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INTRODUCTION

Many aspects of particle transport in tokamaks are not yet clarified. In particular, the existence and nature of an anomalous pinch remain an unresolved issue. From the theory standpoint, two mechanisms leading to an anomalous pinch have been proposed. One is based on turbulent thermodiffusion [1] and predicts a velocity pinch proportional to the gradient of the temperature logarithm $\nabla T_s/T_s$. The second type is often called "Turbulence Equi-Partition" (TEP) [2,3] and predicts a velocity proportional to the curvature of the magnetic field. This problem has been investigated with 3D fluid turbulence simulations of Ion Temperature Gradient (ITG) modes and Trapped Electron Modes (TEM), thus extending previous results obtained with 2D simulations [4]. Both analytical calculations and numerical simulations are used to clarify this issue. The results are compared to a subset of the JET database, corresponding to RF heated plasmas in L-mode. Particle transport in H-mode is presented in a companion paper [5].

1. MECHANISMS FOR TURBULENT PINCH

A set of 5 fluid equations is used here to describe a collisionless ITG/TEM turbulence

$$d_t n_i = i\omega_{dte} (n_{e,eq} \phi - p_e) + S_n \tag{1a}$$

$$d_t p_e = i\omega_{dte} \Gamma (n_{e,eq} \phi - T^2_{e,eq} n_e - 2T_{e,eq} p_e) + S_{pe} \tag{1b}$$

$$\begin{aligned} d_t \Omega \;&= -n_{e,eq} \nabla_{\|} \mathrm{v}_{\| i} - i\omega_{di} (n_{e,eq} \phi - p_i) \\ &\quad - i\omega_{dte} \mathrm{f}_t (n_{e,eq} \phi - p_e) + [p_{i,eq}, \nabla^2_{\perp}\phi] + [n_{e,eq}, \nabla^2_{\perp}\phi] \end{aligned} \tag{1c}$$

$$d_t v_{\| i} = -\nabla_{\|} (\phi - p_i / n_{e,eq}) + S_v \tag{1d}$$

$$\begin{aligned} d_t p_i \;&= - i\omega_{di} \Gamma [p_{i,eq}(1-\mathrm{f}_c T_{i,eq} / T_{e,eq}) \phi - T^2_{i,eq} n_e + 2T_{i,eq} p_i] \\ &\quad - \Gamma p_{i,eq} \nabla_{\|}\mathrm{v}_{\| i} + S_{pi} \end{aligned} \tag{1e}$$

where n_s, T_s, p_s, $v_{\|s}$, f are the normalized density, temperature, pressure, parallel velocity and electric potential (the labels 'e' and 'i' are for electrons and ions). The generalized vorticity W is defined as $\Omega = n_{e,eq} [f_c (\phi-\phi_{eq})/T_{e,eq} -\nabla_{\perp}{}^2\phi]$. The details of the model are described in [6]. The electron precession drift and the ion curvature drift operators are respectively $\omega_{dte} = -i2\varepsilon_a \lambda_t\rho_{s0}\, qr^{-1} \partial_{\varphi}$ and $\omega_{di} =-i2\varepsilon_a \rho_{s0} (\cos(\theta)r^{-1} \partial_{\theta} +\sin(\theta)\partial_r)$. The function $\lambda_t =1/4+2s/3$ characterizes the dependence of the precession frequency on the magnetic shear $s=rdq/qdr$. The other parameters are the fraction of trapped (resp. passing) electrons f_t (resp. $f_c =1-f_t$), the inverse aspect ratio $\varepsilon_a =a/R$ ($\varepsilon_a <1$) and the ion Larmor radius ρ_{s0}. A label 'eq' indicates a flux surface average with normalization to the corresponding reference value. The adiabatic compression index is $\Gamma=5/3$.

When pressure fluctuations are small ($p_e \approx 0$), Eq.(1a) can be recast as $d_t (Hn_e) = 0$, where $H = \exp [\varepsilon_a \int^{\rho} r\, dr(1/2+4s/3)]$. Thus Hn_e behaves as a passive scalar in this case. If the transport due to velocity fluctuations is diffusive, the "natural" density profile is proportional to 1/H, in agreement with the TEP prediction [2-3]. Note that the magnetic shear dependence appears here via the precession frequency of trapped electrons (parameter λ_t). Electron pressure fluctuations are expected to be small when the electron pressure gradient is weak. Hence trapped electrons should behave as "test particles" when the turbulence is mainly driven by ITG modes. A quasi-linear particle flux can be calculated using Eqs(1a) and (1b),

$$\Gamma_e = -f_t D_{ql} \{\partial_\rho n_{e,eq} + 2\varepsilon_a \lambda_t n_{e,eq} - 4\varepsilon_a \lambda_t V_{phe} \partial_\rho p_{e,eq} \tag{2}$$

where

$$D_{ql} = \sum_{k\omega} \frac{k_\theta^2}{\Delta\omega} |\phi_{k\omega}|^2 \ ; \ \ V_{ql} = \left\langle \frac{\omega}{k_\theta} \right\rangle - 2\varepsilon_a \Gamma \lambda_t T_{e,eq} \langle 1 \rangle \ ; \ \langle F \rangle = \frac{1}{D_{ql}} \sum_{k\omega} \frac{k_\theta^4}{\Delta\omega^3} |\phi_{k\omega}|^2 F$$

Here Dwk is a turbulent frequency broadening and $\mathbf{k} = (k_\theta, k_\varphi)$ labels the poloidal and toroidal wave numbers. The "phase velocity" V_{phe} is a shifted poloidal phase velocity ω/k_θ averaged over the turbulence spectrum. The expression (2) indicates that both curvature and thermodiffusion pinches appear in this turbulence model. As expected the TEP result is recovered for zero electron pressure gradient since $dH/Hd\rho = 2\varepsilon_a\lambda_t$. The particle pinch velocity depends on the magnetic shear via the precession drift frequency of trapped electrons. In fact the phase velocity $<\omega/k_\theta>$ cannot be chosen freely in Eq.(2). It is constrained by the ambipolarity condition. A simplified calculation leads to the following expression of the flux

$$\begin{aligned} \Gamma_e = \Gamma_i - f_t D_{ql} \frac{1 + \lambda_t \tau_e}{1 + f_t \lambda_t \tau_e} \Bigg\{ & \partial_\rho n_{e,eq} + 2\varepsilon_a \lambda_t \frac{1 + \tau_e}{1 + \lambda_t \tau_e} n_{e,eq} \\ & + (8\Gamma\varepsilon_a \langle 1 \rangle (\lambda_t T_{e,eq} + T_{i,eq}) - \langle k_\parallel^2 / k_\theta^2 \rangle) \frac{\lambda_t \partial_\rho p_{e,eq}}{1 + \lambda_t \tau_e} \Bigg\} \end{aligned} \tag{3}$$

where $\tau_e = \partial_\rho p_{e,eq} / \partial_\rho p_{i,eq}$ and $k_\parallel$ is the parallel wave number. The structure of Eq.(3) is similar to Eq.(2). In the limit of strong ion heating $\tau_e \rightarrow 0$, the pinch velocity due to curvature is identical to Eq.(2), and the TEP result is recovered. Thermodiffusion induces an inward pinch if the average parallel wave number $k_\parallel$ is large enough. In the opposite limit $\tau_e >> 1$, the curvature pinch velocity is controlled by the ion curvature drift $V = 2\varepsilon_a$. Thus the curvature driven pinch depends at least on the ratio te of the electron to ion pressure gradients. A recent analysis indicates that it also depends on the collisionality [7].

The thermodiffusion flux is directed outward if the electron temperature is large enough. This change of sign is due to a change of direction of the average phase velocity. The latter result depends on the closure assumption in the electron and ion pressure equations (parameter Γ), and on the statistical properties of the turbulence (brackets).

2. NUMERICAL SIMULATIONS

Equations (1(a)-1(e)) have been simulated with the spectral TRB code. Numerical details are given in the reference [6]. In these simulations, the fluxes are fixed rather than the gradients. The particle flux is thus maintained to zero so that any density peaking is an unambiguous signature of a turbulent pinch (the Ware pinch is set to 0). Particle flux and density profiles are shown in Fig.1. The density gradient is finite in the region of zero flux, thus giving a clear evidence of a turbulent pinch. To assess the effect of thermodiffusion, the ratio of ion to electron heating has been changed at constant ion heating source. The density profiles are shown in figure 1 for 3 values of $S_{pe}/S_{pi} = 0.5,1$ and 2. In this set of simulations, the electron pressure profile increases whereas the ion pressure remains mostly unchanged. In the case of dominant ion heating, the profile is more peaked than expected on the basis of a TEP theory alone. This indicates that an inward thermodiffusion pinch takes place as predicted by Eq.(3). The density profile becomes flatter with increasing electron heating. In fact an outward pinch is observed in the edge, consistently with the outward thermodiffusion driven by the electron pressure gradient found in the expression Eq.(3). This outward pinch is only visible in the limit of a large ratio of electron to ion pressure gradient $\tau_e \approx 3$. As already mentioned, the parameters for which this reversal occurs depend on the closure assumption. Therefore the value $\tau_e \approx 3$ is only indicative of the range of parameters for which a thermodiffusion reversal occurs.

3. COMPARISON TO JET RESULTS IN L-MODE.

Experimental evidence for the existence of an anomalous particle pinch has been found in several tokamaks [8, 9, 10]. In JET, evidence has been found in L-mode, performing steady-state analysis of plasmas with dominant ICRH and transient particle transport analysis of density perturbations induced by shallow pellets [11]. Typically, values $D/\chi_e \sim 0.5$ and pinch velocities ~ 1-2 m/s were found, to be compared with a Ware pinch velocity <0.05m/s [10]. Recently, experiments to investigate the parametric dependence of the anomalous particle pinch have been performed at JET. A set of experiments was done in L-mode using Lower Hybrid Current Drive to minimize the loop voltage (and therefore the Ware pinch) combined with Ion Cyclotron heating to decouple the temperature from the q profile. The density peaking factor turns out to be correlated with the internal inductance (fig.2). This is consistent with an inward pinch proportional to the magnetic shear. On the other hand, the same database indicates a weak correlation between the density and temperature peaking factors. Fig.3 shows a hint of density flattening when increasing the electron temperature gradient.

A weak influence of the electron temperature gradient on the density profile was also found in experiments using combined NBI and ICRF in the mode conversion scheme [12]. The electron temperature profile was varied by moving the RF heating location. Figure 4 shows an example where the central electron temperature increases by 50%, whereas ions are slightly cooled. The electron density remains the same in spite of the overall increase of the ratio of gradients $\tau_e = \partial_\rho p_{e,eq} / \partial_\rho p_{i,eq}$. The weak dependence of the pinch velocity on the temperature gradient is not understood, and may result from a trade-off between the various contributions of the temperature gradient in the flux (see Eq.(3)). Also electron and ion temperatures could be in a domain of parameters where the thermodiffusion coefficient reverses its sign.

These results are consistent with previous findings in JET L-modes [11]. Indeed it was found that a mixed Bohm-gyroBohm model with a curvature driven particle pinch works better than a model with thermodiffusion. It is also in line with the observation of a lower particle pinch velocity in Optimized Shear (low magnetic shear) plasmas with pellet injection. As expected, collisionality seems to play some role: the pinch velocity is found to decrease with collisionality.

CONCLUSION.

In conclusion a clear evidence of an anomalous particle pinch has been found when using a fluid model of ITG/TEM turbulence in tokamak plasmas. The pinch velocity due to field curvature agrees with the TEP prediction in the limit of small electron pressure gradient. Thermodiffusion depends sensitively on the ratio of electron to ion temperatures. The corresponding flux is inward for a dominant ion heating and becomes outward when the ratio of electron to ion temperatures is large enough. The latter result depends on the turbulence statistical properties and closure assumptions. An analysis of experiments at JET in L-mode plasmas is consistent with an anomalous pinch proportional to the magnetic shear, but does not bring support for a strong thermodiffusion effect. This finding was confirmed by a series of experiments where the electron temperature profile was changed with ICRF using a mode conversion scheme. The reason why the pinch velocity depends weakly on the temperature gradient is not clear. It may come from the complex dependence of the particle flux on the temperature and its gradient. Also the electron temperature is larger than the ion temperature in these experiments. This may correspond to a range of parameters for which the thermodiffusion coefficient is low.

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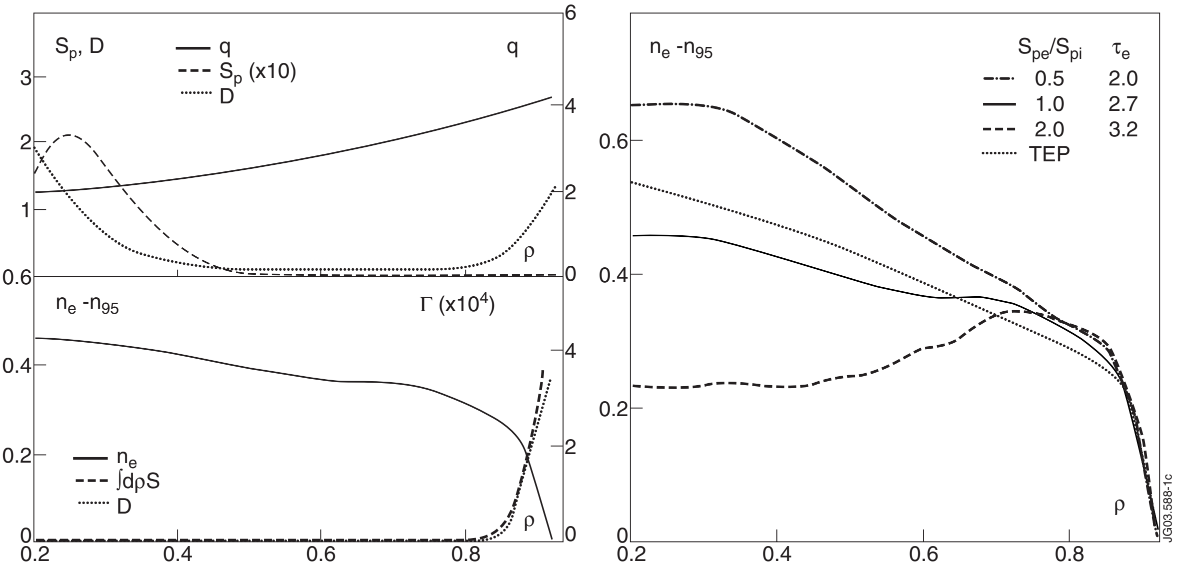

Figure 1: Upper left panel: profiles of safety factor, heat source and collisional diffusion coefficient (top panel). Lower left panel: time average density profiles, sum of diffusive and turbulent fluxes, particle flux calculated from the source. Right panel: density profiles when varying the ratio of electron to ion heating S_{pe} /S_{pi} =0.5,1 and 2. The corresponding values of τ_e at =0.5 are indicated.

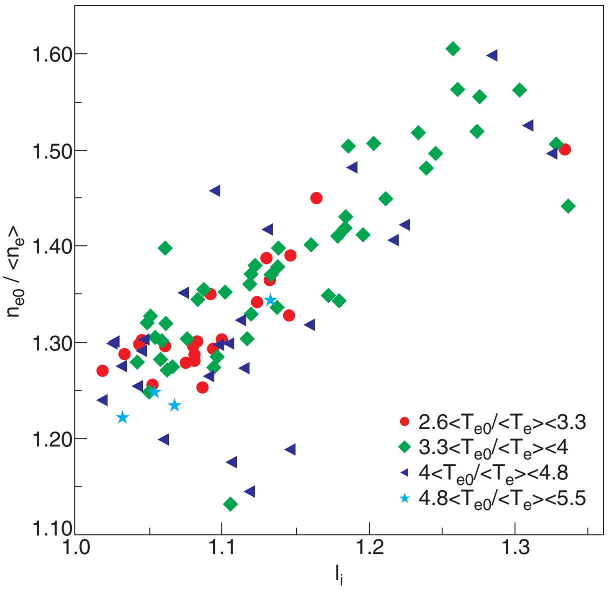

Figure 2.: Density peaking factor versus internal inductance for various ranges of temperature peaking factors.

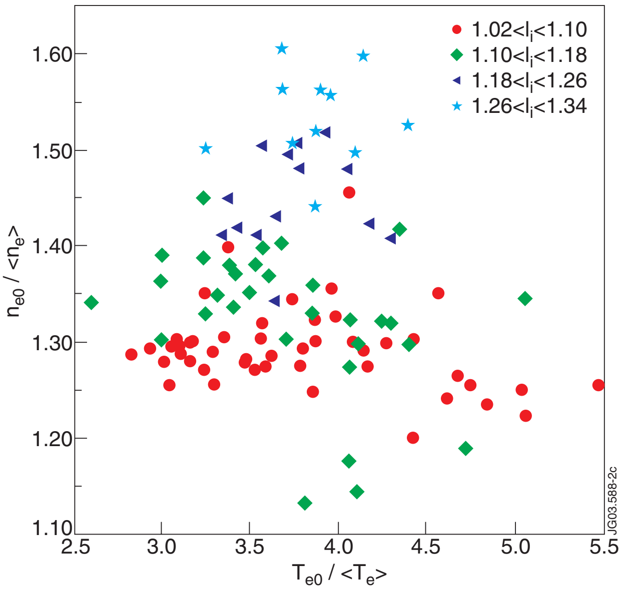

Figure 3.: Density peaking factor versus temperature peaking factor for various ranges of q profiles.

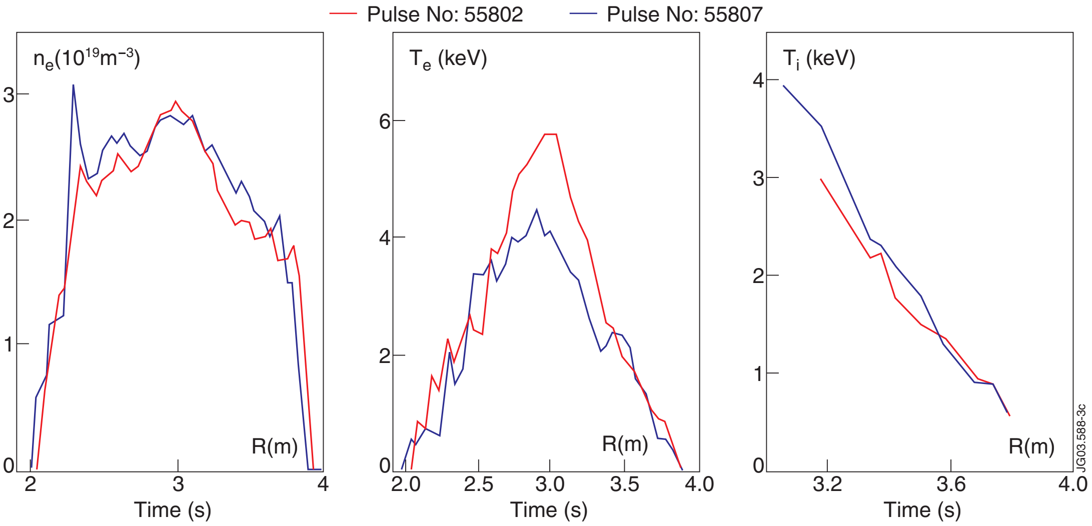

Figure 4: Profiles of density, electron and ion temperature in JET with combined NBI and ICRF heating.