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Fully integrated 3D nonlinear time-dependent modelling of pedestal and scrape-off layer in the JOREK code

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A magnetically confined fusion reactor requires continuous and transient heat exhaust to be managed such that a long lifetime of wall structures can be guaranteed. Detailed understanding of pedestal, scrape-off layer (SOL) and divertor physics, plasma-wall interactions, and their interplay, is necessary to achieve adequate power handling via active and passive control measures. In recent years, the non-linear extended MHD code JOREK has been systematically developed to allow studying such complex nonlinearly coupled problems.
On the one hand, the existing capabilities that distinguish JOREK as a robust computational tool to study edge localised modes (ELMs), their interactions with externally imposed perturbations, and ELM-free regimes have been exploited to further study small and no-ELM regimes [1-3]. Additionally, simulations of ELM suppression with RMP fields in AUG show direct evidence for the penetration of a magnetic island at the pedestal top [4,5]. And, on the other hand, a full-f particle-in-cell kinetic model for neutrals and impurities, which is coupled to the fluid MHD system of equations, has been built to substantially improve the divertor and SOL models [6].
This kinetic PIC model can be used in a flexible manner to include or exclude different particle species (D neutrals can be, for instance, included at the same time as N impurities) as well as different atomic physics processes (for the moment, molecular processes are not included in the kinetic model). The kinetic neutrals and/or impurities can be traced under axisymmetric and non-axisymmetric conditions. Using the axisymmetric approach, high-field-side high-density formation and detachment in ITER was studied as a first application of the kinetic PIC model [6,7]. In a first 3D dynamic application, it was applied to study the effect of resistive peeling-ballooning modes in an EDA H-mode regime on a detached divertor, and the ensuing burn-through [8]. Additionally, the formation, control and loss of an X-point radiator as a potentially reactor-relevant exhaust solution was studied with nitrogen seeding in AUG including transition to a MARFE [9]. Finally, the transport of tungsten in RMP-penetrated AUG plasmas has been studied including the neoclassical transport processes via an appropriate collision operator predicting enhanced radial transport and 3D trapping [10].
These advances demonstrate the increasing scope of JOREK in addressing critical questions in power exhaust, pedestal stability, and impurity transport, and how they couple to each other. By integrating kinetic and fluid models within a nonlinear MHD framework, these simulations can contribute to the development of operational scenarios for next-step fusion devices. Ongoing developments and applications including molecular physics, the interplay between kinetic neutrals and the quasi-continuous exhaust (QCE) regime (fig. 1) in ASDEX Upgrade are described.

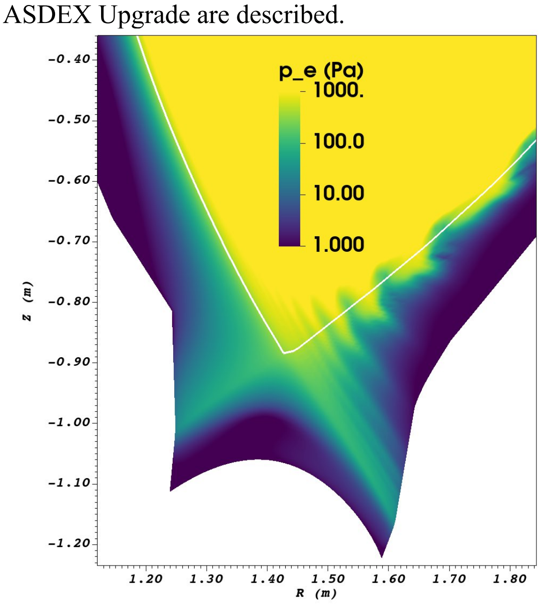

Figure 1: JOREK simulation of peeling-ballooning activity when including kinetic D neutrals with an AUG equilibrium of the QCE regime.

References

[1] Z Liang, M Hoelzl, A Cathey, et al. 2025 Phys. Plasmas
[2] A Cathey, M Hoelzl, L Gil, et al. 2023 Nucl. Fusion
[3] L Meier, M Hoelzl, A Cathey, et al. 2023 Nucl. Fusion
[4] M Willensdorfer, V Mitterauer, M Hoelzl, et al. 2024 Nature Physics
[5] V Mitterauer, et al. in preparation
[6] S Korving, GTA Huijsmans, JS Park, A Loarte, et al. 2023 Phys. Plasmas,
[7] D Maris, 2024 MSc. thesis
[8] M Szucs, 2024 MSc. thesis
[9] YC Liang, et al in preparation
[10] S Korving, V Mitterauer, GTA Huijsmans, et al 2024 Phys. Plasmas