Direction of Impurity Pinch and Auxiliary Heating in Tokamak Plasmas

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A mechanism of particle pinch for trace impurities in tokamak plasmas, arising from the effect of parallel velocity fluctuations in the presence of a turbulent electrostatic potential, is identified analytically by means of a reduced fluid model and verified numerically with a gyrokinetic code for the first time. The direction of such a pinch reverses as a function of the direction of rotation of the turbulence in agreement with the impurity pinch reversal observed in some experiments when moving from dominant auxiliary ion heating to dominant auxiliary electron heating.

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The transport of impurities in the core of a tokamak plasma determines the relative peaking of the impurity density profile with respect to the peaking of the electrons and the main ion plasma components, namely, deuterons and tritons in a fusion reactor. Impurity accumulation has two main drawbacks, the increase of radiation losses, and the effect of plasma dilution with negative consequences on plasma reactivity. Transport of impurities in tokamak plasmas can be measured by experiments in which a small concentration of a high charge impurity is introduced in the plasma by laser ablation and diffusion and pinch velocity are determined by matching the soft x-ray plasma emissivity by assuming a linear relationship between impurity flux and impurity gradient, namely $\Gamma = -D\nabla n + nV$.

In recent experiments, in the high confinement (H) mode, with dominant auxiliary ion heating provided by neutral beam injection (NBI) in ASDEX Upgrade (AUG), the impurity particle pinch is regularly measured directed inwards [1]. On the other hand, in low confinement (L) mode with dominant auxiliary electron heating provided by electron cyclotron resonance heating (ECRH) the impurity pinch is measured directed outwards in the Tokamak à Configuration Variable (TCV) device [2,3]. In the Joint European Torus (JET), experiments of laser ablation have been performed in H mode plasmas in which ion cyclotron radiofrequency heating (ICRH) has been added to NBI heating by two different heating schemes, one in minority heating (MH), delivering the largest amount of radio frequency heating to the ions, and one in mode conversion (MC), heating the electrons. The pinch velocity has been systematically found to change its direction from strongly inwards to slightly outwards depending on whether MH or MC schemes for ICRH where used respectively [4]. These JET results confirm an earlier AUG result [1], in which pinch velocities directed outwards in H mode plasmas were observed in the presence of ECRH well localized on axis.

This set of recent experimental observations indicate that, moving from conditions of largely dominant ion heating to conditions of dominant electron heating, the pinch of an impurity reverses its direction from inwards to outwards. Such a reversal of the direction of the pinch cannot be explained by the neoclassical theory, because generally the measured pinch is much larger than the theoretical one [2–4] and, in any case, even in conditions of largely dominant electron heating the neoclassical pinch remains directed inwards [2,3]. In all these conditions also the impurity diffusivity is measured well above the neoclassical predictions. The reason for such a reversal in the direction of the impurity pinch has to reside in the effects of the so-called anomalous transport, namely, transport produced by a turbulent state of the plasma arising from microinstabilities occurring on time scales which are neglected by the standard collisional theory.

The concentration of laser ablated impurities is small enough that the impurity contribution in the quasineutrality condition becomes practically negligible. In such a limit, the impurity behaves as a trace, or test-particle; namely, its presence does not affect the turbulent state. On the other hand, the background turbulence can transport the trace impurity by several mechanisms.

In this Letter we study such mechanisms and show that the turbulent transport of a trace impurity can produce particle pinch velocities which can be directed inwards or outwards depending on the plasma conditions. To this purpose, we profit by a widely benchmarked code solving the gyrokinetic equation, GS2 [5], which can be applied to an arbitrary number of particle species. The gyrokinetic equation is solved in its linearized form and transport is computed by a quasilinear model [6] which has been recently found to reproduce satisfactorily fully nonlinear simulations. To shed light on the physical mechanisms involved, besides the numerical calculations, we consider a simple fluid model, whose solutions can be derived analytically.

Since a trace can be neglected in the quasineutrality condition, the dispersion relation is independent of the plasma parameters of the trace, and the particle flux Γ_p of a trace impurity becomes linear in the impurity density gradient; namely, it can be expressed in the form

$$R\Gamma_p/n_p = D_p R/L_{np} + RV_p, \tag{1}$$

where the diffusion coefficient D_p and the pinch velocity V_p do not depend on the density gradient of the trace ($R/L_{np} = -R dn_p/dr/n_p$ is the dimensionless logarithmic density gradient, where R is the major radius of the tokamak plasma), but depend on the parameters of the background plasma. Such a linear relationship is demonstrated analytically with the simplified fluid model, and it is found numerically with the gyrokinetic code, as shown in the insert in Fig. 1. In the gyrokinetic calculations the impurity trace has been added as a third species whose charge concentration $n_p Z_p/n_e$ is 1/1000. By such a linear relationship between flux and gradient, a diffusion coefficient and a pinch velocity can be identified unambiguously. Such a procedure provides a rather general method to compute a diffusion coefficient and a pinch velocity from the results of a gyrokinetic code. A deuterium trace in a plasma of deuterons and electrons is found to undergo the same transport as the bulk deuterium.

We consider a plasma composed by two main particle species, electrons and deuterons, and consider separately plasma inhomogeneities which provide sources of free energy for the destabilization of microinstabilities like the ion temperature gradient (ITG) and the trapped electron mode (TEM). The following three cases are considered, the ion logarithmic temperature gradient drive $R/L_{Ti} = 9$, $R/L_{Te} = 0$, $R/L_n = 0$, the electron logarithmic temperature gradient drive $R/L_{Ti} = 0$, $R/L_{Te} = 9$, $R/L_n = 0$, and the logarithmic density gradient drive $R/L_{Ti} = 0$, $R/L_{Te} = 0$, $R/L_n = 6$. All particle species are assumed to have the same temperatures (other parameters are safety factor $q = 1.4$, magnetic shear $s = 0.8$, local aspect ratio $\epsilon = 0.16$). The first two cases represent extreme examples of conditions of largely dominant ion heating, in which ITG is the most unstable mode by microinstability analysis, and largely dominant electron heating, in which TEM is the dominant miscroinstability. The behaviors of D_p and RV_p as a function of the charge of the trace impurity Z_p are illustrated in Fig. 1. Here the mass of the trace impurity A_p is taken proportional to the charge $A_p = 2Z_p$ and the trace impurity has a flat temperature profile (effects of the impurity temperature profile will be discussed later). Even in the limit of very large charge the trace impurity transport does not vanish, since at least the charge independent $E \times B$ transport remains. Moreover, in the case of large electron temperature gradient drive, the impurity pinch is directed outwards, while it is directed inwards in the other two cases. This indicates as well that $E \times B$ is not the only mechanism transporting the trace impurity in the limit of large Z_p. To shed light on the physical mechanisms at play, we consider a simple linearized fluid model composed by a continuity equation, a parallel force balance equation, and an energy balance equation for the trace impurity, e.g., following Ref. [7]. By taking density, parallel velocity, and temperature perturbations proportional to $\exp(-i\omega t + i\mathbf{k}\cdot\mathbf{x})$, the simple fluid model reads

$$-\hat{\omega}\hat{n}_p + (\hat{n}_p + \hat{T}_p)/Z_p - (R/2L_{np} - 1)T_e\hat{\phi}/T_p + \hat{k}_\parallel \hat{v}_{\parallel p} = 0, \quad (2)$$

$$-\hat{\omega}A_p\hat{v}_{\parallel p}/A_i + \hat{k}_\parallel Z_p T_e \hat{\phi}/T_p + \hat{k}_\parallel(\hat{n}_p + \hat{T}_p) = 0, \quad (3)$$

$$(-\hat{\omega} + 5/3Z_p)\hat{T}_p + 2\hat{\omega}\hat{n}_p/3 - (R/2L_{Tp} - R/3L_{np})T_e\hat{\phi}/T_p = 0. \quad (4)$$

In these equations normalizations have been chosen in order to single out dependences on charge and mass. In particular, $\hat{\omega} = \omega/\omega_{Di}$ and $\hat{k}_\parallel = k_\parallel v_i/\omega_{Di}$, where $\omega_{Di} = 2(k_y\rho_i)v_i/R$ is the fluid curvature and ∇B drift frequency, $\rho_i = v_i/\Omega_i$ and $v_i^2 = T_i/m_i$, with Ω_i the ion cyclotron frequency of the main ion species. The perturbed density δn_p, temperature δT_p, and parallel velocity $\delta v_{\parallel p}$ are normalized in the form $\hat{n}_p = \delta n_p/n_p$, $\hat{T}_p = \delta T_p/T_p$, and $\hat{v}_{\parallel p} = \delta v_{\parallel p}/v_i$, where n_p and T_p are the equilibrium density and temperature of the trace impurity species, while the normalized fluctuating electrostatic potential is defined, as usual, $\hat{\phi} = e\phi/T_e$ (note that the system is assumed in the absence of an equilibrium parallel velocity).

The system of Eqs. (2)–(4) is obtained by keeping only the lowest order in $k_y\rho_i$, and by assuming in the fluid closure the ion heat flux equal to the ion diamagnetic heat flow, neglecting parallel heat flows. The system of Eqs. (2)–(4) describes density, parallel velocity, and temperature fluctuations of a trace impurity with charge Z_p, mass A_p, in the presence of a background microinstability with a complex mode frequency ω and a fluctuating potential ϕ. In Eq. (2), the second term arises from the

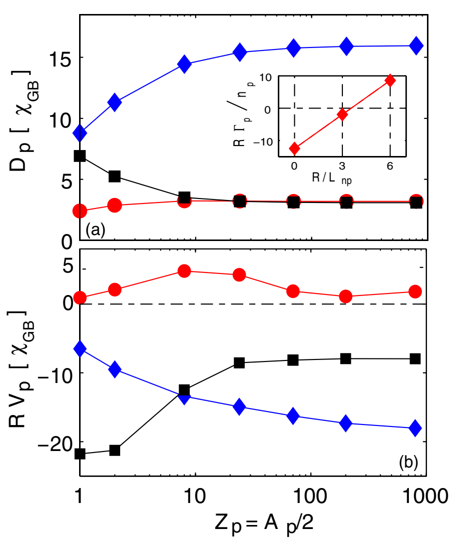

FIG. 1 (color online). Diffusion coefficient D_p and pinch RV_p for a trace impurity as a function of the charge number, in the case of R/L_{Ti} drive (squares), R/L_{Te} drive (circles) and R/L_n drive (diamonds). In the inset, example of linear relationship between the quasilinear particle flux and the density gradient of a trace impurity, as computed by the code GS2, used to determine D_p and V_p for the case $Z_p = 8$, $R/L_{Ti} = 9$.

curvature and ∇B drifts, the third term stems from the $E \times B$ advection and compression, while the last term from the compression in the parallel velocity. In Eq. (3), inertia is balanced by the parallel electric force and the parallel pressure gradient. The system is considered electrostatic. Finally in Eq. (4), the cancellation of terms proportional to the diamagnetic drift has been already made by subtracting the continuity equation.

For such a model, the quasilinear particle transport of the trace impurity can be computed analytically by $\Gamma_p = \langle \delta n_p \delta v_{E\times B}\rangle$. Two limits are considered. The first is obtained by neglecting parallel velocity fluctuations. This decouples the continuity and energy balance equations from the parallel force balance. The impurity particle flux is provided by Eq. (1), where

$$D_p = \frac{\gamma}{k_x^2}\frac{\hat{\gamma}^2}{|\hat{N}|^2}\left(|\hat{\omega}|^2 - \frac{14}{3Z_p}\hat{\omega}_r + \frac{55}{9Z_p^2}\right), \tag{5}$$

$$RV_p = D_p[C_{Tp}R/L_{Tp} - 2(1 + 2C_{Tp}/3)], \tag{6}$$

$$D_p C_{Tp} = \frac{\gamma}{k_x^2}\frac{\hat{\gamma}^2}{|\hat{N}|^2}\frac{2}{Z_p}\left(\hat{\omega}_r - \frac{5}{3Z_p}\right), \tag{7}$$

$$\hat{N} = \hat{\omega}^2 - 10\hat{\omega}/(3Z_p) + 5/(3Z_p^2). \tag{8}$$

We observe that both the diagonal diffusion and pinch term contain terms arising from the $E \times B$ advection and compression, respectively, which are charge independent, as well as terms which decrease with increasing charge which are ascribed to the coupling between density and temperature fluctuations arising from the curvature and ∇B drifts. In particular among these, a term in the pinch proportional to the impurity temperature gradient is obtained. This is the equivalent of the thermodiffusive contribution to the pinch in electron particle transport [8,9]. Similarly, it changes sign depending on the direction of the phase velocity of the background turbulence, but for a trace impurity is directed outwards for microinstabilities rotating in the ion diamagnetic direction and inwards for instabilities rotating in the electron diamagnetic direction, namely, in the opposite direction with respect to the electrons, as also found in recent fluid turbulence simulations [10]. The effect of the thermodiffusion can be identified also in the results of the gyrokinetic code GS2. In Fig. 2 we show the difference between the pinch velocity as computed in the presence of a finite impurity temperature gradient ($R/L_{Tp} = 9$) and the pinch velocities computed in the presence of zero impurity temperature gradient and already shown in Fig. 1(b). Such a difference in the pinch velocity between the two sets of cases is due to the effect of finite R/L_{Tp}, and consistently with the simple fluid model, the thermodiffusive term in the gyrokinetic calculations is directed inwards for modes rotating in the electron direction, namely, the R/L_{Te} and R/L_n drives, and directed outwards for modes rotating in the ion direction, the R/L_{Ti} drive. The thermodiffusive contribution to the particle flux vanishes with increasing

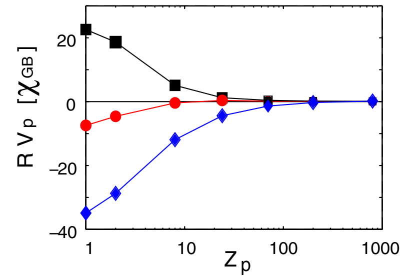

FIG. 2 (color online). Thermodiffusive part of the particle pinch as a function of the charge of a trace impurity (symbol codes like in Fig. 1).

Z_p as predicted by the simple fluid model and consistently is found to not modify the diffusion coefficient D_p computed with the gyrokinetic code. Finally we observe that thermodiffusion, although it can change direction depending on the direction of rotation of the instability, provides impurity particle fluxes in opposite directions with respect to the experimental observations, for which, in the presence of dominant ion heating, namely, in conditions of turbulence propagating in the ion diamagnetic direction, impurity pinches are measured directed inwards.

The second case considered in the simple fluid model is the limit of negligible temperature fluctuations. The system reduces to the coupling between continuity and parallel force balance, which is actually the only coupling remaining in the limit of large Z_p. In this case the particle flux of the trace impurity is still linear in the density gradient of the impurity and provided by Eq. (1), where this time

$$D_p = \frac{\gamma}{k_x^2}\frac{\hat{\gamma}^2}{|\hat{N}|^2}(|\hat{\omega}|^2 + \hat{k}_\parallel^2 A_i/A_p), \tag{9}$$

$$RV_p = -\frac{\gamma}{k_x^2}\frac{\hat{\gamma}^2}{|\hat{N}|^2}(2|\hat{\omega}|^2 + 4\hat{\omega}_r\hat{k}_\parallel^2 Z_p A_i/A_p), \tag{10}$$

$$\hat{N} = \hat{\omega}^2 - \hat{\omega}/Z_p - \hat{k}_\parallel^2(A_i/A_p). \tag{11}$$

Analogously to the previous case, in the expression of the diffusion coefficient D_p and the pinch V_p the first terms are due, respectively, to the $E \times B$ advection and compression. The second term of the diffusion coefficient comes from the parallel density gradient, and vanishes with increasing impurity inertia. On the other hand, the second term in the pinch arises from the parallel electric force and remains finite increasing the impurity inertia as long as the charge of the impurity increases correspondingly. Such a pinch mechanism is pointed out here for the first time. In the presence of a background fluctuating electrostatic potential, parallel velocity fluctuations are produced by the parallel electric force. These cause density fluctuations by parallel compression. Differently from the basic mechanism of a drift wave, density fluctuations of a trace impurity taking place in the presence of a background instability are found to be out of phase with respect to the background electrostatic potential and lead to radial transport. The

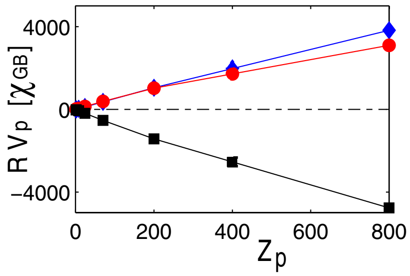

FIG. 3 (color online). Particle pinch of a trace impurity as a function of the charge number with fixed impurity mass (symbol codes like in Fig. 1).

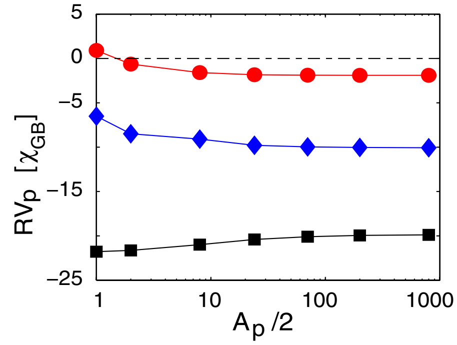

FIG. 4 (color online). Pinch as a function of the impurity mass in the case of fixed impurity charge (symbol codes like in Fig. 1).

pinch is directed inwards for instabilities rotating in the ion drift direction, and outwards for instabilities rotating in the electron drift direction. In the ideal situation in which the inertia of the impurity remains constant, and the charge is increased, this term becomes the dominant term in the expression of the particle flux, and diverges linearly as a function of the charge. This behavior is found as well by the gyrokinetic code, as shown in Fig. 3. In these calculations the impurity mass has been kept fixed $A_p = 1$ and the impurity charge Z_p increased. In these conditions the gyrokinetic particle flux is completely dominated by the pinch term as predicted by the simple fluid model, the pinch being directed inwards for instabilities rotating in the ion diamagnetic direction, namely, the R/L_{Ti} drive, and outwards for instabilities rotating in the electron diamagnetic direction, namely, the R/L_{Te} and R/L_n drives. Differently from thermodiffusion, such a pinch remains finite with increasing both impurity charge and mass, and the reversal of its direction agrees with the reversal of the pinch measured in the experiments when moving from conditions of dominant ion heating to conditions of dominant electron heating. The effect of such a pinch on the impurity trace transport can be removed by considering the ideal limit in which the impurity charge is kept fixed $Z_p = 1$ and the impurity inertia increases, while the Larmor radius term $k_\perp v_\perp/\Omega$ of the impurity is kept at the deuterium value (e.g., see Eq. (2) in Ref. [5]). Then the limit of very large A_p corresponds to the limit of negligible parallel velocity fluctuations. Differently from the results shown in Fig. 1(b), in this case all the particle pinches are found directed inwards, as shown in Fig. 4.

Finally, if the safety factor is increased in the gyrokinetic calculations, such a pinch mechanism is reduced and eventually disappears; namely, in the presence of strong electron temperature gradients the total particle pinch also is found directed inwards. This can be understood as a consequence of the reduction of $k_\parallel \approx 1/qR$, as shown by the simple fluid model in Eq. (10). This theoretically predicted dependence asks for validation (or invalidation) in future experiments and has already found agreement with observations in TCV [3]. More in general, while the present theoretical results are found in qualitative agreement with the above mentioned set of recent experimental observations [1–4], it is unclear the extent to which they can be considered in agreement with a large set of previous results on impurity transport (e.g., Refs. [11–13]). Analyses specific to the actual experimental conditions are certainly required for a more complete validation, possibly including nonlinear simulations and quantitative comparisons.

In conclusion, the pinch of an impurity trace arises from the combination of a large set of physics mechanisms. The final direction of the total pinch is determined by the relative magnitude of each contribution. The pinch mechanism arising from parallel velocity fluctuations, whose relevance is pointed out here for the first time, is large enough to reverse the sign from inwards to outwards in conditions of strong logarithmic electron temperature gradients, and this in qualitative agreement with a set of recent experimental results, indicating impurity pinches directed outwards in conditions of dominant electron heating, and inwards in conditions of dominant ion heating.

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