New Results of Supersonic Molecular Beam Injection on HL-2A

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Recently, a new gas supply system with pressure measurements was installed in the Supersonic Molecular Beam Injection (SMBI) system on the HL-2A tokamak. The quantity of injected particles varies with parameters of SMBI has been measured. Using plasma density profile measured by the multi-channel high power DCN laser interferometer, the mean particle increment in the plasma could be calculated after an SMBI pulse. Fuelling efficiency is estimated as the particle increment of the plasma divided by the quantity of injected particles.

Fuelling efficiency depends on Injection depth which is not only a key issue for fuelling techniques but also an important physical significance. The study on the penetration depth of SMBI has been carried out on the HL-2A tokamak through tangential D_α arrays. The D_α signals show that the SMB consists of a fast component (FC) and a slow component (SC) after passing through a conic nozzle, which is installed on SMB valve to improve the beam performance. The FC can penetrate more deeply such as 8.5 cm inside the separatrix, while the SC is around 4 cm inside the separatrix. Some valuable phenomena with SMBI fuelling in H-mode discharges on HL-2A are also presented.

Keywords: SMBI, fuelling efficiency, injection depth, tokamak fuelling, HL-2A.

1. Introduction

Plasma fuelling is one of a critical task for the next generation experiment, such as ITER, since the fusion fuel, such as deuterium and tritium, has to be supplied into the plasma core as deep as possible; and for nowadays tokamaks, it is important to understand the particle balance and plasma density control. Three fuelling methods have been developed to meet the demand depicted above; there are gas puffing (GP), pellet injection (PI) and SMBI, respectively. As an efficient fueling method and an important auxiliary diagnostic means for fusion plasma, SMBI was successfully developed on the HL-1M tokamak [1-3], and then it was applied to HT-7 [4], HL-2A [5], Tore Supra [6], W7-AS [7], ASDEX-Upgrade [8], and JT-60 [9].

The quantity of injected particles is an important parameter for SMBI and the fuelling efficiency is a common concern for researchers. On Tore Supra [6] and ASDEX-U [6, 10], the DCN interferometer is applied to measure the fuelling efficiency detecting the increment of the line integrated electron density and hence the fuelled particle amount. The reciprocating probe provides the edge profiles of electron temperature and density simultaneously. It is observed that the fuelling efficiency of SMBI is around 30 ~ 60 %, about three to four times as high as that of the conventional gas puffing but not as good as that of pellet injection [11, 12].

Injection depth related with fuelling efficiency is a key issue for fuelling techniques. The SMBI fuelling depth was studied by means of electron-cyclotron emission and soft-X ray diagnostics; and the results indicate that the perturbation depth of heat pulse is poloidally asymmetric and electron temperature (Te) pulses cannot propagate to the plasma centre. Another commonly used diagnostics is H_α/D_α array to determine the injection depth [5, 13]. Simulations based on the transport of neutral hydrogen have been carried out on the HL-1M tokamak, and the main deposition area is outside the normalized radius of 0.75, which means the SMBI can penetrate about several centimeters, such as 5 cm, into the plasma [14]. The SMBI depth is also a key issue to understand its fuelling features.

H-mode discharges have been obtained on HL-2A, with the combined heating of ECRH and NBI. Plasma density profile has clear relationship with plasma confinement mode. It is reported that PI triggers ELMy emission in H-mode discharges [15]. On DIII-D obtain PIH-mode with PI fuelling [16]. The SMBI fuelling plays an important role in the H-mode discharges on HL-2A, including density and fuelling control, reducing the recycling of impurity and particles. Compared to PI, SMBI is not so efficient due to less injection depth, but it still has some benefits to promote H-mode discharges.

This paper focuses on the fuelling efficiency of SMBI on HL-2A. The performance of SMBI in H-mode discharges and the new injection features are also

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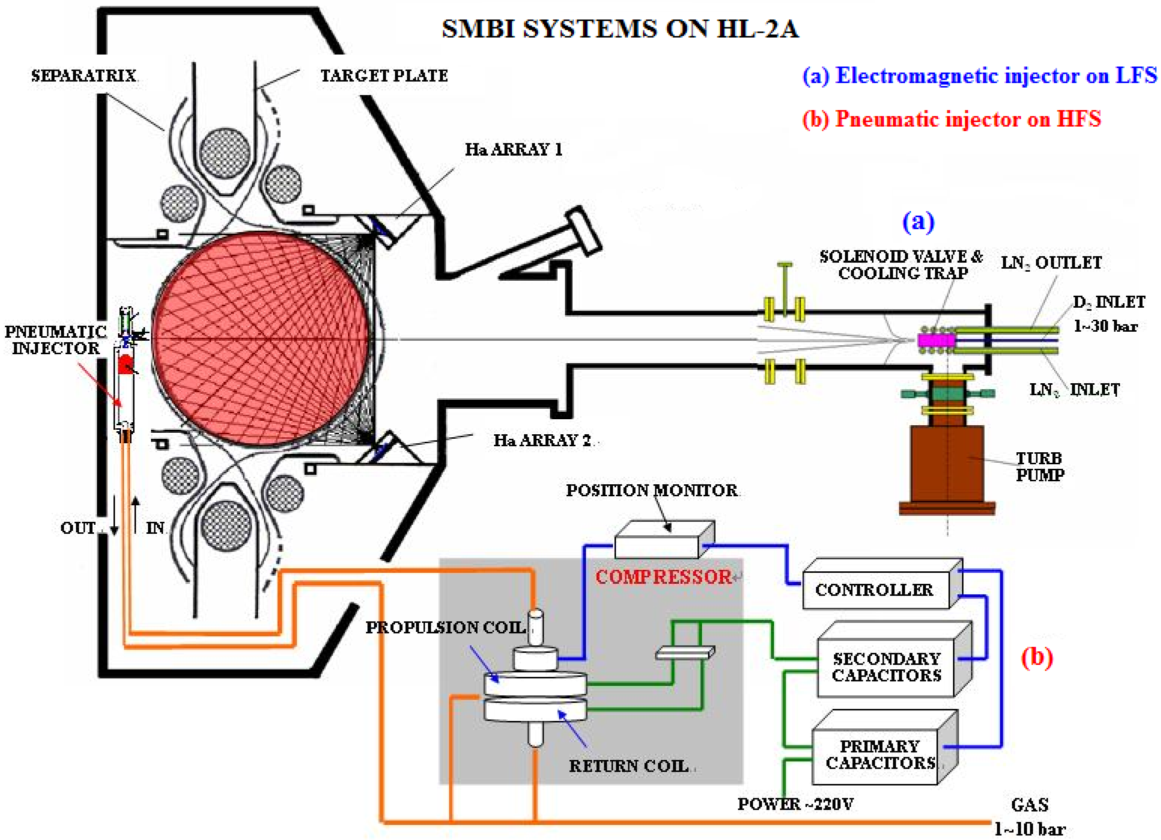

Fig. 1 SMBI systems layout on HL-2A.

a) SMBI system from LFS, solenoid valve, pressure <60 bars, pulse duration >0.5 ms, frequency <70 Hz.

b) SMBI system from HFS, pneumatic valve, pressure <10 bars, pulse duration ≈2ms, frequency <10Hz.

discussed.

2. Experimental setup

HL-2A is a divertor tokomak with the major radius of 1.65 m and the minor radius of 0.40 m which can be operated at limiter and single lower null-divertor configurations in following parameters: toroidal magnetic field $B_t < 2.7$ T, line averaged electron density ne about $1 \sim 6 \times 10^{13}$ cm^{-3} and plasma current 150 ~ 430 kA.

On the HL-2A tokamak, the refueling system consists of GP, PI and SMBI. The PI and SMBI systems share the same port of the torus. The SMBI systems from LFS and HFS are shown in Fig. 1. The injection from LFS is a solenoid valve with rather high flexibility and the other one from HFS is a pneumatic valve, which was provided by Tore Supra [6]. The backing pressure of the LFS could high to 60 bars, and the duration is >0.5 ms, normally each pulse corresponding to the injected deuterium molecular particles of $> 2 \times 10^{17}$. The pulse duration of HFS is about 2 ms, which is not adjustable due to the structure of the valve. The SMBI system from HFS was designed for backing pressure 1 ~ 10 bars, and frequency < 10 Hz. On HL-2A, it works at frequency < 5 Hz, backing pressure 2 ~ 3 bar, corresponding to the injected molecular particle of $2 \sim 3 \times 10^{19}$. The valve of the LFS is about 1.28m away from plasma edge, while the HFS is only several centimeters. Besides, a turbo-molecular pump with the capacity of 450 L/s has been applied to maintain a low background neutral gas pressure during the injection. To detect the SMBI fuelling depth and trajectory of the PI, two poloidal D_α arrays have been installed on the same cross-section as the SMBI port to monitor the poloidal structure of the spot.

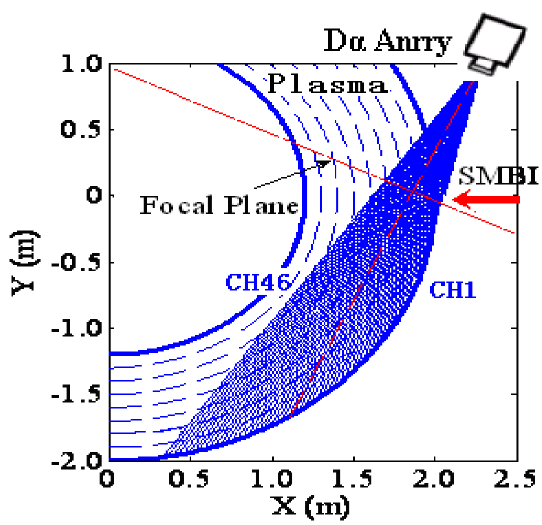

Fig. 2 Schematic arrangement of the tangential. D_α array.

Fig.2 shows the schematic arrangement of the D_α arrays, PI and the SMBI systems.

A new gas supply system with pressure measurements was installed for SMBI systems on HL-2A. Considering two SMBI systems from HFS and LFS, two types of differential pressure sensors were provided to measure the pressure changes in the vacuum and in the gas-pipe, respectively. One is used to measure the pressure changes in the vacuum from LFS, the other is used to measure the changes in the gas-pipe from either side injection. According to the volume of the chamber or the pipes and the corresponding particles injected, we can calculate the averaged injection particle amount per pulse.

To flexibly detect the injection depth of the LFS SMBI, a tangential D_α array is installed at the port, as shown in figure 2. The telescope of the D_α array consists of three lenses and collects the D_α line emission from the plasma and then focus on the Silicon photodiode array. The filter of the tangential D_α array is installed right in front of the silicon photodiode and has the maximum transition at 656.3 nm and the full width at half maximum of 7.0 nm; the photodiodes are Hamamatsu S4114-46Q. The wave length of H_α is 656.1 nm and it is 656.28 nm for D_α, that the anrry detects both H_α and D_α emission. The tangential D_α array is of 46 channels and monitors the half cross-section at low field side with 0.9 cm spatial resolution, and typical sampling frequency is 200 kHz.

A multichannel interferometer with high power DCN laser had been installed to measure linear density and its density profile. The DCN system consists of 8 channels, and each channel is horizontally installed with the spatial resolution of 7 cm. After the large amount of the particles is fuelled by SMBI (typical increment of line averaged density is about 0.2×10^{13} cm^{-3} for one pulse of SMBI), the density profile is also changed [13], i.e. the peaking factor changes. Therefore, to accurately obtain the total number of electrons, Ne is calculated by the Abel inversion code from the line integrated electron density measured by DCN interferometer. In this article, the GP is switched off during the SMBI defaultly if there is no specific denotation.

3. Experiment results

3.1 The calibration of injected particles

There are two method to measure injected particles, one is to measure the gas pressure increment in a small vacuum chamber which is separated from the main vacuum; the other is to measure the pressure decrement in the gas source or in the gas transport pipes after the beam injection. According to the volume of the chamber or the pipes and the corresponding particles injected, we can calculate the averaged injection particles amount per pulse.

For the SMBI from LFS, two ways are available. Deuterium is used as the working gas. As showed in Fig. 3,

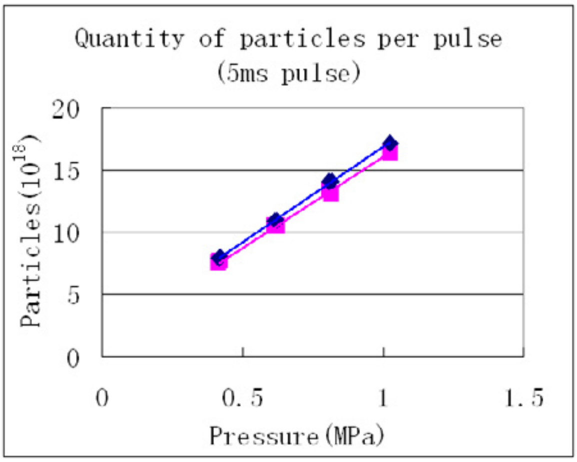

Fig. 3 Quantity of injected particles for SMBI from LFS.

Squares are the particle increment in the vacuum, Diamond are the particle decrement in the gas pipe.

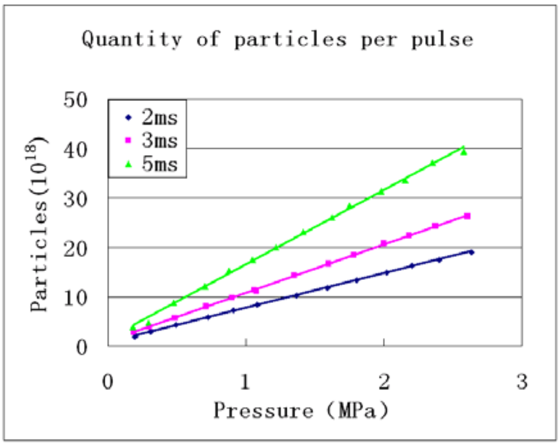

Fig. 4 Calibration of particles for SMBI (LFS).

two measurements fit with each other. From the figure, series 99 valve has a good linear relationship between the injected particles and the pressure of working gas, so that particle calibration is possible. Figure 4 shows the calibration particles of SMBI system from LFS for typical pulse duration, the pressure is from 2 ~ 26 bar. The relation between the quantity of particles and the pressure for the pulse duration of 2 ms, 3 ms and 5 ms can be depicted by the following formula, respectively. Here P is the relative backing pressure and N is the D_2 number.

$$N = [7.0P(MPa) + 0.8] \times 10^{18} \qquad (1)$$

$$N = [9.9P(MPa) + 0.8] \times 10^{18} \qquad (2)$$

$$N = [14.9P(MPa) + 1.6] \times 10^{18} \qquad (3)$$

The injector of the SMBI system from HFS is installed in the main vacuum chamber of the tokamak that only one of the two measurements is available. The SMBI system from HFS typically works at 2 ~ 3 bar, and its pulse duration is not adjustable. The quantity of injected particles is $2 \sim 3 \times 10^{19}$ D_2.

3.2 Fuelling efficiency

A common concern for fuelling techniques is fuelling efficiency, which is defined as the ratio of the increment of the plasma content divided by the number of injected particles. The density increases not so fast compared with HFS injection due to the a 1.3 m distance between the injector (LFS) and the edge of plasma. From the tangential D_α array, the duration of the D_α peak caused by SMBI (LFS) is about 15 ms, which is the timing to estimate the density increment. When injecting SMBI, other fuelling is switched off. The contribution of recycling is included in measuring the increment of the plasma content, that the fuelling efficiency is given as a range.

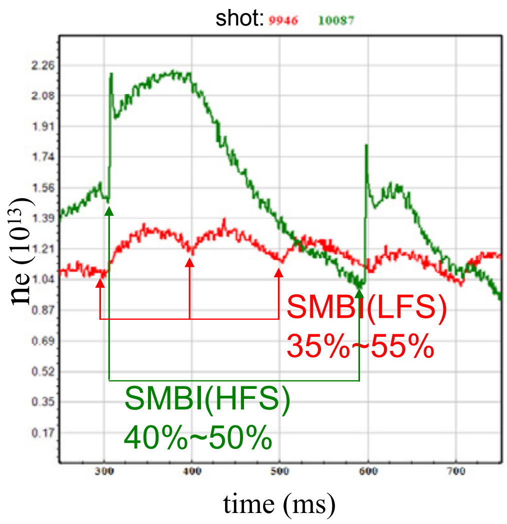

Fig. 5 Temporal evolution of the ne signal with SMBI. Shot 9946 limiter discharge (I_p = 170 kA, B_t = 1.3 T, n_e = 1.3×10^{13} cm^{-3}), SMBI from LFS (1 ms, 1.7 MPa), injected particles 5×10^{18} D_2, fuelling efficiency 35 ~ 55%. Shot 10087 of divertor discharge (I_p = 162 kA, B_t = 1.33 T, n_e = 1.6×10^{13} cm^{-3}), SMBI from HFS (2 ms, 0.3 MPa), injected particles 2.5~3×10^{19} D_2, fuelling efficiency 40 ~ 50%.

The fuelling efficiency of SMBI is 35 ~ 55% from LFS in limiter discharges, that is 40 ~ 50% from HFS, as showed in Fig. 5. The plasma density profile is related with plasma confinement and some other parameters so that the fuelling efficiency changes at a wide range. In contrast with SMBI fuelling efficiency from LFS in limiter discharge, divertor discharge is showed in Fig. 6, which indicates that SMBI fuelling efficiency is lower in divertor discharges, because of the high loss to divertor plate along the separatrix.

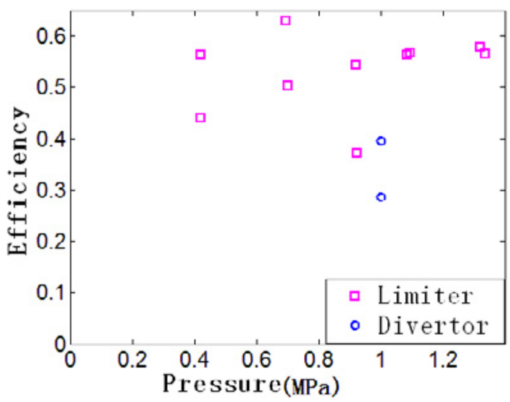

Fig. 6 Fuelling efficiency of SMBI (LFS) in limiter and divertor discharges.

Shots from 9925 to 9934 (square) is limiter discharge, I_p = 170 kA, B_t = 1.3~1.4 T, n_e = 0.7 ~ 1.3 $\times 10^{13}$ cm^{-3}. Shots 10476 and 10477 (circle) is divertor discharge, I_p = 165 kA, B_t = 1.3T, ne = $1.3\times10^{13}cm^{-3}$.

3.3 Injection depth

The fuelling depth is of great interest for fuelling techniques, the deeper means more efficient. Fuelling experiments with PI was reported in [15], changing the volume and speed of the pellet affects the injection depth and fuelling efficiency. Cold SMBI in plasma was also reported in [17], cluster jet lead to deeper injection and more efficient. It is reasonable that improve the parameters of SMB would improve the fuelling efficiency.

SMB forms in the free gas jet expanding through a laval-nozzle. The parameters of the beam are decided by the shape of the nozzle, pressure and temperature of the working gas. A new conic nozzle, which has 0.5 mm diameter and 8° half angle, is installed on the SMB valve from LFS in order to improve the SMBI.

The injection depth is defined as the distance from the plasma edge to the maximum D_α/H_α intensity region. The plasma scenario is Ohmic discharge with plasma radius of 38 cm, the backing pressures are 0.126 and 1.7 MPa with duration of 3 ms and 1 ms for shot 9897 and 9940, respectively. Main parameters specially set for the SMBI

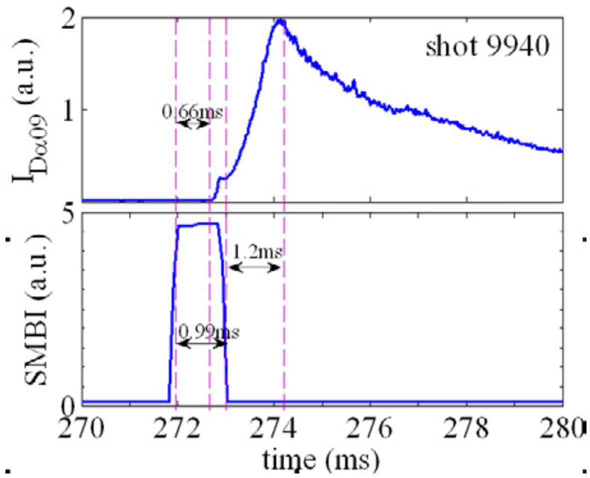

Fig. 7 Temporal evolution of the tangential D_α emission of LFS SMBI.

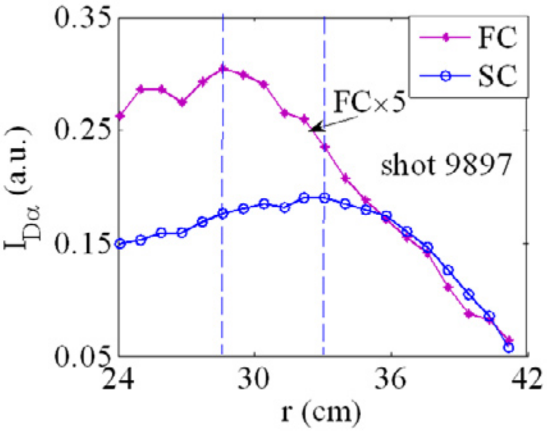

Fig. 8 D_α profile for the first pulse of shot 9897.

experiments are toroidal magnetic field 1.2 ~ 1.4 T, plasma current 160 ~ 180 kA, line averaged electron density 0.4 ~ 2.6 × 10^{19} m^{-3} ,electron temperature in the core 0.6 ~ 1.5 keV. The boundary electron density and temperature measured by Langmuir probe are 0.5 ~ 2 × 10^{18} m^{-3} and 20 ~ 50 eV for the similar discharges. During the SMBI, the D_α signals detected from the tangential array increase to a certain value and then decrease before the maximum intensity appears, as shown in Fig. 7. Assuming each D_α peak is induced by a pulse of the influx of deuterium atom (molecule) and taking the distance between the SMBI nozzle and plasma edge into account, typical time delay of the first peak is about 0.66 ms and the second is 0.99 ms, the corresponding velocity are up to 1940 m/s (FC) and 1300 m/s (SC) as shown in Fig. 7.

The life span of FC is mainly determined by the SMBI duration and ranges from 0.3 to 0.6 ms. The injection depth of FC and SC are rather different. According to the Fig. 8, the position of maximum D_α intensity induced by FC (about 8.5 cm inside the LCFS) is much deeper than that of the SC (about 4 cm inside the LCFS).

3.4 SMBI experiments with H-mode discharge

H-mode discharge was obtained on HL-2A tokamak with the combined heating including ECRH (1.2 MW) and NBI (0.8 MW). It needs a certain heating power and density threshold. The single power of ECRH or NBI is not enough so that combined heating is the only way to reach the power threshold for H-mode. 'Density pump-out' during combined heating was observed, and this particle confinement degradation is disadvantage for achieving H-mode.

GP was used to start-up plasma, but it seems not so efficient to fuel the combined heating plasma that SMBI was used as further fuelling after additional heating power injection. Compared to GP, SMBI has higher fuelling efficiency and deeper penetration position, leads to more peaking density profile. A typical H-mode discharge with SMBI is showed in Fig. 9. The edge electron density rises

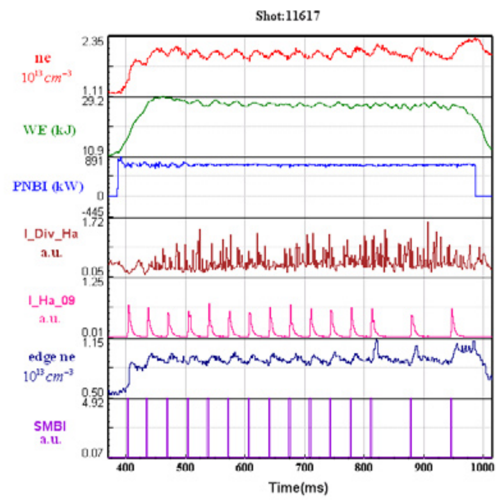

Fig. 9 The diagnostic signals of one H-mode discharge.
I_p = 168 kA, B_t = 1.35 T, $n_e = 2.2 \times 10^{13}$ cm^{-3},

up rapidly just after the first pulse of SMBI, L-H transition takes place later.

4. Summary and discussion

A data base of injected particles was established to further research on SMBI. For the SMBI from LFS, the quantity of injected particles is linear to the pressure of the working gas and pulse duration. The first measuring of fuelling efficiency of the SMBI from both sides is at the range of 30 % to 60 % in limiter discharge, which is much higher than that of the GP and not as good as PI. SMBI in divertor discharge seems to have lower efficiency, but more experiment data are needed. It is not easy to compare the fuelling efficiency of the SMBI from LFS and HFS, for these SMBI systems are rather different.

A tangential D_α array has been developed to monitor the SMB injection depth. The corresponding tangential D_α signal shows that the injection depth of SMBI is deeper than that of the GP and shallower than PI. The new conic nozzle affects the beam performance that the SMBI consists of FC and SC, though there are not other significant benefits for fuelling. The FC can penetrate deeper than SC, reaches 8.5 cm into the LCFS. It needs further study for these two components.

SMBI was used in H-mode discharges to control the density and density profile, reducing the recycling and impurity particles. In some discharges, SMBI could promote L-H transition. Whether SMBI could trigger ELMy emission and even H-mode like PI? Further more researches are necessary.

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