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A NOTE FOR THE MIRNOV SIGNAL ANALYSIS IN TOKAMAKS

By

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A NOTE FOR THE MIRNOV SIGNAL ANALYSIS IN TOKAMAKS

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ABSTRACT

The relation between Mirnov coil signals and the current perturbation on the rational surface is examined analytically by using the approximate Green's function for the case of large aspect ratio circular tokamaks.

Satellite island formation, phase modulation effect due to the poloidal variation of the field line pitch, and the shift effect of the plasma column with respect to the center of the vacuum chamber are examined.

The detectability of these effects from Mirnov coil signals is discussed for TFTR.

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I. INTRODUCTION

Understanding of the current perturbation inside the plasma is important in order to control major disruptions and high β_p MHD activity in tokamaks. Mirnov coils have been a powerful tool to investigate the magnetic field perturbations in tokamaks.^{1,2} Usually each MHD mode has its own frequency, and mode separation in the case of many modes has been possible by using the Fourier analysis techniques.^{3,4} The poloidal mode number m and toroidal mode number n can be determined by analysis of the relative phases of Mirnov coils.⁴ However, efforts to find the internal perturbed current distribution $\tilde{J}_\phi$ from the measured external $\tilde{B}_\theta$ field have not been successful.

The first rough approach to finding the $\tilde{J}_\phi$ distribution from external $\tilde{B}_\theta$ signals is to put a helical current perturbation at the rational surface whose radius can be determined by soft X-ray imaging diagnostics. The magnetic field perturbation by the helical current at the singular surface has been examined by Fussmann *et al.*⁵ In the following section, an integral formula for the poloidal flux due to such a perturbation is derived by using an approximate Green's function. For a large aspect-ratio, circular, low β_p tokamak, the cylindrical approximation is adequate for analysis of the current perturbation inside the plasma. However, toroidal effects produce various modifications to the magnetic field perturbation. For example, satellite island formation has been shown by Fussmann. This effect is reproduced by the Green's function expression in Sec. II. One of the most important modifications due to the toroidicity is the phase modulation of Mirnov signals by the poloidal variation of the pitch of the magnetic field. This effect has been pointed out by Merezkin.⁶ However, the phase structure of the current perturbation in the plasma and the phase structure of the magnetic field perturbations outside the plasma are not necessarily the same. An analytic

expression for the perturbed poloidal flux is derived in Sec. IV for this case.

The analytical formula is applied to TFTR cases and some of the results are shown in Sec. V.

II. GREEN'S FUNCTION EXPRESSION FOR MAGNETIC PERTURBATION

The helical nature of the perturbed current does not affect the signal on the Mirnov coils in tokamaks and it is accurate enough to use an axisymmetric current perturbation for understanding the relationship between the current perturbation and the Mirnov coil signals.

Consider a line current located at (ρ_0, ζ_0) where we use the flux coordinates (ρ, ϕ, ζ) , and we assume that the poloidal cross section of the equilibrium flux surface is a shifted circle. Poloidal flux produced by the line current is expressed as follows:

$$d\psi_{mn} = \frac{\mu_0 X dI}{2\pi} \left(\ln \frac{8X}{\xi} - 2 \right) \quad (1)$$

where, $X = R_c + \Delta_{mn} + \rho_0 \cos \zeta_0$, R_c is the center of the vacuum chamber, Δ_{mn} is the shift of the center of the rational magnetic surface and ξ is the distance between (ρ_0, ζ_0) and (ρ, ζ) .

Integration with respect to ζ_0 gives

$$\psi_{mn} = \frac{\mu_0}{2\pi} \int_0^{2\pi} X \left(\ln \frac{8X}{\xi} - 2 \right) \frac{dI}{d\zeta_0} d\zeta_0. \quad (2)$$

This corresponds to so-called tokamak ordering.

III. SATELLITE ISLAND FORMATION DUE TO TOROIDICITY

We assume at first that $dI/d\zeta_0$ is expressed as follows:

$$\frac{dI}{d\zeta_0} = J_{mn} \cos(m\zeta_0 + n\phi + \phi_0) \quad (|m| \geq 2) \quad (3)$$

where m, n , and ϕ_0 are the poloidal mode number, the toroidal mode number, and the phase delay, respectively. In order to obtain the ζ_0 -integral, we may use the expansion formula given in Appendix I. Substituting Eqs. (3) and (I-1) into (2), we obtain the following expression.

$$\begin{aligned} \psi_{mn}(\rho, \zeta) = & \frac{\mu_0 R J_{mn}}{2} \left\{ \frac{\varepsilon |m|}{|m|} \cos(m\zeta + n\phi + \phi_0) \right. \\ & + \frac{\varepsilon |m+1|}{2|m+1|} \frac{\rho_0}{R} \cos[(m+1)\zeta + n\phi + \phi_0] \\ & \left. + \frac{\varepsilon |m-1|}{2|m-1|} \frac{\rho_0}{R} \cos[(m-1)\zeta + n\phi + \phi_0] \right\} \\ & (|m| \geq 2) \quad (4) \end{aligned}$$

where,

$$\varepsilon \equiv \min \left\{ \frac{\rho_0}{\rho}, \frac{\rho}{\rho_0} \right\}.$$

The first term in the bracket is the cylindrical term and others are satellite modes produced by the toroidicity. This expression has a similar form to that given by Fussmann, which uses essentially the same ordering.

IV. PHASE MODULATION EFFECT ON MAGNETIC PERTURBATION

The poloidal distribution of the helical perturbation $dI/d\zeta_0$ follows as $e^{i(m\zeta_0 + n\phi + \phi_0 + \omega t)}$ within the cylindrical approximation. As is pointed out by Merezhkin, the pitch of the magnetic field decreases for $\zeta_0 = \pi$ and increases for $\zeta_0 \sim 0$ (or 2π). The perturbed current due to a tearing mode tends to flow along the equilibrium magnetic field in order to reduce the perturbed magnetic energy. The magnetic field line equation on a rational surface is well-known in circular plasmas for the low β_p solution⁷ or the FCT model.⁸

$$\frac{\rho_0 d\zeta_0}{B_{\zeta_0}} = \frac{(R + \rho_0 \cos\zeta_0)^2 d\phi}{B_{\phi_0} R} \quad (5)$$

where

$$B_{\zeta_0}(\rho_0, \zeta_0) = \begin{cases} B_{\zeta_0}^0(\rho_0) (1 + \rho_0/R \Lambda(\rho_0) \cos\zeta_0) & (\text{low } \beta_p), \\ \frac{B_{\zeta_0}^0(\rho_0)}{(1 + \rho_0/R \cos\zeta_0) (1 + d \cos\zeta_0)} & (\text{FCT}), \end{cases}$$

$$\Lambda(\rho_0) = \beta_p(\rho_0) + \frac{1}{2} \ell_1(\rho_0) - 1,$$

$$d(\rho_0) = \frac{d}{d\rho_0} \Lambda(\rho_0).$$

Integrating the Eq. (5), we obtain the following field line equation,

$$m(\zeta_0 - \delta \sin\zeta_0) + n\phi = \text{const.} \quad (6)$$

$$m/n = \frac{B_{\phi 0} \rho_0}{B_{\zeta_0} R} \left(1 + \frac{\rho_0}{2R} \delta \right) , \quad (7)$$

$$\delta = \begin{cases} \frac{\rho_0}{R} (\Lambda + 2) & (\text{low } \beta_p) \\ -d + \frac{\rho_0}{R} & (\text{FCT}) \end{cases} .$$

Thus, the field line is bent in the (ζ_0, ϕ) plane. The divergence-free current perturbation flowing along the magnetic field should satisfy the following equations.

$$\frac{\partial}{\partial \phi} (\rho_0 \tilde{J}_\phi) + \frac{\partial}{\partial \zeta_0} \{ (R + \rho_0 \cos \zeta_0) \tilde{J}_{\zeta_0} \} = 0 , \quad (9)$$

$$\tilde{J}'_{\zeta_0} = \frac{B_{\zeta_0}}{B_\phi} \tilde{J}_\phi .$$

Therefore, the current perturbation in the ϕ -direction satisfies

$$\left[\frac{\partial}{\partial \phi} - \frac{n}{m} \frac{\partial}{\partial \zeta_0} \frac{1}{1 - \delta \cos \zeta_0} \right] \tilde{J}_\phi = 0 . \quad (10)$$

This equation is easily solved by changing the variables as follows:

$$\chi = \zeta_0 - \delta \sin \zeta_0 \quad (11)$$

and

$$\tilde{J}_{\phi}^* = \frac{\tilde{J}_{\phi}}{1 - \delta \cos \zeta_0}.$$

Then,

$$\left[\frac{\partial}{\partial \phi} - \frac{n}{m} \frac{\partial}{\partial \chi} \right] \tilde{J}_{\phi}^* = 0. \quad (12)$$

Simplest particular solution of Eq. (12), which is periodic in both χ and ϕ , is

$$\tilde{J}_{\phi}^* = J_{mn} \cos(m\chi + n\phi + \phi_0).$$

Thus, we obtain the following expression for the current perturbation $\tilde{J}_{\phi}$:

$$\tilde{J}_{\phi}(\zeta_0, \phi) = J_{mn} (1 - \delta \cos \zeta_0) \cos[m(\zeta_0 - \delta \sin \zeta_0) + n\phi + \phi_0]. \quad (13)$$

It is easily shown that Eq. (13) satisfies the condition

$$\int_0^{2\pi} \tilde{J}_{\phi}(\zeta_0, \phi) d\zeta_0 = 0,$$

by using the usual Bessel function formula

$$J_{\ell}(z) = \frac{1}{2\pi} \int_0^{2\pi} \cos(\ell \zeta_0 - z \sin \zeta_0) d\zeta_0,$$

$$J_{\ell+1}(z) + J_{\ell-1}(z) = 2\ell \frac{J_{\ell}(z)}{z}.$$

Substituting Eq. (13) into $dI/d\zeta_0$ in Eq. (2), we obtain the following equation for ψ_{mn} :

$$\begin{aligned}
\psi_{mn}(\zeta, \phi) &= \frac{\mu_0 J_{mn}}{2\pi} \int_0^{2\pi} \{ R \left(\ln \frac{R}{\rho^*} - 2 \right) + \rho_0 \cos \zeta_0 \left(\ln \frac{R}{\rho^*} - 1 \right) + (R + \rho_0 \cos \zeta_0) \\
&\times \sum_{k=1}^{\infty} \frac{\varepsilon^k}{k} \cos k(\zeta - \zeta_0) \} (1 - \delta \cos \zeta_0) \cos[m(\zeta_0 - \delta \sin \zeta_0) + n\phi + \phi_0] d\zeta_0 \\
&= \mu_0 J_{mn} \left\{ \frac{\rho_0}{2m} \left[\ln \frac{R}{\rho^*} - 1 \right] (J_{m-1}(m\delta) - J_{m+1}(m\delta)) \cos(n\phi + \phi_0) \right. \\
&+ \sum_{k=1}^{\infty} \frac{\varepsilon^k R}{2m} \{ (J_{m-k}(m\delta) + \frac{\rho_0}{2R} \{ \frac{k-1}{k} J_{m-k+1}(m\delta) + \frac{k+1}{k} J_{m-k-1}(m\delta) \}) \cos(k\zeta + n\phi + \phi_0) \\
&\left. - (J_{m+k}(m\delta) + \frac{\rho_0}{2R} \{ \frac{k-1}{k} J_{m+k-1}(m\delta) + \frac{k+1}{k} J_{m+k+1}(m\delta) \}) \cos(-k\zeta + n\phi + \phi_0) \} \right\}, \\
\end{aligned} \tag{14}$$

where $\rho^* = \max(\rho_0, \rho)$.

The first term in the square bracket is the sausage-like term due to the toroidal effect. The second term in the square bracket contains two terms. One is the cylindrical term $J_{m \mp k}(m\delta)$ and the resonance nature to $m = \pm k$ is modified by the Bessel function. Others are satellite island terms which are seen in Eq. (4). Equation (14) coincides with Eq. (4) for the case $\delta = 0$, as is expected.

V. CALCULATION RESULTS FOR TFTR

There are 19 Mirnov coils inside the TFTR vacuum vessel. The center of the vacuum chamber is at $R = R_0 = 2.65$ m and the minor radius of the Mirnov coils is $a = 1.08$ m. Equicontour plots of the perturbed flux function ψ_{mn} , phase, and amplitude plots of the poloidal field at the Mirnov coil position are made by using the formula given in Appendix II.

Figure 1 shows an example of the results. When the phase modulation effect is not large [Fig. 1(a)], there is a slight toroidal effect on the equicontour plot of ψ_{mn} and no significant phase modulation is seen in the Mirnov coil signals as is expected. However, there is a large amplitude modulation in the Mirnov coil signals. When δ becomes larger [Fig. 1(b) and (c)], the phase modulation is clearly seen in the equicontour plot of ψ_{mn} , and phase modulation can be detected by the phase analysis. However, the poloidal distribution of the $\tilde{B}_\theta$ amplitude is somewhat complicated. There is a tendency that the amplitude at the smaller R side decreases with increasing δ values. The equicontour plot for the larger δ value clearly indicates the formation of a large magnetic island at the larger R side.

The maximum phase difference $\Delta\theta$ between measured phase and $m\theta_1$ (θ_1 is the poloidal angle of a Mirnov coil) is an important quantity to measure the phase modulation effect experimentally. Figure 2 shows the δ and m dependences of $\Delta\theta$. Apparently, $\Delta\theta$ is increasing with δ and m . However, $\Delta\theta$ does not coincide with the rough formula $\Delta\theta = m\delta$. For the fixed δ value, larger phase modulation is expected for higher m modes. ψ_{mn} contour plots for $m = 3$ and 4 cases are shown in Fig. 3, and the higher distortion of the magnetic island structure is expected for high m modes. We must be careful with the plasma displacement Δ_{mn} in reconstructing ψ_{mn} from the measured phase and amplitude information of Mirnov coil signals. Figure 4 shows the Δ_{mn} dependence of $\Delta\theta$. We may have an estimate of the maximum permissible measurement error of Δ_{mn} from this figure to obtain the δ value through the measurement of $\Delta\theta$. Inner plasma shift gives increases in $\Delta\theta$ and the amplitude at the smaller R side, whereas an increase in δ gives increases in $\Delta\theta$ and a decrease in amplitude at the smaller R side. There will be difficulty in detecting the $m > 3$ modes for beam-heated, high- B_p , precompressed plasmas in

TFTR. Figure 4 shows the phase and amplitude plots for a precompressed $\delta=0.5$, $m=3$ mode. The Mirnov coils on the smaller R side are far from the current perturbation and may not detect the proper phases.

VI. CONCLUSION

An analytic expression is derived so that we can examine the relation between the Mirnov coil signals and the current perturbation at the rational surface. Application of the formula to the TFTR case shows that we may reconstruct a rough island structure by the phase and amplitude analysis.

If we can obtain the detailed equilibrium current profile by some method such as TRANSP⁹ or a Faraday rotation measurement, we may proceed to a more realistic radial profile of the perturbed current distribution instead of $\delta(p-p_0)$. This analysis may help us understand the rough structure of the magnetic island in tokamaks by using Mirnov coil signals.

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APPENDIX I

GREEN'S FUNCTION EXPANSION

$G \equiv X (\ln 8X/\xi - 2)$ can be expanded into a Fourier series as follows:

$$\begin{aligned}
 G &= R \left(\ln \frac{8R}{\rho} - 2 \right) + \rho_0 \cos \zeta_0 \left(\ln \frac{8R}{\rho} - 1 \right) \\
 &\quad + (R + \rho_0 \cos \zeta_0) \sum_{k=1}^{\infty} \frac{1}{k} \left(\frac{\rho_0}{\rho} \right)^k \cos k(\zeta - \zeta_0) \quad \left(\frac{\rho_0}{\rho} \leq 1 \right) \\
 &= R \left(\ln \frac{8R}{\rho_0} - 2 \right) + \rho_0 \cos \zeta_0 \left(\ln \frac{8R}{\rho_0} - 1 \right) \\
 &\quad + (R + \rho_0 \cos \zeta_0) \sum_{k=1}^{\infty} \frac{1}{k} \left(\frac{\rho}{\rho_0} \right)^k \cos k(\zeta - \zeta_0) \quad \left(\frac{\rho_0}{\rho} \geq 1 \right)
 \end{aligned} \tag{I-1}$$

where we used the following expansion:

$$\begin{aligned}
 \ln \xi^2 &= \ln (\rho^2 + \rho_0^2 - 2\rho \rho_0 \cos(\zeta - \zeta_0)) \\
 &= \ln \rho^2 + \ln \left(1 - \frac{\rho_0}{\rho} e^{\pm i(\zeta - \zeta_0)} \right) + \ln \left(1 - \frac{\rho_0}{\rho} e^{-i(\zeta - \zeta_0)} \right) \\
 &= \begin{cases} 2 \left(\ln \rho - \sum_{k=1}^{\infty} \frac{1}{k} \left(\frac{\rho_0}{\rho} \right)^k \cos k(\zeta - \zeta_0) \right) & \left(\frac{\rho_0}{\rho} \leq 1 \right) \\ 2 \left(\ln \rho_0 - \sum_{k=1}^{\infty} \frac{1}{k} \left(\frac{\rho}{\rho_0} \right)^k \cos k(\zeta - \zeta_0) \right) & \left(\frac{\rho_0}{\rho} \geq 1 \right) \end{cases}
 \end{aligned}$$

$$R = R_c + \Delta_{m1}.$$

APPENDIX II

USEFUL EXPRESSIONS

The relation between the pseudo-toroidal coordinates (r, ϕ, θ) , the axis of which is at $R = R_c$, and the flux coordinates (ρ, ϕ, ζ) is as follows:

$$\rho^2 = r^2 + \Delta_{mn}^2 - 2r\Delta_{mn} \cos\theta ,$$

$$\tan \zeta = \frac{r \sin\theta}{r \cos\theta - \Delta_{mn}} .$$

Various derivatives are as follows,

$$\frac{\partial \rho}{\partial \theta} = \frac{r}{\rho} \Delta_{mn} \sin\theta \quad (\text{II-1})$$

$$\frac{\partial \zeta}{\partial \theta} = \frac{r}{\rho^2} (r - \Delta_{mn} \cos\theta) \quad (\text{II-2})$$

$$\frac{\partial \rho}{\partial r} = \frac{1}{\rho} (r - \Delta_{mn} \cos\theta) \quad (\text{II-3})$$

$$\frac{\partial \zeta}{\partial r} = - \frac{\Delta_{mn}}{\rho^2} \sin\theta \quad (\text{II-4})$$

$$\left. \frac{\partial \psi_{mn}}{\partial \rho} \right|_{\rho > \rho_0} = \mu_0 J_{mn} \times$$

$$\left[-\frac{\rho_0}{2 m \rho} (J_{m-1}(m\delta) - J_{m+1}(m\delta)) \cos(n\phi + \phi_0) \right.$$

$$- \frac{\rho_0}{\rho^2} \sum_{k=1}^{\infty} \frac{k \varepsilon_R^{k-1}}{2 m} \left\{ (J_{m-k}(m\delta) + \frac{\rho_0}{2R} \left(\frac{k-1}{k} J_{m-k+1}(m\delta) + \frac{k+1}{k} J_{m-k-1}(m\delta) \right)) \right.$$

$$\times \cos(k\zeta + n\phi + \phi_0)$$

$$- (J_{m+k}(m\delta) + \frac{\rho_0}{2R} \left(\frac{k-1}{k} J_{m+k-1}(m\delta) + \frac{k+1}{k} J_{m+k+1}(m\delta) \right))$$

$$\left. \times \cos(-k\zeta + n\phi + \phi_0) \right\} \quad (\text{II-5})$$

$$\left. \frac{\partial \psi_{mn}}{\partial \zeta} \right|_{\rho > \rho_0} = -\mu_0 J_{mn} \times$$

$$\sum_{k=1}^{\infty} \frac{k \varepsilon_R^k}{2 m} \left\{ (J_{m-k}(m\delta) + \frac{\rho_0}{2R} \left(\frac{k-1}{k} J_{m-k+1}(m\delta) + \frac{k+1}{k} J_{m-k-1}(m\delta) \right)) \right.$$

$$\times \sin(k\zeta + n\phi + \phi_0)$$

$$+ (J_{m+k}(m\delta) + \frac{\rho_0}{2R} \left(\frac{k-1}{k} J_{m+k-1}(m\delta) + \frac{k+1}{k} J_{m+k+1}(m\delta) \right))$$

$$\left. \times \sin(-k\zeta + n\phi + \phi_0) \right\} \quad (\text{II-6})$$

FIGURE CAPTIONS

FIG. 1 Equicontour plot of ψ_{mn} and phase and amplitude plots at the Mirnov coil positions.

(a) $\delta = 0.001$, $\Delta_{mn} = 0.0$, $r_g = 0.4m$, $m/n = 2/1$

(b) $\delta = 0.2$, $\Delta_{mn} = 0.0$, $r_g = 0.4m$, $m/n = 2/1$

(c) $\delta = 0.4$, $\Delta_{mn} = 0.0$, $r_g = 0.4m$, $m/n = 2/1$

FIG. 2 The maximum phase difference $\Delta\theta$ as a function of δ and m ($\Delta_{mn} = 0m$, $r_g = 0.4m$).

FIG. 3 Equicontour plot of ψ_{mn}

(a) $m/n = 3/1$, $\delta = 0.02$, $r_g = 0.4m$, $\Delta_{mn} = 0$

(b) $m/n = 4/1$, $\delta = 0.02$, $r_g = 0.4m$, $\Delta_{mn} = 0$

FIG. 4 The maximum phase difference $\Delta\theta$ as a function of Δ_{mn} ($r_g = 0.4$)

(a) $\delta = 0.5$, $m/n = 2/1$,

(b) $\delta = 0.1$, $m/n = 3/1$,

(c) $\delta = 0.1$, $m/n = 2/1$,

FIG. 5 Equicontour plot of ψ_{mn} and phase and amplitude plots at the Mirnov coil positions ($m/n = 3/1$, $\delta = 0.5$, $\Delta_{mn} = 0.4m$, $r_g = 0.4m$).

Fig. 1

Fig. 2

Fig. 3

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Fig. 4

Fig. 5

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