Wall Recycling on the Superconducting Tokamak TRIAM-1M

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Abstract

The study of wall recycling of long duration discharge has been carried out using 2.45 GHz and 8.2 GHz lower hybrid current drive in the superconducting tokamak TRIAM-1M. The recycling coefficient increases with two time constants. One is 1~3 s and the other is ~30 s. These two time constants are common to low ($\sim 2 \times 10^{18} \text{ m}^{-3}$) and high ($\sim 1 \times 10^{19} \text{ m}^{-3}$) density discharges. In the ultra-long discharge, the wall repeats a process of being saturated and refreshed. One possible candidate of the mechanism of wall refreshment is co-deposition of in vessel element (i.e. Molybdenum). In the high density discharge, the wall becomes saturated and the discharge is terminated due to the density increase. The achievable discharge duration becomes shorter as the plasma density is higher.

Keywords:

wall recycling, wall saturation, particle balance, steady state operation, fueling control, superconducting tokamak

1. Introduction

Stable long pulse operation is required for the future fusion device. One of missions of ITER-FEAT is sustainment of $Q > 10$ plasma with the duration of longer than 300s [1]. Moreover, longer discharge duration will be required for a DEMO reactor. For such long plasma operation, understanding of wall recycling and global particle balance inside the vacuum vessel is one of crucial issues. So far, long plasma operation has been carried out in JET [2], Tore Supra [3], LHD [4] and TRIAM-1M [5-7].

In one minute discharge of JET, the gas supply was progressively decreased to keep the density constant during the discharge and finally it became zero around t

~40 s, as the recycling coefficient increased to and above unity [2]. In Tore Supra, uncontrollable density increase occurred during the long pulse operation [3]. As the heating power increased higher, the achievable discharge duration became shorter. The maximum pulse length of Tore Supra is 2 min. The uncontrollable density increase is considered to be caused by an out-gassing of interior elements, located far from the plasma edge, which are slowly heated by the radiated power.

In TRIAM-1M, an ultra-long discharge with the duration of longer than 2 hours was successfully demonstrated [7]. In order to achieve the ultra-long discharge, a gas fueling system and a plasma position control system were developed. For the wall

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conditioning of the plasma vacuum vessel, electron cyclotron resonance discharge cleaning (ECRDC) is carried out. It is effective for removing the oxygen and carbon from the wall, and it is important for not only the plasma production but also the ultra-long discharge [8,9]. Moreover, particle balance and wall recycling have been studied making the best use of features of TRIAM-1M. In this paper, long plasma operation, wall conditioning and wall recycling experiments in TRIAM-1M are reviewed.

2. Experimental Setup and Steady State Operation in TRIAM-1M

TRIAM-1M has 16 superconducting toroidal field coils, which are made of Nb_3Sn . Toroidal magnetic field is up to 8 T and it can be maintained continuously. The plasma vacuum vessel has a D-shaped cross-section with the horizontal length of 0.26 m and the vertical length of 0.38 m. The major radius of the center of the vacuum vessel is 0.84 m. The whole machine is installed inside a bell-shaped vacuum vessel (i.e. a bell-jar) for thermal insulation.

Plasma facing components are made of high Z materials only, i.e., a stainless steel vacuum vessel, molybdenum poloidal limiters and molybdenum divertor plates. Low Z material is not utilized as a plasma facing component and low Z coating has never been carried out at all. Working gas is hydrogen.

Three lower hybrid current drive (LHCD) systems are installed on TRIAM-1M. One is 2.45 GHz LHCD system with the maximum power of 50 kW and the others are 8.2 GHz LHCD systems with each maximum power of 200 kW. Steady state and long duration discharge can be sustained by LHCD power alone.

Three piezoelectric valves are utilized for gas fueling control as shown in Fig. 1. The piezoelectric valve “A” in the figure is for control of the filling pressure inside the vacuum vessel. The piezoelectric valve “B” is used for initial phase of plasma production and for additional gas puff during the discharge. The piezoelectric valve “C” is used for long pulse operation. We have improved the fueling system by adopting feedback control using H_α line intensity as a monitor of the plasma density because there is a possibility of failure in counting the number of fringes of the interferometer for density measurement at the plasma breakdown. The applied voltage of the piezoelectric valve C is feedback controlled to keep the H_α line intensity constant. The H_α line intensity is related with the number of hydrogen atoms that are ionized per unit

Fig. 1 Fueling control system in TRIAM-1M.

Fig. 2 Line-averaged electron density versus H_α line intensity at the central chord [7].

time, i.e., influx to the plasma. In the steady state condition, the line-averaged electron density is proportional to the H_α line intensity as shown in Fig. 2. A typical example of the fueling control is shown in Fig. 3. The plasma current is sustained by 2.45 GHz LH power. It is found that the H_α line intensity follows a preprogrammed waveform (dotted line) as shown in Fig. 3(b) and also the line-averaged electron density is similar to the H_α line intensity.

We also developed the plasma position control with an image processing system to obtain TV images of the plasma cross-section and the poloidal limiter [7]. At the initial phase ($t < 5$ s) of the discharge, the plasma position is feedback controlled by a conventional

Fig. 3 Typical example of gas fueling. Time evolution of (a) plasma current, (b) H_{α} line intensity (solid line) and the reference level preprogrammed (broken line), (c) line-averaged electron density and (d) applied voltage to the piezoelectric valves. Thin and thick lines in the Fig. (d) indicate the applied voltage of the piezoelectric valves "B" and "C" in Fig. 1, respectively.

method with magnetic coils to obtain a fast response of feedback loop. After achievement of steady state condition, magnetic sensors are switched from the magnetic coils to Hall effect sensors, which can directly measure the local magnetic field and are free from drift problem of an analog integrator. In such feedback control, however, the heat flux from the plasma concentrates on a certain area of the poloidal limiter, since the plasma position is fixed. The image processing system can detect the position and the brightness of the interacting area (i.e. hot spot) between the plasma and the poloidal limiter from the TV image. It sends the signal to the feedback control system to change the "reference position" of the feedback control according to the position and the brightness of the hot spot. The plasma is moved so as to prevent the heat flux from concentrating on a certain area of the poloidal limiter.

Fig. 4 Progress of steady state operation using 2.45 GHz LHCD in TRIAM-1M [10].

The progress of steady state operation on TRIAM-1M is summarized in Fig. 4. These discharges were maintained by 2.45 GHz LH power. There are three steps. In the first step, 3 min discharge was achieved using low drift integrators for the position control. The discharge duration was restricted due to accumulation of the drift of the integrator. In the next step, one-hour discharge was achieved using Hall effect sensors as magnetic sensors. However, the plasma position was manually shifted by changing the "reference position" of the feedback control system to avoid the hot spot. The gas fueling was also adjusted manually. In such manual control, achievement of long discharges depends on "know-how" of an operator. In order to avoid these manual control, a fueling control system using H_{α} line intensity and position control with the image processing system were developed as described above and finally the ultra-long discharge with the duration of longer than two hours was successfully demonstrated.

3. Wall Conditioning

In TRIAM-1M, a period of experimental campaign is normally 3 months. Wall conditioning is carried out just before the experimental campaign. At first, extension ports, which connect between the plasma vacuum vessel and the bell jar, are heated up to 110 °C for 2 days. The vacuum vessel is not heated up to avoid thermal load to the cryogenic system. ECRDC is, therefore, carried out for conditioning of the plasma vacuum vessel. The duration of ECRDC is also 2 days. The ECR plasma is generated by the microwave power up to 1 kW supplied by a magnetron with the frequency of 2.45 GHz. The electron density and temperature of the ECR plasma are $\sim 2 \times 10^{16} \text{ m}^{-3}$ and $\sim 6 \text{ eV}$, respectively. The time evolution of the partial pressure of the mass number 18 (H_2O) and 28 (C_2H_4 and/or CO) are shown in Fig. 5. It is found that oxygen and carbon can be removed well from the surface of the first wall by ECRDC. The good wall condition is considered to be

Fig. 5 Time evolution of ion current of mass number 18 (closed circles) and 28 (open circles). Closed and open squares show the partial pressure of mass number 18 and 28 without ECRDC, respectively. The background level of ion current corresponds to 4.0×10^{-7} A for the mass number 18 and 4.5×10^{-8} A for mass number 28 [9].

obtained by ECRDC, since the plasma resistivity of the first ohmic heated plasma is same as that of the final plasma of the experimental campaign where the wall is exposed to the tokamak plasma for totally longer than 7,000 s [9].

4. Global Particle Balance

4.1 Wall recycling

The first wall is exposed to heat and particle loading. The particle flux from the plasma to the wall consists of charge exchange neutrals (i.e. fast neutrals) and diffused ions. Some of them are reflected (ions are neutralized at the wall) and the others are trapped in the wall with the release of the particles which have already been trapped. By these recycling processes, out-flux from the plasma comes back to the plasma. The ratio of in-flux to out-flux on the plasma surface is a recycling coefficient. It is obtained from the following particle

Fig. 6 Time evolution of the recycling coefficients of 2.45 GHz LHCD (triangles) and 8.2 GHz LHCD (circles) plasmas [11].

balance equation inside the plasma,

$$dN_e/dt = \eta S_g + (R-1)N_e/\tau_p, \quad (1)$$

where N_e is the total number of electrons, η is the fueling efficiency, S_g is the gas supply rate by the piezoelectric valve, τ_p is a particle confinement time.

Wall recycling properties of the long duration discharge have been investigated in 2.45 GHz and 8.2 GHz LHCD plasmas in TRIAM-1M. The time evolutions of recycling coefficients of both discharges are shown in Fig. 6. The line-averaged electron densities of 2.45 GHz and 8.2 GHz LHCD plasmas are $0.2 \times 10^{19} \text{ m}^{-3}$ and $0.9 \times 10^{19} \text{ m}^{-3}$, respectively. Both recycling coefficients increase with time. It means that the particle flux from the wall increases with time, namely, the wall is gradually saturated. Solid lines in Fig. 6 are drawn using the following equation to fit the data,

$$R(t) = 1 - R_1 \exp(-t/\tau_1) - R_2 \exp(-t/\tau_2). \quad (2)$$

The values of τ_1 and τ_2 are 1.3 s and 32 s for 2.45 GHz LHCD plasma, and 3.1 s and 35 s for 8.2 GHz LHCD plasma, respectively [11]. It seems to exist two common processes in change of wall recycling at the first one minute of low and high density discharges.

4.2 Experiment of vacuum pumping and gas fueling termination

Particle balance equation for hydrogen atoms inside the plasma vacuum vessel can be written as

$$dN_H^0/dt + dN_H^p/dt = S_g - S_{\text{pump}} - S_{\text{wall-pump}}, \quad (3)$$

where N_H^0 and N_H^p are the total numbers of hydrogen neutral atoms in the vessel and hydrogen ions in the plasma, respectively, S_{pump} is pumping rate by the external pump-unit and $S_{\text{wall-pump}}$ is wall pumping rate. In order to make wall properties clear, an experiment was carried out, on which vacuum pumping and gas fueling were switched off during the discharge [12]. As shown in Fig. 7, the gas fueling was stopped just after closing the gate valve to the pump-unit at $t \sim 33$ s. The plasma was sustained by 2.45 GHz LH power alone. The line-averaged electron density decreased from $1.5 \times 10^{18} \text{ m}^{-3}$ to $1.0 \times 10^{18} \text{ m}^{-3}$ during 6 s after stopping the gas fueling and afterwards it became constant. The plasma current also decreased from 24 kA to 18 kA due to the density decrease. The recycling coefficient must be unity after $t \sim 40$ s from a viewpoint of the particle balance as shown in equation (1), since the density is constant without gas fueling. The wall never pumped at all in that period.

Moreover, additional gas puff was carried out four times ($t \sim 50, 54.5, 61, 68$ s) as shown in Fig. 7(f). The

Fig. 7 Time evolution of 2.45 GHz LHCD discharge (RF power ~ 18 kW). The gas fueling is stopped just after closing the gate valve to the pump-unit at $t \sim 33$ s [12].

electron density increased just after the gas puff but it came back to the former level within ~ 2 s. The neutral gas pressure inside the vacuum vessel also increased just after the gas puff and it decreased to the former level within ~ 5 s. From a viewpoint of particle balance in the vessel, it means that the hydrogen atoms supplied by the gas puff are pumped again by the wall although the wall does never pump before the gas puff. The fluxes of the diffused ions and charge exchange neutrals to the wall are considered to increase due to density rise by the additional gas puff. The increase in those fluxes enhances the wall pumping.

5. Wall Pumping and Wall Saturation Phenomena

5.1 Wall pumping of ultra-long discharge

In this section, wall pumping properties are investigated in an ultra-long discharge with the duration of 70 min. Waveforms of the discharge are shown in Fig. 8. The plasma current is about 20 kA. It can be seen that gas fueling is automatically stopped many times during the discharge, since the H_α line intensity increases above a preprogrammed level. It means that the recycling coefficient becomes unity or more and again decreases below unity, i.e. the wall seems to repeat a process of being saturated and refreshed. The time evolutions of the total number of gas fueling (solid line) and the particles evacuated by the external pump-unit (broken line) are shown in Fig. 8(d). From a viewpoint of particle conservation law, the difference (indicated by "B" in the figure) between the two lines means the number of the particles pumped by the wall. The averaged wall pumping rate from 10 to 40 min is about $1.5 \times 10^{16} \text{ atoms m}^{-2} \text{ s}^{-1}$. It is evaluated from the difference between the slopes of the solid and the broken lines in Fig. 8(d). About 3×10^{20} hydrogen atoms are pumped by the wall for 70 min.

In such long discharge, wall condition continues to change during the discharge as follows: (1) The temperature of the wall changes with a characteristic time of 5 to 30 min as shown in Fig. 9. The temperature increase causes increase in out-gassing. (2) High energy charge exchange neutrals causes the radiation damage, which provides a new particle-trap area. (3) Co-deposition of in-vessel elements, so called "tokamakium", also occurs during the discharge [13]. Co-deposition layer provides the fresh surface. Strong radiation damage and the "tokamakium" have practically been observed in TRIAM-1M [14]. In the surface probe experiment on TRIAM-1M, micro-structure of the "tokamakium" was

Fig. 8 Time evolution of (a) plasma current, (b) H_α line intensity, (c) gas feed rate and (d) total numbers of hydrogen atoms supplied by the piezoelectric valve (solid line) and hydrogen atoms evacuated by the external pump-unit in the ultra-long discharge [11].

Fig. 9 Time evolution of the temperature of the plasma vacuum vessel in the ultra-long discharge as shown in Fig. 8.

observed and its properties concerning with hydrogen retention were studied [15]. A major element of the “tokamakium” is Mo, which is a material of poloidal limiter and divertor plates. The “tokamakium” is considered to be formed by the co-deposition of Mo with O because of its crystal structure (not normal bcc but fcc-like). The co-deposited material of Mo with O can retain one order larger amount of the hydrogen than normal Mo [14,15]. It is one candidate for the refreshment of the wall (“refreshing wall” [16]).

5.2 Wall saturation phenomenon

In the ultra-long discharge, the wall becomes saturated and refreshed. In the high power and high density discharge of 8.2 GHz LHCD, however, the wall saturates and does not recover as shown in Fig. 10. Although the piezoelectric valve was not calibrated in this discharge, typical wall pumping rate of 8.2 GHz LHCD is about 30 times higher than that of 2.45 GHz LHCD [11]. The intensity of H_α line follows a pre-programmed reference level until $t \sim 40$ s. After that, the H_α line intensity increases over the reference level and it cannot be controlled at all even by closing the piezoelectric valve. The plasma current decreases due to the density increase, since the RF power is constant. At last, the plasma cannot be sustained by the RF power alone. The achievable discharge duration depends on the plasma density as shown in Fig. 11. It becomes shorter as the plasma density is higher. This dependence should be attributed to increase of particle loading due to the

Fig. 10 Time evolution of (a) plasma current and line-averaged electron density, (b) H_α line intensity and the reference level for feedback control (broken line) and (c) the voltage of piezoelectric valves in the wall saturation discharge [11].

Fig. 11 The restriction of discharge duration due to the wall saturation as a function of the line averaged electron density [11].

plasma density increase.

The results of the wall pumping and the wall saturation in this section seems to depend on the balance between the particle flux (recycling, out-gassing) from the wall and the wall pumping ability, which continue to change during the discharge as described above.

6. Summary

In TRIAM-1M, long duration and steady state plasma operation has been demonstrated using 2.45 GHz and 8.2 GHz LHCD on the basis of developments of plasma position and fueling systems. ECRDC, which is carried out just before the experimental campaign, is effective for eliminating the oxygen and carbon from the wall surface and is important for not only plasma production but also long-time plasma operation.

The recycling coefficients increase with two common time constants in low ($0.2 \times 10^{19} \text{ m}^{-3}$) and high density ($\sim 1 \times 10^{19} \text{ m}^{-3}$) discharges. One is 1~3 s and the other is ~30 s. It is found that the wall pumped the hydrogen atoms supplied by additional gas-puff even when the recycling coefficient is unity and the wall pumping rate is zero. It suggests that the increase in fluxes of the diffused ions and charge exchange neutrals enhance the wall pumping.

In the ultra-long discharge, interesting phenomenon of wall recycling was observed. The gas fueling was automatically stopped several times during the discharge by feedback control to keep the H_α line intensity

constant. It means that the wall repeats a process of being saturated and refreshed. One possible candidate for the mechanism of wall refreshment is co-deposition of Mo (i.e. in-vessel element) with O. In the high density discharge, the wall becomes saturated and the discharge is terminated due to the density increase. The achievable discharge duration becomes shorter as the plasma density is higher.

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