Observation of Lower-Hybrid Current Drive at High Densities in the Alcator C Tokamak

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A quasi-steady-state lower-hybrid current-drive operation is demonstrated in the Alcator C tokamak at densities up to $\bar{n}_e \simeq 1\times10^{14}$ cm^{-3}. The current-drive efficiency is measured experimentally over a wide range of densities and magnetic fields. The radial distribution of high-energy x rays indicates that the current-carrying electrons peak near the plasma axis.

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Generation of toroidal currents in tokamaks by injection of traveling lower-hybrid waves is currently of great interest in magnetically confined plasma-fusion research.[1] This interest arises from the possibility of steady-state tokamak operation which would make the tokamak concept a more attractive reactor candidate.[2] To present date, efficient "quasi-steady-state" operation has been demonstrated only at relatively low electron densities, namely at $\bar{n}_e \lesssim 8\times10^{12}$ cm^{-3} in the PLT tokamak.[3] This mode of tokamak operation is achieved by terminating the inductive current sources (Ohmic power) as the rf power is injected. Eventually, a pure rf mode of operation appears feasible.[4]

The low-density limit in the PLT experiments is believed to be a consequence of the relatively low frequency ($f=0.8$ GHz) used. In other experiments current drive has been demonstrated by injecting rf power during full Ohmic heating (OH) operation.[5–8] In these experiments significant dc electric fields often exist during rf injection which may modify the rf current drive figure of merit $\tilde{J}/\tilde{P}_d$.[1] In particular, the question of the influence of electron tails generated by the OH electric fields which existed before, or during rf injection, arises. Due to the relatively low frequencies ($f \leqslant 1.3$ GHz) even such "OH-assisted" experiments were carried out mostly at low densities ($\bar{n}_e \lesssim 2\times10^{13}$ cm^{-3}).

In this Letter we present experimental measurements of the efficiency of lower-hybrid current drive at reactor-relevant densities, namely at $10^{13} \lesssim \bar{n}(\mathrm{cm}^{-3}) \lesssim 10^{14}$. The experiments were carried out on the Alcator C tokamak (major radius $R=64$ cm, minor radius $a=16.5$ cm) where the high rf frequency ($f=4.6$ GHz) and high rf powers ($P\lesssim 1.1$ MW) used allowed us to demonstrate rf current-drive operation at high densities.[9] The lower-hybrid waves were launched by two 4×4 wave-guide arrays located 180° relative to each other around the torus. For the current-drive experiments described in this paper the phases of adjacent waveguides in each row were set at 90°. The Brambilla rf power spectrum under such conditions is concentrated between $N_\parallel = ck_\parallel/\omega = 1$ and 2.5 in the OH electron-drift direction, with approximately 30% of the power being in the opposite (negative) direction.[10] The negative portion of the spectrum is concentrated at relatively high values of $N_\parallel$ ($N_\parallel \sim 6$) and is expected to be absorbed by, and heat, the bulk plasma.

In the present experiments the primary winding of the Ohmic heating transformer was open-circuited before application of the rf power. After the OH primary is opened the plasma current decays inductively with a typical time scale of $t_{L/R} \sim 150$ msec. Upon injection of sufficiently high rf power, the current decay is arrested and a constant current with zero loop voltage is maintained by the waves.[9,11] In such cases the vertical-equilibrium magnetic field and the internal inductance were shown to reach a constant value for rf pulse lengths $t_{\mathrm{rf}} > 50$ ms.[11] Hence, in such cases, after about 50 ms into the rf pulse, inductive effects are negligible and the toroidal current is driven by the rf power alone. By monitoring the x-ray spectra in the range 10 to 500 keV, it was verified that just prior to application of the rf pulse a negligible amount of emission was observed. Under these conditions, the rf current-drive efficiency, defined as $\eta \equiv \bar{n}_{14} I_{\mathrm{MA}} R_{\mathrm{M}}/P_{\mathrm{MW}}$, has been determined (where $\bar{n}_{14}$ is the line-average electron density in units of 10^{14} cm^{-3}, I_{MA} is the total toroidal current in units of mega-amperes, R_{M} is the major radius in units of meters, and P_{MW} is the net injected rf power in units of megawatts). We note that η is related to $\tilde{J}/\tilde{P}_d$, the current-drive figure of merit, by the relationship $\eta \simeq 0.002 T_e(\mathrm{keV})\tilde{J}/\tilde{P}_d$.[1]

The rf current-drive efficiency in the quasi steady state (flat-top currents) was determined by plotting the product of the plasma current and the electron density versus rf power [see Fig. 1(a)] or the current divided by the rf power versus density [see

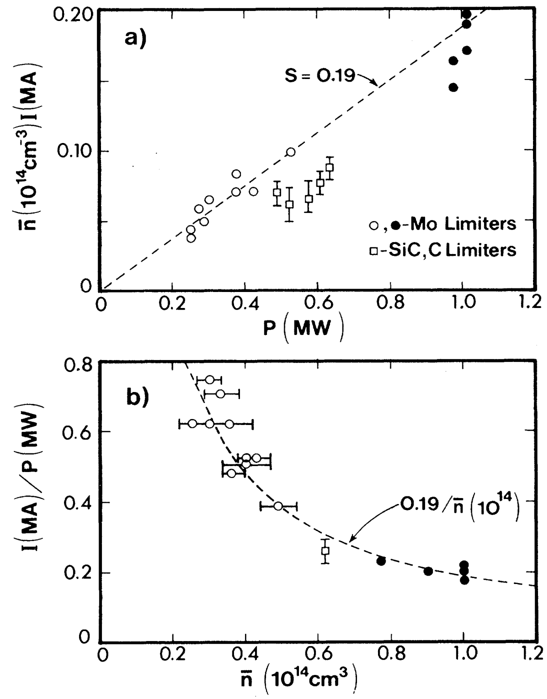

FIG. 1. (a) $\bar{n}_e I$ vs $P_{\rm rf}$ at $B = 10$ T; $dI/dt = 0$; H_2 gas. The solid circles are explained in the text. (b) $I/P_{\rm rf}$ vs $\bar{n}_e$ at $B = 10$ T; H_2 gas; same data as in Fig. 1(a). The dotted curves in Figs. 1(a) and 1(b) correspond to $S = \bar{n}_{14} I_{\rm MA}/P_{\rm MW} = 0.19$.

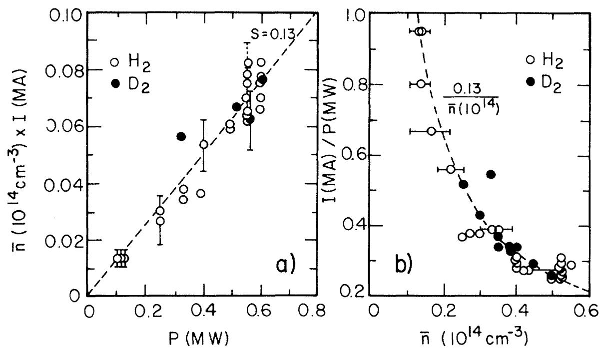

FIG. 2. (a) $\bar{n}_e I$ vs $P_{\rm rf}$ at $B = 8$ T; $dI/dt = 0$; (b) $I/P_{\rm rf}$ vs $\bar{n}_e$.

Fig. 1(b)]. These data points were obtained in hydrogen plasmas at a magnetic field of 10 T. In most cases the limiters used were molybdenum, although some data were also collected by using graphite and silicon-carbide-coated graphite limiters. With the graphite limiters the current drive efficiencies were typically 30% lower than those obtained with molybdenum limiters. Typical currents obtained for these data were in the range of $I \simeq 120$–230 kA. From the data shown in Figs. 1(a) and 1(b) we obtain a current-drive efficiency of $\eta = 0.12$. If we assume an electron temperature of $T_e \simeq 1.2$ keV during the current-drive steady state, (a reasonable value), we obtain $\tilde{J}/\tilde{P}_d \simeq 50$. We note that this analysis does not take into account either profiles or power lost by mechanisms other than collisional relaxation of the tail electrons on the bulk plasma.

At the highest densities ($\bar{n}_e \gtrsim 0.8 \times 10^{14}$ cm^{-3}), power levels of the order of $P \sim 1$ MW were required to maintain the 150–200 kA of plasma current. The consequence of the higher power injected at high densities was significant impurity generation[12] resulting in a drop in current generation efficiency after about 40–50 ms. Hence, we cannot be certain that, for the high-density data shown by the solid dots in Figs. 1(a) and 1(b), inductive effects are negligible. However, results obtained at lower densities and power levels indicate that the power required to flat-top the current at a given density during the first 50 ms provides a good estimate for the current-drive efficiency in our experiments.

As the magnetic field is decreased the current-drive efficiency at a given density also decreases. For example, at $B < 6$ T we found it difficult to maintain rf-driven discharges. At $B = 8$ T the current-drive efficiency data are shown in Fig. 2. Here data for both hydrogen and deuterium plasmas, with molybdenum limiters, are shown at power levels up to $P = 0.6$ MW and densities up to $\bar{n}_e \simeq 5.5 \times 10^{13}$ cm^{-3}. The current drive efficiency is $\eta = 0.08$. The reduced current-drive efficiency at lower magnetic fields may be a consequence of the combined effects of reduced accessibility to low $N_\parallel = ck_\parallel/\omega$ wave packets, and lower central electron temperatures.[13] However, further work is required to determine the exact cause of the reduced efficiency.

In our experiments approximately 30–60% of the rf power deposited in the tail finds its way to the bulk plasma and maintains the bulk temperatures near the original value. This is deduced from charge-exchange neutral measurements of the bulk ion temperature which during the rf-driven operation is usually found to remain within 20% of the Ohmic value.[14] A typical value of the OH power may be ~ 300 kW when ~ 500 kW of rf power is needed to replace it and flat-top the plasma current. The electron temperatures were were not measured directly in these experiments. Possible causes for the less than optimal power balance may be poor confinement of the high-energy electron tail, radiation losses, and poor penetration and/or absorption efficiency of the initially low-$N_\parallel$ power spectrum.

The plasma hard x-ray emission was also measured before and during application of the rf power. In Fig. 3(a) we show chord-integrated x-ray spectra obtained from the plasma center by a 5 cm×5 cm NaI scintillator. These data were obtained at an average density of $\bar{n}_e = 5.5\times10^{13}$ cm^{-3}, $P_{rf} = 670$ kW, and an rf generated flat-top plasma current of $I = 160$ kA. We see that without rf power there is negligible emission, whereas with rf power a high-energy x-ray tail extending out to at least 450 keV is formed. Assuming Landau-type wave-particle interaction with electrons at these maximum energies, the present results indicate that the flat-top plasma current is carried by a high-energy electron tail produced by the rf power with a corresponding minimum $N_{\parallel} \simeq 1.2$. The detector system was moveable so as to permit measurements of the spectrum at different chordal locations on a shot-to-shot basis. The chord-averaged emission from such a scan at two different photon energies is shown in Fig. 3(b). The emission is seen to peak on axis out to at least 200 keV with a half width of about 5–10 cm. Abel-inverted x-ray profiles yield qualitatively similar results. We have also measured the time evolution of the energy-integrated x-ray emission. At a density of $\bar{n}_e \simeq 5\times10^{13}$ cm^{-3} it is found that the rise time of the x-ray emission is 2–3 ms, which agrees well with the theoretically predicted quasilinear plateau-formation time.[1]

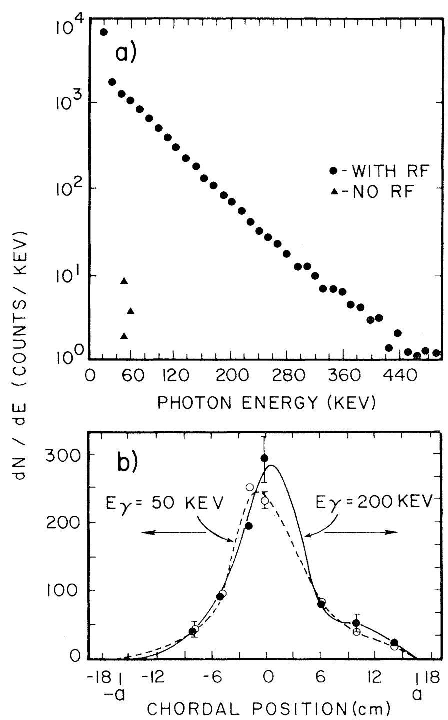

FIG. 3. (a) X-ray spectrum during flat-top current-drive shots; $\bar{n}_e = 5.5\times10^{13}$ cm^{-3}, $B = 10$ T, $I_p = 160$ kA, H_2 gas, $P_{rf} = 670$ kW. (b) Radial plot of the hard x-ray emission at $E = 50$ keV and 200 keV; $\bar{n}_e = 5.5\times10^{13}$ cm^{-3}, $B = 11$ T, $I_p = 200$ kA, H_2 gas, $P_{rf} = 800$ kW.

These results are further corroborated by measurements of the $2\omega_{ce}$ and $\omega \lesssim \omega_{pe}$ emission.[15] We find that while there is moderate (~ 500 eV antenna temperature) emission at frequencies $f \lesssim f_{pe}$ during the rf flat-top current-drive phase, in the post-rf phase a steady increase to highly nonthermal emission is observed which is often accompanied by bursting emission.[15] The enhanced post-rf emission phase is believed to be due to the acceleration of the rf-produced quasilinear plateau electrons (which are at the multi-100-keV level) to multi-MeV levels by the inductive electric fields which develop upon termination of the rf injection in the plasma. In fact, multi-MeV x-ray emission has also been observed in this post-rf phase.[16]

In summary, we have observed lower-hybrid quasi-steady-state rf current drive in a toroidal plasma at densities up to $\bar{n}_e \simeq 1\times10^{14}$ cm^{-3}. The maximum current-drive efficiency $\eta = \bar{n}_{14} I_{MA} R_M / P_{MW}$ at a magnetic field of $B = 10$ T was $\eta = 0.12$ and at $B = 8$ T, $\eta = 0.08$. The upper values of η correspond to a normalized current-drive figure of merit of $\tilde{J}/\tilde{P}_d \approx 50$. In the absence of rf power there is only negligible x-ray emission at energies $\epsilon \gtrsim 30$ keV. Since we launch a high-phase-velocity rf power spectrum, ($N_{\parallel} < 3.0$) a mechanism to upshift part of the rf power spectrum must exist in order to explain these results. Initial modeling by a combined ray tracing, transport, and Fokker-Planck code indicates agreement with these results if a toroidal upshift of the $N_{\parallel}$ spectrum is included.[13] Furthermore, the maximum local value of $\tilde{J}/\tilde{P}_d$ observed in the computer modeling is in the range of 40 to 60.[13]

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