Experiments on High Pressure Supersonic Molecular Beam Injection in the HL-1M Tokamak

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Abstract. Supersonic molecular beam injection (SMBI) was first proposed and demonstrated on the HL-1 tokamak and was successfully developed and used on HL-1M. Recently new results of SMBI experiments were obtained by increasing the gas pressure from 0.5 MPa to over 1.0 MPa. A stair-shaped density increment was obtained with high-pressure multi-pulse SMBI that was just like the density evolution behavior during multi-pellet injection. This demonstrated the effectiveness of SMBI as a promising fuelling tool for steady-state operation. The penetration depth and injection speed of the high-pressure SMBI were roughly measured from the contour plot of H_α emission intensity. It was shown that injected particles could penetrate into the core region of the plasma. The penetration speed of high-pressure SMBI particles in the plasma was estimated to be about 1200 m/s. In addition, the clusters within the beam play an important role in the deeper injection.

1. Introduction

Supersonic molecular beam injection (SMBI) was first proposed and demonstrated on the HL-1 tokamak [1], was successfully developed and used on the HL-1M tokamak [2, 3], and was then applied on the HT-7 superconducting tokamak [4] and the W7-AS stellarator. With the new fuelling method, high densities of $8.2\times10^{19}\,m^{-3}$ and $6.5\times10^{19}\,m^{-3}$ were obtained for HL-1M and HT-7, respectively. SMBI can enhance the penetration depth and fuelling efficiency. It is a significant improvement over conventional gas puffing. This paper will introduce the characteristic properties of high-pressure SMBI and high-performance discharges with high-pressure multi-pulse SMBI in HL-1M.

2. Experimental Results

HL-1M has a major radius R = 1.02 m, minor radius a = 0.26 m, $B_t \le 3$ T and $I_p \le 300$ kA, with two full graphite limiters. The basic principle of the SMB and the experimental set-up of SMBI in HL-1M have been shown in Figs 1 and 2 of Ref. [3].

2.1. Clusters and Their Action during SMBI

The SMB used for the experiments is in fact a free jet. The onset of clustering can be described by an empirical scaling parameter Γ^* referred to as the Hagena parameter [5], $\Gamma^* = k\frac{(d/\tan\alpha)^{0.85}}{T_0^{\,2.29}}P_0$, where d is the nozzle diameter, α the expansion half-angle, P_0 the backing pressure behind the valve, T_0 the pre-expansion temperature, and k a constant related to bond formation. Clustering generally begins for $\Gamma^* >$ 100–300. Γ^* is about 200 in the high-pressure SMBI experiments, so cluster onset may occur. Actually there is a threshold of the pressure P_0 for hydrogen clustering in the SMBI experiments in HL-1M [6]. At pressure $P_0 < 1$ MPa, the H_α emission intensity, which is measured by the detector array located at the top of the beam cross-section, is weak. This means that the gas particles entering into the

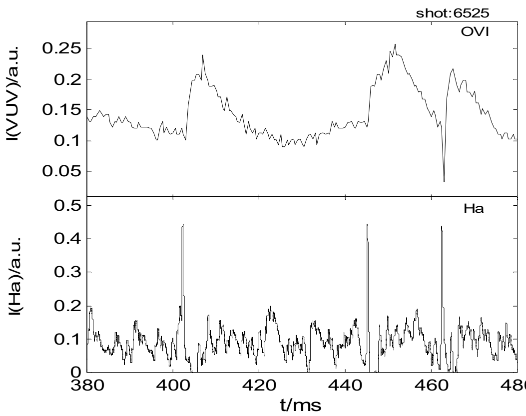

Fig. 1. Variation of emission intensity for H_{α} from the bulk plasma and OVI (103.2 nm) from the core plasma during SMBI.

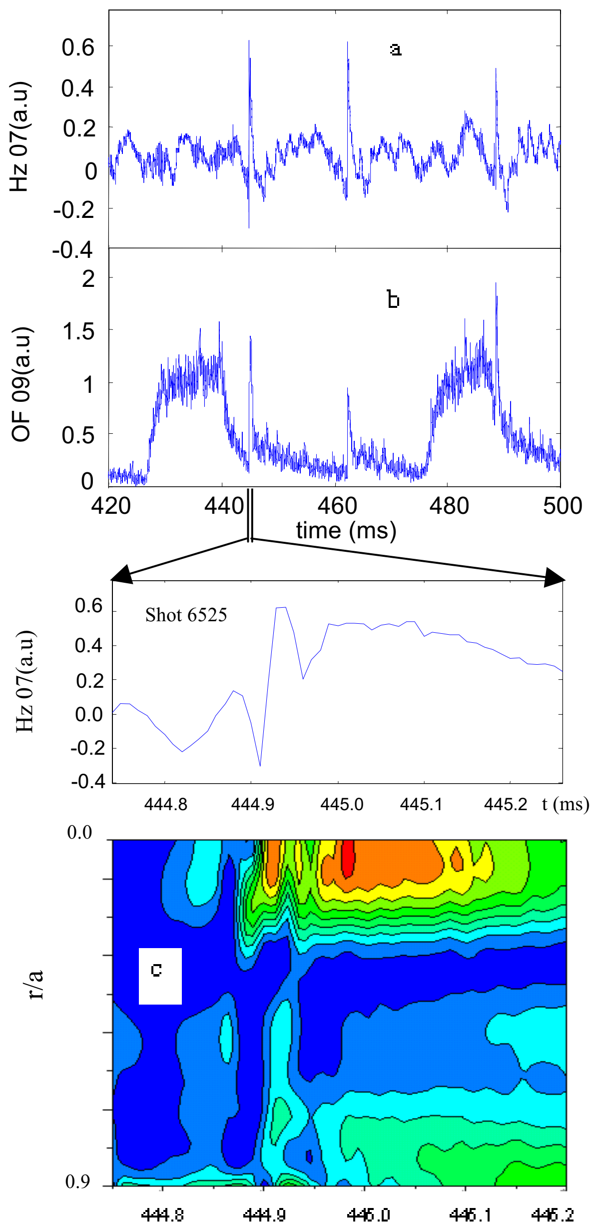

Fig. 2. Variation of H_{α} from (a) the bulk and (b) the edge plasma, and (c) contour plot of H_{α} during SMBI.

plasma are rather few; a large proportion of the injected neutral particles are ionized in the scrape-off layer. When $P_0 \geq 1$ MPa, a few spikes of H_{α} emission appear during the beam pulse or in the interval between two beam pulses in the case of multi-pulse SMBI. The H_{α} emission signals with some spikes for multi-pulse SMBI are similar to the case of multi-pellet injection in HL-1M at the same injection cross-section. The spikes of H_{α} emission from the bulk plasma and the corresponding spikes of the VUV spectrum (OVI 103.2 nm) have been detected, as shown in Fig. 1. This means that within the SMB, hydrogen clusters and oxygen clusters (oxygen is a residual gas but it clusters more easily than hydrogen) simultaneously enter into the center of the plasma. The penetration depth and injection speed of the high-pressure SMB in the HL-1M plasma were roughly measured from the contour plot of the evolution of H_{α} emission intensity, as shown in Fig. 2. It is shown that the particles composed of the clusters could penetrate into the core region of the plasma, and the penetration speed is about 1200 m/s. This speed value corresponds with the diagnostic results from the CCD camera.

2.2. High Performance of High-Pressure Multi-Pulse SMBI

When the pressure of the hydrogen gas source was increased from 0.5 MPa to over 1.0 MPa, a stair-shaped density increment was obtained with multi-pulse SMBI that was just like the density evolution behavior during multi-pellet injection, as shown in Fig. 3. The plasma density increases from $0.77\times10^{19}\,m^{-3}$ to $5.67\times10^{19}\,m^{-3}$ during three-pulse SMBI. The gas pressure of the beam source used for this shot is 1.05 MPa. The hollow profiles of electron temperature after the beam injection give evidence that some of the particles have been

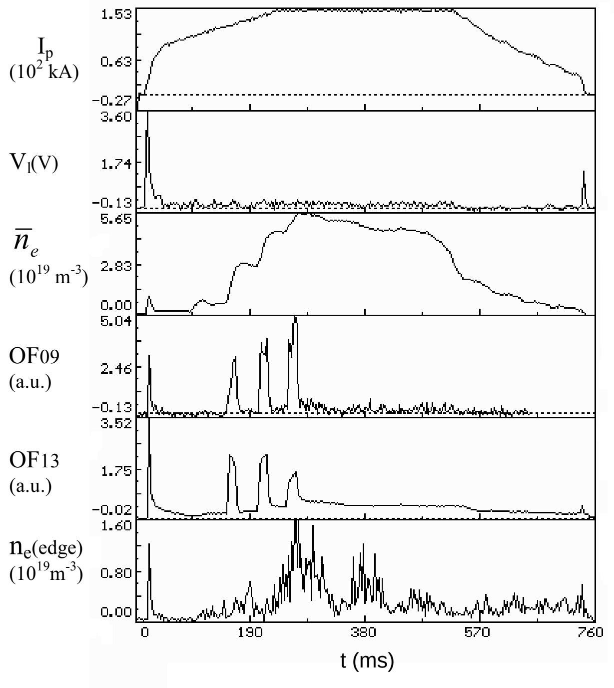

Fig. 3. Plasma density variations during three-pulse SMBI in shot 7300. OF09 and OF13: edge H_α signals around the HL-1M torus; n_e(edge): edge electron density at r = 25.5 cm. Gas puffing from t = 60 ms to 650 ms.

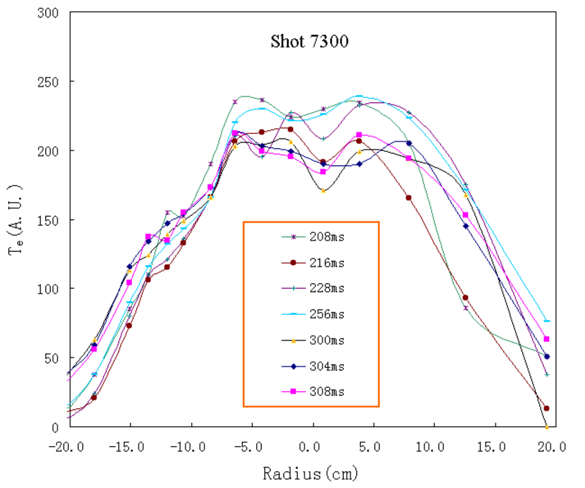

Fig. 4. Variations of electron temperature profiles during three-pulse SMBI in shot 7300.

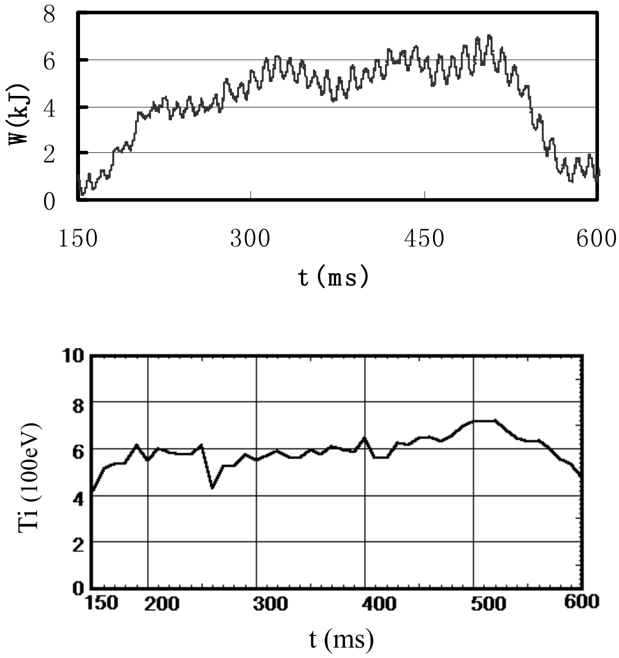

Fig. 5. (a) Plasma stored energy W and (b) ion temperature T_i versus time in shot 7300 during and after SMBI.

injected into the center of the plasma, as shown in Fig. 4. During the period of the first two beam pulse injections, the plasma stored energy W sharply increases and then maintains a stationary state. After SMBI the plasma energy gradually increases, as shown in Fig. 5. The ion temperature detected by a charge exchange neutral particle energy spectrometer increases only after the first beam pulse injection and then maintains a stationary value of 0.6 keV. The plasma energy confinement time measured by diamagnetism was 30 ms in this shot. This demonstrated the effectiveness of SMBI as a promising fuelling tool for steady-state operation.

2.3. Edge Effects Induced by SMBI

A Mach/Langmuir six probe array assembly is mounted on a long shaft in the HL-1M torus [7]. The depth of SMBI penetration into the plasma increases with the increase of the working gas pressure of the beam nozzle, namely the beam injection velocity increases, as shown in Fig. 6. As the pressure increases from 0.3 MPa to 1 MPa, the supersonic flow velocity increases, and the peak value of the plasma poloidal flow velocity V_{pol} has an apparent increment from 3.8 km s^{-1} (at r = 25 cm) to 6 km s^{-1} (at r = 24.5 cm) in the electron diamagnetic direction. When the gas pressure increases from 0.5 MPa to 1 MPa, the peak of Reynolds stress moves from the location r = 25 cm to r = 24.5 cm. The results indicate that sheared poloidal flow can be generated in a tokamak plasma due to variation of the radial Reynolds stress with high-pressure SMBI. The increase of the poloidal rotation velocity shear may reduce the turbulent fluctuations, and the plasma confinement would be improved.

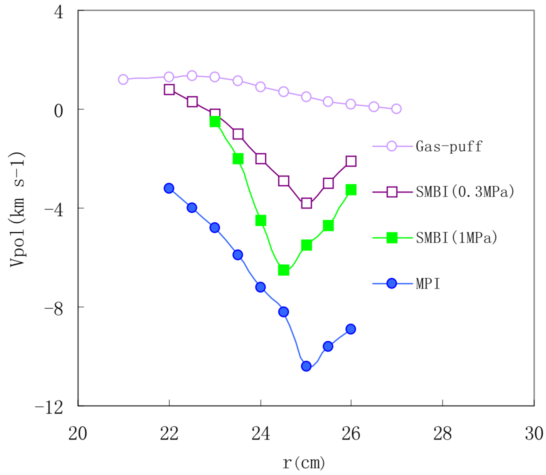

Fig. 6. Radial profiles of V_{pol} in the edge plasma during gas-puff, SMBI and muti-pellet injection, respectively.

2.4. Comparison of Density Increase Rate for SMBI and PI

A comparison of fuelling effectiveness was made for high-pressure SMBI and small ice pellet injection (PI) in the same shot of an ohmic discharge during the period of plasma current plateau. The only difference in the conditions was the injection sequence. The increase rate of electron density, $d\bar{n}_e/dt$, for high-pressure SMBI was slightly above or below that of the small ice PI, as shown in shots 7891 and 7887 in Figs 7 and 8, respectively. The ice cylinder of the pellet was of 1.2 mm diameter and 1.5 mm height, and the average injection velocity of the ice cylinder before it entered the plasma was about 1000 m/s. The $d\bar{n}_e/dt$ values of the high-pressure SMBI and small PI for shot 7891 are $1.5\times10^{21}\,m^{-3}\,s^{-1}$ and $1.2\times10^{21}\,m^{-3}\,s^{-1}$, respectively. For shot 7887, the $d\bar{n}_e/dt$ of SMBI is reduced to $8.7\times10^{20}\,m^{-3}\,s^{-1}$, whereas the value of $d\bar{n}_e/dt$ for the two PI is the same as for shot 7891. The fact that the gas pressure of the SMB for shot 7887 is less than that for shot 7891 by 0.5 MPa may be responsible for the decrease of the $d\bar{n}_e/dt$ value.

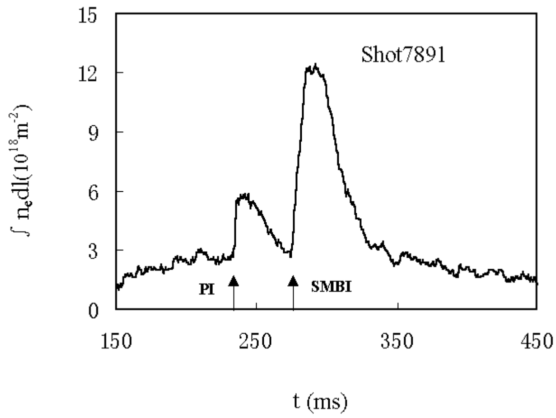

Fig. 7. Comparison of density increase rate for PI and SMBI. P_0 = 11.5 MPa.

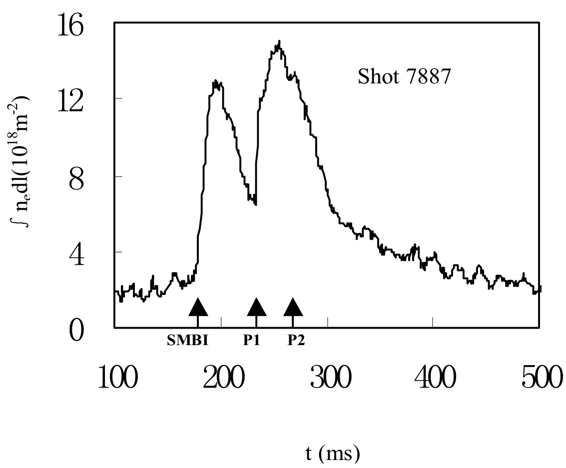

Fig. 8. Comparison of density increase rate for single-pulse SMBI and two-pellet injection.

3. Injection Model of the SMB

There are two mechanisms for interpreting the deeper penetration of the SMB. One is a simple collective model [8] based on the high flux of neutral particles with a very high density of $4.0\times10^{24}\,m^{-3}$. When the SMB is injected into a plasma, within which electrons with limited energy can effectively collide with the dense neutral gas of the surface layer of the SMB, they lose all their energy and finally stop inside this penetration region, so that the neutral gas within this penetration region can protect the bulk particles of the SMB from depositing in the edge plasma zone. So the SMB is surrounded with a cold gas cloud, that is, a cold protecting channel for SMBI is formed in the injection region. The low temperature region in the injection direction was verified in SMBI experiments. The second interpretation is the electrostatic double layer shielding model [9]. When a dense SMB is injected perpendicularly into a plasma and crosses the toroidal magnetic field lines, the background electrons entering into the molecular beam along the magnetic field lines would undergo a series of inelastic collisions, resulting in energy and momentum losses. Because the neutral particle density in the beam is larger than the plasma density, the electrons lose most of their energy and slow down. This will induce an accumulation of electrons near the boundary of the molecular beam to form an electrostatic double layer, the shielding effect of which makes the SMB penetrate a long distance.

4. Summary and Discussion

The original reason for proposing SMBI was an attempt to enhance the penetration depth and the fuelling efficiency [3]. After ten years of practice, SMBI has been developed to become of a useful fuelling method that is already considered an improvement over conventional gas puffing and that can be compared with the method of PI. The high-pressure multi-pulse SMBI takes a further step towards achieving a high performance plasma through the onset of clustering, which acts just like a micro-pellet. It is necessary to continuously increase the gas pressure of the beam source and decrease the gas temperature for enlargement of the cluster dimensions. The opposite way to enhance the injection quality is to increase the gas temperature so as to increase the injected particle speed. The alternative injection mode is to vary the injection location from the low magnetic field side to the high field side.

Normally clustering of hydrogen is very difficult to attain at room temperature. A careful examination of VUV spectroscopic signals during a single-pulse SMBI indicates that there is a second gas injection into the plasma, which resulted from a bounce of the valve poppet from the rubber O-ring seal. In fact, this reopening of the valve is very much weaker compared with the previous opening. However, the influence of this slight reopening of the valve does have a dramatic effect on the cluster formation. A research paper [10] on the clustering of the rare gases Kr and Xe with Rayleigh scattering has verified the “bounce” effect of the valve, and huge clusters as much as 62 times the normal cluster size are obtained under the same conditions.

Acknowledgements

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References

[1] Yao, Lianghua, et al., in Proc. 20th EPS Conference on Controlled Fusion and Plasma Physics, Lisbon, 1993, Vol. 17C(I), 303.
[2] Yao, Lianghua, et al., Nucl. Fusion **38** (1998) 631.
[3] Yao, Lianghua, et al., Nucl. Fusion **41** (2001) 817.
[4] Gao, Xiang, et al., Nucl. Fusion **40** (2000) 1875.
[5] Smith, R.A., Ditmire, T., Tisch, W.G., Rev. Sci. Instrum. **69** (1998) 3798.
[6] Dong, Jiafu, et al., Plasma Phys. Control. Fusion **44 (**2002) 371.
[7] Hong, Wenyu, et al., J. Nucl. Mater. **266 (**1999) 524.
[8] Song, Xianming, et al., J. Plasma Fusion Res. **76** (2000) 282.
[9] Shi, Bingren, Nucl. Fusion Plasma Phys. **4** (2001) 200 (in Chinese).
[10] Liu, Bingchen, et al., Chin. Phys. Lett. **19** (2002) 659.