Calorimetric measurement of kinetic energy of compact toroid in the spherical tokamak CPD

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A compact toroid (CT) injection is expected as an advanced refueling method on fusion plasmas. The CT injection experiments have been carried out in the spherical tokamak CPD (Compact Plasma wall interaction experimental Device). The estimation of the kinetic energy of CT in a main chamber is an important task to investigate the deposition of CT in the plasma, because CT may be able to penetrate up to the point where the kinetic energy density of CT equals to the magnetic field energy density. The kinetic energy of CT in the main chamber was directly measured by the calorimetric measurement on CPD. The target plate (SUS304) was set up in front of the CT injection port on CPD and monitored increase in temperature due to the impact of CT on the target plate with an infrared (IR) camera. It is necessary that the IR camera data is calibrated, because the SUS plate has the low emissivity and the black body paint was not used in the vacuum vessel on CPD. In addition, the speed and the length of CT into CPD were estimated by the use of a high speed camera (1μsec/frame). The kinetic energy of CT estimated by the calorimetric measurement was confirmed with that given by the kinetic measurement.

Keywords: Compact toroid(CT) , CT injection, Kinetic energy, Calorimetric measurement, Apparent temperature.

1. Introduction

The compact toroid (CT) injection is expected as an advanced refueling method on fusion plasmas. The advantages of the CT injection are to refuel it directly to the center of the fusion plasma, and to prevent the energy loss by ionization because any kinds of fuels including ^{3}He can be replenished in the state of plasma. In addition, CT deposits on an arbitrary place and a local fueling is possible, because the CT plasma is small enough compared with the fusion plasma [1].

The CT injection experiments have been carried out in the spherical tokamak CPD at Kyusyu University since 2006 by using UH-CTI (University of Hyogo-Compact Toroid Injector, formerly HIT-CTI) designed and constructed in University of Hyogo. The experiment of UH-CTI in JFT-2M had been conducted in a joint research between University of Hyogo and Japan Atomic Energy Research Institute since 1997[1]. After that, UH-CTI was transferred to Kyusyu University.

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The CT injector is composed of an equipment of formation, acceleration coaxial electrodes, a bias solenoid coil and a gas puff valve. The CT plasma is generated by a magnetized coaxial plasma gun. Typical supplied voltages for the bias coil and the formation bank are V_{bias} ~ 2.4 kV and V_{form} ~20 kV, respectively. The CT plasma is transferred with the acceleration bank of V_{acc} ~ 40 kV. These three voltages are the injection parameters of the CT plasma.

According to the penetration model [2], CT can penetrate up to the point where the CT kinetic energy density $\rho v_{CT}^2/2$ equals to the magnetic field energy density $B_T^2/2\mu_0$. Here ρ is the CT mass density, v_{CT} the CT velocity and B_T the magnetic field strength of the toroidal magnetic field. As for the performance of the CT injector, velocity $v_{CT} \leq 300$ km/s, density $n_{CT} \leq 9\times10^{21}$ m^{-3}, length L_{CT} =0.3 m, diameter D_{CT} = 0.07 m were obtained. All these parameters are demanded from the CT injection experiments in JFT-2M [3] and it seems to be enough to inject in CPD.

These parameters were measured in the drift tube of the CT injector and were not done in the main chamber of JFT-2M. The performance of CT in the main chamber, where the strong magnetic field exists, should be investigated to understand the feasibility of fueling using the CT injection. The estimation of the fueling capability of the CT injection was done in JFT-2M using the increment of density in the main chamber, however the behavior of CT in the plasma is not clear [2,3]. The most important point is whether the above-described penetration model in the magnetic field is accurate or not. To investigate this point, the estimation of the kinetic energy of CT in the main chamber is necessary.

The calorimetric measurement of the kinetic energy of CT was demonstrated on CPD and the accuracy of the estimated value is confirmed by the comparison with the CT velocity measurement using the high speed camera of 1μsec/frame. In section 2, the experimental set up and the calibration of the IR camera for the calorimetric measurements are described. The experimental results and the conclusion are discussed in section 3 and 4, respectively.

2. Experimental set-up and calibration of infrared camera

The calibration of the infrared (IR) camera data should be done, because the target plate made of stainless-steel 304 (SUS304) has the low emissivity and the black body paint to approach the emissivity to the black body's value was not used in the main chamber of CPD, because the contamination of the main chamber should be avoided. The vacuum window for the IR camera made of Zinc Selenide (ZnSe) was installed on CPD.

Figure 1 shows the experimental set-up for the calibration of the IR camera. The heaters and the thermistors were attached in the target plate of SUS304, and a part of the target plate was coated by the black body paint. The emissivity of the black body paint is 0.94. The calibration of the IR camera was done by the comparison of the IR camera's results and the thermistor's, one of the target plate temperature without the black body paint.

Figure 2 shows the comparison of the increment of temperature measured with the thermisitors with the IR camera measurement at the position of the target plate coated with or without the black body paint through the ZnSe window, and just with the black body paint.

The increment of temperature measured with the IR camera in the case of the black body paint without the ZeSe window is same as the thermistor measurement (Solid line in Fig.2). The increment of the temperature measured with the IR camera with the black body paint through the ZnSe window was slightly different from that measured with the thermistors (broken line in Fig.2).

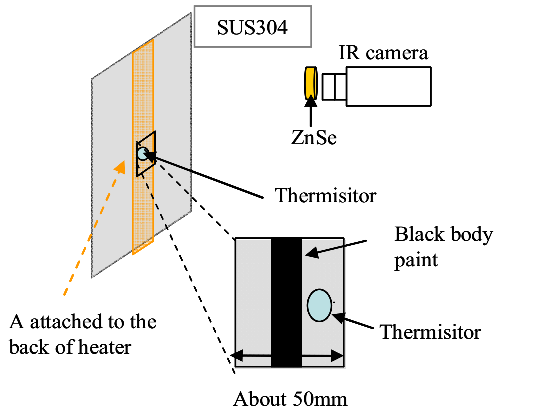

Fig.1. Calibration experiment of set up. The heaters and the thermistors were attached on the target plate of SUS304, and a part of the target plate was coated by the black body paint. The emissivity of the black body paint is 0.94.

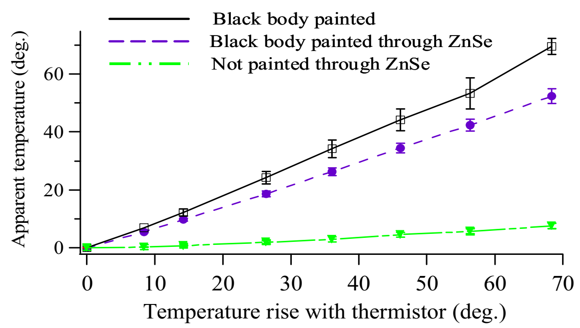

Fig.2. The comparison of the actual temperature of the object measured by two thermistors and the apparent temperature measured by the IR camera.

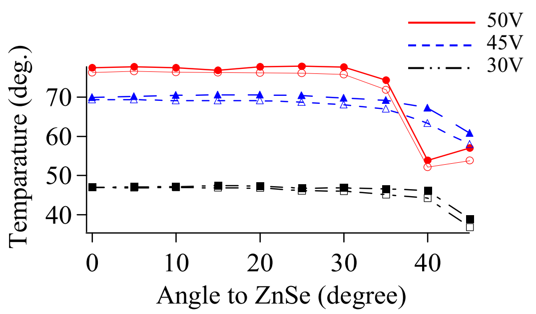

Fig.3. The dependence of the apparent temperature on the installation angle of the IR camera to the ZnSe window. Voltage of heater was adjusted from 30V to 50V and the temperature was measured by the IR camera at two points on the target plate.

In addition, injection angle dependence of the ZnSe window was examined. In fact, the installation angle of the IR camera to the ZeSe window is oblique at 15°~20° when the IR camera was set up on CPD in the CT injection experiments. The oblique angle dependence of the transmissivity of the ZeSe window is also investigated. As shown in Fig.3, if the IR camera is installed obliquely to the ZnSe window at 30° or more, the measured temperature was significantly modified, but there existed no change in the range of 0 ~ 30°.

The IR radiation detected by the IR camera is expressed by

$$W(T') = \eta\varepsilon\sigma T^4 + \eta(1-\varepsilon)\sigma T_a^{\ 4} + (1-\eta)\sigma T_a^{\ 4} \quad (1)$$

where. W(T')= $\sigma T'^4$ and T' is the apparent temperature rendering on the IR camera, which is not accurate. σ is the Stefan-Boltzmann coefficient (5.67×10^{-8} W·m^{-2}·K^{-4}). η shows the transmissivity of the ZnSe window as derived from the measurement shown in Fig.2. ε shows the emissivity of SUS304. T is the temperature of the object and T_a is the temperature of the circumstance. The first and the second terms of right side of Eq. (1) show the emission from the object and the circumstance and the third one shows the sum of the emission and the reflection from the ZeSe window. In this case, the temperature of the ZnSe window is same as that of the circumstance.

It was assumed, η = 0.7 and ε = 0.12, and the value of the apparent temperature (T') was substituted in Eq.(1) and the real temperature of the object (T) was obtained. Figure 4 shows the relation between the apparent temperature T' and the real temperature T. The temperature T, determined using Eq.(1) (solid line in Fig.4) for which the T', the apparent temperature was measured by the IR camera is substituted shows a good agreement with the thermistors data (broken line in Fig.4).

The kinetic energy of CT was directly measured by calorimetric measurement on CPD. The target plate was set up in front of the CT injection port inside CPD and monitored the increment of temperature due to the CT impact on the target plate with the IR camera. Figure 5 shows the layout of the target plate and the IR camera. Two kinds of target plate were used. One is made of SUS plate in a thickness of 1.4 mm and the other is in a thickness of 0.2 mm. In case of thick SUS plate, the increment of surface temperature due to the CT impact was measured (see left view of Fig.5), and this is useful to investigate the shape and the orbit of CT. While, the temperature increment of the thin plate impacted by CT was measured on the opposite surface (see right view of Fig.5), and this is suitable in the calorimetric estimation of the kinetic energy of CT.

Figure 6 shows the positions where the target plate, two wires and the high speed camera were installed on CPD. The speed and the length of CT were estimated from the delay time its hitting to the wires and to the target plate using the image measured with the high speed camera (1μsec/frame).

In order to take a picture of CT injected into the main chamber of CPD by the high speed camera, it is necessary to consider the influence to the camera from the magnetic field. Thus, the distance between the camera and CPD was kept large and connected with an optical fiber.

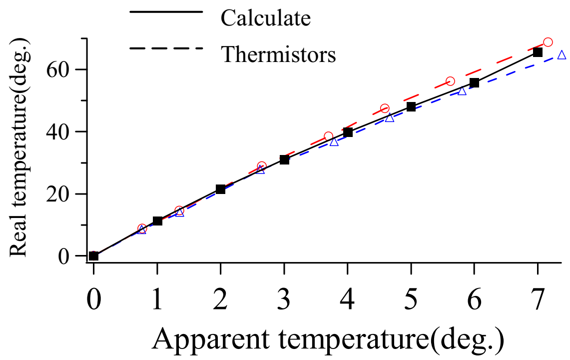

Fig.4 The relationship of the temperature of the object measured by the two thermistors (broken line) and the apparent temperature measured by the IR camera, and the calculated temperature derived from Eq.(1) (solid line) for which the apparent temperature is substituted.

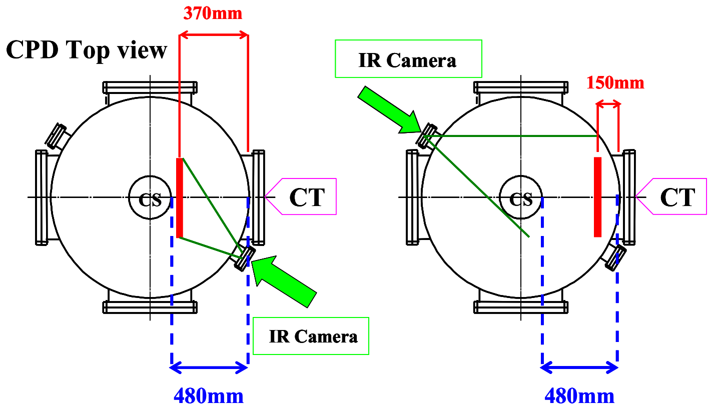

Fig.5 Installation view of the target plate(SUS304) and the IR camera on CPD. Left view shows the target plate of 1.4 mm, set up at a position of 370mm from the edge of vacuum vessel of CT injection port side, and the right view the target plate of 0.2mm set up at the position of 150mm.

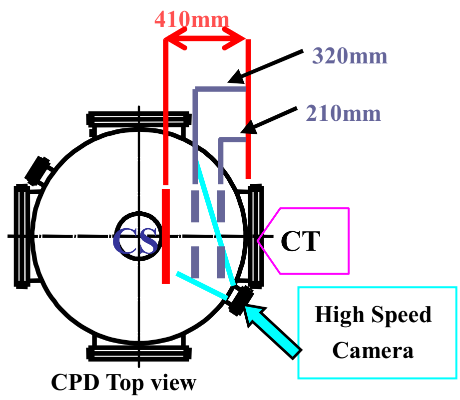

Fig.6 Schematic view of the target plate (SUS304) , the wires, and the high speed camera.

3. Experimnental results

Figure 7 shows the 2D image of the increment of temperature on the target plate detected by the IR camera after a CT impact (V_{bias} =0.6kV, V_{form} =12kV, V_{acc} =27kV) without external magnetic field.

Thermal diffusivity of SUS304 is 4.07 mm^2/s. The delay time of temperature increment can be estimated as $0.2^2/4.07 \sim$ 10ms. The frame rate of the IR camera (33ms) is enough to equalize the temperature in the vertical direction of the target plate. The size of the target plate is 60 cm × 60 cm and the area within the range of taking a picture is 18 cm × 40 cm as shown in Fig.7. We calculated the increment of the area-averaged temperature in the whole range of the viewed picture. If the calorimetric measurement was executed correctly, the increment of the area-averaged temperature will be temporally constant, because it only depends on the kinetic energy of the injected CT.

Figure 8 shows the increment of the area-averaged temperature of the target plate. After CT impacted, the variation is negligible. This indicates that an almost accurate temperature can be estimated by the calorimetric measurement using the IR camera. According to the thermal conduction calculations, the time constant of the target plate is 20 ms and hence 100 ms is enough to conduct heat to the rear of the target plate. The average increment of temperature of the target plate, calculated from this temperature distribution, in Fig.7, is ~ 10.6 degrees.

The shape of the image of the increment of temperature due to the CT impact is circular in the measurement as shown in the left view of Fig.5. The diameter of IR image is about 7 cm, and it is corresponds to the diameter of the injection port (7 cm). Thus we can estimate the diameter of CT in the main chamber.

The total energy of CT in calorimetric manner is estimated as $Q = mc\Delta T$. m is the mass and ΔT is the increment of the area-averaged temperature of the target plate. c is specific heat. The volume of the target plate within the range of taking a picture and the target plate in a thickness of 0.2 mm is derived V_{sus}= 14.4 cm^3. The density of SUS304 is 7.93 g/cm^3, the mass of the target plate is 114.2 g. The specific heat of SUS304 is assumed to be 0.50 J/g·K. The total energy of CT in calorimetric manner is calculated as $Q = mc\Delta T \sim$ 610 J. The kinetic energy density of CT is ~530 kJ/m^3 is estimated from the assumption of the CT length (~0.3 m) in the drift tube on JFT-2M, and diameter (~0.07 m).

The estimated value of the kinetic energy of CT was strongly depends on the supplied voltage to the charging voltage of the acceleration bank as shown in Fig.9.

Figure 10 shows the time trace of the image during the CT injection to CPD measured with the high speed camera. At 29 μs, the CT reaches to the first wire and it touches to the target plate at 31 μs. The length of the CT can be estimated from the time delay and the position of the wires and the target plate.

Considering of frame rate of the high speed camera and the exposure time, CT reaches the first wire at time, t_1 = 29.0±0.5 μs, and leaves the first wire at time, t_1’ = 31.5±0.5 μs as shown in Fig.11. CT reaches the target plate at time, t_2 = 31.0±0.5 μs. The distance from the first wire and the target plate is L_1 = 200 mm and the flight time of CT is $t_2 - t_1$ = 2.0±1.0 μs. The velocity of the CT can be estimated by $v_{CT} = L_1/\ (t_2 - t_1)$. The minimum velocity, v_{CT} is 67 km/s and the maximum velocity, v_{CT} is 200 km/s.

The length of the CT can be estimated from v_{CT} and the time duration, Δt during which the first wire was being hit by the CT plasma. Δt is equal to t_1’ − t_1 = 2.5±1.0 μs. When v_{CT} =67 km/s, Δt =3.0μs±0.5 μs, the minimum and the maximum values of the estimated CT length, L_{CT}, are $L_{CT} = v_{CT}\Delta t$ = 67 × 2.5 =167.5 mm as shown by red broken line in Fig. 11, and 67 × 3.5=234.5 mm, respectively. When v_{CT} =200 km/s, Δt =2.0μs±0.5 μs, the minimum and the maximum values of L_{CT} are $L_{CT} = v_{CT}\Delta t$ = 200 × 1.5 =300 mm, and 200 × 2.5=500 mm as shown by blue broken line in Fig. 11, respectively.

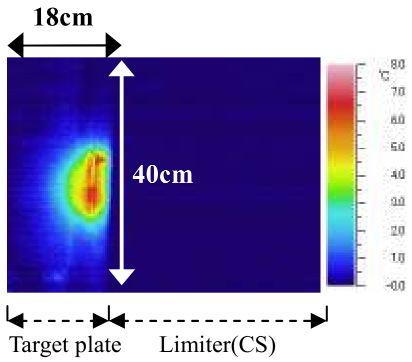

Fig.7 Target plate temperature increase due to a CT impact by using of the IR camera. (Parameter of CT V_{bias}=0.6kV, V_{form}=12kV, V_{acc}=27kV)

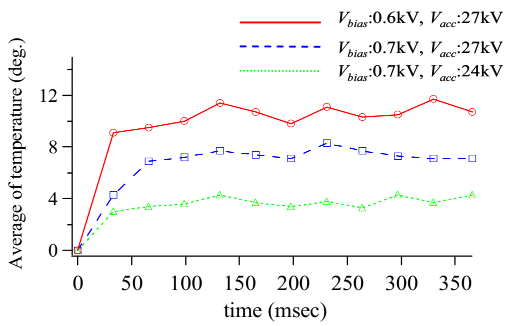

Fig.8 Temperature change of the target plate after CT was hit. Injection parameters are shown in legends. It was a stationary state since the second frame after CT was hit. The origin of time is defined as the previous frame which the increment temperature was caused.

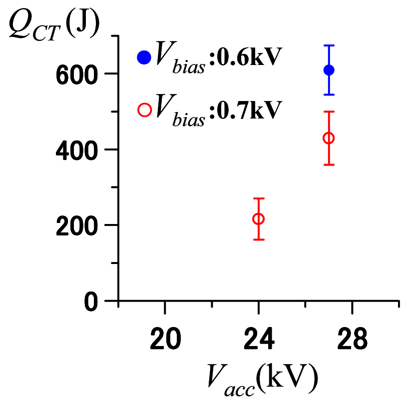

Fig.9 Dependence of the CT kinetic energy on acceleration – bank voltage (V_{acc}=24kV to V_{acc}=27kV) and voltage of the capacitor bank for the bias flux coil (V_{bias}=0.6kV to V_{bias}=0.7kV).

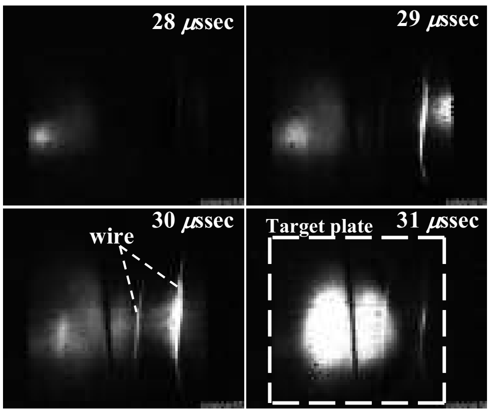

Fig.10 This picture was taken with the high speed camera when CT into CPD. The substance of CT was unable to take a picture. However, the velocity of CT and length were estimated by taking a picture of shines due to impact of CT to the wire and the target plate. (For this sample shot, V_{bias}=0.6kV, V_{form}=8kV, V_{acc}=20kV)

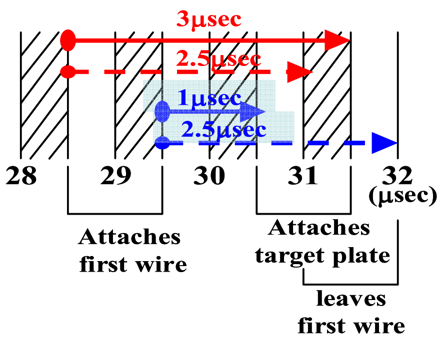

Fig.11 The time until the CT reaches the target plate from the first wire (Solid line) and time duration during which the first wire was being hit by the CT plasma (broken line) estimated from Fig.10. The kinetic energy of the CT is a maximum or a minimum combination. The blank part is exposure time.

The estimated density of CT in the drift tube is 3.0 × 10^{21} m^{-3}. When the velocity of CT is estimated to be 67 km/s and the length is estimated to be 0.17 m, the mass of CT is 6.6 × 10^{-9} kg. The minimum kinetic energy of CT is estimated to be 14.7 J from these velocity and mass of CT. On the other hand, when the velocity of CT estimated to be 200 km/s and the length is estimated to 0.5 m. The mass of CT is 1.9 × 10^{-8} kg. The maximum kinetic energy of CT is estimated to be 380 J. This indicates that the kinetic energy of CT at the supplied voltage, V_{acc}= 20 kV is in the range of 14.7J $< E_{CT} <$ 380 J. Although accuracy of the estimated kinetic energy of CT in this technique is not enough because of the insufficient frame rate of the high speed camera, the estimated value is not conflicted to the kinetic energy of CT measured in the calorimetric manner.

4. Conclusion

The kinetic energy of CT in the main chamber of CPD was measured by two methods. As one method, the kinetic energy of the CT was measured in the calorimetric manner. The target plate (SUS304) was set up on CPD and monitored increase in temperature due to the impact of CT on the target plate by using the IR camera. The effect of the low emissivity of the target plate was calibrated. The kinetic energy of CT was estimated ~ 610 J by this calorimetric measurement, and it has widely changed depending on the supplied voltage of electrode for acceleration and for bias coil.

As another method, the speed and the length of CT in the CPD chamber were estimated from the flight time from the wires to the target plate by using the high speed camera. The estimated kinetic energy of CT is in the range of 14.7 J $< E_{CT} <$ 380 J. The estimated value of the kinetic energy density of CT agrees roughly with the estimation in drift tube of JFT-2M [3].

The kinetic energy of CT estimated by using this technique has no contradiction with that in the calorimetric measurement. This indicates that the calorimetric measurement is suitable in the estimation of the kinetic energy of CT.

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5. References

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