The role of ELM's and inter-ELM phases in the transport of impurities in JET

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Introduction

This contribution is about the experimental and modeling activities carried out at JET in order to assess the physics mechanisms that control the penetration of medium and high Z impurities into the plasma core and to provide physics basis for the ELM-control requirements in ITER. Besides investigating the relative role of Type I ELM and inter-ELM phases in determining the impurity content into the plasma a second important objective of the work was to explore the possibility that JET may approximate the favorable situation expected in ITER, where an outward neoclassical pinch driven by the strong thermal screening should keep W outside [DUX], thus building a hollow W density profile at the edge. In such a situation the question is whether any diffusive component of the ELM could bring W inside the plasma rather flushing it out as ELMs generallydo today in all experiments. The experiments carried out at JET consisted in injecting traces of Ne, Kr (gas puffing) and Mo (Laser Blow Off) in ELMy H-mode discharges at two levels of input power, medium (~ 15 MW) and high (~ 30 MW) respectively. ELM frequency was changed by changing gas puff levels or power. Several results were presented in [VALISA], where, among others details, three aspects were highlighted: a) at the level of the ELM amplitude explored, spontaneous and artificial ELMs induced by vertical kicks [de la LUNA]are equivalent in expelling both the injected species and the intrinsic tungsten; b) Ne, Kr and W content decrease about linearly with the ELM frequency for any fixed source and comparable ELM amplitude; c) the transport analysis of Molybdenum injected via LBO showed that the ELM expelling action is more convective than diffusive, in agreement with [WADE] and also with the various observations of filaments literally expelled during ELMs at several km/s off the plasma [SILVA]. In the present contribution we will focus on novel results regarding in particular two aspects: the evaluation of the amount of neon and electrons ejected by a single ELM event and the dependence on the total power input of the neoclassical convection of W at the edge.

ELM induced impurity losses from single event analysis

With a time resolution of 10 ms, the edge CXRS can resolve to some extent the ELM events when the ELM frequency is below say 30 Hz as shown in Fig. 1.

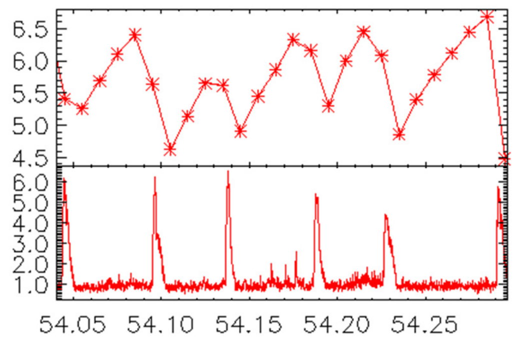

Fig.1. Neon 10+ density time evolution at R=3.7 m (top) crashing at and recovering after ELMs (bottom).

Neon losses due to a single ELM event can be evaluated by comparing the Ne 10+ density profiles soon after the ELM with that recovered just before next ELM. Fig.2a shows such an example in the case of an H-mode discharge (# 89425, 2 MA, 2.1 T) in the so called baseline scenario and with an input power of 12 MW. Fig.2b shows instead the variation experienced by the plasma electron density measured soon before and after the ELM by the High Resolution Thomson Scattering system (HRTS). Subtraction of the density profiles pre and post ELM and integration over the volume of the plasma affected by the event, which spans from approximately R=3.6 m to the separatrix (~R=3.81), allows to state that the amount of neon atoms and electrons expelled, normalized to the average density of each species, is practically the same, confirming what had already been seen on a statistical basis in JET [VALISA, DEVINCK] and other devices [WADE]. In Fig. 3 the exercise of Fig.2 has been repeated for a high power hybrid discharge (#92419, 2.4 MA, 2.75 T) with 26.5 MW of NBI and 5.5 MW of ICRH. Also in this second case the amount of neon expelled by the ELM normalized to the average neon density at the edge corresponds to the analogous normalized value for the electron density. Comparing the two cases at medium and high input power, the amount of particles expelled in the high power case is twice as much that of the former. Not surprisingly the same ratio of 2 is found in the the amplitude of hthe Be emission line in the divertor region that is used to characterize the ELM events. One should remark that the profiles shown in figures 2a and 3a do not indicate the total Ne density but only the Ne10+ density profiles. This does not affect our conclusions, as the temperature profile change across the ELM is relatively small. In Fig. 4 the normalized concentration of Ne W and Kr is shown as a function of the ELM

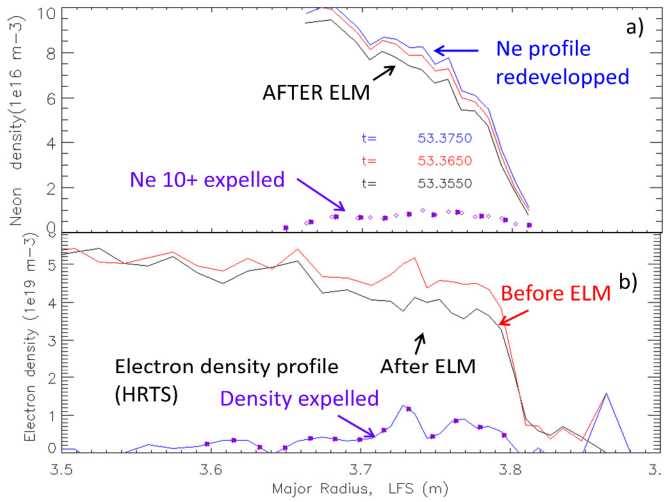

Fig. 2 a) Ne 10+ profiles from edge CXRS at three times soon after an ELM, intermediate and when restored , and the difference between the two extremes. b) Change of the electron density profile between and after the ELM. for discharge 89425 , with 12 MW of NBI.

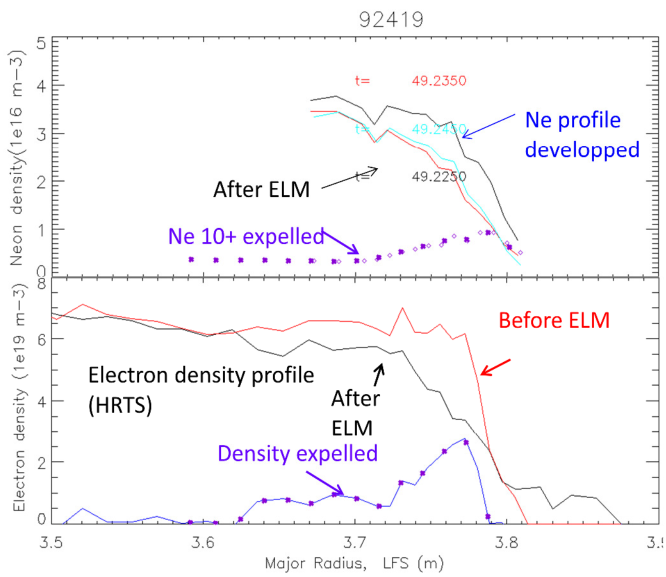

Fig. 3 a) and b) Same as Fig.1 for discharge 92419, hybrid , with 32 MW of NB+ ICRH.

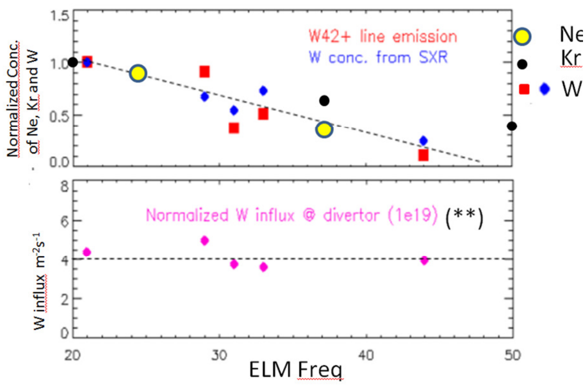

Fig. 4 Normalized concentration of Ne, Kr and W as a function of the ELM frequency (top) and the estimated W influx at the divertor target (bottom)

frequency, which was varied while maintaining fixed the amount of injected impurities. W influx was estimated from monitoring the optical emission of neutral W at the target plate. The relative W concentration was estimated in two ways: by using the SRX emission (PUTTERICH) and by monitoring a W42+ emission line (Bragg spectrometer). For Ne and Kr the Ne 10+ density and the Kr 25+ emission line were used, respectively. The concentration of impurities clearly decreases more or less similarly for all of the species with the ELM frequency, corroborating the result of the analysis of the single ELM events.

Dependence of the edge inward convection of impurities on input power

Interestingly, the inward neoclassical pinch associated to the edge kinetic gradients in the inter-ELM phases and evaluated by means of the NEO code [BELLI] coupled to the JETTO-SANCO [TARONI] transport code is seen to decrease as the total input power is increased. This type of analyses was suggested by the observation that in high power and high performance discharges the ion temperature gradients at the edge was, in proportion, increasing more than the electron density gradient, indicating that in the neoclassical convection expression the screening term proportional to the normalized ion temperature gradient was gaining against the unfavorable term depending on the normalized density gradient. The series of discharges analyzed is listed in Table 1. It includes both hybrid and baseline discharges and compares mid and high power cases, with plasma currents from 1.4 to 3 MA.

The resulting neoclassical velocity is shown in Fig. 4. Neoclassical diffusion is very small, of the order of 1e-2 m^2s^{-1}(not shown). Lower power discharges feature stronger inward convections, while in high power cases the inward pinch reduces and shows the tendency to become positive. The neoclassical velocity depends critically on the kinetic gradients and any spatial mismatch can easily induce errors. A small shift, of the order of several % in ψ, between electron temperature and density gradients is known to exists and has been shown to depend on the gas puffing level and in particular on the total power at the separatrix [STEFANIKOVA]. In particular the density protrudes progressively outwards with respect to the temperature as the power is increased. Also calibration issues could be present. While the clear separation between low and high power cases in the neoclassical velocity profile represents a robust result, details due to such relative shift may introduce local deformation. Comparing hybrid and baseline discharges one may notice that in Fig.4 the hybrid cases have slightly less inward

	#	NBI (MW)	ICRH (MW)	MA/T
Baseline	92222	17	0	1.7/1.7
	92228	10	0	1.7/1.7
	92436	26.5	5.5	3/2.8
	89425	12.3	0	2/2.1
Hybrid	92404	26.5	5.5	2/2.8
	92394	26.5	5	2.2/2.8
	92419	26.5	5.5	2.4/2.75
	90155	13	0	1.4/1.9

Table 1. Discharges (hybrid and baseline) for which the neoclassical velocity of W at the H-mode barrier has been evaluated

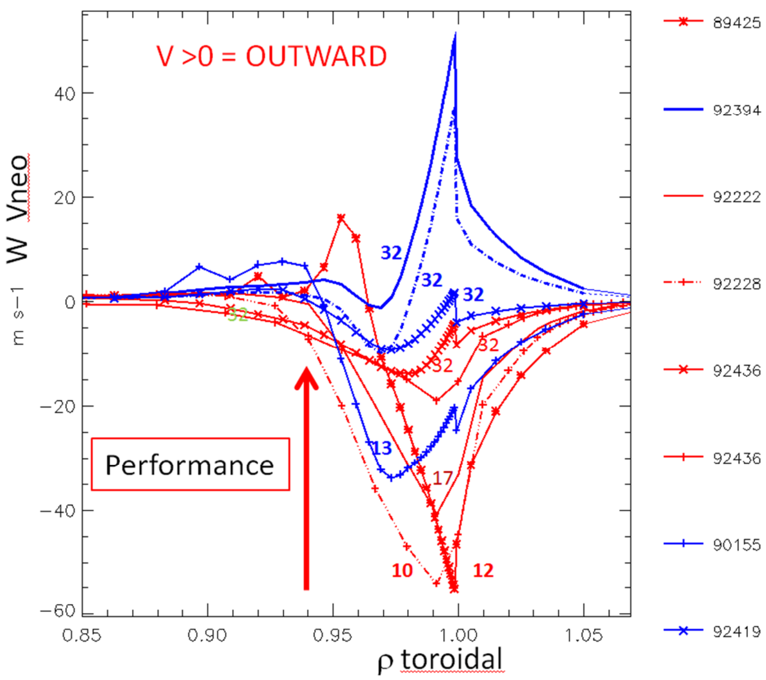

Fig. 4. Neoclassical convection of W for the series of discharges listed in Table 1. In red the baseline and in blue the hybrid cases. The total power input associated to each curve is indicated in MW. Values ov Vneo in the SOL are just extrapolated and not evaluated by NEO

velocity pinch than the baseline for comparable values of power. Two high power hybrid cases feature a W neoclassical velocity that moves into the positive region. Whether this is a real feature or the artificial result in fitting the large density and temperature gradients is not of critical importance. More important is to notice that at those high levels of performance the neoclassical velocity is only marginally inward. One can therefore expect that at moderately higher power JET should eventually reach regimes in which the transport of W at the edge is representative of the one expected in ITER. The analysis of the W content in the selected discharges in order to verify to what extent the reduced pinch velocity was beneficial, will be matter of another task, based on integrated edge-core analysis [PARAIL]. Among others, two aspects are to be considered in that respect. Firstly, the dependence of the W source as power, plasma current and toroidal field are increased: an increased power might in fact enhance the sputtering mechanisms, while an increased magnetic field could beneficially reduce the prompt redeposition length of sputtered W and therefore the overall source of W. In the second place, should turbulence transport increase in the inner region close to the H mode barrier, W could more easily diffuse inward, partially undermining the reduced particle pinch in the barrier.

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