Generation of rf-Driven Currents by Lower-Hybrid-Wave Injection in the Versator II Tokamak

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Experimental verification of lower-hybrid rf current drive in the Versator II tokamak is presented. The experiments show that efficient current drive exists only in low-density discharges ($\bar{n}_e \lesssim 6\times 10^{12}$ cm^{-3}) in the "slide-away" regime where a preformed suprathermal electron tail exists prior to the application of the rf power.

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In tokamak-type plasma confinement devices the confining toroidal current is induced in the plasma by means of a pulsed Ohmic-heating transformer.[1] From the engineering point of view a pulsed tokamak reactor is unattractive, and therefore ways must be found to drive the toroidal current continuously by other means, such as neutral beams[2] or radio-frequency (rf) power.[3] Lower-hybrid traveling waves, launched by a phased array of waveguides, have recently been proposed as an attractive means of efficiently generating toroidal currents in tokamaks.[4,5]

In lower-hybrid injection experiments in tokamaks, changes in the plasma loop voltage have been reported and identified with current drive at relatively low densities (10^{12}–10^{13} cm^{-3}).[6-10] Generation of several amperes of rf current has also been reported in several small devices, e.g., by Wong, Horton, and Ono.[11] In some of these experiments the inferred current was attributed to generation of runaway electrons.[6,8,9] However, in the JFT-2 experiment[7] good agreement with the Fisch theory[4] was claimed even though the rf pulse length, t_{rf}, was much shorter than the L/R time, $t_{L/R}$, so that observation of an rf-induced change in the toroidal current was not possible. Even though in the JFT-2 experiment a weak phase dependence of the loop voltage was found, changes in the loop voltage due to surface currents, current profile modifications, electron heating, and runaway production cannot be excluded. Therefore, the agreement with theory[4,5] must be regarded as unproved. In the present paper we present the first unambiguous demonstration of a lower-hybrid-wave–driven current in a tokamak (which is possible in the Versator experiment since $t_{L/R} \lesssim t_{rf}$). It is also shown that under normal circumstances current generation can be obtained only in the slide-away regime[12] where a tail on the electron distribution exists even before the rf power is applied. Thus the present results show that the Fisch mechanism of efficient lower-hybrid current drive (i.e., raised plateau formation) is not the dominant mechanism in these experiments. Furthermore, all the experimental results reported until now operate in this low-density "slide-away" regime; therefore, at high density some mechanism must prevent the formation of the raised plateau, which is a prerequisite for efficient current generation.[4]

The experiments were carried out on the Massachusetts Institute of Technology Versator II tokamak: $R_0 = 40$ cm, $a_L = 13$ cm, $I_{OH} = 30$ kA, $t_{pulse} = 30$ msec, $\bar{n}_e = (2\times 10^{12})$–$(3\times 10^{13})$ cm^{-3}, $T_{i0} = 120$ eV, $T_{e0} = 200$–350 eV, and $Z_{eff} \simeq 2$. The rf source is an 800-MHz, 150-kW klystron with a modulator-controlled pulse duration of 10 msec, or 30 msec at reduced power. Present results were obtained using a six-waveguide grill antenna which has 0.8-cm gaps separated by 0.17-cm-thick walls and is 24 cm in height. The grill is normally positioned 1 cm behind the limiter and changing the relative phase between adjacent waveguides, $\Delta\varphi$, from 60° to 120° moves the antenna spectrum peak from $N_Z = 4$ to 11 with $\Delta N_Z/N_Z \simeq 0.8$.

The basic effect produced by injection of lower-hybrid power is shown in Fig. 1(a). Total current and loop voltage signals are superimposed for two discharges with and without rf power injection. During the rf pulse there is a large increase in the total current above the case with Ohmic heating only. The difference between the two currents, ΔI_t, exceeds 10 kA at maximum, then decreases after about 15 msec because of a loss of radial equilibrium caused by vertical field supply limitations.

The loop voltage signal initially decreases by 0.15 V, then shows sudden spikes consisting of a rapid increase followed by a slower decrease. It

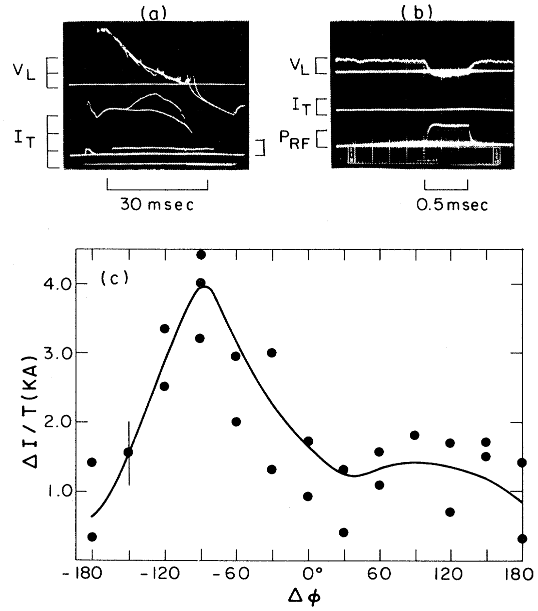

FIG. 1. (a) Superimposed signals with and without rf power: One-turn loop voltage (V_L) 0.8 V/div., total current (I_t) 8 kA/div., rf power 30 kW/div. (b) Loop voltage with $dI/dt = 0$ at high rf power: loop voltage 0.4 V/div., total current 4 kA/div. (baseline suppressed), rf power 30 kW/div. (c) Current increment ΔI_t normalized to rf power transmission coefficient T as a function of array phase $\Delta\varphi$ with a 4-msec rf pulse. Plasma parameters, $I_t = 30$ kA, $\bar{n} = 2\times 10^{12}$ cm^{-3}, $B_\varphi = 8$ kG.

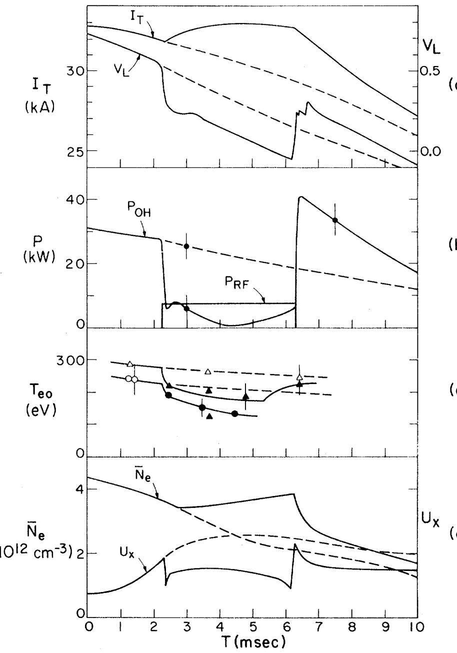

FIG. 2. Signals with (solid lines) and without (dashed lines) applied rf power, $\Delta\varphi = -90°$. (a) Total current (I_t) in kiloamperes and loop voltage ($V_{\rm loop}$) in volts. (b) Ohmic heating power from inductively corrected loop voltage ($P_{\rm OH}$) in kilowatts and rf power ($P_{\rm rf}$). (c) Central electron temperature in electronvolts from two different runs. Open circles and triangles: no rf. Closed circles and triangles: rf applied. The triangular data points were taken with a 3-msec-duration rf pulse. (d) Line-average density $\bar{n}_e$ in units of 10^{12} cm^{-3} and hard–x-ray signal U_x in relative units.

can be seen in Fig. 1(a) that these spikes occur at the same time as sudden small decreases in the time derivative of the total current, dI_t/dt. These voltage spikes generally become larger and more frequent at higher rf power. This voltage behavior has been reported in other lower-hybrid experiments.[8,9]

When a short rf pulse is applied at the time when the Ohmically driven current is beginning to drop, the total current can be maintained at a constant level, $dI_t/dt=0$ [Fig. 1(b)]. The single-turn loop voltage drops through zero and is maintained at a small negative level, $V \simeq -0.1$ V, for the duration of the rf pulse. The observation of negative resistive loop voltage, with $dI_t/dt=0$, eliminates edge heating as an interpretation of the rf effects; increasing the plasma edge conductivity by heating could cause a voltage drop, but clearly could not by itself produce a negative loop voltage.

The incremental current, ΔI_t, normalized to constant transmitted power shows a strong asymmetrical dependence on $\Delta\varphi$ [Fig. 1(c)]. The largest current increments are generated when $\Delta\varphi = -90°$, corresponding to a wave spectrum traveling in the direction of the electron Ohmic drift. Interestingly, when waves are launched opposite to the electron Ohmic drift, $\Delta\varphi > 0$, no decrease in total current is observed: Instead, only a smaller current rise occurs. The central electron temperature during rf injection with waveguide phasing optimized for current drive, $\Delta\varphi = -90°$, does not increase; instead, there is a cooling trend due, at least in part, to a decrease in the Ohmic heating power [Figs. 2(b) and 2(c)]. Bulk electron heating is therefore eliminated as an explanation of the rf-induced changes in current and loop voltage. These cooling effects disappear for positive values of $\Delta\varphi$ (anticurrent-drive injection) and there may be a small temperature increase.

Profile changes in the electron temperature can produce, through conductivity increases, a modification of the current profile and therefore an inductive voltage proportional to $I\,dL/dt$. However, such current-profile changes due to heating will occur on the electron-energy confinement time scale, of the order 0.5–1 msec in Versator II. Constant incremental voltage drops for the duration of the rf pulse, 10–30 msec, have been observed and therefore cannot be explained as profile changes. A model circuit calculation can easily be made to obtain an approximate value for the rf-generated current. Considering the mutual inductive coupling between the plasma current, rf-driven current, and Ohmic-heating transformer a simple expression for the loop voltage can be obtained: $V_L \simeq R_p(I_T - I_{\rm rf} - I_{\rm run}) + \Gamma \dot{I}_T$, where V_L is the loop voltage, I_T is the total plasma current, $I_{\rm rf}$ is the rf-driven current, $I_{\rm run}$ is the current carried by runaway or slide-away electrons, R_p is the Spitzer plasma resistance, and $\Gamma \dot{I}_t$ is the inductive voltage component. This simple model yields good semiquantitative agreement with measured voltage and current signals during rf drive. Furthermore, we find that (a) assumed extreme changes in L cannot account for the observed rise in the current without violating energy conservation; (b) transport code modeling of our experiments (including ray tracing and runaway production) do not indicate significant profile changes and again the $\dot{L}$ term is negligible.[13] Using this expression and the data in Fig. 2(a), we find $I_{\rm rf} \simeq 10–15$ kA, and under optimized conditions $I_{\rm rf} \simeq 20–30$ kA has been obtained.

The power dependence of the current rise [Fig. 3(a)] is approximately linear; ΔI_t is measured 1 msec after the rf-driven current rise, before the onset of any disruptive voltage activity which can occur when $P_{\rm rf} \gtrsim 15$ kW. The current rise, ΔI_t, is approximately independent of density for $\bar{n}_e \lesssim 6\times10^{12}$ cm^{-3} [Fig. 3(b)], but above this density, $\Delta I_t \simeq 0$ and apparently rf current cannot be driven. Also indicated in Fig. 3(b) is an experimental point obtained with $\bar{n}_e \simeq 4\times10^{12}$ cm^{-3} where $\Delta I_t = 0$. Discharges of this type, which we call type II, are obtained by reducing the electric field applied to the plasma during the first millisecond of the discharge and by increasing the initial hydrogen-gas feed rate. At the time the rf is applied, the type-II discharge has nominally the same parameters, I_t, B_ϕ, $\bar{n}_e$, and plasma position as the discharges, type I, supporting current drive; however, the two discharges differ in that type I has a larger preformed suprathermal electron tail than type II.

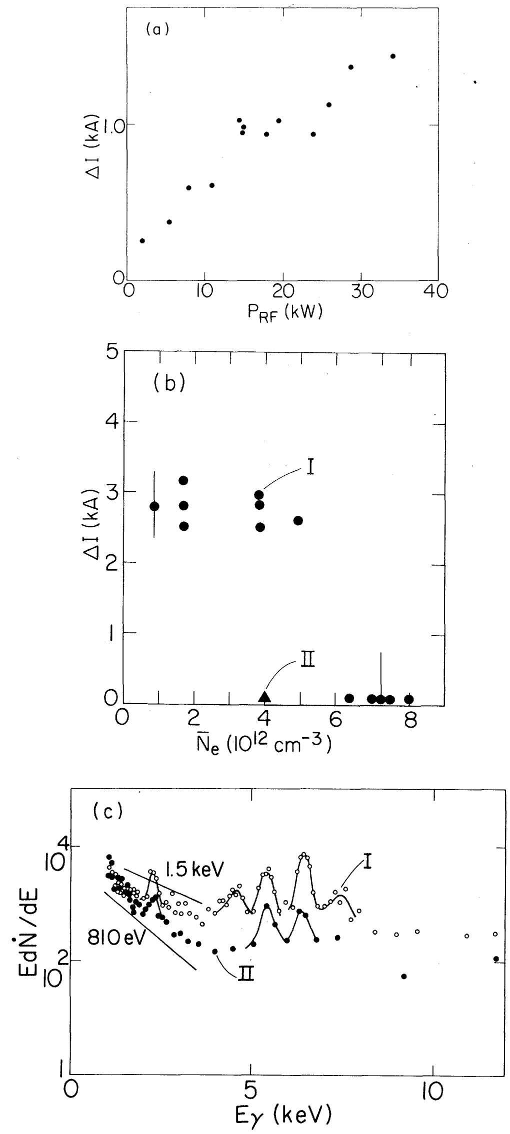

FIG. 3. Dependence of ΔI on rf power measured 1 msec after beginning of current rise (before first disruption). (b) Dependence of ΔI on average density at beginning of rf pulse in units of 10^{12} cm^{-3} in type-I discharges with deuterium plasma, $\Delta\varphi = 90°$, $P_{\rm rf} = 15$ kW (closed circles). Current increment in type-II discharge (closed triangle). (c) Soft–x-ray spectra of type-I and -II Ohmic-heating discharges without rf injection.

Soft–x-ray spectroscopy using a Kevex lithium-doped silicon Si(Li) detector and pulse-height analysis indicates enhanced soft–x-ray emission in the energy range of 2–5 keV, and an elevated tail temperature of typically 1.7 keV in type-I discharges compared to a tail temperature of 900 eV in a type-II discharge [Fig. 3(c)]. Type-II discharges generally exhibit fractionally larger loop voltage levels than type I with other conditions of current and density the same. Therefore, on the basis of these data it appears that a preformed suprathermal electron tail of medium energy is a necessary prerequisite for efficient rf current generation.

We recall that in several past lower-hybrid experiments production of the rf current has been attributed to rf-enhanced runaway production.[6,8,9] However, such a runaway current cannot account for many of the present experimental results, particularly the generation of a negative loop voltage in Fig. 1(b). Transport code studies including quasilinear diffusion and electron runaway effects indicate that runaway production may be associated with the rf current,[13] and in experiments with a four-waveguide antenna with $N_z \sim 4$, rf current has also been obtained. This antenna is expected to interact with higher-energy electrons so that rf-induced runaway production may become more important.

In summary, observations in the Versator II current-drive experiment can be consistently described if we hypothesize that efficient absorption of the lower-hybrid power occurs only by damping on a preformed suprathermal electron tail in the energy range 1–5 keV ($\epsilon/kT_e \simeq 4$–20). This range of energies is equivalent to the "plateau" electron population in the conventional current-drive theory.[4] The tail-absorption picture therefore accounts for the observed density limit, and the different behavior of discharges of types I and II with regard to current-drive efficiency. Since the slide-away tail is asymmetrically weighted in the direction of the electron drift, waves launched in the opposite direction to the electron Ohmic drift do not lead to efficient rf drive in agreement with experiment [see Fig. 1(c)]. At present we do not understand what prevents efficient current generation in a conventional higher density ($\bar{n} > 10^{13}$ cm^{-3}) Maxwellian plasma. In view of these results, to achieve steady-state rf-driven operation at high density, it may be necessary to start up at low density, build up the rf current, and then raise the density by gas puffing or pellet injection. Additional rf power may also be necessary.

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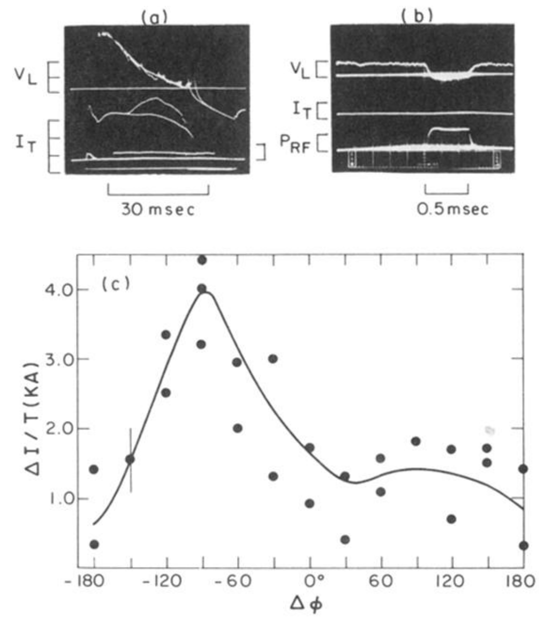

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