Characterization of plasma current quench during disruptions at HL-2A

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Abstract

The most essential assumptions of physics for the evaluation of electromagnetic forces on the plasma-facing components due to a disruption-induced eddy current are characteristics of plasma current quenches including the current quench rate or its waveforms. The characteristics of plasma current quenches at HL-2A have been analyzed during spontaneous disruptions. Both linear decay and exponential decay are found in the disruptions with the fastest current quenches. However, there are two stages of current quench in the slow current quench case. The first stage with an exponential decay and the second stage followed by a rapid linear decay. The faster current quench rate corresponds to the faster movement of plasma displacement. The parameter regimes on the current quench time and the current quench rates have been obtained from disruption statistics at HL-2A. There exists no remarkable difference for distributions obtained between the limiter and the divertor configuration. This data from HL-2A provides basic data of the derivation of design criteria for a large-sized machine during the current decay phase of the disruptions.

Keywords: tokamak, disruption, current quench

(Some figures may appear in colour only in the online journal)

1. Introduction

Tokamak discharges are often terminated by plasma disruption, which causes enormous thermal load and enormous mechanical force on the vessel [1]. The phenomenon of major disruption of the plasma constitutes a serious threat to the safe operation of a tokamak. More specifically, in a large-sized tokamak such as ITER, plasma disruptions are one of the most important issues for the design of the plasma-facing components (PFCs), blanket, and vacuum vessel [2]. The disruption can cause severe damage throughout three aspects: thermal loads, electromagnetic (EM) forces, and runaway electrons (REs). The possible consequences from disruptions, eddy currents and halo current generated during the fastest current decay (\(I_p\) decay) represent the most important design condition for large-sized tokamaks [3]. From an engineering viewpoint against the EM force induced by current quench (\(I_p\) quench), the shortest \(I_p\) quench time is important [4]. Beyond that, due to the secondary generation mechanism, the transition from plasma current to runaway current is theoretically predicted to rely on the \(I_p\) quench rate [5]. It is important to investigate the time traces of the \(I_p\) decay and \(I_p\) quench rate in tokamak disruptions.

For the ITER disruption database, an extensive set of \(I_p\) quench data was established [6] and a disruption warning database of the EAST tokamak had been established by a disruption research group [7]. To date, the database on the \(I_p\) quench rate and the waveform analysis of the \(I_p\) quench have not yet been established at HL-2A. In this paper, for the HL-2A tokamak, detailed studies about characterization of \(I_p\) quench have been investigated in spontaneous disruptions. The experimental setup and methods are described in section 2. The experimental results are shown in section 3. Finally, the conclusions are presented in section 4.
The typical time trace of the main plasma parameters during the quench process is shown in figure 1. The main parameters of this discharge are plasma current \( I_p = 210 \text{ kA} \), safety factor \( q_{95} = 3.37 \), and toroidal magnetic field \( B_t = 1.53 \text{ T} \) with limiter configuration. The appearance of a large negative spike in the loop voltage and a large positive spike in the plasma current is a characteristics of tokamak major disruption. The rapid drop in the ECE signal to almost zero indicated that the thermal quench has happened. The plasma \( I_p \) quenched to almost zero in 5 ms during the disruption. The plasma current derivative is also shown in figure 1(d).

Following the initial \( I_p \) quench in which the time derivative of the plasma current is negative and the \( (dI_p/dt)_{\text{max}} \) of \(-80.9 \text{ kA ms}^{-1}\) appears about 1.5 ms after the \( I_p \) quench starts. The dark vertical dot line corresponds to the time for the maximum instantaneous current quench rate.

Proper specification of the \( I_p \) quench waveforms is important to conduct a robust design for each blanket module against EM force arising from disruptions. According to the \( I_p \) quench rate value, the \( I_p \) quench waves can be classified into the following two types: fast \( I_p \) quench and slow \( I_p \) quench (as applied in JT-60U [13] and J-TEXT [10]). The corresponding time criterion of the two types is approximately 10 ms. Figure 2 shows a typical waveform with a fast \( I_p \) decay. Here, some parameters on the \( I_p \) decay are indicated in the frame. Black closed circles show the experimental value of \( I_p \) decay and the red full line represents the exponential fitting of \( I_p \) decay. For this fastest \( I_p \) quench, the fitting results suggest that the exponential waveform can fit the experimental waveform much better than a linear one. The phenomenon is similar to that in JT-60U [13]. Obviously, this waveform for fastest \( I_p \) quench is accurately fitted by exponential \( I_p \) quench.

It is found that a linear waveform can also fit the experimental waveform for the fastest \( I_p \) quench. Another typical waveform corresponding to a fast linear \( I_p \) decay is shown in figure 3. Although the average \( I_p \) quench time is close to that of no. 17682 discharge in figure 2, the \( I_p \) quench pattern is completely different. The red full line represents the linear fitting of \( I_p \). The average \( I_p \) quench rate and the maximum instantaneous \( I_p \) quench rate are not equal to the results in the above two cases, but the closer extent is more obvious.
for fast linear $I_p$ decay waveforms (in figure 3) than an exponential one (in figure 2). These fitting results show experimental fast $I_p$ quench waveforms are not only fitted by exponential $I_p$ decay but by linear $I_p$ decay.

Similar to the above the fast $I_p$ quench events, figure 4 shows a slow $I_p$ quench waveform with two stages of current termination. There are two different $I_p$ quench rate phases (phase 1, phase 2). White closed circles show the experimental value of $I_p$, the red full line expresses the exponential fitting at phase 1 ($t = 834 - 853$ ms) and the blue arrow line represents the fitting of $I_p$ by linear at phase 2 ($t = 853 - 856$ ms). According to fitting curves under different phases, obviously, $I_p$ quench in phase 1 is more compatibly fitted by exponential $I_p$ decay than the linear one, while the case in phase 2 is the opposite. It is common for the maximum instantaneous $I_p$ quench rate to exceed the average $I_p$ quench rate, as shown in [10, 11]. Depending on the parameters (QR and $(-dI_p/dt)_{\text{max}}$) in figure 4, it is also easy to show that the maximum instantaneous $I_p$ quench rate is several times greater than the average $I_p$ quench rate.

The plasma motion during $I_p$ quench should be investigated to avoid vertical displacement events (VDEs). At the end of a fast VDE, due to the low electrical resistivity, the current will flow into the first wall when the plasma touches it [14]. The measurements of the plasma current and the plasma vertical position during the disruption phases are shown in figure 5. For the fast $I_p$ quench discharge (no. 17682), a large vertical downward displacement of the plasma position (e.g. 32 cm) has been measured, while only a vertical downward displacement (e.g. 6 cm) is observed for the slow $I_p$ quench (no. 16379). The speed of plasma vertical motion is about 35.27 cm ms$^{-1}$ and 4.54 cm ms$^{-1}$, respectively. Based on the comparison of the speed of plasma vertical motion and the value of QR, it is found that the faster $I_p$ quench rate corresponds to the faster speed of plasma vertical motion. It may be the result of the plasma contact with the first wall leading to the faster $I_p$ quench.

The magnitude of the poloidal halo current depends on the edge safety factor $q_a$ ($I_h^{\text{pol}} \approx I_h^{\text{tor}} / q_a$), where $I_h^{\text{pol}}$ is the poloidal halo current, and $I_h^{\text{tor}}$ is the toroidal halo current, respectively. It is preferable to statistically analyze the related parameters under different $q_a$. Figure 6 shows a statistical
survey of the disruption discharges in the HL-2A. It shows a scatter plot of the average \( I_p \) quench time \( \tau_{80-20} \) versus \( q_{95} \) at different toroidal magnetic fields \( (B_t) \). In figure 6, the lower boundary of \( \tau_{80-20} \) appears at 2.2 ms at HL-2A (displayed by the red straight line). The value of \( \tau_{80-20} \) increased as \( B_t \) decreased, although the dependence is not strong.

The essential physics assumption is the \( I_p \) quench rate for disruption. In order to investigate the relationship between QR\(_{80-20}\) and \( (\frac{-dI_p}{dt})_{\text{max}} \), figure 7 shows the statistical plot of \( (\frac{-dI_p}{dt})_{\text{max}} \) versus QR\(_{80-20}\) in the HL-2A. The red dash line is the boundary of this scatter. The \( (\frac{-dI_p}{dt})_{\text{max}} \) values of the largest scatter are (up to 290 kA ms\(^{-1}\)) at QR\(_{80-20}\) \( \approx 25 \text{ kA ms}^{-1} \), but not at the highest QR\(_{80-20}\).

Scatter plotting of \( \tau_{\text{min}} \) with respect to \( q_{95} \) at different \( B_t \) is shown in figure 8 and the \( \tau_{\text{min}} \) range of 0.5–4.5 ms can be obtained. If the \( I_p \) quench is determined by the L/R time of the cold plasma, normalizing the \( I_p \) quench time to the plasma cross-section is physically meaningful [10]. For the poloidal cross-section of plasma of about 0.5 m\(^2\) for HL-2A, it is found that the maximum \( I_p \) quench range is about 2.2 ms, which corresponds to 4.4 ms m\(^{-2}\) on the HL-2A.

In tokamak operation, a limiter plays a number of roles to protect the wall from the plasma when there are disruptions, REs, or other instabilities. The objectives of the divertor configuration are minimizing the impurity content of the plasma and removing the helium ash and the alpha particle power. The first divertor configuration was achieved in the 2003 experimental season for HL-2A. The average \( I_p \) quench time distributions under limiter and divertor configuration are plotted in figure 9. The region of \( I_p \) quench time covered has been divided into intervals 3 ms wide to obtain a sufficient number of samples. From figure 9, the most number of disruption shots, both at the limiter configuration and divertor configuration, mainly concentrate on the range of 3–6 ms. In the divertor configuration, the mean value and standard deviation are about 9.08 and 9.89 ms, respectively. Meanwhile, the mean value and standard deviation are about 8.37 and 9.05 ms, respectively, at the divertor configuration. The results show that there is no significant difference among the distributions obtained at the two different configurations.

### 4. Conclusion

During a disruption the sudden loss of plasma current will produce large induced eddy current and halo current, which results in large EM forces on the PFCs of a tokamak. The systematic investigation of the characterization of \( I_p \) quenches in spontaneous disruptions at HL-2A has been presented. The \( I_p \) quench following disruption has been divided into two categories: fast \( I_p \) quench with linear decay or with exponential decay, and slow \( I_p \) quench with two different stages. The \( I_p \) quench rate is mainly determined by the electron temperature in post-disruption plasmas. The final \( I_p \) quench rate is related to the plasma displacement. With larger plasma displacement, the \( I_p \) quench rate is larger. On the other hand, the statistical analysis of QR\(_{80-20}\) as well as \( (\frac{-dI_p}{dt})_{\text{max}} \)
has been obtained during the $I_p$ quench phases. It is found that the maximum $I_p$ quench rate is about 2.2 ms, which corresponds to 4.4 ms m$^{-2}$ on HL-2A. There is no obvious difference in the distributions of the averaged $I_p$ quench time between the limiter configuration and divertor configuration. This data from HL-2A provides basic data for the derivation of design criteria during the $I_p$ quench phase of disruptions for large-sized machines.

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References