Development of a Quasi-Steady Equilibrium Field System for Plasma Merging ST Startup Experiments on the UTST Device

Hirotomo ITAGAKI, Michiaki INOMOTO, Shuji KAMIO, Qinghong CAO, Koichiro TAKEMURA, Kotaro YAMASAKI, Takenori G WATANABE and Takuma YAMADA

Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa 277-8561, Japan

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A novel equilibrium field (EF) system has been developed for use in the merging start-up of spherical tokamak (ST) plasma in the University of Tokyo Spherical Tokamak (UTST) device. Since the UTST device utilizes external poloidal field (PF) coils to form two STs on the top and bottom of the device by huge induction voltages, it is necessary to decouple the slow EF coil system from the fast-swing PF coils. A new EF system using electric double-layer capacitors was constructed and evaluated through the merging start-up experiment in the UTST. Using a very long duration of the EF current waveform and a thick magnetic shield successfully reduced the induction voltages from the PF coils and prolonged the equilibrium time constant.

Keywords: pulsed power supply, spherical tokamak, equilibrium field, plasma merging, high-beta tokamak

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1. Introduction

A Spherical Tokamak (ST) [1] is a low-aspect-ratio tokamak concept with a favorable confinement property and high beta limit, where the beta value is defined as the ratio of plasma thermal pressure to magnetic pressure. A high-beta ST increases the feasibility of creating an economically viable fusion power plant. However, it has a large technical difficulty with plasma current start-up since the ST facilities usually have a small space in the center of the device for the center solenoid (CS) coil. Various methods of non-inductive start-ups of ST plasma, such as RF current drive [2], coaxial helicity injection [3], and plasma merging [4], are intensively investigated worldwide in ST devices. The University of Tokyo Spherical Tokamak (UTST) [5] device has been designed for high-beta ST start-up using the plasma merging method in which magnetic reconnection [6] is utilized as an effective high-power heating source to establish high-beta equilibrium in a short period.

Prior merging ST experiments such as TS-3 [4], TS-4 [7], and MAST [8] utilized the internal poloidal field (PF) coils to form two initial ST plasmas in a short period; although, internal PF coils are not suitable for future fusion-relevant experiments. One of the unique features of the UTST experiment is that all PF coils are located outside of the thin conducting vacuum vessel to achieve conditions more realistic for a fusion reactor, as shown in Fig. 1. The swing of coil currents flowing in PF #1 and #4 coils will produce a toroidal electric field inside the vacuum vessel to initiate a torus. Very high loop voltages on the external PF coils are required to make a torus discharge across the conducting wall, but this requirement severely conflicts with the quasi-steady vertical equilibrium field (EF) coil and its power supply. In general, a long-pulse power supply with low voltage and high capacitance system has been used to generate quasi-DC equilibrium fields in combination with high-inductance coils. But the swing of external PF coil currents will generate huge induction voltages on the EF coils due to the large mutual inductance between the PF and EF coils. This induction voltage will easily exceed the rated voltage of the EF power supply or the

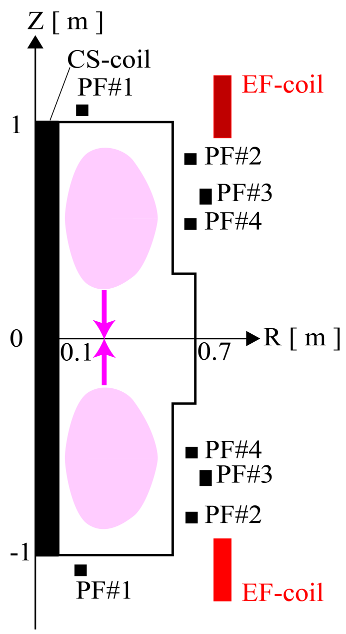

Fig. 1 Schematic of the UTST system.

author's e-mail: itagakihirotomo@ts.t.u-tokyo.ac.jp breakdown voltage of the insulator between coil windings, which might cause a serious system malfunction.

In this paper, we present a newly-developed EF system for plasma merging ST start-up experiments at the UTST; a multi-turn EF coil with a thick magnetic shield, a very-long-pulse power supply using electric double-layer capacitors (EDLCs) [9], and insulated gate bipolar transistors (IGBTs). The huge capacitance of EDLCs enabled us to construct a quasi-steady power supply system with high current and long duration in spite of their relatively low voltage and current ratings and higher internal resistance in comparison with other types of capacitors.

2. Development of Long Pulse EF System

The UTST device is currently in the preliminary experimental stage and operated with a very short pulse length (< 1 ms) with peak plasma current < 150 kA [5]. The next upgrade in the power supply system is scheduled to achieve ST discharge with plasma currents > 200 kA and flat-top times > 10 ms for neutral beam injection heating with 2 MW injection power. Thus, development of a new EF system was required to accomplish the following: (a) flat-top durations > 50 ms, (b) EF-current > 50 kA-turn, with a repetition time of 5 min. To achieve this high repetition rate, (c) the heat generation at the coil should be reduced < 100 kJ to keep the coil temperature within + 5 K from the room temperature on the assumption that the heat transfer coefficient of the coil is 10 $\mathrm{Wm^{-2}K^{-1}}$. The EF system should also be protected from huge induction voltage by external PF coils in the formation phase. The permissible induced terminal voltage is 1 kV (d) due to the DC voltage limit of the EDLC. These requirements for the EF system are summarized in Table 1, and were satisfied by using three EDLCs with capacitances of 29.4 F, with voltage and current ratings of 100 V and 600 A, respectively. These EDLCs are connected in series to have a total capacitance of 9.8 F and a voltage rating of 300 V.

Effective drive conditions for the EF coil were established when the ratio of the voltage and current ratings of the EDLCs matched the ratio of charged voltage and maximum current flowing in the LCR circuit [10], which consists of the EF coil inductance, EF coil resistance and the EDLC capacitance. To achieve a maximum current of 600 A for a charging voltage of 300 V, we designed the EF coils as follows: the two EF coils (on the top and bottom of the UTST device) were connected in parallel, and each EF coil consisted of six parallel-connected coils with 200-turn windings of copper wire with a diameter of 1/8 inch. The estimated inductance and resistance of the whole EF coil system was 75 mH and 0.2 Ω, respectively. Since the EF coil had a large inductance and resistance, the EDLC's relatively large internal resistance of about 60 mΩ had no large impact on the system.

Figure 2 shows the circuit diagram of the developed power supply using three EDLCs and four IGBTs whose current and voltage ratings are 200 A and 1.2 kV, respectively. It was necessary to turn off the switch after the required discharge period in order to save the stored energy and suppress heat generation in the coil. To reduce the surge voltage, four diodes were inserted in parallel with the EF coils to reflux the current flowing in the EF coils after the IGBTs were turned off. The LCR circuit showed monotonic damping conditions with a maximum current of about 600 A for a charging voltage of 300 V. In this circuit, more than 80% of the energy stored in the EDLCs remained after a discharge with 0.6 s pulse width, resulting in a small heat generation of about 60 kJ (in other words, an estimated temperature increase of 0.2 K per discharge) in the EF coils.

Another requirement for the UTST EF system was the decoupling from the fast-rising PF coil system. Since the EDLC has much larger capacitance than conventional capacitors, it was suitable to construct a pulsed power supply with a rise time of several seconds in order to separate it from the time constant of the PF coil current. The PF coils (3 turns) for ST formation are usually energized by the capacitor banks with a charging voltage of more than 12 kV, which might induce several hundred kV of electromotive force on the EF coils (200 turns). For practical use of the EDLC-EF system, the induction loop voltage of the EF coil should be suppressed lower than 1 V, otherwise the total induced electromotive force will exceed the rating voltage of the EDLCs. In order to shield the induction from the PF coil current swing, the EF coils are wound on aluminum bobbins 1-cm-thick and are covered with aluminum plates 2-mm-thick, as shown in Fig. 3. The thickness of the bob-

Table 1 Requirement for the EF system.

(a) EF current	> 50 kA-turn
(b) Flat-top time	> 50 ms
(c) Heat generated at coil	< 100 kJ/discharge
(d)Induced terminal voltage	< 1 kV

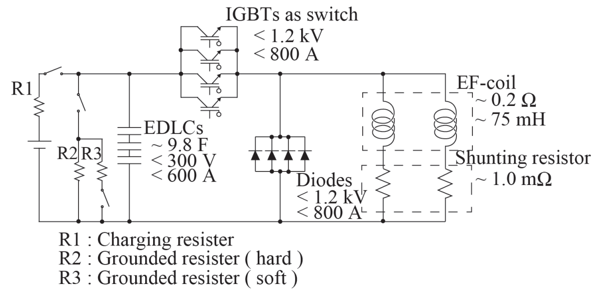

Fig. 2 The circuit diagram of the developed power supply using three EDLCs and four IGBTs.

bins and the cover plates were determined by a finite element method with an assumption of PF coil current (80 kA and 1 kHz). The averaged induced loop voltage on the EF coil was sufficiently reduced lower than 1 V by the thick magnetic shield. The EF coil consists of six coils connected in parallel, and each coil has a winding of 200 turns in 21 layers. A numerical finite element computation predicted that these aluminum shields sufficiently suppressed the induction voltage from the PF coil current swing much smaller than the EDLC or IGBT voltage ratings.

Figure 4 shows the experimental results of EDLC voltage and EF coil current waveforms. Here, the EDLC power supply was charged to 300 V and the IGBT switches were turned on for 0.6 s. The current reached 280 A (or 56 kA-turn) with a flat top duration of about 0.3 s, which is enough to sustain the UTST plasma with a 200 kA plasma current for a duration of several tens of milliseconds. No significant increase in the coil temperature was observed by a radiation thermometer after successive discharges within a 5 min interval.

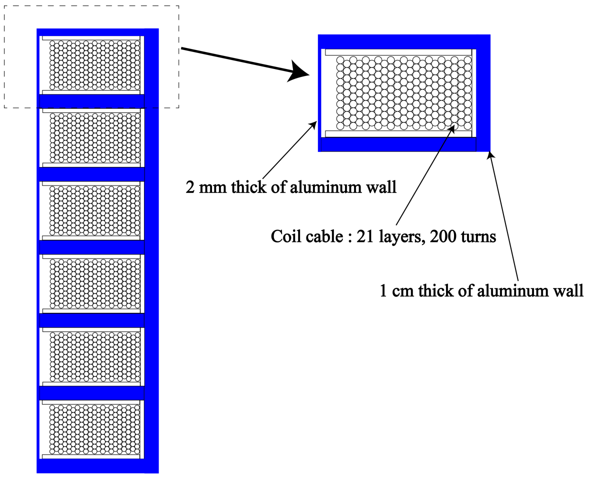

Fig. 3 System diagrams of the newly EF coil.

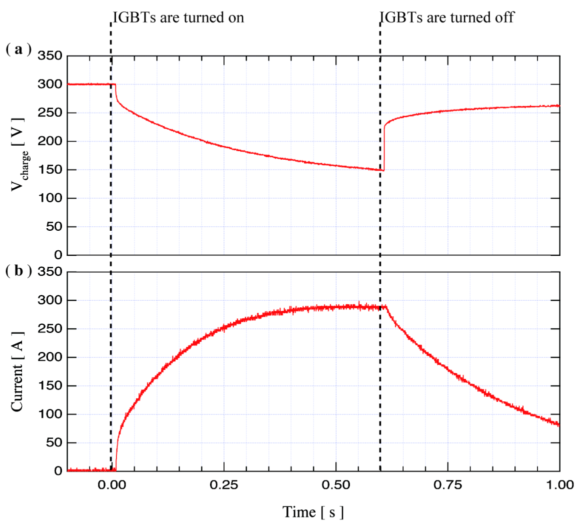

Fig. 4 Time evolution of (a) voltage of EDLCs and (b) current through EF-coil.

3. Performance of the Developed EF System

Besides a TF coil, the UTST device has a CS coil and four sets of PF coils, which are coaxially-arranged and could strongly couple with the EF coil. PF coils #1 and #4 were employed to form two initial STs by the double null merging method [5]. After the formation of two STs, PF coil #2 was energized to accelerate them for the mid-plane of the device to merge. A CS coil was used to drive plasma current of the ST. Figure 5 (a) shows the typical waveforms of PF-coils #1 and #4 (connected in parallel), the CS-coil, and I_p (plasma current). The rapid swing-down of the PF coil current induced the torus discharge on the top and bottom of the device. The two STs merged into one large ST through magnetic reconnection and then its plasma current was amplified to > 100 kA by the CS coil. The red curve in Fig. 5 (b) shows the current waveform of the developed EF system, which shows temporal variation caused by the swing of the PF coil currents, but its influence was < 10% of the quasi-steady value of the EF coil current. Table 2 shows the maximum loop voltages of the PF #2, PF #4, and CS coils with their observed induction loop voltages on the EF coil. The thick magnetic shield largely miti-

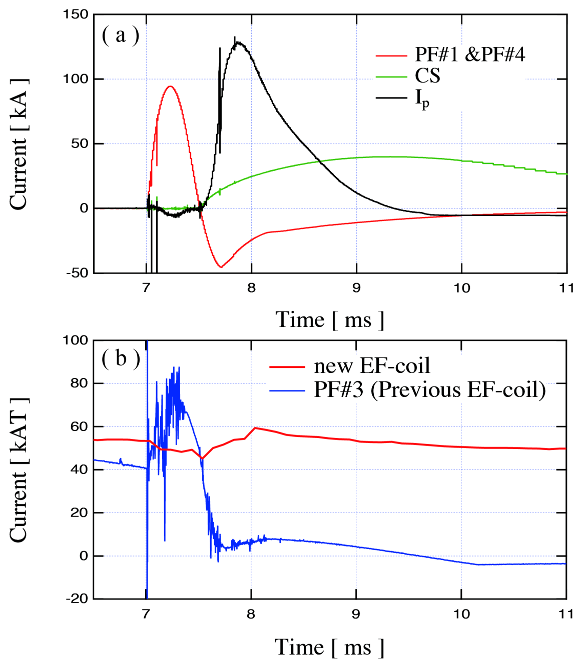

Fig. 5 (a) Time evolution of typical waveforms from the PF coils #1 and #4, the CS-coil, and the plasma current. (b) Time evolutions of a current waveform from the EF-coil utilized for this experiment and the current waveform of PF#3 when it utilized for past experiment.

Table 2 Maximum loop voltages of PF coils and observed induction loop voltages on the EF coil.

	Maximum loop voltage [V]	Induction loop voltage on the EF coil [V]
PF#4-coil(3 turns)	4000	< 0.1
PF#2-coil(3 turns)	2600	< 0.1
CS-coil(110 turns)	36	< 0.09

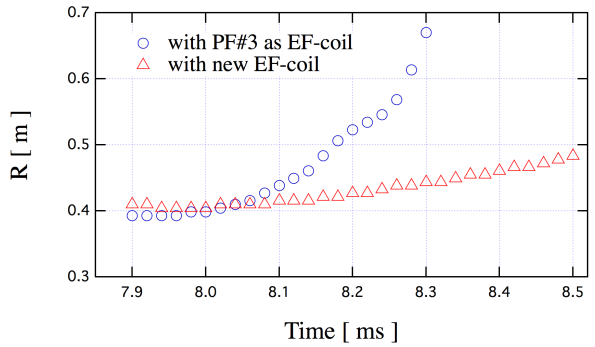

Fig. 6 Time evolutions of the radii of the ST's magnetic axis with the vertical equilibrium field generated by the developed EF system (red triangles) and by the PF coil #3 (blue circles).

gated the induction voltages < 0.1 V, which corresponded to 20 V on the EF coil terminals.

The PF #3 coil (8 turns without magnetic shield) was also utilized to apply the vertical equilibrium field. The blue curve in Fig. 5 (b) shows the current waveform of the PF #3 coil when it was utilized in place of the developed EF system. The PF #3 coil current was severely disturbed by the induction from the PF #1 and #4 coil currents due to their large mutual inductance. This disturbance on the equilibrium coil current gives a fatal impact on the sustainment of the ST plasma formed by the merging method. Figure 6 shows the time evolution of the radii of the ST's magnetic axis with the vertical equilibrium field generated by the EF system and by the PF coil #3. The magnetic axis of the ST with the equilibrium field generated by the PF coil #3 rapidly increased, which is caused by the reduction of the PF #3 coil current by the induction from PF #1 and #4. On the other hand, the ST with an equilibrium field generated by the EF system was sustained steadily for > 0.5 ms in spite of the large induction from the PF coils.

The developed EF system showed good performance and was able to generate a quasi-steady equilibrium field without introducing errors and malfunctions in the present UTST operating regime. The performances of the developed EF system are summarized as follows:
(a) EF current: 56 kA-turn,
(b) Flat-top time: 300 ms,
(c) Heat generated at coil: 60 kJ/discharge,
(d) Induced terminal voltage: < 200 V.

4. Summary

A novel EF system was developed and evaluated. The EF system consists of the multi-turn EF coils with thick magnetic shields and a quasi-steady EDLC power supply, which were necessary to decouple the EF coil from the fast-swing PF coils. The system could provide a quasi-steady equilibrium current with a flat-top duration of 0.3∼0.4 s. The induction voltages from the PF coils were suppressed to be < 20 V, which were small compared with the EDLC voltage rating of 300 V. The effectiveness of the system was confirmed through the ST merging formation experiment. The formed ST was sustained appropriately without severe perturbations from the induction voltages of the PF coils.

Acknowledgments

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