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ABSTRACT

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 175 kA have been maintained for three seconds and 400 kA for 0.3 sec by the rf power alone. The principal current carrier appears to be a high energy (~100 keV) electron component, concentrated in the central 20-40 cm diameter core of the 80 cm PLT discharge.

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 traveling with the proper direction and speed will interact resonantly with fast electrons, maintaining a net current.

Following confirmation of some aspects of the wave propagation and current drive theory,[5,6] a number of experiments 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.[7-13] 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 experiments in which lower hybrid waves have been used to drive currents for extended pulses (400 kA for 0.3 sec and 175 kA for 3 sec) without any inductive field from the ohmic heating transformer. The pulse length was limited only by heating of the ferrite isolators. The loop voltage was reduced to nearly zero to rule out external inductive electric fields as a major factor in the current maintenance. Radial profile and spectral radiation measurements show that a fast electron population is produced in the central core of the discharge by the lower hybrid fields.

The experiments presented here were done on the PLT tokamak (major radius 1.3 m and minor radius 0.4 m).[14] Up to 500 kW at 800 MHz was delivered to the plasma torus by a 6-element phased array (consisting of 3.5 × 22 cm waveguides) placed on the outside of the torus. Before rf turn-on, the plasma was produced with an ohmic-heating transformer. After the plasma current was raised to 300 kA (Fig. 1), 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 second. The loop voltage, following the initial negative transient, remained close to zero. The 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

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

where I is the plasma current, R_p is the resistance of the plasma, $L = \mu_o R(\ell n\, 8R/a - 2 + \ell_i/2)$ is the total inductance of the plasma loop, R and a are the major and minor radii, $\mu_o R\ell_i/2$ is the internal inductance, M_{OH} and M_v are the mutual inductances between plasma current and OH primary coil and vertical field coil and η P 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 clearly dominant. Voltages induced by a change in the net external magnetic flux can be monitored and minimized by adjusting $\dot{I}$ and the loop voltage V to zero. The $I^2\dot{L}/2$ term can be made unimportant by holding R constant and by minimizing current channel shrinkage before rf turn-on.

The time variation of $\Lambda = \beta_\theta + \ell_i/2$ in Fig. 1, obtained from the vertical field required to position the plasma column, shows that the current channel gradually constricts in the absence of rf power (Λ increases from 0.4 to 2, while $\beta_\theta < 0.1$). Application of the rf power halts the constriction, leading to a slight expansion, followed after 300 msec by a steady state in which Λ = constant. We estimate the values of the terms in Eq. (1) after t = 300 msec: $LI\dot{I} < 5$ kW; $I^2\dot{L}/2 < 6$ kW; $M_{OH}I\dot{I}_{OH} < 2$ kW; $M_vI\dot{I}_v < 0$; $I^2R_p \simeq$ 40-80 kW to overcome collisional drag if the current carriers are fast electrons with an energy of 100 keV. The energy input from the rf fields is therefore ~4 to 8 times larger than the sum of the energy input from the induction fields.

The most efficient current drive occurs for phase angles $\Delta\phi$ (between adjacent guides) of 90° to 60°, with the waves traveling opposite to the direction of current flow. Under optimum conditions ($\bar{n}_e < 7 \times 10^{12}$ cm^{-3}) the measured current-drive figure of merit is $F \equiv I\,\bar{n}_e/P = 0.6 \times 10^{13}$ A/W cm^3. If the quasilinear theory of Karney and Fisch[15] is applied to our experiment, assuming that the wave spectrum extends from $n_\parallel = ck_\parallel/\omega = 1.5$ to 3 (interacting with 30-170 keV electrons), then $F \approx 10^{13}$ A/W cm^3. The quasilinear theory alone, however, cannot account for the formation of the electron tail, since $\omega/k_{\parallel} > 6(kT_e/m_e)^{1/2}$.

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 ($\dot{I}$ unchanged). The reason for this density cutoff, also observed in other experiments,[9-13] is not completely clear. One possibility is that a downshift in the $n_{\parallel}$ spectrum occurs near the lower hybrid resonance as a result of toroidal effects, so that the center of the plasma column becomes inaccessible to a large fraction of the power radiated by the grill. Experimentally, the current drive efficiency vanishes if $\omega < 1.6\ \omega_{LH}$ in both deuterium and hydrogen discharges.

To drive current the rf fields must interact with fast electrons, which are traveling at 1/3 to 2/3 of the speed of light (30-170 keV). These electrons are much more energetic than the main body electrons, which are maintained by the rf power at a temperature close to 1 keV ($\bar{n} < 7 \times 10^{12}$ cm^{-3}) as measured by Thomson scattering. Direct evidence for the enhancement of this fast tail has been obtained from synchrotron radiation and from X rays.

The intensity of the emission near the electron cyclotron frequency ($\omega = \Omega_e$) appears to originate from energetic electrons in an optically-thin, low density plasma (Fig. 2a). During the rf pulse, the "radiation temperature" increases to ~10 keV (A normal Maxwellian would give < 1 keV). After the rf pulse, the intensity typically does not return to a low level in contrast with the X-rays intensity decay. The emission at 61 GHz must originate from Doppler-shifted radiation from the fast electrons,[16] 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 (see X-ray data of Fig. 3), then the Doppler-shifted emission requires electrons in the 50-200 keV energy range.

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 two orders of magnitude when the rf is turned on, as shown by NaI detector data in Fig. 2b. A few fast electrons are always present before the rf current drive begins, the number varying with the initial conditions. How this fast electron population is enhanced by the rf fields within ~30 msec has not yet been established. After ~30 msec the X-ray spectrum exhibits an exponentially falling tail with a "temperature" of 50 keV. The spectral shape can be simulated either by an isotropic Maxwellian electron distribution at T = 100 keV, or by an electron beam along B with a 150 keV Maxwellian spread in parallel energy.

The spatial distribution of the fast electron component in the energy range below 30 keV was inferred from vertical scans with a silicon detector. As shown in Fig. 3, 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 the tail electrons must carry most of the current, one can estimate the current distribution from the X-ray profile. Under the assumption that the current density is proportional to X-ray intensity, the data of Fig. 3 show 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 is almost constant. This finding from the X-ray data is in agreement with the fact that $\Lambda = \beta_\theta + \ell_i/2$ changes only slightly during rf current drive (Fig. 1). The X-ray data of Fig. 3 imply $\ell_i/2 = 0.9$, 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.

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 seconds. 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. Although a number of questions, important for reactor-grade plasmas, remain to be investigated (e.g., the nature of the high density cutoff, and the means by which the high energy tail is created during the initial stages of rf current drive), these experiments provide an important impetus to the development of a steady-state tokamak reactor with current driven by radio-frequency waves.

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FIGURE CAPTIONS

Fig. 1. Characteristics of deuterium discharges in the PLT tokamak with and without (dashed and dotted lines) rf power. The current was maintained at 240 kA for 1 second (0.2 sec. beyond computer printout) with 130 kW of rf power $\Delta\phi = 90^{o}$, $B_t = 31$ kG.

Fig. 2. (a) Ordinary mode radiation near the electron cyclotron frequency, $B_t = 32$ kG on axis, $I_p = 270$ kA, $P_{RF} = 175$ kW, $\bar{n}_e = 4 \times 10^{12}$ cm^{-3}. (b) Plasma X-ray spectrum from NaI detector. $B_t = 31$ kG, $I_p = 200$ kA, $P_{RF} = 200$ kW, $\bar{n}_e = 6 \times 10^{12}$ cm^{-3}.

Fig. 3. Radial variation of X-ray intensity at 14 keV from a moveable silicon detector, after Abel inversion, $\bar{n}_e = 5 \times 10^{12}$ cm^{-3}. A: $P_{RF} = 200$ kW, $I_p = 200$ kA, $B_t = 31$ kG; B: $P_{RF} = 250$ kW, $I_p = 210$ kA, $B_t = 15.7$; C: $P_{RF} = 320$ kW, $I_p = 290$ kA, $B_t = 15$ kG.

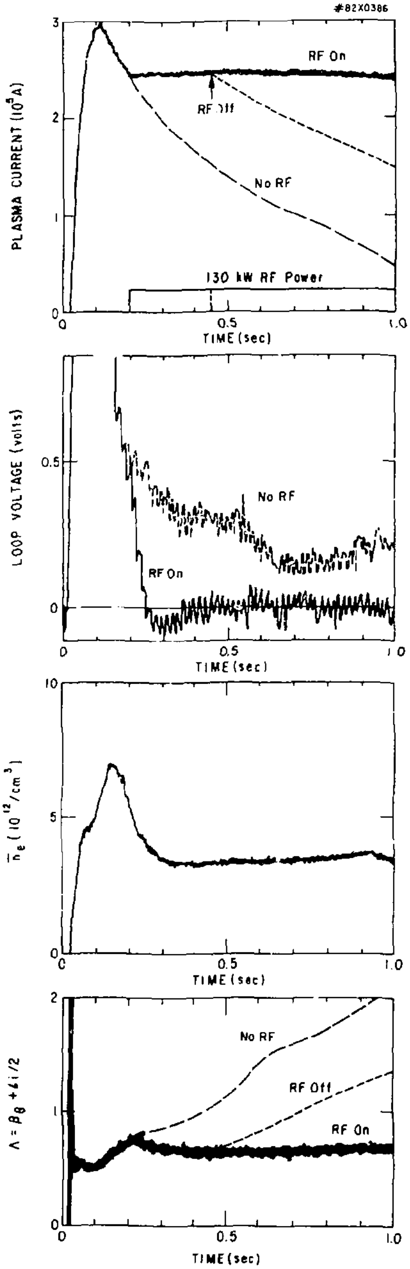
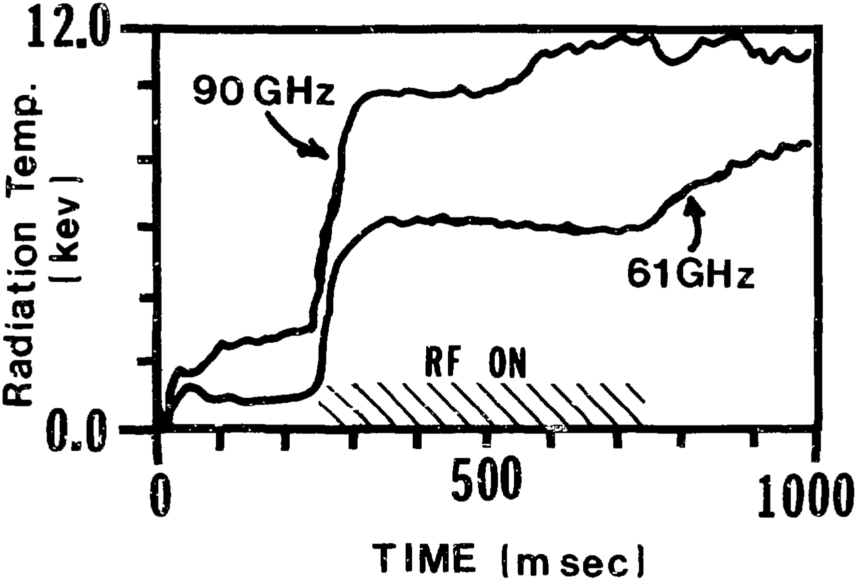
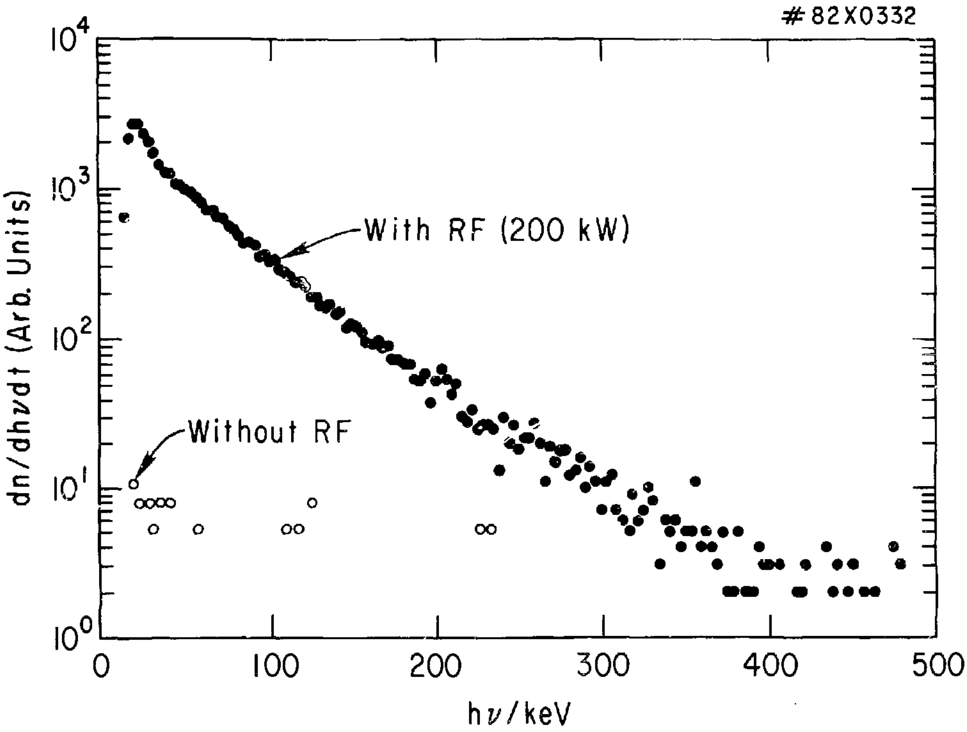

#82X0386
PLASMA CURRENT (10^5 A)
3
2
1
0
RF On
RF Off
No RF
130 kW RF Power
0
0.5
1.0
TIME (sec)
LOOP VOLTAGE (volts)
0.5
0
No RF
RF On
0
0.5
1.0
TIME (sec)
n̄e (10^12/cm^3)
10
5
0
0
0.5
1.0
TIME (sec)
Λ = βθ + ℓi/2
2
1
0
No RF
RF Off
RF On
0
0.5
1.0
TIME (sec)

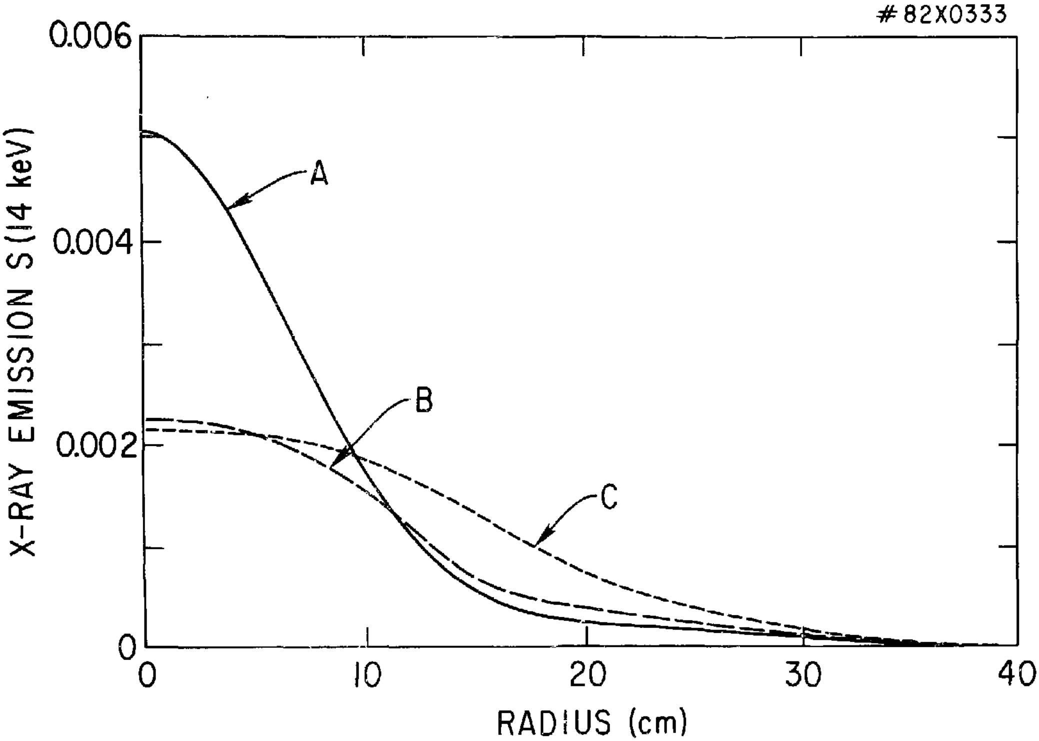
Fig. 1


12.0
0.0
Radiation Temp.
(kev)
90 GHz
61GHz
RF ON
0
500
1000
TIME (m sec)



#82X0332
10^4
10^3
10^2
10^1
10^0
dn/dhνdt (Arb. Units)
With RF (200 kW)
Without RF
0
100
200
300
400
500
hν/keV

Fig. 2b



#82X0333
0.006
0.004
0.002
0
X-RAY EMISSION S(14 keV)
A
B
C
0
10
20
30
40
RADIUS (cm)

Fig. 3