9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Neutral recycling studies with advanced tooling

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The transport of recycling atoms in magnetic confinement plays a key role in plasma-wall interaction, fueling, and diagnostics. Performant and user-friendly tools are demanded to predict their behavior. This is becoming increasingly important as neutrals are relied upon to protect the wall from intense heat fluxes, and neutral diagnostics are relied upon for plasma control. These effects are most important in the edge, where the spatial profile of plasma properties is strongly varying, including both the high-confinement pedestal and the scrape-off layer. Recently, the OpenMC framework has been adapted for atomic physics [1], and this work represents the first physics study using this new capability. OpenMC has been benchmarked against DEGAS2 with respect to accuracy and performance with the inclusion of ionization and charge exchange reactions. Figure 1 shows the accuracy and performance comparison for a simplified box geometry, whereas Figure 2 shows that of a realistic unstructured mesh. In the simplified case, OpenMC outperforms DEGAS2 significantly, whereas in the unstructured mesh, it is modestly slower.

We examine neutral fueling in the pedestal from first principles, paying particular attention to the impact of neutral opacity. The potential for recycling-driven positive-feedback effects on a variety of pedestal shapes are also considered, as is the possibility of scrape-off layer broadening from charge-exchange interaction with ions.

A reduced model for X-point fueling has been developed [2]. This is derived from first principles kinetic theory under the assumption of a linear source of neutrals circumscribing the X-point and a given loss rate for ionization. Generalizations include a spatially-varying loss rate, a model for charge exchange interaction, and planar source geometry. This sub-exponential neutral penetration model agrees well with rigorous kinetic simulations and provides a physically transparent means of interpreting core fueling. The sensitivity of both the model and simulations to the spatial and velocity distribution of the source is highlighted.

These studies showcase the usefulness of this new application of OpenMC, which brings with it advanced capabilities over the existing legacy tools for neutral particle simulation.

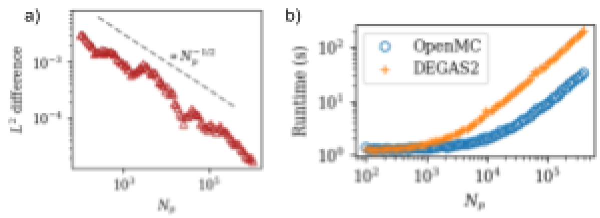

Figure 1. Accuracy (a) and performance (b) benchmark between DEGAS2 and OpenMC for a simplified 1D domain with ionizaiton and charge exchange.

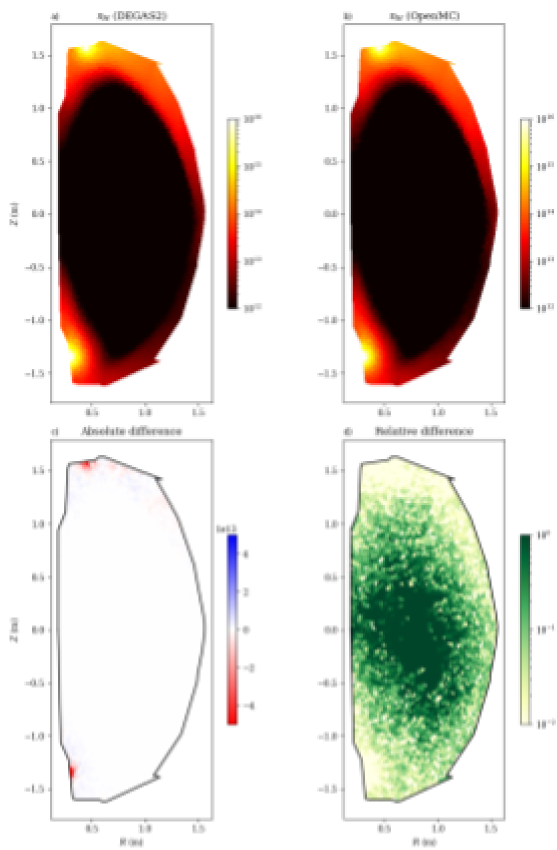

Figure 2. Comparison of full-mesh benchmark between DEGAS2 (a) and AtOMC (b) with absolute and relative difference - (c) and (d) respectively. For this case, OpenMC performance was about 30% slower than DEGAS2.

References:
[1] Wilkie, Romano, Chuchill. "Demonstration of OpenMC as a framework for atomic transport and plasma interaction." *Plasma Physics and Controlled Fusion* 67:055046 (2025) https://doi.org/10.1088/1361-6587/adcc4e
[2] Wilkie. "Analytic model for neutral penetration and plasma fueling". Under review in *Journal of Plasma Physics* (2025) http://arxiv.org/abs/2506.10906