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FLUCTUATIONS AND TRANSPORT IN THE REVERSED FIELD PINCH: CHARACTERIZATION AND REDUCTION

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Abstract

Reduction via current profile control of the low frequency, resonant, tearing mode fluctuations responsible for the stochastic magnetic field in the core of the RFP has been demonstrated in MST using auxiliary inductive current drive. In making this reduction, sawteeth are stabilized, and the energy confinement time doubles. To enhance and maintain current profile control and improved confinement, non-inductive current drive is required. Analytic and numerical studies indicate that electrostatic and RF current drive can stabilize the tearing fluctuations. Experiments to test such methods are in preparation on MST. In a second key area relating to RFP confinement, recent theoretical initiatives have found that, in the presence of tearing fluctuations, the growth rates and mode widths of short wavelength turbulence increases. If such turbulence governs transport at the edge of the RFP, then reduction of tearing modes may improve edge confinement as well.

1. INTRODUCTION

Magnetic fluctuations and transport have been reduced in the Madison Symmetric Torus (MST) reversed field pinch (RFP) by controlling the current density profile with auxiliary poloidal inductive current drive. Magnetic-fluctuation-induced transport has long been considered the dominant loss mechanism in the core of the RFP where resonant tearing fluctuations ($m=1$, $n\sim 2R/a$, $\tilde{B}/B\sim 1\%$) overlap to destroy the magnetic surfaces, allowing particles and energy to stream out along stochastic magnetic field lines. Correlation measurements of large magnetic-fluctuation-induced electron energy [1] and particle [2] fluxes in MST support this view. (However, an ambipolar constraint on the particle loss limits the

convective stochastic diffusion velocity to the ion thermal speed [2].) Auxiliary inductive current drive flattens the current density profile, suppresses sawteeth, reduces the magnetic fluctuation amplitude, and doubles the energy and particle confinement times [3]. Since poloidal inductive current drive requires a change of the toroidal flux embedding the plasma, steady-state current profile control must be accomplished with non-inductive current drivers. Proposed techniques include electrostatic current drive from limiters at the edge of the plasma [4, 5] and RF current drive in the lower-hybrid range of frequencies [6, 7].

The identification of $m=1$ tearing instabilities leads to predictable corrective measures for core transport, but the anomalous transport processes in the plasma edge have proved more difficult to understand. The same techniques which identified large magnetic-fluctuation-induced transport in the core indicate that the fluxes in the edge are small [1, 2]. On the other hand, the electrostatic fluctuation-induced particle flux is large at the edge [8]. Recent theoretical initiatives have found that, in the presence of tearing fluctuations, the growth rates and mode widths of short wavelength resistive interchange turbulence increase to experimentally relevant levels. If this turbulence is responsible for transport in the plasma edge, then tearing fluctuation reduction in the core may reduce transport in the edge as well.

2. POLOIDAL INDUCTIVE CURRENT DRIVE

Because the auxiliary poloidal electric field E_θ is transient, this experiment is referred to as pulsed poloidal current drive (PPCD). A small capacitor bank drives a fast current pulse in the toroidal field winding to induce $E_\theta = V_\theta / 2\pi a$ on the plasma surface (Fig. 1a). The pulse is initiated at 12 ms, marked by the vertical dashed lines. As intended, the pulse increases the plasma poloidal current $I_\theta = 2\pi R(B_o - B_{\phi w})/\mu_o$ shown in Fig. 1b. (The axis magnetic field B_o is estimated using an equilibrium model [9].) To direct E_θ for profile flattening, the average toroidal field $\langle B_\phi \rangle$ and toroidal field at the wall $B_{\phi w}$ must decrease (Fig. 1c).

PPCD flattens the current density profile, suppresses sawteeth [10], and reduces the magnetic fluctuation amplitude. To quantify the shape of the current density profile, I_ϕ, $B_{\phi w}$, and $\langle B_\phi \rangle$ are used to fit parameters α and λ_o in the equilibrium model $\nabla \times \mathbf{B} = \lambda_o(1-r^\alpha)\mathbf{B} + \beta_o \mathbf{B} \times \nabla p / 2B^2$ [11]. Finite pressure is included, but the perpendicular current details weakly affect the parallel current fit since β_o~7%. The time evolution of α is shown in Fig. 2a for a typical PPCD discharge. After PPCD is applied, α increases to near the value characteristic of the profile following a sawtooth "crash" (two of which occur between 8 and 12 ms), and then the profile slowly peaks again. By flattening the current density profile, PPCD slows the growth of the $m=1$ tearing fluctuations and suppresses their associated sawteeth. (Small sawteeth occur during PPCD, but the precursors are $m=0$, and they are less deleterious [3].) The spatial rms $\tilde{B}_\theta$ amplitude measured by 32 sensors on the plasma surface is shown in Fig. 2b for the same discharge; the (time) average value of the amplitude decreases by 25% during PPCD.

PPCD doubles the energy confinement by halving the Ohmic input power while modestly increasing the stored thermal energy. The solid curves in Fig. 3 show shot-averaged waveforms of the electron density, soft x-ray flux, Ohmic input power (E_θ included), and H_α emission from eleven PPCD discharges. The broken curves are averages from eight discharges without PPCD

but otherwise identically produced except for a small additional gas puff at 10 ms to mimic a density increase during PPCD. Thomson scattering was unavailable, but analysis of Be foil filtered x-ray fluxes and Si(Li) spectra indicates the electron temperature increases from 200 eV to 250 eV during PPCD. The charge-exchange ion temperature of 150 eV does not change. Assuming parabolic pressure profiles, the energy confinement time at t=17 ms doubles from $\tau_E \approx 1.0$ ms to $\tau_E \approx 2.2$ ms. The global confinement time in particle transport modeling also doubles, indicated by the increased density and decreased H_α emission.

Since the change in toroidal plasma resistance from increased poloidal field line twist during PPCD almost balances the change from reduced classical resistivity, the input power reduction implies decreased anomalous plasma resistance. The multiplier of the Z=1, flat temperature profile resistance decreases from 3 to 1.5 during PPCD. Bremmstrahlung radiation measurements indicate that Z_{eff} decreases during PPCD, but only by 20%.

In some MST discharges, long periods free of large sawteeth occur spontaneously. These discharges, which appear after extensive wall conditioning using a solid-target boronization technique [12], share elements of confinement improvement seen with PPCD. However, while PPCD consistently yields sawtooth stabilization, these spontaneous events are thus far limited to lower density, extremely clean plasmas.

3. ELECTROSTATIC AND RF POLOIDAL CURRENT DRIVE

PPCD clearly demonstrates a connection between current profile flattening, modest fluctuation suppression, and improved confinement, but it is inherently transient, and greater improvement in RFP confinement is desired. Electrostatic current drive (dc helicity injection) or RF current drive can in principle enhance and maintain an improved state. The original [4] nonlinear, resistive, 3D MHD simulations of electrostatic current injection into a straight, periodic, cylindrical RFP have been extended to larger effective aspect ratio ($R/a=3$) and Lundquist number ($S=10^4$) with varied source geometry [5]. In simulations of the ordinary RFP, the dominant toroidal mode number and spectrum width increase with increased aspect ratio [13], but a good configuration for tearing stabilization via electrostatic current drive can be chosen for any aspect ratio. While deviations from a toroidally symmetric source can destabilize resonant modes, source asymmetry is tolerable if chosen properly. In particular, toroidally localized, poloidally symmetric sources nonlinearly couple to $m=1$ modes and are ineffective for fluctuation suppression. On the other hand, poloidally localized, toroidally segmented sources still reduce the fluctuations by 1-2 orders of magnitude, restoring good flux surfaces in the core. The increased impedance effect of segmentation allows for practical implementation, and an experimental test is in preparation for MST. A prototype current injector generates $\geq$70 A/cm^2 uni-directional current density with no observed increase in impurity concentration.

RF current drive using the fast wave has been proposed for the RFP [6], but the lower hybrid (slow) wave may also be useful for edge current drive and fluctuation suppression [7]. Distinguishing features of RF current drive in the RFP are large ω_{pe}/ω_{ce}, large magnetic shear, and a small trapped particle fraction. Compared to a tokamak, large ω_{pe}/ω_{ce} necessitates a large parallel refractive index $n_\parallel \geq 8$ for wave accessibility. Nonlinear, resistive, 3D MHD simulations of "generic" auxiliary current drive using an ad hoc electron force show that a

Gaussian force profile with FWHM $0.1a$ is optimally centered ~$0.1a$ inside the reversal surface (typically located at $0.8a$) for tearing stabilization. For typical MST parameters, a lower-hybrid wave launched with $n_{\|} \approx 10$ at about 250 MHz will electron Landau damp efficiently in this target zone. To confirm analytic estimates, Brambilla's ray tracing code [14] has been modified to handle RFP equilibria. Figure 4a shows the ray trajectory in a poloidal plane for $n_{\|} \approx 10$ and 250 MHz traced out until the ray energy falls to 0.1% of its initial value. Figure 4b shows the driven parallel current density for 1 MW of RF power which is the approximate value predicted to stabilize a I_ϕ≈400 kA MST discharge.

4. HIGH FREQUENCY TURBULENCE

Recent theoretical work establishes that both electrostatic and magnetic turbulence in the edge is dependent on the tearing modes. Specifically, previous theoretical predictions of electrostatic g-mode turbulence fluctuation levels and transport rates that are far too small to account for the experimental observations [15] are significantly increased if the unstable tearing modes resonant in the core are accounted for in the calculation. This assertion is based on linear stability and nonlinear calculations for the g-mode in a configuration that is populated by a bath of long wavelength, slow time varying magnetic fluctuations [16]. The linear eigenmode equation is derived using a random phase approximation to describe the effect of the background modes. The modified linear theory predicts growth rates and radial mode widths that exceed the resistive MHD prediction for sufficiently large background magnetic fluctuation levels. For a given level of the background mode fluctuation amplitude, the linear growth rate and mode width are given by $\gamma_L = V_A[k_\perp L_S(-2\mu_o p'/rB^2)]^{1/2}[\delta\mathbf{B}\cdot\mathbf{r}/B_o]^{1/2}$ and $\Delta_L = (L_S/k_\perp)^{1/2}[\delta\mathbf{B}\cdot\mathbf{r}/B_o]^{1/2}$, where V_A is the Alfvén velocity, $k_\perp = n/R$ for toroidal mode number n and major radius R, L_S is the shear length, $p' = dp/dr$ is the equilibrium pressure gradient, and $\delta\mathbf{B}$ is a typical amplitude of the tearing mode induced magnetic field fluctuation. The nonlinear g-mode theory is developed by renormalizing the g-mode convective nonlinearities. This simple nonlinear calculation uncovers a turbulent pressure diffusivity given by

$$D = [\delta\mathbf{B}\cdot\mathbf{r}/B_o]^{3/2} V_A (RL_S^3/n)^{1/2}(-2\mu_o p'/rB^2)^{1/2}\Lambda^{3/2}$$

which is basically the mixing length estimate multiplied by a logarithmic factor $\Lambda = (4/\pi)\ln(1/k_\perp\Delta_L)$. Using the experimentally measured background magnetic fluctuation levels as input, the theory predicts an edge electrostatic fluctuation level of $e\phi/T \cong 0.16$ and an edge transport coefficient of $D \cong 25\,\mathrm{m}^2/\mathrm{s}$, both of which are comparable to the observed level.

Though it is not associated with significant transport, the spectrum of high frequency magnetic fluctuations is of considerable interest because its power law decay exponent [2], at variance with the canonical spectrum prediction of MHD [17], should indicate in what ways MHD is modified in the RFP edge. An examination of diamagnetic effects, in conjunction with the coupled evolution of density fluctuations and forcing at long wavelengths by finite amplitude quasi-coherent tearing modes, indicates that a spectral decay index like that measured in MST is possible in the context of Alfvénic turbulence [18]. In particular, the

nonlinear response time associated with a three-field model for 2D magnetic turbulence [19] has both Alfvénic and diamagnetic branches in a direct cascade of magnetic energy in the presence of large scale magnetic fluctuations that dominate the spectrum. If the diamagnetic branch is excited, possibly through matched frequencies with the quasi-coherent oscillations of the tearing modes, the fluctuation spectrum of the modified Alfvénic state is $E = \varepsilon^{1/2}(c_s\rho_s)^{1/2}L_n^{-1/2}k^{-3/2}$ for $k\rho_s < 1$ and $E = \varepsilon^{1/2}(c_s/\rho_s)^{1/2}L_n^{-1/2}k^{-5/2}$ for $k\rho_s > 1$, where ε is the rate of kinetic energy injected into the turbulence, ρ_s is the ion gyroradius evaluated at the electron temperature, c_s is the ion sound speed, and L_n is the density gradient scale length. This result supports the view that high frequency fluctuations are driven by low frequency tearing mode activity, but are also sensitive to local gradients in density and pressure.

5. SUMMARY

Inductive poloidal current drive flattens the current density profile, slows the growth of $m = 1$ tearing fluctuations, suppresses their associated sawteeth, and doubles the energy and particle confinement times. These results strongly encourage the program of fluctuation and transport suppression using current profile control in the RFP. Electrostatic or RF current drive techniques can in principle enhance and maintain profile control. An experiment to test electrostatic current drive is in preparation for MST, and an analytic and computational theoretical study has concluded that lower-hybrid current drive is well-suited for MST plasmas.

Theoretical calculations of edge turbulence models for electrostatic and magnetic fluctuations and comparison with experimental observations indicate that a crucial destabilizing role is played by the long wavelength tearing modes resonant in the core. Consequently, suppression of turbulence in the core may significantly improve both core and edge confinement.

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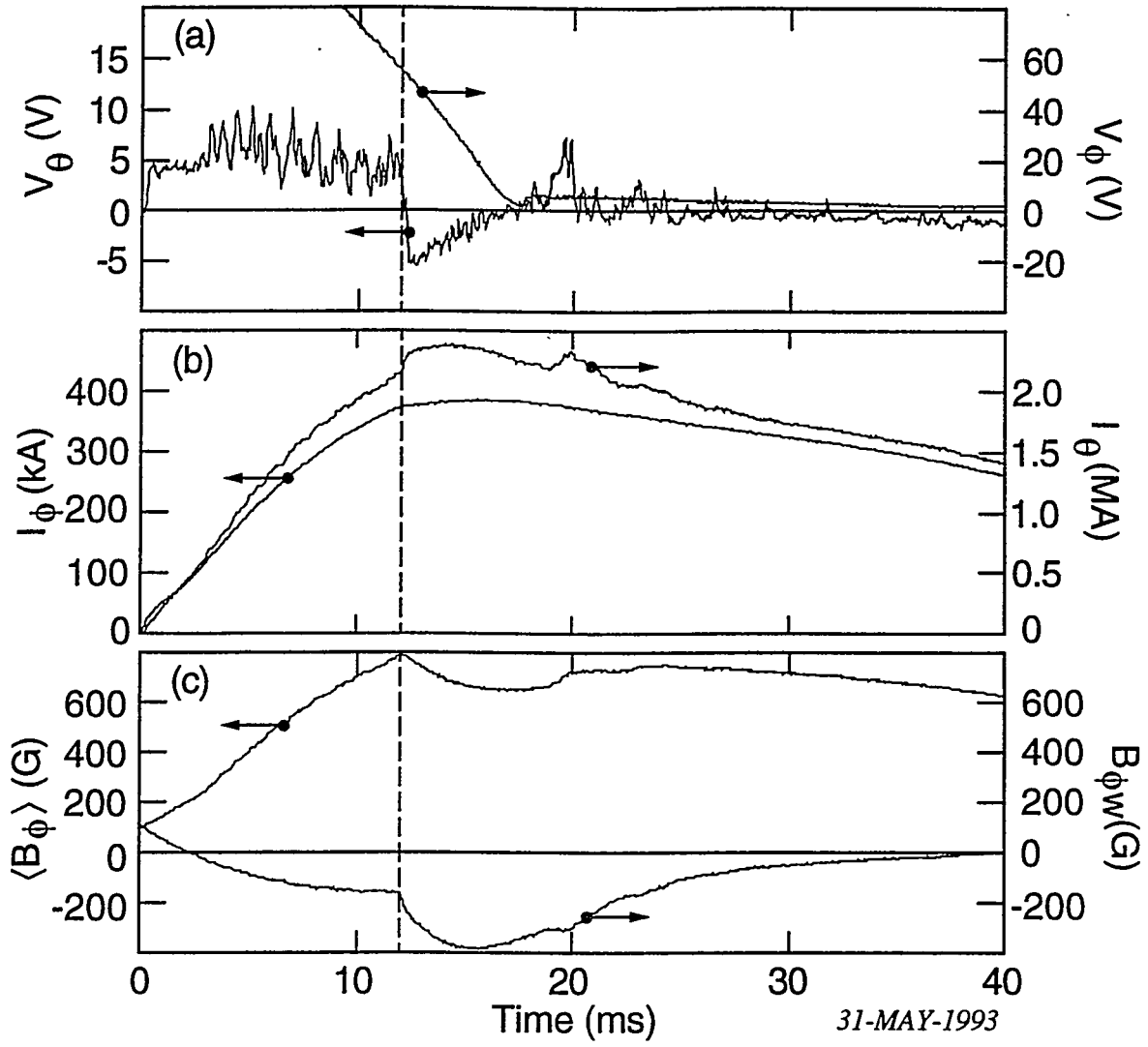


Fig. 1 Shot-averaged waveforms of (a) the surface voltages, (b) the plasma current, and (c) the average and wall toroidal magnetic field during PPCD.

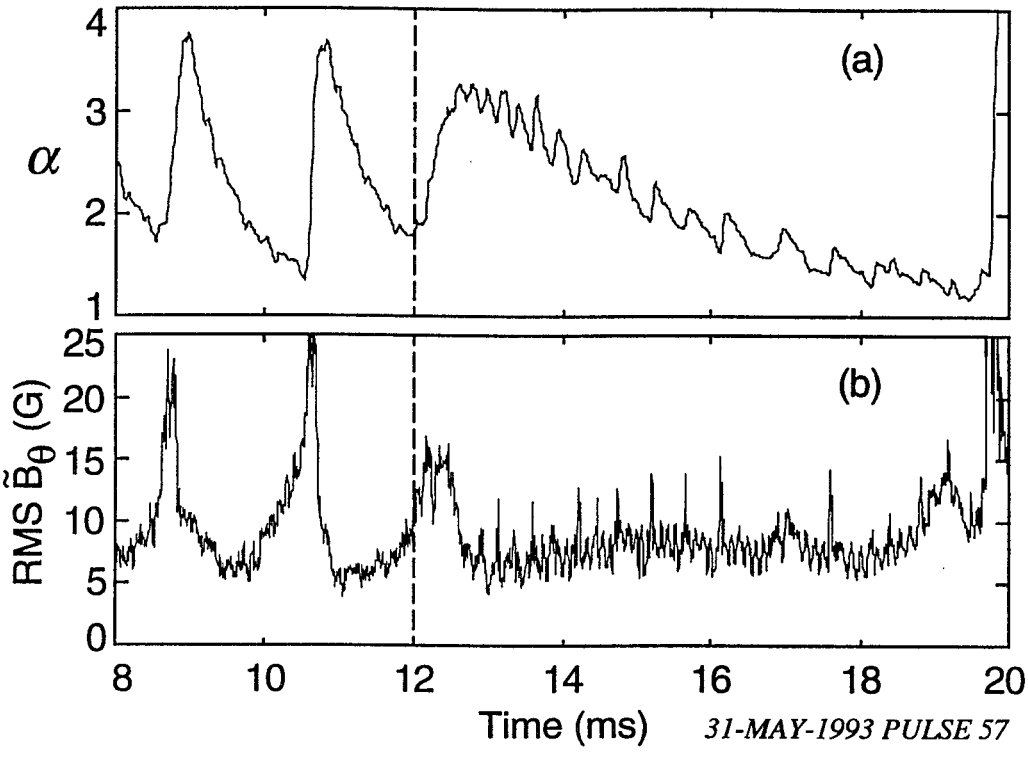


Fig. 2 (a) The current profile shape parameter α during a typical PPCD discharge. (b) The surface rms poloidal magnetic field fluctuation during the same discharge.

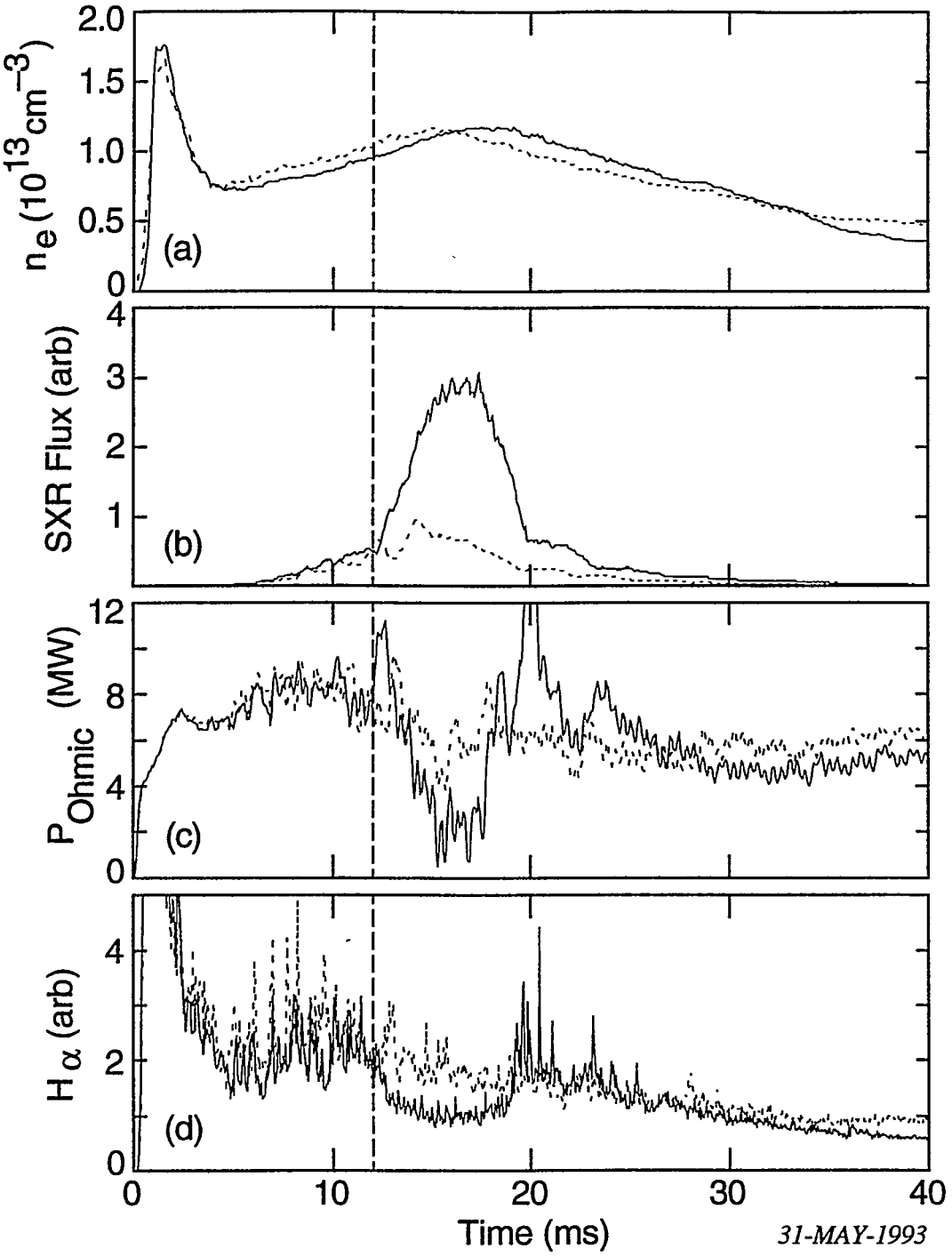


Fig. 3 Shot-averaged waveforms of (a) the central-chord line-averaged electron density, (b) soft x-rays, (c) the Ohmic input power, and (d) H_α emission with (solid) and without (dashed) PPCD.

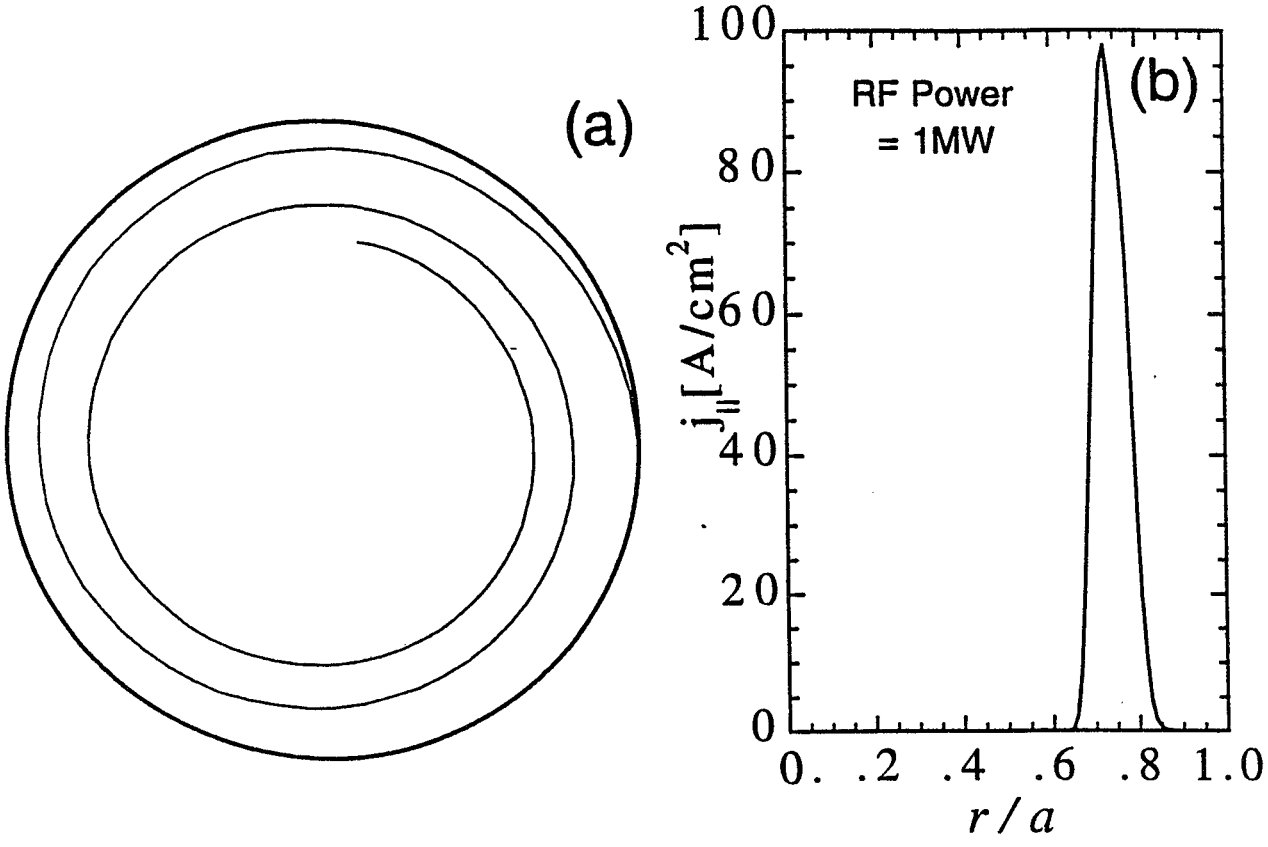


Fig. 4 (a) The trajectory of a 250 MHz, $n_{||} = 10$ lower-hybrid wave projected onto a poloidal plane. (b) The radial profile of RF driven parallel current.

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