Identification of Ballooning-Type Pressure Driven Instability by Tomographic Reconstruction

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This paper deals with the experimental identification of the mode structure for the CDC by the tomographic reconstruction. Theoretically, it was predicted the CDC is triggered by the high-n ballooning mode. In the experiment, the localized density fluctuations at the outboard side are observed at the onset, and this is evidence that the ballooning-like instability triggers the CDC. Still, it was not well confirmed because the mode structure is not experimentally understood yet. To understand the mode structure, a new tomographic reconstruction is developed by coupling the Fourier-Bessel series expansion method and sparse modeling with L1 regularization. Using this, the ballooning-like mode structure of the density fluctuations is successfully reconstructed at the precursor.

Keywords: CDC, ballooning mode, tomography

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The Super-Dense Core (SDC) plasma with the steep pressure gradient along the plasma central chord core by the repetitive pellet injection was found in the Large Helical Device (LHD) experiment [1]. Figure 1 shows (a) the time evolution of the line-integrated electron density, n_el, in the plasma center and (b) the volume averaged beta value, $\langle\beta\rangle$, of an SDC plasma. The n_el achieved 3.0×10^{20} m^{-2}. However, on the decay phase of the n_el, a collapse of the electron density at $t \sim 4.7$ s happens, and then the n_el and $\langle\beta\rangle$ sharply drop. This collapse is so-called the CDC (Core Density Collapse) [2]. Since the SDC plasma is a candidate for the fusion plant scenario [1], suppressing the CDC is a crucial problem. Theoretically, the high-n ballooning mode is predicted to trigger the CDC [3]. On the other hand, in the experiments, the localized density fluctuations at the outboard side as a precursor were observed [4]. Although these results suggest that the high-n ballooning mode triggers the CDC, the mode structure of the high-n ballooning mode has not been identified. To identify the trigger as the ballooning mode, the mode structure needs to be understood. The goal of this study is the experimental identification of the ballooning-type mode structure.

The tomographic reconstruction [5] is an inverse problem to estimate the local profile $\mathbf{f}$ from the projection like the line-integrated signals $\mathbf{g}$ as in the following equation:

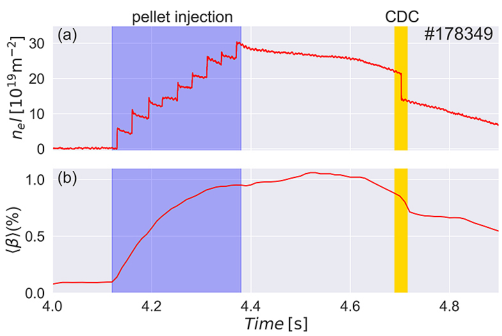

Fig. 1. Time evolution of (a) the line integrated electron density, n_el, and (b) the volume averaged beta value, $\langle\beta\rangle$, of an SDC plasma (#178349).

$$H\mathbf{f} = \mathbf{g}, \quad (1)$$

where H is the geometrical relationship. Usually, the $\mathbf{f}$ is solved by the least square algorithm with the penalty function, and many lines of sight (LOS) are necessary to avoid an ill-posed inversion problem. However, in the LHD, it is difficult to prepare many LOSs due to the limitation of the helical coils. Therefore, to avoid this ill-posed inversion problem, a new tomographic reconstruction method was newly developed [6]. This method combines the series expansion method based on the Fourier-Bessel functions [7] and sparse modeling using L1 regularization to decide the coefficients of the series

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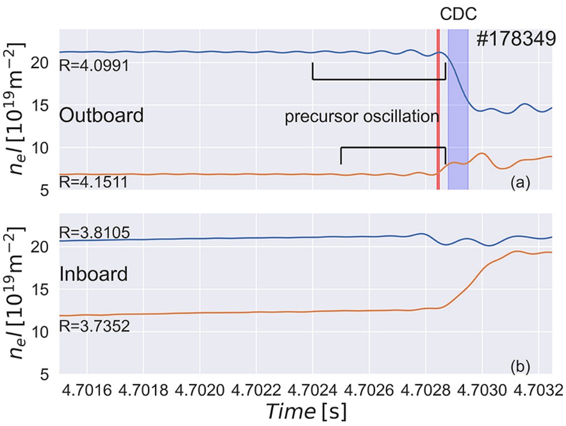

Fig. 2. Comparison between the time evolution of the line-integrated electron density measured by a CO_2 laser interferometer during the precursor and the CDC at (a) the outboard and (b) the inboard sides. R indicates the position of the line of sight in the major radius (#178349). The analyzed data (red) is from 4.702847 to 4.702849 s. The precursor appears only at (a) the outboard side.

expansion. The hyperparameter of the L1 regularization, α, is determined by CV (Cross Validation) [8].

Figure 2 shows the comparison of the $n_e l$, which is measured by the CO_2 laser interferometer [9, 10], in the vertically elongated cross-section, during the precursor and the CDC at (a) the outboard and (b) the inboard side. The precursor appears only at (a) the outboard side, but it does not appear at (b) the inboard side. In addition, the amplitude of the oscillations at the outboard side is increasing toward the CDC, so these oscillations are the ballooning-type mode triggering the CDC.

The density fluctuations, $\widetilde{n_e}$, are reconstructed by the newly developed tomographic reconstruction method. Figure 3 shows (a) measured and reconstructed fluctuations of the line integrated electron density, $\widetilde{n_e l}$, and (b) the mode structure of the $\widetilde{n_e}$. Here, $\widetilde{n_e l} = \Delta n_e l / n_e l = (n_e l - <n_e l>)/n_e l$ and $<n_e l>$ is the moving average of the $n_e l$ from 4.702847 to 4.702849 s. The hyperparameter, α, was roughly 8.0×10^{-10}. In Fig. 3(a), measured and reconstructed $\widetilde{n_e l}$ agree well. The reconstructed mode structure of the $\widetilde{n_e}$ in Fig. 3(b) obviously localizes at the outboard side, and it indicates the precursor is the ballooning-like mode. This result is consistent with the numerical predictions and strongly suggests that the precursor at the outboard side has the ballooning-type mode structure.

In conclusion, the mode structure at the precursor is successfully reconstructed using the newly developed tomographic reconstruction. The reconstructed mode structure clearly indicates the ballooning-type mode structure and agrees with the numerical prediction.

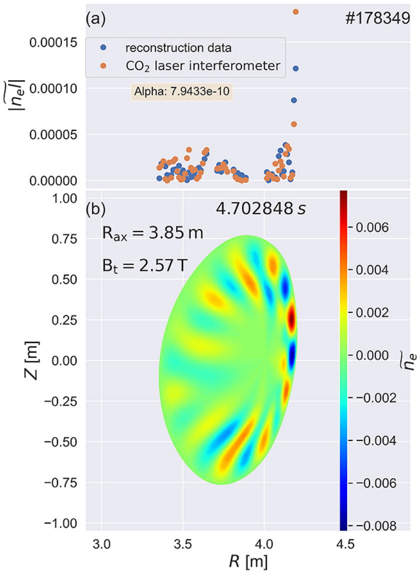

Fig. 3. Comparison between (a) the reconstructed fluctuations (blue) and the experimental value (orange) at the precursor. α in (a) indicates hyperparameter. (b) Reconstructed image of the density fluctuations at time 4.702848 s (#178349). R_{ax} in (b) is the preset magnetic axis. B_t in (b) is the toroidal magnetic field.

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