INFLUENCE OF FROZEN-IN LAW VIOLATION EFFECTS ON TURBULENT EQUIPARTITION IN TOKAMAKS

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During recent years the possibility has been discussed that turbulent transport may drive a plasma towards a state of **turbulent equipartition (TEP)**. It can be regarded as an attractor with a uniform distribution of Lagrangian invariants respected by the turbulent perturbations in the medium; notably, a tokamak plasma.

Assuming low-frequency electrostatic perturbations, one can show that for a tokamak plasma with the first two invariants preserved simple continuity arguments show that there exists for trapped particles a Lagrangian invariant $nq \sim const.$ [1], or $n\oint \frac{dl}{B} \sim const.$, or more complex dependencies. When mixing occurs, this invariant becomes uniformly distributed, and we get $n \sim 1/q(r)$. Such pinched density profiles are experimentally observed in TEXT and in TFTR supershots. Pinched density profiles have also appeared in numerical experiments on the motion of banana orbit centers in a tokamak model field with turbulent electrostatic fields [2].

In more general cases the results can be modified; e. g., by

- passing electrons
- collisions
- electron inertia
- baroclinic effects
- strong turbulence

Some of these modifications are discussed, to explain some experimental data. Recently [3] it was suggested that in DIII-D flatter distributions than $1/q$ could be explained by passing electrons. If inertia is neglected, then the constancy of the longitudinal adiabatic invariant J_p will topologically prohibit turbulent mixing of these electrons.

We analysed the possible causes of topology violation, and found that if electron inertia is taken into account, mixing of passing electrons may take place with conservation of J_p. This is because the curl $\boldsymbol{\Omega}$ of the electron canonical momentum $\boldsymbol{P}_e = m\boldsymbol{V} - e\boldsymbol{A}/c$ is exactly frozen in the electron motion, whereas $\boldsymbol{B}$ is not.

For passing electrons the Poincaré integral adiabatic invariant on the $\boldsymbol{\Omega}$ field lines are mainly determined by the helicity $\boldsymbol{AB}$. The radial dependence of this quantity is rather flat, especially in the central part of the tokamak. To illustrate this, we consider the Poincaré integral over approximately a magnetic field line: $J_0 \equiv \oint \frac{\overline{P_e}\,\overline{\Omega}}{\Omega} dl$. For trapped particles the mechanical part is adiabatically preserved: $J_p = \oint \frac{m\overline{V}\,\overline{\Omega}}{\Omega} dl \approx 4R_0(qR/R_0)\int_0^{\theta_1} m\overline{V_p}\,d\theta$ (where θ_1 is the poloidal angle of the mirror point). For passing electrons, on the other hand, the momentum is completely dominated by its magnetic part, due to the large enclosed flux, and we get: $J_0 = \oint \frac{\overline{P_e}\,\overline{B}}{B} dl = -\frac{e}{c}\oint \frac{\overline{A}\,\overline{B}}{B} dl$.

We have also found that in a strong, turbulent electrostatic field the electron orbits are subject to a breakup, which makes them ”forget” the B_θ - profile, and their mixing dynamics is similar to the 2D case. This gives $n \sim B_\phi$, which is quite flat [4]. Some turbulence is needed to provide pinched profiles of n and T, but a further increase of the turbulence level leads to the disappearance of the pinch.

We have simulated numerically the turbulent motion of plasma electrons with approximately DIII-D parameters. When testing the influence of the turbulent field, it has been enhanced to correspond to 10 times the thermal energy; this is to produce significant results within a reasonable computer time. Fig. 1 shows the simulated density profile of 1000 moving electrons, and for comparison, normalized to the same area, the pinched profile $1/q(r)$ with $q(a) = 4$. Obviously the numerical profile is quite flat. The oscillations near $r = 0$ are probably due to insufficient statistics there, while the slight decrease outwards is felt to be a result of a sink introduced numerically at $r = 2a$. The temperatures become very flat in this case. $T_\perp$ remains close to its initial value, while T_p increases by a factor of 3.

Fig. 2 shows numerical solutions for moderate level of turbulence. When the longitudinal energy dominates over the perpendicular one, almost all particles are passing, and the density pinching is small. In the opposite case, all particles are trapped, and the $1/q$ - profile is expected. Thus, the combined profile of both passing and trapped particles depends on the variable fraction of trapped particles. Fig. 2 shows the solution for an intermediate case when the space-averaged energies are equal, as they are in a global thermodynamic equilibrium. The best power fit of the form $1/q(r)^\beta$ to the density profile in this case gives $\beta \approx 0.53$, which is in good agreement with the experimental scaling [3] $\beta \approx 0.6$.

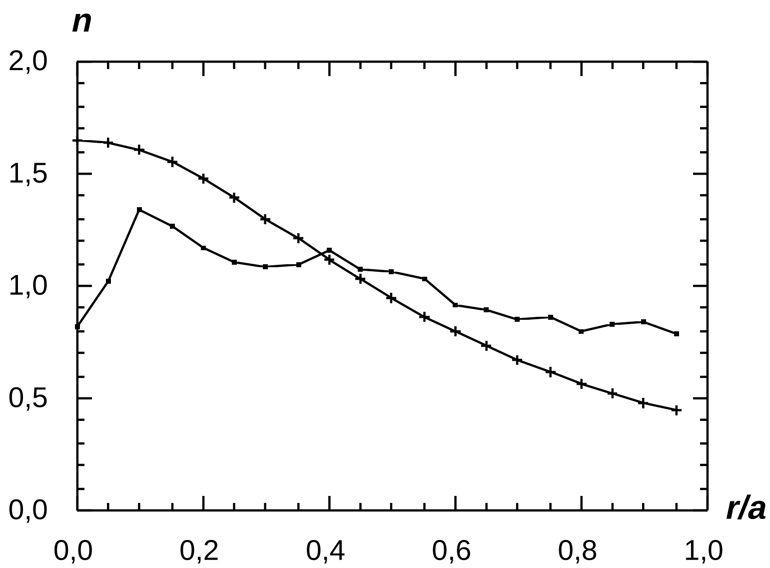

Fig. 1. Normalized density profile (point markers) of the electrons versus normalized radius for strong turbulence. The curve with ”+” signs represents the variation of $1/q$, normalized to the same area under the curve.

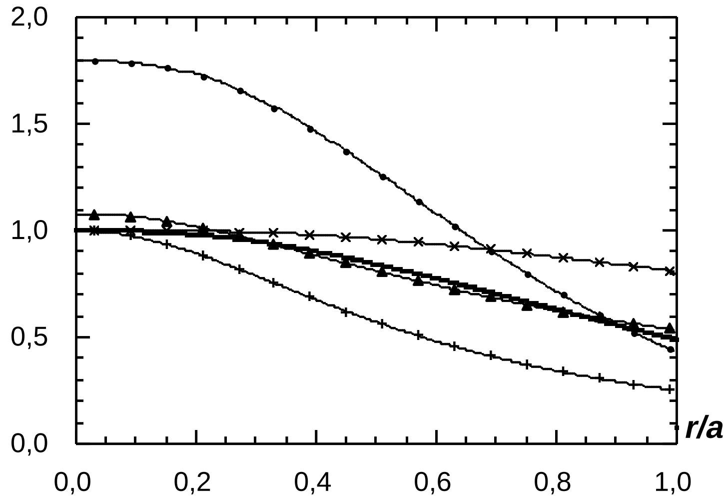

Fig. 2. Density and temperature profiles in the case of moderate turbulent mix of both passing and trapped electrons, versus normalized radius. The curve with ”+” signs is the $1/q$ - profile, and that with ”x” markers is the helicity profile (AB). The solid curve without markers is the density profile in the case of global thermodynamic equilibrium(GTE). The curve with triangle signs is the profile of $1.08/q(r)^{0.53}$, which is the best power fit to the density profile (solid curve). The curve with point markers is the profile of longitudinal temperature in the case of GTE.

References

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