CONFERENCE PRE-PRINT

# PROGRESS ON THE UNDERSTANDING OF 3D TRANSIENT PLASMA DYNAMICS AND CONTROL MEASURES FROM FLUID AND HYBRID FLUID-KINETIC SIMULATIONS WITH THE NON-LINEAR CODE JOREK

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ABSTRACT

The paper presents an overview of recent advances and scientific results obtained with the 3D non-linear extended MHD code JOREK covering physics from the core to the scrape-off layer (SOL) for both tokamak and stellarator geometries. Progress has been made in physics understanding, detailed validations with experiments and their interpretation, thus, giving confidence for predictions of future devices, such as DTT, ITER and DEMO. The topics comprise a wide range: 1) The edge physics of new operation scenarios and ELM suppression. 2) Macroscopic disruptions with a focus on Runaway Electrons (REs) and Vertical Displacement Events (VDEs) as well as disruption mitigation by shattered pellet injection (SPI). 3) The physics mechanisms of flux pumping for experimental validation. 4) The MHD limits of stellarators and work towards incorporating SOL phenomena. 5) Continuing improvements of the code for more efficient hybrid simulations and efforts towards the challenges of advanced computer architectures for MHD simulations.

## 1. INTRODUCTION

This article provides a summary of recent scientific results obtained with the 3D non-linear fluid and hybrid fluid-kinetic code JOREK [1, 2] 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 FEC and the corresponding proceedings article [3]. Some of the community's work has also been covered in broader review articles centered on ELM and pedestal physics [4, 5], the EUROfusion tokamak exploitation work package [6], results obtained with the ASDEX Upgrade tokamak [7], the present understanding of runaway electron induced wall damage [8], and the status of the divertor tokamak test (DTT) design and implementation [9]. Work related to pedestal, scrape-off layer 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, a brief summary is provided in Section 7, and Acknowledgements are given in the very end of the article in Section 7.

## 2. PEDESTAL, SCRAPE-OFF LAYER AND DIVERTOR

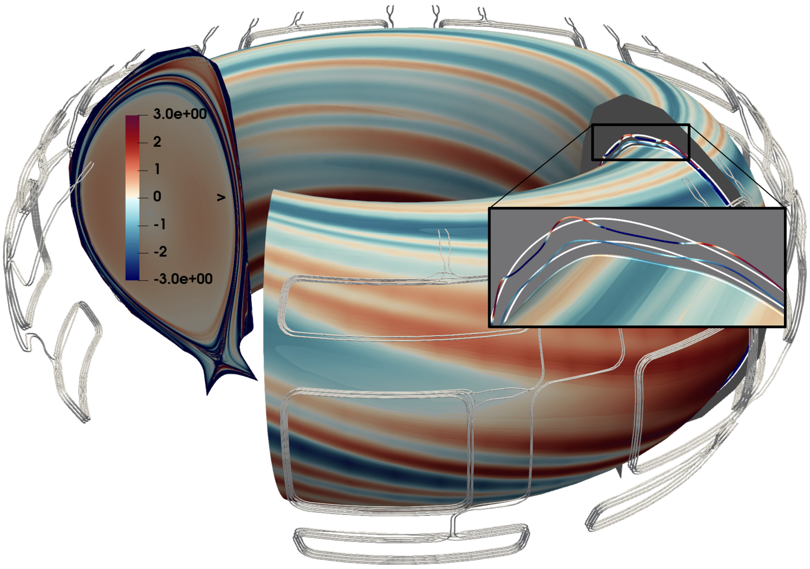


**Figure 1** – Indication of neoclassical cross-field transport direction $v_{\nabla\Psi} \propto \left(\frac{1}{2}\left|\frac{\nabla T}{T}\right| - \left|\frac{\nabla n}{n}\right|\right)$ evaluated at an isosurface of constant temperature in the pedestal of an ITER 15MA ELM-suppressed H-mode scenario. 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 Ref. [10]

Predictive simulations for quiescent H-mode (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 [11]. The characteristic edge harmonic oscillations (EHO) is observed, with asymmetric mode structures across the plasma edge, and QH-mode stability is shown to depend sensitively on the edge safety factor $q_{95}$. For ASDEX Upgrade (AUG), simplified assessments of isotope effects on pedestal instabilities were conducted [12]. Experimental and theoretical work providing evidence for island formation at the pedestal top in ELM suppressed scenarios of AUG by application of resonant magnetic perturbations (RMPs) was published [13]. The JOREK simulations of this work were conducted as part of a PhD thesis [14] in which the JOREK RMP models had been substantially improved exploiting the coupling to resistive wall codes like STARWALL or CARIDDI, validated and applied to experimental scenarios at fully realistic plasma parameters. Using the JOREK-CARIDDI framework, which allows taking into account 3D volumetric wall structures, the RMP screening by eddy currents was studied in a simplified manner [15].

The JOREK hybrid fluid-kinetic models with full-f kinetic neutrals and impurities for advanced modeling of the scrape-off layer and divertor physics were further enhanced and applied to various different questions. A comprehensive study of the X-point radiator (XPR) regime was conducted [16, 17]. With deuterium and nitrogen puffing, the formation of an XPR was demonstrated and quantitatively compared to analytical predictions [18]. When varying the puffing rate, the vertical motion of the XPR and the transition into a MARFE were successfully reproduced and qualitatively agree with experimental observations. Future work will use further advanced models and address also 3D plasma dynamics. 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 [19]. Initial time dependent simulations of detachment control in view of ITER were conducted including benchmarking efforts, advanced diagnostics, and identification of further development needs [20]. With the hybrid kinetic-fluid model, RMP effects on the W transport in the pedestal region have been investigated for an ITER 15 MA H-mode scenario [10, 21]. 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 ExB 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. Based on the same hybrid model, also tungsten (W) sputtering and transport in the EAST tokamak were studied, highlighting the importance of Larmor gyration, sheath acceleration, and energy distributions [22]. 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 [21].

## 3. DISRUPTIONS AND THEIR CONSEQUENCES

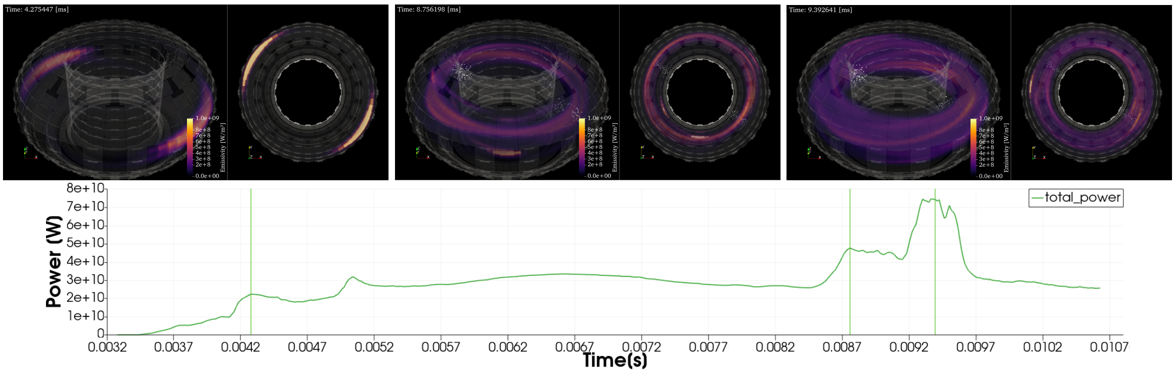


**Figure 2** – The helical radiation band as the fragment plumes penetrate into the ITER plasma core [23]. In the top row the emissivity density is shown for three different times that are indicated by vertical lines in the bottom figure. Results are based on the MHD simulations of Figure 14 from Ref. [24].

In a PhD thesis [30], JOREK is validated for simulating both mitigated (cold) and unmitigated (hot) Vertical Displacement Events (VDEs) by comparing it to experiments from AUG. It shows that JOREK can reproduce key experimental features such as thermal quench (TQ) onset during hot VDEs, halo current magnitude, and vertical forces, while also providing a theoretical explanation for force reduction in radiation-dominated disruptions. Additionally, the coupling of JOREK to the CARIDDI wall code is introduced and tested, enabling more realistic simulations by including eddy current dynamics and complex wall geometries and thus improving predictive capabilities for future fusion devices. Further validation work showed for the first time that both the deposited energy as well as the heat flux width can be reproduced during unmitigated VDEs [31, 32]. While the same Noll's force as in the experiment was found, the lateral force was lower, presumably due to the absence of Ip asymmetries in JOREK, which will be included by the development described below. Using the JOREK-CARIDDI coupling, the evolution of a tearing mode into a thermal quench including interaction with conducting structures was studied [33]. Vertical stability before and after loss of thermal confinement was also assessed for a tokamak configuration that could be shown to minimize vertical control requirements thus eliminating the risk of hot VDEs [34, 35]. VDEs and associated electromagnetic forces were also studied predictively in view of the CFETR tokamak [36].

While the previously described work relied on the existing eddy current coupling of the reduced MHD JOREK model with STARWALL or CARIDDI, developments were done to further generalize and improve the models. On one hand, self-consistent full MHD coupling of JOREK and STARWALL was implemented and tested [37]. On the other hand, the Greens functions based virtual casing principle that is in use for the JOREK coupling to resistive wall codes has been extended theoretically to halo currents which act as source/sink currents from the wall point of view [38]. The respective extensions in CARIDDI have been implemented and verified and completion of the coupling in JOREK is presently on the way.

Full non-linear 3D simulations across the complete TQ and covering also the successive current quench (CQ) in some cases were conducted with JOREK, in particular of mixed deuterium-neon injections, with the goal of validating the disruption mitigiation model and interpreting the extensive shattered pellet injection (SPI) experiments on AUG [39] as well as complementing lower-dimensional studies using the DREAM [40] and INDEX codes [41]. The injection parameters were varied broadly and qualitative experiment agreement was obtained in

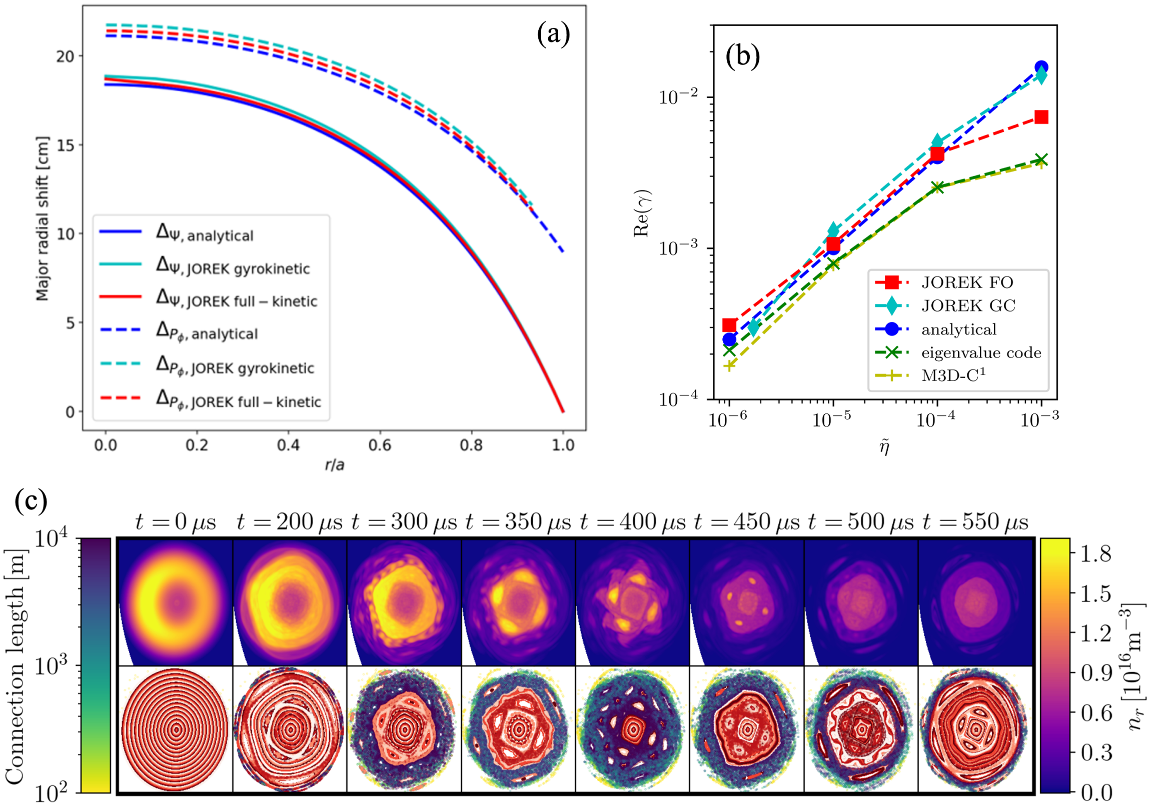


**Figure 3** – Simulation results using the 3D full-f particle-in-cell model for REs [25] self-consistently coupled to the MHD dynamics. (a): Minor radial profiles for the shift of the flux surface and drift orbit surfaces in an ITER-like plasma with a 6MA beam of 50MeV REs, along with analytical predictions from Ref. [26]. (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 Refs. [27, 28]. (c): RE density (upper row) and Poincaré plots (lower row) during a beam termination event in JET assuming 2MeV REs [25, 29].

many respects [42]. Further advanced work [43], taking into account the heat flux limit, eliminates the previous overestimation of the plasmoid drift and the initial loss of thermal energy upon shard arrival and obtains quantitative agreement with experiments e.g. in terms of thermal quench onset and duration as well as the radiated energy fraction. A comprehensive study of mixed deuterium-neon SPI for JET [44] validates 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-thermal-quench radiation were studied revealing qualitative agreements but also some differences in comparison to the experiment that may require further model refinements. For ITER, disruption mitigation via SPI was investigated including dual SPI into baseline and degraded H-mode plasmas [24]. It was found that in baseline H-mode, low-neon SPI triggers strong plasmoid drift and edge stochasticity, reducing mitigation efficiency, while higher neon content or degraded confinement suppresses this drift and improves the radiation fraction. 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.

A comprehensive study assesses the thermal response of the ITER walls to runaway electron (RE) and consequences on the integrity of material structures [45]. Data sets used include 3D-MHD induced RE deposition patterns at different RE energy distributions based on earlier JOREK simulations of the RE formation [46, 47], termination [29], and wall loads [48] in ITER. 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 [49]. 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 [50].

The transport of REs in the 3D MHD fields of ITER disruptions was studied by coupling the particle tracing code

PTC with JOREK [51]. Transport characteristics are analyzed across disruption phases, providing insight into how RE energy and orbit dynamics interact with evolving magnetic structures. Finite orbit width (FOW) 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 [52], the stochastic transport and loss of seed REs in ITER SPI mitigated scenarios was studied. In sufficiently stochastic magnetic fields, a self-similar RE density decay and exponential losses were found suggesting substantial depletion before avalanche onset, while wall impact patterns reveal an asymmetric deposition risks.

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 [25] with particular high 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 [53]. 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 Figure 3a 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 3c. 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 for RE formation during disruptions has been established and carefully validated [54]. And on the other hand, the kinetic avalanche source was implemented and verified in benchmarks [55, 56] requiring both the relativistic large-angle collision operator and an advanced method for periodically resampling the markers.

## 4. CORE PHYSICS

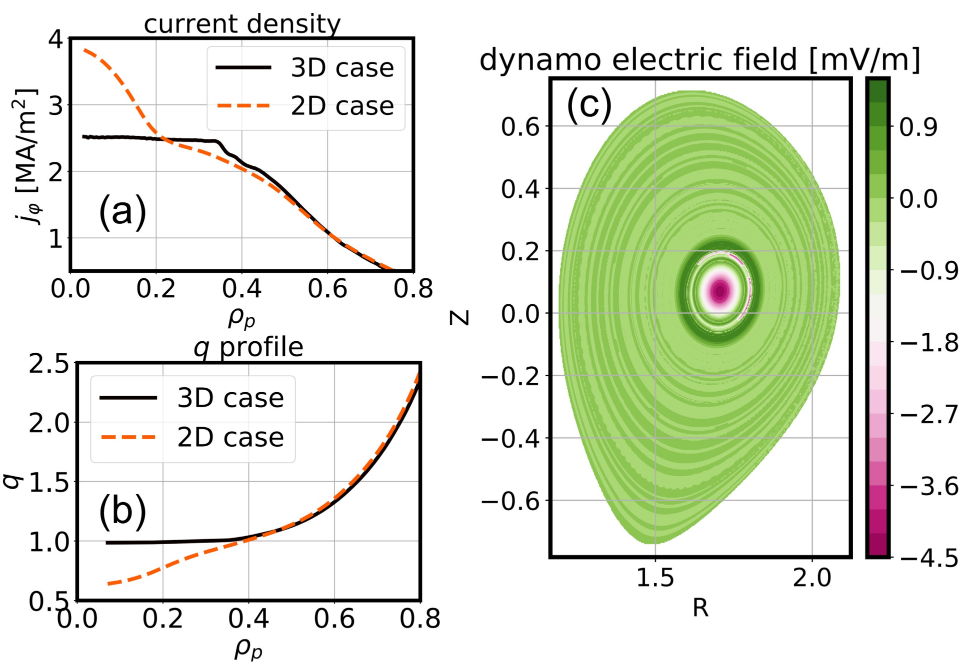


**Figure 4** – Saturated profiles of (a) current density and (b) safety factor from 3D (solid line) and 2D (dashed line) simulations. (c) The negative dynamo electric field generated by the 1/1 mode in the 3D simulation responsible for flattening the core profiles. Further details can be found in Refs. [57, 58].

With respect to the relevance for sawteeth, flux pumping and energetic particle driven instabilities, a comprehensive comparison of MHD and gyrokinetic models for m=1, n=1 instabilities, in particular internal kink modes is being carried out [59]. In view of broad experimental studies on AUG of flux pumping for the control and avoidance of sawtooth instabilities [60], 3D full-MHD simulations crossing millions of Alfvén times at realistic experimental parameters were carried out [57], see Figure 4. They reveal the key effect of the 1/1 quasi-interchange mode in the AUG sawtooth-free hybrid scenario regulating 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. Future work will include extended MHD and finite Larmor radius effects to quantitatively study the transition between sawtooth and flux pumping regimes [58].

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 out [61]. 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 [62].

Based on kinetic capabilities of the gyrokinetic version of JOREK, Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence was modelled electrostatically in X-point geometry both for negative and positive triangularity plasmas [63].

## 5. STELLARATOR MHD

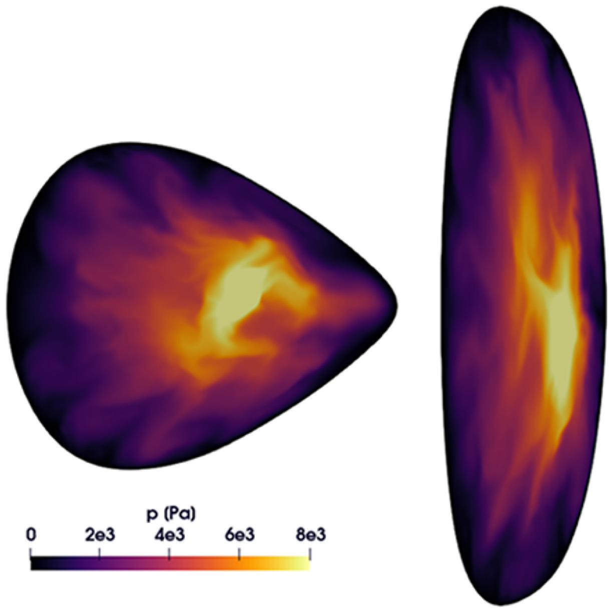


**Figure 5** – Pressure distribution caused by strong non-linear dynamics in a Mercier unstable plasma configuration simulated with the JOREK code. For details, refer to Ref. [64].

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 [64], the nonlinear evolution was explored by comparing Mercier-unstable Wendelstein stellarator configurations (Fig. 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, are examined to inform future stellarator design beyond the Mercier limit. The JOREK stellarator MHD model was also improved by adding an option for incorporating realistic ExB flows and preforming initial assessments of the effect onto ballooning modes in classical l=2 stellarator geometry [65]. Comprehensive studies of ECCD induced MHD bursts in W7-X and more simplified geometries are progressing [66]. 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 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 [67], which makes such studies now possible with one of the first applications planned in the area of advanced RE companion plasma modeling with kinetic neutrals 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 been implemented first with OpenACC and then with OpenMP for better portability [68]. More recently, also the sparse matrix construction needed in the fluid time evolution has been ported to accelerated systems with OpenMP [69] as well as the sparse matrix-vector products in the iterative solver [70]. Further developments and adaptations for both Nvidia and AMD based accelerated architectures have now allowed to conduct first hybrid fluid-kinetic production simulations on such systems [71]. For the stellarator models, where such porting to accelerators is still outstanding, the projections of kinetic particle distributions to the finite element (FE) grid was implemented [72] along with an efficient algorithm for particle localization in the FE grid, forming the basis for general hybrid fluid-kinetic stellarator applications in the future. Dedicated efforts address the iterative solver and preconditioner from a mathematical point of view aiming for better convergence and/or reduced memory consumption [73].

In terms of innovative numerical methods, a self-improving framework combining neural operators and HPC methods was tested with a time-parallel scheme [74]. 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.

Lastly, efforts are being undertaken to integrate JOREK data into IMAS (Integrated Modelling and Analysis Suite), allowing for a standardized way to store simulation data and communicate between 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 [75] or magnetic signals during MHD events [76].

## 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 with 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 multi-disciplinary 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 current quenches. 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 used 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 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.

Recent key developments include a generalization of the hybrid fluid-kinetic modeling capabilities of JOREK, which are of particular relevance for scrape-off layer (SOL), divertor, energetic particles, runaway electrons, etc. The stellarator MHD models are presently also 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.

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

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