Turbulence Regulation with Radial Wavenumber Spectral Shift Caused by LHCD Induced Velocity Shear during ELM Mitigation

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Simulations and scaling have predicted that in magnetic fusion reactor as ITER, the divertor heat flux caused by large ELMs are far beyond the material limitation, and can cause severe erosion on plasma facing components. Thus control of large heat load impulses released by ELMs on the divertor target is a crucial issue in tokamaks. Hence, effective techniques are highly desirable to achieve external control of the ELM size and the heat load. Techniques for ELM mitigation have been developed, such as RMPs [1], pellet pacing [2], SMBI [3], impurity seeding [4]. Recently lower hybrid current drive (LHCD) has been shown to be a new effective method for ELM mitigation [5]. Nevertheless, the reliability of these methods still needs to be demonstrated, and the understanding of the mechanism requires further investigation.

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_0=1.3T, the plasma current $I_p \approx 145$ kA, the plasma line averaged density $\bar{n}_e \approx 1.5-3.2\times 10^{19}\ \mathrm{m}^{-3}$. The auxiliary heating power for neutron beam injection is P_{NBI}=1MW. Lower hybrid wave system is fed by four 3.7GHz klystrons with the passive-active multi-junction (PAM) launcher, and the LHCD absorbed power P_{LH} is 250-600kW. Density profile is measured by a broad band reflectometer in X mode. The electron temperature is measured by electron cyclotron emission (ECE) radiometer. The ion temperature and the plasma toroidal rotation velocity are measured by charge exchange recombination spectroscopy (CXRS). Density fluctuations and the $E\times B$ plasma rotation velocity $V_{E\times B}$ are simultaneously measured by Doppler reflectometer. 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.

ELM mitigation with LHCD has been achieved in the HL-2A tokamak for plasma density higher than n_e=2.5×10^{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 [6]. In Fig.1(c), the spikes in the bolometer signal represent ELMs. Fig.1(b) displays the ELM frequency f_{ELM}, which is defined by the reciprocal of the interval of two consecutive ELMs. The ELM mitigation is characterized by the ELM frequency increase and the ELM amplitude decrease. A severe decrease of the pedestal velocity shear (shear flow) has been observed when LHCD switches on as shown in Fig.2, while the k_r-spectrum of the pedestal turbulence is shifted toward the origin (Fig.1(d)). It has been found that the ELM mitigation is desynchronized with LHCD pulse, but it is closely correlated to the pedestal turbulence enhancement (Fig.1(e)).

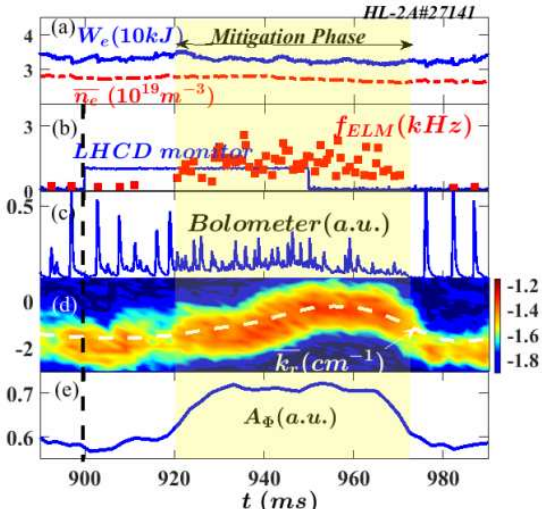

Fig.1 ELM mitigation with LHCD.

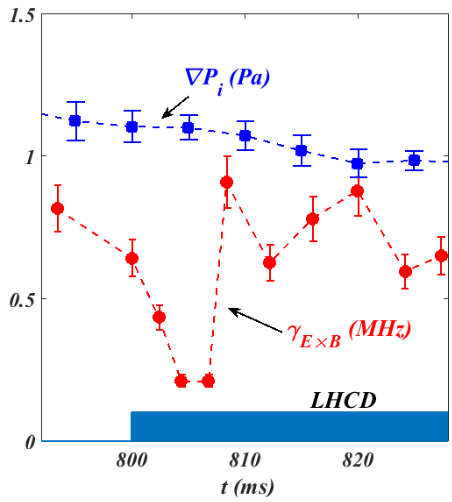

Fig.2 Time evolution of $\gamma_{E\times B}$ and ∇P_i during LHCD.

A plausible mechanism for ELM mitigation can be like this: the application of LHCD induces an edge shear flow decrease, and then a radial spectral shift of the turbulence is produced when the velocity shear decrease exceeds a critical value; then due to the radial spectral shift, the turbulence amplitude starts to increase, and leading to the ELM mitigation. In order 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 external velocity shear, has been developed [7]. The modified spectral shift model includes a nonlinear equation describing the evolution of the turbulence amplitude governed by the velocity shear rate $\gamma_{E\times B} = \alpha|\nabla P| + U$, where α is a constant coefficient, ∇P is the pressure gradient, and U represents the external additional input velocity shear rate.

Fig.3 represents the results of turbulence simulation with external velocity shear in the H-mode plasma. As shown in Fig.3(c), the spectral averaged radial wavenumber caused by the external velocity shear starts to increase with a time delay Δt_k. A longer time delay Δt_Φ has been observed for a significant change of the turbulence amplitude as shown in Fig.3(d). Fig.4 shows the evolution of k_x-spectrum at selected time after the external source input. It can be observed that the turbulence amplitude is increased when the radial wavenumber spectrum of the turbulence shifts toward zero. It should be noted that when the value of the averaged radial wavenumber is under a critical value, the turbulence amplitude collapses.

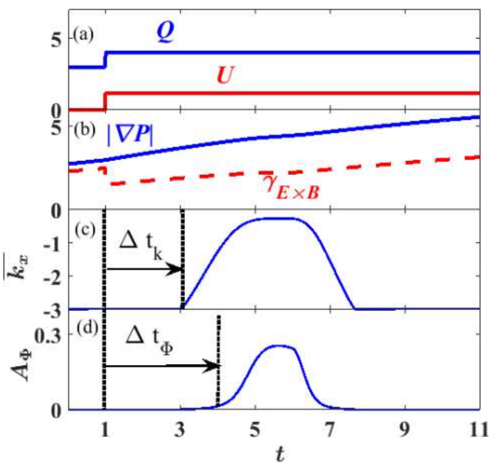

Fig.3 (a) Heat flux source Q and the external velocity shear rate U; (b) the pressure gradient ∇P, the velocity shear rate $\gamma_{E\times B}$; (c) the averaged radial wavenumber; (d) the turbulence amplitude.

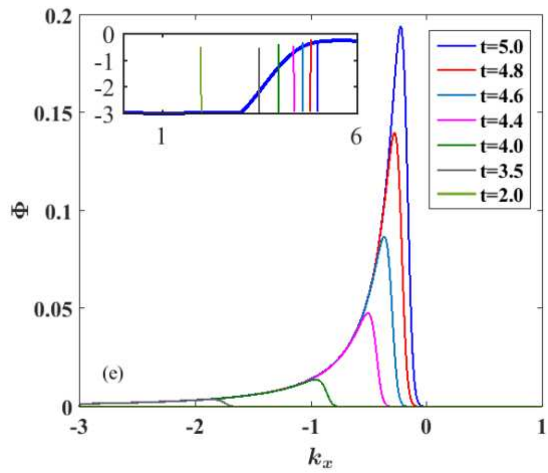

Fig.4 k_x-spectrum of the turbulence for selected time after external source input

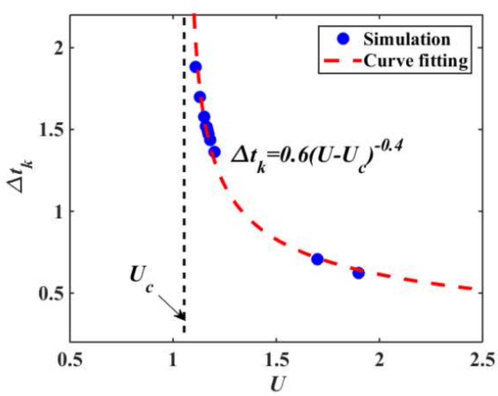

Fig.5 Time delay Δt_k *vs* the external velocity shear rate U.

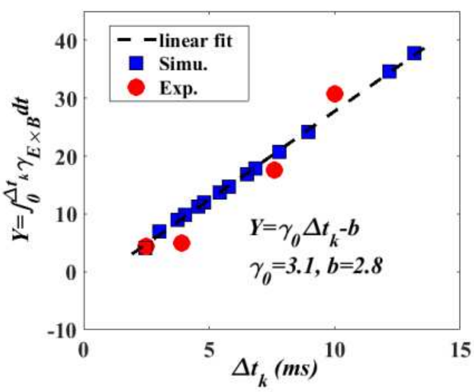

Fig.6 Integral of the shear effect Y *vs* Δt_k.

Fig.5 shows the dependence of Δt_k in function of the external velocity shear rate U. This figure indicates clearly that it exists a critical value of U for triggering the variation of $\overline{k_x}$.

This threshold value U_c is indicated by the dashed line in Fig.5. By fitting the simulation points, an analytical expression has been found for Δt_k and U: $\Delta \mathrm{t_k} = 0.6(U - U_c)^{-0.4}$. Intuitively, the appearance of Δt_k depends strongly on the accumulative effect of the velocity shear. For this reason, the integral of the velocity shear rate $Y = \int_0^{\Delta t_k} \gamma_{E\times B} dt$ is plotted as function of Δt_k in Fig.6. A linear relationship has been found between Y and Δt_k, which can be described as: $\int_0^{\Delta t_k} \gamma_{E\times B} dt = \gamma_0 \Delta t_k - b$, where $\gamma_0 = 3.1$ and $b = 2.8$. This equation can be put under the following form: $\int_0^{\Delta t_k} (\gamma_0 - \gamma_{E\times B}) dt = b$. From this equation, it is very clear that the parameter γ_0 plays a key role for the radial wavenumber shift and the turbulence enhancement, which then lead to the ELM mitigation. Indeed, γ_0 is closely linked to the maximum growth rate of the turbulence. Fig.7 shows the comparison between experimental data and simulation results for the turbulence amplitude A_Φ and $\overline{k_r}$. And good agreement has been found between experiment and simulation.

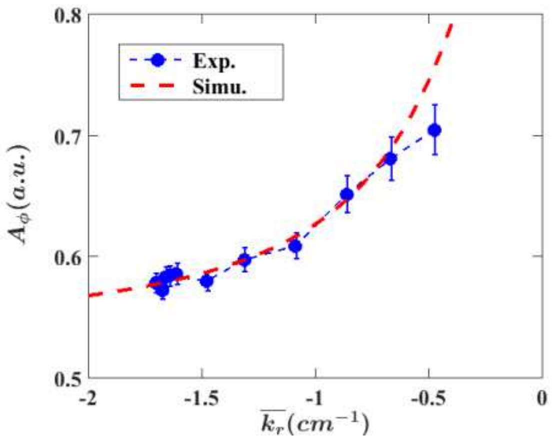

Fig.7 Comparison between experiments and simulation.

In summary, ELM mitigation has been observed with LHCD. The mitigation phase is synchronized with the pedestal turbulence enhancement, but not with the LHCD pulse. The pedestal turbulence enhancement is likely due to the radial wavenumber shift, caused by the velocity shear decrease induced by LHCD. A modified turbulence radial wavenumber spectral shift model has been used. A critical growth rate γ_0 for the turbulence regulation has been identified in this model. It has been found that the turbulence enhancement and ELM mitigation occur when the decrease of LHCD driven velocity shear exceeds a threshold value, which directly depends on γ_0. Good agreement has been found between experiment and theory for the regulation of the turbulence amplitude with its averaged radial wavenumber.

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