Initial Boron Powder Injection Experiments in WEST

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Boron powder (< 150 μm) was injected at various drop rates into lower single null (LSN) L-mode discharges in WEST, using a recently installed impurity powder dropper (IPD) developed at PPPL, with the objective of improving wall conditioning to facilitate H-mode access. These discharges featured $I_p \sim 0.5$ MA, t_{pulse} = 12-30 s, $n_{e,0} \sim 4 \times 10^{19}$ m^{-3}, and $P_{LHCD} \sim 4.5$ MW. During powder injection, a clear reduction in SOL DI and low-Z intrinsic impurity line intensities was observed, suggesting a reduction in recycling and possible screening of low-Z impurities. Additionally, the WI line intensity was observed to increase at both the outer lower divertor and at the ICRH limiter. In the subsequent discharges, however, the pre-injection WI line intensity decreased, possibly indicating a conditioning effect. These WEST experiments also observed improvements in stored energy (up to 25%) during powder injection. The increases in stored energy may be the result of stabilized ion temperature gradient (ITG) modes due to fuel dilution similar to gaseous impurity seeding experiments.

I. Introduction

Tungsten (W) is a leading candidate for potential plasma-facing components (PFCs) in a fusion reactor due to its high melting point, low erosion rate, and low tritium retention. The high-Z nature of W, however, makes it a problematic radiator of energy and W sputtering into the high-temperature plasma core can degrade confinement [1]. To remedy this issue, thin films of low-Z material have been used to coat the PFCs ensuring the plasma interacts with the low-Z elements, rather than the high-Z metal PFCs.

Unfortunately, standard methods of thin film deposition, such as Glow Discharge Boronization (GDB), are not conducive to a fusion pilot plant. GDB uses toxic diborane (B_2D_6) gas and requires the de-energisation of the magnetic field coils, which represent significant safety concerns and time costs for a superconducting fusion device or a steady-state pilot plant. To address these concerns, an IPD has been developed by PPPL to provide real-time wall conditioning of PFCs in fusion devices during the plasma discharge and without the use of diborane gas [2].

Recently, an IPD has been installed on WEST (W Environment in Steady-State Tokamak) [3] to provide real-time wall conditioning of the W PFCs and to possibly facilitate H-mode access. IPDs drop low-Z powders into high temperature plasmas which ablate the powder and deposit the low-Z material onto the PFCs through plasma-wall interactions. Typical IPD operation utilizes 10-100 mg of low-Z powder per discharge. This represents a strong deviation from standard GDB which can use > 10 g of diborane gas for a single Boronization [4].

II.IPD Experiments on WEST

WEST is a superconducting tokamak specializing in the evaluation of the ITER-like divertor W Plasma Facing Units (PFUs) and the investigation of long pulse up to 1000s [5]. The long pulse capabilities of WEST and the full-W environment make it an excellent test bed for studies of plasma-wall interactions on reactor-relevant timescales.

B powder (< 150 μm) was successfully dropped into 10 LSN L-mode discharges on WEST. These plasmas featured $I_p \sim 0.5$ MA, $B_T \sim 3.7$ T, $P_{LHCD} \sim 4.5$ MW, and $n_{e,0} \sim 4 \times 10^{19}$ m^{-3}. A representative equilibrium of these discharges is shown in Figure 1(a) and an image during the B powder drop from a visible camera is shown in Figure 1(b). The optimal drop rate was found to be between 9 mg/s and 17 mg/s.

The effect of B powder on several key plasma parameters is shown in Figure 2. When B powder is first ablated by the plasma at ~ 7s, there is a large increase in n_e and P_{rad}. After ~ 500 ms, the $n_{e,0}$ returns to the target level of 4×10^{19} m^{-3} but the radiated power is maintained at the increased level. I_p and P_{LHCD} seem to be relatively benign to the B powder.

III. Real-Time Wall Conditioning

Conditioning of the WEST PFCs was largely evaluated using an extensive visible spectroscopy (VS) system with views of several key PFCs [6]. This paper will focus on VS measurements at the lower outer divertor, due to the LSN configuration, and at the ICRH limiters, which were set as the outboard limiting surface and are a potential source for large W erosion ($P_{ICRH} = 0$ MW for IPD experiments).

Figure 3 shows BII (419.5 nm), WI (400.9 nm), DI (434.1 nm), and OII (441.5 nm) line intensities for a WEST discharge with B powder dropped from 7 s to 13 s. During powder injection, there is a strong increase in the BII signal, a mild increase in the WI signal, and a strong decrease in the DI and OII signals. The reduction in the OII intensity is a combination

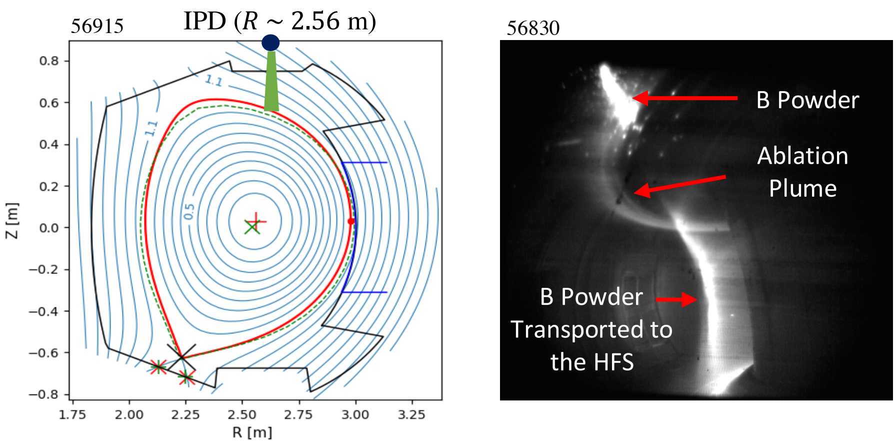

Figure 1. (a) Representative equilibrium from the WEST IPD experimental campaign and IPD location. (b) Visible camera image of B powder being dropped into and ablated by a WEST discharge.

of reduced recycling and direct conditioning from the B powder. The increase in W sputtering during powder injection has additionally been observed in IPD experiments on AUG [7].

While W sputtering is observed during B powder injection, the pre-drop (5.5-6.7 s) level of the subsequent discharges had lower signal intensities. This was concurrent with increases in pre-drop signal intensities of BII, implying possible thin-film deposition on the PFCs. Reductions in the pre-drop level of OII, NII (399.5 nm), and CII (426.7 nm) were also observed. Pre-drop signal intensities of DI at the lower divertor remained constant and slightly increased at the ICRH limiter, implying the recycling reduction is limited to the actual powder drop.

IV. Improvements in Confinement

Several WEST pulses with B powder observed improvements in stored energy W_{MHD}, with one pulse achieving a increase of 25%. These increases in stored energy were achieved without changes to I_p or P_{LHCD} and lasted the entire drop duration, implying an increase in the energy confinement. Figure 2 (e), (f), and (g) shows the stored energy, the DD neutron rate, and plasma inductance ℓ_i for two discharges with B powder and one discharge without powder injection. Along with the stored energy, increases in the DD neutron rate were observed, most likely due to increased T_i, measurements of which were unavailable.

While encouraging, the improved confinement does not seem to be consistent with an L-H transition. Aside from the initial spike in n_e, there is no evidence of a n_e or T_e pedestal. Furthermore, the plasma inductance increases, which is contrary to previously observed L-H transitions on WEST. Instead, the increases in confinement from the B powder may be akin to those from gaseous impurity seeding experiments [8]. Similar increases in the neutron rate have been observed in N_2 seeding experiments on WEST, where main ion dilution was shown to have a stabilizing effect on ITG turbulence [9]. Further analysis is underway to evaluate if similar mechanisms are at play during B powder injection.

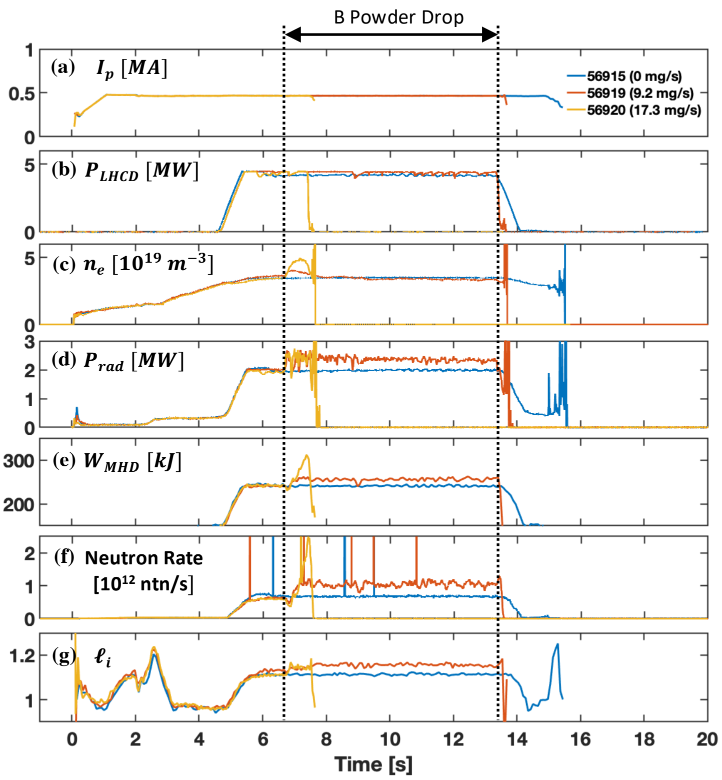

Figure 2. (a) I_p, (b) P_{LHCD}, (c) n_e, (d) P_{rad}, (e) W_{MHD}, (f) neutron rate, and (g) ℓ_i for two WEST pulses with B powder and one without.

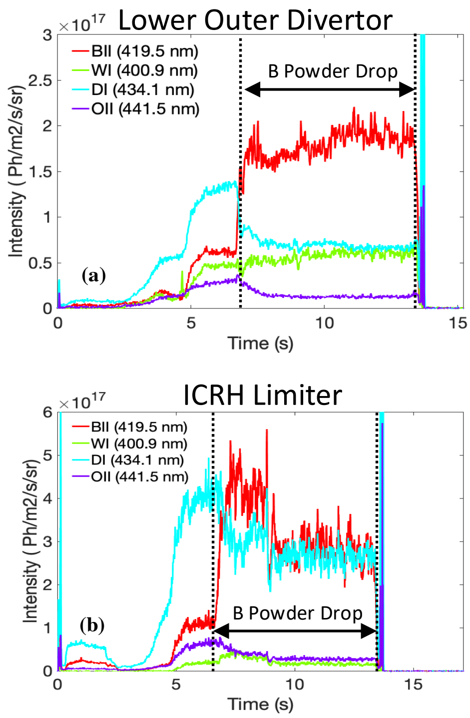

Figure 3. BII (419.5 nm), WI (400.9 nm), DI (434.1 nm), and OII (434.1) line intensities at (a) the lower outer divertor and (b) the ICRH limiter.

V. Conclusion

An impurity powder dropper has been successfully installed and commissioned on WEST to provide real-time wall conditioning and possibly facilitate H-mode access. B powder was dropped into 10 LSN L-mode discharges with P_{LHCD} ~ 4.5 MW. During the B powder drop, VS measurements showed reductions in recycling, low-Z impurity signals, and an increase in WI signal. As more powder was dropped, clear reductions in the pre-drop level of WI and OII were observed, indicating a cumulative conditioning effect from the powder and possible thin film deposition. Lastly, improvements in stored energy (up to 25%) were observed in discharges with B powder, most likely due to main ion dilution.

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