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LA-UR -83-1903

CONF-830908--1

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TITLE RECENT RESULTS FROM THE ZT-40M REVERSED-FIELD PINCH PROGRAM

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SUBMITTED TO The 11th European Conference on Controlled Fusion and Plasma Physics, Aachen, Federal Republic of Germany, September 5-9, 1983.

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RECENT RESULTS FROM THE ZT-40M REVERSED FIELD PINCH PROGRAM

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ABSTRACT: Details of equilibrium control and resultant discharge behavior on ZT-40M will be presented. Interesting results in several operating regimes and possible theoretical interpretations will be discussed.

INTRODUCTION: Recent discharges in the ZT-40M reversed field pinch experiment ($R=1.14$m, $a=0.2$m) at Los Alamos National Laboratory in the 60-240 kA range utilizing power-crowbars and equilibrium control are well-behaved with durations in excess of 20 ms. Segmented poloidal carbon rings are located at four toroidal locations to act as limiters and the aluminum shell and toroidal and poloidal field windings have recently been modified to reduce error fields.[1] For 2-mtorr fill pressure and 120-kA plasma current, ZT-40M achieves temperatures in the 200-300 eV range and average densities in the $1\text{-}3\times10^{13}$ cm^{-3} range. A typical set of waveforms is shown in Fig. 1. This paper will discuss the necessary equilibrium controls needed to maintain a long-duration discharge with minimal wall interaction. It will also discuss two experimental studies performed at different Θ values ($\Theta=B_{\theta,wall}/\langle B_{\phi}\rangle$) and present possible theoretical explanations of the features observed during these studies.

EQUILIBRIUM CONTROL AND FEEDBACK STABILIZATION: As was demonstrated in earlier work[1] application of a small trimming vertical field is able to extend the discharge by 4-5 ms. This constant trimming field is sufficient to produce well-behaved discharges at 120 kA. However, at higher currents or with active density control (gas puffing), the behavior becomes more erratic, particularly near the poloidal flux slot. A correlation between radially inward motion at the gap, the presence of Ni V radiation (indicative of an enhanced plasma-wall interaction), and an increase in resistivity has been observed. Inward motion at the flux slot is also sufficient to cause a reduction in plasma density[2] (Fig. 2). Because a constant trimming field cannot cope with a time-varying displacement, active feedback control of the vertical field has been implemented based on the local radial displacement at the gap. The displacement at the gap may be controlled at a preset level ($R-R_0$=constant) for the duration of the discharge, resulting in reduced Ni V radiation and well-behaved discharges. Vertical motion is also observed and a separate constant field is applied to minimize this motion. The combination is necessary for reproducible plasma behavior, particularly late in time when the effect of the aluminum shell in controlling the equilibrium is reduced.

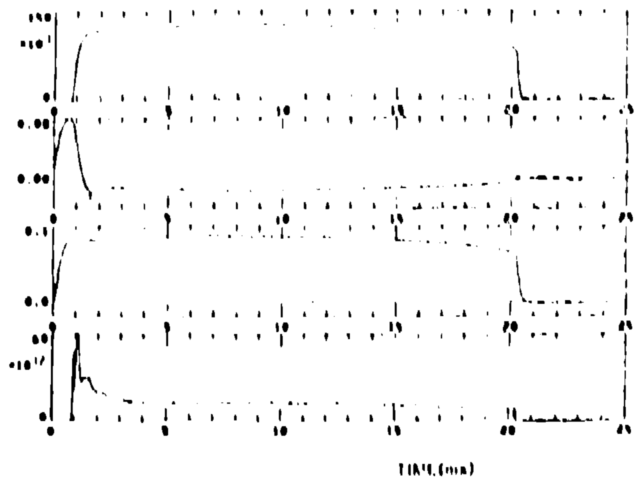

Fig. 1. Typical operating waveforms.

HIGH Θ EXPERIMENTS Discharges taken at high Θ exhibit large-scale magnetic fluctuations at the wall that have both m=1 and m=0 characteristics. Associated closely with these modes are discrete toroidal flux regeneration events and soft x-ray flux modulation ("sawteeth").[3] The threshold Θ value for observation of these large-scale disturbances is between 1.55-1.6. Figure 3 shows the correlation between the magnetic structures at the wall (m=1), the toroidal flux disturbances, and the sawteeth. Examination of many different diagnostics (energy loss, radial density profiles, radial C V profiles) leads us to conclude that the sawtooth event is a manifestation of an internal energy rearrangement that is accompanied by a flattening of the density profile and reduction of the axial temperature. A systematic Θ dependence is observed for the percentage modulation of the sawteeth (Fig. 4). The m=1 mode amplitude reduces somewhat and the m=0 amplitude recedes into the background level as the Θ value is lowered below 1.55-1.6. A possible cause for the sawteeth and m=1 magnetic modes is the theoretically predicted presence of an unstable m=1, n=8-15 current-driven tearing mode (kink) in the interior of the plasma.[4] This mode is the RFP analog of the m=1,n=1 tearing mode that produces soft x-ray sawteeth and profile flattening in a tokamak. The RFP mode results in a lowering of q and flattening of the current profile on axis. The experimentally dominant toroidal mode number (n=12) is in good agreement with the prediction of the theory. The observations are analogous to those in a tokomak. The Θ dependence of the sawteeth is believed to be the result of an effective island width enhancement for the m=1 mode (resulting in a larger interaction volume) due to the coalescence of the m=1 island with the island of an m=0 mode (Θ dependent) resonant at the toroidal

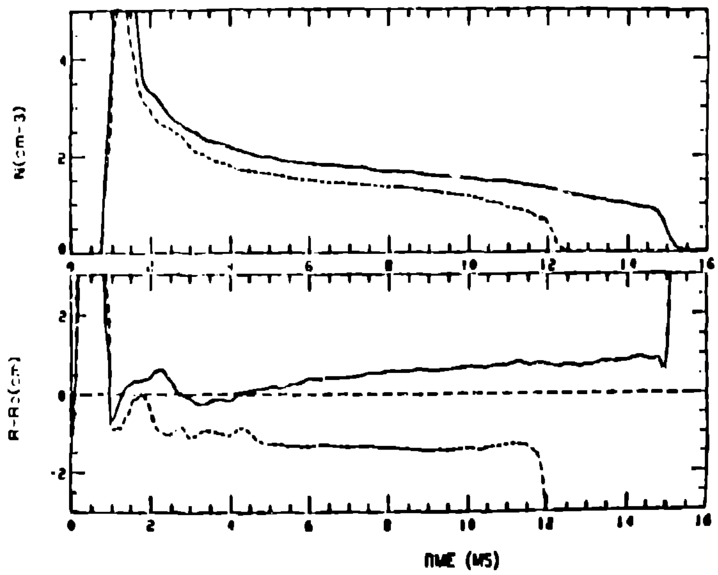

Fig. 2. $\int n d\ell$ and local displacement at the gap.

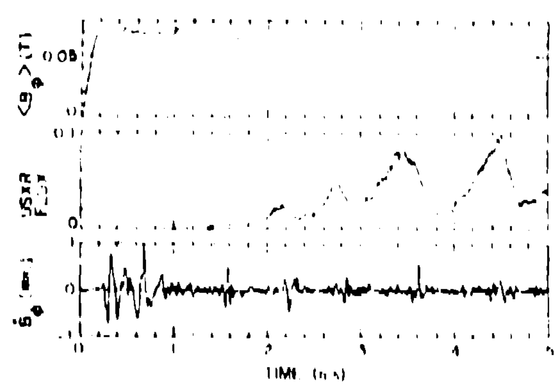

Fig. 3. Correlation between toroidal flux events, sawteeth, and B_θ disturbances.

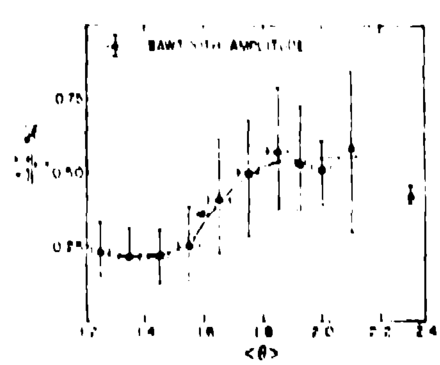

Fig. 4. Θ dependence of sawtooth percentage modulation.

field null. The flux regeneration event could result from a toroidal flux residue left after a tearing and reconnection of helical flux during the kink, but the theoretical connection has not been conclusively demonstrated.

LOW Θ EXPERIMENTS: As Θ is lowered to the usual operating range (1.4-1.5), the large-scale disturbances described above become subdued and it is possible to study in detail the lower-level fluctuations present. One experiment in this range involved the coordinated measurement of toroidal flux disturbances, disturbances in the D_α luminosity radiated from neutral gas near the wall, and a density cavitation in the outer 5 cm of the pinch radius all of which are synchronous.[5] All three phenomena exhibit an apparent motion in the anti-I_ϕ direction. The magnetic signature is an abrupt toroidal flux jump ($|\Delta\Phi|<10^{-4}$ Wb) predominantly with $\Delta\Phi<0$. The $\dot{\Phi}$ signals in Fig. 5 show prominent spikes as this disturbance drifts past the signal loop. The speed varies systematically with flux jump polarity ($\Delta\Phi<0$ has $v=3\times10^4$ m/sec for large events whereas for $\Delta\Phi>0$, $v\geq1\times10^5$ m/sec). The radial field associated with the jump is estimated to have a toroidal extent of about 0.3 m. The density cavitation has a peak fractional depletion of 20% of the undisturbed density. Figure 6 shows the measured $\int\tilde{n}d\ell$ profile of the disturbance (solid line, upper plot), the geometrical model of the disturbance (bottom plot) and $\int\tilde{n}d\ell$ profile of the model (dashed line, upper plot). The estimated particle flux to the wall associated with the cavitation (risetime $\sim$10 μs) is $>10^{22}$ m^{-2} sec^{-1}. The density event has an associated burst of D_α radiation seen in the immediate toroidal vicinity of the multichord interferometer.[6]

The electromagnetic and density disturbances are consistent with the existence and growth of an m=0 island centered around the field reversal surface as predicted by ideal MHD theory. The mechanism by which this island begins to translate in the anti-I_ϕ direction is not understood. Two possible theoretical explanations have been proposed, the first being the presence of an instability driven by the electron diamagnetic drift, and the second being

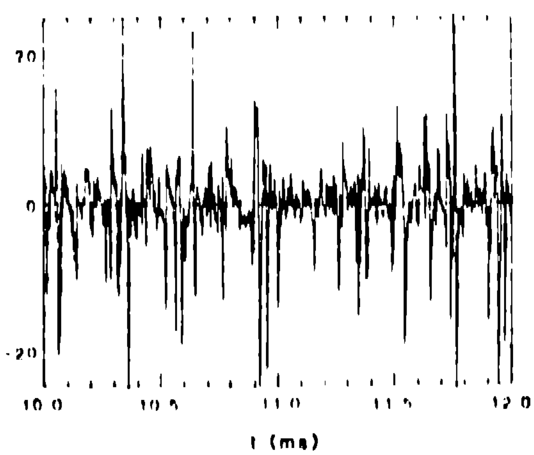

Fig. 5.

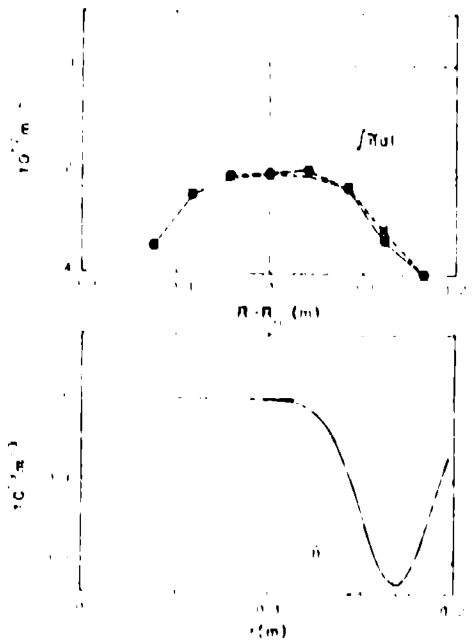

Fig. 6. Density cavitation data and modeling.

a spinup process driven by the density cavitation itself.[7] In this second model, the ion flux to the wall due to ion gyro-orbit scrapeoff is considered to lead to momemtum transfer to the wall in the absence of strong ion cyclotron turbulence. This momentum transfer, in the absence of any flow-broadening mechanism would produce a layer of width ρ_{ci} with velocity approximately equal to $v_{Ti}/2$ in the anti-I_ϕ direction. Unless strong electric fields are present this layer will itself cause flow broadening by placing a lower bound on eddy viscosity (due to velocity gradient driven Kelvin-Helmholtz instabilities) and consequently velocity profile broadening must occur even in the absence of other viscosity sources. Detailed kinetic simulations of this effect lead to the conclusion that in ZT-40M a layer of approximately 0.04-m width may be accelerated up to speeds near v_{Ti}. Experiments which utilize the different scaling of the two velocities involved ($v_{de} \propto T_e/B$ and $v_{spinup} \propto T_i^{1/2}$) may be needed to conclude which of the two candidates is the most likely cause.

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