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Real-time boron injection for plasma-facing component conditioning, tungsten source control, and implications for ITER

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New integrated modeling of boron (B) powder injection for real-time wall conditioning in the DIII-D tokamak and Laser-Induced Breakdown Spectroscopy (LIBS) measurements reveal a relatively uniform toroidal boron distribution on the divertor but a non-uniform poloidal coverage on the wall. This work presents the first validated comparison between modeling and experiment using a full-torus, multi-physics workflow applied to impurity powder injection, resolving erosion, redeposition, and mixed-material dynamics across PFCs. Simulations predict boron-rich coatings exceeding 30% concentration, with growth rates of ~0.9 nm/s during injection via the impurity powder dropper (IPD) at rates of 5–20 mg/s. These B layers dynamically evolve on graphite plasma-facing components (PFCs) via plasma recycling and redeposition processes and can be actively controlled in real time by adjusting injection parameters. The DIII-D simulations covered injection rates of 1–10 mg/s (corresponding to 10^{20}–10^{21} B/s) in a representative L-mode scenario. An integrated workflow combining EMC3-EIRENE (full-torus plasma background, fluid impurity transport), the Dust Injection Simulator (DIS) for macroscopic B particle ablation, and WallDYN3D for dynamic mixed-material surfaces consistently reproduces the broad coverage of plasma-facing components [1].

These results inform strategies for in-situ wall conditioning in long-pulse devices, support solid boron injector development for ITER Q=10 operations [2], and inform impurity control strategies for high-Z wall environments. At lower injection rates (~10^{20} B/s), B surface concentrations stabilize around 35%, forming B-C mixed material surfaces with boron area densities ranging from 0.3–1.4×10^{16} atoms/cm². In contrast, higher injection rates (~10^{21} B/s) significantly enrich the divertor surfaces with boron, forming near-pure boron layers with area densities between 1.8–3.6×10^{16} atoms/cm². Consistent with these simulations, LIBS measurements of the 249.7 nm B-I line experimentally confirmed that the highest boron concentrations occur on the lower divertor. An additional peak at the outer midplane, outside the modeled divertor domain, indicates broader transport extending into the main chamber.. Experiments focused on fuel retention in B-rich layers revealed that the formation of stable B–C–D bonds with desorption temperatures around 1000 K can lead to increased deuterium retention compared to boron films with minimal carbon contamination [3]. These findings underscore the need to reduce carbon impurity influx when applying glow-discharge boronization or boron material injection for plasma-facing component conditioning, as uncontrolled B–C–D bond formation can exacerbate tritium inventory concerns in future high-Z devices and ITER-scale reactors.

Further experiments in the DIII-D V-shaped tungsten-coated divertor (SAS-VW) demonstrated that B powder injection reduced W deposition by 25-50% on midplane collector probes and increased B deposition near the main chamber wall, indicating reduced W leakage into the far scrape-off layer. Boron nitride (BN) powder injection at rates above 20 mg/s more effectively suppressed tungsten erosion via localized radiative cooling and detachment onset, demonstrating greater effectiveness than pure boron for W source suppression. Prior experiments showed that ~10 mg/s boron injection improved wall conditions in the SAS-1 divertor during H-mode operation [4].

The integrated modeling workflow effectively explains the broad coverage of DIII-D PFCs with boron coatings, providing key insights into solid boron injector design for ITER Q=10 operations [2], with implications for impurity control, surface evolution, and tritium management in future high-Z devices.

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References

[1] F. Effenberg et al 2025 Nucl. Mat. Energy 42 101832
[2] J.A. Snipes et al 2024 Nucl. Mat. Energy 41 101809
[3] S. Abe et al 2025 Nucl. Mat. Energy 42 101855
[4] F. Effenberg et al 2022 Nucl. Fusion 62 106015