Particle Pinches in Fluid and Kinetic Descriptions

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Abstract

It has been found that gyrofluid resonances strongly reduce particle pinches in tokamak plasmas. This has been seen both in a standard case parameter scan and for the JET L-mode 51034 by introducing gyrofluid resonances in a normally non-dissipative fluid model. The importance of the treatment of wave-particle interaction for particle pinches is discussed. Extrapolations to quasilinear kinetic models are made.

1 Introduction

Tokamak particle pinches, defined as anomalous inward particle fluxes, are experimentally seen in L-mode discharges [1]. Peaked density profiles have also been seen in low collisionality H-modes. This could be due to anomalous particle pinches but it could also be due to the fuelling, which goes deeper into the plasma and contributes to the peaking. There is however no evidence in present theories that particle pinches are different in L- and H-mode. Particle pinches decrease with increasing collisionality [2].

In a fusion reactor a particle pinch would be welcome for the main ions while an impurity pinch is not desired. There are also other conditions defining the situations where the pinches would be desirable. In ITER the particle source will be located close to the edge while the (alpha) heating will be strong near the axis. This gives a temperature profile which is more peaked than the density profile.

Many models describe particle pinches with different methods and results. A common characteristic is that the pinches given by the models usually are too weak to accurately reproduce experimental density profiles.

Particle pinches were first modelled in slab geometry plasmas [3, 4]. In these models dissipation gave nonadiabatic electrons. The first toroidal derivation used a fluid model for Ion Temperature Gradient (ITG) and Trapped Electron (TE) modes and included both temperature gradient drive (off diagonal part) and a convective part due to the magnetic field gradient [5, 6]. The model is reactive in the sense that no dissipation is introduced by the choice of closure. In the model, henceforth called the reactive model, the particle pinch is strong enough to reproduce experimental density profiles in L-mode [7]. The pinch can be strong also when collisions are included [8] and electromagnetic effects may increase the pinches in the model [9].

Gyrokinetic simulations have been shown to give particle flows where the pinches are too weak to support the steep density profile in Ohmic plasmas. A quasilinear version of the gyrokinetic code GS2 gives an outward particle flux for any positive value of R/L_n when collisionalities near the experimental range are included [10]. The model is not compatible with experimental L-mode density profiles, but in the collisionless limit an inward pinch may appear. Gyrokinetic results from the code GYRO also show a particle pinch that quickly disappears (or requires a higher η_e) when collisions are included and the collision frequency increased [11].

While the reactive model gives a strong particle pinch when the temperature profile is more peaked than the density profile [8], a corresponding quasilinear kinetic model does not give any particle pinch [12].

The objective of this work is to examine one possible reason for the difference between fluid and kinetic descriptions of particle pinches.

2 Relevance of kinetic resonances for particle pinches

Transport in velocity space is a secular effect occurring on the transport time scale and taking particles out of resonance with a wave. This transport relaxes fluid moments without sources, i.e. makes them decay to zero, on the confinement time scale.

One reason for the different pinch results in fluid and kinetic models is the differences in the treatment of wave-particle interaction. This could be described in terms of closure of a fluid model. Each velocity moment of the particle distribution function that is included in a fluid model gives an extra pole in the density response. The reactive fluid closure depends on the nonlinear relaxation of moments higher than those included in the model. In the reactive model the only included moments are the ones with external sources and no dissipation is introduced by the choice of closure.

In gyrofluid models [13] lower order moments are included and all higher order moments are represented by a dissipative gyrofluid resonance. An infinite number of poles would give a fluid model which recovers the dissipative resonances of Landau of magnetic drift type that are seen in kinetic theory.

In a quasilinear kinetic description the effect of all fluid resonances are represented as dissipation. Velocity space relaxation in the quasilinear model is possible but means a complete flattening of the velocity distribution of the main species since all moments are included. This is unlikely to occur due to the wide spectrum of drift waves.

In GYRO and GS2 the relaxation in velocity space is not free since the parallel nonlinearity, and thus the nonlinear Landau damping along the magnetic field, have been ignored. Results from Particle In Cell (PIC) codes [14, 15] indicate that the parallel nonlinearity may be important and are consistent with an incomplete relaxation in velocity space when the parallel nonlinearity is ignored. This interpretation follows from the reduced level of zonal flows and accompanying larger transport, caused by dissipative wave-particle resonances in a gyrofluid model [16]. There are also results from simulations with GYRO and the gyrokinetic PIC code GEM indicating that the parallel nonlinearity is negligible on time scales shorter than the confinement time scale [17]. There is also a perpendicular nonlinearity, associated with the magnetic drift resonance, which may be of importance.

Since the nonlinear relaxation of higher order moments is closely connected to the relaxation in velocity space, a comparison between fluid and nonlinear gyrokinetic results may require that all mechanisms for velocity space relaxation are included in the kinetic code. A significant difference between the quasilinear kinetic and the gyrofluid descriptions is that the fluid resonances allow singularities while the principal part in the quasilinear case is always regular.

The simple 2d systems i Ref:s [5, 12] are well suited for comparison because the treatment of kinetic resonances is the only difference for small Finite Larmor Radius (FLR) and collision frequency. The models represent the simplest possible systems which retain the difference in treatment of kinetic resonances and at the same time have the possibility for particle pinches. The wave-particle resonance is represented by the presence of dissipative kinetic resonances in the quasilinear kinetic model. Nonlinear effects in velocity space may however remove dissipative kinetic resonances and leave only the fluid resonances corresponding to moments which have sources in the experiment. The difference is thus a question of the fluid closure in a nonlinear stationary state [18]. In Ref. [18] it was also found that collisions cannot keep up with nonlinear modifications of the distribution function for typical collisionalities in large, high temperature tokamaks.

3 The model

In the present work we have studied the particle pinch in the reactive model and in a modified version of it where the toroidal part of the gyrofluid resonance of Ref [13] was added. Using only the toroidal part is not a severe restriction and the original models did not include parallel ion motion [5, 12], which the model used here does. The reactive model with the gyrofluid resonances added has the same linear threshold as the gyrokinetic models for the Cyclone base case which includes parallel ion motion [16].

The gyrofluid resonance is included by adding a term to the closure, which in the reactive model is taken as $\mathbf{q}_j = \mathbf{q}_{\star j}$ $(j = i, e)$, according to [13, 19]

$$\nabla \cdot \mathbf{q}_j = \nabla \cdot \mathbf{q}_{\star j} + i\frac{3}{2}\nu n \delta T \omega_{De} \tag{1}$$

where for electrons

$$\tilde{\nu} = 0.7 - 0.8i \tag{2}$$

and for ions

$$\tilde{\nu} = -\frac{3}{4}(1 - i\sqrt{2}) + i\frac{2\tau k_\parallel^2}{\sqrt{\pi}}. \tag{3}$$

Here $\mathbf{q}$ is the heat flux, ν defines the gyrofluid resonance, indexes e = electrons, i = ions, $\star$ = diamagnetic, $\sim$ means that a variable is normalised by the magnetic drift frequency ω_{De}, $\tau = T_e/T_i$ and $k_\parallel$ is the parallel wave number. In the following we also use the notations n = density, e = elementary charge, ϕ = electrostatic potential, $f_t = \sqrt{2\epsilon/(1+\epsilon)}$, where $\epsilon = r/R$, as the fraction of trapped particles, k_x = radial wave number, $\eta = L_n/L_T$ for the density to temperature length scales ratio, $\epsilon_n = 2L_n/R$, $\nu = \nu_r + i\nu_i$, $\nu_{eff} = \nu_{ei}/\epsilon$ for the collision frequency and $\omega = \omega_r + i\gamma$ for the wave frequency.

The temperature perturbation can then be written as

$$\frac{\delta T_e}{T_e} = \frac{1}{\omega - \frac{5}{3}\omega_{De} - \nu}\left(\frac{2}{3}\omega\frac{\delta n_e}{n_e} + \omega_{\star e}\left(\eta_e - \frac{2}{3}\right)\frac{e\phi}{T_e}\right). \tag{4}$$

Including collisions on trapped electrons [20] the continuity equation then gives the density perturbation as

$$\frac{\delta n_e}{n_e} = \frac{1}{\epsilon_n}\frac{(\tilde{\omega} - i\tilde{\nu})(1-\epsilon_n) + \eta_e - \frac{7}{3} + \frac{5}{3}\epsilon_n + \tilde{\nu}_{eff}G_1}{\tilde{\omega}^2 - \frac{10}{3}\tilde{\omega} + \frac{5}{3} - i\tilde{\nu}(\tilde{\omega} - 1) + \tilde{\nu}_{eff}H_1}\frac{e\phi}{T_e} \tag{5}$$

where $G_1 = i\epsilon_n + (i\tilde{\omega} - i\frac{10}{3} + \tilde{\nu})\epsilon_n\Gamma$, $H_1 = i\tilde{\omega} - i\frac{7}{3} + \tilde{\nu}$ and $\Gamma = 1 + \frac{\eta_e}{\epsilon_n}\frac{1}{\tilde{\omega} - 1 + i\tilde{\nu}_{eff}}$.
The electrostatic diffusion coefficient for the trapped electrons in the reactive model is given as

$$D = -f_t\omega_{De}\epsilon_n\tilde{\gamma}^2/k_x^2 Im\left(\frac{\delta n_e}{n_e}\Bigg/\frac{e\phi}{T_e}\right). \tag{6}$$

Without collisions this can be expressed analytically as

$$D = f_t\Delta_n\frac{\gamma^3/k_x^2}{\omega_{De}^2} \tag{7}$$

$$\Delta_n = \frac{1}{N}(A_n + \eta_e B_n + \epsilon_n C_n) \tag{8}$$

$$A_n = \tilde{\omega}_r^2 + \tilde{\gamma}^2 - \frac{14}{3}\tilde{\omega}_r + \frac{55}{9} + \tilde{\nu}_r^2 + \tilde{\nu}_i^2 - 2\tilde{\nu}_r\left(\tilde{\gamma} + \frac{1}{3\tilde{\gamma}}\right) + 2\tilde{\nu}_i\left(\tilde{\omega}_r - \frac{7}{3}\right) \tag{9}$$

$$B_n = 2\tilde{\omega}_r - \frac{10}{3} - \frac{\tilde{\nu}_r}{\tilde{\gamma}}(\tilde{\omega}_r - 1) + \tilde{\nu}_i \tag{10}$$

$$C_n = -\tilde{\omega}_r^2 - \tilde{\gamma}^2 + \frac{10}{3}\tilde{\omega}_r - \frac{35}{9} - \tilde{\nu}_r^2 - \tilde{\nu}_i^2 + 2\tilde{\nu}_r\left(\tilde{\gamma} + \frac{\tilde{\omega}_r}{3\tilde{\gamma}}\right) - 2\tilde{\nu}_i(\tilde{\omega}_r - 2) \tag{11}$$

$$N = \left(\tilde{\omega}_r^2 - \tilde{\gamma}^2 - \frac{10}{3}\tilde{\omega}_r + \frac{5}{3} + \tilde{\nu}_r\tilde{\gamma} + \tilde{\nu}_i(\tilde{\omega}_r - 1)\right)^2 + \left(2\tilde{\gamma}\tilde{\omega}_r - \frac{10}{3}\tilde{\gamma} - \tilde{\nu}_r(\tilde{\omega}_r - 1) + \tilde{\nu}_i\tilde{\gamma}\right)^2 \tag{12}$$

4 Results

The reactive and gyrofluid models have been compared with the standard case parameters [21] as reference. These are $\epsilon_n = 0.7,\ \eta_i = \eta_e = 3,\ \tau = 1,\ k^2\rho^2 = 0.1,\ f_t = 0.5,\ \beta_e = 0,\ a = 1m,\ q = 2,\ s = 1,\ a/R = 1/3,\ r/R = 1/6$ and no impurities, collisions, elongation or electromagnetic effects.

A collision scan confirms previous results [11, 2] that the trapped electron pinch flow is reversed when collisions are introduced and the collision frequency increases. Without collisions or with small collision frequencies there is a pinch flow in the standard case. This is reduced when the gyrofluid resonance is added to the reactive model.

Previous results [11] show that the pinch does not vanish for higher collisionality with the gyrofluid resonance but moves to a higher η_e. With the gyroresonance added to the reactive model, this is true when ion and electron temperature scale lengths are kept equal but not if η_i is kept fixed. Small density length scales reverse the pinch flow.

The two models have also been compared for the stationary L-mode JET shot 51034 [7]. This shot is well suited for the study because of the absence of interior particle sources. The parameters are $\epsilon_n = 0.45,\ \eta_i = 2.5,\ \eta_e = 1.9,\ \tau = 2,\ k^2\rho^2 = 0.1,\ f_t = 0.5,\ \beta_e = 0,\ a = 1m,\ q = 2,\ s = 0.67,\ a/R = 1/3,\ r/R = 1/6,\ n_e = 1.2,\ T_e = 3,\ B_{tor} = 2.6,\ b/a = 1.7,$ and an impurity fraction of 0.04.

Since there are no interior sources a stationary state requires that the particle flux vanishes. The particle flux with both models is positive when the experimental data are used ($L_n = 0.7$). For larger length scales a pinch appears. The particle pinch is insensitive to a variation of only L_{T_i}. The peaked density profile in JET 51034, where the reactive model gave good agreement with the experiment [7], could not be supported when collisions were included as in this case. In Ref [7] collisions were omitted which resulted in a small pinch.

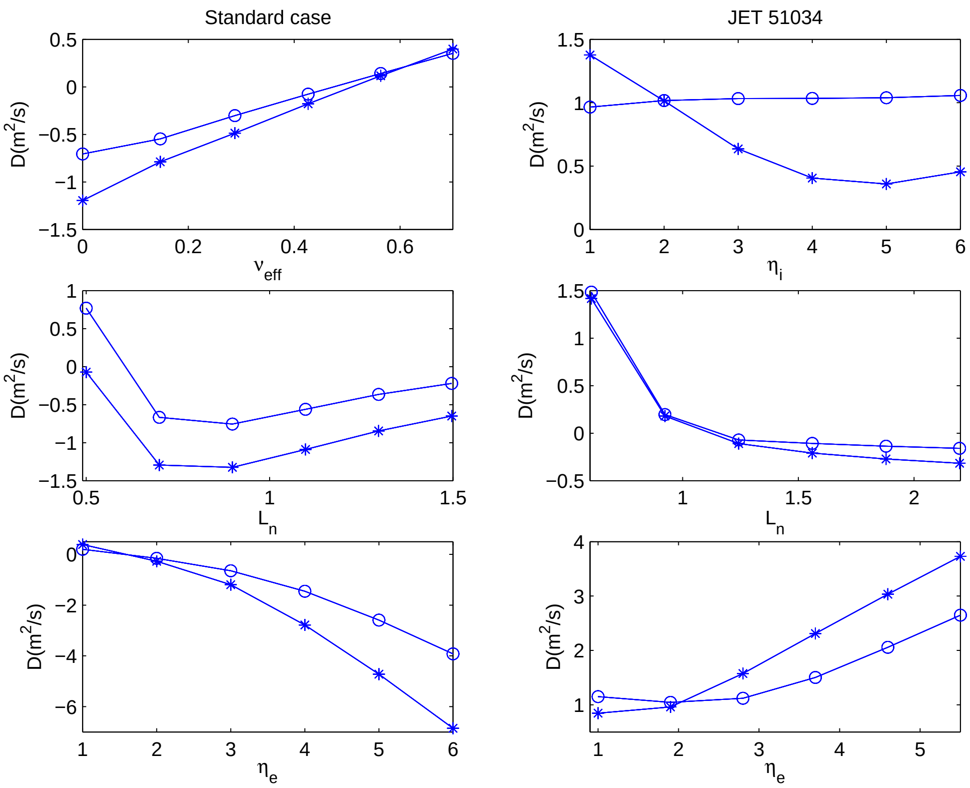

Figure 1: *Particle diffusion coefficients with (circles) and without (stars) the gyrofluid resonance as functions of effective collision frequency (ν_{eff}), density length scale (L_n) and temperature length scale ($\eta_e = L_n/L_{Te}$) for the standard case parameters (left) and for JET 51034 (right); particle pinches are suppressed by the gyrofluid resonance and by collisions.*

The model with the gyrofluid resonance included gives a similar diffusivity at the experimental gradient. The reactive model gave good agreement with the experimental particle transport also in nonstationary cases in L-mode [7].

5 Discussion

The weaker pinch in the gyrofluid case is expected since gyrofluid resonances introduce dissipation in a way similar to collisions that weaken pinches. The dissipation introduced by the gyrofluid resonance indicates irreversible interactions and the absence of it in the reactive model can be seen as a result of a more self-consistent treatment of the energy in the system. A self-consistent treatment would tend to reduce wave-particle resonances. Since a quasilinear kinetic model without the nonlinear relaxation in velocity space includes all fluid resonances in its fixed kinetic resonance we expect even weaker pinches in such a model. This is in agreement with the result of Ref [10] and might mean that nonlinear kinetic codes will have to include self-consistently all nonlinear effects in velocity space and have to be run for a few confinement times in order to obtain strong particle pinches.

A nonlinearity in velocity space gives a self-consistent reversible transfer of free energy, i.e. energy that can be released to drive instabilities, between waves and particles. This freedom will be transferred to the different moments. A pinch occurs due to the reversible transfer of free energy between different fluid moments. This is also closely related to the fact that models which freeze the velocity distribution in order to maintain dissipative kinetic resonances do not conserve energy. Although the total free energy will decrease due to the overall relaxation of the system, the exchange of free energy between different moments corresponds to pinches and is in itself of an energy conserving nature. Thus, it is not surprising that removing the self-consistent transfer of free energy in velocity space has a similar effect on the transfer of free energy between different moments.

6 Conclusions

The presence of a particle pinch in a system of ITG and TE modes depends strongly on the fluid closure in a fluid model, and the pinch is stronger in the more self-consistent reactive model. The aspect of self-consistency can be directly transferred to the inclusion of velocity space nonlinearities in kinetic codes. By comparing the reactive model and a model including the gyrofluid resonance, which is intermediate to the reactive and quasilinear kinetic models, for the standard case parameter set and for JET 51034 we conclude that particle pinches are suppressed by the gyrofluid resonance.

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