1584

191
9/18/79

19. 61
SEPTEMBER 1979

PPPL-1584
UC-20f

STEADY-STATE CURRENTS DRIVEN
BY COLLISIONALLY DAMPED LOWER
HYBRID WAVES

BY

R. MCWILLIAMS, E. J. VALEO,
R. W. MOTLEY, W. M. HOOKE
L. OLSON

MASTER

PLASMA PHYSICS
LABORATORY

DISSEMINATION OF INFORMATION

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by the U. S. Department of Energy
Contract No. EY-76-C-02-3073. Reproduction, translation,
publication, use and disposal, in whole or in part, by or
for the United States Government is permitted.

Steady-State Currents Driven by Collisionally
Damped Lower Hybrid Waves

R. McWilliams, E. J. Valco, R. W. Motley,
W. M. Hooke, and L. Olson

Plasma Physics Laboratory, Princeton University
Princeton, N. J. 08544

ABSTRACT

Low power (~50 W) lower hybrid waves excited in a linear plasma were observed to drive electron currents (a few mA/W) in the direction of the wave momentum when the waves were collisionally damped. An approximate solution of an electron kinetic equation with a Lorentz collision operator predicts an electron current in this experimental regime ($k_{\parallel} v_{Te} / \omega \sim \nu / \omega \ll 1$).

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The attractiveness of the tokamak as a thermonuclear reactor would be considerably enhanced if it were possible to provide a steady state toroidal current in place of the pulsed ohmic heating current. Fisch^{1,2} and Bers¹ have proposed driving steady state toroidal currents by the use of nearly electrostatic lower hybrid waves³ which transfer momentum to the plasma via electron Landau damping. Conversion of wave momentum into current has been demonstrated experimentally using electromagnetic waves⁴⁻¹² and ion cyclotron waves¹³ and theoretical aspects have been discussed by others.¹⁴⁻¹⁸ Decker¹⁹ and more recently Wong²⁰ have performed experiments showing that electrostatic waves can couple via collisionless absorption to electron currents in beam-supported plasmas. In this paper we describe experiments showing the transfer of momentum from lower hybrid waves to electrons in an isotropic plasma via collisional absorption. Also, the theory of current generation by lower hybrid waves has been extended here to include collisional wave damping.

Consider a cylindrical plasma of length L in a straight magnetic field $\vec{B}_0 = B_0 \hat{z}$ with cold ions and with electron-ion collisions the dominant collisional process. One may describe the electron motion approximately by an electron kinetic equation with a Lorentz collision operator:

$$\frac{\partial f_e}{\partial t} + v_z \frac{\partial f_e}{\partial z} - \frac{e}{m} E_z \left(\frac{1-\mu^2}{v} \frac{\partial}{\partial \mu} + \mu \frac{\partial}{\partial v} \right) f_e = \frac{v_t^3}{v^3} \frac{\partial}{\partial \mu} (1-\mu^2) \frac{\partial f_e}{\partial \mu}, \quad (1)$$

where f_e is the electron distribution function, $v_t = (2kT_e/m_e)^{1/2}$,
 $= \frac{2\pi n_e \ln 2}{m_e v_t^3}$, and $\mu = \cos \theta$ with θ the angle of v with respect
 to the confining magnetic field.

The experimental conditions were such that

$$\frac{k_{\parallel} v_t}{\omega} \ll 1 \quad (2)$$

where $k_{\parallel}$ is the wavenumber parallel to B_0 of the lower hybrid wave and ω is the frequency. Assuming end effects in the machine are negligible (i.e. there is no net potential drop along the plasma column), decomposing the fields and distribution function into high and low frequency components, and expanding the low frequency distribution function in a Legendre series allows one (when the high frequency distribution function is calculated to second order in β) to calculate a current density:

$$\langle j \rangle = \frac{-13}{10\pi} \frac{e}{m_e} \frac{\omega_{pe}^2}{L} \int_0^L dz \frac{k_{\parallel} |E|^2}{\omega^3} \quad (3)$$

where $\langle \rangle$ denotes a time average over the wave period $2\pi/\omega$, ω_{pe} is the electron plasma frequency, and $|E|$ is the magnitude of the z-component of the applied rf field. From a single particle point of view, one may consider an electron experiencing a force $m_e dv/dt = -eE \sin(kz - \omega t) - m_e v v$ and arrive at the same answer as (3), aside from a numerical factor. Without collisions the electron response (except for resonant particles, which are considered negligible here) is seen to be purely reactive and hence no momentum could be transferred from the wave to the electrons.

For a lower hybrid wave, obeying the approximate dispersion relation $k_{\parallel}/k_{\perp} = \omega/\omega_{pe}$, launched from a cylindrically symmetric antenna and absorbed in a length less than L , the resultant current in the plasma is found to be approximately

$$I_{\parallel} = -16.4 \frac{e}{m} \frac{P}{L} \frac{1}{T_e^{3/2}} \quad (4)$$

where P is the power input to the lower hybrid wave, $\omega_{pe} = 2\pi/\tau_e$, $\tau_e = 3.5 \times 10^5 T_e^{3/2} / (n)$, $n = 25.4 - 1.15 \log n + 1.45 \log T_e$ (see reference 21, T_e in eV), and $2\pi f = \omega$. The minus sign in (4) indicates that electrons are being driven in the direction of the wave propagation parallel to the magnetic field.

The experiment was performed on the linear B-1 device²², utilizing a helium, neon, or argon plasma approximately 10 cm in diameter and 200 cm long. The confining magnetic field was typically 5-10 kG. The plasma was generated by a pulsed 155 Mhz rf discharge. Measurements were made at different times in the afterglow plasma created by the discharge, during which the electron density varied from $5 \times 10^{11} \geq n_e \geq 2 \times 10^{10} \text{ cm}^{-3}$ and the electron temperature decayed from a maximum of approximately 6 eV, depending on the filling gas. Over most of the afterglow the ion temperature is thought to be held just above the background gas temperature by charge exchange cooling. The electron-ion collision frequency was about 10^3 times the electron-neutral collision frequency, so that electron-neutral collisions could be neglected.

Plasma density was inferred from the phase shift of an 8.6 mm microwave interferometer and from the angle of propagation,

the slope of the resonance cone of the lower hybrid wave with respect to B_0 . Electron temperature was inferred from a Langmuir probe and the blackbody radiation near the electron cyclotron frequency. The radial wavelengths at low densities ($n_e \leq 10^{11} \text{ cm}^{-3}$), the resonance cone width, and the group velocity²³ along the field lines were measured and found to be consistent with the dispersion relation. Current was measured by four B_θ loops, two on each side of the antenna, and by an electrode at the end of the plasma column.

The electrostatic waves were excited by 0.2-5.0 μsec bursts of 60-70 Mhz fields applied to 8 phased loops²⁴ mounted (typically 2.5 cm apart) on the outside of a 9.9 cm diameter fused quartz tube. The waves were excited by phasing adjacent loops on the antenna 90° apart. Shielding by the quartz was a crucial element in the design of the experiment. Unshielded loops, as well as metal end electrodes (in some cases), were found to act as electron sinks during rf excitation, producing a pattern of divergent current flow. Shielded loops always drove electron currents in the direction of the flow of the wave fields.

Appropriate phasing of the loops allowed the lower hybrid wave to be launched with controlled directionality. Figure 1 shows currents generated by waves launched parallel and antiparallel to the magnetic field. The figure shows the current produced by the waves at various delay times in the afterglow plasma. At small delay times where T_e was several eV the current was reduced. This suggests incomplete damping of the wave before it reached the end of the plasma column allowing only a fraction of available wave momentum to be transferred to the

electrons. Such a conclusion is consistent with the measured and calculated wave damping distances. Also displayed in the figure is the dependence of the current on the wave directionality. Waves launched parallel (antiparallel) to B_0 drive an electron current parallel (antiparallel) to B_0 .

The spatial distribution of the current was determined with the aid of moveable B_0 loops. The current was found to be localized radially to the radial range over which the lower hybrid wave existed and was found to be essentially uniform in the z direction.

The current as a function of power is shown in Figure 2. At low powers the current is proportional to the input power. The current is roughly half that predicted by the theory. This difference might be explained as follows. We note that the current measuring probes were calibrated using a cylindrically symmetric current source, while the observed resonance cones were not always cylindrically symmetric. Also, the power measured in the experiment is the power radiated by the phased loop antenna. The fraction of this power carried via lower hybrid waves is difficult to determine. A tendency for the current to saturate is evident for power levels exceeding a few watts. It appears that the plasma cannot sustain current densities much in excess of $j_s \approx ne (kT_e/m_i)^{1/2}$ which would violate plasma charge neutrality. At powers exceeding a few watts we observed that the current substantially terminates within 500 nsec of startup.

The theory, equation 4, predicts that the current should be a function of $\lambda_{||}$. We varied this parameter by changing the phasing of the antenna loops. The results are shown in Figure

3. At low power levels one sees that doubling the wavelength approximately halves the current, as predicted by (4). In the region of saturation the sensitivity to wavelength is reduced.

For a linear device one should consider end effects. Heating of electrons towards one end may cause a change in the end sheath potentials, which would also generate a current. A self-consistent calculation suggests that such an effect, for the parameters of Figure 2, would not generate more than 1 mA/W, which is much smaller than the observed currents.

We gratefully acknowledge the technical assistance of G. Anania, J. Frangipani, and W. Rauch.

This work was supported by the United States Department of Energy Contract EY-76-C-02-3073.

REFERENCES

- ¹A. Bers and N.J. Fisch, in Proc. Third Topical Conf. on RF Plasma Heating (Caltech, Pasadena, CA, 1978), papers E5 and E6.
- ²N.J. Fisch, Phys. Rev. Lett. 41, 873 (1978).
- ³R.J. Briggs and R.R. Parker, Phys. Rev. Lett. 29, 852 (1972).
- ⁴P.C. Thonemann, W.T. Cowhig, P.A. Davenport, Nature 169, 34 (1952).
- ⁵N.A. Borzunov et al., Sov. Phys. - Doklady 8, 914 (1964).
- ⁶R.A. Demirkhanov et al., Sov. Phys. - Tech. Phys. 10, 174 (1965).
- ⁷K. Hirano, K. Matsuura, and A. Mohri, Phys. Lett. 36A, 215 (1971).
- ⁸S.M. Osovets and I.A. Popov, in 5th European Conf. on Cont. Fusion and Plasma Phys. (Grenoble, 1972), Vol. 1, p.8.
- ⁹M. Fukuda et al., J. Phys. Soc. of Japan 41, 1376 (1976).
- ¹⁰R. Klima et al., Phys. Lett. 65A, 23 (1978).
- ¹¹M. Fukuda and K. Matsuura, J. Phys. Soc. of Japan 44, 1344 (1978).
- ¹²M. Fukuda, J. Phys. Soc. of Japan 45, 283 (1978).
- ¹³S. Yoshikawa and H. Yamato, Phys. Fluids 9, 1814 (1966).
- ¹⁴V.I. Perel' and Ya. M. Pinskii, Sov. Phys. - Tech. Phys. 11, 752 (1966).

- ¹⁵R. Klima, Sov. Phys. JETP 26, 535 (1968).
- ¹⁶T. Ohkawa, Nucl. Fusion 10, 185 (1970).
- ¹⁷D.J.H. Wort, Plasma Phys. 13, 258 (1971).
- ¹⁸R. Klima, Plasma Phys. 15, 1031 (1973).
- ¹⁹J.F. Decker and J.L. Hirschfield, Phys. Fluids 11, 372 (1968).
- ²⁰K.L. Wong, Phys. Rev. Lett. 43, 438 (1979).
- ²¹S.I. Braginskii, in Rev. of Plasma Phys., (consultants Brueau, New York, 1965), Vol. 1.
- ²²R.W. Motley, et al., J. of Applied Phys. 46, 3286 (1975).
- ²³R.J. La Haye et al., General Atomic GA-A15125 (1978).
- ²⁴Geometry of antenna suggested by P. Bellan and M. Porkolab, Phys. Rev. Lett. 34, 124 (1975).

FIGURE CAPTIONS

Fig. 1. Current vs. delay time in neon afterglow plasma. Solid and open dots represent waves launched parallel or anti-parallel to B_0 . 70 MHz pulse duration of 2 μ sec. T_e falls from 7.5 eV to 2eV in first 100 μ sec, then falls to 0.9 eV by 400 μ sec.

Fig. 2. Current vs. input power. Solid line is current predicted by equation 4. Dashed line is $j_s A$ where A is approximate area perpendicular to z where the lower hybrid wave existed. Neon plasma, $T_e = 0.9$ eV, $n_e = 2.2 \times 10^{11} \text{ cm}^{-3}$, $f = 70$ MHz, $\lambda_{lh} = 10$ cm.

Fig. 3. Current vs. input power at two different λ_{lh} in argon afterglow plasma. Solid lines are least square fits of degree 2.

FIG. 1. 792708

Fig. 2. 793865

Fig. 3. 793866