Characteristics of grassy ELMs and their impact on the divertor heat flux width

Nami Li¹,2,*, X.Q. Xu¹, Y.F. Wang³, N. Yan³, J.Y. Zhang³, J.P. Qian³, J.Z. Sun² and D.Z. Wang²

¹ Lawrence Livermore National Laboratory, Livermore, CA 94550, United States of America
² School of Physics, Dalian University of Technology, Dalian 116024, China
³ Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

E-mail: li55@llnl.gov

Received 20 April 2022, revised 7 July 2022
Accepted for publication 25 July 2022
Published 16 August 2022

Abstract
BOUT++ turbulence simulations are conducted for a 60 s steady-state long pulse high \( \beta_p \) EAST grassy ELM discharge. BOUT++ linear simulations show that the unstable mode spectrum covers a range of toroidal mode numbers from low-\( n \) (\( n = 10–15 \)) peeling–ballooning modes (P–B) to high-\( n \) (\( n = 40–80 \)) drift-Alfvén instabilities. Nonlinear simulations show that the ELM crash is triggered by low-\( n \) peeling modes and fluctuation is generated at the peak pressure gradient position and radially spread outward into the scrape-off-layer, even though the drift-Alfvén instabilities dominate the linear growth phase. However, drift-Alfvén turbulence delays the onset of the grassy ELM and enhances the energy loss with the fluctuation extending to pedestal top region. Simulations further show that if the peeling drive is removed, the fluctuation amplitude drops by an order of magnitude and the ELM crashes disappear. The divertor heat flux width is \( \sim \)2 times larger than the estimates based on the HD model and the Eich’s ITPA multi-tokamak scaling (or empirical Eich scaling) due to the strong radial turbulence transport.

Keywords: grassy ELM, BOUT++ turbulence, heat flux width

(Some figures may appear in colour only in the online journal)

1. Introduction
Simultaneous control of large edge-localized-modes (ELMs) and resulting high divertor heat loads in H-mode plasma is crucial for steady-state operation of a tokamak fusion reactor [1]. The grassy ELMs, one of small ELMs, are characterized by a high frequency and spatially localized quasi-periodic collapse in the bottom of pedestal near the separatrix [2, 3]. The peak heat fluxes on the divertor target plate for grassy ELMs are reduced by more than 90% as compared to type-I ELMs [4]. Recent experiments, from ASDEX Upgrade (AUG), DIII-D, EAST, and TCV, show that small ELM regimes have the following desired features: (1) good energy confinement; (2) divertor heat flux comparable with type-I inter-ELM level; (3) significantly broadening of divertor heat flux profile; (4) quasi-continuous particle and power exhaust to the divertors.

H-mode plasma regimes with small ELMs compatible with high density, high confinement, and power exhaust compatible H-mode regimes with small ELMs have been achieved in TCV and AUG [5]. The quasi-continuous exhaust (QCE) regime in AUG is observed with enhanced filamentary transport due to small type-II ELMs and significantly broadened power fall-off length \( \lambda_q \) (by a factor up to 4), by operation with increasing fueling [6–8]. JOREK simulations have successfully reproduced type-I ELM cycles and the QCE regime in AUG [9]. Recent DIII-D grassy ELM experiments show a consistent divertor heat flux width broadening and peak amplitude reduction. From the inter-ELM phase to the grassy ELM phase with resonant magnetic perturbations (RMP) 3D fields, the width on the inner divertor target increases about 2 times with low RMP current \( I_{RMP} \approx 1950 \) kA and about 4 times with high \( I_{RMP} \approx 2450 \) kA [10, 11]. The grassy-ELMs exhibit a reduced peak heat flux to the divertor similar to the inter-ELM heat.
flux with good confinement. Since 2016, a high confinement performance grassy-ELM H-mode regime has been achieved in EAST. Heat fluxes of the grassy ELMs are found to be only 1/20th–1/10th of those with large type-I ELMs and they are comparable with inter-ELM levels [4]. BOUT++ simulations for DIII-D, EAST, ITER and CFETR show consistent trends and demonstrate consistent divertor heat flux width broadening and peak amplitude reduction in the grassy ELM regimes [12–16]. A 60 s steady-state long pulse high $\beta_p$ EAST grassy ELM discharge has been achieved with high performance in 2019 [17]. Therefore, H-mode plasma regimes with small ELMs offers a potential solution to future reactor power exhaust as it features many aspects required for the operation of future fusion reactors and has been proposed as the primary ELM-mitigation solution for the Chinese Fusion Engineering Test Reactor (CFETR) [18, 19].

Even though substantial progresses have made in the access conditions of this small/grassy ELM regime for some tokamaks, such as EAST and DIII-D, the grassy ELM experiments for other tokamaks are not yet available and a detailed physics understanding on the underlying mechanism is important. Whether the grassy ELM regime could be accessed and its compatibility with stationary operations in future fusion reactors is still uncertain, further investigation is required.

In order to investigate the characteristics of the grassy ELM and its impact on the divertor heat flux width, BOUT++ turbulence simulations are conducted for a 60 s steady-state long pulse high $\beta_p$ grassy ELM discharge with shot #090949 for EAST. The main parameters for this shot are close to the steady state scenario with $Q > 5$ in CFETR phase 2 performance. The simulation for understanding the physics of this shot is very important for future development of long pulse steady state scenarios for future tokamak reactors. In this study, pedestal linear stability analysis is performed with both ELITE code [20] and BOUT++ turbulence code [21], and the nonlinear dynamics and divertor heat flux width are calculated by BOUT++ six-field turbulence code [22, 23]. The paper is organized as follows. Section 2 contains a description of simulation settings. The simulation results of characteristics of grassy ELMs for EAST #090949 shot are shown in section 3, including (1) linear MHD stability analysis, (2) characterization of ELM nonlinear dynamics, and (3) impact of peeling–ballooning (P–B) mode and drift-Alfven mode on the grassy ELMs. Section 4 shows the divertor heat flux width and a summary of the results is given in section 5.

2. Equilibria for the EAST high-$\beta_p$ long-pulse experiment and simulation settings

The plasma profiles used in this work are based on the experimental measurement from EAST high-$\beta_p$ long-pulse discharge with upper single null divertor configuration. The equilibrium is reconstructed using the kinetic EFIT code [24, 25] with the constraints of experimentally measured total pressure profile and flux surface averaged toroidal current density profile with bootstrap current $I_{BS}$ dominated in the pedestal region. The simulations include the plasma edge, the scrape-off-layer (SOL) region and private flux region (PFR). The simulation domain is shown in figure 1, which ranges from normalized poloidal flux $\psi_n = 0.8$ to $\psi_n = 1.1$, where $\psi_n = 1.0$ is the magnetic separatrix as shown by the red curve in figure 1. The spatial resolution of the grid generated from the equilibrium file (EFIT g-file) is 260 radial grid points and 64 poloidal grid points. In the poloidal direction, there are four grid points for each divertor leg region from x-point to the divertor plate and 56 grid points for the main plasma region above the x-point. In the toroidal direction, we only simulate one-fifth of the torus for the nonlinear simulations.

The detailed main plasma parameters are shown in table 1 with shot numbers #090949. According to the existing tokamak experiments, this parameter space overlaps with that of the grassy-ELM regime. Key parameters of this discharge are summarized in table 1. The duration of this discharge is last for 60 s with high grassy ELM frequency $f_{ELM} \sim 1$ kHz, high poloidal beta $\beta_p \sim 2$, high edge safety factor $q_{se} \sim 7$, high bootstrap current fraction $I_{BS} \sim 45\%$ and improved confinement performance $H_{98,2} = 1.3$. The ratio between central-line-averaged density and Greenwald density is $n_e/n_{GW} \sim 0.8$ with a high-density ratio between separatrix and pedestal top $n_{sep}/n_{ped} \sim 0.53$. This shot is radio frequency (RF) heated only fully non-inductive with high density and collisionality. The radial equilibrium profiles of pressure and current density for this shot are shown in figure 2(a). The initial plasma profiles inside the separatrix of the shot used in these simulations are taken from fits of a modified tanh function [26] to experimental data, mapped onto a radial coordinate of normalized poloidal magnetic flux. For purposes of studying pedestal turbulence, the initial profiles for $\psi_n > 1.0$ extend smoothly into the SOL region with small constant gradient, which is close to 0. Therefore, in this paper, the SOL plasma profile gradient impact on the grassy ELM is ignored. The flux-limited parallel thermal transport is implemented in the simulations. The initial plasma profiles of density and temperature in the simulations are shown in figure 2(b). The difference of ion density $n_i$ and electron density $n_e$ is noticeable from the experimental data, as shown by the blue and red lines in figure 2(b). Therefore, the impurity effect is included in the model with $n_{imp} = n_i + n_{imp}Z_{imp}^2$, where the $Z_{imp} = 6$ is used in the code. Note that, in the simulations, impurity is just used in plasma equilibrium...
3. Characteristics of grassy ELM for EAST shot #090949

3.1. Linear MHD stability analysis

In order to determine the dominated linear instability drive for the grassy ELMs, we first focus on linear simulations by turning off the nonlinear terms in three-field turbulence code.

The linear simulations start from small initial perturbations with random phases. Figure 3 shows the toroidal mode number spectrum of the linear growth rate. The horizontal axis is the toroidal mode number, and the vertical axis is the mode growth rate normalized by the Alfvén frequency at the magnetic axis, \( \omega_A = \frac{B_0}{\mu_0 \sqrt{\mu_0}} \). BOUT++ linear simulations with ideal MHD instability show that perturbations first grow up around the location of the peak gradient of pedestal pressure at the outer mid plane and the most unstable toroidal mode numbers in the range of \( n = 10–15 \) with characteristics of P–B modes as shown by the black curve in figure 3, which shows a similar trend with ELITE as shown by blue curve. Note that typically due to the high safety factor \( q_{sep} \), resonant surfaces are closer to each other in the edge region. A large poloidal mode number need be used for the ELITE simulations. However, for this shot, the most unstable mode is dominated by the low-\( n \) mode. Therefore, this simulation results show similar trend with different setting of \( \text{nmvac} \) in ELITE. The linear simulations of BOUT++ three-field two-fluid turbulence code further find that drift-Alfvén instabilities yield significant contribution to the high-\( n \) modes with \( n = 40–80 \) as shown by the red and green curves in figure 3. Here the red curve shows the modes spectrum with both ideal P–B and drift-Alfvén instabilities, while the green curve without peeling mode. By comparing the red and green curves with the black curve, we can find that, with the drift-Alfvén instability, the linear growth rate for high-\( n \) modes is larger than that either with or without peeling mode. Because the peeling instability dominates at low-\( n \) modes and the drift-Alfvén instability dominates high-\( n \) modes for linear simulations, their impact on the ELM nonlinear dynamics is significant different. More details about the nonlinear analysis will be presented in section 3.3.

3.2. Characteristics of ELM nonlinear dynamics

BOUT++ two-fluid six-field turbulence nonlinear simulations are conducted to capture the physics of the grassy ELM
dynamics and its impact on the divertor heat flux width. The same equilibrium profiles are used in the nonlinear simulations as shown in figure 2. The radial simulation domain covers from normalized poloidal flux \( \psi_n = 0.8 \) to \( \psi_n = 1.1 \), including the pedestal, the SOL, and PFRs. The nonlinear simulations start from small initial perturbations with random phases.

The spatial-temporal evolution of the pressure fluctuation further illustrates the generation of the turbulence. In figure 4(a), the root-mean-square (RMS) value of pressure fluctuation is obtained at the outer midplane (OMP) and normalized by equilibrium pressure at the pedestal top \((4470.7 \text{ Pa})\). The linear phase lasts for about \( \sim 450 \tau_A \) (Alfvén time \( \tau_A = 4.263 \times 10^{-7} \text{ s} \)), the fluctuation saturates at a low level without an ELM triggered. While at \( \sim 750 \tau_A \), low-\( n \) mode grows up at OMP and the fluctuation level increases. Finally, the fluctuations saturate at a relative high level, leading to collapse of the pedestal pressure profile and an ELM event.

In later nonlinear stage, the fluctuation level saturates at around 16% near the location of the peak pedestal gradient. The radial mode structures of pressure fluctuation at OMP in the linear and nonlinear stage are shown in figure 4(b). Before the ELM crash, the mode grows up at the peak pressure gradient location and the perturbation is localized within the pedestal region as shown by the black and red curves in figure 4(b). While in the later nonlinear stage, the perturbation radially spreads on both sides of the pedestal region, reaching into the inner edge region and the SOL, indicating the collapse of pressure pedestal as shown by the blue and green curves in figure 4(b). The time evolution of radial pressure profile demonstrates the profile flattening processes during the ELM bursting activity. The pressure profile keeps dropping inside the separatrix while rising in the SOL, indicating that energy is continuously transported from the edge region to the SOL. In the SOL, the energy is transported along the magnetic field line and is finally deposited onto the divertor targets.

By closely examining the time history of density fluctuation, two different nonlinear saturation stages are found from this grassy ELM simulation, as shown in figure 5(a); (1) the early nonlinear stage from \( t = 480 \tau_A \) to \( t = 900 \tau_A \) as shown between the red-dashed lines; (2) the late nonlinear stage after \( t = 1000 \tau_A \), as shown between the blue-dashed lines. In order to identify the characteristics of two different nonlinear stages, the spectrum of density fluctuation is calculated from the two-point correlation function with two different poloidal grid points at OMP. Figures 5(b) and (c) show the contour plot of density fluctuation vs wave number and frequency in different nonlinear stages. In the early nonlinear stage, the \( k-f \) spectrum is calculated with the time range \( 480 \tau_A \sim 900 \tau_A \). Density fluctuation saturates in a low level with high frequency modes, corresponding to drift-Alfvén modes. The mode frequency is \( \sim 80–100 \text{ kHz} \) and the poloidal wave number \( k_\theta \) is about 0.25 cm as shown in figure 5(b). At the late nonlinear stage, density fluctuation saturates in a high level with several low mode frequencies (\( \sim 32, 65 \) and 91 kHz) dominated and a similar range of poloidal wave number \( k_\theta \), as shown in figure 5(c). These modes correspond to P–B modes, generate large radial transport, and thus trigger an ELM. Because low-\( n \) P–B modes have lower linear growth rates than drift-Alfvén instabilities, they grow up late in the initial value simulation code. Thus, from the simulation, we can find that the low frequency mode (\( \sim 65 \text{ kHz} \)) is stronger and dominated the turbulence transport, leading to the grassy ELM. The simulation results are qualitatively comparable to experiment that the low frequency modes (10–100 kHz) are dominated. However, due to the experiment measurement limit, more detail comparisons need further research in the future.

3.3. Impact of P–B mode and drift-Alfvén instabilities on ELMs

In order to understand the relative role of P–B instability and drift-Alfvén instability in the ELM dynamics, three nonlinear simulations are performed with turning on or off the drift-Alfvén (or ‘eHall’ in the code input option) and peeling (or ‘current’ in the code input option) terms in the equations. Figures 6(a1) and (b1) show the simulation results with both peeling and drift-Alfvén instabilities; (a2) and (b2) show the simulation results without drift-Alfvén instability, while (a3) and (b3) show the simulation results without peeling instability. Without peeling drive in figures 6(a3) and (b3), the fluctuation amplitude drops by an order of magnitude and no ELM crash occurs in comparison with figures 6(a1) and (b1). The pressure profile remains unchanged throughout simulation as shown in figure 6(b3); while the pressure profile collapses in a small range with peeling driven as shown by figures 6(b1) and (b2). In figure 6(b1), simulations results show the profile evolution during an ELM collapsing event, and the profile collapse is small and limited inside the pedestal after the ELM is triggered, and the ELM size is small. It would be the best if we could show a direct comparison with corresponding experimental profile measurements. Unfortunately, the profile evolution data is not available during one ELM event because of lack of capability for fast profile measurements on the order of hundred microseconds for this long-pulse grassy ELM, but the measurements still show that the profile does not change much during a long period, which is just oscillated in a small range. Therefore, from these three nonlinear simulations, we can find that the ELM crash is triggered by peeling mode for this grassy ELM shot even though the drift-Alfvén instabilities dominate the linear growth phase in the initial value simulation.
Figure 4. (a) Spatial-temporal evolution of RMS value of pressure fluctuation vs radius and time at the OMP. The white dashed line indicates the location of separatrix, and the dash-dot line indicates the peak gradient location of the pressure; (b) radial mode structures of pressure fluctuation at OMP at different time slices.

Figure 5. (a) The time evolution of density fluctuation; the wavenumber spectrum for density fluctuation at (b) early nonlinear phase and (c) late nonlinear phase. The data is taken at the peak pressure gradient position at OMP.

code. From the simulation we further find that the drift-Alfvén instability will delay the onset of the ELM and enhance the turbulence transport by comparing the first two columns in figure 6. The fluctuation extends inward beyond peak gradient region with drift-Alfvén instability in figure 6(b1) in comparison with that without it in figure 6(b2) even though their fluctuations saturate in the same level at the later nonlinear stage. Without the drift-Alfvén instability, the ELM can be easily triggered around 480\(\tau_A\) and the relative ELM size, or the energy loss fraction, will be saturated at 0.5% as shown by the red curve in figure 7. While with the drift-Alfvén instability, the fluctuation saturates at a low level first and then grows up again, and finally triggers an ELM crash around 840\(\tau_A\). The onset of ELM is delayed due to the drift-Alfvén turbulence, which acts as a damping effect to reduce the linear growth rate of peeling modes. The ELM size is saturated at a high level \(\sim 1.2\)% with a strong turbulence transport enhanced by drift-Alfvén turbulence as shown by the black curve in figure 7. From the nonlinear simulations, we also find the peeling modes and drift-Alfvén instabilities grow up at different poloidal locations. Figure 8 shows the mode structure at different stages. Figure 8(a) shows the mode structure at linear stage
Figure 6. (a) Time evolution of pressure fluctuation for different toroidal mode numbers and (b) the radial pressure profiles normalized by equilibrium pressure at the pedestal top (4470.7 Pa) at different times. The three columns are for three different linear instability drives: (a1) and (b1) with both peeling and drift-Alfvén drives; (a2) and (b2) with peeling drive only without drift-Alfvén drive; (a3) and (b3) with drift-Alfvén drive only without peeling drive.

Figure 7. Time evolution of 3D relative ELM size with different linear instability drive. The black curve is the case with both peeling and drift-Alfvén drives while the red curve is the case with peeling drive without drift-Alfvén drive. The ELM size is defined as 
\[ \Delta W_{\text{ped}} = \int_{\text{R}_{\text{in}}}^{\text{R}_{\text{out}}} \oint \text{d}R \text{d}\theta (P_0 - \langle P \rangle_{\text{eq}}) \]
where \( \Delta W_{\text{ped}} \) is the ELM energy loss and \( W_{\text{ped}} = \frac{3}{2} \rho_{\text{ped}} V \) is the pedestal stored energy.

\( t = 250 \tau_A \) and (b) shows the mode structure before ELM crash \( t = 840 \tau_A \). Drift-Alfvén instability is generated and grows up first with high growth rate in the high-field side (HFS) with high-\( n \) mode numbers as shown by figure 8(a) and the mode structure is consistent with the case of without peeling drive. There is no ELM crash when it gets into the nonlinear drift-Alfvén stage with a lower-level fluctuation. While in the late nonlinear drift-Alfvén stage, the peeling mode grows large in the low-field side (LFS) with low-\( n \) mode. The ELM is triggered, and the dominated mode structure is comparable with the case without drift-Alfvén instability.

4. Divertor heat flux width

The heat flux distributions on divertor target plates in H-mode plasmas are serious concerns to future fusion devices. Recent experimental scaling on multi-machine H-mode discharges shows that the heat load width follows reasonably well with the Eich scaling law [29, 30] \( \lambda_q \sim \frac{1}{B^\gamma} \), where \( \gamma \) is in the range from 1.11 to 1.27. If the scaling works for future large machines, it would yield a very small \( \lambda_q \sim 1 \text{ mm} \) mapped back to the OMP for ITER 15 MA, \( Q = 10 \) baseline scenario, leading to an intolerable heat load on the divertor target. However, BOUT++ simulations indicate that divertor heat flux width \( \lambda_q \) can be broadening with increasing radial turbulence transport from the ELM-free phase to the small/grassy ELM [12]. Recent experiments also show that H-mode plasma regimes with small/grassy ELMs offers a potential solution to future reactor power exhaust as it features many aspects required for the operation of future fusion reactors. The analytical estimates from BOUT++ simulations show that the ELM energy loss fraction should be smaller than 0.74%, 1.19%, and 2.03% for ITER baseline target, hybrid and SSO scenarios, respectively. The combination of small ELM energy loss fraction (<0.1%–1%) and broadened footprint makes the SSO with grassy ELMs a highly promising operational scenario for ITER, satisfying the constraints on divertor material [15]. The BOUT++ simulation show that the heat flux width is broadened during the small grassy ELMs phase for CFETR hybrid scenario and energy fluence caused by a single ELM pulse is below the tungsten melting limit [18]. Even though the significantly broadening of heat flux width is found for future
large machines, the comparison of simulation with real experiment is still important. Therefore, it important to compare the simulation results with experiment and give a reasonable prediction for the future machines.

In order to investigate the impact of the grassy ELM on the divertor heat load, the BOUT++ turbulence code simulates the evolution of the heat flux during one burst of ELM event. We track the evolution of heat load on the target during an ELM event and both the particle flux width and heat flux width are calculated in the saturation phase on the outer divertor target, as shown by figure 9. Due to diagnostics limitation, the heat flux profile on the divertor is not available. However, we can still calculate the divertor heat flux width from simulations, we apply Eich’s fitting formula to the parallel electron heat flux profile in steady-state phase of nonlinear simulations. Divertor heat flux width calculated based on different models are shown in table 2. From the empirical Eich scaling [29, 30] and HD model [35], the heat flux width is 5.5 mm and 5.7 mm respectively. With the effect of collisionality on parallel transport, the heat flux width will be broadened by ~11% calculated by the GHD model [36, 37] while with the effect of collisionality on radial turbulent transport the width is enhanced by a factor of 2 [38]. Here the collisionality is calculated by $\nu_{c,SOL} = \frac{\tau_{\nu,\text{pol}}}{1.0310^{18} Z_{\text{eff}}}$ Eich turbulence regression is based on the reference [38]:

$$\frac{\lambda_p}{\rho_e,\text{pol}} = (1 + (3.6 \pm 0.19)\alpha_{\text{turb}}^{1.9 \pm 0.14}) \cdot (1.2 \pm 0.05);$$

$$\alpha_{\text{turb}} \simeq \frac{1}{100} \cdot \frac{\dot{q}_{\text{Eich}}}{\nu_{c,SOL}}.$$  

Both BOUT++ transport module mainly focuses on 2D plasma evolution to steady state on a longer transport time scale with a given radial transport coefficients, which is calculated based on the experimental profiles. More detail about the transport code can be found from the reference [33]. To calculate the divertor heat flux width from simulations, we apply Eich’s fitting formula to the parallel electron heat flux profile in steady-state phase of nonlinear simulations. Divertor heat flux width calculated based on different models are shown in table 2. From the empirical Eich scaling [29, 30] and HD model [35], the heat flux width is 5.5 mm and 5.7 mm respectively. With the effect of collisionality on parallel transport, the heat flux width will be broadened by ~11% calculated by the GHD model [36, 37] while with the effect of collisionality on radial turbulent transport the width is enhanced by a factor of 2 [38]. Here the collisionality is calculated by $\nu_{c,SOL} = \frac{\tau_{\nu,\text{pol}}}{1.0310^{18} Z_{\text{eff}}}$. Eich turbulence regression is based on the reference [38]:

$$\frac{\lambda_p}{\rho_e,\text{pol}} = (1 + (3.6 \pm 0.19)\alpha_{\text{turb}}^{1.9 \pm 0.14}) \cdot (1.2 \pm 0.05);$$

$$\alpha_{\text{turb}} \simeq \frac{1}{100} \cdot \frac{\dot{q}_{\text{Eich}}}{\nu_{c,SOL}}.$$  

Both BOUT++ transport [33, 34] and turbulence [22, 23] simulations show the heat flux width for grassy ELM is broadened 2–3 times due to the large radial turbulent transport. From the turbulence simulations, we find the effective radial turbulent transport coefficient $\chi_{\text{radial}} = 3.1$ m$^2$ s$^{-1}$, which is larger than the critical value $\chi_{\text{radial,critical}} = 1.02$ m$^2$ s$^{-1}$ calculated from the formula in the reference [12] for the transition from drift-dominated regime to turbulent dominated regime. Therefore, the heat flux width will not obey the HD-based empirical Eich scaling. It worth to mention that, even though the BOUT++ simulations and Eich turbulence model show the similar broadening (~2–3 times) for the heat flux width, the underlying physics are different. The Eich turbulence model is based on the resistive interchange and drift-Alfvén turbulence. While for the BOUT++ turbulence simulations, the width is broadened due to the large turbulence driven by ideal P–B modes with significant contribution from drift-Alfvén turbulence. Figure 10 shows the time evolution of power deposited on the divertor target with and without drift-Alfvén instability. For the case without drift-Alfvén instability, the power loading
Figure 9. (a) Particle flux at outer divertor target: the open circles are calculated from BOUT++ simulations and the blue curve is a fit to the profile using the Eich fitting formula [29]. The black stars are the experimental measurements by Langmuir probes; (b) parallel heat flux at outer divertor target plate: the black points are calculated from BOUT++ and the red curve is a fit to the profile using the Eich fitting formula.

Table 2. The SOL width based on different physics models.

| Shot East #090949 |
|-------------------|
| $\nu^{*}_{e,SOL}$ | 6.87 |
| HD/GHD: $\lambda_q$ (mm) | 5.5 |
| $\lambda_{q,Eich, nr}$ (mm) | 5.7/6.3 |
| BOUT++ transport: $\lambda_{q,transport}$ (mm) | 10.01 |
| BOUT++ turbulence: $\lambda_{q,turb}$ (mm) | 10.67 |

Figure 10. Time evolution of power deposited on the target. The black curve is the case with both peeling and drift-Alfvén linear instability drives while the red curve is the case with peeling drive only without drift-Alfvén instability drive.

5. Summary and discussion

BOUT++ turbulence simulations are conducted to uncover the fluctuation characteristics of the grassy-ELMs and its impact on the divertor heat flux width for EAST high-$\beta_p$ long-pulse grassy-ELM discharges. BOUT++ linear simulations show that the unstable modes cover a range from low-$n$ ($n = 10–15$) with characteristics of peeling–ballooning modes (P–B) to high-$n$ ($n = 40–80$) modes driven by drift-Alfvén instabilities. P–B modes are generated in the LFS with low-$n$ modes while drift-Alfvén instabilities are generated in the HFS with high-$n$ modes. Even though the drift-Alfvén instabilities dominate the linear growth phase with a wide $n$-spectrum and the fluctuation peaks on HFS, nonlinear simulations show that the ELM crash is triggered by peeling mode on LFS and fluctuation is radially localized near the bottom of pedestal. However, the drift-Alfvén turbulence delays the onset of the ELM crash, the energy loss increases with drift-Alfvén turbulence, and the fluctuation extends to peak gradient region. The saturated ELM size is 0.5% without drift-Alfvén instability while it becomes larger with drift-Alfvén instability due to the enhancement of radial turbulence transport after the ELM crash. Simulations further show that if the peeling drive is removed, the fluctuation amplitude drops by an order of magnitude and the ELM crashes disappear.

BOUT++ turbulence nonlinear simulations show that the turbulence is generated from the peak gradient of pedestal for EAST grassy ELM with shot #090949. The pedestal plasma particles and energy are transported across the separatrix into the SOL, which are then transported along the magnetic field lines, and finally deposited on the divertor plates. The simulated particle flux width is comparable with heat flux width. The magnitude of the particle flux calculated by BOUT++ is comparable with experimental measurements while the width is $\sim 1–3$ times smaller than that of the experimental measurements. The divertor heat flux width given by both BOUT++ transport and turbulence simulations are about 2–3 times larger than the estimates based on the HD model and the Eich’s ITPA multi-tokamak scaling due to strong fluctuations in grassy ELM regimes. For the case without drift-Alfvén instability, the power loading increases first after ELM crash then decays to $\sim 1/e$ times of peak heat flux, indicating that the
power loading possibly fluctuates by 50% during the grassy ELMs. This level of fluctuation is much smaller than that of type-I ELMs, which is a pulsed heat load with an amplitude variation by 10 to 100 times. While with drift-Alfvén instability, more power is slowly transported from pedestal to the SOL and the power loading on the divertor keeps more or less steady, indicating that the power loading is quasi-continuous.

The heat flux width broadening for EAST grassy ELM is similar to those from the BOUT++ simulation for ITER and CFETR, which further suggests that BOUT++ code is an effective tool to simulate the ELM events and predict the heat flux width for future machines. The broadening of heat flux width, small ELM amplitude, and quasi-continuous heat loading on the divertor indicate that operating in a grassy ELM regime will be a promising solution to meet the multiple requirements on divertor heat exhaust mitigation for the future machines like CFETR and ITER. However, due to the limited diagnostic capability, the simulation results described in this work are not able to do direct comparison with experimental measurements, but they strongly motivate the development of better diagnostics and direct comparisons with experimental data in the future.

As we mentioned in instruction, this shot #090949 is a 60 s steady-state long pulse high $\beta_p$ grassy ELM discharge, and its parameters are partly overlapped with those of the steady state scenario in CFETR phase 2 performance with $Q > 5$. This work provides confidence to apply this regime to CFETR. However, it has been generally recognized that pedestal collisionality can significantly influence ELM behaviors. Recently, Knolker et al have shown that type I ELMs heat loads get very large closer to the LH-threshold [39]. Their analysis with high heating power shows overall agreement with the Eich model for ELM energy density, but show the largest scatter in the DIII-D database with discharges marginally above the LH-threshold, which exceeds the predicted ELM energy up to twofold. For this shot #090949, high heating power is needed to get into the grassy-ELM high $\beta_p$ scenario, which is much higher than the LH-threshold [40]. This is probably true for CFETR the grassy-ELM high $\beta_p$ scenario. If the Eich model for ELM energy density holds for grassy ELMs, then the predicted ELM energy density would have smaller scatter because much higher heating power than LH-threshold power is needed to get into the grassy-ELM high $\beta_p$ scenario. The grassy ELM regime for EAST normally achieved with high pedestal collisionality. To make EAST grassy ELM experiments relevant to ITER/CFETR, the access to the grassy ELM regime with low pedestal collisionality is needed.

Acknowledgment

The authors would thank Dr Ze-Yu Li, Tianyang Xia, Ben Zhu, Xiang Liu and Tao Zhang for useful discussions. This work was supported by the National Key R&D Program of China Nos. 2017YFE0301206, 2017YFE03000402 and 2017YFE0301100, the Users with Excellence Programme of Hefei Science Center, CAS under Grant No. 2021HSC-UE014 and National Natural Science Foundation of China under Grant No. 11675037. This work was also performed under the US Department of Energy by Lawrence Livermore National Laboratory under Contract Nos. DE-AC52-07NA27344, LLNL-JRNL-833914.

ORCID iDs

Nami Li https://orcid.org/0000-0003-3870-3134
Y.F. Wang https://orcid.org/0000-0002-0368-9566
N. Yan https://orcid.org/0000-0002-2536-5853
J.Z. Sun https://orcid.org/0000-0002-2862-1437
D.Z. Wang https://orcid.org/0000-0003-0517-7318

References

[1] Loarte A. et al 2003 J. Nucl. Mater. 313–316 962
[2] Hill D.N., Petrie T., Ali Mahdavi M., Lao L. and Howl W. 1988 Nucl. Fusion 29 902
[3] Kamada Y. et al 2000 Plasma Phys. Control. Fusion 42 A247
[4] Xu G.S. et al 2019 Phys. Rev. Lett. 122 255001
[5] Labit B. et al 2019 Nucl. Fusion 59 086020
[6] Faischt M., Eich T., Harrer G.F., Wolfrum E., Brida D., David P., Grienner M. and Stroth U. 2021 Nucl. Mater. Energy 26 100899
[7] Harrer G.F. et al 2021 arXiv:2110.12664 [physics.plasm-ph]
[8] Faischt M. et al 2020 High density, high confinement, power exhaust compatible H-mode regime in TCV and ASDEX Upgrade (Nice) 28th IAEA Fusion Energy Conf. (FEC 2020) (https://conferences.iaea.org/event/214/contributions/17353/)
[9] Cathey A., Hoelzl M., Lackner K., Huijsmans G.T.A., Dunne M.G., Wolfrum E., Pamela S.P., Orain F. and Günter S. 2020 Nucl. Fusion 60 124007
[10] Nazikian R. et al 2018 Nucl. Fusion 58 106010
[11] Xu X.Q. et al 2020 Divertor heat flux broadening by grassy ELMs (Nice) 28th IAEA Fusion Energy Conf. (FEC 2020) (https://conferences.iaea.org/event/214/contributions/17601/)
[12] Xu X.Q., Li N.M., Li Z.Y., Chen B., Xia T.Y., Tang T.F., Zhu B. and Chan V.S. 2019 Nucl. Fusion 59 126039
[13] Li Z.-Y., Xu X.Q., Li N.-M., Chan V.S. and Wang X.-G. 2019 Nucl. Fusion 59 046014
[14] Deng G.Z. et al 2021 Nucl. Fusion 61 106015
[15] Wang X., Xu X., Snyder P.B. and Li Z. 2022 Nucl. Fusion 62 026024
[16] Tang T.F., Xu X.Q., Li G.Q., Chen J.L., Chan V.S., Xia T.Y., Gao X., Wang D.Z. and Li J.G. 2022 Nucl. Fusion 62 016008
[17] Gong X.Z. et al 2022 Nucl. Fusion 62 076009
[18] Li Z. et al 2021 Plasma Phys. Control. Fusion 63 035006
[19] Zhu Y.-R. et al 2020 Nucl. Fusion 60 046014
[20] Wilson H.R., Snyder P.B., Huysmans G.T.A. and Miller R.L. 2002 Phys. Plasmas 9 1277
[21] Xu X.Q. et al 2010 Phys. Rev. Lett. 105 175005
[22] Zhu B., Seto H., Xu X.-q. and Yagi M. 2021 Comput. Phys. Commun. 267 108079
[23] Xia T.Y., Xu X.Q. and Xi P.W. 2013 Nucl. Fusion 53 073009
[24] Lao L.L., St. John H., Stambaugh R.D., Kellman A.G. and Pfeiffer W. 1985 Nucl. Fusion 25 1611
[25] Meneghini O. et al 2015 Nucl. Fusion 55 083008
[26] Groebner R.J. and Osborne T.H. 1998 Phys. Plasmas 5 1800
[27] Knolker M., Osborne T., Belli E., Henderson S., Kirk A., Kogan L., Saarelma S. and Snyder P.B. 2021 Nucl. Fusion 61 046041
[28] Xia T.Y. and Xu X.Q. 2015 Nucl. Fusion 55 113030
[29] Eich T. et al 2011 Phys. Rev. Lett. 107 215001
[30] Eich T. et al 2013 Nucl. Fusion 53 093031
[31] Liang Y.F. et al 2013 Phys. Rev. Lett. 110 235002

9
[32] Xia T.Y., Gui B., Huang Y.Q., Wu Y.B. and Xiao X.T. 2019 Nucl. Fusion 59 076043
[33] Li N.M., Xu X.Q., Rognlien T.D., Gui B., Sun J.Z. and Wang D.Z. 2018 Comput. Phys. Commun. 228 69–82
[34] Li N.M., Xu X.Q., Hughes J.W., Terry J.L., Sun J.Z. and Wang D.Z. 2020 AIP Adv. 10 015222
[35] Goldston R.J. 2012 Nucl. Fusion 52 013009
[36] Li N.M., Xu X.Q., Goldston R.J., Sun J.Z. and Wang D.Z. 2021 Nucl. Fusion 61 026005
[37] Goldston R.J. et al. 2019 Generalization of the Heuristic Drift Model of the SOL for Finite Collisionality (Fort Lauderdale, Florida) APS-DPP (https://meetings.aps.org/Meeting/DPP19/Session/PO6.6)
[38] Eich T., Manz P., Goldston R.J., Hennequin P., David P., Faitisch M., Kurzan B., Sieglin B. and Wolfrum E. 2020 Nucl. Fusion 60 056016
[39] Knolker M. et al. 2018 Nucl. Fusion 58 096023
[40] Yang Q.Q. et al. 2020 Nucl. Fusion 60 076012