Two approaches to the reactor–relevant high–beta plasmas with profile control in the Large Helical Device

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Abstract. From detailed optimization of configuration, volume averaged beta $<\beta>\sim 5\%$ has been achieved in the Large Helical Device(LHD). While the heating efficiency was the main point to be optimized in this approach, to form a more peaked pressure profile is another promising approach towards the high beta regime. A higher electron density profile with a steeper pressure gradient has been formed by pellet injection. From the MHD stability analysis, this peaked pressure profile is stable against the ideal MHD modes. By both approaches, the central plasma beta β_0 reaches about 10%.

1 Introduction

In order to realize economical fusion reactor, high–beta operation of plasma is required in magnetically confined devices. The potential of the Heliotron type configuration as a reactor can be demonstrated if we form a high–beta plasma free from deteriorating effects of the MHD activities with reactor–relevant beta values. To this goal, we have investigated the characteristics of the high–beta plasmas with reduced magnetic fields, since the present heating power does not allow us to reach beta values highly enough to investigate the beta limit.

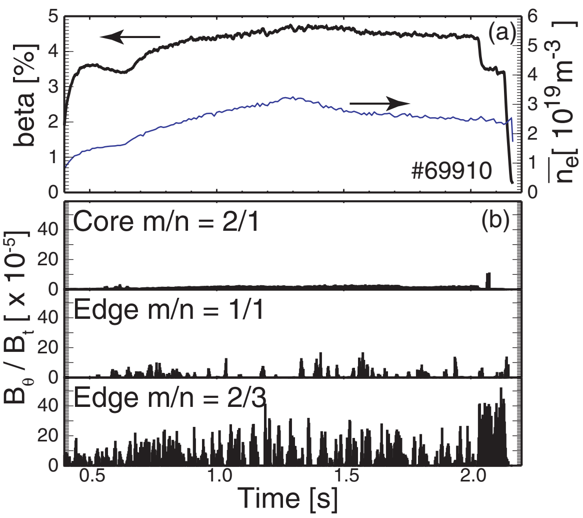

Fig 1: *Time evolution of the plasma parameter in the highest averaged beta discharge. ($Rax^{vac} = 3.6m, B_t = 0.425T$)*

So far, to control the magnetic axis is the mainstream of the optimization scheme to produce high–beta plasmas, since the characteristics of the plasma is drastically affected by the magnetic axis location. 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, they are unfavorable as MHD stability is concerned. Because of a magnetic hill near the magnetic axis, pressure driven modes such as interchange modes easily excite and are neither stabilized by a magnetic well nor by a magnetic shear. In outward–shifted configurations, we expect good MHD stability and bad confinement. We can modify the aspect ratio (A_p) of the plasma by the control of the currents in three layers of the helical winding coils. When the aspect ratio is increased, the rotational transform is increased; the amount of the shift is then reduced. High–beta regime is realized by the increase in the heating power and also by the optimization of the magnetic configuration in order that the neutral beam (NB) heating is effective. The heating efficiency of NB in the lower magnetic field is better when the magnetic axis remains unshifted. We adjust the aspect ratio of the plasma ($A_p \sim 6.6$) so that the Shafranov–shift of the magnetic axis is minimized. Thereby the plasma can be heated well by the NB [1].

Volume averaged beta $< \beta > \sim 4.5\%$ has been achieved in 2006 [2] in this way and improved to 4.8% (Fig. 1) and to 5.0% transiently by detailed optimization in 2007. The magnetohydrodynamics (MHD) instabilities in the core region vanish from the formation of the magnetic well, whereas the edge MHD instabilities remain (See, Fig. 1(b)). Only when the magnetic shear is reduced artificially, the radial width of the instabilities is increased and minor collapses are sometimes observed [3]. However, the magnitude of them are saturated in a low level ($B_\theta/B_t \sim< 10^{-4}$) and do not make a serious deterioration of the confinement. From the dependence on the magnetic Reynolds number, edge MHD modes are identified as the resistive interchange modes [3]. Therefore, the effect will be reduced when the plasma parameters approach reactor–relevant values.

The saturation of edge instabilities is caused by the localization of the eigenfunctions [1]. In other words, the edge MHD instabilities play minor roles in the confinement when the magnetic shear is kept in normal as in standard LHD configurations. In many discharges, this standard high–beta plasma ($< \beta >$ is larger than 4.5%) is sustained for more than 100 times of energy confinement time[4].

Another possible profile for the high–beta plasma is the peaked pressure profile. From an MHD point of view, there are many advantages; the magnetic well is deeper in the core region from the larger Shafranov–shift and the pressure gradient in the edge region is smaller. Overall MHD stability will be improved significantly. If we consider the reactor, the fusion output is larger when the profile is more peaked assuming that averaged beta is kept constant. It is whorthwhile to study the MHD property of a configuration which can be adopted as a reactor scenario. We thefore started to study peaked pressure profiles in the LHD as an alternative approach to obtain the high–

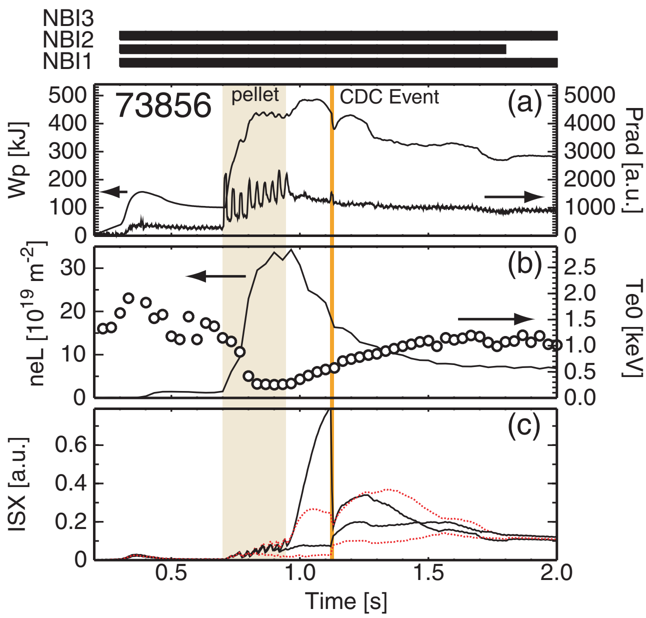

Fig 2: *Time evolution of plasma parameters. The stored energy of plasma and the radiation power (a), the line electron density and the electron temperature on the magnetic axis (b), and the soft X–ray radiation (c) are plotted together. Ice pellets are injected in the time windows shown by shaded area. The timing of CDC events is also shown.* ($Rax^{vac} = 3.75m, B_t = 1.5T$)

beta plasma.

2 High-central–beta approach and core density collapse phenomea

A peaked profile is formed in the recovery phase after sequentially injected hydrogen pellets [5, 6]. While the electron density decreases after the pellets, the electron temperature recovers quickly (See, Fig. 2). In this recovery phase, the pressure profile becomes peaked; high–central–beta plasma is formed (1.0s $\sim$ 1.1s in Fig. 2).

Though the plasma with the peaked pressure is stable, MHD stability is important in the process of the formation. When the vacuum (preset) magnetic axis Rax^{vac} is located inward (e.g. Rax^{vac} = 3.6m), larger levels of MHD fluctuations and sawtooth–like instabilities [7] are activated when the pressure profile is being peaked. Though the effect of those MHD activities is not severe, the formation of the peaked profile is disturbed. When the degree of peaking is estimated as $p = \beta_0 / < \beta >$, $p \sim 2$ and ~ 4 in Rax^{vac} = 3.6m and 3.85m configuration, respectively. Achieved electron density by pellet injection is smaller in inward–shifted configuration[8]. Not only by this lower density but also by the small degree of the peaking, the achievable central–beta is much smaller in inward–shifted configuration than in outward–shifted one

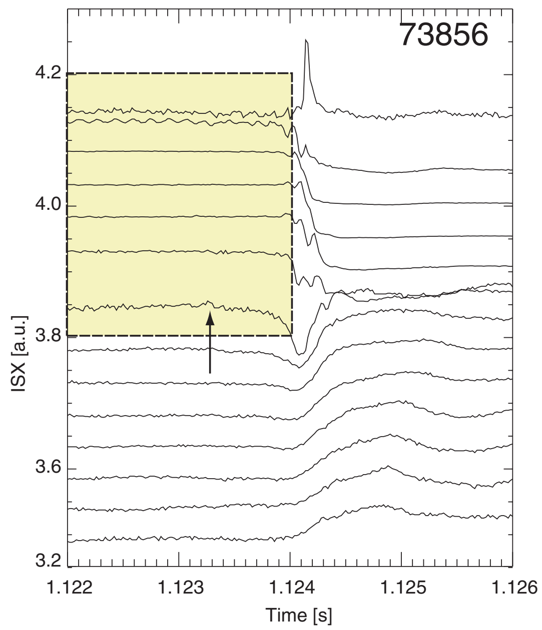

Fig 3: *Time evolution of the soft X–ray radiation signals. Baseline of each trace shows the radial position at vertically elongated section (See, the profile shown in Fig. 4(A)). The amplitude of each channel is normalized by their deviation of the signals. Dashed–line squares indicate the time/space region, where pre–cursor instabilities are observed.*

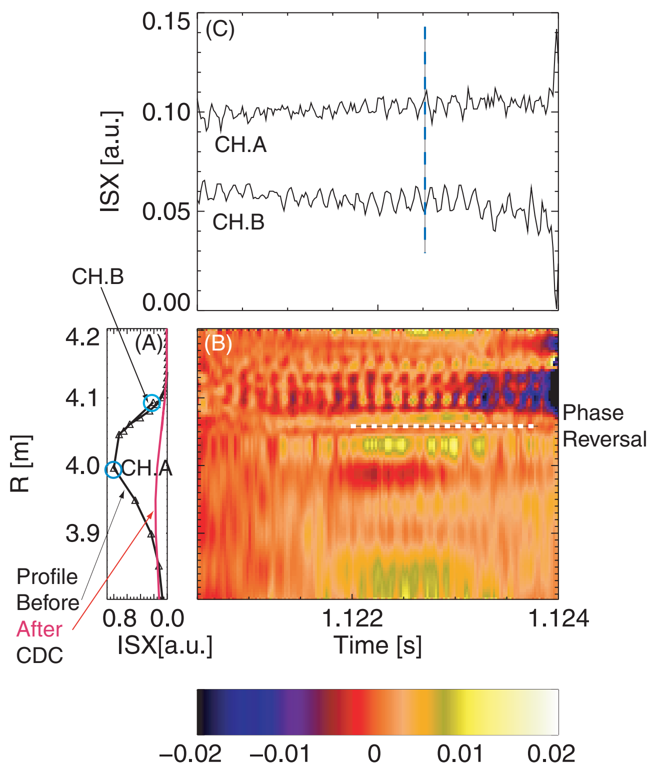

Fig 4: *Fluctuation level of SXR as a function of the time and the measured position (b). The area shown here corresponds to the dashed–line region in Fig. 3. Profile of the SXR is also shown in (a). Two distinctive signals at ch. A and ch. B are shown in (c).*

On the contrary, in the outward–shifted cases ($Rax^{vac} > 3.7$m), the achieved electron density is higher and the density / pressure profile becomes fairy peaked. Therefore, a higher central–beta β_0 can be obtained. However, the increase of β_0 is limited by the so-called core density collapse (CDC) events [6]. CDC is an abrupt event where the core density is collapsed within 1 ms. So far, we do not have understood the mechanism fully. Experimentally, CDC appears when the magnetic axis position exceeds $\sim$ 4.1m (in a holizontally elongated section). Here, we describe the characteristics of the CDC phenomena in detail.

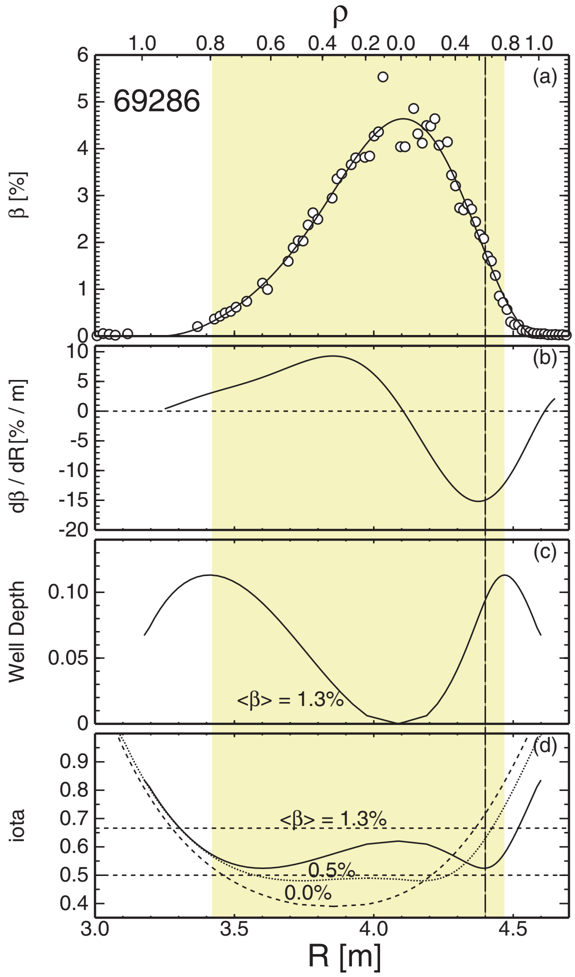

Fig 5: *Profiles of the plasma parameters just before the CDC events are shown. The beta profile (a), the beta gradient (b), the well depth (c) and the rotational transform profile (d) are shown.($Rax^{vac} = 3.85m$)*

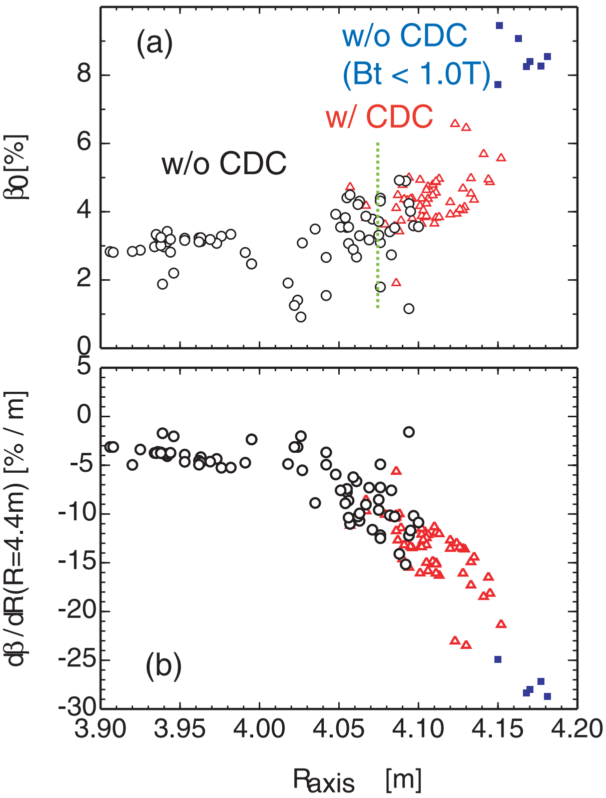

Fig 6: *Central betaβ_0(a) and pressure gradient at R =4.4m (b) as a function position of the magnetic axis $R_{axis}$are shown. Data points with open circle and red open triangle are discharges without CDC and with CDC, respectively. Most of the data point is measured with B_t = 2.54T. Blue square symbols are with the toroidal magnetic field is lower than 1.0T without CDC.*

Time evolution of the soft X–ray radiation (SXR) profile at a CDC event is shown in Fig.3. The magnetic axis has shifted to about 4.01m(vertically elongated section) before the events. The events start with the decrease of the SXR in the inboard (smaller major radius) side (Shown as an arrow in Fig.3). That means the magnetic axis moves outward just before the events. While the SXR at the plasma center is being decreased, discrete peaks in the SXR are often observed in the outboard side (1.242s, 4.0m $\sim$ 4.2m in Fig.3). The phase of the peaks is different in the measurement at different toroidal cross sections (port 3.5 and 6.5).

The magnetic reconnection in the region where the magnetic surfaces are heavily compressed by the large Shafranov–shift is thus promising candidate for the phenomena since the time scale of the events suggests that the transport along the magnetic field lines is important. The characteristics of CDC is consistent with the idea that magnetic reconnection, well–localized one, occurs in the outboard side. Observed peaks in SXR reflect the plasma blobs transferred from the plasma core along the magnetic field lines.

Before the appearance of the CDC, MHD activities with a toroidal mode number n=2 are often observed. These oscillations occasionally appear in the SXR signals by which we can determine the spatial structure of the modes (Fig. 4). The peaks of the fluctuation are localized from the core to the middle of outboard side ($0.0 < \rho < 0.7$). The phase is reversed in the center ($\rho \sim 0.3$) of the radial structure. If these oscillations are explained by mode structures with a poloidal mode number m, m is an odd number. Since the waveform is smooth and similar to the trigometric functions, low mode number, i.e. m/n = 3/2 is reasonable estimate considering the rotational transform profile ι .

The out–of–phase motion shown in Fig. 4(c) is suddenly enhanced just before the clash, suggesting an expansion of the disturbed structure. When the modification of the SXR profile completed, the magnetic fluctuations with toroidal mode number n = 2 are observed. Since there is no oscillations in SX signals correlated with magnetic fluctuations, they are localized in the very edge region where the pressure gradient there is increased after the CDC events.

Fig.5 shows the pressure profile just before the CDC events. Estimated profiles of ι and the well depth are shown together[9]. Note that, the axis used in Fig 4 is measured at a vertically elongated section with line–integral over sight lines whereas the electron temperature/density is measured at a horizontally elongated one. The profiles are not to be directly compared. From the linear stability analysis, the core region is stable against ideal MHD modes due to the deep magnetic well[10]. However, other pressure driven MHD modes, e.g. the resistive MHD modes or the ballooning modes[11], are possible candidate to trigger the magnetic

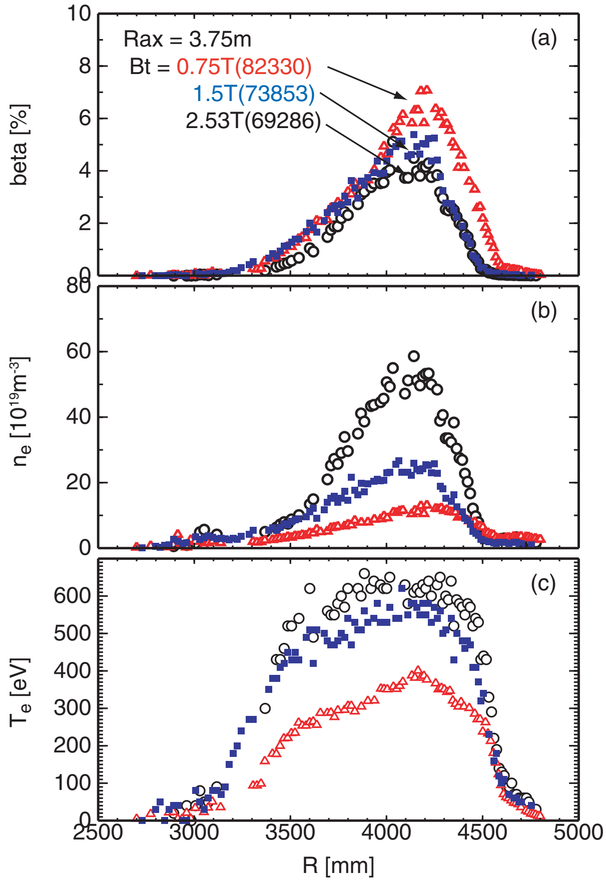

Fig 7: *Profiles of the beta (a), the electron density (b) and the electron temperature(c) are plotted with different magnetic field.*

reconnection.

The parameter dependence of the appearance of the CDC phoneme is therefore examined in Fig. 6. The data are collected at the timing of the maximum β_0 without CDC case and just before the event with CDC case, respectively. There is a clear separation of the parameters; there is a threshold value of the magnetic axis position in Fig. 6 (a) and the local beta/pressure gradient at R = 4.4m. (Here the derivative is done in the outboard side in Fig. 6 (b). The inboard side of profile measured by the Thomson scattering is sometimes distorted by the stray light.) Since the two parameters well correlated, it is not easy to distinguish which parameter governs the phenomena. However, from the control of the ellipticity, we can reduce the Shafranov–shift of the plasma experimentally[6]. We can form a higher central–beta plasma without CDC where the Shafranof-Shift is smaller but the pressure gradient exceeds the thresholds. Therefore, the former threshold is found to be a better parameter for the appearance of the CDC phenomena, though the phsical meaning of the threshold value is not clear now.

In low magnetic field case ($B_t < 1$T), the threshold of the pressure gradient and the magnetic axis position are violated (Fig. 6). There might be hidden parameters we did not notice to influence the CDC phenomena since the plasma parameters, especially the electron temperature, are well diverted in low magnetic field plasma as is shown in Fig. 7. There are thick stochastic region around the plasma in the high–beta plasma[9]. The behavior of the plasma with different parameters in the stochastic field is one candidate to explain the difference of the profile especially edge region. Anyway, we can achieve the central beta $\beta \sim 10\%$ with toroidal magnetic field $B_t = 0.65T$ and $0.75T$.

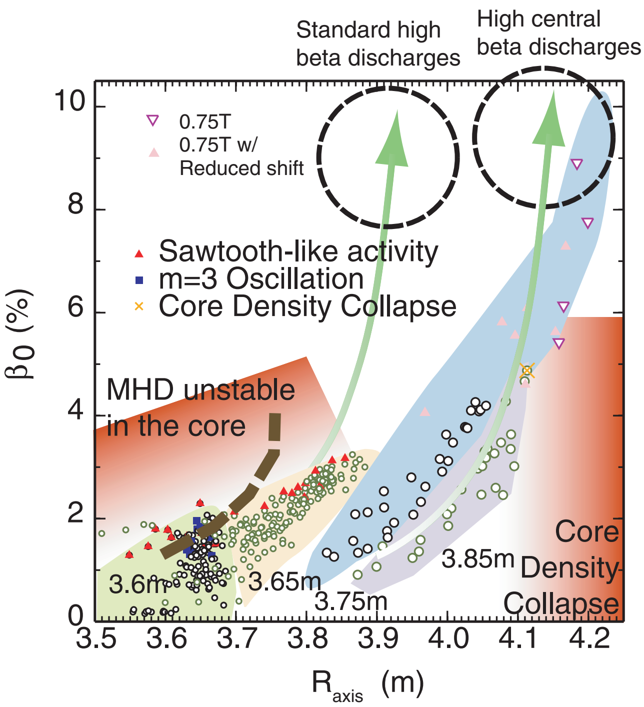

Fig 8: *Operational regime of high–beta experiments is shown. Each group of data surrounded by the shaded area corresponds to experiments with different vacuum magnetic axis (3.6m, 3.65m, 3.75m and 3.85m). Red triangles and blue squares represent sawtooth–like activity and m=3 MHD activity, respectively. Thick dashed line indicate the Mercier criterion for m/n = 2/1 modes(left had side of the line is unstable.).*

3 Operational regime for high beta plasmas

We have discussed MHD related phenomena that restricts the operation regime high–beta plasma. They are summarized in Fig. 8. There are two approaches to make high–beta plasmas. One is normal standard averaged–central–beta scenario (left arrow). We start from the vacuum magnetic axis 3.6m, where the heating efficiency and the confinement are relatively good. We barely touch the boundary of the MHD unstable region at the beginning of the discharge. After m/n = 2/1 mode is stabilized we can access higher beta region.

The other is new high–central–beta scenario (right arrow). In order to avoid the CDC events, the vacuum magnetic axis should locate inward since there is much space for the Shafranov–shift. Therefore, the best way to achieve the high central beta is to keep the magnetic axis between 3.7m and 4.1m in the formation phase of the peaked profile, avoiding these two unstable regions. The magnetic configuration suitable for the peaked profile is thus different from the one in the standard averaged–high–beta discharges. The highest β_0 (#80586) is obtained with Rax^{vac} = 3.65m (Bt = 0.65T), which is the smallest value where the peaked pressure profile can be formed at the present. The central beta (9.9 %) is comparable to the value in the highest averaged–beta discharge (#69910, Rax^{vac} = 3.6m and B_t = 0.425T) with a higher toroidal magnetic field. This higher magnetic field is one merit in high–central–beta scenario. The deterioration of the heating efficiency with outward–shifted magnetic axis is mitigated when the magnetic field is larger.

One demerit about the high–central–beta plasma is its short duration time. It is several hundreds ms to several tens ms when the peaked pressure profile is maintained, though it is much longer than the energy confinement. Another demerit is the undoubtedly CDC. Though a peaked pressure profile plasma whose central beta is comparable to the normal averaged-high-beta plasmas is achieved without the CDC in low B_t case, the CDC is potential threat since we do not know the cause of the phenomena. In order to investigate the CDC further, experiments with different collisionality and different shape of the flux surface are planned. Two kinds method can control the magnetic axis in the LHD. One is ellipticity control as is explained in the last section (See, the two kinds of plots at B_t = 0.75 in Fig. 8.) The other method is to control the vertical field in order that the plasma is pushed back to inward direction.

In summary, the relation of the MHD phenomena with a peaked pressure profile is investigated. In 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, a larger central beta was obtained; it is another promising approach to make a high–beta plasma. Though CDC events suppress the increase of the beta when the Shafranov–shift is too large, we have several methods to control them. The highest central beta is achieved by this scenario with a higher magnetic field, where the plasma parameters are closer to the values in fusion reactors.

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