The role of the edge barrier in the penetration of impurities in the JET ELMy H-mode plasmas

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1. Background and motivation Control of W contamination in H-mode high energy conf inement plasmas requires conditions that simultaneously minimize the erosion of the plasma facing components, hamper the penetration of W through the separatrix and the edge transport barrier (ETB) into the main plasma and, finally, prevent the accumulation of W in the plasma core. Regarding the second condition, in present day experiments the main way to avoid the W density build up at the edge due to the dominant inward neoclassical pinch in the edge gradient region is to operate in regimes with sufficiently frequent ELMs. ELMs expel all particles irrespective of their mass **[Valisa 16]** and reset gradients. In JET the ELM frequency may be controlled by increasing the level of gas fueling or by ELM triggering via pacing pellets or vertical kicks (vertical displacements of the whole plasma columns) **[de la Luna].** ELM control has proven to be essential also in the exit phase of the H mode, when the reduction of input power decreases the edge density and temperature and the ELM frequency slows down, allowing for the edge W density increase [F **Koechl**]. Alternative ways of controlling the edge contamination is through an enhancement of the local particle transport, as for example in the EDA regime of Alcator C-mod **[Greenwald]** or in the negative triangularity regimes **[Marinoni].**

In the ITER baseline scenario the combination of density and ion temperature profiles of the ETB is expected to repel heavy impurities between ELMs, moving the maximum of W concentration towards the separatrix and thus creating a situation where ELMs might reverse their effect causing an injecton rather than an expulsion of W **[Dux].** JOREK simulations indicate that in the ITER case this should indeed be the case because of the superdiffusive nature of the ELM, which produces an in-outward interchange transport [**van Vugt**].

In both baseline and hybrid JET H-mode scenarios it has been observed that increasing the heating power modifies the edge kinetic profiles in a way that progressively reduces the neoclassical inward velocity of impurities **[Valisa 18]** thus approaching the expected ITER condition mentioned above. This is shown in Fig. 1 where the neoclassical velocity of W evaluated at the edge by NEO [**Belli**] is plotted for various hybrid and baseline JET discharges with different total input power values from 12 to 32 MW. Detailed features of the velocity depend on the relative radial shift between density and ion temperature gradients [**Frassinetti**], whose radial position error has not been fully examined in the selected discharges. Nonetheless the trend that shifts toward the positive region the neoclassical velocity as the power is increased is clear.

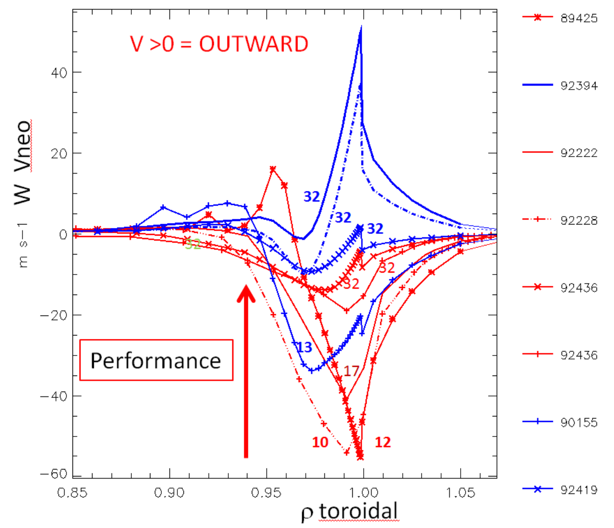

Fig. 1. Neoclassical convection of W for JET discharges of various power input power as indicated in MW for each curve . In red the baseline and in blue the hybrid cases. Values of Vneo in the SOL are just extrapolated and not evaluated by NEO

Two more experimental facts that were shown in [Valisa 17] are of relevance here: 1) the availability of detailed measurements of fully stripped Ne density in the pedestal region from edge CX diagnostics with a time resolution sufficient to analyze the difference of the profiles before and after an ELM event and therefor estimate the effective Ne losses due to the ELM, to be compared with main ion losses. 2) In a statistical approach, that is considering a larger set of discharges, the trend of a proxy for Vneo, defined as proportional to 1/Lne – 0.5 1/Lte, vs the input power confirms the result of Fig.1 with the additional information about a current dependence: the higher the plasma current the higher the power at which Vneo reverses its direction. Altogether, the above experimental evidence has motivated a modeling activity that capturing the main transport processes at the could be used to extrapolate the results to higher power input and plasma currents in order to predict in which conditions an ITER like edge with W repelling ETB might be reached. The idea was to opt for an extension to the edge of the impurity modeling activities of the core **[Casson]**, in the direction of an integrated core-edge description of the impurity behavior that incorporates the way medium and high Z impurities penetrate into the plasma core of JET as ELM frequency and heating power vary.

2. The model Full predictive integrated modeling is based on the coupling of tools available in the JINTRAC suite of codes **[Romanelli]**. It includes the 1.5D fluid JETTO[**Cenacchi**] transport code for the main plasma, associated with SANCO [**Taroni**] transport code for impurities and the 2D fluid code Edge2D [**Simonini**] transport code for the SOL and the interaction with the wall. The kinetic Monte Carlo code EIRENE [**Reiter**] handles the neutral population. Two impurities (Ne, W) have been included so far for simplicity although Be and Ni should be added to more correctly describe Zeff and core radiation. In JETTO, NCLASS calculates the neoclassical transport of main ions and impurities, including the effect of poloidal asymmetries induced by the centrifugal forces. The ionization stages of W are bundled in 6 super-stages to gain in computational times while Neon behavior is grouped in 5 bundles. The fluid model GLF23 [**Waltz**] and the standard Bohm-gyro-Bohm model have been used to describe the anomalous transport. SANCO relies on ADAS [ADAS] for the atomic physics database, including dataset from [Putterich] for the W data. Transport in the ETB assumes an ad hoc reduction of the turbulent transport that brings it closer to but still much higher than the neoclassical values. The radial extension of the ETB region are prescribed, mimicking the experimental case.

ELMs are modeled by an enhancement of the diffusivity of both particles and heat for the duration of the ELM. The radial region of effect of the ELM is given a Gaussian shape centered just inside the separatrix (r=0.98) and large one fifth or more of the plasma radius. In fact there is experimental evidence that the ELM can affect radial Ne and main density profiles at r = 0.6.

The transient change of transport due to the ELM raises in 0.4 ms, remains high for a similar time and then drops in 1 ms. Triggering of the ELM occurs when the edge profiles exceed a prescribed threshold. i.e no MHD analysis is carried out, for simplicity. A detailed description of the ELM fast transients effects requires computational time steps of the order of 0.5E-6 sec or below. In order to reduce the computational needs a partial coupling scheme is available, which diminishes the times JETTO/SANCO and Edge2D/EIRENE are interfaced to exchange boundary conditions during the quasi-stationary inter-ELM phases.

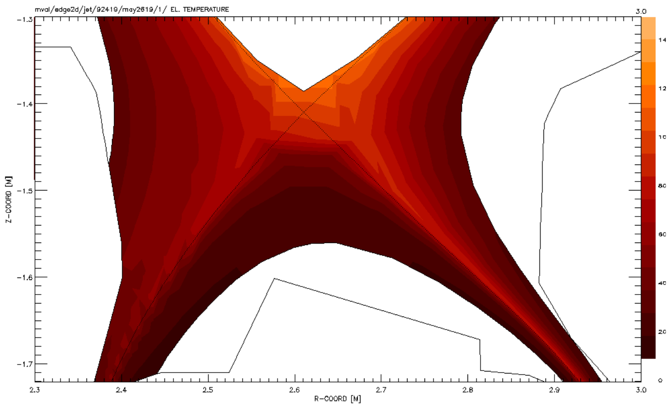

Fig.2 Simulated Te at the divertor

Plasma fueling is represented by injection of neutrals in certain positions and with rates as in the experiment. In the analyzed discharge #92419 a feedback system on the ELM frequency adapted the fueling rate to avoid excessively low ELM frequencies and subsequent W pollution of the core; in the simulation an average value of the experimental gas puff was chosen.

3. Results In this work the target discharge for the code tuning belongs to the hybrid scenario and features 27 MW of NBI, 5 MW of centrally deposited ICRH, 2.4 MA of plasma current and 2.75 T of magnetic field. Traces of Ne were injected in a single short pulse just for diagnostic purposes, in particular to provide ELM resolved Ne density profiles, from core to edge, and study the overall transport of Ne. Fully predictive simulations, in the sense explained above, are approaching a satisfactory reproduction of the experimental pattern. Core Te is well reproduced while ne is overestimated. Temperatures in the divertor region are compatible with the most external points of the Thomson scattering data, which are made consistent with the equilibrium in such a way that the electron temperature at the separatrix is around 100 eV. An example of the 2D temperature distribution is given in fig. 2.

The simulation tends to qualitatively reproduce the sensitivity of the ELM frequency to the gas puffing rate. The former increases as more gas is injected, like in the experiment. The dynamics of the ELM response is still somewhat reduced in the simulation , with the ELM frequency that moves from 30 to 40 Hz when the puffing rate is raised from 0.6 e22 to 1.2 e22 (p/s) , while in the experiment the change is from 20 to 36 Hz. Also the change of the radial shift between temperature and density gradient positions at the edge reproduces qualitatively the experiment [Stefanikova] with the density gradient that is more external in the high puff case while the temperature gradient position shifts slightly inward and the pressure is almost un-

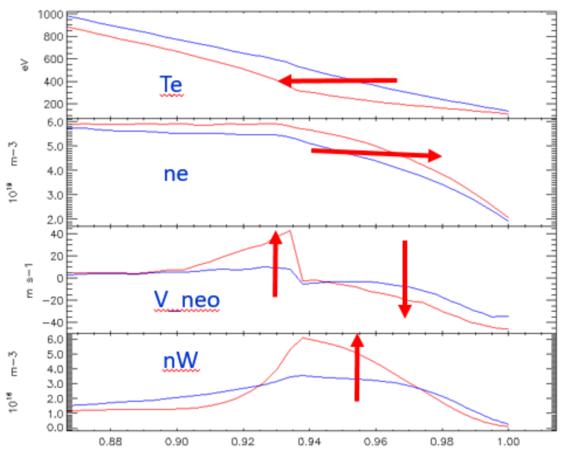

Fig 3 Change in the relative shift of Te and ne gradient positions with increasing puffing (direction of red arrows) and modification of W V-neo and density

changed. The consequence of this radial drifts in opposite directions is that both profile and amplitude of the neoclassical velocity of impurities, particularly of W, change and become more peaked due to the trapping of W between the Te gradient pushing out and the ne gradient pulling in impurities. This is shown in Fig.3. The two simulations are already a good approximation of the experimental case but for the reproduction of the Ne density in the pedestal region, which features a steeper gradient than in the experiment as shown in Fig. 4. This is responsible for an excessive peaking at the edge of both Ne and W densities. Such peaks tend to reduce or even disappear in simulations in which a better match of the Ne profiles with experimental data are obtained. The relevance of such detail is that in presence of such external peaks of mipuritiies the ELM can inject part of W into the core [Koechl].

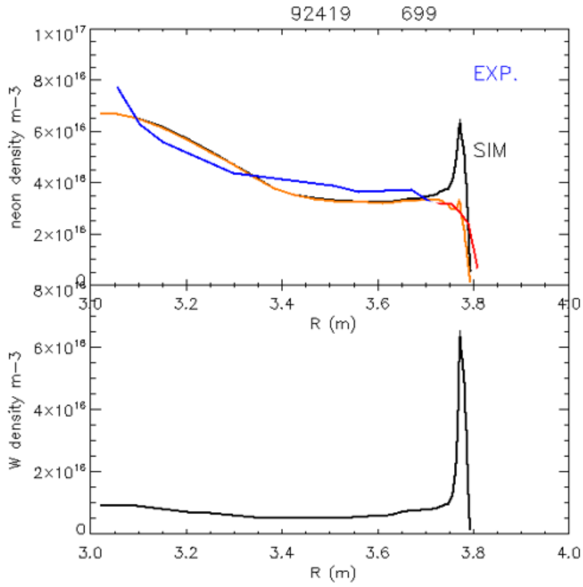

Fig. 4 Ne (top) and W(bottom) density profiles at 49 Sec. Ne X(black) and Ne total (Yellow) are compared with the experimental Ne X (blue and red)

Once optimized the benchmarking with the experiment, predictive runs will include an increase of the total input power to test its effect on the edge barrier and consequently on the W neoclassical values. Subsequently the MHD stability analysis will be included in order to increase the level of self-consistency of the ELM triggering

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4. References

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*See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be publ. in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)