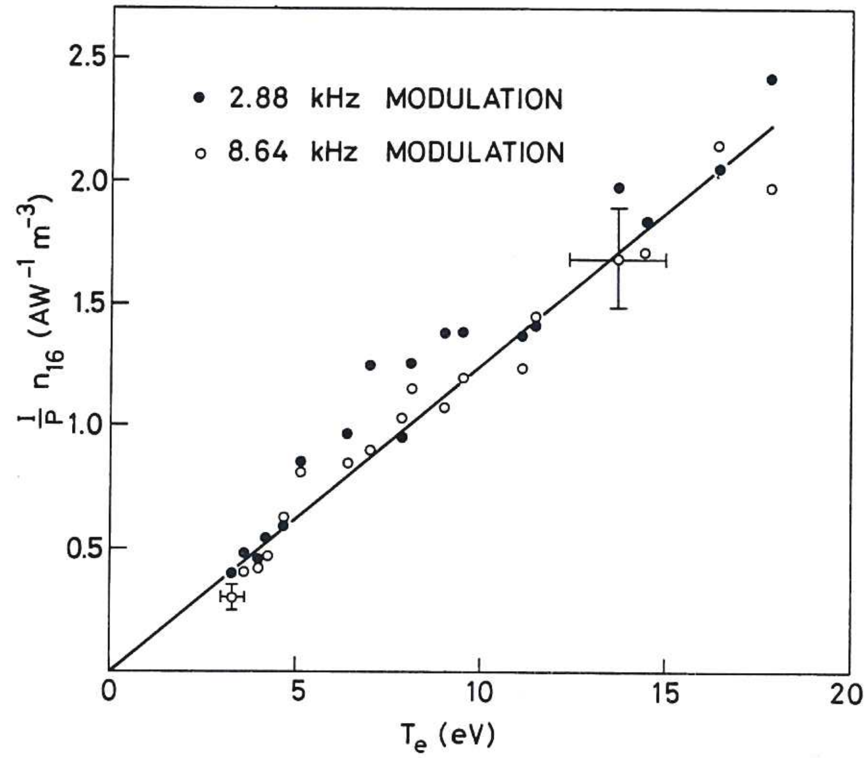

Fig.4 Current per unit power times density (in units of 10^{16} m^{-3}) versus electron temperature.