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# Density control and plasma edge characterisation of ECRH heated plasmas in the TJ-II stellarator

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## Abstract

In the 1999 experimental campaign, the Spanish stellarator, TJ-II ( $R = 1.5$  m,  $a < 0.22$  m,  $B_0 < 1$  T) has been operated under a broad range of parameters, including changes in the magnetic configuration, working gas ( $H_2$  vs He), microwave heating power (100–600 kW, two independent lines at 53.2 GHz, second harmonic X-mode) and plasma-wall interaction conditions (wall conditioning, poloidal vs toroidal limiter). Although a close coupling between the plasmas and the TJ-II vacuum vessel is naturally present in most conditions, a good control of central plasma values has been achieved for both atomic species even under conditions close to the highest power density ( $n_{e0} < 1.7 \times 10^{13}$  cm<sup>-3</sup>,  $T_{e0} < 1.3$  keV). For this purpose, a careful control of wall conditions has been required. In addition, the low electron density and temperature of TJ-II edge plasmas have led to a significant reduction of the expected plasma-wall interaction. In this work, the issues of plasma density control and edge characteristics for the different plasma species and heating power are addressed. Results of new edge diagnostics, as a thermal lithium beam and a supersonic helium beam, among others are presented. © 2001 Elsevier Science B.V. All rights reserved.

**Keywords:** Stellarator; TJ-II; ECRH; Wall conditioning; Density control; Edge plasma; Atomic beams

## 1. Introduction

In the last experimental campaign, the TJ-II stellarator [1] ( $R = 1.5$  m,  $a < 0.22$  m,  $B_0 < 1$  T) has been operated for the first time under full power of electron cyclotron resonance heating (ECRH). This has been achieved by means of two independent microwave lines at 53.2 GHz, second harmonic X-mode, each of them delivering up to 350 kW pulses of <300 ms duration. Both transmission lines are quasi-optical and one of them has a focusing mirror inside the vacuum chamber which leads to a narrower power deposition profile. A central electron temperature up to 1.5 keV at a line averaged electron density up to  $1.2 \times 10^{13}$  cm<sup>-3</sup> (cut-off value at  $1.7 \times 10^{13}$  cm<sup>-3</sup> for TJ-II) has been recorded. Both he-

lium and hydrogen fuelled plasmas have been investigated. In order to get reproducible and controlled discharges, new gas control and wall conditioning techniques have been implemented. This new operation scenario has led to the achievement of ELMy discharges under some conditions [2]. Characterisation of the edge for both types of plasma has been achieved by newly developed atomic beam and probe diagnostics. In this paper, the topics of particle control at high injected power and characterization of the plasma edge for the magnetic configuration characterised as 100-40-63 (described in [1]) are addressed.

## 2. Particle control and central parameters

Previous attempts of density ramping by external puffing at relatively high injected powers were hampered by the strong wall fuelling [3], which led to some erratic behaviour of the discharge parameters. Due to the low

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value of the maximum particle content of TJ-II plasmas (associated to the cut-off limit), the large vessel surface to plasma volume ratio and the loading of the stainless steel (SS) surfaces by the highly recycling He from the overnight glow discharge (GDC), pure H plasmas were only attainable by deep insertion of the poloidal limiters [4], thus strongly reducing the effective plasma volume. In order to overcome this problem a new wall conditioning procedure has been developed [5]. It implies the sequential application of an Ar GDC which removes the implanted He. The retention of Ar in the SS surface is lower and shallower in comparison to that of He and few plasma discharges are needed to remove it completely from the wall. This procedure has been applied even prior to the production of He plasmas in TJ-II. In addition, a more accurate gas fuelling system, which

allows for the monitoring of flow rates up to a factor 10–50 times lower than those typically used in the experiments, has been implemented. As an example of the present situation, Fig. 1 shows the time evolution of some typical plasma parameters for H and He plasmas. Total injected ECRH powers are 400 and 300 kW, respectively. Density values close to the cut-off limit can be achieved by external gas puffing in both cases. The control is significantly easier in the case of hydrogen plasmas, as it is expected from the lower recycling of H in metallic walls. The  $H_\alpha$  signal in Fig. 1(b) indicates the presence of desorbed H in the He plasmas while desorbed He has been observed in H plasmas. This desorption was recorded by optical emission and mass spectrometry. It was found to increase linearly with the total injected power. The residual particle density (i.e.,

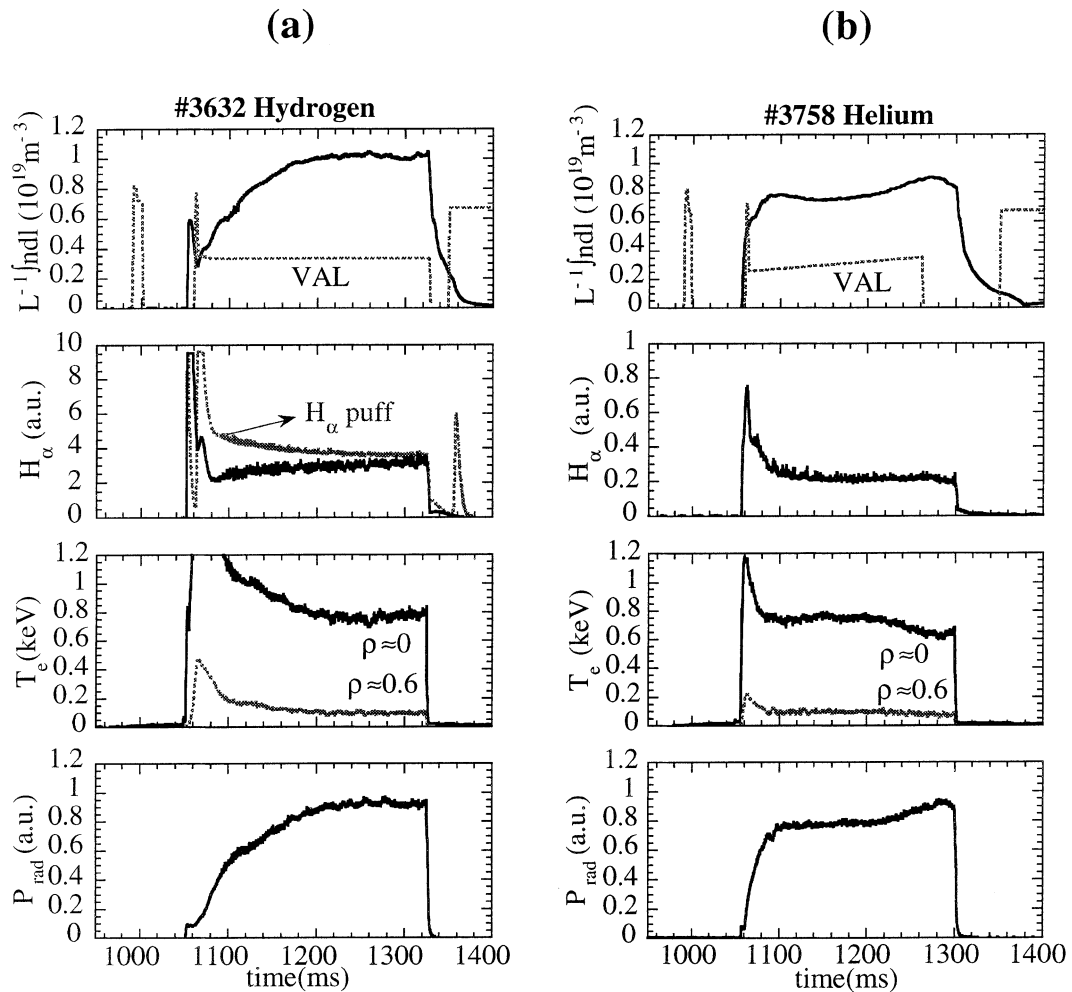


Fig. 1. Typical traces of ECRH plasma parameters in TJ-II. (a) Hydrogen plasma, 400 kW. (b) He plasma, 300 kW. From top to bottom: line average electron density, voltage applied to the puffing valve,  $H_\alpha$  signal at puffing location,  $H_\alpha$  signal at the poloidal limiter, ECE electron temperatures (central and edge) and total radiated power. Note the presence of the prefll pulse for the plasma start up ( $t = 980$  ms) and the 10× magnification of the vertical scale in the  $H_\alpha$  trace in He plasmas.

that produced when gas fuelling is used only for the start up) also rises linearly with power. Fig. 2 shows the case of H desorption in He plasmas, together with the residual density. In H plasmas the residual density obtained for a given heating power is systematically lower. For both types of plasmas a smaller contribution of desorbed species was attained when the highly focussed ECRH line (central deposition) was used, while no dependence on the total amount of particles externally fuelled to the plasma was found.

Contrary to these observations, central plasma parameters have been found weakly dependent on experimental conditions. Basically, the same radial profiles for plasma density and electron temperatures were recorded by Thomson Scattering and electron cyclotron emission (ECE) in H and He plasmas. A quick saturation of electron temperature profiles is observed when the ECRH power is increased above 300 kW. Fig. 3 shows

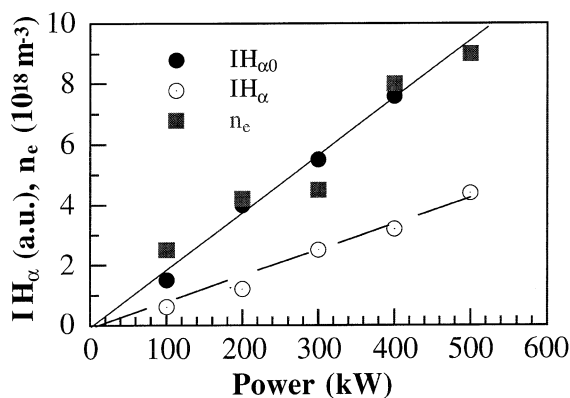


Fig. 2. Dependence of the  $H_{\alpha}$  emission intensity (peak and steady-state values,  $H_{\alpha 0}$  and  $H_{\alpha}$ , respectively, see Fig. 1(b)) and residual electron density (see text) on injected power for He plasmas.

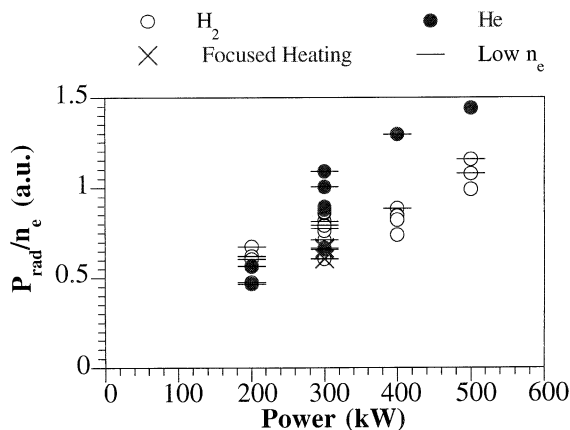


Fig. 3. Total radiated power (bolometer) normalised to the electron density vs ECRH injected power for He and H plasmas. Higher values at each power correspond to lower densities.

the dependence of normalised radiated power on total injected power. A fairly linear dependence can be seen. Total radiated powers were below 20% in all cases, being systematically higher for He plasmas.  $Z_{\text{eff}}$  values deduced from soft X-ray spectra, closely follow the behaviour displayed in Fig. 3, their values ranging from 1.5 to 2.5 in H plasmas and  $<3$  to 4.5 for the He case. Lowest values were always found for higher densities and for central focused ECRH.

### 3. Edge characterisation

The main features of the edge and scrape-off layer (SOL) of the TJ-II plasmas have been previously described [3]. Briefly, the last closed flux surface (LCFS) can in principle be defined by the intersection of the field lines with the part of the vessel surrounding the central helical coil, which acts as a helical limiter, or by two poloidal, movable limiters [6] whose limiting efficiency strongly increases as they are inserted deep into the edge (typically up to 3–5 cm from the nominal LCFS). The SOL topology leads to a spectrum of connection length values, which are strongly dependent on magnetic configuration and radial distance from the LCFS. Values from 2–15 m, for the helical limiter, and 20 to some hundred meters for deep insertion of the poloidal limiters have been calculated. Radial profiles deduced from a Langmuir probe and a Li beam diagnostic have experimentally confirmed such a strong enlargement of connection lengths as the limiters are inserted, and values of the SOL e-folding widths consistent with a Bohm diffusion coefficient have been measured [3].

In the present studies, the newly developed atomic beam diagnostics [7] have been applied to the characterisation of the plasma boundary. A thermal Li beam, located in a top window with an effusive source located at  $\sim 80$  cm from the observation region, has been used for the reconstruction of the SOL and edge parameters in both H and He plasmas. A 16-channel photomultiplier array allows for the continuous recording of the  $\text{Li}^*$  emission radial profile. In order to keep a low background at the 671 nm radiation, the beam was allowed into the plasma chamber only for a few seconds. Due to the edge plasma characteristics, recording of the  $\text{Li}^*$  emission up to 8 cm into the LCFS (corresponding to normalized effective radius  $\rho_{\text{eff}} = r_{\text{eff}}/a$  values of  $<0.7$ ) was possible. Also from a top window, the TJ-II supersonic He beam is launched into the plasma. For the experiments reported here, pulses of 1 ms were produced from the piezoelectric valve, located at  $\sim 90$  cm from the plasma edge. He lines at 667, 706 and 728 nm were monitored, and their spatial profile was measured on a shot to shot basis in H plasmas. Application of a collisional radiative model [8] allowed the reconstruction of the electron parameters at the edge ( $n_e, T_e$ ). Due to the

signal to noise ratio limitations, only partial overlapping of both types of atomic beams was possible. Fig. 4 summarises the results for H and He discharges having the same average electron density, for two values of total ECRH injected power. In the top figure, data from both beams, together with data from the Langmuir probes located on the poloidal limiters, which were slightly inserted into the edge, are displayed for H plasmas. A good agreement is observed among the different edge diagnostics in general. At external positions, the He beam gives systematically lower values of  $n_e$  than the Li beam. This discrepancy could be explained in part by the long relaxation times of the excited He atoms [9] at the low edge densities of TJ-II plasmas, that give rise to a ‘drag’ of information from the outer regions traversed by the beam. Some of the main features observed in a power scan are apparent from the figure. Thus, for example, no significant differences in electron temperatures near the LCFS are seen as the power is varied. Slightly broader density profiles are recorded for higher injected power, while small variations with average electron density were observed. Electron temperatures in the

range of 15–25 eV were typically measured by the Langmuir probes, which, together with the He beam data, confirm the presence of an almost flat  $T_e$  profile from  $\rho_{\text{eff}}$  values  $>0.6/0.7$ , in agreement with ECE and Thomson Scattering profiles [1]. Very similar edge parameter values and features to those described above were found in He plasma edges, as shown in Fig. 4(b), although no electron temperature data at the edge were available for the present study. Examples of typical errors associated to the reconstruction of the density profile from the Li beam data are shown in Fig. 4(b).

#### 4. Discussion and conclusions

Contrary to tokamak plasmas, the edge characteristics and parametric dependence of plasmas in stellarators are much less documented. This is partially due to the specific magnetic configuration at the plasma boundary of each device, that in many cases leads to the presence of a natural divertor [10]. This is not the case for the configuration used in the present studies. For the

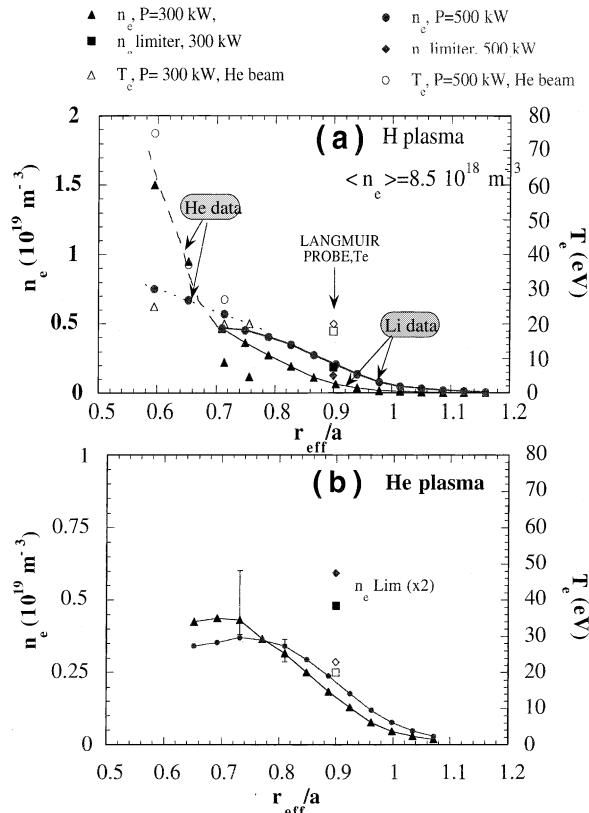


Fig. 4. Radial profiles of edge parameters for H and He plasmas as deduced from several diagnostics. Two cases with 300 kW ECRH in the non-focused line and 0/200 kW of ECRH in the focused line are shown. Points linked with solid lines correspond to Li beam data. He beam data (in H plasmas) and Langmuir probe results ( $\rho_{\text{eff}} = 0.9$ ) are also shown. Electron densities in both types of plasmas are inferred from saturation currents and temperatures assuming the same proportionality factors.

edge conditions here reported, a rather internal particle source is expected (ionization length  $\lambda_{iz}$  for He  $\sim 6$  cm,  $\lambda_{iz}$  for H<sub>1 eV</sub>  $\sim 10$  cm). Besides, even for the broad power deposition line, microwave absorption takes place mostly at the plasma centre [1]. The observed lack of sensitivity of plasma edge parameters to the experimental conditions (plasma species, injected power, total density) could be due to a hindered transport of both, particles and energy, to the plasma periphery. An alternative explanation based on a dramatic enhancement of transport coefficients at the edge is also possible. Indeed the latter could be the case for a ripple dominated transport in TJ-II, strongly dependent on self-generated electric fields [11]. The presence of strong losses at specific toroidal locations (i.e., between toroidal coils) has not yet been investigated. On the other hand, simple energy balance considerations at the powers used here should yield edge temperature values for a factor of 3–6 times higher than observed, as reported in other ECRH heated plasmas [12] thus making physical sputtering of metals the main source of plasma contamination. The low values of  $Z_{\text{eff}}$  and radiated power recorded support the idea of a weak plasma wall interaction taking place at the limiting surfaces, as indicated by the measured boundary characteristics. This points to the hypothesis of gaseous species (He, H, CO, water etc.) as the outcome of such interaction. Due to the physical proximity of material surfaces to the confined plasma, the observed characteristics are essential for the density and power control achieved in the operation of the device. In fact, the recently observed ELM activity under the conditions here reported, which behaves as the onset to a higher confinement mode prevented by the low cut-off value of the ECH plasmas, would appear as consequence of a high power density-low wall contribution plasma, otherwise impossible under the metallic wall conditions used until now in TJ-II. More work oriented to the understanding of particle and energy confinement in TJ-II is obviously required.

## 5. Summary

- A general insensitivity of the edge characteristics to the operational parameters, such as plasma species, injected power, total density, has been observed in

TJ-II ECRH plasmas, at least in the magnetic configuration used for the present studies.

- The tenuous plasma edges so created prevent from plasma radiative collapse at the higher powers, that would be a natural consequence of the close geometrical coupling existing between plasma and vacuum vessel in TJ-II if physical sputtering of metals was dominant.
- Even when gaseous desorption makes particle control below the cut-off limit a challenging task, specially at high injected powers, advanced wall conditioning techniques have shown to be able to provide controlled density conditions.

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## References

- [1] C. Alejandre et al., *Plasma Phys. Control. Fus.* 41 (1999) A539.
- [2] I. García-Cortés et al., *Nucl. Fus.* 40 (2000) 1867.
- [3] F.L. Tabarés et al., in: *Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics*, Maastricht, Netherlands, vol. 23J, 1997, p. 369.
- [4] E. de la Cal et al., *J. Nucl. Mater.* 266–269 (1999) 465.
- [5] D. Tafalla, F.L. Tabarés, these Proceedings.
- [6] E. de la Cal et al., these Proceedings.
- [7] F.L. Tabarés, D. Tafalla, E. de la Cal, B. Brañas et al., *J. Nucl. Mater.* 266–269 (1999) 1273.
- [8] M. Brix, in: *Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics*, Berchtesgarden, vol. 21A, 1997, p. 1837.
- [9] B. Schweer et al., *J. Nucl. Mater.* 196–198 (1992) 174.
- [10] K. Uo, *J. Phys. Soc. Jpn.* 16 (1961) 1408.
- [11] V. Tribaldos et al., in: *Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics*, Maastricht, Netherlands, vol. 23J, 1999, p. 349.
- [12] P. Grigull et al., *J. Nucl. Mater.* 196–198 (1992) 101.