ENHANCED H-MODE BY BORON POWDER INJECTION AND IMPLICATIONS FOR REACTORS

EX-P

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Transient ELM-free enhanced H-mode (~200ms, β_N peaks at 2.2) was achieved with boron powder injections over various q95 values (3.5-4.4) and NBI powers (2.8-4.6MW) for the first time, which provides valuable data and insights on the effects of low-Z impurities injection on pedestal and potential advancement in the suite of FPP-compatible scenarios. Improving pedestal performance is crucial for success in ITER and FPPs, aligning with key goals of fusion research for viable commercial energy. Built upon previous works on low-Z powder injections, this work highlights new insights into the underlying pedestal physics of edge turbulence triggered by low-Z impurity and powder dropping, combining advanced diagnostics with control strategies.

Boron powder injection induced transient ELM-free enhanced H-mode pedestals in DIIID. Enhanced H-mode (EH-mode) pedestals with transient ELM-free periods that last for hundreds of milliseconds have been achieved at DIII-D by injecting boron powder from the Impurity Powder Dropper (IPD) for the first time, similar to the transient ELM-free EH-mode with lithium powder injection nearly a decade ago [1]. Figure 1 shows the preliminary results of the pedestal profiles and timeseries for the boron shots, in which panel a) shows the transition of pedestal density n_e and electron/ion temperature, T_e and T_i, as a function of normalized poloidal flux Ψ_n from the base state (black curve) to the EH state (blue curve). During the EH state, the pedestal shifts inwards, which yields lower density and temperature gradients near the separatrix. Moreover, the pedestal density increased by approximately 10%, and electron/ion temperatures increased by > 30%. Figure 1b) shows a comparison of Li and B powder-dropping shots, with ~18mg/s (Li) and ~5mg/s (B), respectively. In both boron (blue) and previous lithium experiments (red), the pedestal pressure and temperature surged by a factor of 2, leading to more than a 60% increase in global energy confinement compared to a non-EH state. The inward-shifting pedestal also indicates an increased pedestal width to about 2x of that from EPED, which is confirmed during the EH state as shown in the bottom panel of Figure 1b).

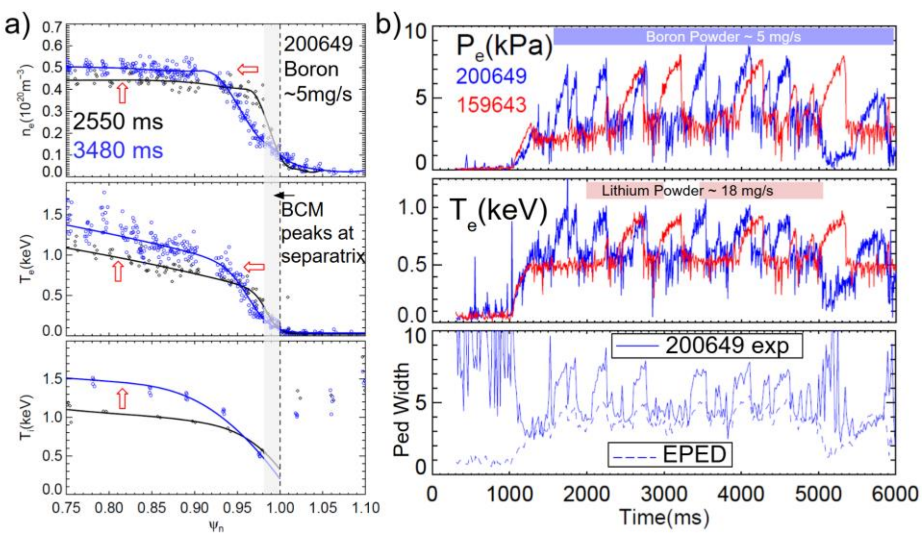

Figure 1: a) Pedestal profiles of electron density, temperature, and ion temperature of 200649 before and after Enhanced H-mode (EH) phases showing a pedestal inward shift, resulting in decreased pedestal gradients near the boundary. b) Timeseries of pedestal pressure, temperature, and width compared with lithium powder dropping reference shot 159643. The boron shots were conducted without lithium in the device. Similar enhancements of pedestal properties were found for boron with a lower injection rate at ~ 5 mg/s.

The enhancement in pedestal height and width increases with NBI power and remains robust in different q95 values. We verified robust access to the powder-induced enhanced H-mode based on previous target shots [2] over a moderate range of NBI power (2.8-4.6MW) and q95 window with different powder injection rates, finding a high I_p EH mode in terms of higher absolute pedestal pressure and global β_N (peaks at 2.2, with ~200ms duration by boron injection.

The BES and high-frequency DBS data reveal new insights into the pedestal dynamics of low-Z powder injection. Low-frequency Bursty Chirping Mode (BCM) is observed in pedestal fluctuation measurements, i.e. BES and ECEI, similar to that studied in previous lithium-dropping experiments [1][2]. Figure 2a) shows a BES spectrogram with a coherent 50-70kHz structure near the separatrix (also shown near the grey box in Figure 1a) which is directly confirmed by the ECEI. The BCM with low k is thought to reduce density and temperature gradients near the separatrix, stabilize the Peeling-ballooning mode, expand the stability boundary, and is beneficial to achieve a much higher and wider pedestal pressure. Our preliminary results of the nonlinear BOUT++ simulations have found similar fluctuations with similar frequency (around 60 kHz) as observed in the experiment and confirm the possible edge flattening effects on the pedestal profiles. Moreover, we have discovered higher frequency modes with intermediate k captured by the DBS data at approximately 1.5MHz for the first time (Figure 2b). The BCM and high-frequency modes appear to compete each other during the EH state, indicating the potential involvement of micro-instabilities could also play a role in the pedestal dynamics during the EH state and potentially lead to a wider pedestal than KBM-constraint EPED scaling. Further analysis of the mode's driving mechanism is underway.

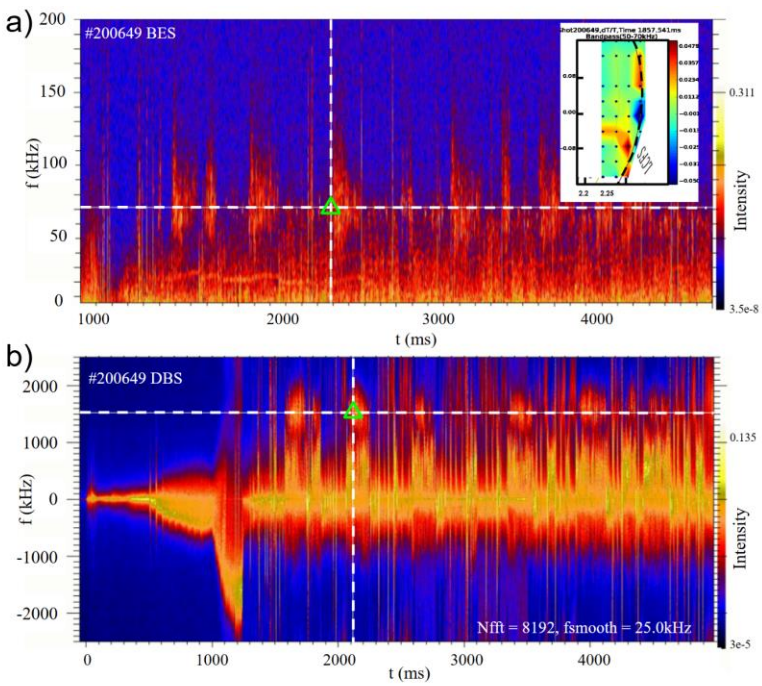

Figure 2: a) Bursty-Chirping Modes (BCM) in boron injection plasma were observed by BES. The green marker shows a peak power frequency near 70kHz. ECEI shows that BCM is located near the separatrix. b) A 1.5MHz broadband turbulence was found in DBS data, which appears simultaneously as BCM.

Low-Z impurity injections and their implications for reactors. The new data on boron-induced EH-mode suggests that more impurities could work to access EH-mode, which could be a more general phenomenon with low-Z impurities that helps to improve pedestal performance and confinement if the same physics holds. With a better understanding of the underlying physics, the robust access to EH-mode provides insights into improving pedestal performance using impurities and manipulating the pedestal turbulence and transport. The comparison against Enhanced Pedestal H-mode, wide-pedestal H-mode in NSTX, and boron ELM-suppression in EAST will be used to further understand the impurity or wall conditioning techniques on the pedestal and stability, which are important for ITER and FPP [3][4].

In summary, this work presents the first success in achieving an impurity-induced transient ELM-free enhanced H-mode using boron powder injection. This study uniquely compared the results from both lithium and boron injections and scanned them through different injection speeds, q95 windows, and neutral beam powers. Furthermore, more comprehensive diagnostics have been used in this study to uncover pedestal turbulence from low to intermediate k and pedestal dynamics over a large range and will be used to validate the pedestal modeling.

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