Particle Transport Investigation in HL-2A Using ECRH and SMBI

X.L. Zou[a], W.W. Xiao, S.D. Song[a], X.T. Ding, J. Rao, J. Zhou, M. Huang, L.C. Li, D.L. Yu, L.H. Yao, B.B. Feng, C.Y. Chen, X.M. Song, Y. Zhou, Z.T. Liu, H.J. Sun, Z.B. Shi, Y.G. Li, X.Q. Ji, Yi Liu, L.W. Yan, Q.W. Yang, J.Q. Dong, X.R. Duan, Yong Liu and HL-2A Team

Southwestern Institute of Physics, P.O. Box 432, Chengdu, China

a) CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

e-mail contact of main authors: xiao-lan.zou@cea.fr, xiaoww@swip.ac.cn

Abstract: Experiments have been performed in HL-2A with ECRH and SMBI for particle transport investigation. The ECRH driven density pump-out phenomenon (negative density perturbation) in the central region has been observed, and also a positive density perturbation in the peripheral region. The edge density increases is due to the out-gassing caused by ECRH. Correlation between the turbulence increase and the density pump-out has been found. Turbulence reduction has been observed during the pump-out/pinch transition. Strong asymmetry for the negative and positive density perturbation propagation has been observed, which is very similar to that observed in cold and hot pulse heat transport. The outward convection (negative velocity) has been observed during pump-out transient phase. The particle transport during constant ECRH phase is also investigated with SMBI modulation. The convective velocity is outward for low density in both ECRH and OH regimes, and the absolute value of the convective velocity is much larger in ECRH than in OH.

1) Introduction

Particle transport under electron cyclotron resonance (ECRH) heating is an important issue in magnetically confined fusion plasmas. As shown previously [1, 2], ECRH may affect strongly the density profile and the stored energy, typically in the low density regime. This effect, not really understood, is thought to be governed by transport process. It can be an interesting control tool in the fusion reactor for the removal of the alpha particles produced by fusion reactions from the center, for the density peaking reduction to increase β limit, and for controlling impurity concentrations.

Density pump-out, namely the flattening of the density profile and the loss of the energy during the ECRH, has been also observed in HL-2A tokamak. In the previous works, the profile analysis is often used to investigate this phenomenon in calculating the density peaking factor for the steady state before and after the pump-out. The density peaking is directly linked to the ratio between the convective velocity V and the particle diffusivity D. Here V and D are always associated. Perturbation transport experiments with ECRH modulation and the supersonic molecular beam injection (SMBI) [3] have been performed to investigate the particle transport. As shown in [4], the density modulation experiment can be an effective way to determine separately the particle diffusivity and the particle convective velocity. It should be noted that the perturbation method is also useful for the investigation of the particle transport barrier [5]. In this dynamic approach, the transient phase of the density pump-out phenomenon is investigated effectively.

2) Pump-out and Out-gassing

The plasma main parameters in the present experiments are: major radius R=1.65 m, minor radius a=0.40 m, toroidal magnetic field B_T=1.3T, plasma current I_p=160kA. The plasma is circular with limiter or divertor configuration. The density profile is measured by a broadband O-mode reflectometer of 26.5-40 GHz [6], which covers a density domain of 0.8 to $2.0\times10^{19}\,m^{-3}$. The line averaged density is measured by a HCN interferometer. The electron temperature is measured by the diagnostic of electron cyclotron emission (ECE). The ECRH system in HL-2A has 3 Gyrotrons at 68 GHz with maximum output power of 1.5 MW and duration of 1s.

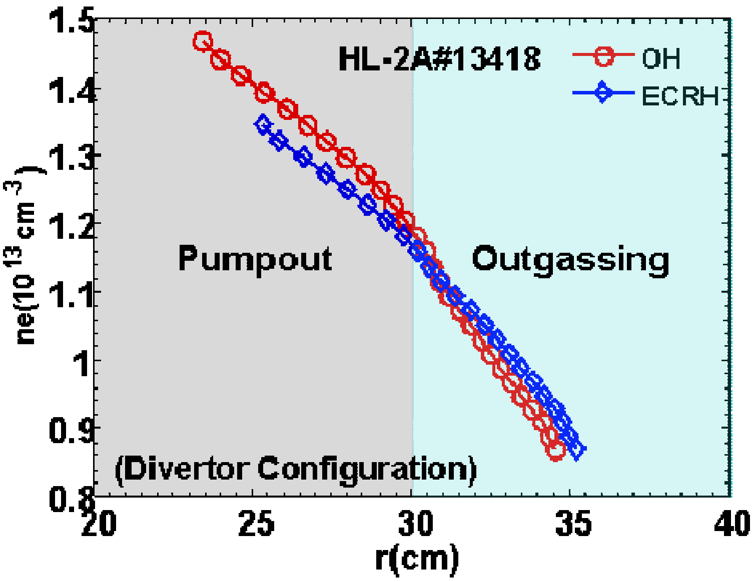


Fig. 1 Density profile measured by reflectometry in Ohmic regime (blue) and in ECRH regime (red).

During the ECRH heating, the density in the central region decreases, while the density in the peripheral region increases as shown in Fig.1. The drastic negative density perturbation in the central region represents the density pump-out. The edge density increase or positive perturbation is due to the out-gassing caused by the ECRH. Generally the out-gassing effect is much larger in limiter configuration than in divertor configuration, due to the displacement of the limiter plasma contact point after the ECRH. The inversion point for the density perturbation in the present case is located around r=30cm. Of course, this inversion point can move according to the plasma configuration, more peripheral in divertor configuration than in limiter configuration. The 2D images of the density perturbation during the ECRH for divertor and limiter configurations are shown in Fig.2 and Fig.3, respectively. In divertor configuration, the dominant perturbation in the probed region by the O-mode reflectometry is negative because the out-gassing effect is reduced. In limiter configuration, the dominant perturbation in the probed region by the O-mode reflectometry is positive due to the distinct out-gassing effect. The negative density perturbation propagates from the center to the edge, while the positive one propagates in opposition direction *i.e.* from the edge to the center. Intuitively the pump-out propagation velocity from the center to the edge can be estimated to be roughly 5m/s from Fig.2. The separation of different physical processes is a crucial point before using Fourier analysis.

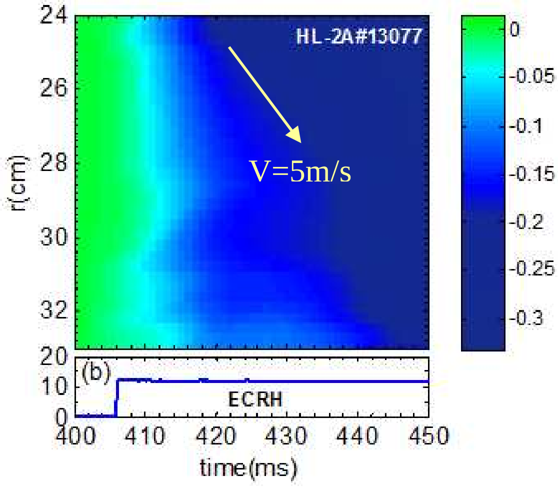


Fig.2 2D image of the negative density perturbation during ECRH with divertor configuration

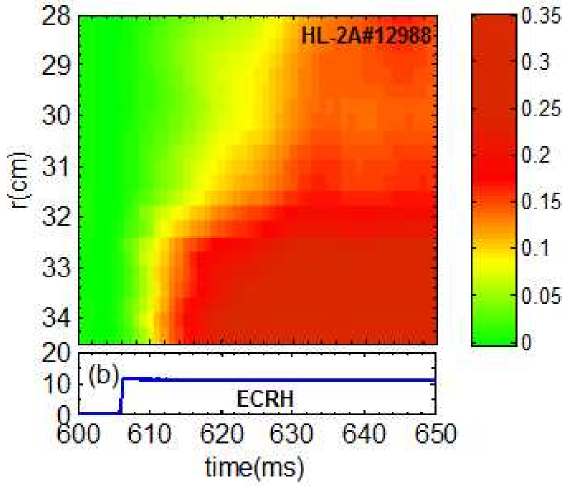


Fig.3 2D image of the positive density perturbation during ECRH with limiter configuration.

3) Turbulence and Pump-out

Doppler reflectometry is an effective tool for the measurement of the turbulence poloidal rotation and its level with high spatial resolution [7]. During the ECRH modulation experiments on HL-2A, the turbulence is measured with the Doppler reflectometry [8]. Fig.4 shows the time evolution of the turbulence frequency spectrum during ECRH modulation. The ECRH deposition is located at the center, and the measurement of the turbulence is located at r=26cm. Strong correlation has been observed between the turbulence level and the ECRH. Here the density effect is not taken into account. Indeed, when the density is modulated by the ECRH, the cut-off layer of the Doppler reflectometry is also modulated, thus the measurement points for the turbulence change during the ECRH. Fig.5 displays the turbulence spectra with ECRH (red spectrum) and without ECRH (blue spectrum) for the same densities. The time intervals to obtain the two spectra are indicated in Fig.6, the interval A for the ECRH regime, and the interval B for ohmic (OH) regime. From this figure, we can see that the turbulence level explodes during the ECRH, and is nearly 10 times higher than that in OH.

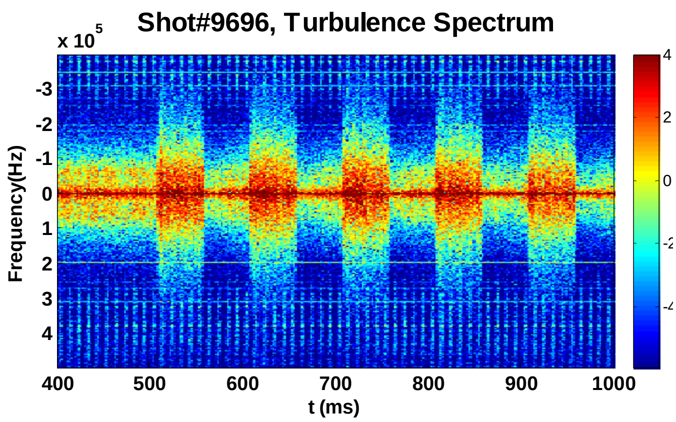


Fig. 4 Time evolution of the turbulence frequency spectrum measured by reflectometry during the ECRH modulation.

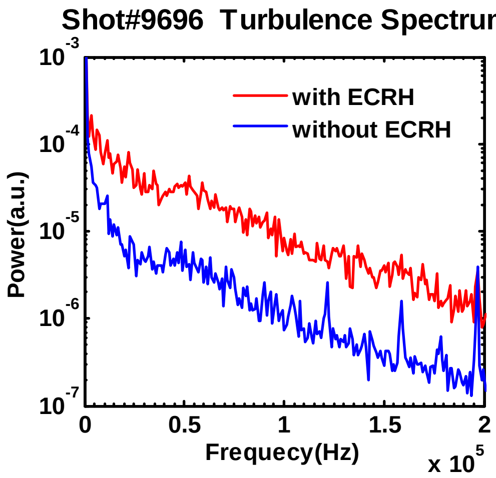


Fig.5 Turbulence frequency spectra with ECRH (red) and without ECRH (blue) for the similar density. The time intervals to obtain the two spectra are indicated in the figure 6.

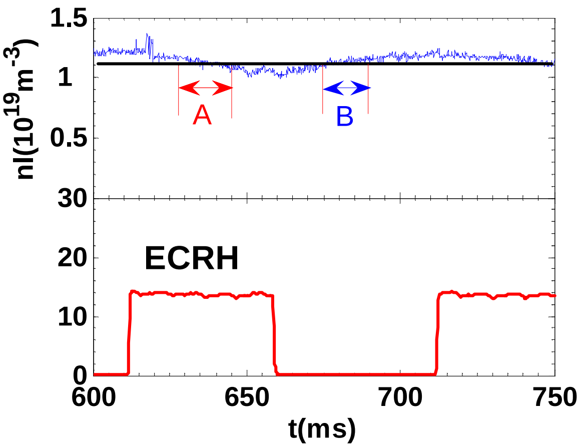


Fig.6 Line averaged density (top) and ECRH signal (bottom). The time intervals A and B correspond respectively to the spectra without ECRH (in red) and with ECRH (blue) shown in Fig.5.

During constant ECRH phase, the behavior for the density is generally characterized by a transient phase with density decrease (pump-out) then a steady state phase. Sometimes different behaviors are observed: as shown in Fig.7, when the ECRH is applied, after the density decreasing phase, a density increasing occurs immediately. The latter can be due to a strong inward convection (pinch). During this pump-out/pinch transition, the internal energy, as well as the electron temperature increases significantly, while the H_α signal is reduced. Fig.8 show the turbulence spectra before (blue) and after (red) this transition. We can see that the turbulence level is lower after the transition. It should be noted that this reduction is underestimated in our case. Indeed after the transition, the density is higher, and the measurement point for the turbulence is shifted outward, and the turbulence is larger due to its radial profile dependence. This illustrates a possible correlation between the pump-out/pinch transition and the turbulence reduction.

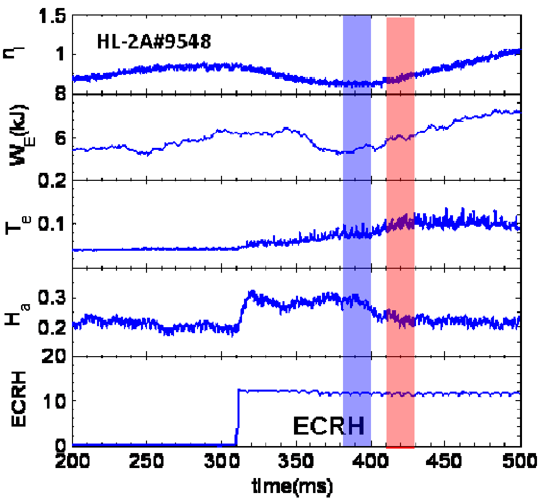


Fig.7 Time evolution of the density, the internal energy, the electron temperature, the H_α signal and ECRH signal (from top to bottom).

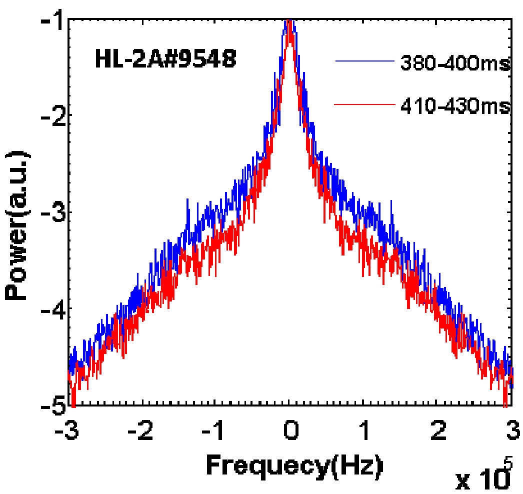


Fig.8 Turbulence frequency spectra before (blue) and after (red) the pump-out/pinch transition. The time intervals to obtain these spectra are shown in Fig.7.

4) Perturbation transport analysis

Up to now, the usual method for the investigation of the density pump-out is to calculate the density peaking factor. This factor is a good parameter to characterize the pump-out in the steady state [1] [2]. Indeed, in steady state and outside the source region, this factor is directly linked to the transport coefficients:

$$D\frac{\partial n_e}{\partial r} + Vn_e = 0 \quad (1)$$

thus

$$\text{Density peaking factor} = -\frac{1}{n_e}\frac{\partial n_e}{\partial r} = \frac{V}{D} \quad (2)$$

where D is the particle diffusivity and V is the particle convective velocity. However in this steady state approach, the transient phase of the pump-out is not considered, and the diffusion and the convection are not separated. In this work, a dynamic approach using modulation technique is proposed to investigate the transient phase of the density pump-out. Fig.9 shows the amplitude and the phase of the 1^{st} harmonic of the Fourier transform of the density modulated by the ECRH, respectively in limiter (a) and divertor (b) configurations. The perturbation source is determined by the position of the minimum of the phase. In limiter configuration (Fig.9a), the particle source for the positive density perturbation lies at the plasma edge (a=37cm). Simulation with an analytical linear transport model [9] show that the positive density perturbation propagates from the edge to the center, crossing two different areas: 1) core outward convection region (28.3cm<r<33.2cm) with D_1=0.4m^2/s, and V_1=-4m/s; 2) peripheral inward convection (pinch) region (33.2cm<r<37cm) with D_2=0.8m^2/s, V_2=15m/s. The convective velocity is defined here as positive for inward and negative for outward. In this case the out-gassing can be considered as particle test for the transport. On the other hand, in divertor configuration (Fig.9b), the negative density perturbation (pump-out) source is located in the central region, outside the probed region by O-mode reflectometry. It propagates from the center to the edge with D=1.5m^2/s, and V=-10m/s. Note that the values of D and V are much larger for the negative density perturbation than for the positive one, *i.e.* the negative density perturbation propagates much faster than that in the positive case. The strong asymmetry in D and V for the negative and positive density perturbation (see Tab.1) is very similar to that observed in cold and hot pulse heat transport. By analogy, this difference can be explained by the fact that the positive density perturbation is due to the particle propagation, while the negative density perturbation can be due to the turbulence spreading [10] [11]. The outward convection (negative velocity) has been observed only during pump-out transient phase. It should be noted that the particle convection is always inward in steady state before and after the pump-out phase. Theoretical work has shown that the turbulence driven by trapped electron mode (TEM) can lead to an outward convection via thermo-diffusion in the tokamak [12]. Thus the previous observations can be a serious indication for the presence of TEM during the pump-out. Thus the density pump-out could be result from the combination of two effects: a large particle outward convection (-4m/s), probably driven by TEM, and more important a dramatic turbulence radial spreading with strong outward convection (-10m/s).

	Positive density perturbation ***(Particle propagation)***	**Negative density perturbation** ***(Turbulence spreading)***
Diffusion (D)	**0.4 m2/s**	**1.5 m2/s**
Convection (V)	**- 4 m/s**	**- 10 m/s**

Tab.1 Diffusivity and convective velocity for the positive and negative density perturbation.

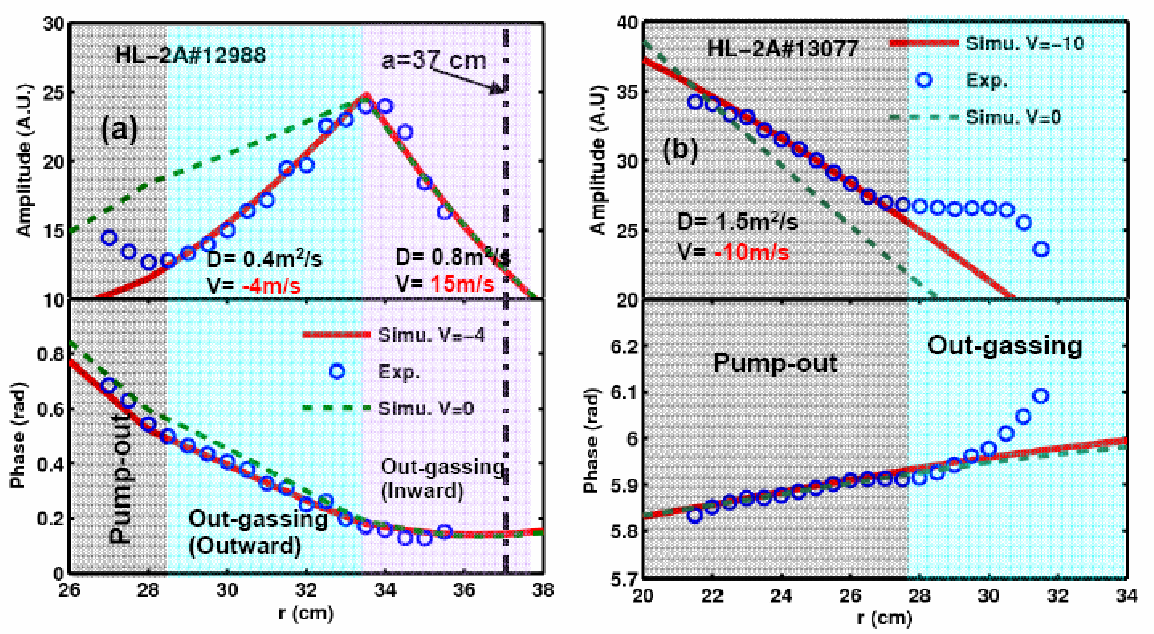


Fig.9 Amplitude and phase of the 1st harmonic of the Fourier transform of the density modulated by ECRH in limiter configuration (a) and in divertor configuration (b). Open circle is the experimental data; the solid lines represent the simulation with convection; the dash lines represent the simulation without convection (V=0) in the corresponding domain.

5) SMBI modulation

The particle transport during constant ECRH phase is also investigated with SMBI modulation. Fig.10 shows the SMBI modulation with or without ECRH heating. For Fourier analysis, it is essential that the averaged density should be nearly constant over the analysis window. In our case the analysis window is from t=600ms to t=800ms during the ECRH phase. For the OH phase from t=300ms to t=500ms, as the averaged density increases and not constant, we can no longer use the Fourier method for studying particle transport. For the comparison, we use another shot (HL2A#7543) for the OH phase. Fig.11 and Fig.12 show respectively the phase and the amplitude of the fundamental harmonic of the density modulated by SMBI. The squares and circles are respectively the experimental data in the ECRH regime and in the OH regime. The blue solid line represents the simulation in the ECRH case, while the red one represents that in the OH case. In the OH case, the particle source is located at r=27.5cm, and the particle diffusivity is D=0.25m^2/s for r=0.28m-0.33m, and a negative convective velocity has been found V=-2.2m/s for r=0.28m-0.31m, V= -4.2m/s for r=0.31m-0.33m. In the ECRH case, the particle source is located at the plasma edge, outside the probed region by the reflectometry, and the particle diffusivity is D=0.7m^2/s, and a negative convective velocity has been found V=-10m/s. The displacement of the particle source location toward the edge seen in ECRH is consistent with the empirical scaling law of the penetration depth for SMBI obtained in HL-2A [13], where the penetration depth decreases strongly with the electron temperature. As expected the particle diffusivity in the ECRH regime is larger than in the OH regime. The particle convective velocity is outward in both regimes, and the absolute value of the convective velocity is much larger in the ECRH regime than in the OH regime.

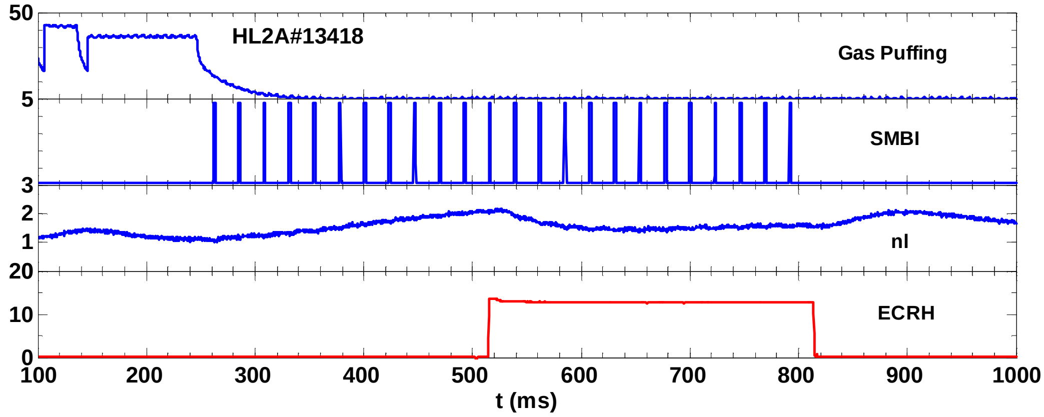
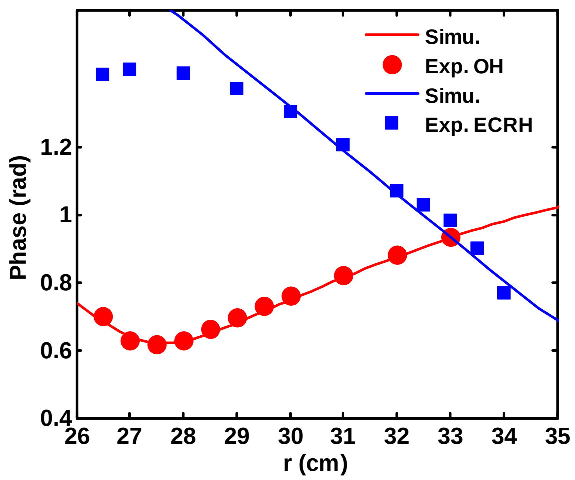


Fig.10 Time evolution of the gas puffing signal, the SMBI signal, the line averaged density, and the ECRH signal.



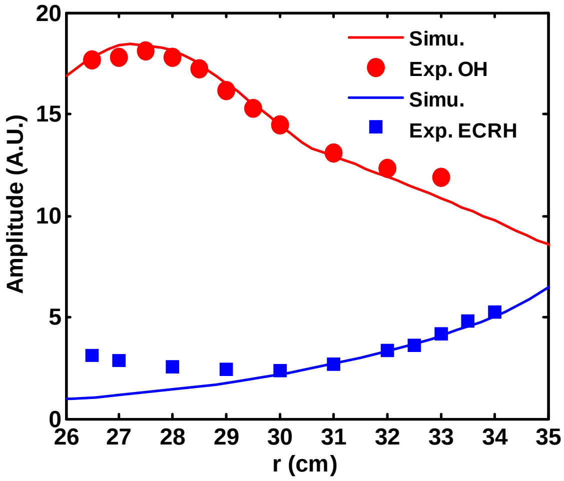


Fig.11 Phase of the fundamental harmonic of the density modulated by SMBI. The squares (circles) correspond to the experimental points in ECRH (OH). The blue (red) solid line represents the simulation in the ECRH (OH) regime.

Fig.12 Amplitude of the fundamental harmonic of the density modulated by SMBI. The squares (circles) correspond to the experimental points in ECRH (OH). The blue (red) solid line represents the simulation in the ECRH (OH) regime.

6) Conclusions

Experiments have been carried out in HL-2A with ECRH and SMBI for particle transport investigation. In ECRH regime, the density pump-out phenomenon, characterized by a negative density perturbation in the central region, has been observed. Simultaneously a positive density perturbation in the peripheral region has been observed. This edge density increases is due to the out-gassing caused by ECRH. The out-gassing effect is much larger in limiter configuration than in divertor configuration. Strong correlation between the turbulence increase and the density pump-out has been found. Turbulence reduction has been observed during the pump-out/pinch transition. Different to the previous works, a dynamic approach using modulation technique has been performed for the investigation of the pump-out phenomenon (transient phase). Strong asymmetry for the negative and positive density perturbation has been observed. It can be explained as for the heat transport by the fact that the positive density perturbation is due to the particle propagation, and the negative density perturbation is due to the turbulence spreading. The outward convection (negative velocity) has been observed during the density pump-out transient phase. The previous observations can be a serious indication for the presence of TEM during the pump-out. The particle transport during constant the ECRH phase is also investigated with SMBI modulation. The particle source deposited by SMBI is much peripheral in the ECRH regime than in the OH regime. The convective velocity is outward for low density in both ECRH and OH regimes. But the absolute value of the convective velocity is much larger in the ECRH regime than in the OH regime.

Acknowledgments

The authors are grateful to all colleagues of HL-2A team for their enthusiastic support and valuable discussions. This work was supported within the framework of the cooperation between the French Commissariat à l'Energie Atomique (CEA) and the China National Nuclear Corporation (CNNC). It was also supported by the National Natural Science Foundation of China under Grant Nos. 10805015, 10795049, 10675043 and 10975049, and partly by the Great Foundation of China 2009GB104007 and National Magnetic Confinement Fusion Science Program 2010GB101004.

References

[1] H. Weisen, I. Furno, TCV Team, Nucl. Fusion **41**, 1227 (2001)

[2] C. Angioni, A.G. Peeters, X. Garbet, *et al.*, Nucl. Fusion **44**, 827 (2004)

[3] L.H. Yao et *al.*, Nucl. Fusion **38**, 631 (1998)

[4] W.W. Xiao, X.L. Zou, X.T. Ding, *et al.*, Rev. Sci. Instrum. **81**, 013506 (2010)

[5] W.W. Xiao, X.L. Zou, X.T. Ding, *et al.*, Phys. Rev. Lett., **104,** 215001(2010)

[6] W.W. Xiao, Z.T. Liu, X.T. Ding, *et al.,* Plasma Science & Technology, Vo1.8, No.2 (2006)

[7] X.L. Zou et al., Proc. 26th EPS, Vol.23J, p.1041 (1999)

[8] W.W. Xiao, et al. Plasma Science & Technology, Vol.10, No.4, 430 (2008)

[9] S.P. Eury, E. Harauchamps, X.L. Zou *et al.* Phys. Plasmas **12**, 102511 (2005)

[10] O.D. Gurcan, P.H. Diamond, T.S. Hahm, Phys. Rev. Lett., **97,** 024502(2006)

[11] X. Garbet, Y. Sarazin, F. Imbeaux *et al.*, Phys.Plasmas **14**, 122305 (2007)

[12] X. Garbet, L. Garzoti, P. Mantica *et al*., Phys. Rev. Lett. **91**, 035001 (2003)

[13] L.H. Yao, B.B. Feng, C.Y. Chen *et al*., Nuclear Fusion **47,** 1399 (2007)