Neoclassical stellarator impurity flux driven by electrostatic potential variations on magnetic surfaces

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Although there exist encouraging exceptions [1, 2], the accumulation of highly charged impurities in the plasma core of stellarators is consistently observed [3], leading not only to fuel dilution but also to unacceptable energy losses by radiation. Since heavy metals like tungsten are the preferred materials for the plasma-facing components of magnetic confinement fusion devices, impurity accumulation becomes an obstacle in the path towards stellarator reactors. This is why impurity transport is one of the most active research areas in the stellarator community.

Let us denote by Ze the electric charge of the impurity species, where e is the proton charge. The standard argument to explain the accumulation of impurities with $Z \gg 1$ relies on the, in principle, large inward pinch in the neoclassical radial impurity flux Γ_z caused by the typically negative stellarator radial electric field E_r. This argument was proven to be flawed, at least in some important cases, by Helander *et al.* [4]. In this reference it was shown that if the main ions have low collisionality and the impurities are collisional, then Γ_z does not depend on E_r. This result was interpreted in a positive way because it diminished the prevalence of E_r in Γ_z and made "temperature screening" (that is, the reduction or absence of impurity accumulation thanks to the contribution of the temperature gradient to Γ_z) more likely than previously thought.

In [4], the effect on Γ_z of the component of the electrostatic potential that is non-constant on magnetic surfaces, φ_1, was not included. In the last few years, however, it has been established that φ_1 can affect radial impurity transport [5]. In this contribution, that summarizes the work [6], we take the maximal ordering $Ze|\varphi_1|/T = O(1)$ (here, T is the temperature of the main ions and the temperature of the impurities, that are assumed to be equal) and give an analytical calculation of Γ_z for low collisionality main ions and collisional impurities, incorporating the effect of φ_1. We show that this effect can be very strong for $Z \gg 1$ and that, once it is taken into account, the dependence of Γ_z on E_r reappears. In addition, we prove that such an effect is stellarator specific: when $\varphi_1 \equiv 0$, Γ_z does not depend on E_r either in a tokamak or in a stellarator; when $\varphi_1 \neq 0$, Γ_z is still independent of E_r in a tokamak but not in a stellarator. A careful analysis of the final expression for Γ_z in stellarators (that reduces to the expression derived in [4] when $\varphi_1 \equiv 0$) reveals that the impact of φ_1 on Γ_z is non-negligible for $Ze|\varphi_1|/T = O(\epsilon^2)$, where ϵ is the inverse aspect ratio. Finally, we provide realistic examples in which the inclusion of φ_1 leads to impurity expulsion.

References

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