ELM Control Physics with Impurity Seeding and LHCD in the HL-2A Tokamak

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Abstract

ELM control with impurity seeding and lower hybrid current drive (LHCD) have been achieved in the HL-2A tokamak. The divertor peak heat load released by ELM has been significantly reduced during the mitigation phase. It has been found that the mitigation of ELMs in these experiments is due to the pedestal turbulence enhancement generated by the external source induced. The E×B velocity shear induced by LHCD and impurity seeding modifies the turbulence radial wavenumber (k_r) spectrum by varying the averaged radial wavenumber from large negative value to zero, reducing the turbulence dissipation term (∼k²). A modified turbulence spectral shift model has been used to simulate the experimental observations. A critical growth rate γ are the turbulence regulation is identified in this model and experimentally determined. Good agreement has been found between experiment and theory for the regulation of the turbulence intensity by its averaged radial wavenumber.

1. INTRODUCTION

Ever since the first attempt of high confinement mode (H-mode) on ASDEX [1], intensive investigations have been carried out in the past three decades, because it is regarded as a standard operation scenario envisaged for future reactors, such as the international tokamak experimental reactor (ITER) [2]. H-mode is generally accessed through the formation of an edge transport barrier (ETB) with sharp plasma pressure gradient, also referred to as H mode pedestal, due to the turbulence suppression by the edge E×B velocity shear [3,4]. This leads to steep pedestal pressure gradient and strong self-driven plasma currents, which can drive magnetohydrodynamic instabilities, known as edge localized modes (ELMs) [5,6]. These ELMs generate transient confinement collapses, and produce large, repetitive particles and heat bursts loading to divertor plate. Simulations and scaling have predicted that in large magnetic fusion reactor like, the divertor heat flux caused by large ELMs would be far beyond the material limitation and can cause severe erosion on plasma facing components [2, 7]. Thus, understanding physics of ELM control and reducing large heat load impulses released by ELMs are therefore crucial issues in tokamak fusion research.

Several techniques for ELM mitigation have been developed, such as resonance magnetic perturbations (RMPs) [8], pellet pacing [9], supersonic molecular beam injection (SMBI) [10]. Recently, experimental observations show that the lower hybrid current drive (LHCD) and impurity seeding are also effective for ELM mitigation [11, 12]. In the LHCD experiments, the ELM mitigation was interpreted as the consequence of the ergodization of the edge magnetic topology, produced by LHCD induced helical current filaments in the scrape-off layer, like RMPs [12]. Then the experimental results in HL-2A show that the ELM mitigation is strongly correlated to the pedestal turbulence enhancement [13], pointing out the key role of the pedestal turbulent transport in the ELM mitigation. Similar role has been found in the impurity seeding experiments in HL-2A [11].

Turbulence suppression by E × B velocity shear was firstly attributed to the decorrelation mechanism [14, 15]. However, gyro-kinetic simulation showed that the effect of the EB velocity shear on the turbulence amplitude was much stronger than that predicted by the decorrelation formula [16]. Then a quench rule for the turbulence amplitude reduction by EB velocity shear was introduced [16, 17], and successfully used in interpreting linear drift wave stability calculations and in validation of quasilinear transport models with experiment [18]. Later it had been shown that the quench rule was incomplete to correctly calculate the toroidal Reynolds stress induced by E×B velocity shear [19, 20]. A new approach with the radial wavenumber spectral shift was proposed for EB velocity shear suppression of the turbulence, and it fitted the gyro-kinetic simulation results much better [21, 22].
This spectral shift analytical model combining with a thermal transport equation was used to explain the fast L-H transition [23]. In this paper, the experimental setup is briefly introduced in section 2. The experimental results of ELM control with impurity seeding and LHCD are reported in section 3. A modified theoretical model, based on the regulation of the turbulence by its radial wavenumber spectral shift due to the externally driven E×B velocity shear, is described and its proprieties are presented in section 4. Quantitative comparisons are also made between the experimental data and simulation results in this section. Section 5 is the conclusion.

2. EXPERIMENTAL SETUP

In the present experiments in the HL-2A tokamak, the plasma parameters are: major radius $R=1.65m$, minor radius $a=0.4m$, the toroidal magnetic field $B_t=1.3T$, the plasma current $I_p\approx145$ kA, the plasma line averaged density $\bar{n}_e \approx 1.5 - 3.2 \times 10^{19}m^{-3}$. The auxiliary heating power for neutron beam injection is $P_{NBI}=1$ MW. Lower hybrid wave system is fed by four 3.7GHz klystrons with the passive-active multi-junction (PAM) launcher, and the available power is 1.0 MW for 1 s., and the LHCD absorbed power is 250-600 kW. Density profile is measured by a broad band reflectometer in X mode. The electron density profile is measured with an eight-chord HCN laser interferometer ($\lambda=337 \mu m$) [24] and the edge density profile is measured with frequency modulated continuous microwave reflectometers (MR) [25]. Density fluctuations and the poloidal plasma rotation velocity are simultaneously measured by Doppler reflectometer [26, 27]. The electron temperature is measured by the electron cyclotron emission (ECE) radimeter [28, 29]. The ion temperature is measured by a charge exchange recombination spectroscopy (CXR) with 32 channels [30]. A set of infrared camera system has been installed to monitor the surface temperature of the outer divertor plate. The plasma radiation power is measured by an array of bolometer [31]. Line emission is measured by an extreme ultraviolet (EUV) spectrometer [32]. Soft x-ray emission is detected by soft x-ray cameras with 25μm Beryllium (Be) filters.

A laser blow-off (LBO) impurity injection system has been built for HL-2A [33, 34]. A YAG laser with a pulse length of 10 ns and the wavelength of 1064 nm is employed for the LBO system. Its energy can reach up to 2 J. The target metal material is deposited onto a 42 mm×42 mm×2 mm quartz substrate with the thickness of several microns. The target plate is placed inside a vacuum tube located at the mid-plane diagnostic port of HL-2A, of which the position is approximately 710 mm away from the plasma boundary. The diameter of the LBO laser spot can be changed in the range of 2-6 mm. The LBO system has following advantages for impurity injection: (1) well-controlled injected particle quantity; (2) localized deposition of the injected particles; (3) precise control of injection time. Different fuelling tools have been used to control the density profile: gas puffing (GP) from the low/high-field side (LFS/HFS), SMBI from the LFS and HFS, and pellet injection (PI) from the LFS mid-plane. Particularly, SMBI is widely used and considered to be an improvement over conventional GP for its high fuelling [35].

3. EXPERIMENTAL OBSERVATIONS

ELM mitigation with LHCD has been achieved in the HL-2A tokamak for plasma density higher than $\bar{n}_e \approx 2.5 \times 10^{19}m^{-3}$ and LHCD absorbed power larger than $P_{LHCD}=300$ kW. The divertor peak heat load induced by ELM has been significantly reduced during the mitigation phase [13]. The ELMs are represented by the spikes in the bolometer signal (Fig.1c). The ELM frequency shown in Fig.1b is defined by the reciprocal of the interval of two consecutive ELMs. The ELM mitigation is characterized by the ELM frequency increase and its amplitude decrease as shown in Fig.1b and Fig.1c, respectively. The radial wavenumber spectrum is obtained by radial correlation with multi-channel Doppler reflectometry. The averaged radial wavenumber $\bar{k}_r$ is -1.5 cm$^{-1}$ before the mitigation and -0.13 cm$^{-1}$, which is very close to zero, during the mitigation as shown in Fig.1f. The negative value of $\bar{k}_r$ means that the turbulence radially propagates inward. Fig.1d and Fig.1e present the time evolution of $\bar{k}_r$ and the pedestal turbulence intensity calculated by integrating the frequency power spectrum, respectively. The $k_r$-spectrum of the pedestal turbulence is shifted from large negative value to zero during the ELM mitigation. It is very clear that the ELM mitigation is desynchronized with the LHCD pulse, but closely correlated to the pedestal turbulence enhancement (Fig.1e). A severe decrease of the pedestal $ExB$ velocity shear was observed with LHCD switching on as shown in Fig.1g, while the ion pressure gradient remains nearly constant.
Fig. 1. H-mode discharge triggered by neutral beam heating (~1 MW) with ELMs mitigated by LHCD (plasma current 145 kA, toroidal field 1.3T, major radius 1.65 m, minor radius 0.4 m). (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 pedestal turbulence \( k_r \) spectrogram and the averaged radial wavenumber (white dashed); (e) the pedestal turbulence intensity; (f) the radial wavenumber spectra before (blue solid) and during (red dashed) the ELM mitigation; (g) the \( \mathbf{E} \times \mathbf{B} \) velocity shear (red solid circle) and the ion pressure gradient \( \nabla P_i \) (blue solid square). [37]

Fig. 2(a) is the absorbed LHCD power in the plasma, and Fig. 2(b) is the bolometer signal at the plasma edge, in which the spikes manifest the activities of ELMs. In Fig. 2(c) the time trace of heat flux peak is presented. Fig. 2(d) represents the profile of the divertor heat flux in the vertical direction for no mitigation (blue dashed line) and mitigation (red solid line) case respectively. The divertor heat flux peak in low field side during mitigation period is relatively small shown in Fig. 2(c). As the temporal resolution of the infrared camera system is about 0.84 ms, which is larger than the ELM peak rising time, the value of the spikes in Fig. 2(c) do not represent the actual value of the ELM driven heat flux peak. However, a conclusion about the divertor heat flux can be drawn: the maximum heat flux peak during ELM mitigation is reduced at least by a factor of 4. Fig. 2(d) shows a strong reduction of the divertor heat flux during ELM mitigation over all profile. These illustrate the high efficiency of LHCD for reducing the divertor heat flux. [13]

Fig. 2. Time evolution of the absorbed LHCD power (a), the edge bolometer signal (b), and the divertor heat flux peak in low field side (c). (d) represents the profile of the divertor heat flux in the vertical direction before (blue dashed line) and during (red solid line) ELM mitigation. [13]
Previous results of ELM mitigation with LBO seem to indicate that the occurrence of the ELM mitigation depend on the quantity of electron injected with seeded impurity, or Zeff of the impurity. Therefore, ELMs can be controlled by regulating the quantity [11]. Further analysis shows that the velocity shear induced by LBO is also a crucial issue, which is similar to the observations of ELM mitigation with LHCD. Fig.3 shows the Time evolution of the radial profile of plasma radiation power density for shot 29301. It can be observed that there is a sharp variation in the radiation power density and the maximum amplitude is located at minus radial $a = 0.36 \text{m}$, Thus, the spontaneous impurity is deposited mainly around $a=0.36m$. The pedestal bottom is determined by data from the reflectometry. This indicates that the injected spontaneous impurity particles penetrate the pedestal region, as shown in Fig.3.

**FIG. 3.** Time evolution of the radial profile of plasma radiation power density for shot 29301. (a) and (b) Are the contour map and the 3D profile of the plasma radiation power density, respectively. The pedestal bottom is determined by measurements of the reflectometry. [32]

**FIG. 4.** H-mode discharge with ELMs mitigated by LBO impurity seeding. (a) the bolometer signal, (b) the ELM frequency; (c) the $E\times B$ velocity shear; (d) the pedestal turbulence $k_r$ spectrogram ($\log(S_k)$); (e) the pedestal turbulence intensity; (f) the radial wavenumber spectra before (blue solid) and during (red dashed) the ELM mitigation.

Fig.4 is the H-mode discharge with ELMs mitigated by LBO impurity seeding. The ELM mitigation is characterized by the ELM frequency increase and its amplitude decrease as shown in Fig.4b and Fig.4a, respectively. After LBO impurity injection, the $E\times B$ velocity shear decrease sharply as shown in Fig.4c. Similar to what has been observed in the LHCD experiment, the wavenumber spectral shift is observed. The radial wavenumber spectrum from multi-channel Doppler reflectometry in Fig.4d and Fig.4f shows that the averaged radial wavenumber $\overline{k}_r$ is about $-2.75 \text{cm}^{-1}$ before the mitigation and $-1 \text{cm}^{-1}$ during the mitigation. At this moment, the turbulence intensity is enhanced. The experimental results of ELM mitigation with impurity seeding further indicate that the turbulence enhancement by $E\times B$ velocity shear induced turbulence radial wavenumber spectral shift is responsible for the ELM mitigation.
4. TURBULENCE REGULATION THEORY

From the above experimental observations, a plausible mechanism for ELM mitigation can be inferred: the application of LHCD induces an edge $E \times B$ velocity shear reduction, and with some time delay a radial wavenumber spectrum spectral shift of the pedestal turbulence is produced when the $E \times B$ velocity shear reduction exceeds a critical value; then due to this spectral shift, the pedestal turbulence intensity starts to increase, causing a reduction of the pedestal pressure gradient, which is responsible for the ELM mitigation. To understand the mechanism of the turbulence enhancement during ELM mitigation, a theoretical model, based on the regulation of the turbulence amplitude by its radial wavenumber spectral shift caused by externally driven $E \times B$ velocity shear, has been developed. The modified spectral shift model includes a nonlinear equation describing the evolution of the turbulence amplitude [21, 22], a thermal transport equation [23] and a velocity shear equation derived from the radial force balance equation with external source input, as described in the following equations:

$$\frac{\partial \phi}{\partial t} = \gamma_k \phi + \gamma_{E \times B} k_\phi \phi / (\partial k_2) - \left( c_k k_2^2 + c_k k_2^2 \right) \phi^2 + D(\phi^2)/(\partial k_2)$$  \hspace{1cm} (1)

$$\frac{\partial |\nabla p|}{\partial t} = Q - (\chi + \chi_0)|\nabla p|$$  \hspace{1cm} (2)

$$\gamma_{E \times B} = a|\nabla p| + U_0 - U$$  \hspace{1cm} (3)

In Eq.(1), $\phi$ represents the magnetic flux surface averaged Fourier amplitude of the turbulence, donated by $\phi = \left| e \phi_{k_\phi,k_2}/T_e \right|^{1/2}$ $a/\rho_s$, where the poloidal wavenumber $k_y = k_\phi \rho_s$ and the radial wavenumber $k_x = k_r \rho_s$. Here, $\rho_s = c_i/\Omega_i$ is the gyration radius, $c_i = \sqrt{T_i/m_i}$ is the sound speed, $\Omega_i = eB/m_i$ is the ion gyration frequency, $\gamma_{k_y}$ is the linear growth rate of the most unstable mode. $\gamma_{E \times B}$ is the $E \times B$ shear velocity shear rate $\left(\gamma_{E \times B} = \left(\tau/\delta \tilde{E} \cdot \tilde{B}(q q / \tilde{r})/\tilde{r}\right)\right)$. The coefficients $c_x, c_y$ determine the strength of dissipation and the time scale for turbulence suppression. $D$ is the turbulence intensity in phase space. In Eq.(2), $|\nabla P|$ is the pressure gradient, $Q$ is the heat flux source, $\chi_0$ is the residual thermal diffusivity, $\chi = 1/2k_{\phi \text{max}}$ is the turbulence-driven thermal diffusivity. In Eq.(3), $a$ is assumed to be constant for linear simplified relation between pressure gradient and velocity shear rate. $U_0$ is the plasma own velocity shear rate, and $U$ represents the values of the reduction of the velocity shear rate caused by the external source input. In this work, $U_0$ is assumed to be zero. $\alpha = 0.837$, the parameters such as $\phi = \left| e \phi_{k_\phi,k_2}/T_e \right|^{1/2}$ $a/\rho_s$, $\chi_0$ and $D$, are normalized with the typical value in the HL-2A tokamak. Thus, the electron temperature at pedestal foot $T_e = 600 \text{kV}, k_y = 0.1, \chi_0 = 5 \times 10^{-4}, D = 0.001, c_i = 500, c_s = 1000$. Besides, all growth rates and shear rates are normalized to $\tau = c_i/\alpha = 6.5 \mu s$. The expression of $\gamma_{k_y}$ depends on the nature of the mode. In this simulation, the ion temperature gradient driven mode (ITG) is considered, and the growth rate of the most unstable mode is given by $\gamma_{k_y} = A|\nabla P|^{1/2} \cos(\theta_a)$ [24]. Here, $A$ is a constant parameter ($A=4$), the ballooning angle of the most unstable mode $\theta_a \approx \delta^{1/3}$ is the maximum tilted poloidal angle with $\delta = \gamma_{E \times B}/(2sA|\nabla P|^{1/2}), s$ is the magnetic shear and $s \approx 2$ in this simulation.

To understand the mechanism of the turbulence enhancement during ELM mitigation, a theoretical 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 [5]. This external velocity shear can be from SMBI, impurity injection or LHCD. A typical simulation result is given in Fig.5. The heat source $Q$ and the reduction value of the velocity shear $U$ are both induced by the external source input at time $t=t_c$ (Fig.5a). 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.5b. Meanwhile the averaged radial wavenumber $\bar{k}_r$ starts to increase with a time delay $\Delta t_0$ after the external source input (Fig.5c). A longer time delay $\Delta t_0$ has been observed for a significant change of the turbulence intensity (Fig.5d). Fig.4e display 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 (as shown by the blue solid line to the red dashed line in Fig.5c). Onwards, the turbulence intensity decreases with the averaged radial wavenumber $\bar{k}_r$, 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.
Fig. 5. (a) Heat source $Q$ and the reduction value of the $E \times B$ velocity shear rate $U$; (b) the pressure gradient $\nabla P$ and the velocity shear rate $\gamma_{E \times B}$; (c) the averaged radial wavenumber $\bar{K}_x$; (d) the turbulence intensity $I_\Phi$. (e) $k$-spectrum shift. [37]

Fig. 6 shows the dependence of $\Delta t_k$ in function of $U$. This figure clearly indicates that there exists a critical value of $U$ for triggering the variation of $\bar{K}_x$. This threshold value $U_c$ is indicated by the dashed line in Fig. 6. By fitting the simulation points, an analytical expression has been found for the relationship between $\Delta t_k$ and $U$: $\Delta t_k = 0.6(U - U_c)^{-0.4}$.

Fig. 6. Time delay $\Delta t_k$ vs the externally driven velocity shear rate $U$. [37]

Intuitively, the appearance of $\Delta t_k$ depends strongly on the accumulative effect of the velocity shear. For this reason, the integral of the velocity shear rate $Y = \int_{t_U}^{t_U+\Delta t_k} \gamma_{E \times B} dt$ is plotted in function of $\Delta t_k$ in Fig. 7a. A linear

Fig. 7. (a) Integral of the shear effect $Y$ vs $\Delta t_k$. (b) Relationship between the $U_c$ and $\gamma_0$. [37]
A relationship is found between $Y$ and $\Delta t_k$, which can be described as: $\int_{t_U}^{t_U+\Delta t_k} \gamma_{E\times B} dt = \gamma_0 \Delta t_k - b$, where $\gamma_0 = 2.02$ and $b = 1.82$. This equation can be put under the following form: $\int_{t_U}^{t_U+\Delta t_k} (\gamma_0 - \gamma_{E\times B}) dt = b$. The criterion for triggering the spectral shift and the turbulence enhancement can be deduced via the following function: $Z(t) = \int_{t_U}^{t_U+\Delta t_k} (\gamma_0 - \gamma_{E\times B}) dt$. If $Z(t) < b$ for any $t$, there is no spectral shift, thus no turbulence enhancement; the radial wavenumber spectrum starts to shift only when there exists $\Delta t_k$ verifying $Z(t_U+\Delta t_k) > b$. The constant parameter $\gamma_0$ represents the critical growth rate for the turbulence regulation. Simulations with parameter scan have shown that $\gamma_0$ is closely linked to $k_y$ and $\gamma_{k_y}$, but independent of parameters such as $\alpha$, $D$, $c_y$, $c_x$, $t_U$ [25]. It should be emphasized that $\gamma_0$ plays an essential role for the turbulence regulation by $E\times B$ velocity shear induced spectral shift. Experimental data corresponding to 4 cases of the ELM mitigation, represented by the red solid circles, have been added in Fig.7a. These points match very well with the simulation results, confirming the linearity between $Y$ and $\Delta t_k$. This allows the experimental determination of the constant parameter $\gamma_0$. Fig.7b plots $U_c$ as a function of $\gamma_0$, showing a linear relationship between them: $U_c = 0.63 \gamma_0 - 0.22$. This indicates that the threshold $U_c$ is directly related to $\gamma_0$, and does not depend on the external source input. Fig.8 plots the turbulence intensity $I_{\Phi}$ as function of $k_r$. The red dashed line is the simulation results, showing that the turbulence intensity increasing along with the $k_r$ spectrum shifting to zero. The blue solid circles represent the experimental data. Good agreement has been found between experimental data and simulation results.

5. CONCLUSION

In conclusion, the ELM mitigation has been achieved with both LBO impurity seeding and LHCD. A strong reduction of the pedestal EB velocity shear could be immediately induced by LHCD or LBO impurity seeding. Then with some delay but prior to the pedestal turbulence enhancement, the pedestal turbulence radial wavenumber spectrum is shifted from negative value toward zero. A modified turbulence radial wavenumber spectral shift model has been successfully used to simulate the experimental results. The results show that the radial wavenumber spectrum of the turbulence is shifted from large negative value to zero due to the external source input. As the radial wavenumber shift to zero, the turbulence dissipation term ($\sim k_r^2$) would decreases, and then leads to the pedestal turbulence enhancement, which is responsible for the ELM mitigation. A critical growth rate $\gamma_0$ for the turbulence regulation has been identified in this model, then experimentally determined. Besides, good agreement has been found between experiment and theory for the regulation of the turbulence amplitude with its averaged radial wavenumber. It should be noted that it is possible to use this theoretical approach for analysing the turbulence regulation by the velocity shear modification with other external source input techniques, such as NBI and SMBI.
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