*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, D-5.003 (2008)*

Observation of a Natural Particle Transport Barrier in HL-2A Tokamak

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

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

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

Particle transport barriers with energy confinement improvement have been observed in tokamaks, as the H-mode [1] at the edge of the plasma and ITB [2, 3, 4, 5] in the core. These regimes have been often obtained with high power external input auxiliary heating as the neutral beam injection [1, 5], off-axis minority ion-cyclotron heating [3, 4], or large external input particle source as the pellets [2]. Mechanisms responsible for these barriers are reversed magnetic shear, or $E \times B$ rotation shear. Here we report the observation of a natural or spontaneously generated particle transport barrier in purely ohmically heated plasmas in the HL-2A tokamak with no externally applied momentum or particle input.

The plasma parameters in the present experiments are: major radius R=1.64 m, minor radius a=0.40 m, toroidal magnetic field B_T=1.45 T, plasma current I_p=185 kA. The plasma is circular with limiter configuration. The density profile is measured by a broadband O mode reflectometer of 26.5-40 GHz, 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. Internal particle transport barriers (pITBs) have been observed in ohmic plasmas in HL-2A with standard gas puffing when the electron density exceeds a well defined threshold. This phenomenon is perfectly reproducible. Fig.1 shows the temporal evolution of the density profile at selected times for a typical discharge with transition to pITB, when the density increases slowly: before the appearance of the transport barrier (+ 250 ms); at the beginning of the formation of the barrier (Δ 420 ms); strong barrier (❍ 480 ms); in higher density after fuelling with supersonic molecular beam injection (SMBI) [6] (☐ 520 ms). The barrier is located around r=29*cm*. The parameter characterizing the pITB is the normalised density gradient $-a\nabla n_e / n_e = a / L_n$. Fig.2c displays a 2-D image of the normalised density gradient, showing clearly the trace of pITB around r=29cm. Before t=400*ms*, no clear barrier has been observed. Starting from this time, the pITB appears progressively. The critical density corresponding to this transition is $\overline{n}_c = 2.2\times10^{19}\,m^{-3}$. After the injection of a particle pulse by SMBI at t=510*ms*, identified by a sharp increase of the H_α signal, the pITB trace is much more visible, and the density gradient is steeper. This is a strong indication of the presence of the transport barrier. It should be emphasized that the Mirnov coil signal shows no change during the pITB transition (Fig.2b). Hence this pITB is not due to MHD activities. No significant change has been observed on the temperature profile during the pITB.

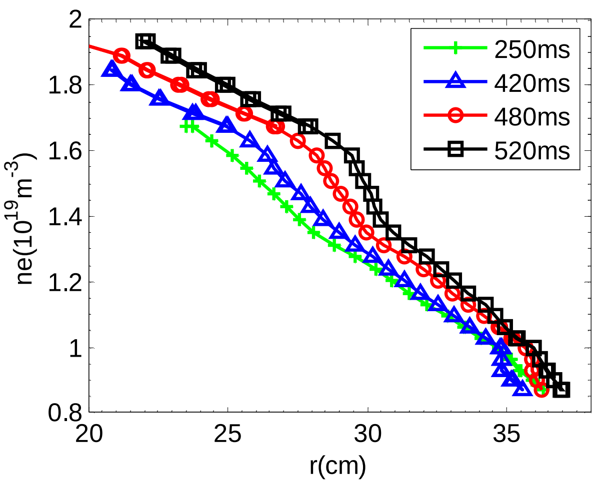

Figure 1 Shot #7557. Temporal evolution of the density profile at selected times. Before the appearance of the barrier (+ 250 ms); at the beginning of the formation of the barrier (Δ 420 ms); strong barrier (○ 480 ms); just after a particle pulse injected by SMBI (□ 520 ms).

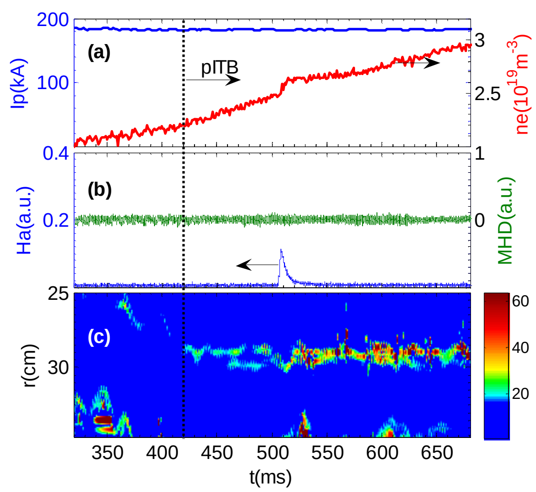

Fig.2 Shot #7557. (a) Temporal evolution of the plasma current I_p (kA), the central line averaged density $\bar{n}_e(10^{19}\,m^{-3})$. (b) Temporal evolution of the Mirnov coil signal and H_α signal. (c) 2-D image of the density gradient.

The width of the barrier is 1~2 cm. A drastic change has been observed in the density gradient through this barrier: $L_n \approx 10cm$ at the barrier location, $L_n \approx 50cm$ inside the barrier, and $L_n \approx 25cm$ outside the barrier. In a region without particle sources and in steady state, the particle flux $\Gamma = -D\nabla n_e - V n_e \approx 0$, where D is the particle diffusivity, V is the particle convective velocity defined as positive for inward pinch, and negative for outward. Thus the ratio D/V is directly equal to L_n, $L_n = D/V$. The shape of the density gradient length gives interesting indications on the feature of *D* or *V*. Thus the barrier observed here is well-like and not step-like.

A simple profile analysis does not allow to separate *D* and *V*. The modulation experiments allow normally to separate the diffusivity term and the convection term, by using the fact that on one hand the phase of the particle wave generated by the modulation is very sensitive to the diffusivity but less sensitive to the convection, and on the other hand the amplitude of the particle wave is sensitive to diffusivity but very sensitive to the convection [7]. In our experiments, the density modulation has been generated by SMBI. In the present case, the SMBI modulation frequency is 9.6 Hz, the duration of SMBI pulse is about 6 ms, the gas pressure of SMBI is 1.3 MPa. The time resolution of the reflectometry is 1 *ms*. Profile analysis shows a pITB around $r \approx 26-27cm$ for this plasma. The figures 3a, 3b display respectively the phase and the amplitude of the 1st harmonic of the Fourier transform of the modulated density. From Fig. 3a, the minimum of the phase is at $r \approx 25.3cm$, which generally determines the particle source location. The particle source location found here is in agreement with that observed from H_α and ECE signals. From Fig.3b, a first peak in amplitude has been found at $r \approx 24cm$, slightly shifted inwards compared to the particle source location. This indicates the presence of a significant particle pinch in this region. At the barrier location $r \approx 27cm$, a second peak has been found in the amplitude, and strong effect has been observed in the phase.

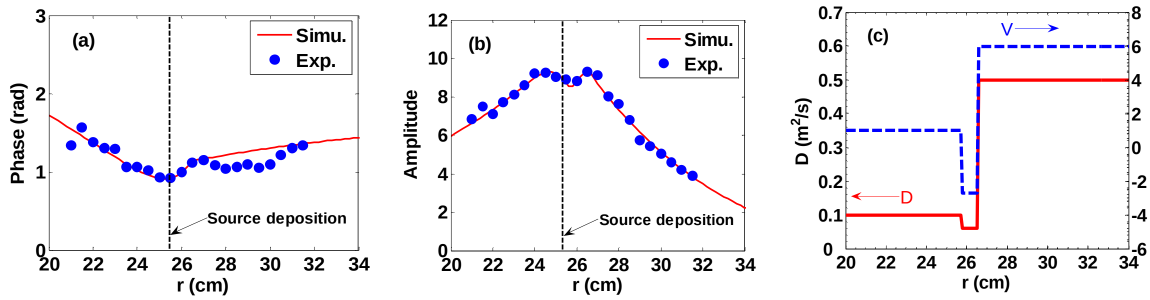

Fig. 3 Shot #7593 with transport barrier, $\bar{n}_e = 2.6\times10^{19}m^{-3}$. *Phase (a), amplitude (b) of the 1st harmonic of the Fourier transform of the modulated density. Comparison between experiment (circle) and simulation (solid). Diffusivity D (solid), convective velocity V (dash) for the simulation (c).*

Simulation has been made with an analytical model [8]. For the simulation, the following parameters are used: the modulation frequency $f_0 = 9.6Hz$, the particle deposition $r_{dep} = 25.3cm$, the minor radius $a = 40cm$, the transport barrier is between $x_1 = 25.6cm$ and $x_2 = 26.7cm$, the particle source is given by a Gaussian distribution with the amplitude $S_0 = 0.69\times10^{19}m^{-1}s^{-1}$ (the total particle injected per second is $N_p = 2\pi RS_0$), and the width $w = 0.03a$. On the figures 3a and 3b, the solid lines represent the simulation. A satisfactory agreement has been found between the experimental points and the analytical calculation, and we have found (Fig.3c): in the domain 1 ($r < x_1$): $D_1 = 0.1m^2/s$, $V_1 = 1.0m/s$; in the domain 2 or in the well $(x_1 < r < x_2)$, $D_2 = 0.045m^2/s$, $V_2 = -2.7m/s$; in the domain 3 ($r > x_2$),

$D_3 = 0.5m^2/s$, $V_3 = 6.0m/s$. In the present case the neoclassical Ware pinch [9] $V_{ware} \approx \sqrt{r/a}E_\phi / B_\theta \approx 0.6m/s$ around the barrier**,** where E_ϕ is the toroidal electric field, and B_θ is the poloidal magnetic field. The pinch velocity found in the domain 3 is much larger than the Ware pinch, while the velocity found in the domain 1 is very close to the latter.

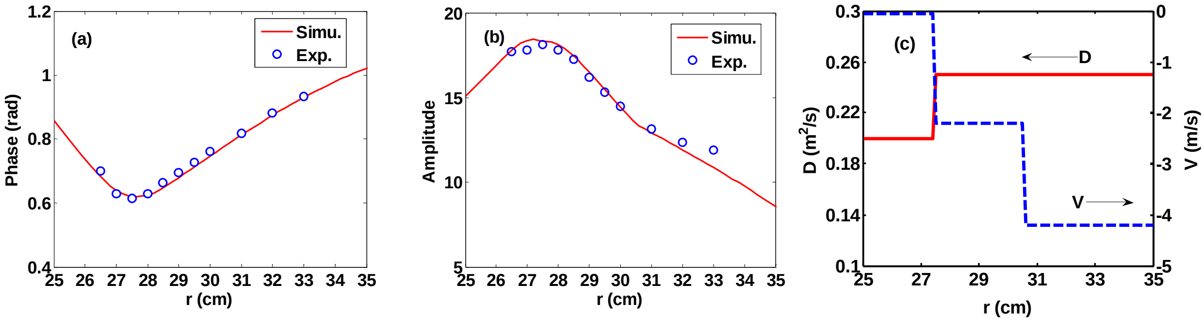

Fig. 4 Shot #7543 without transport barrier, $\bar{n}_e = 1.9\times10^{19} m^{-3}$. Phase (a), amplitude (b) of the 1st harmonic of the Fourier transform of the modulated density. Comparison between experiment (circle) and simulation (solid). Diffusivity D (solid), convective velocity V (dash) for the simulation (c).

For comparison, SMBI modulations have been also performed for a discharge with a density $\bar{n}_e = 1.9\times10^{19} m^{-3}$ lower than the critical value $\bar{n}_c$ (Fig. 4). In this case, no barrier has been observed. The diffusivity obtained by this method is $D = 0.25m^2/s$ for *r*=28-31*cm*, and a negative convective velocity has been found $V = -2.2m/s$ for *r*=28-31*cm*, *V*=-4.2*m/s* for *r*=31-33*cm*. Measurements of the turbulence rotation velocity by Doppler reflectometry confirm that the appearance of this barrier is correlated to a drastic change in the turbulence rotation shear.

References

[1] F. Wagner, G. Faussmann, D. Grave *et al*., Phys. Rev. Lett. **53**, 1453 (1984)

[2] M.J. Greenwald, D.A. Gwinn, S. Milora *et al.*, Phys. Rev.Lett. **53**, 352 (1984)

[3] C.L. Fiore, J.E. Rice, P.T. Bonoli *et al.*, Phys. Plasmas **8**, 2023 (2001)

[4] J.E. Rice, P.T. Bonoli, E.S. Marmar *et al.*, Nucl. Fusion **42**, 510 (2002)

[5] E.J. Doyle, G.M. Staebler, L. Zeng *et al.*, Plasma Phys. Controlled Fusion **42**, A237 (2000)

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

[7] N.J. Lopes Cardozo, Plasma Phys. Control. Fusion **37**, 799 (1995).

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

[12] A.A. Ware, Phys. Rev. Lett. **25**, 916 (1970)