Modelling work of Grassy-ELM operation regime in CFETR

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1. Introduction

China Fusion Engineering Test Reactor(CFETR) is being proposed as the next-generation fusion facility in China, which aims to bridge the technological gaps between ITER and a fusion demonstration reactor(DEMO). With the initiation of the engineering design phase of CFETR, a method to control ELMs, compatible with the desired operating scenarios and engineering constraints, is a major challenge.

In this work, we have identified a robust grassy-ELM operation regime for future tokamak reactors. The regime exists within a pedestal top electron collisionality(ν^*) window at high global poloidal beta(β_p). Using EPED and BOUT++, a theoretical model that quantitatively explains the physics of the grassy-ELMs within the window, which distinguishes them from small mixed-ELMs at lower ν^*, is presented for the first time.

2. Self-consistent equilibrium construction

The first step of performing a reliable edge stability analysis is to construct a self-consistent equilibrium. In such an equilibrium, α_{ped} and I_{ped} are strongly coupled through the pedestal bootstrap current. On the other hand, the marginal stability condition(peeling ballooning mode) is strongly influenced by the core equilibrium parameters. To account for these two factors, a self-consistent workflow for CFETR is employed to generate a set of equilibria, following a method previously developed by Meneghini[1]. By coupling EPED, TGYRO, ONETWO and EFIT with OMFIT[2], we could model the iterative interaction between the core and pedestal. Pressure and current profiles from the output of EFIT can be easily converted to BOUT++ grid files, and density and temperature profiles used by BOUT++ are extracted from ONETWO.

3. Linear stability analysis of CFETR operation scenarios

Based on the CFETR R=6.6 m phase II baseline case[3] and starting at low n_{e_ped}, results of EPED shows a trend of rising pedestal height with density(or ν^*), reaching a peak at some intermediate density, after which it starts to decline. In these equilibria, the strong Shafranov shift at high β_p enhances the good-curvature weighting leading to a reduced flux-surface averaged pressure gradient drive. Specifically, the driving term $< \kappa \cdot \nabla P >$ shows a minimum at intermediate ν^*, which is shown in Fig. 1.

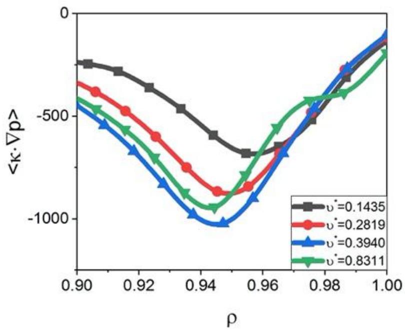

Figure 1. The flux-surfaced averaged pressure gradient drive for different collisionalities.

Moreover, we also examine the most unstable mode spectrum with low, intermediate and large ν^*(Fig. 2). There is an intermediate ν^* window where the instability is dominated by kink-peeling drive($n \leq 10$), e.g., the case with $\nu^*=0.39$.

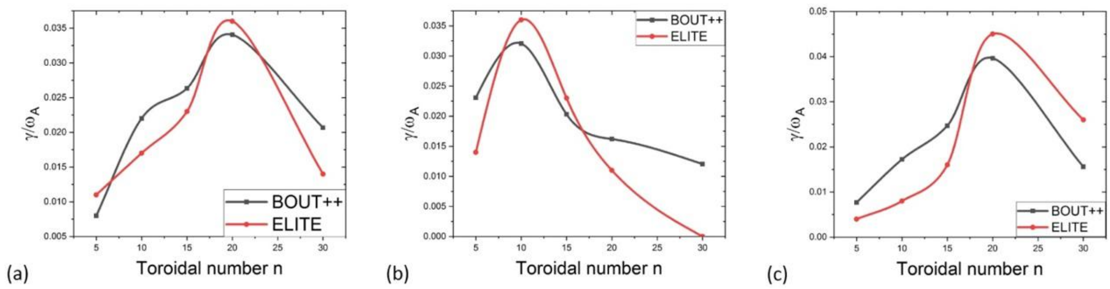

Figure 2. Unstable mode spectrum by BOUT++ and ELITE at (a) low collisionality(0.14), (b) intermediate collisionality(0.39) and (c) high collisionality(1.31).

4. Nonlinear simulation of ELM behavior along the peeling-ballooning boundary

In the last section we have identified three different ν^* regimes along the PB stability boundary. For the purpose of detailed understanding of ELM behavior, nonlinear simulations with BOUT++ 3-field model[4] is executed. It is found that there is a robust grassy ELM window with ν^* between 0.3-0.7, which is shown in Fig. 3. The grassy-ELM is driven by unstable kink-peeling modes with lower n numbers and characterized by a rapid oscillation/recovery. The ejected energy in a single crash $\Delta W/W_{ped}$ is very small(<<1%). At ν^* above and below the grassy-ELM window, we also confirmed that the ELM behavior falls into the Type-I category.

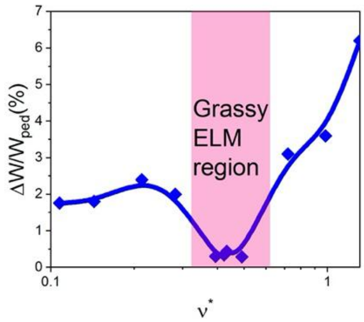

Figure 3. Plot of energy loss of single ELM activity versus pedestal electron collisionality in CFETR.

Furthermore, five DIII-D discharges that cover a broad range of β_p (0.6-2.2) and ν^* (0.06-6.0) have been surveyed to select specific time slices where representative ELM behaviors are clearly identifiable, as shown in Fig. 4. These experiments correspond well to our CFETR simulation results, and comparison with JT-60U data[5] would be worthwhile in the future.

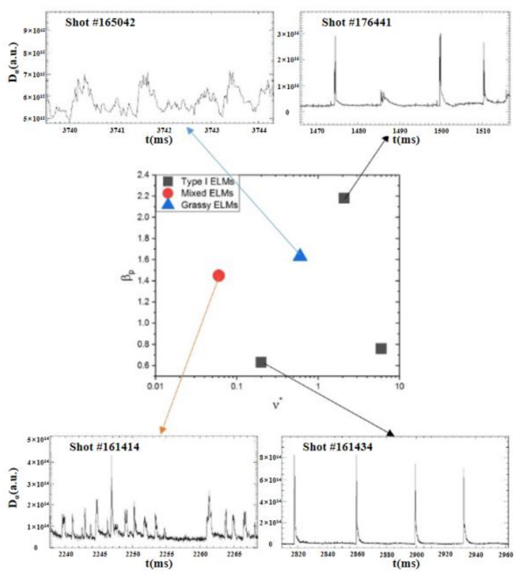

Figure 4. Change of ELM character with β_p and ν^*. Triangle indicates a small amplitude grassy ELM discharge,

squares indicate discharges of giant Type-I ELMs and circle indicates a mixed-ELM regime.

5. Conclusion

Using a combination of linear and nonlinear analyses of self-consistently constructed equilibria, we have identified a robust grassy-ELM operation regime for future tokamak reactors, in particular the China Fusion Engineering Test Reactor (CFETR). The change in density corresponds to a change in ν^* that affects the pedestal bootstrap current. High β_p leads to a strong Shafranov shift, which affects the flux surface averaged pressure drive. The two effects combine to create a peeling-dominated window in ν^*. Only the peeling-dominated regime shows a rapid cyclic behavior during ELM crash, reminiscent of grassy-ELM dynamics.

Our theory predicts a grassy ELM with $\Delta W/W_{ped} \sim 0.1\%$, which is shown in Z.Y. Li's paper[6] to be acceptable for divertor material erosion lifetime. Conventional definition of grassy ELM which is based on experimental observation[7] can have $\Delta W/W_{ped} \sim 1\%$ or higher. This may not be tolerable for divertor material erosion.

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