# Current Rampup by Lower-Hybrid Waves in the PLT Tokamak

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Recent lower-hybrid current-drive experiments have clearly demonstrated that the current in a tokamak discharge can be maintained by rf drive alone. We have extended the operating regime of such plasmas to include ramping up of the current. We find that at densities of $\sim 2\times 10^{12}$ cm$^{-3}$ approximately 20% of the launched rf power is converted to magnetic field energy.

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In the years since Fisch[1] proposed that lower-hybrid current drive (LHCD) would be an efficient means of maintaining the current in a tokamak, LHCD experiments have amply demonstrated that this is so.[2-5] Steady-state currents have been maintained in a tokamak by rf drive alone, without the help of an Ohmic-heating (OH) transformer.[2] Furthermore, it has also been shown that tokamak discharges can be initiated and the plasma current ramped up from zero by LHCD alone.[6,7] In order for LHCD to be useful in assisting the OH transformer of future plasma devices, a high-efficiency conversion of rf to poloidal field energy is needed. This need applies generally to plasma initiation, to recharging the OH transformer, and to current rampup.

However, it is not immediately obvious that high efficiencies can be obtained. Whereas the OH transformer exchanges flux with the plasma column, LHCD creates flux on or near the axis of the column. In the former case, the flux, in penetrating the plasma column, creates an electric field parallel to the plasma current, which maintains or increases the current. In the latter case, LHCD, the external flux (and the off-axis internal flux) must come from the flux created on axis by the rf drive: In leaking outward, this axial flux creates an electric field $E$ antiparallel to the current. This field $E$ should cause a back current to flow in the bulk of the plasma, thus opposing the buildup of the current. Moreover, because LHCD interacts with a population of superthermal electrons,[8,9] a strong possibility exists that under the influence of this field some of these electrons could run away in the backward direction, generating a second opposing current of high conductivity. Both of these back currents would act to oppose increases in the net plasma current.

On the other hand, a theory of current drive in the presence of a dc electric field has been developed by Fisch and Karney[10] and Karney, Fisch, and Jobes,[11] which shows that current drive can be quite efficient in the presence of an opposing electric field. In essence, the theory calculates the ratio of the power given by the current-carrying electrons to the opposing field (i.e., to the poloidal field) to the power lost by collisions. From this ratio, a rampup efficiency is derived which is shown to be a function of the ratio of electron velocity to runaway velocity.

In view of the need for high efficiencies and the possibility that they might not be obtainable, we have carried out experiments on the Princeton Large Torus (PLT) tokamak to measure and optimize the efficiency of ramping up of plasma current. The experiments were performed on discharges which had been initiated but not maintained by the OH transformer. At low densities ($\bar{n}_e \sim 2\times 10^{12}$), we have achieved rampup efficiencies, $\epsilon$, of up to 20%, where $\epsilon = \dot{W}/P_{\rm rf}$, $\dot{W}$ is the power flowing into the poloidal field energy, and $P_{\rm rf}$ is the average rf power launched into the plasma.

For these experiments, the tokamak was run with deuterium plasmas; the plasma current $I_p$ ranged from 150 to 400 kA and the density from 1.5 to $6\times 10^{12}$ cm$^{-3}$. Typically, the OH transformer primary was precharged to $\sim 5$ kA, and then reversed, as in normal PLT operation, but then the primary current was clamped (that is, the OH input power reduced to $\sim 0$) and the plasma current sustained by LHCD. It is this turning off of the OH power which distinguishes these PLT experiments from other current-drive experiments which leave the OH transformer on at normal power levels.[3-5] In some of these experiments[3,4] the current indeed ramped up, but since the OH power levels were sufficient to maintain the current nearly constant and were comparable to the power flowing into the poloidal field, no clear statement can be made about rf rampup. The PLT experiments were designed to minimize the effects of the OH transformer.

The LHCD apparatus on PLT consisted of a six-waveguide grill, with each waveguide independently driven by a 160-kW, 800-MHz source.[2,6,12] The parallel phase velocity $v_{\rm ph}$ of the wave was determined by the relative phasing of the individual waveguides. The phase difference $\Delta\phi$ between waveguides was set electronically at the inputs to the sources; for the experiments reported here, $\Delta\phi$ was 60°, 90°, and 135°, corresponding to an average $N_\parallel$ ($= c/v_{\rm ph}$) of 1.5, 2.3, and 3.4. The spectral width (at half maximum) of the grill was $\Delta N_\parallel \sim 1.5$. At the highest phase velocities,

$\Delta\phi = 60°$ and $N_\parallel = 1.5$, some of the spectrum is inaccessible[13] to the plasma, even at the lowest densities.

rf rampup is illustrated in Fig. 1, which shows the $I_p$ wave form for several different rf powers. At the lowest power, 40 kW, the rf drive was just sufficient to maintain the current constant for these experimental conditions, i.e., $\bar{n}_e = 2.2\times 10^{12}$ cm$^{-3}$, $I_p \sim 200$ kA, $\Delta\phi = 60°$. At the highest power, 260 kW, the current ramps up at 125 kA/sec during the time the density is constant. Since $l_i/2 \sim 0.55$, $\dot{l}_i/2 \sim -0.24$, and $I_p = 208$ kA, this is an inductive rampup power of 70 kW. Since the external power contributed 19 kW, the net rampup power was 51 kW and $\epsilon = 20\%$. At and above this power, however, the plasma limiters were excessively heated. Because of this heating, the higher-power pulses were restricted to 300 msec, whereas the lower-power pulses were 350 msec.

The inductive energy of the plasma, $W = I_p^2 L/2$, can be evaluated from the equation for the inductance of a torus:

$$L = \mu_0 R_0 [\ln(8R/a) - 2 + l_i/2], \quad (1)$$

where $R_0$ and $a$ are the major and minor radii of the plasma column and $l_i/2$ is the (unitless) internal inductance of the plasma column. $l_i/2$ can be determined from the Shafranov equilibrium equation

$$4\pi B_{ef} R_0 = \mu_0 I_p [\ln(8R/a) - \tfrac{3}{2} + l_i/2 + \beta_\theta], \quad (2)$$

where $B_{ef}$ is the transverse magnetic field required for equilibrium and $\beta_\theta$ the plasma pressure term. $\beta_\theta$ is not well known in PLT; we estimate the component of $\beta_\theta$ resulting from the energetic electron tail to be $\sim 0.1$–$0.2$, or approximately a 5% effect. In all calculations presented here we assume $\beta_\theta = 0.15$, and, furthermore, ignore the first 50 msec of the rf pulse, which is when $\beta_\theta$ builds up to its large value.

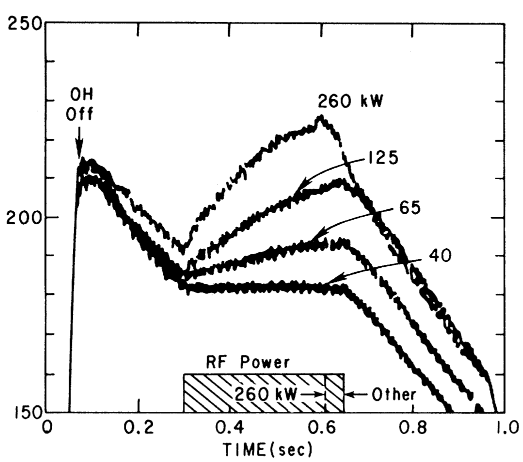


FIG. 1. Current rampup for various rf powers, and $\bar{n}_e = 2.2\times 10^{12}$ cm$^{-3}$.

The power flow into the inductive energy, $\dot{W}$, is not by itself an adequate measure of the ability of the rf drive to ramp up the plasma current because the OH and equilibrium-field (EF) coils are also contributing power to the plasma. For most of the experiments described here, the OH power supply was clamped at various output currents. The clamping was not perfect, so the OH transformer added approximately 15 kW of drive. For some data points, however, the OH supply was open circuited, and therefore supplied no power. On the other hand, since the EF is approximately proportional to the plasma current, the EF system always supplies power to the plasma when the plasma current is increasing; this EF power is $\sim 11\%$ of $\dot{W}$. Since these powers are small compared to $\dot{W}$ for the largest rampup cases, we define a corrected inductive power $\dot{W}' = \dot{W} - P_{ext}$, where $P_{ext}$ is the sum of the OH and EF powers, and an efficiency $\epsilon \equiv \dot{W}'/P_{rf}$. $\dot{W}'$ and $\epsilon$ are not constant in time, and for the examples in Fig. 1(a), they both start relatively high and decrease in time over the first 100 msec or so of the rampup. This behavior is not general, and on other shots they increase or stay about the same. This transient behavior has been eliminated from our analysis by averaging all quantities from the beginning of the rf pulse either to the end of the pulse or until the density had increased by $0.5\times 10^{12}$ cm$^{-3}$ (which sometimes happened during high-power pulses). The averaged values of $\dot{W}'$ and $\epsilon$ are our measure of the effectiveness of rampup.

$\dot{W}'$ is shown in Fig. 2(a) as a function of $P_{rf}$ for three different phasings, corresponding to $N_\parallel = 1.5$, 2.2, and 3.4 (peak of the spectrum). $I_p$ was 200 kA. In this figure, the faster wave (smaller $N_\parallel$) gives the better rampup, and, in general, the best results were obtained with the fastest waves and the lowest density. In Fig. 2(b), $\epsilon$ is shown as a function of $P_{rf}$ for these best conditions, $N_\parallel = 1.5$, $\bar{n}_e = 2.2\times 10^{12}$. At low power $\epsilon$ is negative because the rf power is less than the dissipation, $D$, in the plasma. When these balance, $\epsilon$ is zero (at equilibrium, $D \sim I_p \bar{n}_e R N_\parallel^2$).[1] Above that power level, $\epsilon$ increases rapidly until it reaches a plateau, which in this case is $\sim 20\%$. The power at which the plateau is reached is approximately three times the $\epsilon = 0$ power. In other cases, with higher density or current, or larger $N_\parallel$, the dissipation is larger, the $\epsilon = 0$ power is also larger, and the point at which the plateau is reached is at a much higher power; the plateau, however, is also lower.

The back current in the bulk of the plasma is given by $I_b = V/R$, where $V$ is the axial loop voltage and $R$ the bulk (Spitzer) resistance. Although $V$ can be determined, $R$ is generally unknown. However, $R$ can be estimated from the few Thomson-scattering measurements of $T_e$ that were taken during current drive (although during steady-state current drive and at a

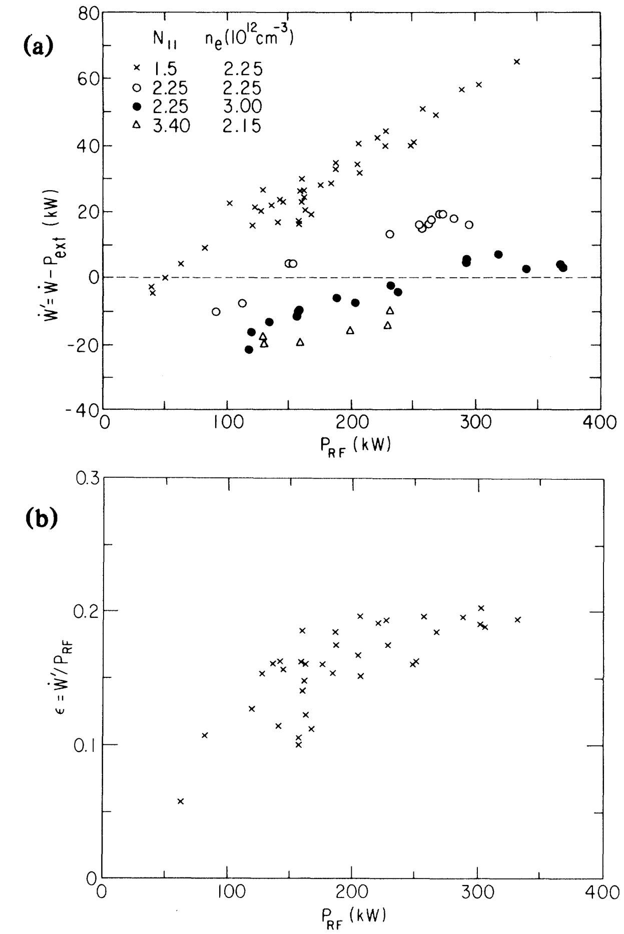


FIG. 2. (a) Corrected inductive power $\dot{W}' = \dot{W} - P_{\text{ext}}$ as a function of rf power for the four different conditions shown in the legend. For all conditions, the plasma current was 200 kA. $\beta_\theta$ of 0.15 was assumed in the calculation of $\dot{W}'$. (b) The ratio of corrected poloidal energy flow $\dot{W}'$ to net rf power $P_{\text{rf}}$ as a function of $P_{\text{rf}}$ for the condition shown by crosses in (a).

somewhat higher density), and with $Z_{\text{eff}} = 4$ estimated from x-ray measurements. Typically, $T_e$ was about 1 keV (peak) for which the calculated $R = 9\ \mu\Omega$. For the 260-kW case of Fig. 1, then, the thermal back current would be 44 kA and the $L/R$ time of the bulk electrons $\sim \frac{1}{3}$ sec. If a power-balance model is used to estimate $T_e$, with both the containment time (15 msec) and the temperature profile $[1-(r/a)^2]^m$, $m=4$, taken from an average of the Thomson-scattering measurements, then electron temperatures of less than 1 keV would be expected for the lower-power cases of Fig. 1, but greater at the higher powers. For the 260-kW case, the calculated $T_e$ is 1.35 keV and the bulk back current 70 kA, which is about $\frac{1}{3}$ of the forward current.

The possibility of an enhanced tail of runaway electrons in the backward direction during rampup is a major concern. Unlike a bulk back current, these electrons would not be slowed down by collisions, and could constitute a highly conducting back current, which would shield out all subsequent changes in current. The properties of the energetic electron tail were studied by x-ray pulse-height analysis with use of NaI(Tl) detectors working in the range of $20 < h\nu < 750$ keV. The detectors viewed the plasma both parallel and perpendicular to the magnetic axis of the tokamak. During steady-state current-drive discharges ($\epsilon = 0$), the bremsstrahlung emission typically reaches a constant value after $\sim 50$ msec, and then does not change; changes in bremsstrahlung emission with time are usually associated with the action of electric fields in the plasma. Since bremsstrahlung emission at high energies is highly directional, an increase in emission in a given direction can be interpreted as an increase in the tail in that direction. (The terms forward and backward emission will be used to denote emission parallel and antiparallel to the rf wave.)

Systematic x-ray data are available for only a few rampup discharges. Data were taken, however, for a case where $P_{\text{rf}} = 200$ kW, $\epsilon \sim 15\%$, $L\dot{I} \sim 0.16$ V, and $\bar{n}_e \sim 2\times10^{12}$ cm$^{-3}$; for these conditions, which are similar to those shown in Fig. 1, we infer a runaway energy of $\sim 200$ keV. The backward bremsstrahlung emission increased by a factor of $\simeq 1.5$ during a 250-msec rampup pulse, as shown in Fig. 3(a). The rate of buildup of backward emission slowed after the first 150 msec of rf. The forward x-ray emission showed a small but statistically insignificant decrease with time [Fig. 3(b)]. These x-ray measurements indicate that the electric field is indeed reversed in the plasma and suggest that the backward suprathermal electrons may carry of the order of 10% of the forward current.

In the course of our rampup experiments, we have achieved efficiencies of up to 20% at densities of $2\times10^{12}$ cm$^{-3}$. Above three times the power required for current equilibrium (where $\dot{I} = 0$), the efficiency remains essentially constant. For the highest rampup rates, the induced back current would appear to be (30–50)% of the forward current. These results are in substantial agreement with the theory of Karney, Fisch, and Jobes, as shown in Ref. 11. Transformer recharge efficiencies up to 10% have recently been reported[14] on the Asdex tokamak at Garching.

If comparable rampup efficiencies can be achieved on larger machines, such as TFTR or TFCX, then rf rampup is a viable means of assisting or replacing OH transformers and can lead to fusion devices without the need for these transformers.

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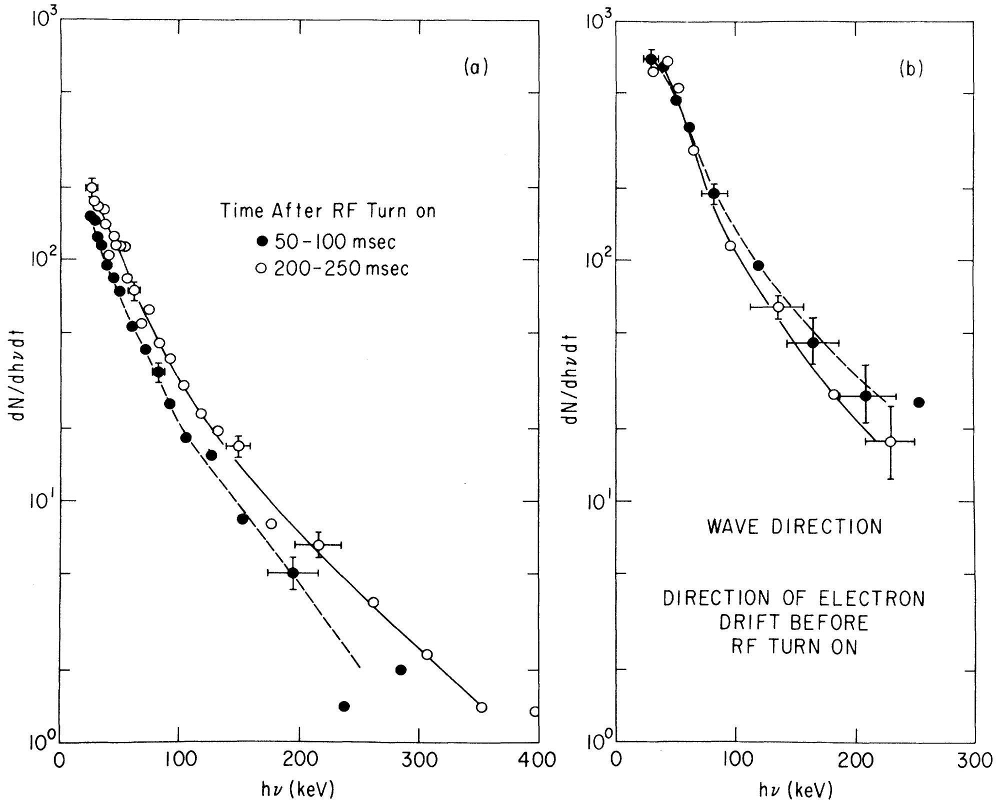


FIG. 3. (a) Hard-x-ray photon counts vs energy taken at two different times. The viewing angle is in the plane of the plasma center line and intersects the plasma center line at an angle of 28°. The direction is approximately antiparallel to the direction of the rf wave-phase velocity. The spectrum taken at the later time shows a factor of ~ 1.5 increase in emission. (b) Photon counts vs energy viewed approximately parallel to the direction of the rf wave-phase velocity.

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