Abrupt flushing of the high-density core in internal diffusion barrier plasmas and its suppression by plasma shape control in LHD

J. Miyazawa, R. Sakamoto, S. Ohdachi, M. Kobayashi, S. Masuzaki, T. Morisaki, S. Sakakibara, M. Goto, S. Morita, I. Yamada, K. Narihara, H. Funaba, K. Tanaka, C. Michael, Y. Suzuki, K.Y. Watanabe, N. Ohyabu, H. Yamada, A. Komori, O. Motojima, and LHD experimental group

National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan

(Received day month year / Accepted day month year should be centered 10-point type)

A super-dense core of the order of 10^{20} m^{-3} is formed inside the internal diffusion barrier (IDB) during the reheat phase of the central pressure after pellet injection in LHD. Large Shafranov shift of the plasma center is observed in IDB plasmas and it reaches roughly 50 % of the plasma minor radius. In some cases, abrupt flushing of the central density takes place and this event is called as "core density collapse (CDC)". CDC must be suppressed since it inhibits further increase of the central pressure. CDC is always accompanied by large Shafranov shift of the plasma center exceeding a critical position. Theoretically, it is predicted that vertical elongation of the plasma shape ($\kappa > 1$) is effective to mitigate the Shafranov shift and the κ is controllable with the quadrupole magnetic field, B_Q. According to this prediction, B_Q scan experiment has been performed in LHD. Shafranov shift is indeed mitigated by increasing κ. As a result, CDC is suppressed and high central β values reaching ~ 7 % have been achieved in vertically elongated plasmas.

Keywords: heliotron, pellet injection, SDC, Shafranov shift, beta limit, equilibrium, elongation.

1. Introduction

In toroidal plasmas, the vertical component of dipole magnetic field induced by the Pfirsh-Shlüter (PS) current, $B_z^{\rm PS}$, causes the shift of magnetic axis from R_0 to $R_0 + \Delta$. This is called the Shafranov shift. Since the PS current is proportional to the pressure gradient, Δ is determined by the central plasma beta, β_0 [1]. Large Shafranov shift, reaching a half of the plasma minor radius, a, for example, causes destruction of magnetic surfaces that leads to loss of confinement. From this point of view, it is expected that there will be an equilibrium beta limit at $\Delta \sim 0.5\ a$ [2]. Mitigation of Shafranov shift is therefore an important issue to achieve high β_0.

A discovery of internal diffusion barrier (IDB) plasmas in LHD [3] makes it possible to realize the high central plasma pressure reaching 1.3 atm [4,5]. IDB plasmas are produced by hydrogen ice pellet injection and characterized by a strongly peaked density profile with relatively low density in the edge region, which is called "mantle". The low mantle density enables deeper penetration of heating beams reaching the plasma center. As long as the central heating power is kept constant, the central pressure increases with the density, following the preferable density dependence in the global confinement scalings, such as ISS95 and ISS04 [6]. IDB plasmas are also characterized by large Shafranov shift due to the high β_0. Recently, an unexpected phenomenon has been found in IDB plasmas. This takes place when the Shafranov shift of the plasma center exceeds a critical position. Then, the density in the core region is flushed out to the mantle region within < 1 ms [7], while the temperature profile scarcely changes. We call this event as "core density collapse (CDC)" [4,5]. CDC must be suppressed since it inhibits further increase of the central pressure and the fusion triple product. Since CDC is always accompanied by large Shafranov shift, its mitigation might affect CDC.

At least three methods are effective for Shafranov shift mitigation, *i.e.* 1) plasma position control with a vertical magnetic field that compensates $B_z^{\rm PS}$, 2) increase of the rotational transform, $\iota\!\!\!- = \iota / (2\pi)$ (note that the PS current and $B_z^{\rm PS}$ is inversely proportional to $\iota\!\!\!-$ and as a result, $\Delta \propto B_z^{\rm PS} / \iota\!\!\!- \propto 1 / \iota\!\!\!-^2$), and 3) vertical elongation of the plasma shape. The first method is straightforward and will be effective only if it is applied with feedback control. Use of a strong vertical field from the beginning of a discharge is not preferable, because the initial magnetic configuration should be strongly inward shifted and MHD instabilities are expected to be unstable in such configurations [8]. Unfortunately, feedback control of the

author's e-mail: miyazawa@LHD.nifs.ac.jp

vertical field is not equipped on LHD, to date, although it is under discussion as a future program (available magnetic field strength is expected to be low). As for the second method, this indeed works as reported in [9]. In LHD, ι is controllable by changing the magnetic configuration, and especially, ι increases with the aspect ratio of the torus. However, the magnetic field strength available in high aspect ratio configurations is limited to ~ 1 T, for instance. Therefore, the third method of vertical elongation is the only possible solution applicable at the maximum magnetic field strength of ~ 3 T.

In this study, experimental results of the elongation scan and its impact on CDC are reported.

2. Plasma shape control by the quadrupole field

In toroidal plasmas, the PS current is induced to cancel the charge separation due to the variation in the magnetic field strength, ΔB, on flux surfaces, which is proportional to $1/R$. Therefore, vertical elongation, which reduces the characteristic length of the torus in the major radius direction, ΔR, is also effective to reduce the $\Delta B \propto \Delta R$ and thus the PS current. The magnetic surfaces in heliotron plasmas with l = 2 as in LHD can be approximated by rotating ellipse, *i.e.* a horizontally elongated ellipse and a vertically elongated ellipse appear alternately as the toroidal angle changes. The plasma elongation, κ, is defined as a toroidally averaged ratio of the minor radius in the vertical direction to that in the major radius direction of the last closed flux surface (LCFS). In LHD, we measure two kinds of line-density, nL_{FIR} and nL_{MMW}, passing through the “major axes” of vertically and horizontally elongated ellipses, by a far-infrared (FIR) interferometer and a millimeter wave (MMW) interferometer, respectively. Here, we define an effective elongation $\kappa_{\mathrm{eff}} \equiv nL_{\mathrm{FIR}} / nL_{\mathrm{MMW}}$. Note that these line densities include the information outside the LCFS (called ergodic region), and therefore κ_{eff} is merely an approximation of κ.

Both in helical plasmas and tokamaks, κ is controlled by the quadrupole magnetic field, B_{Q}. In the standard configurations of LHD, the quadrupole component generated by two helical coils is 100 % cancelled by the quadrupole field generated by poloidal coils and therefore κ = 1. Hereinafter, the B_{Q} that results in κ = 1 is called “B_{Q} = 100 %”. When B_{Q} is decreased to < 100 %, the κ becomes larger than 1, *i.e.* the plasma is vertically elongated. The relation between B_{Q} and experimentally measured κ_{eff} in low beta plasmas at R_{ax} = 3.75 and 3.85 m is shown in Fig. 1. The elongation of the LCFS estimated from the vacuum magnetic data for R_{ax} = 3.60 m is also shown in Fig. 1 (the point at B_{Q} = 150 % is measured). Even though κ_{eff} includes the information of the ergodic region, it well approximates the elongation of LCFS.

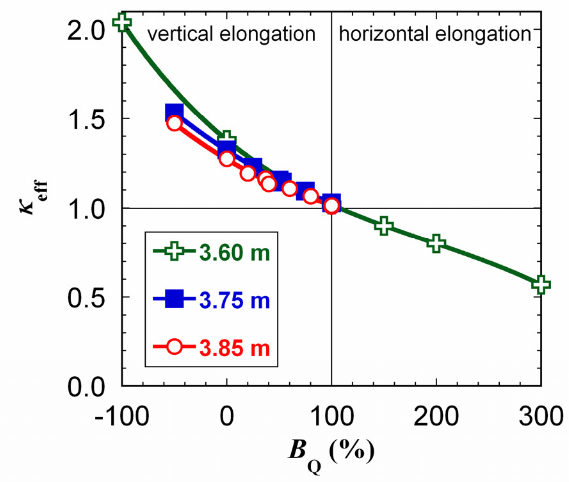

Fig. 1 Relation between the quadrupole magnetic field, B_{Q}, and the effective plasma elongation, κ_{eff}, in low beta plasmas of R_{ax} = 3.75 m (filled squares) and 3.85 m (circles). The LCFS elongation estimated from the vacuum magnetic data for R_{ax} = 3.60 m, except the point at B_{Q} = 150 % that is measured κ_{eff}, is also shown (white crosses).

3. Core density collapse event

A super-dense core of the order of 10^{20} m^{-3} is formed inside the IDB during the reheat phase of the central pressure after pellet injection in LHD [3, 4]. Waveforms in a typical IDB discharge are shown in Fig. 2. Large Shafranov shift of the plasma center measured on a horizontally elongated slice, R_0^{h}, is observed during the reheat phase (t = 0.95 – 1.12 s) and it reaches roughly 50 % of the plasma minor radius. In some cases, abrupt flushing of the central density is observed (t ~ 1.13 s in Fig. 2). This is what we call CDC. The CDC event finishes within < 1 ms, according to the fast soft X-ray measurement (not shown) [7]. At CDC, the Shafranov shift $R_0 + \Delta$ exceeds ~ 4.1 m on a horizontally elongated slice (this value is insensitive to the magnetic configuration, at least for R_0 = 3.75 – 3.90 m).

Radial profiles of the plasma pressure (beta) before and after CDC are shown in Fig. 2, which are taken from the same discharge shown in Fig. 1. The plasma center shifts outward (from left to right in Fig. 1), as the central beta increases from ~ 4.5 % (t = 1.0 s) to ~ 5.5 % (t = 1.1 s). At the same time, the inboard side plasma edge also shifts outward (see also R_{90}^{in} in Fig. 1 (c), which denote the inboard side radial position of $\beta = 0.1\ \beta_0$). Just after CDC (t = 1.134 s), both the plasma center and the inboard side edge moves inward, and the pressure profile changes from strongly peaked to approximately parabolic. It should be noted that the temperature profile is hardly affected by CDC. This is the reason why we call this

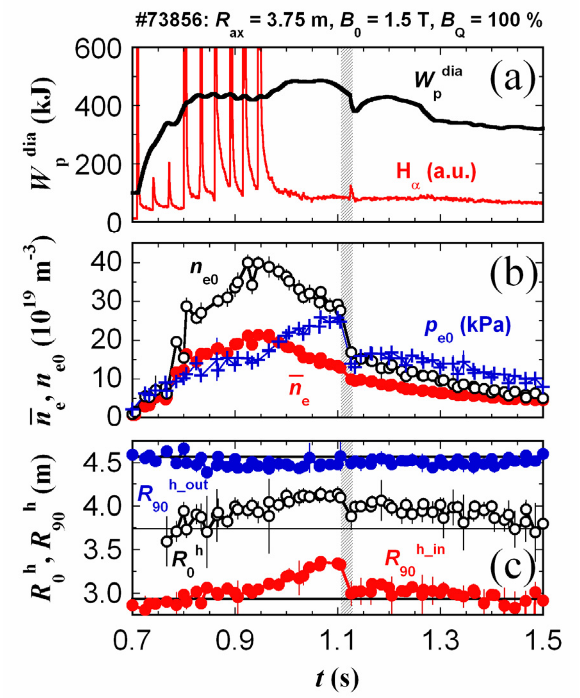

Fig. 2 Typical waveforms in an IDB discharge, where (a) the diamagnetic stored energy, W_p^{dia}, and the H_α intensity, (b) the central electron density, n_{e0}, the central electron pressure, p_{e0}, and the line-averaged electron density, (c) positions of the plasma center, R_0^h, and the inboard (outboard) side plasma edge, $R_{90}^{h\_in}$ ($R_{90}^{h\_out}$), where $\beta = 0.1$ β_0, on a horizontally elongated slice, are shown from top to bottom. CDC takes place at t ~ 1.13 s (shaded).

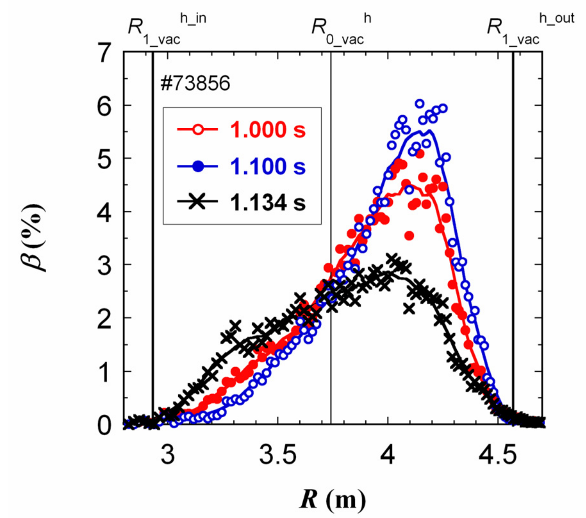

Fig. 3 Temporal change of the plasma beta profile (measured on a horizontally elongated slice), in the discharge shown in Fig. 1. Vertical lines denote radial positions of the inboard (outboard) side LCFS, $R_{1\_vac}{}^{h\_in}$ ($R_{1\_vac}{}^{h\_out}$), and the magnetic axis, $R_{0\_vac}{}^{h}$, in vacuum.

“density collapse”.

CDC must be suppressed since it inhibits further increase of the central pressure and the fusion triple product. Since CDC is always accompanied by large Shafranov shift, it is expected that CDC can be suppressed if the Shafranov sift is mitigated. This working hypothesis has been examined by the elongation scan experiment described below.

4. CDC suppression by vertical elongation

As was explained in section 2, the plasma elongation is controlled by the quadrupole field, B_Q. Vertical elongation with $B_Q < 100$ % that results in $\kappa_{eff} > 1$ (see Fig. 1) will mitigate the PS current and thus the Shafranov shift. In Fig. 4, compared are the radial beta profiles in discharges with $B_Q = 100$ % ($\kappa_{eff} \sim 1.0$), which is identical to that shown in Fig. 3 (t = 1.1 s), and $B_Q = 25$ % ($\kappa_{eff} \sim 1.2$). Even though β_0 of ~ 5.5 % is similar for both cases, the Shafranov shift of the plasma center is smaller in the case of $B_Q = 25$ %.

Since the Shafranov shift is a function of β_0, the

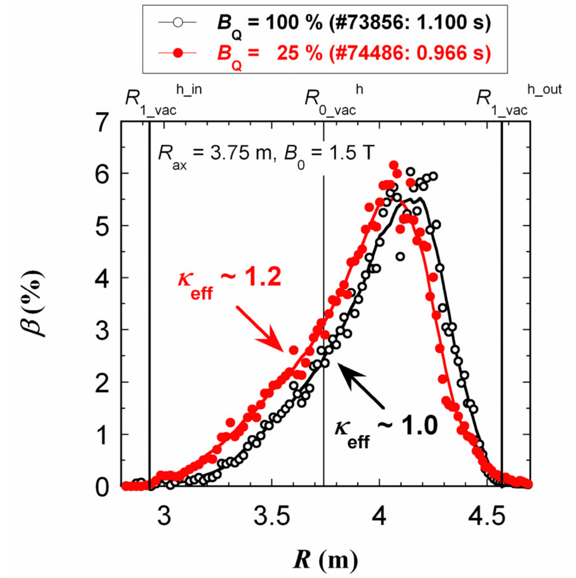

Fig. 4 Comparison of the plasma beta profiles (measured on a horizontally elongated slice), in two discharges with $B_Q = 100$ % ($\kappa_{eff} \sim 1.0$) and $B_Q = 25$ % ($\kappa_{eff} \sim 1.2$). Vertical lines denote radial positions of the inboard (outboard) side LCFS, $R_{1\_vac}{}^{h\_in}$ ($R_{1\_vac}{}^{h\_out}$), and the magnetic axis, $R_{0\_vac}{}^{h}$, in vacuum.

impact of vertical elongation on Shafranov shift mitigation is clearly observed when it is plotted against β_0, as in Fig. 5. The difference between $B_Q = 100$ % and 25 % is clearly seen at high β_0 of over 3 %, while it is small in low β_0 cases. Compared at $\beta_0 \sim 5.5$ %, R_0^h reaches ~ 4.15 m and CDC takes place in the case of $B_Q = 100$ %, while R_0^h is

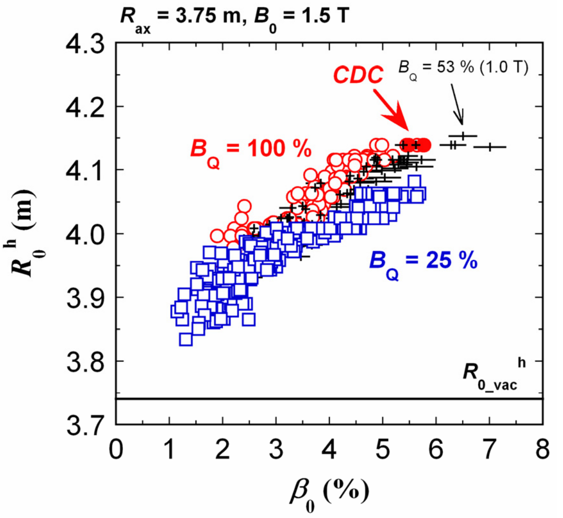

Fig. 5 The radial position of the plasma center position on a horizontally elongated slice, R_0^h, versus the central plasma beta, β_0. The magnetic field strength, B_0, is 1.5 T in the cases of B_Q = 100 % and 25 %, denoted by circles and squares, and B_0 = 1.0 T in the case of B_Q = 53 % ("+" with horizontal error bars). Filled circles denote the data just before CDC.

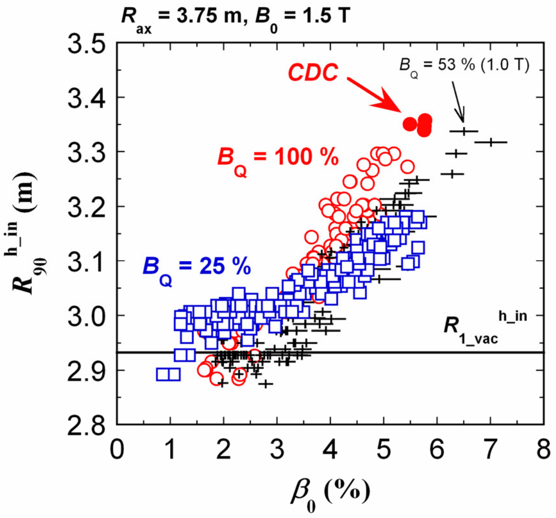

Fig. 6 The radial position of the inboard side plasma edge on a horizontally elongated slice, $R_{90}^{h\_in}$, where $\beta = 0.1\ \beta_0$, versus the central plasma beta, β_0. The magnetic field strength, B_0, is 1.5 T in the cases of B_Q = 100 % and 25 %, denoted by circles and squares, and B_0 = 1.0 T in the case of B_Q = 53 % ("+" with horizontal error bars). Filled circles denote the data just before CDC.

below 4.1 m and no CDC is observed in the case of B_Q = 25 %. Also shown in Fig. 5 is the data obtained in an intermediate case of B_Q = 53 %, where B_0 is decreased to 1.0 T to achieve higher β_0 under a limited heating power condition of ~ 10 MW. In this case, R_0^h is ~ 4.1 m at β_0 ~ 5 % and reaches ~ 4.15 m at β_0 > 6 %. The highest β_0 of ~ 7 % is achieved without CDC in this configuration.

The influence of vertical elongation is also recognized for the inboard side plasma edge position, R_{90}^{in}, as is shown in Fig. 6. CDC takes place when R_{90}^{in} reaches ~ 3.35 m at β_0 ~ 5.5 % in the case of B_Q = 100 %. In small B_Q cases, R_{90}^{in} remains less than 3.35 m even with high β_0 of > 6 %. It is expected that CDC will also take place in vertically elongated plasmas as in the case of B_Q = 100 %, but at higher β_0. It remains, however, for future study to explore the higher β_0 regime of > 7 %.

5. Discussion

It has been shown that plasma elongation is effective for Shafranov shift mitigation. No CDC is observed as long as the shift of the plasma center (or, the inboard side plasma edge) is kept apart from a critical position. In this sense, CDC seems to be related to the equilibrium limit. On the other hand, it is widely believed that the equilibrium limit will appear as a "soft limit" at which no fast event like CDC is expected. There still is a possibility that CDC is a phenomenon resulted from an unknown instability. This instability, if it really exists, should have a characteristic that it is stabilized in vertically elongated configurations. Because high β_0 reaching ~ 7 %, which is higher than those observed at CDC, is achieved in vertically elongated plasmas without CDC. It should be also noted that in vertically elongated plasmas, the pressure gradient, which might be a source of this instability, is similar to, or even larger than, those at CDC.

Acknowledgement

The authors are grateful to the LHD operation group for their support. This work is supported by NIFS07ULPP517.

References

[1] For example, V. D. Pustovitov, *Reviews of Plasma Physics* ***21*** (Consultants Bureau, New York, 2000) p. 1 – 201.
[2] A. Weller *et al.*, Plasma Phys. Control. Fusion **45**, A285 (2003).
[3] N. Ohyabu *et al.*, Phys. Rev. Lett. **97**, 055002 (2006).
[4] H. Yamada *et al.*, *34th European Physical Society Conferences on Plasma Physics 2007 (Warsaw, Poland)*, I4.004 (submitted to Plasma Phys. Control. Fusion).
[5] R. Sakamoto *et al.*, submitted to Plasma Fusion Res.
[6] H. Yamada *et al.*, Nucl. Fusion **45**, 1684 (2005).
[7] S. Ohdachi *et al.*, this conference, P1-051.
[8] O. Kaneko *et al.*, Phys. Plasmas **9**, 2020 (2002).
[9] O. Motojima *et al.*, Nucl. Fusion **45**, S255 (2005).