# On the penetration of heavy impurities in the JET ELMy H-mode plasmas

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**Introduction** - This paper reports the main outcomes of the recent modeling activities carried out at JET, in which the dependence of the penetration of medium and high Z impurities into the plasma with ELM frequency and heating power has been investigated.
The ultimate motivation is to assess and provide physics basis for the ELM-control requirements in ITER [Dux] and in particular to investigate the conditions that might develop in ITER, where heavy impurities are screened at the edge barriers by outward neoclassical convection [Dux]. In nowadays experiments the impurity profiles typically mimic the electron density profile and ELMs expel impurities regardless of their mass, to the point that the control of the ELM frequency, via gas puffing and vertical kicks [E de la Luna], is a well-known means for impurity concentration control [Valisa17]. The possibility that in ITER hollow W density profile develop at the edge in the inter-ELM phases due to favorable kinetic gradients [Dux] raises the question about the role of the ELMs in those conditions. Any diffusive-like component of the transport induced by the ELM would in fact, in such conditions, imply an injection of W in to the main plasma. JOREK [Hujsmans] simulations of an ELM in AUG-like plasmas show that, during the ELM, W particles in the SOL have finite probability to cross the separatrix [van Vugt], meaning that even in present day experiments the ELM effect with respect to impurities might not be only expulsive.
In previous papers [Valisa17, Valisa16], it was shown that indeed in JET ELMs flush particles of any sort regardless of their mass. Kr, Ne, W and electron densities were seen to decrease with the same trend as a function of the type 1 ELM frequency. In particular it was shown that spontaneous and vertical-kicks-induced ELMs at the same frequency have the same effect on impurities. It was also shown that, in the inter-ELM phases, the inward neoclassical velocity of W progressively reduces as the input power is increased and at the highest power levels experimented, around 32 MW, approaches zero both in hybrid and baseline scenarios. This suggests that the addition of some extra power, if compatible with MHD stability criteria, would possibly lead to conditions where W is screened at the edge barrier, opening the way to experiment the effect of ELMs in "ITER-like" regimes.
Recent modeling activity has focused on the simulation of experiments in which traces of Ne have been puffed in ELMy H-mode plasmas with medium (12 MW) and high (32 MW) power injection and in which the ELM frequency was varied by controlling the main gas fueling. The availability of detailed ELM resolved $Ne10^+$ density measurements in the pedestal allows in fact proper qualification of the transport in the edge barrier, which constitutes good grounds for characterization of W based on modeling.

**Modeling of low and high power ELMy discharges**. Modelling activity has concentrated on three discharges: two baseline cases (# 89425 and 89426, 2 MA/ 2.1 T, 12 MW of NBI) with same gas puffing levels, but in 89426 vertical kicks could almost double the ELM frequency of #89425. At high power, #92419, hybrid, 2.4 MA / 2.8 T, 32 MW (27 MW NBI, 5 MW central ICRH) has been chosen. In all cases Ne was injected from the equatorial plane through a 100 ms pulse to the valve and the density evolution of the impurity was monitored by both edge and core charge exchange diagnostic systems. The time resolution of the edge system, 5 ms, is capable to resolve the ELM.

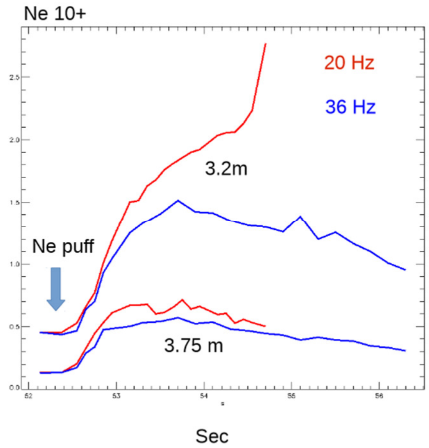


*Fig. 1 Evolution of Ne10+ density in 89245(red) with 2o Hz ELMs and 89426 (blue) with 37 Hz ELMs, at 3.75 and 3.2 m. In the former case, with lower ELM freq. Ne accumulates in the center.*

Same nominal amount of Ne injected in 89425 and 89426 lead to the evolution of Ne density shown in Fig. 1. As expected, the Ne density is higher in the case with lower ELM frequency, but while in both cases the Ne profile is peaked in the center (see below), in the case with lower ELM frequency Ne accumulates in the center following the tendency of the main density to increase its peaking in time.
The evolution of $R/L_{ne}$ and $R/L_{Te}$ is reported in Fig. 2.

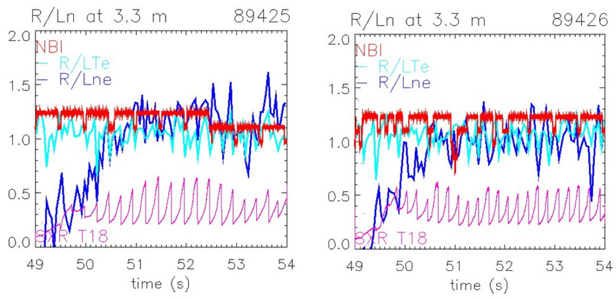


*Fig. 2. $R/L_{ne}$ (blue)and $R/L_{Te}$ (cyan)of #89425 and 89426. The normalized density gradient is higher in 89425 (low ELM freq), which also shows a lower sawtooth frequency.*

Results of interpretive modeling carried out by means of JETTO-SANCO [Romanelli] to yield reference values for the transport parameter are reported in Fig. 3, where for 89425 the reproduction of the Ne density profile vs radius and time are shown till the point where Ne density in 89425 runs away. Fully predictive simulations of the Ne behavior inside the separatrix have started, including, besides Ne, also Be, which in JET characterizes Zeff and W. Simple case with the BgB model for turbulence, NCLASS for the neoclassical transport and a ballooning model for the ELMs allows evaluating the role of ELM's with respect to both Neon and W. The ELM model chosen in JETTO triggers a prescribed increase of the diffusive transport in the barrier region once the pedestal pressure overcomes a threshold. Sample results are shown in Fig. 4, where the evolution of puffed Ne and intrinsic W is followed imposing firstly no ELMs and then ELMs with different frequencies. As in the experiment, the impurity content decreases when the ELM frequency is increased. To reproduce the experiment, in the cases of Fig. 4 the BgB transport coefficient for both particle and energy were multiplied by an adjusting parameter. In order to resort to first principles only, predictive simulation with the QuaLiKiz turbulence

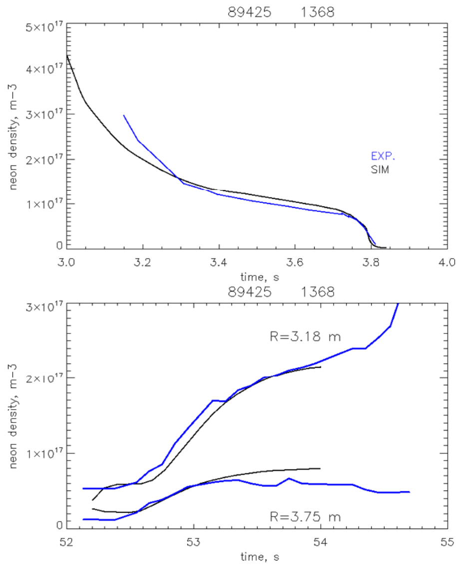


*Fig. 3 Interpretive simulations of the Ne10+ density for 89425 vs minor radius ( top) and time (bottom)*

code [Bourdelle] have also started and a preliminary result is given in Fig. 5. There, the central peaking of neon is not caught by the simulation. It is possible that rotodiffusion, not yet included in the simulation, plays an important role. Analogous simulations have been carried out for the high power case 92419. The results of the JETTO/SANCO simulation with BgB is shown in Fig. 6, where, as for Fig 4, the evolution of both Ne and W are tracked following the Ne puff and again, the impurity content decreases as the ELM frequency is raised. Fig. 7 shows instead the comparison of simulated and experimental profiles. For this high power discharge the simulation has been extended to the edge with the aim of pursuing an integrated approach to the W transport problem. The COCONUT suite of codes [Romanelli] allows coupling JETTO to EDGE2D, which simulates SOL and divertor regions

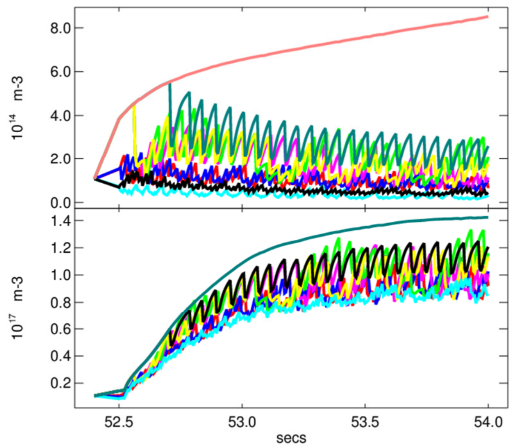


*Fig. 4 Comparison between experiment (Cyan) and simulations of the Neon (bottom) and W (top) density evolution on the top of the pedestal for discharge 89425. Top traces refer to the Elm-free case. The impurity density decreases as the ELM frequency is raised from 0 to 40 Hz.*

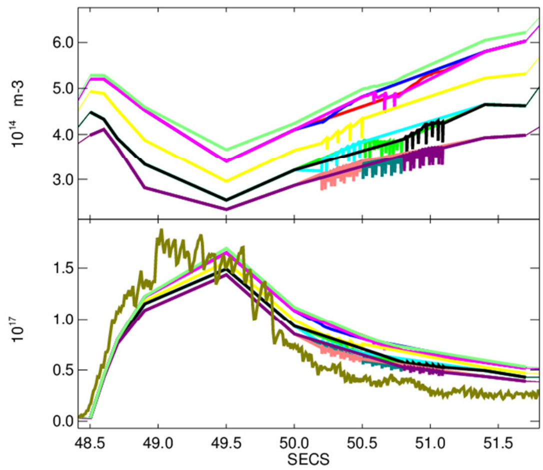


*Fig. 6 Comparison between experiment (Green) and simulations of the Neon (bottom) and W (top) density evolution on the top of the pedestal for discharge 92491. Continuous lines refer to the Elm-free case. The impurity density decreases as the Elm frequency is raised.*

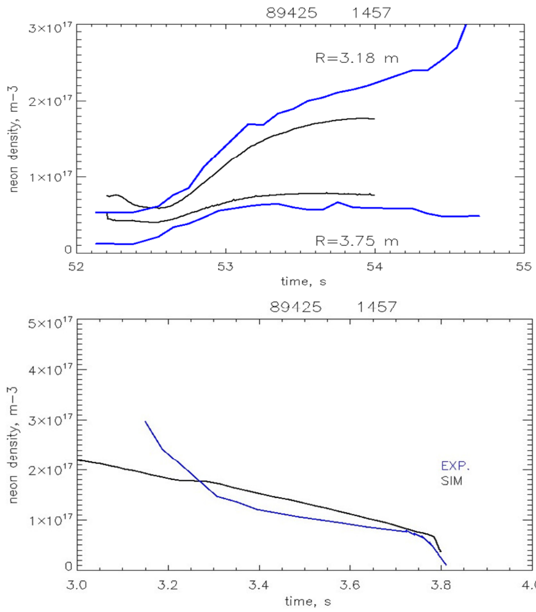


*Fig. 5 Example of full predictive simulation of 89425 with Qualikiz for the turbulent model. This case , in which the rotodiffusion term was not included, does not catch the central peaking of Ne.*

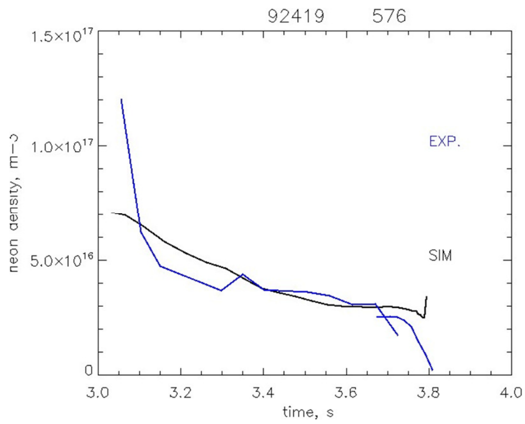


*Fig.7 92419 Neon radial profile @49 sec simulated by JETTO.*

till the wall, where recycling and sputtering are dealt with. Full predictive simulations capable of resolving the ELM are quite time consuming and only preliminary results are available. Transport in the core is simulated by means of the GLF23 model [4]. In the case shown in Fig 8 the edge barrier is particularly strong (very low diffusivity) and Ne density tends to build up a peak at the edge that does not correspond to the experiment. It is however interesting noting how a diffusive ELM, as imposed in the model, after the crash tends to increase the density around 0.8 of the normalized radius rather than reduce it as it occurs in the experiment [ Valisa17]. Along with the exercise of tuning the simulation tools in order to enhance our predictive capabilities of the W behavior in high power JET discharges, we have applied a statistical approach to predict which level of power would be required to reverse the neoclassical pinch velocity of W at the edge. We have thus plotted the proxy for Vneo, 1/Lne – 0.5 1/Lte, vs the input power for a number of discharges. The result is shown in Fig. 9. Increasing the input power decreases the proxy for Vneo decreases. In the same time, increasing the plasma current shifts the curves towards higher powers, meaning that the conditions with W screened at the edge should be reached trying to increase power at a given current, hoping that pressure limits are not hit in the MHD domain.

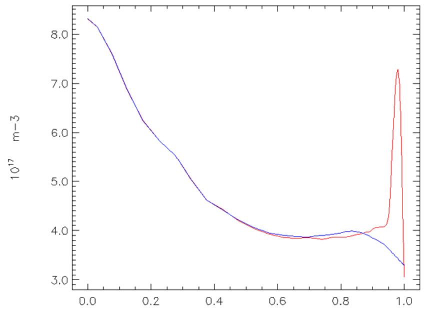


*Fig.8 COCONUT simulation of 92419 showing the Ne profile before (red) and soon after an ELM(Blue) in a case with strong edge barrier that builds a large peak of Ne in the edge.*

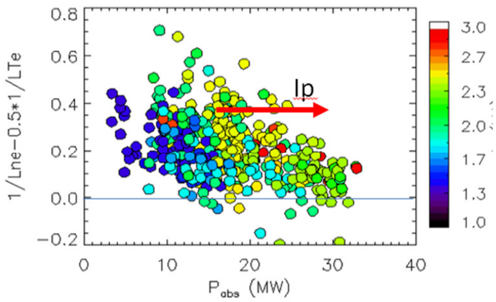


*Fig. 9 Proxy for the neoclassical pinch at the edge vs power for many discharges and various plasma currents*

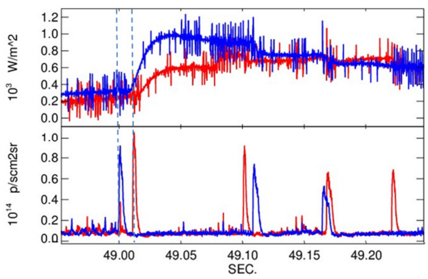


*Fig. 10 Comparison between two LBO injections of Mo, one of which in coincidence of an Elm. Top panel: SXR vertical outer channel. Bottom panel BeII emission*

As a last consideration regarding the role of the ELM it is interesting to note that the relatively low frequencies of the ELM on JET allow to study the impact of single ELMs on impurities. In [Valisa16] the effect of one ELM on the traces of Mo injected via LBO was studied. Here we notice that synchronism between ELM and LBO injection may cast some light on the transport properties of ELMs. Fig. 10 shows an example in which an LBO was fired in coincidence with an ELM. The comparison with a normal case of LBO in between ELMs shows that indeed the amount of Mo reaching the core, indicated by the SXR trace with an impact factor of about 0.7, is lower in the former case, indicating that ELM appear to have indeed a dominant expelling(convective) nature.

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