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** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

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## INTRODUCTION

A full tungsten (W) divertor is proposed for plasma and power exhaust in ITER. Because of the high specific radiation power of W at fusion plasma temperatures and correspondingly low permitted concentrations of $< O(10^{-5})$, the quantification of W sources and transport from the divertor into the core are important issues for reliable tokamak operation. The ITER-like Wall at JET with beryllium (Be) in the main chamber and W in the divertor [1] as well as the all W ASDEX Upgrade (AUG) are suitable for studying ITER-relevant aspects of W-erosion as well as power-handling. This contribution aims to elucidate W erosion in relation to divertor plasma parameters and impurity composition allowing extrapolation toward ITER.

## 1. SETUP AND DIAGNOSTICS

Tungsten erosion was quantified by means of passive emission spectroscopy in both JET and AUG. Several spectroscopic systems were used to observe emission lines from W as well as plasma impurities like beryllium (Be) and nitrogen (N). The outer target at JET is observed by a mirror-link system viewing the horizontal surface from the top (fig. 1) relaying the emissions to a Czerney-Turner spectromete (KT3) [2], while at AUG the vertical outer target is observed by means of relay-fiber optics (Fig.1) covering the outer strike point area [3, 4]. The measured intensities are transformed into particle fluxes using the number of ionisations per emitted photons (inverse photo-efficiences) [5]. For W a multi machine fit formula [6, 7, 8, 9] is applied for the 400.9nm emission line and a line ratio adapted value is used when comparing to the WI (429.55nm) emissions. For the impurity and plasma emission lines ADAS data is being used [10]. Langmuir probe measurements were used to determine profiles of the divertor plasma temperature as well as incident flux.

## 2. RESULTS

The W erosion in the JET divertor was evaluated as a function of the divertor electron temperature in L-Mode discharges with 1MW NBI heating. Data was obtained from a series of 3 discharges (JET Pulse No's: 82195, 81474, 81486) with the first representing a density ramp and the later having 3 destinct density levels. In all cases the divertor electron temperatures are significantly decreased up to a minimum of 7eV. Data from pulses with strong sawtooth activity is used to study both the influence of local temperature and impurity variations (JET Pulse No's: 80889, 80893, 80896).

Figure 2 is shows the "effective" erosion yield of W determined by the peak W particle flux normalized to the saturation current measured by Langmuir probes for both studied cases. Shown are the erosion yields for a temperature range of 5 to 60eV. In figure 2(a) a comparison to calculated yields is given with respect to different Be charge states as well as a comparison to erosion yields determined for the All-W AUG where carbon is the main sputtering partner. The plot shows that the measured erosion yield increases between $15eV < T_e < 45eV$. With respect to the charge states it is not obvious which composition is dominant, the drop to low temperature hints however to a prominent role of $Be^{4+}$. The data is constant with a 0:5% contribution of Be to the divertor plasma while $Z_{eff}$ hints at roughly 1.8–3.6% in the main plasma. We conclude that Be alone can explain the W erosion observed in contrast to the carbon dominated and thus higher erosion yield observed in AUG. At JET the carbon fraction in the divertor is so far estimated to be in the range of 0.05% during theses pulses and is hence negligible with respect toWsputtering. Simulations with EDGE2D/ Eirene indicated that CX neutrals can contribute to up to 60% to the W erosion [11] thus making beryllium and D the main sputtering contributors at JET. Figure 2(b) is utilizing three JET pulses at different levels of density ($1.6-2.8 10^{19} m^{-3}$) and each three steps in ICRH heating power applied (1, 2, 3MW). Here the influx of Be and its impact on the erosion of W in the divertor can be seen. As strong saw teeth activity is changing the divertor temperature a wide range of divertor plasma parameters is scanned. As previously stated (fig. 2(a)) the yield is increasing with Te but in addition a dependency on heating power and main plasma density is observed. The heating seems related to an increase in Be content and thus flux to the divertor, however this is only seen so far via $Z_{eff}$ as indicated above. The detailed picture remains unresolved and maybe related to uncertainties in the data as well as photon efficiencies or other sputtering partners (e.g. CX neutrals).

## 3. H-MODE

With respect to future devices such as ITER in particular erosion during H-Mode plasmas is to be quantified. The large difference between inter- and intra-ELM W sputtering is displayed in figure 3. Here an example is chosen from a pulse with low ELM frequency (10Hz) to allow inter- and intra-ELM comparison by means of the Vis/UV divertor spectroscopy with 40ms time resolution. A detailed analysis for AUG is given by Dux et al [12] (cf. fig.2(a)) For this example the ELM induced sputtering amounts to $9.7\times10^{18}$ atoms/s integrated over the whole outer strikepoint (cf. fig. 3(b)). The inter ELM saturation current amounts to $1.7\times10^{23}$ el/s relating the tungsten flux to a sputter yield of $6\times10^{-5}$ similar to the presented L-Mode results. The intra-ELM sputtering is a factor of ~5 higher, $4.7\times10^{18}$ atoms/ELM. From dedicated H-Mode Pulses (JET Pulse No’s: 81803, 81800, 82196, 81821, 82486, 82202) with higher ELM frequency and thus unresolvable inter- and intra-ELM W sputtering and average value of theWsputtering yield is given as ($4.51 \pm 9\times10^{-6}$) for a 10MW NBI heated H-Mode and ($3.20 \pm 6\times10^{-6}$) for the6MWphase. This is compatible with the rather high densities and low divertor temperatures observed during these H-Mode discharges. and thus clearly at the low end of what is observed during the L-Mode plasmas (cf. 2) Eventhough the fueling was varied, no clear effect is observed here.

## 4. NITROGEN SEEDING

As power handling in future devices will be one of the main issues to be dealt with, impurity seeding is envisioned to ameliorate W-sputtering and divertor heat loads [13, 14]. As an example for the complexity and value of this method a study of W sputtering during $N_2$ seeded L-Mode pulses in JET and AUG is performed. Here L-Mode plasmas with 1MW of additional heating are considered (JET: 1MW NBI, AUG:1MW ECRH). For JET several pulses at different seeding levels are considered (JET Pulse No’s: 82293–82296) while in AUG the level of N2 was controlled by means of divertor temperature measurements stepping the electron temperature down during one pulse (JET Pulse

No: 26289). From the results presented above the impact of intrinsic impurities is clearly seen from the difference between AUG and JET by either carbon or beryllium. It is obvious that extrinsic impurities change the sputtering behavior significantly as they can become the dominant sputtering particles at low seeding levels while causing divertor cooling at higher rates. Figure 4 shows for both JET (a) and AUG (b) the behavior of W particle flux derived from local spectroscopy. For JET WI 400.9nm is used while for AUG WI emissions at 400.9nm as well as at 429.55nm are used (429.55 data is scaled ). With increasing $N_2$ flux different values of $T_e$ are reached.

While initially at low $N_2$ levels the temperature remains high and rather unchanged the W flux, due to increased erosion is going up, reaching a maximum at roughly 20eV where a clear trend to lower W flux due to suppressed erosion is observed. Astonishing when comparing these results with the W sputtering by intrinsic impurities is the paralleled behavior in AUG and JET, representing another hint at the rather different impurity composition in the ILW divertor of JET. When adding a surplus of extrinsic impurities both AUG and JET show the identicalWsputtering at given local temperatures.

## SUMMARY & CONCLUSION

The tungsten source in the all W outer divertor and Be main wall configuration has been quantified mainly during L-mode plasmas and compared to AUG Data both gained from local spectroscopy. Results so far show differences between AUG and JET based on impurities in the plasma changing the sputter behavior. This stresses the need for detailed analysis of the divertor impurity composition and detailed molding in the future analysis. The H-Mode examples indicate at ELM dominated sputtering and a rather low averaged sputtering yield in general. Nitrogen seeding can change the divertor conditions significantly either increasing W sputtering or suppressing it due to local cooling, JET and AUG behave similarly. All together it is clear that by having low divertor temperature or a beneficial impurity composition sputtering can be controlled and is rather low as expected in an all metal environment.

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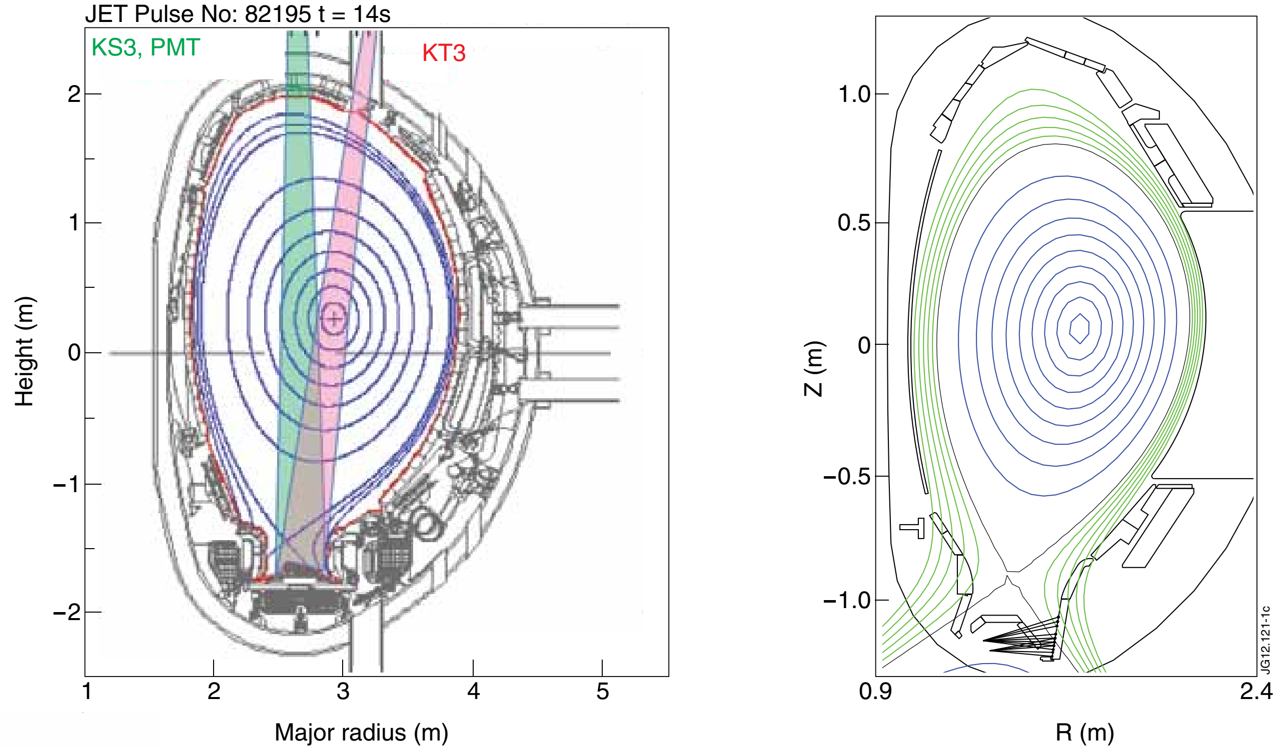
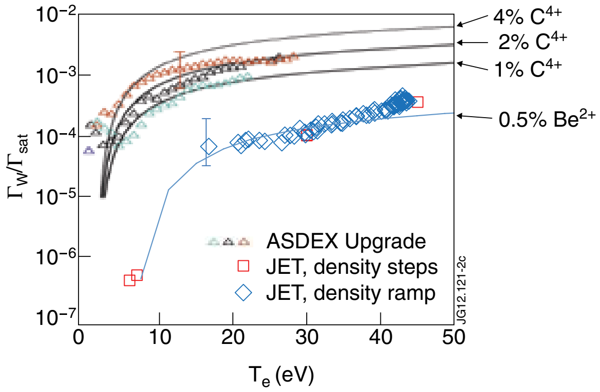



*Figure 1: Typical plasma shape and diagnostic setup*



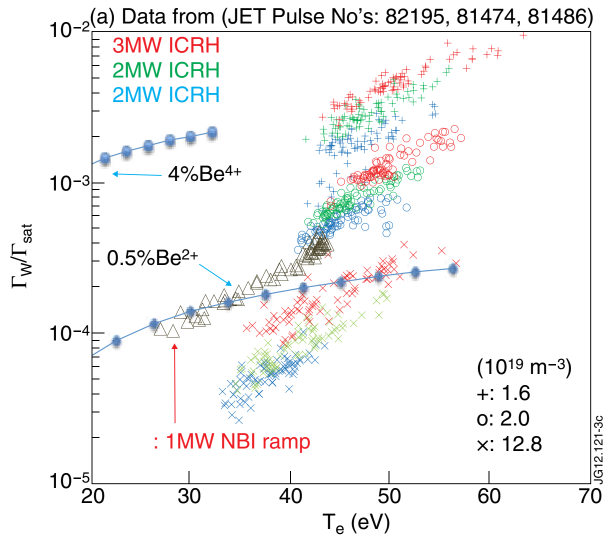
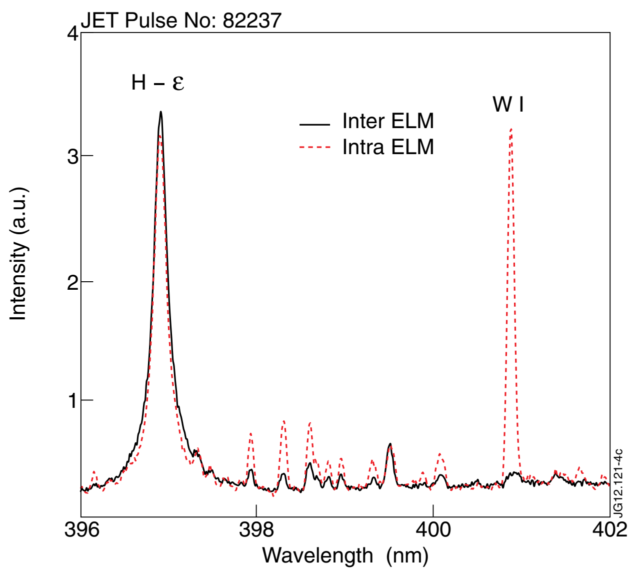




*Figure 2: W sputtering during L-Mode Plasmas at JET and AUG*



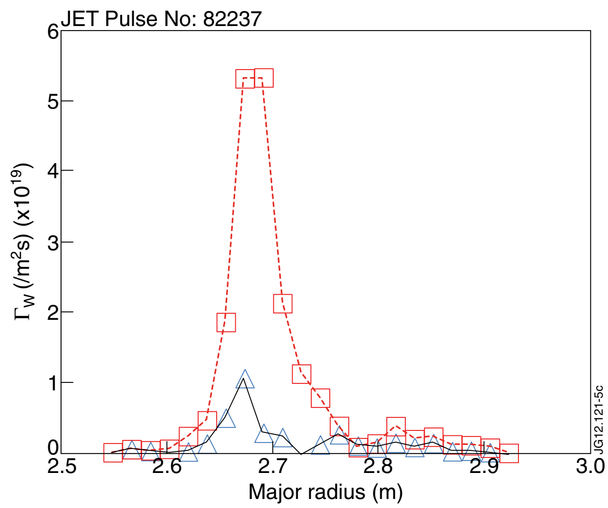




*Figure 3: Intra ELM versus Inter-ELM (JET Pulse No:82237)*

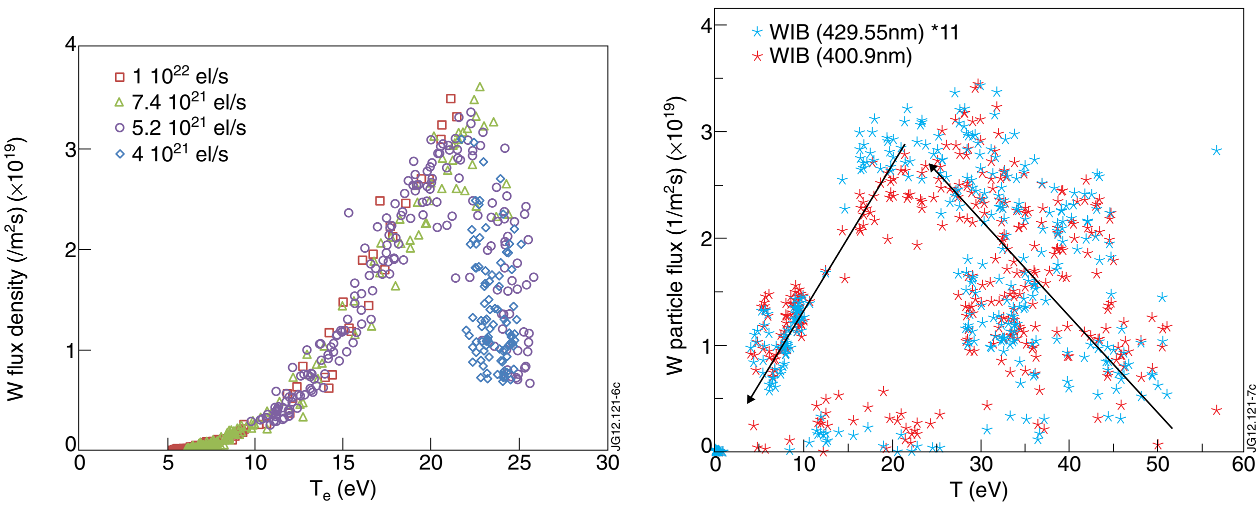



*Figure 4: W particle flux density during $N_2$ seeded L-Mode discharges*