Expansion of the Operation Region of Tokamak Plasmas Using the Stationary Direct Current of a Central Solenoid*)

Osamu WATANABE, Hibiki YAMAZAKI, Yongtae KO, Kotaro IWASAKI and Naoto TSUJII

The University of Tokyo, Kashiwa 277-8561, Japan

(Received 3 December 2020 / Accepted 21 February 2021)

A stationary direct current of a central solenoid (DC_{CS}) can expand the operation region of tokamak plasmas. For tokamak plasma formation experiments using electron cyclotron heating (ECH) alone, the minimum ECH power and plasma current necessary for tokamak plasma formation were reduced using the DC_{CS}, which was applied in the counter rotational direction to the plasma current. In TST-2, the minimum ECH power necessary for the formation of a tokamak plasma was reduced from 3.3 to 1.6 kW when the DC_{CS} was changed from 0 to 184 A. Simultaneously, the plasma current that was needed to sustain the tokamak plasma configuration was reduced to 0.6 kA.

Keywords: tokamak plasma formation, electron cyclotron heating, stationary direct current of central solenoid, operation region of tokamak plasma

DOI: 10.1585/pfr.16.2402059

1. Introduction

On the TST-2 spherical tokamak device [1, 2], tokamak plasma formation by non-inductive heating has been studied using RF heating at 2450, 200, and 21 MHz [3–6]. In the tokamak plasma formation experiments by the 2450 MHz heating, the dependences of tokamak plasma formation on the n-index and injection with O- and X-modes were studied [3]. For the non-inductive heating experiments using the 200 MHz, several new antennas were developed [4, 5] to improve the toroidal plasma current drive efficiency. By heating at 21 MHz, the minimum heating energies necessary for tokamak plasma sustainment were compared between hydrogen and deuterium plasmas [7].

The possibility that a stationary direct current applied to a central solenoid (DC_{CS}) can improve the tokamak plasma stability was described theoretically [8, 9]. The tokamak plasma configuration determined by the vertical magnetic field structure at the plasma region is almost the same with or without the DC_{CS}. This is because a solenoid current (CS) ideally has little leakage magnetic field out of the CS region. As an indirect verification of this theoretical prediction, tokamak plasma formation experiments were performed with a DC_{CS}. Tokamak plasma formation at the same vertical magnetic field should change when a DC_{CS} is applied if the tokamak plasma stability depends on the DC_{CS}.

In the present paper, the tokamak plasma formation experiments using 2450 MHz electron cyclotron heating (ECH) alone were compared to discharges with and without DC_{CS}. The parameters used for tokamak plasma formation experiments at $DC_{CS} = 0$ A by ECH alone are explained using the waveforms of typical discharge in Section 2. In Section 3, the ECH power scan of the tokamak plasma formation with $DC_{CS} = 184$ A by ECH alone are presented. The results are discussed in Section 4, and conclusions are provided in Section 5.

2. Typical Discharge of Tokamak Plasma Formation by ECH Alone

In this paper, all parameters, except the ECH power and DC_{CS}, are common to all discharges. Figure 1 shows the $DC_{CS} = 0$ A cases. The poloidal field coils were connected in series, and a contentious direct current of 30 A/wire turn was applied by a switching DC power supply. The toroidal field coil current was a discharge current from a capacitor bank, as shown in Fig. 1 (A). The ECH power was constant in time and was measured at an incident waveguide as the forward power, as shown in Fig. 1 (B). Figure 1 (C) shows the time evolution of the toroidal plasma currents. The ECH power was scanned down from 4.89 kW, as indicated by the green line (SN171231). The power threshold for tokamak plasma formation was between 3.32 kW (blue line: SN171240) and 3.26 kW (red line: 171242). The start of the current jump was accelerated by the increase of ECH power. The maximum toroidal plasma current, which was 1.2 kA, depended little on the ECH power. When the ECH power was insufficient, a toroidal current jump was not observed, as indicated by the red line (SN171242) in Fig. 1 (C).

author's e-mail: rrwata@gmail.com

*) This article is based on the presentation at the 29th International Toki Conference on Plasma and Fusion Research (ITC29).

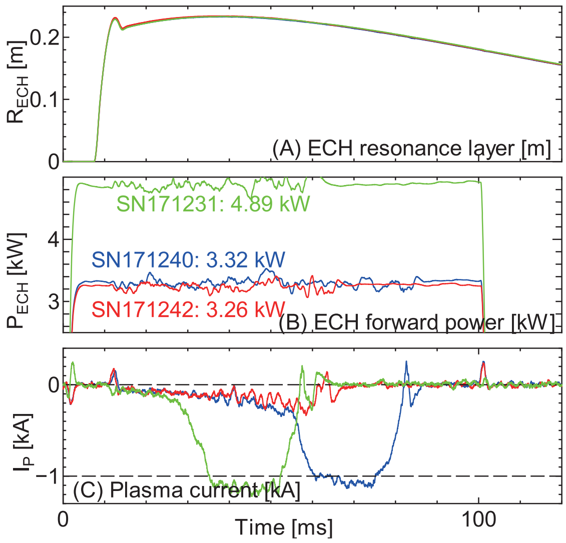

Fig. 1 Typical discharge waveforms when $DC_{CS} = 0$ A. (A) ECH resonance layer radius, (B) power, and (C) plasma current. The red, blue, and green lines indicate SN171242 (P_{ECH} = 3.26 kW), SN171240 (P_{ECH} = 3.32 kW) and SN171231 (P_{ECH} = 4.89 kW), respectively.

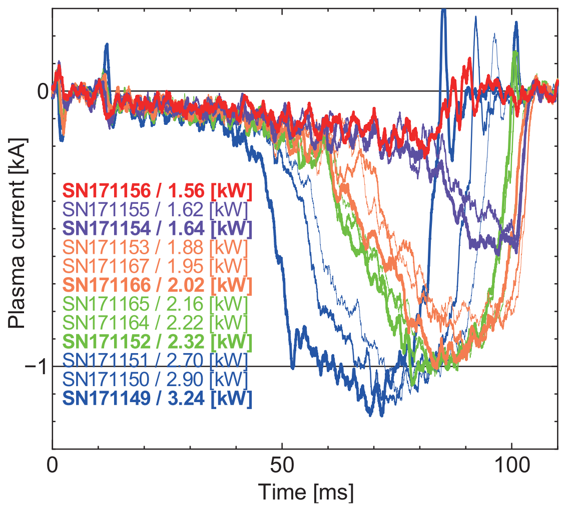

Fig. 2 ECH power scan for tokamak plasma formation with DC_{CS} = 184 A. The maximum toroidal plasma current is gradually reduced by decreasing the ECH power. The current jump was not obtained when the ECH power is reduced to 1.56 kW (red line).

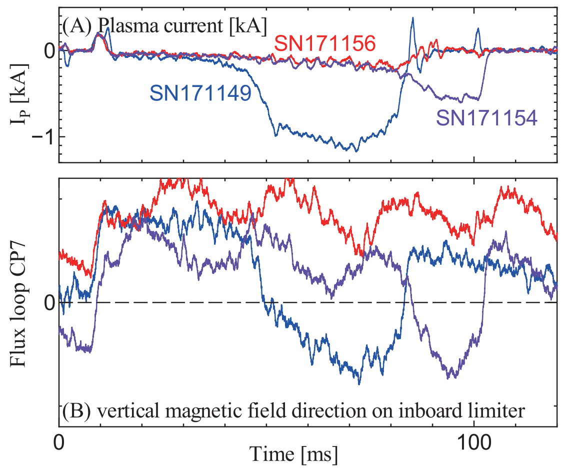

Fig. 3 Confirmation of tokamak plasma formation by a small toroidal plasma current. (A) Plasma current and (B) vertical magnetic field measured by a probeon the inner limiter near the midplane. The plasma current of SN171149 (blue: P_{ECH} = 3.24 kW) and SN171154 (purple: P_{ECH} = 1.62 kW) reached 1.2 and 0.6 kA, respectively. SN171156 (red: P_{ECH} = 1.56 kW) did not have a current jump.

3. Effect of DC_{CS} on Tokamak Plasma Formation by ECH

Tokamak plasma formation by 2450 MHz heating alone was studied with DC_{CS} = 184 A. The DC_{CS} was applied in the counter rotational direction to the plasma current by a switching DC power supply. Compared to when DC_{CS} = 0 A, the current jump was similarly obtained at a lower ECH power when DC_{CS} = 184 A.

Figure 2 shows the time evolution of the toroidal plasma current for the ECH power scan. When ECH power was decreased from 3.24 kW (blue bold line: SN171149) to 1.88 kW (thin orange line: SN171153), the maximum plasma current gradually decreased from 1.2 to 0.85 kA and the current jump was delayed. Around an ECH power of 1.6 kW (purple lines: SN171154 and SN171155), the maximum toroidal plasma currents appeared to step down to less than 0.6 kA. At an ECH power of 1.56 kW, shown by the red line (SN171156) in Fig. 2, the plasma current gradually increased until 80 ms but the current jump was not possible.

To confirm tokamak plasma formation with small toroidal plasma current for SN171154 (purple bold line) indicated in Fig. 2, the magnetic probe signals are indicated by purple lines (SN171154) in Figs. 3 (A) and (B). The probe measures the vertical magnetic field near the midplane (height z = 0.05 m) on the inner limiter (radius R = 0.12 m). Signals for SN171149 (blue) and SN171156 (red) are also indicated in Fig. 3 as the typical tokamak plasma formation case and the failed case, respectively. SN171149 (blue) and SN171154 (purple) show the current jump, and the vertical magnetic fields rapidly changes during the current jump for both cases, as shown in Fig. 3 (B). In contrast, SN171156 (red line) had no current jump in (A), and the vertical magnetic field does not show reversal.

4. Discussion

The minimum ECH power necessary for tokamak plasma formation with a plasma current of 1 kA on the TST-2 was halved when DC_{CS} = 184 A was applied to the 239-turn central solenoid. For non-inductive heating tokamak plasma formation, the decrease of the power threshold by DC_{CS} assistance is easier than enhancement by other

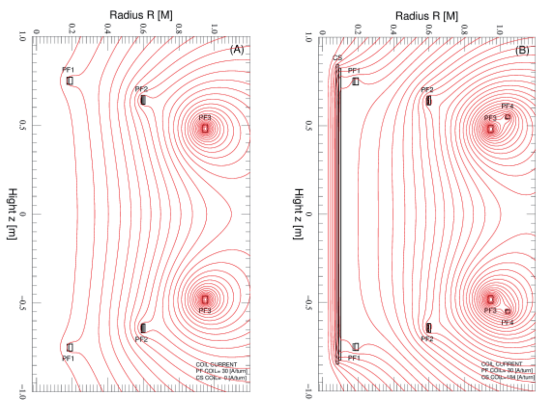

Fig. 4 Difference of the magnetic field structure before tokamak plasma formation (A) without DCCSand (B) with DC_{CS} = 184 A. A pair of PF4 coils in (B) are cancel coils connected to the CS in series. PF1-3 are connected in seriesand carry 30 A/wire turn. The turn number of PF1, PF2, PF3, PF4, and CS are 6, 9, 16, 1, and 239, respectively.

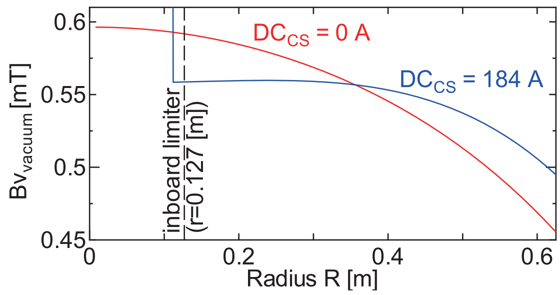

Fig. 5 Vertical magnetic field profiles BVvacuum generated by coil currents on the midplane with and without the DC_{CS} = 184 A. Dashed line is the radius of the inner limiter. On the limiter, the vertical magnetic field with the DC_{CS} = 184 A is 10% lower than the one without the DC_{CS}.

heating power sources. DC_{CS} without temporal change would also be safe to use with very low power in superconducting magnet coils. And, this usage is also convenient to other tokamak devices.

The leakage magnetic field of the CS may reduce the minimum power necessary for tokamak plasma formation in two different ways. One way is by the decrement of the vertical magnetic field [10, 11], and the other way is by the *n*-index change [3].

The magnetic flux surfaces generated by coil currents with and without DC_{CS} = 184 A are shown in Figs. 4 (A) and (B), respectively. The magnetic flux surface near the CS becomes slightly inward convex when DC_{CS} = 184 A. However, in previous experiments in TST-2, it was more difficult to close flux surfaces at lower *n*-index values.

In Fig. 5, vertical magnetic field profiles on the midplane with and without DC_{CS} = 184 A and before tokamak plasma formation. The vertical magnetic field with DC_{CS} = 184 A on the inner limiter is 10% lower than that without DC_{CS}. This may lead to the formation of closed magnetic flux surfaces at 10% lower plasma current at DC_{CS} = 184 A compared to when DC_{CS} = 0 A.

An equilibrium tokamak plasma with a small plasma current sustained by lower power heating should have small major radius and small minor radius. Therefore, the ECH resonance layer length inside the last closed flux surface becomes small and the heating efficiency worsens. To sustain the equilibrium tokamak plasma, it is necessary that the heating energy required for the increase of plasma current exceeds the energy loss that accompanies the reduction of the plasma current. The amount of magnetic field energy in the CS region depends on the plasma current, that can be changed by the DC_{CS} [8, 9]. Consequently, the energy necessary for tokamak plasma formation is modified. As a result, an equilibrium tokamak plasma with small plasma current and small major radius might become sustainable at a lower heating power.

The 50% reduction in the minimum ECH power necessary for tokamak plasma formation is likely due to a combination of these effects [3, 9–11].

5. Conclusions

The ECH power necessary for tokamak plasma formation could be reduced by DC_{CS}. The DC_{CS} expands the operating region of the tokamak plasma into a region that can be sustained at a lower plasma current.

Acknowledgment

The authors would like to thank Prof. Yuichi Takase and Prof. Akira Ejiri for providing the opportunity to perform this experiment on TST-2. Additionally, the authors would like to thank the members of the TST-2 team and graduate students of Takase-Ejiri laboratory, especially, Dr. Hirokazu Furui.

[1] Y-K.M. Peng *et al.*, Nucl. Fusion **26**, 6, 769 (1986).
[2] Y. Takase *et al.*, Nucl. Fusion **41**, 11, 1543 (2001).
[3] J. Sugiyama *et al.*, Plasma Fusion Res. **3**, 026 (2008).
[4] T. Shinya *et al.*, Nucl. Fusion **55**, 7, 073003 (2015).
[5] S. Yajima *et al.*, Nucl. Fusion **59**, 6, 066004 (2019).
[6] A. Ejiri *et al.*, Nucl. Fusion **49**, 6, 065010 (2009).
[7] O. Watanabe *et al.*, Plasma Fusion Res. **3**, 049 (2008).
[8] O. Watanabe, Plasma Fusion Res, **8**, 2401026 (2013).
[9] O. Watanabe, J. Phys. Soc. Jpn. **85**, 9, 094503 (2016).
[10] S.H. Müller *et al.*, Phys. Rev. Lett. **93**, 16, 165003 (2004).
[11] T. Maekawa *et al.*, Nucl. Fusion **52**, 8 083008 (2012).