

## Experimental investigations on plasma disruptions in the KSTAR tokamak

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Plasma disruption is sometimes one of the critical issues for achieving high plasma performance in tokamak device because the in-vessel conducting structures may cause damaged by the heat and electromagnetic loads on them during the disruption. Thus, the study on the plasma disruption has been carried out in most tokamak in order to find the method for mitigating it or reducing the number of its occurrence during plasma discharges [1-2].

For understanding the plasma disruptions which were mostly occurred due to the vertical displacement events (VDEs) in the KSTAR tokamak, the properties of the current quench together with the runaway electron (RE) plateau, eddy currents induced on the in-vessel structure and vessel current in the phase of current phase, and the vertical growth rates and the rotating halo currents during the downward VDEs were investigated for the pre-disrupted plasma current  $I_{p, \text{predisrupt}}$  of 0.4 -1.0 MA during the experimental campaign of 2013- 2017 in the KSTAR.

Firstly, the instantaneous and averaged current quench rates (CQRs) are evaluated by using the maximum value of the time derivative  $|dI_p/dt|_{\text{max}}$  and linear fits for intervals (such as 90 % - 60 %, 90 % - 30 %, and 80 % - 20 % levels of  $I_{p, \text{predisrupt}}$ ), respectively, in the phase of current quench as shown in Fig. 1(a), and the quench times  $t_{\text{CQ}}$  were estimated by using the CQRs.

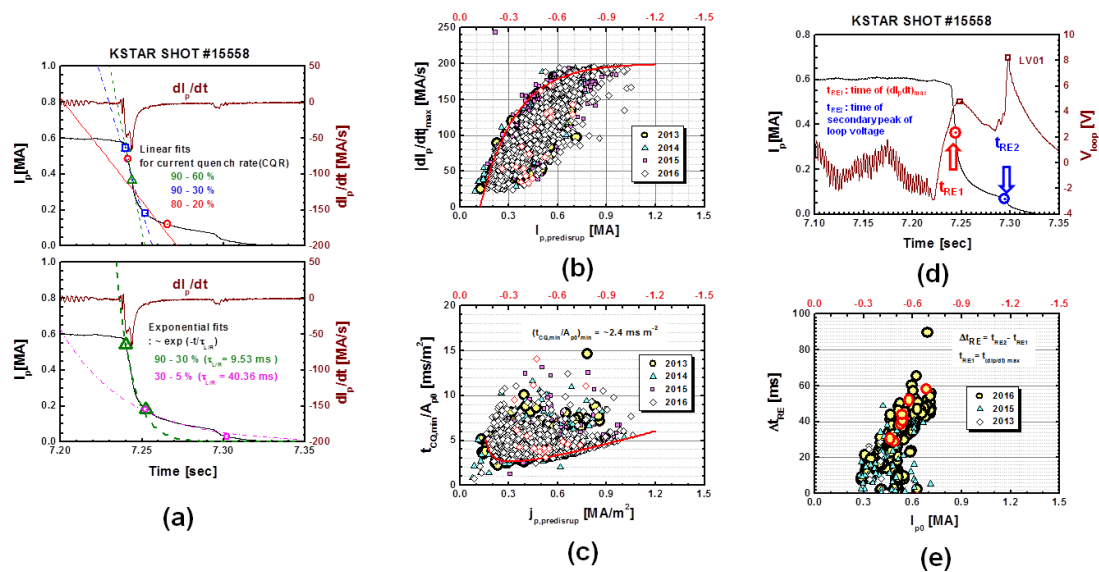


Fig. 1. (a) Typical wave-form of current quench and its time derivative, together with linear and exponential fits on the intervals given in the phase of the quench, (b) the instantaneous current quench rate (ICQR) versus predisruption plasma current, (c) the plasma area-normalized current quench time versus plasma current density, (d) time evolutions of plasma current and loop voltage in the phase of the quench, and (e) sustainment time of the RE plateau versus plasma current. Here, Experimental conditions were following: toroidal field  $B_T = 0.9 - 3.5$  T (mostly, 1.8 T and 2.0 T), plasma elongation  $\kappa = 1.4 - 2.0$ , plasma density  $n_e = (0.5 - 4.0) \times 10^{19} \text{ m}^{-3}$ , and stored energy  $W_{\text{tot}} = 0.04 - 0.8$  MJ.

The instantaneous CQR from  $|dI_p/dt|_{\max}$  increases linearly as plasma current  $I_{p,\text{predisrupt}}$  becomes higher in the range of  $I_{p,\text{predisrupt}} < 0.6$  MA, but it saturates to  $\sim 200$  MA/s above 0.6 MA as shown in Fig. 1(b). Here, experimental data obtained in the experimental campaign of 2013-2016 were used to investigate the relationship between  $|dI_p/dt|_{\max}$  and  $I_{p,\text{predisrupt}}$ . The ‘red curve’ shown in Fig. 1(b) looks like an upper bound of  $|dI_p/dt|_{\max}$ , which was obtained from the exponential fit to the selected data for the disrupted shots in the campaign of 2016. Only maximum value of  $|dI_p/dt|_{\max}$  for a given  $I_{p,\text{predisrupt}}$  was selected as a data point for the fit. From the value of  $|dI_p/dt|_{\max}$ , the plasma area-normalized instantaneous quench time  $(t_{\text{CQ,min}}/A_{p0})_{\min}$  is estimated down to about  $2.4 \text{ ms/m}^2$  and its lower bounded value (‘red curve’) linearly increases as current density becomes larger as shown in Fig. 1(c). The averaged CQR from the linear fit on the interval of 80 – 20 % level of  $I_{p,\text{predisrupt}}$ , as mentioned in the NSTX and the JET [3,4], was about a quarter of the instantaneous CQR and average value of plasma area-normalized quench time was about three times the value of  $(t_{\text{CQ,min}}/A_{p0})_{\min}$ . Secondly, the most of the waveform of current quench had a double exponential decay structure with faster and slower R/L times, which were evaluated from two exponential fits on 90-30 % and 30-5 % levels of plasma current, respectively (see Fig. 1(a)). The slower R/L time was four times the faster one and the slower slope might be due to the formation of the runaway electron (RE) plateau at the lower plasma level ( $< 0.1$  MA) in the phase of the quench. Thirdly, there are normally two positive peaks in the loop voltage in the phase of the current quench, and the first peak appears near the time of  $|dI_p/dt|_{\max}$ , and the second one is detected near the end of the RE plateau as shown in Fig. 1(d), which is quite similar to the result observed in the FTU [5]. The time difference between the two peaks, which corresponds to the sustainment time of the RE plateau, is linearly correlated with the magnitude of plasma current  $I_{p0}$  as shown in Fig. 1(e).

Fig. 2 (a) shows the time evolutions of some parameters, such as plasma current and its time derivative, toroidal vessel current (VC) and vertical displacement, and two toroidal eddy currents (ECs) induced on the upper and lower passive stabilizers (PSs), in the phase of the current quench. The peaked value of the VC linearly depended upon  $I_{p,\text{predisrupt}}$  and its magnitude was up to 0.65 MA for  $I_{p,\text{predisrupt}} = \sim 0.9$  MA. The waveform of the EC at the lower PS has a negative dip followed by a larger positive peak in the case of the downward VDE and the dip and the peak appear before and after the time of  $|dI_p/dt|_{\max}$ , respectively, as shown in Fig. 2(a). The magnitudes of both the dip and the peak exponentially grow for higher value of  $|dI_p/dt|_{\max}$  as seen in Fig. 2(b). In addition, the elapsed time from the dip to the peak and the ratio between the two magnitudes  $I_{\text{eddy,dip}}/I_{\text{eddy,peak}}$  exponentially decrease as  $|dI_p/dt|_{\max}$  becomes higher as shown in Fig. 2(c). The EC with a negative dip followed by a larger positive peak

was also observed during a VDE in the EAST [6].

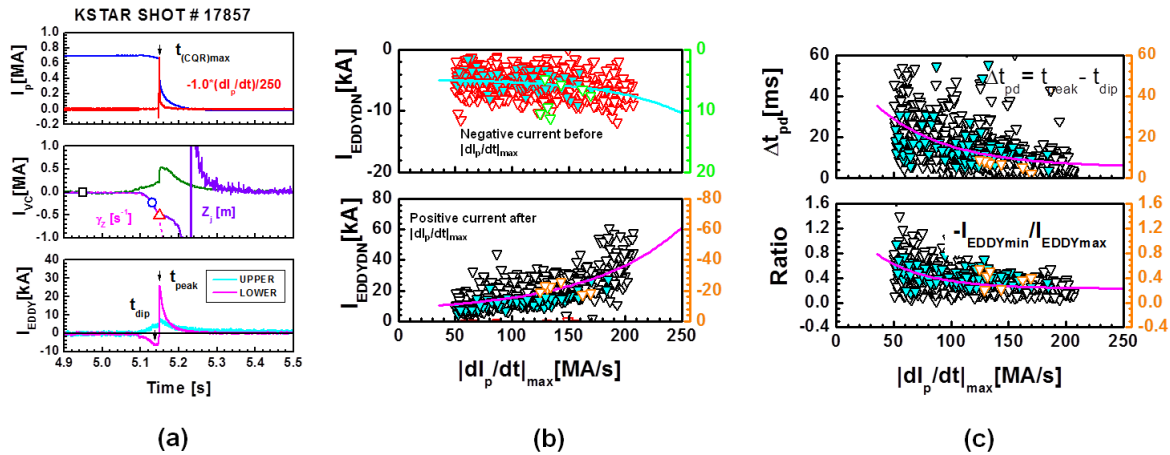


Fig.2. (a) plasma current and its time derivative (top), vessel current  $I_{VC}$  and vertical displacement  $Z_j$  showing the growth rate (middle), and eddy currents induced on the upper and lower passive stabilizers (bottom) during a current quench due to a vertical displacement event, (b) negative (top) and positive (bottom) peaked values of eddy current on the lower passive stabilizer versus  $ICQR$ , and (c) time difference between positive peak and negative dip in the time evolution of the eddy current shown in Fig. 2(a) (top) and ratio between magnitudes of negative dip and positive peak (bottom) versus  $ICQR$ .

The growth rate  $\gamma_z$  of the VDE was evaluated from  $Z_j$  (see middle of Fig. 2(a)) by using the method as mentioned in [7]. Although the values of  $\gamma_z$  were scattered in the downward VDEs during the campaign of 2016, there was a trend that  $\gamma_z$  was increased as  $I_p$  or  $|dI_p/dt|_{max}$  became higher in the range of  $I_p < 0.5$  MA or  $|dI_p/dt|_{max} < 100$  MA/s. The value of  $\gamma_z$  was saturated for above 0.5 MA or 100 MA/s, and its average value was  $80 \pm 28$  s<sup>-1</sup>. In addition, the vertical position of plasma just before the current quench became smaller for higher value of  $|dI_p/dt|_{max}$  and the vertical neutral position was -2 cm for the most VDEs.

Finally, characteristics of the halo current (HC) during the VDE were also investigated by using experimental data in the campaign of 2015 - 2016. The magnitude of toroidal peak factor (TPF) multiplied by halo fraction  $f$  was up to 0.58, and the value of  $f$  was up to 0.45. Recently, the investigation of the non-axisymmetric and rotating HC has been carried out by using experimental data from several tokamaks such as NSTX, JET, DIII-D, Alcator C-Mode and ASDEX-Upgrade [8]. Especially, several revolutions during an HC pulse are observed in the two tokamaks such as the NSTX and JET. The rotating HCs having several revolutions will be a critical issue for the machine safety in the future device such as the ITER when their rotation frequencies match with the resonance frequencies of the various components in tokamaks. The rotating HC is also observed during downward VDEs in the KSTAR tokamak, and its rotation frequency is 0.2 – 1.2 kHz during one (or one and half) revolution, mostly, in the counter- $I_p$  direction as shown in Fig. 3. Interestingly, few rotating HCs in the co- $I_p$  direction (0.1 – 0.6 kHz) are also detected as seen in Fig. 3(b).

From this work, it was found that there was upper bound of  $|dI_p/dt|_{\max}$  in the current quench and minimum area-normalized quench time was about  $2.4 \text{ ms/m}^2$  for  $0.4 - 1.0 \text{ MA}$ , the waveform of the current quench was a double exponential decay structure with faster and slower R/L times, the sustainment time of the RE plateau became longer for higher plasma current, the elapsed time from the dip to the peak in the EC became shorter for higher  $|dI_p/dt|_{\max}$ . In addition, the growth rate of the downward VDEs was about  $10 - 130 \text{ s}^{-1}$ , and the most of the rotating HCs were observed in the counter- $I_p$  direction during downward VDEs and few in the co- $I_p$  directions were also detected. The rotating frequency was  $0.1 - 1.2 \text{ kHz}$  during up to one and half revolution.

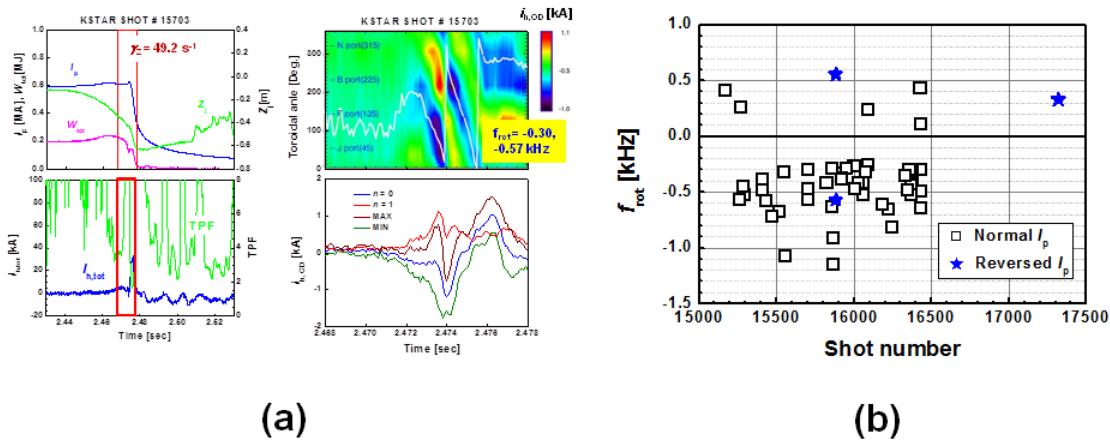


Fig. 3. (a) Time evolutions of parameters for rotating halo current during the downward VDE: plasma current, stored energy and vertical displacement, total halo current and toroidal peaking factor, contour of local halo currents in the lower OD versus time and toroidal angle, together with time dependent phase of  $n=1$  component, for showing the rotating halo current, and magnitudes of  $n=0$  and  $n=1$  components, together with maximum and minimum in toroidal distribution of halo current at the lower OD under experimental conditions such as  $I_{p0} = 0.6 \text{ MA}$ ,  $B_T = 1.6 \text{ T}$ ,  $q_{95} = 4.1$ ,  $W_{\text{tot}} = 0.20 \text{ MJ}$ , and  $\kappa = 1.66$ , and  $P_{\text{NB}} = 3.06 \text{ MW}$ , and (b) the frequency of rotating halo current in counter- and co- $I_p$  direction observed during downward VDEs in the experimental campaign of 2016.

Further investigation on some issues such as the nonlinearity between CQR and  $I_{p,\text{predisrupt}}$  double exponential decay in the quench, effect of RE on CQR, the correlation between the EC and CQR and rotating HCs will be carried out for study on the disruption in the KSTAR. This research was supported by Ministry of Science, ICT, and Future Planning under KSTAR project contract.

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