Plasma Behavior with Hydrogen Supersonic Molecular Beam and Cluster Jet Injection in the HL-2A Tokamak

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Abstract. The experimental results of low pressure supersonic molecular beam injection (SMBI) into the HL-2A plasma indicated that during the period of SMB pulse injection the power density convected at the divertor target plate surfaces was 0.4 times of that before or after the beam injection. The clusters are produced at nitrogen temperature in a supersonic adiabatic expansion of moderate pressure hydrogen gases into vacuum through a Laval nozzle. The averaged cluster size was measured by Rayleigh scattering as large as hundreds atoms. Multifold diagnostics for the cluster jet injection (CJI) experiments have given a coincident evidence that there was a terminal area where a great deal particles from the clusters deposited at, rather than the clusters uniformly ablating along the injection path. A SMB with large clusters, which are like micro-pellets, was of benefit for deeper fuelling and the fuelling efficiency is distinctly better than that of the room temperature SMBI. Another important effect of the CJI or the high pressure SMBI was that the runaway electrons were cooled down to thermal velocity due to a combination of collision and radiative stopping in such a massive fuelling. So the new fuelling technique may become a good treatment to mitigate fast plasma shutdowns and disruptions.

1. Introduction

After more than ten years of practice, SMBI has been developed to become a useful fuelling method that is already considered to be an improvement over conventional gas puffing (GP). The high-pressure (more than 1 MPa) multi-pulse SMBI takes a further step towards high performance discharge of the plasma for the onset of injected particle clustering [1]. There is no rigorous theory to predict cluster formation in a free jet expansion. However, the onset of clustering can be described by an empirical scaling parameter Γ^* referred to as the Hagena parameter [2], clustering generally begins for $\Gamma^* > 100\text{-}300$. In the HL-1M experiment, the Hagena parameter Γ^* is above 200, so cluster onset may occur. The HL-2A tokamak is the first tokamak with diverters in China. The main parameters of HL-2A are R = 1.65 m, a = 0.4 m, B_t = 2.8 T and I_p = 0.48 MA. The divertor of the machine is characterized with two closed divertor chambers, but now it is operated with lower single null configuration [3]. Large hydrogen cluster (>100 atoms) can be produced at low temperature gas. The experiment of hydrogen CJI into the HL-2A plasma was carried out and the particle injection depth and the fuelling efficiency were distinctly better than that of the room temperature SMBI.

1. Experimental set-up of SMBI system in HL-2A

The experimental set-up of SMBI system in HL-2A and the detail structure of the molecular beam valve with cooling trap are shown in *FIG. 1*. The valve used for producing supersonic molecular beam is a solenoid driven pulsed valve S99 with a 0.2 mm diameter cylindrical.

The distance between the nozzle of the valve and the edge plasma is about 1.28 m. The penetration characteristics of SMBI were measured by means of the tangential H_α photodiode detection array as shown in *FIG. 2*. Two arrays of Langmuir probes are installed on the inner- and outer- target plates of the lower divertor, respectively [4].

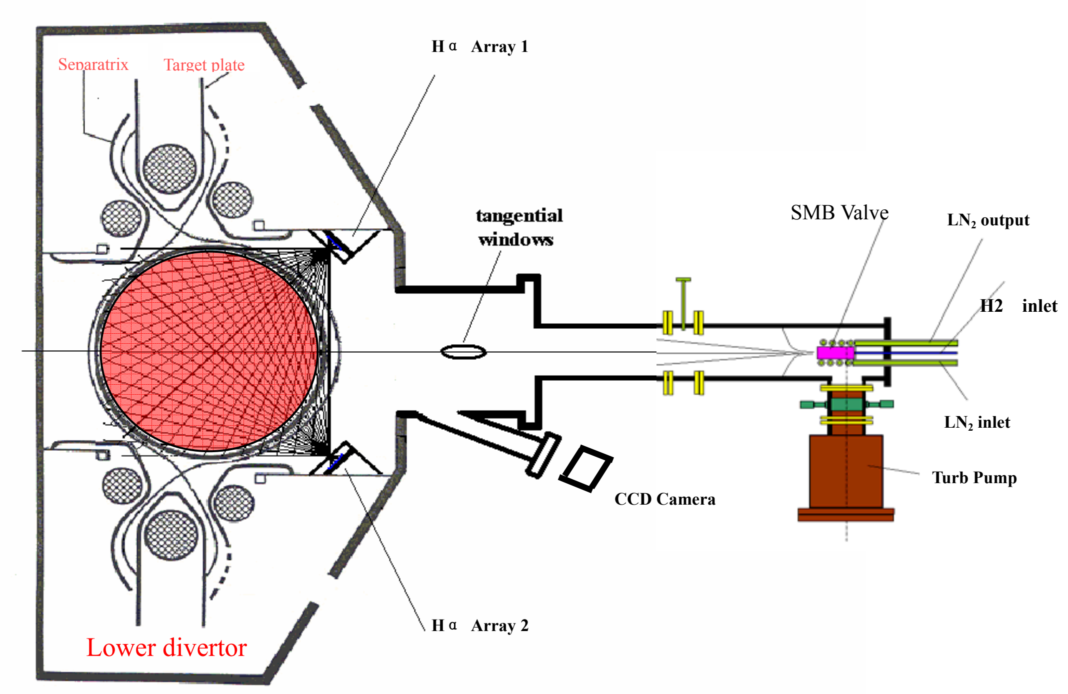

FIG. 1. Supersonic molecular beam injection system in the HL-2A Tokamak

2. The behavior of the recycling flux for low pressure hydrogen SMBI into the HL-2A limiter configuration

One crucial point is the behavior of the recycling fluxes from the vessel wall during the beam injection. *FIG. 3* shows the time traces of the H_α detectors, of which one marked as Ha-046(v) is $H\alpha$ emission intensity from tangential 46th channel. I_Ha_w(v) and I_Ha_s(v) is adjacent to the beam export, and the two others I_Ha_n(v) and I_Ha_e(v) represent the north and the east azimuth H_α emission intensity, respectively. Directly after the pulse beam injection, the H_α intensity drops at a distance from the beam injection location of I_Ha_n(v) and I_Ha_e(v), and is recovered after ≈ 30 ms to the value before the injection. This indicates a transient reduction of the recycling fluxes during the beam injection. It is supported by the heat radiation detected from the Bolometer (BOL_08(v)) and the neutral gas manometer measurement which signal signed as Ph2p, by both of the detectors a reduction of heat emission and the neutral pressure after the beam injection is registered, respectively.

3. The effect of low pressure hydrogen SMBI on the HL-2A divertor

A train of ten pulses of hydrogen molecular beam produce at low pressure 0.2 ~ 0.3 MPa, each pulse duration 10 ms and pulse period 30 ms, was injected at the mid-plane of the HL-2A torus and along the major radius from t = 200 ms and the diveretor function was started up at t = 240 ms. After t = 240 ms the fuelling particles from the later eight molecular beam pulses not only can enter into the main plasma, but also the divertor chamber.

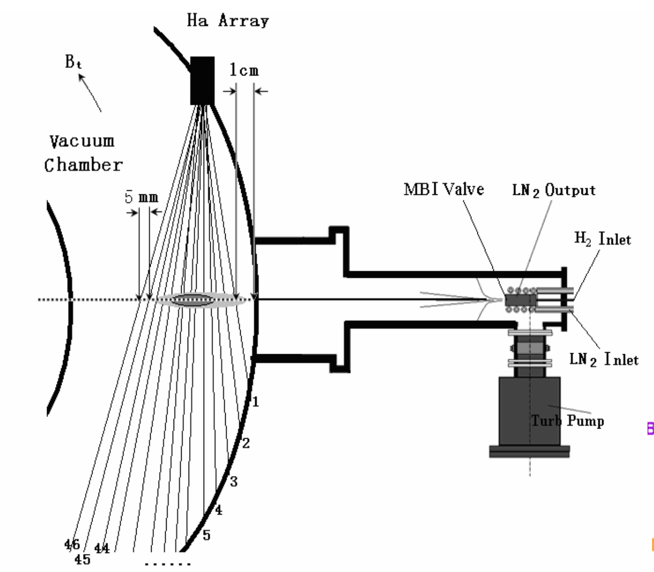

FIG. 2. the scheme of the MBI system and the tangential Ha detection system, total number of the Ha channels is 46, distance between adjacent channels is 5mm along the radius.

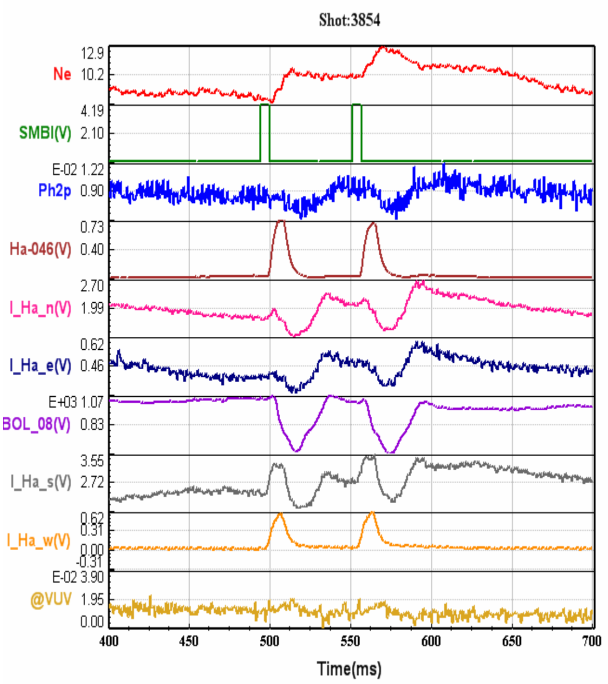

FIG. 3. Reduction of H_α intensity (except the beam injection location), heat emission and neutral pressure after SMBI.

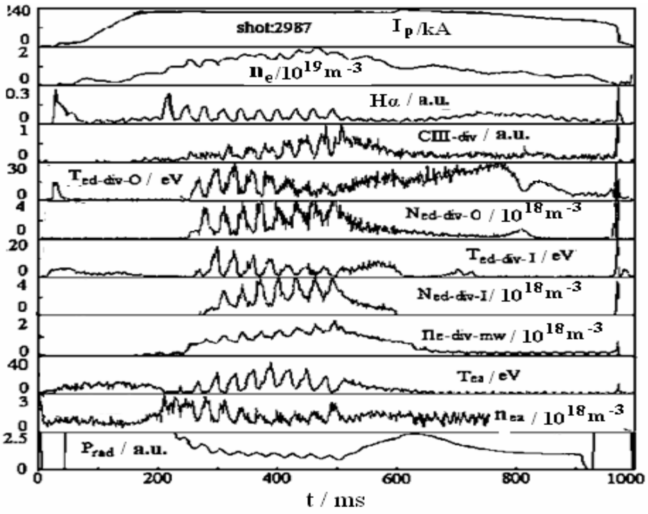

FIG. 4. Behavior of ten pulses of SMBI into HL-2A Plasma.

The fuelling characteristics of the SMBI into HL-2A plasma with and without lower closed divertor configuration for shot 2987 are as shown in *FIG. 4*. During the periods of SMB pulse injection the electron density near by the neutralized plates of the divertor increases an order of magnitude than that in the interval of the beam pulses under the divertor configuration. The electron density on the inner and outer target plate location $n_{ed-div-I}$ and $n_{ed-div-O}$ varies linearly with density n_{ea} in SOL, respectively, i.e. $n_{ed-div-I} \cong n_{ed-div-O} \cong 1.5\times n_{ea}$. On the other hand, the electron temperature on the target plate locations also varies linearly with the upstream temperature, $T_{ed-div-I}$ is approximately equal $^2\!/_3$ of T_{ed} in SOL, as shown in *FIG. 4*. During the period of SMBI fuelling, the electron temperature on the target plate locations is less than 5 eV. So the HL-2A lower divertor was operated at the “linear regime”. There is a boundary condition that is imposed on the conduction of heat in the SOL, which determines the power density q_t that can be convected through the electrostatic sheath at the target plate surface [5]. The ratio of power density q_t', during the SMBI period, to q_t, before or after the beam injection equals 0.4. That is, during SMBI the heat load on the target plate surface is just 0.4 times of that before or after the beam injection. So SMBI may be as a useful fuelling method to decrease the heat load on the neutralizer plates and to make a safe circumstance for the divertor operation. The particle confinement time τ_p increased by a factor of two during the SMBI may incidentally obtained by Staib's model [6] from the measurements.

4. SMBI as a good perturbation source for studying particle transport

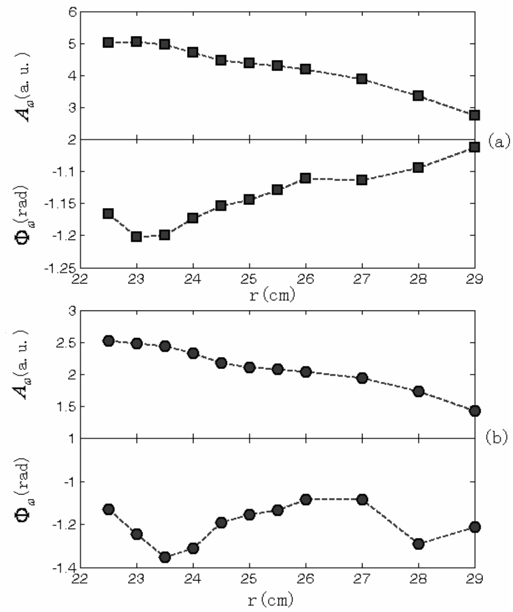

FIG. 5. The amplitude profiles at first, second harmonic in shot 3874, (a) ■first harmonic, (b) ●second harmonic.

Pulsed molecular beam has high instantaneous intensity, higher and approximately uniform speed than normal GP, small spread of velocity with narrow angular distribution. So a train of SMB pulses is used for a particle perturbation source to study the particle transport. A microwave reflectometer with scanning frequency range of 26 GHz to 40 GHz, which corresponding to the density range $(0.8\text{-}2)\times10^{19}m^{-3}$, has been used to measure the electron density profiles [7, 8]. The temporal resolution and spatial resolution are 1 ms and 1 cm, respectively. The pulse duration is 5 ms and the period of the pulse is 55ms. After the fast fourier treatment (FFT) analysis, the amplitude and the phase profiles of the first and second harmonics can be obtained, respectively, as shown in *FIG.5*. The maximum amplitude and the minimum phase in the profiles are nearly in the same radial position. The minimum phase of the second harmonic are located at the same position, r ≈ 28 cm, which means that the pulse perturbation source is mainly located at this position. The particle diffusion coefficient D, which can be determined by $D = \omega/2(\Phi')^2$, is equal to 0.5 ~ 1.5 m^2/ s at the range of r = 26 cm to 30 cm.

5. Rayleigh scattering experiment for the measurement of hydrogen cluster

The hydrogen clusters were produced by the supersonic adiabatic expansion of moderate backing pressure gases into vacuum through a Series 99 valve with a nozzle of 0.5 mm diameter, the temperature of the gas source composed of the valve and its nozzle was cooled to 80K. The Rayleigh scattering method was employed to measure the hydrogen cluster size [9,10,11]. A 532 nm pulsed laser beam was introduced into the vacuum chamber to intersect the hydrogen plume at a right angle. A photomultiplier, which was arranged in the direction perpendicular both to the cluster jet and to the incident laser beam, was used to amplify the scattered light from the hydrogen clusters. In the present experiments, Rayleigh scattered light signal S_{RS} scales with P_0 as $S_{RS} \propto P_0^{1.4}$. The average cluster size $\overline{N}_c$ also is a function of P_0, and varies as $\overline{N}_c \propto P_0^{0.4}$. Averagely there is about 250 hydrogen atoms within a cluster at the backing pressure of 1.0 MPa in this measurements.

6. The penetration depth of the CJ and SMB

There are two diagnostic methods used to reveal the penetration depth of the CJ and SMB: one of them is the tangential H_α detection array that shows the trace-ray of the injected particles and the other is dT_e/dt measured by ECE. The maximum point of dT_e/dt at the radial position corresponds to the center of the concentrating area for the injected particles. As for the GP particles of shot 4049, they can hardly penetrate into the plasma confinement region, the profile of dT_e/dt appears in flatten and the maximum point of dT_e/dt was at the outmost location in the plasma column as shown in *FIG. 6*. The penetration depth of CJI for shot 4413 with 80 K hydrogen is more than that of SMBI for 4512 with room temperature at the same backing pressure 1.8 MPa. The particles from PI of shot 4050 can deposite at the plasma center. The measurement precision is limited by the ECE scanning time of 4 ms.

FIG. 7 shows the distributions of intensities for the tangential H_α emission detected by the array for shot 4413 and shot 4512, respectively. The top point of the H_α profile versus radius corresponds to the area where the injecting particles mainly deposited at. If the particles concentrate in a very small area, then the distribution of the maximum value of H_α emission will be sharp and the measurement precision of the injection depth will be better. The typical example is the profile of shot 4413 in *FIG. 7*. In contract to that, the injecting effects for shot 4512 with room temperature gas, either the measurement precision or the injection depth, were not perfect, the injected particles may concentrate in such a large area, so as can hardly find a tip. A comparison of penetration depth for both of CJ and SMB under the similar discharge condition is listed in the TABLE 1.

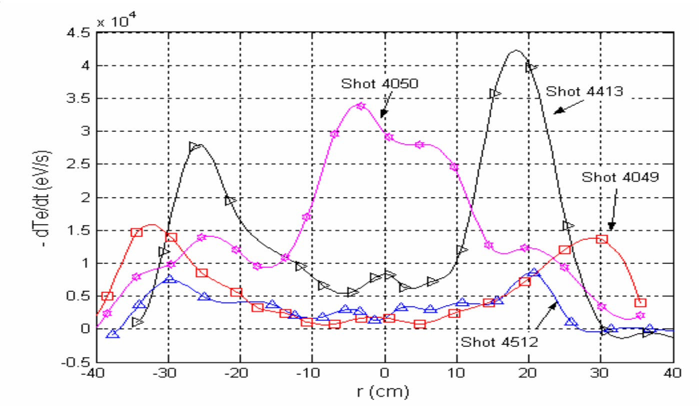

FIG. 6. Comparison of penetration depth for four different fuelling methods. PI: Shot 4050；CJI: Shot 4413, LN_2 temperature gas, 1.8 MPa; SMBI: Shot 4512, room temperature gas, 1.8 MPa; GP: Shot 4049, room temperature gas, 0.2 MPa.

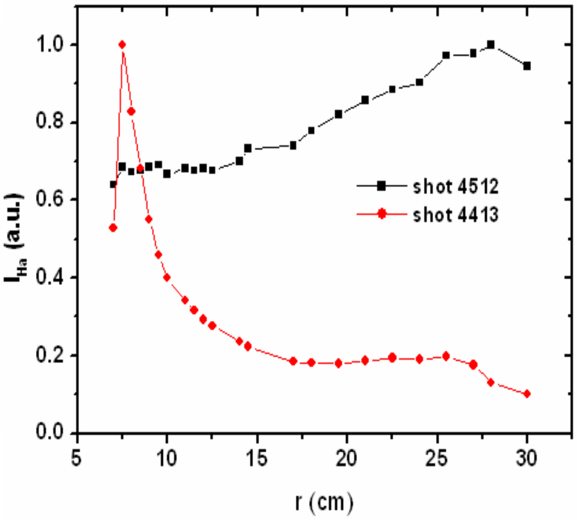

FIG. 7. Profiles of H_α emission measured by the tangential detector array for shot 4413 and 4512

TABLE 1: COMPARISON OF INJECTION DEPTH FOR CJ AND SMB

Diagnostics method	Shot 4413 (LN_2 temperature gas)	Shot 4512 (room temperature gas)
Tangential $H\alpha$ detector array	r = 6 cm	R = 26-28 cm
dTe/dt detected by ECE	r = 18 cm	R = 21 cm

7. The fuelling efficiency of cryogenically cooled gas cluster jet

In the present experiment, the fuelling efficiency for CJI is roughly about 60% under normal HL-2A wall condition, because it is strongly dependent on the plasma parameters and wall condition. A comparison of fuelling effect was shown in *FIGS. 8a and 8b* between CJI of shot 4413 with 80 K hydrogen and SMBI of shot 4512 with room temperature one under approximate discharge parameters. The backing pressure for the both shots was 1.8 MPa and two pulses for each shot. It is in evidence that the cluster jet fuelling effect is strongly dependent on the gas temperature, the density increment for shot 4413 with CJI is twice of that for shot 4512 with SMBI. Even if the velocity for the cluster jet is just one half of that for the beam, but the averaged size of the cluster was as large as hundreds atoms. Apparently, the size of cluster making a contribution to fuelling effect is more important than its velocity.

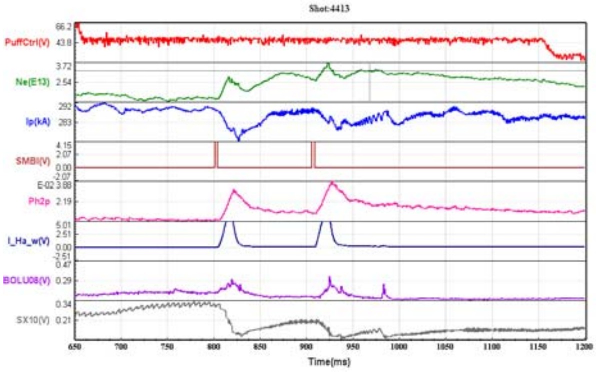

FIG. 8a. Cryogenically cooled gas CJI into HL-2A plasma with divertor configuration for shot 4413, the plasma density increases $2.2\times10^{19}m^{-3}$ from 1.52 to $3.72\times10^{19}m^{-3}$.

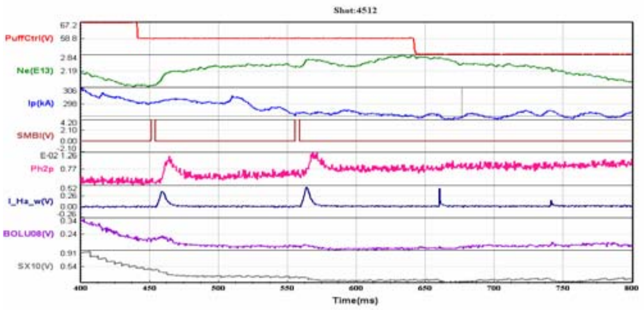

FIG. 8b. Room temperature gas SMBI into HL-2A plasma with divertor configuration for shot 4512, the plasma density increases $1.2\times10^{19}m^{-3}$ from 1.61 to $2.81\times10^{19}m^{-3}$.

8. Variation of ion temperature and radiation power during and after CJI or high pressure SMBI

As is shown in *FIG. 9,* the ion temperature sharply increases during the high-pressure SMBI of 4027 and the CJI of 4413 into the HL-2A plasma, and the plasma radiation power rapidly increases as well. The variations of ion temperature were resulted from a great deal increment of the counting rate of higher energy hydrogen atom at the range of 5 to 7 keV measured by the charge-exchange neutral particle analyzer. An receivable interpretation for this phenomena is due to the hydrogen particles or clusters deeply injecting into the high temperature confinement region of HL-2A and in which a great deal particles depositing in, and resulting in the yield of charge-exchange higher energy hydrogen atom strongly increased. Whereas the counting rate for the charge-exchange neutral particles are not linear increasing along the injecting path, that means the injecting clusters deposited slightly on the way.

In the high pressure gas injection experiments, it was found that the energy of the runaway electrons was limited almost independently of the used gas species [12]. The stopping powers for runaway electrons in hydrogen gas are shown in *FIG. 10* [13]. In such a massive injection, if the average injected neutral particle density $N_m \approx 2\times10^{17}$ atoms / m^3, it is about 0.01 order of magnitude of the average electron density of HL-2A, then the critical field for runaway $E_c = 0.094$ V / m. Normally the electric field E for ohmic discharge in the HL-2A

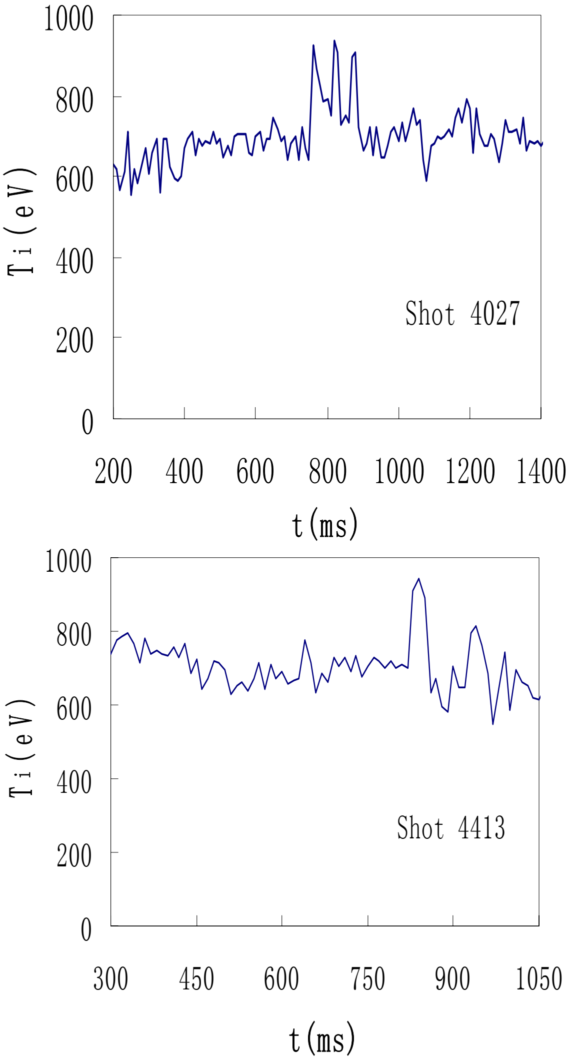

FIG. 9. Ion temperature sharply increases during the high-pressure SMBI of shot 4027 and CJI of shot 4413. Shot 4027: Gas pressure 3.0 MPa, three pulses. Shot 4413: Gas pressure 1.8 MPa, double jets.

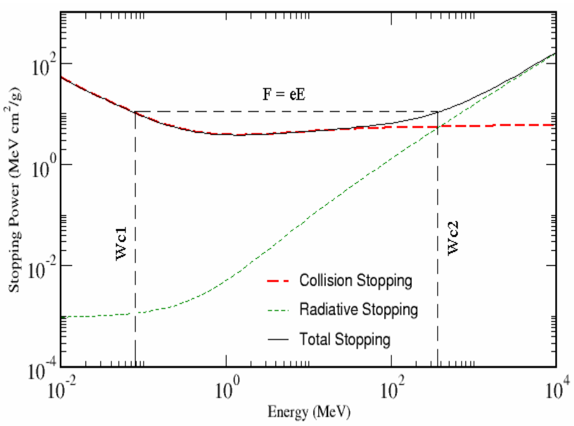

FIG. 10. Stopping powers for runaway electrons in hydrogen gas. The ohmic electric field driving force F = e E. W_{c1} in the collision dominated region and W_{c2} in the radiative dominated region. The electrons return journey between W_{c1} and W_{c2}.

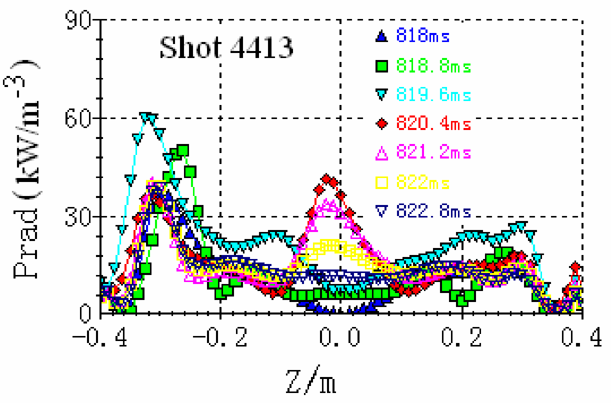

FIG. 11. Radiation behavior of CJI into HL-2A plasma at t = 800 ms, the peaking profile of radiation power appeared in asymmetry at z /a = ± 0.75 from t = 818.8 to 819.6 ms. Then the peaking returns to z = 0 and z /a = -0.75 at t = 821.2 ms.

torus is equal to 0.11 V / m. The ratio $E/Ec \sim 1$ and the radiation stopping power W_{c2} decreases greatly. The effect of the mass gas injection is that even already existing runaways are cooled down by the strong radiation as shown in *FIG. 11* and can not trigger the avalanche process. So this fuelling method not only reduce the energy of runaway electrons, but may become a tool to mitigate their effects during fast plasma shutdowns and disruptions.

9. Conclusion and discussion

The study of plasma behavior with room-temperature gas SMBI fuelling was carried out in the HL-2A experiments with the closed divertor. The fuelling characteristics of SMBI in HL-1M, such as enhancing the penetration depth and fuelling efficiency, reducing surface adsorption of the injected particles and the particle recycling, were reappearance in the HL-2A plasma. In addition, the heat load on the target plate surface is just 0.4 times of that before or after the beam injection, and the particle confinement time τ_p increased by two times

The hydrogen gas at room temperature can not form large cluster (say, more 100 atoms) by the adiabatic expansion even if the backing pressure is as high as 4 MPa or more. It has been confirmed that the hydrogen clusters produced at nitrogen temperature in the process of supersonic adiabatic expansion were measured by Rayleigh scattering. The pulsed MBI with large hydrogen clusters is a effective fuelling method for deeper injection. The diagnostics used for CJI experiments, including the tangential H_α emission detector array, the ECE measurement, the scanning microwave reflectometry and the charge-exchange neutral particle analyzer, gave coincident evidence that the injection particles do not uniformly deposited along the injecting path in the plasma and there is a terminal area where a great deal particles deposited at. The plasma behavior with pulse hydrogen CJI was somewhat similar to that of PI. The idea mentioned at previous work [14], " a supersonic molecular beam with clusters, which are like micro-pellets, will be of benefit for deeper fuelling." has being put into practice in HL-2A. Such a simple technology for producing hydrogen micro-pellets is a great high light for the new fuelling method. In addition, the effect of the CJI or the high pressure SMBI is that even already existing runaways are cooled down and can not trigger the avalanche process. So this fuelling method may become a tool to mitigate their effects during fast plasma shutdowns and disruptions.

Acknowledgments

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