OVERVIEW OF HL-2A RECENT EXPERIMENTS

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Abstract

The mission of HL-2A is to explore the key physics topics relevant to ITER and the advanced tokamaks (e.g. the future HL-2M), such as the access of H-mode, energetic particle physics, edge-localized mode (ELM) mitigation/suppression and disruption mitigation. Since the 2016 Fusion Energy Conference, the HL-2A team has been focused on the investigations on the following areas: (i) pedestal dynamics and L-H transition, (ii) techniques and physics of ELM control, (iii) internal transport barriers (ITB) near q=1 surface, (iv) energetic particle physics and (v) the turbulence modulation by tearing mode (TM). The HL-2A results imply that the increase of the mean $E \times B$ shear flow plays a key role in triggering L-I and I-H transitions, which is mainly resulted from the ion pressure component. Both mitigation and suppression of ELMs have been realized by laser blow-off (LBO) seeded impurity (Ne, Ar, etc). The 30% Ne mixture supersonic molecular beam injection (SMBI) seeding also robustly induces ELM mitigation. The ELMs were mitigated by low-hybrid current drive (LHCD). HL-2A experiments suggest that the formation of the internal transport barrier (ITB) correlates to the evolution of $q_{min}$ (minimum of safety factor $q$) or the associated fishbone activities. The stabilization of $m/n=1/1$ ion fishbone activities by electron cyclotron resonance heating (ECRH) was found on the HL-2A. A new $m/n=2/1$ ion fishbone activities were observed recently, and the modelling indicates that passing fast ions dominantly contribute to the driving of 2/1 fishbone. The non-linear coupling between toroidal Alfven eigenmode (TAE) and tearing mode (TM) lead to the generation of a high frequency mode with $m=n$. It is found that the electrostatic turbulence is modulated by rotating $m/n=1/1$ TM islands in the core plasmas.

1. INTRODUCTION

The mission of HL-2A is to explore the key physics topics relevant to ITER and the advanced tokamaks (e.g. the future HL-2M), such as the access of H-mode, energetic particle physics, edge localized mode (ELM) mitigation/suppression and disruption mitigation. The HL-2A is a conventional tokamak with the major radius $R=1.65$ m and the minor radius $a=0.4$ m. The toroidal magnetic field, plasma current, and central line-averaged density are $B_t=1.3-2.7$ T, $I_p=150-430$ kA, and $n_0=(1-6) \times 10^{19} \text{ m}^{-3}$, respectively. The electron and ion temperatures are up to $T_e=5$ keV and $T_i=2.8$ keV, respectively. The auxiliary heating power was updated since 2016. The second NBI beamline was developed on HL-2A Tokamak. It has been operated since December 2017 and injected neutral beam into plasma since July 2018. Now the highest parameter for single ion source exceeds 15A×40kV, the total injection neutral beam power of this beamline exceeds 0.4 MW, and the total NBI injection power exceeds 1.2 MW in 2018 campaign. The low-hybrid wave (LHW)/current drive (LHCD)
power coupling is optimized using the Passive-Active Multi-junction (PAM) antenna, by which the coupled power has reached 1.4 MW (Fig.1) in H-mode plasma since 0.9 MW was coupled in 2016. These updates significantly enhance the capability for the studies on the advanced plasma physics on the HL-2A.

Since the 2016 Fusion Energy Conference, the HL-2A team has been focused on the investigations on the following areas: (i) pedestal dynamics and L-H transition, (ii) techniques and physics of ELM control, (iii) internal transport barriers (ITB) near q=1 surface, (iv) energetic particle physics and (v) the turbulence modulation by tearing mode (TM). The highlights of the experimental results are summarized in this paper, while the detailed descriptions can be found in the corresponding references.

2. PEDESTAL DYNAMICS AND L-H TRANSITION

In H-mode plasma of magnetically confined devices, the pedestal plays a key role in governing the performance of the core plasma by providing a boundary condition for the stiff core transport. To improve the plasma stability and confinement, it is important to study the pedestal dynamics and understand the underlying physics. This section reports the pedestal dynamics prior to ELM burst and the role of electric field shear in the L-I and L-H transitions.

2.1 Pedestal dynamics

In recent HL-2A H-mode plasma, the increases of density and its gradient were observed in the edge transport barrier prior to each ELM onset in a series. An inward particle flux induced by quasi-coherent mode (QCM) (f=30-70 kHz) was found to be responsible for such changes. The mode localizes in the pedestal, leads to the increase of density gradient, and has strong nonlinear interaction with the turbulence.

The phase 1 in Fig.2 is characterized by the evolution of the edge pedestal without distinct coherent fluctuation. The phase 2 is denoted by the shading area with a duration time about 300 ms. In this phase the coherent fluctuation gradually grows, saturates and starts to decay, and the mode is radially-localized with frequency ~ 30-70 kHz. The electron density keeps increasing until the end of this phase (Fig.2b), similar to the observation by microwave diagnostics. The $L_{ne}^{-1}$ increases abruptly at the end of this phase, while $L_{ne}^{+}$ decreases obviously (Fig.2c), keeping the $L_{pe}^{+}$ changing moderately (d). Here, $L_{ne}^{-1}$, $L_{ne}^{+}$, and $L_{pe}^{+}$ are the inverses gradient scale lengths of the electron temperature, density and the pressure, respectively. The QCM induced inward particle flux also increases firstly and then decreases (Fig.2e). The abrupt variations of electron temperature, density and particle flux indicate a dynamic transition of the plasma prior to the ELM onset. The most striking point here is that the inward particle is synchronized with the appearance of coherent mode, which can induce the particle transport channel coupling with the local density. Then the phase 3 follows, in which, the $D_{n}$ emission increases dramatically, $n_{e}$, $L_{ne}^{-}$, and $L_{pe}^{+}$ decrease rapidly, and the amplitude of the QCM also damps. This is a phase of recovery, which smoothly connects to the phase 1. More detailed experimental and theoretical investigations are needed to make a final conclusion on the instability that affects the pedestal dynamics[1].

2.2 L-H transition

In the pedestal region, the dynamics of the plasma flows, turbulence and pedestal formation across the L-I-H transitions was studied by using Doppler reflectometry [2]. Figure 3 shows the dynamics of shear flows and turbulence in the pedestal region. It indicates that the

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FIG.2. Temporal evolutions of $D_{n}$ and the density fluctuation (a), the pedestal density (b), the inverses gradient scale lengths of the density and electron temperature (c), electron pressure (d), and the particle flux induced by the QCM (e).

FIG.3. Time evolution of key parameters in the pedestal region (a) pedestal E, gradient, (b) GAM and LCO intensity, (c) turbulence intensity, (d) pedestal density gradient.
edge gradient of electric field \( |\partial E_r/\partial r| \) suddenly increases in the L-mode and reaches a maximum value before the plasma transits into the I-phase. Meanwhile, the turbulence intensity (Fig. 3(c)) decreases slightly. After the L-I transition, the intensity of GAM starts to decrease but the intensity of limit cycle oscillation (LCO) increases immediately (Fig. 3(b)) while the turbulence intensity drops, suggesting that the LCO oscillatory flow regulates the turbulence, leading to the increase of density gradient \( |\partial n_e/\partial r| \), as shown in Fig. 3(d). The intensity of LCO tends to decrease just prior to the I-H transition. It should be noted that the edge \( |\partial E_r/\partial r| \) increases abruptly during the decreasing phase of these two oscillatory flows, and at the same time, the pedestal turbulence intensity undergoes a significant decrease. The drop of the LCO intensity could be explained by the increase of the mean \( E \times B \) shear flow, which can reduce the turbulence, leading to the decrease of LCO intensity. Simultaneously, the \( |\partial n_e/\partial r| \) increases abruptly just before the I-H transition. All these observations suggest that mean \( E \times B \) shear flow is responsible for both L-I and I-H transitions.

However, since the time resolution of the Doppler reflectometer for calculating the Doppler shift is about 1 ms, it cannot be excluded that very short pulse of turbulence driven shear flow (<0.1 ms) can trigger L-H transitions as shown in DIII-D [3]. Now the key question is what is the physical mechanism for the increase of mean \( E \times B \) shear flow just before the two transitions. The results show that the abrupt increase of \( |\partial E_r/\partial r| \) observed prior to the L-I and I-H transitions is caused by the ion pressure component \( |\partial E^{\text{IP}}_r/\partial r| \), while the changes due to \( |\partial E^{\text{PH}}_r/\partial r| \) and \( |\partial E^{\text{other}}_r/\partial r| \) are negligible. The HL-2A results imply that the increase of the mean \( E \times B \) shear flow plays a key role in triggering L-I and I-H transitions, which is mainly resulted from the ion pressure component.

### 3 TECHNIQUES AND PHYSICS OF ELM CONTROL

Based on the advantages of the H-mode, it has been chosen over the other improved confinement modes as the primary operating scenario for ITER. However, the strong gradient of plasma edge pressure can trigger repetitive edge-localized modes (ELMs) which usually produce high transient heat loads on plasma facing components (PFCs). Over many years, intensive effort has been dedicated to finding an optimal and robust technique for heat load and ELM control. Especially, it is crucial to develop effective techniques to control ELM, in order to protect PFCs in burning plasma devices. This section presents the ELM control techniques applied on the HL-2A device.

#### 3.1 ELM mitigation by LHCD

![Figure 4](image)

**FIG.4.** A discharge of ELM mitigation experiment. (a) Plasma density (red dashed) and internal stored energy (blue solid); (b) the LHCD monitor signal (blue solid) and the ELM frequency (red solid square); (c) the bolometer signal; (d) the averaged radial wavenumber; (e) the pedestal turbulence intensity; (f) the radial wavenumber spectra before (blue solid) and during (red dashed) the ELM mitigation.
It is found for the first time that the type-III ELMs are mitigated by LHCD. A typical discharge of ELM mitigation experiment with LHCD is shown in Fig.4. The ELM mitigation phase is characterized by the increase of ELM frequency and the decrease of ELM amplitude. The averaged radial wavenumber $\overline{k}_r$ shifts from a large negative value (about $-1.5$ cm$^{-1}$) to zero during mitigation phase (Fig.4(d)). The negative value of $\overline{k}_r$ means that the turbulence radially propagates inward. The spectral shift process is also observed (Fig.4(f)). Besides, the turbulence intensity is enhanced during mitigation phase (Fig.4(e)). Thus, it suggests that the spectral shift process leads to the pedestal turbulence enhancement, which is responsible for the ELM mitigation.

In order to understand the mechanism of the turbulence enhancement during ELM mitigation, a turbulent heat transport model, based on the regulation of the turbulence amplitude by its radial wavenumber spectral shift caused by external velocity shear, has been developed. This external velocity shear can be produced from SMBI, impurity injection or LHCD. A typical computation result is given in Fig. 5. Both the heat source Q and the reduction value of the velocity shear U are induced by the external source inputted at $t=t_U$, see Fig.5(a). This external source input directly causes the variation of the velocity shear rate $\gamma_{E\times B}$, which then increases with the pressure gradient $\nabla P$, as shown in Fig.5(b). Meanwhile the averaged radial wavenumber $\overline{k}_r$ starts to increase with a time delay $\Delta t_k$ after the external source input, see Fig. 5(c). A longer time delay $\Delta t_k$ has been observed for a significant change of the turbulence intensity in Fig.5(d). Figure 5(e) displays a more detailed spectral shift process with the increase of turbulence amplitude. It could be concluded that after the external source input, the turbulence intensity is increased with the shift of radial averaged wavenumber toward zero, (the red dashed line in Fig.5(e)). Onwards, the turbulence intensity decreases with the averaged radial wavenumber $\overline{k}_r$ shifting back to a negative value due to the continuously increasing of $E \times B$ velocity shear. The simulation results indicate that the turbulence intensity can be regulated by the radial wavenumber spectral shift, which also have good agreement with the experimental results.

3.2 ELM mitigation/suppression by impurity

The study on the effect of impurities on plasma confinement and pedestal instabilities, including ELMs and turbulence has been recently emphasized [4,5,6,7]. Beneficial effect of the pedestal deposited impurity injected by laser blow-off (LBO) on ELM mitigation/suppression has been demonstrated in a controlled manner [31-7].

Both mitigation and suppression of ELMs have been realized by LBO-seeded impurity. It has been found that the occurrence of the ELM mitigation and ELM suppression sensitively depends on the LBO laser spot diameter. Measurements have shown that the LBO-seeded impurity particles are mainly deposited in the pedestal region. During the ELM mitigation phase, the pedestal density fluctuation is significantly increased, indicating that the ELM mitigation may be achieved by the enhancement of the pedestal transport. The transition from ELM
mitigation to ELM suppression was triggered when the number of the LBO-seeded impurity exceeds a threshold value.

During the ELM suppression phase, a harmonic coherent mode (HCM) is excited by the LBO-seeded impurity (Fig.6). The frequency range of HCM is from 10 to 100 kHz. More interestingly, the pedestal turbulence measured by the Doppler reflectometry is also nearly suppressed in the ELM suppression phase. Furthermore, it has been found that the strong interaction exists between different harmonics of HCM and background turbulence, and energy transfer can be transferred from the background turbulence to HCM. It suggests that HCM suppresses the pedestal turbulence, reduces the particle transport, and raises the plasma density. These suggest that HCM could extend the Peeling-Ballooning instability limit for ELM triggering, as predicted by theory. As shown by the present experiments, HCM can not only be spontaneously excited in H-mode plasmas, but also externally excited with impurity seeding. In the future our effort will focus on the investigation of the excitation mechanism of HCM.

Besides pure impurity gas (Ne, Ar, etc), one species of impurity gas is mixed with main ion fuelling gas D₂ by different ratio during SMBI on the HL-2A. The first experiment on heat load and ELM control with impurity mixture SMBI seeding has been carried out in H-mode plasmas in 2017. The impurity gases with different Ne ratios (10%, 30% and 100%) were seeded into the ELMy H-mode plasmas. It has been observed that the ELM behavior varied with the impurity ratio of the mixture SMBI. For 10% Ne mixture SMBI, ELMs can be mitigated and this mitigation effect is similar to that of the main ion fuelling D₂. For 30% Ne mixture SMBI seeding, the ELMs are replaced by high frequency bursts (HFBs) with smaller amplitude as seen from the Dα in Fig.7(d) and divertor radiation signals in Fig.7(e). The SMBI gradually increases the plasma density by ~10% in the ELMy H-mode (Fig. 7(b)). As expected, the total radiation power in Fig. 7(c) increases after the SMBI. The evolution of the inner stored energy in Fig. 7(f) shows that the global plasma confinement keeps almost constant. The time delay cross-correlation function was used to evaluate the correlation level between the divertor Dα signal and the electron densities during the occurrence of the HFBs. It indicates that the pedestal electron density is modulated by HFBs which originate from the pedestal region and propagates outwardly. HFBs enhance the pedestal particle transport and reduce the pedestal density gradient. In the present mixture SMBI seeding experiments, no impurity core accumulation was observed, and the plasma confinement was unaffected. The divertor heat flux and radiation power density is significantly reduced. The HFBs induce continuous and lower heat load instead of high transient heat bursts on the divertor plate. The peak heat flux of the HFBs is about 10% of that caused by the unaffected ELMs. However, the ELM frequency decreases by about 50% for the pure Ne seeding discharge. Similar effect induced by pure Ar seeding has also been observed in HL-2A. The HL-2A impurity seeding experiments shows that ELM activities changes with the ratio of the seeded impurity. It suggests that the impurity ions play a role in the pedestal dynamics.

3.3 ELM mitigation by RMP

Resonant magnetic perturbation (RMP) has been experimentally established as an efficient way of controlling
the ELM in H-mode tokamak plasmas. However, the ELM mitigation (but not suppression) is still of significant benefit in terms of reducing the peak heat flux load on the plasma facing components. ELM mitigation has been achieved in HL-2A. We employ MARS-F code to carry out the RMP computation based on the HL-2A experimental configuration. It is found that the edge-peeling response is the main reason leading to the ELM mitigation as discussed below.

A direct comparison is carried out between experiments and modelling for HL-2A. Here, a database of the experimentally measured ELM frequency for a series of RMP discharges was created, where the edge safety factor \( q_{95} \) is varied. In the range of \( q_{95} \) below 3.5, no ELM mitigation is achieved in HL-2A (with odd parity coil configuration). However, clear ELM mitigation is achieved when \( q_{95} > 3.6 \), with more than doubling of the ELM frequency in certain cases. In particular, the MARS-F modeling, based on the edge-peeling response model, predicts a mitigation window (Fig.8(b)) which is slightly shifted towards the lower range of \( q_{95} \). This may be partially due to the way the plasma equilibria are scanned in MARS-F, where only the total plasma current is varied, without modifying other equilibrium quantities such as the current profile and the plasma pressure. In experiments, these quantities may vary from shots to shots. Nevertheless, these MARS-F modeling results for HL-2A, though still not representing an exhausted study, already confirm the role of the edge-peeling response in the ELM mitigation that we have previously found in other devices [8].

4. INTERNAL TRANSPORT BARRIER (ITB) NEAR \( q=1 \) SURFACE

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 \( \beta \), and simultaneously, a large fraction of bootstrap current to minimize the power requirements from auxiliary heating systems. Plasma current density profiles in largely bootstrap current driven equilibria are generally broad resulting in reversed shear or low-shear safety factor profiles. However, the strong pressure gradients required for optimal fusion performance combined with these \( q \)-profiles usually cause deleterious MHD instabilities, leading to strong damping of core rotation and increasing of fast ion losses. Besides the above mentioned un-favorable role of MHD instabilities, they have been shown to be helpful in achieving improved confinement and quasi-stationary discharge conditions. MHD triggering internal transport barrier (ITB) was already observed at DIII-D, ASDEX-U and LHD. To extrapolate these improved regimes to larger sized tokamaks and reactors, it is essential to determine the triggering conditions to form an ITB and to study the associated physics. This section shows the progress of the understanding of the mechanism of ITM formation and the results about the kinetic electromagnetic instabilities in ITB plasmas.

4.1 Formation of ITB at low central magnetic shear

Recently, a kind of ITB has been observed during the nonlinear evolution of a saturated long-lived internal mode (LLM) in HL-2A discharges as the \( q \)-profile formed a very broad low-shear region with \( q_{\min} \sim 1 \). As shown in Figure 9(c), an ITB is formed with a steep ion temperature profile, which is measured by charge exchange spectroscopy. Such steep ion temperature-gradient zone locates around \( r/a=0.5-0.6 \) with \( T_i > T_e \). The observed normalized ion temperature gradient \( (R/L_i) \) is of 10.6, which exceeds the value for a level without ITB of ~6.5. Here, \( R \) is the major radius and \( L_i \) is the scale length of the \( T_i \) gradient defined by \( L_i = \alpha T_i / (dT_i/d\rho) \), where \( \alpha \) and \( \rho \) are the minor radius and the normalized minor radius, respectively. In fig. 9(a), one can observe chirping modes occur at the time of the ITB formation. When the barrier forms, the turbulence is significantly reduced around ITB foot \( r/a=0.6 \), as measured by reflectometry in figure 9(b). The simultaneous excitation of the ITB and the bursting internal mode can only occur if the \( q \)-profile in the core remains flat in the plasma central region. This implies the correlation between the central internal kink instabilities and the ITB formation in reversed or weak shear plasmas.

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 central MHD instabilities (LLM or fishbone) excited by energetic ions play a role in reducing the central magnetic shear via redistribution of energetic ions. 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. This fast ion redistribution process appears to be a good candidate for explaining the origin of the MHD triggering of ITBs in HL-2A discharges. It suggests that the MHD instabilities in the 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.

4.2 High-frequency coherent modes in ITB plasma

In HL-2A ITB plasma with weak magnetic shear, kinetic electromagnetic instabilities (e.g., AITG/KBM) had been confirmed and investigated. The experimental observations suggest that the stability of a high-frequency ($f = 80 - 200$ kHz) coherent modes (HFCMs) is relevant to the ITBs, and the strong $T_i$ gradients potentially have important effects on the HFCMs. Theoretical analysis by the extended general fishbone-like dispersion relation (GFLDR-E) reveals that the mode frequencies scale with the ion diamagnetic drift frequency, and confirms that HFCM is a kind of kinetic electromagnetic instabilities (e.g. Alfvénic ion temperature gradient (AITG)). These AITG modes are more unstable when the magnetic shear is weak in the low pressure gradient regions. The AITG/KBM equation also illuminates why the AITG modes can be unstable for weak shear and low pressure gradients. Here, KBM stands for kinetic ballooning mode. Low-n AITG modes exhibit thermal ion wave-particle interaction mediated by geodesic curvature coupling, and are thus observed in experiments due to the weak magnetic shear and the low pressure gradient. We provide clear experimental evidence of the AITG modes and complex plasma behaviors which are fully consistent with the theoretical framework. Furthermore, the observations reported in the previous work gave the first clear experimental identification of similar phenomenology in some high density ohmic plasmas with weak magnetic shear [9]. This experimental evidence paves the way to a more in-depth analysis of similar phenomena in fusion plasmas with non-perturbative energetic particle populations, with the suggestive possibility of controlling plasma performance by a careful choice of plasma profiles in the weak shear core region typical of burning fusion plasmas [10].

5. ENERGETIC PARTICLE PHYSICS

Studying the interaction of energetic particles (EPs) with collective modes is very important for burning plasmas, because these modes will degrade the confinement of the EPs, which are the plasma self-heating source in a fusion reactor. Moreover, these modes may play an important role in the thermal plasma confinement, helium ash removal, and alpha heating of the plasma. Here, we focused on the mode observation/identification, phase space dynamics, nonlinear mode-mode coupling, and mode suppression as well as multi-scale interaction among Alfvén mode and low frequency MHD mode.
5.1 Stabilization of m/n=1/1 fishbone by ECRH and the newly observed m/n=2/1 fishbone

The stabilization of m/n=1/1 ion fishbone activities by Electron Cyclotron Resonance Heating (ECRH) were found on HL-2A [11]. Here, \( m \) and \( n \) are the poloidal and toroidal mode numbers of an instability, respectively. The m/n=1/1 ion fishbone can be completely suppressed when the injected ECRH power exceeds a threshold (Fig.10). Figure 10 shows a typical experimental result. During NBI, the injected beam-ions stabilize the sawtooth and drive the fishbone instabilities. However after the high-power ECRH is switched on at \( t = 704\,\text{ms} \), the core electron temperature substantially increased, accompanied by a slight density drop. More crucially, the fishbone was completely stabilized. When the ECRH was switched off at \( t = 804\,\text{ms} \), the temperature and density began to change in the opposite direction, and the mode suppression lasted for another \( t_s = 30\,\text{ms} \), which is close to the energy confinement time \( (\tau_E) \). In fact, this experiment suggests that the high-power ECRH induces a sawtooth-free and fishbone-free operation regime during the NBI. Theoretical analysis by the fishbone dispersion relation, including the resistive effect, suggests that the magnetic Reynolds number plays a key role in the fishbone stabilization.

By scanning the ECRH configuration parameters, we found that the fishbone stability depends not only on the injected power, but also on the radial deposition position of ECRH. The fishbone can be completely suppressed, when the injected ECRH power level exceeds a certain threshold. As shown in Fig. 11, at the same power level (\( P_{\text{ECRH}} \approx 1\,\text{MW} \)), when the ECRH power is deposited on-axis (\( \rho \approx 0 \)), the observed mode frequency obviously decreases, but the mode amplitude is only weakly reduced. When the power is deposited outside of the \( q=1 \) rational surface (\( \rho \approx 0.38 \)), the mode is fully stabilized. When the power is deposited off-axis (\( \rho \approx 0.66 \)), the mode is partially stabilized. On the other hand, with the same deposition position (\( \rho \approx 0.42 \)), ECRH at low power (\( P_{\text{ECRH}} \approx 0.37\,\text{MW} \)) has hardly any stabilizing effect on the mode, whilst with increasing the power level, the mode is progressively suppressed, with the full stabilization achieved at about \( P_{\text{ECRH}} \approx 0.6\,\text{MW} \).
The m/n=2/1 ion fishbone activities were also observed recently (Fig.12). The appearance of m/n=2/1 fishbone is perfectly reproducible. Figure 12 shows a typical experimental result. In high NBI heating power P_{NBI} \sim 1\text{MW} and relatively low density plasmas of the line averaged density n_{e} \sim 1.0 \times 10^{19}\text{m}^{-3}, the sawtooth is absent. During the auxiliary heating the classical m/n=2/1 TM is unstable, with a slow rotation frequency (f < 2kHz) and propagating in the electron diamagnetic drift direction. The TM induces the large temperature oscillation, but the Mirnov signal has the small amplitude (|dBθ/dt| < 0.5) due to the slow rotation of magnetic islands. Specifically, it is found that an intense bursting mode is unstable in the presence of the slow rotation TM. The mode-numbers of this new mode are m/n=2/1. The mode frequency fast chirps downward within ∆t = 1\text{ms}. This mode propagates in the ion diamagnetic drift direction, and it is similar to the conventional fishbone instability on HL-2A. This phenomenon only occurs while the TM rotation direction changes from electron to ion diamagnetic drift. Otherwise, the m/n=2/1 fishbone does not appear. All experimental results indicate that the TM resonantly interacts with energetic-ions. Nonlinear hybrid kinetic-MHD simulations using M3D-K reveal that the co-passing energetic-ions are responsible for the driving of the 2/1 fishbone, and the wave-particle resonance condition is satisfied at \omega_{p} - 2\omega_{θ} - \omega = 0. Here, \omega_{p}, \omega_{θ} and \omega are the toroidal and poloidal projections of the transit frequency of passion particles, and the mode frequency, respectively [12]. Furthermore, TAEs and BAEs driven by energetic-electrons were found and investigated on the HL-2A [13].

5.2 Non-linear interaction between the AEs and TM

Multi-scale interactions among Alfven modes and low frequency MHD modes had been observed on the HL-2A during the NBI injection, including nonlinear couplings between TAE/BAE and m/n = 2/1 TM near q = 2 surface, between AITG/KBM/BAE and m/n = 1/1 kink mode near q = 1 surface, and between m/n = 1/1 kink mode and high-frequency turbulence. Here, TAE, BAE,AITG, and KBM stand for the toroidal Alfven eigenmode, beta induced Alfven eigenmode, Alfvenic ion temperature gradient mode, and kinetic ballooning mode, respectively. Experimental results suggest that several couplings can exist simultaneously. Alfvenic fluctuations have an important contribution to the high-frequency turbulence spectra, and the couplings reveal the electromagnetic character.

FIG.12. Typical m/n=2/1 ion fishbone activities on the HL-2A.

FIG.13. (a) The magnetic fluctuations spectrogram of discharge A. (b) Simulation obtained by Krook model. (c) Simulation based on Fokker-Plank model.
Multi-scale interactions via the nonlinear modulation process maybe enhance plasma transport and trigger sawtooth-crash onset [14].

TAE driven by energetic-ion had been observed on HL-2A. The toroidal mode numbers for most unstable TAEs are \( n=1\text{--}3 \). The TAEs were found to nonlinearly couple with TM and result in the appearances of series of Alfvénic modes (AMs). An axisymmetric mode within the ellipticity-induced frequency gap, driven by TAEs coupling with TM, was found for the first time. The squared bi-coherence suggests that two AMs with the same absolute number, but with different propagating directions respect to the diamagnetic drift, couple together and lead to the generation of a high frequency mode with \( n=0 \). The symmetrical mode with an ‘anti-ballooning’ feature was proved to be global Alfvén eigenmodes (GAE) [15].

5.3 Nonlinear wave-particle interaction

Nonlinear wave-particle interaction behaviors with chirping structures belongs to the chaotic regime are observed on the HL-2A. A Vlasov code, \( \delta f \)-COBBLES based on the so-called Berk–Breizman (BB) model, is applied to study the symmetric TAEs, with including Krook and Fokker-Plank collisional models. The analysis results suggest that the Fokker-Plank collision model yields better qualitative and quantitative agreement (Fig.13).

Spectrum of TAEs with main-downward frequency chirping reproduced by BOT with Fokker-Plank model shows a qualitative agreement with experimental observation. The interplay of diffusion and drag effect is essential to strengthen the clump movement, leading to fast ion distribution function clump-clump interactions. The main-downward chirping also shows that clump movement, which indicates energy transfer from wave to particle, is dominant. In many magnetic confinement devices, Alfvén modes were observed with stronger drive, which means main-downward chirping may be excited easier. It explains why main-downward chirping were observed more frequently [16].

6. MODULATION OF TURBULENCE BY TEARING MODE

It is well-known that magnetic islands formed in magnetically confined plasmas have significant influence on plasma profiles and cross-field transport. They are also considered to be key ingredients at the onset of plasma disruptions. In recent years the multi-scale interaction between large-scale modes and micro-scale turbulence has been found to play an important role in regulating turbulent transport and eventually for the transition from low to high confinement mode. Apparently, detailed studies of interaction between macro-scale tearing modes and micro-scale turbulence are essential for further understanding the tearing instability and the island-induced transport, which will ultimately lead to developing a better control of tearing mode and optimization of plasma performance in fusion devices, such as ITER. Here, we report the experimental observation of modulation of both temperature and density fluctuations by a tearing mode (TM) island in the core of the HL-2A tokamak.

Plotted in Figs. 14(a)-(c) are the temporal evolution of the ECEI signal measured inside, near, and outside the \( q=1 \) surface, respectively. It shows that when the X-point moves to the detection positions, the local \( T_e \) increases inside and nearby the \( q=1 \) surface, whereas outside that surface the local \( T_e \) decreases. In Figs. 14(a) and (c), the anti-phase behavior is seen between the \( T_e \) signals inside and outside the \( q=1 \) surface. Near the \( q=1 \) surface, the local \( T_e \) is roughly flattened across the O-point region, as shown in Fig. 14(b). As illustrated in [17], this flat \( T_e \) manifests the tearing mode feature, different from an ideal kink mode.

![Image](image_url)
Figures 14(d) and (e) further display the time history of electron temperature fluctuations $\tilde{T}_e$ (integrated from 20-100 kHz) measured at $R = 182.14$ cm and $Z = 3.46$ cm and chord-averaged electron density fluctuations $\tilde{n}_e$ passing through the island region (integrated from 50-300 kHz), respectively. The envelopes of the temperature and density fluctuations are calculated via the Hilbert transform and depicted by the red curves. The fluctuation amplitudes in $\tilde{T}_e$ and $\tilde{n}_e$ are both modulated during the rotation of the $m/n = 1/1$ island, i.e., minimum at the O-point and maximum at the X-point. The modulation on the envelopes is approximately in phase with the interchange of the O- and X-point, consistent with gradient-driven turbulence since in the O-point region the local $T_e$ or $n_e$ gradient is the minimum. Such a modulation can also be seen in the frequency spectrum of the temperature and density signals.

In addition, highly resolved 2D ECEI measurements show the first evidence that the turbulence modulation occurs solely for large islands and the modulation takes place only in the inner half area of the island due to significant alteration of local profiles and turbulence drives between the X- and O-point. Bi-spectrum analysis indicates strong nonlinear coupling between tearing mode and broadband turbulence. Experimental evidence also reveals that for large islands turbulence spreading takes place across the flatten O-point at the inner half island region. In the zone of the outer half island, the local $T_e$ and O-point are nearly equivalent, and hence, without modulating local turbulence [18].

7. SUMMARY

Since the 2016 Fusion Energy Conference, the HL-2A team has achieved significant progress in the areas of pedestal dynamics and L-H transition, ELM control, ITB physics, energetic particle physics and the turbulence modulation by TM relevant to the HL-2A experiments as summarized below.

(i) HL-2A experimental results imply that the increase of the mean $E \times B$ shear flow plays a key role in triggering L-H and I-H transitions, which is mainly resulted from the ion pressure component. On the HL-2A, an inward particle flux induced by quasi-coherent mode (QCM) was found to be responsible for the increases of density and its gradient in the edge transport barrier prior to each ELM.

(ii) The ELMs are mitigated by LHCD, because of the regulation of turbulence intensity by the radial wavenumber spectral shift during LHCD. Both mitigation and suppression of ELMs have also been realized by LBO-seeded impurity. Furthermore, the 30% Ne mixture SMBI seeding robustly induces the ELM mitigation, and peak heat flux for the mitigation case is about 10% of that caused by the un-mitigated ELMs. The MARS-F modelling results for HL-2A confirm the role of the edge-peeling response in the ELM mitigation, which is consistent with the experimental observation.

(iii) In HL-2A, advanced tokamak scenario with a weak magnetic shear in the plasma centre has been achieved. The analysis of ITB triggering reveals a correlation between the formation of the ITB and $q_{min}$ reaching an integer value ($q = 1$) or fishbone activity. Moreover, in HL-2A ITB plasma with weak magnetic shear, kinetic electromagnetic instabilities (e.g., AITG/KBM) had been confirmed and investigated.

(iv) The stabilization of $m/n = 1/1$ ion fishbone activities by ECRH were found on the HL-2A. A new $m/n = 2/1$ ion fishbone activities were observed recently, and the modelling indicates that passing fast ions dominantly contribute to the driving of 2/1 fishbone. The non-linear coupling between TAE and TM lead to the generation of a high frequency mode with $n = 0$. Nonlinear wave-particle interaction behaviors with chirping structures belongs to the chaotic regime are observed on the HL-2A.

(v) On the HL-2A tokamak, we found the modulation of electrostatic turbulence by rotating $m/n = 1/1$ TM islands in the core plasmas. Highly resolved 2D ECEI measurements show the first evidence that the turbulence modulation occurs solely for large islands and the modulation takes place only in the inner half area of the island due to significant alteration of local profiles and turbulence drives between the X- and O-point.

In addition, several new diagnostics are recently updated and developed. A CO$_2$ dispersion interferometer [18] and a high sensitivity far-infrared laser interferometer [19] were developed for measuring the line-averaged density in time. The diagnostics for measuring density fluctuation were developed, including Phase Contrast Imaging (PCI) [20-22], Beam Emission Spectroscopy (BES) [23, 24] and He Gas-Puss-Imaging (He-GPI)[25]. Coherence Imaging Spectroscopy (CIS) was developed to monitor the 2D flow distribution. A new CO$_2$ laser
collective Thomson scattering system was developed to measure high-k turbulence in the core plasma on the HL-2A. The analysis of some experimental data obtained by the above diagnostics is being carried out and, the associated physical results will be shown in future.

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