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# [REGULAR POSTER TWIN] Simulations of Edge Localized Mode (ELM) Cycles and ELM Control

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**Outline.** We report on major progress regarding simulations of edge localized modes (ELMs). First of a kind simulations of realistic repetitive type-I ELM cycles are presented, reproducing in particular the explosive onset of the ELM crashes for the first time. Key to this achievement were numerical improvements, fully realistic plasma parameters and flows, a self-consistent evolution of the bootstrap current and a matching of pedestal build-up time scales with the experiment. Additionally, these simulations allow us to study ELM control in a more realistic way than possible before. We base our studies on ASDEX Upgrade (AUG) [1], since the pedestal diagnostics available constitute an ideal basis for validating and comparing.

**Motivation.** Unmitigated type-I ELMs which are very common in high-confinement mode (H-mode) tokamak plasmas are intolerable for ITER full current operation due to the large transient divertor heat loads; and even small ELMs are likely incompatible with an acceptable DEMO divertor life time. ELM mitigation and avoidance consequently is a key requirement for successful further development of magnetic confinement fusion, and reliable predictions for mitigation or avoidance scenarios are necessary. Non-linear extended magneto-hydrodynamic (MHD) simulations are essential for developing such robust control scenarios. With JOREK [2], simulations of ELMs [3-5] and ELM control [6-10] via mitigation or suppression by external fields, pacing by pellets or vertical magnetic kicks, or ELM free regimes [11] had already been performed for a large number of different tokamak devices, resulting in very good qualitative and quantitative agreement with experiments regarding many key parameters. A clear shortfall of previous simulations was that the fast time scales of the ELMs were not reproduced and repetitive type-I ELM cycles were not obtained.

**Edge localized modes.** We present first of a kind type-I ELM cycle simulations [12]. Depending on the case, 5-15% of the plasma thermal energy is lost during an ELM crash on a timescale of about one millisecond, in good agreement with experimental observations. Before the violent ELM crash, we observe precursor modes, which affect the pedestal structure, such that the sharp onset of the crash can occur. As mechanism responsible for the explosive onset, we identify that the precursor modes perturb the balance between stabilizing terms (in particular ExB and diamagnetic flows) and destabilizing terms (in particular pressure gradient and current density) in favor of the latter.

When the heating power is modified, the repetition frequency of the ELMs changes consistently with experiments. Below a specific threshold in the heating power, large ELMs disappear, and a transition into a peeling-ballooning turbulent state is observed [13], which reproduces some features of small ELMs in experiments. The pedestal pressure gradient is limited by the fluctuating modes to values comparable with experiments at similar plasmas (high collisionality and low triangularity) [14].

When the distance between plasma and conducting wall is increased to reflect the experimental situation more accurately via free boundary JOREK-STARWALL [15] simulations, the inter-ELM dynamics of the experiment are captured even more accurately. Resistive edge instabilities become linearly more unstable and non-linearly cause a richer inter-ELM mode spectrum with saturated rotating modes that cause considerable transport [16]. Similar to the experiment [17], these modes limit the build-up of the pedestal density, while the pedestal temperature continues to grow.

**ELM control.** The ability to capture the detailed dynamics of ELM crashes and ELM cycles in simulations demonstrated above, allows to investigate ELM control in a more realistic way than possible before. We present first steps in this direction. Pellet injection at various phases during the pedestal build-up was simulated based on the simulations described above [18]. This way, and by including realistic ExB and diamagnetic flows for the first time in pellet ELM triggering simulations, the experimentally observed lag time [19], during which a pellet cannot trigger an ELM crash, was reproduced for the first time. For later injections, the pellets lead to pronounced ELMs crashes, which show different divertor heat flux structures than natural ELMs.

Based on the type-I ELM cycle simulations described above, we also present first free boundary simulations of RMP penetration into AUG plasmas and of the interaction with the MHD modes [20]. These simulations allow for resonant field amplification at the boundary of the computational domain, which earlier fixed boundary simulations did not capture.

**Beyond.** We briefly summarize further research regarding ELMs, pedestal, SOL, and divertor using the JOREK code [6,8,10,21-26] and show further ongoing work. This includes studying collisionality and shaping effects, experimental validation, and the path towards fully predictive simulations.

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