Mechanism of resonant magnetic perturbation screening

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1. Introduction

It was demonstrated on DIII-D [1] and later on JET [2] that the edge localized modes (ELMs) could be suppressed or mitigated by applying resonant magnetic perturbations (RMP) to the high confinement regime (H-regime) of a tokamak. The resonant coils for RMP are installed or planned on almost all large tokamaks: DIII-D, JET, MAST, ASDEX-Upgrade (AUG), NSTX and ITER. The widely accepted mechanism of ELMs suppression during RMP is the reduction of the pressure gradient in the pedestal region below the stability limit for type I ELMs. The main contribution to the pressure gradient decrease is the pedestal density drop – the so-called 'pump-out effect'. The existing models for 'pump-out effect' [3] (and references therein) require knowledge of the level of the magnetic field perturbations in plasma. However, there are evidences [4,5] that the magnetic field perturbations are strongly screened by the plasma so that the resulting RMP are significantly lower that the vacuum ones.

The existing RMP screening models are based on the screening of a separate magnetic island, see, for example, [6]. According to the models of this type plasma inside the non-rotating magnetic island is at rest while outside there is finite poloidal and toroidal rotations. Inertia force (plus classical viscosity in the later works) in the layer adjacent to the island separatrix creates radial currents which are closed by the parallel currents. The latter modify the vacuum magnetic perturbations. The screening effect is calculated in the cylindrical approximation, so that the account of toroidicity effects and turbulent transport, which can modify the structure of the flows in the island vicinity [7], should change the result. Moreover, the screening models for the separate island are not directly applicable to the case of RMP due to overlapping of the magnetic islands and stochastization of the magnetic field. In this situation radial pressure gradient, radial electric field, poloidal and toroidal flows remain finite inside a region of stochastization in contrast with the case of a separate island. Therefore for the case of RMP new approach to the problem of screening is required.

In the present paper the screening effect for the stochastic magnetic field is analyzed. It is demonstrated that in the existing experiments the RMP screening might be rather large and should be taken into account in the simulations of the edge plasma parameters.

2. Model

The stochastic magnetic field generates a radial current of electrons. According to [8] in the low collisionality case the radial current is

$$j_y = i_\sigma enD_{st}\sqrt{\frac{2T_e}{\pi m_e}}\left(\frac{\partial \ln n}{\partial y} - \frac{e}{T_e}\frac{\partial \varphi}{\partial y} + \frac{1}{2T_e}\frac{\partial T_e}{\partial y}\right) \quad . \tag{1}$$

Since the stochastic layer is thin we consider a slab geometry where x is the poloidal, y - radial and z - toroidal coordinates. Here $D_{st} \sim \sum \left|B_{y\vec{k}}\right|^2 / B^2$ is the stochastic diffusion coefficient of the magnetic field lines, $i_\sigma < 1$ is a numerical coefficient. The radial current is the radial projection of the parallel current

$$j_\parallel = \sum j_{\parallel \vec{k}} = j_y \frac{\sum B_{y\vec{k}} / B}{\sum \left|B_{y\vec{k}}\right|^2 / B^2} \quad . \tag{2}$$

Here B_y is the full perturbation of magnetic field in plasma, while B_y^0 is the vacuum magnetic field and $\tilde{B}_y$ is the magnetic field caused by plasma current. Both the parallel current and the magnetic field perturbation are sums of the contributions with different toroidal and poloidal mode numbers which correspond to discrete set of wave vectors $\vec{k}$. One harmonic of the current is related to the magnetic field according to Maxwell equation:

$$j_{\parallel \vec{k}} \approx j_{z\vec{k}} = \frac{c}{4\pi}\left(ik_x \tilde{B}_{y\vec{k}} - \frac{\partial \tilde{B}_{x\vec{k}}}{\partial y}\right) \quad . \tag{3}$$

Combining this with $\nabla \cdot \vec{B} = 0$, and taking into account that the poloidal scale of magnetic field perturbation k_x^{-1} is much bigger than the radial scale of the RMP, we have

$$j_{\parallel \vec{k}} = \frac{c}{4\pi}\left(ik_x \tilde{B}_{y\vec{k}} - \frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2}\right) \approx -\frac{c}{4\pi}\frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2} \quad . \tag{4}$$

Note that the generated magnetic field $\tilde{B}_{y\vec{k}}$ is shifted by $\pi/2$ with respect to the parallel current and therefore with respect to the full magnetic field $B_{y\vec{k}}$. The vacuum field is the difference of the full and the generated magnetic fields which are shifted by $\pi/2$ with respect to each other. Therefore the amplitude of each of these two contributions should be smaller than that of the vacuum field. Combining Eq. (2) with Eq. (4) one obtains

$$\frac{i}{k_x}\frac{\partial^2 \tilde{B}_{y\vec{k}}}{\partial y^2} = \frac{i\tilde{B}_{y\vec{k}}}{k_x L^2} = -\frac{4\pi}{c} j_y \frac{B_{y\vec{k}} / B}{\sum \left|B_{y\vec{k}}\right|^2 / B^2} \quad , \tag{5}$$

where L is the radial scale of RMP. Let us introduce the screening parameter

$$\alpha = \frac{k_x L^2}{B} \frac{j_y}{\sum \left| B_{y\bar{k}} \right|^2 / B^2} \frac{4\pi}{c} \quad , \tag{6}$$

so that $i\tilde{B}_{y\bar{k}} / B = -\alpha B_{y\bar{k}} / B$. Parameter α is independent of $\sum \left| B_{y\bar{k}} \right|^2 / B^2$ since the radial current is proportional to the same factor. Keeping in mind that $B_{y\bar{k}} = \tilde{B}_{y\bar{k}} + B^0_{y\bar{k}}$, we have

$$\frac{B_{y\bar{k}}}{B} = \frac{1+i\alpha}{1+\alpha^2} \frac{B^0_{y\bar{k}}}{B} \quad \text{and} \quad \left| \frac{B_{y\bar{k}}}{B} \right|^2 = \frac{1}{1+\alpha^2} \left| \frac{B^0_{y\bar{k}}}{B} \right|^2 \quad . \tag{7}$$

If the parameter $\alpha > 1$ the screening is large and stochastic diffusion coefficient D_{st} and radial current of electrons are reduced by $(1+\alpha^2)$ with respect to the vacuum values.

3. Estimates of the screening factor

To estimate the screening factor it is necessary to know the parameter $j_y / \left(\sum \left| B_{y\bar{k}} \right|^2 / B^2 \right)$. It can be found from Eq.(1) assuming that the radial electric field is of the order of the neoclassical one. This assumption is justified when $i_\sigma e^2 n D_{st}^{vacuum} / \sqrt{m_e T_e} \le \sigma_{NEO}$ [9], where D_{st}^{vacuum} is calculated in the absence of plasma screening, σ_{NEO} is neoclassical ion radial conductivity.

For MAST H-mode shot with RMP coils switched on [3] the estimate is $\alpha \approx 3 \div 5$. So the stochastic diffusion coefficient should be an order of magnitude smaller than the vacuum one. This is consistent with B2SOLPS5.2 simulations performed in [3].

4. Conclusions

The screening effect for the resonant magnetic field perturbations is calculated. In contrast to the previous models considered is not a separate island but a stochastic region where the plasma parameters are changing gradually through the region. The screening factor larger than unity is predicted for H-mode of modern tokamaks.

References

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