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The shapes of the density profiles of electron, hydrogen isotopes and impurities in the core of tokamak plasmas have important consequences on both the overall plasma stability as well as on the plasma performance. The theoretical understanding of the experimentally observed transport behaviours of electrons and impurities is therefore an important and active field of research in physics of tokamak plasmas. In many conditions, it is observed that particle and impurity transport is produced by non-collisional (anomalous) effects. In this paper we assume that the same instabilities that are thought to be responsible for anomalous core heat losses, are also responsible for anomalous particle transport. We investigate the particle and impurity transport produced by ion temperature gradient (ITG) and trapped electron modes (TEM), considering realistic values of plasma parameters obtained in large tokamak experiments like the Axial Symmetric Divertor Experiment (ASDEX) - Upgrade (AUG) and the Joint European Torus (JET). Transport modelling of anomalous heat transport is often described by means of theoretical models based on quasi-linear (QL) fluid theory. These models compute the transport produced by the most unstable linear modes. While this simplified description can be considered adequate to some extent to describe the heat transport, we show here that this can be largely inadequate to describe particle transport. As it is shown in Fig.1, there are conditions for which the direction of the particle transport, determined by the sign of the phase shift between density and electrostatic potential fluctuations, is found to depend on the magnitude of the poloidal wave number. QL approaches must be based on values of the poloidal wave number which are close to those where the non-linear (NL) transport is maximum to obtain the particle flux in the same direction (inward or outward) as it is obtained in NL simulations. Here we propose a QL model, in which this is achieved by identifying in the linear spectrum the maximum of the ratio $\gamma/\langle k^2_\perp \rangle$, rather than just the maximum of γ as a function of the poloidal wave number [1]. The value of $\langle k^2_\perp \rangle$ is computed by $\langle k^2_\perp \rangle = k^2_y\ (1 + s^2\langle \theta^2 \rangle)$, where $\langle \theta^2 \rangle$ is the average of the squared poloidal angle along the mode structure $\langle \theta^2 \rangle = (\int \theta^2 |\Phi^2| d\theta) = (\int |\Phi^2| d\theta)$. The heat and particle fluxes are then computed by considering the phase shift of temperature or density and electrostatic potential fluctuations at the value of the poloidal wave number for which $= \gamma/\langle k^2_\perp \rangle$ is maximum. This QL model has been successfully compared with simulation results obtained with NL gyrokinetic codes like GENE [1] and GYRO [2]. This QL model is applied to get particle and heat fluxes with the linear gyrokinetic code GS2 [3], considering as input plasma parameters obtained in experiments at AUG and JET. Three main investigations have been undertaken: the first is the existence of anomalous particle pinches and predicted peaked density profiles at realistic collisionality conditions, the second is the relationship between impurity density peaking, and electron density peaking and the direction of the impurity particle fluxes with respect to the electron particle flux. Finally, the third subject is the dependence of the ratio V/D of a trace impurity as a function of plasma parameters. The first subject is motivated by the observed dependence of density peaking on the collisionality in AUG and JET H-mode plasmas [4, 5]. This phenomenon has been explained in the framework of transport modelling with the transport model GLF23 [6] by the effect of collisions on the anomalous pinch. Even though the collisional model of GLF23 provides a good description of the behaviour of the linear growth rate as a function of collisionality [6], the dependence of the particle flux differs significantly from the predictions of the gyrokinetic codes, which involve a Lorentz collision operator. The comparison is presented in Fig.2, where the results of the GYRO code has been taken from Ref. [2]. Given the fact that gyrokinetic codes predict the disappearance of the anomalous particle pinch for values of collisionalities which are much lower than those predicted by GLF23, we have used code GS2 and the above described QL model, to compute the dependence of particle fluxes for electrons, deuterium and carbon for a set of AUG and JET discharges as a function of both the deuterium and the carbon density gradients. The input data for these cases have been selected over a set of the best diagnosed discharges in both the AUG and JET databases [4, 5], covering the range of variation of different plasma parameters, in particular collisionality. In all the cases, we have never found conditions for which the electron particle flux is directed inwards for positive values of the logarithmic electron density gradient. The same conclusion is obtained for normal collisional conditions of OH plasmas in AUG. If the source can be considered negligible, at least in the absence of any form of central fuelling, like for OH plasmas, the working point for the density profiles is determined by the condition $\Gamma = 0$. With measured collisionalities, and measured logarithmic temperature gradients which are found to be above the ITG and TEM linear thresholds, we have not found any experimental set of plasma parameters for which the condition $\Gamma = 0$ is fulfilled in the presence of finite positive values of the logarithmic electron density gradient. This implies that in the framework of the present local description of particle transport in terms of a gyrokinetic model including a Lorentz collision operator, the peaking of density profiles in usual collisional OH tokamak plasmas is not predicted, neither understood. The same conclusion can be drawn by comparing the levels of particle fluxes given by the source and those provided by ITG/TEM instabilities in the case of NBI heated plasmas. Fig.3 shows the results of these calculations for the JET Pulse No: 58894, for which an evaluation of the particle source level is presented in Ref. [7]. The particle flux provided by the source at $r/a = 0.5$ has been evaluated among $\Gamma/n = 0.07 - 0.2$m/s. Considering 0.2m/s as the maximal value, we find that to obtain the experimentally measured logarithmic electron density gradient, which is around $R/L_n = 3$, the source should have been larger by at least a factor 20, or, in other words, with such a source level, the logarithmic density gradient predicted by our model is practically zero, at profile, in disagreement with the experimental observations (the Ware pinch in these conditions is computed to be well below 0.1m/s, and can be neglected).

The other topics we have investigated are related to the transport of an impurity species. This has been done in both the limits of very small charge concentration ($n_Z Z/n_e << 1$), which implies that the contribution of the third species is negligible in the quasi-neutrality condition, namely the third species behaves as a trace (test particle), as well as in the case of non-negligible impurity concentrations, in which case the impurity provides non-negligible additional terms in the dispersion relation. First we present results related to the latter problem. We have performed a double scan on the logarithmic density gradients of both deuterium and carbon in the collisionless limit, in order to find the working point at which particle fluxes of all the particle species cross zero. The results are presented in Fig.4. We find that in the collisionless limit, with $n_C * Z_C/n_e = 0.2$, $R/LT_i = R{=}LT_e = 9$ and Te = Ti (= 0.16, q / 1.4, s = 0.8), the curves of zero electron, deuterium and carbon particle flux intersect in the plane R/L_{nD}, R/L_{nC} for finite values of the logarithmic density gradients of all the species, and specifically for $R/L_{nD} = 4.1$, $R/L_{ne} = 3.6$ and $R/L_{nC} = 1.5$. It is found that in a collisionless plasma, carbon density profile is naturally peaked, but this peaking is smaller than the peaking of the electrons. The direction of the anomalous pinch for the impurity has been investigated in the limit of $R/L_{nD} = R/L_{nC} = 0$, as a function of the logarithmic temperature gradients. It has been found that, like for the electron particle flux, when the rotation the mode dominating the transport is in the electron diamagnetic direction, the carbon flux is directed outwards, whereas when the mode rotates in the ion diamagnetic direction, the carbon flux is directed inward, like the electron particle flux. In the case of calculations with realistic collisionalities, we find that the particle flux of the carbon still crosses zero for finite values of the carbon logarithmic gradient. However, as mentioned before, this is not the case for the electron particle flux with respect to the electron logarithmic gradient. This makes that in collisional runs the working point is predicted to have peaked carbon profiles and flat electron density profiles, in disagreement with the experiments, in which relatively electron density profiles are measured more peaked than the carbon density density profiles [5].

Finally, linear gyrokinetic calculations with the GS2 code have been performed to study the transport of small impuritiy concentration injected by laser ablation in AUG or JET plasmas. The calculations are electrostatic, and include the effects of collisions on all the species. The parameters of the main species have been taken as average values measured in a series of JET plasmas Pulse No: 58141 to Pulse No: 58144 and Pulse No: 58149, at $\rho_\Phi = 0.35$ [8]. These parameters are: r/R = 0.17, shear = 0.3, q = 2.67, $\alpha_{MHD} = 0.5$, $R/L_{Te} = 5$, $R/L_{Ti} = 7$, $T_e/T_i = 0.88$, $T_e = 5$keV, $n_e = 2.5\ 10^{19}$, B = 3.3T. Around this base case, the couples of parameters $[R/L_n, R/L_{Te}]$, $[R/L_n, T_e/T_i]$, $[R/L_n, R/LT_i]$ and $[R/L_n, T_i/T_e]$ have been scanned over intervals which largely cover the experimental variations measured in the different discharges. QL diffusion and pinch velocity for the impurity (nickel) are computed by including for each set of input parameters a third species of nickel ions, in extremely low concetration in order to be negligible in the quasi-neutrality condition. The ion temperature and ion temperature gradient of the nickel are the same as those for the Deuterium, whereas the value of R/L_nN_i (logarithmic density gradient of the nickel) is varied over the three values 0, 3, and 6 for each set of input parameters of the main species. The particle flux of the nickel is found to be a linear function of R/L_nN_i, consistently with the fact that the nickel is a trace in this plasma (Fig.5). From the linear relationship between nickel flux and nickel logarithmic density gradient, the nickel diffusion coefficient and pinch can be identified unambiguously. These, as well as their ratio, are then computed for the full set of input parameters described above. The dependence of D_{Ni} and RV_{Ni}/D_{Ni} of the nickel trace obtained in the scan on $[R/L_n, T_e/T_i]$ is shown in Fig.6. The diffusion D_{Ni} of the nickel are plotted in gyroBohm units. For these JET plasmas at $\rho_\Phi = 0.35$, the nickel has $\chi_{GB} = 0.036\text{m}^2/\text{s}$. It is found that the ratio V_{Ni}/D_{Ni} decreases by increasing both the electron R/L_n as well as the electron temperature. Up to moderately peaked density profiles ($R/L_n = 4$), the impurities are pushed outwards with increasing R/L_{Te} (Fig.7). On the contrary at density profiles and small logarithmic ion temperature gradients (R/$L_n \leq 2$ and R/$L_{Ti} \leq 5$) lead to strong impurity accumulation (RV_{Ni}/D_{Ni} much larger than R/L_n of the main species). This decreases by increasing R/L_{Ti} (Fig.7). On the contrary, for peaked density profiles (R/$L_n > 3$), an increase of R/L_{Ti} leads to an increase of the impurity peaking, and the same does an increase of the ion temperature.

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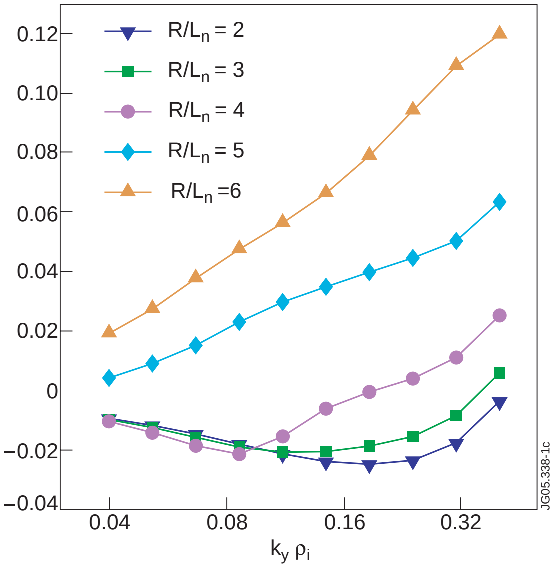


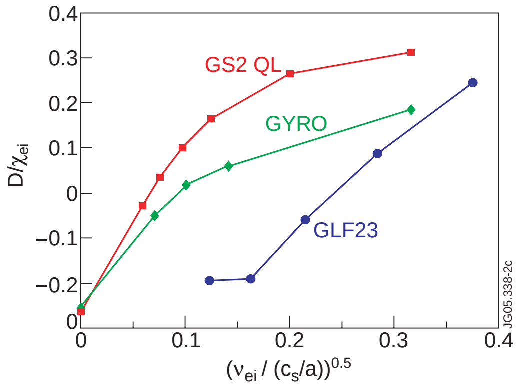
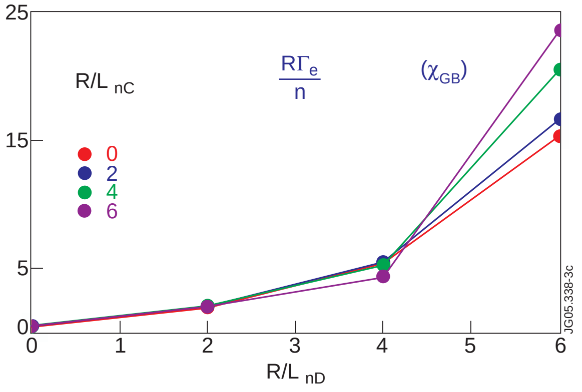


Figure 1: (←) Phase shift between density and electrostatic potential fluctuatons vs the poloidal wave number, for different values of R/L_n.

Figure2: (↑) D/χ as a function of collisionality, computed with the gyrokinetic NL GYRO code and published in [2] (green), the linear version of the GS2 code [3] and the QL model described here (red), and finally the QL gyrofluid model GLF23 [6] (blue).



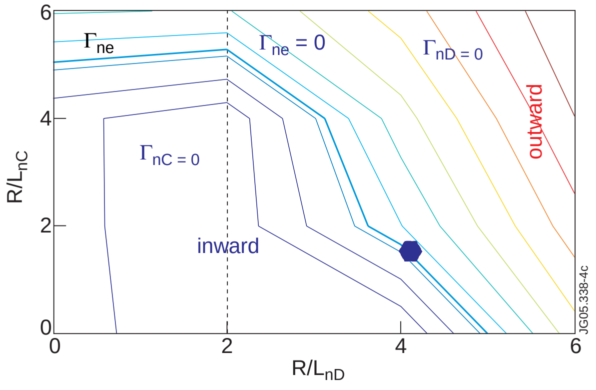


Figure 3: Electron particle flux for different values of R/L_n of both deuterium (and electrons) and carbon (JET Pulse No: 58894 at $r/a = 0.5$, GB = $3.0m^2/s$). In these gyroBohm units , the source level is estimated below or equal to 0.2.

Figure 4: Contour lines of the electron particle flux as a function of R/L_{nD} and R/L_{nC} for a collisionless run. Curves of zero Deuterium and Carbon particle fluxes are also plotted.

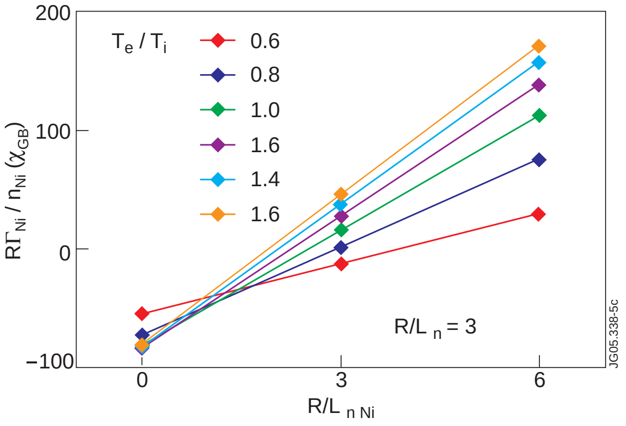


Figure 5: (↑) Trace Nickel particle flux depends linearly on the nickel logarithmic density gradient, $R/L_n = 3$, different values of T_e/T_i.

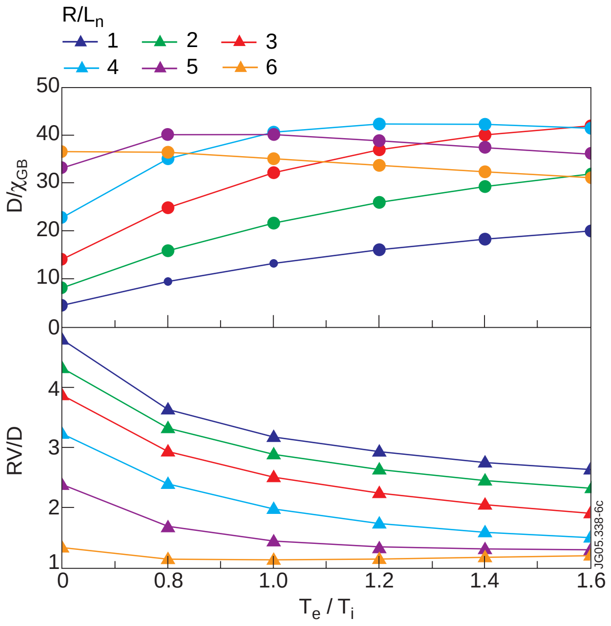


Figure 6: (→) D_{Ni} and RV_{Ni}/D_{Ni} as a function of T_e/T_i, different values of R/L_n [$\chi_{GB} = 0.036m^2/s$].

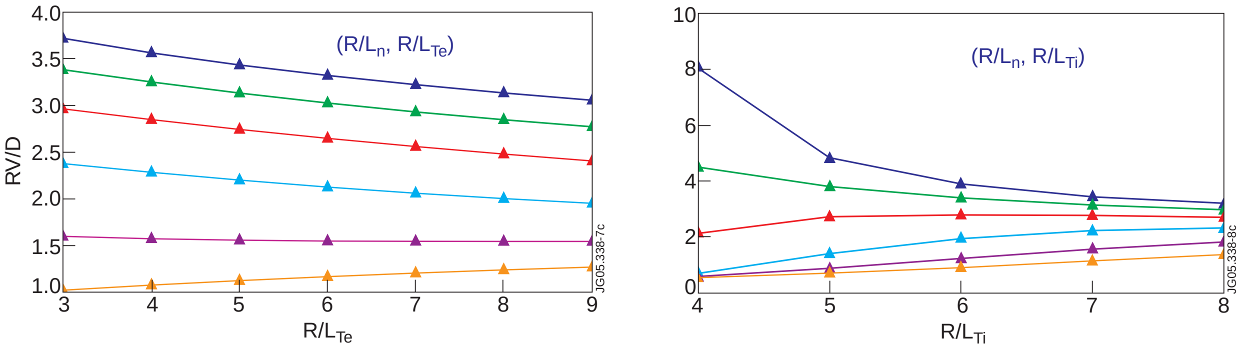


Figure 7: RV_{Ni}/D_{Ni} as a function of R/L_{Te} and R/L_{Ti}, for different values of R/L_n.