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Journal of Nuclear Materials 290–293 (2001) 972–975

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

JET methane screening experiments

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Abstract

Methane screening experiments were performed in JET L-Mode plasmas. Potentially, methane puffing quantifies the SOL processes governing the intrinsic carbon, its penetration to the plasma core, and its removal to the divertor. We measured the perturbations to the core and the SOL plasmas as a function of CD_4 and D_2 injection rates. The deduced screening was independent of the methane injection rate indicating that the methane itself did not significantly perturb the deduced screening. Identification of appropriate reference plasmas is important. For JET L-Modes, the reference plasma should have enough deuterium puffing to achieve the same density as that which occurred with the methane. The screening results are susceptible to systematic errors in the visible and charge exchange determination of the core carbon density. For JET, these two measurements yield screening values that differ by a 'factor-of-three'.

Keywords: Carbon; Plasma properties; Impurities

1. Introduction

The ultimate goal of this research is to understand the magnitude of tokamak impurities. Impurities deplete the fuel ion species in relation to the plasma electron species. The depletion can reduce the fusion power if the electron density is limited (e.g., by the Greenwald limit), or when the total plasma pressure is limited (e.g., by the Troyon limit), or when radiation losses (e.g. Bremsstrahlung) are important in the energy balance. If impurity generation and contamination mechanisms are understood, then impurity control techniques can be envisioned, evaluated, and projected to future experiments. Methane screening experiments relate to these goals since they evaluate the ability of the SOL to ionise carbon and transport it to the divertor, preventing it from contaminating the plasma. This benchmarking is especially relevant for JET since chemical sputtering from the main chamber walls is thought to be a significant source of the dominant (carbon) impurity [1].

The purpose of the present paper is to evaluate the methodology and accuracy of the JET methane screening experiments. Methane screening experiments have been performed on several tokamaks [2–9] however, little systematic evaluation of the methodology has been reported in the literature. Usually, the screening has been reported as a single number or upper limit. The work reported here is being used as a basis for the connection to the intrinsic JET impurities using DIVIMP [10] and those results will be reported elsewhere.

2. Experiment

Methane was injected into JET L-Mode plasmas with 2.5 T toroidal magnetic field, 2.5 MA plasma current,

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and neutral beam heating of 2.5 MW. The power was low enough to ensure L-Mode operation thus avoiding the analysis complications of ELMs. The plasma was attached to the JET Gas Box divertor with the strike points hitting the vertical targets.

The data were collected from a series of 12 plasmas comprising a shot-to-shot scan in the methane puffing rate (seen in Fig. 1 from 16 to 19 s), and a scan in the deuterium puffing rate (seen in Fig. 1 from 20 to 23 s). The time evolution of three plasmas is overlaid in Fig. 1. Although the density rise was about equal from the methane and the deuterium (in Fig. 1), the main purpose was to accomplish both scans and determine the best reference plasma for the methane injection. The methane fuelling was toroidally localised (an extended port of about 0.8 m linear dimensions, 0.5 m away from the plasma edge), at the horizontal, outer mid-plane. The deuterium fuelling was toroidally distributed from the divertor.

Key diagnostics included:

1. Carbon density measurements from charge exchange recombination spectroscopy (CX) [11] (Fig. 1).
2. The line-averaged Z_{eff} measured along a central chord using visible Bremsstrahlung (VB) intensity.
3. SOL density and temperature measurements by the reciprocating Langmuir probe (RCP) [12].
4. The inferred SOL properties from the divertor Langmuir probes using the Onion Skin Model (OSM) [13,14]. Since there are only a finite number of probes, and the SOL properties are inferred along the probe field lines, the strike points were swept about 2 cm from 18.5 to 19 s and from 22.5 to 23 s in order to improve the OSM.

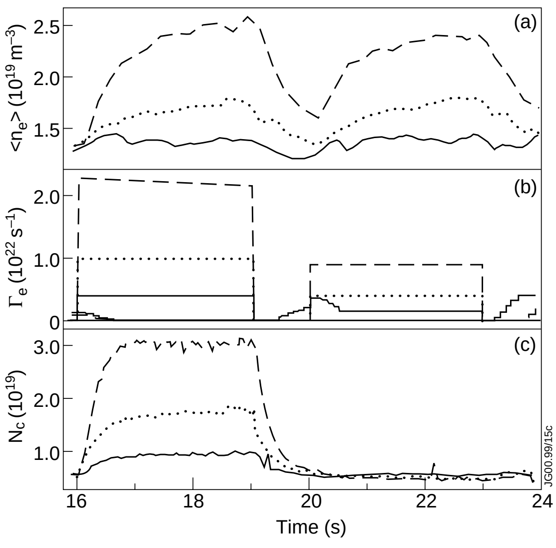

Fig. 1. The time evolution of the density, gas injection rate of electrons, and the total carbon particle number measured by charge exchange recombination spectroscopy for three discharges each with a different gas injection rate. Methane (CD_4) was injected from 16 to 19 s, and deuterium was injected from 20 to 23 s.

The RCP is located in the same toroidal location as the methane puffing, but displaced about 80° poloidally above the horizontal mid-plane. The OSM uses target density and temperatures as input. The OSM temperature and density profiles (predicted for the RCP location) were in good agreement with the direct RCP measurements.

3. Results

While the SOL measurements agree reasonably well, the CX and VB core carbon measurements are discrepant. Commonly, JET H-Mode plasmas have CX Z_{eff} values about 0.75 of the VB values. However, for these L-Mode plasmas the differences are somewhat larger. Since the core carbon content is proportional to $Z_{eff} - 1$, and since the actual Z_{eff} values were small, the differences are magnified resulting in 'factor-of-three' differences in the inferred core carbon content. Each diagnostic has several sources of error, which could cause the discrepancy. Of particular note is that the methane puff itself, seemingly caused a contaminating continuum radiation for VB chords located near the puff (or in its plume). We do not know the origin of the discrepancy, so we quote each potentially valid measurement. Since the VB Z_{eff} is larger, the discrepancy is less likely to originate from an unresolved impurity species and more likely to be due to a misalignment or calibration issue.

The magnitude of the methane injection rate (up to a carbon injection rate of 2.2×10^{21} s^{-1}) did not influence the magnitude of the screening inferred for JET L-Mode plasmas. The methane injection did cause some perturbations to the SOL and core plasmas. The methane modified the plasma's radiation pattern, the core carbon content, the electron density in the SOL, and increased the core electron density (Fig. 1). However, these perturbations did not influence the deduced screening so long as the methane-puffed plasma was compared to a discharge with the same core electron density.

The scan in the injection rates indicates (Fig. 2(b)) that the core density is uniquely related to the deuterium injection rate, whether the deuterons were injected as D_2 or as CD_4. At the same core density, the remaining core and edge parameters are similar for D_2 and CD_4 injections (Fig. 2). Thus we conclude that the carbon content due to the methane puff should be compared to deuterium-fuelled plasmas at the same core density. Notice that the fuelling locations are different (D_2 from top vs. CD_4 from mid-plane, both in the main chamber), and consequently the fuelling efficiencies may be different for deuterium fuelled from the different locations.

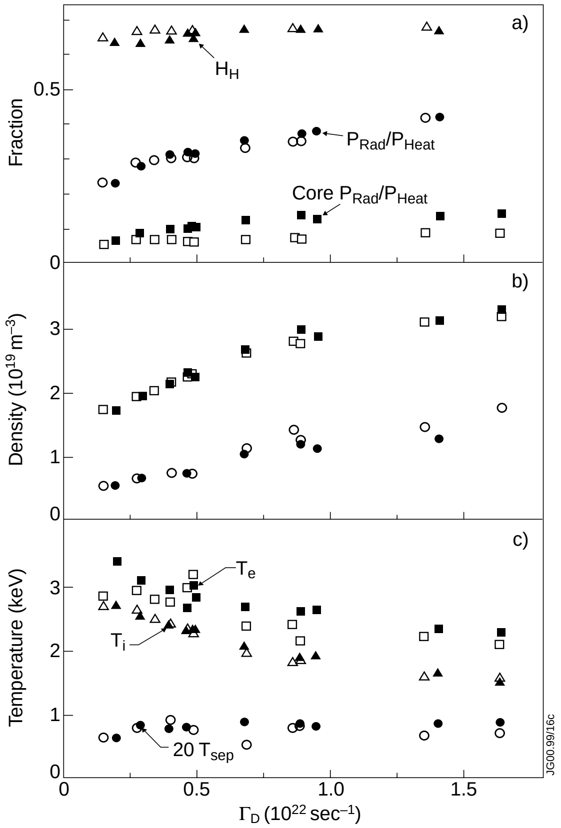

Fig. 2. Variation of the plasma parameters as a function of the deuteron injection rate. The open symbols represent D_2 gas injection, and the closed symbols represent CD_4 gas injection. In (a) are plotted fractions: $H89_H$ (triangles), total radiated fraction (circles), and radiated fraction from the plasma core (squares). In (b) are plotted densities: the central density (squares), and the separatrix density (reciprocating probe measurement extrapolated to the Last Closed Flux Surface). In (c) are plotted temperatures: the central electron temperature (squares), the central ion temperature (triangles), and 20 times the separatrix temperature (circles) (RCP measurements extrapolated to the LCFS).

After normalising to the density, the core radiation, carbon content, and Z_{eff} were the only core parameters that changed due to the methane injection. The core radiation was about twice as high when methane was injected (Fig. 2(a)) as when deuterium was injected. Apparently, the extra carbon in the core caused higher core radiation. However, the core radiation was <25% of the total radiation and was <10% of the power input. From the energy balance perspective, the radiation is insignificant. Moreover, the X-point radiation decreased, making the total radiated power about constant.

In the SOL, the temperature profile was unchanged by the methane puffing (Fig. 3). Also, the electron

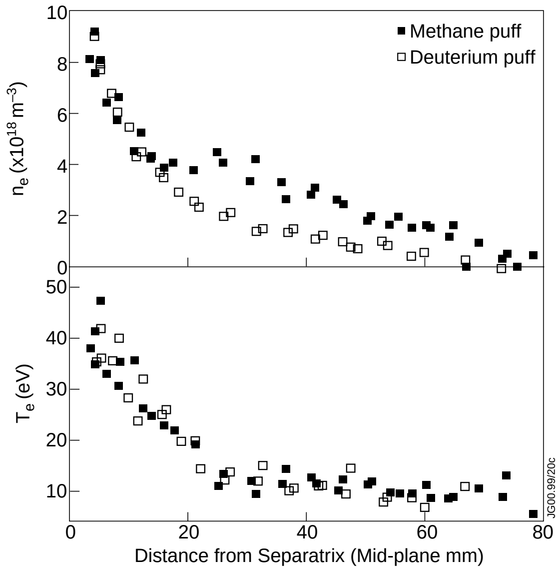

Fig. 3. The temperature and density measured in the SOL by the RCP with the distance being projected back to the horizontal mid-plane. The solid points are with the methane puff, and the open points are at the same core density but with deuterium puff.

density in the 2 cm closest to the LCFS (mid-plane projected distance), was unchanged (Fig. 3), but outside this distance (about 2–5 cm from the LCFS) the density was higher by as much as a factor-of-three for the highest methane injection rates. The density perturbation was proportional to the magnitude of the methane injection, and was clearly related to it. However, the geometry is complicated and the effects of local Z_{eff} changes have not been considered. We do not quantitatively understand the density increase. Wall temperature carbon atoms (0.05 eV) incident normally to the SOL, would be ionised in that region of the SOL (2–5 cm from the LCFS).

The carbon (Fig. 1(c)) approached its new steady-state value exponentially after the methane injection begins (16–17 s), and falls exponentially at the end of the injection (19–20 s). The rate of increase of the carbon in the plasma core, the total carbon content as measured by the charge exchange spectroscopy (CX), and the Z_{eff} as measured by VB all rise in proportion to the methane injection rate (Fig. 4). The methane injection rate is expressed in Fig. 4 as the associated deuterium injection rate. This allows us to plot the deuterium injection plasmas on the same graph, and to relate to deuterium plasmas at the same density as for Fig. 2. The carbon content due to the methane puffing is the difference between the solid and open symbols. At a high methane injection rate, we also performed a scan in deuterium injection rate (the X symbols). For this scan

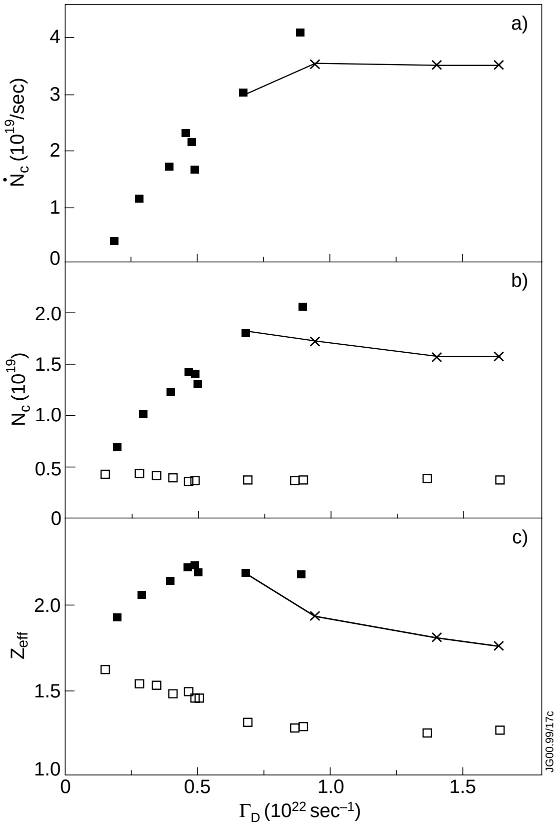

Fig. 4. The change of the signals indicating the core carbon content as a function of the injection rate of deuterium. The solid points had only methane injection, the open points had only deuterium injection, and the X symbols had combined methane and deuterium injection. The line connects those combined injection data having the same methane injection rate. In (a) are plotted the initial rates of rise of the total number of carbon particles (CX) in the core. In (b) are plotted the total number of carbon particles (CX) after steady state was reached. In (c) are plotted the VB Z_{eff} values after steady state was reached.

the carbon rate of rise was unchanged, the CX total carbon content fell about 10%, and VB Z_{eff} dropped from 2.2 to 1.8.

4. Conclusion

The main conclusion of this paper is that, for L-Mode, the methane screening is non-perturbative so long as the carbon content is compared to a similar density, deuterium-fuelled plasma. The principal evidence for this conclusion was that the methane did not change the plasma parameters significantly (Fig. 2) and that the core carbon increased linearly with the methane injection rate (Fig. 4).

Acknowledgements

The authors are grateful to the JET Joint Undertaking, their Operations and Diagnostics groups for their support. Vigorous discussions with G. Matthews and P. Stangby were most helpful. JDS was supported by the US Dept. of Energy.

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