Reduced-MHD Simulations of Edge Localized Modes in ASDEX Upgrade

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The first non-linear reduced-MHD simulations of edge localized modes (ELMs) for ASDEX Upgrade are presented. Qualitative comparisons to experimental observations are shown.

Introduction

ELMs are observed in the high confinement mode (H-mode) of current tokamak devices and may constitute a serious hazard for first wall and divertor structures of larger machines like ITER due to massive localized power loads. While techniques for ELM suppression or mitigation have been established in present-day machines (e.g., resonant magnetic perturbations, pellet ELM triggering), it is unclear if these methods will be applicable to future devices as ELM physics and scaling laws are not fully understood yet. After detailed comparisons to measurements at existing devices, predictive simulations will help to answer these questions. This contribution is the starting point for an extensive benchmark to experimental observations in ASDEX Upgrade which exhibits ideal diagnostic tools for such an approach.

The 3D non-linear MHD code JOREK[1] originally developed by Guido Huysmans [1] is an excellent tool for ELM simulations [2]. Bezier finite elements discretize the poloidal plane [3] and a toroidal Fourier expansion is applied. The time-stepping is fully implicit using a linearized Crank-Nicholson scheme. The system of equations is solved iteratively (GMRES method [4]) with a physics-based preconditioning: The decoupled system of equations for each toroidal harmonic is solved separately with a direct method. The code is MPI and OpenMP parallelized using typically 256 or more CPU-cores for an ELM simulation.

Simulations

The initial conditions of the simulations shown in this paper are based on experimental ASDEX Upgrade data (discharge 23221 at 4.8s). Experimental density and temperature profiles are used as input. The FF'-profile and the poloidal flux at the boundary of the computational domain are taken from the CLISTE equilibrium reconstruction code [5]. To increase accuracy, an option was implemented in JOREK allowing to provide input profiles as lists of data points instead of analytical fits. CLISTE equilibria can be reproduced very well this way as seen from q-profile, flux surfaces, and locations of magnetic axis and X-point.

[1] Physics model 302 (reduced MHD, one-fluid), Repository revision 348

The discharge is characterized by $T_{e,core} \approx 4\text{keV}$, $n_{e,core} \approx 8 \cdot 10^{19}\text{m}^{-3}$, $B_t = 2.5\text{T}$, $I_p = 1\text{MA}$, $P_{\text{NBI}} = 8\text{MW}$, $P_{\text{ECRH}} = 1.5\text{MW}$. Simulations are carried out with resistivity $\eta = 5 \cdot 10^{-7}\Omega\text{m}$ in the plasma core and a $T^{-3/2}$ dependence. In this discharge, the experimental plasma core resistivity is $\eta_\perp \approx 10^{-8}\Omega\text{m}$. The pedestal is modelled by a local reduction of cross-field particle and heat diffusivities. The heat diffusion anisotropy is $\chi_{||}/\chi_\perp \approx 10^{-7}$ in plasma edge and scrape-off layer. In the poloidal plane, the plasma is resolved by about 11000 Bezier elements.

After iterative equilibrium reconstruction, the simulation is started axi-symmetrically ($n = 0$ only) increasing time steps successively such that plasma flows can equilibrate. After this “equilibrium refinement”, simulations are continued with $n = 0$ and one non-axisymmetric mode. Several mode numbers in the range $n = 4 \dots 12$ have been tested giving qualitatively similar results with different widths of the ballooning-fingers. As the simulations with $n = 8$ seem to agree best with ECE-Imaging [6] measurements, these results are shown in the following. Computations incorporating more toroidal modes are planned and will be published elsewhere.

The numerical scheme implemented in JOREK can lead to negative densities in the vicinity of large localized gradients as they occur at ELM filaments. For the shown simulations, this problem was solved by locally increasing the perpendicular particle diffusivity around positions with a density smaller than the vacuum density. Detailed comparisons showed that the global dynamics of the system are not affected by this approach.

Results

The simulations start from the ASDEX Upgrade equilibrium of discharge 23221 at 4.8s. An exponentially growing mode sets in, which becomes visible as a ballooning-instability when non-linear saturation starts: High density structures extend beyond the separatrix and low density structures move inwards. A bit later, density filaments detach from the plasma. They slowly fade away but sometimes remain visible until the computational boundary is reached. A strong heat and particle confinement degradation in the plasma edge occurs. Due to the fast parallel transport, heat is quickly transported towards the target plates and temperature rises significantly in the inner and outer divertor legs. Parallel transport smeares out the temperature such that ballooning structures and filaments are less pronounced than in the density. Figure 1 shows snapshots of density and temperature distributions at several time-points during the ELM simulation. Experiments and simulations qualitatively agree on the following observations:

- The ballooning-structure observed in the simulations right before the ELM crash is very similar to experimental measurements [7] of the electron temperature using ECE-Imaging shortly before an ELM-crash which are shown in Figure 2.
- Sudden loss of confinement reducing density and temperature at the plasma edge.
- Strong heat and particle fluxes into the divertor region.
- Formation of filaments.
- Strong asymmetry between high- and low-field-side structures.
- Spatial discontinuities in the heat fluxes at the divertor targets.

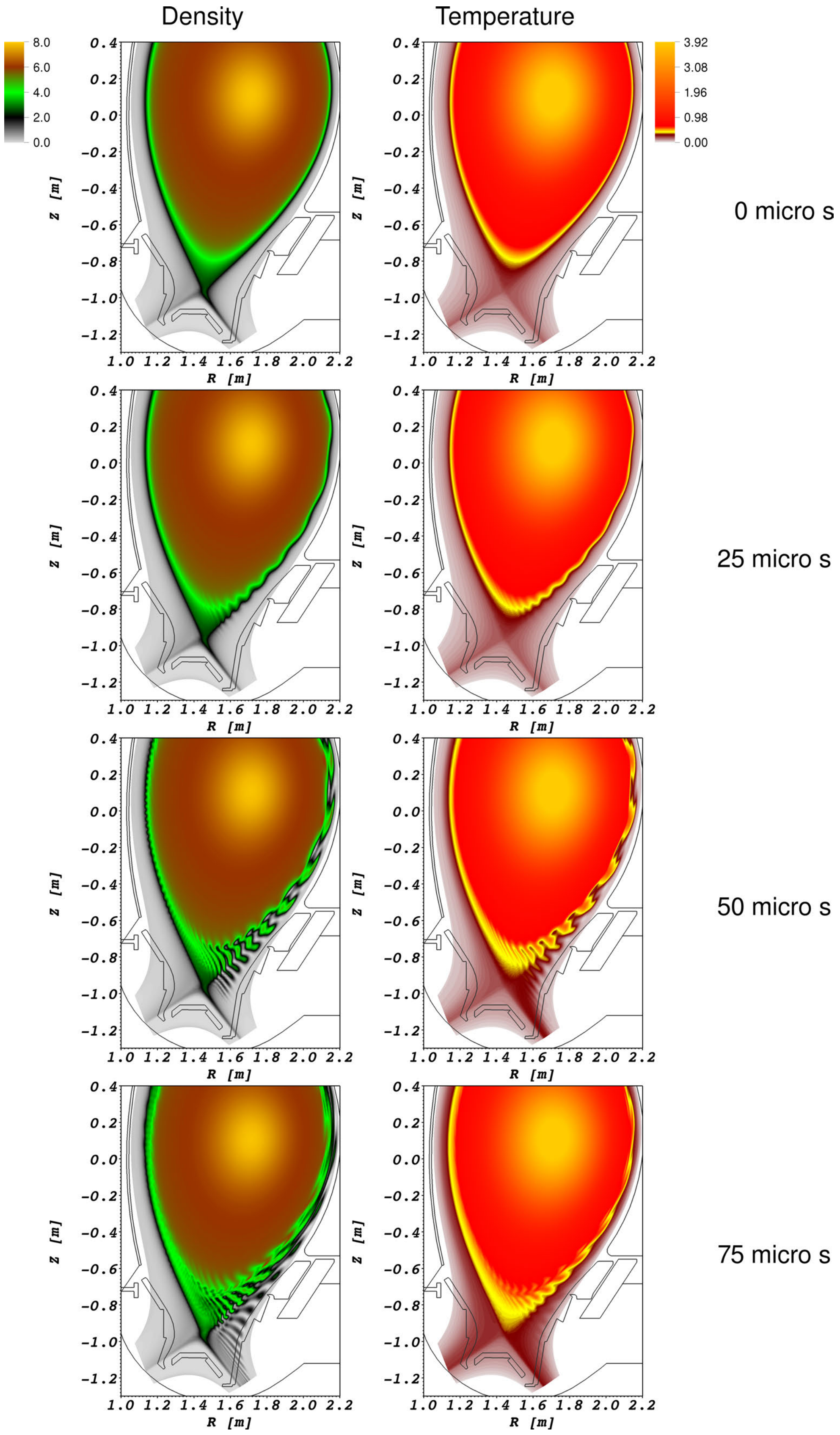

Figure 1: Simulation results for the normalized density (left) and temperature (right) are shown for several time points. The ballooning-instability, the formation of filaments, and the strong heat flux into the divertor can clearly be seen. Density is given in $10^{19}\mathrm{m}^{-3}$ and temperature in keV.

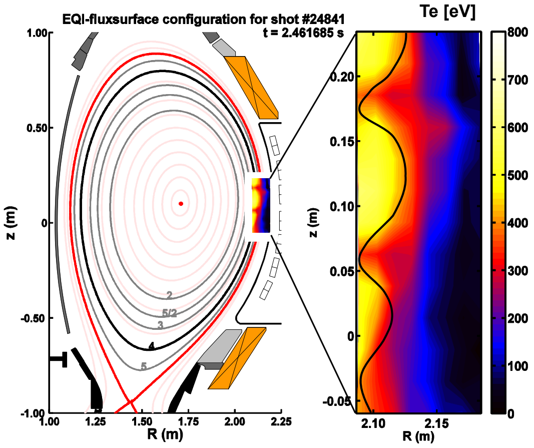

Figure 2: Measurements of the electron temperature shortly before the ELM crash measured by ECE-Imaging in ASDEX Upgrade is shown [7]. From these measurements, dominant poloidal and toroidal mode numbers of about 40 respectively 10 were concluded.

Outlook

The next step will be to perform systematic parameter scans in the simulations, to strongly increase the toroidal resolution and to perform quantitative comparisons to the experimental observations of several diagnostic tools. ASDEX Upgrade is an ideal device for theory-experiment comparisons as it is equipped with a unique set of edge diagnostics (e.g., 1D and 2D ECE, Thomson Scattering, Lithium Beam Emission Spectroscopy, Charge Exchange Recombination Spectroscopy, Langmuir Probes, Mirnov Coils, Bolometry, IR and Visible Light Cameras, Divertor Infrared Thermography). Many of these are fast enough to time-resolve the ELM crash [8]. Due to these outstanding diagnostic possibilities, this can be an important contribution to the extensive validation phase required before predictive simulations for future fusion devices like ITER become possible. Simulations of full ELM-cycles will also be tried.

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