

## Hydrogen control in Alcator C-Mod walls and plasmas

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### Abstract

The control of the hydrogen fraction in D plasmas  $[H/(H+D)]$  is necessary for efficient ICRF minority heating in Alcator C-Mod. Boronizing the chamber when  $H/(H+D) \sim 10\%$  would promptly lower  $H/(H+D)$  to  $\sim 5\%$ . However, the reduction was transitory when the accumulated boron layer was thick ( $>6 \mu\text{m}$ ) and with boron nitride tiles protecting the ICRF antennas, indicating that the H buried under a new B layer diffused back to the surface over time. Prior to the 2005 campaign, all boron on molybdenum tiles and surfaces was removed. Boronization was performed only after  $H/(H+D)$  was down to  $<5\%$  level. Subsequently, the H fraction was found to be nearly constant in the following period of the campaign. The removal of the thick boron layers and better control of  $H/(H+D)$  also contributed to a better plasma performance.

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PACS: 52.50.Qt; 52.40.Hf

Keywords: Wall conditioning; Boronization; Hydrogen control

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### 1. Introduction

ITER and future fusion reactors are projected to use tungsten, a high- $Z$  material, for plasma facing components (PFCs) [1]. However, experimental experience with high- $Z$  metal PFCs is lacking, especially in a real tokamak environment. Being the only major diverted tokamak which has operated exclusively with solid high- $Z$  (molybdenum) PFCs in the world, the Alcator C-Mod tokamak ( $a = 0.22 \text{ m}$ ,  $R = 0.67 \text{ m}$ ,  $B_t \leq 8.1 \text{ T}$ , and  $I_p \leq$

2 MA) is in a unique position to study high- $Z$  operation. Extensive experiments have been carried out since the beginning of 2005 to study the plasma performance and in areas including wall conditioning, impurity control, and hydrogen inventory control [2–4]. Boronization has been shown to be essential to achieve the highest performance plasmas in C-Mod. This paper concentrates on one part of the study: the control of the H fraction in both the walls and the plasmas. This subject is of practical importance for ion cyclotron range of frequencies (ICRF) minority heating ( $B_0 \sim 5.4 \text{ T}$  and frequency = 80 MHz), the primary auxiliary heating method in C-Mod. The hydrogen fraction may significantly affect the single-pass absorption coefficient of the

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launched fast magnetosonic waves [5]. For typical C-Mod plasmas, a hydrogen fraction  $H/(H+D) \sim 3\text{--}6\%$  would have the highest single-pass absorption rate. The H/D ratio was measured by a neutral particle analyzer prior to year 1999 [6]. Since 2000, it has been routinely available from spectroscopic measurement of the ratio of  $H_\alpha$  and  $D_\alpha$  emission near the plasma edge [7]. Because of the relatively broad horizontal view, the spectroscopic measurement has a reasonable average of the edge emission (excluding the divertor), and it has a good poloidal sampling of the recycling mix. In addition, in previous ICRF mode conversion studies (e.g., Ref. [8]), which had relatively high hydrogen fraction, the  $H_\alpha$  and  $D_\alpha$  emission measurement was shown to have a good agreement with the core H/D level that was independently determined from the mode conversion layer location.

In this paper, we will report the dependence of the H fraction on different wall conditions (thick boron layers over Mo, thin layers over Mo, and bare Mo surface), and the correlation of the H/(H+D) level with plasma performance.

Boronization has been used in Alcator C-Mod since 1996 [9,10]. It has been carried out once every one to two weeks in each experimental campaign. The boron layer thickness on the Mo surfaces accumulated steadily [10,11]. Sample tiles from a poloidal circumference of the vessel were removed for surface analysis prior to the 2005 experimental campaign, and measured by non-destructive ion beam analysis. In Fig. 1, we show the poloidal locations of the analyzed tiles and the boron thickness as defined as the depth to the layer of B:Mo = 1:1, derived from the depth profile of B films on the Mo tiles. The thickness was approximately  $\sim 5\text{--}6 \times 10^{-6}$  m on all tiles

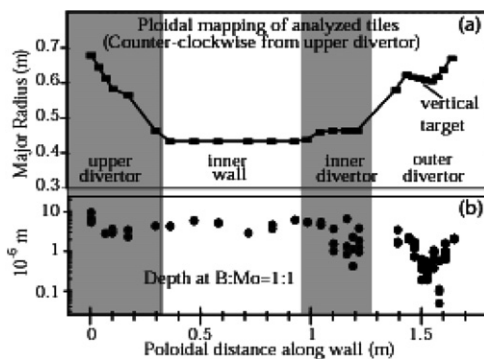


Fig. 1. (a) The poloidal mapping of the analyzed tiles; (b) the poloidal distribution of boron thickness, as indicated by the depth of the layer with B:Mo = 1:1.

except for the outer and inner divertor tiles. These data indicated that the boron deposition has been rather uniform. The average boron layer thickness on inner divertor (installed in 2001) were smaller, consistent a shorter period of installation. The layer on outer divertor surfaces is smaller, presumably due to net erosion of the boron layers. To study plasma performance with and without boronization on high-Z PFCs, the boron layer was cleaned off of Mo tiles prior to the 2005 experimental campaign. The residual boron was measured to be in the range of B:Mo = 10–30%, distributed through the first micron of surface roughness. The boron-nitride ICRF antenna protection tiles [12], first introduced into the vessel in 2000 and also covered by boron, were also removed. As a result, all the PFCs became solely Mo and we had the opportunity to study the efficacy of wall conditioning techniques in reducing H/(H+D).

## 2. H to D changeover after open-to-air

After an open-to-air period, the vacuum vessel is baked at 120 °C for about a week. The baking time is determined by the  $1/e$  decay times for mass 2, 18, 32, and other lines on the RGA, which can be from 1 to 2 days once we reach temperature. After the baking, electron cyclotron discharge cleaning (ECDC) in  $D_2$  gas ( $\sim 0.1$  mTorr) is carried out continuously for 2–3 days. The ECDC system utilizes a 2.5 kW 2.45 GHz microwave from a magnetron, launched through a horn at a fixed toroidal location [13]. The plasmas were produced using toroidal field only. By scanning the on-axis toroidal field from 0.067 to 0.11 T, the EC resonance (0.088 T) cycles between the inner wall and the outer wall. The plasma during ECDC typically have  $T_e \sim 10$  eV,  $T_i < 1$  eV,  $n_e \sim 10^{16} \text{ m}^{-3}$  [13]. By the time of the first tokamak deuterium plasma discharge, the H/(H+D) level is typically at  $\sim 0.5$ .

Fig. 2 compares the trends of H/(H+D) in plasmas at the beginning of the 2005 and 2003 campaigns. The start of 2005 campaign utilized all-Mo PFCs without boron coatings. In each run day, H/(H+D) started low after overnight ECDC, which lowers the H level in the near surface through isotope exchange (D combining with H which then is released from the surface). It then rose steadily, discharge by discharge, as H diffuses back to the surface in a variety of compositions. H can also come from remote areas through water de-trapping or other mechanisms. The H fraction also increased

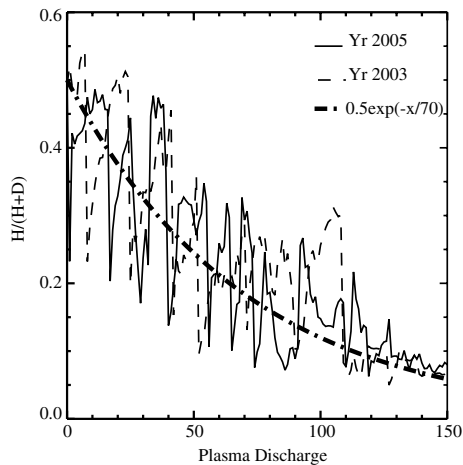


Fig. 2. The trend of the H fraction in the beginning of campaign 2003 (thick B layer and BN protection tiles) and 2005 (B removed) prior to boronization.

when the ICRF antennas were energized, either due to heating of the antenna structures or other surfaces around the vessel. The major differences between the two run campaigns were the boron layer thickness ( $\sim 6 \mu\text{m}$ ) and bulk BN tiles (covered by boron) protecting the ICRF antennas in 2003 while, in 2005, the PFCs were solely molybdenum with the thick B layer removed. In both campaigns, about 150 plasma discharges were required before the H fraction was lowered to 5% for optimal ICRF heating. Such similar total rates of H release with and without boron coverage indicated that the boron layer is not the primary source of H release in the earlier plasmas after an open-air period. However, the boron thickness does affect the H release after the  $H/(H+D)$  is down below  $\sim 10\%$  as shown in Section 3. The number of plasma discharges required for this initial H fraction reduction is a considerable operational cost for C-Mod. To expedite this changeover process, a new method using controlled disruptions [14] has been successfully tested in C-Mod.

### 3. Effect of boronization on the hydrogen fraction

A low H/D level by itself does not necessarily lead to good plasma performance [2–4,9,10]. H-modes can be readily obtained with the strictly Mo PFCs, but the quality is usually poor. Boronization has been used to control the impurity levels in C-Mod since 1996. In practice, we usually performed the first boronization of a run campaign when the H/D level was down to about 10%. In

the 2005 campaign, the boronization was delayed until the H/D level was below 5% even at high ICRF power. Boronization is typically carried out overnight (about 10 h) by ECDC in a gas mixture of 10% deuterate diborane ( $\text{B}_2\text{D}_6$ ) and 90% He. The diborane is released into the vessel from a toroidally semi-continuous tube that has been adjusted to give fairly uniform throughput. Approximately 200 nm of boron was deposited on the wall assuming it is evenly distributed (cf. Fig. 1). Following a boronization, the mass 11, 28, and 32 lines (from  $\text{B}_2$ ,  $\text{B}_2\text{D}_3$ , and  $\text{B}_2\text{D}_5$ , respectively) in the residual gas analyzer spectrum following a discharge are enhanced over the pre-boronization case. These lines decay to pre-boronization levels over one or two run days. The  $H/(H+D)$  level would be noticeably reduced, from  $\sim 10\%$  to around 5%. However, in the campaigns with significantly thicker boron layers (and BN antenna protection tiles), this reduction of  $H/(H+D)$  was shown to be transient. It would rise after a few days of plasma discharges and/or significant RF heating. In Fig. 3, we plot the H/D trends in the 2003 and 2005 campaigns with the first three boronizations indicated. In the 2003 campaign, although the temporary reduction of the H/D level was significant, the H/D level kept creeping back up after each boronization. In contrast, the fraction was nearly constant in the 2005 campaign. This result suggested that covering a wall with boron that still has a large H reservoir only slows down the process of H fraction reduction. The H in the Mo tiles (and the old boron layers) will ultimately be released to the plasma. Such release can also be significant within the plasma discharge

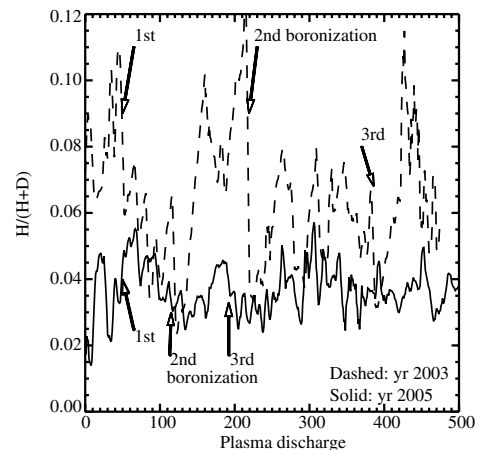


Fig. 3. Average of the H fraction in plasma discharges after boronization. The first three boronizations were labeled.

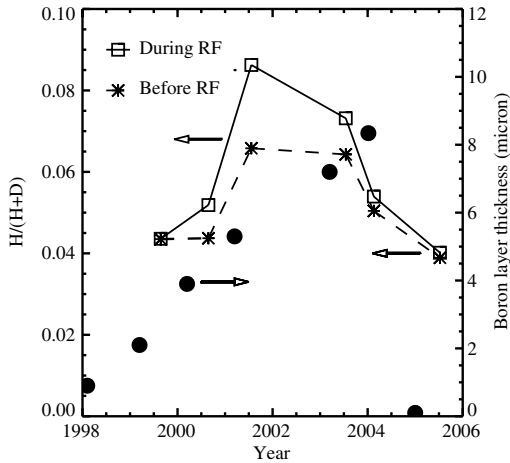


Fig. 4. Average of H fraction in each campaign and the boron thickness.

as shown in Fig. 4. The H fraction of all D(H) ICRF minority heated H-mode discharges after the first boronization in each campaign is averaged. The levels at 50 ms before the ICRF application and the level at the time of maximum plasma stored energy in H-mode are both displayed. The average thickness of the boron layer prior to each campaign is also indicated. It shows a correlation between the controllability of the H fraction and the boron thickness (except the 2004 campaign). In the campaigns with thicker boron layers, the H fraction during the RF pulse can be twice as high as in the 2005 campaign. One exception is that the machine was not opened between 2003 and 2004 campaigns, and such a long period with no vacuum opening (and thus the tiles were not reloaded with H) did not increase the H inventory in the wall, and the H fraction throughout the 2004 campaign was relatively low. This suggests that a machine with thick boron layer will ultimately reduce the H fraction after a long time period. However, this is rarely a practical option.

#### 4. H/D level vs. plasma performance

In ICRF minority heating, the minority concentration plays an important role in determining the single-pass absorption rate of the fast magnetosonic waves, which usually peaked at  $H/(H+D) \sim 3\text{--}6\%$  for typical C-Mod plasmas. In Fig. 5, we plot the plasma performance in terms of plasma stored energy vs. the H fraction. In this experiment, the H/D level was varied by H<sub>2</sub> puff shot by shot, while other plasma parameters, like plasma current, B

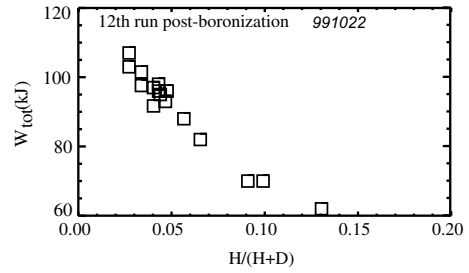


Fig. 5. Plasma performance vs. H fraction. Plasma parameters:  $I_p = 1.0$  MA,  $B_t = 5.4$  T, density in L-mode  $n_{e0} = 1.6 \times 10^{20} \text{ m}^{-3}$ ,  $P_{\text{rf}} = 2.7$  MW.

field, launched ICRF power, and electron density, were fixed. The data were from the 12th run day after a boronization when the boron layer was degraded. The experiment shows that the effectiveness of the ICRF heating is very sensitive to the  $H/(H+D)$  level when wall is not well conditioned. In contrast, an earlier experiment done on the second run after a similar boronization showed no correlation between the performance and the  $H/(H+D)$  level in the range of 2–15% (measured by neutral particle analyzer). These results indicate that in addition to reducing the impurity by wall conditioning [2], controlling the  $H/(H+D)$  level is also necessary to consistently obtain good performance plasmas, especially after the boron layer has degraded. A weaker single-pass absorption rate at higher  $H/(H+D)$  level also raises the far-field RF sheath [15], which in turn can generate more impurity into plasma through the interaction between the sheath accelerated ions and the walls [16]. In Fig. 6, we plot the ICRF power required to obtain plasmas with 160–180 kJ stored energy

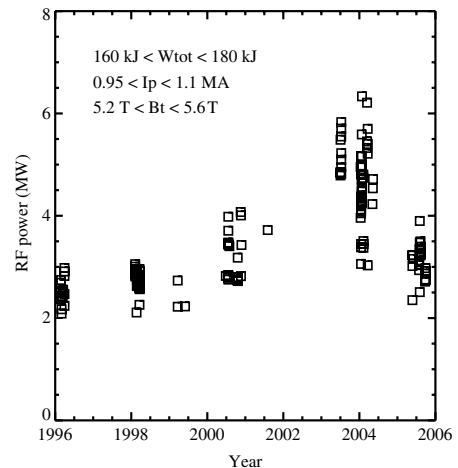


Fig. 6. The ICRF power needed to obtain plasma stored energy between 160 and 180 kJ for 1 MA,  $5.2 \text{ T} < B_t < 5.6 \text{ T}$  plasmas (hydrogen minority central heating).

( $\langle P \rangle \sim 1$  atmosphere) for typical 1 MA, and  $5.2 < B_t < 5.6$  T (central H minority heating) plasmas in C-Mod. The trend of RF power required is strongly correlated to the H/(H+D) level trend shown in Fig. 4. In the periods of 2002–2004, an average H/(H+D) level far exceeding the optimal level for heating may have contributed the observed plasma performance degradation. With the H/(H+D) under control in year 2005, we obtained the best performance plasma in C-Mod, with averaged plasma pressure of 1.8 atm (the world tokamak record) at the ITER baseline  $\beta_N \sim 1.7$  and at the ITER B field.

## 5. Summary

We reported the experience of H/(H+D) control in a high- $Z$  tokamak. We showed that boronization can reduce the H/(H+D) level, but the effect was transient when the total boron layer was thick and in the presence of BN tiles. After the removal of the accumulated boron layer, BN tiles, followed by boronization on the metal surface after H/(H+D) was consistently down to 4–5% level, we achieved the best result in H/(H+D) control and plasma performance.

## Acknowledgments

The authors thank the Alcator C-Mod operation team for running the tokamak. This work is supported at MIT by US DoE Cooperative Agreement No. DE-FC02-99ER54512.

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