1.7 Pellet and Supersonic Molecular Beam Injection Fuelling on the HL-1M Tokamak

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1 Peaked density and improved confinement

An eight-shots pellet injection (PI) and a supersonic molecular beam injection (SMBI) system have proposed and developed on the HL-1M tokamak for advanced fuelling experiments[1, 2]. The peaked density profile and improved confinement are typical feature of PI and SMBI discharge. It strongly depends on the wall recycling conditions of the HL-1M tokamak and injection parameters.

After wall conditioning with siliconization and helium glow discharge cleaning the HL-1M wall is very clear (loop voltage V_L<0. 3 V) and in low recycle case. In this case the electron densities n_e developed with a sawtooth characteristic. Fig. 1 shows the density evolution of PI(a), and SMBI (b) in low recycle and PI in high recycle(c) case respectively. The rapid increase ($dn/dt \geqslant 1\times10^{22}\ m^{-3}\cdot s^{-1}$) in 1 ms and fast drop in ~25 ms for each PI and density peaked factor Q_n reaches 1.8~2.0 in a few millisecond. The increase value of average density $\bar{n}_e$ without distinguishing the values due to low wall recycling and large firing interval. Usually the plasma-stored energy W^{dia} less than 3.5 kJ and confinement time τ_E less than 18 ms is obtained in these PI shots. In multi-pulse SMBI (pulse width of 15 ms interval of 60 ms and p_0=0. 35 MPa) discharges the evolution of densities is similar to pellet injection discharge, but the increase ratio of $dn/dt \geqslant 7\times10^{20}\ m^{-3}\cdot s^{-1}$ is far less than that of PI and the Q_n increased from 1.3 to 1.5 while the Q_n is normally in the range of 1.3 to 1.4 for GP in the HL-1M plasma.

Fig. 1 (c) shows the density evolution of PI in high recycle case. The density raise sharply up to the first maximum value of n_{elmax} and then decrease in each chord. At the outer region (Ch6 r=15 cm) the drop of n_e (in 10 ms) is followed by a slowly rise (in 15 ms) up to second maximum value n_{e2max} ($n_{e2max} < n_{e1max}$=, then slowly decrease again. In center region (Ch2 r =0 cm) it decreases a little in 5 ms, and then keeps flatten in 15 ms and slowly decay. In the inner region (Ch1 r = −6 cm) the n_e decrease continuously. When second and third pellet injected, in center region (Ch2), the n_e (0) rise with a longer time and reached to second maximum value (n_{e2max}> n_{e1max}). The facts that the density in n_e (0) keeps nearly flatten even has n_{e2max} while the density keeps still tip shape in Chl (r = − 6 cm) and $n_{e,Chl} \geqslant n_{e,Ch2} > 2\ n_{e,Ch6}$, the appearance of second rise of n_e in Ch6, even in Ch2 as well as the $Q_n \geqslant 2$, are the characteristics of PI in high recycle case. The diffusion of high density from plasma core region to the edge region after pellet ablation combination with the source from high recycle of the wall are the main reason of appearance of n_{e2max} in Ch6, even in Ch2. In this shot the parameters of W^{dia}=6.0 kJ and the confinement time of τ_E=26 ms are obtained. The central density N_e (0)$\geqslant 6\times10^{19}$ m^{-3} was not measured in excessive (interval less than 25 ms) or large (1.4 mm) PI discharges. It may be due to (a) some fringe signals of HCN interferometer lost during the increased phase of the density due to the modulation frequency of HCN interferometer is only 10 kHz, (b) internal disruption occurs, similar phenomena as seen in Heliotron E[3].

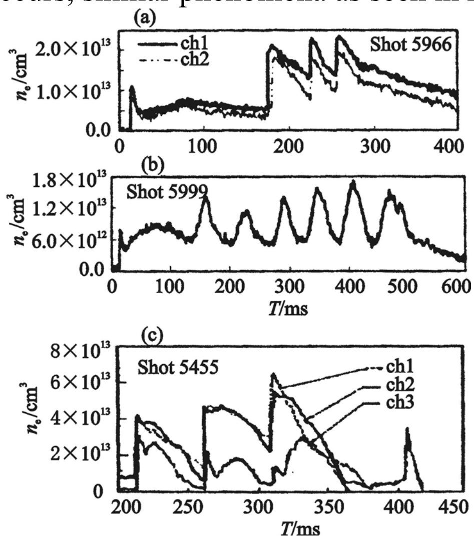

Fig. 1 The density evolution for (a) PI, (b) SMBI in low recycle and (c) PI in high recycle case, respectively

The SMBI is a free jet system in the HL-1M tokamak. The gas passed through the Laval nozzle only a fraction can form supersonic molecular beam, the other succeeding gas followed the molecular beam are also fuelling to plasma. These succeeding gases fuelling can overcome the density sawteeth turbulence and achieve a stationary discharge of high density. The maximum value of $\bar{n}_e = 8.2\times10^{13}$ cm^{-3} and good confinement of τ_E =28~ 30 ms were obtained by very clean wall condition and proper recycle in SMBI (I_p=186 kA, B_T= 2.4 T). The interval of 45 ms for per pulse and stationary ramp-up of d n/d $t < 3.0\times10^{20}$ $m^{-3}\cdot s^{-1}$ is proper. The highest limit is a factor of 1.2 (for PI) and 1.4(for SMBI) of the Greenwald density limit at low current $I_p < 120$ kA plasma, and it was about 80% of Greenwald density limit at high current I_p= 186 kA for this SMBI discharge.

In these PI and MBI discharges, the peaked density leads to improve confinement, the τ_E for PI is usually 20%~30% in higher than that of GP discharges under the average density of $\bar{n}_e < 4\times10^{19}$ m^{-3}, but for SMBI it was better than 10%~30% to gas puffing in whole [$\bar{n}_e = (1 \sim 8)\times10^{19}$ m^{-3}] density range. The maximum and steady state value of $\bar{n}_e$ were achieved only by multi pulse SMBI with the peaked factor of Q_n=1.65.

2 Observation of deposition and penetration depths of PI and MBI

When pellet enter the hot plasma, a high dense ($10^{23} \sim 10^{24}$ m^{-3}) cloud and cold (several eV) plasmoid formed and moved accompanied with the pellet. These plasmoid emitted visible light of H_α that is directly proportional to the pellet ablation rate. We think that the position of the peaking value for H_α intensity indicated the position of the pellet or SMBI in plasma. The Penetration depths λ_p of pellet and SMBI have been immediately measured by means of multi-channel H_α emission signal and the Abel inversion method. The λ_p of 11~26 cm can be easily achieved for PI, and 8~ 20 cm for MBI in the HL-1M ohmic-heated discharges with $T_e(0) <$ 1.0 keV.

The λ_p for 6010 shot is about 24 cm, the average motion velocity v_a of pellet ablation cloud in the plasma is estimated by $\Delta\lambda_p / \Delta t$ and the v_a is about 400 $m\cdot s^{-1}$. However, the free flying velocity v_f of pellet before it entering into the plasma is 460 $m\cdot s^{-1}$ in this shot. The fuel particles deposited always at the center of plasma for PI, at the edge for GP, and the majority particles in SMBI ($p_0 < 0.4$ MPa) deposited outside ρ=0.5, a few of them deposited close to the ρ=0. 5 region of the plasma. When the gas source pressure p_0 increased to 1.1 MPa penetration depth of SMBI fuelling particles can be great than 15 cm and the peaked signals of H_α for pulse SMBI can be also detected on the central chord though the amplitude of H_α signals intensity for SMBI is only one tenth for PI, the Q_n of density increased gradually from 1.3 to 1.6 for SMBI (usually in 300 ms).

The fuelling efficiency ε_f of PI and SMBI fueling were estimated by the increase of particles in the plasma (1~2 ms after PI and 15 ms after MBI respectively) divided by the number of particles with the same pellet or molecular beam injected into the HL-1M vacuum vessel under similar recycle case. Usually the ε_f were about 80% for pellet deep injection, about 50%, for SMBI in high pressure of p_0=0. 7~ 1. 1 MPa, but 10% ~ 20% for GP.

3 The observation of PI ablation and SMBI penetration

The image of pellet ablation cloud with multi-exposures and the images of multi pellets in one discharge have been obtained by a CCD camera in the HL-1M tokamak. An intact pellet with lower velocity (~200 m • s^{-1}) only injected to the outer region (usually outside of q=2 surface), in this situation the ablation cloud is a circular shape. In the deeper penetration case, the pellet crossed to the q= 2 surfaces toward the plasma center and the elongation shape of pellet ablation cloud along the local magnetic field direction are formed[4]. In order to confirm the relation between the inclination direction of pellet clouds and the local magnetic field, the discharges with inverted toroidal magnetic field B_T were carried out in the HL-1M tokamak. The photos of pellet clouds with inverse inclination were obtained in inverted toroidal magnetic field B_T, while in the discharges of SMBI experiment the pattern of the photograph always keeps similar form even though the toroidal field direction inverted. Although the ablation mechanism and the photo shape for SMBI are not completely understood now, the photo shape of SMBI is consistent with deposition region of SMBI in the plasma.

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