Experimental investigation of halo current characteristics in KSTAR

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Small Rogowski coils as halo current monitors (HCMs) are used to measure halo currents during up and downward vertical displacement events (VDEs) under the experimental conditions such as plasma current I_{p0} = 0.2 – 1.0 MA, toroidal field B_T = 1.5 – 3.0 T for elongated plasmas ($\kappa \geq 1.49$) in the KSTAR tokamak. The dependences of halo current I_h on plasma parameters (as plasma current, stored energy, plasma shaping) are investigated in the operational range of I_{p0} and B_T. The maximum value of total halo current $I_{h,max}$ and the toroidal peaking factor (TPF) estimated from the measured local halo currents are 40 % of I_{p0} and 5.0, respectively. The value of maximum halo fraction TPF × $I_{h,max}$ / I_{p0} is up to 0.5. In this work, results from the experimental investigations of the halo currents during the campaign of 2014 in the KSTAR are presented.

The vertical displacement events (VDEs), in which plasma generally moves upward or downward, can be usually occurred by the vertical instability due to a failure of vertical control or a result of the gross magnetic perturbation from a minor disruption for elongated plasmas. The VDEs eventually cause major plasma disruptions that generate large electromagnetic forces and high heat loads, which are critical issues in the future magnetic confinement device such as ITER. Some studies on halo currents flowing into the vacuum vessel through in-vessel supporting structures during the VDEs were carried out in tokamaks [1-5]. After the H-mode discharge was successfully produced in the KSTAR, the study on plasma disruption has been carried out because the disruption is critical issue for plasma current of higher than 1.0 MA with higher heating power that is required as one of missions in the KSTAR project. To study on the disruption due to the VDEs, small Rogowski coils, used as halo current monitors (HCMs) [6], were installed on the supporting structures of back-plates for divertors. However we could not get a clear signal from the HCM measurement due to low signal to noise ratio and noise pick-up from the power supply (with a switching frequency of 4kHz) for the in-vessel control coil (IVCC) until the experimental campaign of 2012 in KSTAR. These issues were clearly solved from the campaign of 2014 after the two improvements in the DAQ system for the HCM by changing the *RC* time-constant in the analog integrators for increasing the amplitude of the HCM signal and by adding electronic low pass-filters between the integrator and the digitizer for reducing noise pick-up from the

IVCC. The HCM measurements were carried out during up / downward VDEs for elongated plasmas (κ ≥ 1.49). In this work, the initial experimental investigations from the HCM measurements in the campaign of 2014 were presented.

The KSTAR upper (lower) divertor consists of inboard divertor (ID), central divertor (CD) and outboard divertor (OD), and each divertor has eight-sectored back-plates equally distributed in the toroidal direction. The supporting structures are mounted at the sectored back-plate for each divertor as following; two structures between two sectored back-plates at the ID, two structures between two sectored back-plates and two structures in the middle of each sectored back-plate at the CD, and one structure between two sectored back-plates and one structure in the middle of each sectored back-plate at the OD. These sectored back-plates are electrically connected in the toroidal direction. Small Rogowski coils as HCMs were used to halo currents flowing through the supporting structures at the divertors during VDEs in KSTAR. The details on the HCM measurements were described in Ref. 7.

During the campaign of 2014 in KSTAR, the cases that the VDEs were occurred 1s after plasma start-up were selected to investigate characteristics of the VDEs. Figure 1 shows typical slides of the TV camera during an upward VDE, together with plasma shapes reconstructed by the real-time EFIT in the KSTAR. The plasma parameters for the selected shots were following; I_{p0} = 0.2 – 1.0 MA, B_T = 1.5 – 3.0 T, q_{95} = 3.0 – 8.0, κ = 1.49 – 2.1. The maximum plasma current quench rate, $-(dI_p/dt)_{max}$ was up to 200 MA/s during VDEs. There is no clear correlation between $-(dI_p/dt)_{max}$ and dZ/dt as shown in Fig. 2. Here, dZ/dt means the vertical shift velocity of the plasma at time of maximum halo current, and the values are 10 – 110 m/s for the selected shots.

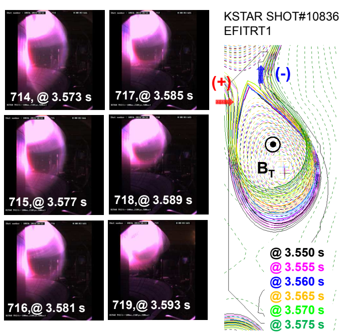

Fig. 1. Upward VDE in KSTAR.

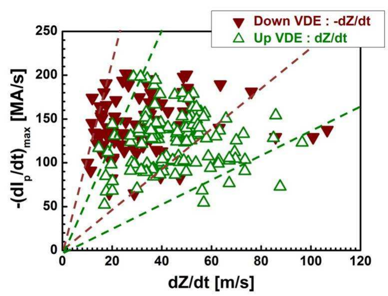

Fig. 2. $-(dI_p/dt)_{max}$ vs. dZ/dt during VDEs.

In addition, there was the linear relationship between the current quench rate and plasma current before disruption as $-(dI_p/dt)_{max}$ [MA/s]= ~ 0.25× I_{p0} [kA]. For a target value of plasma current of 2.0MA in KSTAR tokamak, the maximum plasma current quench rate can be estimated as ~ 500 MA/s from the relationship when the plasma disrupts due to the VDEs.

Since one supporting structure for the outer CD (or the OD), as a halo current channel, covers a toroidal angle of 22.5°, the total halo current I_h (‘source current’) in the plasma halo region at the outer CD and the OD was estimated from 360/22.5 × ($I_{h,outerCD}$ + $I_{h,OD}$) where $I_{h,outerCD}$ and $I_{h,OD}$ were the average current measured by four HCMs equally distributed in the toroidal direction at the outer CD and OD, respectively. Here, $I_{h,k}$ was obtained from local currents $i_{h,k}(\phi)$measured by the four HCMs. Two different ratios of maximum to the averaged halo current were obtained at outer CD and OD, and the higher one of two values was used as the toroidal peaking factor (TPF). Halo fraction, *f*, was obtained by the ratio of the maximum value $I_{h,max}$ in the time evolution of total halo current and the plasma current in the pre-disruption phase I_{p0}.

There are weak corrections between TPF × *f* and plasma parameters as I_{p0} and stored energy before energy quench W_{tot0} during VDEs: the values become slightly smaller as the parameters increases as shown in Fig. 3, which were similar to the parametric dependency of halo currents reported in JT-60U [3]. In addition, the magnitude of the halo currents tended to increase (decrease) with the increase in elongation κ (safety factor q_{95}) as shown in Fig. 4, which were also observed in the COMPASS-D [4] and in the JET [5].

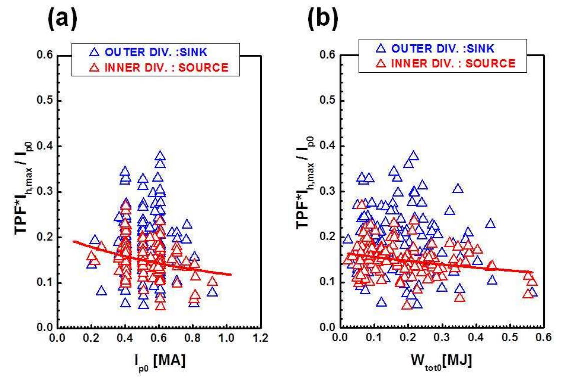

Fig. 3. Dependence of TPF×f on plasma parameters; (a) I_{p0} and (b) W_{tot0} for upward VDEs. Here, ‘source’ means halo currents from wall to plasma and ‘sink’ is the reversed current from plasma to wall.

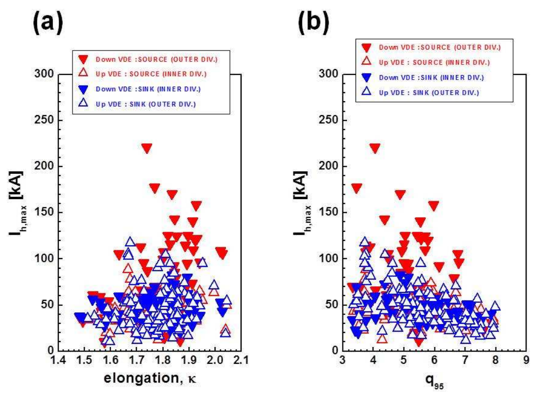

Fig. 4. Dependence of halo current on (a) elongation and (b) safety factor.

In the halo current measurements, the value of *f* is up to 0.4, and the maximum value of TPF is 5.0 as shown in Fig. 5. The value of TPF × *f* is 0.5, which is lower than the maximum value required in the ITER database (0.75). Finally, the upper limit of the halo current is investigated as shown in Fig. 6 by using $I_{h,max} \leq \xi^{\xi/(1-\xi)}/(1-\lambda)I_{p0}/q_{95}$ (where $\xi = \tau_p/\tau_{halo}$ is the ratio of the effective L/R resistive time of the plasma and the halo, respectively) [5].

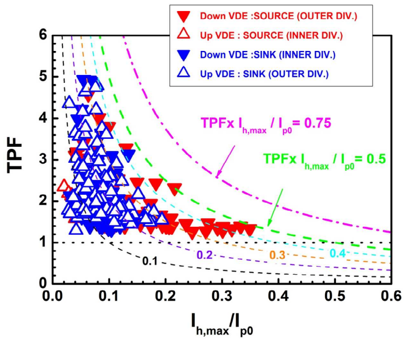

Fig. 5. TPF versus halo fraction.

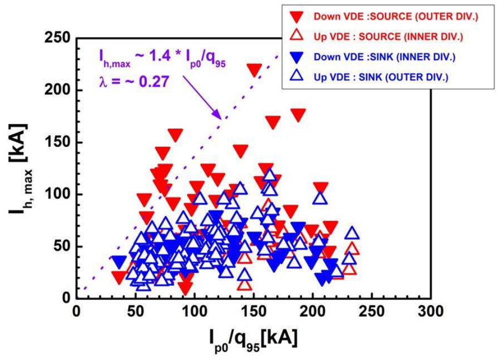

Fig. 6. Maximum of halo current vs. I_{p0}/q_{95}.

213 VDEs (about 10% of total shots in the campaign of 2014, and 136 / 77 shots for up / down VDEs, respectively) were occurred 1s after plasma start-up, which caused eventually to plasma disruptions. From the initial halo current measurements during VDEs, it was found that there were weak dependencies of halo current upon plasma parameters such that the magnitude slightly decreased as parameters (plasma current, stored energy and q_{95}) increased, but the value weakly became higher with as elongation increased. The values of f and TPF $\times f$ were up 0.4 and 0.5, respectively. In addition, the upper limit of the halo current was $I_{h,max} \leq$ ~1.4 I_{p0}/q_{95} (λ = ~ 0.27). The further study on halo current characteristics in KSTAR are required as following; investigations to understand the cause of the differences between 'source' and 'sink' currents in the measurements, to interpret plasma decay time during the plasma current quench, to examine the dependence of the halo-current magnitude on the vertical displacement velocity together with behavior of electron temperature in the halo region, and to detect rotating halo current in KSTAR. This research was supported by Ministry of Science, ICT, and Future Planning under KSTAR project contract.

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