TSC Simulation of Disruptive Current Termination on JT-60U Reversed Shear Plasmas

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1. Introduction
An understanding of current quench behavior of disrupting Reversed Shear (RS) plasmas is considerably important in designing tokamak reactors, because high performance operations sustained by a high bootstrap current should utilize RS plasmas. In disruptions of Positive Shear (PS) plasmas, a positive current spike appears just before a current quench. This positive spike has been considered to be a response of a rapid flattening of peaked current profile, which implies a lowering of the internal inductance \( l_i \) [1]. In JT-60U RS plasmas, however, the positive current spike was still observed [2], even though \( l_i \) of the RS plasmas with hollow current profile is much smaller than that of PS plasmas. In the next section, the current spikes of JT-60U were discussed in detail in contrast to an analytical model neglecting the shell effects. In order to understand the current spike mechanism, we carried out simulations with the Tokamak Simulation Code (TSC) [3] for such events as a \( \beta_p \)-drop and a flattening of current profile including the effects of conducting shells. Finally, we propose the underlying mechanism of the current spikes and generalize it for reactor design.

2. Current spikes observed in JT-60U
In JT-60U experiments, positive current spikes have been normally observed just before current quench, while some discharges do not exhibit any spikes, and others exhibit negative ones. Thus, it is difficult to understand the whole mechanism of such variety of the spikes. Figure 1 shows current spikes \( \delta I_p (= \delta I_p / I_{p0}) \) observed in JT-60U PS and RS disruptive discharges versus the plasma position of current center, \( R_J \). Here, the current spike \( \delta I_p \) was normalized by the initial current \( I_{p0} \). Main plasma parameters before the current spikes are \( \beta_p \sim 1 \), effective safety factor \( q_{\text{eff}} \sim 4 \) - 7, \( I_p \sim 1.8 \) - 2.7 MA for both of PS and RS discharges. Figure 1 implies that the spikes \( \delta I_p \) decrease as the current center, \( R_J \), increases. Positive spikes (\( \delta I_p \sim 10 \% \)) were observed for PS plasmas at an inner \( R_J \sim 3.1 \) m, while negative current spikes (\( \delta I_p \sim -5 \% \)) were observed in RS plasmas positioned at larger \( R_J \sim 3.4 \) m. Thus, the JT-60U experimental results indicate that \( \delta I_p \) depends on the relative position between a plasma and the vacuum vessel.

A distinctive feature of the thermal quench of disruptions is a substantial loss of plasma confinement leading to a \( \beta_p \) collapse (\( \beta_p \)-drop). Neglecting shell
effects, it follows that the $\beta_p$-drop, $\Delta\beta_p$, gives rise to an inward plasma shift and a consequent positive spike. From the conservation of poloidal magnetic flux $\delta\Psi_p = 0$ and the balance of radial force $\delta F_R = 0$ during a thermal quench, we obtain the following relation [4]:

$$\delta I_p = -\frac{\delta \beta_p}{2} \left[ \begin{array}{c} (A + 1 - 2\beta) \\ - (A + 1/2 - 2\beta) \end{array} \right] \Lambda(n - 1) + 1 \right] . \quad (1)$$

where $\Psi_p$ is the total poloidal flux enclosed by the plasma loop. $n$ is the decay index of the externally applied equilibrium field. $A = \ln(8R / a) + (l_i - 3)/2 + \beta_p$. The radial force is given by $F_R = 1/2 \mu_0 I_p^2 \left[ \ln(8R / a) + l_i/2 + \beta_p - 3/2 + 2\pi R B \right]$. Equation (1) indicates that the $\delta I_p$ hardly depends on the plasma position of $R_p (\sim R_j)$, which is depicted by the dashed line in Fig. 1 for the case of $\delta \beta_p = -1.0$. It follows that the analytical model without shell effect cannot explain the experimental correlation between $\delta I_p$ and $R_j$.

3. TSC simulation

The TSC models the axisymmetric behavior of a free-boundary tokamak plasma interacting with conducting walls and sets of axisymmetric conductors self-consistently. Modified magnetohydrodynamic equations are solved inside a computational domain that includes a plasma region, a vacuum region, a specified number of solid conductors and walls. In this section, we present the simulation results on two important issues: the current spike due to a $\beta_p$-drop including shell effects, and the current spike due to an abrupt change in the current profile.

3.1. Inward shift due to $\beta_p$-drop

In order to model the rapid loss of plasma pressure and the resultant current spike, a $\beta_p$-drop from about 1.0 to 0.0 in 500 µs was prescribed. When the plasma is positioned at the outer inside of the JT-60U vacuum vessel ($R_i = 3.8$ m), an inward shift of $\delta R_i \sim -0.2$ m and a negative current spike of $\delta I_p \sim -3\%$ are brought about as illustrated in Fig. 2. The poloidal distribution of induced eddy currents in the vacuum vessel is shown in Fig. 3. The total eddy current $\delta I_{vv}$ at $t = 600$ µs was estimated as $\delta I_{vv}/I_p \sim 7\%$, which conversely forces the plasma current to reduce by the same amount of $\sim 7\%$. While the inward shift of $\delta R_i \sim -0.2$ m due to the $\beta_p$-drop should result in an increase of the plasma current, the amount of which is estimated as $5\%$ by using the analytical model of Eq. (1) without the
shell effects. In consequence, the total plasma current decreases by ~ 2%, which is nearly the same as the negative current spike of $\delta I_p \sim -3\%$ of Fig. 2.

When the plasma is positioned at inner side of JT-60U vacuum vessel ($R_j = 3.1$ m), the $\beta_p$ drop induces toroidal eddy currents ($\delta I_v/I_{p0} \sim 1\%$) in the vacuum vessel. Here, the pressure drop was assumed to be a half of that in the case of Fig. 2 to avoid a collision between plasma and the vessel in the TSC simulation. Figure 4 shows the poloidal distribution of induced eddy currents in the vacuum vessel, where a negative current is induced on the inboard side. This negative current pushes back the plasma outward to hold the position before the $\beta_p$ drop.

Thus the total eddy current becomes smaller than that of the outer position. Figure 5 implies that a $\delta R_j$ drop of ~0.5 leads to inward shift ($\delta R_j \sim -0.1$ m) and a small current spike of $\delta I_p \sim 1\%$. The analytical model estimates an increase of plasma current to be ~ 2.5%, while the TSC including shell effect clarified the eddy current of $\delta I_v/I_{p0} \sim 1\%$. In consequence, the plasma current may increase by ~ 1.5%, which is nearly the same as the current spike of ~ 1%. Hence, it follows that the $\beta_p$ drop causes the different current spikes in accordance with the relative location between the plasma and the conducting shell.

### 3.2. Abrupt change in current profile

Although the $\beta_p$ drop explains the dependence of $\delta I_p$ on $R_j$, it is insufficient to describe the amount of $\delta I_p$ as seen in Fig. 1. The candidate mechanism is an abrupt change in the current profile, i.e., the flattening of plasma current profile experimentally measured in DIII-D PS plasmas. The flattening has been considered to be a prime cause of the positive spike at the thermal quench. In order to reproduce the current profile change, we made use of the TSC model including the "hyper-resistivity"[5], which describes fundamentally nonlinear three-dimensional effects on a two-dimensional axisymmetric field representation as follows:

$$E + v \times B = \eta j - \frac{B}{B^2} \nabla \left( \lambda \frac{\nabla |j|}{B} \right), \quad (2)$$

where $\lambda$ is an arbitrary positive function of position. The second term on RHS, which has successfully modeled a current history for TFTR PS plasma disruption [6], leads to anomalous current viscosity, dissipating energy, but conserving global helicity. TSC simulations of the current profile change were carried out both for PS and RS low $\beta_p$ plasmas. In PS plasmas, the hyper-resistivity modeling has reproduced a redistribution of current profile as shown in Fig. 6. A lowering in $l_1$ appears and results in the positive current spike and associated negative voltage spike similarly to the experiments. In RS plasmas, the model has also reproduced a redistribution of current profile in the same manner as the PS
plasmas, contrary to common understanding that \( l_i \) should increase for RS plasmas. Figure 7 indicates that a further lowering in the internal inductance may occur even in RS plasmas, then a positive current spike may appear together with the associated negative voltage spike.

4. Conclusions

By taking a particular notice of the major events of the thermal quench with the \( \beta_p \)-drop and current flattening, physical mechanisms of plasma current spikes were clarified from TSC simulation. For the first time, the conducting shell effect was incorporated in our modelling of the plasma current spikes due to rapid \( \beta_p \)-drops. It was firstly found that a positive or negative current spike appears in accordance with the location of the initial equilibrium relative to the conducting shell. This new understanding implies that there should be a neutral point of the current spike in the vessel against any big \( \beta_p \)-drops. Secondly, contrary to previous interpretation in the past, a further lowering in \( l_i \), which is similar to that the thermal quench of PS plasmas, was shown to be a possible mechanism of the positive current spike observed even in RS plasmas. The new understanding of the underlying mechanism reasons out the current spikes both of PS and RS plasmas and explicates a variety of them.

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References