ELM Suppression and Recycling Reduction by Boron Nitride and Boron Injection in KSTAR

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Abstract

Periods of ELM quiescence up to 5 s were observed with boron nitride (BN) injection into KSTAR ELMy H-modes with an innovative Impurity Powder Dropper (IPD) [1]. In addition, divertor D_α emission was substantially reduced with boron (B) injection into ELMy H-modes, indicating improved recycling control. In both cases, there was no adverse impact on plasma stored energy. While edge fluctuations decreased overall, it appears that a new mode at ~ 180 kHz frequency appeared in beam emission spectroscopy data, suggesting a possible modification to the edge transport with active impurity injection.

The powders were dropped into 0.5 MA plasmas with 1.6 MW of neutral beam heating and pulse durations of 10 – 20 s. Photodiode signals and real-color fast camera images show the powders entering the plasma. A series of 2.5 mg doses of BN, delivered in 0.1 s bursts, was observed to eventually reduce the ELM amplitude and frequency without changing the stored energy or plasma density. Analysis of the BES data during the ELM-free phase showed increased coherent mode activity near 180 kHz, corroborated by magnetics data. A continuous BN dose of 2.5 mg/s for 10 s reduced the ELM amplitude and frequency, but did not suppress ELMs. In addition, several 2.5 mg doses of B during a single discharge reduced recycling as evidenced by the reduced baseline D_α level during the following shot. A 10 mg dose of B resulted in a disruption.

Introduction

The new Impurity Powder Droppers (IPD) developed by Princeton Plasma Physics Lab have been used on several machines, including ASDEX-Upgrade [2,3], EAST [4], and DIII-D [5]. The effects of powders with sizes between approximately 10 μm to 300 μm, such as lithium, boron, and boron nitride have been studied and the results show that, depending on the machine parameters and choice of powder, powder dropping has many beneficial uses.

Boron has been seen to coat plasma-facing surfaces, resulting in conditions similar to those found after gas-based boronization. Notably, the IPD-based boronization can take place frequently to maintain good wall conditions, unlike gas-based which occurs infrequently and is thus subject to erosion. Boron nitride injection has been observed to enhance pedestal radiation. Experiments with lithium have shown improved plasma performance. The IPD can also be used for core impurity accumulation and impurity transport studies. Here, we present the results of recent KSTAR experiments.

The Impurity Powder Dropper (IPD)

IPD is a device containing four reservoirs for powdered materials that each drop their powders onto a trough that is agitated by piezoelectric actuators when driven with voltage signals at the mechanical resonant frequency (~ 100 Hz) and with sufficiently large amplitude (~ 300 V). The powders drop off of the end of the trough and into a common grounded drop tube that extends several meters down to near the plasma discharge. The falling powder passes through a flow meter consisting of a 2.5-cm-wide beam of light and a photodetector that measures the attenuation of the light. For each powder material, the mass flow rate in mg/s is calibrated against the flow meter signal in bench tests. Flexibility in generating the excitation waveform corresponds to flexibility in the ability to deliver powders to the discharge.

Experimental Results

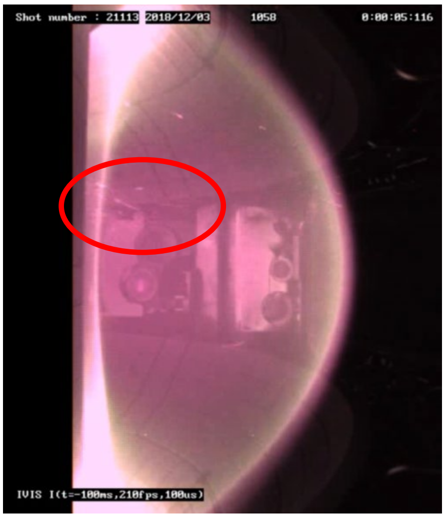

Figure 1: The red oval highlights the location of several pieces of boron powder injected into KSTAR shot #21113.

The IPD was used in 2018 KSTAR experiments to study the effect of dropping BN and B powder into the boundary plasma into lower-single-null ELMy H-mode plasmas lasting 10 s to 20 s with 1.6 MW of neutral beam heating and 0.6 MW of ECH heating. The radius of the injector is just inboard of the radial location of the magnetic axis. Dose rates from 2.5 mg/s to 25 mg/s were used in series of bursts lasting from 0.1 s to 1 s. Note that, in all cases, the time between when the head and tail of the powder bunches enter the plasma is greater than the burst length by approximately 1 s, as powder disperses by bouncing off of the walls of the drop tube. In the final experiment of the run, a continuous drop of BN for 10 s at 2.5 mg/s was used. Figure 1 shows that optical camera images detect the powder when it enters the plasma.

Boron injection at low dose rate into low-power discharges was observed to somewhat ameliorate the ELM behavior, as seen by D_α monitors. At the same time, there was little change in the radiated power, stored energy, or density. This is seen clearly in the data in Figure 2 where the results for KSTAR shot #21121 are displayed. The bottom panel shows that the IPD drop signal was sent from 3.5 – 4 s, 8.5 – 9 s, and 13.5 – 14 s, but that a photodiode looking down the drop tube sees the reflected D_α light from the powder particles somewhat later. After the first bunch of powder reaches the plasma at t ~ 6 s, there is a reduction in the ELM frequency, including several half-second intervals of ELM-free behavior (for comparison, an ELMy reference discharges is displayed in Fig. 3a). The cumulative effect of the total B dropped in shot #21121 was seen before B injection in the beginning of shot #21122, during which the baseline D_α level was 50% lower than it was in shot #21121. This suggests a positive effect on wall conditioning and a reduction in recycling.

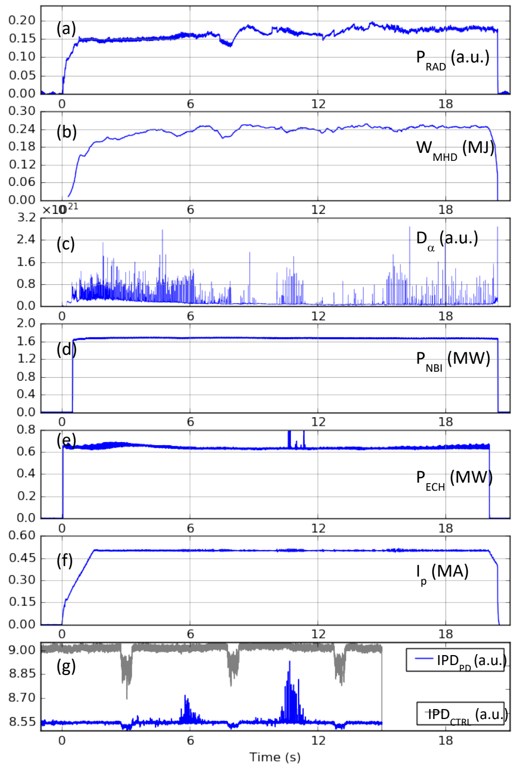

Figure 2: (a) P_{RAD}, (b) W_{MHD}, (c) D_α, (d) P_{NBI}, (e) P_{ECH}, (f) I_p, and (g) IPD control signal (top) and photodiode signal (bottom). There is a delay and dispersion of the powder bunch as it drops; ELM activity is reduced when B enters the plasma.

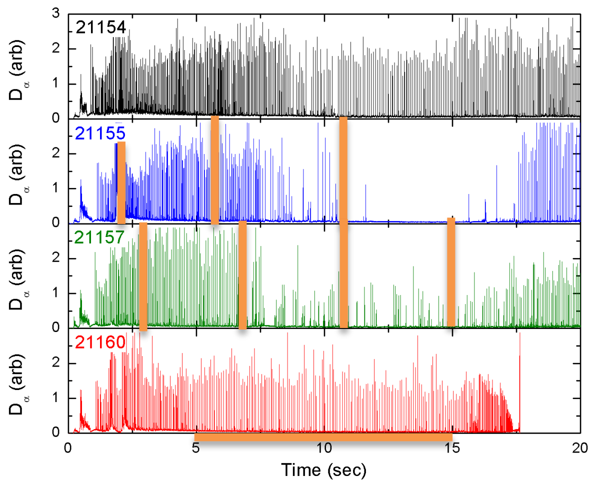

Figure 3: D_α signal for reference shot (#21154), 25 mg/s BN bursts (#21155), 12.5 mg/s BN bursts (#21157), and 2.5 mg/s continuous drop (#21160). Orange lines denote the times of the powder drops.

The effect of boron nitride on D_α activity was clearer to see. Figure 3 shows the D_α signal from reference shot #21154 and from three shots with BN injection. In shot #21155, BN was injected at a dose rate of 25 mg/s in three 0.1 s bursts. The result was an extended period of ELM-free behavior during the second half of the discharge, but with the ELMs returning near the end. Thus, in shot #21157, a fourth burst was added but with the dose rate for all bursts reduced to 12.5 mg/s. It was then observed that the ELM activity was reduced but not eliminated, implying that the lower dose rate was insufficient for ELM suppression. In shot #21160, 2.5 mg/s on BN was injected continuously for 10 s. It can be seen qualitatively in Figure 3, and also in a quantitative analysis of the inter-ELM time, that the ELM frequency was significantly reduced during the BN injection.

The extended ELM-free phase of shot #21155 allowed for further analysis of BES and magnetics fluctuation signals and a comparison of the ELMy phase with the ELM-free phase. Figure 4 shows the BES coherency spectrum for the ELMy phase (red) and the ELM-free phase (black) of shot #21155. The roll-off of the coherency during the ELMy phase begins at ~ 150 kHz, while it begins at ~ 70 kHz in the ELM-free phase. Notably, a coherent structure can be observed with frequency ~ 180 kHz in the ELM-free phase. Moreover, this signature is seen on the LFS magnetics data but not the HFS. Therefore, it may be responsible for edge transport, and therefore the ELM behavior.

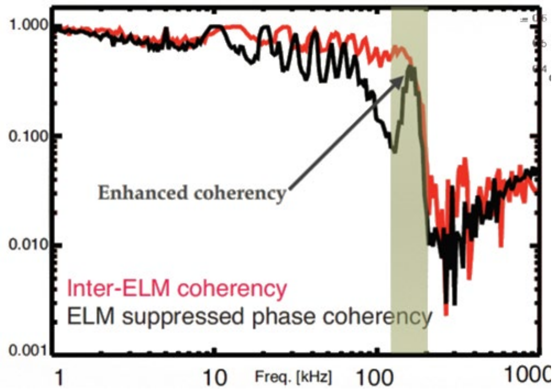

Figure 4: BES coherency spectrum in the ELMy and ELM-free phases of the discharge. A mode with frequency ~ 180 kHz appears during the ELM-free phase that may be related to ELM activity.

Conclusion:

The IPD is a valuable tool for dropping controllable, reproducible, precise quantities of powdered materials into fusion plasmas. Initial experiments using IPD on KSTAR yielded promising results, with both B and BN reducing ELM activity and certain BN injection parameters giving extended ELM-free phases without adverse impacts on the plasma properties. Further experiments will be carried out over a range of plasma and machine settings, as well as a broad range of IPD settings, in order to develop an understanding of the effect of B and BN. Specifically, experiments with a range of heating powers, plasma currents, plasma shapes, IPD dose rates and burst durations will be able to optimize the performance and reach extended, controllable ELM-free regimes in long-pulse high-beta operation.

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