Study of impurity particulate dynamics and impurity transport using the DiMES pellet launcher in DIII-D

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The study demonstrates that tungsten (W) and carbon (C) pellets injected using the DiMES launcher in the DIII-D tokamak provide insights into impurity transport and impurity particulate dynamics under reactor-relevant conditions. A key finding is that pellets consisting of W enclosed in a C shell effectively deposited measurable impurities within the plasma core during H-mode discharges, as confirmed by visible and UV spectroscopy. These results validate theoretical models, highlighting the distinct transport behavior driven by steep density and temperature gradients, SOL flows, and strong forces such as J×B. This research is driven by the urgent need to establish reactor-relevant techniques for managing debris, such as plasma-facing component (PFC) slag (dust and debris), produced during plasma operations. The insights gained from these experiments are essential for addressing challenges related to impurity transport and slag accumulation in fusion reactors.

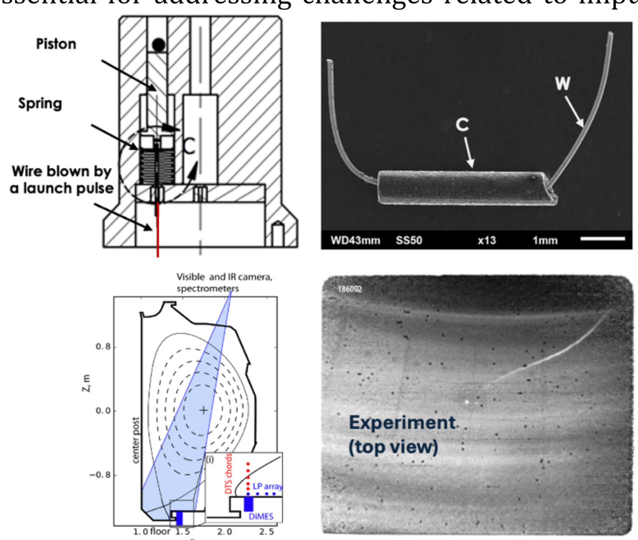

Figure 1. DIII-D DiMES-based launcher (top left) injects 0.5-20 mg spherical projectiles with speeds of 3-10 m/s. Multiple diagnostic systems, including visible and IR cameras (bottom left), are used to record and characterize the pellet behavior. Thin W wire is enclosed in C shell pellet (top right). Visible emission fast framing camera with a direct view of the DiMES port provides precise measurement of pellet trajectory within a field of view (bottom right).

Central to this work is the DiMES pellet launcher, a transformative system developed initially for Frontier Science experiments and now repurposed to study the dynamics of particulates (dust and pellets) injected into the divertor plasma [1]. This innovative tool enables the precise injection of predetermined amounts of particulates with specific properties at controlled times during plasma discharges. The system is inserted through the DiMES port on the lower divertor shelf and leverages a spring-powered mechanism housed within a standard DiMES head to propel pellets vertically into the plasma at controlled velocities of 3-10 m/s. The launcher's ability to synchronize pellet injections with plasma conditions, combined with comprehensive diagnostics focused on the DiMES port, offers a unique capability for studying impurity dynamics and material ablation or melting under extreme heat flux environments (Fig. 1).

Tungsten pellets with carbon shells were designed to overcome the challenge of introducing high-Z impurities into the plasma core. These specialized pellets enabled controlled studies of tungsten ablation and transport, with trajectories and impurity deposition profiles monitored using visible imaging and IR cameras, CO2 laser interferometer, and spectroscopic diagnostics. In addition, two types of carbon pellets were used in these experiments: porous carbon pellets with a radius of 1 mm and a density of 0.8 g/cm^3 and smaller glassy carbon pellets with a radius of 250 μm and a density of 1.4 g/cm^3. These pellets were selected to represent different material properties and their interactions under plasma conditions [2].

L-mode discharges, characterized by broader scrape-off layer (SOL) regions and more gradual plasma gradients, facilitated predictable impurity transport. Carbon pellets injected in these conditions provided valuable insights into the influence of plasma flows on particulate dynamics. In contrast, H-mode discharges, with their steeper temperature and density gradients, introduced complexities such as enhanced ablation and stronger forces acting on the particulates. ELMs in H-mode are known to flush the impurities outwards, a behavior critical for understanding impurity dynamics in future fusion reactors.

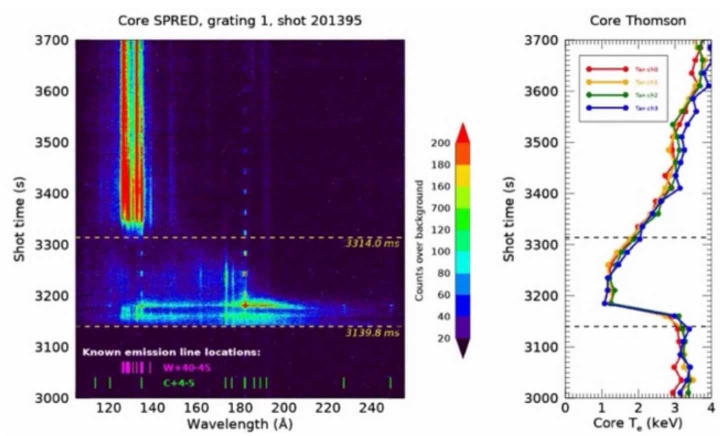

Figure 2. Spectroscopic radiation diagnostic showing fast ablation of carbon shell in DIII-D discharge 201395 at 3140 ms followed by H-to-L transition with core electron temperature going below 1.5 keV. After the H-mode recovery (3315 ms), W+40-45 emission lines dominate the spectrum.

High-speed visible filtered camera imaging and infrared cameras captured 3D trajectories of injected pellets, revealing consistent penetration depths and trajectories between experimental observations and numerical simulations using UEDGE and DUSTT codes. The precise alignment between diagnostics and modeling underscores the utility of advanced tools in refining impurity transport models. Enhanced impurity ablation during ELMs, potentially influenced by 'rocket force' effects, provided valuable observations that can inform future studies on impurity dynamics and ablation behavior.

The DiMES launcher further benefits from its comprehensive diagnostic setup, including high-resolution cameras and spectroscopic tools (Fig. 2), enabling the study of material behavior throughout their trajectories and ablation processes. The flexibility to test a range of materials, sizes, and plasma conditions enhances its versatility for diverse experimental scenarios.

This research represents a critical step forward in understanding plasma-material interactions (PMI) essential for ITER and future reactors. By leveraging the unique capabilities of the DiMES launcher and an extensive suite of diagnostics, the study provides actionable insights into impurity control and PFC design. These findings emphasize the importance of combining experimental techniques with advanced modeling to address the challenges of slag accumulation and impurity management in fusion energy systems.

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[1] Bykov et al., HTPD-2022 (Rochester, NY, 2022)
[2] Orlov, invited talk, APS DPP 2021 (Pittsburgh, PA, 2021)