

# Effects of impurities on zonal flows in tokamak plasmas

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## 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.
- Gyrokinetic theory [3] and simulation [4] indicate that **temperature perturbations induced by turbulent energy flux are also important in driving ZFs.**
- Main findings:**
  - (1) 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.
  - (2) The driving effects of impurity ion temperature perturbations on ZFs can be ignored, due to the low concentration of impurities.

## Theory

Rosenbluth–Hinton collisionless gyrokinetic model for ZFs [5]

$$\partial_t g_{j,k} + (v_{\parallel} \vec{b} + \vec{V}_{d,j}) \cdot \nabla g_{j,k} = \frac{e_j}{T_j} F_{0,j} J_0 \partial_t \delta \phi_k + J_0 S_{j,k} F_{0,j} \quad (1)$$

$$\sum_{j=i,z,e} e_j \left\langle -\frac{e_j}{T_j} n_j \delta \phi_k + \int d^3 \vec{v} J_0 (k_r \rho_{L,j}) g_{j,k} \right\rangle_{FA} = 0 \quad (2)$$

Here,  $[g_j, \delta \phi, S_j] = [g_{j,k}, \delta \phi_k, S_{j,k}] e^{ik_r r}$ . Source term is written as [3]

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

turbulent poloidal Reynolds stress [6]      turbulent energy flux [3,4]

Solution is given by Eq.(1 - 3) [7],

$$\epsilon_r \frac{\rho_M}{B^2} k_r^2 \delta \phi_k(\infty) = \sum_{j=i,z} e_j \delta n_{j,k}(0) - \epsilon_r \frac{1}{B^2} \sum_{j=i,z} n_j \frac{m_j}{e_j} k_r^2 \delta T_{j,k}(0) \quad (4)$$

$\epsilon_r = 1/(1 + 1.6 q^2/\sqrt{\epsilon})$  is the neoclassical polarization factor [5],

$\rho_M = \sum_{j=i,z} n_j m_j$  is the total ion mass density.

### Effects of impurities on ZFs:

- impurities increase  $\rho_M \rightarrow$  enhance classical polarization process  $\rightarrow$  reduce the amplitude of the zonal potential.
- the driving effects of  $\delta T_{z,k}(0)$  on ZFs are much weaker than those of  $\delta T_{i,k}(0)$ , since  $m_z/e_z \approx m_i/e_i$  while  $n_z \ll n_i$ .

To compare with the previous theory [1], the initial zonal potential excited by initial perturbations is considered,

$$\frac{\rho_M}{B^2} k_r^2 \delta \phi_k(0) = \sum_{j=i,z} e_j \delta n_{j,k}(0) \quad (5)$$

Combining Eq.(4) and Eq.(5), we get

$$\delta \phi_k(\infty) = \frac{\delta \phi_k(0)}{\epsilon_r} - \frac{1}{\rho_M} \sum_{j=i,z} n_j \frac{m_j}{e_j} \delta T_{j,k}(0) \quad (6)$$

## Simulation Tools: NLT

NLT: Gyrokinetic global initial-value  $\delta f$  code, which solves gyrokinetic Vlasov equation by using the numerical Lie-transform method [8].

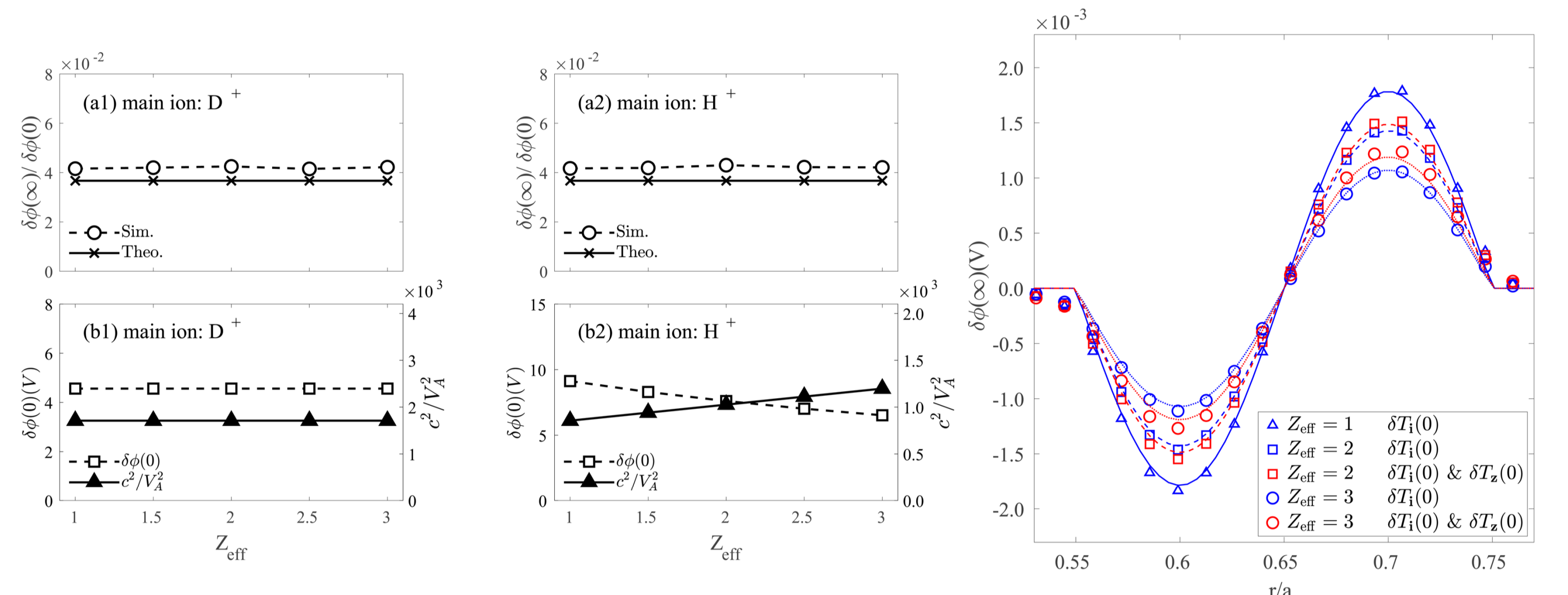
$$\frac{dF_j}{dt} = \frac{\partial F_j}{\partial t} + \vec{X} \cdot \nabla F_j + \dot{v}_{\parallel} \frac{\partial F_j}{\partial v_{\parallel}} = 0$$

$$\vec{X} = \{\vec{X}, H_{0,j} + H_{1,j}\}, \quad \dot{v}_{\parallel} = \{v_{\parallel}, H_{0,j} + H_{1,j}\}$$

$$\nabla \cdot \left( \sum_{j=i,z} \frac{n_j m_j}{B^2} \nabla_{\perp} \delta \phi \right) - \frac{n_e e_e^2}{T_e} (\delta \phi - \langle \delta \phi \rangle_{FA}) = - \sum_{j=i,z} e_j \delta n_{j,gy}$$

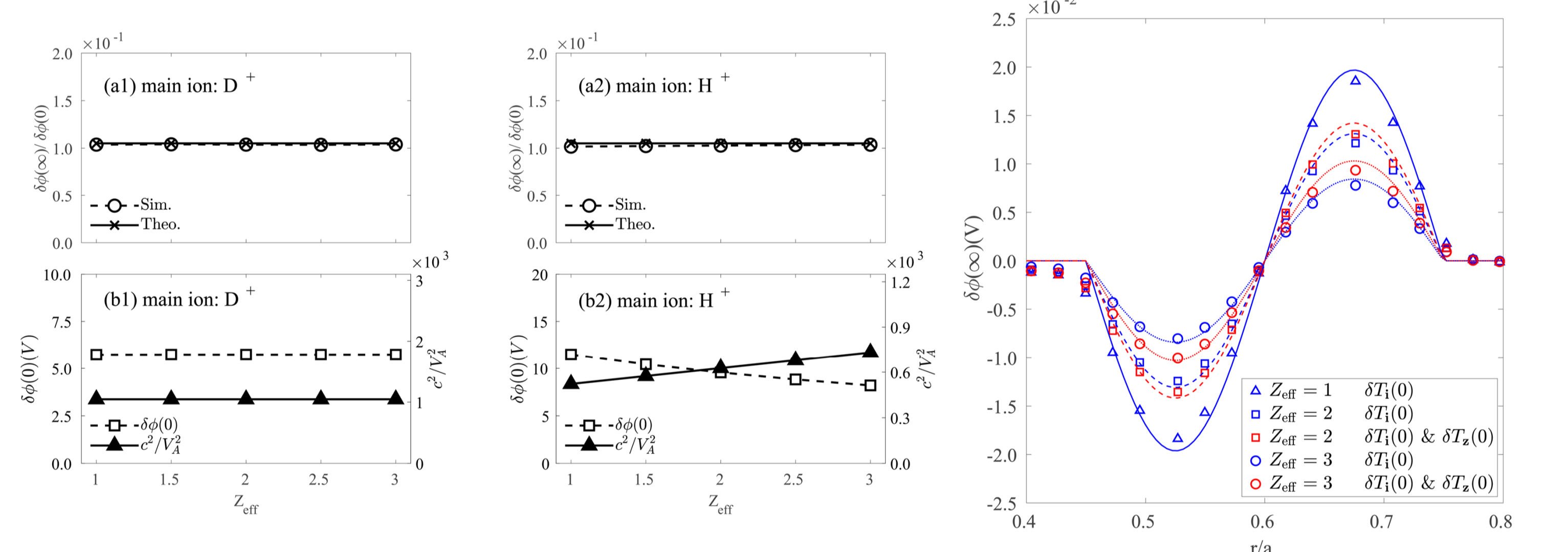
## Simulation Results

### 1. ZF at the edge plasma



- the presence of impurities increases the classical relative dielectric constant, thus decreases the value of the initial zonal potential.
- the presence of impurities decrease the amplitude of ZF driven by  $\delta T_i(0)$ .

### 2. ZF at the core plasma



- the qualitative conclusions remain unchanged for non-flat equilibrium profiles

## Conclusion

- 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.

## Reference

- [1] W. Guo, L. Wang, and G. Zhuang, Nucl. Fusion 57, 056012 (2017).
- [2] X. Wei, H. Yang, S. Li, and Y. Xiao, Phys. Plasmas 25, 082508 (2018).
- [3] S. Wang, Phys. Plasmas 24, 102508 (2017).
- [4] Z. Wang, Z. Dai, and S. Wang, Phys. Rev. E 106, 035205 (2022).
- [5] M. N. Rosenbluth and F. L. Hinton, Phys. Rev. Lett. 80, 724 (1998).
- [6] D. Zhang, Y. Xu, Z. Dai, and S. Wang, Nucl. Fusion 60, 046015 (2020).
- [7] Y. Li, Z. Wang, T. Wu, Y. Qiu, J. Wang and S. Wang, Phys. Plasmas 33, 012510 (2026).
- [8] L. Ye, Y. Xu, X. Xiao, Z. Dai, and S. Wang, J. Comput. Phys. 316, 180 (2016).