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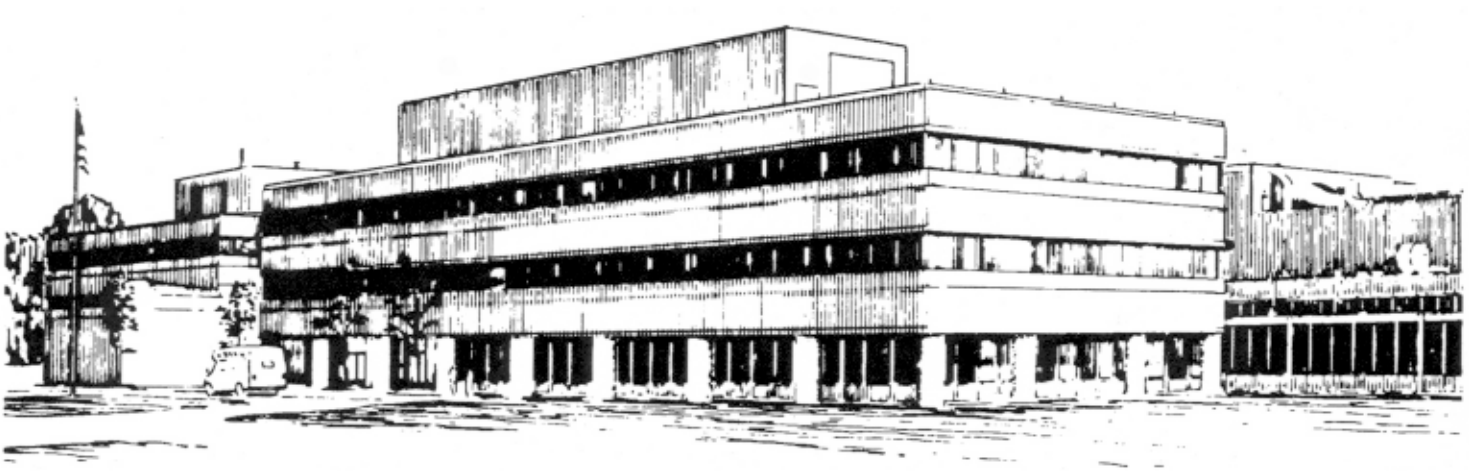

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Abstract:

Boronization of the National Spherical Torus Experiment (NSTX) has enabled access to higher density, higher confinement plasmas. A glow discharge with 4 mTorr helium and 10% deuterated trimethyl boron deposited 1.7 g of boron on the plasma facing surfaces. Ion beam analysis of witness coupons showed a B+C areal density of 10^{18} (B+C) cm^{-2} corresponding to a film thickness of 100 nm. Subsequent ohmic discharges showed oxygen emission lines reduced by x15, carbon emission reduced by two and copper reduced to undetectable levels. After boronization, the plasma current flattop time increased by 70% enabling access to higher density, higher confinement plasmas.

Keywords: wall conditioning, boronization, trimethylboron.

1. Introduction

Wall conditioning has proved to be key to achieving high performance in fusion devices[1]. The reservoir of particles in the wall surface typically exceeds that in the plasma by orders of magnitude and hydrogenic and impurity influx needs to be controlled to permit density control and minimize radiative losses. Wall conditioning techniques include baking and discharge cleaning to deplete the surface of trapped hydrogen, and coatings to modify the properties of plasma facing surfaces. One of the most successful wall coating techniques is the plasma assisted chemical vapor deposition of boron on plasma facing surfaces. This was pioneered at TEXTOR[2] using a radio frequency assisted glow discharge of 80% He, 10% CH_4

and 10% diborane (B_2H_6) that deposited a 40 nm thick amorphous boron/carbon film (a-B/C:D). This film gettered oxygen and resisted chemical erosion and led to tokamak discharges with significantly reduced oxygen and carbon impurities. Boronization using different boron compounds has led to a very high confinement mode (VH-mode) in DIII-D (diborane)[3] and improved access to the H-mode regime in C-mod (diborane) [4] and MAST (trimethyl boron)[5]. Diborane, in particular, needs special handling due to its explosive and toxic properties, but boronization using the less hazardous compound, trimethyl boron (TMB), $B(CH_3)_3$ was found to have similar effects [5,6,7]. A comparison of TMB and decaborane on Phaedrus-T showed three times lower core oxygen for TMB and about 40% higher edge carbon (CII) [8]. Boronization in tokamaks is reviewed in ref. [9]. A comprehensive review of plasma materials issues in next-step devices is presented in ref. [10].

The National Spherical Torus Experiment (NSTX) [11] began operations in February 1999. The research program is aimed at extending the understanding toroidal confinement physics at low aspect ratio in collisionless, high-β regimes and to demonstrate non-inductive current generation and sustainment[12,13]. A range of plasma shapes and configurations have been produced with plasma currents up to 1 MA, with stored energies up to 55 kJ in ohmic plasmas and over 90 kJ in initial experiments with neutral beam heating. The injection of 2 MW of High Harmonic Fast Wave power (HHFW) has produced electron temperatures up to 1.15 keV[14]. The magnetic field line geometry differs from conventional tokamaks in that the outboard edge field line pitch of 45° results in a shorter outer connection length from the midplane to the inner wall. The strong variation in the magnitude of the magnetic field is expected to result in a large mirror trapped ion flux in the SOL. The vacuum vessel of 304 stainless steel has a volume of 30 m^3 and area 41 m^2. It has internal copper passive stabilizing plates and divertor plates both covered with graphite tiles. The 0.2 m radius center column is clad with alternating vertical columns of graphite (Union Carbide, Type ATJ) tiles between columns of 2-D Carbon Fiber Composite (CFC) (Allied Signal, Type 865-19-4) tiles. As expected discharge reproducibility, density control and performance were strongly affected by wall conditions and variety of wall conditioning techniques have been employed[15]. The center column has been baked to 309 C by resistive heating. The divertor plates, passive plates and vessel wall have been baked to 150 C. Deuterium glow discharge cleaning (D-GDC) was found

to be effective in removing impurities from the wall, and helium glow discharge cleaning (He-GDC) for removing residual D. The short connection length on the outboard side and high mirror ratio are unique features of spherical tori and it is interesting to compare the response of NSTX to boronization to that of other machines.

2. Boronization

The NSTX glow discharge (GDC) system has 304-SS anodes at vessel bays K and G (Fig. 1). Deuterated trimethyl boron was used as hydrogen is incompatible with HHFW due to parasitic resonances. The midplane Bay L gas feed system was used to supply TMB and it was exhausted with the existing torus pumping system. To minimize pyrophoric risk, nitrogen was added to reduce the oxygen partial pressure in the exhaust line. Using one turbomolecular pump of the two pump system and with the vessel at room temperature, a standard He-GDC is initiated using a filiament preionization system with 4 mtorr gas pressure, 450 V, 1.5 A per electrode. After approximately 10 minutes of He gas feed, a mixture of 90% He and 10% TMB was added to the pure He in the gas feed. The process continued for about 160 m until the 10 g TMB cylinder was almost exhausted and resulted in about 100 nm thick a-B/C:D film. This was followed by 2 hours of He-GDC to remove co-deposited deuterium from the near surface region of the film and reduce D influx during subsequent high power plasmas. Residual gas mass analysis after boronization indicated a significant reduction in mass 18 (H_2O), mass 28 (CO), and hydrocarbons.

A polished silicon 25mm square sample coupon was located on the vessel wall (major radius, R=169cm) at Bay E and exposed to the first boronization. After boronization, the coupon was retrieved and the deposited film characteristics measured by ion beam analysis. The boron areal density was measured via the ^{11}B (^{1}H, ^{4}He) ^{8}Be nuclear reaction with a 650eV proton beam, deuterium by the ^{2}D (^{3}He,p) ^{4}He reaction with a 700 keV ^{3}He beam and carbon was measured by Rutherford backscattering with a 1500 keV proton beam. The ion beam probes the entire thickness of the film. Four analysis sites were spaced 5 mm apart on a line through the center of the coupon and the results are summarized in Table 1. The B+C areal density was 10^{18} (B+C) cm^{-2} corresponding to a film thickness of 100 nm, similar to the 96 nm calculated thickness of 10 g of TMB deposited uniformly over the $\approx$ 41 m^2 surface area of the vessel. The B/C ratio of 1/3 is consistent with the stoichiometric ratio in TMB (as in TEXTOR (0.38)[2], and

in COMPASS (0.46 on stainless coupons)[7]) while the D/(B+C) ratio was 2/3. The site to site variations are believed to be due to variations in local electric field geometry and possibly redeposition from nearby surfaces. A second coupon was located at R=217 cm at Bay E, beyond the vessel wall and was 477 mm behind a 25 mm aperture. This coupon showed no significant boron (detection limit $\approx 10^{14}$ cm^{-2}).

3. Plasma behavior

The emission from the plasma was monitored with a 0.5 m Czerny Turner spectrometer operating in the range 200 – 700 nm. The instrument was equipped with a reticon detector and the grating was set to monitor emission lines from different elements immediately before and after the boronization. The results are shown in Fig. 2. Frame (a) shows copper emission lines reduced to below the detection limit and oxygen emission reduced by a factor of 15 after boronization. The spectra were integrated over 0.12 – 0.16 s in discharges with similar electron density ($n_eL = 2.1 \times 10^{15}$ cm^{-2} pre- and 1.8×10^{15} cm^{-2} post-boronization). The second frame, (b), shows C II emission in the neighborhood of the (saturated) D-alpha line. The carbon emission is reduced by a factor of two. The second order copper impurity line at 3274Å disappeared after boronization. The line electron density was 1.9×10^{15} and 2.0×10^{15} cm^{-2} pre- and post boronization respectively. Boron emission lines e.g. at 3451Å were prominent after boronization. Oxygen levels after boronization remained low, unless there was a change in type of plasma operations (neutral beam injection, CHI[16], minor vent). Boronization has been repeated 5 times between intervals of 2-3 weeks.

The radiated power profile is measured from a tangential bolometer array located at the midplane. The multi-element detector is a 16-channel XUV diode array[17] and the volume-integrated power P_{rad} is determined using an equilibrium calculated from magnetic measurements, with the assumption that the radiated power density is constant along a flux surface. Before boronization P_{rad} was typically $\leq 40\%$ of the ohmic heating power and was reduced by a factor of two following boronization (Fig. 3). The reduction in impurity influx and radiated power mirrored the experience on other machines, and boronization was particularly useful in NSTX in suppressing copper impurities.

In a pair of comparison discharges, visible bremsstrahlung emission in a 10 Å region at 5230Å decreased by a factor of 2 after boronization. For the post-boronization discharge the line density was somewhat higher so the change corresponded to a factor of 3 decrease in Z-effective (Z_{eff}). Emission in this spectral region was also monitored by a fiberoptically coupled telescope viewing across the vessel at the midplane into the pump duct. The system was absolute intensity calibrated and checked against high density He discharges. Z_{eff} was calculated[18] from the intensity and the electron density and temperature as measured by Thomson scattering and was in the range $Z_{eff} \approx 2$ immediately following the first boronization.

Significant improvements in plasma performance were apparent after boronization in NSTX [12,19,20] as on other machines[9]. Figure 4(a) shows that the duration of the plasma current flat top increased by about 70%. This increase in flattop duration is particularly valuable in spherical tori because of limitations on the OH flux capabilities of the centerstack. Figure 4(b) shows that while the loop voltage temporal behavior was generally comparable pre- and post boronization, the loop voltage at time of highest stored energy (Fig. 4d) in the discharges was reduced by 30%. Fig. 4(c) shows that the volt-second consumption was indeed lower in the post boronization discharge. The combination of constant peak stored energy and the lower loop voltage lead to a 30% higher energy confinement time in the post boronization discharge. The origin of the lower loop voltage is probably reduced carbon, oxygen, and copper impurity levels post-boronization, which lead to a lower radiated power (Fig. 3 and 4(e)) and a reduced plasma resistivity.

A by-product of the longer flat top duration was access to higher densities[12]. The deuterium density limit increased from approximately 60% of the Greenwald limit density to about 75%-80% after boronization, and the helium density limit increased from 75% to 100% of the Greenwald limit. The confinement time increased with increasing density up to 45 ms at 4×10^{19} m^{-3} corresponding to 0.8 n_{eGW} but dropped to about 20 ms at the highest densities (5.5×10^{19} m^{-3}, 1.2 n_{eGW}). At the lower density range of NSTX, the confinement time was similar in pre- and post-boronized plasmas. However the density at which confinement 'rolled over' was higher post-boronization, for both deuterium and helium discharges[12]. It is notable that access to H-mode plasmas was enabled only after the third boronization, and H-mode plasmas generated after the 4^{th} boronization were extended from 8 ms to 65 ms. This suggests that subsequent

boronizations continue to incrementally improve wall conditions [21]. An improvement was also observed on C-mod after boronization where the reduction in radiated power led to a lower H-mode power threshold[4]. A quantitative understanding of complex link between the condition of the wall, the plasma edge and confinement remains obscure and the details hidden by the lack of real-time wall diagnostics[22].

In summary, boronization on NSTX was successful in increasing the current flattop time by 70%, reducing radiated power by a factor of two, reducing Z-effective by a factor of three, reducing oxygen impurities by a factor of x15 and copper impurities to below the detection threshold. These changed enabled access to higher density, higher confinement plasmas, including H-mode conditions.

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Table 1. The boron, carbon, and deuterium areal density after boronization.

Analysis site	B $10^{18}/cm^2$	C $10^{18}/cm^2$	D $10^{18}/cm^2$	B/C ratio	D/(B+C) ratio
1	0.268	0.703	0.600	0.38	0.62
2	0.219	0.675	0.582	0.32	0.65
3	0.238	0.697	0.592	0.34	0.63
4	0.315	0.744	0.637	0.42	0.60

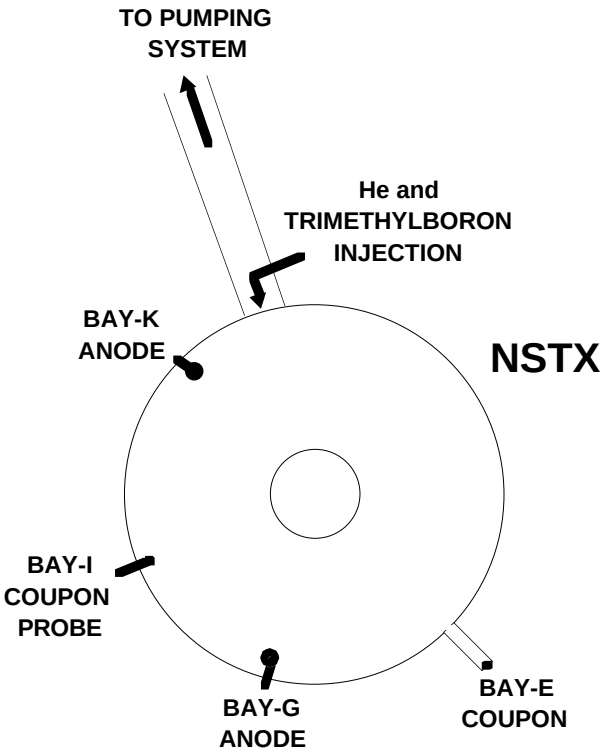

Figure 1 Plan view showing the experimental configuration of NSTX.

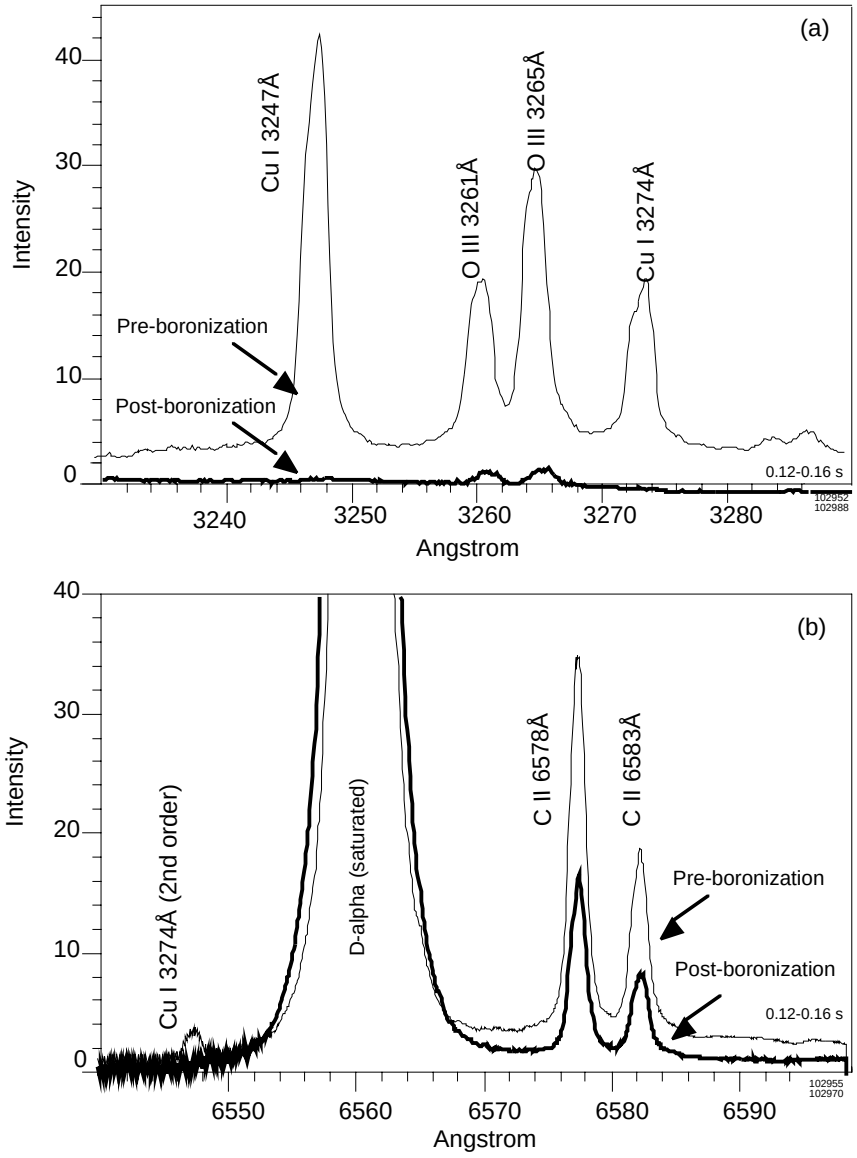

Figure 2 Comparison of impurity emission before and after boronization.

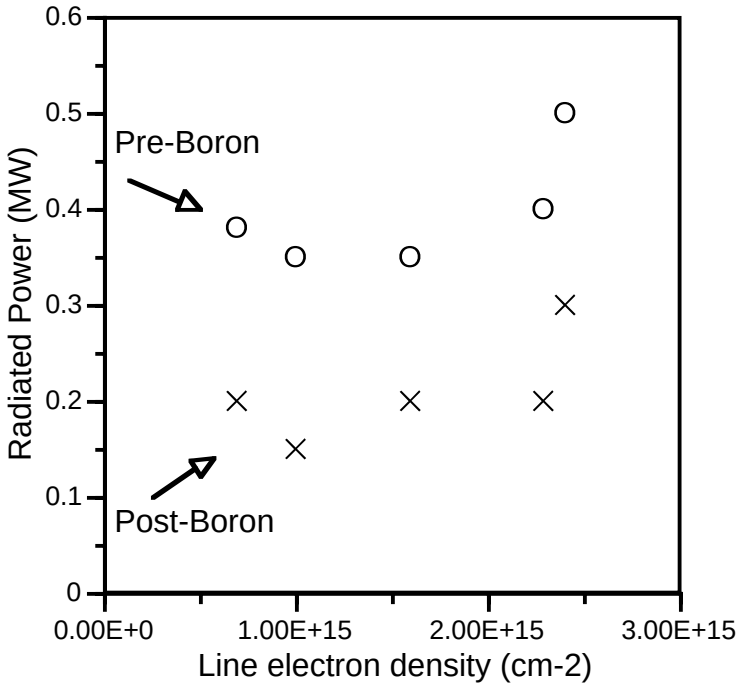

Figure 3 Change in radiated power on boronization.

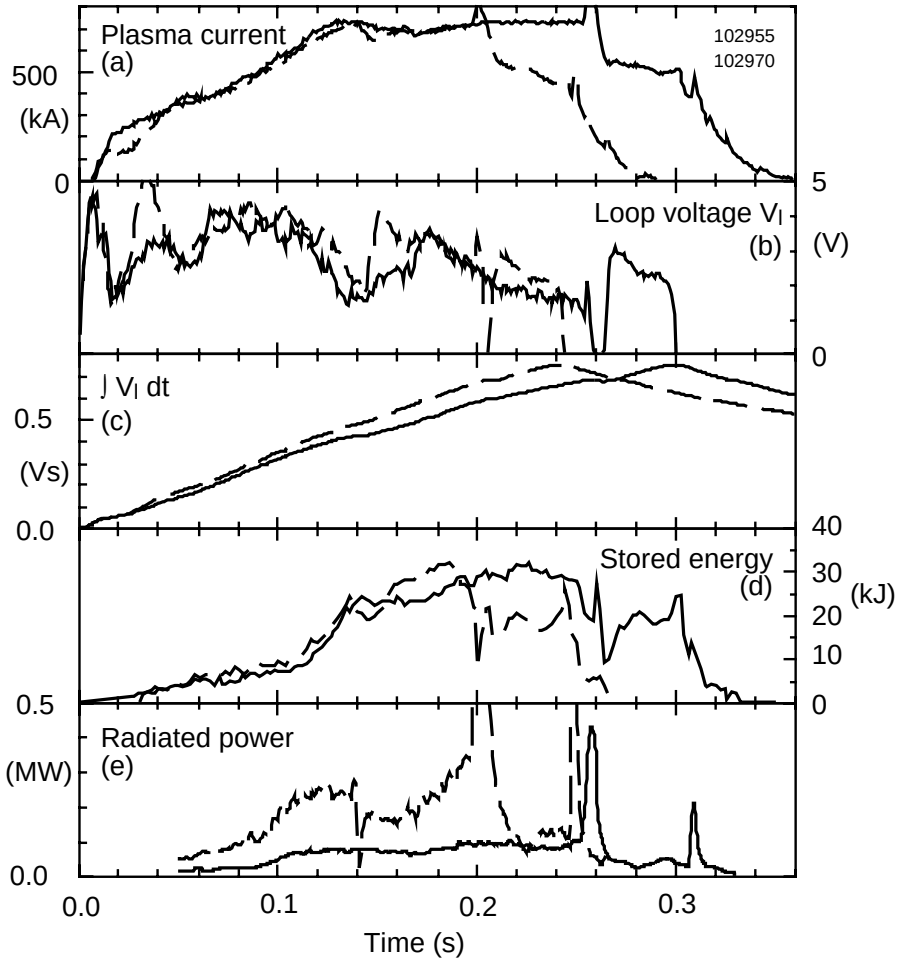

Fig. 4 Comparison of plasma parameters before and after boronization. The dashed trace is pre boronization.

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