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Effects of wall boron coating on FTU plasma operations

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Abstract

To achieve good performance on FTU in a large density range ($0.3–6.0 \times 10^{20}$ m^{-3}), boronization with a mixture of He (90%) and B_2H_6 (10%) (diborane) as the feeding gas has been tested with thermal loads on the limiter surface up to 2.5 MW/m^2. With boronized limiter (TZM alloy with 98% of Mo) and walls (SS AISI 304), the total radiated power drastically drops from 70–90% down to 35–45% and the Z_{eff} decreases from 6.0 to 2.2 at $0.3–0.4 \times 10^{20}$ m^{-3} related to a strong reduction of heavy-metal concentration and to the getter effect of boron on oxygen (<0.5%). During this phase the action of the boron film as particle reservoir and its quick saturation due to the low temperature of FTU walls makes it difficult to obtain reproducible plasmas. Another consequence of boronization is the large dilution of the plasma with the hydrogen particles released from the B film. All these effects decrease after about 60 discharges when boron is eroded by the limiter but it is still present on the chamber walls. During this phase which lasts for more than 500 discharges, oxygen concentration does not increase at all and metal influx is lower than before boronization because the physical sputtering by oxygen ions and atoms is strongly reduced.

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1. Introduction

The walls of FTU tokamak are characterized by a vacuum chamber made of stainless steel AISI 304 and by a toroidal limiter made of TZM (98% of molybdenum). The operating wall temperature ($T_w \approx 77$ K) makes efficient wall conditioning techniques difficult to employ. Wall conditioning is normally performed using careful baking and several clean up pulses, but an oxygen concentration less than 1% is very difficult to obtain and to maintain. Normally, after about 100 discharges, an oxygen concentration of 2% is obtained. No major problems exist for heavy-impurity contamination at high density (1.0×10^{20} m^{-3}) and current (0.9 MA) because the metal influx by O-sputtering is sufficiently low. In these conditions, Z_{eff} is close to 2 and the total radiated power is about 70% of the input power. However, at lower plasma density, i.e. at $\bar{n}_e = 0.3 \times 10^{20}$ m^{-3}, we never obtain Z_{eff} less than 6 even with well cleaned walls when we inject more than 1 MW of additional power (lower hybrid (LH) and/or electron cyclotron (EC) RF waves). This behaviour is typical of metallic first wall machine, as described in Ref. [1]. As a first step to optimize FTU operations, a 'titanization' technique was tested on FTU. A thin Ti layer was deposited onto the vessel walls by evaporating a small amount of titanium between discharges (≈5 monolayers). This conditioning technique promptly allows to maintain very low oxygen and carbon concentrations both at high densities (with $Z_{eff} \approx 1.0$ for $\bar{n}_e \geqslant 1.0 \times 10^{20}$ m^{-3}) and at low density ($Z_{eff} \approx 4.4$ at $\bar{n}_e = 0.3 \times 10^{20}$ m^{-3}), but does not guarantee reproducible plasmas. The second step to overcome this problem has been to exploit the 'boronization' technique.

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In this paper, a brief description of the experimental apparatus and the boron deposition procedure will be given in Section 2, the effects of the boronization on the plasma being described in Section 3. At the end, in Section 4, the conclusions will be drawn.

2. Experimental apparatus and boronization procedure

The FTU walls are coated with a boron film by means of a conventional glow discharge with a mixture of He (90%) and B_2H_6 (10%) (diborane) as the feeding gas. The walls are maintained at 373 K during the film deposition and subsequently they are cooled at 77 K. The design and the installation of the boronization system are based on the previous experience of RFX [2]. The gas mixture is introduced through four vertical ports located 90° toroidally apart from each other, at a pressure of about 7×10^{-3} mbar with 1.7 mbar l s^{-1} of average gas flow rate. The gas is pumped away using two evacuation lines of the main vacuum system placed at two opposite sides of the torus. Each line is connected to a standard 2000 l/s turbomolecular pump, followed by a thermal decomposer. The annexed 60 m^3/h rotary pump is modified to assure a very good vacuum tightness and to dilute the exhaust gas with nitrogen before it comes in contact with the air. Two electrodes, 180° toroidally apart, are inserted from two vertical ports up to the centre of the vacuum chamber. The glow discharge conditions for each electrode are: a voltage drop of +360 V and a driven current of 0.75 A, corresponding to 11 μA/cm^2 of total current density on to the vessel walls. To reach an average film thickness of 100 nm, 3 h are necessary, according to previous laboratory tests on silicon films [3]. In that case, the film thickness was measured by the difference in post- and pre-siliconization weight of different samples of SS 304, with the same mechanical surface treatment as the FTU walls.

3. Plasma discharge characteristics

From the point of view of the vacuum performance, the effects of the boronization are seen as a strong reduction of the overall outgassing rate (up to a factor 2.5) and of the equilibrium pressure, which is reduced by a factor 1.7 after 1–2 days of operation following a fresh boronization, and lasts for a long period ($\geqslant 500$ discharges). The outgassing rate has been evaluated from the relation: $Q_{\text{outgas}} = V\mathrm{d}P/\mathrm{d}t$ where V is the chamber volume and $\mathrm{d}P/\mathrm{d}t$ is the time derivative of pressure in the phase just after the exclusion of the primary pumping system. The residual gas mass spectrometer cannot be used, because water vapour, which is the only detectable impurity of the spectrum before cooling the machine, is then trapped by the cold walls (some sort of extended cryogenic pumping), and its signal normally do not emerge from the quadrupole background.

After a fresh boronization, the restart of operations is immediate (1–2 discharges) and recovery from plasma disruptions is prompt as well as in the case of a pure metallic machine without any contamination of light impurities (O and C). From the point of view of the plasma characteristics, there are two main effects. For an ohmic plasma ($\bar{n}_e \leqslant 1.0 \times 10^{20}$ m^{-3}) the total radiated power typically drops from 70–90% down to 35–40% and for $I_p = 0.5$ MA and $\bar{n}_e = 0.3$–0.4×10^{20} m^{-3}, Z_{eff} decreases from 6.0 to 2.2. This is due to the strong reduction of heavy-metal concentrations, which in the case of molybdenum drops from 6.0×10^{16} to 1.2×10^{16} m^{-3} at $\bar{n}_e = 0.3$–0.4×10^{20} m^{-3}, and to the getter action of boron on the light impurities (oxygen concentration in the plasma is reduced from 2.5% to 0.5% and the carbon flux from the walls drops from 1.0×10^{18} to 1.1×10^{17} part/s/m^2). The radiation losses integrated from $r/a = 0.8$ to 1.0 decrease from 130 to 60 kW for $I_p = 0.5$ MA at $\bar{n}_e = 0.3$–0.4×10^{20} m^{-3}, which is consistent with a strong reduction of the light impurities radiating preferentially from the plasma periphery. Another consequence of the Z_{eff} reduction is a lower loop voltage and a lower ohmic power that is normally observed after the boronization. The lower input power produces in turn electron temperatures up to 1.3 times lower than before. All these effects decrease after about 60 discharges corresponding to the duration of the boron coating on the limiter. This transition can be easily recognized by the behaviour of the net plasma power loss $P_{\text{TOT}} - P_{\text{RAD}}$ as a function of shot number for plasma discharges with $I_p = 0.5$ MA and $\bar{n}_e = 0.3$–0.6×10^{20} m^{-3} before and after boronization (not shown here). Immediately after boronization a substantial increase of $P_{\text{TOT}} - P_{\text{RAD}}$ by a factor of 1.8 is obtained related to the lower radiative characteristics of boron than those of molybdenum. After about 60 discharges this difference drops again corresponding to the partial recovery of the standard plasma conditions, as it will be described later. An unfavourable consequence of boronization is however the difficulty in controlling the plasma density during the first two operation days (about 60 discharges). Outside the operator control, the wall can either pump or release a large amount of H, depending on the saturation degree of the surfaces facing the plasma, similar to what was previously observed after titanization [4]. This fact is evidenced in Fig. 1 by plotting the ratio N_p/N_g (ratio of the total plasma particle content to the total amount of the injected gas particles) versus N_g for pre- and post-boronization discharges with $\bar{n}_e = 0.35$–0.9×10^{20} m^{-3} and $I_p = 0.5$ MA.

In the post-boronization case, the lowest value of the ratio N_p/N_g (0.03) is obtained initially, since the boron film is pumping strongly for the whole duration of the plasma discharge (1.5 s) and the pre-programmed

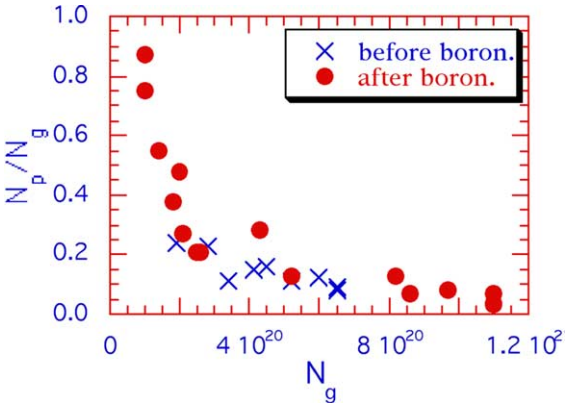

Fig. 1. Plot of the ratio N_p/N_g versus N_g for pre- and post-boronization ohmic discharges ($\bar{n}_e = 0.35$–0.9×10^{20} m^{-3} and $I_P = 0.5$ MA).

density of 0.5×10^{20} m^{-3} is not reached. The highest value (0.87) is obtained later on, after several medium–high density discharges. In these conditions the H or D particles released from the boron film contribute strongly to the plasma density. As a consequence, n_e increases well above the pre-programmed value of 0.4×10^{20} m^{-3}, i.e. up to 0.8×10^{20} m^{-3}, despite the gas is stopped by the feedback system at only 0.3 s. The pumping capability of the wall is partially recovered after disruptions at high plasma current.

When the walls are purely metallic, the variation of N_p/N_g is low. At fixed plasma current, this means a nearly constant effective particle confinement time, $\tau_{eff} = N_p/((dN_g/dt) - (dN_p/dt)) = \tau_p/(1 - R_{eff})$. Here τ_p is the particle confinement time and R_{eff} is the effective recycling coefficient, which takes into account the wall and the scrape-off layer (SOL) contribution. The experimental τ_{eff} ranges from 0.15 to 0.5 s before boronization while it varies from 0.04 to 1.5 s after boronization. Fig. 2 shows how strongly the boronization can affect the recycling, and hence the plasma–wall interaction for a high density pulse. The time evolution of the total plasma particle content, of the gas feed, and of τ_{eff} are indicated for a pulse performed about one day after boronization. Even during the pulse, τ_{eff} can strongly increase if the B layer reaches a saturation, as it happens at $t = 1.0$ s in Fig. 2. At this time, though the gas injection is stopped by the feedback system, a strong increase of H_α emission occurs and a Marfe develops on the high field side of the tokamak. However, no variation of the density from the central chord is observed, probably because the screening of the boundary plasma reduces R_{eff}. Indeed, a large increase in the electron density, up to a factor 4, is measured in the SOL by Langmuir probes after boronization. These phenomena do not occur if only low density discharges are produced, where there is no evidence of B film saturation, and reproducible conditions are achieved. The above effects have not been observed on machines which operate with the walls at high temperature such as TEXTOR [5], where the mechanism of boron film to pump and to release particles has been clearly understood and optimized. Considering these results which emphasize the role of the substrate temperature on the film behaviour, the following interpretation is proposed. The low vessel temperature ($T_{w,FTU} \approx 77$ K) affects strongly the plasma–wall interaction processes because the only

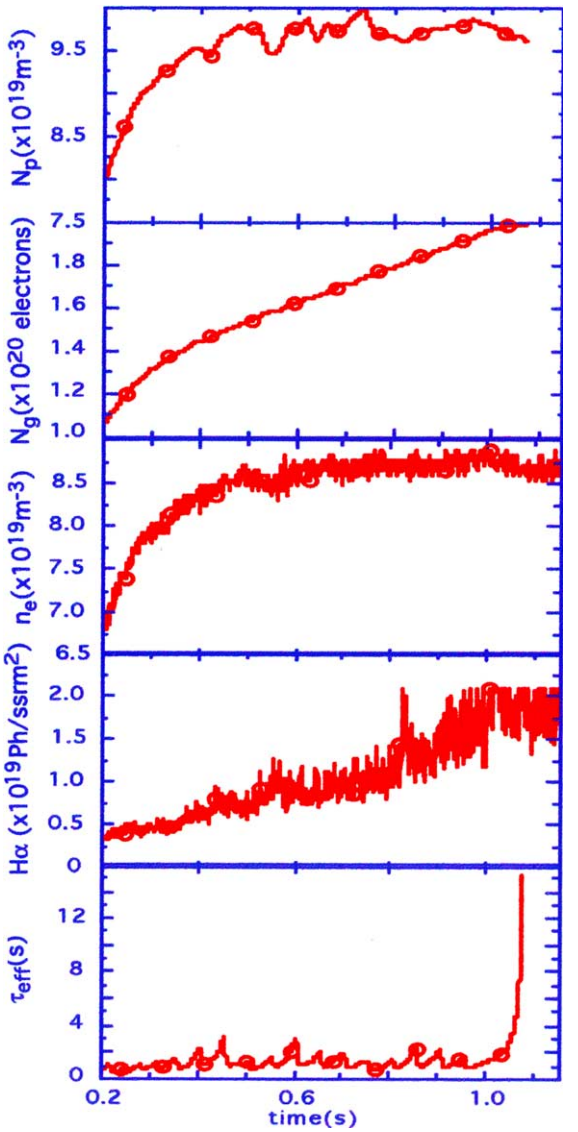

Fig. 2. Time evolution of N_p, of N_g, n_e from the central chord, H_α emission and τ_{eff} for the 23rd shot run after boronization with $\bar{n}_e = 0.9 \times 10^{20}$ m^{-3}, $I_p = 0.5$ MA, $B_T = 6$ T. The flat top phase of the plasma current ends at 1.5 s.

physical surface mechanisms still active are the physical desorption induced by particle bombardment and the high pumping capability due to the cold amorphous structure of the B layers. The latter, however, though quite high for the first few atomic monolayers, is counter-balanced by the extremely slow diffusion of the absorbed molecules into the bulk material. This therefore brings the surface quickly to over-saturation under high particle flux, and then, a strong desorption starts to prevail after some pulses of this nature.

The consequence on the plasma of high recycling following a fresh boronization is still under study. Preliminary observations suggest that a high recycling or a high edge neutral density could hinder the internal transport barrier (ITB) formation in FTU. As shown in Fig. 3, two shots with very similar main plasma parameters develop in a strikingly different way, possibly due to a change in current diffusion. In both cases LH and EC power are applied during the current ramp up phase ($P_{LH} = 1.7$ MW for both, $P_{EC} = 0.35$ MW, for ITB case, $= 0.7$ MW for no ITB case). For the shot 20 859, obtained before boronization, an ITB with very high central temperature, $T_{e0} \approx 12$ keV lasting for about 0.2 s, develops whereas it does not for the shot 21 476 following boronization (T_{e0} reaches only 8 keV), despite the higher P_{EC} and the lower Z_{eff}. The difference in the H_α emission level between the two pulses is large and can also possibly explain the change in plasma behaviour.

Another consequence of boronization is the large dilution of the plasma with the hydrogen particles released from the B film. The ratio of deuterium to hydrogen + deuterium fluxes $q_D/(q_D + q_H)$, as measured by the neutral particle analyzer, can be as low as 40% after a fresh boronization, despite the pure D_2 puffing, then increases slowly to 85% after about 200 discharges. The D dilution, in turn, reduces the plasma performances in term of neutron yield. The target plasma suitable for pellet injection, ($\bar{n}_e = 1.7 \times 10^{20}$ m^{-3}) shows a much lower radiated power than before boronization ($P_{rad}/P_{tot} \approx 35\%$ against 65%, together $Z_{eff} \approx 1$ against $Z_{eff} \approx 1.4$), but the neutron rate decreases up to a factor 5. The observed reduction agrees well with simulations performed with the transport code EVITA [6]. In addition, the same code shows that neither the electron nor the ion transport coefficients show any significant difference after boronization. Assuming a pure deuterium plasma, an increase of the energy confinement time of 1.2 is obtained, due to the lower input power after boronization.

No differences have been found in the impurity transport characteristics. The experimental values of the radiative losses, Z_{eff} and impurity concentration are well reproduced by the results of a one-dimensional transport code assuming an anomalous diffusion coefficient and an inward velocity equal to the FTU standard ones used for ohmic plasmas [7].

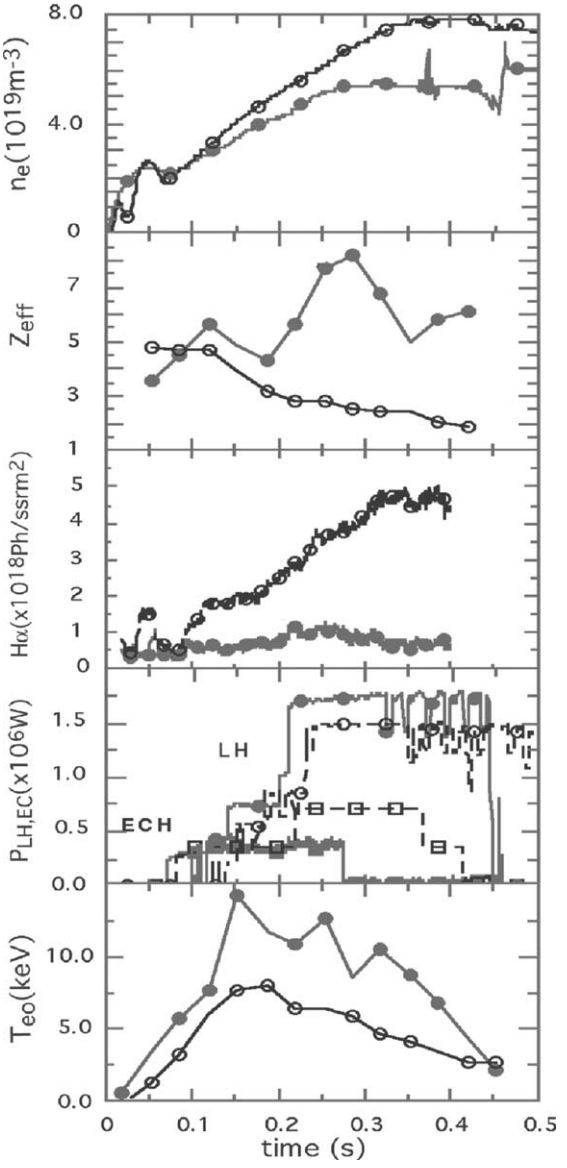

Fig. 3. Time evolution of n_e, average Z_{eff}, H_α emission, LH and EC heating power, T_{e0} for the shot 20 859 (closed symbols) and 21 476 (open symbols).

As for the Si wall coating in FTU [8], a particular situation appears when boron is eroded from the limiter but it is still present on the chamber walls, i.e. after about 60 discharges. During this phase, lasting longer than 500 discharges, the getter action of boron is still large, while the metal concentration increases again. However, it does not reach the pre-boronization values, consistent with a production mechanism dominated by physical sputtering by O ions and atoms. In these conditions, the metal influx can be further reduced by cooling the plasma edge with a deuterium puff. For

$I_p = 0.5$ MA and $\bar{n}_e = 0.4 \times 10^{20}$ m^{-3}, low oxygen (0.4%), molybdenum (0.1%) and iron (0.09%) concentrations are present in the plasma with $Z_{eff} = 3.0$ and a total radiated power close to 65% of the input power.

During this phase, the reduction of Z_{eff} has allowed to reach one of the best performances of FTU in terms of the actual current drive (CD) efficiency η_{CD}. Full CD with $\eta_{CD} = 0.2 \times 10^{20}$ A m^{-2}/W has been obtained on a plasma target with: $I_p = 360$ kA, $B_T = 5.3$ T, $\bar{n}_e = 0.4 \times 10^{20}$ m^{-3} and $P_{LH} = 1.5$ MW, with only a small increase of Z_{eff} from 1.5 to 2.2. With the same plasma target, additional power up to $P_{LH+EC} = 2.6$ MW have been coupled to the plasma with $Z_{eff} = 3.0$ as compared to 6.0 before boronization at a lower power. Very good high density plasmas are also obtained. The density limit at $I_p = 1.1$ MA, $B_T = 7.2$ T, has reached, with gas puffing only, $\bar{n}_e = 3.0 \times 10^{20}$ m^{-3}, two times higher than before boronization. By having reduced the radiated power, the boronization technique has allowed to study in FTU the so called RI mode plasmas [9] at density higher than those of TEXTOR [10]. Neon is used as a cooling gas until a fraction of 90% of the radiated power is achieved with a subsequent peaking of the density profile and an increase of the neutron yield. In this case no significant difference is found between fresh and old boronization. In both cases the density profile peaks, the ratio of the central to the average density, $n_{e0}/\langle n_e \rangle$ goes from 1.2 to 1.5–1.8, the peak electron temperature increases slightly and the energy confinement is a factor 1.2–1.4 higher than that of the target plasma. An increase of Z_{eff} from 1.4 to 1.9 is observed after neon injection. The relative neutron rate production also increases by a factor 3–4 in both cases, but the starting level after a fresh boronization is about five times lower due to H dilution.

4. Conclusions

Boronization is very effective to reduce the impurity content and the radiated power of the FTU plasma on the whole explored range of densities, $0.3 \leqslant \bar{n}_e \leqslant 3.0 \times 10^{20}$ m^{-3} (6.0×10^{20} m^{-3} with pellet), and plasma currents $0.35 \leqslant I_p \leqslant 1.1$ MA both in ohmic and in LH and/or EC heated plasmas (up to 2.6 MW injected). Immediately after boronization, both oxygen and metals are almost suppressed, but improvements of the plasma performances are limited due to the high hydrogen flux coming from the boron film. Boronization causes large differences in the recycling properties, respect to purely metallic walls, which prove to be the best materials for plasma density control ($R_{eff} < 1$). The operational need to maintain the FTU vessel temperature around 77 K during plasma discharges makes it difficult to condition the walls efficiently in order to reduce the hydrogen concentration on the film surface. The best results have been obtained for about 60 discharges after boronization, when boron has been already eroded from the limiter, but it is still present on the chamber wall. The metal influx is lower than before boronization, because the physical sputtering by oxygen ions and atoms is strongly reduced, and it is possible to control the edge temperature with D_2 gas puffing. All the experimental programs benefit by these favourable conditions. The long lasting gettering effect of boron on oxygen (>500 discharges) is most probably associated to the redeposition of the sputtered boron onto the ports and to those regions coated by boron during the glow discharges, but not in contact with the plasma.

To overcome the problem of D dilution, and hopefully exceed the neutron production of the best FTU performances, use of deuterate diborane (B_2D_6) as working gas is scheduled in the near future.

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