β_p-Collapse-Induced VDE and its Underlying Mechanism in the TCV Tokamak

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1. Introduction

It is well known that the interaction between a disruptive tokamak plasma and a surrounding resistive shell plays an important role in the dynamics of a Vertical Displacement Event (VDE) [1]. This paper describes onset mechanisms of VDEs induced by a strong plasma pressure drop (β_p-collapse) in disruptive discharges of the Tokamak Configuration Variable (TCV). Many aspects of the TCV vertical instability have been investigated [2-7]. In this paper, we first compute open-loop growth rates of VDEs in TCV using the Tokamak Simulation Code (TSC) [8], and compare the results with JT-60U. We then investigated the eddy current effects due to a β_p-collapse for disruptive and non-disruptive TCV discharges in nonlinear TSC simulations.

2. TCV Vertical Stability

Since TCV is specifically designed to explore the operational benefits of plasma shaping over a wide variety of plasma shapes [4], it can generate a great variety of vertical instabilities. Vertical growth rates as a function of the magnetic field decay n-index ($n = R/B_Z\,(\partial B_R/\partial Z) = -R/B_Z\,(\partial B_Z/\partial R)$), defined at a magnetic axis, were evaluated by the TSC, as shown in Fig.1. Major plasma parameters are the following : plasma current I_p = 352 kA, toroidal magnetic field B_t = 1.38 T, internal inductance ℓ_i = 1.1. Poloidal beta was taken as a range of β_p = 1.0, 0.5 and 0.0 to clarify the plasma pressure effect on the vertical instability. Figure 1 indicates that the growth rate increases as the magnitude of the n-index increases. The low β_p plasmas are more stable than the high β_p plasmas for a given n-index. Cases with similar shape, indicated by the groups of symbols in Fig. 1, show a decrease in the growth rate for increasing β_p, due to the reduction of the n-index required to produce the given shape.

A simple model of rigid shifts of circular-shaped plasmas states that the linear growth rate is a function of the n-index and the stability index n_s, defined by

$$n + n_s \frac{\gamma \tau_s}{1 + \gamma \tau_s} = 0 \quad . \qquad (1)$$

Here, τ_s is the effective skin time of the resistive shell. The stability index n_s depends on the shell-geometry and the plasma equilibrium.

By means of a least squares fit of Fig. 1 using Eq. (1), the TCV stability indices n_s were evaluated to be 2.41 for low β_p (= 0.0), 2.16 for β_p = 0.5 and 1.91 for β_p = 1.0, respectively. Although the decay time of the antisymmetric eddy current mode is 8.1 msec [4], τ_s was about 2.5 msec, reflecting a reduced coupling between the plasma and the vacuum vessel. The stability index of the JT-60U, where no β_p-collapse-induced VDE has been observed, was as high as n_s = 3.4 for β_p = 0.0 [9], because that the oval JT-60U vacuum vessel with a height-to-wide ratio of 1.3 is close to the plasma. In the TCV, the vacuum vessel has a large height-to-wide ratio, 3.0, and is consequently further from the plasma. As a result, the stability margin given by the definition of $|n_s/n|$ is as low as 1.5 for these equilibria, below 1.1 for extreme equilibria [10], while 2.1 in the JT-60U, providing n = -1.6. This implies that the TCV is more close to the absolute stability limit than the JT-60U, and hence, VDEs might more easily occur under a change of equilibrium state such as β_p-collapse.

3. β_p-Collapse-Induced VDE

3.1 TCV Experiments

Figure 2 shows the TCV disruptive discharge #10890 during the period 310.0 msec - 335.0 msec. The poloidal beta and the internal inductance before the β_p-collapse were β_p = 0.46 and ℓ_i = 1.0, respectively. The plasma elongation κ at the boundary was as high as 1.8. A β_p-collapse of $\Delta\beta_p$ = -0.46 had set in at 327.0 msec and was assumed to last for about 4.0 msec. Some oscillatory behavior of the vertical position can be seen before the β_p-collapse, indicating that the feedback system was already marginally stabilizing the vertical position. A plasma current quench following the β_p-collapse had occurred at 331 msec. While the radial shift of the plasma magnetic axis was observed to be ΔR = -2.0 cm during the period of the β_p-collapse, the vertical position moved upward to around Z = 40 cm at 4 msec after the onset of the β_p-collapse. The experiment of Fig. 2 consequently shows that the strong β_p-collapse has provoked a significant change in the vertical stabilization which could trigger a VDE.

On the contrary, a less elongated discharge #10606 (κ = 1.35) with lower β_p (= 0.38) survived after a small β_p-collapse ($\Delta\beta_p$ ~ -0.2), as shown in Fig. 3. Although the radial shift of the plasma magnetic axis was observed to be ΔR = -1.0 cm, the small β_p-collapse of $\Delta\beta_p$ = -0.2 at 711.0 msec did not result in a VDE.

3.2 TSC Simulation

The TSC simulation was carried out to reproduce the β_p-collapse behavior of the TCV discharge #10890 by introducing a rapid plasma pressure drop of $\Delta\beta_p$ = -0.46 at 327 msec. In the simulation, the vertical feedback control was turned off at 327 msec on the assumption that due to the β_p-collapse the active feedback failed to keep the plasma at a desired vertical position. Figure 4 shows the comparison between the plasma configurations of the experiment and the simulation. The TSC nicely reproduces every equilibrium of the TCV discharge #10890.

Figure 5 shows TSC time-evolutions of the plasma current and the position of the magnetic axis. The β_p-collapse led to the coincident radial shift of the magnetic axis by ΔR = -2.0 cm, as in the experiment. Simultaneously, the n-index, evaluated at the magnetic axis, degraded from n = -1.6 to -1.9 (Δn = -0.3) due to eddy current effects. As in the experiment, a fast VDE occurred, and a large vertical displacement of Z = 40 cm was observed at 4.0 msec after the β_p-collapse. The vertical growth rate at the beginning phase of 327 msec - 329 msec was estimated to be 1300 sec^{-1}. After 329 msec, the magnetic axis moves vertically into a region of a better n-index, and hence, the VDE should be slowed down due to lower absolute value of the n-index, as in Fig. 2.

Figure 1 implies that the pure vertical growth rate before the β_p-collapse was 1000 sec^{-1}, indicating that (a) the loss of plasma β_p improved the vertical instability, and that (b) the degradation of *n*-index leads to a destabilization [9]. The degradation arises from an additional quadrupole moment of magnetic field produced by eddy currents flowing to suppress the inward radial shift of the magnetic axis. The mechanism (b) competes with the improvement (a) during disruptions. When the destabilizing mechanism (b) overcomes the improvement (a), the vertical instability should be enhanced compared with its value before the β_p-collapse. In the case of the discharge #10890, the initial growth rate of 1000 sec^{-1} is reduced to 750 sec^{-1} by the mechanism (a), and then, by the destabilization (b) due to the degradation of Δn = -0.3 the vertical instability is increased up to 1500 sec^{-1}, which is nearly same as the TSC growth rate of 1300 sec^{-1} just after the β_p-collapse. On the contrary, the vertical growth rate of the less elongated discharge #10606 remained much smaller even after the β_p-collapse of $\Delta\beta_p$ = -0.2.

4. Conclusion

The effect on vertical stability of a strong β_p-collapse in the highly elongated TCV tokamak was investigated computationally and experimentally. Disruptive and non-disruptive discharges were classified into those which appeared to have a β_p-collapse-induced VDE and those which survived without a VDE, according to the magnitude of the β_p-collapse and the plasma elongation (the *n*-index) just before the β_p-collapse occurs. One particular disruptive discharge of a highly elongated, rather high β_p plasma presents the typical behavior of the β_p-collapse-induced VDE after a full β_p-collapse. The essential mechanism of the β_p-collapse-induced VDE was confirmed to be an intense enhancement of the vertical instability due to a large and sudden degradation of the *n*-index produced by eddy currents.

Since the destabilizing mechanism due to a β_p-collapse depends on the operational regime of the plasma configuration in addition to the specifics of the shell-geometry, further experiments of higher β_p and elongation are required. These are now under way in the TCV with high power ECH. The authors would like to express their gratitudes to Drs. O. Sauter, B. Duval and I. Bandyopadhyay for the support of our computational studies and the useful discussions. They also wish to thank Professors F. Troyon and M.Q. Tran and Drs. T. Ozeki and R. Yoshino for their continuous encouragement.

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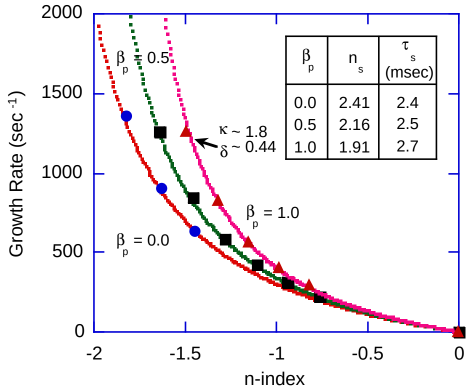

Fig. 1 Vertical growth rates of TCV as a function of decay n-index.

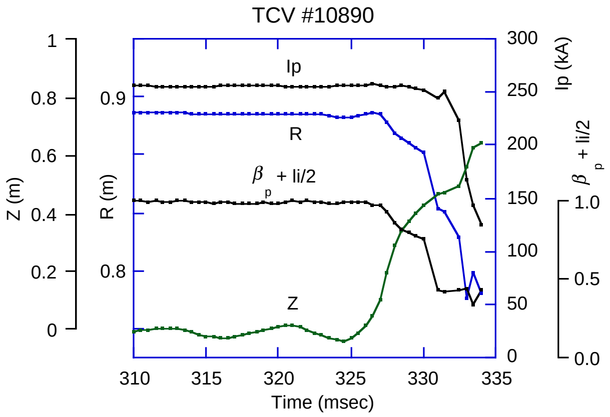

Fig. 2 TCV disruptive discharge #10890 (κ = 1.8) due to full βp-collapse of Δβp = -0.46, which had set in at 327.0 msec. βp-collapse could trigger a VDE.

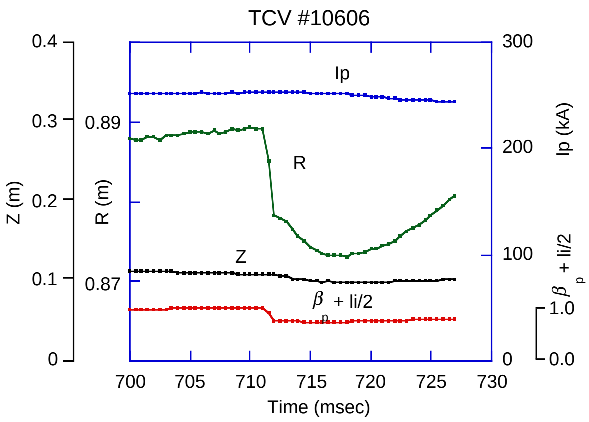

Fig. 3 TCV discharge #10606 (κ = 1.35) with small βp-collapse (Δβp ~ -0.2), which had set in at 711.0 msec.

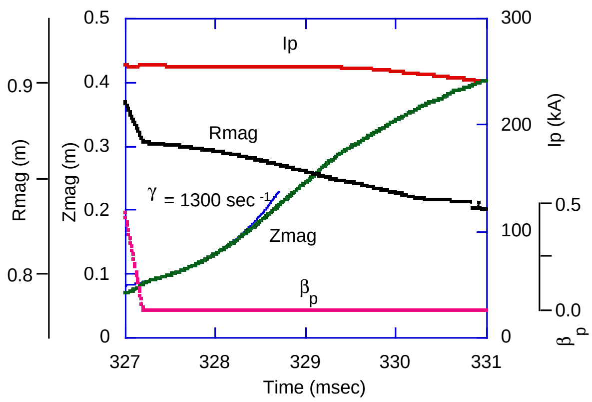

Fig. 5 TSC simulation of TCV disruptive discharge #10890. Vertical growth rate was estimated to be 1300 sec^{-1}.

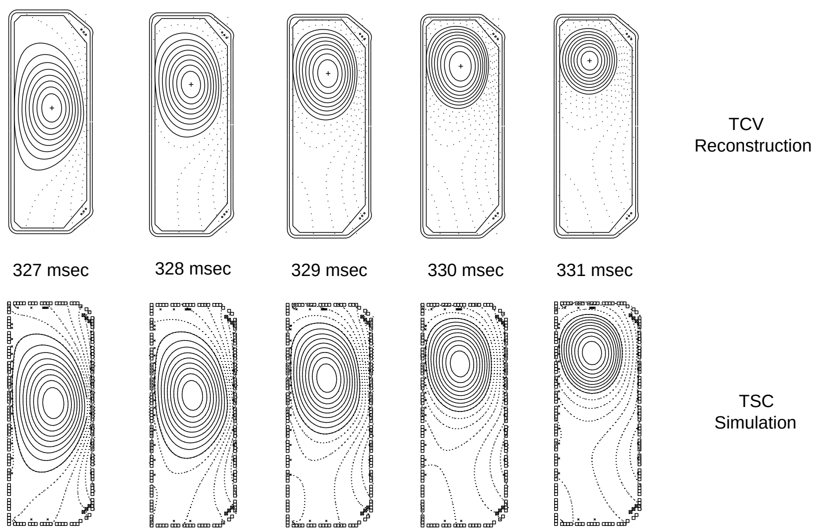

Fig. 4 Comparison of experimental (upper row) and numerical (lower row) configurations of TCV discharge #10890.