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In a vertically elongated ($\kappa \sim 1.5$) , high β_p($\beta_p \sim 1.7$) tokamak with a resistive shell, extremely fast vertical displacement events (VDE's) induced by a model of strong β_p collapse were found through computer simulations using the Tokamak Simulation Code. Although the plasma current quench, which had been shown to be the prime cause of VDE's in a relatively low β_p tokamak ($\beta_p \sim 0.2$) [1], was not observed during the VDE evolution, the observed growth rate of VDE's was almost five times ($\gamma \sim 655\ \mathrm{sec}^{-1}$) faster than the growth rate of the usual positional instability ($\gamma \sim 149\ \mathrm{sec}^{-1}$) . The essential mechanism of the β_p collapse-induced VDE was clarified to be the significant destabilization of positional instability due to a large and sudden degradation of the decay n-index in addition to a reduction of the stability index n_s. It is pointed out that the shell-geometry characterizes the VDE dynamics, and that the VDE rate depends strongly both on the magnitude of the β_p collapse and the n-index of the equilibria just before the β_p collapse occurs. A new guide line for designing the fusion reactor is proposed with considering the impact of disruptions.

Keywords: Vertical Displacement Event, Tokamak Disruption, β_p Collapse, Positional Instability, Tokamak Simulation Code, n-index, Stability Index

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高β_pトカマクディスラプションにおける プラズマのβ_p崩壊による極めて速い垂直移動現象

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（1996年４月15日受理）

抵抗性シェルを有する，縦長断面（κ～1.5），高ベータ（β_p～1.7）トカマクにおいて，強いβ_p崩壊が生じると極めて速い垂直移動現象（ＶＤＥ）が発生することをトカマクシミュレーションコードを用いた計算機シミュレーションを通じて示した。低ベータトカマク（β_p～0.2）における通常のＶＤＥの主因であるプラズマ電流の急激な減少が観測されなかったにもかかわらず，観測されたＶＤＥの成長率(γ～655 sec^{-1}）は位置不安定性の成長率(γ～149 sec^{-1}）のおおよそ５倍であった。本ＶＤＥ発生の基本機構として，安定指数 n_s の減少に加えて，さらにn指数が突然大きく悪化するために位置不安定性がさらに不安定化するためであることを示した。シェルの幾何学的配置がＶＤＥ挙動を特徴付けること，ＶＤＥの成長率がβ_p崩壊の規模および崩壊が起こる前のn指数に強く依存することを示した。ディスラプションによる影響を考慮した核融合炉設計のための新しい指針を提案した。

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1. Introduction

Experimentally observed major disruptions in tokamaks show a rapid plasma current decay (I_p quench) following a β_p collapse, a coincident fast vertical displacement event (VDE), and a shrinking plasma boundary [2-4]. A VDE can cause serious wall damage since the unstable plasma with high internal energy can contact plasma-facing components in the vacuum vessel. VDE's have been especially troublesome in machines with non-circular plasma cross-sections like JET [5], DIII-D [6], ASDEX-Upgrade [7] and JT-60U [4], where the vertically elongated plasma is positionally unstable. It is also well known that a large poloidal Halo current with up to 30 % of the total plasma current can appear after a large vertical shift of the unstable plasma, and can result in substantial electromagnetic forces on structural components [3, 6-9]. The successful operation of next-generation tokamak fusion devices such as ITER [7, 10] will require a detailed understanding of VDE mechanisms and the development of techniques for softening these unfavorable events during tokamak disruptions.

VDE mechanisms for low β_p (~ 0.2) plasmas in the JT-60U tokamak [1, 11] have been investigated using the Tokamak Simulation Code (TSC) [12]. For these cases, the central electron temperature T_e after the β_p collapse is low, ~ 100 eV or less [4]. Therefore, an I_p quench immediately follows the β_p collapse, and a fast VDE coincides with the I_p quench. Experimentally observed growth rates of VDE's (VDE rates) are at least three times higher than the values predicted by positional stability theory which includes the stabilizing effect of the JT-60U vacuum vessel [1]. Moreover, the experimental evidence indicates a close correlation between the I_p quench rate and the VDE rate ; In particular, a rapid I_p quench enhances the VDE rate [4]. TSC computational studies of VDE's showed that the experimentally observed VDE enhancement due to the I_p quench is subject to two major causes [1]. First is the up-down imbalance of attractive forces produced by the eddy current on the JT-60U vacuum vessel, whose shape is slightly asymmetric with respect to the midplane. TSC simulations show a strong dependence of VDE rates on the initial vertical locations of the magnetic axis Z. In particular, plasmas positioned at a neutral location Z ~ 15 cm above the midplane prior to the β_p collapse do not exhibit a VDE [11]. VDE avoidance was experimentally established in JT-60U low β_p disruptions [11], as is consistent with the TSC results.

A second cause of VDE enhancement during the I_p quench was found to be the enhancement of the magnetic field curvature, i. e., the degradation of field decay n-

index ($n = R/B_Z(\partial B_R/\partial Z) = -R/B_Z(\partial B_Z/\partial R)$), arising from large eddy currents induced by the I_p quench. The n-index degradation leads to an enhancement of the growth rate of positional instability and is especially important in highly elongated tokamaks with $\kappa > 1.7$. In summary, it was clarified that the I_p quench plays a key role in VDE acceleration mechanisms in low β_p tokamaks. In JT-60U disruptive discharges, it was also successfully demonstrated that reducing the impurity influxes during the β_p collapse and the direct neutral beam (NB) heating of the plasma core during the I_p quench are beneficial both for reducing the I_p quench speed and for softening the disruption [2].

The results mentioned above suggest that, unless the plasma current quenches rapidly, fast VDE's do not occur. Therefore, a slow VDE will evolve with a growth rate, which is easy to control utilizing a conventional active feedback system. This statement implies that if the electron temperature T_e after a β_p collapse is high enough to prevent a rapid I_p quench, then the VDE will not occur whatever the value of the plasma β_p prior to the β_p collapse. However, in this paper, we report on a new type of VDE caused by a strong β_p collapse in a high β_p tokamak disruption. In these, an I_p quench does not occur, yet a fast VDE is observed.

In the following sections, we describe numerical results on the onset of VDE's induced by a strong β_p collapse and discuss the fundamental mechanism. Throughout our investigations, self-consistent TSC simulations of deformable plasmas were carried out including the stabilizing effect of the resistive shell. The effect of shell-geometry on VDE characteristics is discussed in detail. In section 2, the TSC simulation model is described and numerical evidence for the new VDE is presented. In section 3, an investigation of VDE mechanisms is carried out. Finally, our conclusions are given in section 4.

2. TSC Simulation

2.1 TSC Model

The TSC code can accurately compute the full non-linear axisymmetric and deformable plasma motion including all realistic control aspects, such as an active feedback system, resistive conductors, and circuit and power supply dynamics [12]. However, we will focus on the axisymmetric dynamics of toroidal plasmas electromagnetically interacting only with the resistive shell, because our interests mainly lie in the rapid processes during the β_p collapse and the subsequent VDE index ($n = R/B_Z(\partial B_R/\partial Z) = -R/B_Z(\partial B_Z/\partial R)$), arising from large eddy currents induced by the I_p quench. The n-index degradation leads to an enhancement of the growth rate of positional instability and is especially important in highly elongated tokamaks with $\kappa > 1.7$. In summary, it was clarified that the I_p quench plays a key role in VDE acceleration mechanisms in low β_p tokamaks. In JT-60U disruptive discharges, it was also successfully demonstrated that reducing the impurity influxes during the β_p collapse and the direct neutral beam (NB) heating of the plasma core during the I_p quench are beneficial both for reducing the I_p quench speed and for softening the disruption [2].

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The inclusion of details of plasma transport including impurity influx and degradation of energy confinement is beyond the scope of the computational work in this paper. The functional forms of the plasma pressure profile and plasma density profile are assumed to remain unchanged during the TSC simulation. These are given by $p(\overline{\Psi}) = p_0\, \overline{\Psi}^{3/2}$ and $n(\overline{\Psi}) = n_0\, \overline{\Psi}$, respectively. Here, $\overline{\Psi}$ (= (Ψ-Ψ_s)/(Ψ_{axis}-Ψ_s)) is the normalized poloidal flux. In order to introduce a β_p collapse, the magnitude of the plasma pressure is given as a prescribed time dependence.

In this paper, we also neglect the effect of Halo current on the VDE dynamics. This is justified because JT-60U measurements show no evidence of Halo currents during the first half phase of the disruption [8]. Large amounts of Halo current appear in the second half phase of plasma current termination after a large vertical shift of the magnetic axis [8]. The JT-60U observations are consistent with those of DIII-D and JET [6, 9]. Our main interest here lies in the first half phase of the disruption, consisting of the rapid β_p collapse followed by the fast VDE evolution on a time scale much shorter than the L/R time of the resistive shell. Another reason for neglecting the Halo current in the present study is that here we are interested in mechanisms which accelerate the VDE's, whereas Halo currents mitigate the VDE's. A study of the effect of Halo current on VDE dynamics is planned as future work.

To investigate the vertical stability in detail, a vertically elongated, bottom-diverted, single-null (SN) tokamak similar to JT-60U and ITER was considered as a model tokamak. Figure 1 illustrates the TSC conductors which model the poloidal field coil system (represented by open boxes) and the resistive shell (represented by closed boxes). The poloidal field coil system is similar to the JT-60U system. The resistive shell has an up-down symmetry with respect to the midplane and is discretized into 34 axisymmetric elements. The inboard section of the resistive shell stabilizes the radial shift of the plasma due to the β_p collapse, and the outboard sections passively stabilize the vertical plasma displacement. The shell-geometry is typical of those commonly used in computational studies on controlling the positional instability in tokamaks [13]. The dominant up-down antisymmetric current mode of the resistive shell, which stabilizes a vertical displacement, has a decay time constant of about 18 msec, while the time constant of the eddy current mode which stabilizes the radial expansion of the plasma was estimated to be about 25 msec. The computational domain is the square box spanning 1.5 m to 5.5 m in the major radius direction and -2.0 m to 2.0 m in the vertical direction. This domain was divided into (80 × 80) grids with equal spacing of 5 cm. For reasons of computational efficiency [12], the TSC Alfven time was slowed down by choosing a mass enhancement factor of 50.0. Therefore, the modified Alfven time is around a few tens of microsecond, which is much less than both time scales of the model of the β_p collapse and the L/R time of the resistive shell. It was verified that this artificial enhancement does not affect the results.

Major plasma parameters for the initial equilibrium just before the β_p collapse are the following : plasma current I_p = 1.5 MA, toroidal magnetic field B_t = 3.5 T, plasma minor radius a = 0.76 m, poloidal beta β_p = 1.7, and the plasma internal inductance ℓ_i = 1.5. The plasma shape is characterized by the elongation κ = 1.5, and the triangularity δ = 0.14. The location of the magnetic axis (R, Z) was (3.33 m, 0.0 m). The magnetic field decay n-index produced by the poloidal field coil systems was -1.5 at the magnetic axis. The growth rate of positional instability including the resistive shell effect was calculated to be 149 sec^{-1} using the TSC.

2.2 β_p Collapse-Induced VDE

In order to cause a β_p collapse in the high β_p plasma described above, we introduced a rapid plasma pressure drop lasting for 200 μsec by assuming a prescribed pressure as a function of the time. Although the time scale of the pressure drop might be considerably faster than the experimental observation of the JT-60U β_p collapse time (a few msec) [2], the rapid pressure drop is a convenient model of the β_p collapse. We can clearly separate the axisymmetric dynamics of high β_p plasma disruptions into a rapid radial shift during the β_p collapse followed by a VDE evolution. In our TSC studies, the β_p collapse is considered to be an initial perturbation given to trigger the VDE. Three magnitudes for the pressure drop defining the β_p collapse were chosen, namely $\Delta\beta_p$ = -0.5, -1.0 and -1.5. That is, the β_p values just after β_p collapse were decreased to 1.2, 0.7, and 0.2, respectively. The electron temperature T_e after β_p collapse was assumed to be still sufficiently high (> 3 keV) enough to prevent the VDE-like dynamics caused by the I_p quench.

Figure 2 shows the TSC evolution during the period of 5.0 msec from the onset of the β_p collapse, where the induced eddy current remained nearly constant in time since the L/R time of the resistive shell (~ 18 msec) is much longer than the period of TSC simulations. Figure 2(a) shows three time-traces of the magnetic axis (R, Z) on a poloidal plane. The β_p collapse lead to coincident radial shifts ΔR of the magnetic axis during the period of 200 μsec. The amounts of radial shift, ΔR, at 200 μsec were nearly proportional to $\Delta\beta_p$, the severity of the β_p collapse, i. e., ΔR = -7.5 cm for $\Delta\beta_p$ = -0.5, ΔR = -13.8 cm for $\Delta\beta_p$ = -1.0, and ΔR = -21.5 cm for $\Delta\beta_p$ = -1.5. In every case, the β_p collapse provides a small amount of coincident downward displacement of the plasma magnetic axis. The mechanism of the downward perturbation initiating the VDE in bottom-diverted SN tokamaks has been discussed in detail elsewhere [6].

Extremely fast VDE's were observed in the cases of β_p collapse with $\Delta\beta_p$ = -1.5 and -1.0. For $\Delta\beta_p$ = -1.5, a large vertical displacement of Z = -1.06 m was obtained 5.0 msec after the β_p collapse. For $\Delta\beta_p$ = -1.0, the plasma moved downward to Z = -26.2 cm at 5 msec. For $\Delta\beta_p$ = -0.5, the vertical position of the magnetic axis remained close to the initial location (Z = -5.0 cm at 5.0 msec). Figure 2(b) shows the time evolutions of the plasma current and internal inductance ℓ_i, and the cross-sectional shape (characterized by the elongation κ and triangularity δ) for $\Delta\beta_p$ = -1.0. The plasma current remained nearly constant in time, although the radial shift due to the β_p collapse led to a small increment of $\Delta I_p < 0.1$ MA at 200 μsec. Both the elongation and the current profile remained constant until 4 msec after β_p collapse, while the triangularity decreased largely coinciding with the β_p collapse and remained constant after the β_p collapse. This implies that the vertical displacement after the β_p collapse does not accompany both the plasma deformation and the relaxation of current profile until 4 msec, that is, the displacement during the VDE is nearly rigid. For the case of $\Delta\beta_p$ = -1.5, the rigid shift was observed during the VDE evolution for a period of 2 msec. For $\Delta\beta_p$ = -0.5, the VDE evolved without a deformation for the entire TSC simulation period of 5 msec. The feature of Fig. 2 we wish to emphasize is that a strong β_p collapse can induce an extremely fast VDE without an I_p quench, and that the VDE can become much faster as the severity of the β_p collapse increases.

The β_p collapse is observed to produce an instantaneous degradation Δn of the vertical field n-index at the magnetic axis. A β_p collapse leads to a radial shift of the plasma which induces a restoring eddy current on the resistive shell. The eddy current on the inboard resistive shell flows in the opposite direction to the plasma current, whereas the eddy current on the outboard shell flows in the same direction. Consequently, the eddy currents decrease the vertical magnetic field at the plasma and suppress the inward radial shift of the magnetic axis. Such a distribution of eddy currents provides an additional quadrupole moment of the magnetic field in the plasma region, causing the n-index to degrade. The degradation of the n-index persists for the L/R time of the resistive shell.

Figure 3 shows TSC time-histories of the n-index and VDE evolutions for the three cases. The n-indices with and without the eddy current effects, as well as the exponential fitting curves of the linear growth of VDE's are shown. At 200 μsec, the magnitudes of Δn are -0.3 for $\Delta\beta_p$ = -0.5 as is shown in Fig. 3(a), -0.6 for $\Delta\beta_p$ = -1.0 as is shown in Fig. 3(b), and -1.1 for $\Delta\beta_p$ = -1.5 as is shown in Fig. 3(c), respectively. The small amount of degradation of the n-index neglecting the eddy current effect reflects the fact that the plasma moves inward into a region with a worse equilibrium field n-index. The observed VDE rates were estimated to be 237 sec^{-1} for $\Delta\beta_p$ = -0.5, 426 sec^{-1} for $\Delta\beta_p$ = -1.0, and 655 sec^{-1} for $\Delta\beta_p$ = -1.5, which is almost five times faster than the usual positional instability. It is easy to qualitatively understand why a decrease of the n-index leads to a faster positional instability by the direct application of linear stability theory [14]. However, we will give a more detailed quantitative discussion on the enhancement of VDE caused by the β_p collapse and further investigations of the VDE mechanism in the following section.

3. Mechanism of β_p Collapse-Induced VDE

Figure 4 shows the linear growth rate of positional instabilities as a function of the field decay n-index. The poloidal field coil systems and the resistive shell of the model tokamak utilized in Fig. 4 is the same as Fig. 1. The value of n-indices was assigned by introducing an artificial quadrupole field moment, which is constant in time. Major plasma parameters are the same as Figs. 2 and 3, that is, I_p = 1.5 MA and ℓ_i = 1.5. We consider plasmas with β_p = 1.7, 1.2, 0.7 and 0.2 as well as the preceding section. To evaluate the growth rates of positional instabilities by TSC simulation, first an initial static equilibrium was obtained after specifying plasma parameters of interest. Next, the plasma was given a small vertical displacement ($Z \sim$ -1.0 cm) as an initial condition for the following dynamic simulation, and the TSC time-evolution of the vertical displacement was followed during the period of nearly linear growth. The linear growth in the vertical direction was carefully monitored and it was simultaneously verified that the undesirable change of I_p, β_p and ℓ_i does not appear during the linear growth. The initial location R of the magnetic axis for β_p = 1.7 was 3.33 m, which corresponds to the location eddy currents provides an additional quadrupole moment of the magnetic field in the plasma region, causing the n-index to degrade. The degradation of the n-index persists for the L/R time of the resistive shell.

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Figure 4 clearly indicates both that n-index degradation leads to higher growth rates for positional instabilities and that the high β_p plasma is positionally more unstable than the low β_p plasma. We have observed the large degradation of the n-index caused by the β_p collapse as was shown in Fig. 3. In the case of $\Delta\beta_p$ = -1.5, the resultant n-index due to the degradation Δn of -1.1 was -2.6, and the enhanced VDE rate was 655 sec^{-1}. Utilizing Fig. 4, we can obtain a growth rate consistent with the VDE enhancement seen in Fig. 3(c). Specifically, Fig. 4 shows that the growth rate of positional instability of the plasma with β_p = 0.2 and n-index of n = -2.6 is $\gamma \sim$ 670 sec^{-1} at the radial location R = 3.11 m. To see this, first follow the path (1) along the vertical line of n = -1.5 in Fig. 4, and next, follow the path (2) along the curve of the growth rate in the case of β_p = 0.2. The path (1) corresponds to the β_p collapse of $\Delta\beta_p$ = -1.5, and results in an improvement of the positional instability due to the loss of the plasma β_p. The second path (2) corresponds to the enhancement of positional instability due to the degradation Δn = -1.1. In following the path (1), the effect of coincident degradation of n-index provided by the β_p collapse is neglected. The n-index degradation is taken into account only in the second path (2). In the cases of $\Delta\beta_p$ = -0.5 and -1.0, a similar procedure provides almost the same enhancement of positional instabilities as is shown in Figs. 3(a) and 3(b), respectively. As a consequence of these considerations, we concluded that the mechanism of the β_p collapse-induced VDE is an enhancement of positional instabilities caused by the degradation of the magnetic field decay n-index owing to the eddy current induced in the resistive shell.

In the following, we will discuss the effect of the shell-geometry on the stabilization of positional instabilities. In particular, we consider how the characteristics of positional instabilities depend on the radial location of the plasmas. According to the linear stability theory using a simple model of rigid shifts of circular-shaped plasmas [14], it is well known that the linear growth rate of positional instabilities 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, which was first defined by Fukuyama et al. [14], is a useful measure of the positional stability. It is a function of the shell-geometry and the plasma parameter Λ (= $\ln(8R_p/a) + \beta_p + \ell_i/2 - 3/2$), i. e.,

$$n_s = \frac{2}{\Lambda}\frac{R_p^2}{b^2}\left(1 - \frac{a^2}{b^2}\right)^{-1} . \quad (2)$$

Here, R_p is the plasma major radius, a is the minor radius of the circular plasma, and b is the mean minor radius of the resistive shell. Eq. (1) implies that in the case of $n = -n_s$ the growth rate becomes infinite, practically very large to be 10^{-6} sec^{-1} of the Alfven time. Although Eqs (1) and (2) cannot express the detailed characteristics of positional instabilities of highly elongated tokamaks with a non circular-shaped resistive shell like Fig. 1, they provide a useful guide to the essential mechanism of positional instabilities considered in this paper. For instance, Eqs (1) and (2) show that high β_p plasmas are most unstable, and that the inward radial shift of plasmas also results in an increase of the growth rate.

In Fig. 4, we have presented supplementary TSC results on the linear growth rates of positional instabilities of a plasma with $\beta_p = 0.2$ and $\ell_i = 1.5$. The radial location R was 3.33 m, which corresponds to the location prior to the β_p collapse. The discrepancy between growth rates of the plasmas with the same plasma parameters but located at the different radial positions of $R = 3.33$ m and $R = 3.11$ m can be seen. Utilizing Eq. (2), the stability index n_s of the plasma at $R_p = 3.11$ m is estimated to be 14 % less than the one at $R_p = 3.33$ m. On the one hand, we can obtain a similar reduction of the stability index n_s from comparative studies between TSC growth rates in Fig. 4. For example, the observed growth rates with $\beta_p = 0.2$, $\ell_i = 1.5$ and $n = -2.0$ are 100 sec^{-1} at $R = 3.33$, and 160 sec^{-1} at $R = 3.11$. In this case, utilizing Eq. (1) and assuming $\tau_s = 18$ msec for the time constant of the resistive shell in Fig. 1, the stability index n_s of the plasma at $R_p = 3.11$ m is estimated to be 13 % less than the n_s at $R_p = 3.33$ m. In the case of $n = -2.6$, the observed growth rates are 250 sec^{-1} at $R = 3.33$ and 670 sec^{-1} at $R = 3.11$, and the n_s at $R_p = 3.11$ m was 12 % less than the one at $R_p = 3.33$ m. Therefore, the discrepancy between growth rates at the different radial positions shown in Fig. 4 is identified to arise from the reduction of the stability index n_s given by Eq. (2).

The underlying mechanisms, which characterizes the β_p collapse-induced VDE, are summarized as follows : (a) The loss of plasma β_p improves the positional instability. (b) The inward radial shift of the magnetic axis due to a β_p collapse results in a destabilization owing to the reduction of the stability index n_s. (c) The eddy current on a resistive shell induced by the strong β_p collapse degrades the n-index and leads to a significant destabilization. The mechanisms (b) and (c) depend on the specifics of the shell-geometry, and will compete with the improvement (a) during disruptions. Therefore, a variety of resultant VDE characteristics will be seen in elongated tokamaks with a variety of resistive shells.

4. Conclusions

In a vertically elongated, high β_p tokamak with a resistive shell, extremely fast VDE's induced by strong β_p collapse were found through computer simulations using the TSC. As the magnitude of the β_p collapse increases, the resultant growth rate of the VDE increases. In the case of a strong β_p collapse of $\Delta\beta_p$ = -1.5, the VDE rate can be almost five times as fast as the growth rate of the usual positional instability. A plasma current quench, which had been shown to be the prime cause of VDE's in a low β_p tokamak, did not occur during these VDE events. The essential mechanism of the β_p collapse-induced VDE was clarified to be the intense enhancement of positional instability due to a large and sudden degradation of the decay n-index in addition to a significant destabilization owing to a reduction of the stability index n_s. These both arise from an inward radial shift of magnetic axis due to the loss of the plasma β_p. The eddy current, which is induced by the β_p collapse on the resistive shell to maintain the plasma magnetic axis near the initial location, causes a large degradation of the n-index. It was also shown that the shell-geometry influences the VDE dynamics, and that softening the β_p collapse and the careful selection of the allowable plasma elongation are crucial issues in designing tokamak reactors like ITER.

The acceleration mechanism of the β_p collapse-induced VDE is quite different from the one of the I_p quench-induced VDE. As was discussed in Ref. [1], an I_p quench-induced VDE can be avoided by softening the I_p quench and the optimization of the location of the predisruption equilibrium. However, if a strong β_p collapse of high β_p plasmas occurs, the β_p collapse-induced VDE will occur even if the I_p quench is absent. The particular nature of MHD activity will determine the speed of the β_p collapse, which is usually very fast compared with the L/R time of a resistive shell in most tokamaks. In such a case, any active feedback would be incapable of preventing the VDE, and a large Halo current will be induced on the in-vessel instability. (b) The inward radial shift of the magnetic axis due to a β_p collapse results in a destabilization owing to the reduction of the stability index n_s. (c) The eddy current on a resistive shell induced by the strong β_p collapse degrades the n-index and leads to a significant destabilization. The mechanisms (b) and (c) depend on the specifics of the shell-geometry, and will compete with the improvement (a) during disruptions. Therefore, a variety of resultant VDE characteristics will be seen in elongated tokamaks with a variety of resistive shells.

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A possible approach to mitigate a β_p collapse-induced VDE may be the optimization of the shell-geometry in order both to keep the inward radial shift of the magnetic axis small and to ameliorate the n-index degradation. Moreover, the consequences of a VDE in a mildly elongated tokamak will always be more benign than those in a highly elongated tokamak. Although the studies on VDE mechanisms in a various kind of shell-geometry are now in progress in order to generalize the proposed mechanism in this paper, we mention here the preliminary results for the case of the actual JT-60U tokamak, where the vacuum vessel completely encloses the plasma. TSC simulations for this geometry indicate that the n-index degradation due to the same β_p collapse of $\Delta\beta_p$ = -1.5 remains small ($\Delta n \sim$ -0.6), and that the inward radial shift of the magnetic axis just after β_p collapse is also small (R = 3.15 m). Therefore, the β_p collapse-induced VDE is not observed. The details of the β_p collapse-induced VDE in the JT-60U tokamak is now under investigation and will be reported in the future.

Acknowledgments

The authors would like to express their gratitude to Drs. M. Sugihara and G. Kurita for their fruitful comments on the physical meaning of the stability index n_s, and wish to thank Drs. M. Azumi and T. Tsunematsu for their stimulating interests in our works. Dr. T. Hirayama is also acknowledged for his continuing support.

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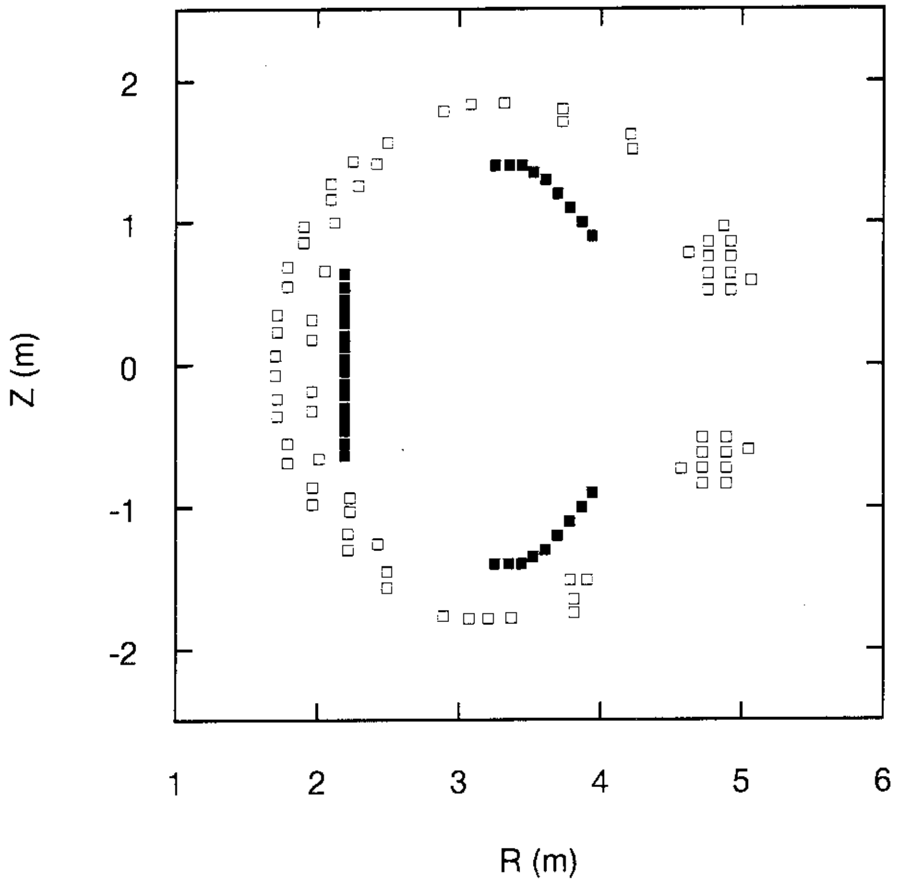

Fig. 1. TSC representation of the poloidal field coil system (open boxes) and resistive shell (closed boxes) : The resistive shell is up-down symmetric with respect to the midplane and represented by a discretized array of 34 axisymmetric elements. The dominant up-down antisymmetric current mode of the resistive shell has a decay time constant of about 18 msec and the time constant of the eddy current mode stabilizing a radial expansion of the plasma is about 25 msec. The computational domain is the square box spanning 1.5 m to 5.5 m in the major radius direction and -2.0 m to 2.0 m in the vertical direction. This domain is divided into (80 × 80) grids with equal spacing of 5 cm.

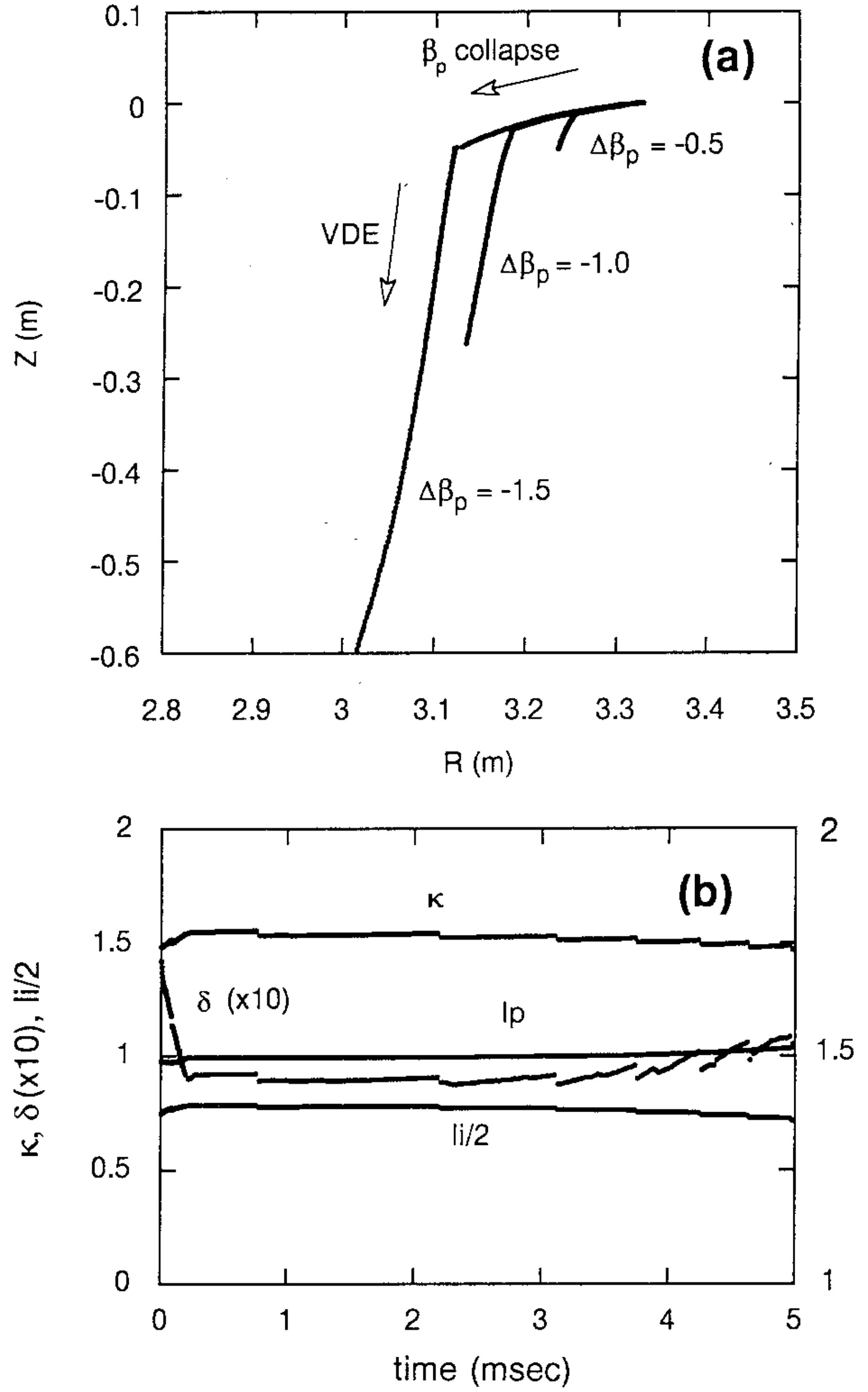

Fig. 2. TSC evolution of plasma displacements during the period of 5.0 msec from the initial equilibrium with I_p = 1.5 MA, β_p = 1.7, ℓ_i = 1.5, κ = 1.5, and δ = 0.14. The initial location of the magnetic axis (R, Z) was (3.33 m, 0.0 m). Three β_p collapse of $\Delta\beta_p$ = -0.5, -1.0 and -1.5 lasted for 200 μsec. (a) TSC time-traces of the magnetic axis (R, Z) on a poloidal plane. Especially for $\Delta\beta_p$ = -1.5, the TSC simulation showed a large vertical displacement of Z = -1.06 m at 5.0 msec. (b) TSC time evolutions of I_p, ℓ_i, κ and δ for $\Delta\beta_p$ = -1.0.

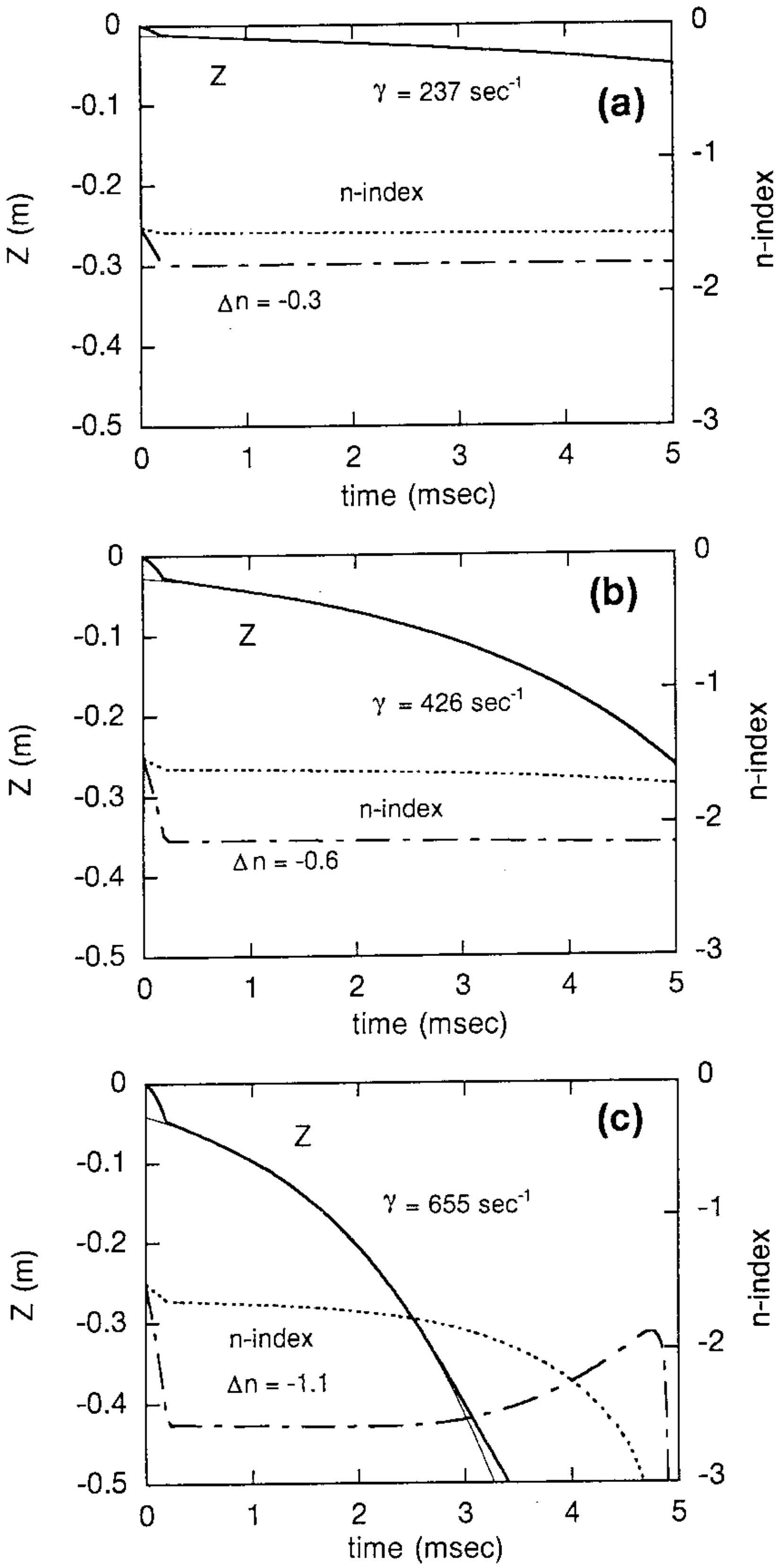

Fig. 3. TSC time-histories of the *n*-index and VDE evolutions. The *n*-indices neglecting eddy current effects and the exponential fitting curves of the linear growth of VDE's are also reproduced. (a) :$\Delta\beta_p$ = -0.5 (b) :$\Delta\beta_p$ = -1.0 (c) : $\Delta\beta_p$ = -1.5

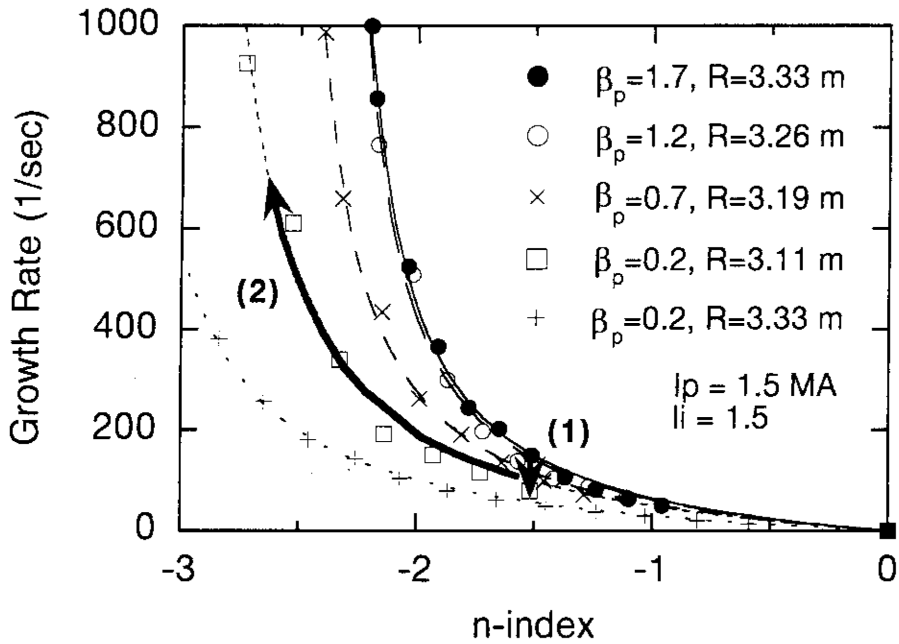

Fig. 4. Linear growth rates of positional instabilities as a function of the field decay n-index. Plasma current is 1.5 MA; plasma current profile ℓ_i is 1.5. The radial locations R of the magnetic axis are 3.33 m for β_p = 1.7, 3.26 m for β_p = 1.2, 3.19 m for β_p = 0.7, and both 3.33 m and 3.11 m for β_p = 0.2, respectivelly. All the vertical locations Z were placed to be on the midplane (Z = 0.0 m). The path (1) corresponds to the event of the β_p collapse of $\Delta\beta_p$ = -1.5, and the path (2) corresponds to the enhancement of positional instability due to the degradation Δn = -1.1. The discrepancy between growth rates of the plasmas with the same plasma parameters of ℓ_i = 1.5 and β_p = 0.2 but locating at the different radial positions of R = 3.33 m and R = 3.11 m can be seen.