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Turbulent transport of impurities in 3D devices

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Impurity transport has been a very active area of research in plasma physics due to the concern that high core impurity concentration represents to the performance of future fusion reactors. In stellarators, where neoclassical transport is larger than in tokamaks, the theoretical and numerical impurity transport problem has been practically limited to the framework of neoclassical theory. In general, the sign of the neoclassical radial electric field, negative (ion root) or positive (electron root) correlates well with long and short, respectively, impurity confinement time. However, the neoclassical formalism has recently undergone an intense revision and included ingredients traditionally neglected, see e.g. [1-4]. These extended formulations and numerical approaches have shown important corrections to the standard neoclassical theory but have not yet fully explained some experimental observations that, to a great extent, motivated them. These are well-known stellarator plasma scenarios with weak or no impurity accumulation, like the impurity hole LHD plasma and the W7-AS High-density-H (HDH) mode discharges, that the standard neoclassical theory does unsuccessfully predict. In addition, recent experiments in W7-X have appended to this set of (somewhat exceptional) scenarios other plasma conditions where neoclassical predictions, and particularly the diffusive part of the radial impurity flux, fall far below what the experimental analyses show [5].

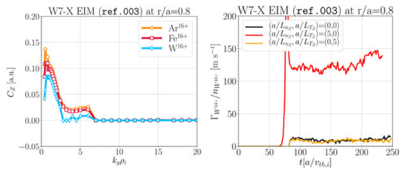

Figure 1: (Left) Curvature pinch C_Z for different trace impurities in W7-X standard configuration at r/a=0.8 (here $C_Z > 0$ contribute to inward positive flux). The gradients of the bulk ions (H+) and electrons ($a/L_{T_i} = a/L_{T_e} = 6.0$ and $a/L_{n_e} = a/L_{n_i} = 1.0$) are such that the dominant instabilities are ITG-driven up to $k_{yi} < 8$ and ETG-driven for $k_{yi} > 8$. (Right) Nonlinear calculation of radial particle flux of W^{44+} with different onset/offset of density and temperature normalized gradients (note that the positive flux level at $\{a/L_{T_Z}, a/L_{n_Z}\} = \{0, 0\}$ implies, contrarily to what quasilinear estimates predict, curvature anti-pinch).

On the other hand, impurity transport calculations in the frame of gyrokinetic theory remain practically unexplored in stellarators. Quasilinear attempts carried out with the gyrokinetic code GS2 [6] can be found among the few examples reported in the literature. Very exceptionally the problem has been addressed with nonlinear multispecies simulations like those performed with GKV and reported in ref. [7]. The amount of numerical studies of impurity turbulent transport remains still anecdotal compared to the equivalent tokamak literature. Apart from these few numerical examples, a recent analytical work [8] has investigated, based on a quasilinear treatment too, some basic properties of the impurity transport produced by background instabilities driven by the bulk-species gradients.

The present work aims at bridging the gap between the analytical quasilinear treatment and nonlinear simulations, performing both nonlinear and quasilinear calculations of impurity transport. The simulations are performed with the flux-tube version of the gyrokinetic stellarator code stella [9]. The motivation comes, on the one hand, from the fact that the analytical treatment does not account for some basic ingredients like the specific structure of the background unstable modes or the magnetic configuration. On the other hand, and more importantly, it is unclear to what extent the conclusions based on quasilinear analyses hold nonlinearly and, consequently, whether it is justified to bring their conclusions to the field of experiments. For an example of discrepancy between quasilinear and nonlinear simulations see Fig. 1, where the sign of the radial particle flux of W44+ at vanishing tungsten density and temperature gradients lead the sign of the so-called curvature pinch Cz to have different sign in the quasilinear calculation (left) with respect to the nonlinear estimation (right). Simulations will be presented for several devices, including W7-X, LHD, HSX and TJ-II.

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