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PLASMA IMPURITY CONTENT, GAS FUELING, AND EXHAUST ON DIII-D OVER EXTENDED PERIODS BETWEEN BORONIZATIONS

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GENERAL ATOMICS

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PLASMA IMPURITY CONTENT, GAS FUELING, AND EXHAUST ON DIII-D OVER EXTENDED PERIODS BETWEEN BORONIZATIONS

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W.P. WEST, M. GROTH,* A.W. HYATT, N.H. BROOKS, G.L. JACKSON,
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*Lawrence Livermore National Laboratory, Livermore, California.

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Abstract

During the 2006 and 2007 DIII-D experimental campaigns the rate of boronization events was reduced significantly from past campaigns with no detrimental effects on discharges, including high-performance hybrid and advanced tokamak discharges. Boronizations were completed early in both campaigns due to preceding entry vents. Over the three-month duration of each campaign, a database of edge and core impurity emission and fueling/exhaust rates from many hybrid discharges was developed that demonstrated little secular change over 7000 plasma-seconds of operations. After 6000 seconds, a set of seven sequential hybrid discharges was executed with no between shot Helium glow-discharge cleaning. While small effects on fueling and exhaust are observed, density remains controlled and fusion performance is held constant. These results, obtained with the all graphite wall on DIII-D, are promising for the next generation of superconducting, long-pulse tokamaks, where studies of stationary, high performance will be of great interest.

I. INTRODUCTION

The plasma edge and plasma-wall interaction community is well aware of the beneficial effects of low Z thin film coatings on the plasma facing surfaces of today's tokamaks. Their use has become very standard in large and small magnetic confinement devices. The use of boronization was initiated on DIII-D in the early 1990's [1,2] and continues to the present. For the best performance with little active pumping during plasma operation, it was found that frequent refreshing of the boronization film was useful, with a fresh film being deposited after 1000 to 1500 plasma-seconds of operation. During the past decade, the capability of active pumping on both the upper and lower divertors has been added, and the program emphasis has shifted from transient performance to the demonstration of scenarios with stationary high performance and scenarios that can extrapolate to true steady-state operation. Such scenarios are likely to be of great interest to the next generation of long-pulse tokamaks such as EAST, K-STAR, SST, and JT-60SA. However, pulse lengths and duty cycles on these devices will be much longer than on DIII-D, and this brings into question the use of thin films for wall conditioning. In 2006 a program to investigate operation of DIII-D with a significantly reduced rate of boronization was initiated. At the same time, the high performance hybrid scenario was of growing interest to the ITER program, and this scenario was frequently used on DIII-D for many physics experiments, allowing the development of a database of performance and impurity content over the long campaigns with no intervening boronizations.

A daily reference shot was also initiated near the beginning of the 2006 campaign, used as a tool to monitor any secular changes in the impurity and fueling signatures in an otherwise well repeated discharge. Data related to the core plasma impurity content and fusion performance parameters, over the course of the 2006 and 2007 campaigns, has been presented in a previous paper [3]. Core plasma performance was shown to have little or no secular trends over the 7000 plasma seconds of operation in each campaign. In this paper we will focus on secular changes in divertor and scrape-off layer (SOL) spectroscopy, comparing to related core spectroscopic signatures, using both the daily reference discharges and the hybrid discharges. In addition, a special set of seven sequential hybrid discharges were repeated without the usual between-shot helium glow-discharge cleaning. We will also present a brief discussion on the short-term secular changes observed in the first 300 plasma seconds after a boronization event.

II. DAILY REFERENCE DISCHARGES

A daily reference discharge was developed to monitor long-term trends in impurity line emission over the duration of these campaigns. The daily reference shots, described in more detail in reference [3] have both L-mode and ELMing H-mode phases. The secular trends as a function of plasma operating time since the previous boronization from the C III emission at 465 nm in the L-mode phase are shown in Fig. 1(a-d) and compared to C VI charge exchange emission from the core plasma [Fig. 1(e)]. The intensity is measured using an array of fiber optics with a narrowband interference filter and a photomultplier system [4], viewing from above onto the outer divertor strike zone region (a) and inner divertor strike zone (b), on the midplane center post viewing radially inward (c), viewing tangentially through the outer SOL at the midplane (d). The measured emission intensity, averaged over a 100 ms period during each shot, is plotted as a function of the total plasma operating time since the previous boronization. The different symbols distinguish four different periods during the 2006 and 2007 campaigns as described in the caption. Linear regression fits to the post-boronization data from 2007, over the 700 to 7000 plasma-seconds time range, are shown as green lines. During the L-mode phase the plasma density is held constant by feedback control of the gas puffing and the neutral beam heating is fixed. In 2007 the set point for the L-mode density was dropped by 20% compared to the 2006 campaign. From the fits to the 2007 data, the secular trends are weak, some increasing and some decreasing in time. Table I shows the change from the beginning of the fit to the end of the fit range, normalized to the initial value, for these L-mode data and for data from the H-mode phase of the daily reference shot. In the H-mode phase the increase in the edge and divertor C III line intensities is significant, reaching almost a factor of 2 in the main chamber SOL, yet there is only a minor increase in the total radiated power and an slight decrease in the core carbon contamination. A slight decrease in the molecular CD emission from the divertor is also observed. The total radiated power is typically about 30% of the injected beam power in the H-mode phase of the daily reference shots. The small decrease in the core carbon content during the H-mode phase does not seem to be associated with a general decrease in H-mode confinement, as a fit to the plasma stored energy shows no change (<1% increase) over the course of each campaign.

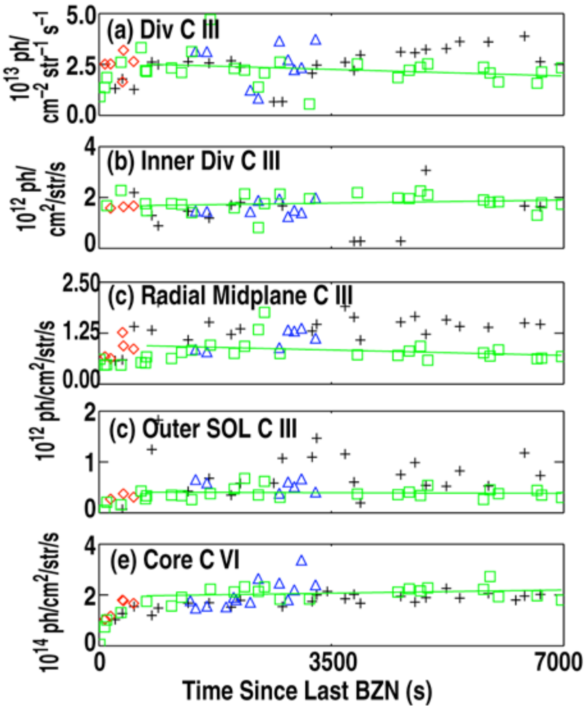

Fig. 1. Divertor and SOL C III emission from the L-mode phase of daily reference shots over the course of the 2006 and 2007 campaigns, plotted as a function of the total plasma seconds of operation since the previous boronization. The different symbols distinguish four different periods: + from 2006 following the first boronization; ◇ from 2006 following the second boronization late in the campaign; △ from 2007 after the maintenance vent but before the boronization in 2007; □ from the post-boronization period in campaign 2007. Linear regression fits to the post-boronization data from 2007, over the 700 to 7000 plasma-seconds time range are shown as green lines.

Table I
The fractional change of edge and divertor C III emission over elapsed plasma operating time of 700 to 7000 seconds since a boronization from the 2007 campaign (L-mode) and from both campaigns (H-mode) along with the fractional change of the molecular CD emission, the radiated power and the core carbon content obtained from linear regression fits to the data, along with the estimated error

Period	Outer Divertor	Inner Divertor	Radial Midplane	Outer SOL	Radiated Power	Core Carbon Content	Peak CD
L-mode	-0.23±20	+0.13±0.14	-0.25±0.19	-0.05±0.18	-0.16±0.6	+0.11±0.10	
H-mode	+0.58±0.19	+0.11±23	+0.76±0.37	+0.58±23	+0.09±0.09	-0.10±0.13	-0.04±0.05

III. HYBRID DATABASE

The hybrid database from the 2006 and 2007 campaigns includes about 300 discharges that achieved hybrid-like conditions. These discharges comprise a wide variety of plasma shapes, current, toroidal field, and auxiliary heating. To show the consistency of high-performance operation, shots were selected with a high performance phase of at least 2.5 s duration, q_{95} between 4.0 and 4.5, the injected beam power of at least 95% in the co-current direction, the line averaged density below 5×10^{19} m^{-3}, and the ion ∇B drift direction away from the dominant X-point. The resulting 44 shots were taken from 18 plasma-seconds to 6075 plasma-seconds after the previous boronization. The fusion performance factor, $\beta_{\rm N}H_{89}/q_{95}^2$, ranges between 0.3 and 0.4 in these discharges with no noticeable secular trend across the campaigns. Several shots with good fusion performance from the post-vent/pre-boronization period early in 2007 are included. The edge emission from the outer midplane of O V and C III [Fig. 2(b) and 2(d)], as measured by a VUV spectrometer is compared to the core oxygen and carbon content [Fig. 2(a) and 2(c)] as measured by charge exchange emission induced by an injected neutral beam. The midplane O V emission and the core oxygen content are seen to rise sharply soon after the boronization, but then drop back to near the original levels over the duration of the campaigns. The exception is the post-vent period (blue triangles) where oxygen is high. We speculate that this is due to the slow desorption of water that has soaked into the exposed graphite during the long vent. The core carbon behavior is similar to that shown in Table I for the daily reference shots. The SOL C III emission shows only a weak rise throughout the campaign, while the divertor carbon emission has no clear secular trend. Nickel and iron are insignificant players in the radiated power and $Z_{\rm eff}$ in these hybrid discharges, but they do show a slow but steady increase through the campaign. An annual boronization is more than sufficient for keeping these metallic impurities at low levels.

Near the end of the 2006 campaign, after 6000 plasma-seconds of operation since the pervious boronization, a set of seven sequential hybrid discharges was executed without using the standard between shot helium glow discharge cleaning. These discharges are upper null with active pumping on both the inner and outer divertor legs. The goal was to investigate the ability to maintain density control using active pumping only. The performance level, density control, and impurity content of these seven discharges was highly repeatable [3]. Two of the shots, 126482 and 126483, were automatically ramped down before the programmed end of the shot due to the appearance of a rapidly growing core tearing mode. The shot to shot trends in the integrated gas puff rate required to reach the target density at 1100 ms into the shot and integrated over the entire shot (for the five full length shots), are shown in Fig. 3, along with the integrated exhaust through 2400 ms, the

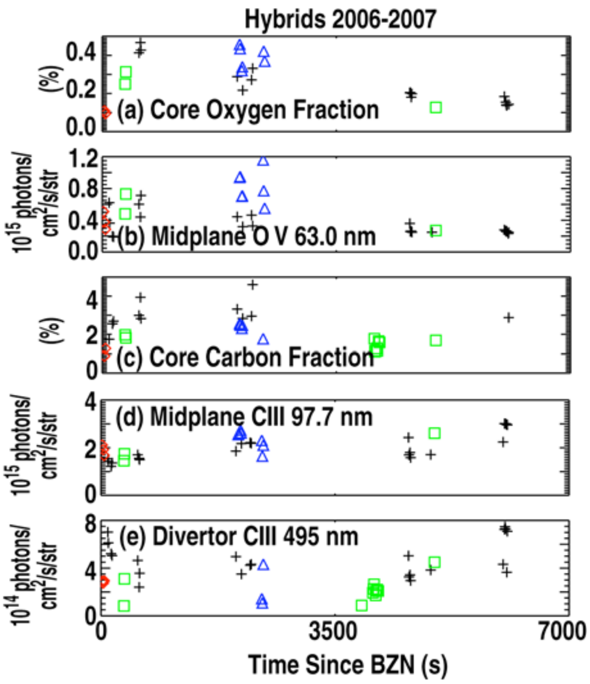

Fig. 2. The oxygen content in the core plasma measured by charge exchange recombination spectroscopy, the O V emision intensity from the edge plasma at the midplane, the core carbon content, the edge C III emission, and the core Ni XXVI emission from similar hybrid discharges plotted as a function of plasma operating time since boronization. The symbols are described in Fig. 1.

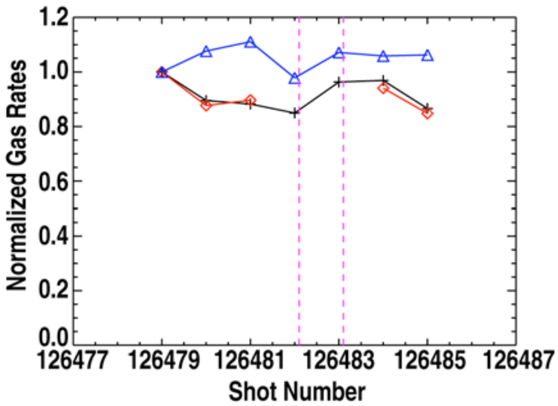

Fig. 3. The integrated gas puffing required to reached the early target density (black plusses), the total integrated gas puffing through the complete shot (red diamonds), and the integrated exhaust through 2400 ms (blue triangles) as a function of shot # with no helium glow discharge cleaning between each shot.

time when density feedback control during the high performance phase is initiated. All rates are normalized to the value on the first shot of the sequence, 126479. The gas input required to maintain the density decreases by about 15% in the first shot with no preceding He glow cleaning and saturates at this lower level until after the shots with the rapidly growing tearing mode. This tearing mode quickly reduces the core energy confinement resulting in a rapid loss of stored energy to the walls. This rapid flux of energy to the walls seems to have the effect of reducing the wall source of D on the following shots, resulting in the need for more gas puffing to reach the target density. The integrated exhaust through the formation phase of these discharges increases when helium glow is terminated, even though the gas input has decreased. Again, this is indicative of an increase in the wall source of D when helium glow is not used, and this effect seems to saturate at an increase of ~10% after only a couple of shots. Since density control is maintained, the strong divertor pumping is readily compensating for the lack of between shot removal of deuterium from the walls by the helium glow cleaning [5].

IV. POST-BORONIZATION EVOLUTION

On the first two days of plasma operation immediately following the boronization late in 2006, a standard hybrid configuration was used to follow the short-term secular trends as the fresh boron film was: (1) depleted of helium gas that is trapped in the film during the helium $+B_2D_6$ plasma vapor deposition process and (2) eroded from the divertor strike plates. In Fig. 4, the core helium (a) and carbon fraction (b), the C III VUV emission from the midplane (c), and the visible C III emission from the region of the outer strike zone (d) are shown as a function of time since boronization. The outflux of helium from a fresh boronzation is quite noticeable. On the first few shots, the He fraction (n_{He}/n_e) of almost 50% indicates a dominant helium plasma during the high power phase of the discharge. The helium fraction drops rapidly with a time constant of roughly 100 plasma-seconds (a day or two of standard operation). Carbon content in the core plasma rises on a similar time scale. The C III emission from the SOL and divertor, both dropping over the first 100 plasma-seconds of operation, do not correlate well with the core carbon content. In these low-density plasmas with high, injected beam power, both the inner and outer divertors are attached and the energy of the incident plasma ions is well above the physical sputtering threshold for carbon. Helium has a higher yield for physical sputtering of carbon than deuterium, and as it is removed from the plasma, the rate of physical sputtering of carbon should drop. The relative intensity of the molecular CD emission from the outer strike zone, measured in the daily reference shots with a high resolution visible spectrometer, is shown as the solid black circles in Fig. 4(d). While the data is sparse (note that the data point on the far right side of the graph, highlighted by an arrow, was actually taken at 6600 plasma-seconds after boronization), qualitatively the CD emission, a signature of chemical sputtering, is better correlated with the core carbon content.

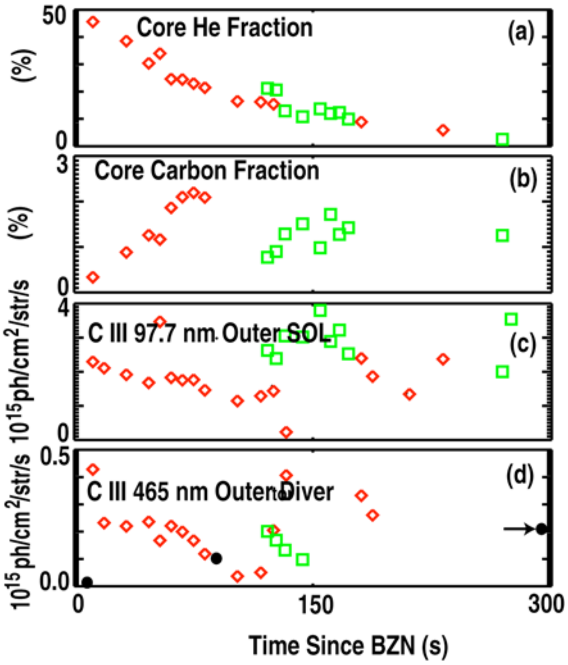

Fig. 4. The fast evolution of core helium content (a), core carbon content (b), SOL CIII emission, and outer divertor strike point emission is presented as a function of plasma operating time since boronization. The symbols are defined in Fig. 1 except for the solid black circles in (d), which are the CD molecular emission measured at the outer divertor strike plate during the daily reference shots, plotted with arbitrary units. Note that the point on the far right, highlighted by an arrow, was taken 6600 s from the previous boronization.

V. CONCLUSIONS

Hybrid scenario performance is maintained on DIII-D, with a dominantly all graphite plasma facing wall and strong divertor pumping, over 7000 seconds of plasma operation with no intervening boronizations. Following a brief transient period of about 150 plasma-seconds after these boronizations early in a campaign, plasma performance, including carbon and oxygen impurity content, density control, and energy confinement, is maintained for at least 7000 plasma seconds of operation. Daily reference shots show a slow but steady increase of C III emission from divertor and SOL regions of the plasma, but core carbon content is held constant. Annual boronizations are useful to reduce oxygen influx following a long entry vent and to keep metallic impurities a negligible levels. These results are promising for the next generation of long-pulse, high duty cycle, superconducting tokamaks, where it would not be reasonable repeat to thin film wall conditioning at a rate of every 1000 plasma seconds of operation.

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