A PROMISING GRASSY ELM REGIME FOR HIGH-PERFORMANCE STEADY-STATE OPERATIONS WITH METAL WALL IN EAST AND CFETR

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Abstract

A highly reproducible stationary grassy ELM regime has been achieved in the EAST superconducting tokamak with water-cooled tungsten upper divertor and molybdenum first wall, exhibiting good energy confinement ($H_{95y2}$ up to 1.4), strong tungsten impurity exhaust capability, and good compatibility with the low rotation, high density (up to $\sim 1.1n_{GW}$), high bootstrap current fraction ($f_{BS}$ up to 70%), radiative divertor and fully non-inductive operation. The accessible parameter space of the EAST grassy ELM regime ($f_{ELM}>0.5kHz$) is $q_{95} \geq 5.3$, $\beta_p \geq 1.1$, $n_{e95}/n_{GW} \geq 0.46$, $\beta_n$ up to 2, limited by the total heating power currently available. High $q_9$, $\beta_p$ and triangularity $\delta_u$ appears to be beneficial for access to this regime. This parameter space overlaps with that of the projected baseline scenario ($q_{95}=5.5-7$, $\beta_N \sim 2$, $f_{BS} \sim 50\%$, $n_{e95}/n_{GW} \sim 0.7$) of the Chinese Fusion Engineering Test Reactor (CFETR), which is a next-step steady-state tokamak fusion reactor currently under active engineering design. This regime is characterized by a relatively high $n_{e95}$, wide pedestal, moderate pedestal density gradient and low pedestal bootstrap current. Nonlinear pedestal simulation with the BOUT++ code has uncovered the underlying mechanism for the generation of the small ELMs. Radiation power feedback control has been developed in the grassy-ELM regime with pulsed divertor impurity seeding (20% $n_{e95}$ on and 80% D$_2$), successfully suppressing the target electron temperature and surface temperature without confinement degradation. This grassy-ELM regime thus offers a highly promising approach towards achieving long-pulse high-performance H-mode operations in EAST, with potential application to CFETR as the baseline scenario and a primary solution for the control of ELMs and divertor heat load.

1. INTRODUCTION

The Chinese Fusion Engineering Test Reactor (CFETR) is a next-step steady-state tokamak fusion reactor with a duty cycle $\sim 30\%$, currently under active engineering design in China [1]. Due to the projected high neutron fluence, the CFETR may not be able to use the in-vessel resonant magnetic perturbations (RMPs) for ELM control. Demonstration of an intrinsic small-ELM H-mode regime with good energy confinement, suitable for tungsten wall and steady-state operation, is one of the urgent tasks for establishing the physics basis of CFETR. The grassy ELM regime found in JT-60U [2] showed that high energy confinement and small ELMs can be achieved simultaneously at low edge collisionality. However, it was obtained with carbon wall and mostly at low density, $n_{e95}/n_{GW} < 0.5$ [3]. In JET, the grassy ELM regime has also been obtained, but a high internal inductance $l \geq 1.1$ (peaked current profile) is typically needed [4]. The type-II ELM regime in ASDEX-U is another option. However, pure type-II is obtained only at high density, $0.85<n_{e95}/n_{GW}<0.95$ [5]. Recently, a highly reproducible stationary grassy ELM regime has been achieved in the EAST superconducting tokamak suitable for steady-state operation.

EAST ($R_{TF}=1.9m$, $a=0.45m$, $B_t=2.5T$) is now equipped with actively water-cooled tungsten upper divertor, graphite lower divertor, molybdenum first wall and dominant electron heating using RF waves [6], including 4.6 GHz and 2.45 GHz LHCD, ECRH, ICRF and two tangential NBIs that are steered into opposite toroidal directions. Lithium wall conditioning is conducted routinely with 10-15g per day. Two cryopumps are behind the outer targets of the upper/lower divertors. The water-cooled graphite guide limiters of LHCD and ICRF antennas have been upgraded to water-cooled tungsten, which successfully suppressed hot spots on the 4.6G-LHCD guide limiter in 2018 [7], allowing the 4.6G-LHCD to operate stably at 3MW (only 2MW before), with reduced $Z_{eff}$ in average.

2. PARAMETER SPACE OF THE EAST GRASSY ELM REGIME

Fig.1 shows statistics of ELM frequency of H-mode discharges on EAST in 2016-2018 with the plasma stored energy $W_p>120kJ$. The ELM size generally decreases with increasing ELM frequency, $f_{ELM}$. Since the tungsten upper divertor has higher power handling capability than the graphite lower divertor, all these discharges were operated in the USN configuration with $dR_{sep} \sim 2cm$ (the lower X point is still in the vacuum chamber). These data include some discharges with favorable $B_i$ direction in 2018 which typically have lower L-H transition power.
threshold \([8]\) than unfavorable \(B_t\). The grassy ELM regime has been obtained with both \(B_t\) directions. The statistics indicate that the most sensitive parameters for the access to grassy ELM regime is \(q_{95}\) and \(\beta_p\). The lower boundaries for accessing the regime with \(f_{\text{ELM}}>0.5\text{kHz}\) is \(q_{95} \geq 5.3, \beta_p \geq 1.1\) and \(n_{e_0}/n_{GW} \geq 0.46\). Higher \(q_{95}\), \(\beta_p\) and upper triangularity \(\delta_u\) appear to be beneficial for the access to higher ELM frequency, which is consistent with the JT-60U grassy-ELM prescription. Although the accessible parameter space is similar to that of JT-60U in terms of \(q_{95}\), \(\beta_p\) and \(\delta_u\), it appears to be in the different density range. The grassy ELM regime in JT-60U is accessible at low density \(n_{e_0}/n_{GW} < 0.5\) [3], while at high density in EAST. It may be due to the different wall materials: metal in EAST vs. carbon in JT-60U. In this regard, the EAST grassy ELM regime is similar to the type-II ELM regime, i.e., accessible at high density. However, pure type-II ELM regime is accessible only in a narrow density range, \(0.85 < n_{e_0}/n_{GW} < 0.95\), in ASDEX-U [5]. The EAST grassy ELM regime appears to be accessible in a much wider density range. Note that the metal wall, tungsten guide limiters of RF antennas and NBI shine-through do not allow EAST to operate at even lower density, and thus very few H-mode discharges have been obtained in the low density range, \(n_{e_0}/n_{GW} < 0.4\). Further investigation is needed to verify whether the grassy ELM regime is accessible at even lower densities. In addition, ELM suppression by LHCD was found previously in EAST under certain conditions due to the LHCD-induced magnetic topology change at the plasma edge [9]. However, access to this regime appears to be independent of the LHCD power and the grassy ELMs are also obtained without LHCD. Thus, the LHCD can be excluded as a basic mechanism for the generation of the grassy ELMs.

![FIG. 1. ELM frequency as a function of \(q_{95}, \beta_p, n_{e_0}/n_{GW}, \) upper triangularity \(\delta_u\) and LHCD power \(P_{\text{LHCD}}\) for EAST H-mode discharges with the plasma stored energy \(W_p > 120\text{kJ}\), indicating the accessible parameter space of the high-frequency small-ELM regime \(f_{\text{ELM}}>0.5\text{kHz}\) is controlled by \(q_{95} \geq 5.3, \beta_p \geq 1.1\) and \(n_{e_0}/n_{GW} \geq 0.46\). High upper triangularity \(\delta_u\) appears to be beneficial for access to this regime. In addition, access to this regime appears to be independent of the LHCD power. The magenta curves indicate the lower access boundaries for these parameters.](image1)

![FIG. 2. Poloidal beta \(\beta_p\) vs. energy confinement factor \(H_{98y2}\) for the pure RF heated (LHCD+ECRH) H-mode discharges with the plasma stored energy \(W_p > 110\text{kJ}\).](image2)

Fig. 2 shows the statistics of \(\beta_p\) vs. \(H_{98y2}\) for the pure RF heated (LHCD+ECRH) H-mode discharges with \(W_p > 110\text{kJ}\). For these plasmas the interplay between ECRH and 4.6G-LHCD leads to peaked current profile; \(l_i\) is mostly in the range of 0.9-1.15. As there is no NBI, the fast ion contribution to the plasma stored energy is negligible. \(\beta_p\) appears to increase linearly with \(H_{98y2}\), \(\beta_p = 2.35H_{98y2} - 1.12\). Better energy confinement and higher \(\beta_p\) are obtained with favorable \(B_t\) than unfavorable \(B_t\) in most cases. Since the \(\beta_p\) is an important parameter for access to the grassy ELM regime, the best energy confinement in EAST is obtained so far in the grassy ELM regime with high \(\beta_p\) and favorable \(B_t\).
Aiming at steady-state operation with low disruption risk, CFETR resorts to high magnetic field, $B_{t0} \approx 6.5$T. The baseline scenario of CFETR is projected to operate at a relatively high $q_{95} = 5.5-7$ with a moderate $\beta_N \approx 2$, which is well below the MHD stability boundary [1]. In addition, the CFETR baseline scenario will use a conservative bootstrap current fraction, $f_{BS} \approx 50\%$, and a relatively low density, $n_{el}/n_{GW} \approx 0.7$, allowing for high external current-drive efficiency and low external current-drive power to achieve high fusion gain $Q$. $\beta_N \approx 2$, $f_{BS} \approx 50\%$ and $n_{el}/n_{GW} \approx 0.7$ at $q_{95} \approx 7$ have been achieved in the EAST grassy ELM regime with the heating power currently available. The parameter space of the EAST grassy ELM regime appears to overlap with the projected parameter space of the CFETR baseline scenario, as shown in Fig. 3. It offers thus a highly promising operational regime for steady-state tokamak fusion reactors, potentially applicable to CFETR and beyond.

For the EAST grassy ELM regime, better energy confinement is usually achieved with ECRH power deposition near the magnetic axis where the ECCD efficiency is high. The synergy between ECRH and 4.6G-LHCD allows deeper penetration of the 4.6G-LHCD power into the plasma core, leading to a relatively peaked current profile with $l_i \geq 0.8$ for $f_{ELM} > 0.5$kHz. The $l_i$ is typically near 1.1 at $q_{95} = 6-7$ and $I_p \approx 0.4$MA. The high $l_i$ (peaked current profile) [10] and the deposition of a large portion of power in the plasma core region where the electron thermal conductivity is lowest were found responsible for the observed good core energy confinement [11].

Low tungsten impurity concentration ($\approx 1 \times 10^{-5}$) 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 tiles in the upper divertor. The decay time of W in the grassy ELM regime is $\approx 50$ms, i.e., 60% shorter than that in the type-I ELM regime ($\approx 130$ms), indicating robust tungsten impurity exhaust capability. The overall tungsten impurity concentration is low in the EAST grassy ELM regime, possibly due to the following factors: 1) Pumpout of impurities in the core by the ECRH and LHCD; 2) Low tungsten source due to low sputtering induced by the grassy ELMs; 3) Strong tungsten exhaust carried by filamentary transport across the pedestal driven by the high-frequency grassy ELMs; 4) Strong neoclassical impurity diffusion at high $q_{95}$.

3. EDGE PROFILE CHARACTERISTICS OF THE EAST GRASSY ELM REGIME

Fig. 4 shows the pedestal profiles just prior to an ELM crash in a typical grassy ELM discharge ($q_{95} \approx 6.8$, $\beta_N \approx 1.8$, $\delta_\tau \approx -0.58$, $\delta = (\delta_u + \delta_t)/2 \approx -0.46$, $\kappa \approx 1.56$, $l_t \approx 1.1$, $n_{el}/n_{GW} \approx 0.6$, $f_{BS} \approx 31\%$, $H_{98y} \approx 1.1$, $V_{98y} \approx 10$km/s, USN, $dR_{sep} \approx 2$cm, unfavourable $B_z$, $f_{ELM} \approx 2.6$kHz, heating power $\approx 5$MW) in comparison with a typical type-I ELM discharge in EAST. These two discharges have similar collisionality $v^* \approx 1.6$ at $\rho \approx 0.96$. $n_s$, $T_e$ and $T_i$ were measured by reflectometry, Thomson scattering and charge-exchange recombination spectroscopy, respectively. The kinetic EFIT equilibria are reconstructed with bootstrap current given by the Sauter model [12].
The EAST grassy ELM regime appears to be characterized by: 1) High $n_e$ at the separatrix with $n_{e,\text{sep}}/n_{e,\text{ped}} \approx 50\%$ in contrast to $\sim 30\%$ for type-I ELMs, as shown in Fig. 5; 2) Wide pedestal, as the pedestal width generally increases with global $\beta_p$, $\Delta P_{\text{ped}} \propto \beta_p^{1/2} \Delta P_{\text{ped}}^{1/2}$ [13]; 3) Moderate pedestal density gradient, as the $n_e$ pedestal width is typically much wider than the $T_e$ pedestal; 4) Low pedestal bootstrap current, as the main contributor to bootstrap current is the $n_e$ gradient [12].

There are several possible explanations for the formation of high separatrix $n_e$ and moderate pedestal $n_e$ gradient: 1) Strong particle transport across the pedestal through the propagation of the filaments driven by the high-frequency grassy ELMs; 2) High neoclassical particle diffusion at high $q_{95}$; 3) The pumping capability of EAST upper divertor is quite low due to the blocking of pumping slot by molybdenum shielding blocks for water pipe protection, which may increase the SOL $n_e$; 4) Lithium wall coating reduces the recycling from the divertor and main chamber, thus reducing pedestal fueling, which helps to form a wide density pedestal. The pronounced reduction of pedestal density gradient, increase of pedestal width and suppression of ELMs, were also observed in NSTX with lithium wall coating [14]. Note that the moderate pedestal $n_e$ gradient should not be induced by coherent modes, as the edge coherent modes [15], which appear sometimes in the pedestal steep gradient region in EAST, are typically absent or significantly weakened in the high-performance grassy-ELM discharges. The high $n_{e,\text{sep}}$ and small density perturbations associated with the grassy ELMs enhance boundary impurity screening and facilitate divertor detachment at a relatively low pedestal top density $n_{e,\text{ped}}$, which are essential for steady-state current drive and sustainment, and thus are beneficial for long-pulse operation in a metal wall environment.

4. \textbf{BOUT++ SIMULATIONS UNCOVER THE UNDERLYING MECHANISM FOR THE GENERATION OF THE GRASSY ELMs}

Fig. 6 shows the nonlinear simulations of grassy ELM crash and type-I ELM crash using BOUT++ code with a 6-field model [16]. The profiles in Fig. 4 are used as the initial profiles of the nonlinear evolution. The simulations find that the perturbations associated with the grassy ELM are localized in the pedestal steep gradient region, while those associated with the type-I ELM extend to a large radial area with a pressure collapse front propagating radially inward, as shown in Fig. 6 (a) and (b), consistent with the experimental observations. The simulations also indicate that the pedestal current-profile relaxation is much slower than the pressure-gradient collapse. The current-profile relaxation is on the resistive current diffusion timescale, which is quite long ($\sim 10\text{ms}$ in this case) in the pedestal, and will be even longer in future reactor-size plasmas as the pedestal collisionality will be much lower. In contrast, the pressure gradient collapse is typically of a few hundreds of $\mu\text{s}$, mainly driven by the radial \textbf{ExB} convection, which is generally independent of the collisionality.
These simulations uncover that the key difference between the grassy ELM and the type-I ELM is whether the pedestal current can continue to destabilize the low-n peeling-ballooning modes (PBMs) when the pressure gradient is reduced. For the type-I ELMs, the high current density and gradient in the pedestal (Fig. 6d) can continue to destabilize the kink/peeling-dominated low-n PBMs, even when the pressure gradient is significantly reduced (Fig. 6b), as reflected by the decrease in the toroidal mode number of the most unstable linear PBMs from intermediate \( n \) (Fig. 6g) to low \( n \) (Fig. 6h). In this case, the pedestal collapse continues with the collapsing front propagating radially inward (Fig. 6f), leading to large ELMs. In contrast, for the grassy ELMs, the pedestal current density and gradient are inherently lower (Fig. 6c), hence the pedestal stability can improve intrinsically against the low-n PBMs. In addition, the strong magnetic shear associated with the high \( q_{95} \) helps to stabilize the pedestal low-n PBMs and also reduces the coupling of the pedestal PBMs to the low order rational surface in the plasma interior area. Furthermore, the compression of the magnetic surface at the low-field-side plasma edge due to a strong Shafranov shift \( \Delta \) at high \( \beta_p \) in combination with high-\( \delta \) effects can significantly enhance the flux-surface averaged favorability of the magnetic curvature, \( \langle \chi Vp \rangle \), which stabilizes the pedestal low-n PBMs [17]. Therefore, the pedestal current cannot sustain the low-n PBMs when the pressure gradient is just slightly reduced (Fig. 6a), so that all PBMs quickly die away (Fig. 6e), leading to small ELMs.

It turns out that the key difference is the kink/peeling-dominated low-n PBMs, as indicated by the simulations that the fluctuation amplitude peaks at low \( n \) shortly after the type-I ELM starts, while it peaks at intermediate \( n \) throughout the grassy ELM period. Compared with the intermediate \( n \), the kink/peeling dominated low-n PBMs usually evolve into larger structures and penetrate deeply into the plasma interior area during the nonlinear evolutions, thus inducing a big crash, as demonstrated in the previous BOUT++ simulations [18]. From this analysis, one can see that the parameter space (high \( q_{95} \), \( \beta_p \) and \( \delta \)) is insufficient for access to the grassy ELM regime; a low pedestal bootstrap current, which is associated with the pedestal profiles, is needed. The low-n PBMs are driven mainly by current density and current gradient. The high \( l_i \) is an indication of low edge current.

5. COMPATIBILITY OF EAST GRASSY-ELM HIGH-LI REGIME WITH HIGH BOOTSTRAP CURRENT FRACTION FULLY NONINDUCTIVE OPERAION

The parameter space of the EAST grassy ELM regime has been extended towards high \( \beta_p \) (up to 3.4 at \( q_{95}=10.5 \) and \( l_i=0.25 \text{MA, #80181} \)) in 2018. Fig. 7 shows a typical high-\( \beta_p \sim 2.9 \) fully non-inductive discharge with high Greenwald density fraction, \( n_e/n_{GW}=0.9 \) (\( n_e=4 \times 10^{20} \text{m}^{-3} \)), high \( l_i=1.6 \) and moderate \( \beta_p=1.8 \), with total heating power 4.78MW, including 2.1MW co-NBI, 1.33MW 4.6G-LHCD, 0.35MW 2.45G-LHCD, 0.8MW ECRH and 0.2MW ICRF. Good energy confinement, \( H_{98y2}=1.3 \), and high bootstrap current fraction, \( f_{BS}=67\% \), have been achieved in this discharge, calculated with ONETWO code, confirmed with TRANSP code. The ELM frequency is 0.8-1kHz. Fig. 8 shows the radial profiles at 5.7s. The kinetic EFIT equilibrium, as shown in Fig. 8 right, is reconstructed with bootstrap current given by the Sauter model [12]. The fast ion contribution to the stored energy is ~42kJ. This discharge was obtained at high \( q_{95}=9 \) and low \( l_i=0.3 \text{MA} \) in the USN configuration with unfavorable \( B_t \). At CFETR relevant \( q_{95}=5.5-7 \) (\( l_i=0.4-0.5 \text{MA} \), \( \beta_p \sim 2 \) and \( f_{BS}=50\% \) can be achieved in this regime with favorable \( B_t \), limited by the total heating power currently available.

FIG. 7. A typical EAST grassy-ELM, high-l_i, fully non-inductive discharge with bootstrap current fraction \( f_{BS}=67\% \) at \( q_{95}=9 \), USN, unfavorable \( B_t \).

FIG. 8. Radial profiles as a function of the normalized toroidal magnetic flux at 5.7s in a typical EAST grassy-ELM, high-l_i, fully non-inductive discharge with bootstrap current fraction \( f_{BS}=67\% \). (a) Electron density, (b) electron temperature (red) and ion temperature (blue), (c) total pressure, (d) bootstrap current density, (e) safety factor, (f) magnetic shear. Kinetic EFIT equilibrium on the right.
6. COMPATIBILITY WITH FEEDBACK-CONTROLLED RADIATIVE DIVERTOR

EAST aims at 400s long-pulse high-performance H-mode operation with a bootstrap current fraction $f_{BS}>50\%$ and good energy confinement, $H_{98y2}>1$, to demonstrate the baseline scenario for steady-state operation in CFETR. A long-pulse H-mode plasma of 101s has been achieved in 2017 with source heating power $P_{\text{source}}\sim 3$MW (pure RF heating: LHCD plus ECRH), $H_{98y2}\sim 1.1$ and $f_{BS}\sim 32\%$. One of the major challenges which currently limits the total heating power is the divertor heat load. High-performance H-mode discharges $>20$s have been achieved in the 2018 experimental campaign, with $P_{\text{source}}\sim 4$MW, $H_{98y2}\sim 1.2$, $n_{e0}/n_{GW}\sim 0.7$, $\beta_p\sim 1.9$, $\beta_n\sim 1.55$ and $f_{BS}\sim 45\%$. However, the peak surface temperature $T_{\text{div}}$ on the outer target of the upper tungsten divertor, as measured by inferred cameras, increased to $\sim 600^\circ\text{C}$ during a 21s discharge, still without reaching saturation. After 6 discharges of such $\sim 20$s long-pulse H-mode plasma, a small leak appeared in the upper divertor water cooling connector. To achieve the 400s goal, on the one hand the divertor surface temperature must be controlled. On the other hand, the electron temperature at the divertor target should be $T_{\text{e}}<10\text{eV}$, as the physical sputtering yields of tungsten by low-Z seeded radiating impurities increase rapidly for $T_{\text{e}}>10\text{eV}$ [19]. Radiative divertor offers an attractive option. However, how to achieve a long-pulse stationary H-mode plasma with radiative divertor but without energy confinement degradation is a great challenge. Full detachment is usually accompanied by energy confinement degradation [19], which is unsuitable for high-performance steady-state operation. Therefore, this experiment does not intend to achieve divertor detachment in steady state, instead, aims to achieve highly dissipative divertor to sufficiently reduce heat load, target electron temperature and surface temperature. Radiative divertor feedback control has been achieved in the grassy-ELM regime with pulsed divertor impurity seeding in 2018. The total radiation power, $P_{\text{rad}}$, is maintained near the programmed $P_{\text{rad}}$ target value, as shown in Fig. 9. The target electron temperature and surface temperature have been successfully suppressed without confinement degradation. This experiment has demonstrated the comparability of the grassy ELM regime with the radiative divertor, thus offering an integrated solution for both ELM-induced transient and steady-state divertor heat load.

![Figure 9](image-url)  
*FIG. 9. Radiation power feedback control in the grassy-ELM regime with pulsed impurity seeding (20% neon and 80% D$_2$, 50ms pulse, 200ms minimum pulse interval) from the outer target plate below the strike point in the upper divertor at the O-Port (as shown in the middle inset). The figure on the right shows the ion saturation current profiles on the outer targets at D-Port and O-Port measured by divertor Langmuir probes. The magenta dashed lines indicate the neon seeding position. The red curves show the strike point positions calculated with the EFIT magnetic reconstruction. $P_{\text{source}}\sim 4$MW, $n_{e0}\sim 4.5\times10^{19}\text{m}^{-3}$, $q_{95}\sim 7.1$, USN, favorable B$_t$. The mixed Neon/D$_2$ gas was seeded through gas puff from the outer target plate below the strike point in the upper divertor at the O-Port, as shown in Fig. 9 middle inset. The seeding effect is significantly reduced when the gas is seeded above the strike point, as most seeding gas directly enters the private flux region without ionization. When the seeding pulse width is longer than 150ms, $P_{\text{rad}}$ increases uncontrolledly until H-L back transition, which is then frequently followed by a disruption, especially for favorable $B_t$, i.e., with $B\times VB$ pointing upwards, as a MARFE-like intense radiation ring forms on the high-field side near the upper divertor entrance. This radiation ring forms near the lower divertor entrance with unfavorable $B_t$. The $B_t$ direction dependence may be associated with the $E\times B$ drift in the divertor. In order to avoid the H-L back transition, $P_{\text{rad}}$ feedback control has been applied with pulsed impurity seeding. Through experimental testing, we found that the optimized setting is 20% neon and 80% D$_2$, with 50ms pulse width and 200ms minimum pulse interval. We have tried a 5% neon and 95% D$_2$ gas mixture; however, it was found to be insufficient to maintain divertor detachment at high heating power, $>3$MW. Note that the $P_{\text{rad}}$ perturbation is sufficiently small with the 50ms pulse width, and the 200ms pulse interval is an optimized value for the recovery of $P_{\text{rad}}$. The delay time for the divertor gas puff pipeline is $\sim 100$ms.*
Fig. 10 shows 3 adjacent discharges with increasing seeding gas and $P_{\text{rad}}$. The $P_{\text{rad}}$ target is 0.7MW for shot #81574 and 1.2MW for #81575 and #81576. The seeding valve voltage is 3.6V for #81574 and #81575 and 3.8V for #81576, as shown in the right table. (b) The plasma stored energy slightly increases, suggesting that the energy confinement property was maintained.

7. COMPATIBILITY WITH OVER GREENWALD DENSITY LIMIT OPERATION

A stationary grassy ELM plasma over Greenwald density limit ($n_{\text{el}}/n_{\text{GW}}>1$) has been achieved in EAST with $n_{\text{e}}=5\times10^{19}\text{m}^{-3}$ at $q_{95}=8$ and $I_p=0.3\text{MA}$ in the USN configuration with unfavorable $B_t$, as shown in Fig. 11. However, the energy confinement degrades from $H_{\text{98y}}=1.2$ to ~0.8, as compared with a discharge at lower density ($n_{\text{e}}/n_{\text{GW}}=0.8$ with $n_{\text{e}}=3.5\times10^{19}\text{m}^{-3}$). The mechanism for the confinement degradation at high density is still unclear. The on-axis toroidal rotation velocity decreases from ~30 to ~10km/s in the co-$I_p$ direction, which may be partially responsible for the energy confinement degradation. Moreover, the LHCD power loss in the SOL increases at high density [20], which may lead to an overestimate of the LHCD absorption power. In addition, a higher ELM frequency is obtained at higher density, as shown in Fig. 11 (g). Further experiment is needed to understand the energy confinement degradation near the Greenwald density limit, and further optimization is needed to improve the energy confinement at high density.

8. SUMMARY

The grassy ELM regime in EAST is a highly robust and reproducible high-performance operational regime. High $q_{95}$, $\beta_p$ and $\delta_u$ appear to be beneficial for access to this regime. The most sensitive parameter is $q_{95}$, and the next
one is $\beta_p$. High $\delta_u$ is not a necessary condition but appears to facilitate access to higher ELM frequency. Although the accessible parameter space is similar to that of the JT-60U grassy ELM regime in terms of high $q_{95}$, $\beta_p$ and $\delta$, the grassy ELM regime in EAST exhibits some different features; for example, it appears to be in the different density range. This grassy ELM regime is accessible at high density, $n_e/n_{GW}\geq 0.46$, even over the Greenwald density limit. It is still unclear whether it is due to the different wall material: metal in EAST vs. carbon in JT-60U. Good energy confinement with $H_{98y2}$ up to 1.4 has been achieved in this regime, especially at high $\beta_p$ with favorable $B_t$. Future steady-state tokamak fusion reactors, such as CFETR, are anticipated to operate at low rotation with metal wall, high bootstrap current fraction, radiative divertor under nearly fully non-inductive conditions. The EAST grassy ELM regime has been demonstrated to be compatible with all these properties. Furthermore, its parameter space overlaps with the projected parameter space of the CFETR baseline scenario ($q_{95}=5.5-7$, $\beta_p-2$, $f_{BS} \sim 50\%$, $n_e/n_{GW} \sim 0.7$). The strong tungsten impurity exhaust capability makes this regime especially suitable for the metal wall environment. However, the right parameter space (high $q_{95}$, $\beta_p$ and $\delta$) appears to be insufficient for the access to this regime. Nonlinear pedestal simulation with the BOUT++ code has uncovered the underlying mechanism for the generation of the grassy ELMs, and identified the characteristic radial profiles in the pedestal as the key to suppressing large ELMs. The radial profiles feature a relatively high $n_{e,sep}/n_{e,ped}$ (up to 0.6), wide pedestal, moderate pedestal density gradient and low pedestal bootstrap current density. Because of the low bootstrap current density in the pedestal, the kink/peeling-dominated low-n PBMs, which usually lead to large ELMs, are stabilized when the pressure gradient only slightly decreases, thus the pedestal collapse stops, leading to small ELMs. Some possible mechanisms for the profile formation have been discussed in the paper. In future reactor-size plasmas, a high $n_{e,sep}/n_{e,ped}$ and low pedestal density gradient could be naturally achieved, as the plasma temperature and density at the separatrix are so high that the recycling neutrals are ionized mostly inside the divertor and SOL, and the penetration of recycling neutrals into the pedestal would be negligible [21]. The pedestal fueling can be further reduced by using closed divertor geometries with strong pumping, deep pellet injection and large plasma-wall gaps. Hence, the grassy ELM regime may be naturally accessible in future steady-state tokamak fusion reactors, such as CFETR, as a potential solution to avoid large ELMs.

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