Extension of Operation Region for Steady State Operation on QUEST by Integrated Control with Hot Walls*)

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The controllability of particle supply during long-term discharge in a high-temperature environment was investigated at the Q-shu University Experiment with steady state spherical tokamak (QUEST). QUEST has a high-temperature wall capable of active heating and cooling as a plasma-facing wall. With this hot wall, a temperature rise test was conducted with 673 K as the target temperature. It was confirmed that the hot wall could maintain the temperature above 600 K. Feedback control of particle fueling was conducted to control Hα emission, which is closely related to influx to the wall. Using this particle fueling control and setting the hot wall temperature to 473 K, it was possible to obtain a discharge of more than 6 h. In this discharge, the fueling rate of particles decreased with time, and finally became zero, losing the particle fueling controllability. However, as soon as the cooling water started to flow through the hot wall, particles could be supplied again, and controllability was restored. Thus, indicating that temperature control of the plasma first wall is important even in the high-temperature environment of 473 K to control particle retention of the wall.

Keywords: steady state operation, long pulse operation, high-temperature wall, spherical tokamak, particle fueling, temperature control, feedback control, QUEST

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1. Introduction

Particle recycling is an essential thing in a long-term discharge of tokamak. However, the controllability of particle fueling becomes difficult in the later phase of long-term discharge. This is because, when discharging for a long time, the temperature rises and thermal desorption occurs from the first wall or other components of the vacuum vessel, and the fueling of unintended particles gradually increases. The effects of particle recycling on long-term discharge have been investigated in many fusion experimental devices [1–6]. Although it is a relatively low parameter (plasma current: 20 kA, density: 10^{18} m^{-3}, and RF power: 7 kW), TRIAM-1 M achieved a discharge of 3 h 10 min. It was also shown that the first wall shifts from particle storage to release as the wall temperature rises during long-term discharge [1]. In LHD, plasma discharge with helium was performed for more than 40 min, and changes in wall pumping in a discharge were observed with global particle balance analysis [2]. According to JET ITER-like wall (ILW) operation, the temperature of the tungsten (W) surface divertor plate, which is not actively cooled, rises with plasma exposure, and the desorption of deuterium atoms or molecules occurs significantly [3]. Alcator C-Mod [4] and ASDEX-U [5] showed that recycling not only divertor but also the main chamber plays a significant role in global particle balance. In Tore Supra, an unintended increase in density was observed with a long discharge of 2 min. It is because the wall of the part far from the plasma and not sufficiently baked was heated by a heat radiation from the plasma and water desorption occurred [6]. Thus, particle desorption occurs at various locations in the device, and it is necessary to actively control so as not to cause unintended fueling recycling.

Q-shu University Experiment with steady state spherical tokamak (QUEST) has a high-temperature wall called a hot wall as a plasma-facing wall, and can actively heat and cool the hot wall [7]. Long-term discharge using a high-temperature wall can reduce the particle retention of the first wall and suppress an unexpected increase in density. Future fusion power plants will operate in high-temperature environment of around 773 K owing to required power generation efficiency. Thus, it is essential to investigate particle recycling in high-temperature environment using a hot wall of QUEST.

The operation of QUEST began in 2008, and non-inductive plasma ramp-up experiments using electron cyclotron waves, and steady state operation experiments were conducted [7, 8]. Since 2010, long-term discharges have been attempted at several magnetic field configurations and wall temperatures. Besides, the experiment using the hot wall started in 2014. The discharge time is increasing

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yearly, and the discharge of more than 1 h was obtained in 2016 [7]. From 2018, the center stack (CS) has been changed from a stainless plate sprayed with APS-W to a small tile made of stainless steel type 316 L to improve maintainability.

2. Experimental Apparatus

2.1 Configuration of hot wall

The hot wall is installed in a conical shape inside the vacuum vessel (Fig. 1), and is attached using a leaf spring to avoid thermal elongation. Its material is stainless steel type 316 L coated with 0.1-mm-thick APS-W. The hot wall structure is described in detail in [9]. The hot wall is divided into 24 sections in the toroidal direction. One section consists of a panel with an electric heater and a thermocouple embedded in it. An oxygen-free copper plate is also sandwiched so that the temperature distribution becomes uniform. In addition, two cooling water pipes are in contact with the hot wall via stainless steel plates, each of which has different thermal resistance. This is because if the cooling water pipe contacts directly with hot walls, it will be overcooled. Radiation shields are installed between the hot wall and the vacuum vessel wall to avoid an excessive temperature rise of the vacuum vessel wall. The radiation shield is made by stacking thin stainless steel plates in layers at intervals. The radiation shield prevents the radiant heat from the hot wall from going directly to the vacuum vessel wall.

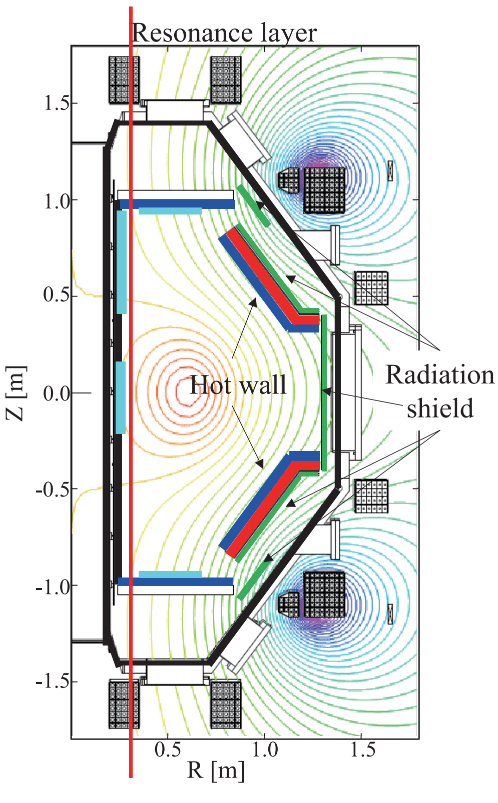

Fig. 1 Poloidal cross section of QUEST.

2.2 Heater system and temperature rise test

Figure 2 shows the toroidal section view of lower hot walls. There are 24 sections of hot walls in the toroidal direction. It is grouped into one for every four sections and has six groups in the toroidal direction. Since it is further divided into a conical part, a horizontal part, and an upper and lower part, it is divided into 24 groups (= 6 in the toroidal direction × 2 in conical and horizontal part × 2 in the upper and lower part) in total. All groups have thermocouples for heater control. Feedback controls of heater powers are conducted based on these temperatures. A total of 200 thermocouples are installed on the hot wall. Besides, many thermocouples are installed in other places to investigate the temperature profile in detail. For example, more than 80 and 50 thermocouples are installed in the vacuum vessel and radiation shield, respectively.

Using such a temperature feedback control system and a measurement function; a temperature rise test was performed. The set temperature of the hot wall and the vacuum vessel were 673 K and 373 K, respectively. Figure 3 shows the results. The test was conducted over 4 d while confirming the safety, such as thermal strain. The vacuum vessel elongation due to thermal strain was also measured using a laser displacement meter. In the temperature rise test, the preset temperature was raised steps by step, such as 473 K, 523 K, and 573 K. It was held at each temperature for about 1 d. Finally, the set temperature was set at 673 K. As a result, most parts of the hot wall exceeded 600 K. The radiation shield plate was heated to 450 K or more by radiant heat from the hot wall.

The temperature rise test at a set temperature of 673 K is only once this time so far. A typical set temperature for long-term discharge using a hot wall is 473 K, and cooling

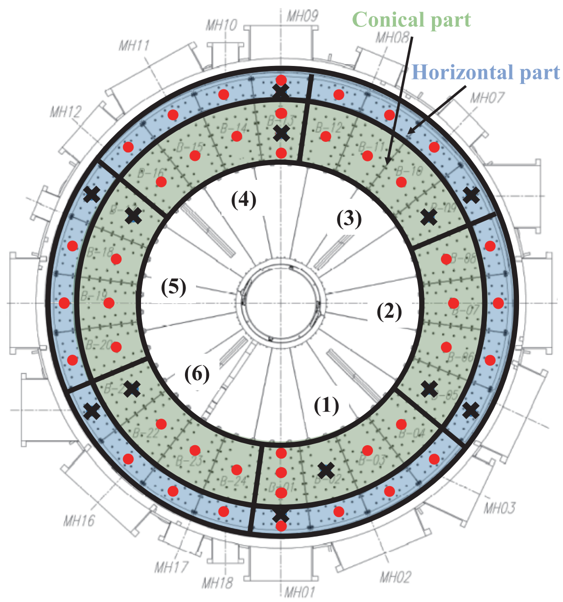

Fig. 2 Toroidal section view of lower hot walls. (Dot: Thermocouples (TC). Cross: TCs for heater control).

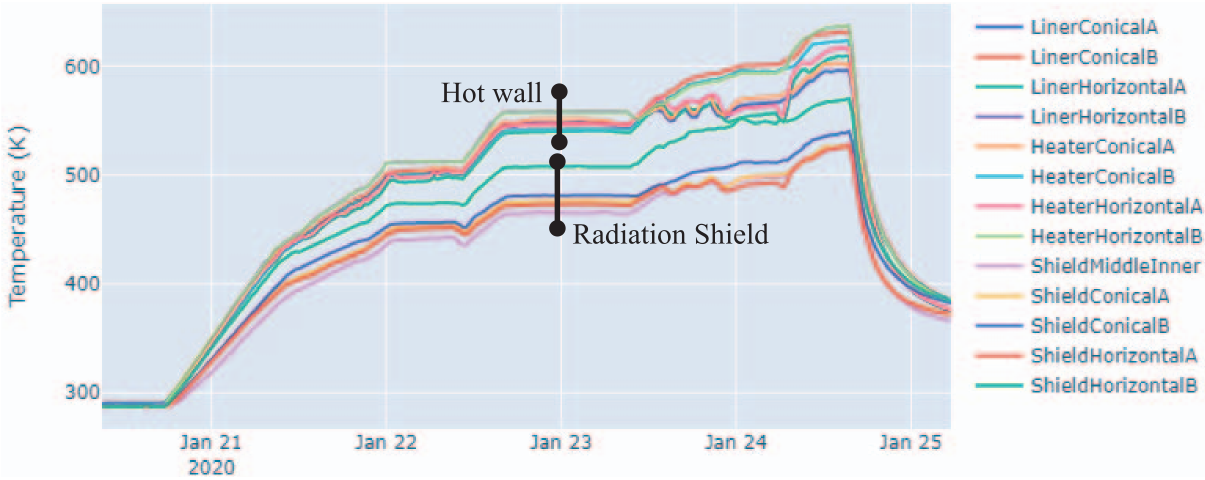

Fig. 3 Hot wall temperature rise test at set temperature 673 K.

water is passed through the CS. Here, the temperature distribution can be divided into three groups: a vacuum vessel, radiation shields, and hot walls, and the temperatures are about 300 K, 400 K, and 450 K, respectively.

2.3 Feedback control of particle fueling

Since plasma emission Hα is closely related to the particle influx to the first wall [10], it is essential to control the intensity of Hα. Therefore, the Hα increases with an increase in particle fueling. Thus, a feedback loop can be constructed with input as the deviation of Hα emission and output as the flow rate (Fig. 4). The flow rate can be controlled by a mass flow controller (MFC). The MFC is a device used to measure and control the flow of liquids and gases. In this experiment, MFC capable of controlling the flow rate of 0.2 to 20.0 mL/min of H_2 gas was used.

First, the particle supply by MFC was given in a stepwise manner to investigate the response of Hα Figure 5 shows its result. In Fig. 5, particles are supplied by gas puff only once at the start of plasma discharge. The plasma was maintained by continuing to apply the RF of 8.2 GHz, and particles were supplied by MFC from 15 s in a stepwise manner. The result showed that the Hα emission increases gradually with a delay of several seconds. One of the reasons for this delay seems to be that the MFC installation position is several meters away from the vacuum vessel. This is because there is a solenoid valve inside the MFC, and it is necessary to avoid the influence of the magnetic field generated by the tokamak device. Other causes of the delay may include particle adsorption by wall pumping. It was obtained that this system is represented by the general transfer function $G(s)$ of eq. 1. It means that this system consists of a delay element τ and a first-order lag element T.

$$G(s) = \frac{K\exp(-\tau s)}{1 + sT}. \tag{1}$$

From Fig. 5, the delay element τ and the first-order lag element T are on the order of a few seconds, which is significantly larger than other parameters that require control on the order of milliseconds, such as the coil current. The plasma control system (PCS) that controls each parameter operates at 4 kHz, and various parameters, such as the coil current, are controlled by a 4 kHz feedback loop by PCS. For simplicity, the feedback control cycle by MFC is set to every several seconds. It means that when the feedback control changes the flow rate, the feedback control is performed again after waiting for a few seconds until the plasma responds. Figure 6 shows the test result of feedback control of Hα emission intensity by MFC. Proportional-Integral-Differential (PID) control starts from 10 s, and the target value of Hα is fixed at 0.5 (a.u.). Calculation of PID control loop is conducted every 15 s; meaning that the particle supply changes every 15 s. Thus, the waveform of

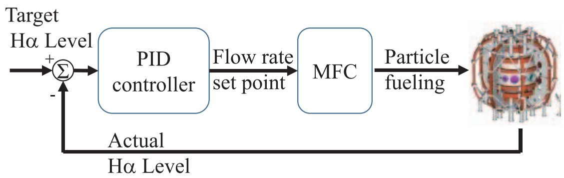

Fig. 4 Particle fueling feed-back control with Hα signal.

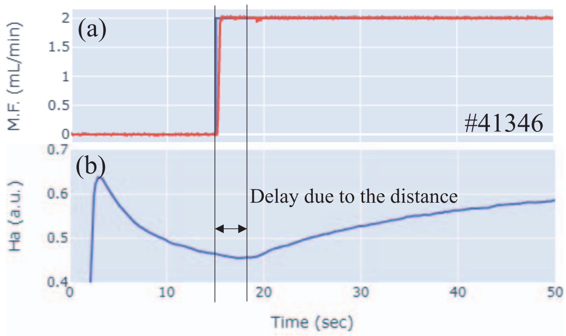

Fig. 5 Step response of Hα by mass flow meter. (a) Fueling rate of MFC, (b) Hα signal of plasma.

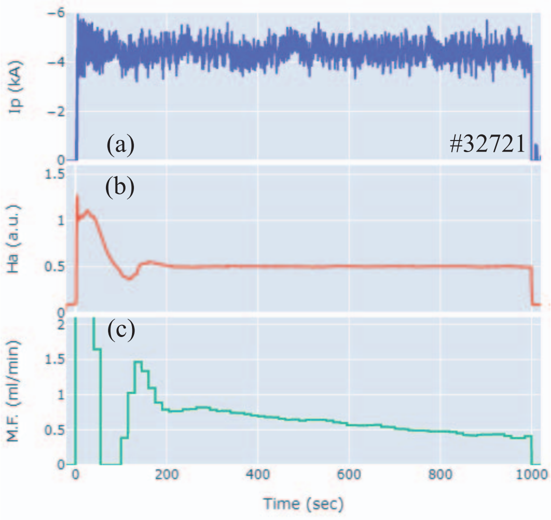

Fig. 6 Test result of feedback control of Hα emission intensity by MFC. (a) Plasma current, (b) Hα emission intensity, and (c) fueling rate by MFC.

Fig. 6 (c) is not smooth. The supply of MFC increases or decreases to keep the Hα level constant at 0.5 at the initial stage of discharge. After that, the fueling supply rate can be gradually reduced for 1000 s, and the Hα level is kept to a constant value of 0.5 and is well controlled.

3. Experimental Results

3.1 Long duration discharge

Using the hot wall and feedback control of fuel supply by MFC described so far, long-term discharge was attempted. In this discharge, the heater-heating system tries maintaining the hot wall at 473 K and the vacuum vessel at 373 K. The toroidal and poloidal magnetic fields at the major radius R = 0.6 m were set to 0.14 T and 8 Gauss, respectively. RF input power is about 25 kW at 8.2 GHz. In this setting, the resonance layer is at R = 0.3 m and the magnetic configuration is a limiter configuration (Fig. 1).

With this setting, plasma discharge over 6 h was obtained with a plasma density of less than $10^{18}\,m^{-3}$ and a plasma current of about 2 kA. Figure 7 shows the limiter configuration plasma in the vacuum vessel of this discharge. The discharge is manually stopped in 6 h. Figure 8 shows the typical wave forms of discharge. In this discharge, feedback control of particle fueling was performed so that the signal level of Hα became constant at 0.35 (a.u.). The total pressure increases slightly from the beginning of discharge (Fig. 8 (d)). In Figs. 8 (b) and (c), Hα level is well controlled and constant at 0.35 (a.u.) by decreasing particle fueling rate gradually in the initial stage of discharge. Besides, Hα level gradually increases after particle fueling rate reaches zero. It means that even in a high-temperature environment of 473 K, particle fueling control cannot be performed in the latter phase of the discharge owing to uncontrollable density rise.

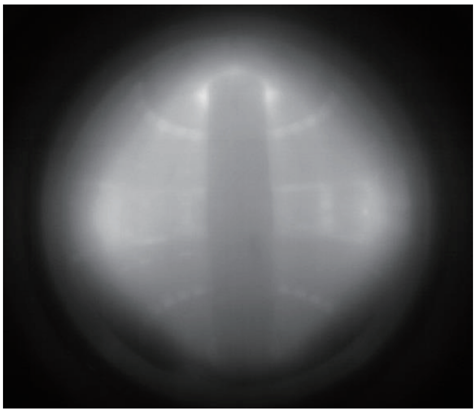

Fig. 7 Inside view of vacuum vessel of 6 h plasma discharge.

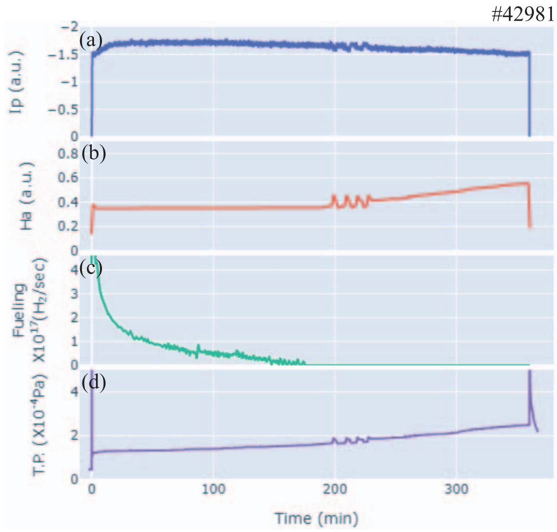

Fig. 8 Wave forms of 6 h long plasma discharge. (a) Plasma current, (b) Hα emission, (c) fueling rate by MFC, and (d) total pressure.

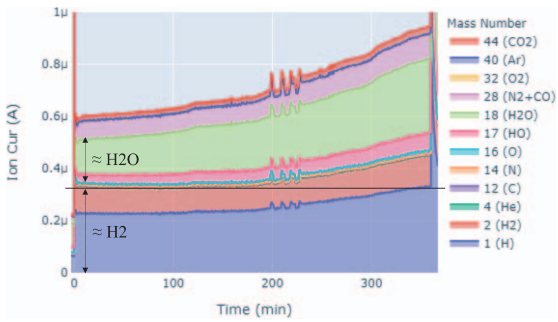

Fig. 9 Stacked line chart of mass spectrometer.

Figure 9 shows the changes in the mass spectrometer during long-term discharge. Although the resolution is not high in these mass spectrometer measurements, the amount that can be caused by hydrogen is constant until the first half of the discharge and gradually increases in the last half. In this discharge, MFC supplied hydrogen

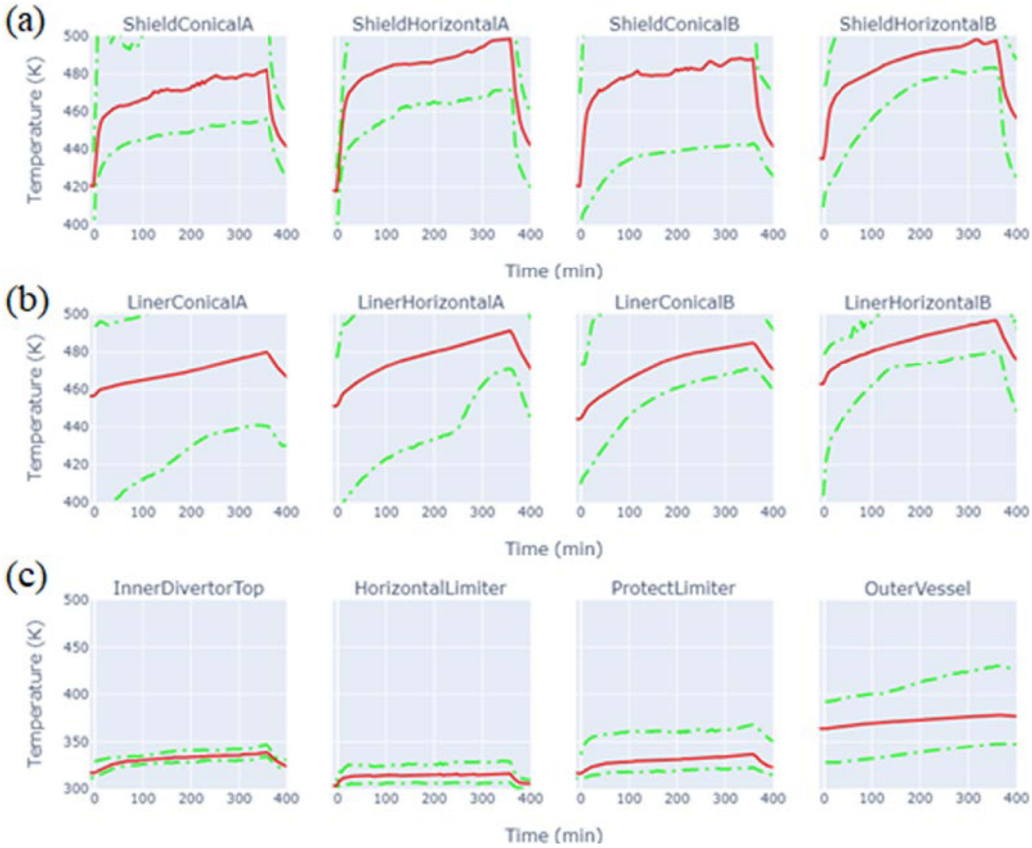

Fig. 10 Temperature changes in each part of (a) hot walls, (b) radiation shields, and (c) vacuum vessel during long discharge. The average temperature (solid line), minimum and maximum temperature (dash dot lines) of the area are shown.

so that the signal Hα level becomes constant. Thus, the partial pressure of hydrogen was kept constant in the first half of the discharge. However, in the latter half of the discharge, it was shown that hydrogen was supplied from other than MFC. Besides, the partial pressure of H_2O has been increasing from the beginning of discharge, which is the same tendency of total pressure of Fig. 8 (d).

Figure 10 shows the temperature changes in each part of QUEST during long discharge. The locations are mainly classified into three groups: hot walls, radiation shields, and vacuum vessel. It can be seen that there is a temperature difference of about several tens of kelvin in every part of each group. The rapid temperature rise in several minutes occurs at radiation shields in the initial phase (Fig. 10 (b)). Since the radiation shields are made by assembling thin stainless steel plates in layers, the heat capacity is small. The small heat capacity can cause a rapid temperature rise. The radiation shield is installed between the hot wall and the vacuum vessel and does not directly face the plasma. Thus, this temperature rise seems to be not direct heating from plasma but resistant heating owing to high frequency multi-reflection of RF. It is worth noting that this increase in temperature does not affect the degree of total pressure. Furthermore, the temperature of the hot walls and the radiation shields gradually rises during the discharge. Some parts of the vacuum vessel are kept at a substantially constant temperature since the cooling water is passed through them.

3.2 Use of active cooling of hot walls

Another long duration discharge over 6 h was obtained. All parameters, such as the preset temperature, poloidal and toroidal magnetic fields, and RF input power were the same as the previous 6 h discharge. However, cooling water at room temperature was flowing from 300 min to the upper hot wall. Before starting the water flow, the inside of the stainless steel cooling water pipe was the atmosphere, and the temperature of the pipe was about 450 K, which is the same as the hot walls. Since cooling water at room temperature is passed from this state, it seems that sudden boiling occurs, but the flow path is the open end. Thus, the increase in pressure inside the pipe can be suppressed and finally water can flow. Figure 11 shows the waveforms of 6 h long plasma discharge with cooling water. The discharge is also manually stopped after 6 h. In Fig. 11 (c), although the particle supply gradually decreased to zero by 300 s, it is resumed at the same time as the start of cooling water flowed. This is because the cooling water was passed through the upper hot wall and the temperature of the upper hot wall became lowered. Figure 12 shows the temperature changes of the upper and lower hot wall. It can be seen that the temperature

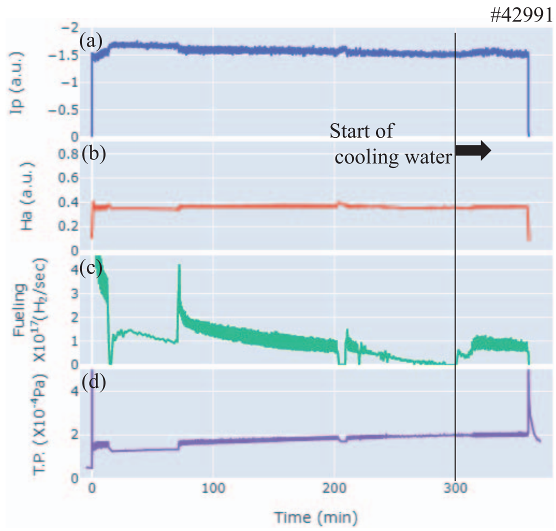

Fig. 11 Wave forms of 6 h long plasma discharge with cooling water. (a) Plasma current, (b) Hα emission, (c) fueling rate by MFC, and (d) total pressure.

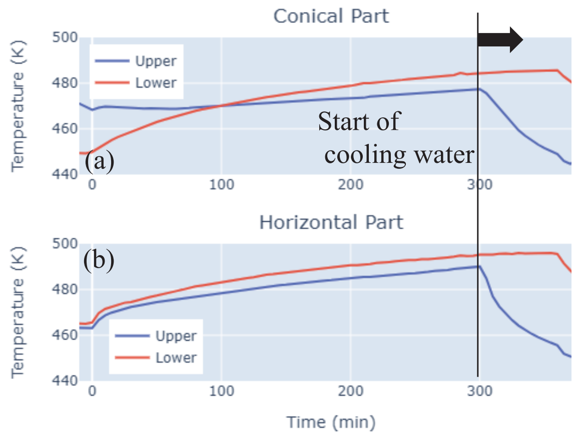

Fig. 12 Temperature change of upper and lower hot wall. (a) Conical part and (b) horizontal part of hot wall.

of the upper hot wall became lowered at a rate of 0.5 K/min by passing cooling water through the upper hot wall from 300 s. It is worth noting that this temperature decrease has a significant effect on particle retention and controllability, even in a high-temperature environment of 473 K.

In this discharge, a phenomenon was also observed where each parameter shown in Fig. 11 oscillates. Figure 13 shows an expanded view of around 71 min when vibration starts in Fig. 11. The plasma current, Hα signal, fueling rate, and total pressure are vibrating in a cycle of about 1 min. The trigger at which the vibration starts seems to be a sudden decrease in the Hα signal. Thus, the MFC feedback control increases the particle supply to raise the Hα signal. However, the Hα signal increases suddenly since it responds nonlinearly to the particle supply. Therefore, the feedback control by MFC is lowering the particle supply to lower the Hα signal, and finally makes it zero.

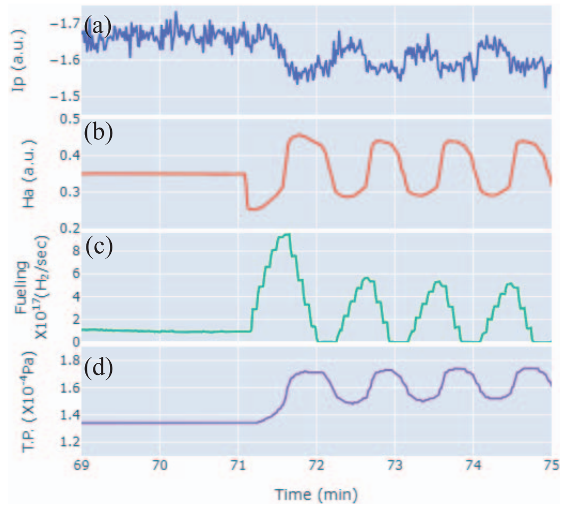

Fig. 13 Waveform at the start of vibrations. (a) Plasma current, (b) Hα emission, (c) fueling rate by MFC, and (d) total pressure.

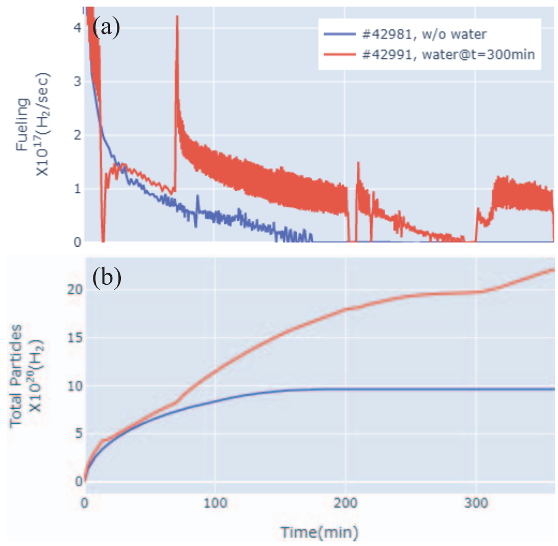

Fig. 14 (a) Fueling rate of two discharge, and (b) total fueled particles.

The Hα signal continues to fall, even after the particle supply is reduced to zero, and finally its value drops below the target value of Hα, so MFC resumes the particle supply. In this way, the vibration continues.

The cause of the sudden decrease in the Hα signal and the nonlinear response of the Hα signal to the particle supply is unknown, but hunting oscillation is occurring. In this discharge, feedback control by MFC is performed every 5 s. Vibration may be suppressed by extending the control interval and waiting for the plasma response. Hunting oscillation is self-excited and is undesirable from the equilibrium viewpoint. However, the situation seems to be a little different regarding this discharge. To show this, the difference in particle supply between the two 6 h discharges is shown in Fig. 14. As shown in Fig. 14 (b), total fueled

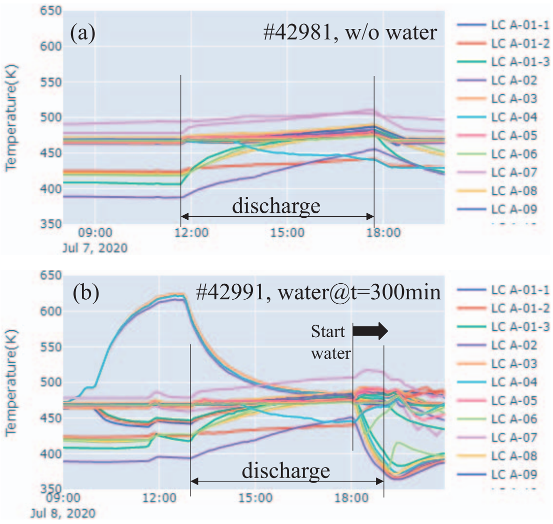

Fig. 15 Temperature change of 24 sections during 6-hour discharge of discharge number of (a) #42981 without cooling water and (b) #42991 with cooling water.

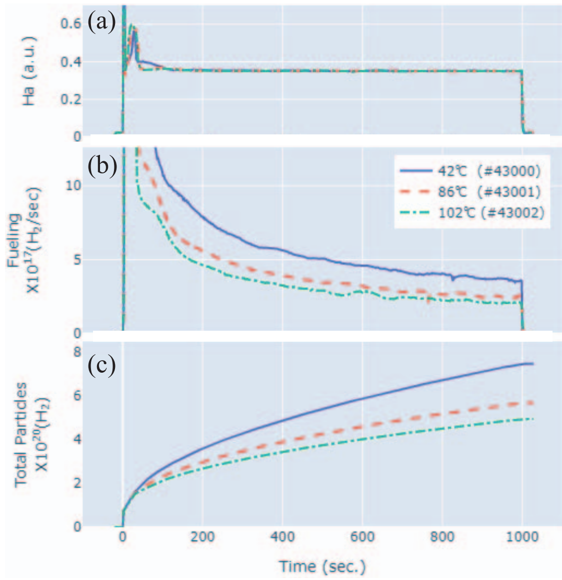

Fig. 16 Particle fueling at different CS temperatures. (a) Hα emission controlled to 0.35 (a.u.), (b) fueling rate by MFC, (c) total fueled particle.

particles are calculated from the time integration of the fueling rate of Fig. 14 (a). In shot number 42981, the particle supply by MFC became zero by 200 min ago, and the particle supply cannot be controlled after that. With discharge number 42991, particles can be supplied up to 300 min before. As shown in Fig. 14 (b), the total number of supplied particles between these two discharges is about twice as large by 300 min. It is worth noting that the particle supply rate of the two discharges is almost the same during the time when vibration is not occurring, as can be seen around 50 min, for example.

Figure 15 shows one of the causes of the difference in particle fueling between these two discharges. Figure 15 shows the temperature change of 24 sections during 6 h discharge of shot number #42981 (Fig. 15 (a)) and #42991 (Fig. 15 (b)). As shown in Fig. 15 (a), most of the sections have a temperature rise of about several tens of kelvin during discharge, or the temperature is kept almost constant. In Fig. 15 (b), the temperature of three of the 24 sections rises before the start of discharge. This is because the heater that heats the area around the thermocouple for control does not operate normally owing to disconnection or ground fault. To raise the temperature of those thermocouples, the output of the peripheral heater also increased, and the temperature of the peripheral part increased. The surface area of the upper hot wall is 4.7 m^2, and the three sections of this are 0.59 m^2. The area of the three sections is less than 3% of the total since the total surface area of the plasma-facing wall is about 23 m^2. In the actual discharge, this abnormal operation was noticed before discharge, and those heaters were stopped manually. Thus, the temperature of the corresponding three sections started decreasing before the start of discharge. Besides, the temperature decreases even during discharge. The decrease in temperature during discharge may affect particle retention, leading to improved controllability of particle fueling. This partial modification of wall temperature is a candidate for controlling the fuel particle balance since the discharge #42991 could be maintained without density raise unlike the discharge #42981.

3.3 Temperature dependence of CS

It has been stated that the preset temperature in a typical long-term discharge is 473 K, and the temperature of CS at this time is about 300 K with cooling water. In the previous CS, APS-W with a thickness of 0.1 mm was sprayed on the base material of stainless steel type 316L, but it was changed to tile-shaped stainless steel type 316 L from 2018. Figure16 shows the difference in particle fueling when the temperature of CS is changed. The temperature was adjusted by stopping the passage of cooling water, and the temperatures at the start of discharge were 42°C (315 K), 86°C (359 K), and 102°C (375 K), respectively. The target value of Hα signal was set to 0.35 (a.u.), and the plasma was discharged for 1000 s (Fig. 16 (a)). The particles can be supplied until the last 1000 s with all three discharges. Although, the surface area of CS is smaller than the surface area of the hot wall, it can be seen that the number of fueled particles decreases with an increase in temperature (Fig. 16 (b)). Owing to the temperature difference of 60°C, the particle supply amount is 1.5 times different by 1000 s (Fig. 16 (c)). Thus, the difference in CS temperature greatly affects the particles' controllability. It indicates that we had better control the CS temperature and the hot wall, and it is a future work.

4. Discussions and Summary

When cooling water was passed through the upper hot wall at a set temperature of 473 K, the temperature of the hot wall dropped and particle fueling was immediately resumed. It indicates that particle retention occurs even in a high-temperature environment of 473 K; it is essential to control the temperature of the hot wall. The radiation shield, which is not the first wall, showed a sudden temperature rise at the initial stage of discharge, but the total pressure did not change accordingly.

The total surface of the plasma-facing wall in QUEST is about 23 m^2, and the surfaces of the upper hot wall and CS are 4.7 m^2 (9.4 m^2 in the upper and lower hot wall) and 2.7 m^2, respectively. As shown in Fig. 1, the discharge is a limiter configuration plasma, and while the central part of CS strongly interacts with plasma, wall pumping seems to occur in the upper and lower parts of CS. Even if the surface area of CS is about 10% of the total, the temperature change at that location has a great influence on the total particle supply. It is considered that this is because the temperature of the CS is lower than that of other parts, or that the CS is in a solid stainless steel state without a deposition layer owing to sputtering, and these cases promote wall pumping [10].

It is of great engineering significance to raise and maintain the temperature of the hot wall of QUEST above 600 K against the operating temperature of 773 K of the fusion reactor in the future. Thus, it is possible to discharge in a situation closer to the operating temperature of the future fusion reactor. It is essential to perform a long-term discharge at a set temperature of 673 K and perform a comparative study with particle recycling at a discharge of 473 K.

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