Impurity effects on residual zonal flow in deuterium (D)-tritium (T) plasmas

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Abstract

Significant effects of impurities on residual zonal flow (ZF) in deuterium (D)-tritium (T) plasmas are found. When the gyroradius of impurities is larger (smaller) than that of main ions, the intermediate scale (radial wavelength between trapped ion radial width $\rho_{bi}$ and trapped electron radial width $\rho_{be}$) residual ZF level is increased (decreased) due to the presence of various impurities with the tolerance concentration in JET and ITER, even for trace tungsten (W). For short scale (radial wavelength comparable to $\rho_{be}$) region, the residual ZF level is increased by most of the impurities. Moreover, the trend of stronger intermediate residual ZF in D–T plasmas with heavier effective isotope mass is weakened by non-trace impurities, but is not influenced by trace W. These results reveal that the presence of impurities can modify residual ZF, and possibly further affect the ZF regulation of turbulence as well as the associated anomalous transport and confinement in magnetic fusion plasmas. The potential relevance of our findings to experimental observations and simulation results is discussed.

Keywords: impurities, residual zonal flow, polarization shielding, hydrogenic isotope mass

(Some figures may appear in colour only in the online journal)
being the electron and impurity equilibrium concentration in magnetic fusion plasmas.

relevance to the effects of impurities on turbulence and confinement. The arbitrary radial wavelength includes three limiting cases: intermediate scale (radial wavelength between trapped ion radial width $\rho_{bi}$ and trapped electron radial width $\rho_{be}$), short scale (radial wavelength that are comparable to $\rho_{bi}$) and large scale (radial wavelengths is much larger than $\rho_{bi}$), where $\rho_{bi} = \frac{B_i}{\sqrt{\gamma T_i}}$ is the trapped particles’ radial width with $B_i$ being the gyroradius of species $\alpha$ and $\alpha = e, i, z$ corresponding to electron, ion and impurity. The general expression for residual ZF is derived by including dynamics of three species, i.e. electrons, ions and impurities. We discuss two kinds of impurities. One is the light or medium-mass impurity (He$^+$) and trapped ion radial width $\rho_{bi}$, which can be produced from the divertor of ITER, particularly including the high temperature helium impurity (He$^{2+}$) from D–T reaction with its tolerance concentration. Here, $Z$ and $A_i$ represent impurity charge number and impurity mass number, respectively. The other is the highly charged trace W, which can be produced from the divertor of ITER and some present-day tokamaks such as JET. Taking impurities into account, we find significant decrease (increase) of intermediate scale residual ZF when $\rho_{bi}$ is smaller (larger) than $\rho_{i,eff}$ with $\rho_{i,eff}$ being the effective ion gyroradius, even to 35% (15%). Surprisingly, we also find that the intermediate scale residual ZF in D–T plasmas is decreased about 15% in the presence of high-Z W even with trace concentration. Moreover, the decreasing (increasing) trend due to the presence of impurities is strengthened with the decrease (increase) of $\frac{\rho_{bi}}{\rho_{i,eff}} \sim A_i T_i / A_{i,eff} T_{i,eff}$, where $T_i$ and $T_{i,eff}$ are the ion and impurity temperature, respectively, $A_{i,eff}$ is the effective isotope mass number of intermediate scale residual ZF in D–T plasmas. The decreasing and increasing trends are also strengthened by further increase of $f_c$. Impurity effects on short scale residual ZF are parametric dependence. The increased (decreased) residual ZF due to the presence of impurities possibly leads to lower (stronger) anomalous transport and better (inferior) confinement. It is also found that the trend of stronger intermediate scale residual ZF in heavier D–T plasmas is weakened with the increase of $f_c$, $A_i$ and $Z$ for light and medium-mass non-trace impurities, while the change of $Z$ for trace W has very weak influence on this trend. Then, the potential relevance of our findings to experimental observations and simulation results is discussed.

This paper is organized as follows. In section 2, the general expression for arbitrary radial wavelength residual ZF including impurities is presented. In section 3, the effects of various impurities on residual ZF in D–T plasmas are analyzed in detail. Finally, a summary and some discussions are given in section 4.
2. General expression for residual ZF with impurities

As pointed out in the original RH residual ZF model [6], the initial charge density perturbation is accompanied by a potential perturbation because of quasi-neutrality condition $e(\delta n_{i,k} - \delta n_{e,k}) = -\rho_k^{NL}(0)$, where $e$ is the elementary charge, $\delta n_{i,k}$ and $\delta n_{e,k}$ are the ion and electron perturbed density, respectively, and $\rho_k^{NL}(0)$ is the initial nonlinear charge source. The initial zonal potential perturbation $\phi_{ZF,i}(t = 0)$ is built by the classical polarization shielding (leading to the particle departure from the gyrocenter) within a time scale of several ion gyroperiods, i.e.

$$
\delta \phi_{ZF,i}(t = 0) = \rho_k^{NL}(0).
$$

(1)

Here, $n_0i$ is the ion equilibrium density, $T_e$ is the electron temperature, $F_{0i(e)}$ is the equilibrium distribution function of ions (electrons), $J_{0i(e)}$ is the zeroth-order Bessel function for ions (electrons). The meaning of other symbols have been explained in previous section. A few of bounce periods later, the neoclassical polarization shielding originating from the gyrocenter departure from bounce center modifies the initial zonal potential perturbation. The long-time behavior of zonal potential perturbation $\phi_{ZF,i}(t = \infty)$ is then determined by the summation of classical polarization and neoclassical polarization

$$
e \left[ \frac{1 - \frac{1}{n_0} \left( \int d^3vF_{0i}J_{0i}e^{-i0_v\omega_{pe}J_{0i}} \right)}{\frac{T_e}{T_i}} + \frac{1 - \frac{1}{n_0} \left( \int d^3vF_{0e}J_{0e}e^{-i0_v\omega_{pe}J_{0e}} \right)}{\frac{T_e}{T_e}} \right] \times \delta \phi_{ZF,i}(t = \infty) = \rho_k^{NL}(0).
$$

(2)

Here, $(\ldots)$ represents the flux surface average, $Q_{i(e)} = \frac{\gamma_i m_i S}{\Omega_i}$ with $v_{i(e)}$ being the ion (electron) parallel velocity, and $I = RB_e$ with $R$ being the major radius and $B_e$ being the toroidal magnetic field, $S$ is the eikonal under assuming all the perturbed quantities to be in an eikonal form $\delta \phi = \sum_\alpha \delta \phi_\alpha e^{iS}$ [6] and $S$ represents the gradient of $S$, $\Omega_{i(e)} = \frac{eB_e}{m_i c}$ is the ion (electron) cyclotron frequency with $B$ being the total magnetic field, $m_{i(e)}$ being the ion (electron) mass and $c$ being the light velocity. Then, the residual ZF level $R_{ZF}$ defined as the ratio of $\phi_{ZF,i}(t = \infty)$ to $\phi_{ZF,i}(t = 0)$, which is a dimensionless quantity, is then written as

$$
R_{ZF} = \frac{\tau_{i,n_0} \left( \int d^3vF_{0i}J_{0i} \right) + \left( 1 - \frac{1}{n_0} \left( \int d^3vF_{0e}J_{0e} \right) \right)}{\tau_{e,n_0} \left( \int d^3vF_{0e}J_{0e} \right) + \left( 1 - \frac{1}{n_0} \left( \int d^3vF_{0i}J_{0i} \right) \right)}.
$$

(3)

where $\tau_i = T_e/T_i$. More detailed interpretations can be also found in [11]. Previous works either focus on ion polarization shielding [6] or include the polarization shielding of electrons [7–10] as well. But, for plasmas containing impurities, the contribution from impurities to the polarization shielding should be also included. Therefore, the general expression for residual ZF with impurities is given by

$$
R_{ZF} = \frac{\tau_{i,n_0} \left( \int d^3vF_{0i}J_{0i} \right) + Z_e^2 \tau_{e,n_0} \left( \int d^3vF_{0e}J_{0e} \right)}{\tau_{e,n_0} \left( \int d^3vF_{0e}J_{0e} \right) + \left( 1 - \frac{1}{n_0} \left( \int d^3vF_{0i}J_{0i} \right) \right)}.
$$

(4)

$$
\begin{align*}
\tau_{i,n_0} &= \int d^3vF_{0i}J_{0i} \times \chi_{i,cl} + \chi_{i,nc} + \chi_{e,cl}, \\
\tau_{e,n_0} &= \int d^3vF_{0e}J_{0e} \times \chi_{e,cl} + \chi_{e,nc}.
\end{align*}
$$

Here, $\chi_{i,cl} = 1 - \frac{1}{n_0} \left( \int d^3vF_{0i}J_{0i} \right)$, $\chi_{e,cl} = \frac{1}{n_0} \left( \int d^3vF_{0e}J_{0e} - J_{0e} \right)$ with $\alpha = e, i, z$ are the classical and neoclassical polarization shieldings, respectively. The neoclassical polarization density is defined as the difference between the gyrocenter density and the bounce center density based on modern gyrokinetic and bounce kinetic theory, and it can be obtained from the pull-back transformation from bounce center to gyrocenter by keeping both the finite Larmor radius

(FLR) effects and finite orbit width (FOW) effects. $\tau_i = T_e/T_i$, and the other symbols for impurities have the similar meanings to those for ions and electrons. The equilibrium quasi-neutrality condition indicates $\frac{n_i}{n_e} = 1 - Z_F$. For simplicity, equation (4) can be rewritten as

$$
R_{ZF} = \frac{\sum_\alpha g_{\alpha}(\chi_{\alpha,cl} + \chi_{\alpha,nc})}{\sum_\alpha g_{\alpha}(\chi_{\alpha,cl} + \chi_{\alpha,nc})}.
$$

(5)
Here, $g_e = 1$, $g_i = \pi(1 - Z_e^2)$, $g_c = \tau Z_e^2 f_c$ are weighting factors corresponding to electrons, ions, and impurities.

The classical polarization shielding has the well-known form, i.e. $\chi_{c,cl} = 1 - \Gamma_0(k_i^2 \rho_{pe}^2 + k_i^2 \rho_{ti}^2)$ with $\Gamma_0 = i_0(k_i^2 \rho_{pe}^2) - \kappa$, and $i_0$ being the zeroth-order modified Bessel function. In the high aspect ratio concentric circular geometry, the generalized expression of $\chi_{c,nc}$ for arbitrary scale was constructed by adding the inverse of three asymptotic forms, and then taking the inverse of the summation [10],

$$X_{c,nc} = \left[ \frac{1}{1 + \frac{\sqrt{8\pi}}{\pi} \Gamma_i} + \left( 1 - \frac{\sqrt{8\pi}}{\pi} \right) \frac{1}{1 + \frac{\sqrt{8\pi}}{\pi}} \Gamma_i \right] \left[ \frac{1}{1 + \frac{\sqrt{8\pi}}{\pi} \Gamma_i} + \left( 1 - \frac{\sqrt{8\pi}}{\pi} \right) \frac{1}{1 + \frac{\sqrt{8\pi}}{\pi}} \Gamma_i \right]^{-1}$$

Here, $\frac{\sqrt{8\pi}}{\pi}$ and $1 - \frac{\sqrt{8\pi}}{\pi}$ are the fractions of trapped particles and passing particles, respectively; $\Gamma_0 \approx 0.92(\sqrt{8\pi} k_i \rho_{pe})^2 (\Gamma_0 = 2 \Gamma_0)$ and $\Gamma_0 = 1(2 \sqrt{\pi} k_i \rho_{pe})^2 (\Gamma_0 = 2 \Gamma_0)$ are related to the neoclassical polarization for trapped particles and passing particles, respectively, where $\Gamma_0$ and $\Gamma_i$ are inversely proportional to the banana width $\rho_{pe} = \frac{\pi}{2} \rho_{pe}$ and the radial deviation from the flux surface for a strongly passing particle $q_i \rho_{ti}$, respectively, in the limit of $\frac{k_i \rho_{pe}}{\rho_{ti}} > k_i \rho_{ti} > 1$ ($k_i \rho_{pe} \ll 1$ and $k_i \rho_{ti} \gg 1$); the factor $\frac{\sqrt{\pi}}{2} k_i \rho_{ti}$ from the inverse of FLR effects was kept in the limit of $k_i \rho_{pe} > k_i \rho_{ti} > 1$. In the opposite limit, i.e. $k_i \rho_{pe} < k_i \rho_{ti} \ll 1$, equation (6) will be reduced to RH neoclassical polarization with a slightly different coefficient. The main point for calculating $\chi_{c,nc}$ is that the orbit width (Larmor radius or banana width) or the radial deviation from the flux surface for passing particle) comparable to the wavelength of fluctuations is the most relevant to the polarization shielding. This is why the FLR effects on neoclassical polarization cannot be ignored in the limit of $k_i \rho_{pe} > k_i \rho_{ti} > 1$ with $\rho_{pe} = \frac{\pi}{2} \rho_{pe}$ being the poloidal gyroradius. The interested readers can refer to [10] for the details of derivation processes. The general neoclassical polarization which was used only for electrons and ions in previous work can be also applicable to impurities.

3. Effects of various impurities on residual ZF in D–T plasmas

In this part, we investigate how various impurities affect the residual ZF in D–T plasmas. We use the following typical parameters: $q = 1.4$, $\epsilon = 0.2$. The isotopic fueling ratios $f_D = n_D/(n_D + n_D)$ and $f_T = n_T/(n_D + n_T)$ are $50\%$ + $50\%$ in section 3.1, and they are changed from $f_T > f_D$ to $f_T < f_D$ in section 3.2. Especially, the tolerance concentrations for $\mathrm{He}^{2+}$ from D–T reaction, $\mathrm{Be}^{4+}$, $\mathrm{Ar}^{18+}$ in ITER are $10\%$, $2\%$ and $0.16\%$ [15], respectively, and $f_c = 10^{-4}$ for trace W [17]. Normally, we assume $\tau = \tau_1(T_i = T_c)$ for most of impurities. Interestingly, the fusion products, i.e. energetic alpha particles dominantly heat the electrons [33], and then exchange energy to ions by collisions. Meanwhile, the slowing down time of alpha particles is typically longer than the energy exchange time, so we assume $\tau = 1(T_i = T_c)$, $\tau_i \leq 1(T_i \leq T_c)$ for high temperature $\mathrm{He}^{2+}$ from D–T reaction.

3.1. Residual ZF in 50% + 50% D–T plasmas with various impurities

In this subsection, we present the effects of various impurities on residual ZF in 50% + 50% D–T plasmas, i.e. $A_{i,eff} = 2.5$. From equation (5), it can be seen that the impurities affect residual ZF mainly through their weighting factors and polarization shieldings. In figure 1(a), we compare the classical and neoclassical polarization shieldings of high temperature $\mathrm{He}^{2+}$ from D–T reaction with $\tau = 0.1$ (blue lines) and $\tau = 1$ (green lines) with those of electrons (black lines) and ions (red lines). Both $\chi_{c,cl}$ and $\chi_{c,nc}$ are comparable to the corresponding components of ions. When $\rho_t > (\rho_{ti})_{eff}$, $\chi_{c,nc}$ changes faster (slower) than $\chi_{i,nc}$. Figure 1(b) shows the effects of light non-trace $\mathrm{Be}^{4+}$, medium-mass $\mathrm{Ar}^{18+}$ with concentration in ITER and W with trace concentration in JET on residual ZF in D–T plasmas, respectively. It is obvious that the levels of intermediate and short scale residual ZFs are affected by impurities even for high-Z W with the trace concentration. To clearly illustrate the different residual ZF levels between the cases with and without impurities, we discuss how the variations of $A$, $Z$, $f_c$ and $\tau$ affect the ratio $R_{ZF} = R_{ZF,0}$ in detail in the following, where $R_{ZF}$ and $R_{ZF,0}$ are residual ZF levels with and without impurities, respectively. The main results are shown in figures 2–5.

Intermediate scale residual ZF, which may be driven by TEM turbulence [34–37], is decreased by the presence of impurities with $\rho_t < \rho_{t,eff}$ as shown in figures 2 and 3. The residual ZF can be even decreased about 30% for $\mathrm{Ne}^{10+}$ with $f_c = 0.01$. Because the contribution from electron is sub-dominant for the intermediate scale residual ZF, the ratio between residual ZF levels with and without impurities then reduces to

$$R_{ZF} = \frac{1 + \chi_{c,cl}}{1 + \chi_{c,cl,0}} = \frac{\chi_{c,cl} + 1}{\chi_{c,cl,0} + \chi_{c,cl,0}} = \frac{\chi_{c,cl} + 1}{\chi_{c,cl,0} + \chi_{c,cl,0}}$$

The influence from $\chi_{c,cl} < \chi_{c,cl}$ for $\rho_t < \rho_{t,eff}$ is stronger than that from the relationship between $\chi_{c,nc}$ and $\chi_{i,nc}$ in this region. This leads to lower level of residual ZF in the presence of impurities with $\rho_t < \rho_{t,eff}$ as can be seen from equation (7). The lower trend is strengthened by the decrease of the ratio $f_c^\prime$ and the increase of $f_c$, as shown in figures 2(a) and (b). In figure 3, the intermediate scale residual ZF level is decreased about 20% for $\mathrm{Ar}^{18+}$ with $f_c = 0.16\%$. But the decreasing trend is not affected by the variation of $T_i/T_e$ with $T_i = T_e$, because $f_c^\prime$ does not change with $T_e/T_i$. These results reveal that impurities have significant influences on intermediate residual ZF. It is believed that ZF can suppress micro-turbulence and reduce the anomalous transport. Therefore, it is possible that impurities may further affect ZF regulation of turbulence and transport. According to the experimental
scaling laws $\tau_e \propto Z_{\text{eff}}^{0.27} \rho_{i,\text{eff}}^{-0.50}$ for SOC plasmas [27] with $Z_{\text{eff}}$ being the effective charge number, higher $Z_{\text{eff}}$ could result in worse confinement. In our results, impurities with higher $f_c$ and higher $Z$ (corresponding to higher $Z_{\text{eff}}$) lead to lower level of residual ZF in the intermediate region. The lower level of residual ZF may be relevant to worse confinement, which is consistent with the indications of experimental scaling laws [27].

In short wavelength regime, residual ZF is increased by the presence of impurities as shown in figures 2 and 3. In this region, the residual ZF may be driven by ETG turbulence, where electron polarization shielding should be taken into account. Both impurities and ions can be assumed to be adiabatic, i.e. $\chi_{z,\text{el}}$ and $\chi_{i,\text{el}}$ approach to unity, while $\chi_{z,\text{nc}}$ and $\chi_{i,\text{nc}}$ decrease to zero. Then, the ratio of residual ZF between the cases with and without impurities can be reduced as

$$R_{ZF,e} = \frac{1 + \chi_{z,\text{nc}} + \chi_{i,\text{el}}}{1 + \chi_{z,\text{nc}} + \chi_{i,\text{el}}}.$$  

Figure 1. (a) The classical (dashed lines) and neoclassical (solid lines) polarization shieldings for electrons (black lines), ions (red lines) and high temperature He$^{2+}$ with $\tau_e = 0.1$ (blue lines) and $\tau_e = 1$ (green lines) and (b) the residual ZF level without impurities (black line) and with non-trace Be$^{4+}$ (red line), Ar$^{18+}$ (blue line) and trace W$^{64+}$ (green line) as a function of $k_i \rho_{i,\text{eff}}$. The impurity concentrations for Be$^{4+}$, Ar$^{18+}$ and W$^{64+}$ are 0.02, 0.0016 and $10^{-4}$, respectively.

Figure 2. Ratio between $R_{ZF}$ for plasmas with and without impurities as a function of $k_i \rho_{i,\text{eff}}$ for different fully ionized impurities with $f_c = 0.01$ in (a) and different $f_c$ with Be$^{4+}$ in (b).

Figure 3. Ratio between $R_{ZF}$ for plasmas with and without impurities as a function of $k_i \rho_{i,\text{eff}}$ for different $T_i/T_e$. The impurity is chosen as Ar$^{18+}$ with $T_e = T_i$ and $f_c = 0.0016$. 

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Therefore, impurity effects on short scale residual ZF are mainly through the summation of ion and impurity weighting factors, \( g_i + g_{i,eff} = \tau_i + ZF_i \rho_i \tau_i (\tau_i Z - \tau_i) \), which reduces to \( \tau_i \) in the absence of impurities. For fully ionized impurities with \( \tau_i = \tau_i \), the summation is greater than \( \tau_i \), i.e. \( g_i + g_{i,eff} = ZF_i \tau_i (\tau_i Z - \tau_i) > 0 \), leading to \( \frac{R_{ZF}}{R_{ZF,0}} > 1 \) as can be seen from equation (8). Higher \( Z, f_i \), and \( \tau_i \) correspond to greater summations, and hence result in higher levels of residual ZF. Although impurity effects on residual ZF in this short wavelength region are relatively weaker as compared to intermediate scale, the increase of residual ZF caused by impurities may lead to better energy confinement. Especially, this may be important for burning plasmas such as ITER, where energetic alpha particles dominantly heat electrons and ETG turbulence is a plausible candidate channel for electron transport.

Interestingly, figure 4 shows that the intermediate scale residual ZF is increased (decreased) about 12% (35%) by high temperature He\(^{2+}\) from D–T reaction with \( f_i = 0.1 \) when \( \frac{\rho_i}{\rho_{i,eff}} \sim \frac{\lambda_i}{\lambda_{i,eff}} \frac{1}{T_i} \). It seems that the relationship between \( \rho_i \) and \( \rho_{i,eff} \) plays a key role in determining whether the impurities increase or decrease the intermediate scale residual ZF. Here, \( \tau_i = 1 (T_i = T_e) \) and \( \tau_i \ll 1 \) are assumed for high temperature He\(^{2+}\) from 50% + 50% D–T reaction. This might be a good news for suppressing TEM turbulence with higher temperature He\(^{2+}\) (\( \tau_i < 0.4 \)) in burning plasmas such as ITER. However, in short wavelength regime, the summation of weighting factors is smaller (larger) than unity for \( \tau_i < (>) 0.5 \), leading to \( \frac{R_{ZF}}{R_{ZF,0}} < (>) 1 \) as shown in figure 4. The higher temperature He\(^{2+}\) (\( \tau_i < 0.5 \)) may be unfavorable for good confinement in the short scale region.

Surprisingly, the intermediate scale residual ZF is decreased about 15% even for trace W\(^{64+}\) as shown in figure 5. This is because \( \frac{\rho_{i,eff}}{\rho_i} \approx 0.018 \) is much smaller than unity for trace W\(^{64+}\). The trace W can enhance the short scale residual ZF, which is similar to the results of non-trace impurities in figures 2 and 3. The non-ignorable effects of W in these two regions are mainly because the impurity weighting factor \( g_i = ZF_i \approx 0.41 \) for \( \tau_i = 1 \) is considerable, although \( f_i \) is very small. The influences of W on residual ZF may be important for investigating the effects of W on energy confinement in the second D–T campaign in JET and ITER.

In large scale region corresponding to \( k f_{i,eff} \ll 1 \), figures 2–5 all show that the introduction of impurities has very weak influence on the residual ZF level. For long wavelength residual ZF, which may be driven by ITG turbulence, electrons can be assumed to be adiabatic. The classical and neo-classical polarization shielding of ions and impurities in this long wavelength limit can be written as \( \chi_{i,cl} = k_i^2 \rho_i^{eff} / f_i^{1/2} \) and \( \chi_{i,nc} = 1.83 g_i^2 k_i^2 \rho_i^{eff} / f_i^{1/2} \). Therefore, the ratio \( R_{ZF} / R_{ZF,0} \) approaches to unity as can be seen from equation (7). In other words, the impurity effects on large scale residual ZF are very weak. This is consistent with [18] for highly charged impurity. Here, we further point out that the effects of the light non-trace impurities on the large scale residual ZF are also invisible.

### 3.2. Impurity effects on the effective isotope mass dependence of residual ZF in D–T plasmas

In this subsection, we vary the mixing ratios \( f_D \) and \( f_T \) to study impurity effects on the \( A_{eff} \) dependence of residual ZF, \( R_{ZF,D}^{0.1D+0.9T}, R_{ZF,D}^{0.3D+0.7T}, R_{ZF,D}^{0.5D+0.5T}, R_{ZF,D}^{0.7D+0.3T}, R_{ZF,D}^{0.9D+0.1T} \) separately represent the residual ZF levels corresponding to plasmas with different mixing ratios in the presence of impurities. Figures 6 and 7 show \( \frac{R_{ZF,D}^{0.1D+0.9T}}{R_{ZF,D}^{0.2D+0.8T}} > \frac{R_{ZF,D}^{0.3D+0.7T}}{R_{ZF,D}^{0.4D+0.6T}} > 1 \) and \( \frac{R_{ZF,D}^{0.5D+0.5T}}{R_{ZF,D}^{0.6D+0.4T}} > \frac{R_{ZF,D}^{0.7D+0.3T}}{R_{ZF,D}^{0.8D+0.2T}} > \frac{R_{ZF,D}^{0.9D+0.1T}}{R_{ZF,D}^{1D+0.0T}} > 1 \), i.e. the larger \( A_{eff} \) corresponds to stronger residual ZF in the presence of various impurities in the intermediate scale region. The \( A_{eff} \) dependence of residual ZF with impurities is similar to the case in the absence of
impurities [31]. As discussed in previous subsection, the electron contribution to residual ZF in the intermediate region is sub-dominant, therefore, the residual ZF can be given by

$$R_{ZF,\tau} \sim \frac{1}{1 + \frac{k_{i,eff}^2}{\kappa_{i,eff}^2}}. \quad (9)$$

From equation (9), it can be seen that the $A_{i,eff}$ dependence of residual ZF is mainly because the influence from larger $\chi_{f_c,i,D+z_{il}}$ for larger $A_{i,eff}$ is stronger than that from the corresponding relationship between $\chi_{f_c,i,D+z_{il}}$ [31]. To further present the impurity effects on the $A_{i,eff}$ dependence of residual ZF, we focus on how impurities with different $A_i$ and $f_c$ affect the above ratios in the intermediate wavelength region.

In figure 6, both $R_{ZF,\tau}^{D+1}$ and $R_{ZF,\tau}^{D+2}$ and $R_{ZF,\tau}^{DT+1}$ and $R_{ZF,\tau}^{DT+2}$ are slightly reduced (enhanced) by the presence of non-trace impurities as compared to the cases without impurities (the lines with $f_c = 0.00$). In other words, the trend of stronger residual ZF in D–T plasmas with larger $A_{i,eff}$ is weakened by non-trace impurities. This is because the presence of light or medium-mass impurities with finite concentration tends to weaken the influence from larger $\chi_{f_c,i,D+z_{il}}$ for larger $A_{i,eff}$. In this region, the magnitude of impurity effects is related to $g_i \chi_{f_c,i} \sim A_{i,eff} f_c (1 - Z_{l}) \sim A_{i,eff} f_c$ for $\tau_i = \tau_{l}$. Therefore, fully ionized impurities with heavier mass and higher $f_c$ have stronger influences on the reduction (enhancement) of the ratios $R_{ZF,\tau}^{D+1}$ and $R_{ZF,\tau}^{D+2}$ and $R_{ZF,\tau}^{DT+1}$ and $R_{ZF,\tau}^{DT+2}$ as shown in figures 6(a) and (b). While, in figure 7, the influences of trace W on the ratios are invisible because $g_i \chi_{f_c,i} \sim A_{i,eff} f_c$ for trace W is too small. In one word, trace W has very weak influences on the $A_{i,eff}$ dependence of residual ZF.

Furthermore, we note that impurity effects on the $A_{i,eff}$ dependence of residual ZF might be relevant to the impurity effects on confinement of magnetic fusion plasmas. Gyrokinetic simulation in [24] showed that the hydrogenic isotope mass dependence of the linear growth rate of ITG is weakened by the presence of impurity. This is qualitatively consistent with our findings that non-trace impurities can weaken the $A_{i,eff}$ dependence of residual ZF.

4. Summary and discussions

The influences of impurities on arbitrary wavelength residual ZF and on $A_{i,eff}$ dependence of residual ZF in D–T plasmas are investigated in this paper. The calculation of this work is simple, and the results are also very easily understood. However, we find significant influences of impurities on the levels of intermediate and short wavelength residual ZF, even for high-Z trace W, which are not addressed in previous works. The main results of this work are summarized in table 1.
Weakened by non-trace $c$, $\rho_i < \rho_{\text{eff}}$: decrease

$\rho_i > \rho_{\text{eff}}$: increase

% \rho_{\text{eff}} \sim \frac{\Lambda}{\rho_{\text{eff}}^2} \frac{T_0}{T_i} f_0 \%
% Weakened by non-trace W
% 
% ETG-driven $g_i + g_i > \tau_i$; increase
% 
% $g_i + g_i < \tau_i$; decrease
% 
% Strengthened by increase of $\tau_i = \frac{\Lambda}{\rho_{\text{eff}}^2} \frac{T_0}{T_i} f_0$ Weak
% 
% $\rho_{\text{eff}} \sim \frac{\Lambda}{\rho_{\text{eff}}^2} \frac{T_0}{T_i} f_0 \%
% 
% Table 1. Overview of the results about impurity effects on residual ZF and on $A_{\text{eff}}$ dependence of residual ZF in D–T plasmas.

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