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Poloidal Magnetic Field Fluctuations in Tokamaks

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ABSTRACT

Elementary nonlinear tearing mode theory in a two-dimensional cylindrical geometry is used to predict accurately the amplitude of the $m = 2$ poloidal magnetic field fluctuations (Mirnov oscillations) at the limiter of a tokamak. The input required is the electron temperature radial profile from which the safety factor profile can be inferred. The saturation amplitude of the $m = 2$ tearing mode is calculated from the safety factor profile using a nonlinear Δ' analysis. This gives an absolute result (no arbitrary factors) for the amplitude of the perturbation in the poloidal magnetic field everywhere, in particular, at the limiter. An analysis of ORMAK and T-4 safety factor profiles (inferred from electron temperature profiles) gives results that are in agreement with the experimental data.

A study of a general profile shows that as a function of the safety factor at the limiter, a maximum occurs in the amplitude of the Mirnov oscillation. The magnitude of the maximum increases with a decrease in temperature near the limiter.

POLOIDAL MAGNETIC FIELD FLUCTUATIONS

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1. INTRODUCTION

Mirnov discovered that the poloidal magnetic field at the limiter of a tokamak is not constant but oscillates with a characteristic frequency and wavelength. In the ORMAK (Oak Ridge Tokamak) device these poloidal magnetic field fluctuations were characterized by a frequency of roughly the magnitude of the electron diamagnetic drift frequency, and the mode with poloidal mode number m equal to two was dominant in many of the discharges. J. L. Dunlap [1] performed a detailed set of measurements on ORMAK, determining the ratio of the amplitude of the poloidal magnetic field fluctuation ($\tilde{B}_\theta$) and the equilibrium poloidal magnetic field B_θ . It was found that as a function of q_ℓ , the safety factor at the limiter, $\tilde{B}_\theta/B_\theta$ for $m = 2$ modes decreased slightly from a value of 0.4% at a q_ℓ of 9 to 0.1% at q_ℓ of ~ 6 but then increased dramatically to 1.5% at a q_ℓ of 4, where the confinement deteriorated [2] (see Fig. 1). On the other hand similar measurements on T-4 [3,4] had shown $m = 2$ activity when q_ℓ was between 2 and 5, also with a maximum signal of $\sim 1.5\%$.

The purpose of this article is to explain these somewhat dissimilar data on the basis of the nonlinear theory [5,6,7,8] of tearing modes [9,10]. The importance of explaining the data is that it has been shown (in Refs [2 and 4]) that the confinement time as a function of q_ℓ is correlated with $\tilde{B}_\theta/B_\theta$. In Ref. [4] Mirnov showed that the confinement

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time data from several machines could be made to obey a universal curve by assuming that the effective radius of each machine is determined by the location of the cold plasma layer.

The basic assumption of the calculation is that the $m = 2$ poloidal magnetic field oscillations are due to a saturated $m = 2/n = 1$ tearing mode [6,7,8]. The calculation is performed both semianalytically and numerically and is based on the radial safety factor profiles inferred from the electron temperature profiles taken from the laser scattering measurements. Both methods are in good agreement with the experimental results. The numerical method, however, enables us to study the interaction of the $m = 2/n = 1$ tearing mode with other tearing modes of different pitch as well as the same pitch. The results indicate that the saturation amplitude is sensitive to the temperature near the limiter.

The remainder of this article is organized as follows. A semianalytic method of calculating $\tilde{B}_\theta$ is described in Section 2. These results are compared with T-4 and ORMAK data in Sections 3 and 4. The analysis of a model profile allows us to draw the general conclusion that $\tilde{B}_\theta/B_\theta$ exhibits a peak as a function of q_ℓ , the magnitude of which can be reduced by decreasing the temperature gradient near the limiter. In Section 4 the numerical results are presented and compared with the semianalytic results. Finally some general conclusions are presented in Section 5.

2. POLOIDAL FIELD FLUCTUATION DUE TO THE $m = 2$ TEARING MODE

In the reduced resistive MHD approximation in cylindrical geometry, the magnetic field $\underline{B}$ is given by [11,12]

$$\underline{B} = -\underline{\nabla}\psi \times \hat{\zeta} + B_{\zeta} \hat{\zeta} \quad (1)$$

where ψ is the poloidal flux function, B_{ζ} is the toroidal field, and $\hat{\zeta}$ is the unit vector in the toroidal direction. If we assume that the poloidal field fluctuation $\tilde{B}_{\theta}$ is essentially due to the $m = 2/n = 1$ tearing mode, then its relative amplitude is

$$\left. \frac{\tilde{B}_{\theta}}{B_{\theta}} \right|_{r=a} = \left. \frac{\partial \psi_{21}}{\partial r} \right|_{r=a} \bigg/ \left. \frac{\partial \psi_0}{\partial r} \right|_{r=a} \quad (2)$$

where ψ_0 is the equilibrium flux and $\psi_{21}(r,t) \cos(2\theta + \zeta)$ is the perturbation in the flux. It is known that the 2/1 tearing mode saturates on a relatively fast time scale. We shall calculate the poloidal field fluctuations for the saturated amplitude of the $m = 2$ tearing mode. We have two ways of performing this calculation. One way is to evaluate Eq. (2) directly in an initial value code [11] (to be discussed in Section 5). On the other hand we can rewrite Eq. (2) as

$$\left. \frac{\tilde{B}_{\theta}}{B_{\theta}} \right|_{r=a} = -q_{\ell} \frac{W_{21}^2}{64} r_s q'(r_s) \left[\frac{1}{\psi_{21}(r_s)} \left. \frac{\partial \psi_{21}}{\partial r} \right|_{r=a} \right] \quad (3)$$

where W_{21} is the saturated island width, r_s is the radius of the singular surface, q' is the shear, and m and n are the poloidal and toroidal mode numbers, respectively.

Because the saturated mode has essentially the same shape as the linear eigenmode, we can estimate the factor in square brackets in Eq. (3) using the linear eigenfunction. This factor has a weak dependence on q_{ℓ} , increasing as the singular surface moves toward the limiter. Thus, the behavior of $\tilde{B}_{\theta}/B_{\theta}$ is dominated by the saturated island width.

In order to calculate the saturation amplitude of the $m = 2$ tearing mode, we employ the concept of a nonlinear Δ' that was introduced by R. White et al. in Ref. [8]. Instead of defining Δ' across the infinitesimal tearing layer, we define it across the finite width of the associated magnetic island:

$$\Delta'(W) \equiv \frac{1}{\psi_{21}(r_s)} \left(\left. \frac{d\psi_{21}}{dr} \right|_{r^+} - \left. \frac{d\psi_{21}}{dr} \right|_{r^-} \right) \quad (4)$$

where $r^\pm = r_s \pm W/2$, and W is the full island width across the separatrix at its widest point. We assume that the saturation width W_s is given simply by $\Delta'(W_s) = 0$. The physical motivation for this assumption is that it was shown in Ref. [13] that Δ' is proportional to the δW obtained for this instability. Consequently, our assumption is predicated on the fact that the mode simply stops growing when there is no more MHD energy available to drive it. In Fig. 2 we compare the results of such an analysis with the results of the more complicated analysis in Ref. [8] which involves resistivity gradients for the peaked current mode. The agreement is quite good.

The criterion that $\Delta'(W_s) = 0$, where W_s is the saturation width, appears to remain valid even if diamagnetic effects and viscosity are included in the analysis. It was reported by D. A. Monticello et al. [14] that the $m = 2/n = 1$ island saturated at approximately the same width even when these effects are included as it does when only resistive MHD effects are considered; this is reasonable because the fundamental argument depends only on the energy associated with δW .

The following equation must be integrated in cylindrical geometry to obtain $\Delta'(W)$ [10]

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d\psi_{21}}{dr} \right) - \frac{4}{r^2} \psi_{21} = \frac{2}{r} \frac{dJ_o}{dr} \frac{1}{F_{21}} \psi_{21} \quad (5)$$

where J_o is the equilibrium toroidal current density, ψ_o is the equilibrium flux function, and F_{21} is given by

$$F_{21} \equiv \frac{2}{r} \frac{d\psi_o}{dr} + 1 = 1 - \frac{2}{q} \quad (6)$$

The equilibrium flux and current density are related by

$$J_o = \frac{1}{r} \frac{d}{dr} \left(r \frac{d\psi_o}{dr} \right) \quad (7)$$

For all but the most trivial safety factor profiles, Eq. (5) must be integrated numerically, subject to the boundary conditions that $\psi_{21}(r = a) = 0$, where a is the minor radius, and ψ_{21} is continuous at $r = r_s$. We employ a uniform grid of 2000 points although we find that the results converge for approximately 200 points. Once ψ has been obtained, it is trivial to evaluate $\Delta'(W)$ and ascertain the value of W at which it vanishes.

3. ANALYSIS OF THE EXPERIMENTAL DATA

In order to analyze the experimental data it is convenient to employ a parametrization of the safety factor profile of the form

$$q(r) = q(o) \left[1 + (r/r_o)^{2\lambda(r)} \right]^{1/\lambda(r)} \quad (8)$$

where

$$\lambda(r) = \lambda_0 + \frac{\lambda''}{2} r^2 \quad (9)$$

Most safety factor profiles can be approximated with Eq. (8) by suitable adjustments of $q(0)$, r_0 , λ_0 , and λ'' ; we use Eq. (8) to fit the ORMAK data [15]. For $\lambda'' = 0$ and $\lambda_0 = 1, 2$, or 4 , this profile reduces to the peaked, rounded, or flattened profiles of Ref. [10], respectively. The experimental measurements of $q(r)$, the parameters of the fit, and the results of the $\Delta'(W)$ analysis for ORMAK are presented in Table I.

The results are particularly sensitive to the fit of $J(r)$ near the limiter because the singular layer is often near the limiter and thus dJ/dr in Eq. (5) must be obtained accurately in that region. The parameter λ'' enables us to obtain a good fit of dJ/dr near the limiter without forcing an artificial flatness in $J(r)$ near the plasma center. In order to illustrate the sensitivity of the saturation width to λ'' , we plot in Fig. 3 the saturation width W as a function of λ'' for three values of λ_0 , $q(0) = 1.08$, and $q_\ell = 4$.

Using Eq. (3) we calculate $\tilde{B}_\theta/B_\theta$, and the results are plotted as a function of q_ℓ in Fig. 4. The agreement with the ORMAK data [1] is quite good including the location of the minimum value.

In order to describe the safety factor profile of T-4, we employ the expression

$$q(r) = q(0) \left[1 - (r/a)^4 + \frac{3}{5} (r/a)^8 - \frac{1}{7} (r/a)^{12} \right]^{-1} \quad (10)$$

obtained from the temperature profile [3]. This model profile was employed to obtain the results in Fig. 5. The agreement between theory

and experiment for T-4 is not as good as for ORMAK; this could be due to the fact that the fit expressed in Eq. (10) is based on the laser scan temperature data at relatively few values of r .

In order to understand these results better, we make an idealized scan and study the dependence of $\tilde{B}_\theta/B_\theta$ on total current. We use Eqs (8) and (9) to model the equilibrium. Specifically, for $q(o) = 1.0$ and $\lambda_o = 1.0$, we study the behavior of W_{21} (Fig. 6) and $\tilde{B}_\theta/B_\theta$ (Fig. 7) as a function of q_ℓ for three different values of λ'' .

We observe that the behavior of $\tilde{B}_\theta/B_\theta$ vs q_ℓ is dominated by the behavior of W_{21} , i.e., as a function of q_ℓ , maxima occur in both W_{21} and $\tilde{B}_\theta/B_\theta$ at approximately the same value of q_ℓ . The value of the maximum resistive MHD activity decreases as λ'' decreases. Figure 7 shows that the poor confinement region, i.e., $\tilde{B}_\theta/B_\theta$ greater than 1%, is localized to a fairly narrow range of q_ℓ . The T-4 data straddle the maximum while the ORMAK data lie to the right of the maximum.

An increase in the parameter λ'' corresponds to a decrease in the temperature near the limiter and could simulate the presence of high radiation losses which depress the temperature in this region. Consequently, a "clean" machine would be more likely to penetrate the large $\tilde{B}_\theta/B_\theta$ "barrier" and operate at lower values of q_ℓ . In order to illustrate the sensitivity of the profiles to λ'' , the toroidal current density is plotted in Fig. 8 for $\lambda = 1$ and $\lambda = 1 + 2r^2$.

4. NUMERICAL ANALYSIS

As was pointed out earlier, another way of calculating $\tilde{B}_\theta/B_\theta$ is by numerically advancing the reduced resistive MHD equations using a nonlinear code [11]. In three-dimensional cylindrical geometry, the resistive MHD equations are (in dimensionless form),

$$\frac{D\psi}{Dt} \equiv \frac{\partial\psi}{\partial t} + \underline{V}_\perp \cdot \underline{\nabla}_\perp \psi = \eta J_\zeta - E_\zeta^W - \frac{\partial\phi}{\partial \zeta} \quad (11)$$

$$\frac{DU}{Dt} \equiv \frac{\partial U}{\partial t} + \underline{V}_\perp \cdot \underline{\nabla}_\perp U = -S^2 \left[\hat{\zeta} \cdot (\underline{\nabla}_\perp \psi \times \underline{\nabla}_\perp J_\zeta) + \frac{\partial J_\zeta}{\partial \zeta} \right] \quad (12)$$

where the subscript $\perp$ denotes perpendicular to the toroidal direction,

ψ is the poloidal flux function, ϕ is the velocity stream function, $J_\zeta = \nabla_\perp^2 \psi / \mu_0$ is the toroidal current density, and $U = \nabla_\perp^2 \phi$ is the vorticity.

The parameter S is the ratio of the resistive diffusion time

$\tau_R [\equiv \mu_0 a^2 / \eta(0)]$, where $\eta(0)$ is the resistivity at the plasma center] and

the poloidal MHD time $\tau_{Hp} [\equiv R_0 / V_A]$, where R_0 is the major radius and V_A

is the Alfvén velocity]. The resistivity $\eta(r)$ is assumed to be constant

in time and given by $E_\zeta^W / J_{\zeta 0}(r)$, where the 0 subscript denotes equilibrium quantities and E_ζ^W is the electric field at the wall (limiter).

The main reason for recalculating $\tilde{B}_\theta/B_\theta$ using the nonlinear code is

to take into account the interaction of the $m = 2/n = 1$ with other modes,

and see if those interactions have any effect on the measured quantity.

Let us first consider the effect of the interaction with modes of the same

helicity; we choose the T-4 case because the growth rates are larger than

for ORMAK.

The $\tilde{B}_\theta/B_\theta$ values obtained numerically for T-4 and those obtained

from the Δ' analysis are compared in Fig. 9. For $q_0 > 2.8$, however, the

numerical results are somewhat larger than the analytic results although the marginal stability points coincide. This effect could be due to the higher modes $4/2$, $6/3$, . . . becoming more important. Consequently, we conclude that except for low values of q_ℓ , the Δ' is valid and gives a reasonable answer when only the $2/1$ mode is involved.

Let us now consider the case where other helicities could be involved. This occurs in ORMAK when $q_\ell \lesssim 4$, so that $q(0) \lesssim 1$ causing the $1/1$ to become unstable; in T-4 when q_ℓ is between 2.5 and 3, the $3/2$ mode is also linearly unstable.

First, we consider $m = 1$ activity associated with the ORMAK safety factor profile B - 2 (see Table I) where initially $q(0) < 1$ with $S = 10^4$ (here η is normalized to one at the magnetic axis). Because $q(0) < 1$, we expect the $m = 1$ tearing mode to be unstable. We initialize the $m = 1$ mode as well as the $m = 2$ to study their nonlinear evolution and possible interaction. The growth of the $m = 1$ is so rapid compared to the $m = 2$ that the $1/1$ helicity flattens the safety factor inside the $q = 1$ singular surface before the $m = 2$ perturbation becomes an eigenmode. As can be seen in Fig. 10, the modification of the q profile does not extend to the region of the $q = 2$ surface; consequently, the effect on the growth rate of the $2/1$ is negligible for this type of profile and does not affect our prediction for the amplitude of the Mirnov oscillations.

We have studied the T-4 profile for $q_\ell = 2.75$ which corresponds to the peak in Fig. 5, and found a large amount of MHD activity. Specifically, both the $2/1$ and $3/2$ modes are unstable, and nonlinearly the $2/1$ mode further destabilizes the $3/2$ and also destabilizes other modes; however, the saturated width of the $2/1$ mode is largely unaffected.

5. CONCLUSION

We conclude that the magnitude of tokamak $m = 2$ poloidal field fluctuations (Mirnov oscillations) and its dependence on the value of the safety factor at the limiter can be explained by elementary non-linear tearing mode theory. The magnitude and dependence of the saturation amplitude of the modes (as measured at the limiter) are predicted accurately for both T-4 and ORMAK by assuming that the mode saturates when the associated magnetic island width W is such that $\Delta'(W)$ vanishes. The prediction is absolute; no arbitrary parameters are adjusted. Only knowledge of the safety factor radial profile is required.

On the basis of our comparison with the experimental data, we conclude that it is unnecessary to incorporate toroidal effects to predict the amplitude of the $m = 2/n = 1$ mode.

We observe that as a function of q_ℓ , the amplitude of the $m = 2$ mode exhibits a maximum in T-4 and a minimum in ORMAK, the position and magnitude of which are predicted by the tearing mode theory. The minimum has been correlated experimentally by Berry et al. [2] and Mirnov [4] with a maximum in electron, ion, and total confinement time. The search for an explanation of this correlation should prove to be a fruitful area of future research.

General profile considerations show that if the safety factor profile is altered in order to correspond to a decrease in the rate of cooling (an increase in temperature) near the limiter, the maximum amplitude of the Mirnov oscillations (as a function of q_ℓ) decreases. The measured correlation between an increase in confinement time and a decrease in fluctuation amplitude would imply an improvement in confinement time under these circumstances. Such an effect may have been observed in Alcator and ISX-A as the effective ion charge is decreased.

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TABLE I. CHARACTERISTICS OF THE ORMAK SAFETY FACTOR PROFILES

Profile	r_0	$q(0)$	$\lambda(r)$	$q(a)$	W_{21}	$\frac{1}{\psi_{21}(r_s)} \frac{\partial \psi_{21}}{\partial r} \Big _a$
I - 1	0.482	0.866	$1 + 1.5r^2$	3.82	0.13	-1.94
I - 2	0.476	0.930	$1 + 1.5r^2$	4.12	0.14	-1.06
I - 3	0.401	0.770	$1 + 2r^2$	4.79	0.11	-0.82
I - 4	0.457	1.143	$1 + r^2$	5.59	0.09	-0.44
I - 5	0.383	1.055	$1 + 2r^2$	7.20	0.10	-0.41
I - 6	0.355	1.139	1.5	9.3	0.12	-0.41
B - 1	0.378	0.896	$1 + 2.5r^2$	6.31	0.07	-0.58
B - 2	0.462	0.837	$1 + 2r^2$	4.0	0.15	-2.15

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FIGURE CAPTIONS

FIG. 1. The experimental correlation between $\tilde{B}_\theta/B_\theta$ and confinement time as a function of q_θ (taken from Ref. 4).

FIG. 2. Comparison of the results of this paper with the results of the more complicated calculation in Ref. 8 for the peaked profile.

FIG. 3. Saturation width W vs $a^2\lambda''/2$ for the general profile with $q(0) = 1.08$; $q_\theta = 4$, and for three values of λ_0 .

FIG. 4. Comparison of the experimental and theoretical values of $\tilde{B}_\theta/B_\theta$ at the limiter as a function of q at the limiter for the ORMAK device.

FIG. 5. Comparison of the theoretical values of $\tilde{B}_\theta/B_\theta$ at the limiter and the experimental values as a function of q at the limiter for the T-4 device.

FIG. 6. Width of the 2/1 island (W_{21}) as a function of $q(a)$ for the model equilibrium.

FIG. 7. The magnitude of $\tilde{B}_\theta/B_\theta$ of the 2/1 mode as a function of $q(a)$ for the model equilibrium.

FIG. 8. Toroidal current density J_ζ for $\lambda = 1$ and $\lambda = 1 + 2r^2$.

FIG. 9. Comparison of $\tilde{B}_\theta/B_\theta$ values obtained numerically for T-4 and those obtained from the Δ' analysis.

FIG. 10. Illustration of the flattening of the q profile inside the $q = 1$ singular surface.

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Fig. 1.

Fig. 2.

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Fig. 3.

Fig. 4.

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Fig. 5.

Fig. 6.

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Fig. 7.

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Fig. 8.

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Fig. 9.

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Fig. 10.

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