TURBULENCE-TRANSPORT COUPLING SIMULATION STUDY OF THE ELM DYNAMICS FROM HIGH RECYCLING ATTACHED REGIME TO IMPURITY SEEDED DETACHMENT REGIME WITHIN EDGE PLASMA COUPLING SIMULATION (EPCS) FRAMEWORK

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Effective control of first wall heat load poses a critical challenge for steady-state operation in future fusion reactors. On one hand, the divertor target must withstand substantial steady-state heat flux in high confinement mode (H-mode). On the other hand, periodic edge-localized modes (ELMs) during H-mode can induce enormous transient heat and particle fluxes from the core confinement region within extremely short timescales, imposing significant transient thermal loads on both divertor targets and the main chamber. To address these challenges, future reactors need to achieve divertor detachment through density enhancement or impurity seeding to reduce steady-state heat/particle fluxes, while simultaneously implementing effective ELM control strategies to maintain pedestal operation in small/no ELM regime for transient heat load mitigation. These requirements must be compatible with maintaining high core confinement performance.

Significant interactions exist between divertor conditions and pedestal ELM dynamics. Large ELMs can periodically disrupt the “gas cushion” required for divertor detachment through intense thermal/particle fluxes (burning through effect), whereas small ELMs (e.g., grassy ELMs) with enhanced turbulent transport may facilitate detachment at lower densities. Conversely, achieving detachment through scrape-off layer (SOL) density enhancement reduces pedestal density gradients, promoting small/no-ELM operation. Impurity seeding not only facilitates radiative detachment but also significantly influences pedestal turbulence and ELM dynamics. Understanding these interactions is crucial for steady-state reactor operation. However, this represents a multi-timescale challenge: detachment involves long-term boundary plasma transport and plasma-neutral interactions, while ELM dynamics involve short-term pedestal magnetohydrodynamic (MHD) instabilities and turbulent processes. Despite existing computational tools for transport modeling (such as SOLPS-ITER [1] etc.) and for turbulence simulations (such as BOUT++ [2] etc.), self-consistent simulations of boundary plasma evolution to the transport timescale remain challenging.

A turbulence-transport code coupling approach offers a viable solution for efficient and accurate long-term self-consistent simulations. Previously, we developed the Edge Plasma Coupling Simulation (EPCS) framework based on Python [3]. EPCS is consisted of various components to provide the interfaces for the specified turbulence and transport codes (BOUT++ and SOLPS-ITER at present stage), the data transfer interfaces between the turbulence and transport code, the code running drivers and the function for configuration of the specified coupling simulation workflow. Using EPCS, we implemented both steady-state and time-dependent coupling workflows and successfully simulated EAST discharges.

This work employs the time-dependent coupling workflow in EPCS to perform self-consistent turbulence-transport simulations of a neon seeded EAST discharge (EAST shot #114688) achieving simultaneous divertor detachment and ELM mitigation. The simulation results are shown in Figure 1. From the temperature evolution of the outer target plate (OT), it can be seen that in the first stage without impurity injection (the gray area from 0.0 to 22.5ms), large ELMs occur in the pedestal region. The transient heat flux generated by the ELM bursts causes a rapid increase in the electron temperature on the divertor target plate. At 22.5ms, impurities are introduced by fixing the impurity ion density (Ne^{8+}) of 5×10^{17}m^{-3} at the core boundary. It can be observed that the impurity ion density at upstream outer mid-plane (OMP) gradually increases and then saturates. Meanwhile, the electron temperature at the OT oscillates significantly in the early stage and eventually varies in a relatively narrow region, which implies a small ELM regime is achieved (from 39.0 to 46.7ms). During these two stages, the electron temperature at the target plate is > 20 eV, indicating that the divertor is in a high-recycling attached regime (referred to as “attached” hereinafter). At 46.7ms, the impurity ion density at the core boundary is further increased to 1×10^{18}m^{-3}. As the simulation continued, it can be seen that the upstream impurity ion density increases, and the temperature at OT decreases, eventually entering a detached regime (T_e < 10 eV). The simulations are ongoing to provide sufficient data to identify the feature of ELMs at this stage, which is expected to be small or no ELMs.

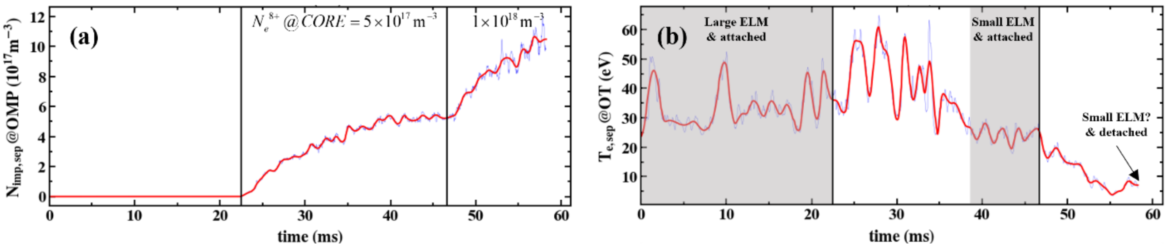

Figure 1. Time evolution of (a) the impurity ion density (Ne^{8+}) at separatrix in outer mid-plane (OMP) and (b) the electron temperature at outer strike point. The blue thin line is the raw simulation data, and the red line is the low-pass filtered curve. The black vertical lines represent the time of impurity seeding: the impurity ion density (Ne^{8+}) at core boundary is set to be $5\times10^{17}/1\times10^{18}$ m^{-3} at 22.5/46.7 ms. The gray regions represent different regime: 0.0~22.5ms large ELMs and attached, 39.0~46.7ms small ELMs and attached.

Figure 2 shows the time evolution of the mean plasma profile from 0.0 to 20.5ms during the large ELMs and attached regime. It can be seen that at the separatrix, the temperature evolution of both the OMP and the OT clearly reflects that three ELM burst events occur successively, with an ELM cycle period of approximately 10 ms (frequency of about 100 Hz). In the figure, each ELM is marked with three dashed lines indicating the time of the three phases of the ELM, namely pre-ELM, ELM crash, and post-ELM. During the ELM crash, the electron and ion temperatures at the target plate increase rapidly and eventually reach their peaks, with $T_{e,\,\max} \approx 45$eV and $T_{i,\,\max} \approx 85$eV. In the inter-ELMs (between post-ELM and the next pre-ELM), the temperatures at the OT remain at a relatively high level, with $T_e \approx 30$eV and $T_i \approx 60$eV, at which time the divertor target plate is in the attached state. The upstream density evolution does not change significantly with the periodicity of the ELM and remains at a relatively constant level in different ELM phases (in fact, the density evolution at the outermost boundary shows more obvious ELM characteristics). Notably, the density at the target plate decreases during the ELM burst, which is due to the rapid increase in the upstream heat flux during the ELM burst.

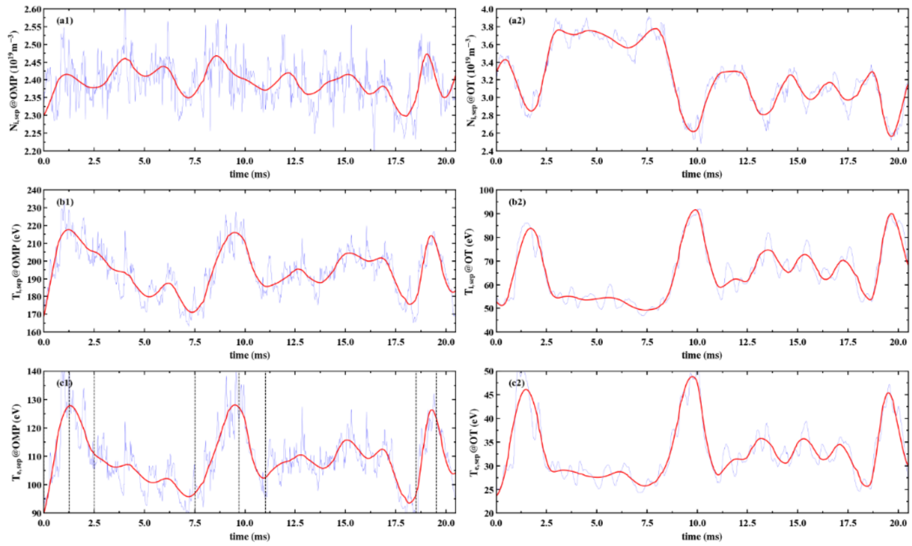

Figure 2. Time evolution of (a1-a2) ion (D^+) density, (b1-b2) ion temperature and (c1-c2) electron temperature at separatrix at large ELMs and attached regime. The left column (a1-c1) is at OMP and the right column (a2-c2) is at OT. The blue thin line is the raw simulation data, and the red line is the low-pass filtered curve.

In summary, the time-dependent coupling simulation workflow of EPCS was successfully used to simulate the evolution of the boundary plasma from the high recycling attached regime to the detached regime, and the transition from large ELM to small ELM is observed, which is qualitatively consistent with the experimental results. Further simulations are ongoing for the identification of the ELM behavior in the detached regime. The detailed analysis on the effects of impurities will be stated on the conference.

REFERENCES

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