DEVELOPMENT OF THE Q=1 ADVANCED TOKAMAK SCENARIOS IN HL-2A

Y. Liu, Wei Deng, D.Liang Yu, Min Jiang, Z.Y.Cui, Zhong.Bin Shi , X.Q. Ji, Jun Chen, Y.B. Dong , J.Y.Cao, W.L. Zhong, J.M.Gao, Yi.Po Zhang, Yong.Gao Li, Q.W.Yang, Ming.Xu, X.R.Duan and HL-2A team

Southwestern Institute of Physics
Chengdu, Sichuan 610041, China
Email: yiliu@swip.ac.cn

Xian.Qu WANG
Institute of Fusion Science, Southwest Jiaotong University
Chengdu, Sichuan 610031, China

Abstract

The advanced tokamak scenario with q close to 1 has been achived on HL-2A tokamak, which might be a internal transport barrier (ITB) at low central shear or a steady state ITB combined with H mode edge barrier. In this scenario, formation of internal transport barrier (ITB) with steep Ti profile is observed to be closely linked to the q=1 magnetic surface and MHD activitis around it, suchg as LLM or fishbone. It was found that the q-profile in the core remains flat throughout the ITB period. Such weak central magnetic shear is sustained by the LLM or fishbone activity in addition to bootstrap current, NBI-driven current. Furthermore, applying central ECRF heating and current drive to such beam heated weak shear ITB discharges shows a substantial effect on MHD stability, affecting the passage of the q profile through q_{min}= 1 and prolonging the weak shear phase, enhancing the strength of ITB with a stronger gradient. Moreover, a stationary advanced tokamak scenario with ITBs in combination with an H mode barrier and weak shear (q_{min} ~1) was maintained for 40 confinement times and several internal skin times with β_N = 2.0. In the ITB/H mode scenario, (1,1) fishbones can not only clamp the current profile development near the q = 1 surface without causing energy confinement to deteriorate but also induce a polodial flow which is beneficial to the suppression of turbulence in the plasma core region.

1. INTRODUCTION

In order to optimize the plasma performance and minimize the cost of electricity, the plasma in a future fusion power plant must operate with high β,and simultaneously, a large fraction of bootstrap current to minimize the power requirements from auxiliary heating systems. Several advanced scenario regimes have been studied in recent years. Enhanced energy and particle confinement have been achieved in many tokamak experiments, mainly through optimization of the current density profile. Plasma current density profiles in largely bootstrap current driven equilibria are generally broad resulting in reversed shear or low-shear safety factor profiles [1]. However, the strong pressure gradients required for optimal fusion performance combined with these q-profiles usually causes deleterious MHD instabilities, leading to strong damping of core rotation and increasing of fast ion losses [2]. Besides the above mentioned unfavorable role of MHD instabilities, they have been shown to be helpful in achieving improved confinement and quasi-stationary discharge conditions. MHD triggering ITB was already observed at DIII-D[3]，ASDEX-U[4] and LHD[5]. To extrapolate these improved regimes to larger sized tokamaks and reactors, it is essential to determine the triggering conditions to form an ITB.

In general, these scenarios could be categorized by different safety factor (q) profiles due to the importance of the q or q shear profiles in confinement improvement and stability. They include (1) strong reversed shear regime, (2) weak shear regime with $q(0)>1$, and (3) regime with central flat q profile and $q(0)\sim1$. For strong reversed shear regime, ITB (L-mode edge) triggered by Neutral Beam Injection (NBI) injection in the current ramp-up phase was observed in JT-60U with a record of DT equivalent fusion gain of 1.25. Also in JT-60U, the combination of ITB and ETB has been observed in the reversed shear mode with no clear influence on the ITB from the giant ELMs. In JET, by improving the LHW coupling, strong reversed shear plasma with strong ITBs had been demonstrated based on Optimized Shear (OS) discharges. In DIII-D, strong reversed shear discharge with ITB was established by off-axis Electron Cyclotron Current Drive (ECCD). Other examples of reversed shear discharge with ITB can be found in. For weak shear regime, one famous example was the JET OS plasma [10]. JET results also suggested the combination of double barriers can only survive with Type III ELMs and ITB. Giant ELM or Type I ELMs usually led to a collapse of ITB. In JT-60U, the high-βp mode with ITB referred to the weak shear regime, both for low negative and even positive shear . DIII-D produced weak reversed shear plasma with weak ITB by using early NBI heating. Double barrier structure in DIII-D was obtained by counter-NBI heating during the H-mode. For central flat q profile regime, weak ITB could be triggered on JET, and improved core confinement was also observed on ASDEX-Upgrade.

Recently, such kind of ITB has been observed[6] during the nonlinear evolution of a saturated long-lived internal mode (LLM) [7] in HL-2A discharges as the q-profile formed a very broad low-shear region with q_{min} ~1.The relationship of the mitigation effect and deposition [19], and the characteristic of the turbulence during ELM mitigation are studied experimentally in this work. This paper is arranged as follows: in section 2, the advanced scenarios developed at HL-2A are described. Section 3 discusses the use of the ECRH for improved ITB scenarios. Operation at steady state ITB combined with H mode edge barrier at low central shear are described in section 4. The summary and discussion are given in Section 5.

2. ITB DISCHARGE WITH WEAK SHEAR AND Q_{MIN}~1

Experiments performed in HL-2A (a = 0.4m; R = 1.65m) have achieved stationary regimes in X-point configuration with Ip = 150kA and B_T = 1.3T and $H_{ITER89-P}$ =1.5, β_N = 2.0, Ti (0) = 1.5keV, Te (0) = 1keV, q(0) in the vicinity of 1. A typical discharge (HL-2A #22485) with the ITB in HL-2A 2017 campaign was shown in figure 1(a). During the discharge, neutral beam injection (NBI) of 1.0MW is applied at 380ms.. This generates a flat q profile when the m = 1, n = 1 activities develops, leading to an observation of ITB characterized by strong ion temperature peaking (figure 1(*b*)). According to the ion temperature profiles and their maximum second derivatives, the ITB foot is localized near r/a=0.55 away from the plasma core.

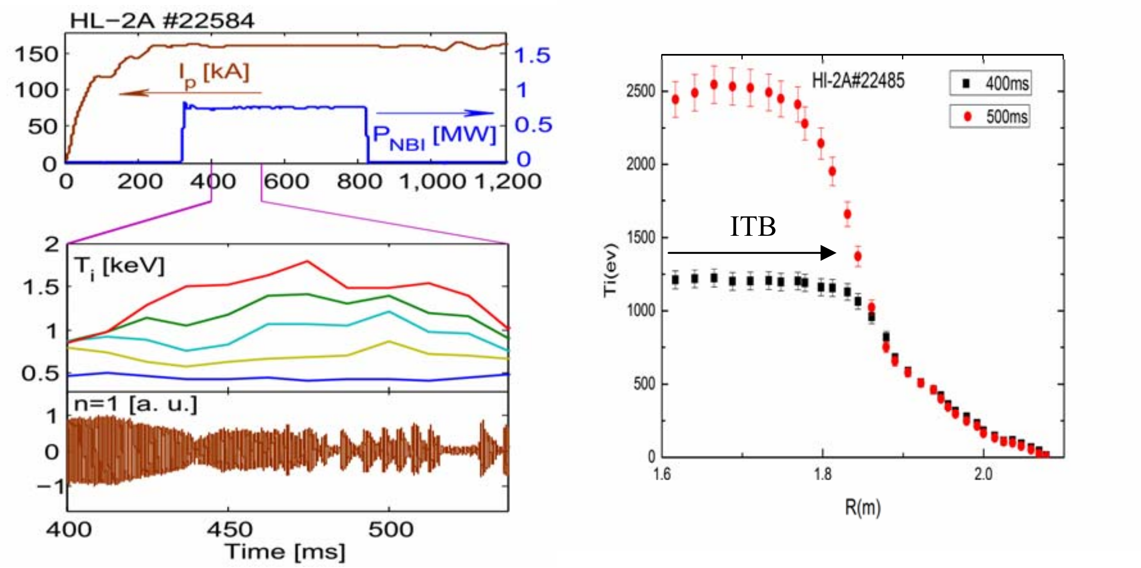


Figure 1. (a) Typical q=1 ITB scenario. The time and duration of the ITB is also indicated in thefigure. (b)Time evolution of the ion temperature profiles during ITB formation of the q=1 scenario.

This regime is accompanied by an n = 1, m = 1 LLM or fishbone activity and an improved energy and particle confinement. To further analyze the normalized scale length of ITB (R/L_{Ti}), the value of R/L_{Ti} is around 4–6 for Ohmic discharges, which can be estimated by CXRS data at the beginning of NBI. And for the shots without iITBs, the typical value of R/L_{Ti} is around 8–10. For shots with iITB, R/L_{Ti} can be up to 15 during the LLM or fishbone oscillations. Another interesting phenomenon is that there are two groups of normalized scale length of ITB are *found, the* ITB phase with LLM has a maximum value of R/L_{Ti} around 18-20 while the one with fishbone is higher than 20 or even up to 25, which will be discussed in section 2.2.

2.1 Clamping of q profile by reconnecting MHD modes

Low shear scenarios with internal barriers were established during the plasma current flat top phase by applying 1 MW NBI. These discharges have an L mode edge due to an enforced limiter configuration or a single null divertor configuration with the ion *rB* drift away from the X point. Steep pressure gradients with central values of Ti = 1.5 keV and Te = 1.0 keV were obtained with NBI heating, but due to both the smaller radius of the barrier and the L mode edge the plasma performance is modest with a confinement enhancement factor $H_{ITERL-89P}$= 1.5 and β_N= 1.8. The bootstrap current amounts to 35% and is peaked at the pressure barrier position (35% ohmic, 10% neutral beam current dive). In the barrier region the ion thermal conductivities is close to the ion neoclassical values, while the transport coefficients strongly increase towards the L mode plasma edge. In the ITB scenario discussed here, the only MHD activities observed in the core of the plasma are strong (1,1) LLM or fishbones which start just after NBI and accompany the entire 1 MW heating phase. These LLM or fishbone oscillations are driven by passing fast particles and behave like a resistive MHD instability similar to sawteeth, but on a much faster timescale of 1 ms.

Safety factor q profile and time evolution of q_0, and the radius of the q = 1 surface inferred from MSE measurements using the EFIT equilibrium code for a stationary ITB barrier discharge are shown in figure2. The measured q profile shows an extended central low shear region with $s \approx 0$ within ρ≈0.35 and q0≈1.

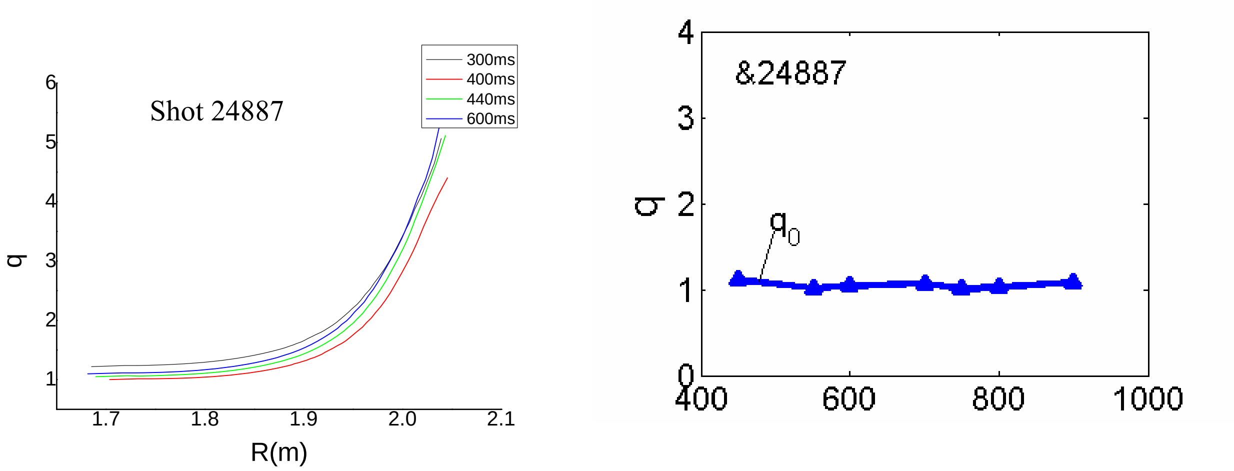


Figure 2. (a) Typical q profiles for q=1 ITB scenario. The time and duration of the ITB is also indicated in the figure. (b)Experimental time evolution of central q values during stationary discharge with a ITB in L mode.

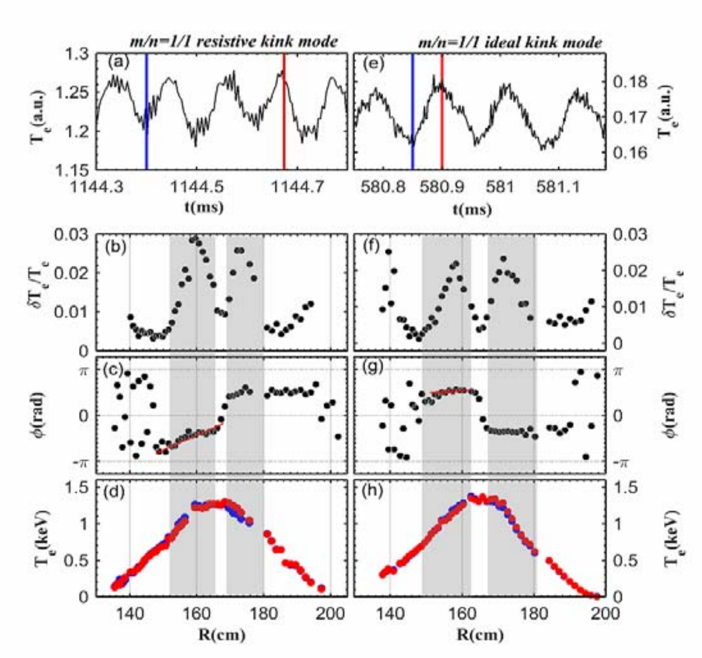


Figure3. Comparison of mode structure for a resistive kink and an ideal kink form ECE measurement.

Figure3 shows the structure analysis of the m/n=1/1 mode during ITB phase (LLM or fishbone) in comparison with normal m/n=1/1 mode before a sawtooth crash. What is interesting here is that the single phase jump in the ideal kink mode structure (figure3 (g)) is not found in the LLM or fishbone structure. As we know if there is an island there will be a corresponding phase shift on one side of the axis, which is the case for the LLM or fishbone (figure3 (c)). In figure 3, we can find the instability is dominated by the m=n=1 harmonic. The mode has a characteristic resistive interchange-like structure. Although this analysis is made over a relatively short time (1–200 ms), this result indicates that reconnection is necessary to explain that $q_0$remains close to 1 for more than 100 ms.

In the last campaign the NBI power in these scenarios has been extended by applying a new beam. More observation show that fishbone can have a much stronger beneficial effect on ITB parameters than expected form an ideal, fast particle driven LLM instability. In Fig. 4 such a discharge is shown where the injected NBI power has been increased. Clearly the threshold for heating power (or torque input) to sustain the ITB is increased with rising density by means of external gas puffing (by about 50% in the case shown). There was no confinement deterioration during strong fishbone burst, and therefore β_N increased, while the density peaking decreased only moderately. Obviously, the improved core confinement properties are related to the effect of fishbone on the background plasma parameters, in agreement with transport caused by the ITG instability. Thus，fishbone can play a significant practical role in ensuring the stationarity of plasma profiles under favourable discharge conditions.

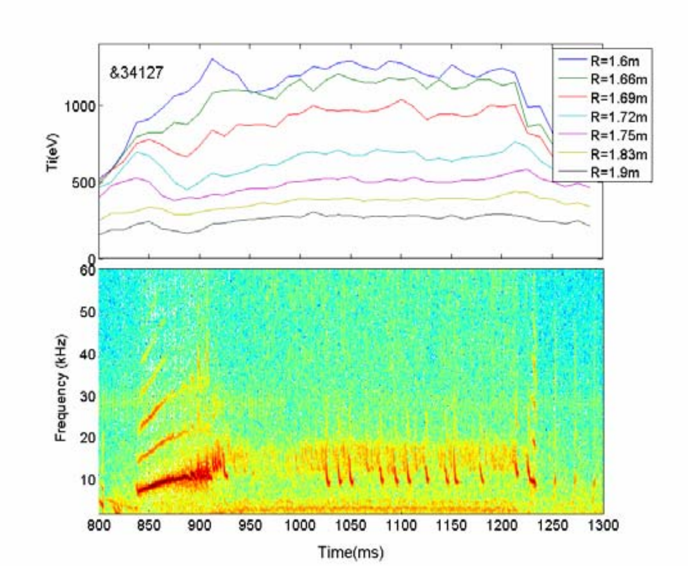


Figure4. Typical advanced tokamak scenario in HL-2A characterized by large temperature gradient length accompanied by strong fishbone bursts.

2.2 Role of fishbone in suppression of turbulence during ITB

Experimental evidence is shown for the link between internal MHD activity and ITB formation. From the detailed analysis of experimental data, a new candidate mechanism is put forward to explain the MHD triggering of ITBs in HL-2A which is consistent with the observation of reduced transport during central MHD activities. The fishbone instabilities excited by energetic ions play a role in reducing the central magnetic shear. As shown in figure5, it was observed that the turbulence is reduced during the burst of fishbone activity.When the central magnetic shear is low enough, ballooning modes become stable for the plasma pressure gradient and an internal transport barrier with a steep ion temperature can exist.

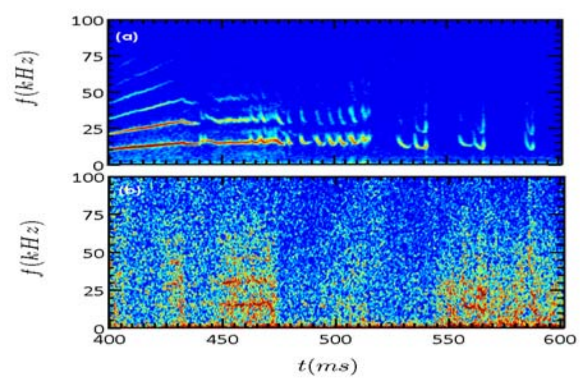


Figure5. Top: Spectrogram of the central soft-X ray signal. Bottom: Spectrogram of the density fluctuation at r/a=0.6 formreflectometry.

In figure 6, the m=n=1 internal instabilities destabilized by energetic particles is shown in linear (t=374) and nonlinear (t=1998) stages, where the time is normalized by Alfven time. After an interval of 1000 Alfven time, there is another n=1 at higher frequency than the primary mode. From the structure shown in figure 6(c) and (d), we can find in the nonlinear stage, the poloidal flow is generated. This result is similar to the excitation of zonal flow through TAE nonlinearity [11,12,13]

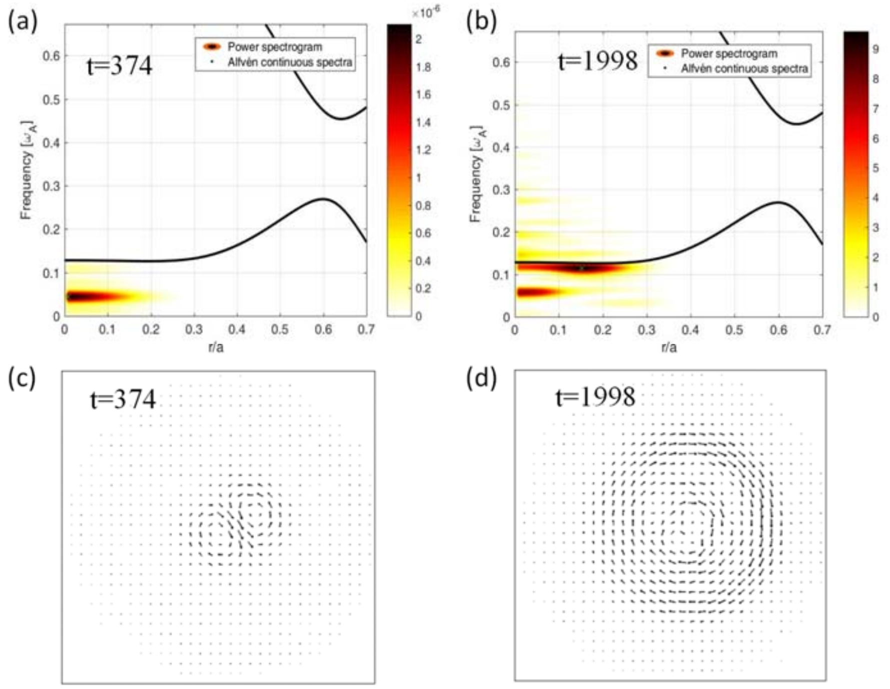


Figure 6. Radial structure of m/n=1/1 mode (a-b) and poloidal velocity profile (c-d) in linear and nonlinear stages of the mode with different time (a) t=374 and (b) t=1998, respectively.

3. TRIGGERING OF FISHBONE BY ECRH FOR ENHANCEMENT OF THE ITB

Control of MHD instabilities in a tokamak plasma is an important task from the point of view of future reactor operation. Initial scoping experiment were performed to obtain a enhanced ITB using electron cyclotron resonance heating (ECRH) of power up to 1MW. Due to the locality of ECRH, it is possible that the current profile in the core plasma will be redistributed by on-axis ECRH due to the change in the temperature and the subsequent change in the conductivity, i.e. the heating effect raises the local temperature, and hence the conductivity and the current density. The increase in current density in the core plasma region will raise the magnetic shear. The original aim was to change the central temperature and therefore the shear near the barrier in order to test the relation observed between the shear and fishbone activity. Indeed, the MHD feature changes significantly, in parts because of power but also because of the regime being triggered.

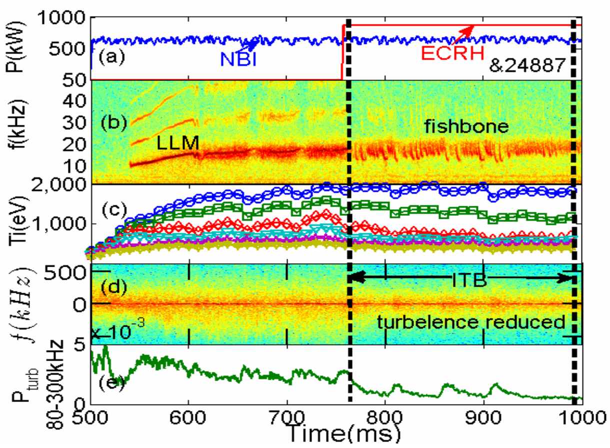


Figure7. (a)Evolution of spectrogram of the central soft-X ray signal, Ti, spectrogram of the density fluctuation and power of turbulence. (b)Evolution of temperature gradient.

Control of MHD activities during the ITB discharge has been studied. In the discharge of HL-2A #24887, the LLM behavior appeared from *t*=520ms which can be observed on soft x-ray signals in the NBI heating phase (fig.7). The appearance of LLM indicated that the central value of safety factor $q(0)<1$ is slightly greater than 1 and the shear is close to 0 but application of ECRH might increase the central shear slightly.

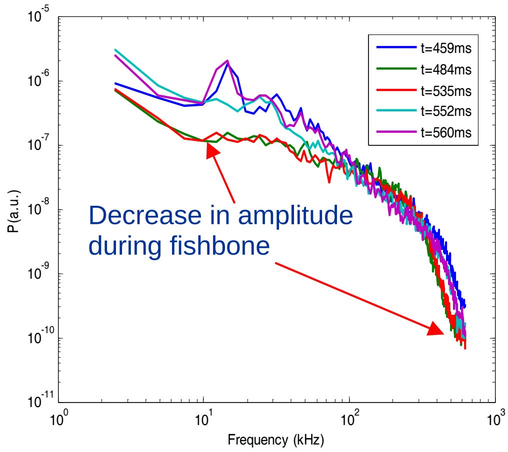


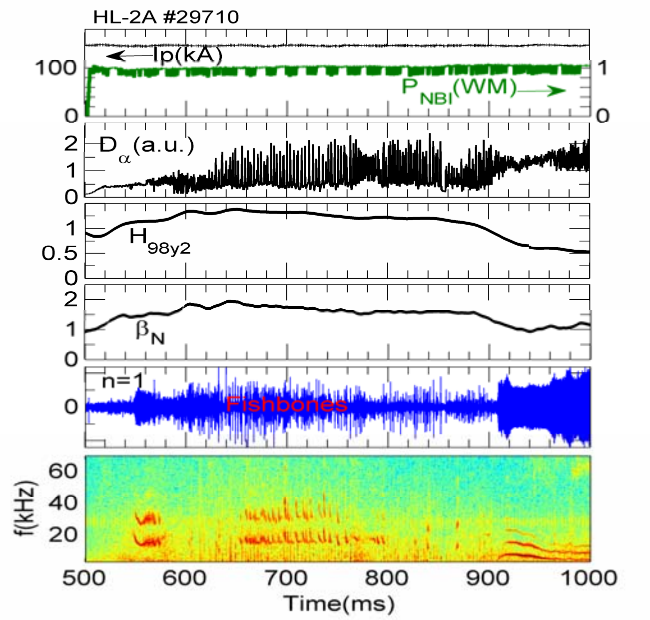
Figure8. Power spectrogram of density fluctuation at r/a=0.6 form reflectometry.

The LLM vanished after ECRH but another MHD activity, i.e. m/n=1/1 fishbone, appeared with a frequency of 3-5 kHz from 780ms to 1000ms during the ITB phase. The fishbone activity can be observed on SXR, ECE, <ne>, and mirnov signals. The 1/1 fishbone activity with frequency chipping down can be clearly observed in the spectra as shown in Figure 7. The presence of the m/n=1/1 fishbone implied $q(0)$ ~1, and leading to a enhanced ITB with much R/L_{Ti} higher than 20 or even up to 25. Figure 8 shows the power spectrogram of density fluctuation from reflectometry. A decrease in amplitude in density fluctuation both in low and high frequency region are observed during fishbone.

4. ITB DISCHARGES COMBINED WITH H MODE EDGE BARRIER AT LOW CENTRAL SHEAR

A stationary regime of operation has been found which shows improved core confinement of both electrons and ions, caused by an ITB in combination with an H mode edge. In Fig. 9, the main plasma parameters of such a discharge are illustrated. After the current flat-top is reached at t = 200ms moderate neutral beam heating of 1.0 MW is applied form t=500ms. ITB is observed and characterized by strong ion temperature peaking (figure 10). After 80ms, the plasma goes into H-mode and the high performance phase starts and lasts for 300ms, corresponding to about 20 confinement times.

This regime is accompanied by an n = 1, m = 1 fishbone activity and an improved energy and particle confinement. Central values of Ti = 1.5keV and Te = 1.0 keV, H_{98y2} = 1.5 and β_N = 2 at q_a = 3.1 are maintained for 300ms, limited only by the duration of the pulse length. In the ITB/H mode scenario, fishbone bursts and ELMs are seen to occur independently of each other. The (1,1) fishbones clamp the q value to the vicinity of 1 and avoid sawteeth, thus merging ITB and H-mode edge with ELM activity in steady state. ITBs in combination with an H mode edge barrier and a flat q profile with $q_{min}\geq 1$ and magnetic shear $s = r(dq/dr)/q\approx 0$ offer stationary, inductively driven H mode operation with enhanced performance in respect of confinement and β.



Figur9. Time evolution for a steady state discharges with ITB and H mode edge of plasma current (Ip), neutral beam heating (P_{NBI}), H factor (H_{98y2}), normalized β (β_N), divertor D_α radiation, line averaged density and central ion temperatures.

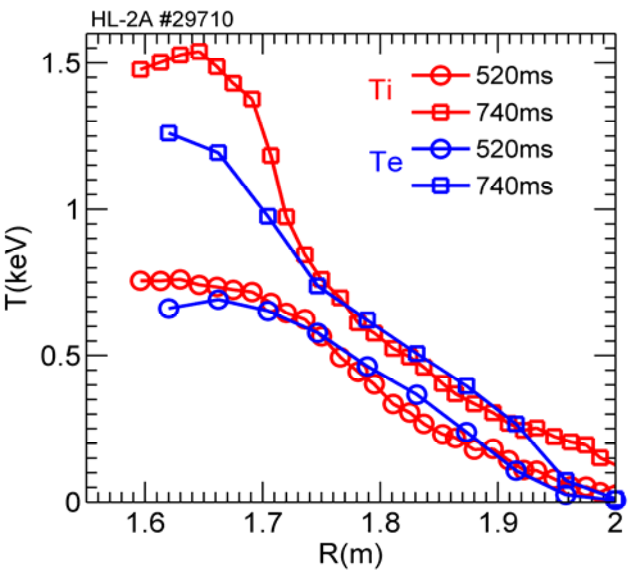


Figure10. Time evolution of the ion and electron temperature profiles for a discharge with ITB and H mode edge.

The profiles of the plasma temperatures, density and toroidal rotation velocity show, in addition to the H mode edge pedestal, an increase starting at ρ= 0.4. Thereby, the central Ti and the toroidal velocities are about a factor of 1.5 above the conventional sawtoothing ELMy H mode level (at the same discharge parameters). These differences are also reflected in the lower performance parameters of the conventional H mode discharge with H_{98y2} = 1.1 and β_N = 1.6. In the central regions of the plasma the ion thermal conductivity drops to neoclassical values, but the electron thermal conductivity is also at a low level, indicating that transport reduction is not limited to the ions as shown in figure 8(b). It suggests that MHD destabilized at the plasma core could provide the drive for bifurcation to improved core confinement. Its confinement performance and steady state (up to 10 confinement times) properties make it quite attractive for advanced tokamak regimes.

5. CONCLUSION AND DISCUSSION

The presence of *m*/*n*=1/1 fishbone instability implied a center flat *q* profile with *q*(0)~1 in ITB discharges with q_a=3.1-3.7. And indeed, it was found that the q-profile in the core remains flat or even hollow throughout the ITB period. Another possible explanation for the LLM or fishbone being able to trigger ITBs is that the interaction between MHD instabilities and fast ion leads to a redistribution of the resonant fast ion. Then, these fast ions stay in the outer region of the tokamak and increase the current density which reduces the q value there. The presence of the ITB and the reduced fluctuation there indicate that the shear is low enough to avoid ballooning modes. The lack of current profile measurement in the discharge prevented further analysis on this issue. In order to identify the ITB plasmas with central *q* profile, new experiment with current profile measurement has been performed on HL-2A tokamak.While the current profile clamping mechanism facilitates establishment of this scenario, active control by external current drive is required for steady state operation with low or reversed shear profiles. First experiments on ASDEX Upgrade using simultaneous strong central ion (NBI heating) and electron heating with ECRF in ITB limiter discharges definitely showed ITBs for both electrons and ions simultaneously, without detrimental effects on the reduced ion transport.

In summary, the internal transport barrier has been achieved by NBI heating in ELMy H-mode discharges on HL-2A tokamak. The location of ITB foot at ~0.5 was observed in ion temperature profile. Transport coefficients calculated by ONETWO code show obvious reduction after the ITB formation. It is speculated from the observation of 1/1 fishbone activity that a flat q profile with q(0)~1 in the central region and is confirmed by the new experimental measurement. The observation of ITB in ELMy H-mode discharges on HL-2A could be similar to the advanced tokamak experiments with ITB and flat central q profile in JET ELMy H-mode discharges. The understanding of β_N degradation and the change of *q* profile requires further study on HL-2A tokamak in the near future.

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6. **REFERENCES**

[1] T.S. Taylor Plasma Phys.Control.Fusion39 (1997) B47.
[2] I.T.Chapman et al Nucl. Fusion 50 (2010) 045007.
[3] K.L.Wong et al Nucl. Fusion 45 (2005)30-39
[4] S.Günter et al 2001 Nucl. Fusion 41 1283
[5] K Toi, et al Plasma Phys. Control. Fusion 53, 024008 (2011)
[6] D.L. Yu, et al Nucl. Fusion **56** (2016) 056003
[7] Deng Wei, Liu Yi et al Nucl. Fusion 54 (2014) 013010.
[8] Gruber O et al Nucl. Fusion 40 (2000) 1145.
[9] S.Günter et al 1999 Nucl. Fusion 39 1535
[10] Gunter, S., et al., Plasma Phys. Control. Fusion **41** (1999) B231.
[11] Y. Todo et al. POP 5 (1998) 1321;
[12] Y. Todo et al.POP 12 (2005) 012503;
[13] Y. Todo et al.POP 13 (2006) 082503