Control of Transient Static Electric Field in the Magnetic Reconnection Experiment with Large Guide Field*)

Taiju SUZUKI, Michiaki INOMOTO, Hailin JIN and Kei NAKATSUKASA

The University of Tokyo, Bunkyo, Tokyo, 113-8656, Japan

(Received 8 January 2023 / Accepted 19 March 2023)

In the magnetic reconnection in the existence of a high guide field, the inductive reconnection electric field and the static in-plane electric field are generated in the reconnection upstream and downstream regions. This self-generated static electric field determines the plasma motion and has large impacts on the energy conversion process in the guide field reconnection. In this paper, to elucidate the effect of the in-plane electric field, a novel experimental technique is proposed to actively control the electrical boundary condition of the magnetic field lines in the downstream region. Moreover, the capability of the developed technique was demonstrated by showing the controllability of the in-plane static electric field using separate electrodes with fast semiconductor switching devices.

Keywords: magnetic reconnection, guide field, particle acceleration, merging start-up, spherical tokamak

DOI: 10.1585/pfr.18.2402033

1. Introduction

Magnetic reconnection (MR) is a ubiquitous phenomenon observed in various situations, such as solar flare emission of astrophysical plasma [1] and sawtooth event in laboratory tokamak plasma [2], among others. Since MR causes conversion from magnetic to plasma kinetic energy, it is highly worth investigating the detailed mechanisms of MR to comprehend solar/astroplasma physics and to improve the performance of the laboratory fusion core plasma.

The reconnection process between antiparallel magnetic field lines is simply described as the balance of the out-of-plane inductive electric field perpendicular to the reconnecting magnetic field in the MHD framework. However, in a realistic situation, MR exhibits significantly different behavior from the simple MHD case with all magnetic fields lying on a plane. Two-fluid or particle treatments and the existence of the “guide” out-of-plane magnetic field will bring about the generation of a static electric field, which is considered to significantly change the reconnection behavior [3]. Thus, it is important to consider both the effect from the static and the inductive electric field.

The static electric field is formed to hold the global coupling condition between electron and ion motions. Decoupling between electron and ion motions takes place in the antiparallel MR on a plane in the two-fluid regime, resulting in the occurrence of in-plane static electric field due to the electric potential difference caused by the Hall effect [4]. Quadrupole electric potential distribution is also observed in high guide field reconnection cases [5, 6]. Particularly, it has considerable importance for MR with high guide field that occurred in the cylindrical coordinate system (r, θ, z), such as a torus plasma merging case employed in many laboratory experiments, as illustrated in Fig. 1. Time variation of in-plane (poloidal) magnetic flux (i.e., the consequence of the plasma motion from upstream to downstream regions) induces the out-of-plane (toroidal) electric field (E_t), and the induced toroidal reconnection electric field is fully parallel to the magnetic field at the X-point. When the toroidal guide field (B_t) is much larger than the in-plane magnetic field in the downstream region, the induced toroidal electric field is near parallel to the magnetic field, resulting in an acceleration of charged particles along the downstream magnetic field lines. Particularly in the global axisymmetric condition, which is assumed in many laboratory experiments, the charge separation in the toroidal direction is canceled, and the separation in poloidal (r–z) plane remains to form the static in-plane electric field. Due to the torus geometry, the gen-

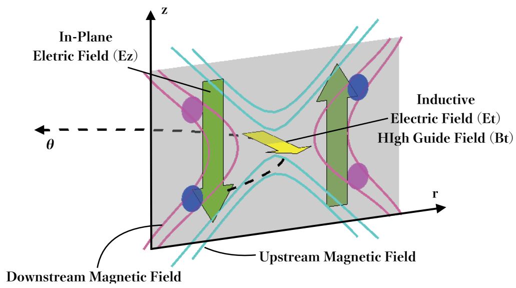

Fig. 1 Diagram of magnetic and electric fields in high guide field reconnection.

author's e-mail: t_suzuki@ts.k.u-tokyo.ac.jp

*) This article is based on the presentation at the 31st International Toki Conference on Plasma and Fusion Research (ITC31).

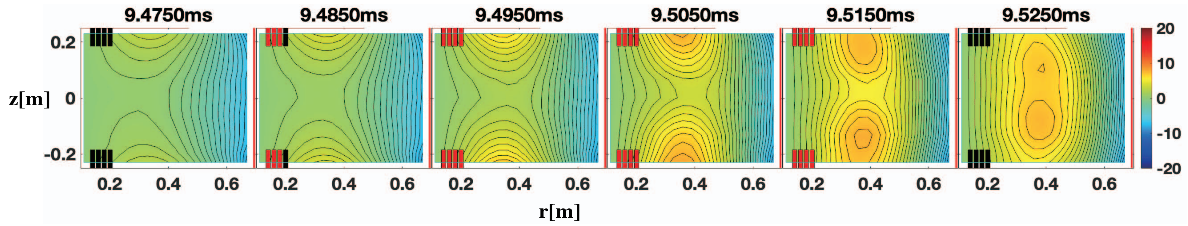

Fig. 2 Magnetic flux surfaces in UTST merging experiment (contour lines and color: magnetic flux). Black and red rectangles represent the pair electrodes installed in the inboard-side downstream region to control the static electric field.

erated static electric field mostly has the axial component (E_z) in the entire downstream region [7]. This static electric field is expected to grow until the parallel component of the inductive toroidal electric field is canceled by that of the static electric field, leading to the steady reconnection condition, in which the electric and magnetic fields are orthogonal in the downstream region. On the contrary, when the static electric field has not sufficiently grown yet, the plasma motion should be described as a combination of the $E \times B$ outflow and the parallel acceleration. The inductive and static electric fields have independent generation mechanisms; therefore, the plasma motion or the energy conversion process in the downstream region of a guide field reconnection could be controlled by changing the downstream electric condition. This study aims to develop the control scheme on the static electric field and to demonstrate its effectiveness.

The rest of the paper is organized as follows. Section 2 explains the measurement setup and the controlling equipment newly developed for this experiment. Section 3 presents the acquired results from the conducted experiment and discusses the role of the in-plane electric field. Section 4 summarizes this study.

2. Experimental Setup

The University of Tokyo Spherical Tokamak (UTST) [8] is the device designed to generate a high-beta spherical tokamak (ST) plasmas by merging start-up scheme. This scheme utilizes MR as a plasma heating method and is employed on several devices, such as TS-6 (The University of Tokyo) [9], MAST (UKAEA) [10], and ST-40 (Tokamak Energy Ltd.) [11].

The typical parameter of the UTST device is introduced below. Two initial STs are formed and merge with maintaining the up-down symmetry into one ST plasma with a major radius of 0.35 m and a minor radius of 0.25 m. Plasma current is 70 - 80 kA, and electron temperature is ~10 - 20 eV. The toroidal (guide) magnetic field in the UTST device is about 0.25 T at the magnetic axis, which is 10 - 20 times as large as the poloidal (reconnecting) magnetic field, providing high guide field reconnection condition particularly in the inboard-side downstream region.

Figure 2 shows the time evolution of the magnetic surfaces observed in the UTST device. Two STs formed at

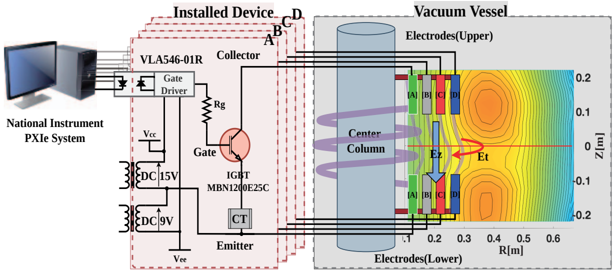

Fig. 3 Diagram of the control system that consists of four independent circuits. One switching device is connected between the upper and lower electrodes located at different radial positions. Electrodes are allocated at four toroidal angles with a 90-degree separation to hold the axisymmetric condition.

the upper and lower sections move toward the central section of the device, and one ST is finally formed through MR process, in which the reconnected magnetic fluxes flow out radially toward the inboard and outboard downstream regions, and the toroidal reconnection electric field is induced due to the time variation of poloidal magnetic flux in the downstream regions. It should be noted that the current flowing in the toroidal field coil mostly generates the toroidal guide magnetic field. A very high guide field condition is established in the inboard-side downstream region.

A preprogrammed control system was constructed to change the downstream boundary condition during the reconnection period of the merging start-up in the UTST device. Figure 3 shows the overall diagram of the constructed system. Four pairs of electrodes ([A][B][C][D]) are mounted on the center stack of the UTST device. Each pair of electrodes is connected to a switching semiconductor device (insulated gate bipolar transistor, IGBT), which has high rating voltage and rating current. The switching periods of the device from Close to Open and Open to Close are within 1 μs, which is sufficiently shorter than the period of the reconnection event of ~20 μs. This condition ensures a clear-cut experiment to investigate the impact of the electrode connection on the reconnection event. Assuming that the magnetic field configuration in the UTST device has an up-down symmetry, each pair of electrodes is located on the same magnetic field lines, as illustrated in Fig. 3. The corresponding magnetic field lines are in a short-circuit condition when the switching device is "Closed," whereas the field lines are not largely affected by the electrodes when the switching device is "Open." Thus, the boundary electric condition can be changed by making a "Close/Open" condition of specific magnetic field lines by controlling the connection of four electrode pairs aligned in a radial direction independently. It should be noted that all the electrode pairs are not always included in the downstream region due to the temporal change of the magnetic field structure. All the electrodes are in an "Open" condition before the initiation of the MR events and are sequentially switched to a "Closed" condition when the electrode pair enters the downstream region. In the case of a "Close operation," the preprogrammed "Close" timing for electrode pairs [A], [B], and [C] is 9480 μs, and electrode pair [D] is 9490 μs, respectively. All the electrodes are "Re-opened" at 9520 μs to examine how fields behave. On the other hand, all the electrode pairs keep to be in an "Open" condition in the case without "Close operation," corresponding to the reference case without artificial control.

Figure 4 shows the locations of the control/measurement system used in this study, together with the observed magnetic field structure measured using the two-dimensional pickup coil array indicated by the black points. As already mentioned, electrode pairs [A][B][C][D] are installed in the inboard downstream region. Red stars represent the positions for tungsten tips of Langmuir probes, measuring the difference of floating electric potential between the upper and lower tips to derive axial in-plane static electric fields (E_z) in the inboard-side downstream region from Eq. (1), where $\Delta\phi_p$ is the plasma potential difference and Δz is the distance between Langmuir probe tips. Assuming uniform T_e profile [6], the difference of plasma potential is approximated by the difference of floating potential $\Delta\phi_f$.

$$E_z = -\frac{\Delta\phi_p}{\Delta z} \sim -\frac{\Delta\phi_f}{\Delta z}. \tag{1}$$

The blue circles represent the position of pickup coils to measure axial magnetic field (B_z) with high spatial resolution. From the measured B_z, the induced toroidal electric field (E_t) is derived from Eq. (2), where ψ is the poloidal magnetic flux calculated from B_z.

$$E_t = -\frac{1}{2\pi r}\frac{d\psi}{dt}. \tag{2}$$

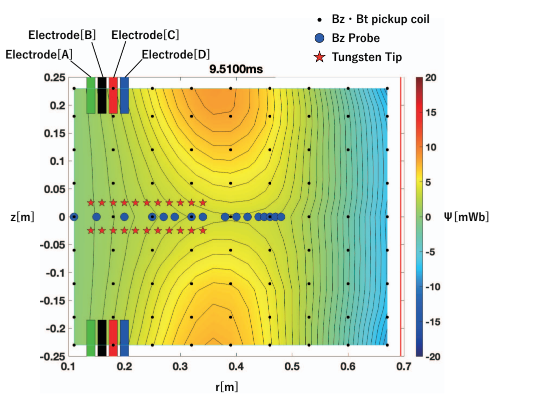

Fig. 4 Measurement system (red stars: tungsten tips of Langmuir probes; blue circle: pickup coils).

3. Experimental Results

Figure 5 shows experimental results from the cases with/without "Close operation." Figures 5 (a) and (b) shows the time variation of E_z radial profile measured at $z = 0$. The typical radial position of the X-point is about 0.35 m, and these figures show the in-plane electric field in the inboard-side downstream region. The in-plane electric E_z field was suppressed in the whole area of the inboard-side downstream region in the case with "Close operation." Figure 5 (c) shows the time evolutions of E_z in an Open case (black) and in a Close case (red) at $r = 200$ mm, where the maximum suppression of E_z was observed in a Close case. E_z in two cases showed approximately the same trend before the fast reconnection period ($t < 9490$ μs). The difference between the Close/Open cases stood out at 9496 μs during reconnection event, which is 6 μs after all electrode pairs were "Closed." The peak value of the in-plane E_z was reduced from 7.2 kV/m to 3.5 kV/m by the "Close operation."

Figures 5 (c) and (d) shows the evolution of the inductive toroidal electric field E_t at $r = 200$ mm and at the reconnection X-point. The absolute value of E_t at

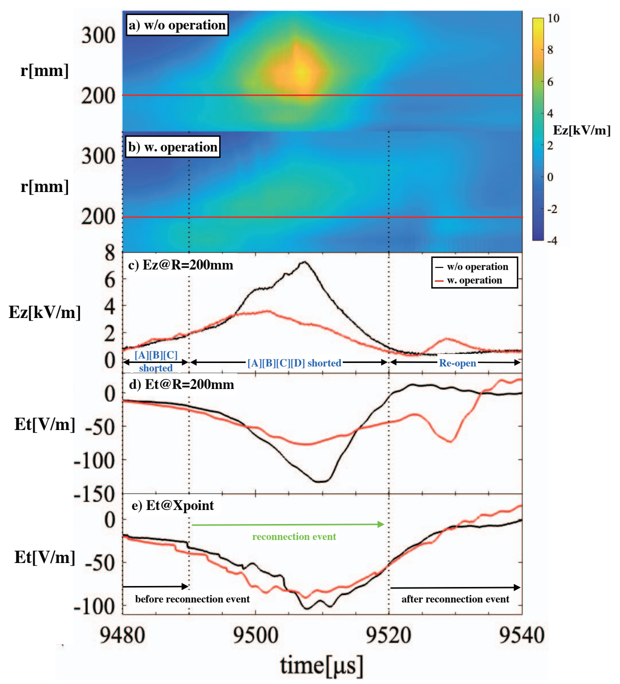

Fig. 5 Spatiotemporal plot of in-plane static electric field (E_z) (a) without and (b) with the "Close operation." Waveforms of (c) E_z at $r = 200$ mm and (d) inductive electric field (E_t) at $r = 200$ mm and (e) at the X-point.

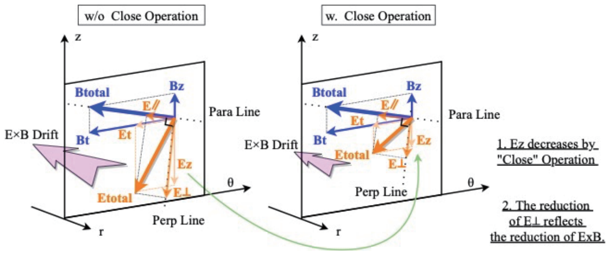

Fig. 6 Diagram for the indirect effect on the $E \times B$ outflow velocity by the in-plane static field E_z. Decrease of E_z reduces the electric field perpendicular to the magnetic field, resulting in the reduction of $E \times B$ outflow velocity.

$r = 200$ mm was suppressed from 132 V/m to 76 V/m by the "Close operation," corresponding to the suppression of E_z of the inboard-side downstream region, while a little difference in E_t was observed at the X-point throughout the reconnection event between cases with/without "Close operation." A significant decrease in E_t at $r = 200$ mm in the case with "Close operation" is considered to be caused by the reduction of static electric field E_z in the downstream region.

Since the in-plane electric field E_z is generated by the charge separation along the magnetic field lines, the "Close operation" is considered to change this charge separation condition. The release of the accumulated charge in the upper and lower sides of the downstream region will directly decrease in the in-plane electric field E_z, leading to the reduction of $E_\perp$ (see Fig. 6), which determines the steady plasma motion of $E \times B$ drift in the downstream region. It causes the reduction of the plasma flow in the downstream region, and E_t or the time variation of the poloidal magnetic flux is also decreased. From this consideration, it was concluded that the mutual relation between E_z and E_t is connected by the plasma motion as, suggested from the experimental results achieved by using the active control technique developed in this study.

As both E_z and E_t at $r = 200$ mm showed a reduction trend during short-circuiting period, re-growth trends of E_z and E_t at $r = 200$ mm were observed at ~5 μs after the "Re-open" operation of the electrode pairs. These results also suggest that the in-plane static field correlates with the inductive field, i.e., the plasma outflow velocity, which was recovered at the location where the short-circuit condition of the magnetic field lines was released.

Since the "Close" or "Re-open" operations take several microseconds to affect E_z and E_t on the controlled magnetic field lines, it may take even longer time to affect the reconnection velocity by the back propagation of the outflow slowing down from the downstream region to the X-point. The delayed response of the in-plane electric field may be due to the electron motion along the magnetic field lines that circulate around the center column many times. This will be discussed somewhere else in the future.

4. Summary

An experimental technique was developed to control the connection condition of the magnetic field lines in the downstream region. This technique successfully demonstrated that the in-plane electric field could be suppressed by "short-circuiting" the magnetic field lines. The inductive toroidal electric field was also reduced by the "short-circuit" operation. It was interpreted that the suppression of the static in-plane electric field would significantly reduce the perpendicular component of the electric field, resulting in the slowing down of the $E \times B$ outflow velocity and thus decreasing the inductive toroidal electric field based on Faraday's law because the poloidal flux change in the downstream region is slowed down.

The presented results will help to understand the global behavior of the MR in the existence of the high guide field. The relationship between the parallel electric field and the parallel current along the magnetic field lines in the downstream region should be investigated to clarify the observed delay of the response in the static in-plane electric field. Moreover, the measurement of the two-dimensional electron density profile is required for further understanding.

Acknowledgment

This work was supported in part by the NIFS collaboration NIFS18KBAR022, NIFS19KBAR027, and JSPS KAKENHI grant numbers JP20H01879 and JP20H00136.

[1] P.F. Chen and K. Shibata, ApJ **545**, 524 (2000).
[2] R.J. Hastie, Astrophys. Space Sci. **256**, 177 (1997).
[3] K. Yamasaki *et al.*, Phys. Plasmas **22**, 101202 (2015).
[4] J.-S. Yoo *et al.*, Phys. Rev. Lett. **110**, 215007 (2013).
[5] P.L. Pritchett and F.V. Coroniti, J. Geophys. Res. **109**, A01220 (2014).
[6] W. Fox *et al.*, Phys. Rev. Lett. **118**, 125002 (2017).
[7] M. Inomoto *et al.*, Nucl. Fusion **59**, 086040 (2019).
[8] M. Inomoto *et al.*, Nucl. Fusion **55**, 033013 (2015).
[9] H. Tanabe *et al.*, Nucl. Fusion **61**, 106027 (2021).
[10] H. Tanabe *et al.*, Nucl. Fusion **57**, 056037 (2017).
[11] M. Gryaznevich *et al.*, Nucl. Fusion **62**, 042008 (2022).