Hydrogen Cluster–Like Behavior during Supersonic Molecular Beam Injection on the HL-1M Tokamak

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ABSTRACT. Pulsed supersonic molecular beam injection (SMBI) has been developed successfully and used in the HL-1M tokamak. It is an attempt to enhance the penetration depth and fuelling efficiency. With a penetration depth of hydrogen particles beyond 8 cm, the rising rate of electron density , dn_e / dt , was up to 7.6×10^{20} $m^{-3} \cdot s^{-1}$ without disruption, and reached the highest plasma density $\overline{n}_e = 8.2 \times 10^{19}$ m^{-3} on HL-1M. With SMBI the plasma energy confinement time, τ_E , measured by diamagnetism is 10-30 % longer than that with gas puffing when other discharge conditions are kept the same. The fuelling method of SMBI has recently been improved to make a survey of the cluster effect within the beam. A series of new phenomena show the interaction of the beam (including clusters) with the toroidal plasma. Hydrogen clusters may be produced in the beam according to the Hagena empirical scaling law of clustering onset, $\Gamma^* = \frac{kd^{0.85} P_0}{T_0^{2.29}}$. If Γ^*>100, clusters will form. In the present experiment Γ^* is about 127.

1. Introduction

As the ITER Expert Group point out [1], a major physics issue is whether or not the fuel can penetrate the SOL to reach the region of the core. The fuelling efficiency is of the order of 10% for gas puffing in ITER. It appears that ITER will probably not provide the necessary central particle fuelling required to sustain a fusion burn, so other methods must be explored. Pulsed supersonic molecular beam injection (SMBI) has successfully been developed and used in the HL-1M tokamak (R = 1.02 m, a = 0.26 m, $B_t \leq 3$ T and $I_p \leq 300$ kA). It is an attempt to enhance the penetration depth and fuelling effect. SMBI could be an improvement over conventional gas puffing (GP) [2].

2. Supersonic Molecular Beam Source

The supersonic molecular beam source used here in fact is a free jet. Figure 1 shows the features of a free jet expansion under continuum conditions and its injection into the HL-1M plasma. The source consists of a small chamber with a nozzle, and the working gas can be kept at a definite pressure P_0 and temperature T_0 in the chamber. The gas is accelerated by imposed pressure difference (P_0-P_b) through the nozzle to get into the vacuum chamber of HL-1M. Beyond the exit the gas flow expands isentropically, as the flow area increases, and the supersonic flow increases velocity. The Mach number continues to increase and becomes far greater than one [3]. The dimension of the supersonic area (zone of silence), X_M, is given by $X_M/d = 0.67(P_0/P_b)^{1/2}$, where d is the diameter of the nozzle.

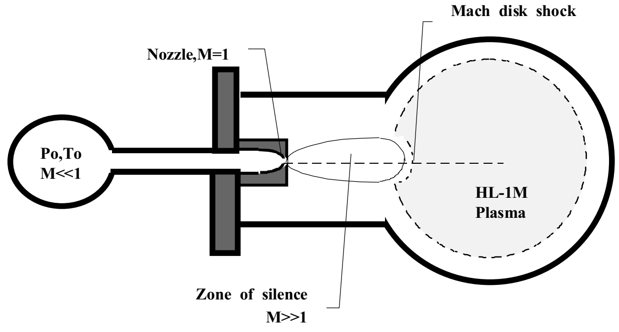

FIG. 1. Schematic diagram of supersonic molecular beam injection into the HL-1M plasma.

3. Experimental Set-up of SMBI

The experimental set-up of pellet injection (PI) and SMBI in the HL-1M tokamak is shown in *FIG. 2*. The CCD camera was mounted 8.7 cm above the mid-plane and at an angle of 13.4 degrees to the PI line, which is along a major radius of the mid-plane. The SMBI line is 9 cm below and parallel to the PI line. A detector array for H_{α} emission intensity which includes 20 channels of PIN diode is located on the top port. The array is on the same plasma cross-section as the PI and SMBI lines. Around the torus there are a series of diagnostics.

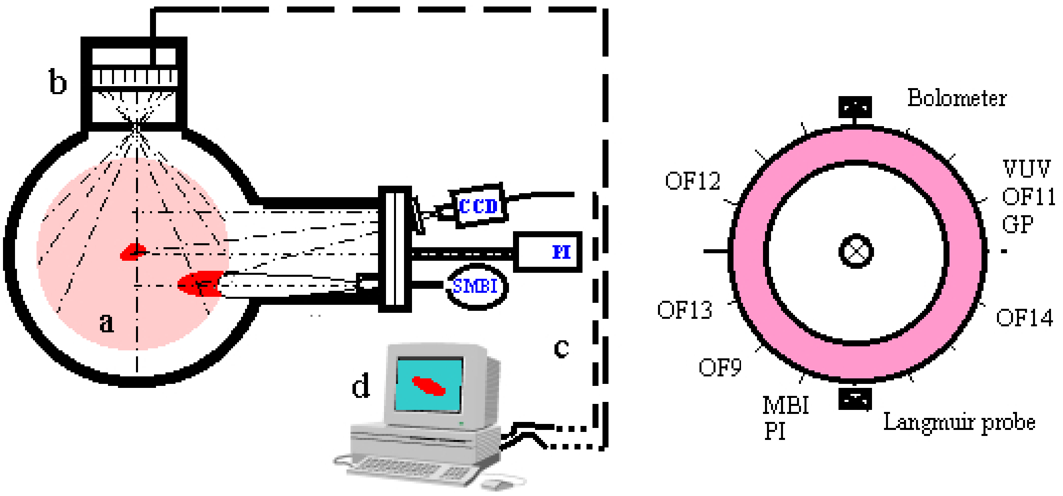

FIG. 2. Experimental set-up of PI & SMBI in the HL-1M tokamak.
(a) ***HL-1M plasma, (b) 20 channel PIN array, (c) 40 m long optical fiber, (d) Computer Data A&P system.***

4. Experimental Results

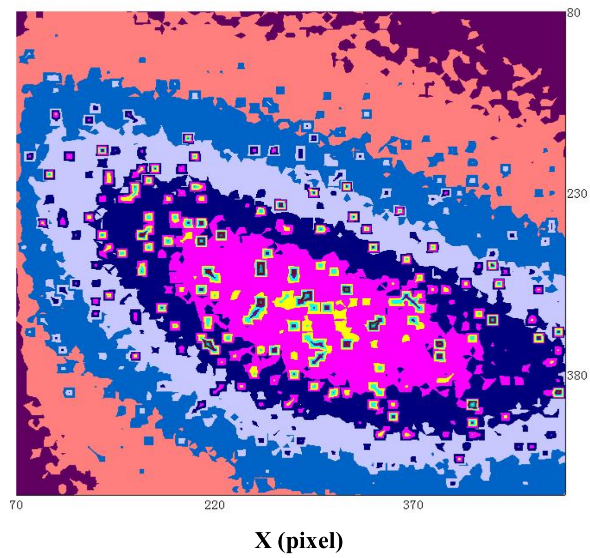

FIG. 3. Contour plot of H_{α} emission for the beam injection into plasma.

To improve the beam source, the nozzle diameter d is reduced from 1.5 mm to 0.1 mm and the pressure ratio P_0/P_b is increased to 5×10^7, so the $X_M \approx 47$ cm, which is longer than the distance from the nozzle to the edge plasma for elongating the dimension of the supersonic area and to avoid the emergence of Mach shock. Then the features of the pulsed supersonic molecular beam appear, such as high instantaneous intensity, high speed, small spread of velocity and small angular distribution.

4.1 Cluster-like Phenomena

Early in 1972 R. Klingelhofer and H.O. Moser presented a proposal [4] that

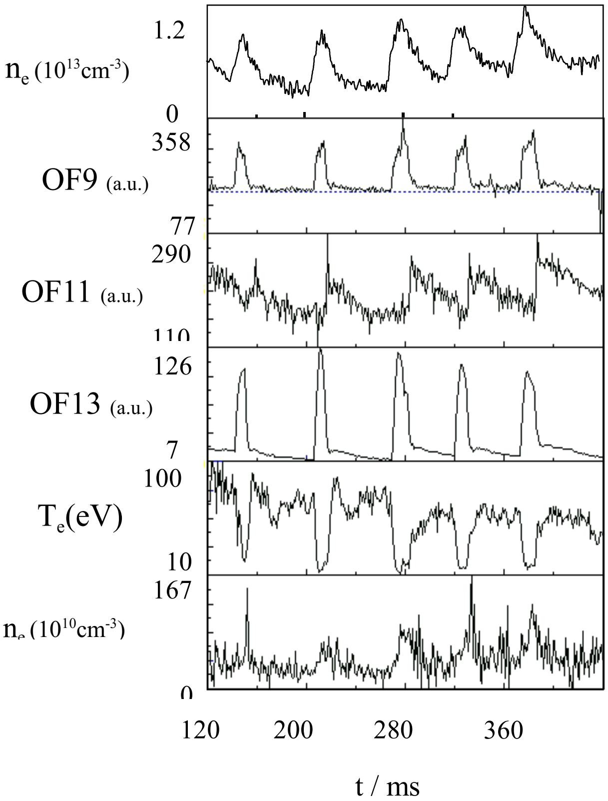

FIG. 4. Edge plasma parameters during SMBI.. HCN-central electron density, OF9,11,13,-edge H_a signals from FIG. 1. T_e & n_e –edge plasma temperature and density at r = 23 cm.

intense hydrogen clusters having a velocity of about 500 m/s can be used for the refuelling of a thermonuclear plasma or for the compensation of particle losses in a thermonuclear device. They produced the hydrogen clusters by expansion of precooled hydrogen gas out of a nozzle into high vacuum. The condensed supersonic molecular beam technique, developed by our recent beam injection experiments, just increases the gas pressure of the gas source. A series of new phenomena show the interaction of the beam (including clusters) with the toroidal plasma. The H_α emission measured with a CCD camera appears as many separate peaks within the contour plot shown in *FIG. 3*. These peaks may show the strong emission produced by the interaction of the hydrogen clusters with the plasma. The H_α signals from the edge show regular variation around the torus during the beam injection. Around the injection port, the edge H_α signals are a positive rectangular wave, which is consistent with that of the injection beam pulses, whereas the H_α signals far away from the injection port become sharp negative pulses. The edge electron temperature measured with movable Langmuir probes decreases by an order of magnitude and the density increases by an order of magnitude as shown in *FIG. 4*. Hydrogen clusters may be produced in the supersonic molecular beam according to the Hagena empirical scaling law of clustering onset [5], $\Gamma^* = \frac{kd^{0.85} P_0}{T_0^{2.29}}$, where d is the nozzle diameter in μm, P_0 the stagnation pressure in mbar, T_0 the source temperature in K, and k is a constant related to the gas species. If Γ^*>100, hydrogen clusters will form within the beam. In our experiment Γ^* is about 127.

4.2 Fuelling Efficiency and Density Peaking

Fuelling efficiency is strongly dependent on wall condition and is a temporal function. Sometimes the recycling particles are the main external fuelling source, especially in high density operation. Accurate calculation of fuelling efficiency requires the data on whole recycling particles, which are difficult to measure. So we adopt the rising rate of electron density $d\overline{n}_e / dt$ instead of the fuelling efficiency $\eta_{f(t)}$ to study and compare the two fuelling methods SMBI and GP. The actual fuelling efficiency of SMBI is approximately twice that for GP under a similar wall condition and high density operation. The density profile peaking factor, $Q_n = n_e(0)/\langle n_e \rangle$, after SMBI reached a maximum value of about 1.65 and the Q_n value normally is less than 1.4 for GP in HL-1M.

4.3 T_e Hollow Profile and Negative Magnetic Shear after SMBI

A "hollow profile" of electron temperature has been measured by electron cyclotron emission (ECE) after helium SMBI into the hydrogen plasma of the HL-1M device [3]. In recent experiment with a hydrogen SMBI plasma, The "hollow profile" phenomena sometimes appeared at the end of the plasma current plateau, where the plasma density already reaches a high level and the density peaking factor continues to increase. It so happened that the ohmic heating power decreases or the radiation losses increase from the plasma center. Ohmic shear reversed configurations have been obtained on HL-1M by combined control of plasma current slow ramp-up and SMBI. They are characterized by hollow electron temperature profiles and peaked density profiles [6].

4.4 Density Limit

The best way to obtain the maximum density is SMBI fuelling with slow current ramp-up under wall surface siliconization. A maximum density $\overline{n}_e = 8.2 \times 10^{19}$ m^{-3} (shot 4965, pure ohmic heating hydrogen plasma with current slowly rising to 186 kA, B_t = 2.4 T) has been obtained, which is about 80% of the Greenwald density limit. It proved that the impurity and recycling from the first wall play an important role in achieving a density limit. The highest density limit is a factor of 1.4 of Greenwald's for a low current I_p = 120 kA plasma. The density limit in deuterium is somewhat higher than that in hydrogen, and the isotope effect scaling is $\overline{n}_e \propto m^{1/3}$ in HL-1M.

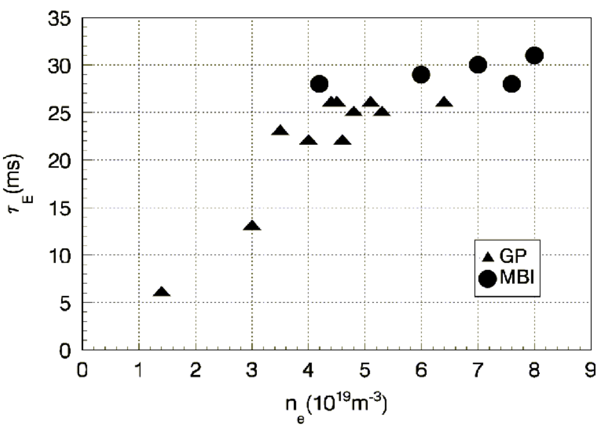

FIG. 5. Plasma energy confinement time τ_E vs $\overline{n}_e$ measured by diamagnetism in HL-1M. I_p = (150- 200) kA, B_t = (2.4-2.5) T, q_{95} = 3.9-5.5.

4.5 Energy Confinement Improvement with SMBI

In the recent experiment, the plasma current increased to the plateau (150-200 kA) with a slow ramp-up rate until t = 200 ms. One of the important results is the plasma energy confinement improvement; in addition, the upper end of the linear ohmic confinement regime has an apparent increment from the critical density of 2.5×10^{19} m^{-3} to 4.0×10^{19} m^{-3}. A comparison of τ_E variation with $\overline{n}_e$ for the two fuelling methods is shown in *FIG. 5*. The results show that τ_E with a SMBI hydrogen plasma is 10% to 30% higher than that with a GP plasma.

It is also significant to investigate the electron energy confinement with SMBI to determine if it is able to open up the linear regime of ohmic energy confinement. The dependence of the gross electron energy confinement on linear averaged electron density is shown in *FIG. 6*. We found that the transition density from the linear ohmic confinement (LOC) to the saturated ohmic confinement (SOC) driven by SMBI is somewhat increased over that driven by GP. The transition density from LOC to SOC with conventional gas fuelling is about 4×10^{13}cm^{-3}, but it is 4.5 × $10^{13}cm^{-3}$ with MBI. It is interesting that the same critical transition density is obtained from different diagnostics of diamagnetism and ECE for SMBI fuelling.

5. Conclusion and Discussion

Previous experimental results show that SMBI could be an advanced method of gas fuelling for small or medium sized limiter tokamaks, such as HL-1M, and it has been introduced in the superconducting tokamak HT-7. Considering the relatively high temperature of the edge plasma in large tokamaks with a divertor, such as JET or ITER, a supersonic beam with clusters, which are just like micro-pellets, will be of benefit to deeper fuelling. The cluster particles should be sufficiently fast and large in order to penetrate the separatrix and provide the necessary central particle fuelling required to sustain a fusion burn.

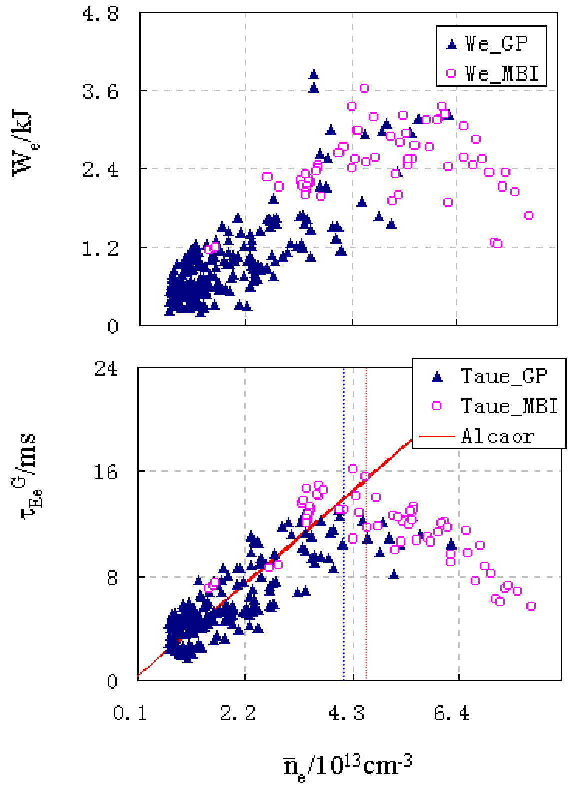

Fig. 6. The dependence of electron stored energy and confinement time on plasma linear average density.

Acknowledgements

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