Study of L-I-H transitions induced by sawtooth crashes on HL-2A tokamak

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1. Introduction:

The study of the transitions from low confinement modes (L-mode) to high confinement modes (H-mode) is very important for predictions of the H-mode access in ITER. An intermediate quasi-periodic process, which is called intermediate phase (I-phase) or limit cycle oscillations (LCOs)[1,2] can often be observed when the heating power is close to the threshold power of L-H transition. The LCOs can also be induced by supersonic molecular beam injection (SMBI) and pellet injection (PI) on HL-2A tokamak[3]. Further more, it was recently observed that L-I-H transitions could be induced by sawtooth crashes at a marginal co-NBI heating power. The process of the phenomena occurrence will be discussed here.

2. The effect of sawtooth crashes on phase evolution

Sawtooth crash is characterized by quasi-periodic collapse in core plasma temperature and density. Then a heat pulse propagates from core to plasma boundary. The effect of sawtooth crashes on LCOs frequency is shown in figure 1. The 1st sawtooth crash triggers an L-I transition, while the 2nd and 3rd sawtooth crashes change the I-phase oscillation frequency from 2.2 kHz to 1.9 kHz, and then to 1.4 kHz, respectively. Finally, the 4th sawtooth crash induces an I-H transition. The sawtooth crashes take important role on confinement modes transition and frequency changes.

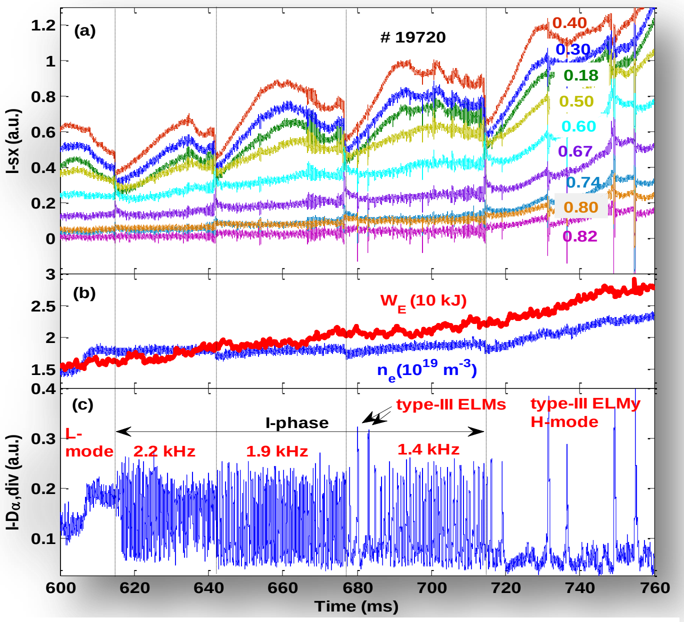

Figure 1. (color online) Evidence of L-I-H transitions induced by sawtooth crashes. (a) soft-x ray signal form core to edge region, (b) plasma store energy (red) and line averaged density (blue), (c) Dα radiation in divertor. The main parameters in #19720 are Ip = 200 kA, Bt = -1.39 T, and P_{NBI} = 0.88 MW with co-NBI heating.

Another kind of interesting phenomena is the L-H transitions modulated repeatedly by a series of sawtooth crashes, as shown in Figure 2. Electron density decrease is induced by periodic sawtooth crashes and plasma current and stored energy is almost not affected by the sawtooth crashes. But it is clear that Dα radiation in divertor is modulated by sawtooth crashes. For example, at t=705 ms, after a sawtooth crash, LCOs occur and last more than 10 ms, then the plasma confinement inters into L-mode again. In the two different confinement conditions, the H_{98} factor does not change obviously.

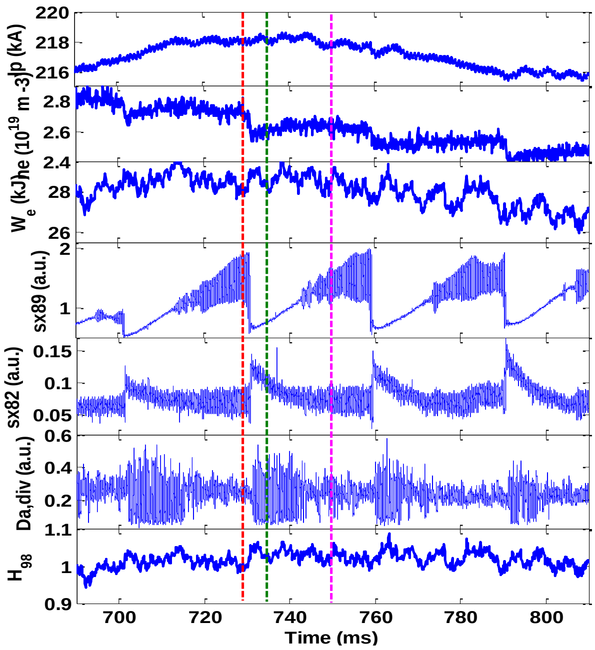

Figure 2. L-I transitions modulated by a series of sawtooth crashes in #9772. The signal from top to bottom are: plasma current, plasma density, plasma stored energy, soft-x ray in central region,soft-x ray in edge region, Dα radiation in divertor and H_{98} factor. The main plasma parameters in this shot are Bt=-1.35 T, P_{NBI} =0.76 MW (420-920 ms), P_{ECRH} =1.68 MW (865-1265 ms).

3. Edge plasma parameters during L-I-H transitions

As we know, sawtooth crashes could expel heat pulses and particles form plasma central region to edge region. Therefore, the plasma temperature and density in the edge region would increase after a sawtooth crash. Figure 3 shows the electron density profiles before and after sawtooth crashes in 19772. The electron density is measured by microwave reflectometer[4]. It is obvious that electron density after sawtooth crashes (735 ms, green colour) is higher than that before sawtooth crashes (730 ms, red colour) in pedestal region. That’s to say, electron density in edge region is higher in I-phase than that in L-mode. Though the edge electron temperature data are not available in these shots, but fortunately, the pressure and pressure gradient parameters are gotten by simplifying multi-channel soft-x ray signal, as shown in figure 4. In the central region of figure 4(a), plasma pressure in the central region is lower after sawtooth crashes than that before sawtooth crashes. And then, with heating continued, the central pressure is recovery again. As was expected, the edge pressure gradient (figure 4(b)) increases gradually from L-mode to H-mode in r/a~0.75 region, where the edge transport barrier (ETB) locates. It is clear that the sawtooth crashes take important role on edge plasma pressure and pressure gradient.

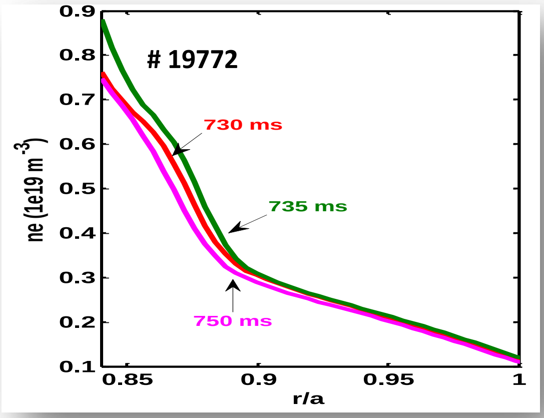

Figure 3. (color online) Edge electron density profiles during L-I transitions induced by a sawtooth crash in #19772. Before sawtooth crash (red), after sawtooth crash and during I-phase (green), and after sawtooth crash and during L-mode (pink).

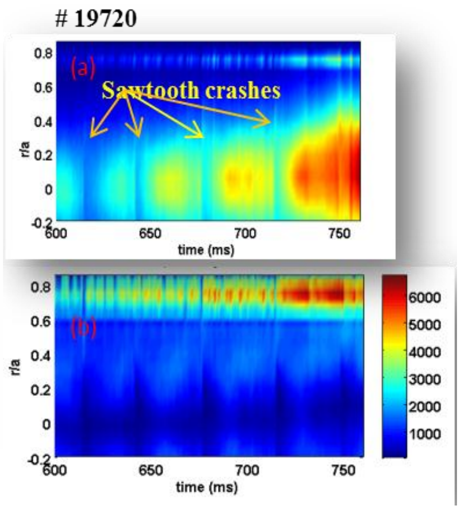

Figure 4. (color online) Pressure and pressure gradient evolution before and after sawtooth crashes in #19720. (a) pressure, (b) pressure gradient.

In order to get the edge turbulence message, Langmuir probes[5] diagnostic was used, and the results are shown in figure 5. The time evolution of the gradients, radial electric field Er, zonal flow shearing rates when the plasma stays in the I-phase is studied to understand the roles of flows on the gradients. Figure 5 left (a)-(d) are the density gradients, temperature gradients, radial electric field, and zonal flow shearing rates dV_{ZF}/dr, respectively, where, the dashed lines are average parameters and the envelopes of zonal flow shearing rates. It is found that there are many peaks in the density, temperature gradients and radial electric field Er which correlate with the zonal flows. After accessing the I-phase, the zonal flows, radial electric field, and temperature gradients increase at the time ~700.8ms. About 706ms, zonal flow shearing rates significantly ramp up and the mean flow evolves sharply. But the mean density gradient rapidly rises up and the oscillatory gradient becomes more significant at ~707ms. This result suggests that the higher flow oscillations result in the more negative mean flows, in turn, sustaining the higher mean gradients. The zonal flow himself sustains the oscillatory gradients. Moreover, after ~709ms, zonal flow shears decrease slowly and the I-phase tends to come back to the L-mode.

The phase relation among gradients, turbulence and zonal flow shears is shown in figure 5 right. Signal (a)-(d) give time evolution of the density gradients, temperature gradients, turbulence intensity and zonal flow shearing rates, respectively. The oscillatory density gradients are anti-phase correlated with the temperature gradients. This result may result from the plasma maintaining the pressure balance. The zonal flow shearing rates lag relative to turbulence about $\pi/2$ which suggests that the zonal flow shears suppress turbulence. The phase shift between zonal flow shearing rates and gradient oscillations is close to zero. The results suggest that turbulence feed zonal flow shears with energy, while zonal flow shear sustains the oscillatory gradients. Thus, the feedback loop for cycle exists among turbulence, zonal flows, and oscillatory gradients.

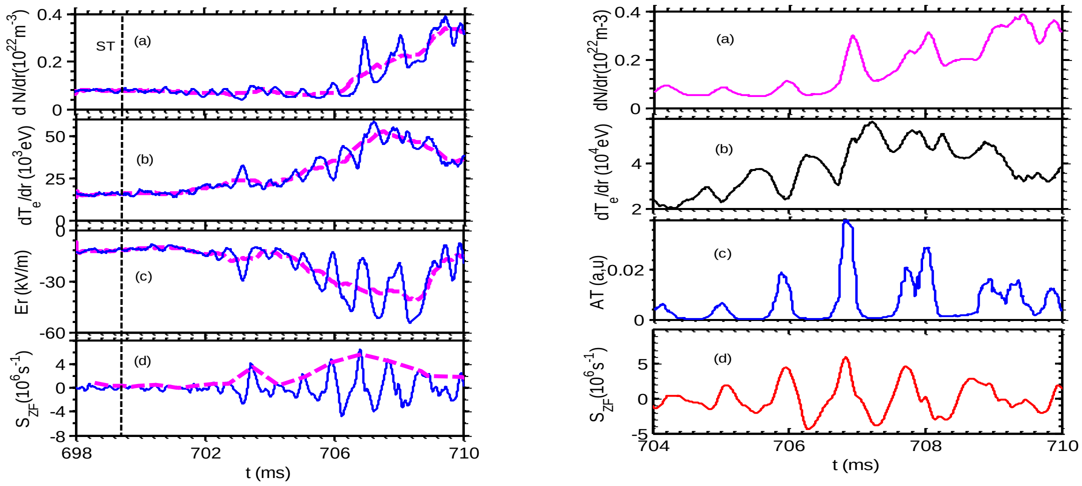

Figure 5. The measurement results of Langmuir probes during L-I transitions induced by sawtooth crashes.In the left figure: (a) edge density gradient, (b) edge temperature density, (c) edge radius electric field Er, (d) zonal flow shearing rates; in the right figure, (a) edge density gradient, (b) edge temperature density, (c) turbulent intensity, (d) zonal flow shearing rates.

4. Summary and discussion

The interesting phenomena of limit cycles oscillations frequency change induced by sawtooth crashes are observed. And edge plasma parameters are studied during L-I-H transitions induced by sawtooth crashes. Sawtooth crashes expel particles and energy from core region to edge region, so edge pressure increases after sawtooth crashes. The measurement results of Langmuir probes show that as the heat pulse propagates to the plasma boundary and modulates edge gradients, the transition from L-mode to LCOs occurs, and the radial electric field Er, Da signals, gradients start oscillation at the same frequency. In LCOs, turbulence feed zonal flow shears with energy, while zonal flow shear sustains the oscillatory gradients. And the feedback loop for cycle exists among turbulence, zonal flows, and oscillatory gradients.

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