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INDUCTIVE EFFECTS DURING SECOND HARMONIC CURRENT DRIVE EXPERIMENTS ON T-10

by

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ABSTRACT

Current drive during second harmonic, electron cyclotron heating experiments performed on the T-10 tokamak have been simulated with the ONETWO transport code to determine the effects of induction on the time evolution of the loop voltage and current density profile. Ray tracing shows the well focused rf power can generate centrally peaked current densities which exceed the Ohmic current densities by a factor of five, causing very peaked plasma current profiles which will be unstable to sawteeth. A Kadomtsev model of the sawtooth shows that a limit cycle is quickly reached which maintains a broad current profile and requires generation of a negative dc component of the loop voltage localized near the magnetic axis. This negative electric field effectively reduces the measured current drive efficiency. A broader profile of driven current, as in the fundamental current drive experiment on T-10, would not suffer this effect.

INTRODUCTION

Recent experiments performed on the T-10 tokamak have shown the existence of an rf driven current during second harmonic electron cyclotron heating [see the paper by V.V. Alikaev et al., this conference]. The efficiency of current drive, as determined by differences in loop voltage measurements during co- and counter-rf current drive discharges, was lower than that of similar experiments performed at the first harmonic [V.V. Alikaev et al., Nucl. Fusion 32, 1811 (1991)] where results agreed with theoretical predictions. If it is assumed the absorption and current generation mechanisms are similar at first and second harmonic, the primary differences between these experiments are related to the difference in rf frequency (81 GHz at first harmonic and 140 GHz for the second harmonic). The launching structures were similar for each experiment; however, the angular divergence (approximately ± 1.5 deg) of the injected rf power for the second harmonic experiment was approximately half that of the first harmonic case. For centrally peaked damping, the width of the power deposition profile as estimated from the Doppler resonance condition is $\Delta R \approx v_t R_0 \Delta k_{\parallel} / \omega_{rf}$; thus, second harmonic power density should be a factor of four greater than in the first harmonic case.

The tokamak transport code ONETWO coupled with the ray tracing package TORAY has been used to analyze the evolution of the current profile for the second harmonic T-10 experiment. Time-dependent profiles of electron density and temperature are estimated from experimental data and are used for calculations. In particular, the tokamak equilibrium is evolved self-consistently with the pressure profile (determined by experimental data) and current profile (determined by TORAY and the Ampère-Faraday equations with neoclassical resistivity with fixed boundary). A Kadomtsev sawtooth model is also included which redistributes current and poloidal flux when various trigger criteria are met {e.g., q_0 decreasing below a predetermined value [W. Pfeiffer et al., Nucl. Fusion 25, 655 (1985)]}.

MODELING OF EXPERIMENT

Due to the strong localization of rf power, the rf driven current density at the center of the plasma is predicted to be a factor of 5 larger than the Ohmic current density. Figure 1 shows electron density and temperature profiles before and after the application of 650 kW of rf power to an 80 kA T-10 discharge. Also shown in Fig. 1 is the rf power deposition profile as determined by a TORAY calculation for a bundle of rays launched obliquely with an angle of 60 degrees to the magnetic axis with a Gaussian power profile of half-power width ± 1.5 degrees. During the rf phase, the magnetic axis of the plasma shifts from 151 to 155 cm, which places the cold electron cyclotron resonance at a major radius 7 cm smaller than the major radius of the magnetic axis, resulting in centrally peaked power deposition. Figure 2 shows the Ohmic current profile, and the calculated ECCD current profile as determined by a model including trapping [R.H. Cohen, Phys. Fluids 30, 2442 (1987) and Phys. Fluids 31, 421 (1987)].

FIG. 1. Electron temperature and density profiles before and during ECH.

FIG. 2. Profiles of Ohmic current before ECH, driven electron cyclotron current, and bootstrap current during ECH. Also shown is sawtooth inversion radius used in simulation.

The value Z_{eff} is determined by matching the loop voltage during the Ohmic phase and is assumed constant throughout the ECH phase (for this discharge $Z_{eff} \approx 2$). The simulation begins in the Ohmic phase, and the initial equilibrium has a current profile consistent with the electron temperature profile. The temperature and density profiles change during the switching-on period of the rf power. The rapid heating of the plasma and the changing conductivity profile can strongly affect the loop voltage measured on the boundary of the plasma and the internal parallel electric field.

Agreement with theory is determined by comparing the measured loop voltage and internal inductance with the predictions of ONETWO. The simulation has been performed for co-current drive with and without sawteeth, and without current drive (to show effects of changing conductivity profile). Distinctly different results were obtained with and without sawteeth. In particular, without sawteeth the quantity ℓ_i was approximately twice the measured value and the $q(0) \approx 0.2$ due to the extremely peaked current density profile. Figure 3 shows experimental data and simulation values for the loop voltage and Fig. 4 for $\beta_p + \ell_i/2$. For both parameters, the agreement is within 10% if the sawtooth model is included. The initial response of the experimental loop voltage is an artifact of the T-10 vertical position feedback circuit responding to the initial outward shift of the plasma and should be ignored. For

FIG. 3. The experimental and simulated loop voltages (with sawteeth) both with and without ECCD.

FIG. 4. The experimental values of $\beta_p + l_i/2$ for co- and counter-current drive, and simulated values with sawteeth (with and without current drive) and without sawteeth.

at which time the sawtooth occurs, redistributing the observed plasma current and raising q_0 to 1. With rf current drive, this paradigm remains valid with the additional effects of a peaked rf current source and Lenz's law generating a strong back emf. In this case we note that the cycle must include a negative dc electric field in the region near the magnetic axis to oppose the large rf current density. Immediately following the sawtooth crash an electric field will appear as the rf driven current is generated, to maintain the current density profile. As this large negative electric field begins to decay, the current density begins to peak until the profile becomes unstable to the sawtooth instability. Figure 5 shows the calculated evolution of the electric field profile interior to the plasma. In contrast with the case without sawteeth, the time scale on which the plasma evolves to a quasi-steady state is much shorter because of the redistribution of current by the sawtooth.

Figure 6 shows the time evolution of the simulated loop voltage on the boundary of the plasma and ECE from a central resonance showing the onset of sawteeth. Note that the loop voltage is decaying with time before the sawteeth and quickly reaches a steady-state when the sawtoothing starts.

of the plasma and should be ignored. For this case, the ONETWO simulation shows that the total current consists of 30 kA of ECCD, 20 kA of bootstrap current and 20 kA of Ohmic current. In spite of a relatively large rf driven current, the difference in loop voltage with and without current drive is small. This is a result of the sawteeth redistributing the current.

SAWTOOTH LIMIT CYCLE

The conditions in this experiment were unique in that local rf-generated current density on axis could be many times the current density in the Ohmic phase. The simulation shows that, as the current profile begins to peak, a large negative electric field is generated in the central region of the plasma to slow the rise of central current density — a result of Lenz's law. In the absence of sawteeth the simulation shows that the loop voltage on the magnetic axis asymptotically approaches the value on the boundary of the plasma on a magnetic diffusion time scale. With sawteeth, a different effect is observed.

In the Kadomtsev model of the sawtooth cycle, the current profile immediately following the sawtooth crash is such that the value of $q_0 \sim 1$. As the current peaks (q_0 decays) the profile becomes unstable to sawteeth. This is numerically determined by the $q = 1$ surface reaching a minor radius corresponding to the sawtooth inversion radius at

FIG. 5. (a) Calculated loop voltage evolution at the plasma boundary and at the magnetic axis with sawteeth. (b) $V_{loop}(r)$ immediately following sawtooth crash.

FIG. 6. Evolution of loop voltage and ECE showing onset of sawteeth and quasi-steady state loop voltage.

Quasilinear Fokker-Planck calculations have shown that negative electric fields strongly degrade the net current drive efficiency [see Harvey et al., this Proceedings]. With sawteeth, the rf driven current would thus be reduced due to the negative axial loop voltage; the self-consistent negative loop voltage would also be reduced. This emphasizes the importance of correctly estimating the effects of rf enhanced (or degraded) conductivity when evaluating current drive efficiencies.

The T-10 discharge is in a unique regime in which the rf-driven current density on axis can greatly exceed the current density of the Ohmic phase. For these discharges the ECCD as estimated by measurement of the loop voltage on the boundary of the plasma can underestimate the correct level of ECCD since much of the current can be cancelled by a sawtooth generated, negative dc loop voltage near the magnetic axis. Furthermore, the effects of rf enhanced (or degraded) conductivity require a self-consistent calculation to accurately determine the real value of ECCD. The close numerical agreement between experimental data and simulations with sawteeth suggest that the differences between first and second harmonic ECCD can be explained by the peaked deposition profile of the second harmonic experiments. Future experiments are planned to examine the effect of spreading of the EC beam. The results emphasize the need to match non-inductive current drive profiles to profiles which are stable to MHD instabilities if the full efficiency of the current drive method is to be realized.

CONCLUSIONS

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