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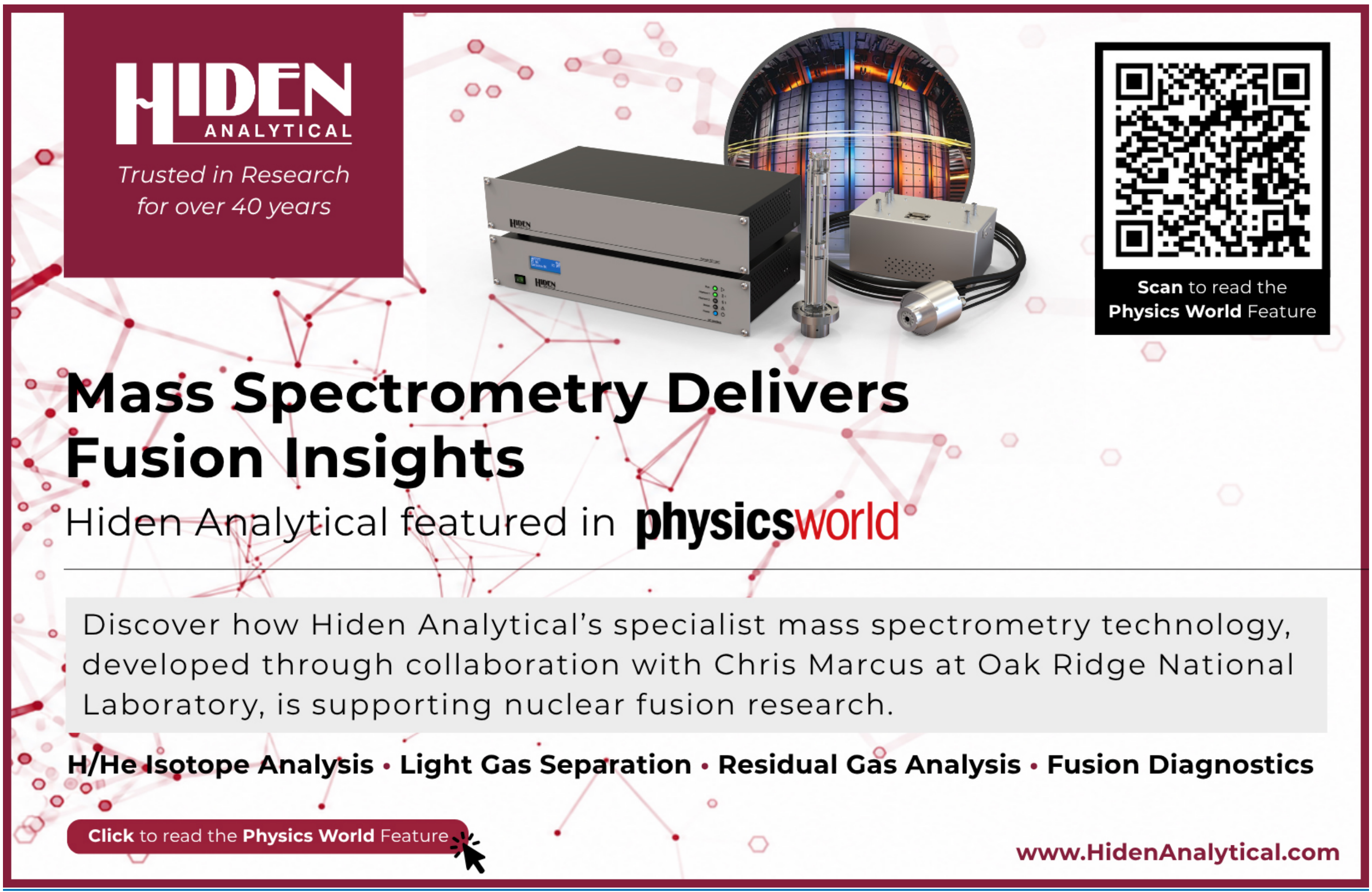
To cite this article: M. Hoelzl *et al* 2026 *Nucl. Fusion* **66** 116006



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IOP Publishing | International Atomic Energy Agency

Nuclear Fusion

Nucl. Fusion 66 (2026) 116006 (13pp)

https://doi.org/10.1088/1741-4326/ae6790

Advances in 3D transient plasma dynamics and control through MHD and hybrid fluid-kinetic simulations with JOREK

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Received 16 December 2025, revised 2 April 2026
Accepted for publication 1 May 2026
Published 2 June 2026

Abstract

Transient phenomena and their control are of high relevance in magnetic confinement fusion plasmas to guarantee a stable and safe plasma operation. Interpretative simulations can maximize the insights gained from experiments on present machines and predictive simulations can help in the preparation of design, mitigation techniques and operational scenarios for future devices. In this article, we provide an overview of recent advances and novel scientific results obtained with the 3D non-linear hybrid fluid-kinetic code JOREK, covering physics of plasma transients from the core to the scrape-off layer (SOL) both for tokamak and stellarator devices. Substantial progress was made in the physics understanding, model validation with experiments and experiment interpretation, thus, giving confidence for predictions to devices like DTT, ITER and DEMO. The topics addressed comprise a wide range: the edge physics of new operation scenarios and edge localized mode suppression; major disruptions with a focus on runaway electrons and vertical displacement events as well as disruption mitigation by shattered pellet injection; the physics mechanisms and operational limits of the flux pumping regime for sawtooth control; MHD limits of stellarators and work towards incorporating advanced edge/SOL/exhaust dynamics; continuing improvements of the code for more efficient hybrid simulations on conventional and accelerated high performance computing architectures.

Keywords: fusion, magnetohydrodynamics, tokamak, stellarator, disruptions

(Some figures may appear in colour only in the online journal)

1. Introduction

On the path towards a fusion power plant, future devices must prove stable operation and robustness against both steady state and transient heat loads, among other technological challenges. For tokamaks, the standard H-mode scenario needs reliable control of edge localized modes (ELMs) [1] and strategies to avoid or mitigate disruptions [2]. New operational regimes promising lower steady state heat loads and the absence of ELMs [3] have therefore become a major research priority in recent years. While stellarators have historically lagged behind due to high neoclassical transport in 3D geometries, several concepts under development are aiming at joining the path towards a working fusion power plant. The code JOREK [4–6] has been significantly extended in recent years to address these challenges. As a non-linear, extended-MHD code coupled to the resistive-wall codes STARWALL [7] and CARIDDI [8], its natural focus has traditionally been core and edge transients such as disruptions and ELMs, respectively. Its reliability and capabilities had steadily improved through the inclusion of fluid impurities, neutrals, and runaway electrons (REs), as well as through extensions to stellarator geometries. With the recent extension to advanced particle in cell based kinetic and hybrid fluid-kinetic models, JOREK evolved into a fully hybrid-kinetic 3D non-linear code, equipped to tackle the key challenges of control and transient behavior [9, 10].

This article provides a summary of recent scientific results obtained with the JOREK code with respect to advanced physics understanding of large-scale plasma instabilities in magnetically confined fusion plasmas and robust control or mitigation strategies. Recent and ongoing developments regarding the physics models, numerical methods, and high performance computing optimizations are addressed as well. The article covers work that has newly been published or started since the previous review given at the 29th IAEA fusion energy conference and in the corresponding proceedings article [6]. Some of the community's work has also been covered in broader review articles centered on ELM and pedestal physics [1, 11], disruptions [2], the EUROfusion tokamak exploitation work package [12], results obtained with the ASDEX Upgrade (AUG) tokamak [13], the present understanding of RE induced wall damage [14], and the status of the divertor tokamak test facility's (DTT) design and implementation [15].

This article is structured as follows. Work related to pedestal, scrape-off layer (SOL) and divertor is summarized in section 2, disruption related findings are covered in section 3, core physics are addressed in section 4 and stellarator-MHD specific studies are summarized in section 5. Finally, work on the numerical methods, HPC adaptations and code structure are reviewed briefly in section 6 and a brief summary is provided in section 7.

2. Pedestal, SOL and divertor

The large temperature and density gradients in the pedestal region characteristic of the H-mode are limited by peeling-ballooning instabilities that lead to periodic MHD burst—ELMs. Several techniques have been developed to alleviate or avoid transient loads of type-I ELMs, such as ELM suppression by resonant magnetic perturbations (RMPs), small ELM or no-ELM regimes [1]. At the same time, high power devices must manage steady state heat loads by operating in detached mode via impurity seeding in the SOL that leads to volumetric radiation thus reducing the particle and energy fluxes to plasma facing components (PFCs).

The recent work with JOREK covers these topics from pedestal stability of H-modes and ELM simulations to ELM-free regimes to RMP suppressed ELMs as described in section 2.1. The fully hybrid fluid-kinetic capabilities of JOREK offer the unique opportunities to investigate plasma wall interaction and SOL physics self-consistently. These phenomena are described in section 2.2.

2.1. Pedestal physics

In view of pedestal stability limits, single temperature simulations with JOREK of the pedestal stability in JET-ILW discharges confirmed the importance of resistive effects, and stressed the importance of self-consistently accounting for the stabilizing effect of diamagnetic drifts [16]. This explains the increasing stability with isotope mass observed in JET discharges, which is qualitatively reproduced in the simulations [16]. For AUG, simplified assessments of isotope effects on pedestal instabilities were conducted for both linear stability analysis and non-linear simulations, where the isotope dependence on pedestal stability was qualitatively reproduced, but found to be significantly milder than in the experiment [17].

Predictive simulations of ELMs in the EHL-2 spherical torus were carried out to estimate transient heat fluxes and sputtering yields during ELM losses [18]. The resulting loss of 10% of the pedestal energy leads to forbiddingly high heat fluxes of $120\,\mathrm{MW\,m^{-2}}$ and high physical sputtering rates of the carbon PFCs, underlining the importance of ELM suppression.

Different naturally ELM-free regimes are explored in current experiments [19] and their viability for a reactor scenario is currently under investigation. The quiescent H-mode (QH-mode), quasi-continuous exhaust regime, the enhanced D-alpha H-mode, negative triangularity plasmas (see section 4) and X-point radiator (XPR, see section 2.2) regimes observe small ELMs or the complete absence of ELMs. Simulations with JOREK aim to better understand the nature of the stability and MHD modes responsible for the absence of type-I ELMs.

Future large tokamaks like ITER additionally rely on ELM suppression by RMPs. However, questions that remain open include the q_{95} access window, the pedestal top density limit above which ELMs return, the detailed mechanisms causing full ELM suppression, and the influence of RMPs on impurity transport. Recent experimental and theoretical work providing evidence for island formation at the pedestal top in ELM suppressed scenarios of AUG by application of RMPs was published [20]. The JOREK simulations in support of this experimental work were conducted as part of a PhD thesis [21], which has enabled this study by a substantially improved RMP model inside JOREK based on the coupling to the resistive wall codes STARWALL and CARIDDI. Further simulations were carried out for the HL-2A tokamak by applying a fixed perturbation at the boundary, where the required coil current is consistent with the experimental threshold for ELM mitigation [22]. Using the JOREK-CARIDDI framework, which allows taking into account 3D volumetric conductive structures, the RMP screening by eddy currents was studied [23] qualitatively reproducing the frequency dependent response of the passive structures, while future fully quantitative studies will require further enhanced resolution and computational efforts.

Predictive simulations for QH-mode in the HL-3 tokamak show the development of a naturally ELM-free plasma dominated by a saturated $n=2$ kink-peeling mode leading to an ergodic edge with enhanced radial transport [24]. The characteristic edge harmonic oscillations is observed with asymmetric mode structures across the plasma edge between the high and low field side, and QH-mode stability is shown to depend sensitively on the edge safety factor q_{95}.

2.2. Edge and SOL physics

The JOREK hybrid fluid-kinetic models with full-f kinetic impurities [25] and neutrals [26] for advanced modeling of the SOL and divertor physics were further enhanced and applied to various questions. In particular, detachment and radiative regimes are investigated as well as the impurity transport and sputtering in different scenarios.

A comprehensive study of the XPR regime was conducted [27, 28]. With deuterium and nitrogen puffing, the formation of an XPR was demonstrated and quantitatively compared to analytical predictions [29]. When varying the puffing rate (Γ_N), the vertical motion of the XPR and the transition into a MARFE (at sufficiently large Γ_N) were successfully reproduced and qualitatively agree with experimental observations. Ongoing and future work uses further advanced models, addresses dependencies on different impurities and addresses also 3D plasma dynamics like the XPR dynamics during an ELM crash or the ELM suppression by an XPR [30].

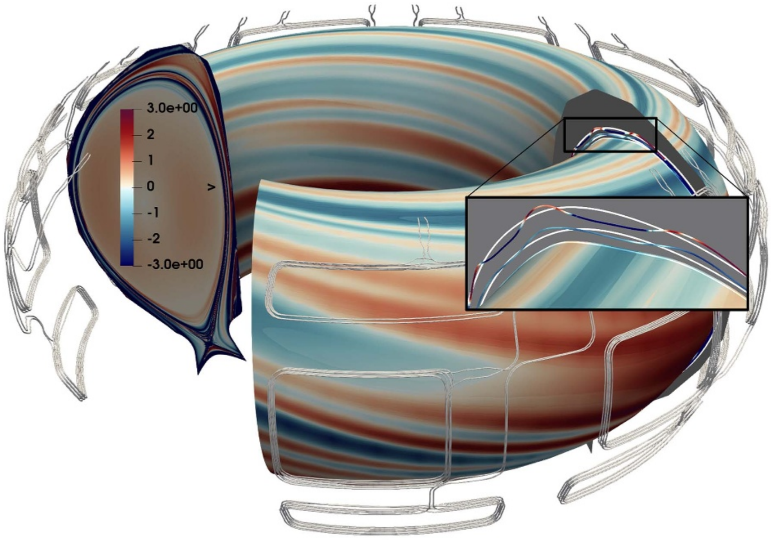

Figure 1. Indication of neoclassical cross-field transport direction $v_{\nabla\Psi} \propto \left(\frac{1}{2}\left|\frac{\nabla T}{T}\right| - \left|\frac{\nabla n}{n}\right|\right)$ evaluated at an isosurface of constant temperature in the pedestal of an ITER 15MA ELM-suppressed H-mode scenario. Red = outwards, blue = inwards. The colored poloidal cross-section shows toroidally averaged $v_{\nabla\Psi}$ values. The Inset shows three colored corrugated iso-temperature surfaces and unperturbed flux surfaces in white. Further details can be found in [32].

Using the same hybrid fluid-kinetic model, first of a kind 3D simulations with JOREK were conducted of the detachment and burn-through by MHD induced heat fluxes for an AUG EDA-H-mode scenario [10]. Initial time dependent simulations of detachment control in view of ITER were conducted including benchmarking efforts, advanced diagnostics, and identification of further development needs [31].

With the hybrid fluid-kinetic model, RMP effects on the tungsten (W) transport in the pedestal region were investigated for an ITER 15 MA H-mode scenario [9, 32]. An important finding is that in spite of the strong neoclassical outward transport expected for ITER, both the collisional neoclassical advection becomes 3D and complex as shown in figure 1, and $E \times B$ vortices forming in the pedestal region as a result of the applied perturbation fields can cause transport of tungsten from outside the separatrix to the pedestal top, requiring potentially a dedicated optimization of the applied RMP field spectrum. Also tungsten sputtering and transport in the EAST tokamak were studied, highlighting the importance of Larmor gyration, sheath acceleration, and energy distributions [33]. The results show reasonable agreement with experimental data and reveal that prompt re-deposition, which is usually not fully captured by fluid models, dominates W behavior [9].

3. Disruptions and their consequences

Instabilities leading to the loss of control and energy of the plasma in disruptions remain a crucial challenge for tokamaks [2]. Large transient heat loads and electro-magnetic (EM) forces during the thermal quench (TQ) and current quench (CQ) require the use of avoidance or mitigation techniques like the shattered pellet injection (SPI). At the same time, the conversion of the plasma current to a RE beam that can lead to highly localized damages and deep melting has to be avoided or minimized. Simulations of these events are challenging due to the fast dynamics of the physics and simultaneously long time scales of up to several hundreds of ms of the CQ. The large density gradients in SPI simulations and high resolution requirements for the ablation plasmoid make it particularly challenging to capture the physics of the plasmoid drift and ablation.

The recent work with JOREK presented in the following covers simulations of unmitigated disruptions to assess thermal and EM loads in section 3.1, of SPI mitigated disruptions in section 3.2 and finally the developments and simulation of the RE models in section 3.3.

3.1. Unmitigated disruptions

In a PhD thesis [34], JOREK was validated for simulating both mitigated and unmitigated vertical displacement events (VDEs) by detailed comparisons to AUG experiments showing that JOREK can reproduce key experimental features such as the TQ onset during hot VDEs, the halo current magnitude, and the vertical forces, while also providing a theoretical explanation for force reduction in radiation-dominated disruptions.

Further validation work was carried out for unmitigated disruptions in JET including detailed comparisons of the currents at PFCs and the deposited thermal energy [35, 36]. It was shown for the first time that the amount of deposited energy as well as the width of the wetted area can be reproduced. Based on these results, non-axisymmetric predictions for ITER 15 MA L-mode are carried out, suggesting only minor melting on the upper first wall panels. While the same Noll's force as in the experiment was found, the actual lateral force in the simulation was lower, presumably due to the absence of I_p asymmetries in the applied JOREK model; this limitation is presently addressed in a joint model development project of the JOREK and CARIDDI codes. Further predictive

VDE simulations for the CFETR tokamak found a lateral force rotating with the plasma modes [37], but are also missing the I_p asymmetry.

Several extensions of the free-boundary module of JOREK have been implemented and are currently under development. First, the eddy current coupling of JOREK to the CARIDDI code allows the inclusion of volumetric, 3D elements for representing more realistic structures and improving the predictive capabilities and incorporate shielding effects more accurately [8]. Second, additional matrices were included and tested to enable free-boundary simulations with the full MHD model [38]. Third, the free-boundary formulation developed for eddy currents based on the virtual casing principle has been extended to halo currents that cross between the plasma-wall boundary [39] and the respective changes are presently being implemented in CARIDDI and JOREK to capture the I_p asymmetries linked to lateral forces during 3D VDEs.

Further work focused on the vertical stability and pathways to disruption. Using the JOREK-CARIDDI coupling, the evolution of a tearing mode into a TQ including interaction with conducting structures was studied [40]. Vertical stability before and after loss of thermal confinement was also assessed for a tokamak configuration designed to minimize vertical control requirements thus eliminating the risk of unmitigated VDEs [41, 42]. Furthermore, first predictive simulations of ITER limiter plasmas due to a radiative edge collapse at 2 MA were carried out to generate virtual magnetic diagnostic signals and assess heat loads on the inner first wall [43].

3.2. SPI mitigated disruptions

Numerically challenging simulations of disruption mitigation by SPI were validated against the existing tokamak devices JET and AUG, and the model is used predictively for ITER. Full non-linear 3D simulations across the complete TQ and covering also the successive CQ in some cases were conducted with JOREK, in particular of mixed deuterium-neon injections, with the goal of validating the disruption mitigation model and interpreting the extensive SPI experiments on AUG [44] as well as complementing lower-dimensional studies using the DREAM [45] and INDEX codes [46]. The injection parameters were varied broadly and qualitative experiment agreement was obtained in many respects [47]. Further advanced work [48, 49], taking into account the heat flux limit for field-parallel transport, eliminates the previous overestimation of the plasmoid drift and initial loss of thermal energy upon shard arrival, thus now providing quantitative agreement with experiments, e.g. in terms of TQ onset and duration as well as the radiated energy fraction. A comprehensive study of mixed deuterium-neon SPI for JET [50] validated 3D nonlinear MHD simulations against experimental data across varying neon/deuterium mixture ratios also using novel virtual diagnostic approaches. Different collisional-radiative and coronal equilibrium models and a non-local ablation model were compared and toroidal asymmetries in the pre-TQ radiation were studied revealing qualitative agreements but also some differences in comparison to the experiment that may require further model refinements. Interpretative JOREK modeling of JET trace neon SPI discharges was also performed, where the neon atomic mixture ratio was varied from 0.016% to 2% [51, 52]. The simulations confirmed the capability of trace neon SPI in suppressing plasmoid drifts and rocket motion, but disclosed unexpectedly short cooling time compared to deuterium SPI. The latter could strongly limit the total core material deposition before the TQ onset and hinder the effectiveness of the trace neon SPI scheme in its ultimate goal of RE avoidance.

For ITER, disruption mitigation via SPI was investigated including dual SPI into baseline and degraded H-mode plasmas [54, 55]. It was found that in baseline H-mode, low-neon SPI triggers strong plasmoid drift and edge stochasticity, reducing significantly the material assimilation, while higher neon content or an already degraded H-mode suppresses this drift and improves the assimilation and radiation fraction. Small pellet sizes have also been found beneficial for total assimilation and reduction of the radiation loads. Heat flux analysis, see figure 2 for an example, shows localized risk of stainless steel melting near injection ports, though tungsten first wall tiles remain below damage thresholds, with injector synchronization further reducing asymmetry and energy impact.

3.3. REs

The modeling of the RE seeds, their amplification in non-axisymmetric magnetic fields and the loads resulting from termination are critical questions for high current tokamaks, which are addressed in the following.

Axisymmetric studies of the RE beam formation in ITER plasmas including VDE effects have been studied in 2D with the RE fluid model JOREK [56, 57] to assess the influence of the vertical motion, impurity quantities and post-TQ current profiles. Furthermore, they have been extended to the termination events [58] and the RE loads are assessed from particle tracing [59]. These modeling results form part of the dataset for a comprehensive study of the thermal response of the ITER walls to RE incidence and consequences on the integrity of material structures [60].

RE formation and deposition during a RE beam termination was also studied in view of an earlier EU-DEMO design including an initial assessment of first wall protection by sacrificial limiters [65]. For the day-0 scenario of the DTT tokamak, predictive simulations of RE generation show that substantial RE beam formation will be avoidable by limiting the amount of impurities injected by the mitigation system [66].

The transport of REs in the 3D MHD fields of ITER disruptions was studied by coupling the particle tracing code PTC with JOREK [67]. Transport characteristics are analyzed across disruption phases, providing insight into how RE energy and orbit dynamics interact with evolving magnetic structures. Finite orbit width effects are found to significantly influence RE transport in the stochastic fields, particularly when the electron drift aligns with the magnetic field deflection. Successively, in a study with PTC based on JOREK-generated fields [68], the stochastic transport and loss of seed REs in ITER SPI mitigated scenarios was studied. In sufficiently stochastic magnetic fields, a self-similar RE

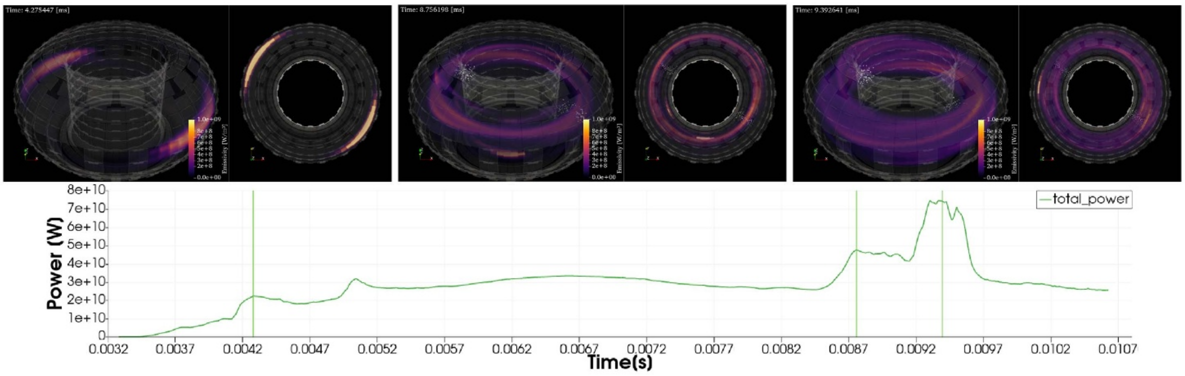

Figure 2. The helical radiation band as the fragment plumes penetrate into the ITER plasma core [53]. In the top row the emissivity density is shown for three different times that are indicated by vertical lines in the bottom figure. Results are based on the MHD simulations of figure 14 from [54].

density decay and exponential losses were found suggesting substantial depletion before avalanche onset, while wall impact patterns reveal an asymmetric deposition risk. A new method of statistical transport in Hamiltonian systems has been developed to take into account the transport in a field line system with chaotic and confined regions. It could reproduce RE losses in 3D fields during JOREK simulations [69].

While previous RE studies were based on an RE fluid model in JOREK or on test particle approaches inside JOREK or in external codes, recent work established an entirely new hybrid fluid-kinetic model for disruption and RE studies with JOREK. The basis for it was established in a full-f full-orbit RE model coupled self-consistently to the MHD background [61] with particular good accuracy in case of highly stochastic fields and the need to assess RE wall deposition patterns. A computationally more efficient drift-kinetic version was established as well [70]. Both models were comprehensively benchmarked in terms of the major-radial force balance of plasma equilibria with REs and in terms of the influence of REs onto the stability of MHD modes in the low-energy limit where comparisons to analytical predictions and fluid models is justified, see figures 3(a) and (b). Furthermore, the robustness of the model for violent termination scenarios, in which the plasma current is initially carried entirely by REs (kinetically described) and converted back into thermal current (represented by the fluid background) within tens of microseconds was demonstrated, see figure 3(c). Also the saturation of tearing modes in RE beams was studied as well and the influence of drift orbits for mono-energetic RE beams as well as realistic phase space distributions of the particles is presently under investigation showing important additional effects beyond the ones captured by RE fluid models.

These developments are complemented by recent developments of the kinetic sources in JOREK in a way suitable for 2D and 3D applications. On one hand, a kinetic modeling of the hot tail process in non-axisymmetric fields for RE formation during disruptions has been implemented into JOREK and carefully validated against DREAM simulations. It has been further applied to DIII-D experiments, showing the effect of stochasticity on the hot tail generation for the first time [71]. And on the other hand, the kinetic avalanche source was implemented and verified in benchmarks [72, 73] requiring both the relativistic large-angle collision operator and an advanced method for periodically resampling the markers.

4. Core physics

Sawtooth instabilities transiently lead to massive perturbations of the core plasma, reducing the plasma temperature and triggering substantial magnetic perturbations that can seed other MHD instabilities like neoclassical tearing modes. Consequently, sawtooth control is an important research area for the safe and efficient operation of large tokamak devices [74]. In view of this, different activities have been carried out. First, with respect to the relevance for sawtooth instabilities, the flux pumping mechanism and energetic particle driven plasma instabilities, a comprehensive comparison of MHD and gyrokinetic models for instabilities at the $q=1$ rational surface has been carried out with particular focus on internal kink modes [75]. Second, in view of broad experimental studies on AUG of flux pumping for the control and avoidance of sawtooth instabilities [76], 3D full-MHD simulations crossing millions of Alfvén times at realistic experimental parameters were carried out [77], see figure 4. They reveal the key effect of the 1/1 quasi-interchange mode in the AUG sawtooth-free hybrid scenarios for the regulation of the core safety factor q_0 to values around unity. Fast oscillating dynamics as well as a stationary long-term dynamo effect are observed reproducing quantitatively the experimental observations. Using nonlinear two-temperature full-MHD simulations, a further extended study conducts parameter scans in dissipation and plasma beta revealing bifurcated regimes including flux pumping, sawteeth, single crashes, and stationary magnetic islands [78]. These transitions are in the focus of present work in order to support the development of fast surrogate models. Future work will include extended MHD and finite Larmor radius effects to quantitatively study the transition between sawtooth and flux pumping regimes.

In view of pellet physics, besides the disruption oriented work on SPI, a dedicated study of the plasmoid drift following massive material injection (MMI) in a tokamak was carried

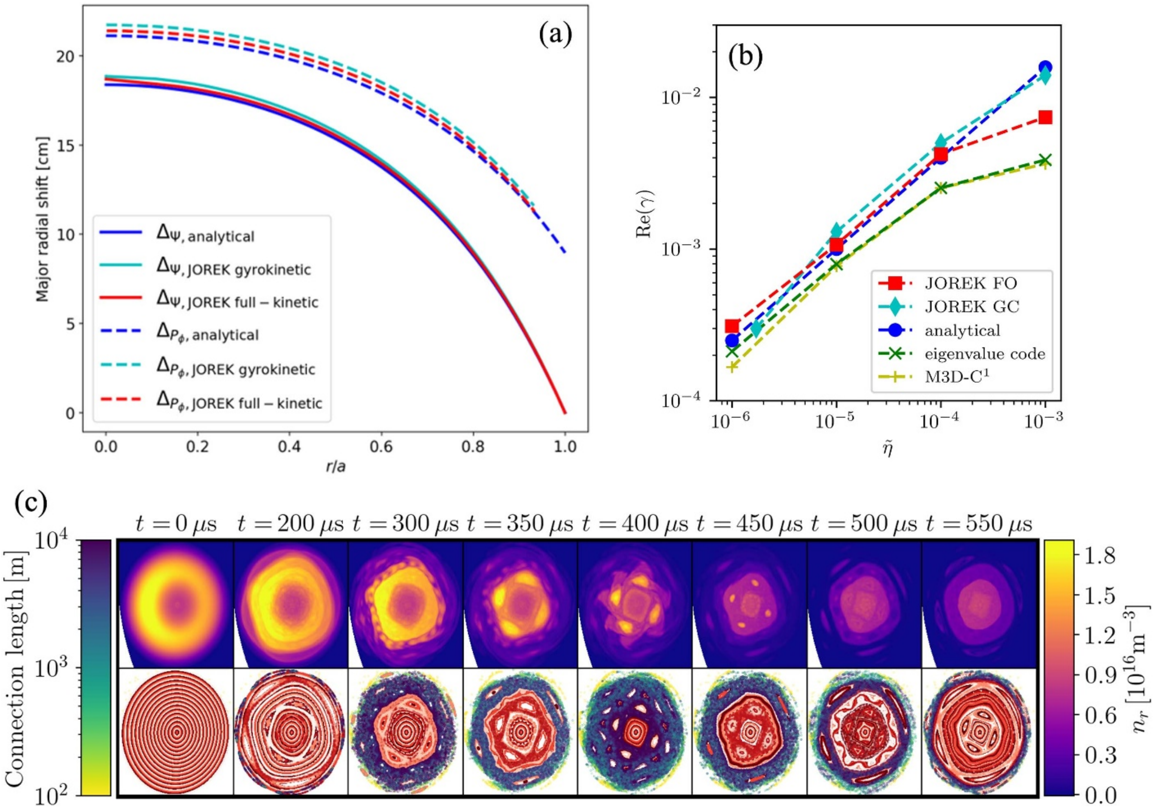

Figure 3. Simulation results using the 3D full-f particle-in-cell model for REs [61] self-consistently coupled to the MHD dynamics. (*a*): minor radial profiles for the shift of the flux surface and drift orbit surfaces in an ITER-like plasma with a 6 MA beam of 50 MeV REs, along with analytical predictions from [62]. (*b*): linear growth rates of a (2, 1) TM instability for a low energy beam of REs calculated using JOREK, along with numerical and analytical predictions from [63, 64]. (*c*): RE density (upper row) and Poincaré plots (lower row) during a beam termination event in JET assuming 2 MeV. REs [58, 61].

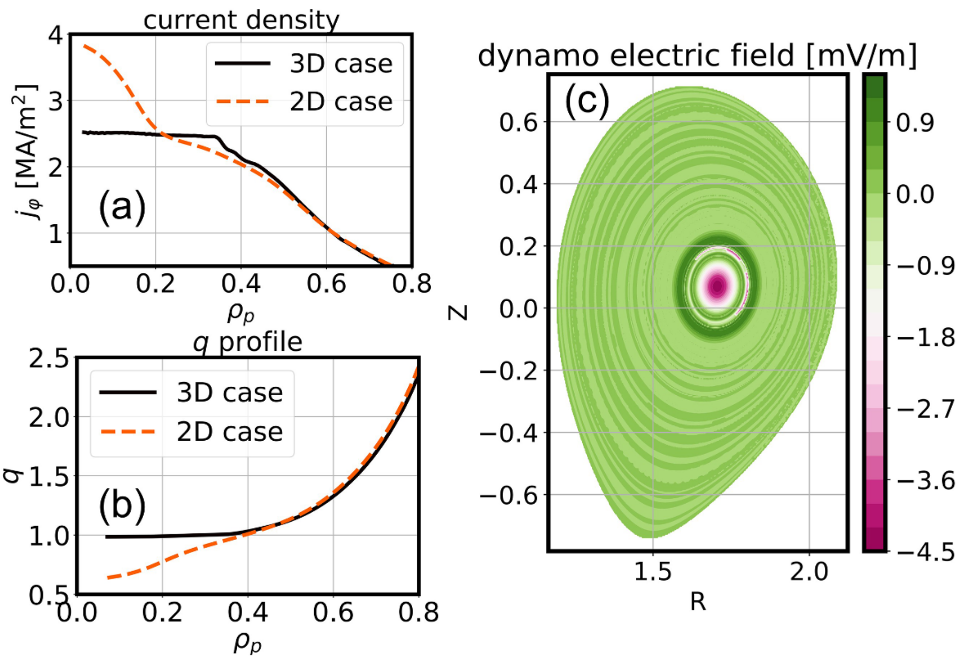

Figure 4. Saturated profiles of (*a*) current density and (*b*) safety factor from 3D (solid line) and 2D (dashed line) simulations. (*c*) The negative dynamo electric field generated by the 1/1 mode in the 3D simulation responsible for flattening the core profiles. Further details can be found in [77, 78].

out [79]. This study investigates plasmoid drift after MMI in JET plasmas, confirming that both shear Alfvén wave (SAW) braking and Pégourié braking limit the drift. SAW braking dominates on microsecond timescales for smaller sources, while Pégourié braking becomes significant earlier for broader sources, aligning well with theoretical predictions. Further work is ongoing that puts particular emphasis on comparing the parallel expansion of the pellet plasmoid and the effects of non-local heating to theoretical predictions [80]. In view of the EHL-2 spherical tokamak, a study of Boron pellet injection was conducted [81]. The simulations predict deep penetration beyond the pedestal up to $\Psi_{\text{norm}} \approx 0.35$, while depositing over 90% of the boron without triggering a TQ. Although local cooling induces transient tearing modes and edge magnetic stochasticity, the core magnetic surfaces remain intact.

Based on the novel kinetic capabilities of the gyrokinetic version of JOREK, ion temperature gradient and trapped electron mode turbulence was modeled electrostatically both for negative and positive triangularity plasmas [82, 83]. The work presents nonlinear full-f gyrokinetic simulations in realistic X-point geometry, showing that negative triangularity plasmas in DIII-D exhibit stronger, more sheared zonal flows, reduced turbulence correlation lengths, and systematically lower heat transport than positive triangularitysimilar to what has been observed in δf simulations of flux tubes [84]. The results reproduce key experimental trends, indicate weak collisionality dependence, and suggest Bohm or broken gyro-Bohm—like scaling, with only modest confinement degradation under reduced toroidal rotation.

5. Stellarator MHD

Mercier's criterion is often treated as a strict stability limit in stellarator design, though both experiments and simulations have shown it can be exceeded, despite limited understanding of the underlying nonlinear mechanisms. In a study with JOREK [85], the nonlinear evolution was explored by comparing Mercier-unstable Wendelstein stellarator configurations (figure 5) with nonlinearly stable quasi-interchange modes in tokamaks, using both high mirror Wendelstein 7-X (W7-X) like simulations and reconstructed W7-AS discharges. Differences between experimental observations and simulations, particularly regarding partial reconnection versus flux pumping, were examined to inform future stellarator design beyond the Mercier limit. In particular, the partial reconnection accompanied by a drop of pressure can point towards the necessity of a current source (bootstrap, NBI, ECCD) to maintain a stable flux-pumping scenario. The JOREK stellarator MHD model was also improved by adding an option for incorporating realistic $E \times B$ flows and preforming initial assessments of the effect onto ballooning modes in classical $l = 2$ stellarator geometry [86]. While current driven MHD instabilities are uncommon in stellarators due to the negligible net current, external current injection can modify the ι profile towards rational values, leading to MHD unstable states. Experiments with current injection were previously carried out in W7-X and analyzed with a simple model [87].

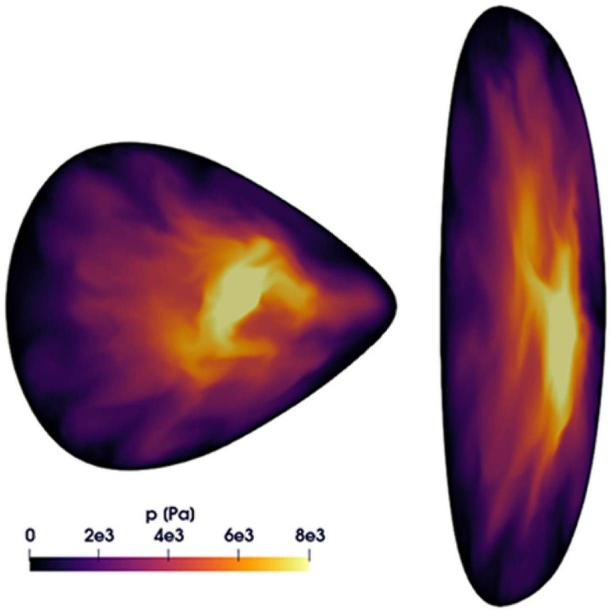

Figure 5. Pressure distribution caused by strong non-linear dynamics in a Mercier unstable plasma configuration in W7-AS simulated with the JOREK code. The sheared $E \times B$ flows acts stabilizing for high-n numbers, allowing to maintain the pressure when including a realistic heat source. For details, refer to [85].

Comprehensive studies with JOREK of ECCD induced MHD bursts in W7-X and more simplified geometries are progressing and are reproducing several different types of MHD bursts with different nature, in particular with different spatial extent of the affected area [88]. Work on pellets described in section 4 will be extended to stellarators and the stellarator models are being extended to allow incorporating kinetic descriptions for some particle species allowing future SOL/divertor like studies for stellarators like they are carried out already routinely with JOREK for tokamaks (see section 2).

6. Numerical methods, HPC adaptations and code structure

There are several main lines of developments for the code in this area. The first aspect addressed concerns the generalization of the hybrid fluid-kinetic capabilities of the code, where it was previously not possible to combine different kinetic species in a simulation in a flexible way. A new framework has been implemented to overcome this limitation [89], which renders such studies now possible. One of the first applications planned addresses advanced modeling of the cold companion plasma in a RE beam with a kinetic treatment of neutral particles and impurities.

The second large development addresses the adaptation of the code to new high performance computing architectures with accelerators. In this respect, a 'GPU' porting of particle pushers had already been implemented in the past based on OpenACC and later also OpenMP pragmas [90]. More recently, also the sparse matrix construction needed in the fluid time evolution has been ported to accelerated systems

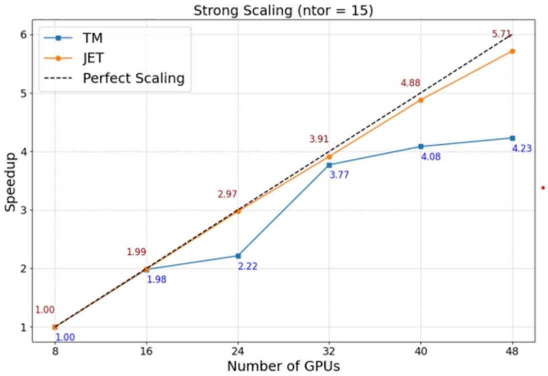

Figure 6. Strong scaling of a large aspect ratio tearing mode and a JET simulation including kinetic runaway electrons.

with OpenMP [91] as well as the sparse matrix-vector products in the iterative solver [92]. Further developments and adaptations for both Nvidia and AMD based accelerated architectures have now enabled first challenging hybrid fluid-kinetic production simulations of RE beam termination on such systems [93, 94], showing good scaling properties as shown in figure 6 and a speedup of 4–4.5 compared to the CPU computation. Further generalizations are needed to be able to carry out the full range of applications on such systems, in particular the free boundary extension has not been adapted at this point. Furthermore, the preconditioner also remains on CPUs so far, which provides a bottleneck on systems with powerful accelerators and moderate CPU performance. These limitations will be addressed in the future and different approaches for the offloading to accelerators will be assessed in comparison to the present OpenMP based solution.

For the stellarator models, where such a GPU porting to accelerators has not yet started, the projection of kinetic particle distributions to the finite element (FE) grid was implemented [95] requiring a substantial generalization of the existing tokamak algorithm. Furthermore, an efficient algorithm for particle localization in the FE grid was implemented. These developments form the basis for a variety of hybrid fluid-kinetic stellarator applications in the future, including energetic particle studies and heat/particle exhaust modeling.

Dedicated efforts address the iterative solver and preconditioner from a mathematical point of view aiming for better convergence and/or reduced memory consumption [96]. This work includes an assessment of deflation techniques and improvements of the matrix condition number by improvements of the boundary condition formulation.

In terms of the exploration of innovative numerical methods, a self-improving framework combining neural operators and HPC methods was tested with a time-parallel scheme [97]. Using Fourier neural operators, a neural coarse-solver is integrated into the Parareal method. The approaches tested here could also be applicable to advanced preconditioning techniques, for which also other mathematical approaches are under investigation. Other HPC optimizations were focused on testing highly optimized solvers for the generalized eigenvalue problems arising in the JOREK-STARWALL and JOREK-CARIDDI couplings [98]. In particular, the Eigenvalue solver for Petaflop Applications, operating on CPUs or GPUs, can be a valid alternative to the state-of-the-art solver from the ScaLAPACK library. Further optimizations of other parts of the coupling using additional HPC software will be studied in the future. Lastly, efforts are being undertaken to integrate JOREK data into IMAS (Integrated Modeling and Analysis Suite) [99], allowing for a standardized way to store simulation data and communicate with different codes. This allows the incorporation of JOREK into workflows for postprocessing or model integration, which has already been employed to obtain virtual bolometer signals in SPI simulations [53, 55] or magnetic signals during MHD events [43].

7. Conclusions and outlook

In terms of pedestal, SOL and divertor physics, regimes without large ELMs like QH-mode, the XPR regime and active RMP ELM suppression remain key areas addressed in the work with JOREK and successively grow together in terms of self-consistent modeling with aspects like detachment, exhaust, and heavy impurity transport.

Disruption related studies address hot and cold VDEs, where fully realistic 3D volumetric conductors can now be incorporated via the coupling to CARIDDI, while further developments with respect to the prediction of lateral electromagnetic forces are ongoing. Disruption mitigation is simulated for further quantitative model validation and experiment interpretation for various devices and joint studies with lower-dimensional codes exploit the complementary strengths of the different approaches. REs as a major concern for large tokamaks like ITER are a focus area of present work. The thermal response of ITER walls to REs is addressed by a multidisciplinary team studying RE generation, vertical motion, 3D termination, wall deposition and material response. EU-DEMO and DTT are also being studied predictively in terms of RE risks and protection measures. An important aspect for the complete understanding of RE formation is related to the realistic kinetic transport of the relativistic particles in 3D stochastic fields of MHD active CQs. Several approaches with RE fluid modeling and test particles have provided insights into this already. Simultaneously, major developments of novel models have been conducted, allowing now for the first time a 3D full-f particle-in-cell treatment of REs in self-consistent coupling with the MHD background.

Regarding the plasma core, the main focus presently lies in a quantitative understanding of flux-pumping for sawtooth prevention. Here, simulations across millions of Alfvén times with the fully realistic plasma parameters of the AUG tokamak were conducted and reproduce the experimental observations and dynamo loop voltage quantitatively, while further extensions of the models will be needed to accurately capture the boundaries between flux pumping and sawtoothing windows. Further work is going into advanced modeling of pellet ablation physics and the resulting plasmoid drifts.

With respect to stellarator MHD, sheared plasma flows were implemented and two-fluid effects will be added. Also a no-wall treatment is under development as alternative to the existing ideal wall boundary condition in the stellarator models. The non-linear dynamics of unstable quasi-isodynamics plasmas has been conducted in view of a potentially efficient stellarator operation beyond the Mercier-criterion. ECCD induced MHD events are under investigation and dedicated pellet fueling studies are in preparation. Plasma edge instabilities will soon be investigated in their interplay with island divertor structures as well as heat and particle exhaust physics, including sheath boundary conditions and kinetically treated neutral particles and impurities. Also pellet fueling and the related plasmoid drift physics will be investigated.

Recent key developments include a generalization of the hybrid fluid-kinetic modeling capabilities of JOREK, which are of particular relevance for SOL, divertor, energetic particles, REs, etc. The stellarator MHD models are presently also being extended to hybrid fluid-kinetic capabilities. Further work aims at a portable adaptation of the code to the newest high performance computing architectures, where accelerators either share the memory with the CPU or require explicit data transfer between both. Advanced mathematical and neural-network based methods for the solver and preconditioner are being explored.

Acknowledgments

JOREK code developments and physics studies profit from national fusion programs, the EUROfusion consortium, various collaborations with the ITER Organisation, and further funding sources (see acknowledgements of the original publications).

Part of this work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them. This work was supported in part by the Swiss National Science Foundation. Within EUROfusion, in particular the Theory and Simulation Verification and Validation (TSVV) projects on MHD Transients (PI M Hoelzl) and REs in disruptions (PI E Nardon), the European HPC infrastructure (presently Pitagora, previously Marconi-Fusion and Leonardo); also JFRS-1 in Japan via the Broader Approach) provided essential support. Fruitful collaborations with the Work Packages Tokamak Exploitation (WP TE) and other work packages have lead to joint work on experiment interpretation, code validation and predictions. Several code optimization projects within the Advanced Computing Hubs (ACHs) have contributed to the code development and helped to make challenging physics studies possible. Part of this work has been carried out in collaboration with the ITER Organization. ITER is the Nuclear Facility INB no. 174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. This publication is provided for scientific purposes only. Its contents should not be considered as commitments from the ITER Organization as a nuclear operator in the frame of the licensing process. This work was supported in part by the Swiss National Science Foundation. Preconditioning development is partly financed by the Dutch Research Council (NWO) Veni grant (PI V. Dwarka).

Please also refer to the author lists and acknowledgments of the original publications.

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