Experimental investigations on plasma current quench during disruptions in the KSTAR tokamak

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The study on the current quench (CQ) in the phase of disruptions are carried out for the plasma current I_{p0} of 0.4 -1.0 MA in the KSTAR tokamak. The selected disruption data in the experimental campaign of 2012 – 2017 are used for the study, and the criteria for the selection were following; the shot duration is longer than 0.40 sec at least, the value of $|dI_p/dt|_{max}$ is higher than 20.0 MA/s, the value of pre-disruption plasma current (before the CQ) I_p^{dis} is above 0.21 MA, and I_p^{dis} is higher than 80 % of the value at the flat-top $I_{p,flat\text{-}top}$ (> 0.3 MA). In this work, the results from the further progress in the investigations on the CQ during disruptions in the KSTAR, which was previously presented at the 44th EPS meeting [1], are reported.

Firstly, it can be expected that the instantaneous current quench rate (ICQR), which is evaluated from $|dI_p/dt|_{max}$ at the phase of the CQ, is in the relation with the pre-disrupted plasma current I_p^{dis} because the increment of the ICQR becomes smaller for higher value of I_p^{dis} as shown in Fig. 1(a). In order to investigate clearly the relationship between ICQR and I_p^{dis}, the scale of the ICQR and the range of I_p^{dis} are divided as twenty three sectors and eight partial ranges, respectively. Here, ΔICQR corresponds to 10 MA/s and ΔI_p^{dis} is equal to 0.1 MA except for the first range (0.2 – 0.35 MA).

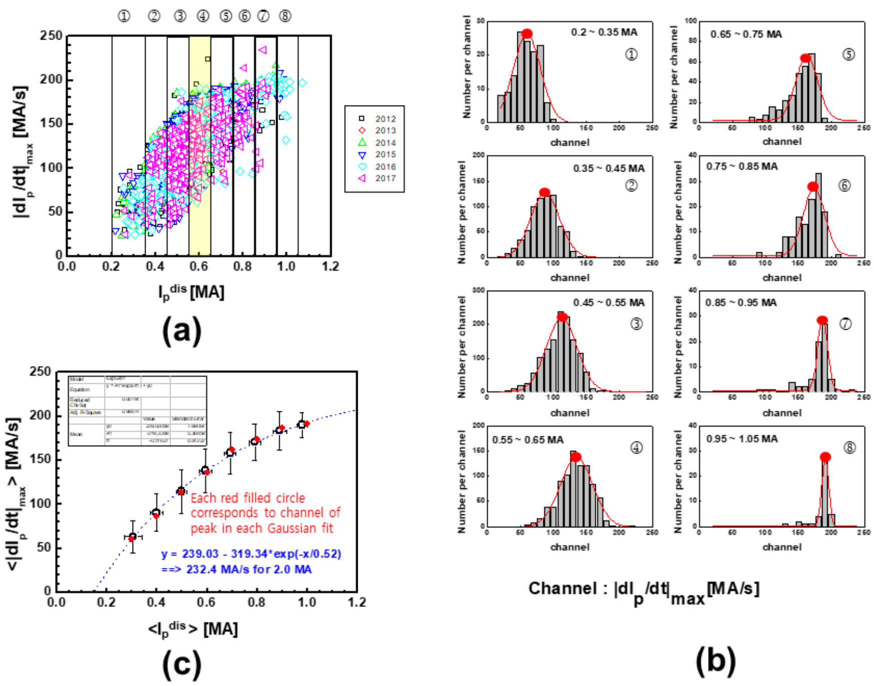

Fig. 1. (a) ICQR versus I_p^{dis}, (b) Eight ICQR distributions at eight ranges of I_p^{dis} and (c) $ICQR_{mode}$ versus $<I_p^{di},>$ (red filled circles) and <ICQR> versus $<I_p^{di},>$ (black blank circles with error bars. Here, Experimental conditions in the campaign of 2012 – 2017 are following: toroidal field B_T = 0.9 – 3.5 T (mostly, 1.8 T and 2.0 T), plasma elongation κ = 1.4 – 2.0, plasma density $n_e = (0.5 – 4.0) \times 10^{19}$ m^{-3}, and stored energy W_{tot} = 0.04 – 0.8 MJ.

Each ICQR distribution for each range seems to have a Gaussian-like one. Thus, the mode (most frequent value) in the

Gaussian fit on the each distribution is selected as a representative value $ICQR_{mode}$, which corresponds to an averaged value $<I_p^{dis}>$ in each range. Note that the width of the distribution is quite narrow for higher value of I_p^{dis} (in the 7th and 8th ranges) as shown in Fig. 1(b). From this process, it is clear found that the most probable magnitude of the ICQR can be estimated up to ~ 200 MA/s at ~1.2 MA and there is non-linear relationship between the ICQR and $<I_p^{dis}>$ as shown in Fig. 1(c). Here, mode value of the ICQR is quite similar to the mean-value of the ICQR.

Secondly, several linear (or averaged) current quench rates (LCQRs) were evaluated from the linear fits for different upper and lower levels of I_{p0} in the time evolution of plasma current during the CQ (see Fig. 1 in Ref.1). From the comparison of ratio between ICQR and LCQR for several LCQRs obtained from linear fits, it is found that the linear fit for the 90 - 60 % level of I_{p0} is the best fit for evaluating the LCQR as shown in Fig. 2(a). The LCQR also had a non-linear relation with I_p^{dis}, and the trend of non-linear relationship between CQR and I_p^{dis} was also seen in EAST and NSTX tokamaks [2,3]. The range of the level for best linear fit is different from the conventional range used in several tokamaks; the LCQRs were obtained from the linear fit for 80 - 30 % level in the EAST [2] and 80 - 20 % level in both the NSTX [3] and the JET [4]. One of the reason why the 90 - 60 % level was used for evaluating the LCQR might be due to the contribution of I_{PS} to the lower level of I_{p0} in the phase of the CQ because eddy current induced the in-vessel components inside vacuum vessel was also in the plasma current measurement by using Rogowski coil in the KSTAR tokamak.

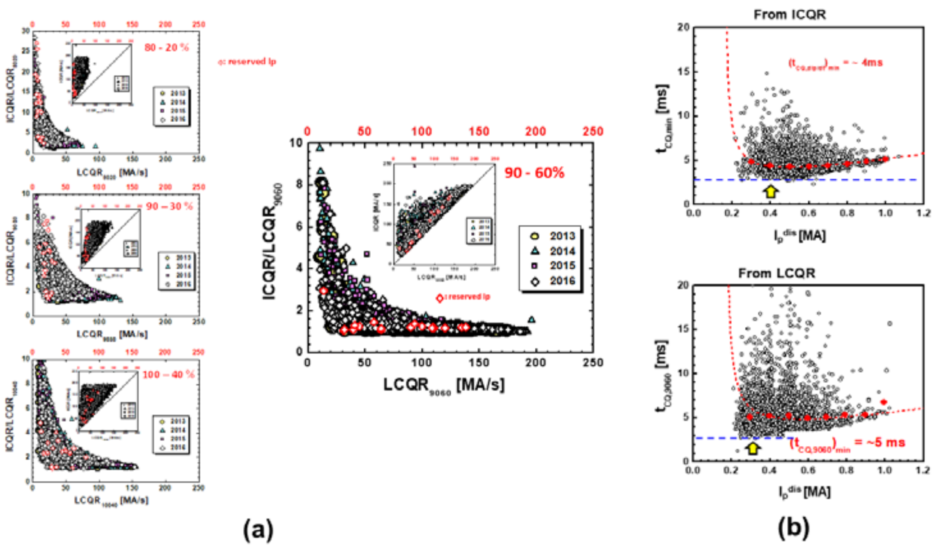

Fig. 2. (a) Ratios between ICQR and LCQR for several LCQRs obtained from linear fits for different levels of $I_{p0,}$ and (b) CQ times from ICQR and LCQR from best linear fit. Here, the best linear fit is obtained from the 90-60 % of I_{p0} (presented as a bigger one) in (a), and the yellow arrows indicate the minimum CQ time equal to ~ 3ms in (b). Here, experimental data in the campaign of 2013 – 2016 are used.

From two CQRs, the lower bound of the CQ times can be expected as ~3 ms and its minimum value are evaluated as ~4 ms and ~5 ms by using exponential fits on eight data points (red filled circles) for ICQR and LCQR, respectively as shown in Fig. 2(b). Interestingly, the minimum CQ time slightly increases up to ~ 5ms as I_p^{dis} become higher.

Thirdly, the dependence of both a vessel current I_{VC} and a passive stabilizer (PS) current I_{PS} on the ICQR was investigated from the time evolutions of the two toroidal eddy currents induced on the vacuum vessel (VV) and the PS during a CQ due to a vertical displacement event (VDE) (see Fig. 2(a) in Ref.1). The magnitudes of I_{VC} and I_{PS} were up to ~ 60 % of I_p^{dis} and up to 60 kA, respectively. There is a correlation between the ICQR and magnitudes of both I_{VC} and I_{PS} as seen in Fig. 3.

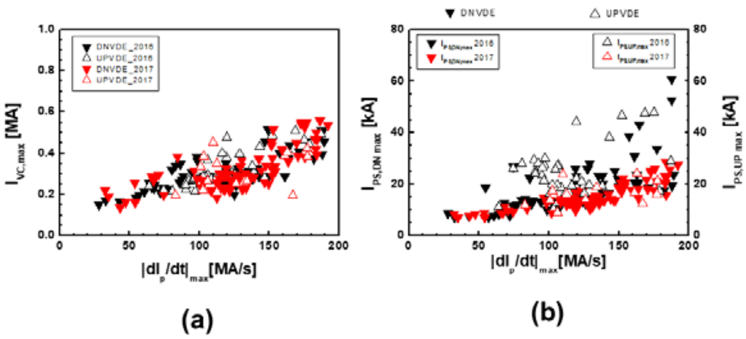

Fig. 3. (a) Vessel current and (b) PS current versus ICQR during vertical displacement events (VDEs) in the experimental campaigns of 2016 and 2017. Here, the PS is one of in-vessel components and is used as conducting shell for vertical control of plasma in the KSTAR tokamak.

Fourthly, the wall times at the VV is obtained from the time evolution of I_{VC} in the phase of the CQ as shown in Fig. 4(a) in order to evaluate the ratio of the CQ time to the wall time τ_{CQ}/τ_{wall} in the KSTAR as shown in Fig. 4(b). The value of τ_{CQ}/τ_{wall} is smaller than 0.2 for τ_{CQ} = 3 – 11 ms. So smaller sideways force due to the asymmetric plasma can be expected during the disruption in the KSTAR as reported in Ref. 5.

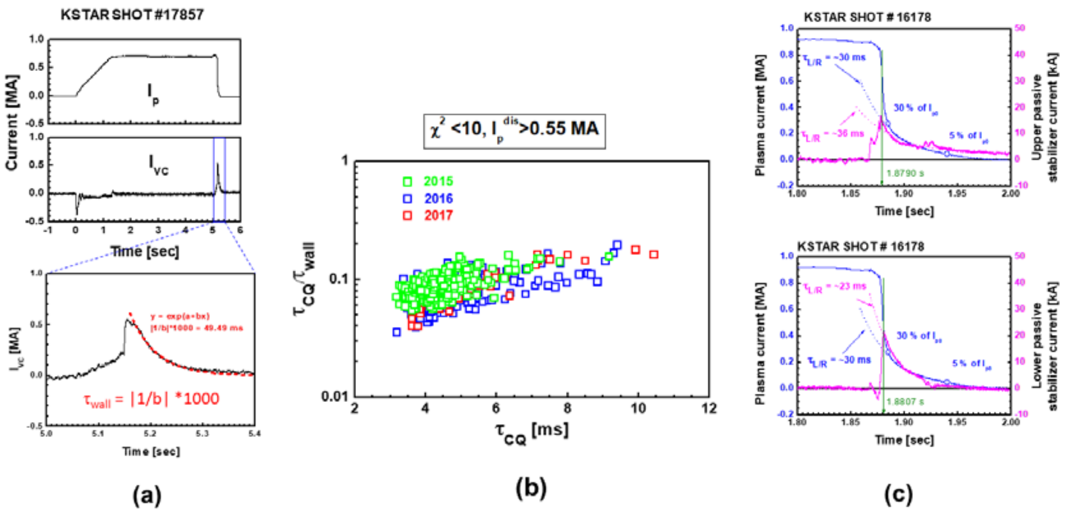

Fig. 4. (a) plasma and vessel currents together with the zoomed vessel current during a CQ, (b) τ_{CQ}/τ_{wall} versus τ_{CQ} and (c) upper and lower I_{PS}s together with a I_p during a CQ in the experimental campaign of 2015 – 2017. Here, τ_{wall} and the decay time at the PS are evaluated from the exponential fits on the two waveforms of I_{VC} and I_{PS} during a CQ, respectively.

In addition, the decay times of I_{PS} at upper and lower PSs is 20 – 40 ms which is almost equal to the decay time of I_p obtained from the exponential fit on the 30 - 5 % level of I_{p0} as shown in Fig. 4(c). Thus, it can be expected that I_{PS} may be contributed to the low level of I_{p0}.

Finally, the toroidal distribution of I_{PS} during the CQ due to the vertical displacement event (VDE) was qualitatively estimated from the tangential component of the poloidal field B_θ measured by the toroidal magnetic probe array mounted on the PS as a preliminary work for the study on plasma current asymmetry in the KSTAR because the studies on the asymmetry in the tokamak [6-8] have been done for the estimate of the sideways forces due to the asymmetry which is one of the important issues in the ITPA-MHD working group. The waveform of B_θ is quite similar to that of I_{PS} as shown in Fig. 5(a). Thus, the asymmetry of I_{PS} may qualitatively be expected from ΔB_θ signals because the magnitudes of B_θ signals located at toroidal angle from 298 to 49 degrees are higher than those at the angle from 118 to 229 degree as seen in Fig. 5(b). In addition, the MHD mode with n = 1 is observed before the asymmetry in ΔB_θ signals appears during the CQ as shown in Fig. 5(c).

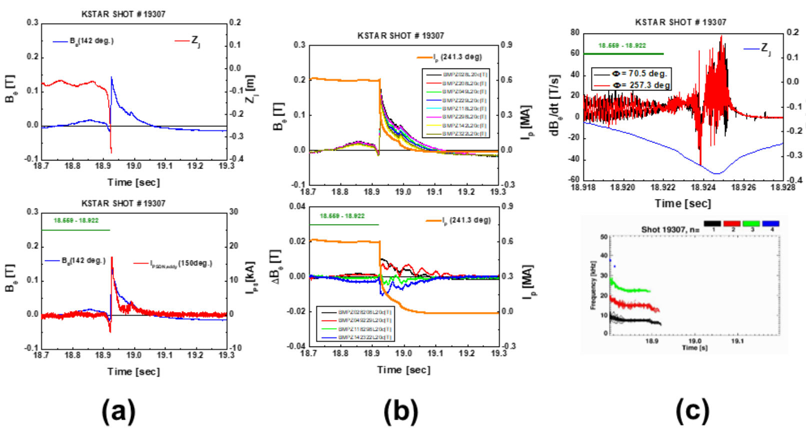

Fig. 5. (a) B_θ signal at the PS together with Z_j and the comparison between I_{PS} and B_θ signals during a CQ, (b) Eight B_θ signals at different toroidal locations and four ΔB_θ signals during a CQ, and (c) n=1 MHD mode together with its harmonics from Mirnov coil signals before the CQ. Here the ΔB_θ signal is the difference between two B_θ signals at the opposite toroidal locations ($\Delta\phi$ =180 deg.)

Further investigation for explaining the reason why there was the non-linear relationship between the CQR and I_p^{dis} and more study on the asymmetric VDE including the characteristic of plasma and halo current asymmetries 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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