

Impact of flow shear on edge-localized mode energy loss for different collisionality regimes

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In this letter, we report the study of synergistic impact of E_r and collisionality on ELM size, i.e., the ELM induced energy losses. The simulation results show that for the low collisionality case, when E_r is increased by about 3 times to $\sim 3E_r$, the energy losses induced by ELM will significantly increase by a factor of 2. On the contrary, we can try to find a way to decrease the shear flow to mitigate the ELM, i.e., change the toroidal rotation while the pressure profile is kept the same, which is applied in our simulations. The experiments with periodically alternating co-NBI and ctr-NBI at high collisionality case have been carried out on EAST. The shear flow is significantly enhanced while the electron density and temperature profiles remain the same at counter-NBI (ctr-NBI) case, resulting a great suppression of ELM. The results are consistent with simulations at high collisionality case and providing a direct evidence that the radial electric field E_r can impact the ELM a lot.

Here, the simulations are conducted using the a simple three-field two-fluid model, which is extracted from a complete set of BOUT two-fluid equations with an additional effect of hyper-resistivity[9][6][1][7]. The model consists of minimum set of nonlinear equations for perturbations of the magnetic flux $A_{||}$, electric potential ϕ , and pressure P , which is described in detail in Ref. [8]. The non-ideal physics effects include diamagnetic drift, $E \times B$ drift for typical pedestal plasma.

To study the physics of nonlinear ELM dynamics, circular cross-section toroidal equilibrium (cbm18_dens6) with fixed pressure gradient near the marginal P-B instability threshold has been applied in our simulation[7]. Yet, the density and temperature profiles are different with increasing central density $n_0 = 5, 9, 12, 20 \times 10^{19} m^{-3}$, $n_{e0}(\psi) = n_0(P_0(\psi)/P_0(0))^{0.3}$, and $T_{e0}(\psi) = P_0/2n_{e0}(\psi)$. Thus, the ion-ion collisionalities on the top of the pedestal can be estimated as $\nu_{n_0=5} = 0.2 kHz$,

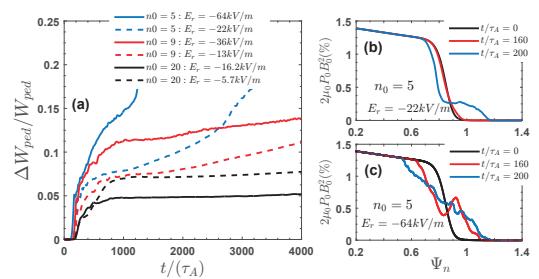


Figure 1: (a) The time history of the plasma ELM loss fraction ($\Delta W_{ped}/W_{ped}$). Profile evolution of pressure at different time for (b) $n_0 = 5 \times 10^{19} m^{-3}$ and (c) $n_0 = 20 \times 10^{19} m^{-3}$.

$v_{n_0=9} = 0.9 \text{ kHz}$, $v_{n_0=12} = 1.9 \text{ kHz}$ and $v_{n_0=20} =$

6.9 kHz . Here, for each scan of the density n_0 , we examine two cases with electric field profiles changed by a factor of ~ 3 , i.e. with $E_r = -64 \text{ kV/m}$ and $E_r = -22 \text{ kV/m}$ for $n_0 = 5 \times 10^{19} \text{ m}^{-3}$, respectively. Here, the toroidal plasma rotation is changed to keep the setup of E_r consist with force balance equation. Then, for each case with different density n_0 and electric field E_r , we reproduce the magnetic equilibrium with toroidal equilibrium module (TEQ) in CORSICA code, while keeping the plasma cross-sectional shape, total stored energy, total plasma current, pressure, the radial location of the top of the pedestal density and temperature, the ratio of the density gradient scale length to the temperature scale length profiles fixed.

To investigate the ELM energy loss scaling with density, the difference between the pre-ELM and post-ELM pressure profiles can be integrated to determine the ELM energy lost at an ELM. We define an ELM size or ELM loss fraction as $\Delta_{ELM} = \Delta W_{PED} / W_{PED} = \langle \int_{\psi_{in}}^{\psi_{out}} d\psi \oint J d\theta d\zeta (P_0 - \langle P \rangle_\zeta) \rangle_t / \int_{\psi_{in}}^{\psi_{out}} d\psi \oint J d\theta d\zeta$, the ratio of the ELM energy loss (ΔW_{PED}) to the pedestal stored energy W_{ped} , the ELM size can be calculated from each nonlinear simulation. Here, P_0 is the pre-ELM pedestal pressure, P is the pedestal pressure during an ELM event, and symbol $\langle \rangle_\zeta$ means the average over bi-normal periodic coordinate. The lower integral limit is the pedestal inner radial boundary ψ_{in} , while the upper limit is the pivot point ψ_{out} (the radial position of the peak pressure gradient), J is the Jacobian.

Figure 1 (a) illustrates the time history of the ELM energy loss fraction Δ_{ELM} for the density n_0 and E_r scan. The signals show that the ELM size keeps increasing, which means the pedestal collapse does not stop during the whole simulation period. With the comparison of the dash lines of different pedestal density, it can be found that the reduction of the ELM size can be approached by increasing the collisionality, which is in agreement with experimental observations[3][2][4]. We also calculate the ELM size at the same pedestal density but with different E_r , as shown for the solid and dash line in Figure 1 (a). For low collisionality case, i.e., $n_0 = 5$, when E_r is times by ~ 3 , the ELM size is significantly increased by $\sim 100\%$, illustrated as the blue solid line. On the contrary, for

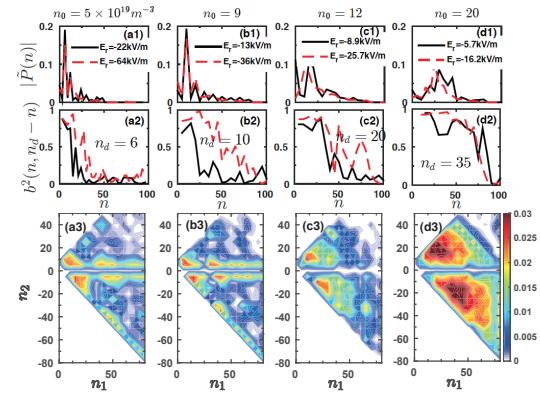


Figure 2: (a1~d1) The amplitude spectrum, (a2~d2) auto-bicoherence of the dominant mode n_d and (a3~d3) bi-spectrum with $n_0 = 5$, $n_0 = 9$, $n_0 = 12$ and $n_0 = 20 \times 10^{19} \text{ m}^{-3}$, respectively. The red dash line represent the amplitude spectrum and bispectrum at larger E_r .

high collisionality case with $n_0 = 20$ and $E_r = -16.2\text{kV/m}$, the ELM size becomes smaller comparing to the lower $|E_r|$ case with $E_r = -5.7\text{kV/m}$. The impact of E_r on pressure profiles have been further studied. Fig.1 (b) and (c) illustrate the profile evolutions at $E_r = -22\text{kV/m}$ and $E_r = -64\text{kV/m}$ with the pedestal density fixed at $n_0 = 5$. In Fig.1 (b), the pressure profile crashes at $t = 160\tau_A$ and relaxes further at $t = 200\tau_A$. Here, $\tau_A = 3.4 \times 10^{-7}\text{s}$ is the Alfvén time. When pedestal crash occurs, filaments are generated and evolve into fully developed turbulence. Here the definition of a filament is a helical coherent structure which moves and bursts radially outward. In Fig.1 (c), the pressure profile remains nearly unchanged before $t = 160\tau_A$ and start to crash at $t \sim 200\tau_A$. The profile evolutions indicate that more negative E_r can accelerate the crash of the pedestal and cause larger outward energy loss.

Fig2 (a1~b1) illustrate the amplitude spectrum in nonlinear simulations with different pedestal density just at the ELM crash. As the pedestal density decreases, the dominant mode number shifts to lower n , which is consistent with linear study[8]. The reason is that the bootstrap current plays a complex dual role in the pedestal. On the one hand, increasing currents drive peeling instabilities at low n ; while at the same time the increasing pedestal current increases the local magnetic shear, which stabilizes high- n ballooning modes.

The impact of nonlinear interaction on the ELM crash has been studied in Ref.[5]. The results indicate that the occurrence of the crash depends on both the linear MHD growth rate $\gamma(n)$ and the phase coherence time (PCT, $\tau_c(n)$), which is dependent by the relative cross phase between the potential and pressure perturbations as defined as $\delta\Phi_{\tilde{P}\tilde{\phi}}(n, \psi, \theta, t) = \arg[\tilde{P}_n(\psi, \theta, t)/\tilde{\phi}_n(\psi, \theta, t)]$, $\delta\Phi \in (-\pi, \pi]$. This theory suggests that ELMs can be controlled by changing the growth rate spectrum or by shortening the phase coherent time.

In the linear growing stage, the impact of E_r on growth rate of peeling mode and ballooning mode show great difference, as illustrated the solid and dash line in Fig.3(a). The results show that with larger amplitude of E_r , the growth rate of peeling mode change from $\gamma_{PM} = 0.060$ to 0.075 for $n_0 = 5$, while at the same time, growth rate of ballooning mode remains almost the same, which can also be seen in Fig.3(a). Yet, the mechanism how the electric field affecting (in-

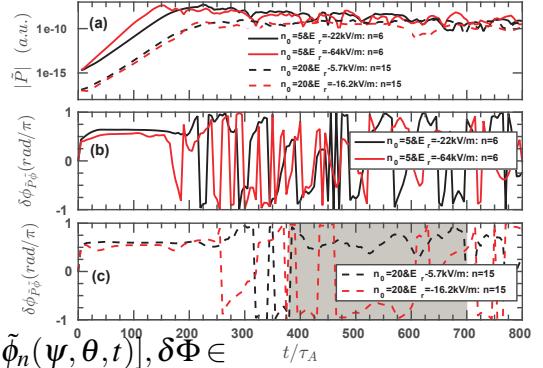


Figure 3: Simulation results for E_r (black) and $\sim 3E_r$ (red). (a) Time evolution of the toroidal Fourier component of pressure perturbation $|\tilde{P}|$; (b) (c) evolution of relative phase $\delta\phi_{\tilde{P}\tilde{\phi}}$ between \tilde{P} and $\tilde{\phi}$ at different collisionality.

creasing the drive or decreasing the damping) on the growth rate of peeling mode needs further study.

All those results indicate that the both collisionality and E_r can affect the ELM energy loss. Unfortunately, when the tokamak size increases to a large fusion reactor like ITER, the collisionality will decrease and amplitude of E_r will increase. Yet, in other words, if we can find a way to reduce the amplitude of E_r , i.e., keep the pressure gradient remain the same but speed up toroidal co-rotation of the plasma or slow down the poloidal rotation, then we may mitigate the ELM from our prediction.

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References

- [1] B. Dudson, M. Umansky, X. Xu, P. Snyder, and H. Wilson. Bout++: A framework for parallel plasma fluid simulations. *Computer Physics Communications*, 180(9):1467 – 1480, 2009.
- [2] A. W. Leonard. Edge-localized-modes in tokamaks). *Physics of Plasmas*, 21(9):–, 2014.
- [3] A. Loarte, G. Saibene, R. Sartori, D. Campbell, M. Becoulet, L. Horton, T. Eich, A. Herrmann, G. Matthews, N. Asakura, A. Chankin, A. Leonard, G. Porter, G. Federici, G. Janeschitz, M. Shimada, and M. Sugihara. Characteristics of type i elm energy and particle losses in existing devices and their extrapolation to iter. *Plasma Physics and Controlled Fusion*, 45(9):1549, 2003.
- [4] I. Nunes, G. Conway, A. Loarte, M. Manso, F. Serra, W. Suttrop, the CFN, and A. U. teams. Characterization of the density profile collapse of type i elms in asdex upgrade with high temporal and spatial resolution reflectometry. *Nuclear Fusion*, 44(8):883, 2004.
- [5] P. W. Xi, X. Q. Xu, and P. H. Diamond. Phase dynamics criterion for fast relaxation of high-confinement-mode plasmas. *Phys. Rev. Lett.*, 112:085001, Feb 2014.
- [6] T. Xia, X. Xu, and P. Xi. Six-field two-fluid simulations of peeling–ballooning modes using bout++. *Nuclear Fusion*, 53(7):073009, 2013.
- [7] X. Q. Xu, B. Dudson, P. B. Snyder, M. V. Umansky, and H. Wilson. Nonlinear simulations of peeling–ballooning modes with anomalous electron viscosity and their role in edge localized mode crashes. *Phys. Rev. Lett.*, 105:175005, Oct 2010.
- [8] X. Q. Xu, J. F. Ma, and G. Q. Li. Impact of the pedestal plasma density on dynamics of edge localized mode crashes and energy loss scaling. *Physics of Plasmas*, 21(12):–, 2014.
- [9] X. Q. Xu, P. W. Xi, A. Dimits, I. Joseph, M. V. Umansky, T. Y. Xia, B. Gui, S. S. Kim, G. Y. Park, T. Rhee, H. Jhang, P. H. Diamond, B. Dudson, and P. B. Snyder. Gyro-fluid and two-fluid theory and simulations of edge-localized-modesa). *Physics of Plasmas*, 20(5):–, 2013.