Enhancement of Nonlinear Regulation Dynamics in SMBI-stimulated L-H transition of HL-2A

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1. Introduction. In magnetic fusion devices, the plasma can transit from low (L-mode) to high confinement mode (H-mode) as the heating power of plasma increases beyond a critical value $P_{th}$. For the physical mechanism, regulation of turbulent transport by edge shearing flows is believed as a most promising mechanism for accessing the H-mode [1, 2].

Theoretic modeling results show that edge plasma shearing flows can trigger or initiate the L-H transition and lower the H-mode power threshold [3, 4], indicating nonlinear regulation dynamics between turbulence and flows plays a key role in the transition. For future devices, like international thermonuclear experimental reactor (ITER), controllable L-H transition and reducing $P_{th}$ are highly desirable when the available heating power is marginal for accessing the H-mode. Experimentally, it has been observed that solid pellet or intense gas puffing can trigger the transition in several tokamaks [5, 6, 7, 8]. Theoretic models have predicted that the L-H transition can be triggered by particle injection when the heating power is below the threshold ($P < P_{th}$) [9]. Understanding the physics behind the stimulated transition is important.

Figure 1: (a) NBI heating power, (b) line-averaged electron density, (c) divertor $D_{\alpha}$ signal of shot 27882, (d) divertor $D_{\alpha}$ signal of shot 27887, (e) monitor of SMBI pulses for these two shots, and (f) stored plasma energy.
for developing a robust technique which can actively control the transition at the marginal H-mode power threshold. In this paper, we investigate the effect of supersonic molecular beam injection (SMBI) on the L-H transition and the underlying dynamics of plasma turbulence and flows in the HL-2A tokamak, whose major and minor radius are $R = 1.65m$ and $a = 0.4m$, respectively.

2. SMBI-stimulated L-H transition. In HL-2A, it has been observed that the L-H transition can be triggered by SMBI, a plasma fueling tool, which has higher fueling efficiency than that of gas puffing and was first proposed in the HL-1 tokamak, then applied on several tokamaks and stellarators [10]. Pulsed molecular beams are passed from a Laval type nozzle and have high instantaneous intensity, high directionality and deep deposition in the plasma.

Figure 1 shows two typical shots with SMBI-stimulated L-H transition. The heating power of neutral beam injection (NBI) is $1MW$ which is closed to the H-mode power threshold of the HL-2A [7]. For shot 27882, the SMB is injected at 545 ms (Fig. 1e) and then the plasma transits into the ELMy H-mode after 10 ms (Fig. 1c) when the plasma density reaches $1.85 \times 10^{19} m^{-3}$ (Fig. 1b). Trajectories of the relation between the plasma stored energy and the plasma density for these two shots are shown in Fig.2. The stored plasma energy increases across the transition for shot 27882. However, the plasma in shot 27887 does not spontaneously transit into the H-mode when the plasma density reaches the transition density $n_e^{L-H}_{\text{ave}}$ of the previous shot. The injection time of SMB is intentionally postponed to 595 ms in shot 27887 (Fig. 1e), then the plasma transits into the H-mode after about 10 ms (Fig. 1d), the transition density is $2.2 \times 10^{19} m^{-3}$ herein and it is higher than that of the previous shot as labeled in Fig.2. It demonstrates that the SMBI triggers the L-H transition. Statistic analysis from multimachine database showed that the H-mode power threshold strongly depends on plasma density [11]. However, the results in Fig.1 and Fig.2 show that the plasma densities of the transition are different even though the heating power and plasma condition are identical. It indicates that the stimulated transition is not attributed to plasma fueling effect of SMBI. SMBI can affect the
plasma turbulence and flows. The effect has not yet been systematically studied in experiments.

3. **Enhancement of nonlinear interactions by SMBI.** Fueling particles are injected into the edge plasma region by SMBI. On the one hand, the edge plasma density will be increased. On the other hand, the edge poloidal shear layer will be flattened by collisional flow damping [12]. It results in a flattening profile of radial electric field \(E_r\). The shearing effect of \(E_r\) on turbulence is also changed. Thus, SMBI could significantly change the edge flow and turbulence behaviors.

The dynamics of turbulence and flows with SMBI during the L-H transition is analyzed, as Fig. 3 shown. In this shot, the NBI power is 1 MW. After the SMBI, a strong GAM is triggered as seen from the spectrogram of \(E_r\) fluctuations in Fig.3b. Then limit cycle oscillations (LCOs) are excited and the plasma transits into the intermediate confinement phase (I-phase) at \(t = 590\) ms. The oscillating feature can also be observed in the divertor \(D_\alpha\) signal as shown in Fig.3a. Figure 3d and 3e are the summed bispectrum integrated over the GAM and LCO frequency, respectively. The summed bispectrum is defined as \(B(f) = \frac{1}{N(f)} \sum_{f=f_1+f_2} B(f_1, f_2)\), where the sums are taken over the area in the \(f_1 \sim f_2\) domain satisfied with the matching condition \(f = f_1 + f_2\) and \(N\) is the number of the satisfied elements. \(B(f_1, f_2)\) is the autobispectrum \(B(f_1, f_2) = \langle |\hat{X}(f_1)\hat{X}(f_2)\hat{X}^*(f_1+f_2)| \rangle\), where \(\hat{X}(f)\) is the Fourier transform of \(E_r\) fluctuations and \(\hat{X}^*(f)\) is the complex conjugate. The angular brackets represents the ensemble average. Since the maximum \(E_r\) gradient is reduced by SMBI as shown in Fig.3f. The turbulence level increases after the SMBI (Fig. 3c). The increased turbulence can provide more free energy for enhancing the GAM intensity. The process of GAM enhancement is observed and the \(B_{GAM}\) starts to increase at 560 ms as shown in Fig.3d, meaning that the GAM and turbulence have strong nonlinear coupling by three-wave interactions.

![Figure 3:](image-url)
interaction. Meanwhile, the turbulence intensity is clamped and slightly decreasing. It indicates that the turbulence is regulated by GAM via the nonlinear interaction. At $t = 590 \text{ ms}$, $B_{LCO}$ starts to increase as shown in Fig.3e and $B_{GAM}$ is decreasing. The lower frequency shear flow of LCOs also plays a role in reducing the turbulence. The turbulence intensity is decreased. The reduction of $B_{GAM}$ might be owing to the loss of free energy from the turbulence and transfer energy to LCOs through nonlinear interactions. The strong nonlinear interactions among GAM, LCOs and turbulence stimulated by SMBI results in the increase of the local density gradient as shown in Fig. 3f. The formation of the steep pedestal will increase the ion diamagnetic component of $E_r$ which is the dominant term in the mean $\mathbf{E} \times \mathbf{B}$ flow [13]. When the $B_{LCO}$ starts to decrease, $E_r$ shear takes over the role in reducing the turbulence. As Fig.3f shown, it increases at 606 ms. The further turbulence suppression assists the plasma in transiting into the H-mode.

It should be noted that the $E_r$ gradient at the L-H transition is not higher than that before the SMBI, suggesting that SMBI could reduce the $E_r$ shear threshold of L-H transition. The effect of SMBI on the threshold and the underlying physics are being studied.

In summary, L-H transition can be triggered by SMBI. SMBI changes the edge plasma turbulence and flows. It has been found that GAM enhancement and turbulence regulation is externally stimulated by SMBI. These enhanced nonlinear regulation dynamics can quench the turbulence and maintain the turbulence collapse. Then, the lower frequency shear flow of LCOs is excited and it also plays a role in reducing the turbulence. Finally, $E_r$ shear increases, the turbulent transport is reduced and the L-H transition is triggered. The results reveal that the non-linear regulation dynamics between turbulence and shear flows are externally enhanced by SMBI. The enhancement plays a key role in facilitating the L-H transition.

References