Integrated core+edge+SOL+MHD modelling of ELM mitigation at JET

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Introduction:

In JET C and W/Be wall experiments, the usability 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 ameliorate 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]. On basis 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].

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* See the Appendix of F. Romanelli et al., Proc. 24th IAEA Fusion Energy Conference (2012), San Diego, USA

- The effect of kicks at low vs. high kick amplitude / bootstrap current 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 and compared against experimental findings with JINTRAC in fully integrated mode.

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 on basis of a high precision equilibrium calculation performed by HELENA. To reduce the computational time, MISHKA is called at a prescribed frequency (0.3 - 4 kHz 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 and if the shape of the eigenfunctions for that mode passes several validity checks (to avoid artefacts from background noise), an ELM is triggered in the simulation. 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. [3] For pellets injected from the LFS and VHFS into a representative ELMy H-mode ILW target plasma (#82806, see Figs. 6-7), ELM instabilities are triggered in the simulation if time-resolved particle deposition source and heat sink profiles considering the plasmoid ExB drift are taken into account for small fuelling-sized pellets (r_p = 1.2 mm), whereas no ELM is triggered for a LFS pellet with reduced size (r_p = 1.025 mm). It should be noted though that any trigger threshold that is inferred from JINTRAC calculations can only be considered as an upper limit, as the initial locality of the pellet perturbation with enhanced local pressure gradients is not considered.

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 #73244 vs. #73247), gas fuelling rate or shape of the kick perturbation (ILW cases #82848 vs. #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 mechanisms more efficient, as the induced current perturbation is more pronounced at lower resistivity. Finally, simulation results 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, allowing 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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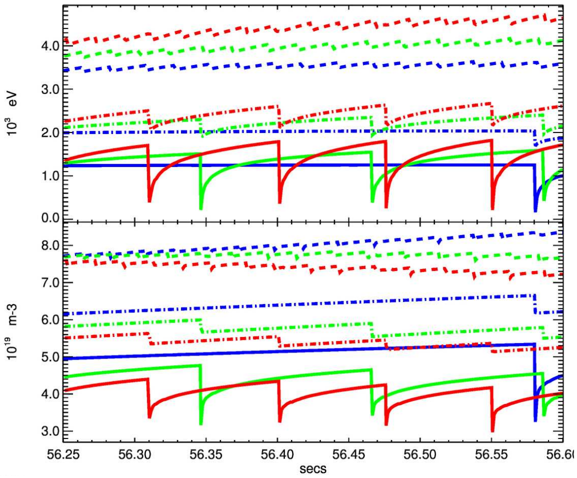

Figure 1 – On-axis (dashed), average (dash-dotted) and pedestal top (solid) electron temperatures (top) and densities (bottom) for an H-mode phase with natural ELMs in the JET C wall discharge #73247 with 7 MW of NB power (blue), compared to two cases with enhanced NBI heating of 10 MW (green) and 13 MW (red) for t > 56 s. 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.

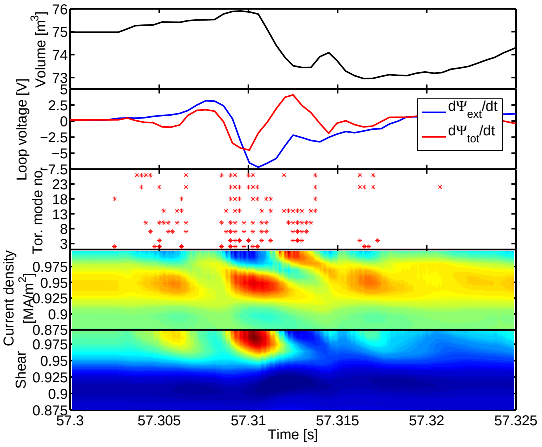

Figure 2 – From top to bottom: plasma volume, externally imposed and total edge loop voltage, toroidal mode numbers found to be unstable by MISHKA, edge current density and shear contour plots for the application of a kick in the JET discharge #73247. ELMs are not triggered in this simulation. In the experiment, an ELM appears at the time t ~ 57.313 s.

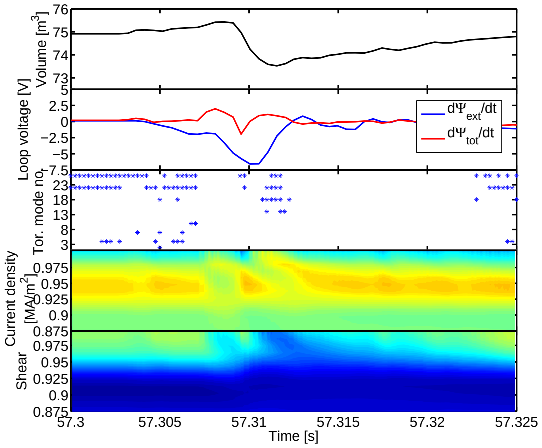

Figure 3 – Similar plots as in Fig. 2, for a kick with weaker amplitude in the JET discharge #73244. Fewer MHD modes are classified by MISHKA as unstable, in particular those with low n in the later phase of the kick, as the edge current perturbation is more benign. Still, more unstable modes are found than expected, which is a consequence of non-smooth edge plasma profiles, the latter being caused by non-smooth transition regions between domains of different transport regimes, as well as by a reduced grid resolution of 100 points only for the entire plasma core region.

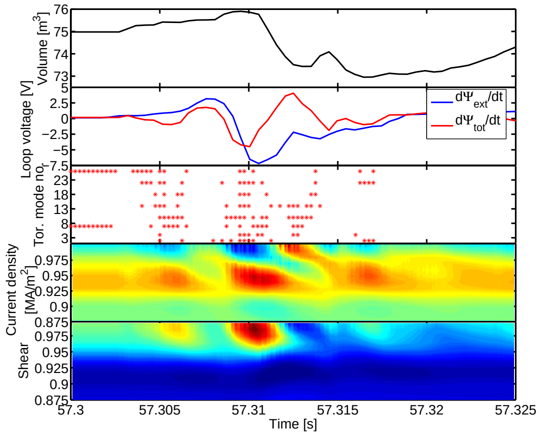

Figure 4 – Similar plots as in Fig. 2; same simulation as shown in Fig. 2 with sharper transition between domains of different transport regimes yielding less smooth plasma edge profiles, for comparison with Fig. 5.

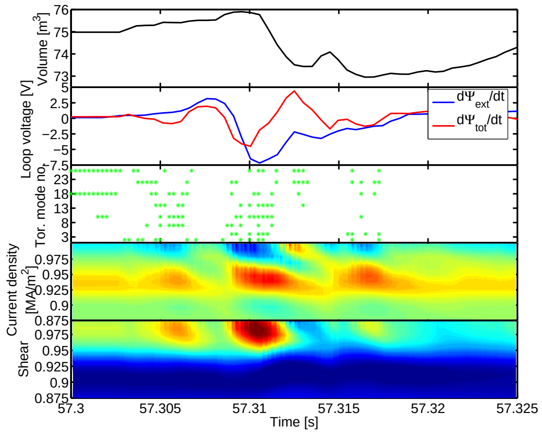

Figure 5 – Similar plots as in Fig. 2; rerun of the simulation shown in Fig. 4 with increased gas puffing rate, resulting in a ~15% increase in density and a reduction of ~15-18% in temperatures on top of the pedestal. In this case, the plasma current perturbation is too small to drive low to medium n modes unstable in the later phase of the kick.

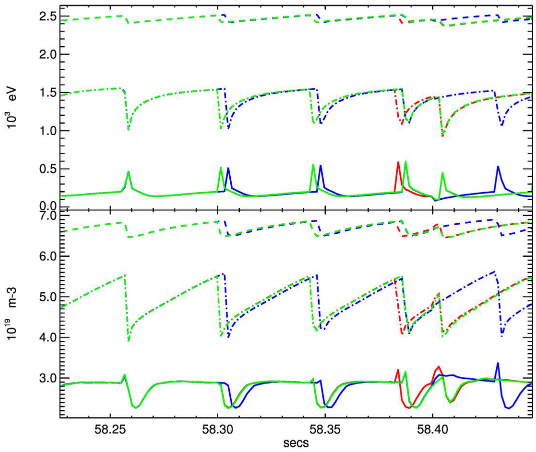

Figure 6 – Average (dashed), pedestal top (dash-dotted) and separatrix (solid) electron temperatures (top) and densities (bottom) for integrated core+edge+SOL+MHD simulations of the JET ILW discharge #82806. A LFS pellet (red) and a VHFS pellet (green) with r_p = 1.2 mm, and a LFS pellet with r_p = 1.025 mm (blue) are injected at t = 58.4 s.

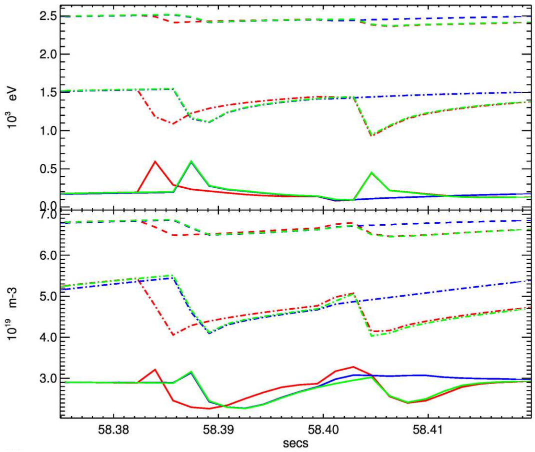

Figure 7 – Zoom of the time window when a pellet is injected for the simulations shown in Fig. 6. High n MHD modes become unstable and ELMs are triggered for the two larger pellets, whereas the smaller pellet is not capable to trigger an ELM.