A reproducible stationary high-confinement regime with small “edge-localized modes” (ELMs) has been achieved recently in the Experimental Advanced Superconducting Tokamak, which has a metal wall and low plasma rotation as projected for a fusion reactor. 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 the pedestal, thus providing a physics basis for mitigating ELMs in future steady-state fusion reactors.

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A key challenge currently encountered in the development of tokamak fusion energy is the erosion of the plasma-facing components by heat pulses induced by the large-amplitude “edge-localized modes” (ELMs), so-called type-I ELMs [1], which cause a quasiperiodic relaxation of the edge transport barrier, termed the “pedestal,” in the high-confinement (H-mode) plasmas [2]. The demonstration of an intrinsic small 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 in fusion development. The grassy ELM regime found in Japan Tokamak 60-Upgrade (JT-60U) [3], and also obtained in the Joint European Torus (JET) [4], showed that high-energy confinement and small ELMs can be achieved simultaneously at a low edge collisionality. A key outstanding challenge to apply this regime to future steady-state fusion is the compatibility with metal walls, which requires strong impurity exhaust, low risk of major disruptions, and high density in the plasma boundary to reduce the source and enhance the screening of impurities. However, it was obtained with a carbon wall in JT-60U and JET mostly at a low edge density [5] or with a metal wall in ASDEX Upgrade (AUG) but needs strong gas fuelling and high edge collisionality [6,7]. Furthermore, the underlying mechanism for mitigating large ELMs in this regime is still unclear [8]. Recently, we have achieved a highly reproducible stationary grassy ELM regime in the Experimental Advanced Superconducting Tokamak (EAST) with a metal wall and the aforementioned properties [9] and, uncovered, for the first time, the underlying mechanism for this grassy ELM regime via nonlinear numerical simulations.

EAST ($R_0 \approx 1.9$ m, $a \approx 0.45$ m, $B_t \approx 2.5$ T) is equipped with a water-cooled tungsten monoblock upper divertor, a molybdenum first wall, and dominant electron heating, including a low-hybrid current drive (LHCD), electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH), and two oppositely directed tangential neutral beam injection (NBI) systems, allowing low net torque injection [9]. Good energy confinement at a low rotation can be achieved in the EAST grassy ELM regime with a confinement improvement factor $H_{98,2}$ up to 1.4, especially at high poloidal beta, $\beta_p$, in the favorable $B_t$ direction, i.e., $B \times \nabla B$ toward the main X point. This regime exhibits good compatibility with the high bootstrap current fraction ($f_{BS}$ up to 70%), radiative divertor, and fully noninductive operation [9]. The access parameter space for ELM frequency $f_{ELM} > 500$ Hz is $q_{95} \geq 5.3$, $\beta_p \geq 1.1$, and $\beta_N$ up to 2, limited by the total heating power currently available. Here, $q_{95}$ is the edge safety factor at the 95% flux surface, and $\beta_N$ is the normalized beta. Higher $q_{95}$, $\beta_p$, and triangularity $\delta$ appear to facilitate the access to a higher ELM frequency. This regime is accessible in the whole density range for the $H$-mode operation with both $B_t$ directions, i.e., $f_{GW} = q_{91}/n_{GW} \geq 0.4$, even over the Greenwald density limit ($f_{GW} \sim 1.1$) with the central-line-averaged electron density $n_e$ up to $6 \times 10^{19}$ m$^{-3}$, while mostly at a relatively low density in JT-60U [5].

High $\beta_p$ facilitates the achievement of high $f_{BS}$, thus reducing the demands on the external current drive, while high $q_{95}$ can dramatically reduce the tokamak disruption...
risk [10]. This regime is particularly suited for a high magnetic field steady-state tokamak reactor, such as the China Fusion Engineering Test Reactor (CFETR) [11] with its engineering design being started recently, 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 ($q_{95} = 5.5-7$, $\beta_N \sim 2$, $f_{GW} \sim 0.7$, and $f_{BS} \sim 50\%$) with 1 GW fusion power production [11]. This regime is thus proposed as the primary ELM-mitigation solution for CFETR [12] and potentially offers a highly promising operational scenario for future steady-state fusion beyond ITER. Moreover, a low tungsten impurity concentration ($\sim 1 \times 10^{-5}$) has been achieved in this regime, which is critical for the steady-state operation of a fusion reactor. We have studied the decay of tungsten impurity radiation intensity following tungsten droplet events, which were induced by melting leading edges in the tungsten upper divertor. The decay time in the grassy ELM regime is $\sim 50$ ms, i.e., 60% shorter than that in the type-I ELM regime ($\sim 130$ ms), indicating robust tungsten impurity exhaust capability.

Figure 1 shows a typical grassy ELM discharge in EAST, obtained at $q_{95} \sim 6.8$, $\beta_p \sim 1.8$, $\delta = (\delta_\rho + \delta_i)/2 \sim 0.46$ with upper triangularity $\delta_i \sim 0.58$, elongation $k \sim 1.6$, and internal inductance $l_i \sim 1.1$, in the upper single null (USN) divertor configuration as shown in Fig. 2(g), with the distance between the separatrix and the flux surface through the lower X point at the outer midplane, $dR_{sep} \sim 2$ cm, and unfavorable $B_i$ direction, with $\sim 4.4$ MW heating power, including 1.2 MW LHCD at 4.6 GHz, 0.4 MW LHCD at 2.45 GHz, 0.5 MW ICRH, 0.3 MW ECRH, 1.5 MW co-NBI, and 0.5 MW counter-NBI. The loss power $\sim 3.7$ MW is $\sim 2.2$ times the $H$-mode threshold power. The grassy ELM regime has also been obtained with a loss power (up to 5 MW) much higher than the $H$-mode threshold power ($\sim 0.7$ MW) with favorable $B_i$ [9].

Good energy confinement with $H_{98y2} \sim 1.1$ [Fig. 1(a)] was sustained at low toroidal rotation, $\sim 10$ km/s, at both the plasma center and the edge during the counter-NBI injection [Fig. 1(b)]. The average frequency of the grassy ELMs is $\sim 2.6$ kHz [Fig. 1(d)]. The peak heat flux on the divertor target plate is largely below 2 MW/m$^2$ [Fig. 1(e)], which is reduced by more than 90% as compared to type-I ELMs. $n_{el}$ was maintained at $\sim 58\% n_{GW}$ [Fig. 1(c)] under active feedback control with the supersonic molecular beam injection (SMBI) [13]. A fully noninductive condition is nearly achieved with $f_{BS} \sim 31\%$. The collisionality at the pedestal top is $\nu_{e,ped} \sim 1$ in this discharge. The access to the grassy ELM regime appears to be insensitive to the pedestal collisionality. This grassy ELM regime has been achieved at very low collisionality $\nu_{e,ped} \leq 0.1$ in JT-60U [5] and recently in DIII-D with the assistance of Resonant Magnetic Perturbations [14], at medium collisionality $\nu_{e,ped} \sim 0.4$ in JET [4], and at relatively high collisionality $\nu_{e,ped} \sim 1$ in AUG [6] as well. Better core confinement is usually achieved in EAST with ECRH power deposition near the magnetic axis. The synergy between ECRH and LHCD at 4.6 GHz allows deeper penetration of the LHCD power into the plasma core, leading to a relatively peaked current profile, and thus a high $l_i$ [15] and hence a relatively strong Shafranov shift [Fig. 2(g)], which increases with $\beta_p + l_i/2$.

Figure 2 shows the pedestal profiles just prior to an ELM crash in a typical grassy ELM discharge in comparison with a typical type-I ELM discharge in EAST. These two discharges have similar collisionality, $\nu_{e,ped} \sim 1.6$, at $\rho \sim 0.96$. The electron density $n_{e}$, temperature $T_e$, and ion temperature $T_i$ were measured by reflectometer, Thomson scattering, and charge-exchange recombination spectroscopy, respectively. The kinetic Equilibrium Fitting code equilibria are reconstructed using a standard method [16] with the bootstrap current given by the Sauter model [17]. The grassy ELM regime is characterized by a wide pedestal, as expected at high $\beta_p$, high $\delta$, and low rotation [18], with a low density gradient in the pedestal, a high density at the separatrix, and a high density ratio between...
the pedestal foot and top, $n_{e,\text{exp}}/n_{e,\text{ped}}$ up to $\sim$60\% in contrast to typically $\sim$30\% in the type-I ELM regime, while the temperature gradients are as steep as the type-I ELM regime. The density pedestal width appears to be much wider than the $T_e$ pedestal. The main contributor to the bootstrap current is the density gradient [17]; the low density gradient and wide pedestal thus lead to a relatively low bootstrap current density and gradient in the pedestal [Fig. 2(d)]. A wide pedestal at low rotation has recently been found to be the key to achieve a no-ELM regime in DIII-D [19], where the pedestal remains stable against the instabilities responsible for ELMs, in contrast to small ELMs.

To sustain the low density gradient and high separatrix density, strong particle transport in the pedestal is needed. It is noted that once the grassy ELM regime is accessed, the low density gradient can be self-consistently sustained by strong cross-field transport through the propagation of the filaments driven by the small, high-frequency ELMs [9]. In addition, the neoclassical particle diffusion is high at high $q_95$, which also helps to enhance the pedestal particle transport. The coherent modes [20,21], which usually appear in the pedestal steep-gradient region driving particle transport in EAST, are typically absent or significantly weakened in this grassy ELM regime, except for a coherent mode near 20 kHz sometimes appearing on the pedestal top, peaking at $\rho \sim 0.81$.

Neutral fueling in the pedestal plays an important role in determining the pedestal density profile. Extensive lithium (Li) wall coating has been applied in EAST, significantly reducing the neutral recycling from the first wall due to the pumping effect of Li [22]. The main fueling is thus from divertor neutral recycling. This helps to form a wide density pedestal, as demonstrated in a systematic study on the type-I ELM regime in EAST with Thomson scattering measurements [23]. A pronounced reduction of the pedestal density gradient, increase of the pedestal width, and suppression of ELMs were also observed in National Spherical Torus eXperiment with Li wall coating [24]. Furthermore, the pumping capability of the EAST divertor is low due to blocking of the pumping slot by molybdenum shielding blocks for water pipe protection, which also helps to increase the separatrix density [25]. The high separatrix density, strong particle exhaust, and small density perturbations induced by the grassy ELMs enhance boundary impurity screening and facilitate divertor detachment at a relatively low pedestal top density, which are essential for steady-state current drive and sustainment and, thus, are beneficial for long-pulse operation in a metal wall environment.

Pedestal linear stability analysis with the ELITE code [18] indicates that the pedestal in the grassy ELM regime is near the peeling boundary [Fig. 3(a)], while the pedestal in the type-I ELM regime is more near the corner [Fig. 3(b)]. This differs from the grassy ELM regimes in JT-60U [3], JET [4], and AUG [6] or type-II ELM regimes [7], in which the pedestals were all near the high-$n$ ballooning boundary.

Pedestal linear stability analysis using the BOUT++ code with both a three-field mode and a six-field model [26] indicates that the grassy ELMs and type-I ELMs are both triggered by marginally unstable intermediate-$n$ peeling-ballooning modes (PBMs) and the radial envelopes of the most unstable PBMs for the type-I ELM regime (toroidal
mode number \( n = 20 \) are even narrower than the grassy ELM regime \(( n = 15 \) (see Supplemental Material [27]) and are mostly localized in the pedestal steep-pressure-gradient region, which thus does not explain why the pedestal collapse in the type-I ELM regime is wider. Therefore, the linear analysis indicates that the PBMs responsible for the onset of the grassy ELMs are not necessarily high-\( n \) ballooning modes or more localized than the type-I ELMs.

Nonlinear simulations, using the BOUT++ code with a six-field model [26], have now revealed the underlying mechanism of the grassy ELMs. The profiles in Fig. 2 are used as the initial profiles for the ELM nonlinear evolution. The simulation setups and involved dissipation parameters are introduced in Supplemental Material [27]. For each time point during the evolution, we calculate the pedestal PBM stability diagrams [Figs. 4(k) and 4(l)], using the dynamic profiles averaged in the toroidal angle [Figs. 4(a)–4(h)] generated from the nonlinear simulations to track the motions of the working point and stability boundary. The simulations indicate that the flattening of pressure or density profiles associated with the grassy ELM is localized only in a small radial area around the middle of the pedestal, where the PBM linear growth rate is maximum and the pressure or density gradients near the pedestal top and foot become even steeper [Figs. 4(a) and 4(c)]. Note that these two steepened regions are also steep-current-gradient regions [Fig. 4(e)], where the kink drive is located. The pedestal current profile is almost fixed during this period [Figs. 4(e) and 4(f)], as the current relaxation is on the resistive current diffusion time, which is quite long \((\sim 10 \text{ ms})\) in the pedestal of the current experiments and will be even longer in future reactor-size plasmas, as the pedestal collisionality will be even lower. Thus, the working point almost does not move vertically, while both the peeling and ballooning boundaries expand significantly [Fig. 4(k)], so that the working point falls into the stable region just shortly after the initial ELM crash. Thus, both instability growth and pedestal collapse stop [Fig. 4(i)], and the inverse cascading of PBM toroidal mode numbers stops at intermediate \( n \), leading to a small ELM crash. Then, the pedestal recovers to its precrash state (Fig. 4 at \( t = 600 \tau_A \)).

The expansion of the peeling boundary is due to the stabilization of the kink or peeling modes by the steepened pressure gradients near the pedestal top and foot. It is well known that the pressure gradient is stabilizing for the kink or peeling modes when the flux-surface average magnetic curvature \( \langle \kappa \cdot \nabla \rho \rangle \) is favorable [28]. The strong plasma shaping, i.e., high \( \delta \) and closeness to a double-null configuration, as well as the compression of the flux surfaces at the low field side due to a strong Shafranov shift at high \( \beta_p + l_i/2 \), can significantly increase the flux-surface averaged favorability of the curvature as well as the Pfirsch-Schlüter current, which can enhance this stabilizing effect [28]. This may explain why the strong shaping, high \( \beta_p \), and high \( l_i \) are favorable for the access to the grassy ELM regime. Furthermore, the strong magnetic shear associated with the high \( q_{95} \) helps to stabilize the pedestal PBMs and also reduces the coupling to the low-order rational surface in the plasma interior area. In addition, the expansion of the ballooning boundary is mainly due to an inward motion of the \( \alpha \) peak [Fig. 4(g)] [29]. Here, \( \alpha \) is the normalized pressure gradient.

For the type-I ELM, the pressure or density gradients are reduced immediately in the whole pedestal region [Figs. 4(b) and 4(d)] with a collapse front extending deeply into the plasma interior area, consistent with the experimental observations. The \( \alpha \) peak moves inward to where \( q \) is lower [Fig. 4(h)]; thus, a higher pressure gradient...
is needed to achieve the same $\alpha$ value, as $\alpha \propto q^2 \nabla p$. This effect counteracts the pressure gradient reduction, and thus the peeling boundary shifts only slightly upward, while the working point moves nearly horizontally to the left with the decrease of $\alpha$, making the working point stay in the unstable region. Therefore, the instability growth and pedestal collapse continues [Fig. 4(j)], and the inverse cascading proceeds from intermediate $n$ to low $n$, leading to a large ELM crash. In addition, the ballooning boundary is reduced, mainly due to a decrease in the diamagnetic stability effect.

Further nonlinear simulations by varying the pedestal pressure and current profiles using the _VARYPED_ code [16] indicate that the qualitative behavior of ELM crashes and the mechanism of grassy ELMs are insensitive to a certain variation of the initial linear growth rates or closeness of working point to stability boundary (see Supplemental Material [27]). However, to make the mechanism work, a wider pedestal and flatter density profile are important, as it gives a relatively lower pressure gradient and bootstrap current [Figs. 2(c) and 2(d)], thus a mild initial instability development and pedestal crash. If the initial crash directly reaches the pedestal top before the mechanism comes into play, then a large ELM will inevitably appear. This therefore suggests that a wide pedestal coupled with a particularly wide and flat density pedestal is essential to achieve such a grassy ELM regime.

In summary, a stationary, high-confinement, small grassy ELM regime has been demonstrated in EAST. Future steady-state tokamak fusion reactors beyond ITER, such as CFETR, are designed to operate in a similar parameter space to this grassy ELM regime, i.e., at high $q_{95}$, high $\beta_p$, and low rotation with a metal wall, high $f_{GW}$, high $f_{BS}$, and a radiative divertor under nearly fully noninductive conditions [11]. The EAST grassy ELM regime has been demonstrated to be compatible with all these properties. The strong tungsten impurity exhaust capability and high separatrix density make this regime especially suitable for the metal wall environment. The nonlinear simulations reveal, for the first time, that the key mechanism for the grassy ELMs is the expansion of the peeling boundary due to radially localized steepening of the pedestal pressure gradient induced by a radially localized collapse [28]. This new understanding points to a potentially very promising direction for future pedestal optimization to mitigate large ELMs.

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*Corresponding author.*

gsxu@ipp.ac.cn

*Corresponding author.*

bnwan@ipp.ac.cn

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