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IN THE PLT TOKAMAK

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ABSTRACT

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 $\sim 2 \times 10^{12} \text{ cm}^{-3}$ approximately 25% of the launched RF power is converted to magnetic field energy.

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In recent years, lower hybrid current drive (LHCD) experiments have amply demonstrated that a steady-state current can be maintained in a tokamak by RF drive alone, without the help of the ohmic heating (OH) transformer.¹⁻³ Furthermore, it has also been shown that tokamak discharges can be initiated and the plasma current ramped up from zero by LHCD alone.^{4,5} 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, recharging the OH transformer, and to current ramp-up.

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 E-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 E-field antiparallel to the current. This E-field 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,^{6,7} a strong possibility exists that under the influence of this E-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.

In view of the need for high efficiencies and the possibility that they might not be obtainable, we have carried out experiments on the PLT tokamak to measure and optimize the efficiency of ramping-up 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 ramp-up efficiencies, ϵ , of greater than 25%, where $\epsilon = \dot{W}/P_{rf}$, $\dot{W}$ is the power flowing into the poloidal field energy, and P_{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 $6 \times 10^{12} \text{ cm}^{-3}$. Typically, the OH transformer primary was precharged to ~ 5 kA, and then reversed, as in normal PLT operation, but then the primary current was clamped and the plasma current sustained by LHCD.

The LHCD apparatus on PLT consisted of a 6-waveguide grill, with each waveguide independently driven by a 160 kW, 800 MHz source.^{1,4,8} The parallel phase velocity v_{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 $N_{\parallel}$ ($= c/v_{ph}$) 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, $\Delta\phi = 60^\circ$ and $N_{\parallel} = 1.5$, some of the spectrum is inaccessible⁹ to the plasma, even at the lowest densities.

RF ramp-up is illustrated in Fig. 1a, which shows the I_p waveform 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., $\bar{n}_e \approx 2.2 \times 10^{12} \text{ cm}^{-3}$, $I_p \sim 200$ kA, $\Delta\phi = 60^\circ$. At the highest power, 260 kW, the current ramps up at 120 kA/sec, which is an inductive ramp up power of 82 kW. Since the external power contributed 19 kW, the net rampup power was 63 kW and $\epsilon = 24\%$. At and above this power, however, a subsidiary effect limited the ramp-up process. A small hot spot ($< 1 \text{ cm}^2$) appeared on

one of the limiters; subsequently, an uncontrolled increase in density (possibly caused by out-gassing from the hot spot) then curtailed further ramp-up. The density increase was accompanied by a large increase in carbon V emission. The density trace for the 260 kW case is shown in Fig. 1b, illustrating this effect. Also shown are the loop voltage and the internal inductance signal, $\beta_\theta + \ell_i/2$. Because of this hot spot, the higher power pulses were restricted to 300 msec, whereas the lower power pulses were 350 msec. These times are all short compared to the L/R time (>1 sec) of the plasma column.

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

$$L = \mu_0 R [\ln(8R/a) - 2 + \ell_i/2] ,$$

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

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

where B_{ef} is the transverse magnetic field required for equilibrium and β_θ the plasma pressure term. β_θ is not well-known in PLT; we estimate the component of β_θ due to the energetic electron tail to be ~ 0.1 - 0.2 , or approximately a 5% effect. However, in all calculations presented here we neglect β_θ .

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 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 field 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 ramp-up cases, we define a corrected inductive power $\dot{W}' = \dot{W} - P_{\text{ext}}$, where P_{ext} is the sum of the OH and EF powers, and an efficiency $\epsilon \equiv \dot{W}'/P_{\text{rf}}$. $\dot{W}'$ and ϵ are not constant in time, and for the examples in Fig. 1a, they both start relatively high and decrease in time over the first 100 msec or so of the ramp-up. 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 to either the end of the pulse or until the density increased by $0.5 \times 10^{12} \text{ cm}^{-3}$. The averaged values of $\dot{W}'$ and ϵ are our measure of the effectiveness of ramp-up.

$\dot{W}'$ is shown in Fig. 2a 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 ramp-up, and, in general, the best results are obtained with the fastest waves and the lowest density. In Fig. 2b, ϵ 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 ϵ is negative because the RF power is less than the dissipation, D , in the plasma. When these balance, ϵ is zero (at equilibrium, $D \sim I_p \bar{n}_e R N_{\parallel}^2$).¹⁰ Above that power level, ϵ increases rapidly until it reaches a plateau, which in this case is $\sim 25\%$. The power at which the plateau is reached is approximately twice the $\epsilon = 0$

power. In other cases, with higher density or current, or larger N_p , 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.

A theory of current drive in the presence of a dc E-field has been developed to explain these ramp-up results.^{11,12} In essence, the theory divides the current carrying electrons into two categories; those with parallel velocities less than and those greater than the runaway velocity V_R associated with the E-field and the plasma density. Because the E-field is opposed to the velocity of these electrons, it does not cause them to run away, but rather acts to slow them down. In so doing, they give up energy to the E-field, which means putting energy into the associated poloidal field. Collisions, too, slow down the electrons, and, simultaneously with both slowing down processes, the electrons also regain energy from the RF wave. Electrons with velocities greater than V_R are more likely to lose energy to the E-field than by collisions, whereas the slower electrons are more likely to slow down by collisions. Thus ramp-up with electrons faster than V_R should be more efficient than with slower electrons. The theory determines the fraction of RF power which is converted into electric field energy.

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 resistance. Although V can be determined, R is generally unknown. However, R can be estimated from the few Thomson scattering T_e measurements that were taken during current drive (although during steady-state current drive and at a somewhat higher density), and using $Z_{eff} = 4$ estimated from X-ray measurements. Typically, T_e was about 1 keV (peak) for which $R = 9 \mu\Omega$ and the bulk plasma L/R time constant 0.37 sec. For the 260 kW case of Fig. 1 then, the back current would be

44 kA. If a power balance model is used to estimate T_e , taking both the containment time (15 msec) and the temperature profile $[1 - (r/a)^2]^m$, $m = 4$ 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 1/3 of the forward current.

The possibility of an enhanced tail of runaway electrons in the backward direction during ramp-up 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 using 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 ~ 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 ramp-up discharges. Data were taken, however, for a case where $P_{rf} = 200$ kW, $\epsilon \sim 15\%$, $LI \sim 0.16$ V, $\bar{n}_e \sim 2 \times 10^{12} \text{ cm}^{-3}$; for these conditions, which are similar to those shown in Fig. 1, we infer a runaway energy of ~ 200 keV. The backward

bremstrahlung emission increased by a factor of ≈ 1.5 during a 250 msec ramp-up pulse, as shown in Fig. 3a. 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. 3b). 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 ramp-up experiments, we have achieved efficiencies of up to 25% at densities of $2 \times 10^{12} \text{ cm}^{-3}$. Above 2-3 times the power required for current equilibrium (where $\dot{I} = 0$), the efficiency remains essentially constant. For the highest ramp-up rates, the induced back current would appear to be 30-50% of the forward current.

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

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REFERENCES

- 1 G. Bernabei et al., Phys. Rev. Lett. 49, 1255 (1982).
- 2 T. Maekawa et al., Phys. Lett. 85A, 339 (1981).
- 3 T. Yamamoto et al., Phys. Rev. Lett. 45, 716 (1980)
- 4 F. Jobses et al., Phys. Rev. Lett. 52, 1005 (1984).
- 5 K. Toi et al., Phys. Rev. Lett. 52, 2144 (1984).
- 6 S. von Goeler et al., in Proceedings of the Fifth Topical Conference on
Radio Frequency Plasma Heating (University of Wisconsin, Madison,
Wisconsin, 1983), p. 96.
- 7 J. Stevens et al., in Proceedings of the Fifth Topical Conference on
Radio Frequency Plasma Heating (University of Wisconsin, Madison,
Wisconsin, 1983), p. 164.
- 8 F. Jobses et al., Physica Scripta T2/2, 418 (1982).
- 9 R. Motley et al., in Proceedings of the Fifth Topical Conference on
Radio Frequency Plasma Heating (University of Wisconsin, Madison,
Wisconsin, 1983), p. 176.
- 10 N. Fisch, Phys. Rev. Lett. 41, 873 (1978).
- 11 N.J. Fisch and C.F.F. Karney, Princeton Plasma Physics Laboratory Report
PPPL-2132 (1984), submitted to Phys. Rev. Lett.
- 12 C.F.F. Karney, N.J. Fisch, and F.C. Jobses, Princeton Plasma Physics
Laboratory Report PPPL-2152 (1984), submitted to Phys. Rev. Lett.

FIGURE CAPTIONS

Fig. 1a. Current ramp-up for various RF powers, and $N_0 = 2.2 \times 10^{12} \text{ cm}^{-3}$.

Fig. 1b Density, loop voltage, and internal inductance parameter $(\beta_0 + \beta_1/2)$ waveforms for the 260 kW case of Fig. 1a.

Fig. 2a Corrected inductive power $\dot{W}' = \dot{W} - P_{\text{ext}}$ as a function of RF power for the four different conditions shown in the table. For all conditions, the plasma current was 200 kA.

Fig. 2b The ratio of corrected poloidal energy flow $\dot{W}$ to net RF power P_{rf} as a function of P_{rf} for the condition shown in X's in Fig. 2a.

Fig. 3a Hard X-ray photon counts versus energy taken at two different times. The viewing angle is in the plane of the plasma centerline and intersects the plasma centerline 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.

Fig. 3b Photon counts versus energy viewed approximately parallel to the direction of the RF wave phase velocity.

Fig. 1a

Fig. 1b

85X0055

Fig. 2a

Fig. 2b

Fig. 3

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