PLASMA CONFINEMENT AND PEDESTAL DYNAMICS RESPONSES TO IMPURITY SEEDING IN HL-2A H-MODE PLASMAS

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Abstract

In ELMy H-mode plasmas of the HL-2A tokamak, impurity seeding experiments by using supersonic molecular beam injection (SMBI) system have been performed, recently. The neon gas is mixed with the main ion fuelling gas by different ratios. It has been observed that the ELM behavior and plasma confinement varied with the impurity ratio of the mixture SMBI. For 30% Ne impurity seeding, large ELMs can be replaced by high frequency bursts which have smaller amplitude compared to the ELMs, and the divertor radiation power density is considerably reduced. For the pure neon or Aron SMBI seeding, the ELM frequency decreases and the plasma confinement is improved moderately. Experimental observations suggest that the impurity mixture gas plays a role in changing the pedestal dynamics and there should be an optimal impurity ratio for efficient heat load control in ELMy H-mode plasmas.

1. INTRODUCTION

In high confinement mode (H-mode) of magnetic confinement devices, like tokamaks or stellarators, an edge transport barrier (ETB) or pedestal with steep density and/or temperature profile is often spontaneously formed at the plasma edge region [1,2]. In addition to the high confinement of the pedestal itself, the pedestal also plays a key role in governing the performance of the core plasma by providing a boundary condition for the stiff core transport [3]. Based on the advantages of the H-mode, it has been chosen over the other improved confinement modes as the primary operating scenario for ITER [4]. However, the strong gradient of plasma edge pressure can trigger repetitive edge-localized modes (ELMs) which usually produce high transient heat loads on plasma facing components (PFCs) [5]. The event occurs in very short timescales. For Type-I ELM, it causes intense energy flux from the pedestal to the divertor target with typical durations of 100-400 μs. At the aspect of ELM energy loss (△W_{ELM}/W_{ped}) normalized to the pedestal energy (W_{ped}) for ITER plasmas with low pedestal collisionality, type-I ELMs would release 20MJ plasma energy which is about 20% of the pedestal stored energy [6]. The peak heat load could exceed the tolerable material limits of the PFCs. In order to protect the PFCs, an ELM energy loss should be less than 1 MJ in ITER as predicted by calculations [7, 8]. Thus, it is crucial to develop effective techniques for protecting PFCs in burning plasma devices.

Over many years, intensive effort has been dedicated to finding an optimal and robust technique for heat load and ELM control [9, 10], such as resonant magnetic perturbation (RMP), pellet pacing, RF current drive or heating, impurity seeding and vertical jogs. In particular, supersonic molecular beam injection (SMBI) [11], a plasma fuelling tool has been first demonstrated for ELM mitigation in HL-2A [12], and then successfully applied in EAST [13] and KSTAR [14,15]. Additionally, it has been reported that impurity seeding can control ELMs and reduce the divertor heat load in several devices [16-21]. On the one hand, it can reduce the heat load by converting the heat into impurity seeding radiation. On the other hand, it can control the ELM activities by affecting the pedestal dynamics and instabilities. In HL-2A, the study on the effect of impurity on plasma confinement and instability has been emphasized [22]. It has been observed that a broadband electromagnetic (EM) turbulence can be driven by peaked impurity density profile at the edge plasma region, and governed by double critical gradients of the impurity density [23]. The excited pedestal instabilities play an important role in regulating the pedestal turbulent transport.

To effectively control the heat load in ELMy H-mode plasmas, a newly developed SMBI system with mixture impurity gas has been recently used in HL-2A. One species of impurity gas (Ne, Ar or N2) is mixed with the main ion fuelling gas D2 by different ratio. The major objective is to find whether there is an optimal impurity mixture ratio, which is beneficial for forming an edge radiation layer and avoiding impurity core accumulation.

For the experiments presented in this paper, the impurity gases with different neon ratios (10%, 30% and 100%) are seeded into the ELMy H-mode plasmas by using SMBI in the HL-2A tokamak. The gas pressure of the
SMBI is 5-10MPa and the pulse width is 1-1.5ms. The plasma parameters are: the plasma current of 140-160kA, the toroidal magnetic field of 1.3T, the NBI heating power of 0.6-1MW, the ECRH heating power of 0.6MW, and the LHW heating power of 0.6MW.

2. IMPURITY SEEDING WITH SMBI

2.1. Ne mixture SMBI seeding

The first impurity seeding experiments with impurity mixture SMBI have been carried out in the 2017 experimental campaign of the HL-2A tokamak. The Ne is mixed with D₂ gas and the mixture gas is externally seeded into the plasma by the SMBI. In the experiment of figure 1, 10% Ne mixture gas was seeded in the ELMy H-mode plasma. The monitor of the SMBI pulse is shown in figure 1a. The pulse width is 1.2ms. The fuelling effect induced by the SMBI causes the moderate increase of the plasma electron density as shown in figure 1b. The total plasma radiation power shown in figure 1c increases gradually after the SMBI. In terms of ELM activities, the ELM amplitude is reduced and the corresponding frequency is increased from t=850ms to 890ms as indicated by the Dₐ (figure 1d) and divertor radiation signals (figure 1e), meaning that the ELM is mitigated by the mixture SMBI. The previous experiments in HL-2A showed that the main ion fuelling SMBI increases the ELM frequency by a factor of 1-2 and the mitigation effect of single SMBI pulse lasts for 20-30 ms [12]. However, for the impurity mixture case, the result in figure 1 shows that the mitigated ELMs are irregularly mixed with smaller bursts. Dₐ (figure 1d) displays a complex nature of ELM effluxes. It might be interpreted by that the number of small filaments is increased and that of the larger amplitude one is reduced during the ELM mitigation phase, as statistically studied by Langmuir probes in HL-2A [24]. The global plasma performance is not undergone noticeable degradation after the mixture SMBI, as seen from the evolution of the inner stored energy (figure 1f). In general, the effect of the 10% Ne mixture SMBI on the H-mode plasma is similar to that of the main ion fuelling injected by pure D₂ SMBI.

Figure 1. Time traces of main parameters for the impurity seeding experiment by 10% Ne mixture SMBI in HL-2A: (a) monitor of the SMBI pulse, (b) line-averaged electron density (blue) and plasma current (red), (c) total plasma radiation power, (d) Dₐ signal, (e) divertor radiation from the divertor bolometer array, (f) inner stored energy Wₑ of the plasma.

In order to further study the effect of the impurity mixture SMBI on ELMs, the Ne content is increased to the ratio of 30%. A typical experiment performed by 30% Ne mixture SMBI is shown in figure 2. Compared to the shot of figure 1, the main discharge parameters are identical. The mixture gas was seeded at 843ms as shown in figure 2a. The SMBI pulse width is 1.2ms. The SMBI gradually increases the plasma density by a factor of about 10% in the ELMy H-mode (figure 2b). As expected, the total radiation power (figure 2c) increases after the SMBI. In contrast to the result of figure 1, the ELMs are replaced by high frequency bursts (HFBs) with smaller amplitude as seen from the Dₐ (figure 2d) and divertor radiation signals (figure 2e). The spectra of the Dₐ signal show that the characteristic frequency of HFBs is about 0.8 and 1.6kHz, as illustrated in figure 3.
The results from figure 1 and figure 2 indicate that the responses of ELMs to the ratios of the impurity are different and the impurity mixture gas plays a role in changing the pedestal dynamics and underlying instabilities. The duration of the HFB sustains for about 50 ms, which is longer than that of the mitigation in figure 1. The baseline of the Dα signal rises during the occurrence of the HFBs, suggesting that the HFB enhances the pedestal particle transport compared to the level of the inter-ELM phase before the SMBI. However, the evolution of the inner stored energy (figure 2f) shows that the global plasma confinement keeps almost constant.

2.2. Pure Ne SMBI seeding

In addition to the Ne mixture SMBI, the effect of pure Ne on ELMs and heat load has also been studied by using the SMBI in HL-2A. In order to evaluate the effect solely contributed by the impurity, the edge cooling effect...
caused by the perturbation of the SMBI in the main plasma should be minimized. By controlling the backpressure and pulse width of SMBI, the amount of the impurity particle can be optimized. Figure 4 shows a typical H-mode discharge, in which the Ne impurity was externally seeded by 100% Ne SMBI at 892 ms. As seen from the plasma density in figure 4b, the SMBI does not contribute noticeable fuelling effect to the plasma. The plasma radiation slightly increases after the SMBI (figure 4c). With regard to the plasma temperature, the edge electron temperature (figure 4d) measured by ECE system are not undergone decrease. The evolution of the plasma temperature indicates that the cooling effect of the SMBI is negligible. The core electron temperature (figure 4e) keeps constant. The temperature behaviors are not similar to that of previous experiments in several devices, where Ne, Ar or N seeding improved the plasma confinement. In JT-60U, higher core and pedestal temperatures were found in Ar seeding plasmas [25]. The response of ELMs to the 100% Ne SMBI can be revealed from the Dα signal in figure 4f. Qualitatively, the inter-ELM period is prolonged after the SMBI. The ELM frequency shown in figure 4e is defined as the inverse of the time interval between two adjacent ELMs. It shows that the ELM frequency decreases after the SMBI by a factor of about 50%. However, the ELM amplitude does not increase. It means that the ELMs impacted by the pure Ne impurity SMBI do not satisfy the relation \( \Delta W_{ELM} \times f_{ELM} = \text{constant} \) which holds for intrinsic and mitigated ELMs on several tokamaks. The frequency-decreased ELMs after SMBI cause the increment of the plasma density by longer inter-ELM periods instead of the fuelling effect induced by the SMBI. The result shows that the Ne impurity improves the pedestal stability. Similar result has also been observed in the Ar-seeded H-mode plasmas in HL-2A.

Figure 4. Time traces of main parameters for the impurity seeding experiment by pure Ne SMBI in HL-2A: (a) monitor of the SMBI pulse, (b) line-averaged electron density, (c) total plasma radiation power, (d) edge ECE signal, (e) core ECE signal, (f) Dα signal, (g) ELM frequency.

Observations from the mixture and pure impurity seeding show that ELM activities change with the ratios of the seeded impurity, suggesting that the impurity ions play a role in the pedestal dynamics. Figure 5 shows the change of the ELM frequency as a function of the ratio of the Ne impurity mixture SMBI. The change of the ELM frequency is defined as the ratio of the ELM frequency or the frequency of the HFB (for the case of 30% Ne mixture SMBI) after the SMBI to the frequency of the natural ELMs. The value is less than 1 meaning the ELM frequency decreases. As shown in figure 5, the ELM frequency decreases by about 50% for the pure Ne seeding discharge. On the contrary, the ELM frequency increases for the Ne ratios of 10% and 30%. It should be noted that the ELMs are replaced by small amplitude HFBs for the 30% Ne discharge. The results indicate that the effect of the impurity ions on pedestal stability plays a role in the ELM mitigation besides the contribution from the main ion fuelling particles.
3. RESPONSE OF PEDESTAL DYNAMICS AND DIVERTOR RADIATION TO 30% NE SMBI

As shown in figure 2, the baseline of the $D_a$ signal rises during the occurrence of the HFBs, suggesting that the HFBs enhance the pedestal particle transport compared to the level of the inter-ELM phase before the SMBI. With regard to the pedestal density fluctuations, figure 6 gives the results from the 46GHz X-mode Doppler reflectometry, which measures the plasma turbulence in the pedestal region. Figure 6b is the Doppler spectrogram representing the turbulence of a specific perpendicular wave-number ($k_\perp$). The $k_\perp$ is determined by the incident angle of the microwave, microwave frequency, plasma density profile and magnetic field, and the corresponding value is in the range of 7-9$\text{cm}^{-1}$ for the shot of figure 6. It shows that the turbulence intensity during the occurrence of the HFBs becomes stronger than that in the inter-ELM phase before the SMBI. The amplitude spectrogram which is proportional to the density fluctuations shows that the HFBs enhance the fluctuations, especially in the frequency of 50-300kHz, as seen in figure 6c. It indicates that the high frequency turbulence is enhanced. For the electron density measured by the microwave reflectometer, figure 7 shows that the pedestal gradient is softened during the occurrence of the HFBs compared to that in the inter-ELM phase, further supporting the deduction that the HFBs enhance the pedestal particle transport.

Figure 5. Change of the ELM frequency versus the ratio of the Ne impurity mixture SMBI.

Figure 6. Divertor $D_a$ signal and monitor of 30% Ne SMBI, (b) Doppler spectrogram and (c) amplitude spectrogram of the 46GHz Doppler reflectometry.
The profile of the radiation power density is measured by the bolometer array. Figure 8a and 8b present the raw radiation signal before and after the 30% Ne SMBI, respectively. The high intensity bursts are induced by the ELM crashes. It shows that the radiation intensity decreases significantly after the SMBI. Figure 8c is the time evolution of the radiation power density profile along the outer divertor plate. The 30% Ne mixture gas was seeded at 843ms. After that, the radiation power density decreases considerably. The low level radiation lasts for about 50ms accompanying with radiation bursts caused by HFBs. Regarding to the radiation near the striking point, figure 8d shows that the ELM crash induces high transient radiation. The radiation level during the HFBs is reduced considerably compared to the ELM. However, it is higher than that in the inter-ELM period before the SMBI. These results indicate that the HFBs provide quasi-periodic and continuous heat flux to the divertor region and avoid the high transient heat loads of the large ELMs deposited on the divertor plate.

4. SUMMARY

Recently, impurity seeding experiments by using SMBI have been performed in ELMy H-mode plasmas of HL-2A. The effect of impurity ions on ELM dynamics and the plasma confinement has been studied. Besides pure impurity gas, one species of impurity gas is mixed with main ion fuelling gas $D_2$ by different ratio. The first experiment on heat load and ELM control with impurity mixture SMBI seeding has been carried out in the 2017
experimental campaign of HL-2A. The impurity gases with different Neon ratios (10\%, 30\% and 100\%) were seeded into the ELMy H-mode plasmas. It has been observed that the ELM behavior varied with the impurity ratio of the mixture SMBI. ELMs can be mitigated by the 10\% Ne mixture SMBI. The mitigation effect of the 10\% Ne is similar to that of the main ion fuelling injected by D\textsubscript{2} SMBI. For the 30\% Ne mixture SMBI seeding, the ELMs are replaced by HFBs which have much smaller amplitude compared to ELM. In the present mixture SMBI seeding experiments, no impurity core accumulation was observed, and the plasma confinement was unaffected. The divertor radiation power density is reduced significantly. The HFBs induce continuous and lower heat load instead of high transient heat bursts on the divertor plate. The peak heat flux of the HFBs is about 10\% of the one caused by the natural ELMs. However, the ELM frequency decreases by about 50\% for the pure Ne seeding discharge. Similar effect induced by pure Ar seeding has also been observed in HL-2A. The confinement is improved by the pure gas impurities. HL-2A is an all carbon (all-C) wall device. The HL-2A results are quite different to that of the all-C wall plasmas with Ne and N\textsubscript{2} seeding by gas puffing in JET [26]. However, the result is consistent with the energy confinement improvement with low or medium Z impurity seeding in metallic wall plasmas [17,18]. The impurity seeding experiments show that ELM activities change with the ratios of the seeded impurity. It suggests that the impurity ions play a role in the pedestal dynamics. Experimental observations indicate that there should be an optimal impurity ratio for efficient heat load control in ELMy H-mode plasmas.

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