Characterization of Axisymmetric Disruption Dynamics toward VDE Avoidance in Tokamaks

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Abstract Experiments and axisymmetric MHD simulations on tokamak disruptions have explicated the underlying mechanisms of Vertical Displacement Events (VDEs) and a diversity of disruption dynamics. First, the neutral point, which is known as an advantageous vertical plasma position to avoiding VDEs during the plasma current quench, is shown to be fairly insensitive to plasma shape and current profile parameters. Secondly, a rapid flattening of the plasma current profile frequently seen at thermal quench is newly clarified to play a substantial role in dragging a single null-diverted plasma vertically towards the divertor. As a consequence, the occurrence of downward-going VDEs predominates over the upward-going ones in bottom-diverted discharges. This dragging effect is absent in up-down symmetric limiter discharges. These simulation results are consistent with experiments. Together with the attractive force that arises from passive shell currents and essentially vanishes at the neutral point, the dragging effect explains many details of the VDE dynamics over the whole period of the disruptive termination.

1. Introduction

With regard to an area concerned for future tokamak reactors, the Vertical Displacement Events (VDEs) and its concatenate generation of halo-currents and their associated vessel forces is recognized as a crucial issue, and one that must be dealt with by disruption mitigation. Therefore, an underlying mechanism of the VDE was investigated by means of axisymmetric MHD simulations [1, 2]. For a tokamak with an up-down asymmetric passive shell, the simulation using the Tokamak Simulation Code (TSC) [3] clarified that the eddy currents induced by the plasma current quench give rise to a vertical imbalance of forces, causing a VDE [4]. If the current centroid of the pre-disruptive plasma is chosen to be close to the neutrally balanced vertical position (the so-called neutral point), the attractive forces due to the eddy currents will cancel at that point, and thus the VDE may be avoided. However, if the pre-disruptive plasma is positioned away from the neutral point, it will exhibit either an upward- or downward-going VDE, according to the initial position, consistent with JT-60U experiments [5]. It has also been demonstrated that for plasmas initially positioned at the neutral point and with feedback position control activated, an almost VDE-free and halo-current-free disruption can be made to occur [6, 7].

While such progress has been made, some recent observations of the plasma equilibrium response to transient disturbances due to ELMs and sawteeth indicate that the precise position of the neutral point are somewhat sensitive to profile parameter variations, and raise into question the practicality of controlling VDEs through the neutral point in future reactors [8]. This paper first describes the sensitivity of the neutral point to a variety of plasma shape and current profile parameters. We then describe a generalization of the VDE modeling to include the change of the plasma current profile during the disruption.

2. Neutral Point

The location of the neutral point is supposed to be linked up closely with a geometry of shell structures and probably with an arrangement of plasma shaping coils which differs from tokamak to tokamak. Therefore, much different VDE characters from the JT-60U can appear in the Alcator C-Mod and ASDEX-Upgrade.

2.1. Validation Experiment on Alcator C-Mod

In Alcator C-Mod, disruption experiments conducted by injecting killer-pellets into plasmas with five pre-disruption equilibria were carried out to identify the location of the neutral point (Fig. 1). The disruptive plasmas initially positioned around the numerically determined neutral point (Z = + a few cm, taking the much different shell-geometry from the JT-60U into consideration) exhibit upward- or downward-going VDEs as predicted by the TSC. And further, the plasma positioned close to the numerically determined neutral point stayed for ~ 40 msec. It thus follows that the neutral point is experimentally confirmed to widely exist as the TSC prediction as well as the JT-60U.

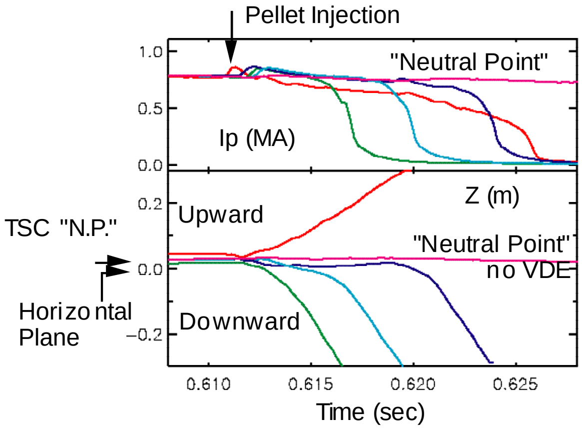

FIG. 1. Disruption dynamics of relevant VDEs to plasma current decay forced by killer-pellet injection in Alcator C-Mod. Neutral point is experimentally confirmed to exist as TSC prediction.

2.2. Neutral Point of ASDEX-Upgrade

The TSC simulation, which models a plasma current quench without the current profile change, reproduced a large variety of VDEs according to respective bottom-diverted ASDEX-Upgrade equilibria prior to the current quench (Fig. 2). Although the VDE rate significantly depends on the plasma shape and current profile parameters, neutral points that are seen to exist at ~ +5 cm above the horizontal midplane are not sensitive to those parameters with elongation of κ = 1.5, 1.6, 1.7, triangularities of δ = 0.1, 0.25, 0.4, and a range of current profiles characterized by l_i = 0.7, 0.9, 1.1, 1.3 [9].

The ASDEX-Upgrade experiment (see Fig. 3) illustrates a new feature that was not

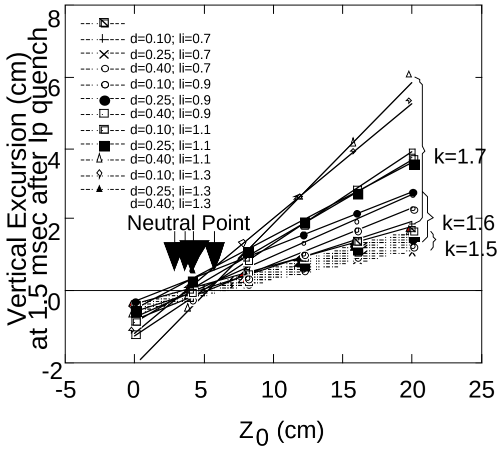

FIG. 2. TSC vertical excursions versus initial vertical positions of bottom-diverted ASDEX-Upgrade plasmas. Neutral points are found at ~ +5 cm above horizontal midplane, being insensitive to plasma shape and current profile.

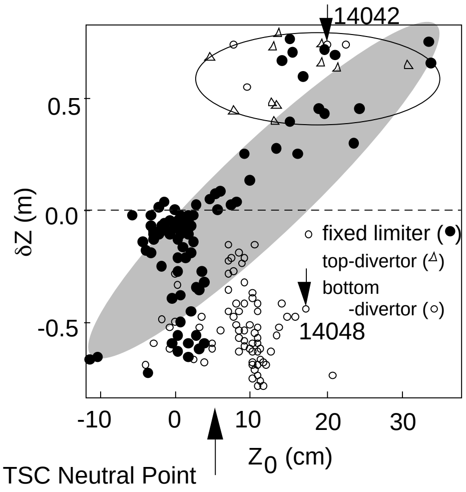

FIG. 3. Experimental excursions versus initial position. Neutral point of limiter plasmas is seen at ~5 cm above horizontal midplane as Fig. 2, whereas bottom-diverted plasmas exhibit downward (#14048) or upward VDEs (#14042).

observed in the TSC simulations shown in Fig. 2. The vertical excursions of the plasma current centroid due to the disruption induced VDE depend on whether the initial plasma configuration is diverted or not. For limiter discharges, which are essentially up-down symmetric (closed circles), the neutral point can be seen at ~ +5 cm above the horizontal midplane, consistent with the simulation results shown in Fig. 2. On the other hand, diverted discharges exhibit a wide variety of VDE behaviors, implying that a unique neutral point does not exist in ASDEX-Upgrade, as it does in the JT-60U [4] and Alcator C-Mod. For the bottom-diverted configuration (open circles), notice that even the discharges initially positioned considerably above the numerically determined neutral point exhibit downward-going VDEs, contrary to the TSC prediction (*e.g.* #14048). However, several exhibit upward-going VDEs in accordance with the TSC (*e.g.* #14042) [9].

3. Dragging effect due to profile change of plasma current

Both initial equilibria of the shots #14042 and #14048 are very similar (see Fig. 4), *e.g.* $\kappa = 1.6$, $\delta = 0.25$, and they are positioned at $Z = 19.8$ cm (#14042) and at $Z = 17.3$ cm (#14048), being well above the TSC neutral point (~ 5 cm). A remarkable disparity between these two disruptions is the different change of the internal inductance, Δl_i, which is often observed during the thermal quench stage prior to the plasma current quench [10]. Note the large, rapid (< 1.0 msec) decrease of $\Delta l_i \sim -0.7$ at the thermal quench stage of #14048 ($t = 4.922$ sec in Fig. 4(a)) and the relatively small, slow (~ 5.0 msec) decrease of $\Delta l_i \sim -0.3$ at the thermal quench stage of #14042 ($t = 4.901$ sec in Fig. 4(b)).

The TSC simulation of a rapid change of the current profile clarifies a vertical dragging of single null-diverted plasmas, which predominates over the growth of vertical instabilities (Fig. 5): as the current profile becomes broad ($\Delta l_i < 0$), the plasma tends to drag itself toward divertor, whereas a current peaking ($\Delta l_i > 0$) pulls the plasma out of the divertor [9]. Those substantially depend on a measure of the up-down asymmetry γ (= Z_l/Z_u). A value of $\gamma = 1$ denotes an up-down symmetric, double null-divertor configuration, while $\gamma > 1$ ($\gamma < 1$) denotes a bottom (top)-divertor.

It thus follows that the significant change of $\Delta l_i \sim -0.7$ may drag the bottom-diverted

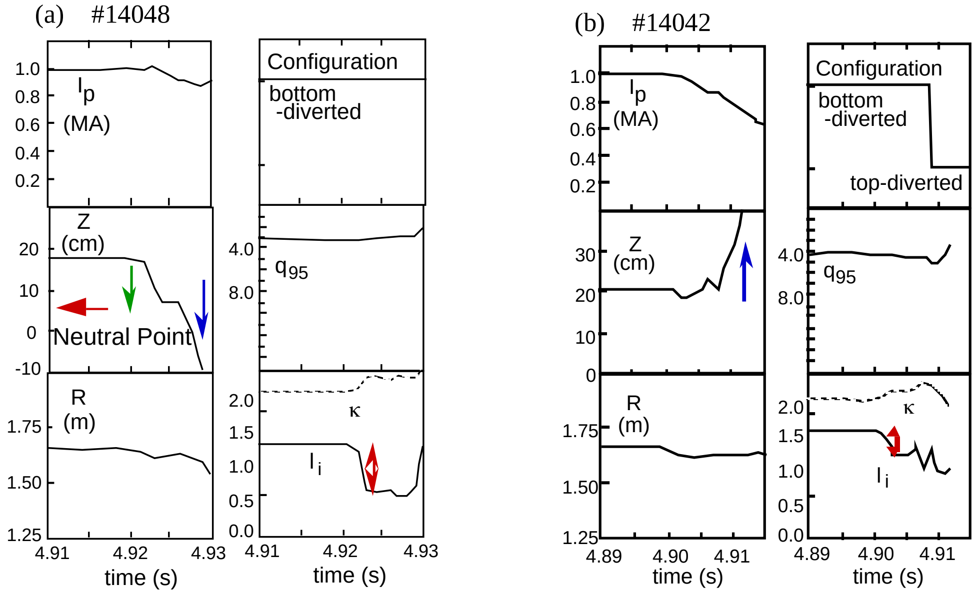

FIG. 4. Discharges of (a) downward (#14048) and (b) upward (#14042) going VDEs. However, both equilibria prior to disruptions are similar, e.g. bottom-diverted, $\kappa = 1.6$, $\delta = 0.25$, and closely positioned as $Z = 19.8$ cm of #14042, while $Z = 17.3$ cm of #14048 (much above the TSC neutral point of ~ 5 cm). Note a large decrease of $\Delta l_i \sim -0.7$ at 4.922 sec (#14048), whereas a small decrease of $\Delta l_i \sim -0.3$ at 4.901 sec (#14042).

plasma (#14048) below the neutral point to cause a downward VDE due to the following plasma current quench. Meanwhile, the small change of Δl_i ~ -0.3, being insufficient to dragging the plasma (#14042) downward, leaves the plasma much above the neutral point even after the thermal quench. Consequently, it undergoes an upward VDE. In case of the limiter or double null-divertor ($\gamma = 1$) (such as the closed circles, Fig. 3), the dragging effect is always absent, consistent with the simulation (Fig. 2).

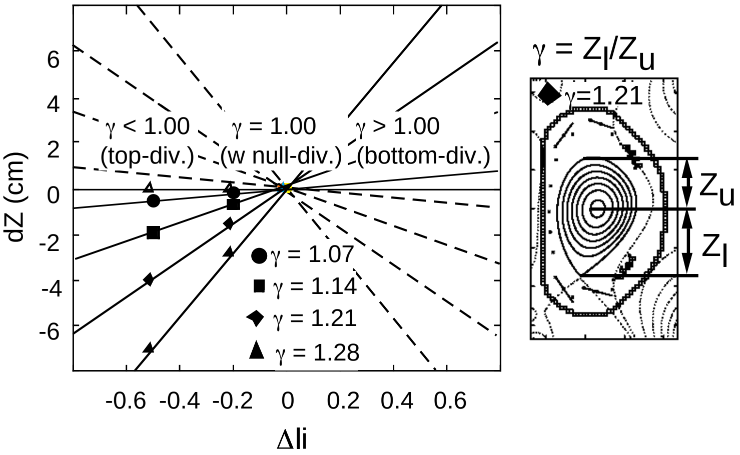

FIG. 5. Current profile changes (Δl_i) and vertical dragging effect (dZ), which substantially depends on up-down asymmetry γ (= Z_l/Z_u) of single null-divertor, and is absent in double null-divertor (γ = 1). Z_l or Z_u means respective vertical distance between magnetic axis and bottom or top edge of outermost flux surface. Dragging toward divertor at flattening (Δl_i < 0), whereas pulling out of divertor at peaking (Δl_i > 0).

4. Behavior details of axisymmetric disruption dynamics

The present VDE modeling now enables us to explain the precise details of axisymmetric disruption dynamics in ASDEX-Upgrade [9]. As an illustration, we consider in detail the shot #12086, shown in Fig. 6, which exhibits many of the characteristics generally important for disruption dynamics. Note that switchovers between the bottom-diverted (marked with gray) and top-diverted (not marked) configurations took place. At the pre-disruption phase (a), the bottom-diverted plasma positioned at ~ 10 cm above the horizontal midplane, a little higher than the neutral point (~ 5 cm), starts to flatten the plasma current profile.

For the duration of the following thermal quench phase (b) that lasts for 2 msec, a decrease of the internal inductance of Δl_i ~ -0.5, *i.e.*, a rapid flattening of the current profile caused by a minor collapse of the highly peaked current profile, appears together with an associated positive current spike of δI_p ~ 40

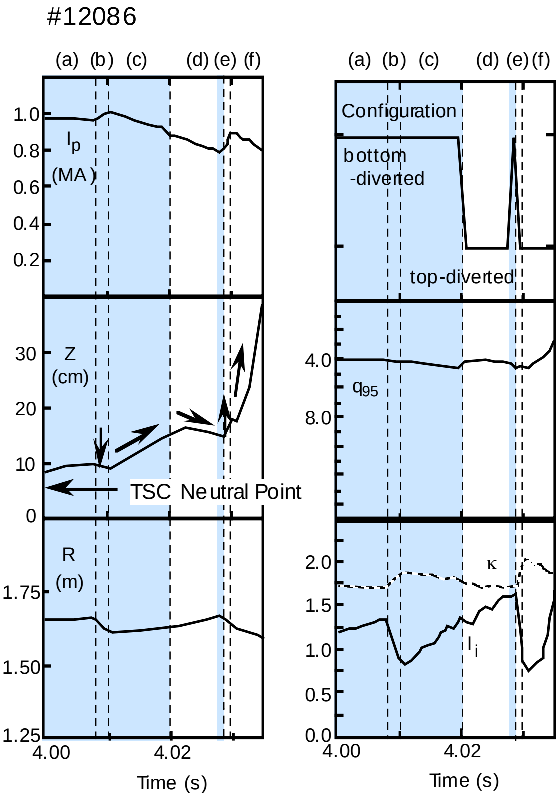

FIG. 6. Disruption dynamics of #12086. (a) : pre-disruption plasma positioned a little above neutral point (~ 5 cm). (b) : first thermal quench with Δl_i ~ -0.5 drags bottom-diverted plasma downward. (c) : attractive force due to plasma current quench along with current sharpening drags the plasma positioned above neutral point upward. (d) : after switchover from bottom to top-divertor at 4.020 sec, sharpening begins to drag plasma downward, and ceases upward VDE. (e) : second thermal quench with Δl_i ~ -0.75 drags top-diverted plasma upward. (f) : plasma positioned much above neutral point undergoes upward VDE due to current quench.

kA and an inward radial shift of ~ 5 cm. Simultaneously, as expected, the bottom-diverted plasma exhibits a small vertical dragging toward the divertor. In the phase (c), the bottom-diverted plasma that still stays above the numerically determined neutral point exhibits an upward-going drift due to the combination of the attractive force of the induced eddy current and the upward dragging effect of the profile sharpening.

At 4.020 sec of the phase (d), the bottom-diverted configuration switches over to the top-diverted. The profile sharpening now begins to drag the plasma away from the top-divertor (downward), while the current quench continues to pull up the plasma that remains above the neutral point. Consequently, the upward-going VDE ceases in phase (d). Within a short duration of 1 msec in phase (e), a considerable decrease of Δl_i ~ -0.75 and an associated positive spike of δI_p ~ 100 kA again occur. This drags the top-diverted plasma toward the divertor, *i.e.*, upward, contrary to the downward in the previous phase (b). Finally, the current quench starts again in phase (f), and the plasma, which is now well above the neutral point, exhibits an upward-going VDE, regardless of the top- or bottom-diverted configuration.

5. Summary and conclusions

Concerning the VDE avoidance, any tokamak has been verified to possess its own advantageous neutral point which the present study revealed to be fairly insensitive to plasma shape and current profile parameters. And furthermore, a vertical dragging effect that arises from the plasma current flattening has been newly introduced to successfully explicate the predominant occurrence of the disruptive VDEs toward divertor, specific to the ASDEX-Upgrade. It is also demonstrated how the dragging effect, together with that of the imbalanced attractive force that may vanish at the neutral point, can explain the precise details of VDE dynamics.

It turned out that the new concept of the dragging effect strongly depends on a measure of the up-down asymmetry of the single null-diverted plasmas which closely connects with how apart a divertor coil is standing from the plasma, *e.g.* a far divertor coil of the ASDEX-Upgrade (outside the toroidal field coils) in contrast to near ones of the JT-60U and Alcator C-Mod (inside the toroidal field coils). As a consequence, it has been clarified that the dragging effect is more remarkable in the ASDEX-Upgrade than the others, and that such various dragging effect brings the disrupting plasmas a diversity of VDE dynamics.

In a future advanced tokamak like the ITER-FEAT phase, the disruptions will be associated with an advanced performance plasma operation regimes with reversed magnetic shear [11]. Therefore, the destruction of such a magnetic shear profile is expected to sharpen the current profile and consequently cause a VDE motion away from the divertor, in contrast to disruptions of normal shear plasmas with significant flattening. An integrated study on such details of the VDE in a reversed shear plasma is now under investigation.

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