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Impact of wall conditioning and gas fuelling on the enhanced confinement modes in TJ-II

F.L. Tabarés *, D. Tafalla, R. Balbín, B. Brañas, T. Estrada, I. García-Cortés, F. Medina, M.A. Ochando

Association EURATOM/Ciemat. Av. Complutense 22, Madrid 28040, Spain

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Abstract

The TJ-II helical stellarator has been operated under full metallic first wall conditions until mid 2001. This scenario has proven fully compatible with the ECR production and heating of plasmas. Under those conditions, several modes with enhanced confinement have been found. In the last experimental campaigns, however, boronisation of the first wall of the TJ-II has been carried out. This has lead to strong changes in edge parameters and density control. Namely, a rise of the electron temperature at the limiter of a factor of ~3, and a strong (<4×) increase in the required fuelling rate for the same density respect to the metallic case have been observed. According to the observation in the metal case, these two facts would in principle prevent the transition to the enhanced particle confinement mode. However, the same features associated with such mode have been reproduced. Moreover, a simultaneous increase in the total energy content, not achieved in the former wall scenario, was found for some conditions. The implications of these findings to the present understanding of the enhanced modes in TJ-II are addressed.

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Keywords: Enhanced confinement; Stellarators; Boronisation; Plasma edge

1. Introduction

The achievement of enhanced confinement modes in tokamaks and stellarators has been unambiguously associated to the strict control of plasma impurities and therefore, wall conditioning [1], among other factors. In spite of that, the impact of the conditioning technique (gettering, carbonisation, boronisation, ...) on confinement itself is still rather controversial [2]. Thus for example, first wall boronisation has been found to significantly improve the energy confinement in some divertor tokamaks, as in Alcator-C [3] while not such improvement has been found in other machines as Asdex Up. Concerning medium size stellarators, a weaker improvement than in tokamaks has been found in enhanced confinement modes [4], of the same order as in limiter tokamaks. Moreover, a stronger sensitivity to wall conditions and gas puffing rates is typically seen [5]. Transition to an enhanced confinement mode for plasma particles (EPC) has been observed in ECRH plasma in the medium size TJ-II stellarator [6]. Only under some specific magnetic configurations, was enhancement in energy confinement also observed [7]. Some of the conditions required achieving such modes for particle confinement under metallic first wall scenarios have been experimentally identified [8]. Thus, for example, strict control of the gas puffing rate, together with the presence of a critical electron density, were clearly established as pre-requisites, and no special magnetic configuration or heating scheme (central, focused, vs. unfocussed microwave beam) were required in the EPC mode.

* Corresponding author. Tel.: +34-91 34 66 458; fax: +34-9 1346 6124.
E-mail address: tabares@ciemat.es (F.L. Tabarés).

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In the present work, the impact of first wall boronisation on plasma parameters and, more specifically, on achieving enhanced particle and energy confinement modes is described.

2. Wall conditioning

For density control under metallic walls scenario, an Ar GDC was required for the removal of the He implanted overnight [9]. In this way, access to the EPC mode was possible by careful control of the external puffing rate. In the last campaign, and motivated by the higher thermal and particle fluxes expected during the in-coming NBI operation, boronisation with *o*-carborane, at room temperature was performed [10]. In order to increase the uniformity of the B/C film, four ovens were installed in symmetrical positions of the TJ-II vacuum vessel. A total amount of 4 g of *o*-carborane (1 g each oven), enough to cover the inner wall of TJ-II exposed to plasma with a B/C film of about 50 nm, was injected during He GD. The He pressure during the glow was about 5×10^{-3} mbar and a total plasma current of 2 A (1 A per anode) was applied in order to obtain a cracking efficiency $\geqslant 90\%$ (based in extrapolations from laboratory experiments). Carborane injection was carried out by heating the ovens continuously during the GD. A system of electrical heaters controlled by thermocouples allows a smooth rise of the temperature in the ovens. The continuous ramp-up of the temperature made it difficult to estimate the cracking efficiency from the RGA data during the deposition. The presence of masses 70 and 144 in the mass spectra indicated that the carborane was not completely cracked, as intended for a good uniformity of the deposited film. No condensation of carborane on the walls or the injection line was observed after deposition. Finally, a 20–30 min He GDC was run on the film for H removal. This was done systematically everyday before plasma production. The coating generated by this method lasted more than 500 discharges for the 300 kW ECRH plasmas used in the present work. Although a rail limiter, also exposed to the boronisation, was used in some cases, the features here presented were basically insensitive to its insertion, at least up to a nominal position of 1 cm within the SOL location determined by the first wall. The magnetic configuration used was the same as in previous works (central iota = 1.51) [6].

3. Impact of boron coating in plasma parameters

As in other similar devices, a strong modification of plasma parameters such as edge temperature, impurity composition and total concentration and radiated power take place upon boronisation of the TJ-II device. Table 1 summarizes some of the most relevant changes. Total radiation after wall boronisation is a factor of 3–4 lower than before. Also, the radiation profiles are broader and hollow, respect to their metal counterpart, and the SXR signal level drops to its minimum detectable level. Edge temperature at the LCFS was measured by triple Langmuir probe located at the limiter. Interestingly, central ion temperatures are lower in the boronised case, even when central electron temperatures can be higher for the same electron density value. This would be consistent with a higher average neutral density, and therefore higher energy loses through CX processes in the boron wall surrounded plasmas. In that respect, it must be noted that one of the strongest effects of boronisation in TJ-II is the control of plasma density by external gas puffing. There are two effects that could contribute to the observed increase of the required gas fuelling at a given electron density, namely, wall recycling and plasma contamination. As for the first, there is a systematic trend to lower external fuelling required as the wall, initially depleted of hydrogen by He GD conditioning, is being gradually loaded by the plasma. It is worth noting that record low densities, of $\sim 2.5 \times 10^{18}$ m^{-3}, could be achieved under boronised conditions. These low values have been previously precluded by the contribution of wall degassing (mostly highly recycling He due to the GDC in metal walls) to the plasma [11]. The strong similarity existing in the time evolution of the recycled H signal (H_α) to that of the line density, at low value of $\langle n_e \rangle$ clearly reflects the state of plasma cleanness that can be reached with B coating in our ECRH plasmas, as deduced from bolometry and SXR data. Since low Z_{eff} values were already achieved in full metal scenarios, as displayed in the Table, the wall loading effect appears as the main factor for the higher fuelling rates in B coatings. In order to recover control over the density evolution after the wall saturation, one discharge with no puffing during the gyrotron pulse was able to revert the situation to an external-fuelling controlled one.

Fig. 1 shows the edge characteristics of similar discharges, using the average density as reference parameter, for both wall scenarios. Atomic beams (thermal

Table 1
Characteristic plasma parameters for metallic and boronised first wall scenarios in TJ-II

Wall	$T_e(0)$ (keV)	T_{edge} (eV)	n_{edge} ($\times 10^{17}$ m^{-3})	T_i (eV)	P_{rad} (kW)	Z_{eff}
Metal	0.75	17	6.5	100	57	1.5
Boronised	0.95	50	6.5	80	15	~1

The $\langle n_e \rangle$ line value is 0.65×10^{19} m^{-3} in both cases.

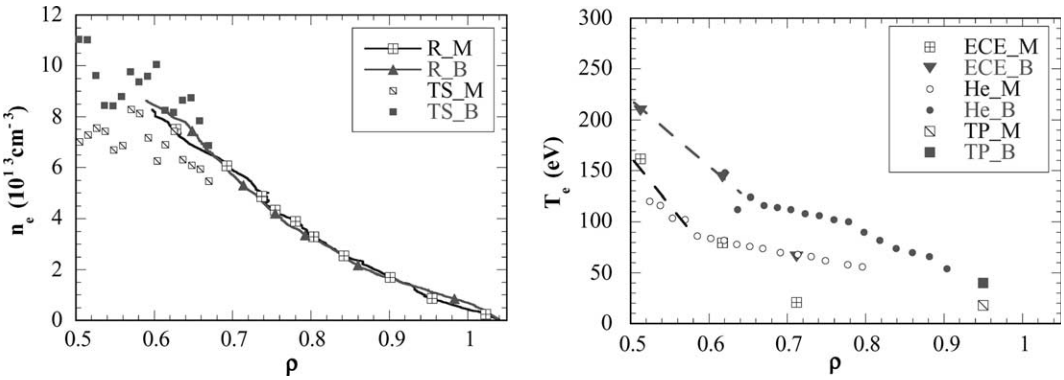

Fig. 1. Edge profiles of plasma parameters for similar discharges under boronised (B) and metallic (M) first wall conditions, at $n_{e_{line}} = 6 \times 10^{18}$ m^{-3}. ECE, R (reflectrometer) He (He beam), ST (Thomson scattering) and TP (triple probe) data are shown. The lower values for the ECE temperature data at the outermost positions are due to the lack of plasma opacity for the local values of density.

lithium and supersonic He [11]) provided information on edge density and temperature radial profiles. Reflectrometry [12] was used to monitor the density profiles in a range farther inwards, but partially overlapping with the Li beam. Langmuir probe data were crosschecked against the beam diagnostics when available. As seen in the figure, while electron density profiles do not exhibit any significant difference, higher electron temperatures are systematically recorded in the boronised case. Very similar decay lengths for the electron density in the SOL (∼1 cm) are deduced from the Li beam data in both scenarios. However, no quantitative estimate of the global particle confinement time has yet been possible for the operational range of boronised walls.

4. The EPC mode under boronised walls

The EPC mode of the TJ-II stellarator [6] can be characterised by a strong, spontaneous enhancement of the line integrated to LCFS density, $\langle n_e \rangle / n_a$, ratio. This leads to an increase in the global particle confinement time by a factor of >3. The conditions for the achievement of the transition to the mode under metal walls include a critical trimming of the gas puffing waveform and a critical density, $\langle n_e \rangle_{crit} \sim 6 \times 10^{18}$ m^{-3}. Evolution of the floating potential radial profile and edge electron temperature pointed to a fast drop in the latter parameter induced by a short gas puffing as the triggering condition [8]. However, reversal to the initial mode was also achieved by excess of gas injection. In the last campaign, i.e. under full boronised walls, this transition has also been found. Fig. 2 shows examples of the transition in both cases. As it can be seen, some of the main features, such as sudden increase of the effective fuelling rate ($dN_e/dt/Q_{gas}$) and the constancy or decline of the H_α signal and saturation current are found in both cases. However, while the edge temperature (electron cyclotron emission (ECE) traces) shows a fast dip at the time of gas pulse injection in the metallic wall case, not such a feature is seen in the boronised counterpart. Edge temperatures remain high in the latter, even at the outermost position (Langmuir probes, not shown). Also interesting is the fact that total gas fuelling rates during the transition are much larger in the boron case. Finally, an increase in the total energy content, following that of the electron density, takes place in this case. This appears as a direct consequence of the constancy in the electron temperature profile during the transition, as opposed to the metallic wall scenario. Fig. 3 shows the evolution of some of the edge parameters during the transition. While steepenning of the density profiles is clearly seen in the reflectometric signals, a constant (boronised) or declining (metal) temperature profiles can be found.

5. Discussion and conclusions

Although some of the main features found in the plasma parameters are standard in the change from metallic to boronised walls, some others have direct implications in the previous estimates on energy and particle balance in ECRH, TJ-II plasmas. In order to correlate the change in edge parameters with central ones, a proper account of the energy losses has to be performed. So, the absolute values of radiated power would in principle imply a negligible contribution of this channel to the total energy flux diffused to the edge. The strong change in electron temperature at the LCFS motivated by the slight decrement, ∼40 kW, of the total radiated power after boronisation indicates that other energy loss channels are strongly competing. From the estimated particle fluxes, F, N_{tot}/τ_p, edge electron temperature, $T_e(a)$, and electron and ion temperature profiles, the power balance can be evaluated:

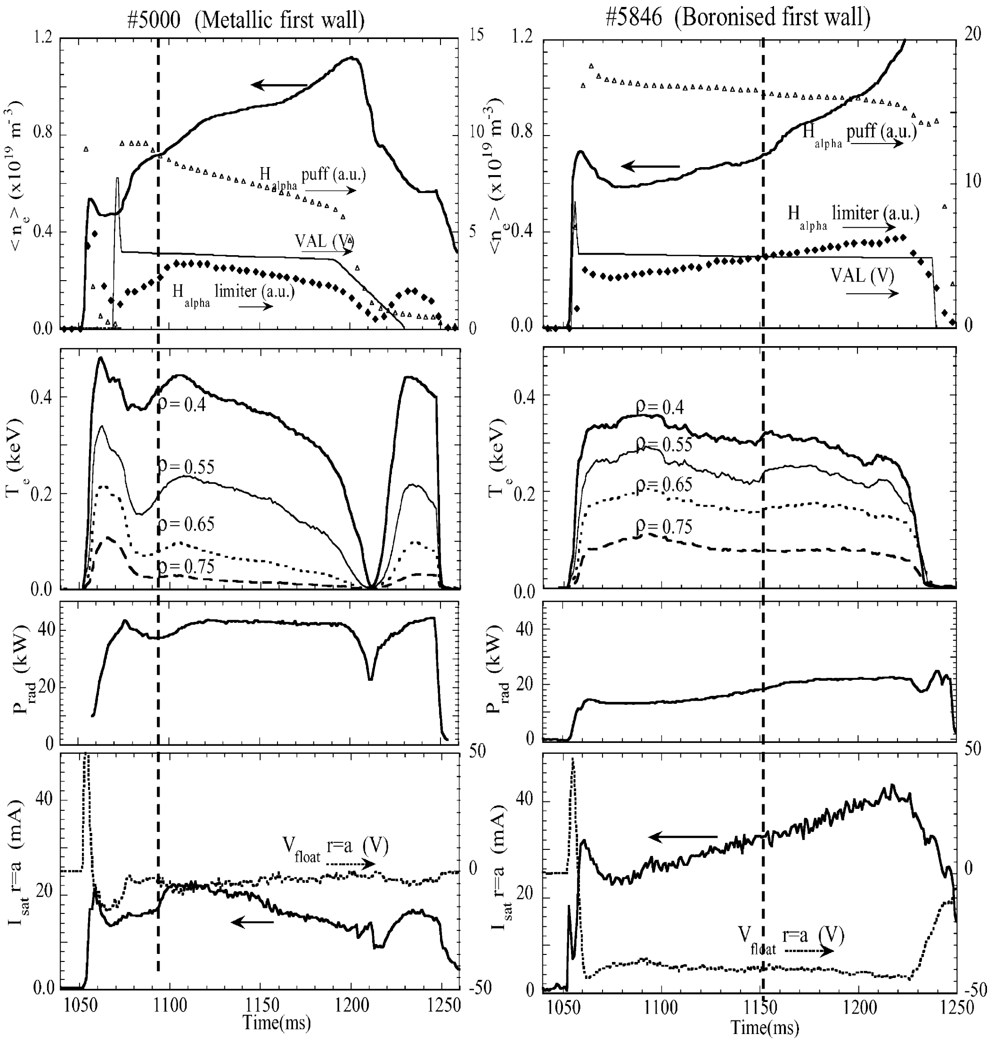

Fig. 2. Typical traces of plasma parameters during the transition to the EPC mode. Left, metallic walls, right, boronised walls. Transition takes place at $t = 1105$ and 1150 ms, respectively.

$$P_{in} - P_{rad} - P_{CX} - P_{loss} = F\gamma T_e(a), \quad (1)$$

where γ stands for the total heat transmission factor ($\sim$8 for H), P_{in} represents the absorbed power that diffuses to the SOL and P_{loss} stands for other, convective, energy losses, such as ripple induced orbit losses. From the values in Table 1, and the measured T_e and n_e profiles, a value of $P_{in} - P_{loss} \sim 100$–120 kW is found for both wall conditions, if similar particle confinement times are assumed [6]. Indeed, uncertainties in this calculation exist, due to the lack of data in the edge ion temperature and absolute CX losses, together with the possible SOL asymmetries that would have impact on the determination of particle confinement. However, this first-order estimate gives already the idea of strong convective energy losses taking place in the ECRH plasmas in TJ-II. In this respect, it is worth noting that diffusion coefficients D_{SOL} deduced in TJ-II were significantly lower, although following the same trend, than those from the W–7As stellarator if the nominal heating power, i.e., uncorrected for radiation and convective losses, was used as reference [6]. The low net power transmitted to the edge under metal scenarios would also be responsible for the edge cooling observed in the early stages of the density ramp shown in Fig. 2. As seen in boron case, higher T_e values, unperturbed during the ramp-up, are also compatible with the EPC mode, although the higher net power available in that case allows for a simultaneous enhancement of the energy confinement as well. Finally, although many models stressing the critical role

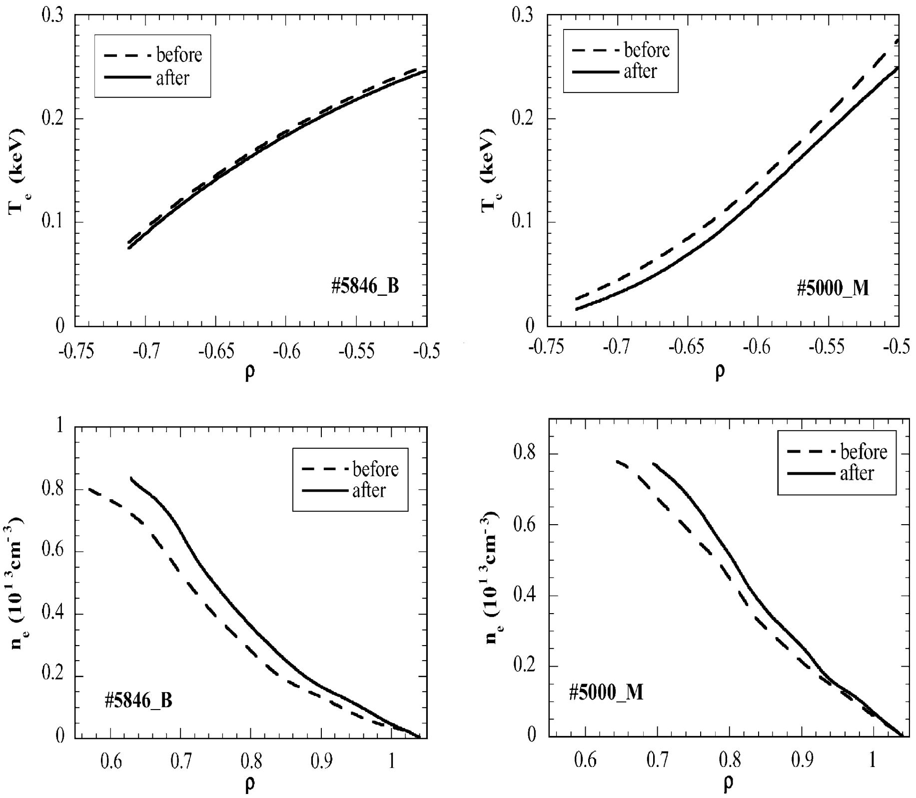

Fig. 3. Evolution of the edge temperature and electron density profiles during the transition for boronised (#5846, left) and metallic (#5000, right) wall conditions.

that neutrals play in the achievement of enhanced confinement modes have been developed [13], it is remarkable that at least the EPC mode in TJ-II has been observed under quite different gas fuelling conditions, such as strong wall contribution and the very low recycling conditions (i.e. strong external puffing) obtained upon He GDC conditioning of the boronised walls.

In conclusion:

- TJ-II has been operated under metallic and boronised walls and similar plasma parameters have been achieved.
- Boronisation has lead to a much lower total radiation level and a different gas fuelling scheme.
- Edge temperatures higher than in the metallic counterpart by a factor of 2–3 have been measured. This enhancement is not in agreement with a simple energy balance if the nominal heating power and the (low) absolute radiated powers in both cases are taken into account.
- Significant convective energy losses are required for total power accountability. These losses could be directly associated to ripple trapped particle heating, although a quantitative estimate from the experimental evidence is still lacking.
- The EPC mode under boronised walls is easily achieved, provided that the gas puffing waveform is properly tailored. The conditions for the transition are in general more relaxed than in the metallic case, and enhanced energy content at constant heating power is reached under some conditions.
- Comparison between the required conditions in both types of wall conditions indicate that no fast cooling of the edge is required for its triggering. Also, the constraints in puffing waveform seem to be rather linked to the power balance at the edge region.

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