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UNDER CONTRACT DE-AC02-76CH03073

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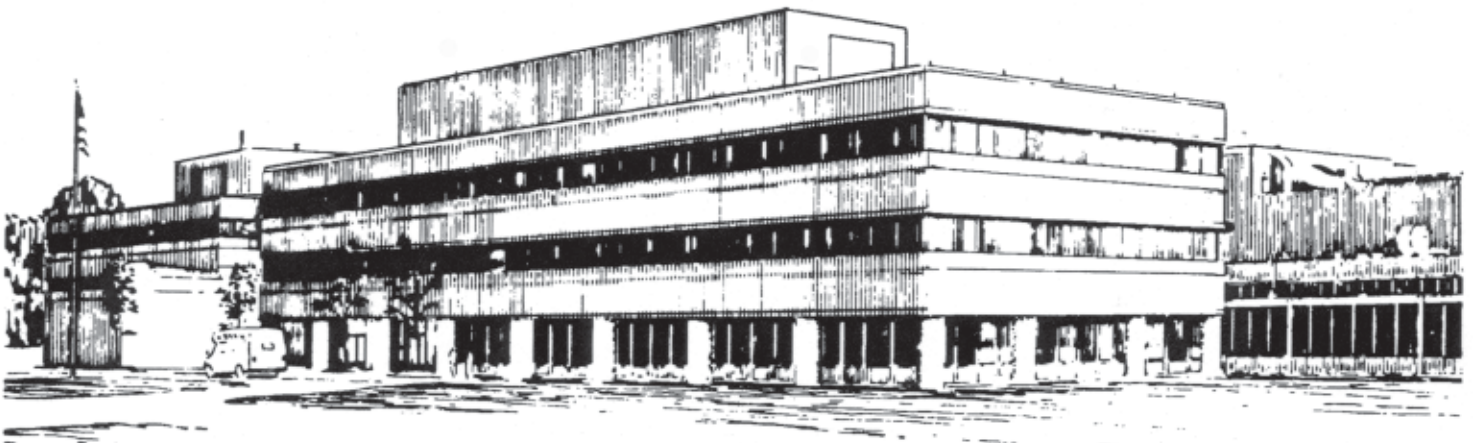
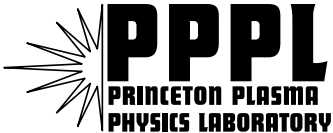
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**Simulation Studies of the Role of Reconnection  
in the “Current Hole” Experiments in the Joint European Torus**

by

J.A. Breslau, S.C. Jardin and W. Park

January 2003



**PRINCETON PLASMA PHYSICS LABORATORY  
PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY**

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# Simulation studies of the role of reconnection in the “current hole” experiments in the Joint European Torus

J.A. Breslau, S.C. Jardin, W. Park

*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543*

## Abstract

Injection of lower hybrid current drive into the current ramp-up phase of Joint European Torus (JET) discharges has been observed to produce an annular current distribution with a core region of essentially zero current density [Hawkes, *et al.*, Phys. Rev. Lett. **87**, 115001 (2001)]. Similar “current holes” have been observed in Japan Atomic Energy Research Institute (JAERI) Tokamak 60 Upgrade (JT-60U) discharges with off-axis current drive supplied by bootstrap current [T. Fujita, *et al.*, Phys. Rev. Lett. **87**, 245001 (2001)]. In both cases, the central current does not go negative although current diffusion calculations indicate that there is sufficient non-inductive current drive for this to occur. This is explained by Multi-level 3D code (M3D) nonlinear 2D and 3D resistive magnetohydrodynamic (MHD) simulations in toroidal geometry, which predict that these discharges undergo  $n = 0$  reconnection events — “axisymmetric sawteeth” — that redistribute the current to hold its core density near zero. Unlike conventional sawteeth, these events retain the symmetry of the equilibrium, and thus are best viewed as a transient loss of equilibrium caused when an  $\iota = 0$  rational surface enters the plasma. If the current density profile has a central minimum, this surface will enter on axis; otherwise it will enter off-axis. In the first case, the reconnection is limited to a small region around the axis and clamps the core current at zero. In the second case, more typical of the JET experiments, the core current takes on a finite negative value before the  $\iota = 0$  surface appears, resulting in discrete periodic axisymmetric sawtooth events with a finite minor radius. Interpretation of the simulation results is given in terms of analytic equilibrium theory, and the relation to conventional sawteeth and to a recent reduced-MHD analysis of this phenomenon in cylindrical geometry [Huysmans, *et al.*, Phys. Rev. Lett. **87**, 245002 (2001)] is discussed.

## I. Introduction

A great deal of interest has recently been generated by reports from experimental teams at the Joint European Torus (JET)<sup>1</sup> and JAERI Tokamak 60 (JT-60)<sup>2</sup> tokamaks of a newly observed phenomenon in which, following the application of large off-axis toroidal current drive sources, a region develops in the plasma around the nominal magnetic axis in which the toroidal current density is zero to within the measurement error. A noteworthy feature of this “current hole” region is that it defies<sup>3</sup> the prediction made by a simple one-dimensional numerical model: that the transient effect of strong off-axis current drive will be the induction of *negative* current in the center, which should persist until the driven current has time to diffuse inward resistively. Still more remarkable is the fact that, despite the absence of the current that would be needed to give rise to a finite rotational transform in the core, and thus, presumably, of regular nested flux surfaces in that region, these equilibria show good confinement<sup>4</sup> and are quite stable, with the current hole remaining intact for the entire several-second duration of the discharge. Clearly, any satisfactory explanation of this phenomenon must account for both these unusual effects.

The first problem to be confronted, however, regards the mere existence of current hole equilibria. In Greene, Johnson, and Weimer’s classic 1971 paper on tokamak equilibrium,<sup>5</sup> an expression was derived for the Shafranov shift which appears to diverge in regions of zero toroidal current, suggesting that configurations containing such regions are unphysical.

A recent re-evaluation of that analysis by Chu and Parks, however, has shown that this is not the case.<sup>6</sup> By matching zero-current and finite-current solutions to the first few orders in GJW’s large-aspect-ratio expansion of the equilibrium equations, they have shown that there *are* physical current hole equilibria that are expected to be accessible (and, additionally, negative current equilibria that are not). The question of whether the JET and JT-60 current hole plasmas are actually in this sort of equilibrium, and, if so, how they arrive at it, remains to be decided.

In this paper, we employ the parallel 3D nonlinear extended magnetohydrodynamics (MHD) code M3D<sup>7</sup> to provide an answer to this question. We show that when the central current density is reduced inductively below a threshold negative value, a surface with zero rotational transform  $\iota$  (or safety factor  $q = \infty$ ) appears in the plasma, either at the magnetic axis or at finite minor radius. This leads immediately to an axisymmetric motion in which the core region interior to the  $\iota = 0$  surface shifts outward, undergoing a sawtooth-like reconnection. The effect of this reconnection is to eliminate the negative current, effectively clamping its value near zero. Under certain circumstances, such “axisymmetric sawteeth” are expected to repeat for many cycles. The effect is robust enough to persist in three-dimensional MHD modeling, confirming the predictions of previous 1D reduced MHD cylindrical<sup>8</sup> and toroidal<sup>9</sup> and 2D full MHD<sup>10,11</sup> studies.

## II. Predictions of the 1D Model

Our reference experiment is discharge number 53488 in JET.<sup>1</sup> Motional Stark effect (MSE) measurements taken 3.1 s into this shot, following about 1.6 s of off-axis lower hybrid current drive, indicate that the core toroidal current density is essentially zero out to approximately one-third of the plasma minor radius. The electron temperature profile has a high plateau across the current hole region at this instant and the density profile is flat. The discharge continues for several more seconds following the MSE measurement without substantial energy loss from the core.

The standard way in which to attempt to numerically model such an experiment is with a 2D equilibrium/transport code, such as the Tokamak Simulation Code (TSC),<sup>12</sup> which is designed to predict the gross behavior of tokamak plasmas on the transport timescale by evolving through a sequence of two-dimensional MHD equilibria. Because this code employs flux coordinates, however, it breaks down when the  $\iota = 0$  surface enters the plasma; at that point, the surfaces traced out by the magnetic field lines are no longer uniquely labeled by their enclosed poloidal flux. To follow the evolution of the current density beyond the breakdown point, a 1D code using a cylindrically symmetric equilibrium, and the minor radius  $r$  as the space coordinate, was applied to this problem. This code, informally titled “GOJET”, simply evolves the 1D magnetic field diffusion equation with a source term,

$$\frac{\partial \psi}{\partial t} = \eta \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) - J_{CD} \right], \quad (1)$$

where  $\psi$  is the poloidal flux,  $\eta$  is a constant resistivity, and  $J_{CD}$  is a non-evolving analytic fit to the plasma current density response to the lower hybrid current drive as predicted by ray tracing calculations performed by the Lower hybrid Simulation Code (LSC).<sup>13</sup> The response of the current profile to the sudden application of an off-axis source is shown in Fig. 1. It is seen that in the absence of any 2D reconnection events, a large negative value will develop on axis in stark disagreement with the experimental results. It is therefore clear that more sophisticated modeling is required.

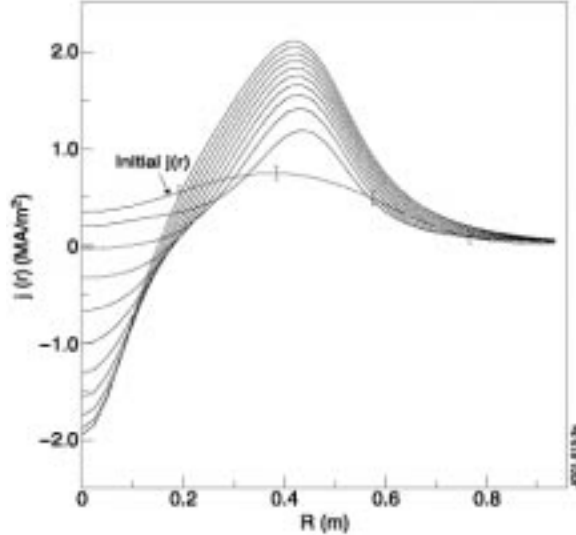


Figure 1: The current density evolution predicted by the 1D tokamak transport code.

### III. The 2D Current Hole Problem

We next turn to full two-dimensional modeling of the discharge with the M3D code, which takes MHD equilibria as input and evolves them nonlinearly. In order to model off-axis current drive numerically, we modify the usual MHD Ohm's law equation to read

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta(\mathbf{J} - \mathbf{J}_{CD}) \quad (2)$$

where the drive term  $\mathbf{J}_{CD} = J_{CD}R_0\nabla\varphi$  is given by the analytic expression

$$J_{CD}(r) = c_1 + c_2r^2 \left[ \frac{1 - c_3r^2}{c_4^2 + (r - c_5)^2} \right]. \quad (3)$$

Here  $\varphi$  is the symmetry angle,  $R_0$  is the nominal major radius,  $\eta$  is the plasma resistivity (assumed constant) and  $r$  is the normalized minor radius. For all further cases discussed in this paper, the parameters chosen are  $c_1 = 9.2092 \times 10^{-2}$ ;  $c_2 = 0.1003$ ;  $c_3 \approx 1.214924$ ;  $c_4 = 0.15$ ; and  $c_5 = 0.54$ , producing the hollow current drive profile shown in Fig. 2. The profile is peaked at about  $r = 0.56$ , is small but finite on axis, and falls to zero at the plasma edge. This form gave a reasonable fit to the results of ray-tracing calculations using LSC.

#### A. JET cross-section

We start with a 2D reference numerical JET equilibrium with  $\beta = 2\mu_0\langle p \rangle / B_T^2 \approx 9 \times 10^{-4}$ . The current drive term is switched on at time  $t = 0$ , and the plasma state is evolved in 2D (assuming axisymmetry) using the nonlinear, single-fluid MHD version of the M3D code.

The initial response of the plasma in the simulation is essentially the same as that predicted by the 1D code. The current density, which is initially nearly flat about the magnetic axis, begins to increase where the drive term is strong and to decrease at the center until it becomes slightly negative somewhere in the central region (Fig. 3). Note that, as illustrated in the Figure, the current density under these conditions will cross zero *off-axis* (at a major radius of approximately 2.74) first rather than at the axis (at  $R = 3.05$ ).

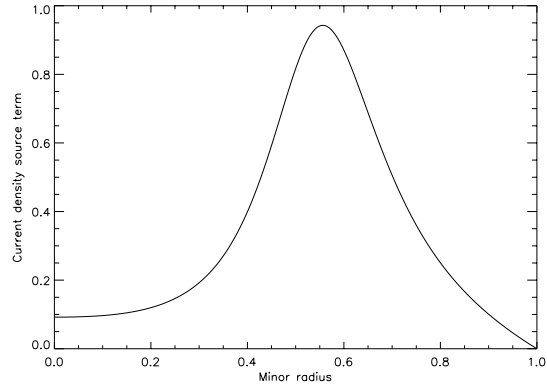


Figure 2: The form of the hollow-current off-axis current drive term.

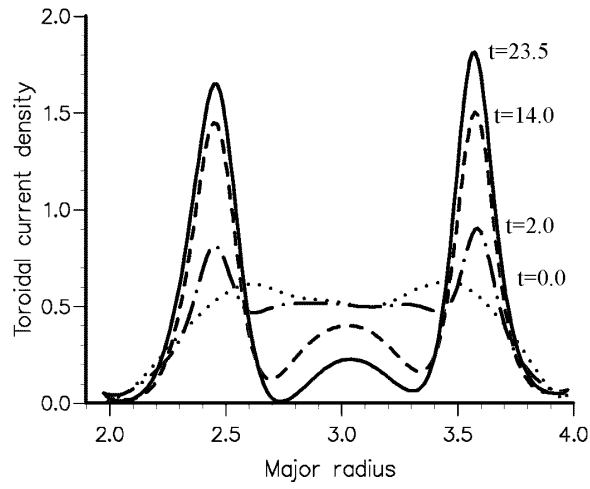


Figure 3: Current density along midplane during initial phase of JET profile evolution.

This is significant because it means that the  $\iota = 0$  surface will appear in the plasma not immediately after the current density becomes locally negative, but only after it has become sufficiently negative that the *net* toroidal current contained within some flux surface is zero.

At the instant the  $\iota = 0$  surface appears, at finite minor radius, the  $q$ -profile is as shown in Fig. 4a. The current inside this surface has not yet reached zero, so there are still good flux surfaces both within and exterior to the surface (Fig. 4b) with a stochastic region in between. One intuitively expects this plasma state to undergo reconnection. The  $q = \infty$  region is clearly incapable of supporting the inner set of nested surfaces against the forces that give rise to the Shafranov shift, because the poloidal field vanishes there. This is indeed what we observe (Fig. 5). The central region, which still has finite rotational transform, shifts outward axisymmetrically, slipping past the stochastic lines near the rational surface and reconnecting with the outer region. As a result of the reconnection, the toroidal currents mix, and the outer positive current is rapidly redistributed to the inner region, canceling out its small negative component.

## B. Circular cross-section

As Fig. 5 illustrates, there is a strong poloidal mode number  $m = 2$  component to the flux contours seen in the simulation using the JET cross-section. We postulated that this was due to the elongation of that equilibrium and switched to a simpler, circular cross-section to eliminate this geometrical effect. As predicted, the behavior of the plasma was similar, but the reconnection now took place as an  $m = 1$  mode, resembling classic Kadomtsev reconnection,<sup>14</sup> only axisymmetric (Fig. 6).

For sufficiently low viscosity and resistivity, the axisymmetric sawtooth repeats for several cycles. Over the resistivity range  $5 \times 10^{-5} < \eta < 2 \times 10^{-4}$ , the sawtooth period is proportional to  $\eta^{-0.55}$ , consistent with the expected rate of magnetic reconnection in MHD. As a result of this continual redistribution of current, the central density remains clamped near zero (Fig. 7).

## IV. Current Holes in 3D

In order to investigate the possibility of toroidal dependencies in the sawtooth mode structure, we next extend our circular cross-section study into the third dimension. The qualitative behavior of the plasma in this case is substantially the same as in two dimensions. After the central current density has gone negative and the  $\iota = 0$  surface has appeared, an  $m = 1, n = 0$  mode sets in and flattens the current at zero. There is also some indication of periodicity (Fig. 8).

However the behavior of the current hole in three dimensions is complicated, as seen in the Figure, by the presence of additional higher  $n$  and  $m$  modes. For  $\eta$  greater than about  $5 \times 10^{-5}$ , the strongest of these is an  $m = 4, n = 1$  mode localized around the  $q = 4$  surface, with a linear growth rate of about  $0.05 \tau_A^{-1}$ . At  $\eta \approx 3 \times 10^{-5}$ , this mode is surpassed in intensity by an  $m = 3, n = 1$  mode at the  $q = 3$  surface with a growth rate of  $0.03 \tau_A^{-1}$ . Evidently these two modes have different resistivity dependencies.

## V. Summary and Conclusions

When strong off-axis current drive is applied to the plasma discharges under discussion, the axial current decreases only until it reaches zero or becomes at most slightly negative. At that point, a  $q = \infty$  surface appears, leading to an instability in which an axisymmetric

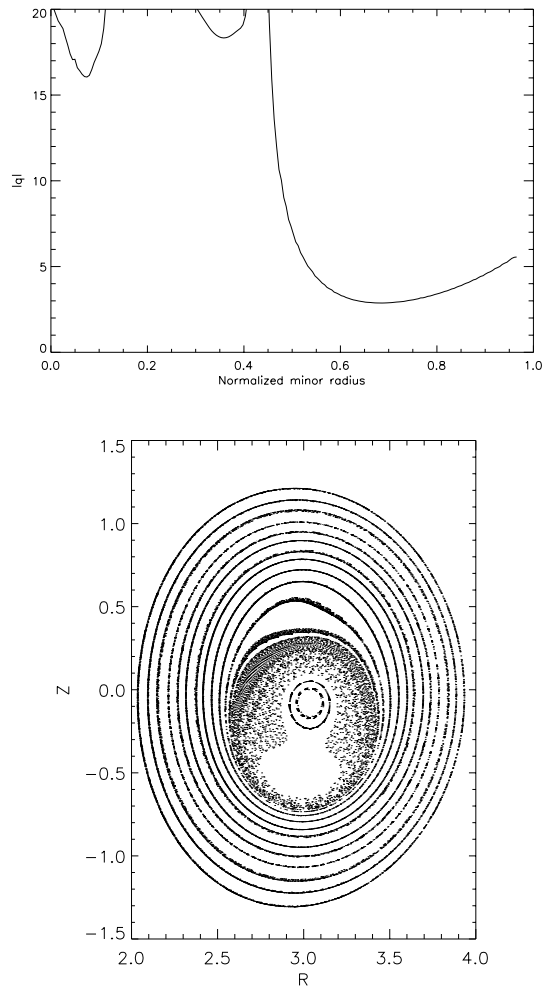


Figure 4: a. Safety factor ( $q$ ) profile for simulated 2D JET current hole discharge when current density becomes negative. b. Poincaré plot showing locations of flux surfaces at the same instant.



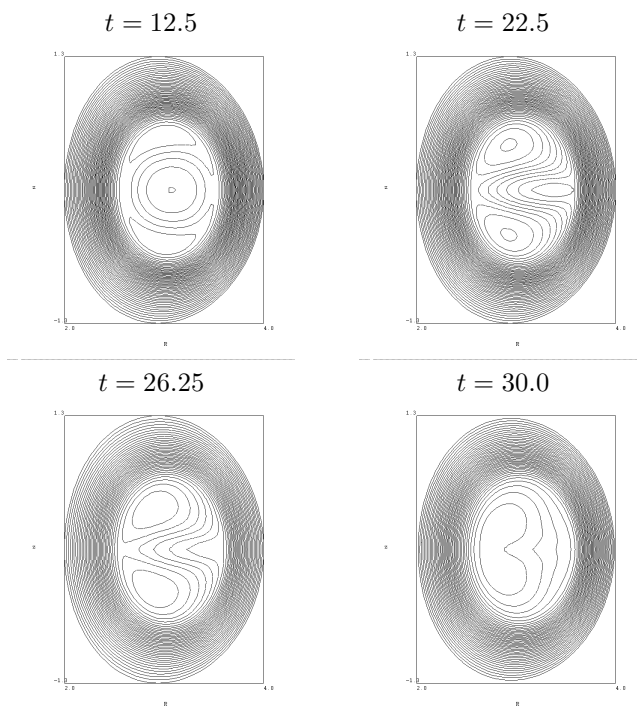


Figure 5: Poloidal flux contours for simulated 2D JET current hole at several times following the appearance of the  $\iota = 1$  surface, illustrating reconnection.

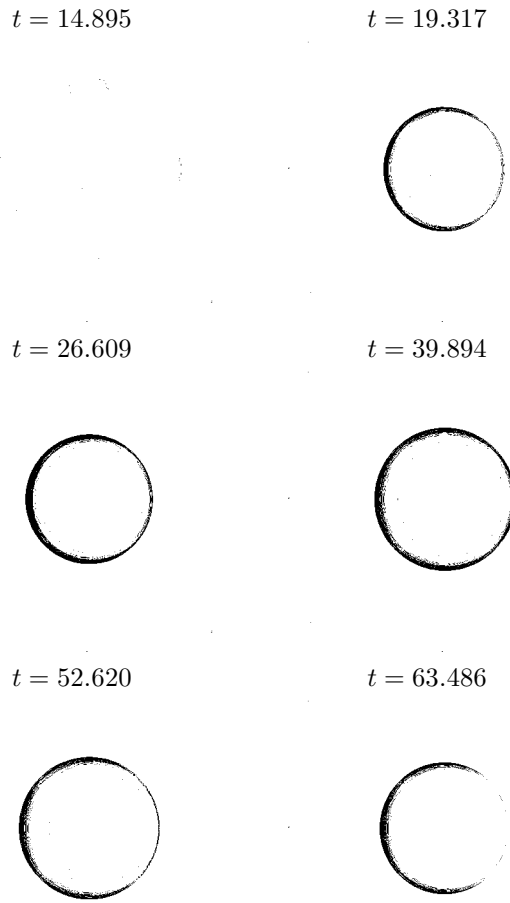


Figure 6: Poloidal flux contours for simulated 2D circular cross-section current hole discharge at several times following the appearance of the  $\iota = 1$  surface, illustrating 1,0 reconnection.  $\eta = \mu = 10^{-3}$ . Contours are drawn only in the region of nonmonotonic  $\psi$  for clarity.

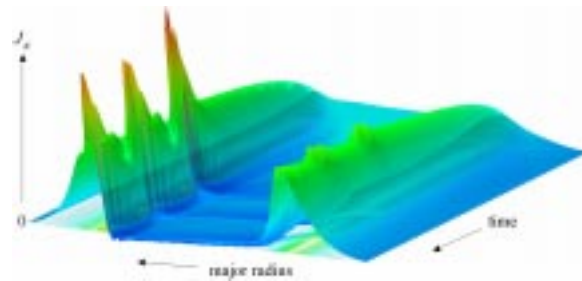


Figure 7: Time history of toroidal current density along midplane during 2D circular cross-section simulation.  $\eta = \mu = 10^{-4}$ .

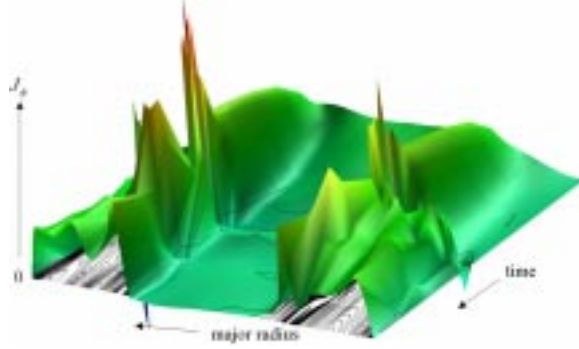


Figure 8: Time history of toroidal current density along midplane at  $\phi = 0$  during 3D circular cross-section simulation.  $\eta = \mu = 10^{-4}$ .

sawtooth occurs. The sawtooth redistributes the current, increasing its central value until the rational surface again vanishes. If the drive term is maintained, the sawteeth will repeat for several cycles. Over longer times, viscous damping will lead to a steady state with zero core current. On the still longer resistive timescale, the current density will grow again until it matches the drive term and is everywhere positive.

### ACKNOWLEDGMENT

It is a pleasure to acknowledge useful discussions with B. Stratton, L. Zakharov, G. Huysmans, N. Hawkes, and E. Solano. This work was supported by USDOE Contract No. DE-AC020-76-CH03073.

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