3rd Asia-Pacific Conference on Plasma Physics, 4-8,11.2019, Hefei, China

Advances in understanding high-performance small/no ELM H-mode regimes

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A key challenge currently encountered in the development of tokamak fusion energy is the large-amplitude ‘edge-localized modes’ (ELMs). Demonstration of an intrinsic small or no ELM regime with good energy confinement, suitable for low rotation and steady-state operation in a metal wall environment, is one of the urgent tasks for the next step fusion development. After a very brief review of recent worldwide progress in developing small/no ELM H-mode regimes for stationary high-performance operations in future tokamak fusion reactors and advances in physical understandings, this talk will focus on the small/no ELM H-mode regimes discovered in the EAST superconducting tokamak, which is capable of long-pulse H-mode operations with metal wall and low plasma rotation as projected for a fusion reactor.

A reproducible high-performance stationary H-mode regime with high-frequency grassy ELMs, f_{ELM} = 0.5-3 kHz, has been achieved in the EAST tokamak [1] in the parameter range $q_{95} \geq 5.2$ and $\beta_p \geq 1.1$ with a confinement improvement factor H_{98y2} up to 1.4 and β_N up to 2, limited by the total heating power currently available. This regime exhibits good compatibility with high bootstrap current fraction (f_{BS} up to 70% has been achieved) and fully non-inductive operation, accessible in a broad density range, n_{el}/n_{GW} = 0.4-1.1, with the central-line-averaged electron density, n_{el}, up to $6.4\times10^{19}\mathrm{m}^{-3}$. Particle transport carried by the grassy ELMs provides strong impurity exhaust and good density control, which is important to achieve long-pulse operation with sustained high performance in a metal wall environment.

We have uncovered that this small ELM regime is enabled by a wide edge transport barrier (pedestal) with a low density gradient and a high density ratio between the pedestal foot and top. Nonlinear simulations reveal, for the first time, that the underlying mechanism for the observed small ELM crashes is the upper movement of the peeling boundary induced by an initial radially localized collapse in the pedestal, which stops the growth of instabilities and further collapse of pedestal, thus providing a physics basis for mitigating ELMs in future steady-state fusion reactors.

This regime is achieved with high poloidal beta β_p which facilitates the achievement of high bootstrap current fraction f_{BS}, thus reducing the demands on the external current drive, while high edge safety factor q_{95} can dramatically reduce the tokamak disruption risk. This regime is particularly suited for a high magnetic field steady-state tokamak reactor, such as the China Fusion Engineering Test Reactor (CFETR), as a high magnetic field can offset the reduction in fusion power associated with high q_{95}. The parameter space of the EAST grassy ELM regime appears to overlap with that of the projected baseline scenario of CFETR (q_{95} = 5.5-7, $\beta_N \sim 2$, $f_{GW} \sim 0.7$, $f_{BS} \sim 50\%$) with 1 GW fusion power production. This regime is thus proposed as the primary ELM-mitigation solution for CFETR and potentially offers a highly promising operational scenario for future steady-state fusion beyond ITER.

High separatrix density makes this regime especially suitable for operation with divertor detachment. A new detachment feedback control scheme, so-called Probe-Radiation-Detachment (PRD) control scheme, has been demonstrated, which use divertor Langmuir probe T_{et} to judge detachment entry, then use divertor radiation signal to achieve sustained detachment. Energy confinement is typically enhanced by 10% in the grassy ELM regime with neon seeding. As heat accumulation in divertor targets and tungsten sputtering by large-ELM induced heat pulses are the key obstacles to achieve long-pulse high-performance H-mode operation, the grassy ELM regime combined with detachment feedback control provides an integrated solution for power and particle exhaust and long-pulse H-mode operation, applicable to CFETR and beyond.

A non-inductive spontaneous no-ELM regime has been achieved in EAST with extensive lithium wall coating or real-time lithium powder/granules injection at relatively low heating power [2]. In this regime, the recycling neutral from the wall surface and pedestal fueling are significantly reduced. Low pedestal fueling is expected in future fusion reactors with high edge pressure. Unlike the high-recycling no-ELM regime with strong electrostatic edge coherent mode (ECM) [3], this regime is accessible at low density ($n_{el} < 3\times10^{19}$ m^{-3} at I_p = 450 kA and $n_{el} < 3.5\times10^{19}$ m^{-3}, at I_p = 500 kA) and has no clear correlation with pedestal fluctuations. ELITE/NIMROD simulations indicate that the low pedestal-foot density and the ion diamagnetic stability effect may play a key role in access to this regime. This regime changes into a low-power small-ELM regime by increasing the pedestal-foot density. The small ELMs greatly facilitate impurity control, which is critical for achieving long-pulse H-mode operations. The record 101s H-mode plasma was obtained in this regime.

References

[1] G. S. Xu et al.,“A Promising High-Confinement Regime for Steady-State Fusion”, accepted by PRL.
[2] Y. Ye, G.S. Xu*, et al.,“Experimental study on low recycling no-ELM H-mode in EAST”, accepted by Nuclear Fusion.
[3] Y. Ye, G.S. Xu*, et al.,“A stationary long-pulse ELM-absent H-mode regime in EAST” Nuclear Fusion, 57 (8), 086041 (2017).