§3. Suppression of Core Density Collapse by Plasma Elongation Control

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Core density collapse (CDC) is observed in internal diffusion barrier (IDB) plasmas [1]. CDC inhibits further increase of the central pressure and the fusion triple product. Therefore, it is fairly important to suppress CDC. Necessary conditions for CDC has been investigated in [1], i.e. $\beta^* \geq 3.5 \%$, $R_0^h \geq 4.1 \text{ m}$, and $R_{99}^{b,\text{in}} > R_1^{\text{v,\text{in}}}$, where $R_0^h$, $R_{99}^{b,\text{in}}$, and $R_1^{\text{v,\text{in}}}$ denote the radial positions of the plasma center, $\beta^* = 0.1 \times \beta^*$ at a horizontally elongated slice (inboard side) and the last-closed-flux-surface (LCFS) at a vertically elongated slice in the vacuum configuration (inboard side), respectively. The third threshold means that the CDC takes place when the inboard side plasma edge on the equatorial plane becomes circular in the toroidal direction. This deformation of the plasma shape is due to the large Shafranov shift.

In LHD, a set of magnetic field coils is equipped to control the quadrupole field. The magnetic field induced by this coil is called as “$B_0$”. and $B_{99}$ is defined as 100 % when it completely cancels the quadrupole magnetic field in the vacuum configuration. The plasma elongation is controllable with this $B_0$. Here, we introduce an effective elongation parameter, $\kappa_{\text{eff}}$, which is defined by the ratio of the central line-density measured on a vertically elongated slice to that measured on a horizontally elongated slice. The $\kappa_{\text{eff}}$ increases with decreasing $B_0$, for example. In the case of $B_0 < 100 \%$ ($B_0 > 100 \%$), the plasma shape is compressed horizontally (vertically) at any toroidal angle, and we call this vertical (horizontal) elongation. The maximum plasma volume is obtained at $B_0 = 100 \%$. Vertical elongation is effective to suppress the Shafranov shift and therefore the deformation of the plasma shape as is shown in Fig. 1, where $R_{99}^{b,\text{in}}$ is plotted against $\beta^*$ for $B_0 = 25 \%$ and 100 %. In the case of $B_0 = 100 \%$, $R_{99}^{b,\text{in}}$ increases with $\beta^*$ and CDC takes place when $\beta^*$ reaches ~5.5 % and $R_{99}^{b,\text{in}}$ becomes $R_1^{\text{v,\text{in}}}$. In the case of $B_0 = 25 \%$, on the other hand, $R_{99}^{b,\text{in}}$ is kept well below $R_1^{\text{v,\text{in}}}$, even though $\beta^*$ exceeds 5.5 %. As a result, no CDC is observed in the case of $B_0 = 25 \%$.

Results of the $B_0$ scan experiments performed in outward shifted configurations of $R_m = 3.75 \text{ m}$ and $3.85 \text{ m}$ are summarized in Figs. 2 and 3, where $R_{99}^{b,\text{in}}$ is plotted against $\kappa_{\text{eff}}$ for fixed ranges of $\beta^*$. In low $\beta^*$ datasets, $R_{99}^{b,\text{in}}$ monotonically increases with $\kappa_{\text{eff}}$ as is expected for vertical elongation. A nonlinear response of $R_{99}^{b,\text{in}}$ is recognized in the high $\beta^*$ datasets of $\beta^* > 2 \%$ in $R_m = 3.75 \text{ m}$ (Fig. 2) and $\beta^* > 3 \%$ in $R_m = 3.85 \text{ m}$ (Fig. 3). Because of this nonlinear response, there is an optimum $\kappa_{\text{eff}}$ to keep $R_{99}^{b,\text{in}}$ apart from the CDC threshold of $R_{99}^{b,\text{in}} > R_1^{\text{v,\text{in}}}$. The optimum $\kappa_{\text{eff}}$ for $R_m = 3.75$ and 3.85 m are ~1.2 and ~1.3, respectively. It should be also noted that the margin to the CDC threshold is larger in $R_m = 3.75 \text{ m}$ than in $R_m = 3.85 \text{ m}$.

Reference

Fig. 1. $\beta^*$ dependence of $R_{99}^{b,\text{in}}$ in a vertically elongated configuration of $B_0 = 25 \%$ (closed circles) compared with that in the normal configuration of $B_0 = 100 \%$ (open circles). CDC takes place in the case of $B_0 = 100 \%$ (marked by crosses).

Fig. 2. Summary of $\kappa_{\text{eff}} (B_0)$ dependence in an outward shifted configuration of $R_m = 3.75 \text{ m}$ and $B_0 = 1.5 \text{ T}$. Different symbols denote the range of $\beta^*$.

Fig. 3. Summary of $\kappa_{\text{eff}} (B_0)$ dependence in an outward shifted configuration of $R_m = 3.85 \text{ m}$ and $B_0 = 2.0 \text{ T}$. Different symbols denote the range of $\beta^*$.