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GENERATION BY UNIDIRECTIONAL
ELECTRON PLASMA WAVES

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Experimental Observation of Current
Generation by Unidirectional Electron Plasma Waves

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ABSTRACT

A slow wave structure was used to launch electron plasma waves traveling preferentially in one direction. The current generated by the waves was observed. The magnitude of the current can be estimated from momentum conservation in the wave-particle interaction process.

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Plasma currents driven by traveling waves were first observed by Thonemann et al.¹ in 1952, and the experiment was later repeated in Soviet Union^{2,3} and Japan.⁴ In principle, any wave with a net momentum can generate a current via any damping mechanism caused by the charged particles in the plasma. Ion cyclotron waves have been used to produce a current in the Princeton Model-C Stellarator,⁵ and current generation by whistler waves⁶ has been reported recently. The application of rf driven current to steady-state tokamak reactors has been considered by a number of authors.⁷⁻¹⁰ If the current is carried by the main body electrons, the rf power becomes too large to be practical.^{7,10} Recently, it was proposed to generate a current carried by the electrons in the tail of the distribution function¹⁰ via Landau damping of lower hybrid waves.^{11,12} This idea relies upon the momentum transferred from the waves to the tail electrons and therefore requires unidirectional waves which can be generated by 90° phased metal plates or waveguide arrays.¹³ In this paper, we report the first experimental observation of current generation by the unidirectional electron plasma waves via wave particle interaction. Electron plasma waves are called lower hybrid waves when the wave frequency is near the lower hybrid frequency. These waves are attractive to magnetic fusion research due to the desirable features of the launching structure (phased waveguide arrays) and the readily available technology to produce the necessary rf power corresponding to the tokamak reactor parameters.

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Consider the electron plasma wave which obeys the following dispersion relation:

$$\omega = \frac{k_z}{k} \frac{\omega_{pe}}{(1 + \omega_{pe}^2/\omega_{ce}^2)^{1/2}}, \quad (1)$$

where k_z is the wave-number along the magnetic field, k is the total wave-number, ω , ω_{pe} , and ω_{ce} are the wave frequency, the electron plasma frequency, and the electron cyclotron frequency respectively. Let E_0 be the electric field amplitude of the wave and let ϵ be the plasma dielectric function. The parallel component of the wave momentum density is:

$$P_z = \frac{E_0^2}{16\pi} \frac{\partial}{\partial \omega} (\omega \epsilon) \cdot k_z = \frac{1}{8\pi} E_0^2 \frac{k_z}{\omega} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\right). \quad (2)$$

If the wave momentum is absorbed by the electrons, it will generate a current density

$$J_z = -\frac{e}{m} \frac{E_0^2}{8\pi} \frac{k_z}{\omega} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\right), \quad (3)$$

where e/m is the electron charge to mass ratio. In a toroidal plasma, the resonant electrons moving parallel to the magnetic field are confined. The wave-generated current will increase as long as there is a nonzero slope in the electron velocity distribution function for Landau damping until electron-ion collision transfers the electron momentum into the ions. In linear machines, the resonant electrons leave the plasma through the end of the machine before electron-ion collisions occur. Consider a pulsed wave packet of power P_w and pulse length τ .

If the wave is completely damped by electrons, the total charge that leaves the plasma due to end loss is:

$$Q = I\tau = \frac{e}{m} P_w \tau \left(\frac{k_z}{\omega} \right)^2 \quad (4)$$

where I is the current generated by the waves. The loss of electrons will create an ambipolar potential in the plasma which tends to transfer the electron momentum into the ions. In order to obtain clean experimental results, Q must be kept small so that the potential is not strong enough to stop the resonant electrons from leaving the plasma. In addition, ionization and plasma heating by the waves should be avoided.

The experiment was performed in the Princeton L-3 device with the following parameters: magnetic field $B \sim 1.3$ kG, plasma density $n \sim 10^{10} \text{ cm}^{-3}$, electron temperature $T_e \sim 2-3$ eV, ion temperature $T_i < 0.1$ eV. The neutral pressure was about 2×10^{-4} Torr, and the argon plasma was produced by a multi-filament source.¹⁴ The slow waves were launched by a 20 cm long slow wave structure¹¹ consisting of eight rings driven by an rf oscillator. The rf power divider imposes a 90° phase difference between adjacent rings so that the waves propagate preferentially in one direction. Figure 1 shows a schematic of the experimental set up. To identify the waves excited by the antenna, a boxcar integrator was used to measure the wave electric field at a sequence of times by a sampling technique.¹¹ The data shown in Fig. 2(a) clearly indicate that the waves obey the dispersion relation given in Eq. (1). It is apparent that the phase velocity of the waves is propagating radially outward while the wave energy propagates inward. This

is because it is a backward wave in the radial direction which is a characteristic of electron plasma waves. Figure 2(b) shows the amplitude profile of the waves on the two sides of the antenna. It is apparent that about 30% of the power ($P_w \propto E_0^2$) propagates in one direction which agrees with the calculated spectrum shown in Fig. 2(c). The net power P_{rf} transmitted by the antenna can be precisely measured by a calibrated dual directional coupler, but the fraction that goes into the electron plasma waves cannot be accurately determined. Based on probe measurements, we estimate that $P_w \sim (0.3 - 0.9) P_{rf}$. A ferrite core current monitor¹⁵ (20 nsec rise time, 1.0 Volt/amp sensitivity, 0.06%/μsec droop) was used to measure the wave-generated current collected by the floating end plate which was connected to ground through a 40 MFD capacitor. The capacitance is large enough so that the charge collected by the end plate does not change the plate potential. An air core Rogowski loop was used to double check the current monitor measurement. Figure 3(a) shows the current generated by a short (200 nsec) rf pulse. The arrival time of the current peak approximately corresponds to the time of flight of the resonant electrons ($v_z \sim 5.5 \times 10^8$ cm/sec). This has been verified for various antenna locations and various wave frequencies and it is consistent with the results from previous investigation¹¹ of Landau damping of electron plasma waves in this device (L-3). The total charge Q collected by the end plate can be obtained by integrating the current signal. The wave-generated current ($I = Q/\tau$) was found to be proportional to the power level of the rf pulse as shown in Fig. 3(b). If one assumes $P_w = 0.5 P_{rf}$, then the current predicted by Eq. (4) agrees very well with the

experimental data. As expected, the current is independent of the plasma density as long as the waves are totally damped before they reach the end plate.

When the direction of the wave is reversed, namely, propagate the wave towards the plasma source, one may expect the current to change direction also. Instead, the electrons keep flowing towards the end plate as shown in Fig. 4. This is because there are no resonant electrons (40 - 120 eV) traveling towards the plasma source. It should be noted that the bulk plasma electron temperature is only 2 - 3 eV, therefore the resonant electrons must come from the hot filament plasma source (filament biased at -90 V) and travel towards the end plate. Hence, Landau damping can occur only to those waves propagating from the source to the end plate. Judging from the time of flight, one can see that the first current peak in Fig. 4 is due to the waves propagating directly towards the end plate and that the larger peak is due to the waves reflected from the plasma source. The total current I collected by the end plate is of course smaller than that when the wave propagates directly towards the end plate because only a fraction of the wave is reflected ($\sim 20\%$ judging from I). In addition, currents can be slightly reduced by electron collisions during the relatively long time of flight.

In conclusion, we have observed experimentally that currents can be generated via Landau damping of unidirectional slow waves and the magnitude of the current can be estimated from momentum conservation in the wave-particle interaction. In order to generate a steady-state current for toroidal plasma confinement, one has to rely upon electron collisions to maintain a nonzero slope in the electron distribution function which is necessary

for Landau damping. The feasibility of employing this mechanism to operate a steady-state tokamak remains to be proved in toroidal plasma experiments.

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¹⁵Current monitor Model 2100 manufactured by Pearson
Electronics, Inc. Palo Alto, California.

FIGURE CAPTIONS

Fig. 1. Schematic of experimental set up. The plasma column is about 260 cm long. The slow wave structure is about 20 cm long. Its axial location can be varied between 120 cm to 220 cm from the end plate.

Fig. 2. (a) Wave electric field at a sequence of times measured by the sampling technique with density $n \approx 8 \times 10^9 \text{ cm}^{-3}$, parallel wavelength $\lambda_z \approx 11 \text{ cm}$, wave frequency $f \approx 50 \text{ MHz}$, magnetic field $B \approx 1.3 \text{ kG}$. (b) Radial electric field profile on the two sides of the antenna, the solid line is for the wave at the preferred direction. (c) Calculated spectrum for the slow wave structure.

Fig. 3. (a) The top trace shows the 200 nsec rf pulse and the bottom trace shows the electron current collected by the end plate (50 mA/div) when the waves are launched towards the end plate with $\lambda_z = 11 \text{ cm}$, $f = 50 \text{ MHz}$, $P_{\text{rf}} = 30 \text{ watts}$. (b) Total current collected by the end plate as a function of rf power with $\lambda_z = 11 \text{ cm}$, $f = 50 \text{ MHz}$, $\tau = 200 \text{ ns}$. The solid line represents the current calculated from Eq. (4) with the assumption that $P_w = 0.5 P_{\text{rf}}$.

Fig. 4. The top trace shows the 200 ns rf pulse and the bottom trace shows the electron current collected by the end plate (5 nA/div) when the waves are launched towards the plasma source with $\lambda_z = 11 \text{ cm}$, $f = 50 \text{ MHz}$, $P_{\text{rf}} = 30 \text{ watts}$.

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