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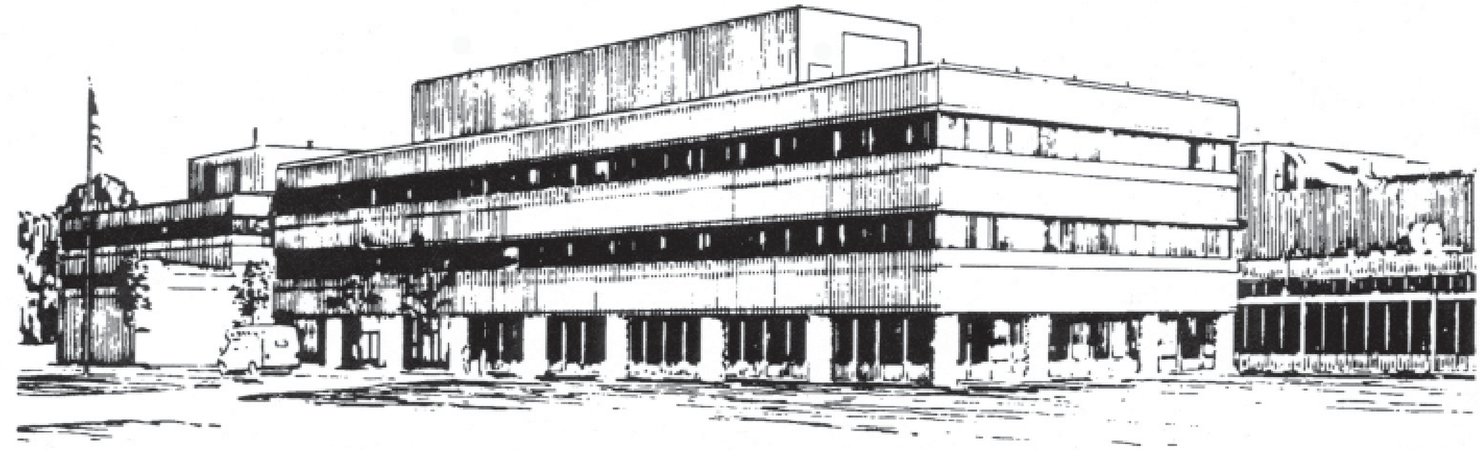

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Impact of the Wall Conditioning Program on Plasma Performance in NSTX

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ABSTRACT

High performance operating regimes have been achieved on NSTX through impurity control and wall conditioning techniques. These techniques include HeGDC-aided boronization using deuterated trimethylboron, inter-discharge HeGDC, 350 °C PFC bake-out followed by D_2 and HeGDC, and experiments to test fueling discharges with either a He-trimethylboron mixture or pure trimethylboron. The impact of this impurity and density control program on recent advances in NSTX plasma performance is discussed.

Keywords: wall conditioning, impurity control, boronization, boron fueling

1. Introduction

The physics principles of spherical torus (ST) geometry, characterized by strong magnetic field curvature, high beta-toroidal, and close-wall passive plate stabilizers are being evaluated by the National Spherical Torus Experiment (NSTX) [1]. Recent NSTX results include achieving a β_T of ~ 31% at Ip = 1.5 MA and B_T=0.3 T using 5 MW of 80 keV neutral beam heating [2]. In the highest stored energy discharges (280 kJ), the central ion temperature was ~ 3 keV and the central electron temperature ~ 1.4 keV [2]. H-modes have been accessed routinely with confinement times up to 120 ms [3]. High Harmonic Fast Wave heating has achieved central electron temperatures of T_e >3 keV and discharges which exhibit apparent internal electron transport barriers [4]. Coaxial helicity injection, under investigation as a non-inductive current drive technique has achieved toroidal currents of 390 kA [5]. In a relatively brief period since first plasma (1999), noteworthy results have been obtained, and new and interesting phenomena have been encountered [1]. Impurity control and wall conditioning have been essential in achieving high performance NSTX operating regimes. In 1999-2000, the initial wall conditioning of NSTX for ohmic plasma operations applied modest bake-outs of plasma facing components (center column to 309 °C, passive plate PFC's to 220 °C), and extensive glow discharge cleaning (GDC) in deuterium and helium [6]. Beginning in late 2000, the installation of 5 MW of neutral-beam injection (NBI), 6 MW of high harmonic fast wave (HHFW) radio-frequency heating, and high toroidal current (390 kA), Coaxial Helicity Injection (CHI) for non-inductive startup has required upgrading the wall conditioning techniques to provide additional impurity and density control. These techniques include HeGDC-aided boronization using deuterated trimethylboron, inter-discharge HeGDC, 350 °C PFC bake-out followed by D_2GDC and HeGDC, and experiments to test fueling of deuterium discharges with a He-trimethylboron mixture and pure trimethylboron.

2. HeGDC/TMB Boronization

Boronization has significantly improved plasma performance [7] and allowed routine access to H-modes [3]. A 90% He and 10% deuterated trimethylboron (TMB) [$B(CD_3)_3$] mixture was injected into a HeGDC. Separate He and He-TMB gas injectors were set for equal flow rates, to give a 95% He and 5% TMB application mixture. Ten g of TMB was applied over 160 minutes [8]. Residual Gas Analyzer (RGA) spectra indicate high oxygen impurity removal rates (H_2O, D_2O, CO), during the TMB boronization process due to PFC sputtering by the process constituents. Each boronization was followed by about 120 minutes of pure HeGDC to remove residual deuterium co-deposited during the process. Measurements of sample coupons exposed on a reciprocating probe on the mid-plane near a GDC anode indicated the film deposition thickness was about 70 nm per application with B/C ratios of 0.37 and D/(B+C) ratios of 0.63 [6]. More recent results from a toroidal array of coupons indicate about a factor of 5 variation in deposition thickness measured on the mid-plane; the thickest deposition occurred on a coupon between the injection point and a GDC anode. Reference D_2 discharges before and after the first boronizations showed about a 94% reduction in centerline oxygen luminosity, and about a 50% decrease in carbon luminosity [7]. The loop voltage was reduced by 20-30%, during the plasma current flat top, and ohmic flux consumption during current ramp-up decreased by 20%, extending the duration of the plasma current flat top by about 70%. The D_2 density limit increased from approximately 60% of the Greenwald limit scaling to about 75%-80% after boronization, and the He density limit increased from 75% to 100% of the Greenwald limit scaling. Access to H-mode plasmas occurred after the 3rd boronization. The peak H-mode energy confinement exceeded 100 ms and the highest toroidally averaged Beta exceeded 25% [9]. More recently, toroidally averaged values of toroidal beta have reached about 31% [2]. HeGDC/TMB has been applied on 16 separate occasions, or about every 300-400 discharges. Fiducial discharges performed between boronizations indicate that HeGDC boronization consistently reduced oxygen and carbon and improved performance. Fig.1 shows the reduction in oxygen and carbon luminosities for boronizations 1 through 5.

2. HeGDC Between Discharges

HeGDC has been applied each morning for about 20-30 minutes prior to the start of operations. In addition, HeGDC applied between discharges was found to significantly enhance impurity control during NBI discharges and density control in ohmic plasmas [6]. Typical NSTX discharge repetition rates are between 7-12 minutes. Using pre-ionization filaments, HeGDC can be initiated between discharges at the subsequent operating pressure (4 mTorr) and bias voltage (400V) [8], and applied for 5 to 10 minutes depending on the experimental needs. RGA spectra measured before and after between-discharge HeGDC indicate about a net factor of ~10 reduction in D_2 fuel gas, and H_2O and CO that had presumably diffused to PFC surfaces by power deposition during a discharge**.**

3. Bake-out to 350 °C Aided by D_2GDC and HeGDC Impurity Removal

After the 10th boronization, a new bake-out system was used to perform a uniform bake-out of the PFC's to 350 °C with the vacuum vessel at 150 °C. The inner PFCs are heated resistively by passing current through the inner inconel tube of the vacuum vessel while the outer PFCs are heated by circulating high-pressure helium through internal tubes. The nominal plasma-facing area of the vessel interior is 41 m^2; about 75.6% (31 m^3) consists of graphite tiles and the remaining 24.4% is vessel wall (304-SS). The mass of the graphite PFC's is $1.3x10^3$ kg. During vessel bake-out, the PFC temperature is raised from room temperature to 350 °C over 1 day; the 350 °C phase proceeds for about 2-3 days, and 1 day is used to cool down to room temperature. During the entire bake-out, the vessel is pumped at the normal rate of 3.4×10^3 l/s (for D_2). The rate of temperature rise was chosen to minimize mechanical vessel stress. At this rate of temperature rise, the vessel base pressure peaks in the range from about $5x10^{-5}$ Torr to $5 \, x10^{-4}$ Torr (depending on the recent vacuum history) and is dominated by the partial pressures of mass 18 AMU (water) and to lesser extent mass 28 AMU (CO). Typically, after the maximum in base pressure is reached at 350 °C, the subsequent decrease in the primary partial pressure components at constant temperature is exponential with at least 2 time constants. The water desorption, for example, decreases a factor of 2 in 4.5 hrs, which after 8 hrs of D_2GDC and 8 hrs of HeGDC, becomes much slower, with a decrease of a factor of 2 in 35.8 hrs. The CO desorption is slower than that of water, decreasing a factor of 2 in 8 hrs, which after GDC decreases a factor of 2 in 35.8 hrs. The initial fast desorption rate of these partial pressures may be due to the liberation of lightly-adhering, near-surface gases, while the slower desorption rate, may be due to volume diffusion to the surfaces. It was found that a 350 °C bake-out by itself was insufficient to obtain the desired reductions in spectroscopic oxygen and carbon but that boronization following bake-out was essential to obtain a very strong and lasting effect on oxygen suppression (Fig.2 shows the relative intensities of O and B for discharges before and after Bake-out and subsequent boronization). In addition, a similar trend occurred in the discharged-average H/D ratio for deuterium discharges which decreased from values exceeding 0.2 for some discharges, to below 0.05 after bake-out followed by boronization, and continued decreasing. This behavior can be understood as due to possible insufficiently baked water sources, and to the ongoing diffusion of hydrogen containing impurities from the large PFC bulk volume to the near-surface region where fast desorption and plasma sputtering occur.

4. Plasma Boronization: Fueling With 90%He and 10% TMB

Previously, it was found that boron gases injected into the plasma edge of large aspect-ratio tokamaks re-boronizes plasma-wetted surfaces and improved plasma performance [10,11]. More recently on PISCES [12], the injection of carborane ($C_2B_{10}H_{12}$) into the plasma edge resulted in very high boron film deposition rates on target samples (up to 30 nm/s). This was attributed in part to high rates of ionization and dissociation of the injected carborane, and to good transport of the products to the plasma wetted target. Motivated by these results, NSTX has performed preliminary investigations of the re-boronization of plasma eroded surfaces by direct injection of the 90% He and 10% TMB mixture into the edge plasma to determine its behavior in the close-wall NSTX geometry. This experiment was performed under relatively clean wall conditions (3 weeks after 7th boronization). Before and after the discharge fueling sequence, 0.8 MA Lower Single Null (LSN) Ohmic fiducial discharges, 0.9 MA NBI heated LSN fiducial discharges, and 1.0 MA NBI heated Inner Wall Limited (IWL) fiducial discharges were performed. Fig. 3 (top) shows the discharge fueling sequence for the direct injection of 90% He and 10% TMB into an 800 kA, D_2 Ohmic discharge. The fueling sequence was started with about 1 Torr-liter injected into the discharge. As the fueling reached 8 Torr-liters per discharge, about 75% of the discharge power was being radiated, and all the available inductive flux swing was used by the end of the current flat top. As the fueling reached 15.8 Torr-liters per discharge, the 800 kA fiducial discharge was only able to reach 500 kA with a short 75 ms flat top, at maximum available volt-sec consumption. This reduced performance at the highest fueling rates is attributed in part to excessive radiation and recycling by the He component in the fueling gas. In order to prevent radiative collapse of the discharge, the fueling for the subsequent 6 discharges was reduced to about 6 Torr-liters per discharge (11 discharges total). The total amount of injected TMB mixture (90% He and 10% TMB) was 65.9 Torr-liters. This corresponded to 17 mg of BC_3, and a deposition of thickness of only 0.2 nm if spread uniformly over the 40.1 m^2 PFC internal area. In PISCES (12) the injected fuel is promptly ionized and is then transported along field lines to plasma-wetted surfaces. In this case, the deposition thickness in a Lower

Single Null NSTX diverted plasma with 1 cm wide wetted widths on a divertor region of area 0.15 m^2, the deposition thickness would be 58 nm (assuming no re-sputtering), which is comparable to average thickness achieved in standard HeGDC-aided boronization. No experimental information is available at this time on the erosion coincident with the deposition. During the fueling sequence most of the vessel view-port shutters were closed to prevent possible depositions resulting in decreases in view-port transmission; the exceptions included the more distant spectroscopic view-ports. During the fueling sequence, it was found that edge O and C luminosities were comparable to before TMB fueling, within the limited statistics, due to the initially clean conditions (Fig.3). Core oxygen was reduced, and as was found previously in larger aspect ratio tokamaks [10,11]. Edge fueling with the TMB mixture did not increase core B V and C VI for the close-wall NSTX geometry (Fig.3). Plasma boronization lead to better ohmic performance. A comparison of NBI heated Center-Stack Limited (CSL) discharges found plasma boronization lead to lower radiated power and steeper outer edge profiles. A comparison of LSN, 1 MA, 1.5 MW, NBI fiducial discharges before and after fueling showed ~50% decrease in central radiation. An NBI heated LSN diverted discharge following plasma boronization lead to lower radiated power and an H-mode transition not seen in the discharge before TMB fueling.

These plasma boronization results indicate that direct injection of relatively small amounts of 90% He/10% TMB leads to better plasma performance. No information on the duration of the improvements in performance *versus* discharge number, following the fueling sequence could be obtained due to the experimental schedule. However, it was found during the subsequent NBI LSN H-mode experiments that the preceding plasma boronization obviously facilitated the transitioning of discharges into the H-mode. The results from fueling with 90% He and10% TMB indicated that the presence of helium in the TMB fuel mixture injected into deuterium discharges at the highest fueling rates reduced performance, and that this was due in part to excessive radiation and recycling by the He component. Hence, this would make this fuel inconvenient to use for near-continual injection into every deuterium discharge for maintaining plasma performance. This motivated experiments using pure TMB fueling to optimize re-boronization and to investigate the effects of cladding the plasma edge in a low-Z mantle

5. Plasma Boronization: Fueling With 100%TMB

An initial fueling experiment was performed by injecting 100% pure TMB into deuterium discharges. About 185 mg of boron compound was deposited in the fueling sequence shown in Fig. 4 (top). Initially, each TMB fueling discharge was followed by an NBI fiducal discharge to allow characterization of incremental changes. Later in the TMB fueling sequence, NBI fiducial discharges were taken only after sequences of 4 to 10 fueling discharges. It was found that the fraction of radiated power to total power during NBI fiducial discharges before and after the fueling sequence remained about the same at about 0.11. This is suggestive of the possible screening of the B and C components of TMB molecules discussed previously [10]. In addition, it was found that although the oxygen and carbon impurity levels decreased initially, and that the plasma performance continued to improve during the fueling sequences, these O and C luminosities remained relatively high. Fig. 4 shows that the O VIII/C VI luminousity ratio decreased relative to the NBI fiducial discharges by about a factor of 2. This may be due in part to a decrease in temperature during the TMB fueling discharge. Analysis of filtered USXR spectra indicates that about a 30% reduction in central T_e occurred. Additional analysis of this and the influence of possible transport effects is awaiting future measurements of impurity profiles. Although starting from cleaner wall conditions would have been desirable, it is noteworthy that there was sufficient improvement in edge conditions that one of the highest central electron temperatures $T_e(0) \sim 1.6$ keV in NBI heated discharges to date was observed in a fiducial discharge following a TMB fueling sequence (Fig. 5).

6. Conclusions

It has been found that high temperature bake-out (350 °C) is needed to expedite the removal of water and CO absorbed on the plasma facing surfaces and near-surface regions of the graphite PFC's. Daily HeGDC and inter-discharge HeGDC are required for impurity and density control during high power operations. Experiments exploring the potential for real-time maintenance of boron films and the effects of cladding the plasma in a particular low-Z mantles have shown interesting promise and will be continued. The wall conditioning effort described in this work has facilitated a broad range of encouraging advances.

Acknowledgements

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Figure Captions

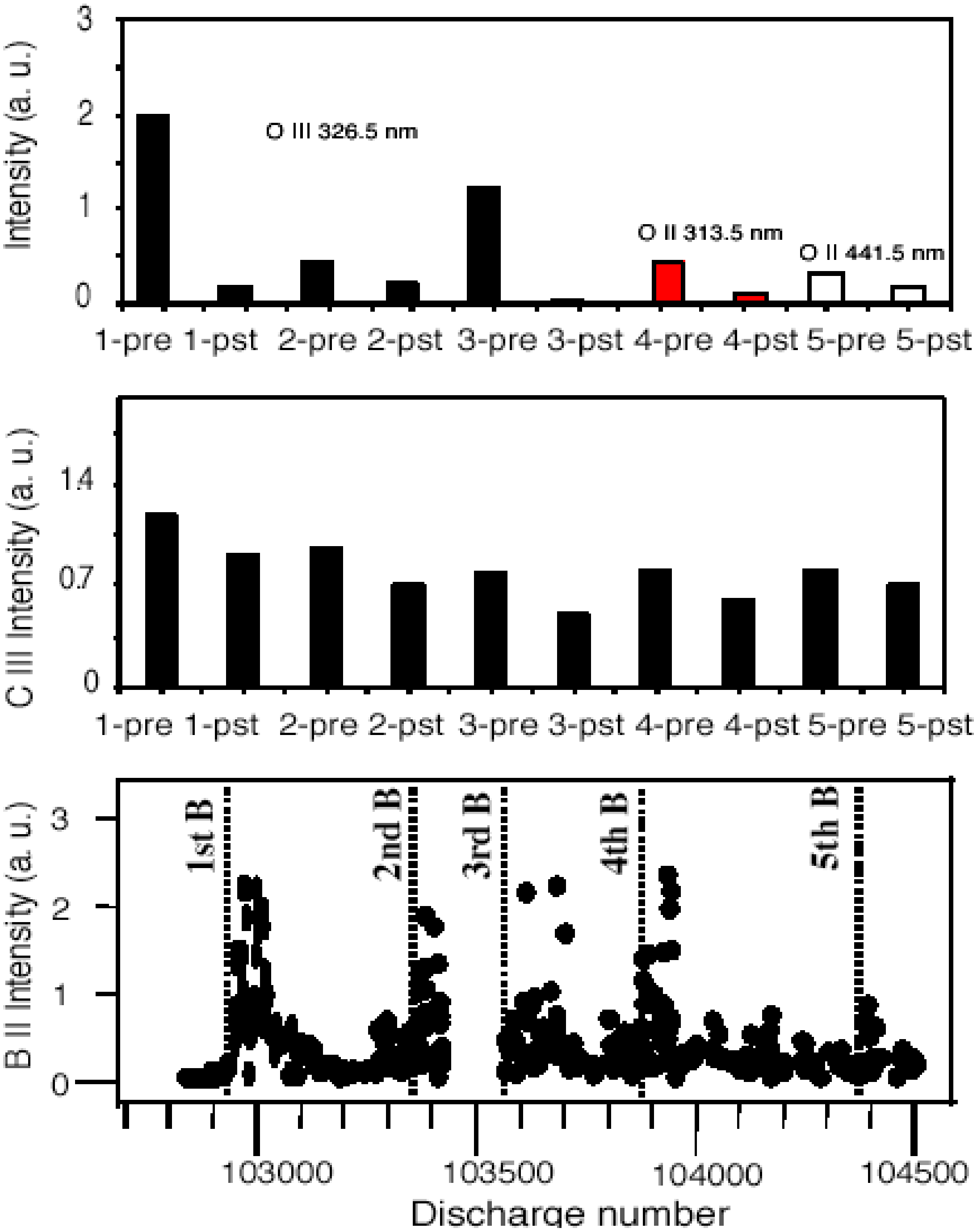
Figure 1. Oxygen and carbon luminosities for boronizations 1 through 5. GDC boronization with deuterated TMB consistently reduced oxygen and carbon. The results are must comparable for a given boronization because some change in the fiducial discharges occurred between boronizations.

Figure 2. Relative intensities of O VIII/C VI (top) and B V /C V (bottom) for discharges before and after Bake-out and subsequent boronization.

Figure 3. The 90% He-10% TMB fueling discharge sequence (top), and oxygen, carbon, and boron luminosities. The clean initial edge conditions were only marginally improved. Edge fueling with TMB did not increase B V and C VI.

Figure 4. The TMB (100%) fueling discharge sequence (top), and the oxygen, carbon, and boron relative intensities.

Figure 5. Comparison of electron temperature, and pressure profiles for one of the highest central electron temperatures, $T_e(0)$~1.6 keV achieved in NBI heated discharges observed in a fiducial discharge following a TMB fueling sequence (solid), and a fiducial discharge of the same density before TMB fueling started (dashed).



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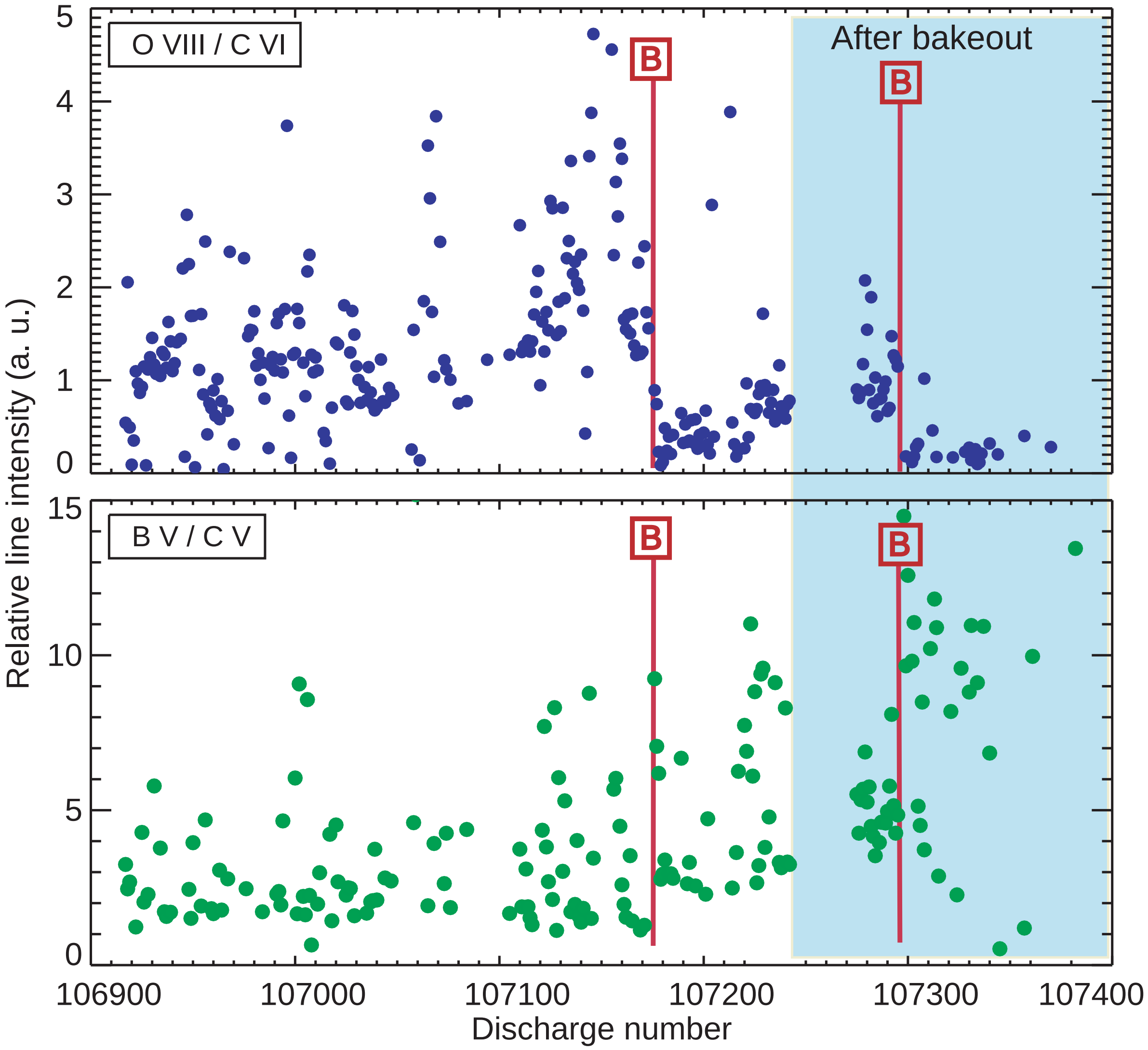
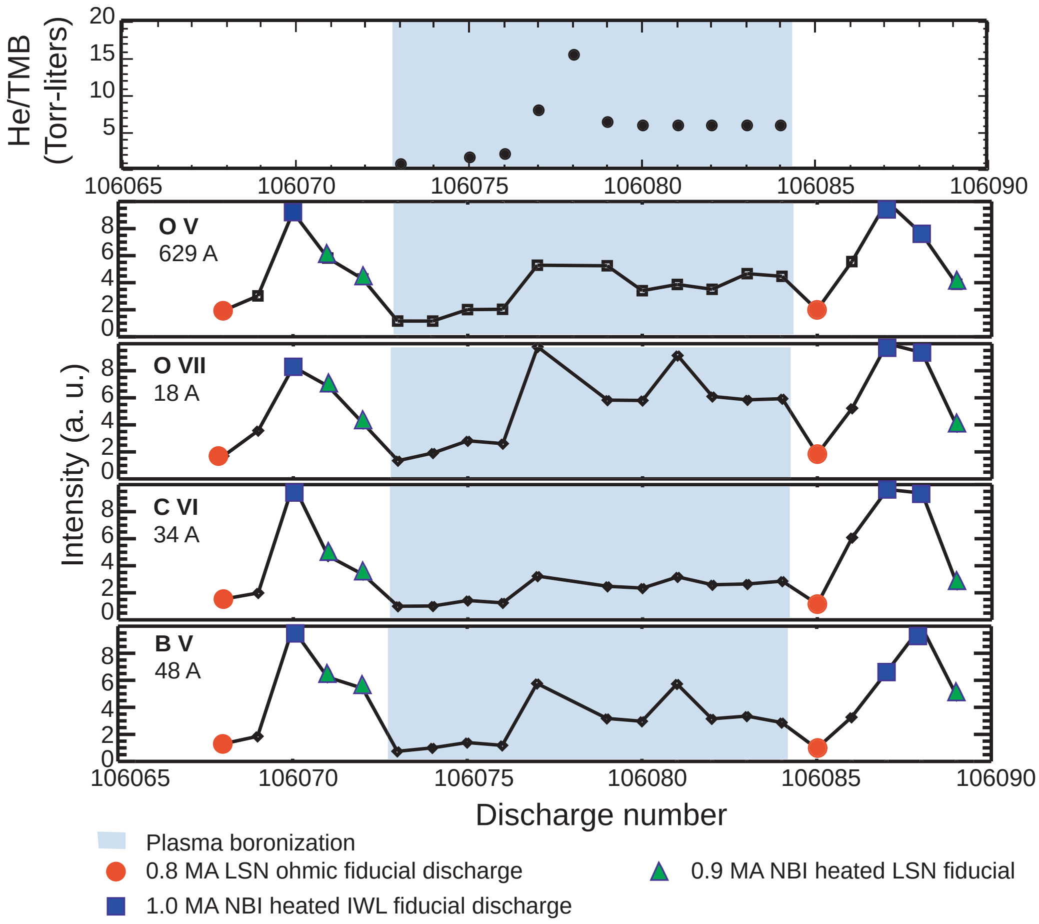


Fig.2. Relative intensities of O VIII/C VI (top) and B V /C V (bottom) for discharges before and after the Bake-out and subsequent boronization.



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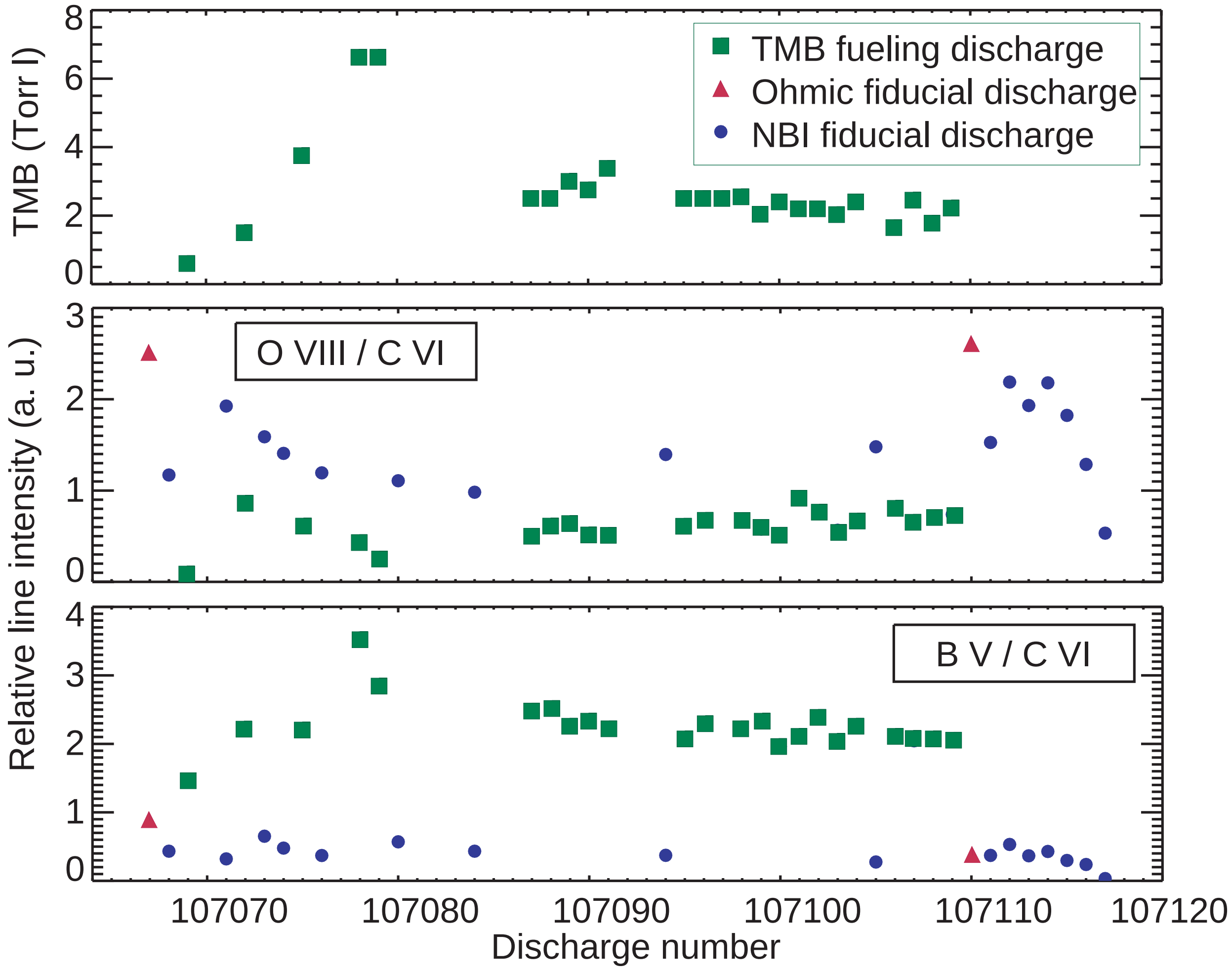

Fig.4 The TMB (100%) fueling discharge sequence (top), and the oxygen, carbon, and boron relative intensities.

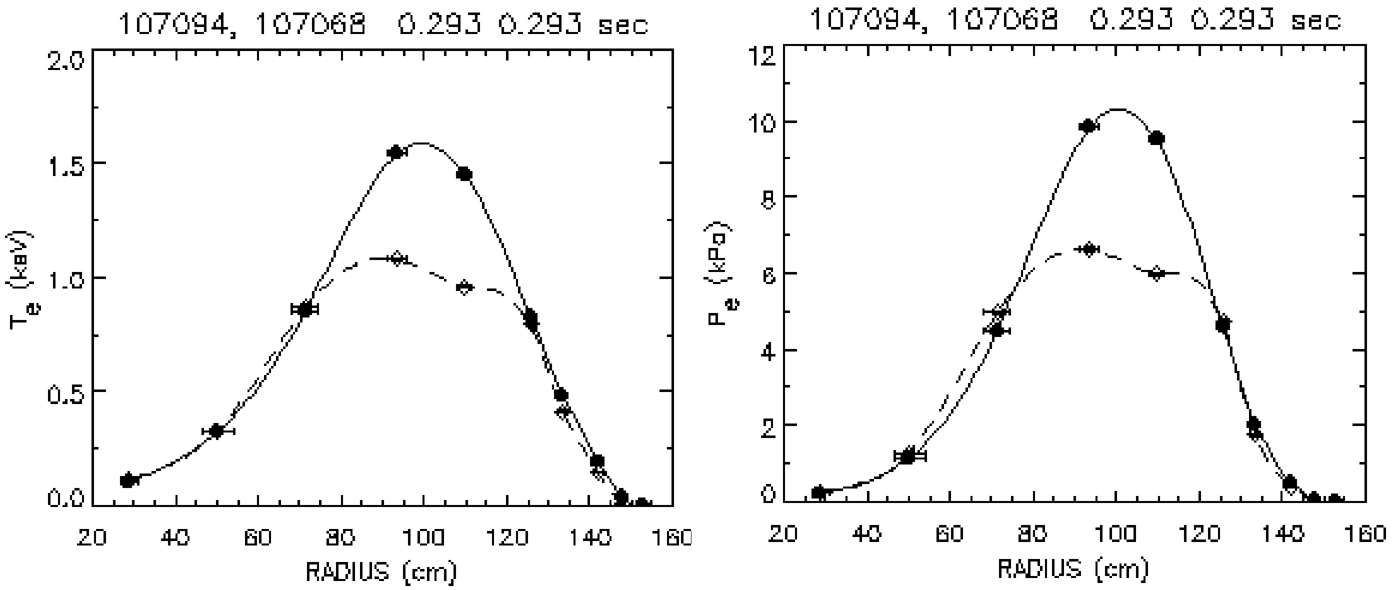

Fig.5. Comparison of electron temperature, and pressure profiles for one of the highest central electron temperatures, $T_e(0)$~1.6 keV achieved in NBI heated discharges observed in a fiducial discharge following a TMB fueling sequence (solid), and a fiducial discharge of the same density before TMB fueling started (dashed).

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