Gyrofluid edge turbulence simulations on isotope effects

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Introduction

Recent experiments suggest improved confinement properties as the plasma constituents mass is increased [1]. This is supposedly due to enhanced zonal flow dynamics, which act as transport barriers to suppress turbulence and hence reduce radial particle transport. In this work we seek to model the isotope effect employing a 3D local isothermal flux-tube multi-species gyrofluid code [2] based on the GEM3 model [3]. Results from numerical simulations of hydrogen-deuterium, deuterium-hydrogen, deuterium-tritium and tritium-deuterium plasmas are presented. In each case the first ion species dominates the second by 80 : 20 in background concentration.

Model Equations

The two-moment gyrofluid model of [3] formulated in 3D local flux-tube geometry with coordinates $\{x,y,s\}$ where x is a flux-surface label, y is a field-line label and s is the position along the field-line, is given in terms of evolution equations for density and parallel velocity, coupled through parallel dynamics, curvature and electromagnetic induction:

$$\begin{aligned}
\frac{d_z n_z}{dt} &= -B\nabla_{\parallel}\frac{u_{z\parallel}}{B} + \mathscr{K}\left(\phi_G + \tau_z n_z\right) \ , \\
\widehat{\beta}\frac{\partial A_{\parallel}}{\partial t} + \varepsilon_z \frac{d_z u_{z\parallel}}{dt} &= -CJ_{\parallel} - \nabla_{\parallel}\left(\phi_G + \tau_z n_z\right) + \mathscr{K}\left(\varepsilon_z \tau_z u_{z\parallel}\right) \ , \\
\nabla_{\perp}^2 A_{\parallel} &= -J_{\parallel} \ .
\end{aligned}$$

The system is closed by the gyrofluid polarisation equation

$$\sum_z a_z \left[\Gamma_0^{1/2} n_z + \frac{\Gamma_0 - 1}{\tau_z}\phi\right] = 0 \ ,$$

and z is a species label. Operators are defined as

$$\begin{aligned}
\frac{d_z}{dt} = \frac{\partial}{\partial t} + \{\phi_G, \ \} \ , \ \nabla_{\parallel} &= \frac{1}{B}\frac{\partial}{\partial s} - \widehat{\beta}\{A_{\parallel}, \ \} \ , \\
\nabla_{\perp}^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) \ , \ \mathscr{K} &= \omega_B\left(\sin s\frac{\partial}{\partial x} + \cos s\frac{\partial}{\partial y}\right) \ , \\
\{f,g\} &= \partial_x f \partial_y g - \partial_y f \partial_x g \ ,
\end{aligned}$$

where $\phi_G = \Gamma_0^{1/2}\left(\rho_z^2 k_{\perp}^2\right)\phi$ is the (species dependent) gyro-screened potential and we use Padé approximate forms $\Gamma_0(b) \approx (1+b)^{-1}$, $\Gamma_0^{1/2}(b) \approx (1+b/2)^{-1}$ for the gyroaveraging operators.

Shear-Alfvén activity, parallel electron response and curvature effects are controlled by the free parameters

$$\widehat{\beta} = \frac{4\pi p_e}{B^2}\left(\frac{qR}{L_\perp}\right)^2 \ , \ C = 0.51\frac{\nu_e}{c_s/L_\perp}\frac{m_e}{M_D}\left(\frac{qR}{L_\perp}\right)^2 \ , \ \omega_B = \frac{2L_\perp}{R} \ ,$$

respectively. R is the major radius, $L_\perp$ a characteristic profile scaling length and q the safety factor. Species are characterised by their background parameters $a_z = Zn_z/n_e, \tau_z = T_z/ZT_e, \mu_z = M_z/ZM_D, \rho_z^2 = \mu_z\tau_z/B^2, \varepsilon_z = \mu_z\left(qR/L_\perp\right)^2$, characterising background concentration, ion-electron temperature ratio, ion mass ratio and scale ratio for the parallel dynamics (connection length/profile scale) respectively. Based on the parameters we introduce the effective gyrofluid mass as $m_{\text{eff}} = a_z\mu_z + a_D\mu_D$ yielding $m_{\text{eff}} < 1$ for hydrogen dominated runs and $m_{\text{eff}} > 1$ for tritium dominated runs.

Simulation Details

The numerical scheme is a third order Karniadakis time-stepping scheme where the Poisson brackets are evaluated using Arakawa's scheme and employing finite-differences for other partial derivatives. The computation domain $\{L_x, L_y, L_s\} = \{64\rho_s, 256\rho_s, 2\pi\}$ is discretized on $\{64, 256, 16\}$ nodes respectively yielding a resolution of $1\rho_s$ in the drift plane ($\rho_s = c_s/\Omega_D = c\sqrt{M_D T_e}/eB$ is the drift scale). Simulations are run into the nonlinearly saturated state over which statistics are taken ($\approx 500 - 200$ in normalized time units). Fixed parameters are $\widehat{\beta} = 1, \omega_B = 0.05, (qR/L_\perp)^2 = 18225, \widehat{s} = 1, \nu_{\shortparallel} = 0.003, \nu_\perp = 0.002$, where the latter are artificial hyperviscosity coefficients implemented as in [4] and $\widehat{s}$ is the magnetic shear . In the following we distinguish between cold ions ($\tau_{i_1} = \tau_{i_2} \equiv \tau = 0$) and runs with FLR effects ($\tau = 1$).

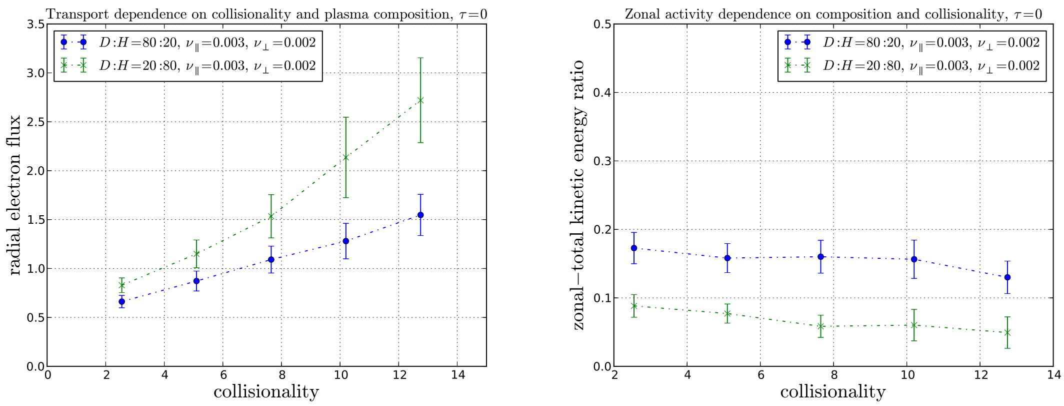

Figure 1: Transport (left) and zonal-energy (right) scaling for runs with two different D:H ratios similar to [1] - cold ions.

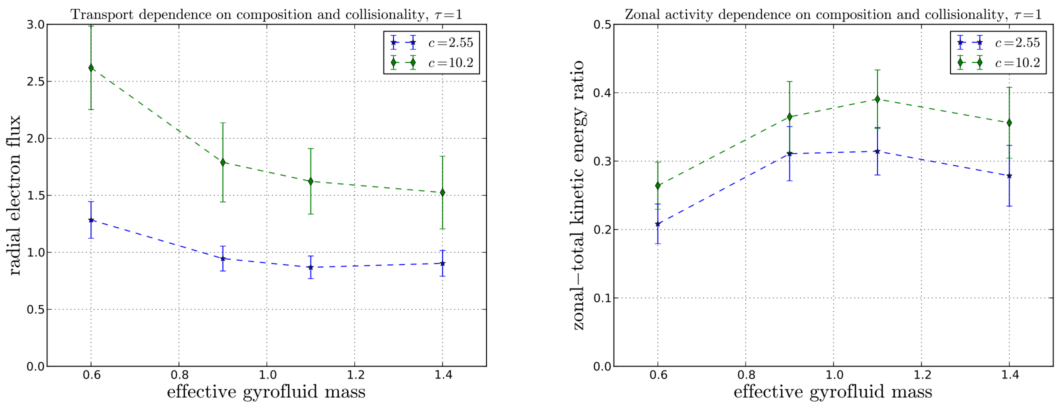

Figure 2: Transport (left) and zonal-energy (right) scaling for runs with varying plasma composition and different parallel electron response - warm ions.

Results

In the following we show cold ion results for plasma compositions similar to the experimental setup of Ref. [1] and warm ion results for weakly adiabatic ($C = 2.55$) and strongly non-adiabatic ($C = 10.2$) electrons. From Fig. 1 we clearly deduce a mass dependence of the radial transport, showing improved confinement for the heavier isotope plasma over a wide range of relevant adiabacity conditions (in the edge of ASDEX Upgrade $C \approx 7.65$). Furthermore we find that the kinetic energy contained in zonal structures, which we have quantified by their ratio to the total flow kinetic energy, also exhibits a mass scaling, giving some indications that signatures of the isotope effect are present in our (isothermal) model. The presented mass scaling seems to hold also for warm ions (cf. Fig. 2), indicating that the isotope effect is not (exclusively) a FLR effect. However, taking into account also tritium-deuterium cases, the effect is weakened or vanishing. Future work adressing the mechanism behind this apparent enhanced zonal activity for certain isotopes should include temperature dynamics in order to describe ITG turbulence which is a vital part of tokamak edge turbulence and not yet present in our model.

References

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