

Effects of impurities on zonal flows in tokamak plasmas

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1. Introduction

Recently, several studies [1,2] show that the presence of impurities has a very weak influence on the residual zonal flow (ZF) level driven by initial charge density perturbations in the long-wavelength limit. However, gyrokinetic theory [3] and simulation [4] indicate that the temperature perturbations induced by turbulent energy flux are also important in driving ZFs. Therefore, it is important to investigate the effects of impurities on ZFs driven by temperature perturbations. In this work, it is found that the presence of impurities increases the total ion mass density of plasmas, and thus significantly reduces the amplitude of mesoscale ZFs driven by the main ion density and temperature perturbations. The driving effects of impurity ion temperature perturbations on ZFs can be ignored, due to the low concentration of impurities.

2. Theory

We begin with the Rosenbluth–Hinton collisionless gyrokinetic model [5] for ZFs. The source term S_j given in Vlasov equation, representing density and temperature perturbations, can be written as [3],

$$S_{j,k} = \delta(t) \left[\frac{\delta n_{j,k}(0)}{n_j} + \left(\frac{K}{T_j} - \frac{3}{2} \right) \frac{\delta T_{j,k}(0)}{T_j} \right]. \quad (1)$$

Here, $S_j = S_{j,k} \exp(ik_r r)$. $j = i, z$ denoting main ions and impurity ions, respectively. k_r and r denote the radial wave number and the minor radius, respectively. The delta function $\delta(t)$ should be understood as a function whose width is longer than a gyro-period but shorter than a bounce period[5]. $\delta n_{j,k}(0)$ and $\delta T_{j,k}(0)$ denote the initial density and temperature perturbations, which represent the turbulent poloidal Reynolds stress [6] and the turbulent energy flux [3,4], respectively.

By solving the Vlasov-Poisson problem in a multi-ion axisymmetric system in the long-wavelength limit, the temporal asymptotic zonal potential $\delta\phi_k(\infty)$ can be written as

$$\epsilon_r \frac{\rho_M}{B^2} k_r^2 \delta\phi_k(\infty) = \sum_{j=i,z} e_j \delta n_{j,k}(0) - \epsilon_r \frac{1}{B^2} \sum_{j=i,z} n_j \frac{m_j}{e_j} k_r^2 \delta T_{j,k}(0) \quad (2)$$

The details of derivation can be found in Ref. 7. Here, ϵ_r is the neoclassical polarization factor [5], $\rho_M = \sum_{j=i,z} n_j m_j$ is the total ion mass density. e_j and m_j denote charge and mass. B denotes magnetic field. In pure plasma, the present theory recovers the previous theory [3] on the driving effects of main ions. From Eq. (2), one can find that the driving effects of temperature perturbations are enhanced by the same neoclassical polarization factor ϵ_r (the toroidal geometry effects) as the asymptotic zonal potential, while the driving effects of density perturbations are not.

Note that the total ion mass density, ρ_M , includes impurity mass density and is related to the classical dielectric constant of plasma. This indicates that impurities increase the total ion mass density, ρ_M , thus enhance classical polarization process, and finally reduce the amplitude of the zonal potential. In addition, since $m_z/e_z \approx m_i/e_i$ while $n_z \ll n_i$ in typical tokamak plasmas, the driving effects of impurity ion temperature perturbations $\delta T_{z,k}(0)$ on ZFs are much weaker than those of the main ion temperature perturbations $\delta T_{i,k}(0)$.

3. Simulations

To verify these results, a set of simulations is performed using the global gyrokinetic code NLT [8]. NLT is a δf gyrokinetic initial value code, which solves the gyrokinetic Vlasov equation using the numerical Lie-transform method. ZFs in the edge plasma are simulated. The major/minor radius is $R_0/a = 1.67 \text{ m}/0.878 \text{ m}$. The magnetic field at the magnetic axis is $B_0 = 2.1 \text{ T}$. Impurity species is chosen as C^{6+} . The safety factor, equilibrium density and temperature are set as constants with $q = 3$, $n_e = 2 \times 10^{19} \text{ m}^{-3}$, $T_e = T_i = T_z = 180 \text{ eV}$. The initial perturbations are set as follows:

$$\delta T_j(0) = \begin{cases} T_j \sin[k_r(r - r_1)], & \text{for } r \in [r_1, r_2], \\ 0, & \text{for } r \notin [r_1, r_2]. \end{cases} \quad (3)$$

Here, $k_r = 2\pi/(r_2 - r_1)$, with $r_1/r_2 = 0.55a/0.75a$, which satisfies long-wavelength limit. Effective charge numbers Z_{eff} are chosen to represent the impurity concentration. $Z_{\text{eff}} = \sum_{j=i,z} n_j Z_j^2 / n_e$, with Z_j denoting the charge number of ion species j .

Figure 1 shows that the simulation results of the ZF amplitude driven by the main ion temperature perturbations $\delta T_i(0)$ for $Z_{\text{eff}} = 2$ and 3 (blue squares and circles, respectively) are both lower than that for $Z_{\text{eff}} = 1$ (blue triangles). The simulation results all agree well with the theoretical prediction [Eq. (2)] (blue lines), which verifies that the presence of impurities decreases the amplitude of ZF driven by the main ion temperature perturbations.

In addition, it can be seen that when $Z_{\text{eff}} > 1$, the amplitude of ZF driven by both $\delta T_i(0)$ and $\delta T_z(0)$ (red symbols) is close to that only driven by $\delta T_i(0)$ (blue symbols). The small deviation indicates the weak driving effects of $\delta T_z(0)$ on ZFs. This simulation result verifies that the driving effects of impurity ion temperature perturbations on ZFs can be ignored.

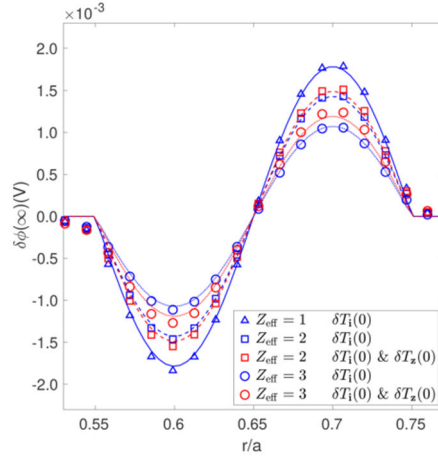


Fig. 1. ZFs driven by ion temperature perturbations for $Z_{\text{eff}} = 1, 2,$ and $3,$ when the main ion is deuterium D^+ .

4. Summary

In summary, we have investigated effects of impurities on mesoscale ZFs in tokamak plasmas. The presence of impurities increases the total ion mass density of plasmas, and thus significantly reduces the amplitude of mesoscale ZFs driven by the main ion density and temperature perturbations. The driving effects of impurity temperature perturbations on ZFs can be ignored, due to the low concentration of impurities.

5. Acknowledge

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