On the occurrence of regimes of suppressed anomalous impurity transport in W7-X and implications for stellarator reactors

Thilo Romba[1], Felix Reimold[1], Sebastian Bannmann[1], Oliver Ford[1], Peter Zsolt Poloskei[1], Marco Zanini[1], and the W7-X team*

[1] Max Planck Institute for Plasma Physics, 17491 Greifswald, Germany
* See O. Grulke et al 2024 Nucl. Fusion 64 112002

In view of feasible reactor operation regimes, the transport of impurities must be governed by a trade-off between low impurity confinement of helium ash and small inward transport of edge-sourced impurities. Therefore, identifying, understanding, and predicting reactor scenarios of compatible impurity transport is crucial on the path to self-sustained fusion burn.

The Wendelstein 7-X (W7-X) stellarator was optimized for low neoclassical transport in the $1/\nu$-regime, which led to transport of energy [1], particles [2], and impurities [3, 4] being governed by anomalous processes under standard operating conditions. In high-performance scenarios with tokamak-like confinement, anomalous transport is reduced [5], with impurity transport governed by neoclassical processes [6, 7]. The neoclassical convection is inward-directed and causes the impurity density profiles to strongly peak. Consistent with neoclassical predictions, the peaking strength scales linearly with impurity charge. The transition into the neoclassically dominated regime is found to be governed by a critical a/L_{n_e} of unity. The threshold value is present across several magnetic configurations and experimental scenarios, causing impurity accumulation to appear across a significant range of the W7-X parameter space.

In W7-X high-performance plasmas, high triple products and centrally peaked impurity profiles have always coincided. We show that the inward impurity transport present is incompatible with sufficient helium ash removal in a reactor scenario. This stresses the importance of tailoring impurity transport in a stellarator-type reactor, where possible routes to success have already been identified in core electron root confinement regimes [8] or active density control schemes that allow for steering the level of anomalous impurity transport utilizing external actuators.

[1] Wappl et al. PPCF submitted
[2] Bannmann et al 2024 Nucl. Fusion 64 106015
[3] Geiger et al 2019 Nucl. Fusion 59 046009
[4] Romba et al 2023 Plasma Phys. Control. Fusion 65 075011
[5] Bannmann et al Phys. Review Letters, in preparation
[6] Romba et al 2023 Nucl. Fusion 63 076023
[7] Romba et al 2025 Plasma Phys. Control. Fusion, accepted
[8] Beidler et al 2024 Nucl. Fusion 64 126030