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Violent transient plasma instabilities in magnetic confinement fusion plasmas and their control

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Violent transient plasma instabilities in magnetic confinement fusion plasmas can lead to changes of local or global plasma parameters by orders of magnitude within 10s of µs to several ms. Heat fluxes to material surfaces become comparable to a starship during re-entry. Striking similarities to astrophysical phenomena like solar flares and coronal mass ejections include fast magnetic reconnection and particle acceleration to relativistic velocities. Besides interest from fundamental plasma physics, understanding major disruptions and edge localized modes (ELMs) is critical for realizing a fusion power plant. In particular, robust control is needed to prevent deteriorated component lifetime or instantaneous damage. Mitigation and suppression strategies, but also an assessment of worst-case scenarios, are needed to secure a safe operation of ITER and beyond.

This presentation describes violent transient phenomena in tokamaks from the simulation and theory point of view. Fundamental processes and the risks for the roadmap towards a fusion power plant are explained. Physics models to capture the mutually interacting dynamics of plasma, scrape-off layer, divertor, conducting structures, and supra-thermal particles in realistic divertor tokamak geometry are discussed.

State-of the art extended MHD simulations using the JOREK code [1,2] provide insights into relevant key processes of major disruptions and ELMs, as well as their active and passive control [3-19]. Milestones for verification, benchmarking, experiment validation and optimization are shown as well as cutting-edge predictive ITER simulations. Figures 1 and 2 show selected highlights. An outlook to future work for tokamaks and stellarators is provided.

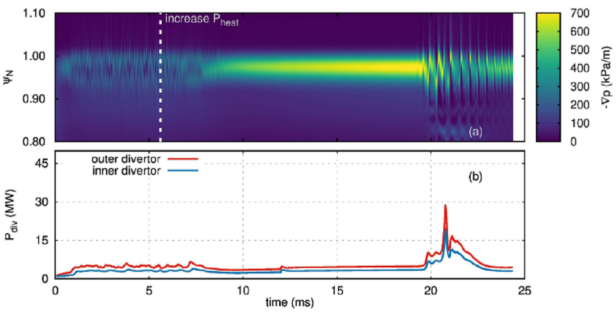

Figure 1: Simulation for the ASDEX Upgrade tokamak. In the small ELM regime (up to t~6ms), a quasi-stationary state arises with moderate heat fluxes (bottom) to divertor targets as turbulent MHD modes prevent the pressure gradient close to the plasma edge (Ψ_N=1) from building up (top). Increased heat sources (from t=6ms) cause a decay of the MHD modes and pressure gradient build-up leading to a large ELM crash (t~21ms) with strong transient heat fluxes. Figure from Ref. [13].

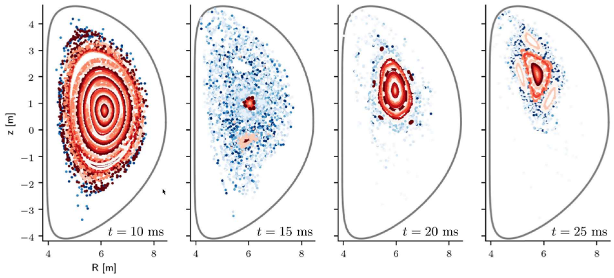

Figure 2: First of a kind simulations of the 3D "current quench" during a mitigated major disruption in ITER provide promising predictions for the dangerous horizontal forces onto the vacuum vessel [11]. The MHD activity persisting throughout the vertical plasma motion causes ergodic field topologies and thus prevents the formation of a beam of relativistic electrons in this scenario [14]. Figure from Ref. [14].

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