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1 Tokamak Experimental Diagnoses and Tokamak Engineering

1.1 Plasma Behavior with Molecular Beam Injection in the HL-1M Tokamak①②

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A new method of gas fueling has been introduced in the HL-1M Tokamak. The method consists of a pulsed high speed molecular beam formed by a Laval-type nozzle. The velocity of well collimated hydrogen beam is about 500 m · s^{-1}. About 6×10^{19} molecules pass through the nozzle and into the vacuum chamber in each pulse. A series of helium pulses was injected into the HL-1M low density ($\bar{n}_e=4\times10^{18}$ m^{-3}) hydrogen plasma. With penetration depth up to 12 cm, the ramp-up rate of electron density d$\bar{n}_e$/dt was as high as 3.1×10^{20} m^{-3} · s^{-1} at steady state and the resulting plasma density reached $\bar{n}_e=5.6\times10^{19}$ m^{-3}. The profile peaking factor of electron density, $Q_n=n_e(0)/\langle n_e\rangle$, of about 100 ms after helium molecular beam injection (MBI) reached a maximum value of more than 1.51. The energy confinement time τ_E measured by diamagnetism is 26 ms which is over 30 % longer than that of gas puffing (GP) results under the same operation conditions. The improvement of τ_E and increase of Q_n for MBI were comparable to those of small pellet injection (PI) in HL-1M, as well as those of slow PI in ASDEX [Kaufmann M et al. Nucl. Fusion 28 (1988) 827]. It is argued that the peaked density profile induced by

① Supported by the Nuclear Industry Science Foundation of China (94C03033) and the National Nature Science Foundation of China (19775011)

② Entire article was published in Nuclear Fusion, Vol. 38, No. 4 (1998) 631 the deepened particle injection is a factor essential for the confinement improvement apart from the isotope effect of helium particles, because the density peaking factor Q_n is normally less than 1.4 for GP plasma in HL-1M. The particle confinement time with MBI increased sixfold in comparison with that before injection.

1 Supersonic molecular beam

The molecular beam source is a small chamber in which the working gas can be kept at a definite pressure and temperature. Stream of particles from a Laval-type nozzle can pass through a skimmer orifice permitting the passage to the vacuum chamber only those molecules which form the core of the beam. This core consists of atoms or molecules flying with adequate velocities in adequate directions while the rest of the beam is deflected and pumped off by high speed pumps.

Pulsed molecular beams have high instantaneous intensity, high speed, small spread of velocity and small angular distribution, and low gas consumption. Gas pulses of tens to hundreds of milliseconds are commonly used in this work to control the edge recycling and to satisfy the general requirements of HL-1M gas fueling.

The quantity of gas passing through the nozzle is calculated from the equation

$$j=\left[\frac{\gamma R T_0}{\mu}\right]^{1/2}\left[\frac{2}{\gamma+1}\right]^{\frac{\gamma+1}{2(\gamma-1)}} n_0 A \quad (1)$$

(particles/s)

where $\gamma=\frac{c_p}{c_v}$ is the heat capacity ratio ($\gamma=\frac{5}{3}$ for a monoatomic and $\gamma=1.4$ for a diatomic gas), R is the molar gas constant, 8314 J/kmol · K, T_0 is the temperature in Kelvin in gas source, μ is molecule (atom) mass in kg, n_0 is the gas particle number (number of atoms) per cubic meter in the gas source, A is the cross-section at critical diameter of the nozzle.

2 Penetration depth of MBI and density Peaking

The penetration depth of MBI into the plasma depends mainly on the electron density and temperature of the target plasma. Beam quality parameters include beam velocity and angular distribution, especially the flux density of the beam stream. In order to distinguish the injected particles from the particles of target plasma and to reduce particles entrapped in the graphite limiters and protective barriers, a helium molecular beam was injected into the HL-1M Tokamak with low density ($\bar{n}_e = 4\times10^{18}$ m^{-3}) target hydrogen plasma. The helium particle penetration of up to 12 cm was observed with a PIN diode (He I 587.6 nm) detector array and treated by Abel transformation.

A single- and six-channel HCN laser interferometers were used to measure, respectively, the line-averaged electron density and density profile of the HL-1M plasma. The peaked-density profiles were the result of MBI fueling and recycling control at the edge plasma. Hydrogen recycling was decreased by degassing procedures employing siliconization and pure helium glow discharge cleaning that removed hydrogen entrapped in the graphite limiters. The line-averaged electron density of the target plasma prior to the MBI was found to be correlated with both the enhancement of the energy confinement time and the ratio of $n_e(0)/\langle n_e\rangle$ during injection. When the target density was increased during injection, the density profile broadened and the energy confinement time decreased. Sometimes plasma current disruption may occur due to the strong injection resulting in channel pinching with the subsequent MHD instability. In order to reduce the injected gas reabsorption in the first wall, helium was selected as the working gas for pulsed molecular beam. Normally, helium MBI fueling was carried out at low target density of hydrogen plasma. For example, in shot 4116, $\bar{n}_e = 4\times10^{18}\,m^{-3}$, the ramp-up of line-averaged electron density $d\,\bar{n}_e/dt$ is as high as $3.1\times10^{20}\,m^{-3}\cdot s^{-1}$ during injection, and the resulting plasma density after 100 ms injection reaches $\bar{n}_e = 5.6\times10^{19}\,m^{-3}$.

Density profile peaking is one of the most important features of the present fueling method. The He beam pulses start from $t = 150$ ms to 250 ms in which the peaking factor of density profile $Q_n = n_e(0)/\langle n_e\rangle$ reaches 1.51.

3 Confinement improvement with MBI

In the experiment on HL-1M, for GP fueling hydrogen plasma, the energy confinement time τ_E as measured by diamagnetism increases linearly with the density below $\bar{n}_e = 2\times10^{19}\,m^{-3}$. When the density is further increased, τ_E increases slowly with the density. When the working gas is a mixture of H_2 and He, the critical density increases to $2.5\times10^{19}\,m^{-3}$, beyond which τ_E increases continuously but further enhancement is rather slow. In the experiment of MBI fueling with helium into hydrogen plasma, τ_E increases with increasing plasma density till $n_e = 6\times10^{19}\,m^{-3}$. This result is over 30% Larger than that of previous GP results in the density range of $(3.5\sim6)\times10^{19}\,m^{-3}$, The plasma behavior with He MBI into hydrogen plasma is in shot (4116). The energy confinement time τ_E of the HL-1M small pellet injection plasma enhances by about 30% in comparison with that of GP plasma in the density range of $(1\sim3)\times10^{19}\,m^{-3}$. The ranges of the discharge parameters for the τ_E study are: $B_t = 1.9\sim2.3$ T, $q_{95} = 5\sim7$, $I_p = 100\sim120$ kA.

It is interesting to compare the present results with the slow pellet (velocity 200 $m\cdot s^{-1}$) injection in ASDEX. With ohmically heated deuterium plasma of starting density $\bar{n}_e = 1.3\times10^{19}\,m^{-3}$, penteration depth of up to 7 cm was observed. The relative density profile peaks afterwards, reaching a value of $n_e(0)/\bar{n}_e$ about 10% higher than before. During this nonstationary phase of injection the energy confinement time τ_E rose, continuously starting from 60 ms to a value of around 100 ms and was clearly above the standard GP values in the linear part of the

Table 1 Comparison of the effects of two fueling methods

Fueling method	Working gas	Mean velocity /m · s^{-1}	Target density /10^{19}m^{-3}	$\Delta\left[\frac{n_e(0)}{\langle n_e\rangle}\right]$	$\Delta\tau_E$	Mode
MBI	$He+H_2$	350	1.0	≥10%	>30%	Stationary
Slow pellets	D_2	200	1.3	≈10%①	~50%②	Transient

① It is the value of $n_e(0)/\bar{n}_e$

② Non-stationary phase

$\tau_E(\bar{n}_e)$ curve. Except for particle velocities, the experimental results of the MBI fueling in this paper are quite similar to those of the slow pellet fueling in ASDEX. A comparison of the effects for the two fueling methods is listed on Table 1.

The particle confinement time τ_p is obtained by measuring the outgoing particle flux with edge Langmuir probes. The enhancement of τ_p with MBI is pronounced. For instance, the ratio of τ_p before and after MBI fueling is 1 : 6 in shot 4116. The corresponding value for strong GP fueling is 1 : 3 (shot 4160) under similar conditions of discharge.

5 Conclusion and discussion

We report an effect of the new fueling method of high speed molecular beam injection on Tokamak confinement improvement. The present method is an improvement of conventional GP, with performance comparable to the small pellet injection in HL-1M and also to the slow pellet in ASDEX.

It has been noticed for a long time that central fueling, such as pellet injection and high energy neutral beam injection, can improve the confinement of Tokamak plasmas relative to ordinary gas puffing. This improvement is usually attributed to the density peaking which tends to stabilize the so-called η_i mode. As mentioned above, a similar confinement improvement is observed both in our "very low energy neutral beam injection" (MBI) experiments and in the slow pellet injection experiments in ASDEX. As contrasted with central fueling, these experiments are characterized by a hollow fueling with the position of maximum deposition near the plasma edge. The fact that a shallower fueling can lead to a similar confinement improvement as a deep one suggests that there may exist a critical position in a Tokamak plasma such that any kind of fueling will have a better confinement as long as it can give rise to density peaking at the critical position. This point of view could be supported by QU's theoretical study where, based mainly upon the electron temperature profile consistency, a critical position $\rho_c=r/a\approx0.7$ is argued to exist and it is shown that the global confinement property, at least for the electron, is basically determined by the local anomalous thermal conduction at this critical point.

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1.2 Improvement of Plasma Performance with Wall Conditioning in the HL-1M Tokamak[①]

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Key words Plasma performance Plasma-facing materials Wall conditioning

Studies and selection of plasma-facing materials continue to be a concern for future fusion devices, and ongoing efforts are being made in the HL-1M Tokamak. The advanced methods of wall modification adop ted by HL-1M are surveyed. Significant improvements in Tokamak plasma performance have been obtained by using boron, silicon or lithium-containing substance as a material for wall coatings. The siliconization technique is highlighted. The lithiumization as the newest technique will be investigated further.

The new type of wall conditioning is called PCVD, i. e. plasma chemical vapour deposition that was proposed firstly by Veprek et al. for regeneration of the first wall in fusion devices in 1976. In situ coating of the first wall to modify the wall condition is a simple, economic and efficient method. The pioneering work in area of wall conditioning at the TEXTOR Tokamak has been recognized and developed further now. Winter gave a detailed description and outlook in his review paper. This article gives an overview of experimental methods and results in HL-1M. The modification of the wall and improvement of plasma performance are summarized as follows.

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