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Experimental Study of Perturbative Particle Transport in the HL-2A Tokamak

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Abstract: *Perturbative transport experiment was performed in the HL-2A tokamak. Plasma current and background density were fixed at 170kA and 1.4×1019m-3, while neutral beam injection (NBI) heating power varied from 400kW to 1MW. Plasma density was modulated by supersonic molecular beam injection (SMBI). Density profile and fluctuation were measured with a fast sweeping Q-band frequency modulated continuous wave (FMCW) reflectometer with the temporal resolution as high as 6μs, which covered a normalized radius range of ρ=0.75~1. Spatiotemporal behaviors of radial profiles of density and density gradient were observed. Particle diffusivity and pinch velocity were evaluated by fitting the phase and amplitude profile of density perturbation. In order to confirm whether the particle transport in HL-2A is diffusive, the relations between particle flux and density gradient were also studied.*

Keywords: Tokamak; plasma; particle transport; SMBI

1. Introduction

Particle transport is one of the key issues in Tokamak plasma physics. Understanding its mechanism is important for improving plasma confinement and fueling efficiency in future fusion reactors [1]. However, compared with heat transport and momentum transport, particle transport is more difficult to study, because diffusion and convection usually are coupled in particle transport.

Recently, perturbative method has been proved to be one of the most effective ways to study particle transport in plasma, and some progress on transport barriers and transport mechanism have been achieved with perturbative method [2,3], but many questions still remain unsolved.

In Tokamak, usually particle transport is considered to be non-diffusive because it is dominated by turbulence [4]. To confirm the diffusivity of particle transport, perturbative particle transport experiment has been conducted in HL-2A Tokamak with SMBI, and microwave reflectometer is used as the main diagnostic system to study particle transport.

2. Experimental setup

Perturbative particle transport experiment is conducted in the HL-2A Tokamak. The parameters in the present experiment are as follows: major radius R=1.65m, minor radius a=0.4m, magnetic field B_0=1.35T, plasma current I_p=170kA and background electron density n_e= 1.4×10^{19}m^{-3}.

Fig.1 shows the temporal evolution of these parameters of a typical discharge, where the electron temperature is measured by electron cyclotron emission radiometer and line average density measured by far infrared rays (FIR) laser interferometer. The discharge lasts for about 1900ms and keeps stable from 200ms to 1700ms. 400kW neutral beam injection (NBI) heating is injected at 500ms, and lasts for about 500ms, during which the stored energy is obviously increased. In this experiment, Supersonic molecular beam injection (SMBI) is used as the perturbative source, as it has the advantage of deep penetration and high fueling efficiency [5]. SMBI modulation is added during 500ms and 1000ms to periodically disturb electron density. The modulation frequency of SMBI is 16.67Hz, and pulse width is 2ms. As shown in Fig.1, the line average density is obviously modulated by SMBI.

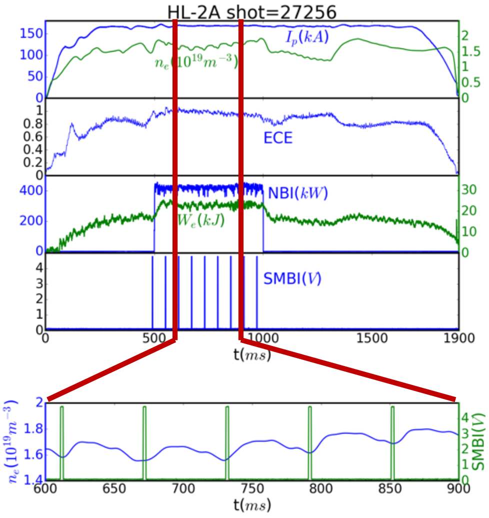

Fig. 1. parameters of perturbative particle transport experiment

3. Experimental results

To study perturbative particle transport, a high temporal resolution microwave reflectometer is developed to measure the density profile and perturbation evolution. The temporal resolution is up to 6us by optimizing system matching. Besides, dynamic calibration method of VCO is developed, and dispersion of the transmission system is taken into account to reduce measurement error. Fig.2(a) is the experimental beat frequency extracted from the spectrogram in a sweeping period, which is mostly credible except for some frequency jump points. After correcting frequency jumps, the radial density profiles and evolution of density perturbation are reconstructed, which are shown in Fig.2(b) and Fig.2(c).

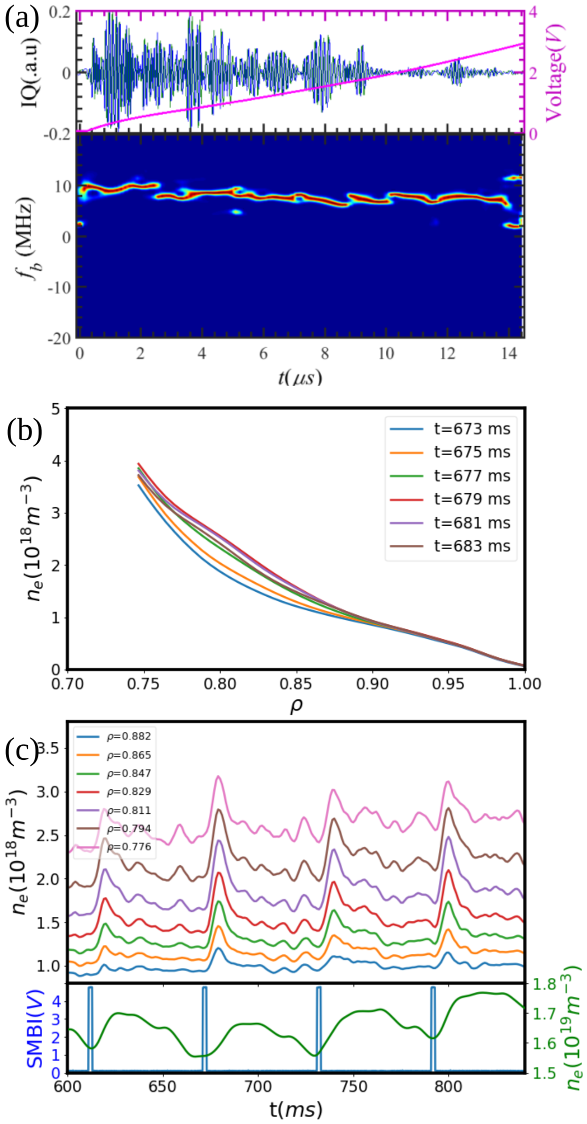

Fig. 2. experimental signal and reconstructed density profile measured by microwave reflectometer

It is clearly shown that after SMBI, a strong perturbation is introduced to the density, and the density is modulated at different radii. Therefore, FFT (fast Fourier Transformation) analysis is one of the best ways to analyze modulated perturbation.

Fig.3 shows the FFT result of the density perturbation at normalized radius 0.81. Fig.3(a) is the spectrum of density perturbation, and high harmonics as well as first harmonic are observed. According to the spectrum, the amplitude and phase of the perturbation are obtained. By doing FFT analysis to all the perturbation at different radii, the profiles of amplitude and phase are obtained, as Fig.3(b) shows.

Table 1. Values of D and V for different zones.

	Zone I 0.776 < ρ < 0.804	Zone II 0.804 < ρ < 0.84	Zone III 0.784 < ρ < 0.9
D (m^2/s)	0.2	0.7	0.11
V (m/s)	10	-22	-6

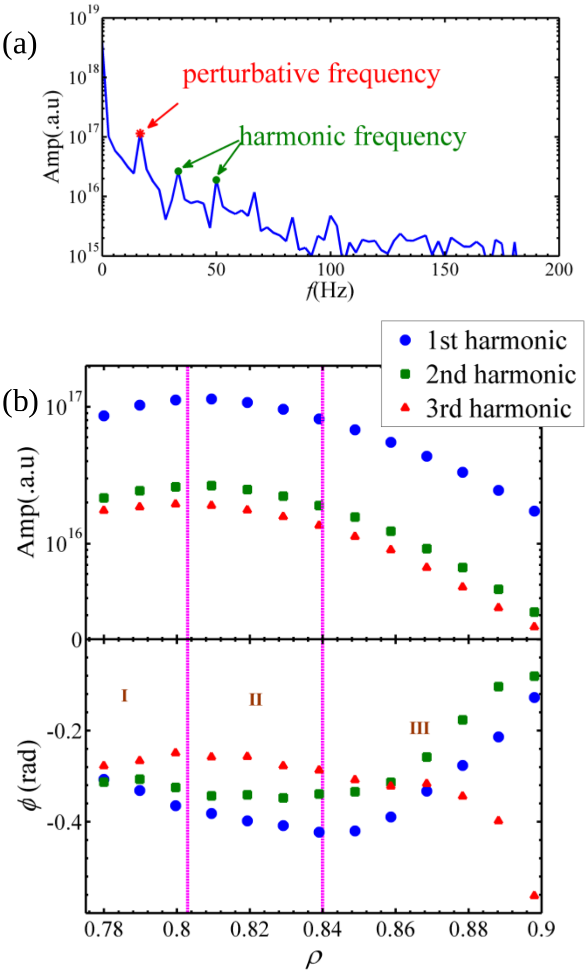

Fig. 3. FFT analysis for density perturbation. (a) spectrum of density perturbation. (b) amplitude and phase profiles of density perturbation

According to the peak of amplitude and the bottom of phase, the whole region is divided into three regions, and transport coefficients are estimated by fitting the profiles with simulation [6], which are shown in Table 1.

4. Discuss

FFT analysis is based on the diffusive transport model. To confirm the diffusivity of transport, it is necessary to analyze the density evolution after SMBI injection. The density contours and gradient contours after SMBI at 671ms are shown in Fig.4(a) and Fig.4(b) respectively. Fig.4(a) clearly shows that the edge density keeps increasing after SMBI and reaches the maximum at 679ms, which is regarded as the source phase. After 679ms the density starts to decreases, which indicates the particle transport process is source-free.

During the source-free transport process, it is clear that there are three different phase. Firstly, from 679ms to 685ms, the edge density starts to decrease, while the line average density still keeps increasing. This indicates that the center density as well as line average density are increasing, and there is a strong inward particle flux during this phase. It should be noted that during this phase, the density gradient at the edge almost keeps the constant, which indicates that the inward flux may be driven by pinch. Next from 685ms to 700ms, the line average density stops increasing and keeps almost the constant. At the same time the edge density decreases slowly and continuously, and density gradient is relaxed. After 700ms the transport reaches the third phase, while the line average density starts to decrease, and the edge density shows some intermittent decays. To conclude, the transport induced by SMBI is mixed by different mechanisms.

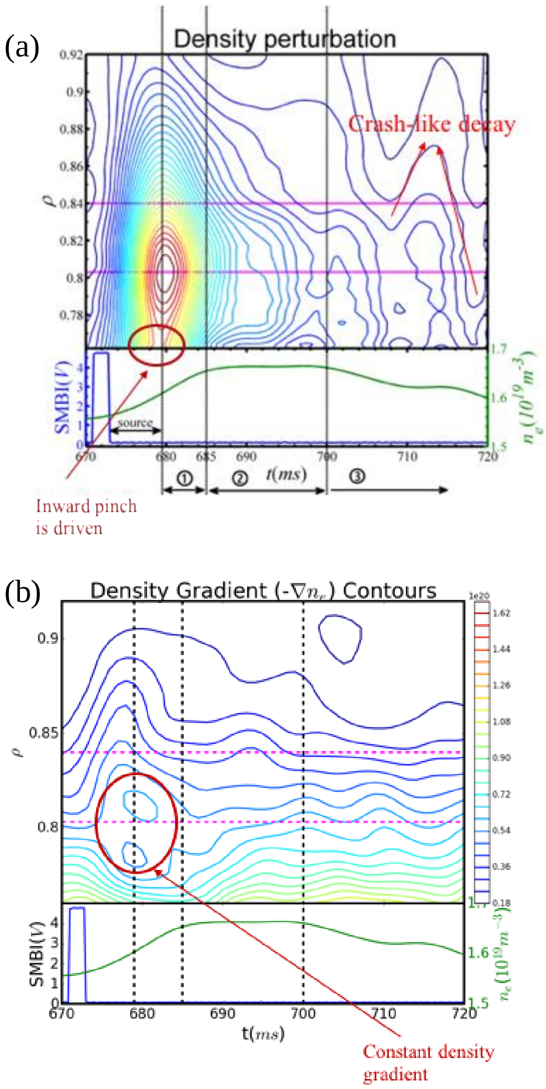

Fig. 4. contours of density perturbation and gradient

The transport process can be shown more obviously from the flux-gradient relationship. The flux is obtained by integrating the variation of density:

$$\Gamma = \int_0^a -\frac{\partial n_e}{\partial t} dV$$

Because of the limited waveband, the reflectometer can only cover part of the radial density profile. Therefore, to estimate particle flux, the radial profile is divided into three parts: the edge part, the inner part, and the core part:

$$\Gamma = \int_0^{r_{core}} -\frac{\partial n_e}{\partial t} dV + \int_{r_{core}}^{r_1} -\frac{\partial n_e}{\partial t} dV + \int_{r_1}^{a} -\frac{\partial n_e}{\partial t} dV$$

In the core region, density is hardly affected by edge fueling, thus flux from core region is neglected. According to the measured density at the edge, the density at inner region changes little during SMBI, thus the integration is regarded as 0. Therefore, the flux is simplified as following:

$$\Gamma = \int_{r_1}^{a} -\frac{\partial n_e}{\partial t} dV$$

The flux is calculated according to the formula above, and the dependence of flux and gradient at different radial positions is given in Fig.5. It is clearly shown that the transport after SMBI is a complex process. From 679ms to 685ms, the outward flux increases abruptly, while the density gradient almost keeps the constant. Then from 685ms to 695ms, the flux and gradient is relaxed slowly. It is noted that according to the flux-gradient relationship, the transport seems to be diffusive during this phase. Lastly, after 695ms, there is an intermittent edge decay phase.

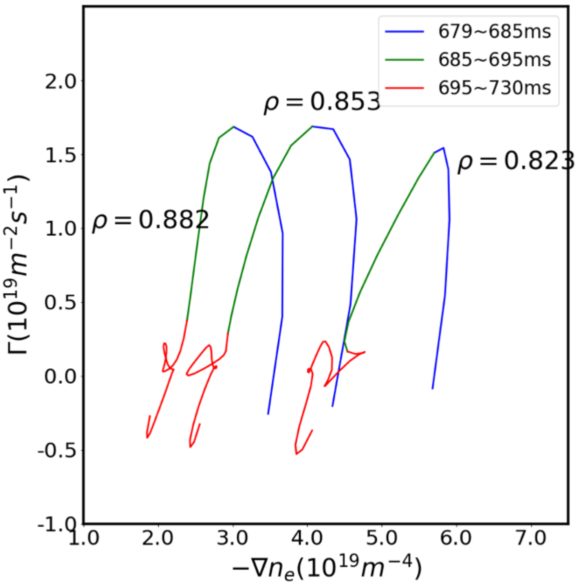

Fig. 5. flux—gradient dependence

5. Conclusion

Perturbative transport by SMBI is a complex process, which undergoes three different phases. The first phase is inward flux phase shortly after SMBI injection. During this phase, the edge density starts to decrease, keeping the density gradient constant. At the same time, a strong inward particle flux is driven, resulting to the increase of core density. The second phase is edge relaxing phase. The core density stops increasing and keeps constant, while edge density still decreases. The edge density gradient decreases linearly along with flux. The third phase is intermittent decay phase. The core density starts, and some intermittent structures break out at the edge. Among the three phases, only the second phase is diffusive, which means FFT analysis is insufficient for perturbative particle transport study.

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