

## Active conditioning of ASDEX-Upgrade tungsten PFCs through boron particulate injection

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### Abstract

The injection of boron (B) and boron nitride (BN) powders into ASDEX-Upgrade (AUG) H-mode discharges have shown the ability to effectively control tungsten influx in low density/collisionality operational regimes, similar to conventional boronization methods. Sub-mm powder particles are gravitationally accelerated into the upper edge of a lower single null H-mode plasma with a boundary shape roughly conforming to the shape of the poloidal midplane limiter. Boron nitride injection rate was varied from  $\sim 8 \times 10^{18}$  to  $\sim 4 \times 10^{20}$  atoms/discharge. Visible spectroscopy measurements at the outer limiter showed increases in both boron and nitrogen signal levels, as well as elevated boron levels in the divertor and an increase in  $P_{\text{RAD}}$  by greater than a factor of 2. Globally the BN injection improved energy confinement by 10-20% associated with improvements in pedestal performance similar to gaseous nitrogen injection. Discharges with increasing B injection rates were also performed. Injecting  $9.2 \times 10^{21}$  atoms of pure B resulted in minimal impact on plasma performance. To test the conditioning effect of B powder, a sequence of discharges with magnetic perturbations for ELM suppression were conducted afterwards. All three attempts to run low density discharges with ELMS suppressed by magnetic perturbations were successful. These preliminary results suggest that the application of B containing powders can be used to both improve plasma performance in real-time and improve wall conditions.

### 1. INTRODUCTION

Present day tokamaks often use low-Z wall conditioning to either improve access to low collisionality and/or improve energy confinement. For ITER operations there is a concern that high-Z impurity contamination could result in a reduction in fusion power capability and ultimately lead to plasma disruption initiated by radiative collapse [1]. However erosion of the Be first wall and re-deposition into the divertor may help to protect the tungsten divertor, providing a natural *de facto* wall conditioning in a quasi-continuous manner to maintain an acceptable machine state for experimental operations. If dedicated wall conditioning techniques are needed, the ITER operational duty cycle

could require alternate wall conditioning techniques as compared to those favored by most present day operations. In addition, the utilization of superconducting magnets on ITER and the desire to minimize the frequency with which the coils are exposed to current ramping stresses eliminates the possibility of an inter-shot or even daily repetitive glow discharge cleaning as a means to improve wall conditions.

To explore the possibility of utilizing particulate injection as an intershot conditioning technique an impurity powder dropper was developed by PPPL and tested on ASDEX-Upgrade (AUG). The injection of boron (B) and boron nitride (BN) powders into AUG H-mode discharges has shown the ability to effectively control tungsten influx in low density/collisionality operational regimes, similar to conventional boronization methods. In these experiments, B and BN were separately and controllably injected via gravity into H-mode discharges. Total radiated power and plasma energy confinement increased with BN injection, in a manner qualitatively similar to nitrogen gas injection. In addition, pure B injection provided compelling evidence of post-shot residual conditioning, allowing access to low collisionality H-modes with zero flat-top gas fueling. These initial results hold the promise of rapid wall re-conditioning and possibly the ability to operate with more stable and uniform wall conditions between routine boronizations. In the remainder of this paper we will describe the effects of standard boronizations on AUG, describe the Impurity Powder Dropper (IPD), and examine the effects of particulate injection into AUG H-Modes.

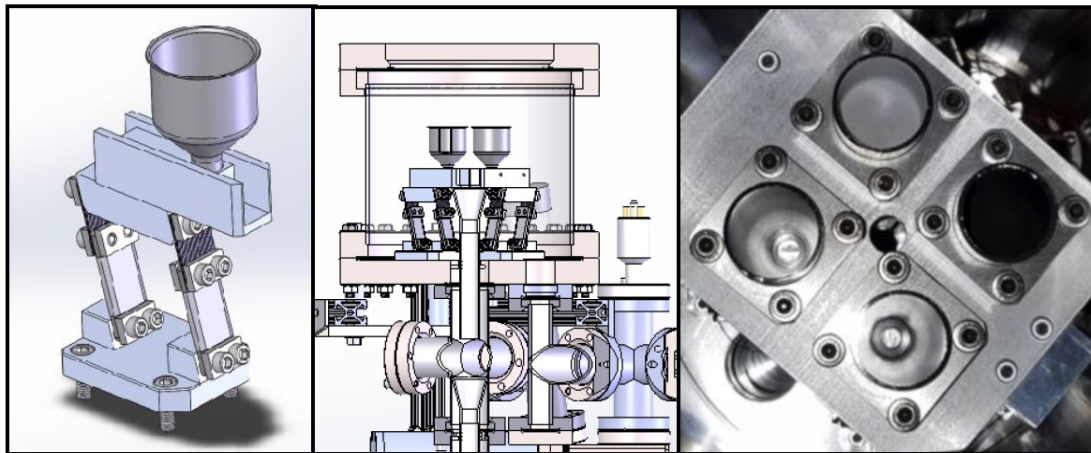


Figure 1: Powder dropper assembly : From left to right are displayed an individual powder feeder assembly with powder reservoir and piezoelectric shakers, the interior of the impurity powder dropper where 4 such feeders are arranged around a central drop tube, and a top down view of the powder dropper as installed on AUG with a filled BN chamber at the 12 o'clock position and a filled B chamber at the 3 o'clock position with two empty chambers.

## 2. EFFECTS OF BORONIZATION IN ASDEX-UPGRADE WITH FULL METAL WALLS

The AUG divertor PFCs are comprised of bulk tungsten tiles, while the remainder of the interior surfaces are coated with 10 microns of vapor deposited tungsten. Operations in AUG with non-boronized walls led to restrictions in the operational space. Central accumulation of W in discharges with density peaking eventually generates H-L back transitions [2]. These events were controlled with ECRH central heating and gas puffing as a means to enhance the ELM frequency. The elevated ELM frequency is in turn used to flush W influx from the edge-pedestal region before it has a chance to penetrate further and degrade core performance.

In AUG the injection of 10% concentrations of B<sub>2</sub>D<sub>6</sub> gas into helium glow discharges has been demonstrated [3] to be an effective method to condition the plasma facing components. The regular application of a 10 hour boronization has been found to deposit approximately 8 g of boron mainly on the main chamber resulting in an approximately uniform 10 nm thickness. These coatings are able to mitigate the W influx without supplemental gas injections and thus enable access to low plasma

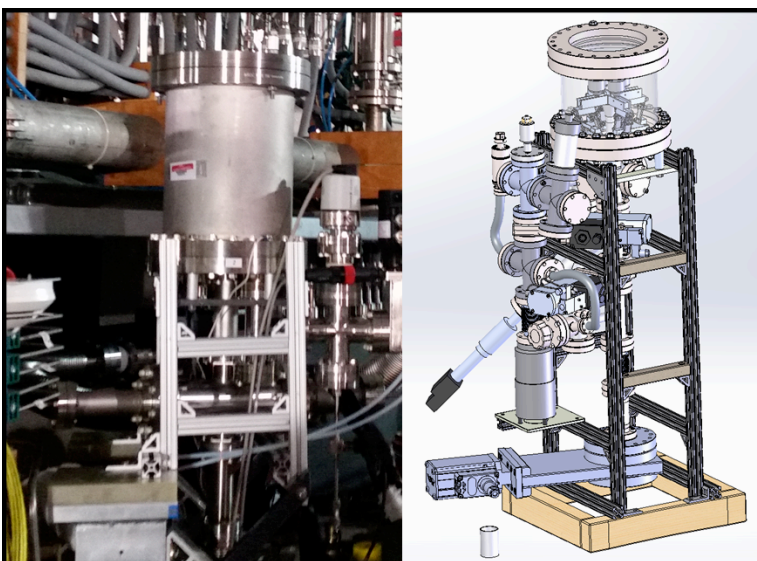


Figure 2: Impurity Powder Dropper: This figure shows the full model of the impurity powder dropper and also an image of the dropper as installed on ASDEX-Upgrade.

density and collisionality regimes. One such scenario where low density operation is critical is the utilization of resonant magnetic perturbations (RMP) to suppress ELMs [4].

In addition, it has been seen that ICRF heated discharges are particularly susceptible to enhanced impurity influx due to the sheath rectified electric fields which can be found at the antenna limiters [5]. After a boronization event, more favorable conditions have been observed at the location of the ICRF limiters, thus making this a natural location to focus our observation efforts to determine the efficacy of particulate boronization.

## 3. IMPURITY POWDER DROPPER APPARATUS

An Impurity Powder Dropper (IPD) [6] has been installed onto the AUG tokamak. The dropper contains 4 independent powder reservoirs connected to individually controllable piezoelectric shaker trays as shown in figure 1. These powder feeders are arranged at 90

degrees around a circle with the output end pointed toward a central aperture. For these experiments, two feeders were filled, the first with 5 $\mu$ m diameter BN powder, and the second with 70  $\mu$ m B powder (99%+ purity) while the other two assemblies are left empty. Powder is fed to the individual IPD heads by means of a conical reservoir with cylindrical secondary reservoir placed above it. The powder is advanced down the feed tray by means of an amplified sinusoidal voltage administered to the piezoelectric crystals below the feeder tray. Crosstalk between the injectors is avoided by engineering distinct resonant frequencies for each slide tray. The selected powder is driven off the end of the tray into a 2.5 m vertical guide tube connected to the main vacuum vessel as shown in figure 2. As the falling powder transits the vertical drop tube it passes by a calibrated flow meter. In the flow meter a fiber fed LED source is used to generate a collimated beam which intersects the powder path and is then refocused into a return fiber connected to a photodiode. As the powder falls it partially obstructs the beam from the photodiode. The greater the occultation provided by the transiting powder, the larger the attenuation. The attenuation of the photodiode voltage signal is then compared to a species specific flow meter calibration which provides an estimate of the mass drop rate. This information and the duration of the drop allows an estimation of the total quantity of material deposited into the discharge. For these low-z compounds drop rates which range from 2 mg/s to 200 mg/s have been reliably and repeatably achieved.

#### 4. BORON POWDER INJECTION EXPERIMENTS

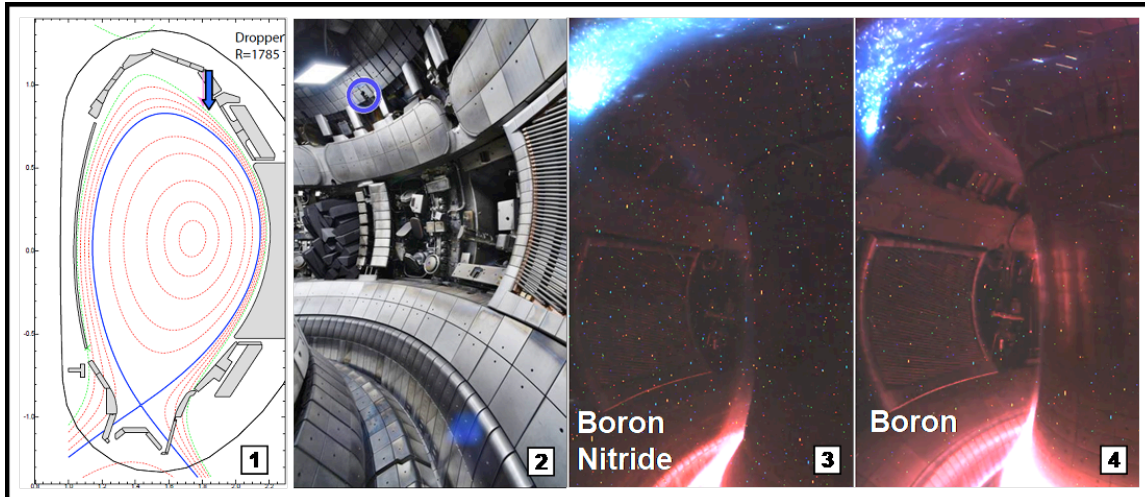


Figure 3: Powder dropper injection site : Panel 1 displays the location of powder injection (blue arrow) with respect to the poloidal cross section of the conformal discharge reconstruction. The blue circle in Panel 2 displays the location of the entry tube within the vacuum vessel. Panels 3 and 4 display the boron nitride and boron injections. The blue shadow in the divertor in panel 2 is an image artifact.

Plasma conditions for the particulate injection shots were as follows :  $I_p = 0.8$  MA,  $B_T = 2.5$  T,  $P_{NBI} = 10$  MW,  $P_{EC} = 0.8$  MW with a conformal plasma shape and a density of  $n_e = 6.5 \times 10^{19} \text{ m}^{-3}$  so as to generate robust ELM activity thus providing maximum contact between the SOL and the PFCs. It is believed that filamentary structures associated with



the outward radial ELM transport are responsible for both initial boron distribution as well as sputtering and redistribution, providing a net material transport to the divertor surfaces over the course of the discharge. The introduction of boron rich powders (both elemental boron and boron nitride) was performed at injection levels up to 60 mg/s for 3 seconds during the H-mode flat top.

Figure 3 shows the injection geometry for the impurity powder dropper. As shown in the panel 1 poloidal cross section, the drop tube is located in a position near the crown of a LSN discharge, shaded slightly towards the low field side of the discharge. The physical location of the dropper tube entrance hole is denoted by the highlighted circle in panel 2. Panels 3 and 4 are a true color wide-angle camera recording of boron nitride and boron powder injection respectively. In both cases the bright blue emission is believed to be due to singly ionized boron at 412.2 nm. We note that the emission zone seen with the boron nitride injection seems to be more uniform than that observed for boron. We believe this to be due to the propensity of the boron microparticles to aggregate into larger clumps. This results in the boron clusters providing concentrated particle sources as they are ionized and ablated. This behavior allowed deeper penetration into the discharge due to the self-shielding of the larger particles as observable from the formation of ionized field aligned emissions.

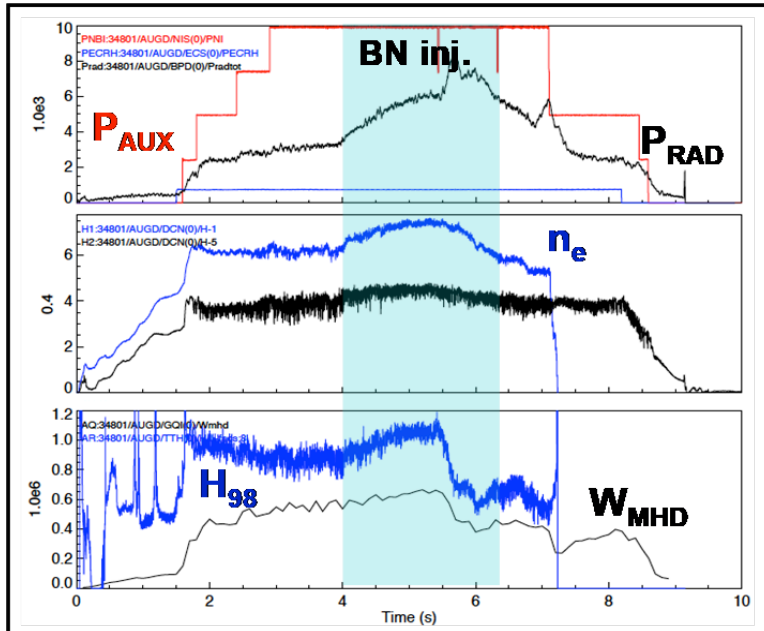


Figure 4: Effects of boron nitride injection on overall plasma parameters for discharge #34801. The introduction of boron nitride powder to the edge of the discharge has a strong effect on overall plasma behavior. Due primarily to the simultaneous introduction of nitrogen with the boron there are strong increases in the radiated power. In addition there are also observable increases in the stored energy and confinement.

The first experiments in the series were performed with a ramping series of boron nitride injections as seen in table 1. Boron nitride was chosen because of the enhanced delivery accuracy of the IPD at lower injection levels. In these discharges the injected B was varied from  $\sim 4 \times 10^{18}$  atoms/discharge to  $\sim 4 \times 10^{20}$  atoms/discharge. The largest achievable particle injection rate was determined by the simultaneous introduction of strongly radiative nitrogen in equal quantities along with the boron. For boron nitride injection

rates of 12 mg/s,  $n_e$ ,  $P_{RAD}$  and  $W_{MHD}$  were all seen to increase from the start of the injection until  $t = 5.5$ s at which point the discharge becomes MHD unstable as can be seen in figure 4. The observed enhancements to performance, with  $W_{MHD}$  increasing from 0.55 to 0.66 MJ and  $\beta_N$  reaching a neoclassical tearing mode threshold of 2.7, are similar to those observed during nitrogen seeding in metal walled machines such as AUG and JET where the injection of  $N_2$  gas improved energy confinement [7, 8]. Visible spectroscopy measurements at the outer limiter showed increases in both boron and nitrogen signal levels, as well as elevated boron levels in the divertor. A change from BN to pure B injection was then undertaken as the pure B allowed a larger material introduction without the subsequent (albeit positive) effect on discharge performance.

ASDEX Discharge	Injection Species	Quantity of boron injected (atoms)	Cumulative boron injection
34796	BN	$3.7 \times 10^{18}$	$3.7 \times 10^{18}$
34798	BN	$3.0 \times 10^{19}$	$3.4 \times 10^{19}$
34799	BN	$1.0 \times 10^{20}$	$1.3 \times 10^{20}$
34801	BN	$4.2 \times 10^{20}$	$5.5 \times 10^{20}$
34803	BN	$2.7 \times 10^{20}$	$8.2 \times 10^{20}$
34808	B	$8.3 \times 10^{20}$	$1.6 \times 10^{21}$
34809	B	$4.2 \times 10^{21}$	$5.8 \times 10^{21}$
34825	B	$9.2 \times 10^{21}$	$1.5 \times 10^{22}$

Table 1: List of IPD boron powder injection discharges with injected quantities and cumulative boron deposition.

Following the BN injection experiment, three discharges with increasing B injection rates were performed. The highest level of boron injection,  $9.2 \times 10^{21}$  atoms over the course of the discharge, resulted in minimal impact on plasma performance. Injection rates up to 60 mg/sec were well tolerated with only a 5% increase in electron density and a 20% increase in radiated power. In addition, as seen in figure 5, there was no strong

variation in plasma stored energy due to the injection of atomic boron.

## 5. OBSERVATIONS OF CONDITIONING EFFECTS

Wall conditioning test shots were interleaved with the powder deposition discharges (both BN and B). For the test shot chosen,  $D_2$  fueling was stopped at  $t = 3.5$  s allowing for core tungsten accumulation leading to an unstable discharge evolution. For discharge AUG\_34797 which was undertaken at the start of the powder injection program there was an observed strong MHD event at  $t = 5.8$  s followed by a radiatively induced disruption event at  $t = 8$  s. This is contrasted with discharge AUG\_34810 which was undertaken after cumulative injection of  $5.8 \times 10^{21}$  boron atoms. This discharge was successful in reaching the  $I_p$  rampdown at  $t = 9$  s with reduced levels of radiative losses albeit while still exhibiting some unstable behavior. In addition observations of the time averaged brightness of the BII and OII emission at the limiter during the H-mode flat top shows an increase in the former by 25% and a decrease in the latter by 30% over the course of the injection discharge series as is consistent with the newly deposited boron substrate gettering the available oxygen [9].

To test the conditioning effect of B powder, a sequence of discharges with magnetic perturbations for ELM suppression were conducted afterwards. Historically these

discharges are very sensitive to wall conditions, and are only attempted within a few days of a standard boronization. Following the B conditioning discharges, all three attempts to run low density discharges with ELMs suppressed by magnetic perturbations were successful. As a fraction of the total inventory, 88% of the total injected boron was introduced in the final two discharges, with 60% being deposited in the final conditioning discharge. Thus the observed good wall conditions are likely due to the final one or two conditioning discharges, as opposed to cumulative conditioning from the full sequence of nine B and BN discharges.

Note that these experiments were undertaken after a series of wall loading discharges and

prior to a scheduled boronization. Thus it was not expected that the plasma would be able to access the low collisionality regime necessary for RMP ELM suppression to be successful. As such a pre-injection null shot to confirm that the RMP ELM suppression regime could not be accessed was not undertaken and thus these results remain suggestive but not conclusive. Indeed while these results are consistent with the deposition and coating of the relevant surfaces with an effective boron layer, it must be noted that there were no direct measurements made of the wall composition or coating thickness as a result of these injections.

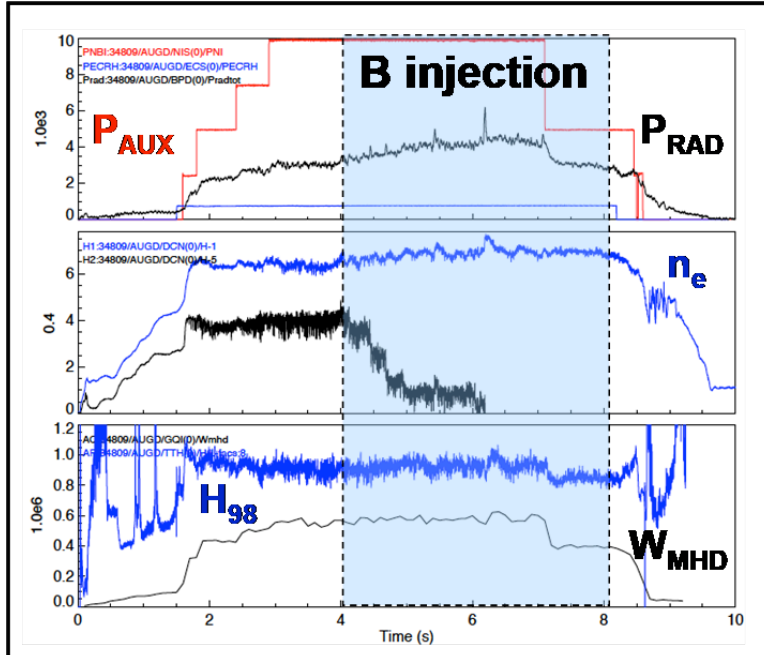


Figure 5: Effects of boron injection on overall plasma parameters for discharge #34809. The introduction of boron particulates into the discharge has a small effect on the density and creates a 40% increase in the radiated power, however the effects on confinement as evidenced by the  $H_{98}$  and  $W_{MHD}$  traces are minimal. Note that the indicated drop in the edge density (black trace, middle panel) is a false artifact, due to fringe jumps in the interferometer signal.

## 6. CONCLUSION

We observe that the cumulative effects of the boron injection, consisting of a total of approximately 340 mg, deposited over a range of 30 discharges appears to enable successful operation in low density plasma regimes which nominally require the presence of freshly boronized walls. As the deposition of the material is localized to areas of active plasma activity, this method of coating replenishment is expected to be especially effective in extending the lifetime of deposited boron layers on areas prone to rapid erosion such as the plasma strike points and limiting surfaces. These preliminary results

suggest that the application of B containing powders can be used to both improve plasma performance in real-time, and improve wall conditions. Furthermore as the injection system is capable of injecting a wide number of impurities (B, BN, B<sub>4</sub>C, Li, C, Sn, Mo, W, ...) it can be utilized for a range of studies.

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