1.6 Fuelling efficiency and penetration of supersonic molecular beam injection in HL-2A tokamak plasmas

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Supersonic molecular beam injection (SMBI), as an effective fuelling method, was first successfully developed on the HL-1M tokamak and then widely adopted by other devices such as HL-2A, Tore Supra and ASDEX-Upgrade due to its high fuelling efficiency, simplicity of structure and low cost. On HL-2A, the SMBI can fuel plasma both from the low field side (LFS) with an electro-magnetic valve and the high field side (HFS) with a pneumatic valve. The distance from plasma to HFS nozzle is several centimeters only, whereas the LFS is about 1.28 m. In addition to two Dα arrays and a CCD camera which are installed in the same cross-section with respect to the SMBIs, a 46-channel tangential Dα array monitors the half cross-section on the LFS with 0.9 mm spatial resolution and typical acquisition frequency of 200 kHz. Besides, a tangential CCD camera can be utilized to study the penetration characteristics of LFS SMBI. The preliminary database of fuelling efficiency of LFS SMBI has been established.

For each LFS SMBI pulse, the tangential Dα signal peaks twice. The delay time with respect to the SMBI signal are 0.7 ms and 1 ms for the first and the second peak, respectively, indicating that SMBI consists of two components, one is the fast component (FC) with velocity of 1.9 km s⁻¹ and the other is slow component (SC) with velocity of 1.3 km s⁻¹ only. The appearance of the FC is due to the installation of the additional conical nozzle, which is set right after the valve to optimize the beam and make it more concentrated. The FC has not been observed before the installation of the conical nozzle, and by doping different percentage of hydrogen into deuterium the magnitude and velocity of FC keeps almost no change; therefore, the reason induces the FC is not due to the isotope effect. In addition, the FC is also observed by Hα array on Heliotron J device.

To study the features of the SMBI, the Dα emission is analyzed. For the case of SC, the time integrated Dα intensity is linearly proportional to the backing pressure for each channel. As the pulse duration is fixed at 3 ms, the injected inventory is proportional to the pressure. In other words, the time integrated Dα emission is proportional to the injected molecular inventory for the SC. As for the FC, the duration is about 0.3 ms only and the rising time is about the half; so the time integrated Dα emission is replaced by the maximum intensity for the sake of simplicity. The maximum intensity of Dα is proportional to the backing pressure. Since the duration of FC is approximately the same, therefore, the Dα emission is proportional to the injected particles, which is the product of the backing pressure and the pulse duration. Estimated from the intensity of Dα, the SC is the major part of the SMBI, whereas the FC is the minority. And hence the fuelling ability of FC is very limited.

![Graph](image)

Fig. 1. Dependence of the penetration depth on backing pressure for the FC and SC. The maximum Hα intensity is induced by the FC in (a) and by the SC in (b).

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The penetration characteristics of SC and FC are quite different, as shown in Fig. 1. The maximum $D_u$ intensity of FC locates more deeply than the SC, such as 8.5 cm inside the last closed flux surface (LCFS), while the SC penetrates around 4 cm.

In shot 9940, a series of 11 pulses SMBI are injected to study the influence of plasma density on SMBI penetration, and the electron density increases from $6 \times 10^{19} \text{ m}^{-3}$ to $2.6 \times 10^{20} \text{ m}^{-3}$. Although the electron density continuously rises, the maximum intensity of $D_u$ along minor radius stays at channel 9 of the array, corresponding to the radial position of $r = 34$ cm. In other words, the SMBI fuelling depth keeps almost invariant for different electron density.

Another interesting phenomenon is that the injection depth is very weakly dependent on the backing pressure of the SMBI, as shown in Fig. 1. Fig. 1(a) and (b) show the maximum $D_u$ intensity locates around channel 14 and 9 for FC and SC, corresponding to the minor radii of 29.5 cm and 34 cm, respectively. Although the backing pressure of the seven shots increases from 0.126 MPa to 1.7 MPa, the maximum intensity of $D_u$ locates at the same channel for the SC and varies only about one or two channels for the FC (the spatial resolution of tangential $D_u$ array is 0.9 cm).

As a complement of the tangential $D_u$ array, a CCD camera is alternatively utilized to observe the interaction between SMBI and plasma with typical exposure time of 0.3 ms. Because of the frame-transfer rate limitation of the CCD camera, the pictures are captured shot by shot by changing the delay time with respect to the SMBI trigger signal.

Fuelling efficiency of SMBI is also measured. The typical fuelling efficiency of SMBI is around 30% – 60% for a limiter configuration on HL-2A as shown in Fig. 2(a); and the fuelling efficiency increases with the decay time ($\tau^*$) of post-SMBI line averaged density, which is closely related to the particle confinement, as shown in Fig. 2(b). Since the penetration of SMBI measured by $D_u$ array does not vary much, therefore, it is the variation of the decay time of the post-SMBI electron density that is more responsible than that of the injection depth for the large scatter of the measured fuelling efficiencies.

Comparisons of SMBI fuelling efficiencies from LFS and HFS are carried out by injecting identical particle number. The latter is slightly higher than the former for the ohmic heated plasma. Moreover, when the plasma is heated by the ECRH power of 1.3 MW, the fuelling efficiency drops to about half for the LFS while it decreases slightly for the HFS.

The penetration ability of FC is better than SC due to weaker influence from self-blocking effect. Among the GP, HFS and LFS SMBI, it is evident that the HFS SMBI has the highest fuelling efficiency, especially for the plasma heated by high ECRH power.