Screening of external magnetic perturbation fields due to sheared flow

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1. Introduction

Plasma response of the external magnetic field plays an important role in suppression or mitigation of the edge localized modes (ELMs) in tokamaks [1-4]. It is known that the single fluid theory predicts various screening regimes [5, 6] when plasma responds to the externally applied 3D magnetic field perturbations. One particular regime of screening, which occurs only at very slow flow, is associated with toroidal averaged curvature effect and referred as the GGJ-regime [7]. It has been shown in Ref. 6 that this effect can induce additional screening of the field pitch aligned components of the RMP field. From the experimental viewpoint, this can be an interesting regime, when the plasma flow locally vanishes near one rational surface in the pedestal region of the H-mode plasma.

While investigating the effect of RMP field penetration under the condition of vanishing flow near the rational surface, in a toroidal plasma with finite equilibrium beta, it is un-avoidable to enter into the GGJ screening regime. Therefore, in this work, much of our effects will be devoted to study how the radial profile of the plasma flow affect the GGJ screening. We shall also compare the screening in the so-called resistive-inertial (RI) regime [5], which occurs at faster flow than the GGJ regime.

2. The MARS-F plasma response model

We used the MARS-F code [8] to compute the plasma response to the external magnetic field under the dc condition, while prescribing a radial profile for the plasma toroidal flow speed $\mathbf{V}_0 = R\Omega\hat{\phi}$. We refer to [8] for detailed description of the computational models for the linear plasma response.

In order to better understand the numerical results from the code, we shall consider a simple equilibrium, as that described in Ref. 6. All the results in Ref. 6 were obtained

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assuming a uniform equilibrium rotation profile. In this work, we consider sheared flow, with special choices of the rotation profiles. More specifically, we define two types of shear flow profiles.

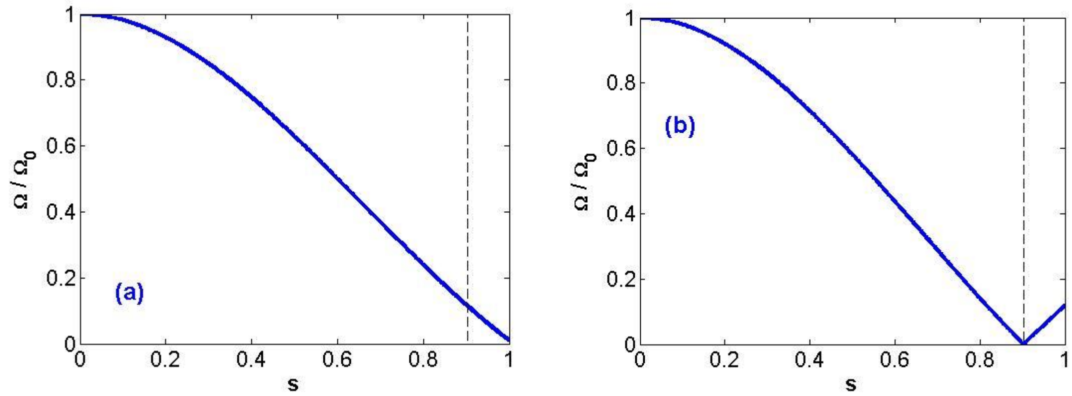

Figure 1. Radial profiles of the equilibrium toroidal rotation frequency, with the dash lines indicating the location of the $q = 2$ rational surface, which is the only rational surface for the chosen equilibrium and the chosen n=1 magnetic perturbation. (a) without, and (b) with, a strong local variation of flow speed near the rational surface.

2.1. A sheared rotation profile without strong local variation near the rational surface

Such a profile is prescribed by the following model

$$\Omega = (\Omega_0 - \Omega_1)(1 - 2s^2 + s^3) + \Omega_1 \tag{1}$$

where Ω_0 is the amplitude of the plasma rotation frequency at the magnetic axis, and Ω_1 is defined as the rotation frequency at the plasma surface [8]. An example of such a profile, normalized to unity at the magnetic axis, is shown in figure 1(a).

2.2.Flow profiles with strong local variation near rational surface

In order to investigate the relative effect of the flow shear and the flow amplitude, at the rational surface, on the plasma response to the external magnetic field, we also consider another family of profiles, with nearly vanishing flow speed at the rational surface. The profile is defined as

$$\Omega = \left| \frac{(1 - 2s^2 + s^3) - (1 - 2s_q^2 + s_q^3)}{2s_q^2 - s_q^3} \Omega_0 \right| + \Omega_q \tag{2}$$

where s_q is the radial position of the rational surface $q = 2$, and Ω_q is the plasma rotation frequency at this surface. Figure 1(b) shows one example of the radial equilibrium plasma rotation frequency profile, where again Ω is normalized to unity at the magnetic axis. In further numerical simulations, the on-axis rotation frequency Ω_0 is one plasma parameter that scans.

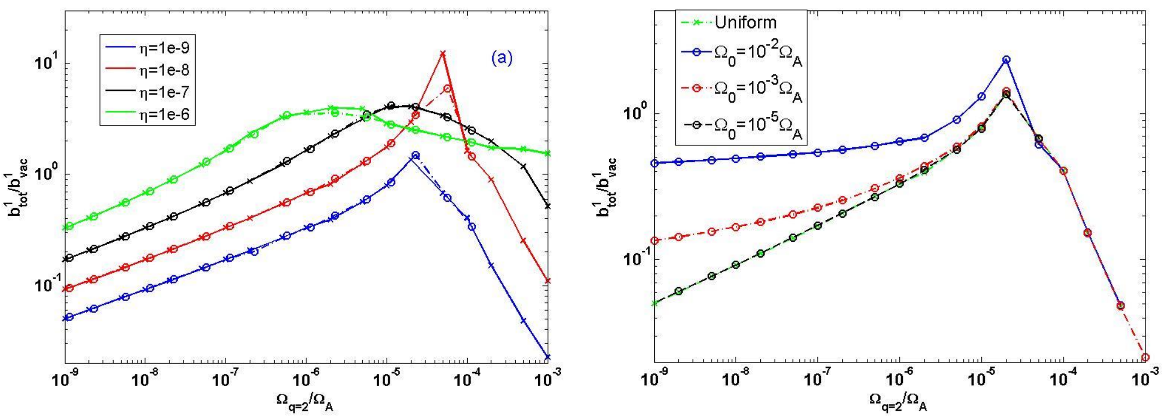

Figure 2. The effect of different rotation profiles on the plasma response to the n=1 external field. (a) comparison of the plasma response between the uniform plasma flow profile (solid) and that defined in Section 2.1 (dash-dotted), while assuming various values for the normalized plasma resistive (the inverse of the Lundquist number). (b) plasma response with the flow profile as defined in Section 2.2., with various choices of the flow amplitude, compared also with the uniform flow case. Note a good overlap between the uniform flow case and the case with very slow flow in (b). The plasma response is measured by the m/n=2/1 resonant harmonic of the radial field, computed at the q=2 surface and normalized by the corresponding quantity for the vacuum field.

3. Numerical results

Extensive modelling and analysis efforts have been carried out, in order to identify the screening physics associated with the local variation of the plasma flow speed near the rational surface. The results are summarized in Fig.2. Figure 2(a) compare the modelled plasma response, assuming two types of flow profiles – one is the uniform flow, the other is a flow profile as defined in Section 2.1 and shown in Fig. 1(a). The key point here is that, we plot the response, defined as the amplitude of the m/n=2/1 resonant harmonic of the perturbed radial magnetic field component at the q=2 surface, against the *local* rotation frequency at the same q=2 surface, for different types of the flow profile.

The fact that the curves, obtained with two types of flow profiles, nearly overlap for various choices of the plasma resistivity, indicates that the plasma screening (in both the GGJ-regime and the RI-regime) of the external magnetic field is quantitatively determined by the magnitude of the local plasma speed at the rational surface. No strong variation of the local flow shear has been allowed in this type of scans shown in Fig. 2(a).

A subtle difference, however, appears, if we do allow a strong local variation of the flow near the q=2 surface, as shown in Fig. 1(b). The computed plasma response from this flow scan is summarized in Fig. 2(b). The separation between the GGJ screening regime and the RI-regime is again separated by the *local* flow speed at the rational surface, as expected. On the other hand, when the ratio between the on-axis flow and the local flow speed becomes very large (enhanced by orders of magnitude), the global radial shape of the plasma flow also starts to affect the screening in the GGJ-regime, essentially reducing the GGJ-screening.

4. Conclusion and discussion

Based on a simple toroidal equilibrium, we try to computationally understand the screening of the external 3D magnetic fields by the toroidal flow. In particular, we investigate how the screening changes when the local flow speed approaches zero at the rational surface. According to the single fluid theory, the relevant screening regime at slow flow is the GGJ-regime. Without a strong local variation of the flow profile, the *local* magnitude of the flow at the rational surface is the dominant factor affecting the GGJ screening. With a strong local variation of the flow (and thus a large variation of the global flow profile), the GGJ screening is reduced.

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