Observation and analysis of halo current in EAST*

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Plasma in a typically elongated cross-section tokamak (for example, EAST) is inherently unstable against vertical displacement. When plasma loses the vertical position control, it moves downward or upward, leading to disruption, and a large halo current is generated helically in EAST typically in the scrape-off layer. When flowing into the vacuum vessel through in-vessel components, the halo current will give rise to a large $J \times B$ force acting on the vessel and the in-vessel components. In EAST VDE experiment, part of the eddy current is measured in halo sensors, due to the large loop voltage. Primary experimental data demonstrate that the halo current first lands on the outer plate and then flows clockwise, and the analysis of the information indicates that the maximum halo current estimated in EAST is about 0.4 times the plasma current and the maximum value of TPF $\times I_{\rm h}/I_{P0}$ is 0.65, furthermore $I_{\rm h}/I_{\rm p0}$ and TPF $\times I_{\rm h}/I_{\rm p0}$ tend to increase with the increase of $I_{\rm p0}$. The test of the strong gas injection system shows good success in increasing the radiated power, which may be effective in reducing the halo current.

Keywords: EAST, halo current, toroidal peaking factor, mass gas injection

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1. Introduction

Disruptions are of great concern for tokamaks, primarily because they will possibly damage the divertor, first wall, and other plasma facing components.[1] Plasma in a typically elongated cross-section tokamak is inherently unstable against vertical displacements. When plasma loses the vertical position control, it will move downward or upward, leading to disruption, and a large halo current is generated helically in ex-plasma (typically in SOL) and flows into the vacuum vessel through in-vessel components, which gives rise to a large force acting on the vessel and the in-vessel components.[2]

The halo current has been studied in a large number of tokamak devices, such as JT-60U,[3] C-MOD,[4] JET,[5] and NSTX.[6] In EAST, many discharges were disrupted after failure of the feedback control of the vertical instability.[7] For measuring the halo current, four sets of halo sensors were installed in the last EAST experiment, and these halo sensors were located at different toroidal positions.[8] Experimentation showed that the halo current in EAST first lands on the outer baffle plate, goes through the dome and finally goes back to the plasma. The present EAST data show that the maximum halo current ($I_{\rm h}$) reaches 0.4 times the plasma current, and the maximum value of TPF $\times I_{\rm h}/I_{P0}$ is 0.65, where $I_{\rm h}$ is the total halo current estimated by four sets of toroidal halo sensors, $I_{\rm p0}$ is the plasma current before disruption and TPF is defined by the maximum measured halo current divided by the average halo current. Further analysis indicates that $I_{\rm h}/I_{\rm p0}$ and TPF $\times I_{\rm h}/I_{\rm p0}$ tend to increase with the increase of $I_{\rm p0}$: when neutral beam injection (NBI) heating is applied in the next campaign, the plasma current will increase to a value of MA, so halo current mitigation will be a key issue for the EAST device in the future.

The rest of this paper is organized as follows. In Section 2, the experimental set up and diagnostics, and the calibration of experimental data are described. In Section 3, experimental results including reversed current spike, halo current flow, and toroidal peaking factor are discussed. In Section 4, a test of the mitigation system is introduced. Finally, some conclusions are drawn from the present study in Section 5.

2. Experimental set-up and the calibration of halo currents

EAST is a superconducting device and composed of inner and outer vessels.[9] In the inner vessel, there are located 16 sets of divertors that are isolated toroidally from each other, and connected to the vessel with supports. In the last EAST campaign, all magnetic sensors were newly fabricated and installed in the vacuum chamber. A Rogowski coil, as one part of the EAST magnetic diagnostic system, was used to measure the halo current, the voltage across both ends of the Rogowski coil is given by $V_{\rm sensor} = \mu_0 ns \cdot I$, where I is the current to be measured, s is the cross-section area of the Rogowski coil, n is the number of turns per unit length in the coil, and $\mu_0 ns$ for these Rogowski coils is given by 2.0×10^{-7} V/A, the output from an integrator, i.e., integrated $V_{\rm sensor}$, is $V_{\rm output} = \frac{G}{RC} \int V_{\rm sensor} {\rm d}t$, where RC is the time con-

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stant of the integrator and G is the magnification.[10] In the EAST tokamak, for measuring the halo current, all Rogowskii coils are arranged around the supporting structure of the divertor plate and dome, so that they can measure the current collected by individual plate tiles. Each sensor is located every 90° from the top view, the total halo current is measured from these four sets of toroidal angles as shown in Fig. 1.

Owing to the non-uniformity of Rogowski coil's winding, diagnostic error caused by some external currents including poloidal field currents and plasma current is obtained. These diagnostic error fields can be eliminated by canceling the error field for each current as shown in Fig. 2, where the signal marked in the dash–dotted line represents the origin current and the solid line denotes the processed current. Thus the resulting halo current ($I_{\rm h}$) is the real current signal, and is expressed as

$$I_{\rm h} = I_{h0} - \sum (c_i \times pf_i + c_{\rm p} \times I_{\rm p}). \quad (1)$$

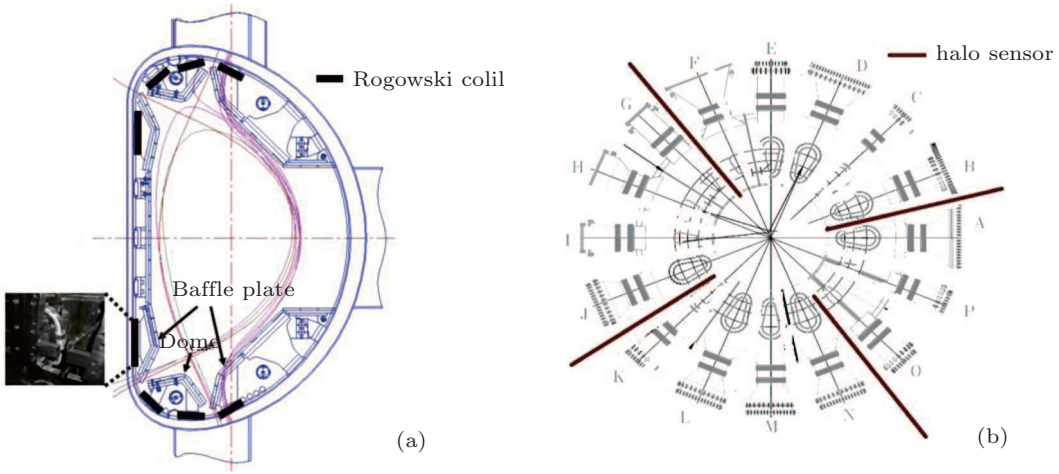


Fig. 1. (color online) (a) Poloidal cross section of EAST device, showing the locations of halo current coils marked in bold line, (b) arrangement of halo current sensors from the plane view of the vacuum vessel.

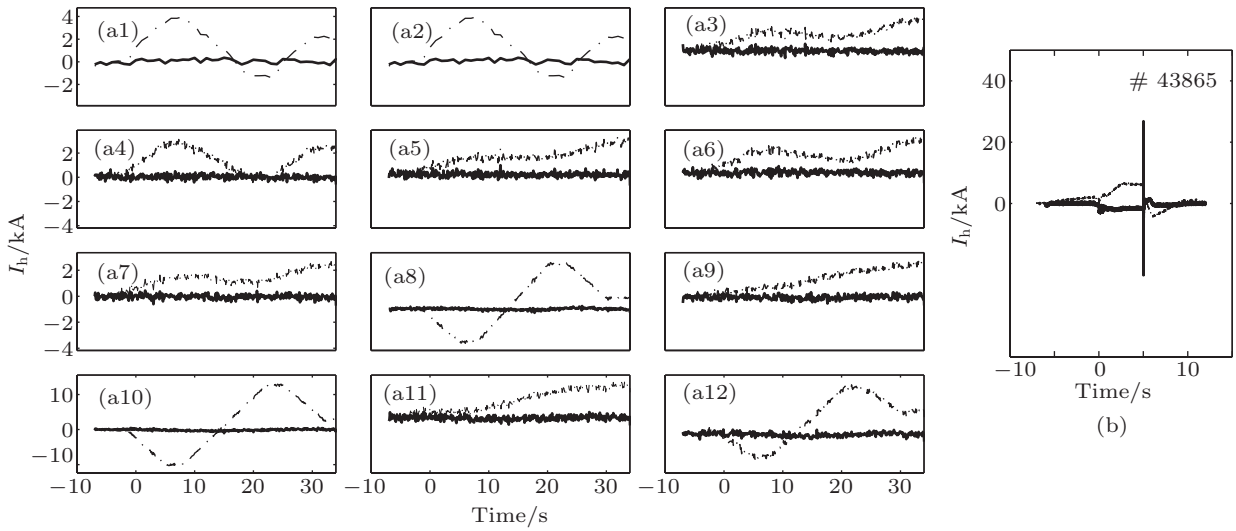


Fig. 2. (a) Halo current signals before cancelling the error field (dash–dotted line) and halo fraction after cancelling the error field (solid line), (b) the plot in the left part shows the values of coefficient $c_{\rm i}$ for 12 independent PF coils, and the plot in the right part denotes ones for normal discharge before and after cancelling diagnostic error.

3. Experimental result analysis

3.1. Analysis of current spike in halo sensor

In EAST tokamak experiments, almost each of all the halo current signals has a current spike as shown in Fig. 3: these spikes have not been observed in other tokamaks. Further research demonstrates that the trace of this spike is correlated with the loop voltage and eddy current (marked in red line), especially in the plasma startup period, as shown in Fig. 3(a); it is well known that toroidal current is easily driven by toroidal voltage. From the plot, the current measured in the Rogowski coil is 4 kA for one tile, occupies a small part of the eddy current (∼ 100 kA), so this halo current can be proved to be one part of the eddy current, the same as in the disruption period, where a large toroidal voltage (∼ 200 V) is induced by the rapid plasma current ($\mathrm{d}I_{\rm p}/\mathrm{d}t$), so such an eddy current is also measured in halo sensors (see Fig. 3(b)), and it is the

reason why this current spike occurs.

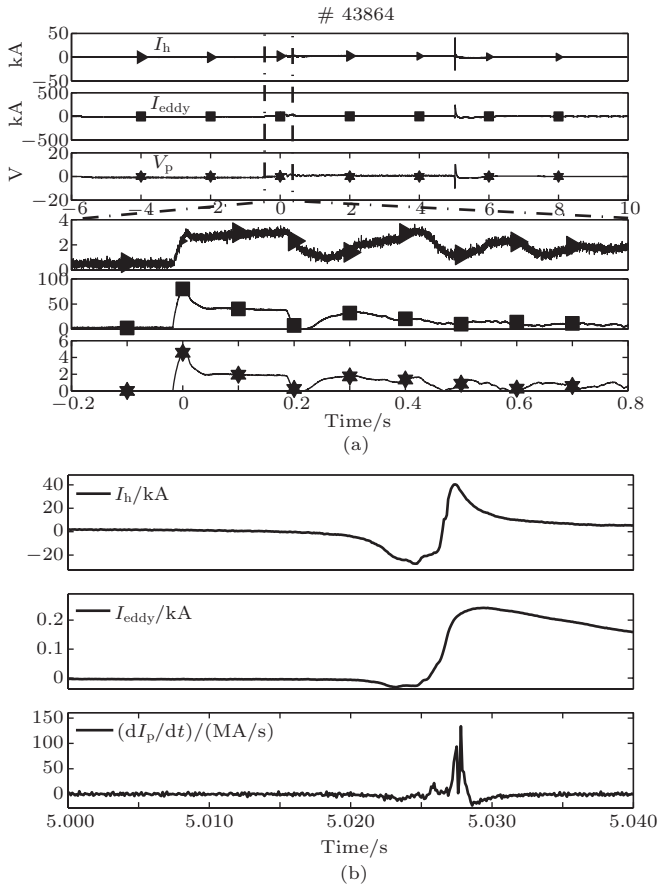


Fig. 3. Comparison of halo current, eddy current, and loop voltage between in start-up (a) and disruption period (b).

3.2. Observation of halo current in EAST

In a vertical displacement event (VDE) period, the plasma continues to move into the wall, reducing the plasma area, typically little changing the total plasma, and developing a pronounced ex-plasma halo current that flows in the wall-contacting ex-plasma region through the structures that the plasma contacts.[11]

In this EAST tokamak experiment, VDEs are triggered by shutting down the fast control power supply (IC) coils, then the plasma moves upward or downward randomly; in the next event, one discharge (#43864) with downward-movement is discussed, with $I_p \sim 400$ kA, $n_e \sim 2.37 \times 10^{19}/m^3$, and $B_\phi \sim 2.0$ T, but with no LHW heating. In EAST, B_ϕ and plasma current are anticlockwise from the top view of the EAST device, therefore, the current in the scape-off layer (SOL) will be clockwise theoretically. Figure 4 shows the halo current collected by the outer-plate tile, I_p measured by the inner Rogowskii coil, and ECE[12] measured by electron cyclotron emission. In the time range from 5.0 s to 5.01 s, the plasma continues to fluctuate vertically on a small scale because an open loop happens, soon afterwards at 5.01 s the plasma loses its vertical control. In Fig. 4, it is clearly seen that the plasma moves into the down divertor, and finally lands on the outer baffle plate. Meanwhile, the electron cyclotron emission signal (ECE) begins to decrease due to the movement of the plasma. At 5.026 s, the plasma arrives at the lowest position with the halo current reaching a maximum value, soon after, the plasma has begun to decrease rapidly with a large current spike in the halo current sensor, which has been explained in the last section.

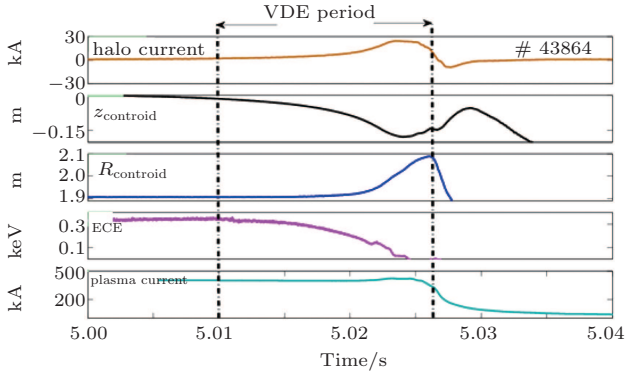


Fig. 4. (color online) Waveforms of the halo current in VDE period (between two vertical lines). When open loop happens, plasma continues to fluctuate vertically, then moves straight to the first wall, and finally disrupts.

3.3. Sketch of halo current flows

In the EAST device, eight Rogowskii coils were arranged in one sector. They are used to measure the local halo currents that go through the supports into the vessel. Owing to these halo sensors, the detailed information about the halo-wall interaction can be easily obtained in poloidal cross section.

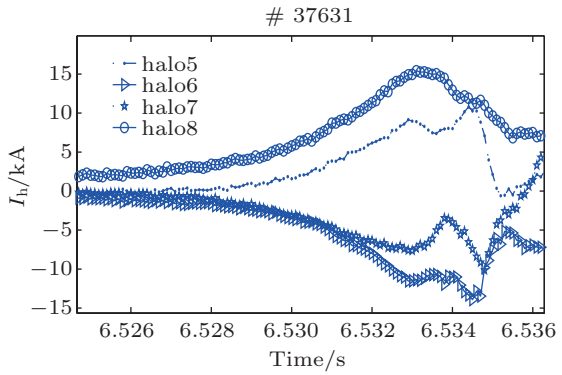


Fig. 5. (color online) Poloidal local halo currents measured in the supports of divertor.

From the waveforms of halo currents measured by poloidal Rogowskii coils at different locations, it follows that halo8 (halo current measured in the outer plate support) is much larger than the one measured at other positions, and that the traces of halo5 (halo current measured in the inner support of the dome) and halo6 (halo current measured in the outer support of the dome), coincide with each other very well, similarly with the halo7 (halo current measured in the support of the inner plate) just as shown in Fig. 5. The traces of these halo currents show that when the plasma lands on the outer plate, the large halo current generated in the SOL area flows into the vessel through the outer support (about 15 kA), then flows

to the inner plate through the dome (about 10 kA) and finally goes back to the plasma through the inner support, as shown in Fig. 6. Therefore, the halo current typically flows clockwise, meanwhile, this current path can prove that toroidal field (B_ϕ) in the EAST tokamak is anticlockwise from the top view.

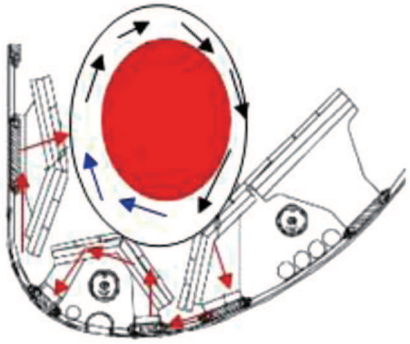


Fig. 6. (color online) Sketch of the poloidal halo current flowing.

3.4. Analysis of halo current in EAST

It is found that the poloidal halo current has toroidal asymmetry, and kink modes are believed to cause large asymmetries of the halo current. The toroidal peaking factor (TPF) is defined as the ratio between the maximum halo current in one sector and the toroidally averaged halo current.[13] From the trace of R–Z signal, it follows that the plasma moves toward the outside plate, soon afterwards the halo current flows into the vessel structure from the plasma through the support. In EAST, the TPF fluctuates in the fluctuation range from 1 to 2, and finally reaches a uniform state with a fluctuation of about 1.4 ∼ 1.6; a kink mode with larger toroidal mode (n) will gives rise to a larger TPF.[11] Analysis of recent data indicated that the maximum total halo current has reached 40% of the plasma current and the limit of TPF × $I_{h,max}/I_{p0}$ is 0.65 as shown in Fig. 7. Further research demonstrates that each of I_h/I_{p0} and TPF × $I_{h,max}/I_{p0}$ has a good correlation with I_{p0} as seen in Fig. 8. In the next campaign, the high power neutral beam injection (NBI) (beam power 4MW and energy 80 keV)[14] heating will be applied. The NBI has been verified to be applicable for the current drive, so halo current mitigation will be the next key issue.

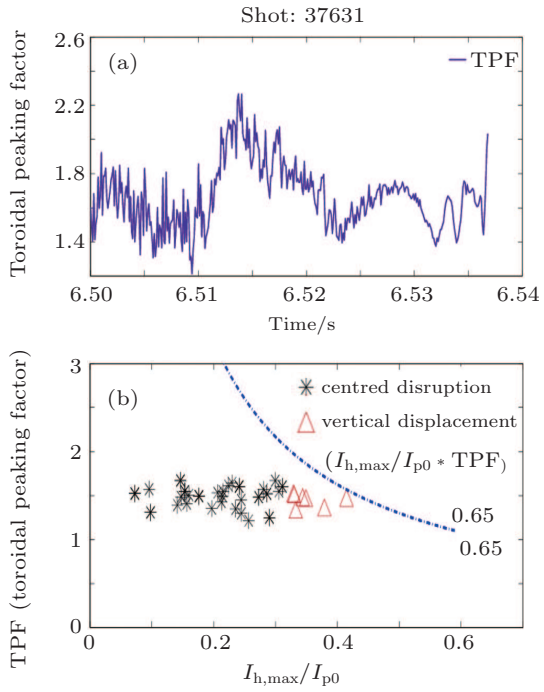


Fig. 7. (color online) (a) The toroidal peaking factor (TPF) fraction versus time and (b) maximum halo current TPF versus maximum halo current fraction ($I_{h,max}$), where star (∗) represents the central disruption and triangle (▽) denotes deliberate VDE disruption.

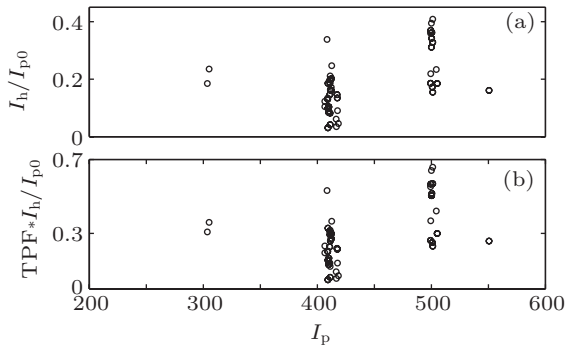


Fig. 8. (a) I_h/I_{p0} and (b) TPF × $I_{h,max}/I_{p0}$ versus I_{p0}.

4. Test of mitigation system

Disruption is a major concern for tokamaks, especially the electromagnetic loads on conducting structures due to the halo current. An injection of massive quantities of gas is proved to be an effective method of reducing the halo current.[15] As the plasma moves downward and finally touches the wall, the energy stored in the magnetic field is dissipated and transferred to the wall, which can be accompanied with a rapid decay of the plasma current. However, when a large amount of high Z gas is injected, a fraction of the power dissipated on the wall is radiated.[16]

In EAST, a fast valve for disruption mitigation is successfully developed (see Fig. 9), which could release noble gas from 0 mbar to 700 mbar (1 bar = 10^5 Pa) in 0.5 ms after a trigger signal.[17] Charge #44062 is one discharge with injecting a mixed gas of 1% Ar and 99% He. The injected gas was triggered at 5.982 s, 8 ms later, and then jet hits the plasma edge seen from edge electron–cyclotron emission signal. Afterwards, the plasma center begins to cool followed by the rapid enhancement of ultraviolet (AXUV) photodiodes radiation. The relevant results are shown in Fig. 10. In the next EAST campaign, a mass–gas injection (MGI) system will be used to reduce the halo current.

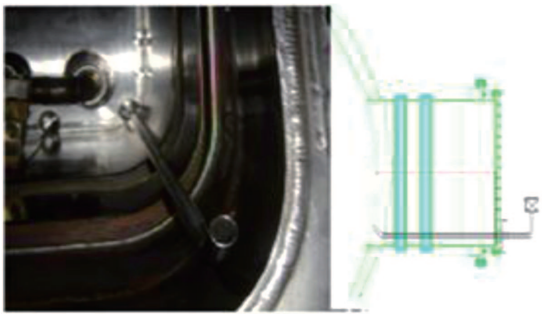


Fig. 9. (color online) Tube of strong gas puffing system.

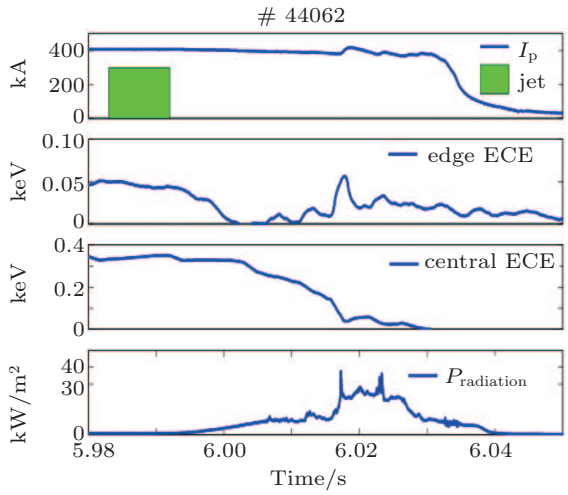


Fig. 10. (color online) Test of strong gas injection system with mixed gas.

5. Conclusions

In this paper, the waveform and magnitude of the halo current are described and the reverse current spike is explained as an eddy current. Furthermore, the maximum halo current and TPF are measured in EAST by using a set of Rogowski coils. The results show that the maximum I_h/I_{p0} reaches 40%, the limit of TPF $\times$ $I_{h,max}/I_{p0}$ is 0.65, these two values are both correlated with the plasma current, also as the sketch of poloidal halo current flows clearly shows, the current flows clockwise in the poloidal cross section. Massive quantities of the gas injection system are tested in EAST, showing good success in reducing the plasma temperature and increasing the radiated power. The next experiment will be used for mitigating the halo current.

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