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Abstract. It is a key goal on the way to fusion to better understand the role that magnetohydrodynamic (MHD) instabilities do play in plasma confinement in helical systems. We experimentally study the evolution of pressure driven modes in the Large Helical Device (LHD) using images measured by a fast, tangentially–viewing soft X-ray camera. Sawtooth–like MHD activity occurs in high–density plasmas when the pressure gradient in the core region exceeds a certain limit. It is found that the magnetic surfaces are strongly deformed just before the sawtooth crash. The magnetic reconnection due to this deformation may causes a rapid energy flow from the core to the edge.

1 Introduction

Magnetohydrodynamic instabilities are a major thread to magnetic confinement in toroidal fusion devices. Within this paper we present experimental evidence on the evolution of such instabilities as seen by a fast framing camera mounted on the LHD device. Although helical devices are less sensitive to current driven instabilities, pressure driven modes might limit the beta values to be achieved, and may thus finally become essential for an economic realization of a helical fusion reactor. The highest stored energies and volume–averaged beta are obtained in so–called inward–shifted configurations, (e.g., the radius of the magnetic axis $R_{axis} = 3.6m$) in LHD. These inward–shifted plasmas are characterized by favorable orbits of the charged particles; they stay close to the magnetic flux surfaces and we expect a good confinement of high–energetic particles. However, this is unfavorable as MHD stability is concerned. Because of a magnetic hill near the magnetic axis, pressure driven modes such as interchange modes easily exite and are neither stabilized by a magnetic well nor by magnetic shear. For these reasons, the effect of the MHD instabilities in such inward–shifted configuration has been extensively studied. Experimentally, no serious effects, e.g., disruptive increase in transport, has been found in normal plasmas on LHD though the local transport gradually degrades with the increase of beta [1]. It is found experimentally that the pressure gradient near the rational surfaces does not exceed the limit predicted from simulations with low–m modes. It is to be pointed out that small amplitude instabilities cause a flat pressure profile around rational surfaces; this fact would improve the achievable beta values [2]. However, in order to achieve high beta plasma with improve the confinement, we need to study the effect of pressure driven modes with a pressure gradient close to the stability limit at rational surfaces. In this way, we can evaluate the risk caused by pressure driven modes in helical devices.

Relaxation events, similar to sawtooth phenomena as observed in tokamaks, have been as well been found in smaller heliotron type devices, e.g., Helitron-E[3, 4, 5] and Compact Helical System [6, 7]. On the LHD, similar events have been observed under special conditions, i.e. in pellet–injected plasmas with peaked pressure profiles [8] and in plasmas with large net toroidal current[9]. In this paper, we investigate plasmas where the pressure gradient at the rational surface significantly exceeds the one within normal gas–puffed plasmas, and we study the pressure driven MHD modes and their non–linear evolution.

Since MHD mode amplitudes depend non–linearly on the pressure gradient, it is not straightforward to make theoretical predictions of mode structures and amplitudes, and thus determine their effect on confinement. For this reason non–linear MHD simulation codes have been developed to study the MHD phenomena close to the stability limit. From results of the non–linear MHD code RESORM it appears, that as the MHD modes grow, they overlap and there is at higher beta values a non–linear coupling between them. The vortices approach each other and this phenomenon results in burst–wise energy losses. The number of the vortices is twice the poloidal mode number[10].

To learn more about such kind of phenomena, a tangentially viewing soft X–ray camera is a powerful experimental tool. Because of the two–dimensional imaging, the spatial structure of the MHD modes and their time evolution can directly be derived. We basically use a pinhole camera with a fast framing video camera attached which detects the soft X–rays via a (CsI) scintillator. It can record tangential images of the plasma with 100×100 pixel resolution. The maximum framing rate is about 20 kHz [11, 12].

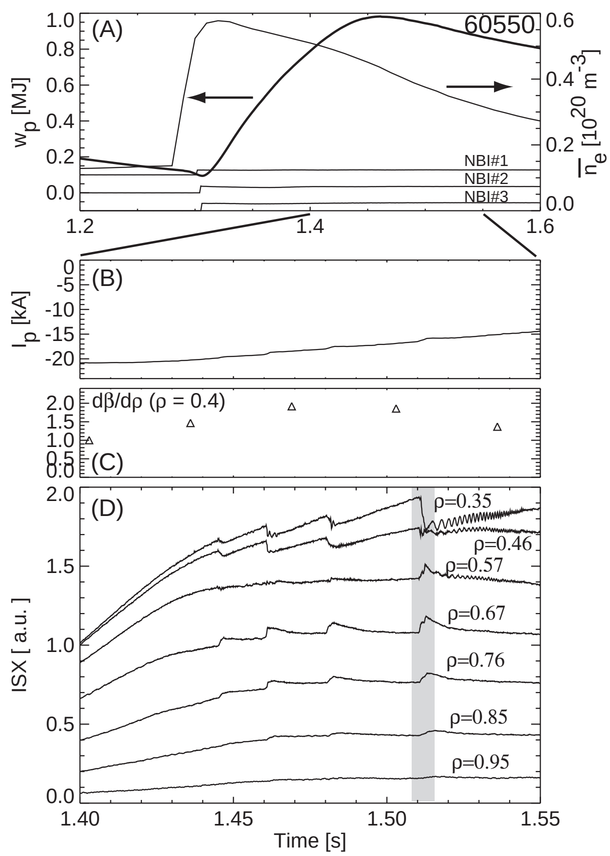

Fig 1: *Time evolution of plasma parameters. The stored energy of plasma and the line averaged electron density (A), an extend view of the plasma current (B), the estimated pressure gradient at* $\rho = 0.4$ *(*ι *= 1/2) (C), and soft X–ray radiation (D) are plotted together. The shaded area in (D) will be used in Fig. 2.*

2 Experiments

LHD is an m = 2, ten field period heliotron type device. The rotational transform increases with the small radius toward the plasma edge, typically from 0.4 (center) to 1.5 (edge). Instabilities are expected to be suppressed mainly by the magnetic well in the core region and by the magnetic shear in the peripheral region. The magnetic well is, however, not formed under inward–shifted operations. Fairly high–density plasmas (line averaged electron density $\overline{n_e} > 10^{20} m^{-3}$) are produced by the sequentially injected hydrogen ice pellets[13]. Sawtooth like oscillations are observed in this type of discharges when the magnetic axis is inward shifted (

$R_{axis} = 3.55m, 3.6m$ and $3.65m$). Figure 1 shows the time evolution of the plasma parameters. The plasma is strongly heated just after the last pellet injection (1.27s). The toroidal magnetic field at the magnetic axis $B_t = 2.75$T and $R_{axis} = 3.6$m. The electron density profile is hollow first because the particle deposition is localized near the edge under our experimental conditions, whereas the electron density decreases and the profile shape becomes gradually peaked. Together with the peaking of the electron temperature, the pressure gradient at $\rho \sim 0.4$ (i.e.,$\iota \sim 1/2$) increases and is 2 ∼3 times larger than found under normal operation with gas fueling.

As the pressure gradient increases, sawtooth–like events begin (1.44s-1.51s in Fig.1(D)). At the time when these sawtooth–like events appear, the line-averaged electron density continuously decreases and the electron temperature gradually increases. Thus, we can investigate the influence of resistivity on the mode behavior by comparing cases with similar pressure gradients and different electron temperatures. Fig.2 shows the fluctuating components of the image from the tangential soft x–ray camera at the time of the maximum fluctuation amplitude (1.516 s in Fig.1). First, an m = 3 mode evolves within 100 ms and deforms the magnetic surface (Fig.2 (B2) bright area). The m = 3 triangular structure expands and reaches the region around $\rho = 0.4$. When the mode saturates, an enhanced heat flux from the core to the edge is observed, thereby causing a flattening of the pressure profile. The SX emission from the outer plasma increases after that event (see Fig.2 (B3)). Unlike tokamak sawteeth, these events are not related to the $q = 1$ rational surface. When the pre/post cursor oscillations are observed with sawtooth–like events, we can identify rational surfaces by their poloidal mode numbers. In discharges like Fig. 1, among all

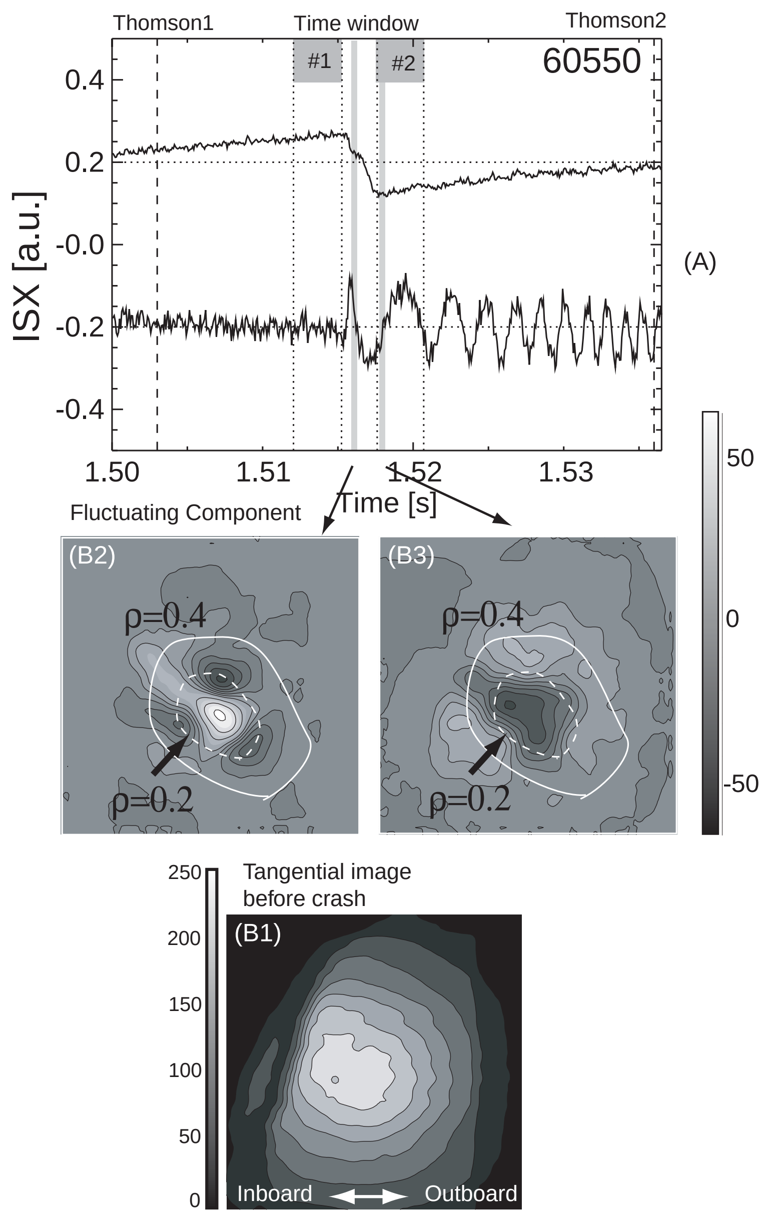

Fig 2: *Two-dimensional structure of the soft X-ray radiation profile during a sawtooth–like events are shown in (B). The exposure time is indicated in the figure (A).*

the events the last ones are obviously related to m = 3 activities. Post–cursor oscillations persist for typically 0.1 – 0.3s. Changes of the profile with the m = 3 events are shown in Fig. 3. The rotational transform ɩ profile calculated by use of the VMEC code assuming a certain pressure profile is shown in Fig. 3 (A).

The rotational transform ɩ measured by motional stark effect (MSE) [14] has shown that the actual ɩ profile and this pre–calculated profile are undistinguishable under this particular experimental condition. The soft X–ray radiation profiles just before and just after the event(Fig. 3(C)) show that, the change is localized in the core region, where the rotational transform is close to 1/3. Large amplitude m = 3 post cursor oscillations are observed in this area as well.

The difference in the soft X–ray radiation, $\Delta I_{sx}/I_{sx}$ is about 25% at the center, where the change in the density $\Delta n_e/n_e$ is about 10 %. Considering $\tilde{I}_{sx} \propto \tilde{n}_e{}^2$, the change of the SX radiation is mainly due to the change in the electron density. This agrees with the observation that change in the electron temperature measured by the electron cyclotron emission (ECE) is very small (Fig.3(F), (G)). Although we were not able to measure the core region by ECE, the increase in the outer region is fairly small($\Delta T_e(\rho = 0.5) < 80$eV). This is confirmed by the fairly small change in the profile measured by Thomson scattering (Fig. 3(G)).

While m = 3 type crashes are located in the core region, there is another type of crash, of annular type, related to the ɩ = 1/2 rational surface. They frequently appear early, i.e., before the m = 3 activities show up. Fig.4 shows the fluctuating components of an image with m = 2 events. From the change in the profile, it is clear that only the SX radiation in the ring–shaped area decreases (blue area in Fig. 4 (B2)). At the beginning of the crash, a deformation of the magnetic surface with m = 2 is observed (Fig. 4 (B3)). However, the relation of this deformation to the annular type crash–event is presently not well understood. One of the reasons for the lack of information is that the magnetic shear near the rational surface m = 3 is weak; the radial extent of the perturbations is suf-

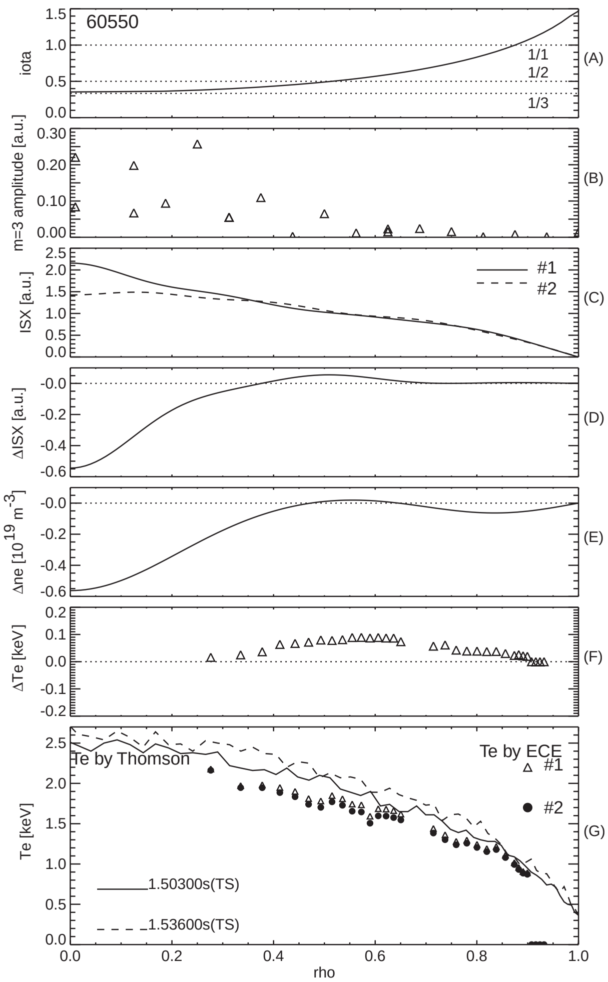

Fig 3: *Modification of the profile with the sawtooth–like (ɩ = 1/3) event is shown. Measuring points in time are indicated in Fig. 2. The rotational transform profile (A), the profile of the amplitude of m = 3 post–cursor oscillations (B), the soft X-ray radiation profile, reconstructed from the line–integrated data(C) before (solid line) and after (dashed line) the event (C), its difference (D), the difference of the electron density profile (E), the difference of the electron temperature profile (F) and the electron temperature profile itself (G) are shown as a function of averaged minor radius* ρ.

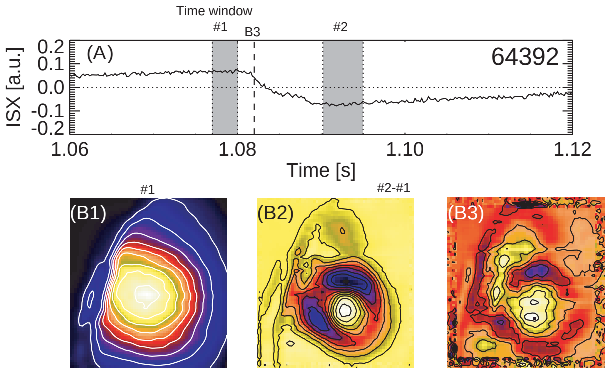

Fig 4: Two-dimensional structure of the soft X-ray radiation profile during a sawtooth-like event is shown in (B). The exposure time is indicated in the figure (A).

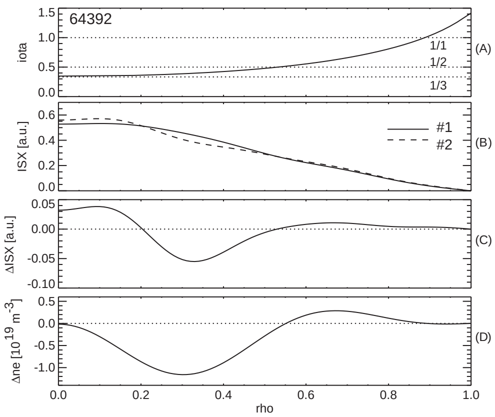

Fig 5: Modification of the profile with the sawtooth-like ($\iota = 1/2$) event is shown. The rotational transform profile (A), the soft X-ray radiation profile before and after the event (B), its difference (C), the difference of the electron density profile (D) are shown as a function of averaged minor radius ρ.

ficiently large to be seen. In the m = 2 case, the size of the deformation is too small to be distinguished by our 2D camera system. Changes of the profile in m = 2 type crash are shown in Fig. 5. It is also confirmed that only a limited area around $\iota = 1/2$ ($0.2 < \rho < 0.5$) is affected. Pre/post cursor oscillations with m = 2 poloidal mode number are sometimes seen around the $\iota = 1/2$ surface. The condition for the appearance of pre/post cursor is not yet clarified. The SX radiation and the electron density at the core ($\rho < 0.2$) region are increased after m = 2 type events. These phenomena do reproduce fairly well. An increase in the radiation at the core starts at the middle of the crash events (e.g. 1.085s in Fig 4(A)). This might be related to the way reconnection takes place. However, the mechanism for the increase is not yet understood. We have observed similar sawtooth–like activity near different rational surfaces, e.g., $\iota = 1/3, 1/2, 1/1$, with m = 3, 2, 1. Although the pressure profile is modified by the sawtooth–like activity, the effect onto global confinement is small. The decrease in stored energy is less than several % when the sawtooth-like activity is present.

3 Discussion

The conditions for the appearance of the sawtooth–like events have been studied. The pressure gradients at the rational surface are plotted in Fig. 6(A) as a function of the net plasma current I_P, where the positive(negative) I_p stand for the current in the co-(counter-) direction. There is an onset of MHD events when the pressure gradient exceeds a certain limit ($|d\beta/dr| \sim 1$ %). The value at an onset does not change significantly when the plasma current modifies the iota profile. An influence of the magnetic shear on the onset value is, not clarified yet. From the linear stability calculation, m/n = 3/1 modes destabilized when the beta at the magnetic axis β_0 is larger than 1.2 %. It is consistent with the onset value. MHD mode with m/n = 2/1 are unstable where $\beta_0 > 0.5$ % with the same pressure profile.

In higher temperature plasmas instead of the sawtooth–like events, m = 3 saturated oscillations without sawtooth-like events are can sometimes be observed. The magnetic Reynolds number S ($= \tau_R/\tau_{Alfven}$) is introduced as a measure of the resistivity. For similar pressure gradients, sawtooth activity occurs for lower values of S and saturated oscillations occur at higher values of S (Fig.6 (B)). This can be understood qualitatively from the following model. The amplitude of the MHD instabilities increases with the pressure gradient. It saturates (Point D in Fig.6(C)) when there is a balance between the fluctuation–driven flux and the pressure gradient. However, in higher resistive plasmas, reconnection occurs more easily at the same instability amplitude. Thus, sawtooth-like events are triggered (path A-B-C-A in Fig.6(C)) in plasmas with lower S. This model is consistent with the observation that the repetition rate is larger when the electron temperature is low.

We do not observe the flattening of the electron temperature after the crash events. The electron temperature profile keeps peaked with sawtooth-like events. Full reconnection model include emission of the magnetic axis[5] is thereby not applicable. Partial reconnection, toroidally localized one, might explain the experimental observation. However, the detailed study of a topological change through reconnection is still future work to be studied.

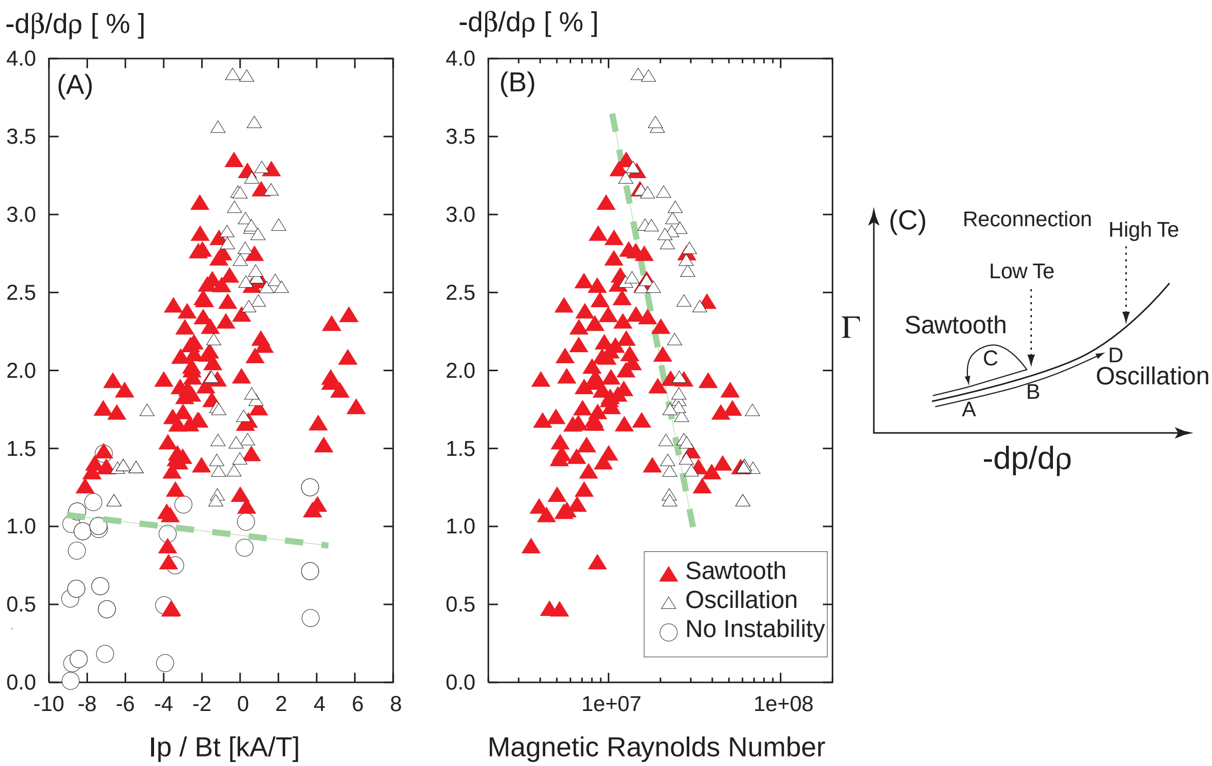

Fig 6: Measured pressure gradient as a function of the plasma current at is shown (A). Dotted line roughly indicates the onset value of the sawtooth-like events. Measured pressure gradient as a function of the magnetic Reynolds number is shown (B). Schematic drawing of the model of the sawtooth-like event is drawn (C).

In summary, we observed sawtooth-like events driven by pressure driven instabilities. In the m = 3 type crash, flow pattern is similar to the non-linear MHD simulation. After the triangular structure extend from the core to $\rho = 0.4$, rapid energy flow from the core to the edge is observed. The enhanced flux could be caused by reconnection where the magnetic surfaces are heavily compressed due to an interchange mode. In the case of the $\iota = 1/2$ events, it is annular type of crash; only limited area around $\iota = 1/2$ is affected. Relation of the m = 2 modes and this limited modification is an unsolved question to be solved. Though the profile, especially the electron density profile, modified considerably by the sawtooth-like events, they does not affect the global confinements significantly even with the pressure gradient $|d\beta/d\rho| > 2\%$.

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