Lower-Hybrid Current Drive in the PLT Tokamak

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Order-of-magnitude improvements in the level and duration of current driven by lower-hybrid waves have been achieved in the PLT tokamak. Steady currents up to 165 kA have been maintained for 3.5 sec and 420 kA for 0.3 sec by 800-MHz rf power alone. The principal current carrier appears to be a high-energy (~ 100-keV) electron tail, concentrated in the central 20- to 40-cm core of the 80-cm-diam discharge column.

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The development of steady-state current drive would considerably enhance the prospects for a tokamak fusion reactor. It has been proposed that the conventional Ohmic-heating transformer be replaced by particle[1] or radiation beams.[2] One of the most promising methods involves the launching of lower-hybrid waves[3] from a phased waveguide array.[4] Waves propagating in the proper direction and with the appropriate speed will interact resonantly with fast electrons, maintaining an asymmetric parallel velocity distribution and therefore a net current.

Following confirmation of some aspects of the wave propagation and current drive theory in linear plasmas,[5,6] a number of experiments in toroidal plasmas with gradually increasing power (up to 150 kW) have shown that short pulses (< 40 msec) of lower-hybrid waves can lower the loop voltage by more than 50% and increase the current by up to ~10 kA.[7-15] The presence of fast electrons in these low-density discharges has been inferred from sharp rises in the synchrotron radiation and in the soft–x-ray intensity.

In this paper we report the first tokamak discharges in which the plasma current was maintained by lower-hybrid waves alone for extended durations (420 kA for 0.3 sec and 165 kA for 3.5 sec); the loop voltage was reduced to nearly zero to rule out external inductive electric fields as a factor in the current maintenance. The pulse length was limited only by heating of the ferrite isolators. Radial profile and spectral radiation measurements show that a fast-electron population in the range of the phase velocity of the launched waves is produced in the central core of the discharge.

The experiments presented here were done on the PLT tokamak (major radius 1.32 m and minor radius 0.4 m).[16] Up to 500 kW at 800 MHz was delivered to the plasma torus by a six-element phased array (consisting of $3.5\times 22\text{-cm}^2$ waveguides) placed on the larger-major-radius side of the torus. Before the rf power was turned on, the plasma was produced with an Ohmic-heating transformer. After the plasma current was raised to 300 kA [Figs. 1(a)– 1(d)], the current in the transformer primary was held fixed to minimize the inductive drive. With no rf power the plasma current decayed with a time constant of ~0.6 sec. The application of 130 kW of power maintained the plasma current at 240 kA for a period up to 1 sec. The loop voltage, following the initial negative transient, remained close to zero. The line-average electron density was initially raised to 7×10^{12} cm^{-3} to suppress electron runaway and then decreased to a constant level of 3.5×10^{12} cm^{-3}.

In a toroidal system the current flow can be strongly influenced by electric fields induced by changes in the poloidal magnetic field. The power flow is given by

$$I^2R_p + d(LI^2/2)/dt = I(M_{\rm OH}\dot{I}_{\rm OH} + M_v\dot{I}_v) + \eta P, \quad (1)$$

where I is the plasma current, R_p is the resistance of the plasma, $L=\mu_0R(\ln 8R/a - 2 + l_i/2)$ is the total inductance of the plasma loop, R and a are the major and minor radii, $\mu_0Rl_i/2$ is the internal inductance, $M_{\rm OH}$ and M_v are the mutual inductances between plasma current and OH primary coil and vertical field coil, and ηP is the rf power driving the current. To demonstrate rf current drive we have produced conditions such that the I^2R_p and ηP terms of Eq. (1) are dominant. Voltages induced by a change in the net external magnetic flux can be monitored and minimized by adjusting $\dot{I}$, V, and $\dot{R}$ to zero. The power input from the induction field for the conditions in Figs. 1(a) to 1(d) is < 13 kW, i.e., an order of magnitude less than the input from rf fields. Figure 1(e) shows a long-pulse discharge in which a plasma current of 165 kA was maintained for ~3.5 sec.

The most efficient current drive occurs for phase angles $\Delta\varphi$ (between adjacent guides) of 90° to 60°, with the waves propagating opposite to the direction of current flow. Under optimum conditions ($\bar{n}_e < 7\times10^{12}\ \mathrm{cm}^{-3}$, $\Delta\varphi = 60°$) the measured current-drive figure of merit is $F \equiv I\bar{n}_e/P = 0.8 \times 10^{13}$ A/W cm^3. If the quasilinear theory of Karney and Fisch[17] is applied to our experiment with the assumption that the wave spectrum driving the fast electrons extends from $n_\parallel = ck_\parallel/\omega = 1.5$ to 3 (30–170 keV electrons), then $F \approx 10^{13}$ A/W cm^3.

The fast-electron tail is much more energetic than the main-body electrons, which are maintained by the rf power at a temperature at the center close to 1 keV ($\bar{n} < 7\times10^{12}\ \mathrm{cm}^{-3}$) as measured by Thomson scattering. Direct evidence for the enhancement of this fast tail has been obtained from x rays and synchrotron radiation.

Hard x rays from the limiter (>400 keV) usually decrease by a factor of 2–5 during the rf pulse, but x rays from the plasma increase by up to 2 orders of magnitude after the rf is turned on, as shown by the NaI detector data in Fig. 2(a), taken at right angles to the magnetic field. After a transient period of ~30 msec the x-ray spectrum exhibits an exponentially falling tail with an effective temperature of 50 keV. The spectral shape can be simulated by an isotropic Maxwellian electron distribution at $T = 100$ keV, by an electron beam along B with a 150-keV Maxwellian spread in parallel energy, or by an incompletely isotropized electron distribution within the above limiting energy ranges.

The spatial distribution of the fast-electron component in the energy range below 30 keV was inferred from vertical scans with a silicon detector (enhanced emission occurs for x-ray energies greater than 8 keV). As shown in Fig. 2(b), the x-ray emission, after Abel inversion, is strongly peaked near the center of the plasma ring, within a radius of 10–20 cm, depending on the current and the toroidal magnetic field. Since there exists no externally imposed electric

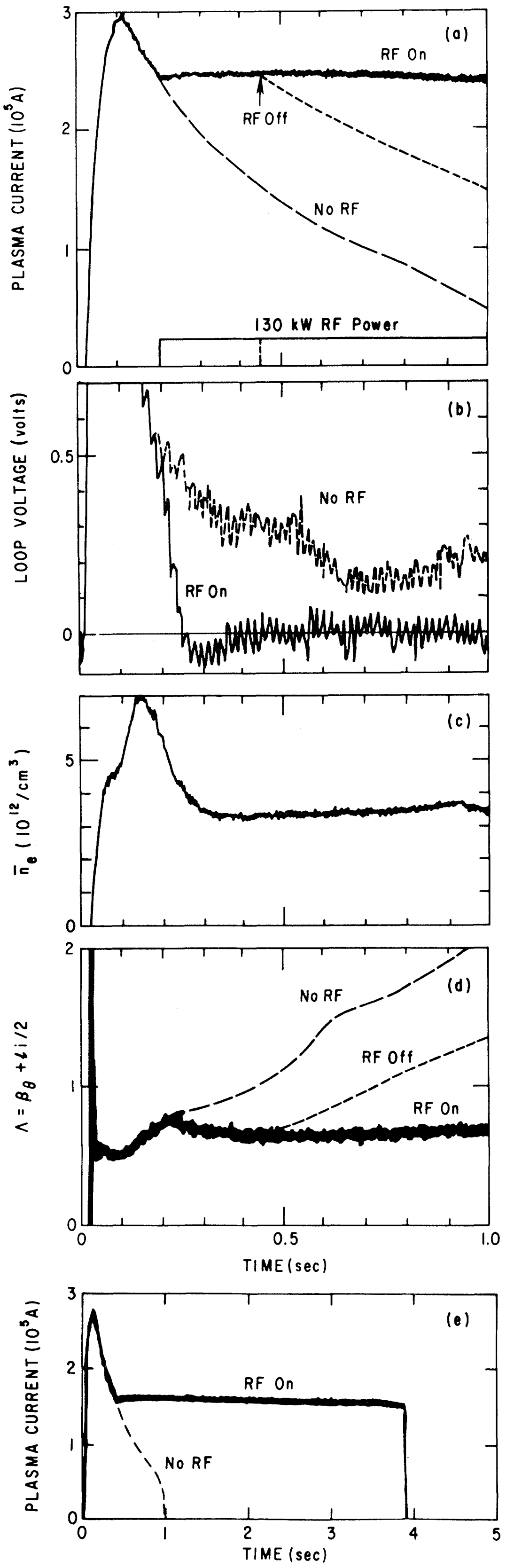

FIG. 1. (a)–(d) Characteristics of deuterium discharges in the PLT tokamak with and without (solid and dashed lines) rf power. The current was maintained at 240 kA for 1 sec (0.2 sec beyond computer printout) with 130 kW of rf power. $\Delta\varphi = 90°$, $B_t = 31$ kG. (e) A long-pulse (3.5-sec) discharge. rf power $\simeq$ 70 kW, $\Delta\varphi = 90°$, $B_t = 23$ kG.

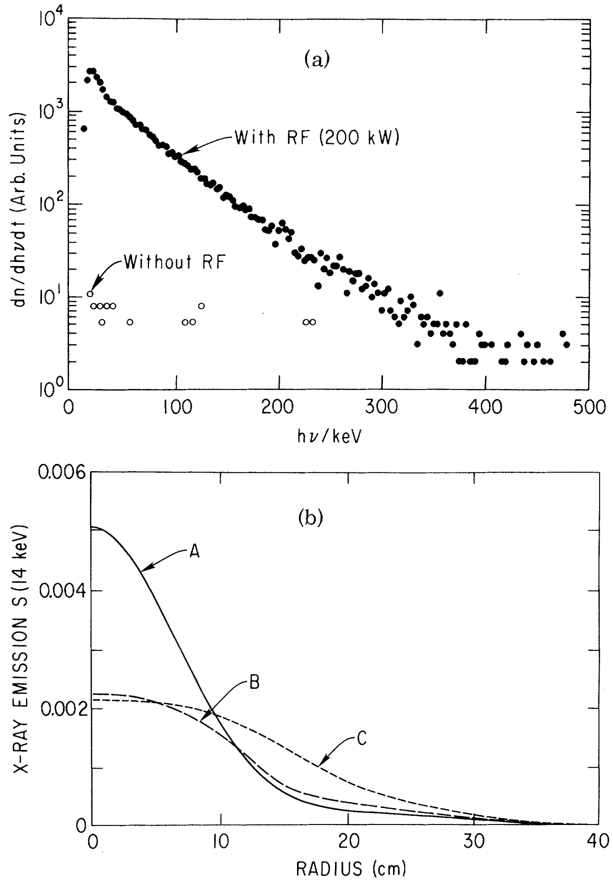

FIG. 2. (a) Plasma x-ray spectrum from NaI detector. $B_t = 31$ kG, $I_p = 200$ kA, $P_{\mathrm{rf}} = 200$ kW, $\bar{n}_e = 6 \times 10^{12}$ cm^{-3}. (b) Radial variation of x-ray intensity at 14 keV from a movable silicon detector, after Abel inversion, $\bar{n}_e = 5 \times 10^{12}$ cm^{-3}. Curve A: $P_{\mathrm{rf}} = 200$ kW, $I_p = 200$ kA, $B_t = 31$ kG; curve B: $P_{\mathrm{rf}} = 250$ kW, $I_p = 210$ kA, $B_t = 15.7$ kG; curve C: $P_{\mathrm{rf}} = 320$ kW, $I_p = 290$ kA, $B_t = 15$ kG.

field, the tail electrons must carry most of the current and the current distribution can be estimated from the x-ray profile. Under the assumption that the current density is proportional to the x-ray intensity, the data of Fig. 2(b) imply that q varies from slightly less than 1 at the plasma center to 3–10 at the plasma edge. These profiles are similar to those obtained in normal Ohmic-heating discharges on PLT.

The creation of energetic electrons produces a plasma of high conductivity in which the current profile remains nearly unchanged from that before the rf was turned on. This finding from the x-ray data is in agreement with the fact that $\Lambda = \beta_\theta + l_i/2$ changes only slightly during rf current drive [Fig. 1(d)]. The x-ray data of Fig. 2(b) imply $l_i/2 = 0.9$, 0.7, and 0.6; values of $\Lambda = 1.0$, 0.8, and 0.6 are inferred from the vertical field. The fast-electron component constitutes about 4% of the electrons near the plasma center and >50% of the total plasma energy.

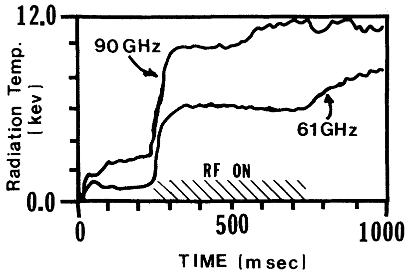

FIG. 3. Ordinary mode radiation near the electron cyclotron frequency; $B_t = 32$ kG on axis, $I_p = 270$ kA, $P_{\mathrm{rf}} = 175$ kW, $\bar{n}_e = 4 \times 10^{12}$ cm^{-3}.

The emission near the electron cyclotron frequency Ω_e originates from energetic electrons in an optically thin, low-density plasma (Fig. 3). During the rf pulse, the energy of the radiation is equivalent to an effective temperature of ~10 keV. The emission at 61 GHz must originate from Doppler-shifted radiation from the fast electrons,[18] since this frequency corresponds to the value of the field at $R = 191$ cm, a position outside the vacuum vessel. If these electrons are near the center of the discharge, then the Doppler-shifted emission requires electrons in the 50–200-keV energy range.

After the rf pulse, the cyclotron emission does not return to a low level. At the same time the intensity of the high-energy x rays (>200 keV) increases or remains unchanged for ~100 msec while that of the low-energy x rays decreases rapidly after the rf is turned off. (In this period, since $\dot{I}$ is no longer zero, an induced dc electric field develops which sustains the fast electrons.)

With no Ohmic heating, and with the plasma density above 1.0×10^{13} cm^{-3}, the rf power produces no observable effect on the current in a deuterium discharge. The reason for this density cutoff, also observed in other experiments,[9-13] is not understood. One possibility is that a downshift in the $n_\parallel$ spectrum occurs near the lower-hybrid resonance as a result of toroidal effects,[19] so that the center of the plasma column becomes inaccessible to an increasingly large fraction of the power radiated by the grill. We also found that the cutoff density is ~30% higher in a deuterium plasma than in a hydrogen plasma; clear-cut deductions from this result cannot be drawn because of the uncertainties in Z_{eff}.

Analysis of the waveguide coupler shows that the lower-hybrid waves should interact primarily with electrons with energies greater than 30 keV. This prediction is consistent with the x-ray and microwave radiation spectra. How the electrons from the 1-keV background plasma are raised to this energy has yet to be explained in this experiment and indeed is one of the principal unresolved problems in rf current drive.

This work represents a very significant step in the development of a steady-state current drive for tokamak plasmas. Discharges have been produced in which essentially all of the power to maintain a high current is derived from the rf fields for periods up to 3 sec. There is strong evidence that the current is carried by high-energy (~100-keV) electrons, which are concentrated in the inner core of the discharge.

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Experiments on Vortices in Rotating Superfluid ^{3}He-A

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A satellite peak has been observed in the NMR spectrum of rotating ^{3}He-A; the peak intensity depends linearly on Ω at the high angular velocities, $\Omega = 0.6$–1.5 rad/s, needed to resolve it. The frequency shift of the satellite is independent of Ω. These results strongly suggest the existence of vortices in rotating ^{3}He-A with the vortex density proportional to Ω. Another satellite peak also has been observed which probably is due to solitons.

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Singularities in superfluid ^{3}He, as well as in other ordered media, have interested experimentalists and theorists during recent years.[1-7] However, because of the experimental difficulties, rotating superfluid ^{3}He has not been explored until very recently. Rotation is a well-defined way to produce singularities in superfluids and, in addition, creation of singularities