Fluid Model for Turbulent Particle Transport in Non-Trace Impurity Doped Tokamak Plasma

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Introduction

Following the installation of a Liquid Lithium Limiter (LLL) in the Frascati Tokamak Upgrade (FTU), experiments exhibit significantly improved particle confinement and higher electron density peaking factors compared to standard metallic limiter scenarios [1].

The first gyrokinetic analysis performed with GKW [3] of the FTU-LLL discharge #30582 using a Lorentz-type collision operator was published in Romanelli et al. [2]. In this paper we extend the analysis and point out the importance of taking into account the full collision operator. We show that if the energy scattering and friction terms are included, varying the lithium concentration can change the direction of the deuterium and electron flux. The gyrokinetic simulations are complemented by a quasi-linear fluid model that contains the necessary physics needed to capture the main aspects of the observed particle transport. The fluid approach allows us to analyse all the eigenmodes of the system and estimate their diffusive, thermodiffusive and pinch contributions to the particle flux separately [4]. The validity of the linear and quasi-linear analysis is confirmed by a non-linear gyrokinetic simulation of the experimental case.

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Gyrokinetic Analysis

In this section the gyrokinetic analysis of FTU #30582 performed with GKW is shown. The simulations have been done in the good confinement region at the radius of $r/a = 0.6$. The early stage of the discharge at $t = 0.3$s is investigated, characterized by $Z_{\text{eff}} = 1.93$ due to the high lithium concentration and a strong inward electron and outward lithium flux. The input parameters of the simulations are the same as in [2]. The fluxes calculated in a linear gyrokinetic simulation are proportional to the phase difference between the density and potential perturba-

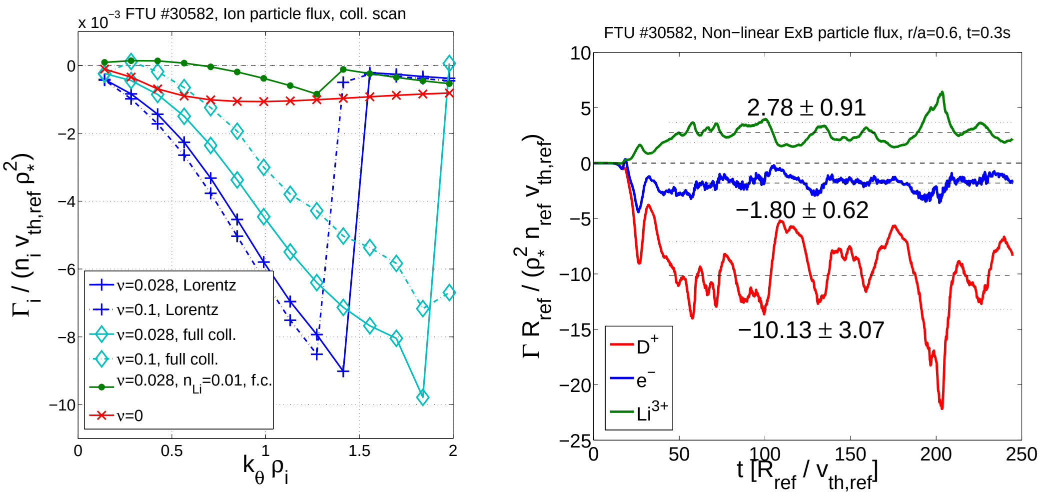

Figure 1: Collisionality scan of the quasi-linear deuterium flux as a function of bi-normal wavenumber (left) and time-traces of the non-linear flux (right) in the experimental case at $t = 0.3$s.

tions but do not carry information about their saturated value. Their sign indicates whether the flux is inward (negative) or outward (positive).

As shown on figure 1, the deuterium particle flux driven by ITG modes is directed inward with both Lorentz-type and full collision operator at the two different collision frequencies. However, at reduced impurity concentration the flux driven by modes below $k_\theta \rho_\mathrm{i} \approx 0.6$ is outward. This reversal only takes place when the full collision operator is taken into account. In the collisionless case TEM-s are dominant. The non-linear analysis of the experimental case at $t = 0.3$s with Lorentz-type collision operator shows that the particle transport maintains its direction in the saturated phase.

Quasi-linear Fluid Analyis

The quasi-linear fluid model applied for this problem consists of equations continuity and energy balance equations for deuterium, impurity ion and trapped electron species, and parallel momentum equations for the ions. Bounce averaged parallel trapped electron motion is neglected. Passing electrons are adiabatic. The impurities are treated as non-trace species, i.e. their density perturbation is considered in the quasi-neutrality equation. Gyro-viscous cancellation is taken into account according to Chang and Callen [5], electron collisions according to Nilsson and Weiland [6] and magnetic shear effects according to Hirose [7]. The equations are radially local, and fluctuations in the bi-normal and parallel direction are considered. The model is similar to the one used by Moradi [8] for impurity transport studies. The saturation level of the electrostatic potential for estimating quasi-linear fluxes is approximated using the Weiland model [9].

After linearizing and substituting Fourier-mode solution, the ion (subscript s) continuity, parallel momentum and energy balance equations become

$$\frac{\hat{n}_{s,1}}{n_{s0}}\left(2\omega_{D,s}-\omega-\omega\frac{1}{2}k_y^2\rho_{th,s}^2\right)+\frac{\hat{T}_{s,1}}{T_{s0}}\left(2\omega_{D,s}-\omega\frac{1}{2}k_y^2\rho_{th,s}^2\right)+$$
$$\frac{Z_s e}{T_{s0}}\hat{\phi}_1\left(2\omega_{D,s}-\omega_{*s}^n-\omega\frac{1}{2}k_y^2\rho_{th,s}^2\right)+k_\parallel\hat{v}_{\parallel s}^1\left(1+\frac{1}{2}k_s^2\rho_{th,s}^2\right)=0 \quad (1)$$

$$-\frac{m_s}{T_s}\omega\hat{v}_{\parallel s}^1+k_\parallel\left(\frac{\hat{n}_{s1}}{n_{s0}}+\frac{\hat{T}_{s1}}{T_{s0}}+\frac{Z_s e}{T_{s0}}\hat{\phi}_1\right)=0 \quad (2)$$

$$\left(\frac{10}{3}\omega_{D,s}-\omega\right)\frac{\hat{T}_{s1}}{T_{s0}}+\frac{2}{3}\omega\frac{\hat{n}_{s1}}{n_{s0}}-\frac{Z_s e}{T_s}\hat{\phi}_1\omega_{*s}^n\left(\eta_s-\frac{2}{3}\right)=0 \quad (3)$$

where $\hat{n}_{s,1}$, $\hat{T}_{s1}$, $\hat{v}_{\parallel s}^1$ and $\hat{\phi}_1$ are the Fourier components of the density, temperature parallel velocity and electrostatic potential fluctuations, respectively, the corresponding quantities with a 0 subscript denote the equilibrium values. $k_\parallel$ and k_y are the parallel and bi-normal wavenumbers, $\rho_{th,s}=(m_s v_{th,s})/(Z_s eB)$ is the species' thermal Larmor-radius. ω is the mode frequency, $2\omega_{D,s}=k_y\vec{y}\cdot\vec{v}_{D,s}$ is the magnetic drift frequency and $\omega_{*s}^n=-k_y T_s/(Z_s eBL_{n,s})$ is the diamagnetic frequency, $L_{n,s}=-\frac{n_s}{\nabla n_s}$ is the density gradient scale-length and $\eta_s=L_{n,s}/L_{T,s}$.

The trapped electron continuity and energy balance equations are written as

$$\frac{\hat{n}_{e,1}}{n_{e0}}(2\omega_{D,e}-\omega-i\nu_{th})+\frac{\hat{T}_{e,1}}{T_{e0}}2\omega_{D,e}+\frac{Z_e e}{T_{e0}}\hat{\phi}_1(2\omega_{D,e}-\omega_{*e}^n-i\nu_{th}\Gamma)=0 \quad (4)$$

$$\left(\frac{10}{3}\omega_{D,e}-\omega\right)\frac{\hat{T}_{e1}}{T_{e0}}+\frac{\hat{n}_{e1}}{n_{e0}}\left(\frac{2}{3}\omega-bi\nu_{th}\right)-\frac{Z_e e}{T_e}\hat{\phi}_1\left[\omega_{*e}^n\left(\eta_e-\frac{2}{3}\right)+bi\nu_{th}\right]=0 \quad (5)$$

where $n_{et,0}=n_{e0}f_t$ and the trapped electron fraction is calculated as $f_t=\sqrt{2r/(r+R)}\approx 0.55$ in this case. $\nu_{th}=\nu_e/\varepsilon$, $\varepsilon=r/R$ the inverse aspect ratio, $\Gamma=1+\frac{a\eta_e\omega_{*e}^n}{\omega-\omega_{D,e}+i\nu_{th}}$. $a\approx 1$ and $b\approx 1.5$ are factors determined in [6] in order to recover the strongly collisional TE response with the simplified collision operator.

In figure 2 we show the growth rate (left), total particle flux of the species (middle), and deuterium flux separated to slab and curvature terms of diffusive, thermodiffusive and pinch contributions (right) as a function of the bi-normal wavenumber with the experimental $c_{Li}=15\%$ lithium concentration, and in figure 3 with a reduced $c_{Li}=1\%$. In the presence of high c_{Li} the strong outward slab diffusive term is compensated by the inward curvature pinch in the $0.3<k_\theta\rho_i<0.7$ region leading to an overall inward flux. In the reduced lithium case the slab diffusion term is dominant in a wider k_θ range resulting outward deuterium tranport.

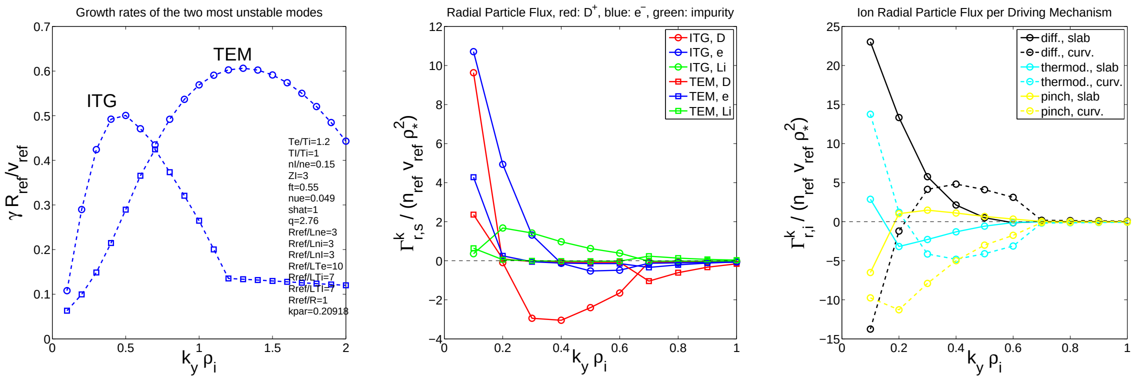

Figure 2: Fluid analysis at $t = 0.3$s with 15% lithium concentration.

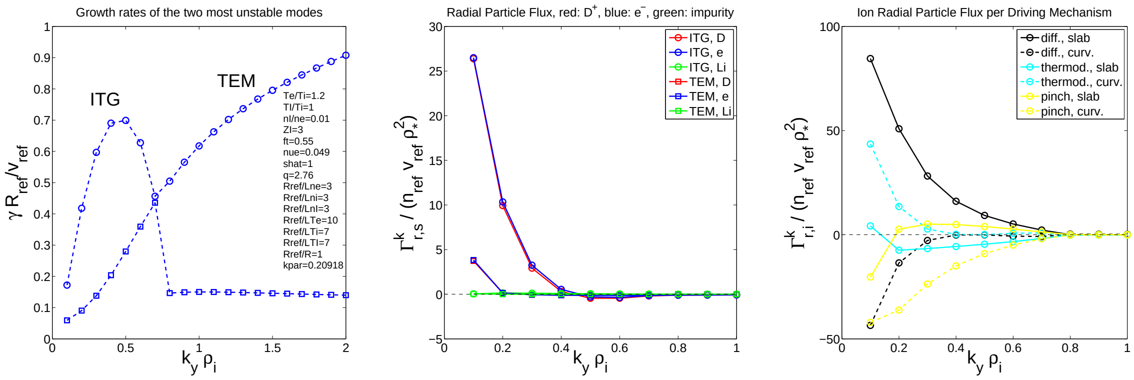

Figure 3: Fluid analysis at $t = 0.3$s with 1% lithium concentration.

Conclusions

Gyrokinetic and fluid analysis of the turbulent particle transport in the FTU-LLL discharge #30582 were presented. Both models show that the lithium concentration in the early phase of the discharge is in fact the cause of the inward deuterium and outward lithium flux due to the typical spatial scales (Larmor-radii) of the two ion species. This conclusion can only be drawn when the full collision operator is taken into account in the GKW simulations.

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