Energy confinement and threshold power with SMBI to the ELMy H-mode plasmas in HL-2A

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1. ***Introduction.*** To preciselly predict the H-mode power thrshold in ITER is one of the most critical issues with relation to the H-mode studies[1, 2]. However, the interval of the estimation on the threshold power for the L-H transition in ITER is still unacceptable. The physics behind the L-H transition is not fully understood. From the experimental point of view the L-H transition needs a minimum power threshold and it is affected by magnetic field configuration, bulk ion species, wall condition and the direction of the magnetic gradient drift of the ions. For the favourable condition (D plasma, ion ∇B drift toward the X-point) the needed power for the L-H transition can be estimated by [3]

$$P_{th,\ scal08}\ (D) = 0.049\ B_T^{0.80} n_e^{0.72} S^{0.94} \qquad (1)$$

On the other hand the dependence of the power threshold on plasma density is non-monotonic and exhibits a minimum at the density labelled $n_{e,min}$ [2]. Below $n_{e,min}$, in the 'low-density branch', the power threshold increases when density decreases. The increase of the power threshold towards low density is not well documented in the different devices and at present no prediction can be made for ITER on this topic.

In the HL-2A tokamak the first H-mode with type III ELMy has been obtained in 2009 with combined the ECRH and NBI heating [4]. After that the H-mode with type I like ELMy has also been realized with high heating power. Meanwhile, the threshold power for the L-H transition has been significantly reduced and the H-mode can be obtained with NBI alone. Therefore, a series of statistics for the H-mode energy confinement
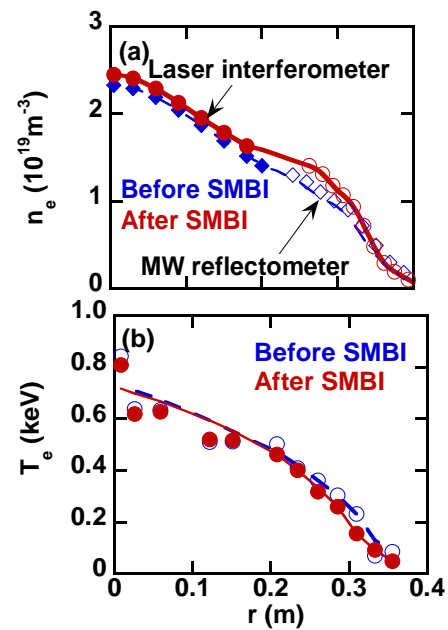

Figure 1. Radial profiles of electron density and temperature before and after the supersonic molecular beam injection.

time (τ_E) and the power threshold depending on plasma density is experimentally studied, particularly in the low density regime in this paper.

2. ***H-mode power threshold.*** In the HL-2A tokamak, one of the routinely used gas fuelling techniques is the supersonic molecular beam injection (SMBI) which can easily control the injection gas amount and have higher fuelling efficiency when comparing with the general gas puff. The backing pressure of the SMBI system can increase up to 6 MPa with the pulse duration of 0.5–5 ms and the corresponding injected deuterium molecular inventory of 2×10^{17}–6×10^{19}. The velocity of the SMBI particles is estimated as
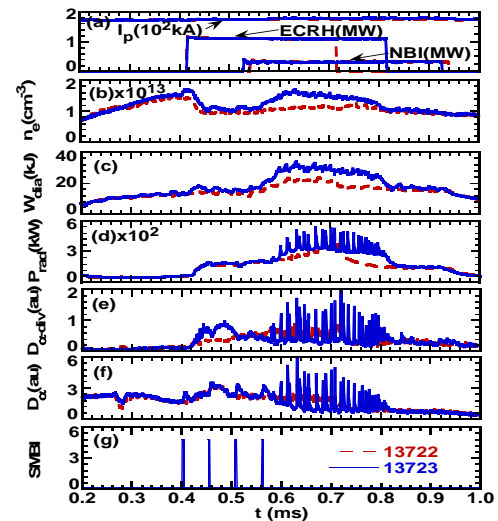

Figure 2. Time evolution of the main parameters of two typical discharges with SMBI and GP, respectively. The heating powers for two discharges are same. The H–mode can be achieved with SMBI.

1.3–1.8 km/s. The beam can penetrate 4–8 cm inwards from the last closed flux surface (LCFS), which depends on the plasma parameters before injection and its backing pressure. A typical electron density and temperature profile is presented in Fig. 1 (a) and (b), respectively. The comparisons between the profile before and after SMBI are plotted. The electron density is measured by an eight-chord HCN interferometer (full symbols) at r < 0.2 cm and an MW reflectometer (open symbols) at r > 0.2 cm, while the electron temperature is measured by the ECE diagnostic. It shows in Fig. 1(a) that the density has a significant increase at the region of r=0.2-0.35 cm, particularly having an increment of about 20% at r=0.26 cm. The gradient of density at edge strongly increases. Meanwhile, the temperature near the last closed flux surface (LCFS) slightly decreases. But the gradient of temperature at edge has also been increased.

Therefore comparing with the GP discharge the slight increase of the gradient of n_e and T_e at edge with SMBI could expect some kinds of advantage for the L-H transition. The experiments did show that the H mode can be realized with SMBI rather than the GP if the heating power is similar. Otherwise, it needs higher heating power for the GP to achieve the H mode discharges comparing with the SMBI H-mode. Two typical discharges with identical plasma parameters are
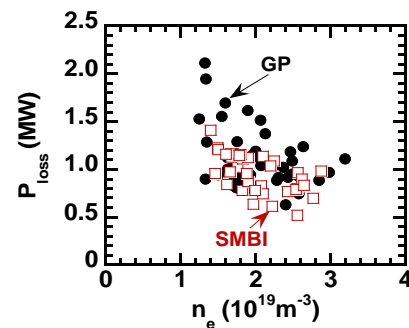

Figure 3. Comparison of the needed power for the L-H transition with GP and with SMBI.

plotted in Fig. 2, where the discharge 13722 with GP and the discharge 13723 with SMBI are compared. The heating power for 13722 with GP is $P_{ECRH}=1.16MW$ and $P_{NBI}=0.42MW$ and for 13723 with SMBI is $P_{ECRH}=1.15MW$ $P_{NBI}=0.41MW$. The experiment shows that the H-mode can be realized with SMBI but can not be obtained with GP.

The threshold power for the L-H transition with

Figure 4. Plot of P_{rad} as a function of P_{th}.

and without SMBI are compared in Fig. 3 based on a dataset which has been assembled from more than eighty H-mode discharges in the HL-2A tokamak. It shows that the threshold power for the SMBI H mode has been significantly reduced by more than 30% comparing to the GP H mode, especially in the low n_e range.

In the HL-2A device the siliconization has been generally carried out for the wall conditioning. In 2012 experiment campaign the lithium coating was applied and the combination between the lithiumization and the siliconization has also been done. The impuity content and the radiated power are obviously decreased after the newly wall conditioning procedure has been adopted [5]. The observations show that the threshold power decreases with the reducing radiation power. The results is shown in Fig. 4, where the lower radiation power, the less threshold power is needed.

3.   *Confinement*. In the HL-2A tokamak the H mode with type III ELMy can be realized with combined the ECRH and NBI heating, and with NBI heating alone. The H mode discharges covers wide plasma parameters as follows: $150 < I_p(kA) < 320$, $1.2 < B_t(T) < 2.5$, $1.5 < n_e(10^{19}\,m^{-3}) < 4$. In order to study the H-mode energy confinement a database which includes about 500 observation slices are assembled based on the experimental campaigns from 2009 to 2012. In Fig. 5(a) the dependence of energy confinement time τ_E on the plasma density is plotted. The typical feature of τ_E increasing with density is shown. The most reliable ELMy H-mode thermal energy confinement scaling is the IPB98(y, 2) [6] which is expressed as follow,
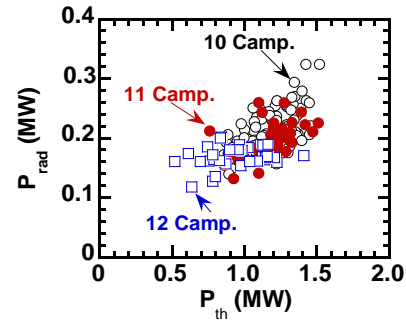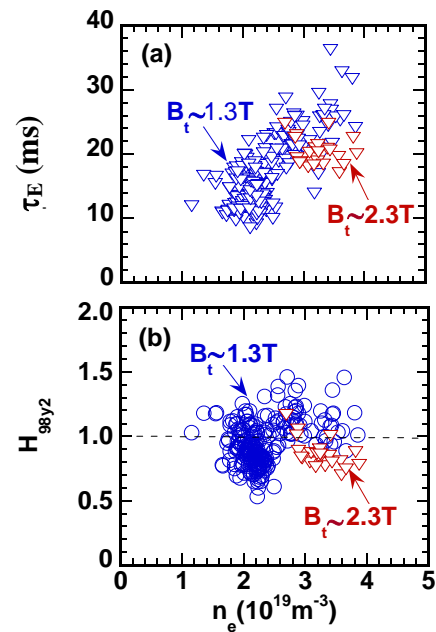

Figure 5. Plot of (a) energy confinement time and (b) H_{98y2} factor as a function of electron density from the HL-2A H-mode database.

$$\tau_{th,98y2} = 0.0562 I_P^{0.93} B_T^{0.15} n_e^{0.41} P_L^{-0.69} R^{1.97} \varepsilon^{0.58} \kappa_\alpha^{0.78} M^{0.19}, \qquad (2)$$

where the units are s, MA, T, 10^{20} m^{-3}, MW, m, respectively. The comparison between the HL-2A H-mode τ_E and the IPB98(y, 2) scaling has been presented in Fig. 5 (b). The data shows that most H-mode discharges in the HL-2A tokamak agree well with the IPB8(y, 2) scaling and the H factor is around 1. However, the scattering still exists and the H factor is between 0.5 and 1.5. The fact that the years' experimental data may have various plasma conditions, especially the wall condition, could cause the scattering of the data.

4.   *Summary*. A series of statistics on the energy confinement and the threshold power of the ELMy H-mode have been experimentally studied in the HL-2A tokamak based on 4-year experimental data. The density dependence of the threshold power indicates a minimum needed power for the L-H transition. When the density is lower than this value which is $n_{e-min}=3\times10^{19}$ m^{-3} in the HL-2A device the threshold power P_{th} increases with decreasing density. The experimental observation indicates that the SMBI could create a favorable condition for the L-H transition comparing with the general gas puff. The reduction of the threshold power by more than 30% is observed when the SMBI is applied instead of the GP. The measured plasma density and temperature profiles indicate that both gradients at edge have been increased when the supersonic molecular beam is injected. This could help the L-H transition and might be one of the mechanisms to reduce the threshold power. The effect of the wall conditioning on the H mode performance has also been investigated. The experimental data shows that the threshold power could also be reduced when the impurity content and the radiation power decrease.

The energy confinement of the HL-2A ELMy H-mode plasmas has also been statistically studied. The results indicate that the energy confinement time for most the H-mode discharges in the HL-2A tokamak agrees well with the IPB8(y, 2) scaling law and the H factor is around 1.

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