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PLASMA RESPONSE IN CYLINDRICAL TOKAMAKS

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Abstract: Resonant magnetic perturbations (RMPs) have been used in tokamaks to control edge localized modes (ELMs). In order to calculate accurately the magnetic field inside the tokamak, it is necessary to take into account the plasma response to these perturbations. In this work, the plasma response to a magnetic ergodic limiter is simulated by a resonant helical current sheet on a rational plasma surface with the condition that the radial total magnetic field is null on that surface. This model is developed for cylindrical plasmas. We show that the islands formed by RMPs are smaller than those obtained by neglecting plasma response.

keywords: MHD equilibrium, resonant magnetic perturbation, numerical simulation, chaos control.

1. INTRODUCTION

Resonant magnetic perturbations (RMPs) are capable of mitigating plasma edge localized modes (ELMs) in high confinement (H-mode) plasmas in tokamaks [1-4]. However, the plasma is also affected by RMPs and modifies the magnetic field line transport [1]. In this work, it is presented a model of plasma response to RMPs due to helical wires for a cylindrical geometry. The plasma response is modeled as a RMP generated by a helical current sheet with the condition that the radial magnetic field is null at this surface [3].

2. RESONANT MAGNETIC PERTURBATIONS

Resonant magnetic perturbations (RMPs) are studied in order to modify edge instabilities and enhance plasma confinement in tokamaks [5, 6]. In this work, cylindrical coordinates with contravariant components (r,θ,z) and covariant base $(\vec{e}_r,\vec{e}_\theta,\vec{e}_z)$ are employed to describe a cylindrical plasma with radius a and periodic length $2\pi R_0$ along the z axis and contained within a cylindrical reactor with radius b.

Since RMPs generated by helical wires or helical current sheets are employed in this work, the following parameter expresses the winding law:

$$u_h = m_0\theta - n_0\left(\frac{z}{R_0}\right) \qquad (1)$$

where m_0 and n_0 are mode numbers.

The surface current $\vec{J}_h$ that generates the RMP is defined along the direction $\vec{e}_{\text{hel}}$ associated to a helix with the winding law expressed in Eq. (1) as:

$$\vec{J}_h = j\delta\left(r-r_j\right)\vec{e}_{\text{hel}} \qquad (2)$$

where $\delta\left(r-r_j\right)=0$ if $r \neq r_j$ and $\delta\left(0\right)=1$.

The magnetic field $\vec{B}$ at vacuum generated by a RMP located at the surface $r=r_j$ and resonant to the surface $r=r_0$ can be expressed as the gradient of a scalar function ϕ and it is calculated by the following equation:

$$\nabla^2\phi = 0 \qquad (3)$$

The magnetic field discontinuity $\Delta\vec{B}$ at the surface $r=r_j$ defines the boundary condition associated to Eq. (3):

$$\Delta\vec{B} = \frac{\mu_0 j}{\sqrt{b^2\alpha^2+1}}\left(-b\alpha\vec{e}^{\,z}+b\vec{e}^{\,\theta}\right) \qquad (4)$$

where $\alpha = d\theta/dz$ is calculated along the helix with the winding law expressed as Eq. (1).

In order to solve Eq. (3), the following function is defined:

$$F_{k_\theta}(k_z\alpha r)=\begin{cases} I_{k_\theta}(k_z\alpha r), \text{ if } r\le r_j \\ k_{k_\theta}(k_z\alpha r), \text{ if } r> r_j\end{cases} \quad (5)$$

where $I_{k_\theta}(k_z\alpha r)$ and $K_{k_\theta}(k_z\alpha r)$ are, respectively, the modified Bessel function of the first and second kind with order k_θ and argument $k_z\alpha r$.

Equation (3) has the following general solution:

$$\phi(r,\theta,z)=\sum_{k_z=-\infty}^{\infty}\sum_{k_\theta=-\infty}^{\infty}C_{k_z,k_\theta}F_{k_\theta}(k_z\alpha r)e^{i(k_\theta\theta-k_z\alpha z)} \quad (6)$$

The constant C_{k_z,k_θ} is calculated from the boundary condition shown in Eq. (4).

3. MAGNETOHYDRODYNAMIC EQUILIBRIUM

The equilibrium magnetic field is obtained from the Grad-Shafranov equation [5], which provides the following:

$$\vec{B}_0\cong\frac{\mu_0 I_p}{2r^2\pi}\left[1-\left(1-\frac{r^2}{a^2}\right)^{\gamma+1}\right]\vec{e}_\theta+\frac{\mu_0 I_e}{2\pi R_0}\vec{e}_z \quad (7)$$

where I_p is the plasma current and I_e is the poloidal current.

The parameters employed in this work are based on the geometry and the operation of the TCABR tokamak [7]. Table 1 presents these parameters.

Table 1 – Parameters used to perform calculations.

Parameter	Value
Plasma current: I_p (kA)	70
Poloidal current: I_e (MA)	4.0
Plasma column radius: a (m)	0.18
Cylinder radius: b (m)	0.22
Constant γ	3.0
Characteristic length: R_0 (m)	0.61

The safety factor (q) along the plasma cross section is shown in Fig 1.

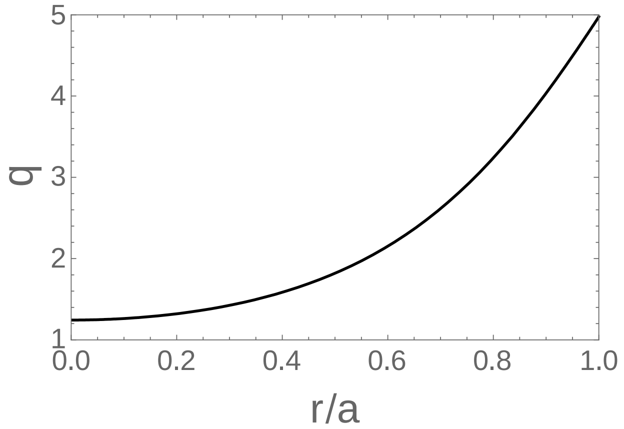


Figure 1 – Safety factor along the plasma cross section.

4. HELICAL WIRES PERTURBATION

The first RMP shown in this work is composed by two helical wires conducting electrical current I_h in opposed senses at the surface $r_j = b$ with winding laws $0=m_0\theta-n_0(z/R_0)$ and $\pi=m_0\theta-n_0(z/R_0)$. The resonant surface is located at $r_0/a=0.896$, which corresponds to a safety factor $q=m_0/n_0=4/1$. Figure 2 shows Poincaré sections for I_h = 1.0%I_p and I_h = 1.5%I_p.

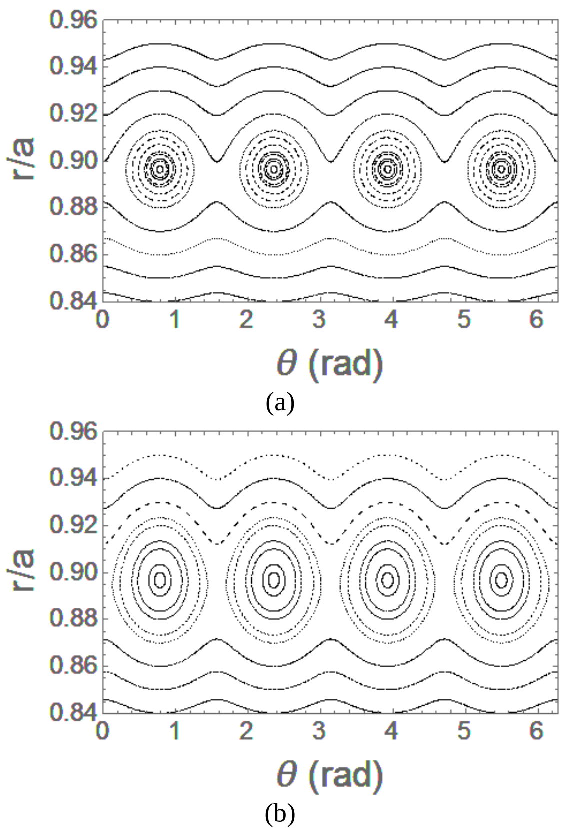


Figure 2 – Poincaré sections for modal numbers m_0 = 4, n_0 = 1 and: a) I_h = 1.0%I_p; b) I_h = 1.5%I_p.

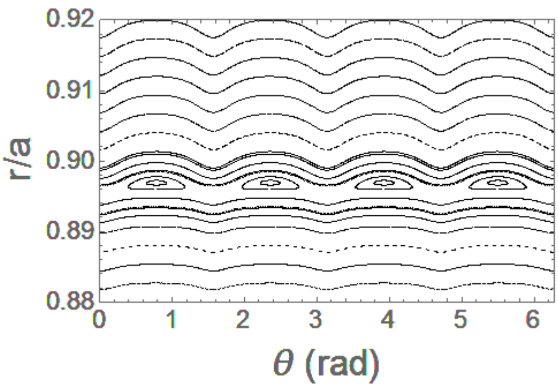
5. PLASMA RESPONSE

In order to simulate the effect of plasma response attenuating the magnetic islands observed in Fig. 2, it is imposed that the component of magnetic field orthogonal to the helical current sheet has magnitude zero [3]:

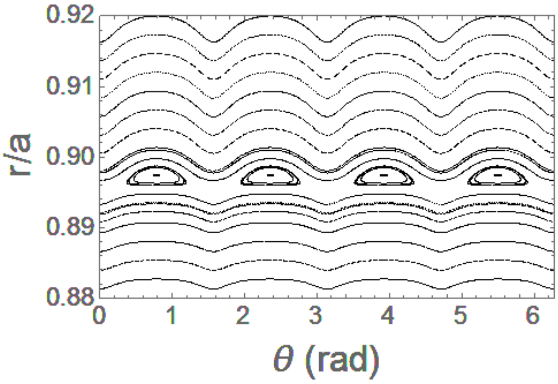
$$\vec{B}\cdot\nabla r=0 \quad (8)$$

where the magnetic field is the superposition of the fields generated by the helical windings and the current sheet.

Figure 3 shows Poincaré sections including the plasma response for I_h = 1.0%I_p and I_h = 1.5%I_p.



(a)



(b)

Figure 3 – Poincaré sections with plasma response for modal numbers $m_0 = 4$, $n_0 = 1$ and: a) $I_h = 1.0\%I_p$; b) $I_h = 1.5\%I_p$.

As can be observed in Fig. 3, in comparison to the results presented in Fig. 2, the inclusion of the plasma response has the effect of reducing magnetic islands around the resonant surface. Despite the attenuation observed when the plasma response is taken into account, larger magnetic islands are verified when the perturbation current I_h is increased.

6. CONCLUSION

This work has presented a model of plasma response in cylindrical geometry using resonant magnetic perturbations. It was shown that the plasma response has the effect of attenuating magnetic islands in Poincaré plots. Although the plasma response model presented in this work has been applied to cylindrical geometry, additional studies are being conducted to investigate toroidal geometries.

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