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LOWER HYBRID CURRENT RAMP-UP IN THE PLT TOKAMAK*

R. MOTLEY, R. BELL, S. BERNABEI, A. CAVALLO,
T.K. CHU, S. COHEN, B. DENNE, P. EFTHIMION,
N.J. FISCH, E. HINNOV, W. HOOKE, J. HOSEA,
F. JOBES, C.F.F. KARNEY, E. MAZZUCATO,
E. MESERVEY, J. STEVENS, S. SUCKEWER,
G. TAYLOR, J. TIMBERLAKE, S. von GOELER,
R. WILSON
Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey,
United States of America

Abstract

LOWER HYBRID CURRENT RAMP-UP IN THE PLT TOKAMAK.

A study of radiofrequency current ramp-up in the PLT tokamak is reported. The plasma current was first raised to 200–300 kA by the Ohmic heating transformer, and the current in the transformer primary circuit was then held constant to remove the OH drive. After the current fell below 200 kA, up to 300 kW of the toroidally directed RF power at 800 MHz was transmitted into the PLT plasma via a 6-element phased waveguide array. Current ramp-up rates between 0 and 120 kA/s for a 0.35 s time interval ((1/2–1/3) L/R time) were measured at densities between 2 and 4 × 10^{12} cm^{-3}. It is estimated that about 20% of the RF energy introduced into the vacuum vessel was converted into poloidal magnetic field energy, $LI^2/2$, where $L \approx 3\ \mu H$ is the total inductance of the plasma current loop. This conversion ratio should depend on a variety of factors, including the percentage of RF power absorbed by resonant electrons and the magnitude of the back current induced by the changing poloidal flux LI. The high ramp-up efficiencies are predicted theoretically in the regime in which the PLT ramp-up experiments operate, i.e. where the phase velocity of the waves is approximately equal in magnitude to the runaway velocity due to the back voltage. Comparison of the raw data with theory suggests that about 1/2 to 3/4 of the incident RF power is absorbed by resonant high-velocity electrons.

INTRODUCTION

Following initial theoretical suggestions [1] and favorable results on a number of tokamaks, PLT [2], ALCATOR C [3], JFT-2 [4], WT-2 [5], VERSATOR-II [6], JIPP-T-II [7] and PETULA [8], lower hybrid current drive has been developed to the point where it is now seriously considered in the design studies for

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proposed large tokamaks such as TFCX and INTOR. Both transient and steady state ($\tau > L/R$) tokamak discharges have been created, as well as current startup and ramp-up by RF means alone.

The future development of this method of non-inductive current drive remains uncertain because of the need for high RF power levels. However, a more clearly defined, near-term role for lower hybrid waves has emerged: to help the air-core transformers in large tokamaks such as TFTR achieve higher currents, and therefore better ion confinement, during neutral beam heating. With this end in mind, we have studied the efficiency with which RF energy can be converted to poloidal field energy during current ramp-up experiments on the PLT tokamak.

The minimum power needed to maintain an RF-driven discharge depends on the frequency of the collisions between current-carrying tail electrons and the background plasma. The presence of a dc electric field during current ramp-up, however, destroys this simple relationship between collisions and power dissipation. Collisions during ramp-up can also be beneficial, since they prevent electron runaway in the presence of the (backward-directed) electric field induced by the change of magnetic flux linked by the torus. We can distinguish three regimes of operation, which are characterized by the relative strength of the electric field and the collisional friction on the electrons which interact with the rf waves. If collisions are dominant, then most of rf energy is wasted in heating the plasma. If the electric field is dominant, there is a high probability of the electron running away in the backward direction. If the backward runaways are confined, they will drain substantial energy from the poloidal field. Finally, if the two effects are comparable, i.e. the wave phase velocity is about equal to the runaway velocity, then a substantial fraction of the rf energy may be converted into poloidal field energy without runaway production. The ramp-up experiments on PLT appear to fall in this last favorable regime, or in a regime in which some runaways are created, but not long confined.

THE EXPERIMENT

The 800 MHz lower hyrid current drive apparatus on PLT consists of a 6-waveguide grill, with each guide independently driven by a 160 kW source [2]. The phase difference $\delta\Phi$ between waveguides is set electrically and arbitrarily at the inputs to these sources; for the measurements reported here $\delta\Phi$ was 60°, 90° and 135°, corresponding to an average $n_{\parallel}$ of 1.5, 2.3 and 3.4. The spectral full width (at half maximum) of the grill is $\delta n_{\parallel} \approx 1.5$. At the highest phase velocities, $\delta\Phi = 60°$ and $n_{\parallel} = 1.5$, some of the spectrum is inaccessible to the plasma, even at the lowest densities.

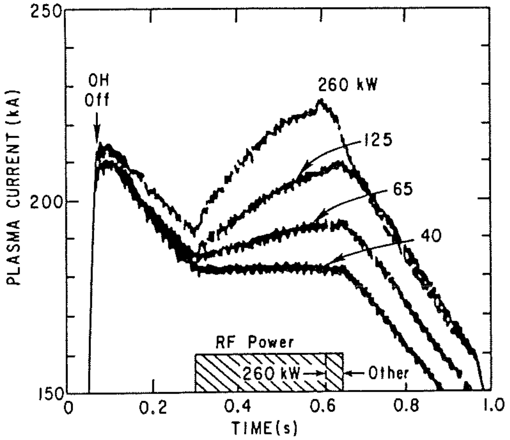

FIG.1. Current ramp-up using RF power (40–260 kW). The OH transformer was turned off: $\bar{n}_e = 2.2 \times 10^{12}$ *cm*$^{-3}$.

For these experiments the tokamak was run with deuterium plasmas, and with the plasma current I ranging from 150 to 400 kA and the density from 1.5 to 6 × 10^{12} cm^{-3}. Typically, the OH transformer primary was biased and then the current was reversed, as in normal PLT operation, but then the primary was clamped and the plasma current sustained by lower hybrid current drive. Often the clamping was not perfect, so that the OH transformer added approximately 15 kW of drive. For ~ 25% of the data reported here, however, the current in the primary was in fact set to zero, and the power supply open circuited; in these cases the OH transformer supplied no drive power. In either case, however, the equilibrium field coil (EF) supplied some drive to the plasma, in an amount approximately proportional to $\dot{I}$, and typically 10% of the total power flowing into the poloidal field energy.

Figure 1 shows a set of ramp-up experiments. The plasma was initiated by the OH transformer and the plasma current brought up to ~ 210 kA. At 100 ms into the discharge, the primary current was clamped and the plasma current allowed to decay. The density was 2.2 × 10^{12} cm^{-3} and after the 100 ms point the OH transformer contributed ~ 6 kW of drive - a loop voltage of 33 mV. After 300 ms, at which time the current had decayed to approximately 180 kA, the RF was turned on for over 350 ms (300 in the 260 kW case), which is ~ 1/3 of an L/R time. Forty kilowatts sufficed to maintain the current nearly constant under these plasma conditions and additional power caused ramp-up, with 260 kW producing an $\dot{I}$ of ~ 120 kA/s.

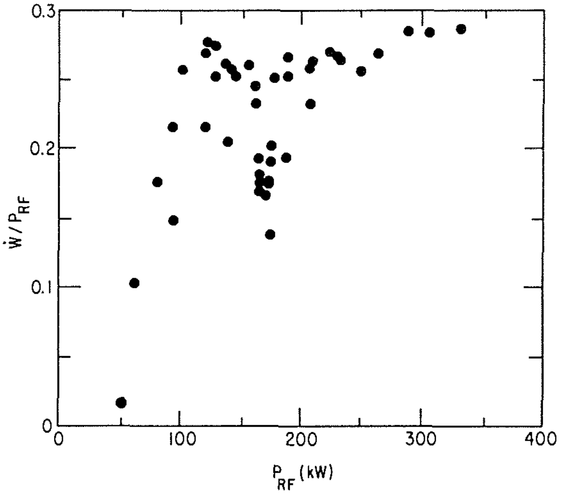

FIG.2. The ratio of poloidal energy flow $\dot{W}$ to net RF power P_{RF} as a function of P_{RF}. $\dot{W}$ has been corrected for inductive coupling from the OH and equilibrium coils.

This high ramp-up rate was sustained for only 200 ms; after that, a hot spot appeared on a limiter which caused a sudden density rise, which in turn reduced the ramp-up rate. No hot spots appeared in the other cases shown in Figure 1, and the density remained constant. The hot spots occur at high power and long pulse times.

A measure of the effectiveness of current-drive ramp-up is given by the conversion ratio $\varepsilon = \dot{W}/P_{RF}$, where P_{RF} is the net RF power going into the plasma, and where $\dot{W} = (d/dt)LI^2/2 - P_{ext}$, and P_{ext} accounts for the power coupled via the EF and OH windings of the tokamak. The ramp-up efficiency is not constant, but is a function of RF power and phase velocity, and plasma current and density. Figure 2 shows the variation of ε with RF power input for $\bar{n}_e = 2.2 \times 10^{12}$ cm^{-3}, $I \approx 180$ kA, $\delta\Phi = 60°$. Below 40 kW, ε is negative, i.e. the RF power is insufficient to hold the current constant. Above 50 kW, ε rises rapidly to a maximum of ~ 25%. Under other conditions (higher density or phase angles > 60°), the maximum ε varies between 12 and 20%.

THEORY

It is convenient to distinguish between the different channels for power flow in the system. An rf source of power P_{RF} is transmitted into the system, of which some fraction η is absorbed by resonant electrons. The absorbed power, $P_{in} = \eta P_{RF}$,

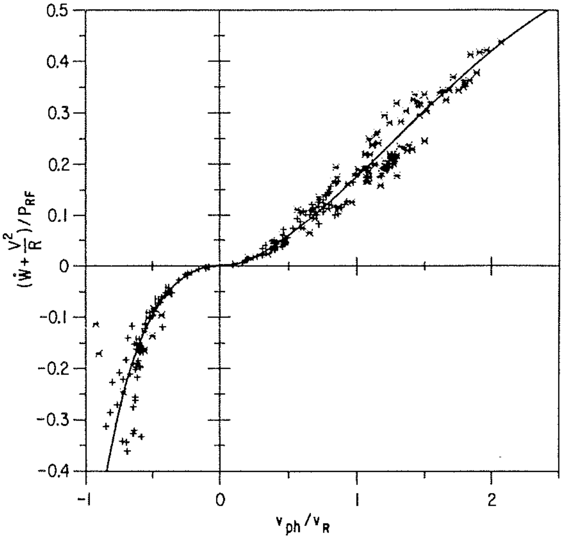

FIG.3. The efficiency $(\dot{W} + V^2/R)/P_{RF}$ *as a function of the ratio of the phase velocity* v_{ph} *to the runaway velocity* v_R. $\overline{n_e} = (1.5-6.0) \times 10^{12}\ cm^{-3}$; $I = (150-400)$ *kA.* $\Delta\phi$ *values are:* ✖ *60°;* ✚ *90°.*

flows in two directions: a power P_H goes into Coulomb collisions, causing bulk heating, and the remainder $P_{el} = P_{in} - P_H$ is available to increase the poloidal field energy. The change in poloidal field energy is given by $\dot{W} = P_{el} - V^2/R$, where V^2/R represents the resistive bulk heating of the back current, i.e. work done by the field on the background plasma; V is the loop voltage; R is the plasma resistance.

From the above discussion, it is reasonable that the conversion efficiency, P_{el}/P_{in}, depends primarily on the dimensionless ratio $\langle v_{ph}\rangle/v_R$, where the runaway velocity v_R, which is related to the Dreicer velocity, is given by $v_R^2 = |4\pi n_e e^3 \log \Lambda/Em_e|$ and $\langle v_{ph}\rangle$ is the average phase velocity of the waves. The problem may be formulated in terms of the Langevin equations for an electron suffering collisions and being decelerated by an electric field [9]. When the waves increase the energy of a particle, there is a resulting increase in the energy flowing into the poloidal field, $e\int Ev_{\parallel}\,dt$. The ratio of these two increments gives P_{el}/P_{in}, which depends only on $\langle v_{ph}\rangle/v_R$ and the ion charge Z.

In order to compare the theoretical results with the experimental data, we plot P_{el}/P_{RF} (where $P_{el} = \dot{W} + V^2/R$)

against $\langle v_{ph} \rangle / v_R$. Here R is taken to be the Spitzer resistance of the background plasma, based on Thomson scattering measurements, and V is the calculated loop voltage. The runaway velocity is obtained from the measured density and loop voltage, and $\langle v_{ph} \rangle$ is estimated by taking the peak of the Brambilla $n_\parallel$ spectrum and multiplying by a factor of 1.4.

The theoretical efficiency P_{el}/P_{in} differs from P_{el}/P_{RF} by the absorption factor η. We therefore plot $\eta\, P_{el}/P_{in}$ and adjust η to give the best fit. The comparison between theory (line) and experiment is shown in Fig. 3. In this case, we took Z = 5 and fitted $\eta = 0.75$. There are two points worthy of note. When the experimental data are plotted in this way, there is very little scatter in the points, despite the fact that Fig. 3 includes the results of over 200 discharges operating in a variety of regimes. The second point is that the experimental data closely follow the theoretical curve. Note that there are only two adjustable parameters in this fit - the absorption factor η, and the $n_\parallel$ upshift factor. If there is no upshift of $n_\parallel$, then $\eta = 0.5$ gives the best fit.

SUMMARY

Measurements of lower hybrid current ramp-up following ohmic discharges in the PLT Tokamak show that 15-25% of the RF input power can be converted into poloidal field energy. Calculations show that this conversion ratio is reasonable, because the phase velocity of the waves is comparable to the velocity for electron runaway in the (back) electric field induced by the current ramp-up.

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DISCUSSION

S. TANAKA: In your current ramp-up experiments, I_p is increased while the electron density is constant. What change is observed in the electron velocity distribution function, especially in the high energy tail electrons?

R. MOTLEY: In our analysis we assume that the shape of the electron distribution function is not reflected by ramp-up. We have, however, no experimental evidence for this yet.

G. FUSSMANN: Do you have any information on the confinement time of the 'tail electrons'?

R. MOTLEY: We have no direct evidence showing whether the surface tail electrons are formed at the centre or on the periphery. Since the electron temperature is so low and the confinement so poor at the edge, we believe that the electrons diffuse from the core.

V.E. GOLANT: What can you say about the role of fast electron losses in the energy balance of your current drive experiment?

R. MOTLEY: First, we estimate that only 5–10 kW of power (out of about 200 kW) is sufficient to account for the limiter hot spots observed. Secondly, a lower limit to the hot electron confinement time during current drive at the lowest densities can be established by assuming that all the power is lost in the tail. By this method we obtain $T_{hot} \leqslant 30$ ms.