MHD instabilities with sharply peaked pressure profile after ice-pellets injection in the Large Helical Device

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The effect of peaked pressure profiles on the MHD behavior of the Heliotron type plasma is investigated. The pressure profile is more peaked with the ice-pellet injections than with normal gas-puffing. The degree of the peaking depends on the vacuum magnetic axis position. In inward-shifted plasma, where the interchange modes are unstable in the core region, larger levels of the MHD fluctuations are observed. Sawtooth-like relaxation events, which terminate the peaking, are also observed when the pressure gradient exceeds a threshold value. Existence of these MHD instabilities may explain the fact that we do not obtain internal density barrier discharge with inward shifted configurations.

Keywords: LHD, MHD instabilities, pellet, relaxation

1 Introduction

In the Large Helical Device (LHD), the highest volume-averaged beta are obtained in so-called inward-shifted configuration (the radius of the vacuum magnetic axis, $R_{axis} \sim 3.6$ m) because this configuration is favorable for particle confinement and heating efficiency. However, they are unfavorable as MHD stability is concerned. Therefore, it has been believed that MHD stabilities are not important for normal operation in LHD; the pressure driven instabilities are saturated at a certain level and they do not deteriorate the confinement of the plasma seriously. Then, the next fundamental question is that in which experimental condition do MHD activities affect the confinement. We have observed several MHD related phenomena having impact on the confinement of the plasmas. They do restrict the operational regime of the LHD considerably. One is the configuration with low magnetic shear. When the magnetic shear is reduced at $\iota = 1$ surface, an m/n = 1/1 structure evolves and results in a minor collapse phenomena [3]. Another examples is that when the neutral beam injection is switched from the co-direction to counter direction, the magnetic shear at the $\iota = 1/2$ rational surface is reduced and m=2 MHD oscillations with large amplitude are observed [4].

The other experimental condition where the MHD instabilities affect the operational regime is the peaked pressure profile whose gradient is much larger than the Mercier–stable condition. When ice-pellets are injected into the plasma sequentially, the pressure profile is getting peaked after the last pellet. Several MHD related event have been observed in this experimental regime where the Mercier condition is profoundly violated [5]. The acievable pressure gradient in this type of discharges depends on the vacuum magnetic axis position (See, Fig. 1). When the R_{axis} is larger than 3.75m, a fairly high central beta value β_0 is realized. This kind of plasma is called as 'the internal diffusion barrier (IDB) plasma' or 'the super dense core (SDC) plasma' [1, 2]. In this paper we investigate the effect of the pressure driven modes with a pressure gradient exceeds the stability limit, which depends on the location of the vacuum magnetic axis.

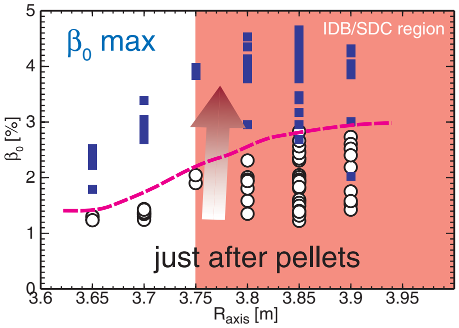

Fig. 1 Increase of the β_0 as a function of the vacuum magnetic axis R_{axis}.

2 Experiments

Typical time evolution of high-density plasma with pellet injection is shown in Fig. 2. After the last injection, a peaked density profile and a flat electron temperature profile are made (Fig. 3(a)). While the density is slowly de-

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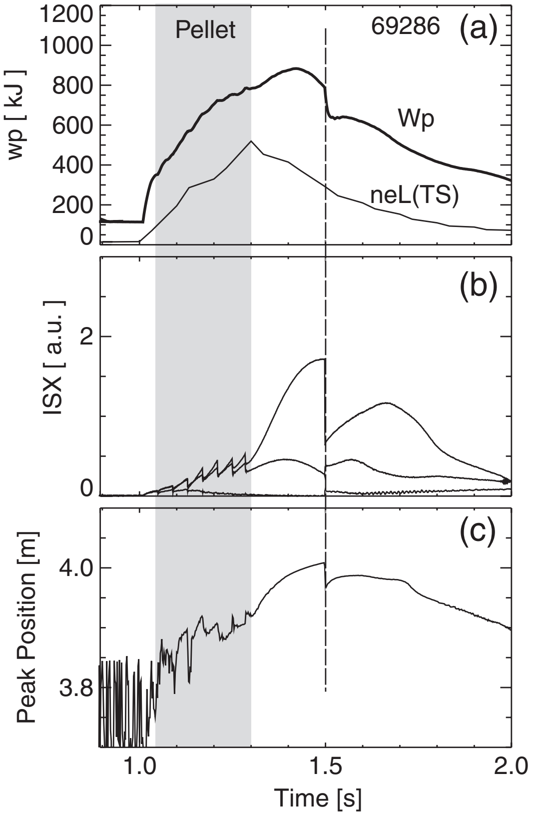

Fig. 2 Time evolution of the plasma parameters with pellet injection. The stored energy w_p and the line integrated electron density (a), soft X-ray radiation intensity(b) and the magnetic axis position estimated by the soft X-ray radiation profile (c) are shown. Vacuum magnetic axis in this discharge is 3.85m.

creased, the electron temperature increases and its profile is peaked. The recovery of the electron temperature is faster than the decrease in density. The pressure profile is thereby peaked. After the maximum of the stored energy, peaking of the profile still continues, which can be seen from the position of the magnetic axis estimated from the soft X-ray emission profile (Fig. 2(c)).

This peaking of the pressure is terminated at 1.5s by the so-called core density collapse (CDC) event (dashed line in Fig. 2). The plasma density at the center is decreased within 1 ms and the core plasma is redistributed to outer region, as is shown in Fig. 3(c)-(d).

In contrast to the case of the outward-shifted plasma, sawtooth-like activities are often observed inward-shifted plasmas. Time evolution of the discharges with R_{axis} = 3.65m and 3.75m are shown in Fig. 4. At the timing of the shaded stripes in Fig. 4, small relaxation events can be seen in the soft X-ray radiation (ISX). The waveforms are similar to those in the sawtooth phenomena observed on Tokamaks. The location of the inversion radius tells us that this instabilities are related to the $\iota = 1/2$ rational surface. Mode numbers of the precursor oscillations (m=2), which are rarely observed, support this.

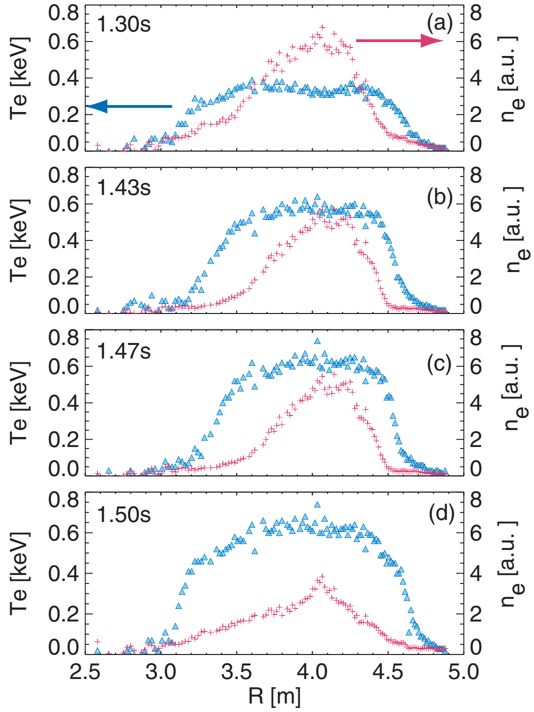

Fig. 3 The electron temperature and the electron density profile of #69286 after the pellet injection.

Though the effect of these events on the confinement is small, the increase of the central beta (estimated by the magnetic axis position) is saturated by the sawtooth-like events; the events affect the peaking speed of the pressure profile. This is one example where MHD instabilities do affect the pressure profile.

3 Discussion

The evolution of the β_0 as a function on the magnetic axis position R_0 is shown in Fig. 5. The thick curves show the Mercier stability criterion, $D_I = 0$, estimated at the $\iota = 1/2$ rational surface. The area right side of the lines is stable region; when the magnetic axis is shifter outward the magnetic well depth is deeper. Three lines are corresponding to different pressure profiles; assumed pressure profile is $p(\rho) = p_0(1-\rho^2)(1-\rho^8)$ (dashed line), $p(\rho) = p_0(1-\rho^4)(1-\rho^8)$ (dotted line) and $p(\rho) = p_0(1-\rho^2)^2$ (solid line), respectively. The symbols in Fig. 5 show the time evolution of the central beta in the recovery phase after pellet injection.

Inward shifted plasmas ($R_{axis} < 3.75m$) are always Mercier–unstable at $\iota = 1/2$ in the recovery phase after the pellet injection. Sawtooth-like repeated relaxation events are destabilized as the pressure gradient increases. The corresponding area is shown in the shaded ellipse in Fig. 5. There exists a threshold value of the pressure gradient for the appearance of the instabilities. It is estimated as ($d\beta/d\rho \sim 1\%$) [5].

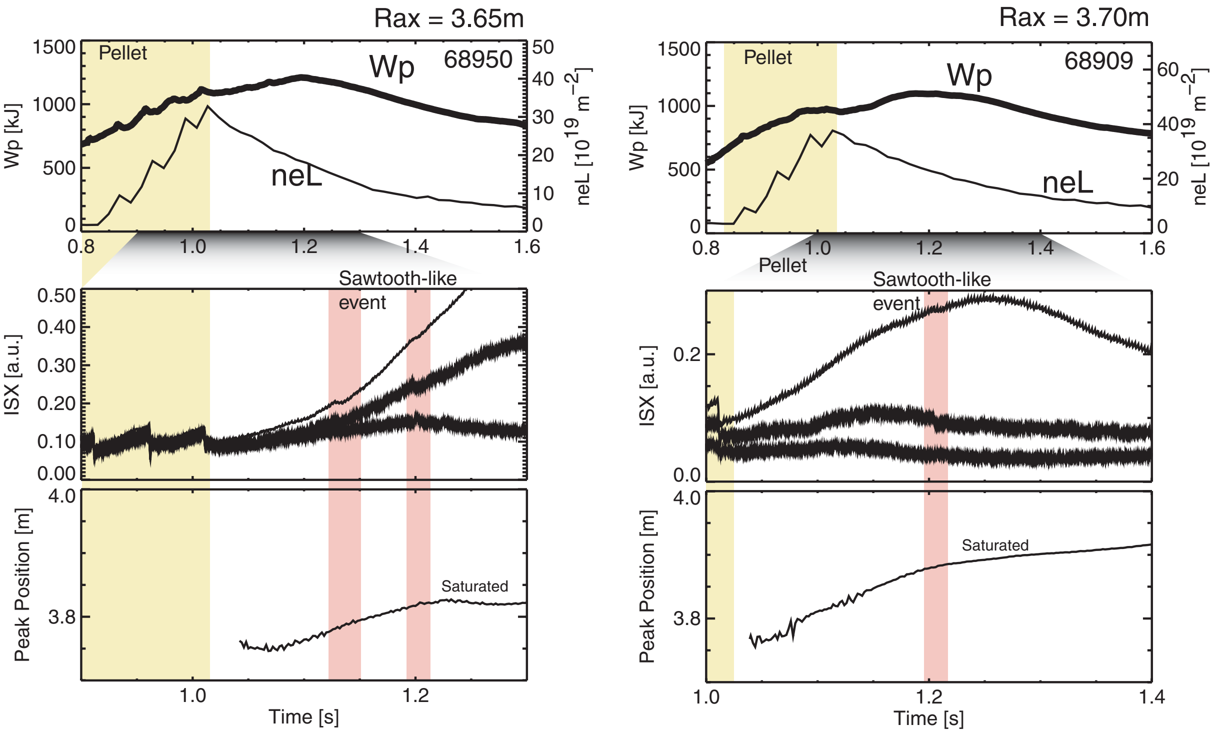

Fig. 4 Time evolution of the plasma parameters with sawtooth-like relaxation. Stored energy Wp and line-integrated density and the soft X-ray radiation and the magnetic axis position are shown together.

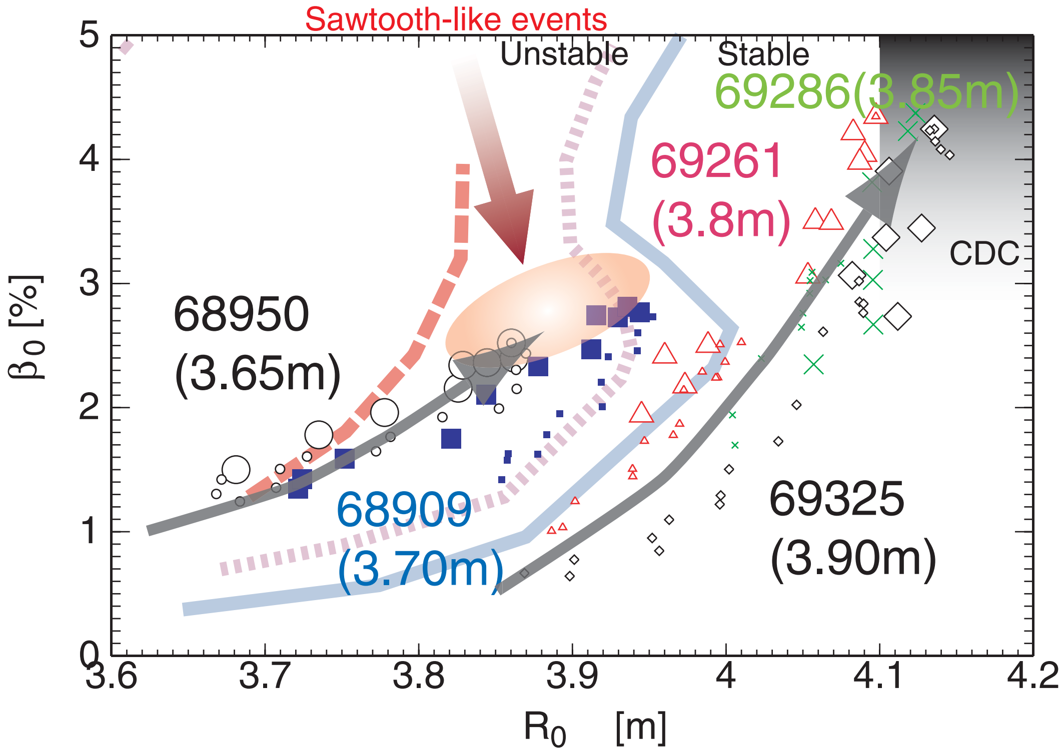

Fig. 5 Central beta value β_0 as a function of the magnetic axis position is shown. Thick lines show the stability boundary of Mercier mode. Three lines are corresponding to different pressure profiles; assumed pressure profile is $p(\rho) = p_0(1-\rho^2)(1-\rho^8)$, $p(\rho) = p_0(1-\rho^4)(1-\rho^8)$ and $p(\rho) = p_0(1-\rho^2)^2$, respectively. Open circle (R_{axis} = 3.65m), closed square (R_{axis} = 3.70m), open triangle (R_{axis} = 3.8m), cross (R_{axis} = 3.85m) and open diamond (R_{axis} = 3.9m) show the time evolution of the parameters after the pellet injection. Larger (smaller) symbols correspond to the period when the pressure profile is being increased (decreased).

Notice that the traces of 69286 ($R_{axis} = 3.85m$) or 69325 ($R_{axis} = 3.90m$) avoid the MHD unstable region in Fig. 5. In outward-shifted configurations ($R_{axis} > 3.75m$), Mercier stable condition for the core MHD mode is always satisfied that way. Achievable beta values are then higher than with inward-shifted configuration. However, as is already shown in Fig. 2, when the magnetic axis is shifted too large and exceeds a certain value (e.g. 4.1m), the CDC events are triggered and the further increase of the β_0 is terminated. Detailed mechanism of the CDC has not been clarified so far. However, there is a evidence that the magnetic axis position is a key parameter for the CDC event; when the Shafranov shift is reduced by the vertical elongation of the plasma, the achievable central beta is increased up to 7%[6]. Therefore, the fact the highest central beta can be obtained with $R_{axis} = 3.85m$ (Fig. 1) can be understood by the following way. Outward shifted plasma (e.g. $R_{axis} = 3.85m$) is free from core MHD instabilities and there is much space for the Shafranov shift until the CDC limit in configurations with $R_{axis} = 3.80, 3.85m$.

In addition to the sawtooth-like instabilities, broadband MHD fluctuations are enhanced in inward-shifted plasmas. The spectra of the magnetic fluctuation with different vacuum magnetic axis position are shown in Fig. 6. Coherent MHD fluctuations related to the rational surfaces located in the edge region (e.g. m/n = 1/1) make the small peaks in the spectra. It is clear that the fluctuation levels theemselves are larger when the vacuum magnetic axis is shifted inward (MHD unstable). The peaking speed of the central beta after pellet is slower in the inward-shifted plasma (See, Fig. 7). The anomalous transport due to the enhanced magnetic fluctuation can be a candidate for this.

In summary, the plasma performance with a peaked pressure profile with pellet injections is investigated. In MHD unstable inward-shifted plasmas, larger levels of the MHD fluctuations and sawtooth-like instabilities that affect the plasma confinement are activated. Whereas the outward-shifted plasma, larger central beta was obtained with smaller MHD fluctuations. Increased transport due to the larger MHD fluctuations and/or the sawtooth-like relaxation events might explain the fact that we do not obtain IDB/SDC plasma in inward-shifted configurations.

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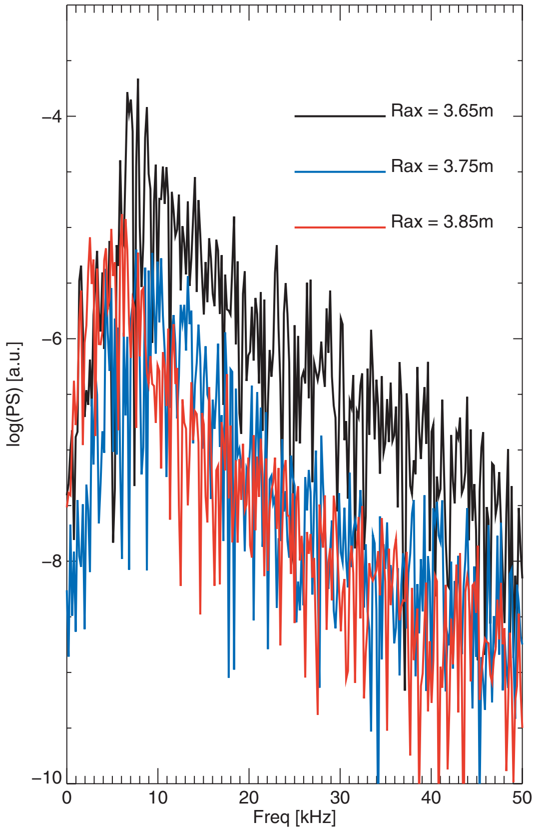

Fig. 6 Spectra of the magnetic fluctuations with different magnetic axis. The spectra are calculated when the stored energy take its maximum value.

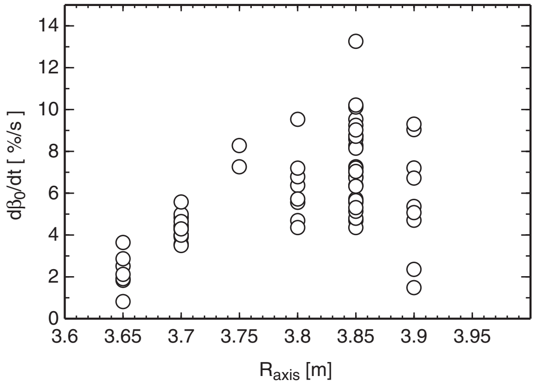

Fig. 7 The rate of the recovery speed of the central beta.