Deuterium and tritium anomalous transport in generalized Hasegawa-Wakatani resistive drift wave turbulence model with finite ion Larmor radius

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Abstract

Anomalous transport of mixed deuterium-tritium plasma in edge of magnetic fusion reactors is investigated using numerical solutions of resistive drift wave turbulence model equations including finite Larmor radius effects that are derived within generalized Hasegawa-Wakatani framework. The anomalous cross-field diffusivities of deuterium and tritium are compared in turbulence regimes with different values of electron adiabaticity parameter controlling existence of zonal flow. Dependence of the tritium-to-deuterium diffusivity ratio on the deuterium and tritium densities and the logarithmic density gradients is analyzed and a scaling relation is obtained.

I. Introduction

Energy generation from deuterium (D) and tritium (T) nuclear fusion reaction is the main goal of magnetic confinement fusion research. Transport of these two hydrogen isotopes from the plasma core to the outer walls in tokamak fusion reactors plays a fundamental role in plasma confinement that is a basis for achieving and maintaining optimal rate of fusion reaction. It is well established that cross-field plasma transport is dominated by plasma turbulence both in the core and the edge tokamak plasma regions [1]. Thus, studies of turbulent transport of mixed deuterium and tritium plasma are essential for fusion development.

The existing literature on this topic largely focuses on theoretical and experimentally obtained scaling dependencies of global confinement times on engineering parameters, including hydrogen isotope mass dependence [1-7]. Such studies produced a wide range of often inconsistent mass scalings, physical meaning of which is difficult to interpret. Non-linear gyro-kinetic simulations have been used to investigate the mixed plasma transport in the core region driven by ion/electron temperature gradients (ITG/ETG) and trapped electron mode (TEM) turbulence demonstrating asymmetry between deuterium and tritium fluxes and important role of collisions, E × B shear, zonal flow, and electron parallel dynamics [8-13]. As well, quasi-linear models have been developed for modeling the turbulent core plasma transport to gain insight on the experimentally observed confinement time scalings [14-17]. However, the core plasma results may not be applicable to the edge region, as edge plasma turbulence is dominated by different instability mechanisms.

The resistive drift wave (RDW) instability is one of the main mechanisms of turbulence generation in edge plasma of magnetic fusion devices. The RDW turbulence has been actively studied using both theoretical and computational approaches [18-26]. One of widely used such approaches is Hasegawa-Wakatani (HW) model describing RDW turbulence in tokamak edge plasma in 2-dimensional approximation [27]. The original HW model assumes single cold ion species, neglecting finite Larmor radius (FLR) effects on ion transport. Recently, a generalized HW model has been developed that describes turbulence in multi-species plasma with FLR effects [22]. However, in that work the FLR effects only on impurities with trace concentrations, where they do not affect turbulence vorticity, were numerically investigated. A number of modeling works also considered impurity ions as passive tracers on HW turbulent plasma background [23-26]. In this paper we apply the generalized HW framework with FLR effects [22] to study anomalous transport of deuterium-tritium mixed plasma with varying ratios of the densities and the density gradients.

II. Model equations

We consider resistive drift wave plasma turbulence in (x, y) plane geometry, where x is the radial and y is the poloidal coordinates. The constant uniform magnetic field B is applied in z direction. Considering first order isothermal perturbations in cross-field ion velocities and following derivation procedures of the generalized Hasegawa-Wakatani model including FLR effects for resistive drift wave turbulence [22] we obtain dimensionless model equations for arbitrary number and concentration of ion species. In the derivation we retain FLR related terms associated with density perturbations in ion polarization velocity component for all ion species assuming $T_i \neq 0$, as well as terms related to ion viscosity and friction between ion species, leading to the following normalized equations for vorticity and ion densities

$$\partial_t \left(\nabla_\perp^2 \varphi + \sum_i R_i S_i \nabla_\perp^2 n_i \right) =$$
$$-\{\varphi, \nabla_\perp^2 \varphi\} + D_{eff} \nabla_\perp^4 \varphi - \sum_i R_i S_i (\nabla_\perp \cdot \{\varphi, \nabla_\perp n_i\} - D_i \nabla_\perp^4 n_i) + \alpha(\tilde{\varphi} - \tilde{n}_e), \quad (1)$$

$$\partial_t (n_i - R_i \nabla_\perp^2 n_i - Q_i \nabla_\perp^2 \varphi) =$$
$$-\{\varphi, n_i\} - \partial_y \varphi + R_i (\nabla_\perp \cdot \{\varphi, \nabla_\perp n_i\} - D_i \nabla_\perp^4 n_i) + Q_i (\{\varphi, \nabla_\perp^2 \varphi\} - D_i \nabla_\perp^4 \varphi)$$
$$+ \sum_j \nu_{ij} \left(R_i P_{ij} \nabla_\perp^2 n_i - R_j P_{ji} \nabla_\perp^2 n_j \right), \quad (2)$$

where $\{a, b\} \equiv \partial_x a \cdot \partial_y b - \partial_y a \cdot \partial_x b$ is the Poisson's bracket and $\tilde{a} \equiv a - \int a\, dy / \int dy$. In the model equations the following parameters are used: $\alpha \equiv k_\parallel^2 \frac{T_e}{\kappa_e \Omega_{eff} m_e \nu_{ei}}$ is the electron adiabaticity parameter, $R_i \equiv \frac{T_i}{T_e}\frac{M_i}{M_{eff}}\frac{1}{Z_i^2}$ is the parameter describing strength of the FLR effects for ion species 'i', $S_i \equiv Z_i\frac{\kappa_i}{\kappa_e}\frac{N_i}{N_e}$ describes contributions of different ion species to FLR related terms in vorticity equation, $Q_i \equiv \frac{\kappa_e}{\kappa_i}\frac{M_i}{M_{eff}}\frac{1}{Z_i}$ is related to coupling between vorticity and ion density fluctuations, $D_i = \eta_i\frac{eB}{c\kappa_e T_e}$ is the normalized ion viscosity coefficient η_i, and $P_{ij} \equiv \kappa_i Z_i\frac{\mu_{ij}}{M_i}$ is the normalization coefficient for ion friction terms. Here, m_e, N_e, T_e and M_i, N_i, T_i are the mass, density, and temperature of electrons and plasma ions of kind 'i', respectively, Z_i is the 'i'-type ion's charge number, $\nu_{ij} \equiv \frac{K_{ij}N_j}{\kappa_i Z_i \kappa_e \Omega_{eff}}$ is the normalized frequency of momentum exchange collisions for ions of kind 'i' with ion species 'j' having rate K_{ij}, $\mu_{ij} \equiv \frac{M_i M_j}{M_i+M_j}$ is the reduced mass for 'i' and 'j' ions, $M_{eff} \equiv \frac{\sum_i N_i M_i}{N_e}$, $\Omega_{eff} \equiv \frac{eB}{cM_{eff}}$, $\rho_{eff}^2 \equiv \frac{T_e}{M_{eff}\Omega_{eff}^2}$, $D_{eff} \equiv \frac{\sum_i N_i M_i D_i}{N_e M_{eff}}$, $\kappa_e \equiv -\rho_{eff}\frac{d(\ln N_e)}{dx} = \frac{\sum_i Z_i N_i \kappa_i}{\sum_i Z_i N_i}$, $\kappa_i \equiv -\rho_{eff}\frac{d(\ln N_i)}{dx}$, e is the elementary charge, c is the speed of light, ν_{ei} is the collisional frequency for electrons with ions, and $k_\parallel$ is the characteristic wave number of plasma perturbations along the magnetic field lines. The coordinates and variables in equations (1) and (2) are normalized as follows $\kappa_e\Omega_{eff}t' = t$; $\frac{\vec{r}'}{\rho_{eff}} = \vec{r}$; $\frac{e\varphi'}{\kappa_e T_e} = \varphi$; $\frac{n_e'}{\kappa_e N_e} = n_e$; $\frac{n_i'}{\kappa_i N_i} = n_i$, where t' and $\vec{r}'$ are the dimensional temporal and spatial coordinates, φ', n_e', n_i', and are the perturbation magnitudes of dimensional electric potential, electron, and ion densities, respectively.

In the considered here case of warm plasma ions, the vorticity and continuity equations (1) and (2) become mutually interconnected, where ion density fluctuations contribute to FLR effects in vorticity, and vorticity is coupled with the density fluctuations. We also recall that vorticity equation (1) implies quasi-neutrality of the plasma, i.e. $N_e = \sum_i Z_i N_i$, which together with equation (2) gives

$$\partial_t n_e = -\{\varphi, n_e\} - \partial_y\varphi + \alpha(\tilde{\varphi} - \tilde{n}_e), \tag{3}$$

where the normalized electron density perturbations are related to the ion ones as $n_e = \frac{\sum_i Z_i N_i \kappa_i n_i}{\sum_i Z_i N_i \kappa_i}$. We note that the FLR effects do not contribute to the electron continuity equation (3). Hence, for a case of single ion species the FLR effects effectively enter only in vorticity equation (1).

In this study, we are primarily interested in turbulent cross-field plasma transport, which is described by dimensionless spatially averaged cross field flux of species $s = e, i$

$$\langle\Gamma_s\rangle \equiv -\int n_s\,\partial_y\varphi\, d^2\vec{r}/\int d^2\vec{r} \tag{4}$$

that has normalization units of $\kappa_s N_s \kappa_e\left(\frac{T_e}{M_{eff}}\right)^{1/2}$. Accordingly, the dimensional anomalous particle diffusivity is proportional to the normalized flux as $D_\Gamma = \frac{c\kappa_e T_e}{eB}\langle\Gamma_s\rangle$ [23].

We also should note that the resistive interchange (RI) instability can be an important player in edge plasma turbulence in tokamaks. Considering RI instability in the HW framework, it is possible to show that RI turbulent source term is controlled by parameter $\alpha_{RI} = 2\rho_{eff}/R\kappa_e$, where R is the major radius of a tokamak, similar to the electron adiabaticity parameter α for RDW turbulence. Assuming parallel wave number $k_{||} \sim 1/qR$, where q is the safety factor, the ratio $\alpha_t = \alpha_{RI}/\alpha \approx 2\sqrt{\frac{m}{M_{eff}}} q^2 \frac{R}{\lambda_C}$ (here λ_C is the Coulomb mean free path) defines relative strength of RI and RDW turbulent drives. Therefore, the RDW drive governs turbulence for α_t values substantially smaller than one, which can be the case in tokamak edge due to smallness of the electron-to-ion mass ratio. Our present manuscript focuses on this turbulence regime and we plan extending the generalized HW model to include RI drive in future publications.

In addition, the used HW-like model is local, as it is isothermal and the logarithmic density gradient parameters, e.g. κ_e, are assumed constant. Thus, the model is applicable in regions where conditions for the model parameters alike of $\frac{d\kappa_e}{dR} \ll k_x \kappa_e$, where k_x is a characteristic turbulence radial wave number, are satisfied. We can assume that except edge regions where transport barriers are formed such approximation is reasonably applicable, which would include L-mode and periphery of H-mode plasmas.

III. Numerical parameters

We obtain numerical solutions of RDW turbulence equations (1) and (2) with FLR effects using pseudo-spectral code Dedalus [28]. The equations are solved in a square domain of size $L = 2\pi/\Delta k$, where $\Delta k = 0.1$ is the smallest resolved wave number. We use Fourier basis functions on uniform square grid of size 256×256 with de-aliasing factor $3/2$. The time integration is performed using (3-ε)-order 3-stage Runge-Kutta method with time step $\Delta t = 10^{-3}$ and the simulations continued for 10^4 dimensionless time units. All plasma transport characteristics discussed further in Section IV are considered in fully developed non-linear turbulence stage.

The numerical solutions are obtained for mixed deuterium-tritium edge plasma of tokamaks, assuming $M_i = 2$ and 3 a.u. for D and T ions, respectively, magnetic field $B \sim 3 \times 10^4$ G, plasma density $N_e \sim 3 \times 10^{13}\ \mathrm{cm}^{-3}$ with characteristic decay length $[d(\ln N_e)/dx]^{-1} \sim 1$ cm, and plasma temperature $T_e \sim T_i \sim 50$ eV. For these conditions we evaluate the normalized viscosity coefficient $D_i \sim 2 \times 10^{-3}$, the normalized collision frequency $\nu_{ij} \sim 0.2$, which define corresponding dissipative terms in the model equations, and the proportionality coefficient between the anomalous diffusivity and the dimensionless particle flux $\frac{c\kappa_e T_e}{eB} \sim 0.7\ \mathrm{m}^2/\mathrm{s}$. We consider two values of the electron adiabaticity parameter $\alpha = 0.01, 0.1$ and various values of other parameters corresponding to deuterium density fraction $N_D/N_e = 0.25, 0.5, 0.75$, and the ratio of deuterium-to-tritium logarithmic density gradients $\kappa_D/\kappa_T = 0.3, 1, 3$, see Table 1. As one can see in the table, the values of parameter R_i related to strength of FLR effects are not very different from one due to the similarity of deuterium and tritium ion masses.

We note that the used generalized HW theoretical model and the corresponding numerical results are essentially dimensionless and applicable to a wide range of edge plasma conditions.

The specified dimensional plasma parameters are used mostly to estimate physically relevant values of the dissipative and friction coefficients in the model equations, which do not limit applicability of the obtained results. We also note that many existing computational RDW studies with HW-like models use artificial (both in functional form and value) dissipative terms just for the purpose of dissipating enstrophy cascade at high wave numbers.

κ_D/κ_T \ N_D/N_e		0.25				0.5				0.75			
		R_i	S_i	Q_i	P_{ij}	R_i	S_i	Q_i	P_{ij}	R_i	S_i	Q_i	P_{ij}
0.3	i=D, j=T					0.8	0.23	1.73	0.011				
	i=T, j=D					1.2	0.77	0.78	0.025				
1	i=D, j=T	0.73	0.25	0.73	0.024	0.8	0.5	0.8	0.024	0.89	0.75	0.89	0.024
	i=T, j=D	1.09	0.75	1.09	0.016	1.2	0.5	1.2	0.016	1.33	0.25	1.33	0.016
3	i=D, j=T					0.8	0.75	0.53	0.036				
	i=T, j=D					1.2	0.25	2.4	0.008				

Table 1. Set of model parameters for the different simulated N_D/N_e and κ_D/κ_T.

IV. Results

IV.A $\alpha = 0.01$

For $\alpha = 0.01$ the simulated turbulence forms large size vortex-like structures, Figure 1(a) and (b), as compared to smaller vortices observed without FLR effects [20-23,25]. This may rise concerns about effects of the periodic boundary conditions on the simulated turbulence. For validation, we repeated simulations with the doubled domain size L, while preserving the spatial grid cell size, for selected $\alpha = 0.01$ cases. The simulations with the doubled domain size showed qualitatively and quantitatively similar results to the presented below. As the simulations of the larger system are more expensive computationally and take much longer time, we include here more complete results for the numerical parameters outlined in Section III.

The simulated deuterium and tritium density fluctuations are close, but not identical, to each other, Figure 1(c). The amplitude of normalized density fluctuations of tritium is somewhat smaller than that of deuterium with the respective standard deviations equal 34 and 37. However, tritium density fluctuations are more strongly correlated with the radial plasma velocity $-\partial_y\varphi$ than deuterium ones, where the corresponding tritium and deuterium Pearson's correlation coefficients are equal 0.055 and 0.043, respectively. This causes noticeable differences in modelled deuterium and tritium dimensionless radial fluxes, equivalent to differences in anomalous diffusivities of the two hydrogen isotopes, as discussed above. We note, that within the generalized HW model of multi-species plasma turbulence without FLR effects all plasma ions have the same anomalous diffusivities, as was shown in previous work [23]. Thus, the observed differences are a direct consequence of FLR effects on the ion transport.

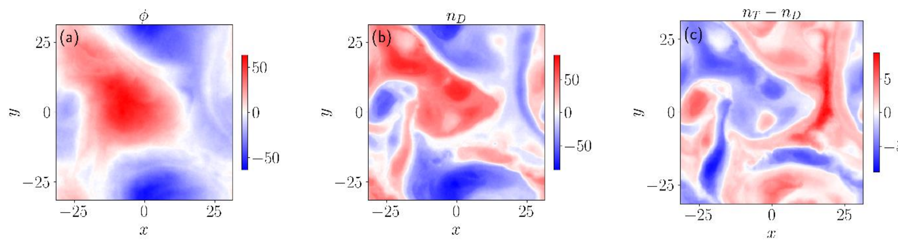

Figure 1. Snapshot at $t = 9999$ of simulated fluctuation profiles of (a) the electric potential, (b) the deuterium density, and (c) the difference between tritium and deuterium densities for the case $N_D/N_e = 0.5$, $\kappa_D/\kappa_T = 1$, and $\alpha = 0.01$.

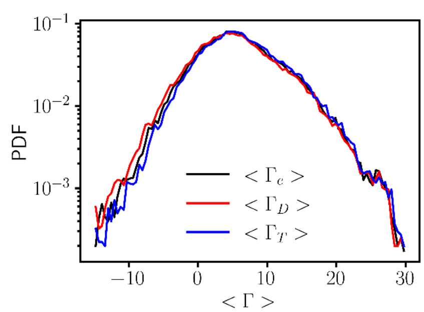

Figure 2. Probability distributions of temporal fluctuation amplitudes of the domain averaged electron, deuterium, and tritium dimensionless fluxes for the case $N_D/N_e = 0.5$, $\kappa_D/\kappa_T = 1$, and $\alpha = 0.01$.

The representative simulated probability distribution functions (PDFs) of the temporal fluctuations of the domain averaged fluxes, Eq. (4), are shown in Figure 2 for $N_D/N_e = 0.5$ and $\kappa_D/\kappa_T = 1$. They show that amplitude of the temporal fluctuations of fluxes averaged over small volume is large in comparison to the mean flux, similar to previously observed increase of flux fluctuations amplitude of heavy ions due to FLR effects [22]. It is also notable that the tritium flux is generally slightly more positive (radially outward) than the deuterium one. This tendency is observed for all simulated system parameters. As expected from ambipolarity condition, the electron flux values are in-between of the two ion species.

κ_D/κ_T \ N_D/N_e	0.25			0.5			0.75		
	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$
0.3				4.62	5.48	5.73			
1	5.12	5.68	5.87	5.60	6.00	6.41	5.44	5.63	6.20
3				5.31	5.39	5.62			

Table 2. Simulated time-averaged mean dimensionless fluxes of plasma species for the cases with $\alpha = 0.01$.

The mean dimensionless fluxes averaged in time for the plasma species are given in Table 2. The mean values follow the same relation between deuterium, tritium, and electron fluxes as mentioned above for all simulated cases. Remarkably, the T-D dimensionless flux (anomalous diffusivity) ratio practically independent of T-D concentration ratio and depends weakly on the ratio of logarithmic density gradients, κ_D/κ_T, see Figure 3. The dependence can be fitted by scaling formula

$$\frac{\langle\Gamma_T\rangle}{\langle\Gamma_D\rangle} = 1.14\left(\frac{\kappa_T}{\kappa_D}\right)^{0.068} . \qquad (5)$$

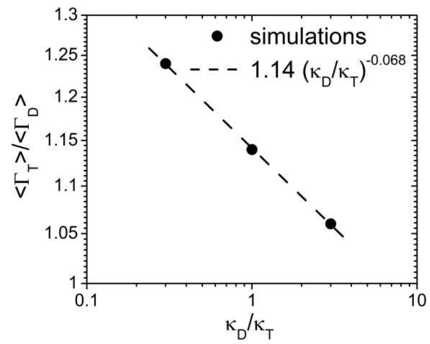

Figure 3. Dependence of the tritium-to-deuterium dimensionless flux (anomalous diffusivity) ratio on the logarithmic density gradient ratio κ_D/κ_T for $\alpha = 0.01$.

As discussed above, the difference in deuterium and tritium anomalous diffusivities is a consequence of the FLR effects. Therefore, the generally larger tritium diffusivity, as compared to deuterium, can be attributed to the correspondingly stronger FLR impact for tritium, related to parameter R_i, see Table 1. Equating factor 1.14 on right-hand side of expression (5) to $(M_T/M_D)^p$ for the given plasma conditions, we find value of the mass exponent $p = 0.33$, which is smaller than expected from gyro-Bohm scaling $p = 0.5$ [2]. In addition, the dependence of the diffusivity ratio (5) on the density gradients may partially explain differences between various experimentally obtained transport scalings on isotope mass, which do not explicitly include the gradient dependence. Although, the empirical global confinement scalings often exhibit negative values of the mass exponent and can be influenced by many processes in both the core and the edge plasmas that are beyond this work considerations [3-17].

We also note that the friction term in ion continuity equation (2) can lead to difference in fluxes of different ion species. Namely, friction force due to mismatch of diamagnetic poloidal ion flow velocities causes radial drift of deuterium and tritium ions in opposite directions. However, due to smallness of the parameter P_{ij} (see Table 1) and relatively small normalized collisional frequency ν_{ij} the contribution of friction in the ion flux is small for the considered plasma conditions.

IV.B $\alpha = 0.1$

In case of $\alpha = 0.1$ the simulated plasma turbulence develops zonal flow, see Figure 4. The amplitudes of density fluctuations in this case are greatly reduced in comparison to the case $\alpha = 0.01$, while tritium density amplitudes remain smaller than deuterium ones with the respective standard deviations equal 4.4 and 4.9. The correlations between the density and radial velocity are increased for both tritium and deuterium, but as in the previous case the tritium correlations have the larger Pearson's coefficient of 0.21 vs. 0.19 for deuterium. As can be seen in Figure 4(b), characteristic size of density structures in this case is much smaller than for $\alpha = 0.01$ and they are to some extent confined in the poloidal flow zones separated by shear, Figure 4(c), similar to previous simulation results without FLR effects [29]. Such confinement inhibits turbulent plasma mixing between the flow zones.

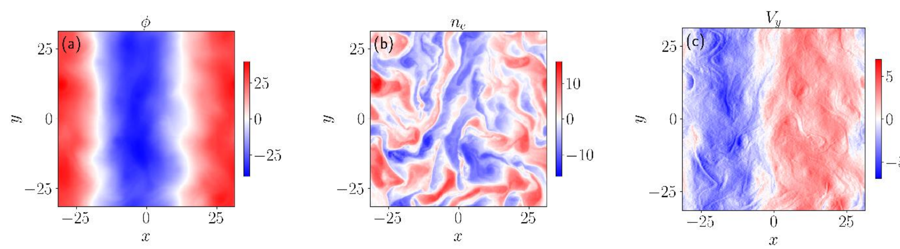

Figure 4. Snapshot at $t = 9999$ of simulated fluctuation profiles of (a) electric potential, (b) electron density, and (c) poloidal velocity for the case $N_D/N_e = 0.5$, $\kappa_D/\kappa_T = 1$, and $\alpha = 0.1$.

κ_D/κ_T \ N_D/N_e	0.25			0.5			0.75		
	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$	$\langle\Gamma_D\rangle$	$\langle\Gamma_e\rangle$	$\langle\Gamma_T\rangle$
0.3				0.88	0.87	0.87			
1	0.90	0.90	0.90	0.84	0.83	0.82	0.91	0.91	0.90
3				0.79	0.78	0.76			

Table 3. Simulated time-averaged mean dimensionless fluxes of plasma species for the cases with $\alpha = 0.1$.

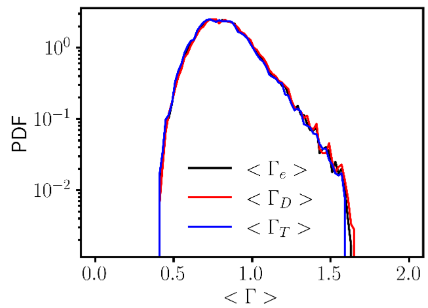

Figure 5. Probability distributions of temporal fluctuation amplitudes of the domain averaged electron, deuterium, and tritium dimensionless fluxes for the case $N_D/N_e = 0.5$, $\kappa_D/\kappa_T = 1$, and $\alpha = 0.1$.

As a result, the formation of zonal flow greatly reduces both the mean and the temporal fluctuation amplitudes of the domain averaged radial particle fluxes, Figure 5. Moreover, the flux probability distributions of all plasma species become virtually indistinguishable, as the differences between the tritium and deuterium in density fluctuation amplitudes and in their correlations with radial plasma velocity nearly compensate each other. As one can see in Table 3, where the time-averaged mean dimensionless fluxes are presented, the T-D flux ratio is practically equal to one for all simulated cases with $\alpha = 0.1$ independent of T-D density and logarithmic density gradient ratios. Therefore, zonal flow formation dominates plasma transport strongly suppressing FLR effects on RDW turbulent deuterium and tritium fluxes.

V. Conclusions

In this work resistive drift wave turbulence model equations for multi-species plasma are obtained within the generalized Hasegawa-Wakatani framework including FLR effects [22]. We use the developed model to investigate numerically anomalous cross-field transport of fully ionized deuterium-tritium mixed plasma in fusion edge region. We found that in the turbulence regimes with the small electron adiabaticity parameter $\alpha = 0.01$, characterized by absence of zonal flow, the tritium anomalous diffusivity exceeds that of deuterium due to stronger FLR impact on T transport. It is also shown that in this case the T-D anomalous diffusivity ratio does not depend on T-D density fractions. A scaling dependence of the T-D diffusivity ratio on T and D logarithmic density gradients is obtained. The obtained dependence indicates that the diffusivity scaling with ion mass has the exponent value of 0.33 that is weaker than expected from gyro-Bohm scaling with the mass exponent of 0.5. In the plasma turbulence regimes with the larger electron adiabaticity parameter $\alpha = 0.1$, characterized by existence of zonal flow, the anomalous plasma transport is greatly reduced and the T and D cross-field diffusivities become effectively identical. Therefore, zonal flow strongly suppresses FLR-related differences in RDW turbulent transport of hydrogen isotopes. The obtained results can have important implications for consideration of fueling rates in future fusion reactors in order to maintain optimal T-D density ratio in burning core plasma.

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Author Declarations

Conflicts of Interest

The authors have no conflicts to disclose.

Data Availability

The data that support the findings of this study are available from the authors upon reasonable request.

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