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Impurity desorption behavior from low activation ferritic steel installed in the JFT-2M tokamak

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Abstract

Compatibility of a low activation ferritic steel, F82H, with plasma has been investigated in the JFT-2M tokamak with three stages. The tokamak experiments in the third stage have just started, where the vacuum vessel is fully covered with the ferritic steel. Prior to the tokamak experiment, vacuum properties of F82H were investigated using a test-stand. The outgas rate is less than 6×10^{-8} Pa m^3/sm^2 after baking at 120 °C for 10 days. As is predicted from the results, the base pressure of 6×10^{-6} Pa, which is the same as the previous level, was obtained in JFT-2M. In spite of the magnetic effect, the Taylor discharge was obtained without any difficulties and removal of oxygen was clearly observed. Tokamak discharges were obtained with the ferritic steel wall. The improved confinement mode (H-mode) was obtained with a neutral beam of 800 kW with a single-null divertor configuration. Within the preliminary results, the radiation loss did not increase due to the ferritic steel wall.

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1. Introduction

Low activation ferritic steel is a leading candidate for a blanket of a demo-reactor [1,2]. However, it is ferromagnetic material, and thus, there is some concern that the plasma confinement and stability might degrade due to the error field. In addition, impurity release might be a problem because the ferritic steel easily rusts in the air and oxygen retention is several times larger than that of stainless steel [3]. Thus, it is important to investigate the compatibility with plasma, before installation in a reactor. As for the vacuum properties, it was demonstrated by test-stand experiments that the outgas rate is less than 10^{-8} Pa m^3/sm^2 with pre-baking at 350 °C and in situ baking at 250 °C [4]. The rate is sufficiently low for tokamak devices, as demonstrated in HT-2 [5]. However, the oxidation during exposure to air and the resulting degradation of the vacuum properties might be a critical issue for the application. The impurity release during a plasma discharge might also be a problem because the retained oxygen might be released due to chemical and physical sputtering.

In the JFT-2M tokamak ($R = 1.31$ m, $a = 0.35$ m, $B_T < 2.2$ T) [6], ferritic steel plates (FPs) have been installed step by step to investigate the compatibility with the plasma mainly in terms of ferromagnetism and impurity desorption [6,7]. In the first stage, the FPs were installed outside the vacuum vessel (VV). The magnetic effect of the ferritic steel was investigated separately from the impurity desorption [6,7]. In the second stage, about 20% of the VV was covered with FPs to make a

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preliminary investigation of the compatibility of the ferritic steel with plasma [6,7]. It was demonstrated that both the magnetic effect and the impurity release aren't remarkable [6,7] with the proper treatment of FPs according to Ref. [4] and a quick installation lasting ~10 days. Now, we finished the second stage and just entered the third (final) stage, where the VV is fully covered with FPs. The plates are installed along the VV keeping the plasma facing surface 30 mm from the VV. Almost all of the in-vessel components such as magnetic probes and graphite limiters are replaced with new ones without major changes in their configuration [6,7]. The position of the graphite tiles is 50 mm from the FPs. The high filed side was fully covered. The divertor region and low field side were covered discretely. It took almost a year for the installation. Though the same treatment was applied to the FPs before the installation, the larger surface area and the longer duration of installation compared to the second stage might increase the impurity level. To check the effect, the vacuum properties of the FPs were investigated in a test-stand. The results are summarized in Section 2. The behavior during conditioning (pumping and discharge cleaning) and tokamak discharges of JFT-2M is shown in Sections 3 and 4, respectively.

2. Investigation of vacuum property in a test-stand

The main chamber of the test-stand was made of stainless steel (400 mm in diameter, 400 mm in height, and 1 m^2 in surface area). It is pumped by a turbomolecular pump (300 l/s) and a rotary pump. The pumping line is equipped with a gate valve and the effective pumping speed is ~100 l/s. The total and partial pressure are measured by an ion gauge and a quadrupole mass spectrometer, respectively.

The ferritic plates (FPs), which are actually installed in JFT-2M and exposed to the air for 2 months, are used as the sample. They rust slightly during the installation process and the oxidized layer was removed with a wire brush. The typical size of the FP is $300 \times 300 \times 6$ mm^3 ($W \times D \times t$). Several plates are inserted in the main chamber. The total surface area of the samples is 1.3 m^2, which is comparable to that of the main chamber. The vacuum property of the graphite tiles was also investigated. Several tiles with a typical size of $240 \times 240 \times 20$ mm^3 ($W \times D \times t$) were installed in the chamber and the surface area was 1.2 m^2.

The experimental procedure is as follows: (1) the main chamber is baked at 140 °C to reduce the back ground pressure, (2) vented with N_2 gas, (3) the samples are installed (~30 min), (4) pumped for 3 days, (5) baked at 120 °C for 10 days, and then, (6) cooled down. The time evolution of the total and partial pressure are measured automatically with an interval of 10 s. The mass pattern and the outgas rate without pumping are measured once a day.

Fig. 1 shows the time evolution of the total pressure before the baking. The pressure with FPs and graphite tiles are almost the same and higher than that without samples. The mass patterns are shown in Fig. 2. The main residual gas component from the FPs and the graphite are H_2O and C_xH_y, respectively. The outgas rate estimated from the base pressure is $3 \sim 5 \times 10^{-7}$ Pa m^3/sm^2. To distinguish a diffusion limited process (like H_2, CO, etc.) and the equilibrium state of absorption and desorption (like H_2O), the outgas rate without pumping is also measured. The partial pressure of mass 18 saturates and those of mass 2 and 28 increase linearly. The rates are summarized in Table 1. The base pressure of the gas species in the equilibrium state depends on the

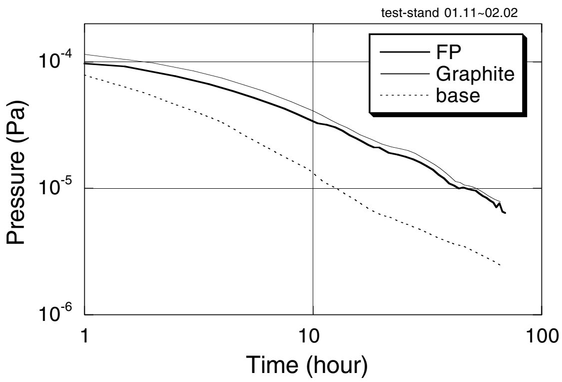

Fig. 1. Time evolution of the total pressure of the vacuum test-stand without a sample (base), with ferritic steel, and with graphite before baking. The pressure with a sample is higher than that without a sample.

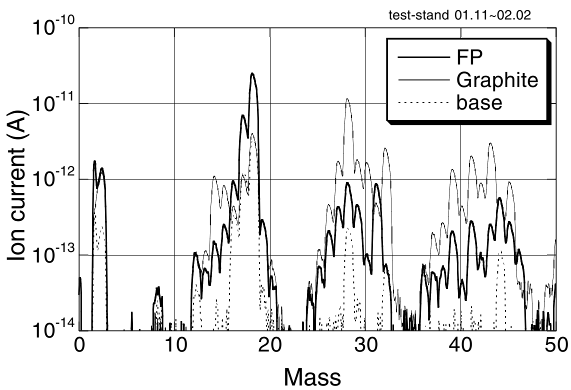

Fig. 2. Mass patterns of cases without a sample (base), with ferritic steel, and with graphite before baking. Main components are H_2O and C_xH_y for ferritic steel and graphite, respectively.

Table 1
Vacuum properties before baking

	Total pressure (Pa)	Outgas with pump ($Pa\,m^3/sm^2$)	Outgas w/o pump ($Pa\,m^3/sm^2$)	Prediction in JFT-2M (Pa)
FP	6.4×10^{-6}	3×10^{-7}	4×10^{-8}	4×10^{-6}
Graphite	7.8×10^{-6}	5×10^{-7}	5×10^{-7}	9×10^{-6}

Table 2
Vacuum properties after 120 °C baking for 10 days

	Total pressure (Pa)	Outgas with pump ($Pa\,m^3/sm^2$)	Outgas w/o pump ($Pa\,m^3/sm^2$)	Prediction in JFT-2M (Pa)
FP	6.7×10^{-7}	$\ll 9 \times 10^{-8}$	6×10^{-9}	8×10^{-8}
Graphite	6.7×10^{-7}	$\ll 9 \times 10^{-8}$	1×10^{-8}	8×10^{-8}

ratio of the pumping speed and the surface area [8]. This ratio is almost identical for the test-stand and JFT-2M, hence, the base pressure should be the same. The total outgas through the diffusion limited process is simply proportional to the surface area. The base pressure with JFT-2M conditions can be predicted from the above experiments. The numbers are indicated in Table 1.

During the 120 °C baking, H_2O and C_xH_y are mainly released from the FPs and the graphite, respectively. The desorbed amount is estimated to be $\sim 10^{21}$ molecules/m^2 in both cases. After baking, the base pressure became 6.7×10^{-7} Pa in both cases, and the mass pattern is almost identical. The main residual gas component was H_2O. It means that the base pressure was defined by desorption of H_2O from the chamber and the outgas from the samples was much smaller than that. Similarly to the case before baking, the outgas rates are summarized in Table 2. The rates are comparable to the values reported in Ref. [4]. It means that the outgas rate is not degraded by exposure to air for 2 months and the slight oxidation of the surfaces. The predicted values for JFT-2M are much smaller than the typical base pressure (6×10^{-6} Pa).

3. Behavior during wall conditioning of JFT-2M with full coverage FPs

The evacuation of JFT-2M with full coverage by FPs started with encouraging results up to now. Baking at 120 °C for 3 weeks and Taylor discharge cleaning, TDC (during the baking) for 27 h were applied, which is the conventional evacuation procedure at JFT-2M. The time evolution of the total pressure is shown in Fig. 3. The pressures during baking are highest in the case without ferritic steel. The total pressures after the baking are almost identical in all cases. The total pressure before and during the baking depends on the activities during an air vent, and thus, it is not reproducible. The

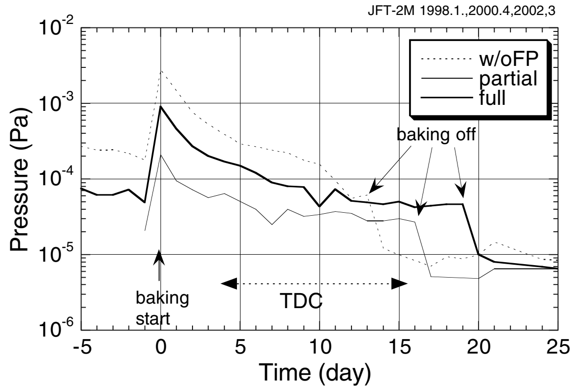

Fig. 3. Time evolution of total pressure during initial pumping of JFT-2M with full coverage by ferritic plates (FPs). For comparison, the behavior in the cases with partial coverage by FPs and without FPs is shown.

obtained base pressure (6×10^{-6} Pa) is a typical value of the JFT-2M. Thus, it is concluded that the base pressure is affected by neither the full coverage by FPs nor the graphite tiles, as is predicted from the results in Section 2.

Another concern with the ferritic wall is the effect of the ferromagnetism on plasmas during discharge cleaning. The vertical field is shielded by the FPs. The toroidal field is also affected mainly by the stray field from the port sections. In the case of TDC (magnetic field $\sim$0.1 T), the toroidal field ripple increased from 2% to 20% at the low field side, which was measured by a 3D magnetic measurement system [7]. So, it was afraid that the Taylor discharge cleaning (TDC) could not obtain or is not effective for wall conditioning. However, the initial TDC was performed without any difficulties. The discharge conditions are as follows; working gas: H_2, pulse length: $\sim$10 ms, interval: 0.7 s, pressure: 2×10^{-4} Pa. Fig. 4 shows the behavior of the water vapor desorption after the ignition of the TDC. The desorption rate was

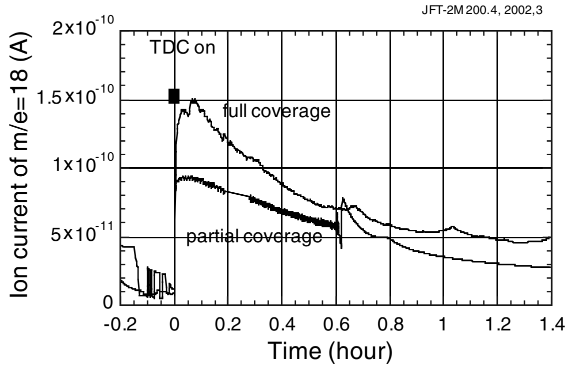

Fig. 4. Time evolution of the ion current at $m/e = 18$ around the beginning of TDC. The pressure clearly increases, which means that oxygen is removed from the wall by the TDC.

higher with the full coverage by FPs. The partial pressures of CO and CO_2 showed similar behavior. It is difficult to compare the effects of the discharge cleaning directly because both wall materials and the plasma characteristics had changed. However, it can be concluded that the TDC showed certain effects for wall conditioning, even when the VV is fully covered with ferritic steel. A glow discharge with helium had also been used mainly for the reduction of a hydrogen recycling. There was some concern that the discharge was affected by the residual magnetization of the wall. However, it ignited without difficulties and it was effective for the reduction of hydrogen recycling.

4. Effect of ferritic steel on tokamak discharge

Tokamak discharges were obtained without a marked change in the plasma control system. This

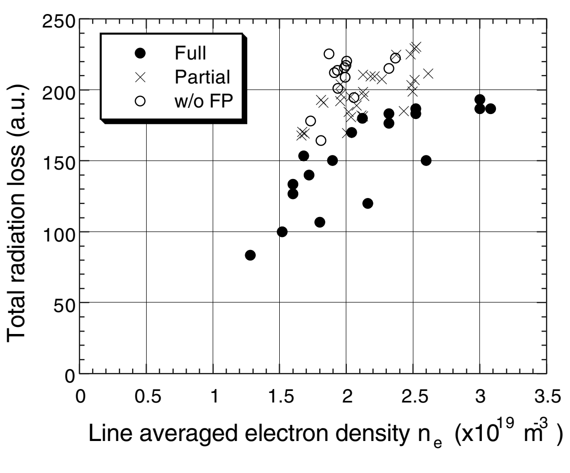

Fig. 5. Total radiation loss against line averaged electron density. The radiation loss rather decreases with full coverage by FPs.

agrees with calculated results showing that the effect of ferritic steel on the magnetic sensors is in the order of several percent. The total radiation loss before and after (partial and full) the installation of the ferritic steel is shown in Fig. 5 in the case of ohmically heated plasma in a single-null divertor configuration ($B_T = 1.3$ T, $I_p = 200$ kA, duration ~ 1 s). The radiation loss rather decreased with the full coverage by FPs. It means that the impurity release from the FPs is not large. The small improvement of the radiation is probably due to the replacement of the graphite tiles. The improved confinement mode (H mode) was obtained with a neutral beam of 800 kW in a single-null divertor configuration. Thus, no remarkable effect of the ferritic steel on the plasma discharges has been observed in the JFT-2M.

5. Summary

The vacuum properties of the low activation ferritic steel, F82H, were investigated with a test-stand. The ferritic plates (FPs), which were installed in JFT-2M and exposed to air for 2 months, were used as samples. The outgas rate was less than 6×10^{-8} Pa m^3/sm^2 after baking at 120 °C for 10 days. The rate seems to be comparable to the value reported in Ref. [4]. It means that the outgas rate did not increase due to exposure to air for 2 months and the slight oxidation of the surfaces. The vacuum property of graphite tiles was also measured. The outgas rate after the baking is 1.3×10^{-8} Pa m^3/sm^2. These values are sufficiently low for the JFT-2M tokamak.

The ferritic steel had been installed inside the JFT-2M tokamak, by which the inside of the VV was fully covered, after the encouraging results in the vacuum test and partial coverage. As for the conditioning of JFT-2M, the base pressure of 6×10^{-6} Pa, which is the same as the previous level obtained with the conventional procedure, namely, 120 °C baking and TDC. In spite of the magnetic effect, the Taylor discharge was performed without difficulties and removal of oxygen from the surface was clearly observed.

Tokamak discharges were obtained without marked changes in the plasma control system. The improved confinement mode (H mode) was obtained with neutral beam heating of 800 kW in a single-null divertor configuration. According to preliminary results, the radiation loss did not increase with ferritic steel wall.

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