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CURRENT GENERATION BY
UNIDIRECTIONAL LOWER HYBRID WAVES
IN THE ACT-1 TOROIDAL DEVICE

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LABORATORY

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ABSTRACT

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All existing tokamaks are capable only of pulsed operation, since the toroidal plasma current is driven by an inductive method. Obvious advantages of a steady-state tokamak reactor include: a longer first-wall life in the absence of cyclic thermal and mechanical excursions; elimination of a thermal storage system for continuous power production; removal of the ohmic heating coils. A steady-state current can be driven by radio frequency waves,¹⁻⁹ but if the current is carried by the main body electrons, the rf power required is too large to be practical.⁴ Far less rf power is required if the current is carried by the electrons in the tail of the distribution function. This can be accomplished via Landau damping of the lower hybrid wave.^{8,9} In this paper, we report the first unambiguous experimental observation of current generation by unidirectional lower hybrid waves in a toroidal plasma.

Consider a lower hybrid wave propagating in a magnetized plasma ($\vec{B}_0 = B_0 \hat{z}$) with parallel phase velocity ω/k_z . The wave obeys the electrostatic dispersion relation

$$\epsilon(\vec{k}, \omega) = 1 - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2} \frac{k_{\parallel}^2}{k^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{k_{\perp}^2}{k^2} = 0 \quad (1)$$

To calculate the current generated by the wave, one can study the evolution of the space-averaged electron distribution function $f(v_z, t)$ in the presence of rf waves by the one-dimensional Fokker-Planck Equation^{9,10}

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial v_z} D_{rf} \frac{\partial}{\partial v_z} f + \left(\frac{\partial f}{\partial t} \right)_c \quad (2)$$

where D_{rf} is the quasi-linear diffusion coefficient, and $(\frac{\partial f}{\partial t})_c$ is the collision term. The rf generated current can be calculated from the steady-state solution of Eq. (2). Let us assume that $D_{rf}(v_z) = \infty$ for $v_1 < v_z < v_2$ and zero elsewhere, then $f(v_z)$ plateaus for $v_1 < v_z < v_2$ and this gives rise to a current in the plasma. Let E_0 denote the amplitude of the wave electric field, then, the total plasma current density is

$$J = \frac{ne}{\sqrt{2\pi kT}} \frac{(v_2^2 - v_1^2)}{2} \exp(-\frac{mv_1^2}{2kT}) + \frac{n_z^2 - 1}{n_z^2} \cdot \frac{e}{m} \frac{E_0^2}{8\pi} \frac{k_z}{\omega} (1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}), \quad (3)$$

where n , T , and n_z denote the electron density, electron temperature, and the wave parallel index of refraction. The first term in Eq. (3) is due to the resonant electrons in the plateau of $f(v_z)$, and the second term (usually small compared with the first term) is due to the non-resonant electrons which support the wave. It is apparent that after $f(v_z)$ plateaus, additional rf power can only raise the current density via the second term in Eq. (3).

In order to optimize the current generation efficiency, one has to confine the current carrying electrons inside the torus. Due to the magnetic field line curvature and the field gradient, electrons can leave the torus by drifting across the magnetic field (vertically downward in ACT-1) with the drift velocity

$$\vec{v}_d = \frac{v_z^2}{\omega_{ce}} \frac{\vec{R} \times \vec{B}_0}{R^2 B_0} + \frac{v_\perp^2}{2\omega_{ce}} \frac{\vec{B}_0 \times \nabla B_0}{B_0^2} . \quad (4)$$

These electrons can be confined in the torus by adding a small vertical magnetic field

$$\vec{B}_v = \frac{v_d}{v_z} B_0 \frac{\vec{R} \times \vec{v}_z}{|\vec{R} \times \vec{v}_z|} , \quad (5)$$

so that the vertical component of $\vec{v}_z$ cancels the drift velocity $\vec{v}_d$. Here $\vec{R}$ denotes the radius of curvature of the field line and ω_{ce} is the electron cyclotron frequency. Note that the direction of $\vec{B}_v$ changes with the direction of $\vec{v}_z$.

The idea of lower hybrid wave current drive relies upon momentum transfer from the waves to the resonant electrons and therefore requires unidirectional waves which can be generated by 90° phased metal plates or waveguide arrays. Excitation of unidirectional waves and momentum transfer from waves to tail electrons have been experimentally demonstrated¹¹ in the Princeton L-3 linear device. In a toroidal device, the current carrying electrons are confined and therefore the current generation efficiency (Amperes/watt) should be much better. The experimental data reported in this paper demonstrate an order of magnitude increase in current drive efficiency compared with previous linear machine results.^{6,11}

The experiment was performed in the Princeton ACT-1 device¹² (Advanced Concepts Torus I), a new toroidal machine designed primarily for rf heating and rf current generation

research. It has a pure toroidal magnetic field without rotational transform. The plasma equilibrium is maintained by a small vertical current which flows to the limiter and completes the electrical circuit. Figure 1 shows the schematic of the device. The experiment was performed with the following plasma parameters: plasma density $n \sim 2 \times 10^{10} \text{ cm}^{-3}$, electron temperature $T_e \sim 5 - 10 \text{ eV.}$, ion temperature $T_i \sim 0.5 \text{ eV.}$, toroidal magnetic field $B_0 \sim 3 \text{ kG}$ on the minor axis, neutral pressure $p_0 \sim 2 \times 10^{-5} \text{ torr}$, plasma radius $\sim 9 \text{ cm}$. The helium plasma was produced by 200 watts of rf heating near the electron cyclotron frequency (9 GHz), and also by a hot tungsten filament inserted into the torus. Lower hybrid waves at 160 MHz were launched by two sets of antenna of parallel wavelengths 5.1 cm and 7.6 cm. Each set of antenna consists of four electrostatic rings with a 90° phase difference between the rf voltage applied on adjacent rings. Figure 2a shows the schematic of the rf network. In order to verify the directionality of the antenna, the radial profile of the wave amplitude was measured with a double-tip probe one port away from the antenna, and the result is shown in Figure 2b. When the antenna phasing is chosen to launch a wave propagating towards the probe, the wave amplitude detected by the probe is much larger than when the wave is launched away from the probe. The two peaks in the amplitude profile correspond to the resonance cones emanating from the two sets of antenna. Interferometry measurements of the wavelength show that the wave satisfies the dispersion relation [Eq. (1)]. The current generated by the wave was measured by a 1000 turn Rogowski loop as shown

in Figure 3a. The Rogowski loop sensitivity (1.3 mV/Amp) and the response time ($\sim 0.3 \mu s$) was experimentally determined by sending a known pulsed current through the loop. Figures 3b and 3c show that, as expected, the rf generated current changes direction when the wave propagation is reversed. One should note that the RC time constant of the Rogowski loop signal is $100 \mu s$ and the slowly varying current signal in Figures 3b and 3c is due to the droop of the RC integrator. The oscillograms show overlay of four consecutive pulses which demonstrate the reproducibility of the experiment. The outer half of the Rogowski loop picks up a signal larger than the inner half, indicating that the current profile peaks outside the minor axis. Up to 10 amperes of current has been driven by 500 watts of rf power. Calculation of the rf generated current requires an accurate value of $f(v_1)$. Put $T = 8 \text{ eV}$, $f_0 = 160 \text{ MHz}$, $\lambda_1 = 5.1 \text{ cm}$, $\lambda_2 = 7.6 \text{ cm}$, $v_1 = \frac{1}{2} f_0 \lambda_1$, $v_2 = \frac{3}{2} f_0 \lambda_2$, $n = 2 \times 10^{10} \text{ cm}^{-3}$, Eq. (3) predicts $I \sim 10$ amperes which is in rough agreement with experiment. It should be noted that Eq. (3) can only give an order-of-magnitude estimate because of the uncertainties in $f(v_1)$, v_1 , v_2 , and the profile effects.

A small vertical magnetic field $\vec{B}_v$ (up to 10 G on the minor axis) can be applied by two 80-turn coils situated inside the bore of the torus. The spiraling magnetic field line was traced out by a tenuous 100 eV electron beam emitted from a small electron gun. The value of $\vec{B}_v$ determined from the pitch of the helical field line and the toroidal field $\vec{B}_0$ are in

excellent agreement with the measurements by a Hall probe gaussmeter. Figure 4 shows the variation of the rf generated current with the vertical field $\vec{B}_V$ (values taken on the minor axis). As expected from Eq. (5), the optimum value of $\vec{B}_V$ changes direction when the wave propagation direction is reversed. Putting $v_z = 10^9$ cm/sec, which is the average parallel phase velocity of the waves, and assume $v_\perp^2 \ll v_z$, Eqs. (4) and (5) predict an optimum $B_V \approx 1$ Gauss which is in reasonable agreement with the experimental results presented in Figure 4. The discrepancy can be qualitatively explained by the fact that the current peaks outside the minor axis of the torus. If $v_\perp$ is a substantial fraction of v_z due to collisions, then Eq. (6) will predict a B_V larger than 1 Gauss also.

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Figure Captions

Figure 1. Schematic of the ACT-1 device.

Figure 2. (a) Schematic of the rf network for wave excitation.

(b) Radial profiles of the wave amplitude when the wave is launched towards the probe (solid line) and away from the probe (dotted line).

Figure 3. (a) Integrated Rogowski loop for current measurements.

(b) Current generated by a 200 watt 120 μ s rf pulse with $\vec{V}_g \cdot \vec{B}_0 > 0$. ($\vec{V}_g$ denotes the group velocity of the wave.) Top trace shows the rf pulse and bottom trace shows the Rogowski loop signal (c) $\vec{V}_g \cdot \vec{B}_0 < 0$.

Figure 4. Variation of rf generated current I with vertical magnetic field $\vec{B}_V$. The currents flow in opposite directions for the two cases ($\vec{V}_g \cdot \vec{B}_0 > 0$ and $\vec{V}_g \cdot \vec{B}_0 < 0$). Only the magnitude of the currents are plotted here for easy comparison.

Fig. 1. (PPPL-803626)

Fig. 2. (P2PL-803624)

$$\vec{V}_g \cdot \vec{B}_0 > 0$$

$$\vec{V}_g \cdot \vec{B}_0 < 0$$

Fig. 3. (PPPL-803627)

Fig. 4. (PPPL-803625)