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**Plasma Current Fluctuations and Decay Rate
Behavior in the ZT-40 Device**

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PLASMA CURRENT FLUCTUATIONS AND DECAY RATE BEHAVIOR IN THE ZT-40 DEVICE

by

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ABSTRACT

A detailed examination of the behavior of the fluctuations of dI_{plasma}/dt in the ZT-40 device over 2500 shots is presented. Historical variations in these fluctuations are discussed along with several possible explanations of these variations. The dependence of these fluctuations on fill pressure, B_{ϕ} at the wall, and the relation of these $\dot{I}_{\phi}$ fluctuations to the decay of the plasma current are examined. A physical picture consistent with the observed data is presented to explain the relation between the current decay and fluctuations, and the dependence of the fluctuations on B_{ϕ} wall.

The ZT-40 Reversed Field Pinch (RFP) at Los Alamos National Laboratory operates with plasma currents as high as 600 kA and fill pressures between 1-20 mtorr.¹ Figure 1 shows a sample trace of plasma current I_{ϕ} , $\dot{I}_{\phi}$, and B_{ϕ} at the wall. Variations in both the current decay (dI_{ϕ}/dt) as a function of time and the mean square deviation of the current decay from its mean $\{\Delta t_{\text{sample}} \cdot [(dI_{\phi}/dt)^2 - \langle dI_{\phi}/dt \rangle^2]^{1/2} / I_{\phi, \text{peak}}\}$ are prominent features of the discharges, particularly at low pressure (5-10 mtorr) in reversed field operations. A detailed study of these effects has been conducted for a series of 2500 shots encompassing operations both with and without power crowbars in the poloidal and toroidal field systems. The shots involved in the study have all had reversed toroidal field at the wall, which may have been generated by either plasma reversal (self-reversal) or externally imposed reversal (aided reversal).

The quantities under discussion are the current decay and mean square deviation of that decay from the mean (on a fast time scale, $t \leq 20 \mu s$) as defined in the previous paragraph. Particular characteristics of interest

here are quiet periods and flattops in the current decay. In this report we shall define a quiet period as any period of time during a discharge in which the fluctuation level becomes $< 10\%$ of that level present near peak current (if such periods occur between $150\text{--}330\ \mu\text{s}$ after the start of the toroidal plasma current). Two such periods are labeled A and B in Fig. 1. A flattop refers to any period during the same time window in which the decay of the current drops to a value $< 50\%$ of the average decay (defined as $0.6 I_{\text{max}}/[\text{time to } e^{-1} \text{ of } I_{\text{max}}]$). Such a period commences at $\sim 300\ \mu\text{s}$ in I_ϕ in Fig. 1. It should be noted that experimentally there are two distinct types of quiet periods in this device, one which is sharply delimited by a higher fluctuation level before and after (A), and one in which a sharp delimiting prior to the quiet period occurs but in which the period extends beyond the end of the data acquisition period (B), which is typically $1\ \text{ms}$. No attempt has been made to distinguish between the two in this report.

I. HISTORICAL EFFECTS

Figure 2 is a plot of the fluctuation level in percent (defined above) as a function of shot number for all shots between 1600–3600 in which the

Fig. 1.

Typical current, I_ϕ , and B_ϕ wall traces for aided reversal of ZT-40 with a ceramic liner. Note the two distinct types of quiet periods marked A and B in the figure.

Fig. 2.

Fluctuation level history in ZT-40 with the ceramic liner.

toroidal field at the wall reversed. The three curves refer to which particular operating mode was used to achieve B_ϕ reversal (pitch programming refers to a mode in which the timing between B_ϕ and I_ϕ is varied to allow pitch convection into the bulk of the plasma to occur). There were several historical periods of time (labeled A in Fig. 2) when high fluctuations were present. The first period of high fluctuations ($> 2\%$) occurred when the machine was first run utilizing the full I_ϕ power crowbar bank (I_ϕ -PCB). Because of saturation worries about the poloidal iron cores, ZT-40 was later dropped to $\sim 30\%$ of the I_ϕ -PCB (labeled B in Fig. 2) and the fluctuation levels dropped back down coincident with this. Later still the full I_ϕ -PCB was restored (A) and again fluctuations increased in amplitude. At approximately shot 2800 the I_θ power crowbar bank (I_θ -PCB), as well as a set of RC networks on the I_θ mixer, was installed (labeled C in Fig. 2). Coincident with this the fluctuations again dropped in amplitude and remained $< 1.5\%$ from then on. Exactly what the physical connection is between the fluctuation amplitude and I_ϕ -PCB is unclear. It doesn't seem to be simply an energy input phenomenon because the level doesn't increase with the energy stored in the I_ϕ -PCB system in any obvious manner. Suggestions based on code calculations (data from R. A. Gribble, Los Alamos National Laboratory) have been made that resonances may occur between the I_ϕ and I_θ circuits that may be reflected in fluctuations in the plasma. The abrupt decrease in fluctuation level when the I_θ -PCB and RC snubbers were installed is believed to be due to the snubbers acting as shock absorbers to dampen the oscillations (via I_θ - I_ϕ cross talk within the plasma). Had the oscillation damping been associated with the I_θ -PCB bank itself, one would have expected to see some change in damping when the transformer primaries were shorted, which effectively eliminated the entire bank. The level stayed low regardless of whether the primaries of the I_θ -PCB transformers were shorted or not (in either case the snubbers remained in the I_θ circuit).

Another historical effect was observed when examination was made of the incidence of quiet periods and flattops in the self-reversal and aided modes for blocks of shots before and after I_ϕ -PCB installation ($\sim$ shot 1900). The results are shown in Table I. The apparent radical change in the incidence of quiet periods may be quantitatively checked by making the assumption that the incidence of quiet periods was distributed normally. One may examine, for instance, all aided-reversal shots between 1900-3600 (fill pressure between

TABLE I
INCIDENCE OF QUIET PERIODS, FLATTOPS IN ZT-40
FOR SHOTS 1600-3600 (330-470 kA)

SELF-REVERSED			
<u>Pressure Range</u>	<u>I_{Q.P.} (%)</u>	<u>I_{F.T.} (%)</u>	<u>Shot Range</u>
3-7 mtorr	80	20	1'00-1900
10-20	100	12.5	1600-1900
3-7	3.3	7.6	1901-3600
10-20	40.8	14	1901-3600
AIDED REVERSAL			
3-7 mtorr	88	35	1600-1900
10-20	91	47	1600-1900
3-7	12.5	20	1901-3600
10-20	10.0	6.6	1901-3600

3-7 mtorr), for which a large sample size (146 shots) is available. If these shots are distributed normally, one may predict a probability of 0.125 that a quiet period will occur on a given shot, if no change in the input physics has occurred. Using this estimate applied to those shots between 1600-1900, one may predict for the smaller sample size present (26 shots) that the predicted number of quiet periods in this sample should be 3.25 ± 1.7 . Because the actual number observed was 23 (or 11 standard deviations from the predicted value) it is clear that the physics was vastly different prior to shot 1900 than thereafter. These same types of arguments may be applied to the incidence of flattops and for the 10-20 mtorr fill pressure range in order to determine if any statistically meaningful changes occurred in the incidence of quiet periods and flattops for all these conditions. The results of such analysis indicate that in all cases the incidence of flattops was unaffected historically (observations were within 2 of the predictions), whereas the incidence of quiet periods decreased radically after shot 1900. This second conclusion, which seems to reinforce the previous observations, should be viewed in the same light as the historical behavior of the fluctuations in general, i.e., as a possible indication of the effect of the power crowbars and snubbers on the plasma. It should be pointed out that due to these

historical effects one must be cautious when he tries to compare different blocks of shots in search of physical effects concerning the plasma fluctuation level.

II. FILL PRESSURE EFFECTS

It has been observed in other reversed field pinches² that the fluctuation level $\delta B/B$ increases as the fill pressure is lowered. This effect was also observed in ZT-40 for those shots in which the higher $\dot{I}_\phi$ fluctuations occurred. Figures 3 and 4 are plots of the fluctuation level vs fill pressure for the self-reversed and aided cases, respectively. In both modes an upward trend can be seen at low pressures for the period when only the I_ϕ power crowbar (100%) was running. This dependence seems much subdued as long as the overall fluctuation level is not allowed to become large (either by a small or absent I_ϕ -FCB or by the I_θ shock absorber mentioned earlier). Indeed, in both modes in the low fluctuation level ($< 2\%$) case, within the statistics one cannot say if there is any dependence at all. No explanation has yet been given for the increase as one goes to higher fill pressures in the aided reversal case, but the small sample size at 15 and 20 mtorr makes the trend

Fig. 3.
Fluctuation level vs fill pressure for the self-reversed mode of operation.

Fig. 4.
Fluctuation level vs fill pressure for the aided-reversal mode of operation.

suspect. Over half of the increase in these points can be accounted for by the error bars on the two points. Such is not the case in the low pressure region, as in that case the sample size was quite large (most of these discharges occurred between 5-10 mtorr). The difference between this apparent lack of fill dependence in ZT-40 (in most conditions) and obvious dependence in other machines is not yet explained. It must be noted that ZT-40 utilized a ceramic (insulating) vacuum vessel during these runs, whereas the other machines had conducting liners. Whether the presence of image currents in a metal liner very near the plasma will remedy this difference should be answered when ZT-40 is put back in operation with its own metal liner.

III. TOROIDAL FIELD EFFECTS

Perhaps the most intriguing result to come out of this study is the dependence of the fluctuation level and the incidence of quiet periods on the behavior of B_ϕ at the wall. Figure 5 is a plot of instantaneous fluctuation level vs instantaneous B_ϕ at the wall for discrete points in time during a single discharge (shot 1959). Examination of such a plot (and many others like it for different discharges) reveals a monotonic increase in the fluctuation level as the reversal at the wall deepens. This feature seems to remain valid regardless of the peak fluctuation level on any given shot. It should also be pointed out that fluctuations remain relatively low after the field becomes positive again. The physics of that effect is probably different than that of the reversed configuration, depending as it probably does on thermal contact with the wall, which may not be present in the reversed case.

Another very important observation has to do with the incidence of quiet periods as related to B_ϕ at the wall. Figures 6 and 7 are histograms showing, for the aided-reversal and self-reversal modes, respectively, the number of quiet periods plotted against the field at the wall during the quiet period. The points for $B_\phi > 0$ reflect the earlier statement that a positive field results in a fairly low fluctuation level. This effect can be eliminated by application of the I_0 -PCB to hold the field $B_\phi < 0$. The important points of these histograms are clearly shown by the self-reversed plots (Fig. 7). The incidence of quiet periods monotonically decreases as the toroidal field becomes more and more negative (HWHM = 300-400 G) and the peak incidence occurs in the region between 0 and -200 G. This behavior is consistent with a

Fig. 5.
Instantaneous fluctuation level vs instantaneous field at the wall (B_{ϕ}) for discrete times during a particular shot (1959).

Fig. 6.
Histograms showing the relationship with the toroidal field at the wall and the presence of quiet periods for the aided-reversal mode of operation.

need for wall stabilization of plasma modes because for small field reversals, the reversal point (and plasma edge) is closest to the conducting shell without actually being in contact with the ceramic.

IV. CORRELATION BETWEEN FLATTOPS AND QUIET PERIODS

An important physics question confronting the RFP is what the primary energy loss channels are. One of the possible channels is enhanced transport due to large amplitude fluctuations. For that reason an attempt was made to determine whether any correlation existed between the behavior of the current decay and the behavior of fluctuations. The decay is controlled to some extent by the plasma resistance (and hence temperature) and changes in the plasma hopefully will be mirrored by the decay. Conversely, any obvious change in the decay must correspond to a change in the plasma, and because a change in $\Delta t \delta \dot{I}_{\phi} / I_{\phi}$ is an external indication of a change in the turbulence properties of the plasma, a correlation hopefully can be observed between the two if fluctuations are important.

The results of searching for such correlations are shown in Figs. 8, 9, and 10. For the current range 330-470 kA and fill pressure range 3-7 mtorr, all aided or self-reversed shots that had either a quiet period (of either type) or a flattop were picked out and, for a given mode, the current decay vs time and fluctuation level vs time were averaged. Figures 8 and 9 show such averages (for shots with quiet periods) for the aided-reversal case for the historical period before addition of the I_ϕ -PCB and after, respectively. In each case the current decay has a reduced level during the period of time around 0.3 ms and in each case this reduction in current decay is coincident with (or followed by) a significant reduction in the fluctuation level. Later in time the decay increases again but no increase in fluctuations is observed.

The final figure (Fig. 10) is similar but encompasses only three shots. It is intended to demonstrate that in some cases the reduction in fluctuations may lag the flattop by as much as 60-70 μ s. Detailed examination of these three shots also shows that the portion of the fluctuation curve prior to ~ 0.4 ms is actually the result of a delimited quiet period separated from a

Fig. 7.

Histograms of B_ϕ wall vs incidence of quiet periods for self-reversed operation.

Fig. 8.

Fluctuation level and current decay (average behavior) for aided-reversal shots with quiet periods between 330-470 kA and 3-7 mtorr, for the period prior to installation of the I_ϕ power crowbar.

Fig. 9.
Fluctuation level and current decay (average behavior) for aided-reversal shots with quiet periods between 330-470 kA and 3-7 mtorr, for the period after installation and application of the I_{ϕ} -PCB.

Fig. 10.
Fluctuation level and current decay averages for three aided-reversal shots with quiet periods showing the lag time between the decay rate change and drop-off in the fluctuation level.

nondelimited quiet period after 0.4 ms. Such fine scale effects are lost due to the averaging process but the correlation (perhaps after a lag) between the reduced current decay and reduced fluctuations remains as a statistically significant observation. These same observations held up regardless of operating mode or whether selecting for quiet periods or flattops. There was, however, no repeatable correlation between actual quiet periods and flattops, only between reduced decay rates and a reduction (not necessarily to Q.P. levels) in the fluctuations.

V. DISCUSSION

Two important results came out of this study: (1) the incidence of quiet period peaks with B_{ϕ} close to zero (but negative) at the wall and (2) the fact that there is a correlation between the occurrence of a flattop on the current decay and the subsequent reduction of fluctuations on the $\dot{I}_{\phi}$ probe. Two independent physical processes may account for these observations. A possible explanation for the dependence of the quiet periods on B_{ϕ} is that when the field reverses at the wall, the plasma edge moves radially inward with

increasing reversal. Fluctuations (and accompanying fields) in the plasma can be stabilized by mirror currents in a conducting shell (the primary in this case). Because such stabilization is inherently more effective if the image currents are close to the source than if they are far away, the loss of quiet periods with depth of reversal may simply be a result of less effective wall stabilization for deeper reversals. The fact that the quiet periods, particularly in self-reversal, are clearly peaked for $B_\phi < 0$ probably has to do with the fact that for $B_\phi > 0$ the plasma may be in physical contact with the ceramic, as well as with the fact (theoretically) that the presence of a reversed field enhances the stability of the equilibrium in the RFP. The consequent energy loss simply due to thermal conduction may drain enough energy from the plasma that the necessary precursors of the quiet periods (probably related to temperature and energy confinement) simply are not present. This energy loss may also drain energy from the fluctuations near the wall, accounting for the generally low fluctuation levels for $B_\phi > 0$, but this is clearly a different fluctuation effect (experimentally) than are the quiet periods.

The correlation between flattops and reduced fluctuations has a possible explanation in anomalous resistivity due to the fluctuations themselves. It has been observed in other experiments and simulations³ that high turbulence levels can create anomalous resistivity. If this is the case here, such resistivity could easily help heat the plasma ohmically in the vicinity of the fluctuations. Increased temperature would result in a drop in plasma resistance with consequent flattening out in the decay rate. It may also result in a drop in fluctuation (if an increased temperature is indeed a precursor condition of quiet periods) so that the flattop and quiet periods are both results of anomalous resistivity. Once the fluctuation level is reduced, this resistivity no longer maintains a high heating rate, so the normal energy losses become more dominant and the decay again increases, as was observed. Whether this and the previous explanation do indeed explain the behavior of ZT-40 is of course an open question, and must remain so until some experimental test can be devised to check on their validity.

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REFERENCES

1. D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, J. N. Di Marco, J. N. Downing, A. Haberstick, R. B. Howell, A. R. Jacobson, K. S. Thomas, R. G. Watt, and S. Ortolani, "Initial Reversed Field Pinch Experiments on ZT-40 and Recent Advances in RFP Theory," Eighth Int. IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium (1980), paper L-2-1.
2. A. Buffa, S. Costa, R. De Angelis, L. Giudicotti, C. W. Gowers, G. F. Nalesso, C. Ortolani, M. Pulatti, P. Scarin, M. R. C. Watts, "Optimization and Properties of Reversed Field Pinches in the ETA-BETA II Experiment," Proc. of the Reversed Field Pinch Theory Workshop, Los Alamos, New Mexico (1981), paper 1B-3.
3. A. G. Sgro and C. W. Nielson, Phys. Fluids 19, 12 (1976).