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A. Eriksson, L Garzotti, J. Weiland and JET EFDA contributors

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A. Eriksson[1], L Garzotti[2], J. Weiland[1] and JET EFDA contributors*

[1]*Department of Radio and Space Science, Chalmers University of Technology, S-412 96 Göteborg, Sweden.*
[2]*Consorzio RFX, Assocoation EURATOM-ENEA, 35127 Padova, Italy.*
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ABSTRACT.
It has been found that gyro-fluid resonances strongly reduce particle pinches. This has been seen both in a parameter scan and for the JET L-mode Pulse No: 51034 where only a non-dissipative model is able to support the peaked experimental density profile. Extrapolations to quasilinear kinetic models are made.

INTRODUCTION

Evidence for particle pinches in tokamak plasmas has for a long time been seen in L-mode discharges [1]. Although the interpretation of the observed peaked density profiles in H-modes at low collisionality, as resulting from anomalous pinches, is still a matter of controversy, there is no evidence in present theories that particle pinches show different behaviour in L- and H-mode. In a reactor a particle pinch would be welcome for the main ions while an impurity pinch is not desired. Particle pinches were seen in slab models of Ion Temperature Gradient (ITG) modes using dissipation to get nonadiabatic electrons already in the late 1970's [2, 3]. The first toroidal derivation used a reactive fluid model for 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 [4]. Reactive here means that no dissipation is introduced by the choice of closure. In this model the particle pinch is strong when the temperature profile is more peaked than the density profile, even when collisions are included [5]. This situation occurs when the particle source is close to the edge while the heating is strong near the axis (alpha heating), which will be the case for ITER. The impurity ion pinch is weaker than the main ion pinch because pinches are proportional to the magnetic drift frequency which is inversely proportional to the charge [5, 6]. Also electromagnetic effects can contribute to particle pinches [7].

While the reactive model gave a strong particle pinch in situations where the temperature profile is more peaked than the density profile, a corresponding quasilinear kinetic model did not give any particle pinch [8]. A quasilinear kinetic model has also been shown not compatible with experimental density profiles in L-mode [9] while the reactive model is [10]. The two simple 2d systems i Ref:s [4, 8] are particularly well suited for comparison because the treatment of kinetic resonances is the only difference for small Finite Larmor Radius (FLR) and collision frequency. Thus they represent the simpliest possible systems which retains the difference in treatment of kinetic resonances and, at the same time, have 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 [11]. In Ref. [11] it was also found that collisions cannot keep up with nonlinear modifications of the distribution function for typical collisionalities in large, high temperature tokamaks.

Relaxation here means that fluid moments without sources decay to zero on the confinement time scale. This would be due to transport in velocity space. This transport is always directed so as to take particles out of resonance with a wave. Since it is a transport it occurs on the transport timescale and is a secular effect. In a quasilinear kinetic model the dissipation represents the effect of all fluid resonances up to infinite order while it in gyro-fluid models [12] represents only the fluid resonances of moments of higher order than the moment where the gyro-fluid resonance was introduced. A significant difference here is that the fluid resonances allow singularities while the principal part in the quasilinear case is always regular. Since a reactive closure depends on the nonlinear relaxation of moments higher than those included in the model and this relaxation is closely connected to the relaxation in velocity space, a comparison with nonlinear gyro-kinetic results requires that all mechanisms for velocity space relaxation are included in the kinetic code. In the quasilinear model we could also have velocity space relaxation but this would require a complete flattening of the velocity distribution (relaxation of all moments) of the main species which is unlikely due to the rather wide spectrum of drift waves. However, in a gyro-fluid model only the moments higher than that where the gyro-fluid resonance is introduced (represented by the gyrofluid resonance) would need to be relaxed in order to get a reactive model.

Recently, the particle transport in JET discharges have been studied with the nonlinear gyro-kinetic codes GS2 and Gyro [9]. The result was that the particle pinch was too weak to support the steep density profile in Ohmic plasmas. In the codes the relaxation in velocity space is not free since the parallel nonlinearity has been ignored. This means that the nonlinear Landaudamping along the magnetic field has been ignored. Recent results from Particle In Cell (PIC) codes [13, 14] 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 gyro-fluid model [6]. It should be noted that there is also a perpendicular nonlinearity, associated with the magnetic drift resonance, which should be included.

In a reactive model corresponding to the gyro-fluid model without the gyro-fluid resonance, the zonal flow level is about twice as large for the Cyclone base case [15]. This is consistent with the fact that the transport from a reactive model with larger linear growthrate was smaller than that from a gyro-fluid model with smaller linear growthrate [15] when effects of zonal flows are included. Such effects were implicit in the reactive model since it had been normalised to absorbing boundary for long wavelength. The weak particle pinch obtained with GYRO, ignoring the parallel nonlinearity, has also been demonstrated in cases where very small collisional dissipation was sufficient to completely cancel the particle pinch [16].

In the present work we have studied the particle pinch in our reactive model and in a modified version where the toroidal part of the gyrofluid resonance of Ref [12] was added. Using only the toroidal part is not a severe restriction and the original models, discussed above, did not include parallel ion motion [4, 8]. The reactive model with the gyrofluid resonances added actually has the same linear threshold as the gyrokinetic models for the Cyclone base case as pointed out in Ref[6].

This case includes parallel ion motion. We will in the following use the reactive Weiland model [17], in the following referred to as the reactive model. For comparison with gyro-fluid models we will also add gyro-fluid resonances to the reactive model. This is done by adding a term to the closure, which in the reactive model is taken as $\mathbf{q_j} = \mathbf{q_{*j}}$ ($j = i, e$), according to [19]

$$\nabla \cdot q_e = \nabla \cdot q_{*e} + i\frac{3}{2}\; v \tag{1}$$

where

$$\tilde{v} = -\frac{3g(\theta)}{2\tau}\,(1 + \mathrm{i}\sqrt{2}). \tag{2}$$

Here $\mathbf{q}$ is the heat flux, v defines the gyrofluid resonance, $g(\theta) = \cos(\theta) + s\theta\sin(\theta)$, where s is the magnetic shear, $\tau = T_e/T_i$ is the temperature ratio, indexes e = electrons, i = ions, * = diamagnetic and ~ means that a variable is normalised by the magnetic gradient and curvature drift frequency ω_{De}. In the following we also use the notations n = density, e = elementary charge, ϕ = electrostatic potential, $f_t = \sqrt{2\in/(1+\in)}$, where $\in = r/R$, as the fraction of trapped particles, k_x = radial wave number, $\eta = L_n/L_T$ for the density to temperature length scales ratio, $\in_n = 2L_n/R$, $v = v_r + iv_i$, $v_{eff} = v_{ei}/\in$ for the collision frequency and $\omega = \omega_r + i\gamma$ for the wave frequency.

The temperature perturbation can then be written as

$$\frac{\delta T_e}{T_e} = \frac{1}{\omega - \frac{5}{3}\,\omega_{De} - iv}\left(\frac{2}{3}\,\omega\,\frac{\delta n_e}{n_e} + \omega_{*e}(\eta_e - \tfrac{2}{3})\,\frac{e\phi}{T_e}\right) \tag{3}$$

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

$$\frac{\delta n_e}{n_e} = \frac{1}{\epsilon_n}\,\frac{(\tilde{\omega} - i\tilde{v})(1 - \epsilon_n) + \eta_e - \frac{7}{3} + \frac{5}{3}\epsilon_n + \tilde{v}_{eff}\;G_1}{\tilde{\omega}^2 - \frac{10}{3}\tilde{\omega} + \frac{5}{3} - i\tilde{v}(\tilde{\omega} - 1) + \tilde{v}_{eff}H_1}\,\frac{e\phi}{T_e} \tag{4}$$

where

$$G_1 = i\in_n + (i\tilde{\omega} - i\frac{10}{3} + \tilde{\nu})\in_n\Gamma,\; H_1 = i\tilde{\omega} - i\frac{7}{3} + \tilde{\nu}\; and\; \Gamma = 1 + \frac{\eta_e}{\in_n}\,\frac{1}{\tilde{\omega} - 1 + i\tilde{v}_{eff}}$$

The electrostatic diffusion coefficient for the trapped electrons in the reactive model is given as

$$D = -f_t\,\omega_{De}\in_n\tilde{\gamma}^2 / k_x^2\, Im\left(\frac{\delta n_e}{n_e}\Big/\frac{e\phi}{T_e}\right) \tag{5}$$

Without collisions this can be expressed analytically as

$$D = f_t\,\Delta_n\,\frac{\gamma^3/k_x^2}{\omega_{De}^2} \tag{6}$$

$$\Delta_n = \frac{1}{N}(A_n + \eta_e B_n + \epsilon_n C_n) \tag{7}$$

$$A_n = \tilde{\omega}_r^2 + \tilde{\gamma}^2 - \frac{14}{3}\tilde{\omega}_r + \frac{55}{9}\tilde{v}_r^2 + \tilde{v}_i^2 - 2\tilde{v}_r\left(\tilde{\gamma} + \frac{1}{3\tilde{\gamma}}\right) + 2\tilde{v}_i\left(\tilde{\omega}_r - \frac{7}{3}\right) \tag{8}$$

$$B_n = 2\tilde{\omega}_r - \frac{10}{3} - \frac{\tilde{v}_r}{\tilde{\gamma}}(\tilde{\omega}_r - 1) + \tilde{v}_i \tag{9}$$

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

$$\mathrm{N} = \left(\tilde{\omega}_r^2 - \tilde{\gamma}^2 - \frac{10}{3}\tilde{\omega} + \frac{5}{3} + \tilde{v}_r\tilde{\gamma} + \tilde{v}_i(\tilde{\omega}_r - 1)\right)^2 + \left(2\tilde{\gamma}\tilde{\omega}_r - \frac{10}{3}\tilde{\gamma} - \tilde{v}_r(\tilde{\omega}_r - 1)\,\tilde{v}_i\tilde{\gamma}\right)^2 \tag{11}$$

The reactive and gyro-fluid models have been compared first with the Standard case parameters [18] as reference. These are $\in_n = 0.7$, $\eta_i = \eta_e = 3$, $\tau = 1$, $k^2\rho^2 = 0.1$, $f_t = 0.5$, $\beta_e = 0$, a = 1, $q = 2$, $s = 1$, $a/R = 1/3$, $r/R = 1/6$ and no impurities, collisions, elongation or electromagnetic effects.

Collisions were included in the reactive model in Ref [20] and were included in the ITER simulations [5] in order not to overestimate the particle pinch. The collision scan in Figure 1 confirms the previous results [16, 21] that the trapped electron pinch flow is reversed when the collision frequency increases. Without collisions or with small collision frequencies there is a pinch flow in the Standard case [16]. This is reduced when the gyro-Landau fluid resonance is added to the reactive model. Both models give a pinch. Flatter density profiles increases the pinch and smaller density length scales reverses the flow rapidly, especially when the gyro-Landau resonance is added. We note that the sensitivity to collisions is much larger when gyro-fluid resonances are included. Thus, the difference in sensitivity to collisions in the reactive model and GYRO [16] is more due to the kinetic resonance than due to difference in collision models.

Previous results [16] show that the pinch does not vanish for higher collisionality with the gyro-fluid resonance but moves to a higher η_e. With the gyro-resonance 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, Figure 2.

The two models have also been compared for the stationary L-mode JET shot 51034 [10]. This shot is well suited for the study because of the absence of interior particle sources. The parameters are $\in_n = 0.45$, $\eta_i = 2.5$, $\eta_e = 1.9$, $\tau = 2$, $k^2\rho^2 = 0.1$, $f_t = 0.5$, $\beta_e = 0$, $a = 1$, $q = 2$, $s = 0.67$, $a/R = 1/3$, $r/R = 1/6$, $n_e = 1.2$, $T_e = 3$, $B_{tor} = 2.6$, $b/a = 1.7$, 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 in the reactive model is indeed small when the experimental data are used. The gyro-Landau resonance increases the transport to about 2 m^2/s and a flatter density profile is required to recover a stationary state, Figure 3. Increased values of η_i or η_e do not give a significant change in diffusivity. When the gyro-fluid resonance is included a stationary state requires either a combination of shorter ion and electron temperature length scales, Figures 4 and 5, or as seen above larger density length scales.

The results are in agreement with what was expected according to the discussion in the introduction. In particular, the peaked density profile in JET 51034, where the reactive model gave good agreement with the experiment [10], could not be supported when the gyro-Landau resonance was included. This experimental agreement with the reactive model is verified here, the particle flux in Figure 3 is very close to zero at the experimental gradient. Actually the flux is slightly inward if collisions are omitted as they were in Ref [10]. The model with the gyro-fluid resonance gives a diffusivity close to 2 m^2/s at this gradient. The reactive model got good agreement with the experimental particle transport also in nonstationary cases in L-mode[10].

The weaker pinch in the gyro-fluid case is expected since gyro-fluid resonances introduce dissipation in a way similar to collisions which weaken pinches. The dissipation introduced by the gyro-fluid 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. We also know that a self-consistent treatment would tend to reduce waveparticle 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 [9]. 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.

The aspect of self-consistency can be taken one step further due to the close correspondence between velocity space and fluid moments. If we fix velocity space we will also fix fluid moments. On the other hand, if we keep the nonlinearity in velocity space we will have 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 (e.g. from temperature gradient to density gradient). 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. On the other hand we know from experience that we need sources for the moments in order to maintain them. This is true also if we can have pinches.

We have shown that 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 gyro-fluid 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 gyro-fluid resonance. If the strongly peaked density profiles in L-modes can be explained by a system of ITG and TE modes it seems unavoidable to conclude that this requires a situation where a reactive fluid closure is valid.

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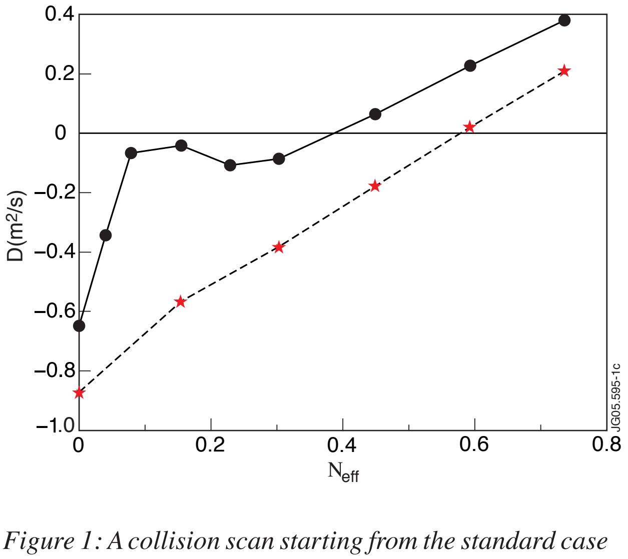

Figure 1: A collision scan starting from the standard case [16] (collisionless) with (circles) and without (stars) the gyrofluid resonance included; the standard case is without collisions. The particle pinch is suppressed by the gyrofluid resonance and by collisions.

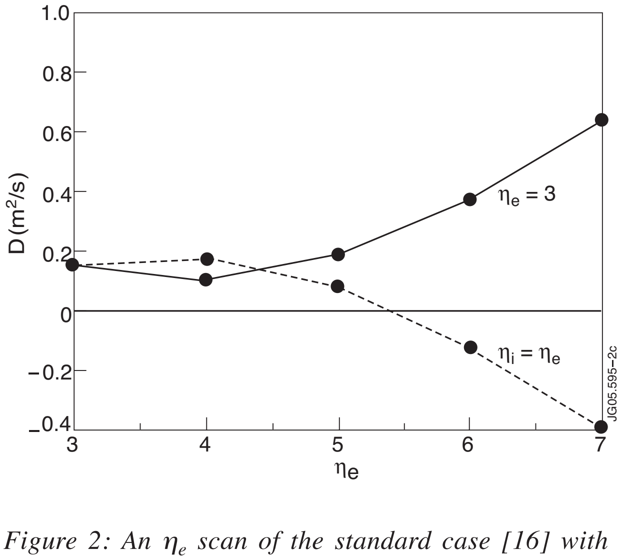

Figure 2: An η_e scan of the standard case [16] with collisions added; the gyrofluid resonance is included. The standard case parameters are $\eta_e = \eta_i = 3$. When £bi is kept fixed to three the pinch does not appear for higher values of η_e, but with an increasing η_i the flux decreases.

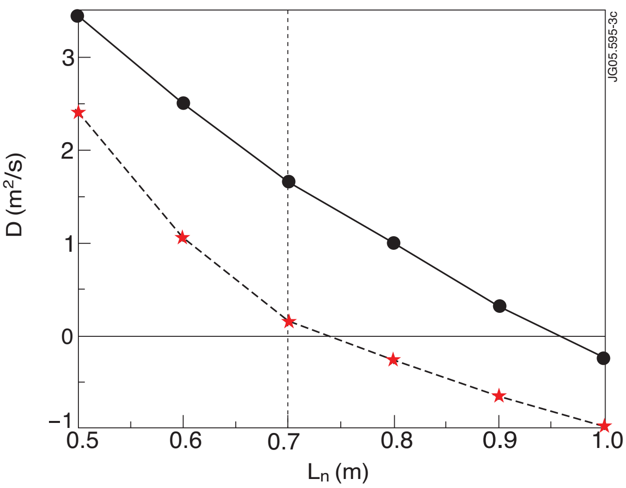

Figure 3: An L_n scan of JET Pulse No: 51034 with collisions, with (circles) and without (stars) the gyrofluid resonance added; the dotted line shows the experimental point. The model with the gyrofluid resonance requires a much flatter density profile to support a stationary state.

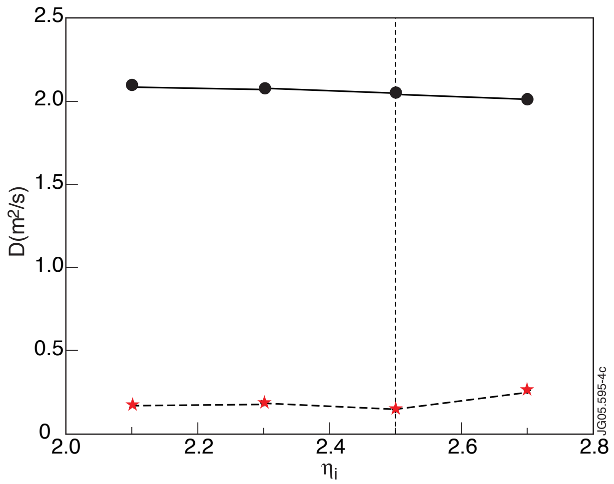

Figure 4: An η_i scan of JET Pulse No: 51034 with collisions and with (circles) and without (stars) the gyrofluid resonance included; the dotted line shows the experimental point.

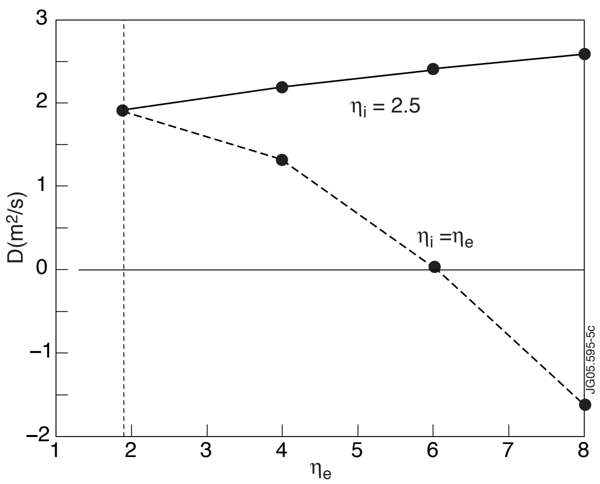

Figure 5: An £be scan of JET Pulse No: 51034 with collisions with the gyrofluid resonance included; the dotted line shows the experimental point. When £bi is kept fixed to the experimental point the pinch does not appear for higher values of η_e, but with an increasing η_i the flux decreases.