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## **INTRODUCTION:**

In JET C and W/Be wall experiments, the use of ELM pacing at high ELM frequency as a tool to mitigate the ELM impact on plasma facing components and for impurity control has been successfully investigated. To improve the understanding of ELM mitigation mechanisms at JET in view of ITER and to examine dependencies of the ELM trigger efficiency on available actuators, modelling schemes are required, combining the evolution of the plasma core, edge and SOL and the analysis of MHD stability in an integrated way. The JET transport suite of codes JINTRAC [1] has been used in fully integrated mode [2,3] to study and assess physical processes that appear to be relevant in case of ELMs triggered (a) by application of magnetic field perturbations that cause a sudden displacement of the plasma (“kicks”) and (b) by injection of pellets. Whereas induced edge current perturbations were found to be relevant to destabilise the plasma edge in case (a) [4], local and plasmoid-driven pressure perturbations are held responsible for the appearance of an ELM in case (b) [5]. In the context of previous integrated simulation studies of ELM pacing / mitigation by kicks and pellets at JET [3], recent advances are reported on the following subjects:

- ELM mitigated regimes are analysed with JINTRAC in fully integrated mode in a refined way using a new tool for the evaluation of the MHD stability at runtime with HELENA+MISHKA [6,7].
- The effect of kicks at low vs. high kick amplitude / gas fuelling rate in JET C and W/Be wall discharges on MHD stability is analysed and compared against experimental findings with JINTRAC+CREATE-NL [8].
- The effect of pellets injected from the low and high field side in JET W/Be wall plasmas on MHD stability is analysed with JINTRAC in fully integrated mode.

## **1. INTEGRATED MODELLING OF NATURAL, KICK AND PELLET INDUCED**

### **ELMS:**

Thanks to a recent upgrade of the JINTRAC modelling code suite, an unprecedented level of integration in the modelling of tokamak plasmas can be reached via the simultaneous calculation of plasma transport in the core, edge and SOL regions including a self-consistent model for the trigger of MHD events such as ELMs. The MHD stability is analysed at runtime with MISHKA (version MISHKA-1) on basis of a high precision equilibrium calculation performed by HELENA with input from JINTRAC for the plasma profiles (incl. jbs) and shape. To reduce the computational time, MISHKA is called at a prescribed frequency (0.3–4kHz in the simulations presented below) and run in parallel for a predetermined representative set of toroidal mode numbers  $n$ . If a mode is found to be unstable with the growth rate exceeding a predefined minimum level ( $\gamma^2 > 10^{-4}$ ) and if the shape of the eigenfunctions for that mode passes several validity checks (in terms of barycentre location, continuity and amplitudes to avoid artefacts from background noise), an ELM is triggered in the simulation. The ELM amplitude and duration is prescribed and inferred from experimental data. JINTRAC is perfectly well suited for the analysis of transient events such as ELMs thanks to the numeric robustness of its core and edge solvers and thanks to the availability of state-of-the-art

transport and source models that are suitable for that purpose. In a first attempt to apply this new integrated modelling scheme, representative JET ELMy H-mode plasma conditions with natural ELMs have been simulated (see Fig. 1). The effect of perturbations due to kicks and pellets on MHD stability has been analysed (see Figs.2–7). Both with kicks and pellets, MHD modes are found to be destabilised allowing for an increase in ELM frequency and an associated mitigation of the impact of ELMs on PFCs. The ELM-induced heat load to the target does however not scale with  $1/f_{\text{ELM}}$  due to density depletion and reduced target protection at low  $n_e/T_e$  in the SOL [3]. For pellets injected into an ELMy H-mode ILW target plasma (see Figs.6-7), ELM instabilities are triggered for small fuelling-sized pellets ( $r_p = 1.2\text{mm}$ ) for both LFS and VHFS launch, whereas no ELM is triggered for a LFS pellet with reduced size ( $r_p = 1.025\text{mm}$ ). In all cases the time-resolved particle deposition source, heat sink and the plasmoid  $E \times B$  drift are taken into account. It should be noted that any trigger threshold that is determined with JINTRAC can only be considered as an upper limit, as the initial locality of the pellet perturbation with enhanced local pressure gradients is not considered in the transport calculation and MHD analysis.

## **2. DEPENDENCIES OF THE EFFICIENCY OF VERTICAL KICKS FOR ELM**

### **TRIGGERING:**

Pairs of JET discharges with comparable plasma configuration but varying kick amplitude (C wall cases Pulse No's: 73244 versus 73247), gas fuelling rate or shape of the kick perturbation (ILW cases Pulse No's: 82848 versus 82366) have been analysed with JINTRAC in combination with the free boundary equilibrium code CREATE-NL, using HELENA+MISHKA for the evaluation of MHD stability. Results are shown in Figs.2–5. Clearly, the kick-induced edge plasma current variation becomes larger with stronger kick perturbations, increasing the probability for the appearance of an ELM. In case of reduced gas fuelling (resulting in higher  $T_e/n_e$  ratio), the plasma seems to get closer to the MHD stability limit making ELM triggering by kicks more efficient, as the induced current perturbation is more pronounced at lower resistivity. This trend is in line with experimental observations [4]. Finally, simulation results (not shown below) indicate that an increased resistivity associated to lower plasma temperatures at the edge might also be the cause for a reduction in the efficiency of ELMs triggered by kicks in ILW plasmas.

### **CONCLUSIONS**

With the new JINTRAC feature for the evaluation of the MHD stability at runtime with the help of HELENA+MISHKA, a new level of plasma model integration for the modelling of tokamak plasmas in the entire plasma domain has been reached. This allows for the study of ELMs and ELM mitigation techniques in a simplified and convenient manner. Another important step has been taken towards the development of a fully inherently consistent plasma modelling scheme. First successful examples of application have been presented: plasma perturbations at the edge induced by vertical kicks and pellets were shown to destabilise MHD modes in the pedestal region. Experimental trends for the kick and pellet ELM trigger efficiency could be reproduced.

## ACKNOWLEDGEMENTS

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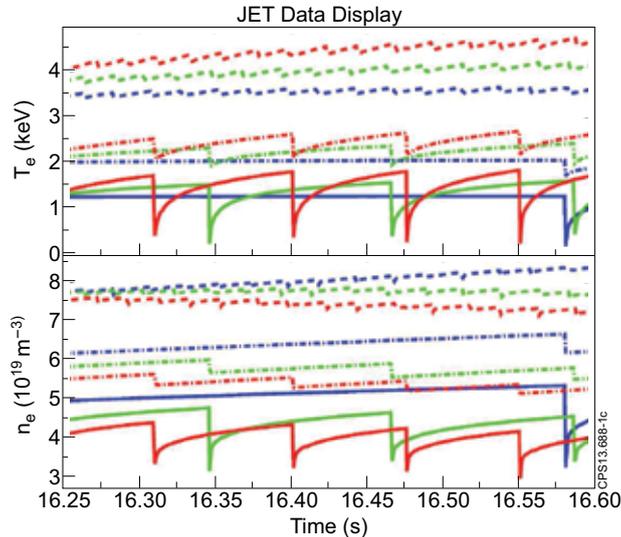


Figure 1: On-axis (dashed), average (dash-dotted) and pedestal top (solid) electron temperatures (top) and densities (bottom) for an H-mode phase with natural ELMs in the JET C wall Pulse No: 73247 with 7MW of NB power (blue). In quasi-steady state, the local deviation for  $T_i / T_e / n_e$  from experimental measurements taken by LIDAR / CX spectroscopy diagnostics is  $< 20\%$ . The natural ELM frequency in Pulse No: 73247 is  $f_{ELM} \sim 5\text{Hz}$ . Two additional simulation cases with enhanced NBI heating of 10 MW (green) and 13MW (red) for  $t > 16\text{s}$  are shown as well. An ELM is triggered in the simulation, if an edge-located MHD mode is found to be unstable by MISHKA. The ELM frequency increases with heating power in agreement with experimental observations.

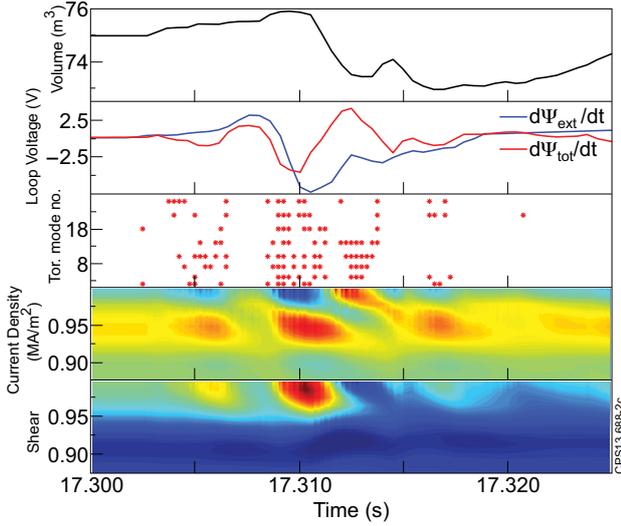


Figure 2: From top to bottom: plasma volume, externally imposed and total edge loop voltage, toroidal mode numbers found to be unstable by MISHKA, edge current density and shear contour plots for the application of a kick in the JET Pulse No: 73247. The ELM transport model has been switched off in this simulation. In the experiment, an ELM appears at the time  $t \sim 17.313s$ .

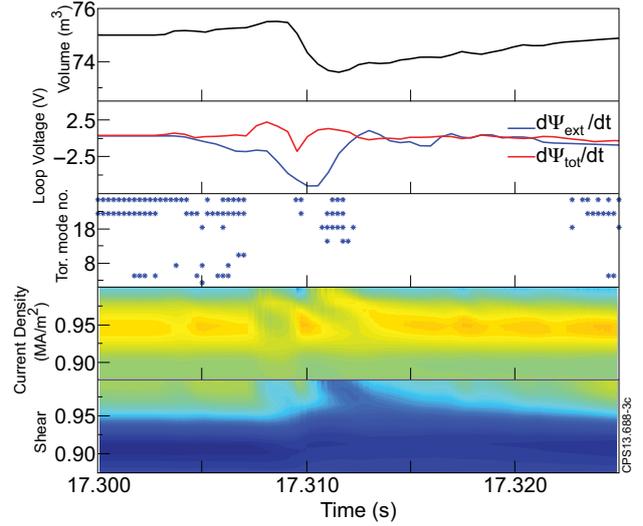


Figure 3: Similar plots (and same colour scales for contour plots) as in Fig.2, for a kick with weaker amplitude in the JET JET Pulse No: 73244. Fewer MHD modes are classified by MISHKA as unstable, in particular those with low  $n$  in the later phase of the kick, as the edge current perturbation is more benign. Still, more unstable modes are found than expected (no ELM is triggered in the experiment), which is a consequence of the plasma being already close to the MHD stability limit before the kick (first kick event) and non-smooth edge plasma profiles, the latter being caused by non-smooth transition between domains of different transport regimes (core versus ETB), as well as by a reduced grid resolution of 100 points only for the entire plasma core region (causing larger discontinuities in transition regions).

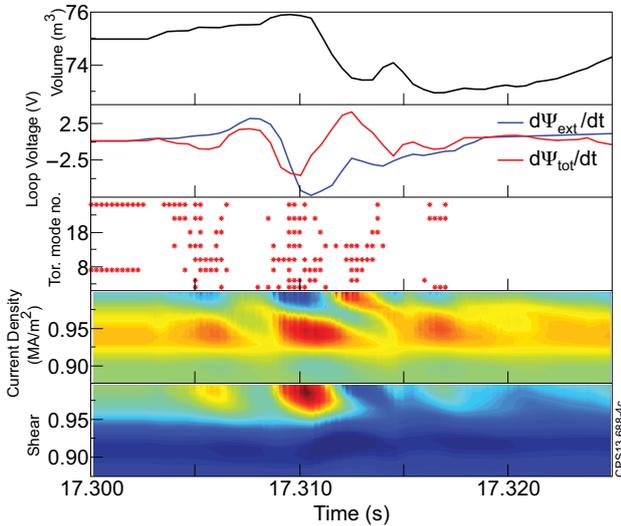


Figure 4: Similar plots as in Fig.2; same simulation as shown in Fig. 2 with sharper transition between domains of different transport regimes yielding less smooth plasma edge profiles, for comparison with Fig.5. A neutral influx of  $\sim 1.1 \cdot 10^{21} s^{-1}$  at the separatrix has been prescribed in combination with a recycling factor  $R = 0.94$ .

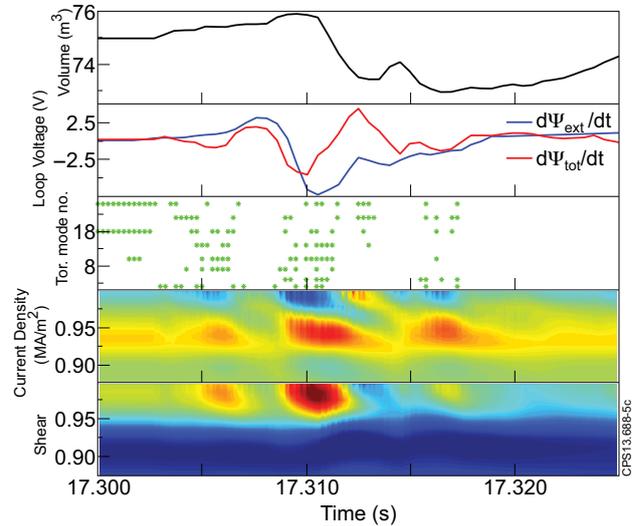


Figure 5: Similar plots (and same colour scales) as in Fig.2; rerun of the simulation shown in Fig. 4 with increased gas puffing rate ( $\sim 4 \cdot 10^{21} s^{-1}$  at the separatrix), resulting in a  $\sim 15\%$  increase in density and a reduction of  $\sim 15-18\%$  in temperatures on top of the pedestal. In this case, the plasma current perturbation is too small to drive low to medium  $n$  modes unstable in the later phase of the kick, however, instabilities are found for higher  $n$  modes.

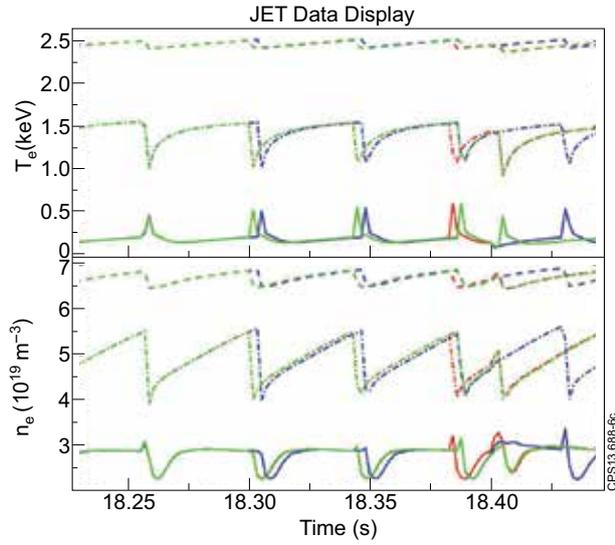


Figure 6: Average (dashed), pedestal top (dash-dotted) and separatrix (solid) electron temperatures (top) and densities (bottom) for integrated core+edge+SOL+MHD simulations of a JET ILW plasma similar to Pulse No: 82806, but with enhanced temperature ( $DT \sim 0.5\text{--}1\text{keV}$ ) and density peaking ( $n_{ax}/n_{ped} \sim 1.8$ ). A LFS pellet (red) and a VHFS pellet (green) with  $r_p = 1.2\text{mm}$ , and a LFS pellet with  $r_p = 1.025\text{mm}$  (blue) are injected at  $t = 18.4\text{s}$ .

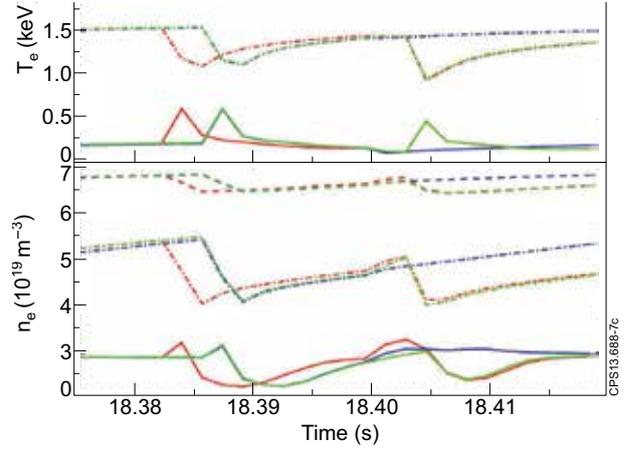


Figure 7: Zoom of the time window when a pellet is injected for the simulations shown in Fig.6. High  $n$  MHD modes become unstable and ELMs are triggered for the two larger pellets, whereas the smaller pellet is not capable to trigger an ELM.