OPERATIONAL SPACE OF SMALL ELM AND ELM-FREE REGIMES ON HL-3 TOKAMAK

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High confinement mode (H-mode) with type-I ELMs will pose unacceptable transient heat fluxes on the divertor target and impurity production, thus it must be controlled or replaced by small ELMs in ITER and future fusion reactors. Natural small ELMs and ELM-free are promising operation regimes in the future fusion reactors, such as grassy ELMs achieved on JT-60U [1] and EAST [2], type-II ELMs[3] or quasi-continuous exhaust (QCE) regime obtained in ASDEX upgrade [4, 5], type-V ELMs observed in NSTX[6] and baseline small ELMs (BSEs) on JET[7]. Grassy ELMs show a dependence on high poloidal β_p, high triangularity δ and high q_{95}, while type-II/QCE is more easily obtained in high density discharge with larger triangularity and elongation. Enhanced D-alpha (EDA) regime obtained on Alcator C-Mod [7] is a ELM-free regime. Both grassy ELMs and EDA ELM-free regimes have fine core-edge integration performance. HL-3 has the ability of high current and high beta operation [8], the exploration of the operational space for small ELMs and ELM-free regimes with high operational parameters on HL-3 could provide direct reference for the burning plasma in future fusion reactors.

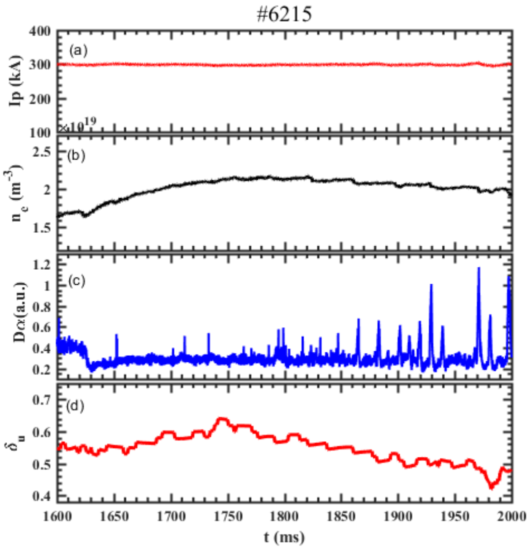

Fig. 1 The effect of the triangularity on the ELM behaviors: (a) the plasma current, (b) the plasma density, (c) the divertor D_α,and (d) the upper-triangularity.

Small ELMs and ELM-free regimes have been obtained recently on HL-3 with plasma current Ip = 0.3-1.5 MA, toroidal Bt = 0.6-1.7 T and toroidal beta $\beta_N > 3$. ELM behaviors varied under different parameters, such as plasma current Ip, electron density n_e, heating power, edge safety factor q_{95}, and plasma configuration parameters have been investigated, and the results show that **1) the ELM-free regime exhibit a strong dependence on the upper-triangularity δ; 2) Elevated density n_e and enhanced q_{95} promote the suppression of large-amplitude ELMs, achieving small ELMs in moderate-to-high upper-triangularity configurations**.

Typical experimental results are displayed in Fig. 1, which show that the ELM amplitude (Fig. 1(c)) increases obviously with the upper-triangularity (Fig. 1(d)) decreases. Fig. 2 presents a statistical analysis of the parametrical dependence between ELM-free operational and upper-triangularity. The ELMy H-mode usually occurs when the upper-triangularity is low, as marked by the blue diamonds in Fig. 2, but there is a transition to the ELM-free regime when the upper-triangularity exceeds critical threshold, as indicated by the red circles. This law is suitable for different current platform discharges. What is more, the q_{95} also has an effect on the sustainment of ELM-free regimes, beacuse high q_{95} favors the pedestal particle transport, that is possible attributed to the appearance of pedestal quasi-coherent mode (QCM), which is helpful to the sustainment of the ELM-free regime, and further analysis is ongoing.

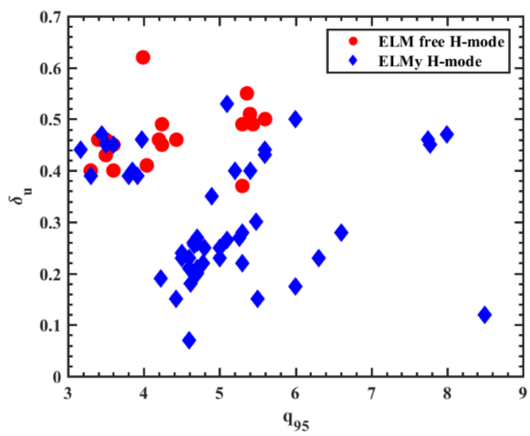

Fig. 2 The dependence of ELM-free regime on triangularity shown by the statistical results, each data represent one shot discharge.

The parameters of upper-triangularity δ_u, edge safe factor q_{95} and density n_e play an important role in achieving small ELMs on HL-3. Fig. 3 provide the corresponding statistical law, and the colorbar represent the stored energy loss ratio $\delta W_{ELM}/W_E(\%)$ induced by ELMs, which shows that there are large ELMs when operated in high upper-triangularity and medium density, and the small ELMs appear during the inter-large ELMs (large ELM mixed with small ELMs) with density increases when $\delta_u > 0.4$. Based on this mixed-ELM regime, it could be converted to small ELMs completely by two approaches, one way is to enhance the density $n_e/n_G > 0.85$, and this small ELM regime is similar to the QCE as observed on AUG[4, 5], which is considered to be triggered by the resistive ballooning mode near the separatrix; Another way is to raise the $q_{95} > 6.2$, this is similar to the requirement of grassy ELM in on JT-60U[1] and EAST[2], which required high triangularity δ and q_{95}. The stored energy loss ratio induced by small ELMs decreased to $\delta W_{ELM}/W_E(\%) < 2\%$ with high $\beta_N > 2$ and $H_{98} > 1.1$ on HL-3. In one word, it is favorable to obtain small ELMs by raising the δ_u, n_e and q_{95} based on recent experimental results, the physics probable is attributed to the effect of Shafranov shift on the pedestal stability in high δ_u and high collisionality near the separatrix in high n_e, further physical analysis will be carried out.

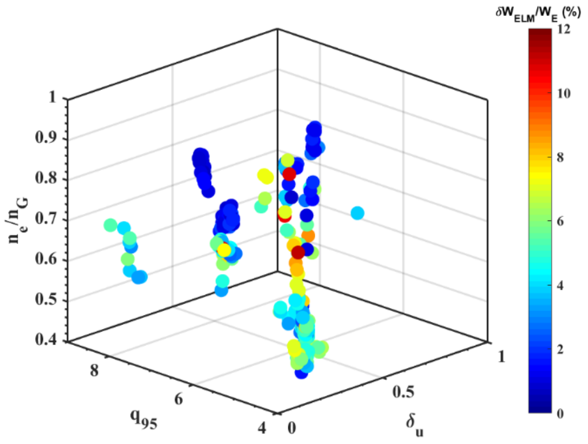

Fig. 3 The dependence of the stored energy loss induced by ELMs on upper-triangularity, q_{95} and density normalized by Greenwald limit

HL-3 tokamak has the ability of high parameter operation, aiming to resolve the critical physics questions for future reactors, thus further exploration of small ELMs and ELM-free regimes with high parameters on HL-3 is necessary. In the future, we will focus on the two points: 1) The role of q_{95} in the excitation of pedestal QCM and the underlying physics on the sustainment of ELM-free regimes; 2) The physical mechanism of small ELMs and its application in core-edge integration scheme for fusion reactors.

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REFERENCES

[1] Oyama N. *et al* 2010 *Nuclear Fusion* **50** 064014
[2] Xu G. S. *et al* 2019 *Physical Review Letters* **122**
[3] Stober J. *et al* 2005 *Nuclear Fusion* **45** 1213-1223
[4] Dunne M. *et al* 2024 *Nuclear Fusion* **64** 124003
[5] Harrer G. F. *et al* 2022 *Physical Review Letters* **129** 165001
[6] Maingi R. *et al* 2005 *Nuclear Fusion* **45** 264-270
[7] Terry J. L. *et al* 2005 *Nuclear Fusion* **45** 1321-1327
[8] Zhong W. *et al* 2024 *The Innovation* **5** 100555