# Validation of the current decay model in the initial phase of current quench in high $\beta_p$ disruptive discharges of JT-60U

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## 1. Introduction

The precise prediction of plasma current decay time, $\tau$, is important in order to estimate the electromagnetic forces acting on vacuum vessel and in-vessel components during the tokamak disruption. The so-called $L/R$ model often used to predict the current decay time in ITER [1] is based on a simple series circuit considering the plasma resistance $R_p$ and inductance $L_p$, which are constant in time. In the "$L/R$ model", the current decay time represents with $\tau_{L/R} = L_p/R_p$. If the plasma resistivity is defined by Spitzer resistivity [2], the current decay time is mainly determined by the electron temperature $T_e$ and effective charge $Z_{eff}$. However, the systematic research of the relationship between the current decay time during disruption and the measurement value of $L_p$ and $R_p$ has rarely been done until now.

In the 2008 JT-60U experimental campaign, the current decay in the radiative disruption generated by massive neon gas puff has been investigated [3]. In ref. [3], the current decay during the initial phase of current quench, which is the time region that plasma current decays to 90% of the plasma current just after the current quench start, was investigated through a comparative analysis with the time evolution of $R_p$ and $L_p$, which were evaluated by the measurement values of magnetic sensor and $T_e$. It was found that time derivative of $L_p$ is dominant in the determination of current decay time. And the current decay time predicted by the modified $L/R$ model, in which the time derivative of plasma inductance taken into account, gave a good agreement with the experimental current decay time, $\tau_{exp}$.

In the fusion reactor (DEMO), the generation of a lot of spontaneous currents such as bootstrap current is necessary to increase the economic efficiency. In order to generalize the modified current decay model, it is necessary to validate the current model under high bootstrap current in addition to validation in ref [3]. In this paper, we investigated the validation of current decay model in high $\beta_p$ disruptive discharges of JT-60U.

## 2. Experimental setup

In Fig. 1, $\beta_p$ just before the thermal quench is plotted against $\tau_{exp}$. In this figure, $\tau_{exp}$ is evaluated by using the following equation:

$$\tau_{exp} = I_{p0} / \left( \Delta I_p / \Delta t \right). \qquad (1)$$

Here, $I_{p0}$ is the plasma current just after the thermal collapse, $\Delta I_p$ is 10% of $I_{p0}$, and $\Delta t$ is the time interval between $I_{p0}$ and $0.9 \times I_{p0}$. In high $\beta_p$ disruptive discharges, we focused attention on the initial phase of current quench similar to the previous analysis in the radiative disruption generated by massive neon gas puff [3]. The reason why we focused on the initial phase of current quench is that $L_p$ and $R_p$ could be evaluated because these measurements are very noisy except the initial phase due to influence of eddy currents. The value of $\beta_p$ just before the thermal quench is evaluated from the magnetics and an equilibrium calculation code (CCS code [4]). From Fig. 1, $\beta_p$ values just before the disruption in high $\beta_p$ disruptive discharges are above 1.4 and are about 10 times as large as those in the radiative disruption. The plasma inductance is evaluated from the following equation,

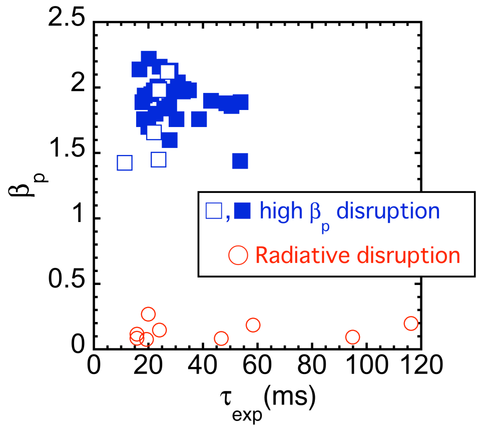


Fig. 1 The poloidal beta just before the disruption is plotted against the experimental current decay time. Open symbols are the analyzed data in this paper.

$$L_p = \mu_0 R_0 \left( \Lambda - \beta_p + \ln\left( 8R_0/a \right) - 2 \right). \qquad (2)$$

Here, $\Lambda$ is Shafranov lambda, $R_0$ is major radius and $a$ is minor radius. As shown in Eq. (2), the assessment of $\beta_p$ and $\Lambda$ is important to obtain $L_p$. Shafranov lambda is evaluated by using the magnetics and the CCS code in JT-60U. Because the toroidal flux generated by eddy currents would strongly affect the evaluation of $\beta_p$ by the magnetics during the current quench phase, the $\beta_p$ is assessed from $T_e$ profile evaluated by using electron cyclotron emission (ECE) measurement and line-averaged density evaluated by using far infrared (FIR) interferometer. In this paper, the time evolution of $\beta_p$ is evaluated by the following equations:

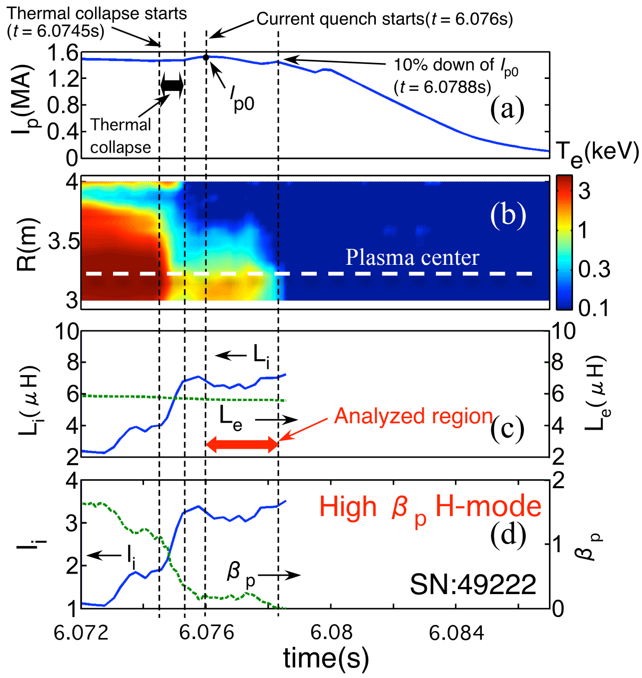


Fig. 2 Typical waveforms of (a) plasma current, (b) profile of electron temperature, (c) plasma internal and external inductance, (d) internal inductance and poloidal beta in high $\beta_p$ disruption.

$$\beta_{\rm p} = \frac{\langle \beta_{\text{p-CCS}} \rangle}{\langle \beta_{\rm p} \rangle} \frac{\int_0^a T_{\rm e}(r) n_{\rm e} r dr / S}{I_{\rm p}^2 / 8\pi^2 a^2}. \qquad (3)$$

where $<\beta_p>$ and $<\beta_{p\text{-CCS}}>$ are the average value of $\beta_p$ evaluated by Eq. (3) and CCS code just before the thermal quench, respectively and $S$ is the plasma cross section. In this analyzed data, $T_e$ profile could be evaluated in only 5 shots due to the difficulty of measurement during disruption. The analyzed data in this paper are represented by opened squares in Fig. 1.

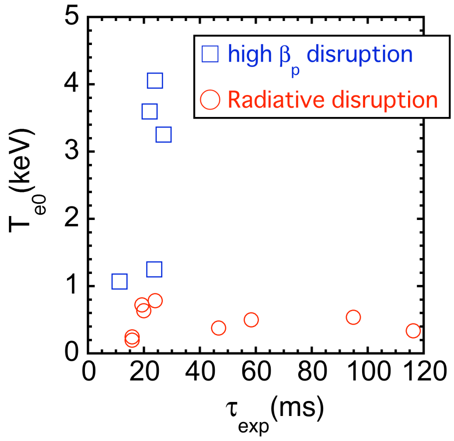


Fig. 3 The electron temperature of plasma center just after the thermal quench is plotted against $\tau_{exp}$. The electron tempareture during disruption is evaluated by using ECE measurement.

**3. Results**

Typical waveforms of plasma current, $I_p$, profile of $T_e$, internal inductance, $l_i$, and $\beta_p$ during disruption in high $\beta_p$ disruptive discharges are shown in Fig. 2. The magnetic configuration of plasma discharge in Fig. 2 is reversed magnetic shear. In Fig. 2, the thermal collapse occurs at $t$ = 6.0745 s. It should be noted that the thermal collapse means that the rapid loss of the plasma energy here. After the thermal collapse starts, $l_i$ increases because the current density profile changes from reversed to peaked shape during the thermal collapse. The current quench starts at $t$ = 6.076 s and $l_i$ gradually increases. In this discharge, $\tau_{exp}$ is 23.7 ms and $T_e$ at the plasma center is above 1 keV during the initial phase of current quench. On the other hand, the time evolution of $l_i$ and $T_e$ during current quench in the radiative disruptions (positive magnetic shear) is different from these in the high $\beta_p$ disruptive discharges. In radiative disruption, $l_i$ decreases after the thermal collapse starts because the current density profile changes from peaked to flat shape during the thermal collapse. During the current quench, $l_i$ gradually increases similar as the high $\beta_p$ disruption. $T_e$ at the plasma center during current quench is less than 0.8 keV in radiative disruptions.

In order to investigate influence of $T_e$ on the current decay time in high $\beta_p$ and the radiative disruptions, $T_e$ of plasma center, $T_{e0}$, just after the thermal collapse are plotted against $\tau_{exp}$ in Fig. 3. In the high $\beta_p$ disruptive discharges, $T_{e0}$ is higher than 1 keV; especially, $T_{e0}$ in 3 shots exceeds 3 keV. In contrast, $T_{e0}$ is less than 0.8 keV in the radiative disruptions under the almost same current decay time observed in high $\beta_p$ disruptions. This experimental result indicates that the electron temperature itself plays no major role in determination of the current decay time in the initial phase of the disruption.

In order to validate the current decay model in various discharges, we evaluated the experimental and predicted current decay time during the current quench in high $\beta_p$ disruptive discharges. Fig. 4 shows the predicted current decay time, $\tau_{model}$, in the high $\beta_p$ disruptive discharges, as a function of $\tau_{\rm exp}$. In this figure, $\tau_{\rm model}$ was evaluated by using *L*/*R* model and modified *L*/*R* model represented by the following equation,

$$\tau_{\rm L/(R+dL/dt)} = \overline{L_{\rm p}} \Big/ \left(\overline{R_{\rm p}} + \Delta L_{\rm p} / \Delta t\right), \qquad (4)$$

where $\overline{L_{\rm p}}$ and $\overline{R_{\rm p}}$ are time-averaged values of $L_{\rm p}$ and $R_{\rm p}$, respectively and $\Delta L_{\rm p}/\Delta t$ is time derivative of plasma inductance during the initial phase of current quench. As shown in Fig. 5, the values of $\tau_{\rm model}$ predicted by modified *L*/*R* model give good agreement with $\tau_{\rm exp}$, while $\tau_{\rm model}$ predicted by *L*/*R* model is two orders of magnitude larger than $\tau_{\rm exp}$ in high $\beta_{\rm p}$ disruptive discharges. This result indicates that the effect of time derivative of $L_{\rm p}$ should be taken into account in the current decay model in high $\beta_{\rm p}$ disruptive discharges. The modified *L*/*R* model can be adapted both for high $\beta_{\rm p}$ and radiative disruptions.

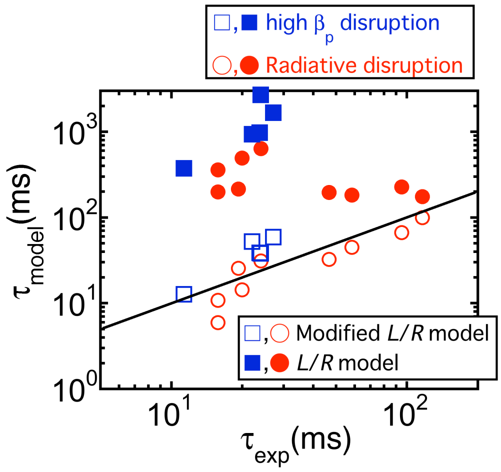


Fig. 4 The predicted current decay time, $\tau_{\rm model}$, in the high $\beta_{\rm p}$ disruptive discharges and the radiative disruptions with neon massive gas-puff are plotted against $\tau_{\rm exp}$. Open symbols are the current decay time predicted by the modified *L*/*R* model, and close symbols are one predicted by *L*/*R* model.

## 4. Summary

The validation of current decay model during the current quench was investigated in high $\beta_{\rm p}$ disruptive discharges on JT-60U. It is experimentally confirmed that the electron temperature does not play an important role in the determination of the current decay time in the initial phase of current quench and that values obtained from *L*/*R* model are two orders of magnitude larger than the experimental current decay time. The current decay time predicted by the modified *L*/*R* model, in which the time derivative of plasma inductance is taken into account, is in fairly good agreement with the experimental data. In future work, we need to perform the MHD equilibrium code for free-boundary condition such as DINA [5] and TSC [6] code under the axisymmetric assumption in order to clear up the determination mechanism of time derivative of plasma inductance.

## 5. Reference

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