Impurity Transport in Tokamaks: Progress and Open Challenges

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Our understanding of impurity transport has shown remarkable progress in the last decade. Low and high-Z impurity transport is often investigated separately because although the same principles govern both, different transport mechanisms dominate. Gyrokinetics modeling quantitatively explains the experimentally observed density gradients of low-Z impurities over most of the parameter space, except for strongly ITG-dominated plasmas where the observed gradients are below the model predictions, i.e., experimental profiles are often hollow, while models predict flat profiles. Further, a non-monotonic dependence of impurity diffusion on mode frequency ω_r, with a maximum close to $\omega_r \sim 0$ as predicted by nonlinear gyrokinetics models, was experimentally confirmed. The dependence of the light impurity transport on the electron-to-ion heat flux ratio was demonstrated, showing the importance of off-diagonal flux components.

The accuracy of the high-Z impurity modeling was dramatically improved by realizing the importance of sonic rotation effects and introducing them in the neoclassical drift-kinetic code NEO. The poloidal asymmetry of heavy ions in fast-rotating plasmas can increase the collisional transport by an order of magnitude, high enough to often dominate over turbulent flux in the inner core. Improved understanding of the temperature screening dependence on rotation in the banana regime led directly to developing a low-collisionality, fast-rotating hybrid scenario on JET, which efficiently screened W in the peripheral region of the plasma and prevented detrimental on-axis accumulation. Other methods for avoidance of impurity accumulation were developed as well. The most common is the wave heating, where particularly ECRH can very efficiently suppress the W accumulation by enhancing turbulent transport. But also, modifying the rotation profile with counter-current NBI or enhancing the poloidal electric field via the temperature asymmetry of ICRH and NBI fast ions can significantly alter the neoclassical pinch of high-Z impurities.

Integrated modeling for ITER indicates a weak role of core neoclassical transport, particularly due to a low rotation, low collisionality, and negligible particle source from neutral beams. The modeling indicates a possibility of a significant temperature screening in the pedestal, exceeding the inward neoclassical pinch, which dominates current experiments. Dominant pedestal Ti-screening leads to a quantitatively different behavior compared to existing experiments. ELMs will not flush impurities out, they will allow W penetration in the plasma. Also, degradation of pedestal confinement will lead to W influx and should be avoided. Therefore, the ELM-free scenarios should be preferred to take advantage of pedestal temperature screening.

Despite the significant advancement in the field of impurity transport, there are still remaining open issues. Likely the most important issue for ITER is the reliable prediction of the pedestal top impurity density in no-ELM and small ELM regimes. Such a prediction is particularly challenging because it requires detailed knowledge of the edge impurity source, SOL, divertor transport, and transport in the pedestal with mitigated ELMs. Both modeling and experimental measurement in these regions is demanding. The other remaining challenges are, for instance, RMP-induced transport, MHD-driven transport, or the effect of pedestal poloidal asymmetries on impurity flux.

Topical area: Impurity transport

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