THE REDUCTION OF LOW FREQUENCY FLUCTUATIONS IN RFP EXPERIMENTS

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The Reduction of Low Frequency Fluctuations in RFP Experiments


Abstract

The low frequency fluctuations seen in RFP experiments are found to be correlated with changes in the toroidal flux measured by diamagnetic loops surrounding the discharge. The correlation of the onset of impurity radiation and x-rays with the "crash" seen in experiments is caused by plasma bombarding the metal liner associated with this loss of flux. Efforts should be made to design improved stabilizing shells that will reduce the loss of flux and give improved RFP energy confinement times.

I. Introduction

During the past few years the authors have been studying the low frequency fluctuations\(^1\) (~1 kHz) that were observed on the Los Alamos ZT-40M and other reversed-field pinch (RFP) experiments. Linear perturbation theory predicts the existence of RFP equilibria which are ideal MHD stable when the plasma is totally enclosed in a perfectly conducting shell\(^2\). Unfortunately the RFP stabilizing shells used in experiments are neither perfectly conducting nor completely closed. This departure arises from the fact that in order to set up and maintain the RFP configuration the shell and the vacuum vessel must either be very resistive or have gaps\(^3\) to allow the setup, current drive and equilibrium control electric and magnetic fields that are supplied by the external energy sources to enter the plasma region.

A common assumption is that if the gaps are made small this will be an adequate approximation. The thrust of this paper is to question this premise and to concentrate on the negative effects on the RFP introduced
by the lack of a closed, magnetic flux-conserving shell in actual RFP experiments.

II. The toroidal field electrical circuit.

The toroidal field (TF) circuits, stabilizing shells, and vacuum container walls in various RFP experiments are designed somewhat differently; for this discussion we will use those of ZT-40M as an example. The circuit, Fig. 1, contains an energy source consisting of a capacitor bank with voltage $V_s$, a switch, a transmission line connecting $V_s$ to the load, and an electrically insulated solenoid* wound around a conducting shell having a gap in both the poloidal and toroidal directions. Inside the shell is a resistive vacuum liner which encloses the inductively driven plasma current.

The net changing flux linking the solenoid winding is associated with an induced voltage $V_w$, Fig.2b, across the solenoid terminals. The two voltages, $V_w$ and $V_s$ act together to change the current $I_w$ in the transmission line and TF winding. This is manifest as a change in the toroidal field at the plasma edge, Fig. 2c. Field energy flows in or out of the toroidal region into the external portion of the toroidal field circuit depending on the sign of $V_w$. This voltage depends only on the rate of change of net flux linking the winding.

Local changes of magnetic flux inside the liner, $\Phi$, are measured by single turn loops wound poloidally on the liner at several toroidal locations. A sample waveform $<B\cdot \phi> = \Phi/\text{loop area}$, for one of these loops is given in Fig.2a.

*In ZT-40M the solenoid is made up of fifteen coil sections which can be interconnected electrically in various chosen arrangements. For the present discussion we will assume the sections are connected in series into a single solenoid with two terminals connected to the transmission line.
For the non-symmetric case there is an effect in addition to that discussed above. Since $B$ has zero divergence, local changes of $\langle B-\phi \rangle$ inside the liner, are necessarily associated with deviations of the direction of $B$ causing the field lines to intersect the liner. An equal flux of these intersecting field lines leaves and reenters the plasma region bounded by the liner. Time variations in $\langle B-\phi \rangle$ may be caused by, e.g., MHD disturbances, dynamo action, or by applied toroidal and poloidal voltages. A change in $\langle B-\phi \rangle$ is associated with a corresponding change in local theta value (ratio of poloidal field at the wall to $\langle B-\phi \rangle$) as seen in Fig. 2d. The traces for the plasma toroidal voltage $V-\phi$ and current $I-\phi$ are shown in Fig. 2(e) and 2(f); the combined power entering the liner and plasma from the external poloidal circuit is given in Fig. 2(g). The correlation of the temporal changes of these seven quantities is good.

III. Toroidal Gap currents.

It is clear that any variation of the $\langle B-\phi \rangle$ value with the toroidal angle will lead to toroidal flux leaving and reentering the liner. When these variations are time dependent and the shell has no cuts, the eddy currents induced in the shell by the time varying field penetrating the liner will confine the flux inside the shell for variations rapid compared to the shell resistive time scale. With a gap in the shell this is no longer true as we now describe. If the discharge becomes unstable, being driven into a helical kink, for example, if the discharge moves toward the wall the local poloidal field increases and decreases if the discharge moves away from the wall. Surface currents are induced on the wall, reflecting the movement of the discharge. These currents when faced with the toroidal gap are redirected to flow parallel to the edges of the gap and connecting with surface currents returning in the opposite poloidal direction. These gap currents direct field lines inward and outward through the shell gap. Local perturbations can take
place with different wavelengths but the total radial component flux directed through the gap(s) must be zero because of the zero divergence of B. (Field lines may also leave and/or enter the shell through the poloidal gap as described next.)

V. Poloidal gap currents

When the oppositely directed eddy currents flowing along the edges of the toroidal gap meet a butt-poloidal gap, the positive (negative) gap currents flow around the two ends of the shell, in the negative (positive) direction. The pair of oppositely directed currents flowing along each edge of the poloidal gap produce a radial component of flux through that gap and are detected by "saddle" coils located about the poloidal gap. This loss (gain) of magnetic field is a magnetic field perturbation that can lock a propagating plasma disturbance. An overlapped gap reduces this radial component of flux at the shell gap lowering the field perturbations.

VI. Waveforms of <B-phi>.

We have developed a sharp boundary model to estimate the distribution of surface eddy currents that flow on the surface of the shell, for a constant current, toroidally rotating helical perturbation. The model estimates the waveforms for the redirected currents that flow parallel to the toroidal gap and the associated toroidal flux that leaves and enters the discharge causing an opposite variation in the local internal toroidal flux <B-phi> at each toroidal location. The periodic waveform displays a fast rise, a crash, and slow drop (See the Model column Fig.3D). The corresponding theta wave form has a slow rise followed by a sharp drop as is also shown. The corresponding ZT-40M experimental traces are compared with these model results in Fig.3D. The amplitude and time scales of the model plots are normalized to the experimental results appropriate choices of the free parameters in the model.
The theta and $<B\cdot\phi>$ waveforms are found to be similar for the other cases studied, namely, (1) a discharge compression followed by an expansion a 'sausage' with oscillating minor radius, and an oscillating shift of the same plasma column axis along a major radius\[^8\]. For the special case, $m=0, n=0$ (a radial 'breathing' of the discharge uniform around the toroidal discharge), the model does not apply. In this case, the magnetic field lines remain parallel to the liner and the change in $<B\cdot\phi>$ is toroidally symmetric; the toroidal flux leaves and enters the liner as the plasma column expands and contracts. In all the $n\neq 0$ cases described above a crash in $<B\cdot\phi>$ results.

We note that a description of the $m=0, n=0$ case which assumes sudden cooling of the plasma (e.g., due to a pulse of impurities), followed by toroidally symmetric collapse of the plasma minor radius, will increase the negative flux resulting in a fast decrease in $<B\cdot\phi>$ instead of the rapid increase as seen in experiments at the time of the crash [Fig.2(a)].

The sawtooth $<B\cdot\phi>$ waveform with a rapid increase during the crash is commonly interpreted as a “dynamo event” corresponding to a rapid restoration of the internal positive mean-field magnetic flux. We point out that this need not be the case. Alternatively, since the external flux loops measure the total net flux inside the liner, these crashes may indicate only a rapid expulsion of negative flux as a plasma disturbance moves near the toroidal gap. The total flux in the plasma measured by a toroidal flux loop can increase without any positive flux being created inside. This possibility emphasizes the need for internal magnetic field profile measurements in RFP plasmas.

VII. Bombardment of the wall

A. Impurities.

When toroidal flux inside the liner decreases in a toroidally symmetric fashion, there is an outward pointing vector corresponding to a loss of field energy and an ExB drift of plasma to the liner. For a non toroidally
symmetric flux change there is a parallel flow of plasma along the field lines that intersect the liner. In either case energetic plasma will bombard the wall releasing impurities\textsuperscript{[9]}. In ZT-40M this was manifest by correlations between variations of \( <B\text{-phi}> \) and theta and bursts of carbon, chromium, \( D^e \) radiation and emission of x-ray as shown in Fig 4. (The correlations are not precise due to the different toroidal positions of the magnetic flux loop and radiation detectors.)

VIII. Energetic electrons

Experiments have detected energetic electrons\textsuperscript{[10,11]} near the liner. As flux passes through the liner, it is not surprising that energetic electrons present in the interior of the discharge are brought out close to the detector that is located just inside the liner. In MST\textsuperscript{[10]} correlations are found between the current and temperature of the energetic electrons streaming (observed to be directed opposite the applied toroidal driving E-field) near the wall and the magnetic field fluctuations. In the ZT-40M the observations\textsuperscript{[11,12]} are similar but the correlation between fast electrons and low frequency fluctuations was suggestive but not conclusive.

The detected energetic electrons have been observed to be up to a factor of three hotter than the core temperature and can constitute a primary electron-energy loss channel. They are believed to be energized in the core by the driving E-field where the Dreicer runaway parameter\textsuperscript{[13]} is high. These electrons then subsequently move along stochastic field lines, reverse their direction in the reversed B-field region, and are then detected. This interpretation has been used in support of the kinetic dynamo model\textsuperscript{[14]}. If the above interpretation is correct, to reduce this loss of energy, the toroidal drive voltage must be reduced and/or the plasma density raised.
IX. Discussion.

A. RFP Scaling.

It was found that during the flat-topped operation of ZT-40M\textsuperscript{[15]}, the dependent quantities, including plasma resistance, low frequency fluctuations, and toroidal flux exhibit minima as function of theta for constant value of Iphi. In addition, the minima of the quantities gave the highest poloidal beta. Over the range of conditions examined, the scaling of variables with Iphi is not unique, but depends on the choice of the variation for theta as Iphi is increased\textsuperscript{[15]}. This result suggests to the authors that design changes can enhance RFP performance.

B. Favorable shell configurations

Two experiments, OHTE\textsuperscript{[16]} and TPE-1RM\textsuperscript{[17]} are reported as observing the discharge resistance falling as Iphi\textsuperscript{3/2}. Theta was held constant as Iphi increased for TPE-1RM. The theta variation for this scaling was not reported for OHTE. Both of these experiments had unique shell designs, OHTE had a shell without a toroidal gap, and TPE-1RM a double shell with two gaps, toroidal and poloidal, each corresponding pair rotated 180° with respect each other so that the gaps are covered. Both experiments report some radial outward shift of the discharge position. (When no vertical equilibrium centering is applied, the outward equilibrium shift is limited on the shell diffusion time scale by compressing the poloidal B-field field.) The experiment in Kyoto\textsuperscript{[18]} reports that the discharge resistance is lowered by close fitting shells.

C. Parallel TF coils

We mention the experiment run on ZT-40M\textsuperscript{[19]}, in which the twelve TF coil sections, which were normally connected in series-parallel, were reconfigured to have all of the coil sections connected in parallel. As shown in Fig.5, the low frequency fluctuations were eliminated with the parallel
connection and the discharge resistance at constant Iphi did not increase with a theta as it did in the series-parallel case. At the highest theta tested, 1.7, the toroidal loop voltage was reduced by a factor 1.75\textsuperscript{[19]}.

A similar test was made on the Reversatron\textsuperscript{[20]}. It was found that the m=0, and n ranging from 6 to 12 magnetic activity was reduced during RFP startup. Later in the discharge there was a significant reduction in the external kink modes with m=1 and 3<n<6.

D. Dynamo.

When the TF coil sections of ZT-40M are connected in the usual series parallel arrangement the large, low frequency saw teeth and crashes are not observed at low (< 1.45) average theta <\theta> values. They are present at high values as shown in Fig. 5(a) & (c). When the coil sections are connected in parallel the absence of large saw teeth seen at low <\theta> persists even though <\theta> is high, Fig. 5(b), (c). The discharges obtained at low <\theta> or with the parallel configuration even at high <\theta>, both require a dynamo to sustain the positive flux inside the discharge against resistive diffusion\textsuperscript{[21]}. Since in these cases the flat-topped current was maintained without large low frequency saw teeth, we conclude that the dynamo action does not require these low frequency fluctuations. As discussed in Sec.VI, these saw teeth may not be connected with individual dynamo events as often assumed. We have to date no conclusive experimental determination of how the dynamo generated. A low-amplitude-high-frequency turbulent dynamo, the kinetic dynamo and other mechanisms are possibilities.

E. Field profile modification

Guided by theoretical considerations, other ways are being attempted to reduce these fluctuations such as the injection of current or RF poloidal current drive to flatten the J·B/B\textsuperscript{2} profile near the wall\textsuperscript{[22]}. This is predicted to reduced resistive tearing mode activity and the associated particle and energy transport to the wall. Significant reduction in the fluctuations is observed
when a transient pulse of poloidal current is applied\textsuperscript{22}. Preliminary tests on MST are reported \textsuperscript{23} to show some improvement using electron beam injection.

F. Low Fluctuation Operation

The reports of low fluctuation, crash-free discharges are of interest\textsuperscript{24}. In the early experiments on Zeta\textsuperscript{25}, a period (< 1 ms) of reduced fluctuations was called quiescence. Short, \~100\,\mu s, low fluctuation intervals were also reported in ZT-40\textsuperscript{26} with theta as high as 1.95. More recently, sawtooth-free operation has been reported at high theta values\textsuperscript{27}. It is suggested that the high theta sawtooth-free operation should be investigated to see if it may correspond the helical lowest energy state that Taylor\textsuperscript{28} predicts for theta $\geq 1.6$.

X. Conclusions.

The discussion above supports the contention of the authors, that a high priority question faced by the RFP community today is the reduction of field errors particularly those caused by the gaps in the shell. At present there is no clear design which gives the equivalent of a closed, conducting wall for stability with the freedom needed for setup, current drive, and time varying vertical fields to control the discharge equilibrium shift.

Small simple RFP experiments that are easily and quickly modified are needed \textsuperscript{29}, to test design ideas before installing untried designs on large, expensive, running experiments.

There have been a number of suggestions to attack the above problem. Some have at least been partially experimentally investigated; others have not. More investigation needs to be done. We list some of these ideas and results below:
• It is suggested \cite{30} that a resistive shell with neither toroidal nor poloidal gaps, be investigated experimentally. The shell conductivity and thickness must be high enough to limit the growth of propagating modes such as observed on ZT-40M but have a short enough diffusion time for the slower vertical equilibrium control fields to penetrate the shell. A further constant is that shell currents are limited to acceptable values. Linear stability calculations predict a stabilizing effect of plasma rotation on resistive thin shell modes \cite{31}. A nonlinear theory is needed which includes thick shells.

• The “intelligent shell” concept \cite{32} has been suggested in which the shell is replaced with a wire grid whose mesh is small compared to the modes of interest. Each loop on the grid has radial flux sensing feedback set to keep the flux through each loop zero. This mocks up a perfect shell to the resolution of the grid and will produce its own vertical equilibrium field limiting the outward toroidal shift as a perfectly conducting shell does. Calculations \cite{33} indicate that the power and gain requirements of such a system are moderate. Calculations have also been made to mock up a rotating intelligent shell \cite{34}.

• Passive and active control \cite{35} of thin shell modes was attempted on HBTXIC but no improvement in plasma confinement was obtained.

• The Scyllac feedback research program \cite{36} showed feedback control of the m=1 instability on a theta pinch.

• Experimental investigations \cite{37} of feedback circuits were made on the Reversatron.

• Saddle coil compensation coils were planned for the ZTH toroidal shell gap \cite{38}. Feedback of field-shaping windings to compensate the toroidal gap has been used to give improved performance of RFX \cite{39}.

• The design of ZTH included the following features: (1) a thin copper stabilizing shell supported mechanically by resistive stainless steel overlay to allow slow vertical field control, (2) a compensated poloidal
gap to reduce the field error and (3) a set of compensating parallel connected TF coils close to the shell.

A sampling of the other information relevant to this subject can be found in references 40-45.

In closing, authors suggest the following new idea: Based on the premise that, for a given design theta value, the dominant MHD activity is a low frequency propagating helical disturbance as suggested by the modeling of Sec.VI, we propose exploring replacing the usual toroidal shell gap with a helical shell gap with the same pitch. This motivation is that the ideal closed shell stabilizing eddy currents would then run parallel to the gap. This would then avoid the field errors due to the redirection of currents at the gap discussed in Sec III. One would then explore a ramped start-up using a controlled theta$^{[46]}$. Since the plasma structure will be different from the final nonlinear state in the ramping part of the discharge, starting up with a constant theta at the design value may not be appropriate. The past ramped start-up studies in ZT-40M, suggest starting up with low field reversal to keep the low frequency activity low during the ramping and then near peak current raise theta to the design value. The shell should be kept as close as possible to the plasma region to maximize its stabilizing effect$^{[18]}$. If this shell design is successful, we suggest replacing the conducting shell with a closely-spaced set of helical of wires surrounding the torus. The windings are to be arranged so that the induced voltage for a changing vertical field in each wire circuit is zero so that the equilibrium control vertical field can penetrate. Feedback in the windings can be used to hold the stabilizing winding currents for time scales longer than their resistive diffusion time. If the postulated helical disturbance remains propagating and not mode locked this may not be necessary. This idea needs detailed analysis before any practical design can be made.
The ideas listed in this section (or others) complicate the RFP design, but may be necessary if the RFP is to have energy confinement times sufficient to become a viable alternative reactor\textsuperscript{[47,48]}.

Acknowledgments.

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References.


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45. D. H. Liu, Lab. Report, Alven Laboratory, KTH, Issn 1102-2051, ISRN KTH/ALF?-96-SE.


Figure Captions

Fig. 1. Schematic drawing of the toroidal field circuit used in ZT-40M.

Fig. 2. Ramp discharge showing relationship between seven experimental quantities for a shot in ZT-40M. (a) ave. toroidal magnetic field measured by a poloidal loop on the vacuum liner, (b) Poloidal single-turn voltage measured by the loop in (a), (c) toroidal magnetic field measured by a pickup loop just outside the liner, (d) local pinch parameter computed from traces (a) and (f), (e) toroidal loop voltage, (f) toroidal current, and (g) power entering the liner-plasma volume.

Fig. 3. The model used to estimate the time behavior of the surface currents and corresponding radial flux production at the shell gap for a rotating helical disturbance:
   A. Schematic of the postulated flow of surface currents on the shell at the toroidal gap.
   B. The model with two conducting straight cylinders of radii, $R_1$ and $R_2$, and distance between them, $C$, as a function of azimuthal angle $\alpha$. The inner cylinder rotates represents the plasma and the outer one the shell.
   C. Determination of (a) $C$, (b) $1/C$, (c) the perturbed value of $\langle B-\phi \rangle$ at the gap obtained from integration and normalization and of the gap currents which are assumed to scale as $1/C$. (d) Theta as deduced from the computed time varying $\langle B-\phi \rangle$.
   D. Comparison the model waveforms to the experimental traces. The scales on the model graph are normalized to those of the experiment. The periodic F-theta diagrams are the bottom pair of plots.
Fig. 4. Traces showing a comparison of the time dependence of X-rays and some impurity lines with traces of toroidal voltage, theta, and toroidal field quantities for the flat-top discharge shot No. 28293.

Fig. 5. Comparison of $<\text{B-phi}>$ and theta for the two toroidal winding configurations, series-parallel and parallel on ZT-40M. Note the absence of the large amplitude low frequency fluctuations for the parallel configuration.
Fig. 1.
Fig. 2

Butt poloidal gap.
Fig. 3
X-rays, Impurities and Electrical Parameters

**Flat-top Discharge**

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**Shno 26293**

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**Fig. 4**
Series-parallel TF coils
V-phi 70 V, I-phi 121 kA.

Paralle TF coils.
V-phi 41 V, I-phi 111 kA

(a) (b) (c) (d)

Fig. 5