# Non-linear hybrid kinetic-MHD modeling of the interaction between ELMs and fast-ions using MEGA

J. Dominguez-Palacios[1], S. Futatani[2], J. Gonzalez-Martin[1], M. Garcia-Munoz[1], E. Viezzer[1], Y. Suzuki[3], Y. Todo[3], J.F. Rivero-Rodriguez[1], M. Toscano-Jimenez[1], J. Galdon-Quiroga[4], P. Oyola[1], C. Soria-Hoyo[1], the ASDEX Upgrade* and EUROfusion MST1† Teams

[1] *University of Seville, Seville, Spain*
[2] *Universitat Politècnica de Catalunya, Barcelona, Spain*
[3] *National Institute for Fusion Science, Toki, Japan*
[4] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

Edge localized modes (ELMs) are periodic magnetohydrodynamic (MHD) instabilities driven by sharp pressure gradients and current densities at the plasma boundary that will likely lead to transient, and intolerable, energy and particle losses in ITER. A thorough understanding of ELM physics is, therefore, mandatory to develop robust ELM control and suppression techniques for future fusion devices. Although the main ELM driving force comes from edge thermal plasma pressure and current profiles, recent experimental observations reveal a strong interplay between ELMs and energetic ions in the pedestal region. Intense, localized energetic particle losses and acceleration are routinely observed during ELM crashes in the ASDEX Upgrade (AUG) tokamak [1, 2]. The impact that this strong interaction between ELMs and fast-ions may have on the ELM itself and its implications towards the development of a robust ELM control technique is still unknown.

3D non-linear hybrid kinetic-MHD simulations of an ELM [3] in the presence of energetic particles have been carried out for the first time and are presented here. In a non-linear MHD multi-$n$ simulation, with $n \leq 20$, in a full 3D realistic X-point geometry and including temperature dependent viscosity and resistivity, a spontaneous ELM has been successfully obtained using the MEGA code [4]. In the simulations, ballooning modes grow in the pedestal region in the linear phase. In the non-linear phase, the growth of the harmonics saturates. During the saturation phase, filaments extend into the scrape-off layer and the pressure profile at the edge relaxes, leading to the ELM crash.

To shed light on the interaction between ELMs and fast-ions, hybrid kinetic-MHD simulations have been performed, using an off-axis Neutral Beam Injection (NBI) fast-ion distribution. A scan in energetic-ion beta ($\beta_h$) and birth energy ($E_{birth}$) shows that fast-ions have a strong impact on mode stability. At fixed $E_{birth}$, although the linear growth rate increases with $\beta_h$, the saturated mode amplitude decreases with $\beta_h$ for $E_{birth} > 60$ keV and increases with $\beta_h$ for $E_{birth} < 60$ keV. Similarly, at fixed $\beta_h$, the saturated mode amplitude decreases with increasing $E_{birth}$ with e.g. mode amplitude 3 times larger for $E_{birth} = 20$ keV than for $E_{birth} = 60$ keV. In addition, the electromagnetic perturbation that arises during the ELM crash redistributes the fast-ions in the edge region, as observed in experiments [1, 2]. The impact that these results have on present ELM models will be discussed.

## References

[1] M. Garcia-Munoz *et al.*, Nucl. Fusion **53**, 123008 (2013).
[2] J. Galdon-Quiroga *el al.*, Phys. Rev. Lett. **121**, 025002 (2018).
[3] A.F. Mink *et al.*, Nucl. Fusion **58**, 026011 (2018).
[4] Y. Todo *et al.*, Phys. Plasmas **5**, 1321 (1998).

*See the author list of H. Meyer *et al.*, Nucl. Fusion **59**, 112014 (2019).
†See the author list of B. Labit *et al.*, Nucl. Fusion **59**, 086020 (2019).