SIMULATIONS OF THE INTERACTIONS BETWEEN ELMS AND EDGE TURBULENCES ON FUSION REACTOR SCALE FACILITY

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The high-confinement mode (H-mode) is considered as the main operation scenario for ITER and future tokamaks. However, the larger edge transport barrier in H-mode will cause the periodic crashes of temperature and density profiles, which is named as edge localized mode (ELM). The Type-I ELM, which is considered to be caused by the coupling of peeling and ballooning mode [1], is the most dangerous type to the safety of the first wall and divertors of ITER [2]. Therefore, it is important to understand the ELM behaviours in the physics design of the future fusion reactors.

This paper exhibits the ELM mitigations by self-consistently generate turbulence for the fusion reactor size facilities. Besides ITER, a JET-like compact tokamak and a CFETR-like reactor are studied for the simulations on ELM behaviours, in which the pedestal structures are predicted by EPED1.6 model. Although these pedestals are unstable to ideal Peeling-Ballooning modes (IPBM), the simulations with 6-field 2-fluid model in BOUT++ framework [3, 4], which includes non-ideal effects such as ion diamagnetic effects, Drift Alfven wave (DAW), ion acoustic waves, resistivities, thermal conductions, etc., exhibit small ELM regimes. The high pedestal profiles in the reactor scale facilities leads to strong turbulent transport, which interrupts the normal growth and change the nonlinear mode spectrum of ELM. The Type-I ELM could not get grown and turn to a small one, or even turbulent behaviours.

In the previous simulations on ELM mitigation and suppression, we have found that the existence of turbulence is able to mitigate or even suppress ELMs on EAST [5]. Using an imposed perturbation added as a coherent mode (CM) into the ELM simulation, CM enhances the three-wave nonlinear interactions in the pedestal and reduces the phase coherence time (PCT) [6] between the pressure and potential. In this way, the fluctuations tend to be ‘multiple-mode’ coupling. The competitions of free energy between these multiple modes lead to the lack of obvious filament structures and the decreased the energy loss. Not only the electro-static turbulence has this mitigation effect, the electro-magnetic fluctuations, which is contributed by the filamentary current in SOL generated by Lower Hybrid waves (LHWs) on EAST, also present the similar influence. The above reveals that there is a competitive relationship between turbulence and ELMs, and edge turbulence does effectively reduce ELM energy loss.

Two Pre-Fusion Power Operation (PFPO-1,2) phases of the ITER Research plan proclaimed in 2019 are simulated with the 6-field 2-fluid model. The linear simulation results show that PFPO-1 is unstable to IPBMs, while PFPO-2 is unstable to the coupling of IPBM and DAW instabilities, which is consistent with the DAW unstable thresholds prediction. Different to the grassy ELM regime simulated in [7], nonlinear simulations show that the ELM size of PFPO-2 is almost one third of the grassy ELM, representing a distinct small ELM. However, simulations then show that if the PB instability is removed, the fluctuation amplitude drops by an order of magnitude and the ELM crash disappears, which is in accord with the theory in [8] and the results in [7], confirming that the PB instability is a necessary condition for ELM crash. Furthermore, removing the DAW drive also suppresses ELM crashes, implying that PBM instability is necessary but insufficient for ELM dynamics and that DAW could amplify PBM-driven turbulence. Moreover, simulations indicate that the DAW driving can increase the transport coefficient by enhancing the turbulent transport, leading to heat flux width broadened once the transport coefficient exceeds its critical value [9].

The same model has been applied for the ELM analysis on a CFETR-like reactor on the 15MA conventional H-mode operation scenario with the purpose of Q=15, and a JET-like compact tokamak H-mode with Q=5. For both cases, the pedestal collisionality is around 0.2, which are supposed to be in the Type-I ELM regime. The linear stability analysis shows that both pedestals are ideal peeling-ballooning unstable, which is consistent with the collisionality scaling for ELMs [10]. Take the CFETR-like equilibrium as the example, the linear growth rates are shown in Fig. 1. The PBM model shows the similar growth rates with the full 6-field 2-fluid model with more comprehensive physical effects. This figure means that the contributions of the DAW instabilities are nearly cancelled with the thermal conduction and gyro-viscosity. However, the nonlinear result using the full 2-fluid model obtains a much smaller ELM size ~0.06% compared to the one using PBM model ~0.35%. Notice that although the ELM size of PBM model is smaller than 1%, the total energy is huge (~283MJ) for this equilibrium, so the energy loss is still large and the crash of pressure profile is sufficient. The peak parallel heat flux during this ELM nonlinear evolution is about 850MW/m^2, so some mitigation methods may still be necessary for this operation scenario.

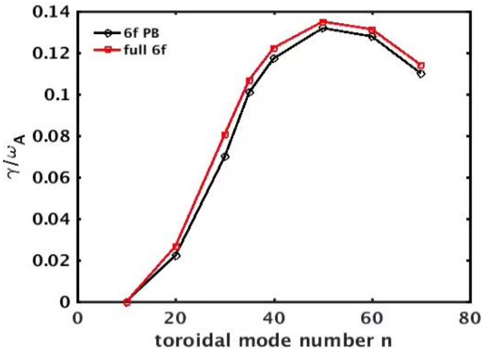

Figure 1 The linear growth rate spectrum for CFEDR-like reactor. The black diamond line is based on the 6-field 2-fluid model but only with PBM driving terms. The red square line represents the full 6-field 2-fluid model.

The interaction between turbulence and ELM is found to cause this suppression effects. To analyse the reason why ELM type is changed based on the different model, we plot the temporal mode evolution in Fig. 2. For PBM model, the zonal component becomes dominant after entering nonlinear phase. The subdominant modes, n=5 and n=30, are much smaller than the dominant mode, which means nearly all the energy from the instabilities is converged to change the profiles. For the comparison, the full 2-fluid model shows that, the dominant mode in the nonlinear phase is n=30, not n=0, which leads to nearly no change of the profiles. This shows a typical DAW turbulence behaviour based on the analysis of phase angle. The existence of DAW in this equilibrium shows a competition relationship with ELM, which is similar to the previous EAST simulations. The difference is that the DAW here is self-consistently driven by the small scale length of the profiles, not added as the background in EAST work. The simulations for the JET-like compact tokamak obtains the similar conclusion.

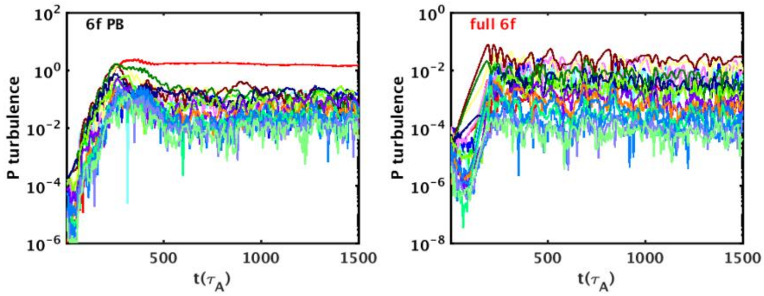

Figure 2 The mode evolutions of ELM simulations for CFEDR-like reactor. Left panel is derived by PBM model, and the right one is based on the full 2-fluid model.

These results proves that the PBM unstable pedestal predicted by EPED1.6 model in the future fusion reactor may lead to a small ELM regime rather than Type-I which was supposed to be based on present understanding. The interaction between self-consistently generated edge turbulence and ELM leads to the much small ELM amplitude, the enhanced edge transport is able to prevent the ELM to evolve to a larger one. In this way, the transient heat flux on divertor targets will be suppressed sufficiently, but the mitigation methods may still be necessary.

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