Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Nuclear Materials 337–339 (2005) 495–499

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Development of NSTX particle control techniques

H.W. Kugel [a,*], R. Maingi [b], M. Bell [a], D. Gates [a], K. Hill [a], B. LeBlanc [a], D. Mueller [a], R. Kaita [a], S. Paul [a], S. Sabbagh [c], C.H. Skinner [a], V. Soukhanovskii [d], B. Stratton [a], R. Raman [e]

[a] *Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543, USA*
[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[c] *Columbia University, New York, NY 10027, USA*
[d] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[e] *University of Washington, Seattle, WA 98195, USA*

Abstract

Density control in NSTX, involves primarily controlling impurity influxes and recycling. We have compared boronization on hot and cold surfaces, varying helium glow discharge conditioning (HeGDC) durations, helium discharge cleaning, brief daily boronization, and between discharge boronization to reduce and control spontaneous density rises. Access to Ohmic H-modes was enabled by boronization on hot surfaces, however, the duration of the effectiveness of hot and cold boronization was comparable. A 15 min HeGDC between discharges was needed for reproducible L–H transitions. He discharge conditioning yielded slower density rises than 15 min of HeGDC. Brief daily boronization followed by a comparable duration of applied HeGDC restored and enhanced good conditions. Additional brief boronizations between discharges did not improve plasma performance, if conditions were already good. Between discharge boronization required increases in the NSTX duty cycle due to the need for additional HeGDC to remove codeposited D.

PACS: 52.25.Vy; 52.40.−w; 52.40.Hf; 52.55.Fa
Keywords: Wall conditioning; Impurity control; Glow discharge cleaning; Discharge cleaning

1. Introduction

The investigation of non-inductive current drive with the goal of eliminating the central solenoid from future machines is a major focus of international Spherical Torus research and the National Spherical Torus Experiment (NSTX) program [1]. Elements of the NSTX current drive research program include High Harmonic Fast Wave (HHFW) current drive (~100 kA achieved) and Coaxial Helicity Injection (CHI) (400 kA achieved). Integrated scenario modeling of NSTX HHFW current drive discharges [2] shows that an average plasma density less than $n_e \sim 3 \times 10^{19}\,m^{-3}$ is optimal for acceptable HHFW current drive efficiency. However, during long-pulse NBI-heated H-modes, the density rises continuously, reaching up to $n_e \sim 7 \times 10^{19}\,m^{-3}$ in 0.3 s. Analysis of the time dependence of these density rises [3] has

---

[*] Corresponding author. Tel.: +1 609 243 3146; fax: +1 609 243 3248.
E-mail address: hkugel@pppl.gov (H.W. Kugel).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.10.065

found $\tau_p^* \sim 0.5$ s or $\sim 10 \times \tau_E$. It has become evident that the existing NSTX particle control techniques [4,5] of gas puffing, high temperature PFC bakeout, boronization on room temperature substrates, and brief HeGDC wall conditioning between discharges need augmenting to provide plasma density control for longer pulse operation.

We report on a comparison of boronization on hot and cold substrates, brief daily boronization, between discharge boronization, extended HeGDC between discharges, and He discharge conditioning to reduce and control spontaneous density rises, and in particular control τ_p^* for improved HHFW current drive efficiency, as well as, for transport studies, and power and particle handling research.

2. Comparison of boronization on hot and cold surfaces

The NTSX plasma facing surface is about 41 m^2, consisting of graphite tiles on power handling surfaces (75.6%), and the 304-SS midplane vessel wall (24.4%). During bakeout following a vent, the graphite is baked to 300–350 °C and the vessel walls to 150 °C. 25 boronizations have been performed on the room temperature plasma facing surfaces using 10 g of deuterated trimethyl boron ($B(CD_3)_3$) injected into a HeGDC [6]. A typical boronization is applied in about 140 min, and is followed by 2 h of HeGDC to remove the codeposited deuterium from the deposition layer. Based on machine performance and spectroscopic signals indicative of relatively higher impurity luminosities, these boronizations have been performed in NSTX most typically about every 200–400 discharges or about every 2–3 weeks for I_p pulse lengths of less than 1 s and duty cycles of 10–20 min between discharges. However, boronization has been applied even more frequently, if necessary, to restore wall conditions when severely degraded following particular experiments. Although such room temperature boronization has been effective in enabling high performance in NSTX to date [4,5], a test of boronization on high temperature substrates was made. The goal of testing the effectiveness of hot boronization on graphite surfaces (300–350 °C) and the vessel wall (150 °C) was to determine if changes in codeposition, deposited film microstructure, and uniformity could reduce impurity traps and, hence change recycling. A hot boronization was performed after pump-down, following a brief venting of the vessel. The hot and cold (room temperature) boronizations were compared using D lower single null (LSN), 600 kA plasma current (I_p), Ohmic, and LSN, I_p 800 kA, NBI fiducial discharges.

Following hot boronization, a significant improvement in the performance of the initial Ohmic and NBI fiducial discharges was observed relative to those following cold boronization. The Ohmic fiducial discharges exhibited the most favorable Ohmic performance to date. The previously elusive Ohmic H-mode was achieved after the 2nd discharge, and maintained in many discharges thereafter. This relatively facile transitioning to the Ohmic H-mode may be related to the lower D_α luminosity observed after hot boronization, which may in turn be due to less retention of codeposited D_2 during boronization on hot surfaces, and possible reduced porosity and trapping sites in depositions on higher temperature surfaces. Laboratory work has indicated that boron films grown at high temperatures exhibit characteristics that imply a different microstructure [7,8]. The D LSN NBI fiducial discharges exhibited the most promising first-day-NBI operation to date following a vent. However, although the first NBI fiducial discharges transitioned easily to H-modes, these discharges exhibited a D_α luminosity comparable to NBI discharges following cold boronization. This may have been due to the D_2 wall loading resulting from the 56 Ohmic discharges that preceded the D LSN NBI fiducial discharges. However, while the initial performance of NBI fiducials following hot boronization was significantly improved relative to cold boronization, as the fluence to the wall increased with succeeding NBI discharges, the operating conditions following hot boronization deteriorated (increased recycling, increased impurity luminosities, later L–H transitions, shorter I_p flattops, lower stored energies), and became indistinguishable from those following cold boronization. These results may indicate that as the fluence to the wall increased, erosion and similar changes to the deposition microstructure eventually dominated over the initial deposition conditions. Fig. 1 shows the behavior of the

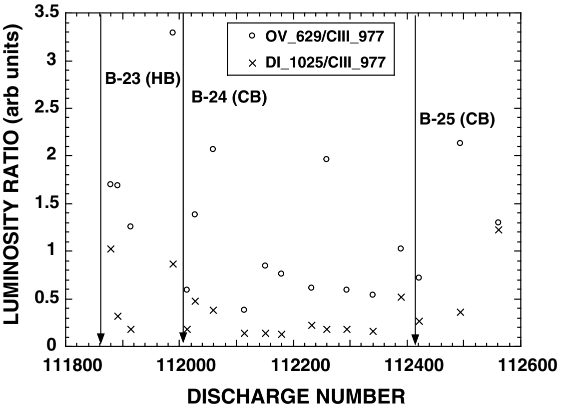

Fig. 1. Core luminosity ratios for LSN NB fiducial discharges after hot (B-23) and cold (B-24, B-25) boronization. The wider interval following B-24 included many cycles of the discharge clock for field-only tests and data acquisition tests without plasma. The differences in impurity behavior following each boronization resulted from the differences in power deposition and plasma configurations used for these experiments.

core luminosity ratios for LSN NB fiducial discharges after hot (B-23) and cold (B-24, B-25) boronization. The wider discharge number interval following B-24 included many cycles of the discharge timing clock for field-only tests and for data acquisition tests without plasma. The differences in impurity behavior following each boronization (Fig. 1) resulted from the differences in power deposition and plasma configurations used for the various experiments. Following B-23 and B-25, for example, wall conditions deteriorated more rapidly following high power, long pulse experimentation as compared to more unchanging configurations used for the H-mode threshold studies following B-24.

3. Comparison of applying HeGDC between discharges and helium discharge conditioning

The duration of between discharge HeGDC was varied from 7 to 15 min to investigate ways to optimize conditions for density control, boundary physics characterization experiments, and sensitive studies of early H-mode access as a method for limiting rapid penetration of the current density during ramp up to achieve access to $q_{\min} \gg 1$. In summary, it was found that at least a 15 min HeGDC between discharges was needed for reproducible timing of the L–H transition. Shorter HeGDC applications were found to delay the L–H transition, and could eventually result in a higher L–H power threshold by mid or latter part of run day. Fig. 2 shows how the time of the L–H transition moves earlier in the discharge as the duration of the applied HeGDC was increased.

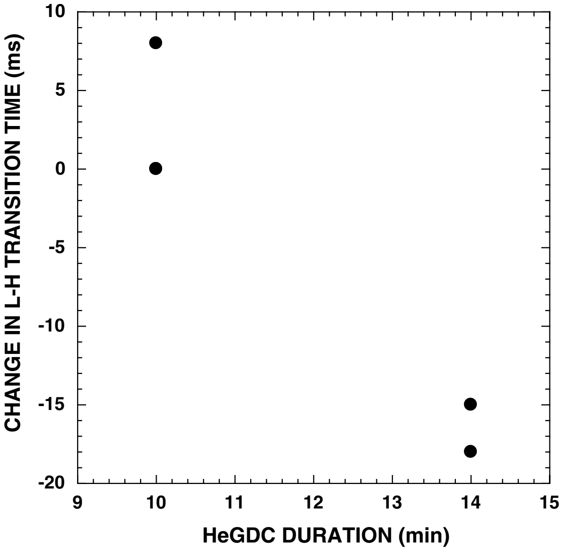

Fig. 2. The change in time (ms) of the L–H transition from the L–H transition in the preceding discharge. The L–H transition moves earlier in the discharge as the duration of the applied HeGDC is increased.

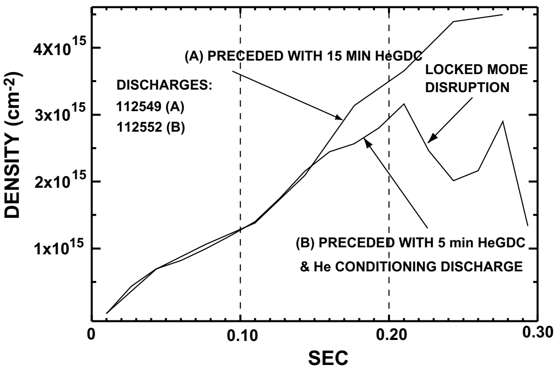

Fig. 3. Comparison of the density rise for D, LSN, NBI discharges after the application 15 min of HeGDC between discharges and a technique which applied a 5 min HeGDC followed by a He, DND I_p 500 kA, Ohmic conditioning discharge. Both D discharges transitioned to H-mode, but the D discharge preceded by the He conditioning discharge exhibited a lower density rise which caused a locked mode (rare in NSTX H-modes).

Fig. 3 shows a comparison of the density rise for D, LSN, NBI discharges after the application 15 min of HeGDC between discharges and a technique which applied a 5 min HeGDC followed by a double null diverted (DND), He, I_p 500 kA, Ohmic conditioning discharge. Both D discharges transitioned to H-mode, but the D discharge preceded by the He conditioning discharge exhibited a lower density rise which caused a locked mode (rare in NSTX H-modes). This lower density rise in NSTX is attributed to the more effective removal of absorbed deuterium in the walls, and the subsequent reduction in recycling, due to the intense and energetic wall conditioning of the He conditioning discharge as compared to that of only applying HeGDC as was also found on TFTR [9]. We intend to investigate if this result is due to the GDC geometry. This provides a prescription for slowing the rise in density during ramp up and improving density control for NSTX experiments sensitively dependent on wall recycling conditions.

4. Comparison of applying daily boronization and boronization between discharges

Experiments were performed to investigate ways that might stabilize conditions between standard full boronizations, and when conditions are good to determine if they could be improved. These experiments focused on the following questions: 'Is a brief daily boronization (e.g., in the morning, prior to daily operation) sufficient?

If brief daily boronization is good, is between discharge boronization even better? Does more frequent, briefer boronization improve reproducibility?'.

Brief daily boronization and between discharge boronization were tested about midway between 2 standard full boronizations. A standard full boronization on NSTX consumes 10 g of deuterated trimethylboron in about 140 min, followed by 2 h of HeGDC to remove codeposited deuterium. In order to determine the optimal balance between the duration of a brief boronization, the required HeGDC for desorbing the codeposited deuterium, and the subsequent fiducial performance, 5 brief boronizations were performed, ranging in duration from 1 min (7.2×10^{-2} g) to 17 min (1.2 g) followed by HeGDC applications ranging from 5 to 30 min. Fig. 4 shows the relative luminosities following a 17 min boronization followed by a 17 min HeGDC, and a 15 min boronization followed by a 30 min HeGDC using high performance LSN NBI fiducials. The 17 min HeGDC following the 17 min boronization was in about the same proportion as the 2 hr HeGDC following the standard full boronization applied in about 140 min. The longer HeGDC was applied after the 15 min boronization to test for the effect of additional removal of codeposited D. It was found that the luminosity ratios for Da/BII (measured at 0.250 s) exhibited the largest fraction change and indicated the presence of considerable residual D from the preceding discharges and the boronization. The BII/CIII luminosity ratio was relatively constant. This may be due to the signals having measured both the fresh and the residual passivated products (B and C) from previous standard boronizations, and hence, sampled approximately the same deposition stoichiometry. Fig. 5 shows the experimental sequence used for comparing the effect of various brief boronizations, different durations of HeGDC, and He conditioning discharges using D DND NB fiducials. In NSTX, preceding the D discharges with He discharge conditioning was more effective than HeGDC alone in restoring good conditions. The resultant conditions were later used to produce D LSN discharges with the highest stored energies for 4.5 MW NBI discharges to date (~300 kJ, $\tau_E \sim 45$–50 ms).

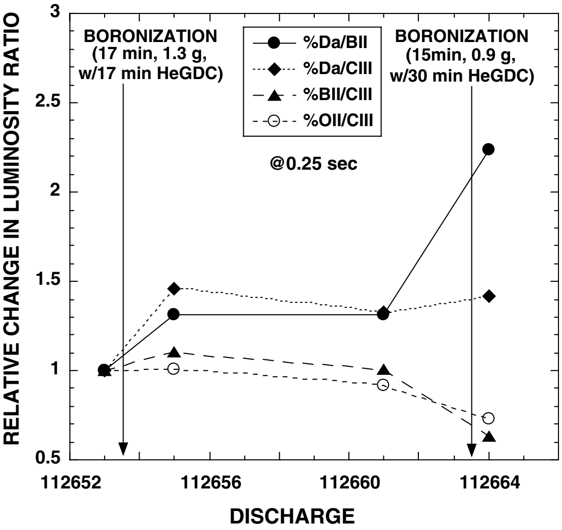

Fig. 4. Relative change in luminosity ratios following brief boronizations followed by a comparable duration of HeGDC to remove codeposited D.

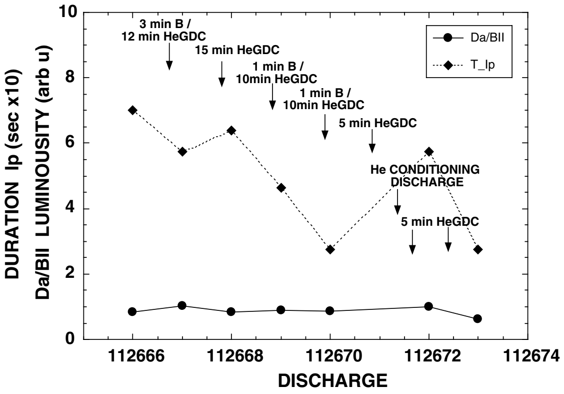

Fig. 5. Conditioning sequence for comparing the effect of various brief boronizations, different durations of HeGDC and He conditioning discharges using D DND NB fiducials.

5. Discussion

It was found that boronization on hot surfaces yields a significant improvement in initial operating conditions (lower recycling, lower impurity luminosities, earlier L–H transitions, longer I_p flattops, higher stored energies) relative to boronization on cold surfaces, but that the duration of the improved operating conditions following hot and cold boronization was comparable as fluence to the wall increased with succeeding discharges. A 15 min HeGDC between discharges was needed for reproducible L–H transition timing. In NSTX, preceding the D discharges with He discharge conditioning was more effective than HeGDC alone in restoring good conditions. This result is consistent with previous work on TFTR [9], although on other machines, HeGDC between discharges has been found to be sufficient. We intend to investigate if this is due to the NSTX GDC geometry. Brief daily boronization followed by a comparable duration of applied HeGDC restored and enhanced good operating conditions. Additional brief boronization between discharges with relatively good operating conditions produced no improvement. Between discharge boronization increased the normal NSTX 10–20 min duty cycle (for I_p discharges less than

1 s) due to the need to apply HeGDC for a sufficient duration to remove codeposited D. Remaining questions involve using between discharge sample analysis to measure changes in microstructure as fluence increases, determining the most sensitive fiducial discharges, and the optimal figures of merit for determining the frequency of applying brief daily boronization. In addition, more work is needed to determine the optimal balance between the frequency of applying boronization, the amount of boronization (duration), and the duration of the succeeding HeGDC for reproducible operating conditions and accessing high performance regimes.

Acknowledgments

This work is supported by US Department of Energy Contracts, DE-AC02-76CH03073, DE-AC05-00OR 22725, DE-FG02-99ER54523 and DE-FG03-99ER 54361, W-7405-ENG-48. We wish to acknowledge the technical contributions of W. Blanchard, J. Winston, T. Czeizinger J. Desandro, J. Gething, J. Kukon and the NSTX Engineering and National Research Teams.

References

[1] E. Synakowski et al., Nucl. Fusion 43 (2003) 1653.
[2] C. Kessel, in: Proceedings of the 20th IAEA Fusion Energy Conference, Vilamoura, Portugal, 1–6 November 2004.
[3] R. Maingi et al., Plasma Phys. Control. Fusion 45 (2003) 657.
[4] C.H. Skinner et al., Nucl. Fusion 42 (2002) 329.
[5] H.W. Kugel et al., J. Nucl. Mater. 313–316 (2003) 187.
[6] W. Blanchard et al., in: Proceedings of the IEEE/NPSS Symposium on Fusion Engineering in Atlantic City, NJ, 21–25 January 2002.
[7] S. Veprek et al., J. Nucl. Mater. 162–164 (1989) 724.
[8] J. Winter, Physical Processes of the Interaction of Fusion Plasmas with Solids, Academic Press, 1996, p. 217.
[9] J.D. Strachan et al., J. Nucl. Mater. 196–198 (1992) 28.