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DENSITY EFFECTS ON SAWTOOTH OSCILLATIONS FOR HIGH- Θ 120 kA DISCHARGES IN ZT-40M

by

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ABSTRACT

The effects of using pulse discharge cleaning and neutral gas refueling to increase the plasma density for 120 kA high Θ discharges on ZT-40M have been studied. Experimentally, increasing the plasma density quenches the sawtooth oscillations. Theoretical analysis indicates that the likely reason for this observation is that increasing the plasma density lowers the on-axis streaming parameter which in turn flattens the effective resistivity profiles leading to smaller (or nonexistent) sawtooth excursions.

I. INTRODUCTION

The ZT-40M Reversed Field Pinch (RFP) device at Los Alamos National Laboratory has characteristically operated in two regimes: a low Θ (or normal) regime ($\Theta \equiv B_\theta(a)/\langle B_z \rangle$), and a high- Θ (or pathological) regime.¹ At low Θ , the global plasma parameters F and Θ ($F \equiv B_z(a)/\langle B_z \rangle$) remain approximately constant for the duration of the discharge² while quasi-continuous, coherent $m=1$ oscillations are observed in the soft x-ray flux.³ The toroidal flux regeneration mechanism (or "dynamo") also operates quasi-continuously and indeed the plasma dynamics cannot be simulated with a 1-D transport code unless the "dynamo effect" is included in the Ohm's law assumption.⁴ In contrast, the high Θ discharges operate in a limit cycle rather than a true steady state. The soft x-ray signal exhibits sawtooth oscillations;¹ the drop in the soft x-ray signal is associated with $m=1$ activity analogous to that observed in the tokamak sawtooth.⁵ Moreover, the plasma dynamics can be simulated by a 1-D transport code during the soft x-ray rise phase of the high Θ sawtooth oscillation without the inclusion of a dynamo.⁶ These simulations indicate that the dynamo may only be present during the sawtooth drop when $m=1$

activity is present. Other studies have indicated $m=1$ tearing modes are a likely source of the dynamo.⁷⁻¹²

However, in order for these 1-D simulations to match the experimental data during the sawtooth rise phase, strong gradients in the resistivity profile had to be assumed (see Fig. 1a).⁶ If Z_{eff} is assumed to be constant as a function of radius, then the classical resistivity relation¹³ leads to a strongly peaked temperature profile as shown in Fig. 1b. Since the sawtooth crash mixes the plasma in this region³ (flattening temperature, Z_{eff} and therefore the classical resistivity) it was suspected that the resistivity profile might be related to anomalous effects. As discussed in Sect. IV, the streaming parameter is large in ZT-40M and thus is a likely candidate for inducing either slideaway electrons or microturbulence.

In order to attempt to determine whether the apparent resistivity profile effect was classical or anomalous, a simple experimental test was devised. Pulse discharge cleaning in conjunction with gas refueling was used to try to raise the density of a series of high Θ discharges. It was hoped that this density enhancement would lower the streaming parameter everywhere and also would preferentially cool the plasma edge region (thus moving the location of the electron temperature gradient inward). The results of this experiment are described in the following section and the corresponding plasma simulation results appear in Sect. III.

Section IV is a discussion section in which a case is made that the steep resistivity profile inferred from the high Θ nonrefueled discharges is caused by a slideaway electron population near the magnetic axis lowering the effective resistivity in this region. Since temperature, Z_{eff} and density profiles are unknown, this interpretation is subject to a large amount of uncertainty. However, the interpretation is consistent with observations in Alcator¹⁴ as well as ZT-40M.

II. EXPERIMENTAL RESULTS

Figure 2 shows the first 14 milliseconds of a standard, low Θ , 120 kA discharge. Note that the fluctuation levels in the current, the toroidal magnetic field at the wall, the toroidal flux and the central chord soft x-ray signal are all small.

Fig. 1a. Effective resistivity vs radius required for the simulation values to match the experimental values for the sawtooth rise phase of a high β nonrefueled discharge.

Fig. 1b. Effective temperature profile surmised from the effective resistivity profile assuming $Z_{\text{eff}} = 2$ and classical resistivity. T_e on axis is the Thomson scattering value.

Figure 3 compares the signals from four toroidal flux loops spaced around ZT-40M (Traces are identified by their device numbers and locations are shown in Fig. 4.) The signals are initialized to zero at 8.0 milliseconds. The fluctuations are small and show no superficially obvious coherent behavior.

In contrast, Figs. 5 and 6 show the same diagnostics as Figs. 2 and 3 for a typical high Θ , nonrefueled 120 kA discharge. In this case there are obvious temporal correlations between a decrease in the toroidal current, deeper toroidal field reversal, an increase in the toroidal flux and a decrease in the central chord soft x-ray signal. (This sawtooth behavior is described in detail in Refs. 1 and 2.) Also of prominence is a traveling $m=0$ magnetic disturbance (see Fig. 6) that results in a net increase in the toroidal flux.

Figures 7 and 8 present the same diagnostics for a high Θ discharge, except now 1.5 minutes of pulse discharge cleaning has been done prior to the shot and 170 torr-liters/s of neutral gas has been added during the shot. The PDC loads the wall with neutral hydrogen which helps maintain the density through about 4 ms while the gas refuel helps maintain the density at later times. The discharge has more fluctuations than the low Θ discharges (shown in Figs. 2 and 3) but lacks the coherent repetitive nature of the high Θ nonrefueled discharge (Figs. 5 and 6). This lack of coherence is evident in the toroidal flux signals (Fig. 8) which do not show a well correlated rotating $m=0$ disturbance.

The difference in the global behavior of the three different cases is also evident in their respective F - Θ diagrams, shown in Fig. 9. These plots show the F - Θ variation for each discharge between 8 and 9 milliseconds. The low Θ discharge stays in a small area as shown in Fig. 9a. Conversely, the nonrefueled high Θ case has two phases that are correlated with the rise and fall phases of the soft x-ray sawtooth, Fig. 9b. During the rise phase, the toroidal current diffuses to the plasma axis (away from a Taylor state)¹⁵ and the F - Θ trajectory moves to the right. During the sawtooth fall phase, or instability phase, the plasma rapidly relaxes (and generates toroidal flux) moving back to the left.

The gas refueled high Θ case has about the same F and Θ parameters as the nonrefueled high Θ case immediately after the sawtooth crash (i.e., the F - Θ trajectories of Figs. 9b and 9c overlap). However, unlike the nonrefueled high Θ case, Θ does not increase as a function of time but remains

Fig. 2. Toroidal current, toroidal field (at the wall), toroidal flux and the ultrasoft x-ray signal vs time for a low Θ 120 kA discharge.

Fig. 3. Toroidal flux oscillations vs time at four different toroidal locations for a low Θ 120 kA discharge.

MAGNETIC DIAGNOSTICS ON ZT-40M

Fig. 4. Toroidal locations of the flux loops shown in Fig. 3 and the current and field measurements in Fig. 2.

Fig. 5. Toroidal current, toroidal field (at the wall), toroidal flux and the ultrasoft x-ray signal vs time for a high θ nonrefueled 120 kA discharge.

Fig. 6. Toroidal flux oscillations vs time at four different toroidal locations for a high Θ , nonrefueled 120 kA discharge.

Fig. 7. Toroidal current, toroidal field (at the wall), toroidal flux and the ultrasoft x-ray signal vs time for a high Θ , refueled 120 kA discharge.

Fig. 8. Toroidal flux oscillations vs time at four different toroidal locations for a high Θ , refueled 120 kA discharge.

Fig. 9a. F vs Θ for 8.0-9.0 ms of a low Θ , 120 kA discharge.

Fig. 9b. F vs Θ for 8.0–9.0 ms of a high Θ , nonrefueled 120 kA discharge.

Fig. 9c. F vs Θ for 8.0–9.0 ms of a high Θ , refueled 120 kA discharge.

approximately constant. In this sense the refueled high Θ case resembles the low Θ nonrefueled case except that the refueled high Θ case has larger fluctuations.

The principal difference between the two high Θ cases is the plasma density, as shown in Figs. 10a and 10b. The central chord average density is almost 50% higher in the refueled as in the nonrefueled case. The impact of the density on the resistivity profile and the dynamo is discussed in the next section.

III. SIMULATION RESULTS

We have attempted to simulate the three discharges described in the previous section using a 1-D transport code¹⁶ (the equations are listed in Table I). Input boundary conditions for the simulations are the time-dependent toroidal magnetic field at the wall and the toroidal voltage. The output parameters that are compared with the experiment are the poloidal field (typically expressed as Θ) at the wall and the total toroidal flux. The thermal conductivity is chosen such that the peak temperature on axis does not exceed the measured Thomson scattering value. Initial field profiles were chosen by expanding the λ profile ($\lambda(r) \equiv \mu_0 \mathbf{J} \cdot \mathbf{B} / B^2$) as a power series to match the initial magnetic fields and toroidal flux at the wall present in the experiment. A summary of the input data and assumptions appears in Table II.

The simulations provide two insights into the plasma behavior. They can indicate whether an instability is present, and in the case of a stable plasma, they can determine an effective resistivity profile necessary for a 1-D transport description to model the plasma.

Since the code is one-dimensional, it does not model the effect of multidimensional fluctuations. Moreover, the code does not model the RFP "dynamo". Indeed, the code predicts the decay of toroidal flux inside the reversal point.

The limitations of the code can be used to analyze plasma behavior. If the code can correctly simulate experimental data for a given resistivity profile, then we conclude that no dynamo is necessary to explain the experimental behavior. Conversely, if the code is unable to reproduce experimental results with any resistivity profile and the toroidal flux in the experiment is being maintained better than in the simulation, then we conclude that a dynamo is present in the experiment.

Fig. 10a. Average plasma density vs time for a high θ , nonrefueled, 120 kA discharge.

Fig. 10b. Average plasma density vs time for a high θ , refueled, 120 kA discharge.

TABLE I. TRANSPORT EQUATIONS

Continuity	$\dot{n} + \nabla \cdot (n\mathbf{V}) = 0$	(ions)
Energy Conservation	$3/2 \ n(T_i \mathbf{V} \cdot \nabla T) + P\mathbf{V} \cdot \mathbf{V} = \nabla \cdot K\nabla T + Q$	(ions and electrons)
Faraday's Law	$\dot{\mathbf{B}} = - \nabla \times \mathbf{E}$	(poloidal and toroidal)
Ohm's Law	$\mathbf{E} = - \mathbf{V} \times \mathbf{B} + \eta \mathbf{J} + 1/en_e \ \mathbf{R}_T$	
Ampere's Law	$\mathbf{J} = 1/\mu_0 \ \nabla \times \mathbf{B}$	
Pressure Balance	$\nabla P = \mathbf{J} \times \mathbf{B}$	
Equation of State	$P = n(T_i + ZT_e)$	
Quasi-Neutrality	$\sum_i Z_i n_i = n_e$	
and	$Q_i = Q_{\text{equilibration}}$	
	$Q_e = (\eta \mathbf{J}) \cdot \mathbf{J} + 1/en_e \ \mathbf{R}_T \cdot \mathbf{J} - P_{\text{RAD}} - Q_i$	
	$P_{\text{RAD}} = P_{\text{cyclotron}} + P_{\text{Bremsstrahlung}}$	

TABLE II. SUMMARY OF INPUT DATA AND ASSUMPTIONS

$$\lambda(r) = \lambda_0 + [1 + a_6 r^6 + a_8 r^8]$$

$$B_z(a, t) = B_z(a, 0) + b_1 \cdot t$$

$$V_z(a, t) = V_z(a, 0)$$

(Values @ 8.1 ms)	Low Θ	High Θ Sawtooth	High Θ Gas Puff
Shot #	17488	17446	17495
F	-0.203	-0.365	-0.425
Θ	1.47	1.50	1.48
λ_0	1.925	2.910	2.880
a_6	-0.575	0	0
a_8	-0.425	-0.862	-0.655
$V_z(a)$ [volts]	40	68	66
$B_z(a)$ [mT]	-0.0160	-0.0313	-0.0370
b_1 [$\frac{mT}{s}$]	0	15.11	0
$\bar{n}_e$ [10^{19} m^{-3}]	1.63	1.56	2.54
$T_e(0)$ [eV]	315	225	205

For the simulations, the effective resistivity profile was treated as a free function since temperature profiles (as well as the relationship between temperature and effective resistivity) are unknown. For illustration, two extremes of resistivity are used; one being constant and the other with strong gradients in the plasma interior. The specific profiles are listed in Table III. These resistivity profiles were varied to try to reproduce experimental behavior. Thus, a successful simulation provides information on what the effective resistivity profile is expected to be in the experiment.

The results for a 450 μ s simulation of a low Θ shot are shown in Figs. 11a and 11b. Note that for both the flat resistivity profile and the strong gradient resistivity profile Θ climbs much higher than the experimental value, and the toroidal flux decays. The strong resistivity gradient case comes closest to matching Θ while the flat resistivity case comes closest to matching the toroidal flux. Consequently, changing the resistivity profile does not help the simulation converge to the experimental values.

This result is in agreement with Caramana and Baker,⁴ who have shown conclusively that a low Θ RFP discharge cannot be simulated by a 1-D transport model since the experiment contains a quasi-continuous "dynamo effect" while the transport model does not. The "dynamo" is responsible for maintaining the toroidal flux in the experiment.

In contrast, Figs. 12a and 12b show the simulation and experiment comparison for the rise phase of a sawtooth oscillation. In this case the simulation can reproduce the experiment provided that the resistivity profile has strong gradients. Note that a strong resistivity gradient is necessary to

TABLE III. ASSUMED RESISTIVITY PROFILES

$$\eta(r) = \eta_{\text{Spitzer}} + \left(\frac{T_e(r)}{T_{\text{eff}}(r)} \right)^{3.2}, \quad Z_{\text{eff}} = 2$$

$$T_{\text{eff}}(r) = T_e(0) * \left[1 + (C_1 - 1) \left(\frac{e^{-C_2 r^2} - 1}{e^{-C_2} - 1} \right) \right]$$

	C_1	C_2
Flat resistivity profile	1.000	--
<u>Strong resistivity gradients¹</u>	0.275	10.0

¹See Fig. 1a

Fig. 11a. Θ vs time (experimental and simulational values) for a low Θ 120 kA discharge.

Fig. 11b. $\langle B_z \rangle$ vs time (experimental and simulational values) for a low Θ 120 kA discharge.

Fig. 12a. θ vs time (experimental and simulational values) for a high θ nonrefueled 120 kA discharge.

Fig. 12b. $\langle B_z \rangle$ vs time (experimental and simulational values) for a high θ nonrefueled 120 kA discharge.

suppress both Θ and the toroidal flux to the experimental values. This profile causes the current to peak on axis and destabilizes tearing modes that are responsible for the dynamo and the sawtooth crash.⁶ If a dynamo were included in this simulation, Θ would be suppressed but the flux would be enhanced, thus the simulation would not converge to the experimental values.

Figures 13a and 13b show the same comparison as Figs. 11 and 12 for a high Θ gas refueled shot. These curves are substantially the same as the low Θ case, namely that changing the assumed effective resistivity profile does not cause the simulation to converge to the experimental values. Note that the toroidal flux decays in the simulations but is maintained in the experiment, (as it does in the low Θ case) indicating the presence of a dynamo in the latter.

We believe that the different behavior of the sawtooth and nonsawtooth discharges is largely a result of the different effective resistivity profiles. In the sawtooth discharges, the strong effective resistivity profile rapidly diffuses current density into the plasma axis during the sawtooth rise phase destabilizing internal tearing modes.^{6,8} Before these modes have a chance to grow large enough to relax the plasma, the equilibrium has diffused considerably past the marginal stability limit and into a robustly unstable state.^{6,8} Consequently, the tearing modes grow to large amplitude resulting in a violent relaxation (the sawtooth drop phase) that moves the plasma well into a MHD stable state (and the sawtooth process then repeats).

In contrast, a flat resistivity profile diffuses current density to the axis much more slowly. This is illustrated by Fig. 14 which compares the current density profiles before and after 450 μ s of diffusion assuming a flat resistivity profile and a resistivity profile with strong gradients. Note that $J_z(0)$ increases in both cases, but it increases much more for the strong effective resistivity profile case. Consequently, the instabilities that relax the plasma are smaller as are the corresponding plasma excursions. The net result is the discharge behavior seen for low Θ discharges and high Θ gas puff discharges; namely that the plasma makes small excursions around an effective steady state with a quasi-steady state dynamo. The suspected causes of the different effective resistivity profiles are discussed in the next section.

Fig. 13a. $\langle \Theta \rangle$ vs time (experimental and simulational values) for a high Θ refueled 120 kA discharge.

Fig. 13b. $\langle B_z \rangle$ vs time (experimental and simulational values) for a high Θ refueled 120 kA discharge.

IV. DISCUSSION

The rationale for using a gas puff on high Θ discharges was the conjecture that the introduction of neutral gas would affect classical resistivity and anomalous resistivity in opposite ways. If the resistivity were classical, the introduction of neutral gas would preferentially cool the plasma edge and the resistivity gradients would be larger than in the nonrefueled discharges. The net result of steeper resistivity profiles would be larger excursions in the Θ parameter.

Another possibility was that the resistivity gradients were anomalous and caused by slideaway electrons which occur in plasmas with a large streaming parameter. (The streaming parameter, ξ , is defined as the ratio of the electron drift velocity, $V_{De} = j_{||}/(ne)$, to the electron thermal velocity, $V_{th} = (kT_e/m_e)^{1/2}$.) If so, then the neutral gas puffing would lower the streaming parameter everywhere resulting in fewer slideaways and hence a more classical resistivity. If the temperature profiles were then relatively flat, the Θ parameter would either make smaller excursions or be quenched entirely.

A large value of the streaming parameter ($\xi \sim 0.2$) should result in a significant production of slideaway electrons and hence provide a likely source for the anomalous resistivity effects. Slideaway electrons can result in either anomalously high resistivity due to microturbulence or subclassical resistivity due to reduced classical electron-ion collisions. The experimental data are consistent with either reduced collisionality on axis or microturbulence in the outer plasma region.

Figure 15 shows the streaming parameter as a function of radius (assuming flat density profiles and either flat or parabolic temperature profiles) at 8.1 ms. The temperature is taken from Thomson scattering measurements while the $J_{||}$ profile is surmised by fitting the λ profile to the global F and Θ parameters. For the high Θ nonrefueled discharge, this time corresponds to the beginning of the sawtooth rise phase. Since no radial density or electron temperature information is available for ZT-40M, a range of profiles was examined.

Note that the on-axis streaming parameter for the high Θ nonfueled discharge is considerably higher than the streaming parameter for the low Θ discharge even though the discharges have the same density and plasma current. The high Θ refueled discharge has a streaming parameter comparable to the low Θ discharge. The streaming parameter for the high Θ nonrefueled case is well

Fig. 14. Current density vs radius (120 kA, low Θ) for: (a) initial profiles, (b) $t = 450 \mu s$, flat resistivity, and (c) $t = 450 \mu s$, strong resistivity gradient.

Fig. 15. Drift parameter vs radius for different discharges assuming flat density profiles and either flat or parabolic temperature profiles. Alcator slideaway regime is shown on left axis.

into the range where electron slideaways and subclassical resistivity were observed on Alcator.¹⁴ The streaming parameters corresponding to the beginning of the Alcator slideaway regime are also shown in Fig. 15. Consequently, we believe that the most likely cause of the strong resistivity gradients inferred from the transport simulations of the high Θ nonrefueled discharges is electron slideaways leading to subclassical resistivities near the plasma axis.

V. CONCLUSIONS

A comparison has been made between 120 kA low Θ discharges, high Θ discharges, and high Θ refueled discharges on ZT-40M. Of these three types of discharges, only the high Θ nonrefueled discharges have sawtooth oscillations and their associated bursts of MHD-like activity.

One-dimensional transport simulations indicate that the high Θ nonrefueled discharges are the only ones that do not have a quasi-continuous dynamo. In these discharges, the dynamo is apparently confined to the sawtooth drop phase. Strong gradients in the resistivity profile are required in order for the simulations to match the experimental data.

We believe that these strong resistivity gradients are the cause of the periodic sawtooth behavior observed in high Θ nonrefueled discharges. The strong resistivity gradients rapidly diffuse the toroidal current to the plasma axis, which in turn drives violent $m=1$ tearing mode instabilities. These instabilities are large enough that the plasma relaxes well past the marginal stability limits to a stable state. The diffusion/instability process then repeats.

The most likely cause of the strong resistivity gradients is subclassical resistivities near the plasma axis due to slideaway electrons in this region. The streaming parameter on the plasma axis for nonrefueled high Θ discharges is similar to the value where slideaways (and subclassical resistivities) were observed on Alcator. Refueling the plasma lowers this streaming parameter and quenches the sawtooth oscillations.

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REFERENCES

1. R.G. Watt, R.A. Nebel, Phys. Fluids 26, 1168 (1983).
2. D.A. Baker, et al., 9th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN41, Paper H2, Baltimore, Maryland (1982).
3. G.A. Wurden, Phys. Fluids 27, 551 (1984).
4. E.J. Caramana, D. A. Baker, Nucl. Fusion 24, 423 (1984).
5. B.V. Waddell, M.N. Rosenbluth, D.A. Monticello, R.B. White, Nucl. Fusion 16, 528 (1976).
6. K.A. Werley, R.A. Nebel, G.A. Wurden, Phys. Fluids 28, 1450 (1985).
7. A. Sykes, J.A. Wesson, Proceedings of the 8th European Conference on Controlled Fusion and Plasma Physics, Prague, 1977 (Czechoslovak Academy of Sciences, Prague, 1977), p. 80.
8. E.J. Caramana, R.A. Nebel, D.D. Schnack, Phys. Fluids 26, 1305 (1983).
9. A.Y. Aydemir, D.C. Barnes, Phys. Rev. Lett 52, 930 (1984).
10. J.A. Holmes, et al., Phys. Fluids 28, 261 (1985).
11. D.D. Schnack, E.J. Caramana, R.A. Nebel, Phys. Fluids 28, 321 (1985).
12. A.Y. Aydemir, et al., Phys. Fluids 28, 898 (1985).
13. S.I. Braginskii, Reviews of Plasma Physics, (Edited by M. A. Leontovich, Consultants Bureau, New York, 1965), Vol. 1, 205.
14. B. Coppi, et al., Nuclear Fusion 16, 309 (1976).
15. J.B. Taylor, Phys. Rev. Lett 33, 1139 (1974).
16. R.A. Nebel, et al., Los Alamos Scientific Laboratory report LA-8185-MS, (1980).