Divertor impurity seeding with a new feedback control scheme for maintaining good core confinement in grassy-ELM H-mode regime with tungsten monoblock divertor in EAST

G.S. Xu, Q.P. Yuan, K.D. Li, L. Wang, J.C. Xu, Q.Q. Yang, Y.M. Duan, L.Y. Meng, Z.S. Yang, F. Ding, J.B. Liu, H.Y. Guo, H.Q. Wang, D. Eldon, Y.Q. Tao, K. Wu, N. Yan, R. Ding, Y.F. Wang, Y. Ye, L. Zhang, T. Zhang, Q. Zang, Y.Y. Li, H.Q. Liu, G.Z. Jia, X.J. Liu, H. Si, E.Z. Li, L. Zeng, J.P. Qian, S.Y. Lin, L.Q. Xu, H.H. Wang, X.Z. Gong, B.N. Wan and the EAST team

1 Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
2 University of Science and Technology of China, Hefei 230026, China
3 School of Mechanical Engineering, Anhui University of Science & Technology, Huainan 232001, China
4 General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, United States of America

E-mail: gsxu@ipp.ac.cn and qpyuan@ipp.ac.cn

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Abstract

Small perturbations and strong impurity exhaust capability associated with the small grassy ELMs render the grassy-ELM regime a suitable candidate for achieving steady-state H-mode operation with a radiative divertor, especially in a metal-wall device, such as the Experimental Advanced Superconducting Tokamak (EAST). As the degradation of pedestal performance with excessive divertor impurity seeding or accumulation tends to be accompanied with significantly increased radiation near the divertor X point, feedback control of the absolute extreme ultraviolet (AXUV) radiation near the X point has been employed to maintain the confinement property in EAST. However, the absolute value of the AXUV radiation at the outer target varies with plasma conditions as during the divertor detachment process. Thus, a new feedback-control scheme has been recently developed and applied to grassy-ELM H-mode plasmas in EAST to achieve stationary partial detachment while maintaining good global energy confinement with $H_{98,Y2} > 1$. In this scheme, electron temperatures ($T_{et}$) measured by divertor Langmuir probes are used to identify the onset of detachment, and then the plasma control system (PCS) switches to the feedback control of one channel of AXUV radiation near the X point, where a steep gradient in the radiation profile is present. The feedback is performed through pulse-width-modulated duty cycle of a piezo valve to seed impurities with mixed gas (50% Ne and 50% D$_2$) from the outer target plate near the strike point in the upper tungsten monoblock divertor. $T_{et}$ near the strike point is maintained in the range of 5–8 eV, and peak surface temperature on the outer target plate ($T_{IR,peak}$) is suppressed and maintained at ~180 °C, based on infrared camera measurements. The plasma stored energy maintains nearly constant over the entire
feedback-control period. It thus offers a highly promising plasma control scenario suitable for long-pulse high-performance H-mode operation in EAST, which is potentially applicable to future steady-state fusion reactors as an integrated solution for the control of both ELM-induced transient and steady-state divertor heat loads while maintaining good core confinement.

Keywords: divertor impurity seeding, radiative divertor feedback control, partial detachment, grassy-ELM H-mode regime, tokamak

(Some figures may appear in colour only in the online journal)

1. Introduction

For future tokamak fusion reactors such as ITER, the heat flux on the surface of plasma-facing components for steady state power exhaust must be kept below ~10 MWm$^{-2}$, the engineering limit of ITER-like tungsten monoblock divertor, which can only be achieved with detachment [1–4]. In a metal-wall device with low intrinsic impurity radiation and high heating power, impurity seeding is required to achieve detachment [5–7]. Albeit complete detachment, i.e. detachment over the entire inner and outer target plates, is desirable for mitigating divertor heat flux and may be required to eliminating sputtering erosion in a steady-state reactor beyond ITER but it has been found to be problematic for maintaining good core plasma performance [7]. With complete detachment, the location of the ‘detachment front’ or ‘radiation front’, i.e. the upper end of cold, high-density, radiating plasma region, can penetrate into the closed flux surface region near the X point forming an ‘X-point MARFE’, reducing the pedestal top temperature and thus the global energy confinement, even leading to a transition back to the L-mode [5–20]. Furthermore, helium ash exhaust may be problematic in future D-T fusion reactors with complete detachment, as particle fluxes will be significantly reduced [21, 22]. Therefore, partial detachment in a conventional vertical-target-plate divertor is adopted for ITER [1–4], where significant plasma pressure loss and heat flux density reduction are attained near the strike point region while further out into the scrape-off layer (SOL) the plasma pressure and heat flux densities are relatively unchanged [5, 6]. However, there is a very small operational parameter window in which a partially-detached plasma can be maintained on a conventional vertical-target-plate divertor [23–25] and the transition from partial detachment to complete detachment, i.e. the process that detachment front moves from the vicinity of outer target to the X-point region, is usually very fast and sensitive to divertor impurity concentration [26–32]. This poses a great challenge for active feedback control. To maintain stable partial detachment and good confinement, one needs a divertor operational scenario where the transit time of the detachment front along the outer divertor leg from the target plate to the X point is long enough to fight it with the feedback-control response time of impurity seeding. Therefore, significant attention is focused on developing divertor detachment feedback control schemes to achieve this target. Maintenance of good core confinement under relatively steady conditions has been achieved in a number of tokamaks [33–45]. However, a robust scheme suitable for long-pulse operation in a metal wall environment still needs to be demonstrated, which is an important research task for superconducting tokamaks with metal wall, aiming at long-pulse high-performance H-mode operations, such as the Experimental Advanced Superconducting Tokamak (EAST) [44–46].

On the other hand, large-amplitude edge-localized modes (ELMs) transiently reattach the target plates in the detached H-mode plasmas, which lead to unacceptable transient heat fluxes and sputtering erosion [47], must be mitigated or replaced by small ELMs or benign pedestal fluctuations. Furthermore, large ELMs cause large-amplitude disturbances of the boundary plasma, especially in the form of particle left behind in the SOL by the ELMs, stimulating the divertor to jump between states, which make the effects of ELMs hard to remove through merely optimizing the feedback-control algorithm. These disturbances induce large-amplitude perturbations and irregular noise in the feedback sensor signals which make it very difficult to achieve reliable detachment control [35]. Small grassy ELMs make much smaller disturbances so that the problem can be simply solved by implementing a low-pass filtering to the sensor signals. More important, the grassy-ELM regime is less prone to large jumps in the divertor conditions and thus more tolerable for maintaining a stable detachment state.

Grassy-ELM regime is such an H-mode regime with good energy confinement, characterized by high-frequency small ELMs with transient heat fluxes typically only ~1/20 of the large type-I ELMs, which is acceptable for ITER and beyond [48–52]. This regime is accessible in a relatively high $\iota_{95}$ range (typically $>5$), applicable to low pedestal collisionality as projected for a fusion reactor. The grassy-ELM regime has been achieved in EAST in a broad parameter range [53]. This regime exhibits strong particle exhaust capability both for impurity flush out and density control, mainly due to filamentary transport at the edge driven by the small, high-frequency grassy ELMs. In addition, there is a relatively high plasma density at the separatrix, which enhances boundary impurity screening and facilitates divertor detachment at a relatively low pedestal top density, which is essential for minimizing the influence on the core confinement, thus beneficial for long-pulse H-mode operation with a stationary radiative divertor in a metal wall environment.

Feedback control of total radiation power $P_{\text{rad}}$ has been achieved in EAST with impurity seeding through supersonic molecular beam injection (SMBI) from the outer midplane [44] or feedback control of ion saturation current $j_{\text{sat}}$ measured by the divertor Langmuir probe with impurity seeding from the
The AXUV data is used to estimate the local as well as the core region, providing the measurements of radiation near the upper and lower divertor regions as well as the plasma target is shown in figure 1. The distribution of the Langmuir probes (LP) at the divertor and Port D, respectively, separated toroidally by 112.5°. Sensors for feedback control and other diagnostics scheme in section 2.1. The experimental results are described in section 3. Finally, discussions and conclusions are presented in section 4.

2. Experimental setup and the feedback control scheme

2.1. Sensors for feedback control and other diagnostics

The measurement of $T_{ei}$ is based on the triple-probe technique [55]. There are two sets of poloidal arrays located near Port O and Port D, respectively, separated toroidally by 112.5° [56]. The distribution of the Langmuir probes (LP) at the divertor target is shown in figure 1. The fan of AXUV arrays covers the upper and lower divertor regions as well as the plasma core region, providing the measurements of radiation [54]. The AXUV data is used to estimate the local as well as the total radiation power, calculated from the following equation:

$$P_{rad} = \sum_{i} 2\pi R_i \Delta r_i P_i.$$  Here, $R_i$ is the major radius of the center of viewing chord, $\Delta r_i$ is the averaged width between the $i$th chord and the $(i+1)$th chord, and $P_i$ is the radiated power integrated along the $i$th chord, which can be calculated as:

$$P_i = \frac{\int_{\text{chord}} P_d \, d\theta}{\Delta P}.$$  Here, $P_d$ is the radiated power received by the $i$th detector, $A_d$ and $A_a$ are the areas of detector and aperture, $\theta$ and $\theta'$ are the viewing chord angle from the normal of detector and aperture, respectively, and $l$ is the distance from the detector to the aperture. The overlap of chords between the two arrays is subtracted. The sensitivity of the AXUV photodiode detector decreases sharply for photon energy below 20 eV. However, good sensitivity is available near the X point where $T_e$ is typically >20 eV.

The impurity line emissions in the upper divertor region, such as tungsten (W), neon (Ne), carbon (C), lithium (Li) and deuterium (D), are measured by a divertor tungsten spectroscopy system with two spectrometers: iHR320 and iHR550 with the wavelength in the range of 396.26–427.66 nm and 396.56–434.35 nm, respectively [57]. The chord-integrated (across the core plasma) line emissions of CVI (33.73 Å), NeIX (13.5 Å) and NeX (12.1 Å) are measured by two fast spectroscopy systems: Div-W (yellow): upper-divertor tungsten spectroscopy; EUV (orange): extreme ultraviolet spectrometer; TS (red): Thomson scattering; GP (magenta): gas puff inlets.

Figure 1. EAST cross section and distributions of diagnostics, gas inlets and cryo-pumps. LP (black): divertor Langmuir probes; AXUV (blue): absolute extreme ultraviolet photodiode arrays; Div-W (yellow): upper-divertor tungsten spectroscopy; EUV (orange): extreme ultraviolet spectrometer; TS (red): Thomson scattering; GP (magenta): gas puff inlets.
Figure 2. The separatrix (red) from EFIT magnetic equilibrium reconstruction for a discharge in EAST, shot #87 887 at $t = 6$ s. The outer strike point is located near No.10 at Port D and No.23 at Port O divertor Langmuir probe. The gas inlet on the upper outer target is located near No.21 divertor Langmuir probe at Port O, which is slightly below the strike point in the SOL.

2.2. Actuator for feedback control and experimental setup

The actuator is gas puffing from the outer target plate of the upper divertor (UO-GP) near No.21 divertor Langmuir probe toroidally near Port O, which is the same poloidal location of No.8 probe near Port D, as shown in figure 2 [63–65]. A gas mixture of 50% Ne and 50% $\text{D}_2$ is seeded from this gas inlet controlled by a piezo valve connected through a tube of ~4 m long. The percentage of gas mixture is controlled through adjusting the pressure in the gas storage tank. The amount of injected gas is measured by the pressure drop in the gas tank. The gas takes ~100 ms to travel through the tube, with a delay time of control response of 80–200 ms depending on the gas pressure in the plenum. The delay time for radiation response is even longer, usually >200 ms for neon seeding, as impurity diffusion takes time. The Ne impurity removal time has been estimated using the decay time of Ne line emissions following a single short Ne injection pulse (50–100 ms) in a discharge under similar conditions. The decay time is ~0.5 s for the divertor NeII emission and 0.7–0.8 s for the core EUV NeX and NeIX emissions, which is much longer than the feedback control response time. Thus, the response time of gas puff is sufficient to achieve the feedback control of the Ne impurity concentration. All discharges in this study are operated with favorable $B_c$, i.e. $\mathbf{B} \times \nabla \mathbf{B}$ drift pointing upwards, in an upper single null (USN) divertor configuration with the outer strike point located near No.10 (at Port D) and No.23 (at Port O) divertor Langmuir probe. Figure 2 shows the separatrix calculated from EFIT magnetic equilibrium reconstruction in a typical discharge #87 887 at $t = 6$ s. With this arrangement of the strike-point location, the impurities are seeded into the SOL slightly below the strike point.

Figure 3. Schematic of the radiative divertor feedback control flow. Electron temperatures ($T_{el}$) measured by divertor Langmuir probes are used to identify the onset of partial detachment, and then the plasma control system (PCS) switches to the feedback control of one channel of AXUV radiation near the X point.

2.3. Feedback control scheme and algorithm

The impurity seeding feedback control is implemented in the EAST plasma control system (PCS) which is an integrated comprehensive control system for tokamak operation [66]. All calculations are performed within the PCS. The overall logic of the feedback control scheme is as follows. First, $T_{el}$ measured by divertor Langmuir probes are used to identify the onset of partial detachment at the outer target plate, and then the PCS switches to the feedback control of one channel of
Figure 4. Feedback control of divertor neon seeding in a grassy-ELM discharge in EAST, shot #87 887. (a) central-line-averaged density (black) and loop voltage (blue), (b) LHCD power (black) and ECRH power (blue), (c) radiation power from the main plasma (black) estimated with the AXUV array channel 11–55 and from the divertor regions (blue) estimated with channel 1–10 and 56–64, (d) ELM frequency (black) and neon-X line emission at 1.213 nm (blue) measured by a EUV chord passing through the plasma core, (e) the effective Z.

Figure 5. AXUV channel7 measures radiation near the lower X point, showing (a) grassy ELMs before neon seeding at $t = 3.018$ s and (b) grassy ELMs with higher ELM frequency during neon seeding at $t = 5.656$ s in shot #87 887.

AXUV radiation near the X point, as indicated by the control flow schematic in figure 3. The feedback control is performed through the pulse-width modulated duty cycle of a piezo valve.

Since the frequency of the grassy ELMs is typically more than 1 kHz, $T_{et}$ and AXUV signals are smoothed in the PCS through a low-pass filter with a time window of ~20 ms, which is sufficient to reduce the ELM-induced perturbations.

The initial AXUV target level is set well above the AXUV signal value, generating a large deviation as input to a proportional-integral-derivative (PID) controller, such that gas is injected at a default setting parameter for the piezo valve duty cycle with maximum pulse width and minimum time interval, i.e. at a largest injection rate, so that $T_{et}$ can quickly decrease. However, too large an injection rate and too fast a $T_{et}$ decrease will lead to an overshoot, which will be discussed later in this paper. Hence, the maximum pulse width and the minimum time interval should be set to reasonable values. In the meantime, the PCS compares $T_{et}$ with its onset value $T_{onset}$. Once the condition $T_{et} < T_{onset}$ has been satisfied within a period of continuous detection time, the AXUV target is reset to $I_{target} = (1 + \delta)I_{AXUV}$, where $I_{AXUV}$ is the smoothed AXUV value at this moment and $\delta$ is an offset. The offset $\delta$ is a parameter used to control the detachment depth. A large offset $\delta$ leads to the injection of more gas so that $T_{et}$ will further decrease. The detachment depth can also be controlled through adjusting $T_{onset}$. Complete detachment is usually achieved with $T_{onset}$ being set at 5 eV or less. Thus, the detachment depth is controllable through a combination
of the two parameters, \( T_{\text{sonet}} \) and \( \delta \). From this moment until the end of control, the PCS performs AXUV-signal feedback control with the error \( \Delta I = I_{\text{target}} - I_{\text{AXUV}} \) as input to a PID controller to generate an actuator command to adjust the piezo valve voltage in width modulation mode. The PID parameters are optimized based on experience accumulated in the experiments. The value of the valve voltage does not change during the discharge. But it can be modified between discharges. Feedback control of the amplitude of valve voltage has been achieved in a previous EAST experiment [45, 46].

3. Results of divertor neon seeding feedback control experiments

3.1. A typical discharge maintaining good confinement

Figure 4 shows a typical discharge \#87 887 with sustained partial detachment at the outer target plate while maintaining good energy confinement in a grassy-ELM H-mode plasma. This discharge is operated in favorable toroidal magnetic field direction with \( B_t = 2.48 \) T, plasma current \( I_p = 400 \) kA, edge safety factor \( q_{95} = 6.5 \), poloidal beta \( \beta_p = 1.4 \), internal inductance \( l_i = 1.2 \), upper triangularity \( \delta_u = 0.56 \), elongation \( \kappa = 1.57 \), the distance between the separatrix and the flux surface through the lower X point at the outer mid-plane, \( d_{R\text{sep}} = 2.4 \) cm in the USN divertor configuration. The central-line-averaged electron density \( n_e \) is maintained at \( 4.6 \times 10^{19} \) m\(^{-3} \) during the discharge with feedback control, which is about 73\% of the Greenwald density. The loop voltage increases from \(-0.1 \) V before impurity seeding to \(-0.2 \) V during the feedback control period (figure 4(a)). The loop voltage is still too high to achieve long-pulse operation.

The total injected power is \( P_{\text{inj}} = 2.5 \) MW, including 1.3 MW LHCD at 4.6 GHz, 0.4 MW LHCD at 2.45 GHz, 0.7 MW ECRH at 140 GHz (figure 4(b)) and 0.09 MW Ohmic heating during impurity seeding. The seeding starts at \( t = 3 \) s with a gas mixture of 50\% Ne and 50\% D\(_2\). However, there is a delay of \(~0.4 \) ms before \( P_{\text{rad,main}} \) and \( P_{\text{rad,div}} \) start to increase. Here, \( P_{\text{rad,main}} \) is the radiation power from the main plasma estimated with the AXUV array channel 11–55 and \( P_{\text{rad,div}} \) is the radiation power from the divertor regions estimated with channel 1–10 & 56–64, as shown in figure 1. During Ne seeding, \( P_{\text{rad,div}} \) is about 21\% of the total radiation power \( P_{\text{rad}} = P_{\text{rad,main}} + P_{\text{rad,div}} \). \( P_{\text{rad,div}} \) could have been underestimated as the low-field-side divertor region near the outer target is not covered by the AXUV arrays. \( P_{\text{rad,main}} \) increases from \(-0.34 \) MW to \(-1.0 \) MW (figure 4(c)) and the effective \( Z \), \( Z_{\text{eff}} \), increases from \(~1.74 \) at \(~3.28 \) s to \(~2.47 \) at \(~6 \) s (figure 4(e)), suggesting that there is significant penetration of Ne impurity into the core plasma. The loss power \( P_{\text{sep}} = P_{\text{inj}} - P_{\text{rad,main}} \) decreases from \(~2.16 \) MW to \(~1.5 \) MW, which is still \(~2.1 \) times of the L-H transition threshold power \(~0.7 \) MW with favorable \( B_t \) [67]. The total radiation power increases from \(-0.47 \) MW to \(-1.27 \) MW, leading to a power reduction of 0.8 MW to the divertor targets, in which 82.5\% is due to radiation increase in the main plasma region, suggesting that the power reduction to the divertor targets is mainly due to a considerable increase of the core radiation and thus a
In the meantime, fully maintains the AXUV59 radiation near its target level.

is set to 5% in shot #87 887. The feedback control success-
to criterion large, which drives gas injection at a large rate. When the
signal value onset value, which is set to 8 eV in this discharge. In the begin-
ning ELM frequency (figure 5(a)). During the
seeding, they are still small grassy ELMs, but with a higher
ELM frequency (figure 5(b)), suggesting that the plasma is
maintained in the grassy ELM regime with the divertor neon
seeding under these plasma conditions.

The AXUV signal most sensitive to the pedestal performance in shot #87 887 is channel59. It starts to increase
~700 ms for neon concentration and radiation power increase to a certain
level. Then, it takes ~3.9 s (figure 4(d)), delayed by ~900 ms, when the
neon concentration and radiation power increase to a certain
level. Then, it takes ~700 ms for \( T_{\text{sat}} \) to decrease down to the
onset value, which is set to 8 eV in this discharge. In the beginning,
the AXUV target \( I_{\text{target}} \) is set well above the AXUV
signal value \( I_{\text{AXUV}} \), so that the error \( \Delta I = I_{\text{target}} - I_{\text{AXUV}} \) is
large, which drives gas injection at a large rate. When the
criterion \( T_{\text{sat}} < T_{\text{onset}} \) is satisfied, the AXUV target is reset
to \( I_{\text{target}} = (1 + \delta)I_{\text{AXUV}} \) (figure 6(b)), where the offset \( \delta \) is
set to 5% in shot #87 887. The feedback control successfully maintains the AXUV59 radiation near its target level.

In the meantime, \( T_{\text{sat}} \) is maintained just below its onset value,
\( T_{\text{sat}} = 5–8 \) eV, achieved with a neon impurity injection rate of
\( 5.5 \times 10^{19} \) particles/s. Although the gas was injected at
one toroidal location near No.21 probe at Port O, the toroidal
asymmetries in \( T_{\text{sat}} \) appear to be small. As shown in the figure
6(a), the \( T_{\text{sat}} \) measured by No.23 probe near Port O is very
close to that measured by No.10 probe at the same poloidal
location near Port D, separated toroidally by 112.5°, probably
because that cooling is dominantly induced by recycling impurities from the divertor targets rather than the impurit-
ies just injected from the gas inlet. Good core confinement is
maintained with the energy confinement improvement factor
\( H_{\text{98,2}} > 1 \) and the plasma stored energy \( W_{\text{MHD}} \) keeps nearly
constant over the entire feedback-control period (figure 6(c)).

Figure 7 shows the electron temperature \( T_{\text{el}} \) and ion saturation
current \( j_{\text{sat}} \) distributions along the outer target plate of the
upper divertor, as measured by divertor Langmuir probes. The
probe signals have been averaged over 100 ms to reduce the
influence of plasma fluctuations. The error bars for \( j_{\text{sat}} \) measures-
ments are caused mainly by the effective collecting area
of the probe tips with a systematic error of about ±10%. The
errors for \( T_{\text{el}} \) measurements with the triple probe technique are
estimated to be roughly ±50% [56]. The strike point is located
near No.23 probe at Port O as indicated by the \( j_{\text{sat}} \) peak. The
gas is injected from the outer target plate with the gas inlet loc-
ated in the SOL near No.21 probe at Port O. \( T_{\text{sat}} \) near the strike
point is reduced down to below 5 eV (figure 7(a)), while \( T_{\text{sat}} \) in the
far SOL is nearly unchanged, characterizing the access to
partial detachment. However, \( j_{\text{sat}} \) near the outer strike point
does not decrease, even slightly increases (figure 7(b)), indic-
ating that the \( j_{\text{sat}} \) rollover, a common phenomenon appearing
at detachment [5], does not occur. Note that the $j_{\text{sat}}$ rollover still appears at the inner target plate, i.e. $j_{\text{sat}}$ near the inner strike point can decrease. This is a common feature observed in EAST with favorable $B_t$ when impurities are seeded from the SOL side of the outer target plate. This phenomenon does not occur or is much weaker, i.e. $j_{\text{sat}}$ still decreases, when pure deuterium gas [64] or a gas mixture with a low impurity fraction is injected, e.g. 5% of neon in reference [45]. This phenomenon becomes even stronger, i.e. $j_{\text{sat}}$ increases more significantly, with higher impurity fraction or impurities of higher Z, e.g. argon appears to be stronger than neon. For unfavorable $B_t$, the phenomena on the inner and outer target plates are reversed, i.e. $j_{\text{sat}}$ rollover appears at the outer target plate while $T_{\text{e}}$ near the outer strike point does not decease. Note that the $j_{\text{sat}}$ consists of deuterium ion current and neon ion current, $j_{\text{sat}} = j_{\text{satD}} + j_{\text{satNe}}$, and an impurity ion may carry more than one positive charge, thus contributes more effectively to $j_{\text{sat}}$.

Figure 8 shows the AXUV chords in the divertor region. The channel59 chord intersects the divertor outer leg at a point near the upper X point. Figure 8(c) shows the time evolution of radiation power estimated from AXUV signals in the upper divertor region labeled with AXUV channels. The channel59 appears to locate where a steep gradient in the AXUV radiation profile is present. The peak of the profile is located roughly at channel56 before neon seeding and channel57 during the seeding. The AXUV radiation starts to increase at the same time (~3.2 s) that the divertor neutron concentration starts to increase, as indicated by the NeII line emission at 421.97 nm, as measured by the upper-divertor tungsten spectroscopy system. The colors of the AXUV chords are the same as the colors in the pseudo-color figure 8(c), corresponding to radiation power as indicated in the color bar. The AXUV radiation signals suggest that there is a radiation region (toroidally a radiation belt) located in the high-field-side SOL near the X point and its peak moves from channel56 to channel57 with increasing intensity and area, as indicated by the yellow ellipse schematics in figures 8(a) and (b). The channel59 is located at the edge of this radiation region where a steep radiation gradient is present, thus it is very sensitive to the change of the radiation region. This radiation region is quite similar to the high field side high density (HFSHD) region observed in ASDEX-U with favorable $B_t$ [68–70]. However, in ASDEX-U it was observed that the divertor impurity seeding suppresses the HFSHD, rather than enhances it [71]. When this radiation region expands across the separatrix, intrudes onto the closed flux surfaces near the X point, it forms a confinement-degrading ‘X-point MARFE’ [7–9]. Radiation in this region cools down the local plasma, which in turn reduces the pedestal top temperature. As a result, core plasma confinement, which is intrinsically tied to the pedestal top temperature, tends to degrade [7–9]. Therefore, it is a key to find a signal sensitive to this radiation region for the maintenance of good confinement with radiative divertor. This explains why the feedback control using one channel of AXUV signal near the X point can be successful. On the other hand, since the formation of an ‘X-point MARFE’ is usually coincident with complete detachment [7–9], the divertor partial detachment can be maintained through the control of the radiation region to avoid the formation of an ‘X-point MARFE’.

The peak surface temperature on the outer target plate ($T_{\text{IR, peak}}$) is reduced from ~300 °C to ~180 °C and maintained at that temperature (figure 9(b)), based on infrared camera measurements. Figure 9 shows the time evolutions of Neon-II (NeII at 421.97 nm), Carbon-II (CII at 426.7 nm), Tungsten-I (WI at 400.9 nm), Deuterium-δ (Dδ at 410.06 nm) line-emission distributions and one channel of Deuterium-α (Dα at 656.1 nm) line emission measured by the upper-divertor tungsten spectroscopy system [57]. The vertical axis shows the distance to the divertor corner along the outer target plate. The CII line emission is significantly reduced, which indicates that carbon sputtering is reduced, as the sheath potential is reduced with decreasing $T_{\text{e}}$. The Dδ line emissions are also significantly reduced, but the Dα line emission does not decrease, i.e. Dδ/Dα increases, which indicates an increase of $n_e$ near the outer target plate [72]. The carbon is mainly from deposition, as the lower divertor and the NBI shine-through dumpers at the inner wall are covered with graphite tiles. WI line emission is just slightly reduced within a range of ~10 cm near the divertor corner. The WI line emission is quite weak, as the Lithium wall coating is daily applied, which effectively suppresses the tungsten sputtering, except the region near the strike point [73].

3.2. Sensitivity of the feedback control sensor

The AXUV signal near the X point appears to be very sensitive to the change in the pedestal performance and $T_{\text{e}}$. Figure 10
Figure 11. Time traces of (a) plasma stored energy, (b) AXUV radiation channel54 (black), 58 (blue) and 59 (red), (c) electron temperature channel22 (black) and 23 (blue) near the outer strike point of the upper divertor near Port O measured by divertor Langmuir probes. The two shaded areas mark two dips in the plasma stored energy. The vertical dashed lines indicate the time points for pedestal density profiles shown in figure 12 with corresponding colors.

Figure 12. The pedestal density profile changes across a dip in the plasma stored energy in the same discharge as shown in figure 11, measured by a reflectometer at the outer midplane.

shows the magnetic separatrix in the upper divertor region for two USN discharges with different X-point locations. The most sensitive AXUV signal changes with the movement of the X-point location, i.e. channel59 for shot #88 149 with \( I_p = 400 \) kA and channel60 for shot #88 165 with \( I_p = 550 \) kA.

One can see that the most sensitive AXUV signal is always the channel with the chord-divertor-leg intersection point just above the X point.

There are two dips in the time trace of the plasma stored energy \( W_{\text{MHD}} \) with ~10 kJ (~7%) reduction in shot #88 149 (figure 11(a)), indicating a minor degradation of the confinement. The AXUV signals below/above channel58 are positively/negatively correlated with the \( W_{\text{MHD}} \) time trace, respectively (figure 11(b)). The channel58 is the turning point with nearly no correlation. The chord of channel58 just passes through the X point (figure 10). The channel59 is the first channel above the turning point channel58. \( T_{\text{e}} \) near the outer strike point appears to be correlated with the channel59 in time (figure 11(c)). Therefore, the AXUV channel59 is a good sensor to achieve the control objectives.

Figure 12 shows the pedestal electron density \( n_e \) profiles during the second \( W_{\text{MHD}} \) dip in figure 11(a), measured by a reflectometer at the outer midplane [62]. The time points are indicated by vertical dashed lines with corresponding colors in figure 11(a). The pedestal \( n_e \) gradient appears to decrease and then recover. The pedestal \( T_{\text{e}} \) change is quite small relative to the error bar of the Thomson scattering measurements. The \( W_{\text{MHD}} \) decrease is mainly induced by the pedestal \( n_e \) profile change in this case.

Figure 13 shows the corresponding time traces for shot #88 165. In this shot, the channel59 is the turning point with nearly no correlation and the channel60 is the first channel.
Figure 14. Optimization of the feedback control algorithm to reduce the overshoot through modifying the AXUV59 target before $T_{et}$ reaches its target. For these shots, the lower cryo-pump is off. For shot #87 887, both upper and lower cryo-pumps are on. (a) High AXUV59 target, (b) low AXUV59 target, (c) ramp-up AXUV59 target, (d) slower ramp-up AXUV59 target.

above the turning point. The perturbations in the channel appear to be correlated with those in $W_{MHD}$ and $T_{et}$, especially between 6 s and 7 s.

3.3. Control algorithm optimization and effect of cryo-pump

Before $T_{et}$ decreases down to its target value, the AXUV target is set well above the AXUV signal value. However, if the gas injection rate is too large, there will be an overshoot and a subsequent oscillation in $T_{et}$ and the AXUV signal, which usually leads to a minor confinement degradation, as reflected by a drop in $W_{MHD}$ in figures 14(a)–(c). The feedback control algorithm is optimized to reduce the overshoot through modifying the AXUV59 target value before $T_{et}$ decreases down to its target value. Firstly, a smaller AXUV59 target value is used (figure 14(b)). The overshoot is smaller, but still exists. Secondly, a ramp-up slope of the AXUV59 target value is introduced (figure 14(c)). However, the overshoot does not decrease. Finally, the AXUV59 target value is further reduced with a slower ramp-up slope (figure 14(d)). The overshoot is successfully mitigated, i.e. the $T_{et}$ oscillation disappears and the AXUV59 signal follows its target value quite well. Unfortunately, currently the PID controller by itself could not prevent the overshoot. Mitigation of the overshoot is thus achieved through adjusting the target value. It is still required to develop a better PID algorithm in the future, so that we can just set the target value we want. Although there are some fluctuations in the plasma store energy $W_{MHD}$ and energy confinement factor $H_{98,y2}$ mainly due to the overshoots, $H_{98,y2}$ are generally above unity, suggesting that good energy confinement is maintained in these shots.

In the discharges shown in figure 14, we turned off the lower cryo-pump by design to study the effect of pumping on the detachment feedback control. Compared with shot #87 887
where both upper and lower cryo-pumps are on, it is much more difficult to achieve steady feedback control. Note that the control system is more prone to overshoot. Furthermore, it is more difficult to maintain $T_{et}$ below its target value, as shown in figure 14. Since the pumping is reduced, the neon impurity concentration and radiation decay much slower, so that the required amount of injected gas decreases, leading to no gas injection for long time periods. Therefore, $T_{et}$ runs away at times longer than 6 or 7 s. This $T_{et}$ run-away does not appear when the two cryo-pumps are on, such as in shot #87 887 (figure 6). This implies that to maintain $T_{et}$ below its target value continuous gas injection near the divertor strike point is required, and stronger pumping is beneficial to achieve steady-state operation of a radiative divertor with neon seeding.

3.4. Detachment dithering and deep partial detachment

In figure 15, the $T_{et}$ target value is reduced step by step, and the divertor transitions from partial detachment to deep partial detachment. When the $T_{et}$ target value is set to 18 eV (figure 15(a)), partial detachment is achieved and detachment dithering with large amplitude appears. For these shots, the plasma current $I_p = 450$ kA. Detachment dithering also appears in $I_p = 400$ kA shots, such as #88 142, #88 146, #88 149 and #88 151 in figure 14. However, the amplitude is much lower and the repetition frequency is much higher. With the time-averaged $T_{et}$ increasing, the duty cycle of the dithering increases (figures 15(a1) and (b1)). When the $T_{et}$ target value is set to 12 eV (figure 15(b)), $T_{et}$ decrease to ~5 eV (may be <5 eV, but cannot be resolved with the triple probe measurement) and the detachment dithering disappears during 4–5.6 s, then reappears as the time-averaged $T_{et}$ recovers. When the $T_{et}$ target value is set to 8 eV (figure 15(c)), deep partial detachment is obtained and the detachment dithering completely disappears. Confinement degradation occurs at ~4.2 s, as indicated by a drop in $W_{MID}$ and a bump in AXUV radiation. The energy confinement factor $H_{98,2}$ decreases to below 1 when the partial detachment is getting deeper as shown in figures 15(b) and (c). It was found on EAST that it is very difficult to maintain good confinement and steady-state operation with a deeply partial-detached divertor where $T_{et}$ is <5 eV at the outer target plate except in the far SOL, as found on other tokamaks.

The detachment dithering only appears with $B_t$ in the favorable direction, which has been investigated in the DIII-D tokamak recently, and appears to be associated with the so-called ‘$T_e$ cliff’ phenomenon induced by $E \times B$ drifts [31, 32]. The detachment dithering is a divertor state compatible with good core confinement, thus steady-state operation can be achieved in this state. However, $T_{et}$ can transiently recover to >20 eV (figure 15(a1)), and even higher at larger $I_p$ (figure 13(c)). This may cause unacceptable sputtering in future fusion reactors. The detailed discussion of the detachment dithering in EAST is beyond the scope of this paper and will be reported in a following paper.

4. Summary and discussion

4.1. Summary of the EAST experimental results

A new feedback-control scheme for sustaining partial detachment at the outer target plate has been developed on EAST and recently applied to grassy-ELM H-mode plasmas while maintaining excellent core confinement with $H_{98,2} >1$. Currently, the lower divertor and the NBI shine-through dumpers at the inner wall are still covered with graphite tiles. The upper divertor is tungsten with the ITER-like monoblock technology [74]. Most of the inner wall, baffles and other low-heat-load area are covered with molybdenum tiles. The lower divertor will be upgraded to tungsten in the near future. The experiments were conducted in the USN divertor configuration with the upper tungsten divertor, which is a conventional vertical-target-plate divertor. This type of divertor was pioneered on Alcator C-Mod [23] and, due to its adoption as the base-line design for ITER [1–4], has been the major focus for world research on boundary and divertor plasma physics. EAST experience indicates that it is very difficult to maintain good

Figure 15. Detachment feedback control with different electron temperature $T_{et}$ targets: (a) 18 eV, (b) 12 eV and (c) 8 eV. With lower $T_{et}$ target, deeper partial detachment is obtained, detachment dithering disappears and maintenance of good confinement becomes difficult. For these shots, $I_p = 450$ kA. Compared with $I_p = 400$ kA shots, the detachment dithering exhibits higher amplitude and lower repetition frequency.
confinement and steady-state operation with complete detachment or even deep partial detachment ($T_{\text{et}}$ decreases down to below 5 eV at the outer target plate except in the far SOL) in this type of divertors. There is a quite small operational target window in which good confinement can be maintained in a partially-detached plasma with a conventional vertical-target-plate divertor. Therefore, the key is to find a signal that is sensitive to both the pedestal performance and $T_{\text{et}}$ at the divertor target plate to serve as a sensor of the feedback control system. EAST experiments indicate that the AXUV with the chord-divertor-leg intersection point just above the X point can provide the most sensitive signal, suitable for a feedback control sensor. There is a radiation region (toroidally a radiation belt) located in the high-field-side SOL near the X point (figure 8). The AXUV signal is located at the edge of this radiation region where a steep radiation gradient is present, thus it is very sensitive to the change of the radiation region. When this radiation region expands across the separatrix and intrudes onto the closed flux surfaces near the X point, it forms an ‘X-point MARFE’ [7–9], reducing the pedestal top temperature and thus the global energy confinement [5–20]. Thus, there is a strong correlation between the pedestal performance and the AXUV signal. This explains why feedback control of one channel of AXUV signal near the X point can be successful. In addition, the small edge perturbations associated with the small grassy ELMs further facilitate the feedback control.

On the other hand, the control of the AXUV radiation alone is insufficient to maintain the divertor in a partially detached state, as the absolute value of the AXUV radiation approaching partial detachment at the outer target plate varies with plasma conditions. Therefore, $T_{\text{et}}$ measured by divertor Langmuir probes is used to identify the onset of the partial detachment. Once the partial detachment state is reached, it is no longer needed to control $T_{\text{et}}$, as the AXUV signal and $T_{\text{et}}$ are anti-correlated with each other (figures 11 and 13). The experimental results indicate that the partial detachment state and good confinement can be maintained through the feedback control of the AXUV signal when there is sufficient divertor pumping. Compared with the divertor Langmuir probes, the AXUV photodiode array provides a more suitable sensor to be applied to long-pulse high-performance H-mode operation, which is a high-priority research task of EAST.

4.2. Challenges facing development of a truly reactor-relevant scheme

Although we have demonstrated a feedback control scheme that successfully mitigates divertor heat flux while maintaining core confinement in EAST, there are still some clear challenges for applying this scheme to future fusion reactors. Firstly, the loop voltage is still too high to achieve long-pulse operation and the effective $Z$ is still relatively high with neon as seeding impurity, i.e. $Z_{\text{eff}} \approx 2.47$ at $\sim 6$ s in shot #87 887. The partial detachment needs to be achieved at a much smaller impurity seeding rate, or more power for current drive and a larger bootstrap current fraction are needed. It is presently almost impossible in EAST using neon as seeding impurity to achieve long-pulse H-mode operation over 20 s with a conventional vertical-target-plate divertor. In future large devices, the pedestal plasma density and temperature may be sufficiently high to screen the seeding impurities. A closed divertor, such as the Small-Angle-Slot (SAS) divertor recently developed in DIII-D [75, 76], may allow significant reduction of the required impurity seeding rate. EAST is now upgrading its lower divertor to a more closed tungsten divertor so that detachment can be achieved with a much smaller impurity injection rate, which is expected to reduce the collisionality and loop voltage. In addition, more LHCD power for current drive and a larger bootstrap current fraction will be available after this divertor upgrade, which will also help to achieve a lower loop voltage and longer pulse with radiative divertor.

Secondly, divertor Langmuir probes may be inapplicable in a long-pulse fusion reactor due to the erosion of probe tips, even though they are just used at the start of the discharge in this control scheme. A system is required to allow retracting the probe tips to protect them after the plasma ramps up or a more reactor-relevant sensor is required to detect the onset of detachment.

Thirdly, it was found on EAST that partial detachment with $T_{\text{et}} \approx 5–8$ eV near the outer strike point is a reliable window to achieve steady-state operation without confinement degradation. However, in future fusion reactors beyond ITER, $T_{\text{et}}$ needs to be held below 5 eV across the target plates to meet the requirement of divertor target erosion rate. At this $T_{\text{et}}$, the divertor tends to go beyond partial detachment, moving into deep partial detachment or even complete detachment and forming a confinement-degrading x-point MARFE [7–9]. This increases the challenge for steady feedback control. There may not even be a window for detachment and acceptable erosion rate without a significant reduction in core confinement with a conventional vertical-target-plate divertor. Furthermore, the detachment dithering appears with $B_t$ in the favorable direction, accompanying the partial detachment, may be problematic due to sputtering in future fusion reactors, as $T_{\text{et}}$ can transiently recover to $>20$ eV (figure 15(a1)), and even higher at larger $I_p$ (figure 13(c)), leading to unacceptable erosion of the divertor target plates. Although this phenomenon does not appear when operating with unfavorable $B_t$. However, the L-H transition threshold power is expected to be significantly higher with unfavorable $B_t$ [67], which increases the recirculating power and thus capital cost of a reactor. ITER is thus designed to operate with favorable $B_t$ [3]. EAST results indicate that, in order to avoid the detachment dithering, the divertor also needs to be operated below 5 eV at the outer target plate. Therefore, new divertor concepts and control strategies beyond the conventional vertical-target-plate divertor are desired to allow reliable operation with a completely detached divertor where $T_{\text{et}}$ is held below 5 eV along the entire outer target plate (including the far SOL), while maintaining excellent core confinement. This will be explored in EAST in the near future with the upgraded new lower W divertor.
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ORCID IDs

G.S. Xu https://orcid.org/0000-0001-8495-8678
K.D. Li https://orcid.org/0000-0003-0486-7368
J.C. Xu https://orcid.org/0000-0001-5886-3114
Q.Q. Yang https://orcid.org/0000-0002-6354-1408
L.Y. Meng https://orcid.org/0000-0002-8633-5383
K. Wu https://orcid.org/0000-0002-8585-5408
N. Yan https://orcid.org/0000-0002-2536-5853
R. Ding https://orcid.org/0000-0002-2880-9736
Y.F. Wang https://orcid.org/0000-0002-0368-9566
Y.Y. Li https://orcid.org/0000-0002-2978-908X
E.Z. Li https://orcid.org/0000-0002-3713-4833
L. Zeng https://orcid.org/0000-0003-4968-1401
L.Q. Xu https://orcid.org/0000-0002-7388-6055
H.H. Wang https://orcid.org/0000-0002-3034-0925

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