ELM AND ELM-CONTROL SIMULATIONS


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Abstract

In recent years, increased HPC resources and performance has enabled significant advances in the quality and reliability of non-linear MHD simulations of tokamak instabilities. In the domain of Edge-Localised-Modes, validation of the JOREK code has been achieved by addressing various characteristics of this instability. The necessity to control ELMs, in order to reduce divertor heat-fluxes in ITER, while maximising the flushing of high-Z impurities, motivates a thorough validation of the numerical and physical model, so that reliable predictions can be provided for future devices. With increasing concordance between simulation results and experimental observations, non-linear MHD is starting to provide insight into several open questions about ELM physics and ELM-control techniques, in time for the development and exploitation of ITER operation.

1. INTRODUCTION

As fusion devices progress towards reactor-relevant conditions, the exhaust of particles and heat onto plasma facing components (PFCs) is acknowledged to be a major challenge [1]. In JET, the tungsten divertor is subject to damage in high power discharges, and there is growing concern that divertor heat loads will be one of the main restricting factors for operation capabilities in ITER [2]. Energy deposition on the divertor materials, due to steady-state heat fluxes as well as transient MHD events like Edge-Localised-Modes (ELMs), will be considerably increased in burning plasma experiments like ITER. Most of the energy that crosses the separatrix into the Scrape-Off Layer (SOL) is transported along field lines to the divertor targets, and this effect is enhanced by increased heat conductivity at higher temperatures [3-5]. Combined with the large amplitude of these heat-fluxes, the longer duration of experimental pulses in reactor-sized devices will induce significant strain on the tungsten tiles, possibly leading to erosion and melting [6]. The tungsten tiles of the ITER divertor are designed to withstand up to 10 MW/m² in steady-state, and several thousands of transient events of up to 20 MW/m² [7,8].

Ultimately, heat fluxes on PFCs are determined by how much energy escapes from the well-confined region inside the separatrix. It is well established that non-diffusive transport is responsible for this energy crossing the separatrix [9], and it is also well established that this occurs either in the form of turbulence filaments (blobs), or in the form of large-scale ELM filaments [10-13]. Hence, elaborate physics models (Fluid, MHD, drift-kinetic etc.), combined with an accurate description of the plasma geometry (including X-point, SOL and wall-surfaces), are indispensable to yield a robust understanding of non-diffusive transport in tokamaks. Non-linear simulations of ELMs are progressively reaching a level of reliability, with respect to current experiments, that opens the path towards predicting ELM dynamics and ELM control in future devices, one of ITER’s urgent requirements.

In this paper, we present an overview of results obtained using the JOREK code [14,15] in the domain of ELM simulations and their control. Section-2 presents the JOREK code and its position in the frame of the
international non-linear MHD community. Section-3 describes the recent progress in terms of ELM-physics understanding from the perspective of numerical simulations across several tokamaks. Section-4 details results of ELM-control simulations using various candidate methods for ITER. Section-5 gives a summary and perspective towards short- and long-term goals.

2. THE NON-LINEAR MHD APPROACH

2.1 International status of non-linear MHD simulations of ELMs

Several non-linear MHD (and extended-MHD) codes, such as JOREK [14,15], BOUT++ [16], HESEL [17], EMEDEGE3D [18], M3D-C1 [19], NIMROD [20] and MEGA [21-23], can obtain advanced ELM simulations, with challenging physics effects like bi-fluid diamagnetic rotation and current, with low resistivity and viscosity levels, as well as high poloidal/toroidal resolutions. The variety in numerical methods used for each code has led to a wide range of physics analysis and understanding in the ELM community. The strategy of non-linear MHD codes is to focus numerical power on a certain aspect of ELM dynamics. For example, by describing simplified or reduced geometrical equilibria, the numerical capacity can be focused on higher toroidal resolution and elaborate extended-MHD models, while targeting the numerical capability onto an accurate geometrical description of X-point equilibria enables the study of energy transport from the pedestal to divertor and first-wall surfaces. In the last decade, these non-linear MHD codes have achieved advanced qualitative agreement with experimental observations, by considering key ELM characteristics, like the cyclic and onset properties of ELMs, the ejection of hot plasma filaments across the separatrix, the collapse of the pedestal pressure, and the transport of energy to the divertor and first wall components. In this paper, we describe recent JOREK results obtained across international tokamak devices, in the field of ELMs and their control.

2.2 Description of the JOREK code

The 3D nonlinear MHD code JOREK was developed by Huysmans et al. with the specific aim to produce simulations of Edge-Localised-Modes [14,15]. The reduced MHD model used for the present paper is similar to that used in previous JOREK studies [24,25]. It is a six-field reduced MHD model for the variables $\psi$ (poloidal magnetic flux), $\Phi$ (electric potential), $v_{//}$ (parallel velocity), $\rho$ (ion density), $T$ (total temperature), $\rho_n$ (neutral density). The model contains all pedestal-relevant plasma flows, including two-fluid diamagnetic effects, neoclassical poloidal velocity and NBI toroidal rotation [26]. A time-evolving Sauter bootstrap current source is also used. In certain cases, kinetic extensions are used to follow tungsten particles or electrons along the 3D fields computed by the fluid models [27,28].

The perpendicular mass and thermal diffusivities $D_\perp$ and $\kappa_\perp$ are ad-hoc coefficients with a well at the pedestal region to represent the H-mode transport barrier [24]. The Spitzer resistivity is used: $\eta \sim T_e^{-3/2}$, and the same $T_e$-dependence is used for perpendicular viscosity. The Braginskii model is used for parallel thermal conductivity: $\kappa_{//} \sim T_e^{5/2}$. Hyper-diffusive coefficients $\mu_{hyp}$, $\eta_{hyp}$ and $D_{hyp}$ are also used in simulations, but with values small enough not to influence the physics results (e.g. $\eta_{hyp} \sim \eta^2$).

As described in [25], the neutrals part of the model evolves $\rho_n$ spatially using diffusive coefficients in the $(R,Z,\phi)$-directions, which reduces the numerical size of the system compared to fully convective model, and as a result charge exchange is not included. The coupling terms between neutrals and other variables are: ionisation,
recombination, Bremsstrahlung and background impurity radiations. Neutrals are reflected at target boundaries such that \( D_s \cdot n = -\xi_e \rho v_s \cdot \hat{n} \), where \( \hat{n} \) is the normal to the target, and \( \xi_e \) is the reflective coefficient.

The boundary conditions applied to all surfaces with incident magnetic field are Bohm (Mach-1), \( v_i = \pm c_s = \pm \sqrt{\gamma(y_T)} \), and sheath boundary conditions, \( \kappa \nabla \cdot T = (y_a-1) nTV_a \) where \( y_a \) is typically chosen between the electron and ion sheath transmission coefficient [9], \( y_a = \gamma/2 \). Note that the incidence and direction of magnetic field lines (and thus the sign of \( v_i = \pm c_s \)) may change along boundary surfaces. A threshold is used for Mach-1 boundary conditions, when the sign reverses across zero, which requires that the angle \( \alpha \) between the magnetic field and the boundary is larger than \( \alpha \), approximately twice the lower limit given by Geraldini et al. [29]: \( \alpha \gg \sqrt{(m_e/m_i)} \).

The spatial discretization of JOREK is made of a 2D poloidal grid with pseudo-spectral Fourier representation in the toroidal direction. The poloidal grid is composed of isoparametric bi-cubic Bezier finite elements [15]. This grid is aligned to equilibrium flux surfaces for the three regions of the core, the SOL and the private region. The grid can also be extended arbitrarily to any first-wall structure. This new feature of the grid-generator, illustrated in Figure-1, enables a more accurate treatment of SOL and divertor dynamics.

The time stepping is done using implicit time-schemes (eg. Gears or Crank-Nicolson), so that the size of time-steps depends only on the time scale of the instabilities that are simulated. These schemes result in sparse linear systems, solved using a Generalized Minimal RESidual Solver (GMRES). The preconditioner for the iterative GMRES is obtained by solving independently each sub-matrix corresponding to each Fourier harmonics, (block-Jacobi preconditioner). These sub-matrices are solved with the direct parallel sparse matrix solver PaStiX [30].

The free-boundary version of JOREK-STARWALL [31] couples the boundary conditions of JOREK to the STARWALL calculation of magnetic fields outside the first-wall. Detailed 3D structures of coils and conducting structures are included in STARWALL. Used mainly for disruption studies, this extended JOREK version can also be used to study ELM-triggering by vertical kicks as well as QH-mode, as shown in Section-4.

3. UNDERSTANDING ELM PHYSICS THROUGH NUMERICAL SIMULATION

3.1 A multi-device approach

In recent years, ELM simulations with JOREK have been applied to several tokamaks worldwide, offering an analysis of numerous characteristics of ELM physics. Beyond the variations of engineering configurations across current devices, each one is equipped with its own specific set of diagnostics, which often provides a unique insight into a specific aspect of ELM dynamics. Considering the filament rotation with the KSTAR 2D-ECEI [32], the detailed divertor heat-flux measurements with the JET-ILW IR-cameras [33,34], the 3D-visualisation of filaments with the MAST fast-imaging cameras [10], or the mode-number evolution during ELMs with the AUG magnetic measurements [35], as well as other diagnostics, a convincing validation of JOREK simulation is being achieved across multiple devices. Along with this continued validation activity, these studies have also provided a broad extension of our physics understanding of ELM dynamics, particularly with respect to the onset of ELMs and the importance of non-linear dynamics in the ELM cycle. Simulations can now be obtained at experimental levels of resistivity, an essential aspect of numerical MHD computation.

3.2 JET-ILW results

One of the most important aspects of ELMs, with regards to future devices and ITER’s operation, is certainly the high heat-fluxes they induce on divertor tiles. As filaments rip away from the confined plasma, they breach through the separatrix, causing a stochastic fragmentation of the pedestal magnetic field. This change in magnetic topology results in field lines that connect the divertor target with regions far inside the pedestal, providing a route for particles to escape the confined region. As a result of convection and conduction along these open field lines, large energy fluxes reach the divertor target. Using the IR-measurements on the JET tokamak during CFC and ILW campaigns [33,34], an extensive analysis has been conducted with JOREK to validate this essential aspect of simulations. As shown in Figure-2b, divertor peak heat-fluxes are in reasonable agreement with experiments, although slightly lower on average. Further work is ongoing to improve this agreement. Particularly, the ability of simulations to reproduce the divertor heat-fluxes of high-current, low-collisionality pulses, provides a robust basis for the application of JOREK to larger devices like ITER.

3.3 JT-60U results

Simulations of JT-60U pulses have been performed in an attempt to validate JOREK prior to its application to JT-60SA scenarios. Experimental resistivity was used to address the issue of pedestal position and its role in ELM energy losses. The pedestal \( n_e \) and \( T_e \) profiles were shifted (together) with respect to the separatrix position, ranging from \( \psi_s = 0.955 \) to \( \psi_s = 0.975 \). As a result, the ELM energy losses increase, but the behaviour is different between the two pulses considered: pulse E49228 and E49229. In both cases, the divertor heat-fluxes increase as the pedestal is shifted outward, but the duration of the ELM burst shortens for E49229, while it remains constant for E49228. As a result, while the rate of energy loss increases for E49229, the shorter MHD activity results in a similar total energy loss at the end of the ELM.
Figure-2a: ELM simulation of JET-ILW pulse 83334, using the wall-extended grid, showing a zoom on the divertor region. The divertor heat-flux reaches 380 MW m$^{-2}$, very close to the IR-measurement of 360 MW m$^{-2}$ (pulse-average).

Figure-2b: Simulations of JET-CFC and JET-ILW pulses give reasonable agreement with IR-measurements, including at high-$I_p$, low-$v^*_{ped}$, demonstrating that JOREK can describe parallel energy transport between pedestal and divertor. The green $v^*_{ped}$ theoretical scans are obtained by varying $n_e$ & $T_e$ at constant $p_{ped}$.

These pulses both have the same field and current (4T and 1.6MA), similar pedestal pressure levels ($n_{ped} = 2 \cdot 10^{19}$ m$^{-3}$ and $T_{i,ped} = 2.1$ keV), but the direction of the NBI heating is reversed between the two pulses, such that the toroidal rotation profile is also reversed. As demonstrated in [36], changes in edge rotation can affect high-$n$ ballooning modes. Such high-$n$ modes ($n>40$) cannot yet be resolved with JOREK at experimental resistivity levels. However, using medium-$n$ modes ($n\leq18$), both with and without toroidal rotation, results in similar ELM sizes.

This suggests that detailed variations in the $n_e$ and $T_i$ profiles are responsible for the different increase in ELM duration as the pedestal is shifted. Although both pulses have similar $p_{ped}$ values, it should be noted that the respective shift, $\Delta \psi_{ped} = \psi_{ped}[T_i] - \psi_{ped}[n_e]$, between the $n_e$ and $T_i$ pedestal position, is slightly different for the two pulses. As illustrated by Figure-4 in [36], $\Delta \psi_{ped} = -1\%$ for E49228, while $\Delta \psi_{ped} = +0.5\%$ for E49229. This difference is not negligible when considering the present scan in pedestal position, from $\psi_e = 0.955$ to $\psi_e = 0.975$, ie. the order of $\Delta \psi_{ped}$. Previous JT-60 studies [37], and JET-ILW results [38], also found that slight changes in $\Delta \psi_{ped}$ can have drastic effects on ELM stability.

3.4 AUG results

Using magnetic pick-up coils on ASDEX-Upgrade for pulse #33616 (2.5T, 800kA, 4MW), the evolution of toroidal mode numbers was analysed during ELMs, which appear to be dominated by low-$n$ mode structures $n=2-5$, with lesser contributions from intermediate mode numbers $n=6-10$ [35]. ELM simulations of the same pulse demonstrated that similar mode numbers were observed with JOREK. In particular, while the ELM crash seems to begin with intermediate mode numbers, in the non-linear phase low-mode numbers become dominant. In these simulations, non-linear coupling with $n=1$ was observed to be an essential ingredient in order to reproduce experimental results [35].
Comparison of cold-front penetration between simulations and experiments on ASDEX-Upgrade also revealed that the stochastic degradation of the pedestal occurs on short time scales [39]. Field lines connecting the target to the pedestal can reach as far as $\psi_n = 0.75$ in under 300$\mu$s. At the ELM onset, due to an almost instantaneous stochastic burst, the fast conductive losses along stochastic field lines lead to an immediate penetration of the cold-front into the plasma. As measured in the experiments and illustrated in Figure-4a, after this initial burst, a slower propagation of the stochastic layer reaches the inner pedestal ($\psi_n < 0.85$) [39].

In addition to the fluid MHD model used for standard ELM simulations, a particle-tracker module has been developed to study the dynamics of tungsten transport during ELMs. For ASDEX-Upgrade simulations, starting with a peaked W-population inside the pedestal, the ELM rapidly redistributes the tungsten particles outside the separatrix, due to radial $E \times B$ flows generated by the ELM filaments. Further developments are under way to add collisions and sputtering to the particle-module, and study W-flushing on ITER [27].

3.5 KSTAR results

In the KSTAR device, the rotation of filaments is observed during ELM precursors [32]. The rotation of ELM precursors in JOREK simulations of KSTAR were compared to these experiments [40] in order to validate the two-fluid diamagnetic model and the neoclassical rotation effects implemented in the model [26]. These effects, together with the toroidal rotation profile (taken from the experiments), are essential to reproduce the ~5km/s rotation of filaments in the ion diamagnetic direction (in the poloidal frame).

In addition to the filament rotation, diamagnetic effects have a major role in the non-linear coupling that occurs between ELM cycles. This aspect of the simulations was studied by observing the activity of toroidal modes in time between ELM cycles. In agreement with KSTAR experiments (and with ASDEX-Upgrade results described in the previous section), low-n mode numbers are observed during the inter-ELM phase, as illustrated in Figure-5. In KSTAR as well as ASDEX-Upgrade, it is observed that the ELM starts with intermediate mode numbers (n=7,8), while lower-n modes (n=1,2) become dominant in the later phase of the ELM. During the inter-ELM period, activity of the mode n=6 is observed.

3.6 MAST-U results

MAST-U simulations are being run using the wall-extended grid, together with the neutrals model [25], to investigate the properties of detachment and ELM burn-through in super-X configurations. The magnetic equilibria

Figure-4a:
The connection length (from midplane to divertor targets) is plotted over time, at various radial locations, for ASDEX-Upgrade pulse #33616 (M.Hoelzl [39]). Note fully white means no connection to the divertor. Stochasticity appears with a rapid burst at the ELM onset (<300$\mu$s) and then progressively reaches further inwards. In experiments, a cold front propagation is also observed with similar time scales (cyan dots) [39]. The fast initial burst (phase-1) is also followed by slower propagation of the cold front during the later phase of the ELM (phases-2&3).

Figure-4b:
Simulations of ASDEX-Upgrade were used to study tungsten-flushing, using a recently developed particle-tracker module (D.VanVugt [27]). In this simulation, a peaked population of tungsten particles is initiated at the top of the pedestal. Due to the radial $E \times B$ velocities induced by the ELM filaments, tungsten is flushed across the separatrix during the ELM.

Figure-5:
M.Becoulet: ELM cycles simulations of KSTAR ELMs [40]. The first ELM appears to be dominated by intermediate mode numbers (n=7,8) in its early phase, while the later phase is dominated by low-n modes (n=1,2). Rotating precursors n=6 in inter-ELM phase followed by a second ELM due to n=6.
used here are combined with previously measured (and simulated [41]) pre-ELM $n_e$ and $T_e$ profiles from past MAST type-I ELM discharges. In these simulations, 95% of the ion density is reflected (into neutrals) at the wall surfaces. Although charge-exchange is not present in the model (diffusive neutrals fluid rather than convective), the coupling terms included for the ionisation, line-radiation and recombination effects, are sufficient to reproduce detachment of the target plasma. As illustrated in Figure-6a, performing a scan in separatrix ion density (at the outer mid-plane) results in a roll-over of the target density out-flux $\Gamma_n = \rho \vec{v}$ at the strike point.

Once a stationary equilibrium with detachment is obtained (here for the case $n_{sep} = 0.45 \times 10^{20} \text{m}^{-3}$), the ballooning mode $n=20$ is set free, leading to the filamentation of the outer plasma region, and thus a crash of the pedestal pressure. As described in the previous two sections, the rapid fragmentation of the pedestal magnetic flux surfaces leads to open field lines connecting the target to the pedestal, in addition to plasma being directly convected outside the separatrix. With the fast electron conductive transport included in simulations, pedestal $T_e$ levels quickly reach the target, and the plasma re-attaches, as shown in Figure-6b, already at the early phase of the ELM. These are preliminary simulations, and further work is under way to validate JOREK detachment simulations against more elaborate SOLPS simulations [42]. Additional scans of the neutrals density level in the divertor region will be performed to study the extent of the ELM burn-through, and scans of the magnetic configuration, ranging from a conventional to a super-X separatrix, will also be performed prior to MAST-U operations.

![Figure-6a](image)

**Figure-6a:** Simulations of MAST-U are used to study detachment in Super-X configuration. A scan in midplane separatrix density shows that, once stationary equilibrium is obtained, at higher $n_{sep}$ levels, the density flux at the target strike point rolls-over into a detached regime (S.F. Smith, to be published).

![Figure-6b](image)

**Figure-6b:** Using the case $n_{sep} = 0.45 \times 10^{20} \text{m}^{-3}$ from Figure-6a, an ELM is simulated using the mode number $n=20$. In the early phase of the ELM, soon after the filaments start crossing the separatrix, high parallel conduction causes $T_e$ to rapidly increase at the target. Further work is ongoing to study the extent of the ELM burnthrough in MAST-U (S.F. Smith PhD thesis).

### 3.8 Towards Full-MHD

As described in previous sections, JOREK is mostly run using reduced MHD models [43]. However, work is under way to implement a full-MHD model for non-linear studies. This work, partly described in [44], requires adequate boundary conditions for Mach-1 flows at plasma boundaries, and in some cases, numerical stabilisation of fast-waves using the VMS method. Test-cases of internal kink-modes in circular plasmas, as well as ballooning modes in X-point plasmas, have been performed, as shown in Figure-7. Further work is in progress to benchmark ballooning simulations against reduced-MHD models, and handle the non-linear phase of the instability.

![Figure-7](image)

**Figure-7:** The development of a full-MHD model in JOREK is beginning to bear results. Benchmarks are under way for circular internal kink-modes, as well as ballooning modes, including the X-point geometry and Mach-1 boundary conditions on the divertor targets. Further work is now needed to expand the capability of this full-MHD model in order to address physics issues relevant to experimental plasmas (G. Huijms & B. Nkonga).

### 4. THE MECHANISMS OF ELM-CONTROL

Beyond the intriguing physics of ELMs and their filamentary characteristics, there persists a decisive reason for improving our understanding of ELMs: they are both undesirable and necessary for future devices. Undesirable of course because of the large heat-fluxes they induce on plasma-facing components. Yet necessary because of the
role they play in flushing-out excess impurities from the plasma, as shown in Figure-4b. In recent JET-ILW experiments, it was found that by controlling the ELM frequency, tungsten accumulation can be avoided during the current/power ramp-down at the end of the discharge, enabling a smooth termination of the discharge [45]. While uncertainty remains in the efficiency of W-flushing by ELMs in ITER, experimental campaigns in recent years at JET-ILW and ASDEX-Upgrade have clearly demonstrated that W-accumulation has to be avoided in order to access prolonged pulse-durations [46-51]. Thus, both regarding divertor heat-fluxes and impurity accumulation, it is necessary to increase the ELM frequency, which is the purpose of all ELM-control techniques. Through non-linear simulations, it is possible to explore the mechanisms of ELM-control techniques, evaluate their efficiency, and confirm whether divertor heat-fluxes are in fact lowered as desired.

4.1 Plasma Response to Resonant Magnetic Perturbations

One of the main candidates for ELM-control in ITER is the Resonant Magnetic Perturbation technique (RMP), which introduces a magnetic perturbation at the edge of the plasma by using coils inside the vacuum-vessel of the machine. Although the current amplitude in RMP coils is relatively small compared to the total plasma current, this method can have significant effects on the dynamics and stability of the ELMs. In order to understand how RMP coils interact with ELMs, it is imperative to understand first how the plasma itself is affected by RMPs. The magnetic field perturbation created by the RMP coils penetrates into the plasma, which in turn responds to this perturbation in a complex manner. For some parameters of the edge plasma, this perturbation is amplified by the coupling of kink-peeling modes with the RMP field [52], while in other parameter regions (eg. lower bootstrap currents), the penetration of RMP fields can be screened by the plasma rotation [53,54]. This is illustrated by Figure-8, which shows the magnetic perturbation of RMP coils with and without plasma response. These simulations were performed for an ITER 15MA scenario, with $n_{\text{RMP}} = 3$ and $I_{\text{RMP}} = 45kA$, and including $n=1,9$ toroidal modes for the description of non-RMP asymmetries like TF-ripple, Ferritic Inserts and Test-Blanket Modules.

4.2 ELM Stabilisation by Resonant Magnetic Perturbations

Simulations have successfully reproduced some of the aspects of experimental results obtained on ASDEX-Upgrade for ELM-mitigation and ELM-suppression. As described in Figure-9, X-point lobes reaching the divertor targets due to RMPs could induce localised heat-fluxes on the divertor. In order to spread these footprints along the
toroidal direction of the divertor, the RMP field may be rotated by alternating the direction of currents between the RMP coils. In addition to this rotation, it is possible to change the phase of the RMP field (between lower/middle/upper coils), so that their perturbation is aligned (or not) to the magnetic field. This phase shift, which determines to which extent the magnetic perturbation is in resonance with the plasma, has been observed to play a major role in ASDEX-Upgraded experiments [59].

As in these experiments, simulations find that changing the phase leads to an enhanced stabilisation of the ELM. As described in Figure-10a, for non-resonant magnetic perturbations, the ELM has a similar size as a natural ELM, while resonant perturbation result in a mitigated ELM and, with increased current, total ELM suppression. It is important to note that the suppression of the ELM, in simulations, is not solely due to the change in pedestal pressure profiles. As the RMP phase and amplitude is changed, the averaged pressure profile is affected due to increased transport. However, when simulating ELMs without RMP fields, and scanning between these various edge pressure profiles, the ELM crash is almost unaffected (negligible compared to suppression). This suggests that local changes in filed line curvature, due to the corrugation of the outer plasma [60,61], together with coupling between ballooning modes and the RMPs [62], is responsible for the ELM suppression. This is essential as it demonstrates that ELM-suppression may be achieved without requiring a degradation of the pedestal pressure.

As demonstrated by several experimental studies, ELMs are closely linked to the loss of poloidal/toroidal momentum in the pedestal [63-65]. Simulations of ELM-suppressed and ELM-mitigation by RMPs for ASDEX-Upgrade have revealed that the E_r-well collapses during ELMs and mitigated ELMs, while it remains intact during ELM-suppressed simulations. This is consistent with some ASDEX-Upgrade CXRS measurements of the E_r-well during RMP discharges and ELM cycles (although at higher collisionality), which show that during full-suppression, the E_r-well is not degraded, while during ELM-cycles, the E_r-well may come to vanish at the peak of the ELM crash [64]. However, more comparisons with experiments are needed. This loss of momentum during mitigated ELMs, and its persistence during suppressed ELM simulations, is shown in Figure-10b [66].

4.3 Pellet ELM-triggering

ELM-triggering by pellet injection has been addressed for several tokamak devices [67,68], and most recently for the JET-ILW discharge #84690 (2T, 2MA, 11MW). Simulations of a natural ELM are compared with a pellet-triggered ELMs. Using the same equilibrium it is shown that, launching pellets before the peeling-balloonning modes have had time to create a crash, the ELM is triggered before the natural ELM, as illustrated in Figure-11a. The size of the pellet-triggered ELM, including the divertor heat-load deposition, is similar to that of the natural ELM, as shown in Figure-11b. This is coherent with experiments [69], and with the assumption that the ELM size is related to the pedestal height, not the trigger-mechanism. In addition, although the total (toroidally integrated) divertor heat-load of pellet-triggered ELMs is similar to the natural ELM, the toroidal distribution is highly asymmetric, which supports the interpretation that the pellet plays a major role in the non-linear dynamics of the ELM. This asymmetry is typically observed during simulations as well as experiments [68], and due to the strong \( n=1 \) perturbation induced by localisation of the pressure perturbation resulting from the pellet entering the plasma at
a particular toroidal location. This aspect of pellet-triggered ELMs is particularly important, to determine if divertor heat-fluxes are globally reduced (due to ELMs being triggered at lower $p_{\text{ped}}$ levels by pellets), or whether toroidally localised regions of the divertor still sustain substantially high heat-fluxes during these smaller pellet-triggered ELMs. Simulations of pellets at lower $p_{\text{ped}}$ (ie. no natural ELM) did in fact result in smaller ELM crashes, and smaller divertor heat-fluxes.

Figure-11a: For JET simulations of pulse #84690, the magnetic energy of ballooning modes shows that pellets trigger an ELM (colored lines) before the natural ELM would occur (black). Small pellets are also efficient at triggering the ELM due to the high $p_{\text{ped}}$ value of the equilibrium. Simulations are now ongoing for lower $p_{\text{ped}}$ equilibria (ballooning-stable cases). (S.Futatani, EPS-2018).

Figure-11b: The time traces of the total divertor heat-load appear to be very similar for natural and pellet-triggered ELMs (same colors as Figure-a), consistent with experiments [69]. Simulations starting with lower $p_{\text{ped}}$ values are no running to determine whether smaller heat-loads are obtained for pellets triggering ELMs below the ballooning-stability limit (S.Futatani, EPS-2018).

4.4 ELM triggering by vertical kicks

Using the free-boundary module JOREK-STARWALL, detailed simulations of kick-triggered ELMs have been performed [70]. Using the full description of the ITER wall, coils and conducting structures, vertical kicks are applied to the plasma by applying currents in the vertical stabilisation coils, as illustrated in Figure-12a.

Figure-12a: ITER simulations using the free-boundary module JOREK-STARWALL have been run using the detailed wall and coils structures, as well as passive wall structures. The top vertical stabilisation coil VS3 is used to kick the top of the plasma and trigger ELMs. (FJ.Artola, EPS-2018).

Figure-12b: Evolution of the magnetic axis plotted with the onset-time of the ELM. By changing the VS3 coil current, the plasma is kicked at increasing speeds. However, the speed does not seem to play a major role in the trigger. Instead, a threshold is observed in the amplitude of the plasma displacement. (FJ.Artola, EPS-2018).

In this 7.5MA-2.7T scenario, by applying a positive or negative current in the VS-coil, the upper separatrix is either contracted or expanded. Although the plasma pressure gradient $\partial p/\partial \psi$ changes slightly, the change in plasma volume induces an increase/decrease of the edge current, which destabilises the ELM for downward-kicks (ie. the ELM-trigger threshold is the $j_{\text{ped}}$, not $\partial p/\partial \psi$). In upward-kicks, the lowered edge current does not lead to the ELM trigger. This result suggests that the peeling component of the ELM plays a major role in its trigger mechanism.

Scans in downward kick amplitudes have also revealed that the speed at which the upper separatrix is displaced does not play any role in the triggering of the ELM, but rather the amplitude of the displacement itself is responsible. There appears to be a threshold in separatrix displacement (or plasma volume), beyond which the ELM is triggered. This aspect of the kick-triggered ELMs, illustrated in Figure-12b, has also been observed in recent experiments on JET-ILW [71].
4.5 Small-ELMs and ELM-free H-mode regimes

At last, a solution for controlling ELMs relies on the control of the operational regime to restrict the types of ELMs that are activated. In fact, both small-ELM (eg. type-II, grassy) and ELM-free (QH-mode, I-mode, M-mode) regimes could provide potential candidates for operational regimes in ITER and future devices [72-76]. However, access to these regimes is still poorly understood from the theoretical perspective, and further studies of ELM physics is required.

QH-mode experiments at DIII-D in support of developing ELM-free scenarios for ITER [74,77,78] have been accompanied by numerical studies using both the standard JOREK and its free-boundary JOREK-STARWALL version [79-81]. Simulations of DIII-D have shown that the $E \times B$ rotation at the plasma edge can stabilise high-n modes while the mode $n=2$ instead becomes more unstable, enabling a sustained QH-mode. However, rotation is not required for a QH-mode, and simulations without $E \times B$ rotation also result in a saturated $n=1$ mode, comparable to the Edge-Harmonic-Oscillation (EHO). Also, in agreement with [77], it was observed that an increased $E \times B$ shear at the plasma edge is essential to obtain an improved confinement level (ie. pedestal particle losses are reduced at increased $E \times B$ shear). Simulations of ITER plasmas have revealed that a saturated EHO can be obtained at 15MA, although the resulting density transport is reduced compared to DIII-D. Further simulations are under way to understand the dynamics of this density transport, and whether it can be high enough in ITER to sustain high-confinement while avoiding ELMs. Figure-13a shows a simulation of ITER with the free-boundary module, to study the effect of a resistive wall on saturated $n=1$-5 Kink-Peeling Modes (KPMs).

Several small-ELM simulations have been obtained with JOREK in recent years, but comparison to experimental data needs to be addressed. Simulations of a small-ELM discharge in the MAST tokamak, pulse #30312 (0.4T, 0.6MA, 1.8MW) have been performed to attempt a reproduction of ELM-cycles. As illustrated in Figure-13b, the frequency of the bursts is ~3kHz, and the energy loss of each burst is ~1.5% of the pedestal pressure, which is coherent with the type-III ELMs of this discharge. Further scans of heating and fueling amplitudes are now under way to modify the behaviour of the ELMs, however, such simulations are CPU-costly, as they require both small time-steps (to resolve diamagnetic effects and ELM-filaments) and long time-scales (to obtain saturated states of ELM-cycles). Comparisons with BES measurements [82] are also planned to investigate the role of pedestal rotation and non-linear coupling between filaments in the ELM-mechanism.

5. TOWARDS PREDICTIONS FOR ITER AND FUTURE DEVICES

In this paper, we have demonstrated that JOREK(-STARWALL) can produce non-linear simulations of ELMs and ELM-control for 15MA ITER plasmas. Progress is continuously ongoing to improve the numerical stability of simulations in highly non-linear phases, and spacial resolutions are pushed every year in order to attain experimental levels of resistivity and viscosity. In addition to this work, validation of ELM and ELM-control simulations has been undertaken on several tokamak devices worldwide. In the next 5 years, a common effort need to be sought by the JOREK team to provide cross-machine validations using key engineering figures, such as ELM size and divertor heat-fluxes. This will enable the full validation of the code, and open the way towards reliable quantitative predictions for ITER and other future devices. At this point, given the considerable progress attained in recent years across various ELM-physics areas, it seems reasonable to predict that this validation will be ready for the start of ITER operations, and that ITER session leaders will make use of JOREK simulations in the development of their experimental scenarios.
6. SUMMARY AND CONCLUSION

The study of ELMs and ELM-control using non-linear MHD modelling has progressed in recent years to provide a wide set of validating comparisons to experiments. The exploitation of recent numerical developments, like the wall-extended grid, the particle-tracker and the JOREK-STARWALL module, has opened up new areas of physics, and improved our understanding of ELM physics, while contributing further to the validation of JOREK.

Regarding ELM simulations, divertor heat-fluxes on JET have been quantitatively compared to multiple pulses for CFC and ILW campaigns, showing that JOREK is able to reproduce, to some extent, high-current, low-collisionality discharges. Simulations of JT-6U have been performed to study how ELMs are affected by the pedestal position with respect to the separatrix, and revealed that the position of the $n$, and $T_e$ profiles is not only essential for obtaining the correct ELM size, but the respective shift between the $n_e$ and $T_e$ themselves plays a major role in the duration of the ELM crash. At ASDEX-Upgrade, good agreement is found between JOREK and experiments concerning the evolution of dominant toroidal mode numbers during ELMs. In addition, comparisons to measurements of cold-front penetration has given strength to the interpretation that the stochastic fragmentation of the separatrix plays a major role in the energy loss mechanism of the ELMs. Using the new particle-tracker applied to tungsten particles on ASDEX-Upgrade, simulations of W-flushing were performed, providing a foresight of prospective studies of W-transport for ITER, a major issue with respect to prolonged pulse duration. Rotating precursor modes were compared between simulations and experiments on the KSTAR tokamak, describing how diamagnetic terms, neoclassical effects, and NBI rotation play an essential role in the correct description of peeling-ballooning mode dynamics. For the future MAST-U tokamak, simulations of detached plasmas and ELM burn-through provide an encouraging start into the new area of divertor physics and predictions for future experiments. Also, the full-MHD model is progressively starting to yield results for circular and X-point plasmas, and further efforts in coming years will aim at bringing full-MHD into the validation procedure of JOREK.

Regarding ELM control, simulations of RMPs have demonstrated that JOREK is able to reproduce the plasma response that is observed experimentally through the existence of lobes near the X-point, as well as divertor heat-flux footprints, as a result of the stochastic breaking of the separatrix. In addition, the application of resonant and non-resonant MP fields on ASDEX-Upgrade have demonstrated the ability of JOREK in reproducing experimental results regarding the mitigation and suppression of ELMs. On JET-ILW, pellet-triggered ELM simulations have been compared to natural ELMs, and further work is now under way to obtain ELM-triggering below the ballooning stability limit. In addition, kick-triggered ELMs simulated for ITER have successfully reproduced one of JET-ILW’s experimental observations: that a threshold in plasma contraction is responsible for the triggering of the ELM. At last, the study of small-ELMs and ELM-free regimes is progressing, with simulations of saturated EHO for QH-modes in DIII-D and ITER, as well as small-ELM cycles for MAST experiments.

The next step is to combine the multi-machine aspect of JOREK applications, and provide a cross-device, quantitative validation of JOREK across international tokamaks. The aim of the JOREK team is to achieve this within the next five years, in time to provide predictions of ELMs for the start of ITER operations.

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