Investigation of compact toroid penetration for fuelling spherical tokamak plasmas on CPD

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Abstract. In previous Compact Toroid (CT) injection experiments on several tokamaks, although CT fuelling had been successfully demonstrated, the CT fuelling process has been not clear yet. We have thus conducted CT injection into simple toroidal or vertical vacuum magnetic fields to investigate quantitatively dynamics of CT plasmoid in the penetration process on a spherical tokamak (ST) device. Understanding the process allows us to address appropriately one of the critical issues for practical application of CT injection on reactor-grade tokamaks. In the experiment, the CT shift amount of about 0.26 m in a vertical magnetic field has been observed by using a fast camera. In addition to toroidal magnetic field, vertical one appears to affect CT trajectory in not conventional tokamak but ST devices operated at rather low toroidal fields. We have also observed CT attacks on the target plate with an IR camera. The IR image has indicated that CT shifts 39 mm at the toroidal field of 261 G. From the calorimetric measurement, an input energy due to CT impact in vacuum without magnetic fields is also estimated to be 530 J, which agrees with the initial CT kinetic energy.

1. Introduction

A compact toroid (CT) injection has been proposed as a method of direct fuelling the central plasma in a fusion reactor [1]. The experimental demonstrations have been successfully conducted on several tokamaks [2-11]. The new technology for CT injection has been researched and developed to enhance CT injection performance [12-14].

Recently in Japan, CT injection experiment has been performed on the Compact Plasma wall interaction experimental Device (CPD) in Kyusyu University to study on advanced fueling into Spherical Tokamak (ST). The purposes of the experiments are as follows; 1) Development of refueling method into the core plasma in a reactor with researching interaction between a high-temperature plasma and a CT plasmoid (magnetic reconnection, helicity conservation, excitation of waves), 2) Investigation of ability of ST plasma start-up by CT injection, 3) Drive of plasma flow by tangential CT injection on a poloidal or toroidal plane in ST to promote the development of the research of two-fluid effects on high-β ST plasmas. The UH-CTI (the former HIT-CTI) of a CT injector, the power supplies and the related equipment [15,16], which had been used for CT injection on JFT-2M, were moved from Japan Atomic Energy Agency (JAEA, formerly JAERI) to the Advanced Fusion Research Center in Kyusyu University in 2005. Withstand voltage tests on the power supply units and bench tests of the CT injection system were successfully conducted. Performance tests were also carried out in a stand-alone set of CT injector. The currents of CT formation and acceleration have reached the rated currents of 350 kA and 400 kA, respectively, resulting in successful CT formation and acceleration. Here, in simple theory [1], the central penetration of a CT into a ST plasma requires that the kinetic energy density of the CT $D_{\mathrm{CT,E}}$ should exceed the magnetic energy density of the toroidal field $W_\mathrm{B} = B_\mathrm{T}^2/2\mu_0$ at the ST plasma center. The kinetic energy density for deuterium CT plasma was investigated by varying the charging energy storage capacity of the CT accelerator bank ($E_{acc.}$) [16]. For the UH-CTI, the average $D_{CT,E}$ at $E_{acc.}$ > 12 kJ ($V_{acc.}$ = 16 kV) exceeds $B_T^2/2\mu_0$ = 36 kJ m^{-3} under typical conditions of B_T = 0.3 T on CPD. The CT injector, thus, has performance enough to inject CT plasmas deeply in CPD. Figure 1 shows the CPD device and the CT injector installed perpendicularly to the magnetic axis on the midplane. Profiles of the toroidal field (TF) at currents of 10 kA and 70 kA, and contour lines of the vertical field generated by the poloidal field coil (PF) 1,7 and 2,6 at 4 kA are also shown. In the experiment our primary focus is on the investigation of dynamics of CT plasmoid in the penetration process on the ST device. CT fuelling process has been not clear yet, although CT fuelling has been studied in several tokamaks. Understanding the process is one of the critical issues for practical application of CT injection. Thus, for simplicity, CT injection into toroidal or vertical vacuum magnetic fields has been conducted. This paper describes such CT penetration into CPD

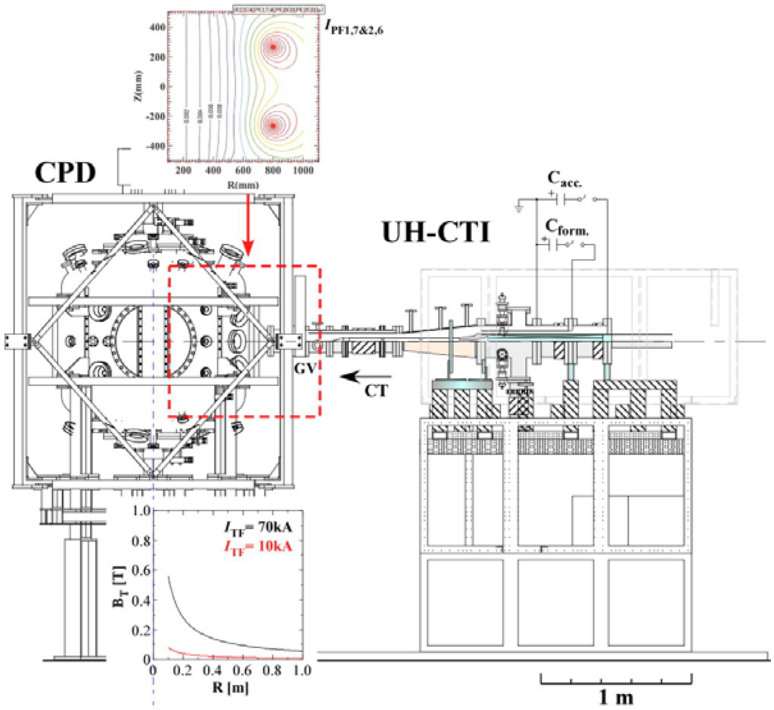

FIG.1 Experimental setup of UH-CTI and CPD including toroidal field (TF) profiles at the coil currents of 10 kA and 70 kA and contour lines of poloidal field by the PF1,7 and 2,6 coil at 4 kA .

2. Experimental setup

Experiments to investigate CT penetration in CPD have been conducted using a fast camera (HPV-1, 1 μs x 100 frames) and an infrared (IR) camera (TVS-700, 8-14 μm). The experimental measurement systems are shown in fig.2. The fast camera is mounted on the window port at the angle-A and B, and the IR camera is at B, C and D. The ports at the angle-B, C and D are positioned on the midplane, but that at the angle-A inclines 35.2 degrees down from the midplane. The fast camera provides visible images of CT and its trailing plasmas penetrating into CPD. The IR camera detects temperature variations on target plates made of 304 stainless steel with thicknesses of 1.4 mm and 0.2 mm. Their respective positions are at *R*= 230 mm and 450 mm in front of the CT injection port in CPD. The plate facing to injected CTs at *R*= 230 mm can be captured from the angle-D, and the back shot of the plate at *R*= 450 mm can be taken from the angle-B. For the calorimetric measurement of CT kinetic energy on the target plates, the data have been calibrated since the 304 SS plates have a low emissivity [17]. At the angle-C the IR camera monitors the W-limiter (R= 0.13 m) wound around the center stack (CS) of CPD. CT parameters are also monitored at P3 and P4 with the magnetic probes and the He-Ne laser interferometer. The parameters can be controlled by varying the voltage for accelerator bank $V_{acc.}$ and that for the bias poloidal coil bank V_{bias} [15]. That for the formation bank $V_{form.}$ is set at 12 kV.

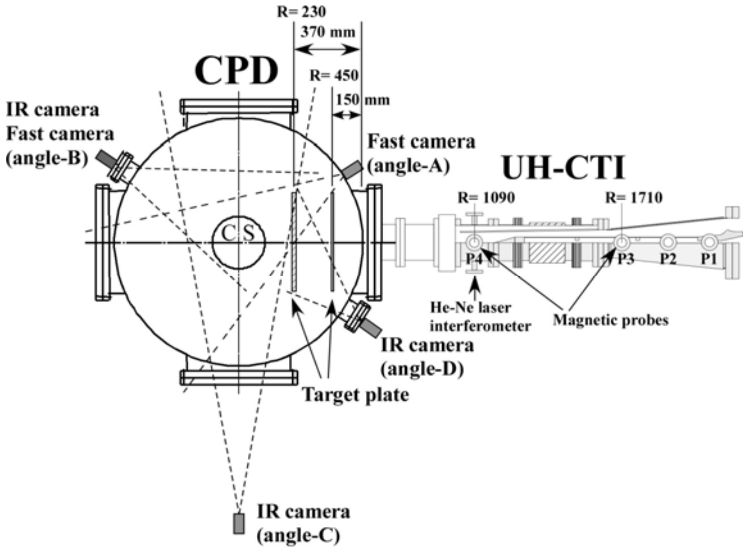

FIG. 2 Top view of CPD and UH-CTI. The window ports at the angle-B, C and D are positioned on the midplane. The port at the angle-A inclines 35.2 degrees down from the midplane.

3. Experimental results and discussions

Initially, experiments to observe CT penetration into vacuum magnetic fields were performed using the fast camera. We obtained visible images of CT and its trailing plasmas injected into toroidal and vertical fields. In figure 3, as a reference shot, each frame of the movie data taken at the angle-B shows CT injection in a vacuum without magnetic fields; (a) a CT plasmoid ejected from the injection port has just reached the W-limiter, and then (b) goes around and behind that. The CT was fired at V_{bias}= 0.6 kV, $V_{form.}$= 12 kV and $V_{acc.}$= 27 kV. Here, the speed of the traveling CT is calculated to be 192 km s^{-1} by time of flight between P4 at the nozzle of the CT injector and the W-limiter. The time of CT attack on the limiter can be determined from the frame number of the movie.

We monitored the W-limiter with the IR camera at angle-C which is 90 degrees in a clockwise direction away from the CT injection port. The observed IR images with scanning $V_{acc.}$= 0 to 27 kV at V_{bias}= 0.7 kV, and that at $V_{acc.}$= 27 kV and V_{bias}= 0.6 kV for comparison are shown in fig.4. This indicates that a CT

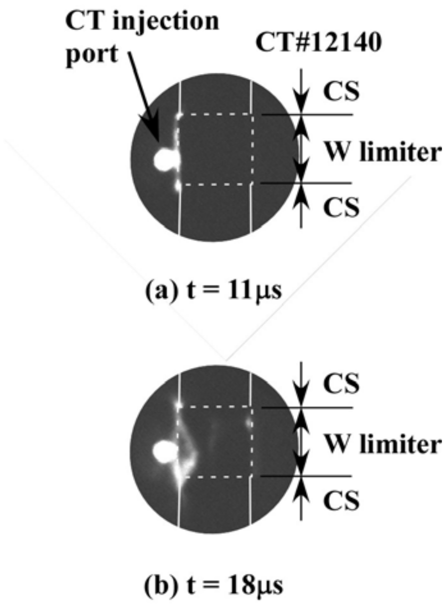

FIG.3 Visible images of a CT penetrating into a vacuum without magnetic fields. The observation port at the angle-A is 32.5 degrees apart from the CT injection port

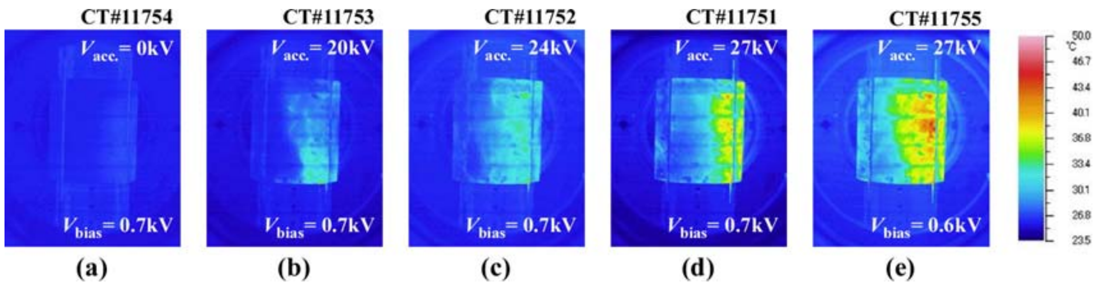

FIG. 4 Observed IR images on the W-limiter with scanning $V_{acc.}$ at the angle-C.

with higher kinetic energy by increasing $V_{\mathrm{acc.}}$ or decreasing V_{bias} impacts on the limiter, leading to rise in temperature on the surface. The details of the heat load measurements on the W-limiter have been reported in ref. [18].

The fast camera at the angle-A also provides movies of CT penetrating into toroidal and vertical fields. In the CT injection at V_{bias}= 0.6 kV, $V_{\mathrm{form.}}$= 12 kV and $V_{\mathrm{acc.}}$= 27 kV, a frame of the movie data shows that, in vacuum without the magnetic field, CT plasma travels in a straight line to collide head-on the W-limiter in fig.5(a). On the other hand, in fig.5(b) for CT penetration into a vertical magnetic field, the direction of which is from the bottom to the top of CPD ($I_{\mathrm{PF1,7\&2,6}}$= -4 kA), the frame shows that a CT plasmoid is grazing by the right side of the limiter. Thus CT plasmoid penetrates into the vertical magnetic field with horizontal shift to right. In the opposite vertical field ($I_{\mathrm{PF1,7\&2,6}}$= +4 kA), the CT shift was left as shown in fig.5(c). The CT shift amount seems to be same as the diameter of W-limiter (0.26 m) at the poloidal field coil current of +/-4 kA. In addition, the traveling CT speed is calculated at 156 km s^{-1} between P4 and the limiter. It decreases by 26 % from the accelerated CT one of 211 km s^{-1} obtained between P3 and P4. Although such a CT shift motion has been observed in previous experiments, it is due to toroidal field. On CT injection into rather low toroidal field such as ST devices, effects of vertical field on CT penetration should be considered.

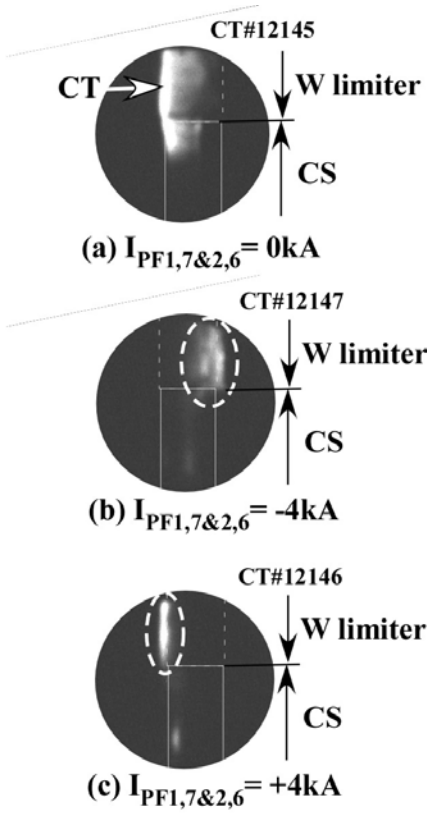

FIG. 5 Visible images of a CT penetrating into a vacuum without and with a vertical magnetic field. The observation port at the angle-A is 32.5 degrees apart from the CT injection port.

In the experiment we observed increase in temperature due to impact of a CT on the W-limiter and CT shifts in the magnetic fields. In order to investigate the CT kinetic energy and trajectory in CPD, we monitored the target plates mounted in CPD with the IR camera. An IR image was taken from the angle-D on the target plate at R= 0.23 m, as shown in fig.6(a). The CT was fired at V_{bias}= 0.6 kV and $V_{\mathrm{acc.}}$= 27 kV, and injected in the toroidal field of 261 G on the plate. We trace the peak points in the isothermal diagram for toroidal fields of 0 G (I_{TF}= 0 kA), 174 G (5 kA) and 261 G (7.5 kA) on the target plate in fig.6(b). Results indicates that CT shifts from y = 0 to 39 mm with increase of a toroidal field. Here, the CTs injected at 0 G, 174

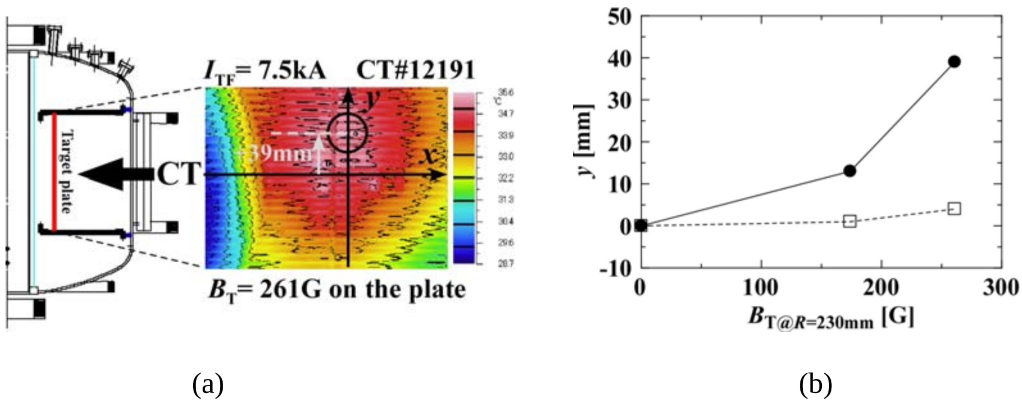

FIG. 6 (a)an observed IR image of the target plate taken at the angle-D for CT injection into a toroidal field of 261G. (b)the trace of peak points in the isothermal diagrams of IR image for toroidal fields of 0, 174 and 261 G.

G and 261 G have respective kinetic energy densities of 88 kJ m^{-3} (v_{CT}= 197 km s^{-1}), 57 kJ m^{-3} (179 km s^{-1}) and 67 kJ m^{-3} (185 km s^{-1}).

In addition, we obtained the full-width at half-maximum (FWHM) of the temperature profile on x and y axes from the isothermal diagrams, as shown in fig.7. The FWHM corresponds to the diameter of a CT plasma penetrating into a magnetic field. It appears that a CT plasma moving in B_T expands radially and the expansion is larger with increase of the toroidal field.

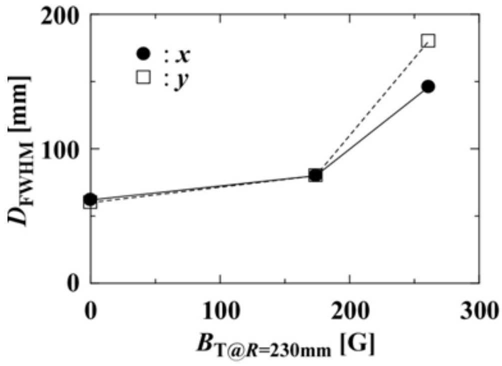

FIG. 7 the full-width at half-maximum (FWHM) of the temperature profile from the isothermal diagrams.

The IR camera captured thermal images on the rear surface of the target plate at R= 450 mm at the angle-B. An observed image for CT impact without a toroidal field is shown in fig.8(a). From the heat deposition in the plate, the CT kinetic energies $E_{CT,cal}$ were estimated and plotted in fig.8(b). the plotted $E_{CT,cal}$ were 138, 328 and 530 J at V_{bias}= 0.7 kV and $V_{acc.}$= 24 kV, 0.7 kV and 27 kV, and 0.6 kV and 27 kV,

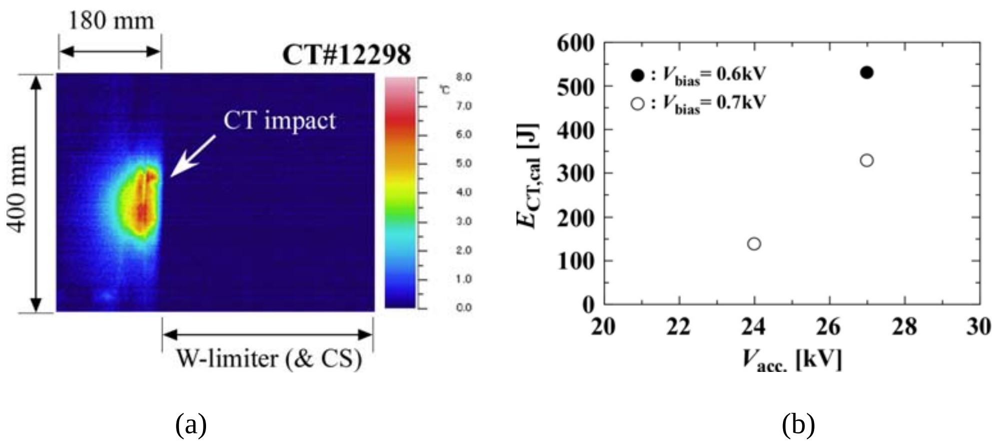

FIG.8 (a)an observed IR image on the reverse face of the target plate at R= 450 mm, taken at the angle-B for CT injection into a vacuum without magnetic fields. (b)the CT kinetic energies calculated from the heat depositions due to CT impact.

respectively. For $E_{CT,cal}$= 530 J, the CT kinetic energy density of 460 kJ m^{-3} is obtained by assuming a CT length of 0.3 m and a diameter of 0.07 m. This result agrees with the estimation of CT kinetic energy density in the previous experiment [15].

4. Summary

We performed CT injection into simple toroidal or vertical vacuum magnetic fields to investigate the penetration of CT plasmoids on CPD. In the experiment, the CT shift amount of about 0.26 m has been observed in a vertical magnetic field by using the fast camera. Therefore, in addition to toroidal magnetic field, vertical one appears to affect CT trajectory in not conventional tokamak but ST device, which is operated at a rather low toroidal field. We also observed CT impacts on the target plate with an IR camera. The trace of the peak point in the isothermal diagram has indicated that CT shifts 39 mm at the toroidal field of 261 G. From the calorimetric measurement of the heat deposition in the target plate, an input energy due to CT impact in vacuum without magnetic fields is also estimated to be 530 J, which agrees with the CT kinetic energy in the previous experiment. Understanding such CT penetration allows us to address appropriately one of the critical issues for practical application of CT injection on reactor-grade tokamaks.

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