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Particle confinement and density profile behaviour on HL-1M*

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In this paper the density profile behaviour and the particle confinement operation regime on HL-1M have been studied under the pellet injection (PI), supersonic molecular beam injection (SMBI), gas puffing (GP) and lower hybrid current drive experimental situations. The relationships between density profile, particle confinement time and edge safe factor have been explored. The density profile, which is measured by six-channel far-infrared ray laser interferometer has been analysed by using the peaking coefficient calculation code. Changes of the outward and inward diffusion velocities before and after the peaking of the central density profile have been calculated using the global particle balance equations. The particle confinement operation regimes have been discussed. The peaking density profile can be easily obtained under the condition of efficient fuelling. In ohmic discharges, confinement time increases as the peaking density profile factor rises, and is saturated at a critical value related to the fuelling efficiency. The particle confinement time of SMBI lies between the values of GP and PI, and its value is about 3–5 times of the energy confinement time.

Keywords: particle confinement, density profile, fuelling method
PACC: 5240, 5255G, 3640

1. Introduction

Several high performance tokamak operation regimes have been achieved experimentally in the experiments with peaking density profiles. The regimes include the improved ohmic confinement in ASDEX,[1] the pellet-enhanced performance mode in Alcator-C,[2] and the super-shot mode in TFTR.[3] In these regimes, peaked core density profiles are always present, and almost always go with the internal transport barriers that are generally produced by sheared radial electric field. In addition to the enhanced confinement, the peaked density profile is also needed for studying the optimized fusion reaction rate and alpha heating power in tokamak plasma, and the combined peaked density profile and peaked temperature profile would make the ignition condition obtained easily. It is desirable to seek and analyse the control schemes of density profile that effectively lead to density profile peaking in experimental investigation of particle transports.

Larger devices seem to have more pronounced L-mode characteristics that are obtained already under the ohmic discharge conditions. However, there is no good database for density profiles in small devices. In this paper, we shall study HL-1M device density profile under different discharge conditions and discuss the relationship between the peaking factor $n_e(0)/\langle n_e\rangle$ and particle confinement time.

2. Experimental setup

HL-1M is a tokamak of circular cross section[4] with major radius R=1.02m, minor radius a=0.26m, toroidal field $B_t < 3$T, plasma current I_p <350kA, electron density $\bar{n}_e=(1\text{–}8)\times10^{19}\text{m}^{-3}$, electron temperature $T_e(0)=(0.5\text{–}1.2)$keV and pulse duration about 1sec for normal plasma operations. The electron density was measured by vertical six-channel HCN interferometer.[5] The positions of the six channels are –6, 0, +3, +7, +11 and +15 cm along the radial direction respectively; the negative value denotes the location on the high field side and the positive value on the low field side. The H_α radiation along the central chord is observed at different positions by 8

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PIN diodes. A set of edge electrical probes is installed for the measurement of the edge electron temperature T_e and density n_e. The density profile comes from the asymmetry Abel inversion[6] with the far-infrared (FIR) interferometer experimental database. The density peaking factor Q is defined as $Q = \frac{n_e(0)}{\langle n_e \rangle}$, where, $n_e(0)$ is the central electron density, and $\langle n_e \rangle$ is the volume averaged electron density. The particle confinement time can be calculated by Staib's model[7]

$$\tau_p = \frac{\langle n_e \rangle}{n_e(a_0)} \frac{2\pi^2 a_0^2}{q_a l_M} \frac{eB_T}{3kT_e(a_0)}, \qquad (1)$$

where $\langle n_e \rangle$, $n_e(a_0)$, $T_e(a_0)$, l_M, q_a are the volume-averaged density, edge density, edge temperature, maximum rotational transform allowed by the geometry, and the q values at the boundary respectively.

3. Experimental results

Efforts have been made to understand the mechanism for various fuelling method, and the purpose is to obtain the enhanced confinement. General fuelling methods are gas puffing (GP), pellet injection (PI) and supersonic molecular beam injection (SMBI), which have different fuelling characteristics.

3.1. The density profile in pellet injection

Pellet injection can effectively produce peak electron density profile. In HL-1M experiments, the volume of the pellet is about ϕ1mm×1mm, and the jet speed is between 400 and 600m/s. The plasma current in the PI experiments ranges from 100 to 200kA, and the injecting pellet can reach the plasma central region. By the pellet injection the energy confinement time can increase 30% while the background line average density is$1.5 \times 10^{19}\mathrm{m}^{-3}$. When the background density is within $(0.2 - 0.3) \times 10^{19}\mathrm{m}^{-3}$, double-pellet injection enables the electron density to increase up to $2.5 \times 10^{19}\mathrm{m}^{-3}$ continuously, and the peaking of the density profile leads to increase plasma energy confinement time by three times. Figure 1 shows the evolution of the density profiles before and after the pellet injection. The peaking factor reaches 1.6–1.8, and persists in about 30ms. The density peaking profile can be formed at 10–40ms after the pellet injection, and holds a long time in this new peaking profile situation. As the central energy radiation increases, the electron temperature of the plasma decreases, but the temperature profile has no change. This result is very similar to the report of Ref.[8].

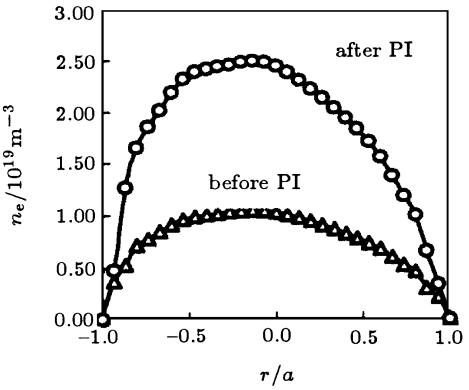


Fig.1. The density profiles just before and after pellet injection.

In order to understand the relationship between the particle confinement behaviour and the peaking density profile, the changes of the outward diffusion velocity and inward pinch velocity before and after the peaking of the central density profile have been calculated by global particle balance equations.

Assume the particle flux consists of two separate effects: a diffusive term due to the density gradient and a convective term characterized by pinch velocity, thus the radial electron particle flux can be given by

$$\Gamma_e = -D\nabla n_e + n_e V_p. \qquad (2)$$

Here D is the particle diffusion coefficient and V_p is the particle pinch velocity.

After the pellet injection and when the discharge reaches its steady state, $\Gamma_e = 0$, we have

$$V_p/D = \frac{\nabla n_e}{n_e}. \qquad (3)$$

The increase of the ratio V_p/D in HL-1M experiment after pellet injection is illustrated in Fig.2, with considering the quasi-stationary profile of n_e and the value V_p/D in the source-free region. Comparisons of n_e profiles and the ratios of V_p/D at the beginning (in the gas-puffing phase) with the end of the injection for a series of pellets , show that in the region of minor radii $r < 22.75$ cm, the ratio of V_p/D increases by a factor of 2, and clearly corresponds to the peaking profile $n_e(r)$. The increment of V_p/D is possibly caused mainly by the decrease of D through the density profile change induced by the pellet injection.[9]

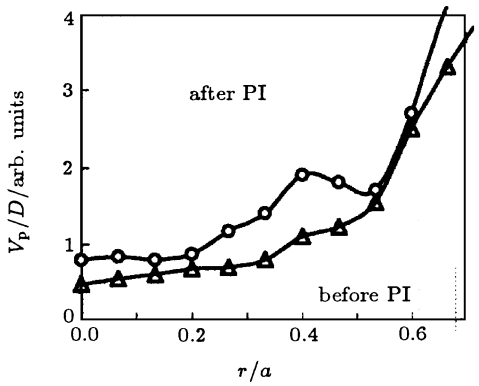


Fig.2. The behaviour of V_p/D before and after pellet injection.

3.2. The density behaviour in SMI discharges

As a new gas fuelling method, the SMBI has been developed in HL-1M tokamak.[10] The SMBI efficiency lies between GP and PI. A small volume of gas at a high pressure expands through a Laval nozzle into the plasma chamber within 1–2 ms. The high instantaneous intensity, high speed, small spread of velocity with a narrow angular distribution, and low operation cost are the advantages of SMBI, which can be considered an improvement over GP and can be compared to the method of slow PI using small pellets in HL-1M.

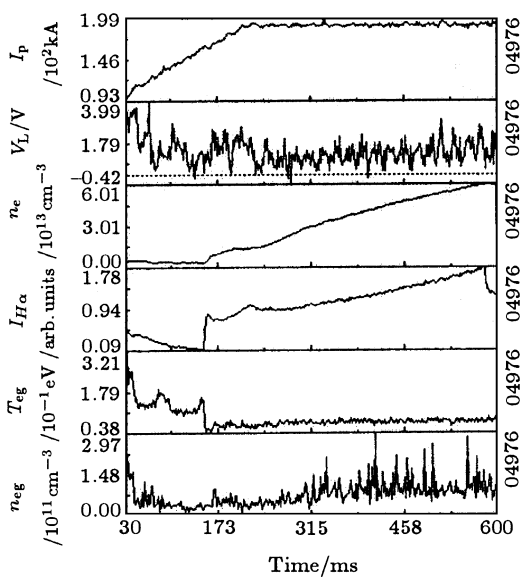


Fig.3. Typical discharge waveform of SMBI.

The typical discharge waveform of SMBI on HL-1M is shown in Fig.3. I_p is plasma current, V_L is loop voltage, $I_{H\alpha}$ is the H_α signal near the SMBI port, n_e is the average line density, T_{eg} and n_{eg} are edge temperature and density respectively. In 20ms after the SMBI is applied, the central density rises, while the edge density keeps unchanged, and H_α and edge temperature decrease. Particle confinement time increases from 16 to 58ms. Density peaking factor increases from 1.4 to 1.8. Therefore, particle confinement is improved accompanying the peaking of density.

One of the reliable mechanism for improving the confinement by SMBI may be caused by the rapid decay of the plasma temperature in the plasma edge. The experiments indicate that there is a cold injection passage in the injection port and nearby region during SMB pulse.[11] Plasma pressure is transferred intensively in this region, and induces changes of the radial electric field, which also induces a sheared field, and thus produces enhanced confinement.

3.3. Improvement of density profile and particle confinement in lower hybrid current drive plasma

A series of experiments have been developed in HL-1M for improving confinement. It contains plasma parameter profile control, and magnetohydrodynamic disturbance restraint.[4]

The improvement of the lower hybrid wave (LHW) on plasma density has been studied under the condition of 2.45GHz, LHW power $P < 850$kW. Experiments show a density increase, which in lower hybrid current drive (LHCD) phase is only in the lower background plasma density ($\bar{n}_e \leq 1.4 \times 10^{19}$m^{-3}) regime. The lower background density corresponds to a large density increment, this increment can reach 10%–14% in the experiments. Generally, core plasma density upswing always accompanies, with H_α and edge density decreasing, so that the particle confinement time increases. During the LHW pulse, the density peaking factor Q decreases, the value of which is lower than 1.4, and meanwhile the density profile broadens and becomes symmetric.

3.4. Density peaking factor in different operation regimes

The density profile peaking factors under different confinement conditions in HL-1M are shown in Fig.4. The density peaking factor Q is evidently dependent on the edge safety factor in GP ohmic discharges. Although it is not good for fusion reaction, the high Q density discharge is easily obtained in low current and small discharge channel. Along with the increase of fuelling efficiency, the relationship between Q and q_a becomes less obvious. The density peaking factor in

SMBI lies between the values of PI and GP under the same conditions as for other discharge. It is shown that the confinement performance of SMBI is better than that of GP. The experimental results in LHW discharge are also shown in Fig.4. In these cases, the Q is independent of q_a, the relationship between n_e profile and q_a in SMBI and PI is not suitable for LHW discharge.

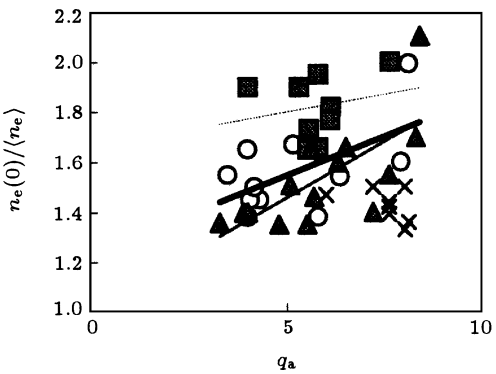


Fig.4. Relation between density peaking factor and q on HL-1M tokamak. Triangle is for GP discharge, circle for SMBI discharge, square for PI and cross for LHW discharge.

Comparisons of τ_p with Q in the three fuelling methods are shown in Fig.5. The ranges of the discharge parameters are I_p=110–190kA and B_t=2–2.3T. The results show that the τ_p increases with Q linearly, and $\tau_{pGP} < \tau_{PSMBI} < \tau_{pPI}$. These results are consistent with the metrical results of energy confinement time.[10] The particle confinement time is about 3–5 times of its energy confinement time on HL-1M. There are no saturation on Q-τ_p curves in the parameter regime of our experiment.

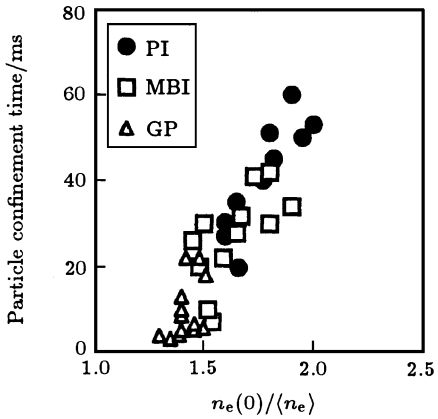


Fig.5. Dependence of particle confinement time on density peaking factor.

4. Conclusion

Different plasma density profiles can be obtained under different fuelling methods. The peaking density profile can be easily obtained under the condition of efficient fuelling method. In ohmic discharge, particle confinement depends on the density profile, and confinement time increases with the peaking density profile, hence the peaking factor can be used as a parameter to denote the particle confinement level. In PI improved confinement experiments, we find that the density profiles change from flat to peak are relative to the changes of the particle diffusions, the improved confinement comes from the decrease of the outward particles. A set of probes at the plasma edge gives the change of the direction and the value of the radial electron field during the discharge. It is noted that there is a flow sheath in the edge region, in which the outward going of plasma particles is avoided; and this is one of the reason for the improved confinement in SMBI plasmas.

References

[1] Soldner F X *et al* 1998 *Phys. Rev. Lett.* **61** 1105
[2] Greenwald M J *et al* 1984 *Phys. Rev. Lett.* **53** 352
[3] Hawryluk R J *et al* 1986 *Plasma Phys. Control. Nucl. Fusion Res.* **1** 51
[4] Wang E Y 1996 *16th IAEA Fusion Energy Conference* (Oct. 7–11 1996 Montreal, Canada) CN-64/AT1–14
[5] Deng Z C *et al* 1997 *Fusion Engin. Design* **34-35** 403
[6] Zhou Y *et al* 2000 *J. Plasma Fusion Res. Ser.* **3** 158
[7] Yan L W *et al* 2001 12th *ITC on Plasma Physics and Controlled Nuclear Fusion* (Dec. 11–14 2001 Toki City, Japan)
[8] Wagner F and Stroth U 1993 *Plasma Phys. Control. Fusion* **35** 1321
[9] Kaufmann M *et al* 1988 *Plasma Phys. Control. Nucl. Fusion Res.* **1** 229
[10] Yao L H *et al* 2001 *Nucl. Fusion* **41** 817
[11] Jiao Y M *et al* 2003 *Plasma Phys. Control. Fusion* **45** 2001