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J.D. Strachan[1], G. Corrigan[2], M. Stamp[2], J. Spence[2], J. Zacks[3]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*PPPL, Princeton University, Princeton NJ, 08543, USA*
[2]*EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*
[3]*Queen's University Belfast 2008, University Road Belfast, BT7 1NN, Northern Ireland, UK*
* See annex of M.L. Watkins et al, "Overview of JET Results ",
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ABSTRACT

 This paper compares experimental JET carbon and hydrogen light emission to EDGE2D/NIMBUS calculations. The calculations themselves indicate that: (1) the deuterium ionization in the SOL or in the divertor is proportional to the D· photon flux density from those locations, (2) the carbon ionization in the SOL or the divertor is proportional to the calculated CIII light, and (3) the ratio of line integrated photon fluxes from a vertical chord to a horizontal chord indicates whether the main chamber SOL content originated primarily from a wall source or from ion flow out of the divertor. Comparison was made to JET gas box divertor plasmas. The database comprises inter-ELM H-Mode periods and L-Mode data. The core contamination was caused by carbon sputtering arising primarily from the main chamber. The L-Mode carbon yield was 1-4% in the main chamber. The inter-ELM H-Mode sputtering yield was about twice as large.

INTRODUCTION

Erosion, migration, and contamination phenomena are important issues for a fusion reactor. However, understanding these issues on present machines is difficult. One difficulty is ambiguity about the location and magnitude of impurity sources [1]. In this paper, JET carbon impurity sources are studied indicating that the main chamber wall source dominates the core contamination. This finding is different than previous JET results [2] based upon methane screening experiments, probably indicating that those measurements were influenced by divertor leakage.

In a sufficiently large diverted tokamak, impurities contaminate the core by first contaminating the main chamber SOL, and subsequently, transporting across the field lines into the core [3]. Direct penetration and impurity ionization in the core is negligible at separatrix temperatures above about 50eV. The SOL can be contaminated by two mechanisms;

1. Ionization in the SOL from impurity neutrals generated at the main chamber wall. This release is imposed by neutral bombardment from escaping charge exchange neutrals from the core as well as ion bombardment which can be enhanced by SOL turbulence.

2. Ion out flux from the divertor of impurities sputtered near the outer strike point. Direct neutral escape from the divertor is thought to be small since the mean free path for impurity ionization is typically much smaller than the divertor size [3].

EDGE2D/NIMBUS is used to interpret the JET CIII (465nm) and D· spectroscopic signals in terms of the spatial origin of the deuterium and carbon ionization in the main chamber SOL. EDGE2D indicates that the carbon source is dominated by main chamber sources.

The JET plasmas were from the intrinsic Zeff data base described in the JET carbon screening experiments (see Sections 2.3 and 3.3 of [2]). These include the L-Mode and inter-ELM H-Mode plasmas with the JET MKGB Divertor (July 1998 to March 2001). Both of these plasma types are free of ELMs and thus avoid the complications that ELMs present to the spectroscopic signals.

These plasmas include all the available MKGB plasmas having plasma current >1.5MA, main chamber clearance >5cm, neutral beam heating (1.5-8MW), and toroidal magnetic field >1.5T.

ICRF heating was not studied since such plasmas might have an additional impurity source in the vicinity of the RF antennae. Also, the data base was restricted to plasmas with moderate triangularity ($\delta < 0.4$) avoiding impurity sources from the top of the machine where the second X-Point (being just outside the vessel) draws plasma contact to that region. 108 L-Mode and 41 inter-ELM plasmas achieved these criteria and this represents a large JET database of L-Mode plasmas at 1.85 or 2.35MA. The inter-ELM plasmas had ELM periods longer than 0.6 sec isolating a distinct inter-ELM time phase.

This data set was used previously [2] to conclude that that core contamination by divertor impurity sources was significant. The conclusion here is different since the methane screening from divertor locations was influenced by previously unknown leakage from the methane gas injection module [4]. The leakage allowed some of the divertor injected methane to escape directly into the main chamber making the fuelling efficiency (core contamination) of divertor carbon sources appear higher than probably occurred.

EDGE2D/NIMBUS [6] is a SOL boundary code designed specifically for single null JET plasmas. It has been used to understand a variety of phenomena. The charged particles are described by the fluid conservation equations for density, parallel momentum, and energy while the neutral particles (deuterium and carbon) are described by the Monte Carlo code NIMBUS. The principal limitation is the lack of hydrocarbons since the carbon is introduced as atoms (i.e. C rather than CD_4). In this study, a further limitation is that spatially constant transport coefficients (with no pinch velocities) were used, except for one calculation.

The approach [3] in this paper is to form an ensemble of EDGE2D runs where many of the input parameters are individually changed. In this manner, variations in the experimental data can be encompassed. The parameter variations included the carbon diffusion coefficient (0.2 to $1 m^2/s$), the deuterium diffusion coefficient (0.2 to $1\ m^2/s$), the electron and ion thermal conductivities (0.2 to $1\ m^2/s$ and assumed to be equal), the SOL power (2 to 10MW), the edge density ($n_{sep} = 0.8$ to $1.2\ 10^{19}\ /m^3$), and the initial carbon energy (0.1 to 10eV). Variation of the deuterium gas injection rate caused the density variation.

Three ensembles were formed with different carbon sources:

1. An outer strike point source of injected carbon was used to identify effects due to divertor sources. This source extended 5cm above the outer target.

2. A sputtering carbon source was also used which originated due to deuterium and carbon bombardment of the carbon walls and targets. Physical sputtering was always included, while chemical sputtering was considered using various chemical sputtering coefficients [7-12]. Cases with physical sputtering only were also part of this ensemble.

3. A uniform wall source of carbon injected was used to identify effects due to wall sources. This source did not extend into the divertor. The variations for the uniform wall source were fewer once it was established that the SOL variations did not change the carbon ionization in the SOL.

The poloidal distribution of the carbon ionization for the three ensembles indicated the different carbon source locations. When the source is located at the outer strike point, there is little carbon ionization in the main chamber SOL.

On the other hand, when the source is located uniformly in the main chamber, then the carbon ionization is entirely in the main chamber SOL. The sputtered source produced a carbon ionization pattern that seemed to be a combination of the outer strike point source and the uniform wall sources.

On each EDGE2D calculation in the ensemble, the spectroscopic signals (figure 1) were simulated [13] according to the charge states calculated by the ADAS coefficients for the plasmas along the diagnostic sight-lines. The sight-lines of the JET CIII and D· spectroscopic signal that were most useful in this study were the horizontal view, the vertical view that did not include the divertor, and the wide angle view of the entire divertor [14]. The CIII excitation was almost entirely due to electron impact, with charge exchange forming a commonly 5% contribution and recombination forming a typically 0.5% contribution. Notice that detached cases were not part of any ensemble. The EDGE2D/NIMBUS calculations indicated that the 465nm CIII spectral line viewing the plasma horizontally near the mid-plane is proportional to the carbon ionization rate in the main chamber SOL. Regression to the ensemble (figure 2) of sputtered EDGE2D calculations indicates:

$$S_C = 2.3 \ 10^7 \ C_3H \tag{1}$$

www.ccaoccasions.com/is the ionization rate (/s) of carbon in the main chamber SOL, while C3H is the local intensity of the CIII 465nm spectral line along the horizontal sight-line. The underlying assumption is that the local emission arises entirely from the SOL and is not influenced by nearby vessel structure. Figure 2 indicates that the CIII light is a good indicator of carbon ionization rate independent of the SOL transport coefficients, the sputtering yield, or the carbon source. The uniform wall source of carbon in EDGE2D resulted in about 40% more CIII light per carbon ionization than the intrinsic sputtering sources. On the other hand, the outer strike point source produces 10 to 100 times less main chamber SOL carbon ionization and correspondingly less CIII light.

The vertical CIII signal which views outside of the divertor on the large major radius side (figure 1) is also proportional to the carbon ionization in the main chamber SOL but additionally has a dependence upon carbon ions flowing out of the divertor into the sight-line. For a uniform EDGE2D wall source, the vertical and horizontal channels yield similar signals (figure 3) even though the SOL volume seen by the vertical channel is larger. However, for EDGE2D outer strike point sources and for sputtered carbon sources, the vertical signal is about 10 times larger than the horizontal signal. EDGE2D is indicating that the carbon ions originating in the divertor are accelerated by the thermal force into the line-of-sight of the vertical spectrometer, enhancing this signal. The experimental JET L-Mode data has a ratio of vertical to horizontal CIII signals that is in agreement with a uniform wall source with no indication of any signal enhancement due to

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ions being extracted from the divertor (figure 3). The inter-ELM H-Mode data indicates a further factor-of-two enhancement of the horizontal signal as if to indicate that the carbon source is more oblate than uniform and is more strongly located near the mid-plane. For the EDGE2D ensembles, the SOL transport coefficients were spatially constant, so a single EDGE2D sputtering case was calculated with an H-Mode pedestal and ELMs [15]. The spectral signals were calculated inter-ELM indicating a factor of 2-3 higher CIIIH/CIIIV signal (star point in figure 3) so that the difference between H-Mode and L-Mode is likely due to a difference in time evolution and pedestal.

Following the logic of figure 2, the relationship of the deuterium ionization to the Dα signal was explored using EDGE2D (figure 4). The horizontal viewing Dα signal (FLW is the toroidal integral assuming toroidal symmetry) is a good indicator of the deuterium ionization rate in the main chamber SOL. Similarly, the wide angle Dα signal viewing the divertor (FLX is the toroidally symmetric integral of this signal) is proportional to the deuterium ionization in the divertor. Regression indicates:

$$S_{Dw} = 24 \text{ FLW} \tag{2}$$

$$S_{Ddiv} = 20 \text{ FLX} \tag{3}$$

S_{Dw} and S_{Ddiv} are the deuterium ionization rates (/s) from the wall and the divertor respectively. The numbers 24 and 20 are in the range of the classic Johnson-Hinnov factor, 15, and might be higher due to molecular processes or high temperature effects [16].

Since these calculations are in steady-state, the deuterium ionization (source rate) is also the deuterium loss rate to the main chamber walls, which therefore can be used to calculate the carbon sputtering yield from the main chamber walls and also the sputtering yield from the divertor. Thus using equation (1) with either equation (2) or (3) produces an EDGE2D formula for the experimental carbon sputtering yield in terms of the spectroscopically measured CIII and Dα light. This spectroscopic definition is a good indicator (approximately 10% high with 5% standard deviation) of the EDGE2D calculated ratio of carbon to deuterium ionization. Since these cases are from the ensemble of sputtered cases, the 15% scatter represents the sensitivity to input parameter variation. The good agreement indicates that the use of the spectroscopic signals to determine the carbon sputtering yield is a good approximation. Also, this good fit indicates that effects such as neutral deuterium penetration to the core, from the divertor to the main chamber, and into the pump are negligible.

The main chamber carbon sputtering yield is approximately equal to Ω the Haasz value [10] as is usually obtained in JET studies (figure 5). The L-Mode sputtering yield is about 5 times larger than expected solely from physical sputtering. Thus chemical sputtering is required in order to achieve the observed main chamber CIII signals. The principal L-Mode dependence was upon the density decreasing from about 4% at a separatrix density of $5 \ 10^{18} /m^3$ to 1.5% at $1.2 \ 10^{19} /m^3$. This decrease was about twice the decrease expected from the Haasz sputtering coefficient which

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decreases from 3% to 2%. Experimentally, the inter-ELM H-Mode plasmas have a factor-of-two higher sputtering yields which was not correlated to the applied power, the plasma current, or the beam energy. Again, the inter-ELM H-Mode EDGE2D calculation also had a factor of two higher sputtering yields than L-Mode (star point in figure 5). This indicates that time evolution and pedestal effects are the likely origin of the larger sputtering yield.

CONCLUSION

the modeling of the impurity sources for these plasmas agrees with previous JET modeling of the magnitude of the carbon sputtering coefficients. The inference of a predominately wall source of carbon in JET plasmas (fig. 3) contrasts with the methane screening experiments [2]. Those experiments were influenced by a leakage path for the injected gas into the main chamber SOL [4]. This present paper confirms that ion escape out of the Gas Box divertor was not observed and that wall sources probably dominate the JET core contamination, at least in the absence of ELMs.

ACKNOWLEDGEMENTS

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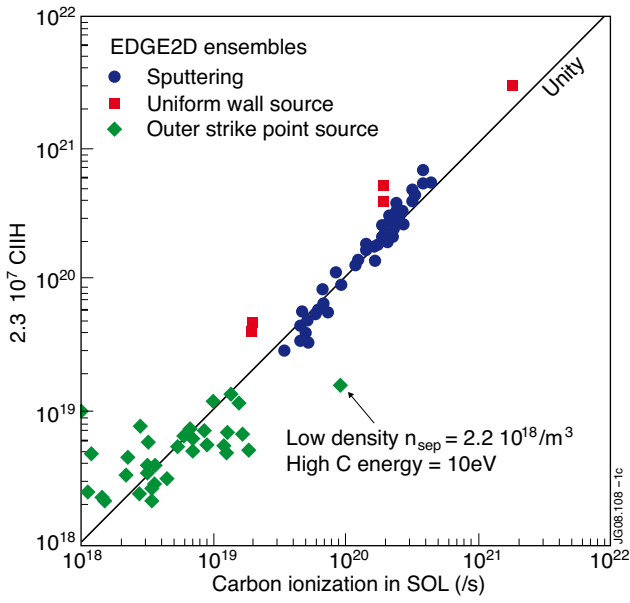[15].   A. Kallenbach, *et al*, Plasma Phys. Control. Fus. **46** (2004) 431.

Figure 1: Poloidal cross-section of JET with the sightlines of the spectroscopic signals indicated. The vertical signal is terminates outside the divertor at larger major radius.
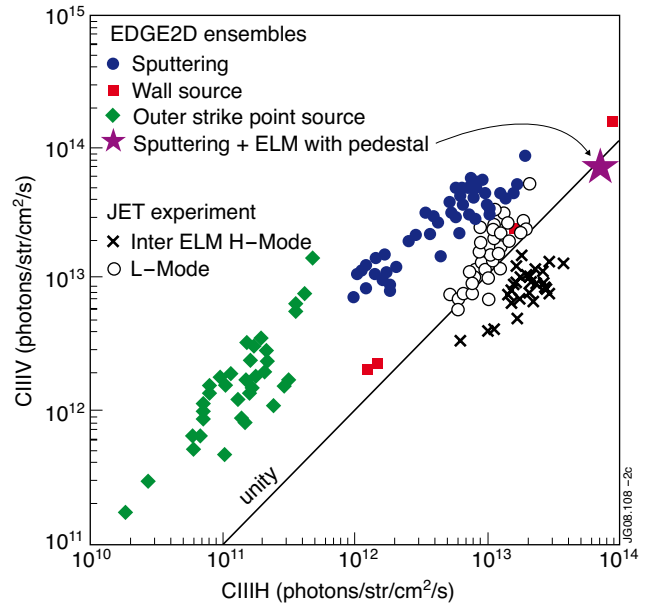

Figure 2: The carbon ionization in the SOL as indicated by Equation (1) is plotted against the actual EDGE2D calculated SOL ionization for each ensemble: the uniform wall (square), the outer strike point (diamond), and the sputtered (circle) sources. Each data point originated from a separate EDGE2D calculation
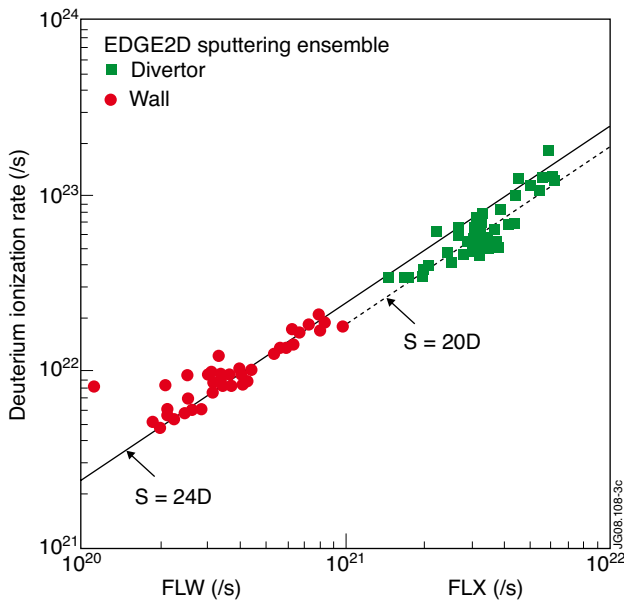

Figure 3: The CIIIV (vertical) signal is plotted against the CIIIH (horizontal) signal for the EDGE2D calculations (solid points for the three sources in figure 1. The star point is a calculation with an H-Mode pedestal and ELMs, but measured inter-ELM.), JET L-Mode experiments (hollow symbols indicating different energies of the heating beams), and JET H-Mode inter-ELM experiments. The line indicates equality of the two signals.
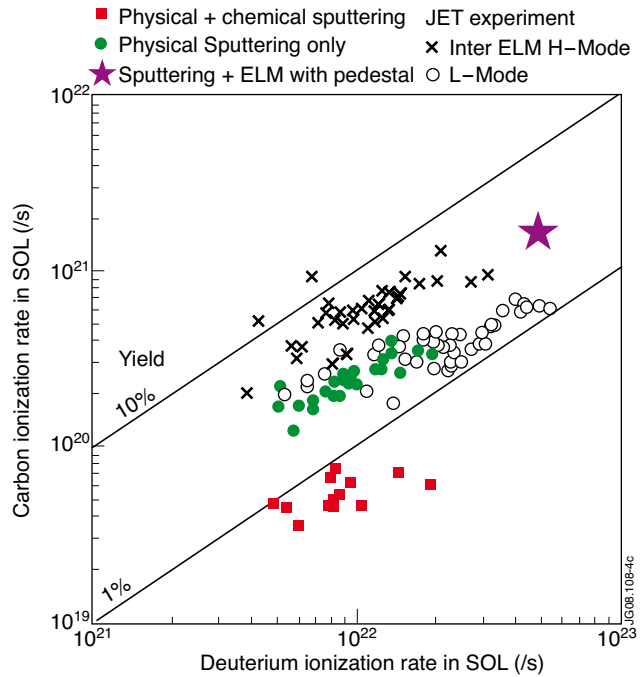

Figure 4: The deuterium ionization rate as calculated for the EDGE2D cases with carbon sources due to sputtering is plotted against the Dα emission integrated toroidally around the vessel.
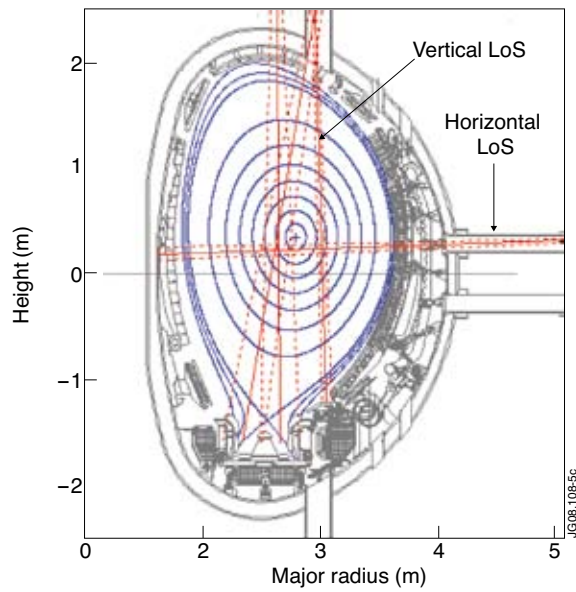
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Figure 5: The carbon ionization rate in the SOL is plotted against the deuterium SOL ionization rate for EDGE2D cases of sputtering (green is physical sputtering $+ ^1/_2$ Haasz chemical sputtering, while red is physical sputtering only. The star point is a calculation with an H-Mode pedestal and ELMs, but measured inter-ELM.), JET L-Mode (open symbols), and JET inter-ELM H-Mode (crosses).