§4. Ballooning Mode that Limits the Operation Space of the High-density Super-dense-core Plasma

Ohdachi, S., Watanabe, K.Y., Tanaka, K., Takemura, Y., Suzuki, Y.

The central beta of the super-dense-core (SDC) plasma in the Large Helical Device (LHD) is limited by a large scale MHD event called "core density collapse" (CDC). The detailed measurement reveals that a new type of ballooning mode, quite localized in space and destabilized from the 3D nature of Heliotron devices, is the cause of the CDC. It is the first observation that the ballooning mode is excited where the global magnetic shear is negative. Avoidance of the excitation of this mode is a key to expand the operational limit of the LHD.

High-density operation is one possible reactor scenario of helical confinement system. In the SDC type discharges [1)], the electron density higher than 10^{21} m^{-3} with toroidal magnetic field B_t = 2.5 T is achieved. However, the central pressure or the central beta of SDC plasma is strongly limited by the CDC [2)]. The ballooning instabilities related with the 3D nature of helical systems, referred to high-n ballooning mode [3)], is considered to be the cause of collapse. The stability of the ballooning mode is determined by the local magnetic shear and the local magnetic curvature. In the Heliotron devices, it was predicted that the local magnetic shear can be reduced significantly around the local pressure gradient peak in the global negative magnetic shear region when the Shafranov-shift is large [3)]. The ballooning mode is driven by the pressure gradient in the bad curvature region when the local shear is reduced.

In the experiments, just before the CDC events, pre-cursor oscillations at around 8 kHz measured by the 80-ch CO_2 laser imaging interferometer have been found only in the outboard side (Fig.1 (B)). If the mode structure of the pre-cursor is localized around a flux tube (See, 3D image of Fig.1 (C)) connected to the outboard side of the horizontally elongated section (worst curvature region), two sharp peaks observed in the fluctuation profile shown in Fig. 1 (B) can be understood; two peaks correspond to mode structure observation at two location marked by closed white circles P1 and P2. A newly developed 2D SX detector array observing the bad curvature region shows that this pre-cursor like movement is aligned to the local magnetic field line (shown by grey pixels in Fig. 1 (C)). This observation also supports that the mode structure is quite localized to the local magnetic field line. Since the amplitude of the pre-cursors increase towards the collapse events, it is reasonable that high-n ballooning mode localized both in radially and poloidally triggers the CDC. It is an open issue why the radially localized mode triggers the global collapse events. From non-linear MHD simulations of the CDC, it is suggested that the evolution of the mode enhances the stochasticity of the magnetic field and may enhance the heat transport, as well.

In order to avoid the CDC for achieving higher central beta, control of the ballooning mode by the reduction of the pressure gradient at the bad curvature region is experimentally performed.. In the relatively low magnetic field experiment (B_t = 1.5T), the pressure profile is broader than the profile with normal magnetic field B_t = 2.5T (Fig. 2 (B)). It is consistent with the smaller growth rate predicted by Hn-Bal code with the smaller beta gradient. The operational boundary observed in the 2.5T can be passed over and the central beta has reached about 10% with B_t = 1.5T and R_{ax0} = 3.75m. It is the highest central beta achieved in the LHD and is comparable to the maximum central beta recorded in B_t = 0.45T experiments.

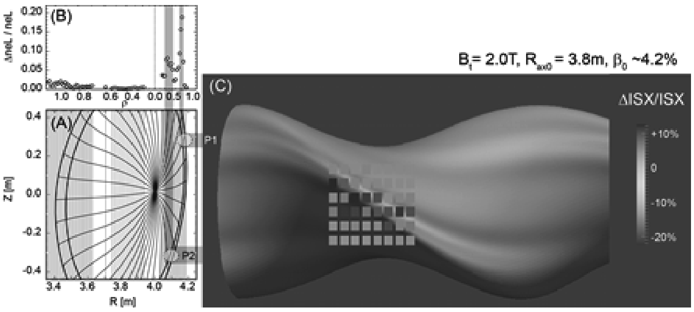

Fig. 1. Sightlines of CO_2 laser imaging interferometer (A), the line-integrated fluctuation profile in the pre-cursor phase (B), and hypothetical mode strucure drawn on the surface of the 3D image of LHD plasma (□~0.8) together with the 2D profile of the change in the SX emission just before the CDC (C) measured by 2D (6chx8ch) SX array.

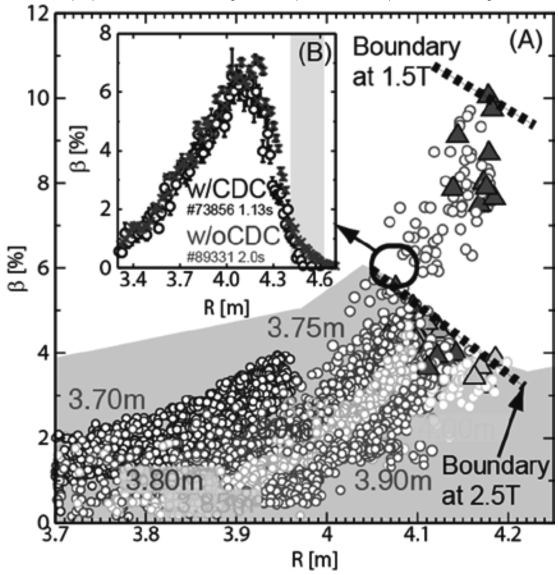

Fig. 2. (A) The central beta as a function of the magnetic axis location is shown with different vacuum magnetic axis location R_{ax0}. B_t = 2.5T for R_{ax0} = 3.8-4.0m and B_t = 1.5T for R_{ax0} = 3.75m. Triangle symbols indicate the appearance of the CDC. (B) Beta profile just before the CDC and without CDC are shown.

1) N. Ohyabu, et. al., Phys. Rev. Lett. **97**, 55002 (2006).
2) S. Ohdachi, et. al., Contrib. Plasma Phys. **50**, 552 (2010).
3) N. Nakajima, Physics of Plasmas **3**, 4545 (1996), **3**, 4556 (1996).