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Total number of authors:
24

Published in:
Nuclear Fusion

Link to article, DOI:
[10.1088/1741-4326/abfe47](https://doi.org/10.1088/1741-4326/abfe47)

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Yan, N., Chen, L., Xu, G. S., Wu, X. Q., Liu, S. C., Wang, Y. F., Meng, L. Y., Hu, G. H., Zhao, N., Lan, H., Naulin, V., Nielsen, A. H., Juul Rasmussen, J., Li, K. D., Wang, L., Yang, Q. Q., Li, M. H., Ye, Y., Ding, R., ... Liu, J. B. (2021). Dependence of upstream SOL density shoulder on divertor neutral pressure observed in L-mode and H-mode plasmas in the EAST superconducting tokamak. *Nuclear Fusion*, 61(7), [076018]. <https://doi.org/10.1088/1741-4326/abfe47>

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To cite this article: N. Yan *et al* 2021 *Nucl. Fusion* **61** 076018

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Dependence of upstream SOL density shoulder on divertor neutral pressure observed in L-mode and H-mode plasmas in the EAST superconducting tokamak

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Received 24 October 2020, revised 29 April 2021

Accepted for publication 5 May 2021

Published 17 June 2021

Abstract

Upstream density profiles in the scrape-off layer (SOL) have been examined in low-confinement mode (L-mode) and high-confinement mode (H-mode) plasmas in the EAST superconducting tokamak. A weak density shoulder forms in the near SOL region in upper single-null configurations when the neutral pressure measured at the lower divertor exceeds a threshold value of 2×10^{-2} Pa in L-mode plasmas. When the neutral pressure is below this threshold, the weak density shoulder is absent and the sidebands of the lower hybrid waves associated with SOL parametric instabilities are reduced. Active detachment control with neon–deuterium seeding demonstrate that the weak density shoulder can form before the onset of the outer divertor detachment as long as the neutral pressure is above the threshold. Furthermore, no remarkable expansion of a shoulder is observed during divertor detachment, suggesting that divertor detachment is not a necessary condition for the formation or growth of a density shoulder. Through the increase in neutral pressure in the lower divertor by an order of magnitude, the weak shoulder was observed to expand into the far SOL and reach the leading edge of the limiter. The results in L-mode discharges identified the neutral pressure in the lower divertor as a primary factor for the formation of an SOL density shoulder in the upper single-null discharges. For the type-I ELMy H-mode plasmas, a similar density shoulder was detected during the inter-ELM phase when the neutral pressure in the lower divertor exceeded a threshold value of 4×10^{-2} Pa. On the other hand, the shoulder was absent when the divertor neutral pressure went below this threshold even though the plasma discharge was conducted with a higher core line-averaged density and divertor collisionality. This is consistent with the observations in L-mode plasmas. The neutral particle ionization of the working gas is thus believed to play a key role during the formation of the SOL density shoulder in the EAST tokamak.

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Keywords: scrape-off-layer, density shoulder, tokamak, divertor, neutral recycling

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

1. Introduction

Plasma particles and heat are continuously transported from the core plasma into the scrape-off layer (SOL) region in a tokamak device. A growing body of evidence in the last few years suggests that cross-field particle transport towards the chamber wall dominates the parallel transport along the field lines at high-density operation [1 and therein]. This process leads to enhanced plasma–wall interaction, including impurity sputtering, material erosion and retention [2 and therein]. Understanding of the plasma transport in the SOL based on present machines is essential for the realization of the high-performance operation of next-step devices such as ITER, DEMO, and ultimately, fusion power plants [3 and therein].

Studies of the upstream density profiles in low-confinement mode (L-mode) plasmas have been carried out on a number of tokamaks such as Alcator C-Mod [4, 5], DIII-D [6], ASDEX-Upgrade (AUG) [7, 8], TCV [9, 10] and JET [11]. In L-mode plasmas, the upstream density profiles at the outboard mid-plane are usually characterized by a two-layer structure. One layer near the last closed flux surface, the separatrix, mainly overlaps with the near SOL region, and the density profile exhibits an exponential decay, while the other layer in the far SOL region shows a broader density profile. It has been observed that the density profile can flatten over the entire SOL region when the Greenwald density fraction f_{GW} exceeds a certain value ($f_{\text{GW}} > 0.45$ in general cases) [4–11] and the break point between the two layers eventually disappears. Here, $f_{\text{GW}} = n_{\text{el}}/n_{\text{G}}$, n_{el} refers to the core line-averaged density and $n_{\text{G}} = I_{\text{p}}/\pi a^2$ to the Greenwald density, with I_{p} and a being the plasma current and minor radius, respectively. Under such conditions, the SOL plasma reaches the first wall or a protective limiter with a density value similar to that at the separatrix, which is referred to as the ‘SOL density shoulder’. At the shoulder formation, the outer divertor plasmas were observed to transit from an attached state to a detached state [7, 12]. However, it is unclear whether the achievement of plasma detachment necessarily triggers the density shoulder or vice versa. This is of particular significance for next-step devices, which require detachment control to prevent a significant amount of power being deposited directly on the divertor plates. Moreover, the density shoulder is identified as being related to parametric decay instabilities [13] in the SOL plasmas, which will lead to a broadening of the wave number spectrum of the lower hybrid waves (LHWs) and cause an anomalous wave power loss in high-density plasmas with a subsequent decrease in the heating and current drive efficiencies. The current drive efficiency of the LHW was found to

recover to a level consistent with empirical scaling after the density shoulder was eliminated [14].

The formation of a density shoulder has been proposed as a result of the enhanced perpendicular transport, which is carried by filamentary structures of enhanced density and temperature propagating out through the SOL region—often referred to as blob structures [15]. Studies in the AUG and JET provided clear evidence that density shoulder formation is associated with a change of dynamical properties of the blob filaments [8]. It was observed that blob filaments changed from a sheath-limited to an inertial regime, which led to the enhancement of the radial particle transport responsible for the shoulder formation. The transition took place when the plasma collisionality near the divertor plate surpassed a threshold of $\Lambda_{\text{div}} > 1$, where Λ_{div} is the effective collisionality in the divertor [8]. This is in line with the condition for the plasma to disconnect from the divertor target, i.e. plasma detachment. This relationship has been further quantitatively confirmed in AUG, JET and COMPASS [16]. In addition, the formation of a density shoulder in the SOL density profile can be obtained through the increase in the effective collisionality in simulations of the SOL transport in the HESEL code, which is in qualitative agreement with experimental observations [17]. Some additional and important information was further uncovered in different devices. The neutral atomic deuterium density in the divertor region was observed to be redistributed from the inner target to outer target during the density ramp in L-mode discharges on AUG, which is considered an important ingredient for both shoulder formation and detachment [18]. JET experiments showed that a density shoulder can only be formed with the operation of a horizontal divertor rather than vertical divertor configuration [11]. Thus, divertor recycling appears to serve as a secondary factor or even a primary one affecting shoulder formation, which is revealed to be better correlated with shoulder formation and growth than divertor collisionality [11]. Experiments performed on MAST showed that far SOL flattening can occur even in the absence of divertor detachment [19]. TCV experiments showed that the density shoulder could form when the local plasma collisionality in the divertor was raised with the increase in the core line-averaged density, but not when the divertor effective collisionality was raised by modifying the connection length [10]. A similar conclusion was drawn from the Alcator C-mod experiments, in which the SOL density shoulder was created through an increase in the local plasma collisionality in the divertor by raising the core line-average density, but not through impurity seeding in the divertor region [20]. These observations are consistent with the results from JET that pure nitrogen seeding in the divertor hardly affects the upstream density shoulder [11]. The results suggest that a high level of plasma collisionality in the divertor could be a

necessary, but not a sufficient condition to trigger a density shoulder in the upstream SOL plasma, and that other additional effects are likely to play important roles in particular situations.

High-confinement mode (H-mode) plasmas with edge-localized modes (ELMs), ELMy H-mode, are considered as a reference regime for next-step devices such as ITER [21]. As ELM events transiently modify the background density at their outwards propagation, the investigations of the SOL density profiles in H-mode regime usually concentrate on the inter-ELM phases to gain physics insight into SOL plasma in a quasi-steady state. These measurements require diagnostics with the capability of high temporal resolution on a time scale of a few milliseconds. Due to these limitations, the documentation for SOL density shoulders in H-mode plasmas is very limited at present. To our knowledge, AUG has taken the first step to investigate shoulder formation during the inter-ELM phases of type-I ELMy H-mode plasmas, finding that the relationship between the plasma filaments and the formation of density shoulder observed in L-mode plasmas is still generally valid in H-mode [22]. A minimum level of deuterium fueling is required for density shoulder formation [15, 22]. Experiments on JET confirm that upstream SOL density shoulders in an H-mode plasma show a dependence on divertor plasma collisionality only at high fueling, as also observed in L-mode plasmas [11]. Besides, SOL density plays a crucial role in pedestal stability and access to small ELM regimes according to existing evidence [23]. In recent experiments, a high density ratio between the foot and top of a pedestal is identified to be a key ingredient for the achievement of grassy ELM operation in EAST [24]. It is observed that high SOL density can induce a transition from type-I ELMs to small type-II-like ELMs in AUG, while maintaining other parameters basically unchanged [25]. Recent study on DIII-D found that high SOL density is essential for access to small grassy ELM regime by flattening the pressure profile near the separatrix to stabilize type-I ELMs [26]. Investigations into the SOL density structure can improve the understanding towards the development of reactor-relevant high-confinement scenarios with intrinsic small ELMs.

2. Experimental setup

The experiments were performed in the EAST device [27], with the setups of the key diagnostics shown in figure 1. EAST is a fully superconducting tokamak with major and minor radii: $R_0 = 1.88$ m and $a = 0.45$ m, respectively. It was designed for long-pulse operations related to next-step, long-pulse fusion devices such as ITER and to provide an important platform to address physics and engineering issues [27]. EAST, outfitted with an advanced divertor configuration and heating scheme in support of ITER and future reactors, is equipped with a molybdenum first wall, an ITER-like monoblock tungsten upper divertor and a carbon lower divertor. The dome of the upper divertor is relatively flat, while the dome of the lower divertor with a W-shaped physically separates the inner and outer divertor chambers in order to minimize the leakage of neutrals to the main chamber [28]. The machine is flexibly operated

Figure 1. Poloidal cross-section of EAST and locations of diagnostics involved in this study: fast reciprocating probes (FRPs), Li-BES, D_α emission of deuterium, Langmuir probe (LP) arrays on the divertor targets and up and down cryopumps underneath the outer divertor target plates. Primary and secondary magnetic separatrix are indicated by a red curve and blue dashed curve, respectively.

in single null (SN) and double null (DN) divertor configurations using the advanced iso-flux control technique. The experiments described in these studies were conducted mostly in the upper single-null (USN) discharges with the tungsten divertor due to its better capability to handle heat loads. Besides, EAST adopts radio-frequency powers as dominant heating for continuous long-pulse plasma operation. A USN configuration is reformed from a DN configuration, by decoupling the primary and secondary separatrices through a set of up-down symmetric poloidal field (PF) coils. This plasma shaping scheme was employed as it was favorable for plasma vertical stability control on the EAST superconducting tokamak, in which the PF coils were far away from main plasma [29, 30]. With the plasma shaping scheme, the lower X-point was typically situated near the lower divertor, as indicated in figure 1. LHW is being predominantly used on EAST due to its high efficiency in plasma heating and current drive. Lithium-wall coating was performed daily to reduce neutral recycling and improve plasma performance [31]. For the present investigations, lithium-wall coatings were performed before plasma operation, requiring 1–2 h to evaporate about 10–30 g lithium. Deuterium was adopted as the working gas, which was injected from the outer midplane. Stable density control was assisted with feedback through supersonic molecular beam injection (SMBI), which reduced the particle retention in the SOL and chamber wall to facilitate long-pulse operation [32]. As shown in figure 1, two in-vessel cryopumps were installed near the

lower and upper divertors, respectively, for particle exhaust and recycling control [33].

To investigate the behavior of the upstream SOL plasma, a Langmuir FRP system on the outboard midplane is employed as the primary diagnostics for its capability of high spatial and temporal resolution [34]. A probe head mounted in the front end of the manipulator scans horizontally from a fixed position behind the limiter towards the separatrix. A round trip cycle takes typically 1 s or less, depending on the configuration of the motion speed. A dwell time of 100 ms at the innermost position is adopted in this study. Most of the experimental data presented below were obtained by a four-pin probe array, as described in [35], which is capable of measuring the radial profiles of the plasma density, n_e , electron temperature, T_e , floating potential, ϕ_f , as well as the turbulent transport. The acquired data were digitized at 2 MHz using a multi-channel digitizer, which is sufficient to resolve turbulent fluctuations in the SOL and obtain reliable statistical results. In addition to reciprocating probes, several other diagnostics, such as a lithium beam emission spectroscopy (Li-BES) system [36], tangential D_α array [37] and divertor triple Langmuir probes [38] are also used to monitor the plasma behavior. The layout of these principal diagnostics is shown in figure 1.

3. Upstream SOL density shoulder investigations in L-mode plasma

3.1. Characteristic of the upstream SOL density shoulder

A density ramp up with fixed plasma current was conducted to access high Greenwald density fractions in a single discharge. This scheme has been commonly adopted in the work for density shoulder investigation. For the experiments in this section, EAST was operated with plasma current, $I_p = 400$ kA, toroidal magnetic field, $B_t = 2.5$ T and USN divertor configuration. The parameter D_{sep} is used to determine the divertor configuration. $D_{\text{sep}} = R_L - R_U$ was defined as the radial separation between primary and secondary separatrices, where R_L and R_U were the lower and upper X-point radii mapped to the outer midplane, respectively. For DN configuration $D_{\text{sep}} \approx 0$, while it is negative and positive for LSN and USN, respectively. For the USN discharges here, $D_{\text{sep}} \sim 2.5$ cm. The experiments were conducted in the ‘normal B_t ’ direction, in which $\mathbf{B} \times \nabla \mathbf{B}$ was pointing downwards, away from the primary X-point and the plasma current, I_p , was in a counterclockwise direction when viewed from the top. Deuterium gas puffing was employed from the outer midplane. The plasma was heated by LHW for stable non-inductive current drive. As shown in figure 2, the core line-averaged electron density, n_{el} , ramped up from $2 \times 10^{19} \text{ m}^{-3}$ to $4 \times 10^{19} \text{ m}^{-3}$ during the plateau of I_p , corresponding to 0.3–0.7 of the Greenwald density fraction. Three probe plunges were implemented around 3.5, 5.5 and 7.5 s, respectively, in the discharge. The FRP manipulator carried the probe head towards the separatrix. After 100 ms dwelling at the innermost position, about 0.5 cm outside the separatrix for the plunges in the discharge, the probe head was carried back to its original departure location in limiter shadow. Indicated by the roll-over of ion saturation current

signal near the upper primary divertor strike point measured by fixed probes embedded at the upper-outer divertor plate (see figure 2(e)), the divertor plasma transited from an attached state to a detached one. At the end of the density ramp, the confined stored energy dropped remarkably (see figure 2(c)). This confinement degradation was commonly observed in plasma detachment experiments using continuous gas fueling.

The SOL density profiles determined by the FRP are shown in the figure 3, where the profile was observed to gradually steepen in the far SOL region when the core line-averaged density, n_{el} , was increased. The density profiles exhibited a linear decay rather than an exponential decay, suggesting that diffusive transport was not the dominant process in the plasmas. A ‘knee structure’ was observed in a near SOL region when the core line-averaged density, n_{el} , was approaching $3.2 \times 10^{19} \text{ m}^{-3}$ (a Greenwald density fraction $f_{\text{GW}} = 0.6$) and the detachment in the outer divertor occurred when the density continued ramping up. This near SOL region refers to a radial region with a distance less than 2.5 cm away from the separatrix, which coincided with the position of the secondary separatrix. In EAST, the location of the magnetic surface is predicted by EFIT code, with an uncertainty of 0.5 cm at the outer midplane and of 1.0–1.6 cm at the location of the strike points [39]. The ‘knee structure’ of the density profile was different to a broad density shoulder reported on other devices, such as Alcator C-mod [4] and AUG [12], where the density flattened over the whole SOL region. Here, we denoted the observed ‘knee structure’ as a ‘weak density shoulder’ to distinguish it from the conventional broad density shoulder observed in Alcator C-mod [4] and AUG [12] and the broad density shoulder on EAST, which will be reported in section 3.4. It is noteworthy that the weak density shoulder observed in EAST was similar in shape to the density shoulder measured on JET [11] and the density shoulder observed in a medium density regime ($f_{\text{GW}} \sim 0.45$ –0.5) in AUG [12], with respect to its small width in the SOL.

As the formation of a density shoulder is usually observed to be related to the blob events on other devices [8], the connection between the blob size and density shoulder was thus examined. The blob events were selected with the conditional average technique [9] by setting the condition for the amplitude of density fluctuation larger than 2.5 times the root mean square of fluctuations. The radial drift velocity of blobs was deduced based on the $\mathbf{E}_\theta \times \mathbf{B}_t$ velocity, where $\mathbf{E}_\theta$ was derived from two floating potential pins spaced in the poloidal direction. The lifetime of a blob, τ_c , was obtained from the auto correlation time of blob events. Figures 4(a)–(c) show the conditional averaged radial size, radial velocity and lifetime of blob events, respectively. It is evident that the blob size increased remarkably in the radial range 0–1.5 cm away from the separatrix and gradually reduced beyond the location of the ‘knee’ in the SOL density profile, implying a connection between the blob transport and a density shoulder. As aforementioned, one probe stroke typically lasted 1 s or more, which posed a restriction on resolving the SOL density profile at various Greenwald density fractions in one discharge. To compensate the weakness of the FRP measurements, a Li-BES system

Figure 2. Temporal evolution of an L-mode discharge #86516. (a) Plasma current I_p , (b) core line-average density n_{el} and its corresponding Greenwald density fraction f_{GW} , (c) plasma stored energy W_{MHD} , (d) auxiliary heating from 2.45 GHz LHWs and 4.6 GHz LHWs, (e) ion saturation current measured by fixed divertor probe near the upper-outer strike point, (f) neutral pressure at the lower divertor P_{nd} , at the outboard midplane P_{nm} and in the upper divertor P_{nu} , (g) R_p , the radial position of the probe head mounted on the FRP with respect to the primary separatrix.

installed at the outboard midplane was employed to determine the blob sizes at various Greenwald density fractions. The radial extension of blobs near the separatrix was reconstructed with conditional averaged fluctuating light intensity of Li-BES. These data were obtained from another pulse with similar discharge conditions. The results in figure 4(d) show that the blob size near the separatrix exhibited a sharp transition around $n_{el} \approx 3.2 \times 10^{19} \text{ m}^{-3}$, consistent with the observation from the FRP measurements. The observation suggested that a connection existed between the shoulder formation and blob transport on EAST and the result also agreed with a similar observation, for example, in, AUG [8].

Three pressure gauges were installed in the distal end of the vacuum tubes connected to the upper divertor, outboard midplane and lower divertor. The locations of the pressure gauges are outside the plotting range of figure 1, and are thus not shown. It should be noted that the conductance of these three pressure gauges was similar, with values in the range of $2.2 \text{ m}^3 \text{ s}^{-1}$ – $2.7 \text{ m}^3 \text{ s}^{-1}$. The gauges had a response time of about 1 ms to changes in the plasma conditions. Thus, the pressure measured by the gauges represented the pressure at the outboard midplane and in the divertors. The neutral (deuterium molecule and atom) pressure measured at these three poloidal locations is shown in figure 2(f). The neutral pressure at the midplane was approximately one order of magnitude lower than the neutral pressure in the upper divertor, which

in turn was two orders of magnitude smaller than the neutral pressure in the lower divertor. Moreover, one should note from figure 2(f) that the neutral pressure in the lower divertor increased remarkably when the density ramped up, while the neutral pressure in the upper divertor and on the outboard midplane did not show significant responses. The asymmetry between the lower and upper divertors has been observed on EAST both in USN and LSN configurations [33, 40]. As indicated in figure 1, two cryogenic pumps were installed near the lower and upper divertors, respectively. Both cryogenic pumps were working at liquid helium temperatures to pump deuterium gas. The effective pumping speed of both pumps is $75 \text{ m}^3 \text{ s}^{-1}$ [33]. Neutral gas was exhausted towards the divertors and created a zone of much lower neutral pressure around the outboard midplane. As in [33, 40], the origin of the higher divertor neutral pressure in the lower divertor rather than in the upper divertor in USN discharges also remained elusive in these studies. The asymmetry between the upper divertor neutral pressure and lower divertor neutral pressure was thought to be related to the divertor closure, where the lower divertor was of a more closed structure than the upper divertor due to the W-shaped dome structure in the lower divertor.

3.2. Correlation between the density shoulder and divertor neutral pressure

Besides the plasma density, the neutral pressure in the lower divertor is a potential or even primary ingredient for shoulder

Figure 3. SOL density profiles measured by the FRP during the density ramping up discharge (#86516). Data in black, blue and red indicate SOL density profiles at different Greenwald density fraction $f_{GW} = 0.5$, $f_{GW} = 0.6$, $f_{GW} = 0.65$, respectively. Linear fit is made for the density decay in the far SOL region. Data in the green rectangle come from the measurements of Li-BES in a similar discharge. Vertical line indicates the radial location of secondary magnetic separatrix.

Figure 4. Estimation of the blob parameters along different radial positions in the SOL based on the FRP measurements. (a) Radial propagating velocity V_r , (b) lifetime τ_c , (c) radial spatial size δ_b , and (d) dependence of blob size on the line-averaged density n_{el} , which is determined by the Li-BES near the separatrix. Gray zones in panels (a)–(c) indicate the locations of the weak density shoulder and the vertical lines in panels (a)–(c) indicate the radial locations of secondary magnetic separatrix.

formation. Studies show that in these plasma configurations the neutral pressure in the lower divertor should surpass a critical value $\sim 2 \times 10^{-2}$ Pa for the formation of a density shoulder, as inferred from figure 2(f). To clarify the dominance between the plasma density and divertor neutral pressure, one dedicated discharge (#86521) was conducted with reduced main gas puff,

as shown in figure 5. The plasma current was the same as in the discharge in section 3.1 and the core line-averaged density was set to $n_{el} \approx 4 \times 10^{-19} \text{ m}^{-3}$. Even though the core line-averaged density decreased to $3.4 \times 10^{-19} \text{ m}^{-3}$ at 7.4 s due to the reduced gas fueling, it was still above the assumed density threshold ($3.2 \times 10^{-19} \text{ m}^{-3}$) for weak shoulder forma-

Figure 5. Temporal evolution of discharge #86521 and #86523. (a) Core line-average density n_{el} , (c) plasma stored energy W_{MHD} , (c) main gas puffing rate Γ_D , (d) neutral pressure in the lower divertor P_{nd} , (e) lithium emission signal, L_{III} ; insets: CCD pictures of plasma without lithium injection (#86521 @ 7.5 s) and with lithium injection (#86523 @ 7.5 s), (f) ion saturation current signal $I_{s\ div}$, (g) the radial position, R_p , of the FRP with respect to the primary separatrix.

tion. As shown in figure 5, the deuterium gas puff at the outboard midplane was reduced from $1.5 \times 10^{21} \text{ e s}^{-1}$ at 1.5 s to $1 \times 10^{21} \text{ e s}^{-1}$ at 7.5 s and the neutral pressure at the lower divertor region showed a sharp decrease starting at about 4.5 s. This sharp decrease was attributed to an overbalance between the fueling rate and pumping rate, as the pumping capability did not change while fueling was reduced gradually. Three probe strokes were implemented around 3.5, 4.5 and 7.5 s, respectively. As shown in figure 6, a clear weak density shoulder was observed in the probe measurements during the first and second strokes, but it vanished in the measured density profile in the third stroke. Concurrently, the density fluctuations and associated particle transport did not show remarkable change near the separatrix for these three strokes, indicating that the particle transport was not the leading factor responsible for the absence of the density shoulder during the third stroke. From observing the time evolution of the neutral pressure in the lower divertor and the SOL density profile, it is clear that the density shoulder disappeared in these plasma configurations

when the neutral pressure decreased to a value below $2 \times 10^{-2} \text{ Pa}$. This is coincident with the observations in section 3.1 on the correlation of density shoulder formation and lower divertor neutral pressure.

In a repeated discharge (#86523), real-time lithium powder injection was performed at 6 s to regulate the wall conditions. The lithium powder was injected/dropped from the top of the upper divertor into the plasma at a flow-rate of $30\text{--}50 \text{ mg s}^{-1}$. Lithium emission was greatly enhanced when lithium flowed into the plasma, as indicated from the signal L_{III} shown in figure 5(e). No density roll-over occurred in the divertor ion saturation current, as indicated in figure 5(f), suggesting that the plasma was in an attached state throughout the discharges. Three probe plunges were implemented in this discharge at the same time as in #86521 to capture the evolution of the SOL density profiles and turbulent particle transport. The SOL density profile evolution is shown in figure 6. As observed in the measurement of #86521, a weak density shoulder was detected in the SOL region during the first and second strokes. However, the shoulder disappeared in the third stroke.

Figure 6. Profiles of the SOL density and turbulent particle transport measured by the FRP, (a) SOL density profiles measured in discharge #86521, (b) SOL density profiles measured in #86523, (c) profile of SOL particle transport measured in #86521, (d) profile of SOL particle transport measured in discharge #86523. Vertical lines indicate the radial location of the secondary magnetic separatrix.

It should be noted that, in this and the subsequent sections, the density fluctuations were retained on top of the density profiles, which made it possible to track the evolution of the amplitude of the density fluctuations. Compared to #86521, blobs events, which were manifested by density spikes protruding on the density profiles, and the turbulent particle transport, were observed to be significantly mitigated during the period of the third stroke (figure 6(d)), which was similar to the effects of lithium injection on ELM filament suppression [41]. In this discharge, the absence of a density shoulder was also observed at a neutral pressure below 2×10^{-2} Pa. Generally, in these two repeated discharges, it is evident that the density shoulder was absent when the neutral pressure decreased to a value below 2×10^{-2} Pa, regardless of whether the particle transport was significantly modified, as indicated in figures 6(c) and (d).

As shown in the figure 7, a clear downshifted sideband of 2.45 GHz LHW was observed in the SOL with the presence of a weak density shoulder and the generated wave sidebands peak at a frequency of 2.433 GHz. The appearance of sidebands signified the occurrence of parametric instabilities in the SOL plasma, which was responsible for the loss of current drive efficiency [42]. Remarkably, the sidebands were observed to be significantly reduced when the density shoulder was absent, as in #86521. This phenomenon was well reproduced in these two shots, regardless of the utilization of lithium injection. This also agreed well with the observation on Alcator C-Mod in which the recovery of current drive efficiency was correlated with a reduction in the density shoulder and

Figure 7. Frequency spectrum of 2.45 GHz LHW at 4 and 7 s detected by the spectrum analyzer, in #86521 and #86523, respectively.

turbulence levels in the far SOL [14]. In this work, we point out for the first time the direct connection between the SOL density shoulder and the parametric instabilities on EAST.

3.3. Impact of plasma detachment on the density shoulder

The relationship between the density shoulder and divertor detachment was observed to be ambiguous. It was observed that the density shoulder appeared together with divertor

Figure 8. (a) Time trace of color map constructed from the ion saturation current density measured by fixed probe arrays embedded in the upper outer divertor target, where d indicates the distance between the probe and the divertor corner. Red line indicates the location of the strike point calculated from EFIT magnetic equilibrium reconstruction, (b) time evolution of the core line-averaged density and the corresponding Greenwald density fraction, (c) time evolution of impurity particle Γ_{mix} (volume ratio: 80% D₂ + 20% Ne) seeding implemented near the strike point at the upper outer divertor, (d) time evolution of the main gas puffing rate Γ_{D} and the neutral pressure at the lower divertor P_{nd} .

Figure 9. Density profiles measured by the FRP during the attached and detached phases during the plasma discharge of #86520. Here, the profiles combine the data measured from both inward and outward probe strokes. R_p indicates the radial position of the probe head with respect to the primary separatrix. Vertical lines indicate the radial location of secondary magnetic separatrix.

detachment in a high-density regime without impurity seeding in AUG and JET [12]. Similarly, the weak density shoulder was also detected in the phase of divertor detachment in EAST, as shown in section 3.1. However, weak density shoulders were

also observed in the attached discharges in EAST, as shown in section 3.2 (#86521 and #86523).

The technique for active control of plasma detachment has been successfully developed using divertor particle flux measured by divertor Langmuir probes as the feedback controller [43]. The control algorithm based on the divertor particle flux worked effectively during the experiments with divertor impurity seeding. This provided an advanced approach to investigate the causality between plasma detachment and the SOL density shoulder. In this study, the plasma discharge was operated with a core line-averaged density of $n_{\text{el}} \approx 3.2 \times 10^{19} \text{ m}^{-3}$ (figure 8(b)), near the density threshold identified in section 3.1. The plasma was still attached to the divertor target for this density value. Detachment control was performed at 3.5 s with a mixture of 20% Ne and 80% D₂ impurity seeding in the divertor to press the plasma into a detachment state (figure 8(c)). As shown in the color map of the ion saturation current in figure 8(a), the particle flux flowing into the divertor was mitigated significantly. During the neon–deuterium seeding, the core line-averaged electron density n_{el} increased slightly. From the observations at JET and Alcator C-mod in L-mode plasmas, a pure impurity (nitrogen) seeding failed to trigger density shoulder formation in the SOL [11, 19]. Pure neon or deuterium seeding was not examined in this study, as it tended to cause plasma disruption [44]. Moreover, on EAST, the nitrogen seeding is not allowed in a lithium coated

Figure 10. Time evolution of a high-density discharge #90044. (a) Plasma current, (b) core line-averaged density, n_{el} , and its corresponding Greenwald density fraction, f_{GW} , (c) input heating power, (d) D_α emission line at the outer divertor target, (e) neutral pressure in the lower divertor P_{nd} , at the outboard midplane P_{nm} and in the upper divertor P_{nu} , (f) R_p , the radial position of the FRP with respect to the separatrix.

Figure 11. SOL density profiles measured by the two strokes of the FRP shown in figure 9(f). Linear fits (dashed lines) were performed for the observation in the evolution of the radial gradients of the SOL density shoulders. Vertical lines indicate the radial location of secondary magnetic separatrix.

wall, as lithium and nitrogen will react to produce compounds. Hence, a direct comparison to JET, AUG, and Alcator C-mod on nitrogen seeding is not available in the EAST experiments.

As indicated in figure 8(d), the neutral pressure in the lower divertor was well above 2×10^{-2} Pa from 2–8 s. The density profiles measured by the FRP during the attached and detached phases are compared in figure 9 and it is clear that a weak SOL density shoulder was already formed in the attached plasma. This result suggests that plasma detachment was not a direct trigger of the weak shoulder formation on EAST, while

sufficient neutral pressure was the precondition for SOL density shoulder formation. The ‘knee’, situated 2 cm away from separatrix, did not shift outwards when the divertor plasma entered into a detached phase. The weak density shoulder detected in this impurity seeding-induced detached plasma was similar to the weak density shoulder observed in the detached plasma induced by the density ramp, as presented in section 3.1. In both cases, the radial range of the knee structure was 2 cm away from the separatrix. Therefore, a flattened SOL density profile towards the far SOL region was not achieved on EAST when the plasmas were driven into a detached state.

3.4. Radial expansion of the weak density shoulder

To explore the SOL density profile in a higher-density regime, the density was ramped up at a plasma current of $I_p = 400$ kA, as in section 3.1. The operation approaching the Greenwald density limit was attempted at a lower plasma current, in which the plasma current gradually decreased to $I_p = 340$ kA from 4 to 6 s, with the aid of a strong heating power (2.45 GHz LHW 1 MW, 4.6 GHz LHW 1 MW, and co-current NBI heating power 1.5 MW). In this scheme, higher-density regimes ($0.8n_G$ – $0.9n_G$) were accessed reproducibly. The experiments were conducted in a normal B_t direction, $B_t \times \nabla B_t$ pointing away from the primary X-point, which was favorable for preventing the plasma transiting from L-mode to H-mode confinement. The results and discharge information are depicted in figure 10. The plasmas accessed to H-mode confinement from 2.1–2.9 s and then the plasmas transited back into L-mode with the increase in plasma density. Two probe strokes were performed to capture the SOL parameters in the L-mode plasma stage.

As shown in figure 11, a weak density shoulder was observed to persist in the high-density regime around $0.8n_G$. However, a transition from a weak shoulder to a strong/broad shoulder was observed when the plasma approached a density around $0.9n_G$. The magnetic configuration, including the distance between the primary and secondary separatrices ($D_{\text{sep}} \sim 2.5$ cm), remained almost constant during these fueling ramps. Distinct from the weak density shoulder reported in sections 3.1–3.3, the strong density shoulder expanded through the entire radial region of the SOL and reached the leading edge of the limiter. It resembled the characteristic of a standard density shoulder reported from Alcator C-mod [4] and AUG [12]. To survey the difference in SOL plasma behavior around 0.8 and $0.9n_G$, a sudden increase in the D_α signal baseline was found when the plasma density approached $0.9n_G$. A CCD camera demonstrated that an MARFE-like instability was triggered near the X-point in the high-field side in such a high-density operation, as shown on the right of the figure 10(d). However, the MARFE-like instability was not responsible for the strong shoulder formation, as it was locked on the high-field side and no hint of such instability was detected in the FRP signals measured on the low-field side. As shown in figure 10(e), the neutral pressure in the lower divertor still remained highest with respect to those at the upper divertor and outboard midplane. The neutral pressure in the lower divertor reached a value of about 2.5×10^{-1} Pa, one order of magnitude larger than the threshold of the weak shoulder. The shoulder expansion was successfully achieved under this enhanced neutral pressure condition. Moreover, the density fluctuations, specifically for the innermost position of probe measurement, did not show a remarkable increase at the formation of a density shoulder, suggesting that the blob activity was not a direct trigger for the transition. Hence, the shoulder expansion was regarded as being mostly correlated to the increase in the divertor neutral pressure in the lower divertor.

3.5. Correlation of a density shoulder to divertor neutral pressure and divertor collisionality

Effective collisionality Λ_{div} at the divertor was proposed as an essential quantity for upstream density shoulder formation [8]. It was defined as $\Lambda_{\text{div}} = (L_{\text{eff}}/\nu_{\text{ei}}) (\Omega_i/C_s\Omega_e)$, where L_{eff} [m] referred to the connection length from the outboard midplane to the divertor target, ν_{ei} [s^{-1}] to the electron–ion collision frequency, C_s [m s^{-1}] to the ion sound speed, and Ω_i [s^{-1}] and Ω_e [s^{-1}] to the gyro-frequency of ions and electrons, respectively [8]. $\Lambda_{\text{div}} > 1$ was commonly observed at the shoulder wetted area on a divertor in AUG [8], JET [11] and TCV [10] and it was considered to be a necessary condition for shoulder formation. The correlation of a density shoulder and the effective collisionality in EAST was also examined here within the database of the investigated L-mode plasmas. As the density shoulders were observed to form initially in the near SOL in EAST, Λ_{div} was thus determined near the strike point. Figure 12 demonstrates the relationship among the shoulder formation, the plasma collisionality at the upper-outer divertor and neutral pressure in the lower divertor. The scattered data

Figure 12. Parametric dependence of the SOL density profile on divertor collisionality and neutral pressure in the lower divertor in the investigated L-mode discharges with a fixed plasma current $I_p = 400$ kA.

show that shoulder formation takes place both in the high collisionality branch $\Lambda_{\text{div}} > 1$ and the low collisionality branch $\Lambda_{\text{div}} < 1$. Thus, $\Lambda_{\text{div}} > 1$ did not appear to be a necessary condition for a shoulder formation regardless of a weak shoulder or a strong one. Moreover, a high neutral pressure in the lower divertor seemed to be imperative for the strong shoulder formation. A weak shoulder required a minimum value of about 2×10^{-2} Pa in the lower divertor in USN discharges and a broad shoulder was observed only when the neutral pressure in the lower divertor was larger than 2.5×10^{-1} Pa. The data shown by the red rhombus represent plasmas of divertor neutral pressure much larger than 2.5×10^{-1} Pa and much higher divertor collisionality, where the collisionality was rescaled for viewing convenience. The results presented in this work suggest that neutral pressure in the lower divertor was a primary condition for the density shoulder formation rather than the divertor collisionality or plasma density. It should be noted here that recent experiments on JET have provided strong evidence that the divertor recycling acts as the primary parameter for density shoulder formation on the top of the divertor collisionality [11]. The results from EAST confirm the conclusion from previous studies in JET [11], TCV [10] and Alcator C-mod [20] that divertor collisionality is not the sole parameter for controlling the shoulder formation.

4. Survey of SOL density shoulder in type-I ELMy H-mode plasmas

The type-I ELMy H-mode plasmas in this study were attained in a lower edge safety factor domain ($q_{95} < 6$, q_{95} signifying the safety factor at the 95% normalized poloidal flux surface). As type-I ELMs significantly modify the plasma density profiles in the SOL, the investigations in the type-I ELMy H-mode regime focused on the inter-ELM phases. To avoid damage of the probe head by large ELM-induced heat load, the Li-BES diagnostic installed at the outboard midplane was employed as a primary diagnostic for the density shoulder study in this section.

Figure 13. Time evolution of #69195 and #78893. (a) Plasma current; (b) core line-averaged density n_{el} , (c) plasma stored energy, (d) safety factor at 95% normalized magnetic flux, (e) divertor collisionality near the primary upper strike point, (f) neutral pressure at the lower divertor P_{nd} , (g) ion saturation current collected by a fixed divertor probe near the strike point on the upper-outer divertor, (h) zoom-in of the signal shown in the panel, (i) magnetic configurations reconstructed by EFIT.

As shown in figure 13, a stable reference type-I ELMy H-mode discharge (#69195) was established with plasma current $I_p = 500 \text{ kA}$ and $q_{95} \sim 5$. The core line-averaged density was stably maintained at $n_{el} \sim 3 \times 10^{19} \text{ m}^{-3}$ with feedback control by SMBI. The plasma current was gradually reduced to 300 kA during the time period from 3–7 s. The corresponding Greenwald density fraction increased from 0.4 to 0.55. During this period, the magnetic configurations, specifically the location of the strike points at the outer divertors were almost fixed by the plasma control system (figure 13(i)). To avoid the modification of the SOL density profiles by ELMs, all the density profiles mentioned in this section were determined during the inter-ELM phases. As shown in figure 14, a pronounced density shoulder developed in the near SOL when the core line-averaged density exceeded $0.45n_G$ at 5 s. The radial extension of the shoulder from the separatrix was less than 2 cm, while the leading edge of the limiter was situated at a position 3.5 cm from the separatrix in these discharges. With further increase in the Greenwald density fraction, the density shoulder did not extend further outwards. The amplitude and radial range of the shoulder appeared to be saturated. This behavior generally agreed with the tendency of the SOL density evolution in L-mode plasmas, as discussed in sections 3.1–3.3. The effective collisionality near the strike point in the upper divertor was

calculated based on the density and temperature measured by the divertor probes. This shows that the formation of a density shoulder took place when the effective collisionality Λ_{div} near the upper-outer strike point exceeded 1. On the other hand, if one assumes the neutral pressure in the lower divertor to be a key factor for the shoulder formation, the threshold for the shoulder formation is anticipated above $4 \times 10^{-2} \text{ Pa}$ (at 5 s in #69195).

In order to further explore the influence of the density on the SOL density shoulder formation, we repeated the current ramping-down operation (in another discharge #78893) with a larger Greenwald density fraction, but a reduced neutral pressure in the lower divertor to a value below the anticipated threshold of $4 \times 10^{-2} \text{ Pa}$ in this discharge. The steady-state control of the line-averaged density was mainly achieved by SMBI rather than by neutral gas puff. As shown in figure 13, the setup of discharge #78893 was basically kept unchanged compared with #69195, except for a higher line-averaged density $n_{el} \sim 4 \times 10^{19} \text{ m}^{-3}$. The plasma current was gradually reduced from 500 to 300 kA and the Greenwald density fraction increased from 0.55 to 0.86. Figure 13(h) shows the ELM dynamics from measuring the ion particle flux onto the upper-outer divertor target by a fixed Langmuir probe near the upper-outer strike point. No visible change in the ELM

Figure 14. (a) Measurements of density profiles of five different time slices measured by Li-BES in the type-I ELM discharge #69195 and the weak density shoulder measured by the FRP in L-mode discharge #86521 signified by open circles; (b) measurements of density profiles of five different time slices in the type-I ELM discharge #78893. Vertical lines indicate the radial location of secondary magnetic separatrix.

amplitude and frequency was observed compared to #69195, indicating similar ELM dynamics for the two discharges. In discharge #78893, the effective collisionality in the divertor was determined to be larger than 1 from 2.5 s and onwards. In spite of this, a density shoulder was not observed during the inter-ELM phase in this higher-density regime until the end of the discharge, as shown in figure 14(b). These results suggest that the formation of density shoulders did not linearly depend on a core line-averaged density or a Greenwald density fraction. Instead, the neutral pressure in the lower divertor appeared to play a key role in the shoulder formation. The radial expansion of the density shoulder during the inter-ELM phase here was similar to the weak shoulders observed in L-mode plasmas (see sections 3.1–3.3), which was limited to the radial gap between the primary and secondary separatrices.

5. Discussion on predominant role of neutral pressure in the lower divertor on density shoulder formation

The neutral pressure in the lower divertor is typically one order of magnitude larger than in the upper divertor in USN discharges. This asymmetry has been noted in previous studies [32, 39]. Given its W-shaped dome hardware structure, the lower divertor has a more closed structure than the upper divertor. Moreover, the lower strike point of the secondary magnetic flux surface in USN configurations are situated at the pump slot in the lower divertor, as indicated in figure 1, which facilitates the neutral gas collection. These two factors may be responsible for an asymmetric distribution of neutral pressure in the two divertors.

From the SOL measurements implemented in both L-mode and H-mode plasmas, it is clear that the neutral pressure, specifically in the region of the lower divertor, is strongly

correlated with the formation of the upstream density shoulder in USN discharges with a tungsten divertor. Different to density shoulders observed in other tokamaks, which are located in the far SOL, weak density shoulders observed in EAST are located in a near SOL region and the radial expansion of weak density shoulders is smaller than D_{rsep} , the radial separation of primary and secondary separatrices. The observations suggest that the ionization of neutral particles in the divertor could be responsible for the formation of the weak density shoulders. In this study, no clear correlation was observed between the shoulder formation and the neutral pressure in the upper divertor. However, it is stressed that the three neutral pressure gauges are single-point measurements, without the capability to provide the spatial resolution. In this case, the distribution of neutral particle density in the entire SOL poloidally was not resolved in this work. Even though the neutral pressure in the lower divertor region was identified as having the strongest influence on the shoulder formation, the contribution from other neutral particle sources cannot be ruled out. The role of the upper divertor on the shoulder formation will be further explored in our future work, with improvement in the diagnostic capabilities of neutral particle distribution in the upper divertor.

Divertor probe measurements suggests that in these USN configurations, both the peak particle flux and integral ion current are stronger at the upper-outer divertor than at the lower-outer divertor in the investigated plasmas. This indicates that the higher neutral pressure in the lower divertor is not directly related to the particle flux and plasma recycling in the outer divertor regions. The influence of distance of the strike point to the outer pumping plenum was recently studied in experiment and SOLPS simulation, but only for the upper divertor [45, 46]. The mechanism for the asymmetry of the neutral pressure between the upper and lower divertor is still not concluded in EAST. As highlighted in this work, showing that the

neutral pressure in the lower divertor pressure plays the more critical role in the density shoulder formation than the neutral pressure in the upper divertor, the density shoulder formation will be revisited when the origin of the pressure distribution is explained in future experiments.

6. Summary

SOL density shoulder was examined in both L-mode and H-mode plasmas in the EAST tokamak. A ‘weak density shoulder’ formed in the near SOL in L-mode discharges with an ITER-like tungsten divertor, when the core line-averaged density exceeded $0.6n_G$ (n_G referring to the Greenwald density) and neutral pressure in the lower divertor was larger than 2×10^{-2} Pa. The neutral pressure in the lower divertor region was identified as the most critical parameter for the shoulder formation in this work. The studies reveal that the shoulder can be regulated by the neutral pressure in the divertor region. The density shoulder was absent when the neutral pressure in the lower divertor was lower than a threshold value of 2×10^{-2} Pa. Besides, the underlying SOL parametric instabilities signified by the sidebands of LHW were found to be depressed with the elimination of density shoulder. The density shoulder was observed to form in the attached plasma as long as the divertor neutral pressure was larger than the threshold. The plasma detachment achieved with impurity seeding showed a weak effect on the shoulder broadening. However, the density shoulder was extended to the leading edge of the limiter with increasing the neutral pressure to be of one order of magnitude larger. The density shoulder was further explored in the type-I ELMy H-mode discharges. It has been found that the threshold pressure for shoulder formation was larger by a factor of two in the investigated H-mode plasmas than the L-mode plasmas. By lowering the neutral pressure below the threshold pressure, the density shoulder disappeared even for a higher Greenwald density fraction and a higher divertor collisionality. The results in this study suggest that neutral pressure in the lower divertor region is a primary factor for the density shoulder formation dominating the effects of the core line-averaged density and divertor collisionality in EAST.

Acknowledgments

The first author would like to acknowledge D. Carralero, N. Vianello and Y.W. Yu for useful suggestions. The authors thank an anonymous referee for constructive comments that improved the presentation significantly. This work was supported by the National Natural Science Foundation of China under Grant Nos. 11975275, U19A20113, 1200544, 12005263 and 11905143, the Science Foundation of Institute of Plasma Physics, Chinese Academy of Sciences under Contract No. DSJJ-18-02, the Key Research Program of Frontier Sciences, CAS, under Grant No. QYZDB-SSW-SLH001, the National Magnetic Confinement Fusion Energy R & D Program of China under Grant No. 2018YFE0302100 and the K. C. Wong Education Foundation.

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