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Impurity release and deuterium retention properties of a ferritic steel wall in JFT-2M

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Abstract

Impurity release and the deuterium retention properties of the low activation ferritic steel, which is a candidate material for a demo-reactor, have been studied in the JFT-2M and in the laboratory. In the case when the inside vacuum vessel wall is fully covered by ferritic steel plates, enhancement of the oxygen influx and the emission of iron ion lines were not observed. This means that the impurity release from the ferritic steel has no deleterious effect on JFT-2M. From irradiation experiments, the retained amount of deuterium in the sample with an oxide layer was one order of magnitude larger than that of the mechanically polished sample for the low fluence case. However it became comparable at the high fluence case, and was roughly the same as that of SUS-316L. Retained amount of deuterium in the sample exposed to JFT-2M plasmas was similar to that exposed to the deuterium ion beam.

1. Introduction

Low activation ferritic steels are a leading candidate structure materials for a fusion demonstration reactor [1]. But a concern is that not only iron but also oxygen impurity concentration in plasma might increase because of the steels easy oxidation in the atmosphere. Therefore, compatibility of ferritic steels with high performance plasmas has been studied step-by-step (three stages: outside vacuum vessel wall plates, partially covered inside vacuum vessel wall, and fully covered inside vacuum vessel wall) in JFT-2M under the Advanced Material Tokamak Experiment (AMTEX) project [2–5]. The results of the second stage were presented in previously [2], and showed that the impurity release from the ferritic steel, F82H (8%Cr, 2%W), is not large. However, enhancement of the impurity release in the third stage was still a concern because the surface area is larger (20–100% coverage) and the duration of the installation is longer (10 days to 6 months). To investigate this effect, the impurity behavior has been studied mainly by spectroscopic measurements.

The deuterium retention properties were another important issue with the ferritic steel because it affects the fuel hydrogen recycling and the tritium inventory. These have not been sufficiently investigated so far. The deuterium retention properties of the F82H steels have been also studied by thermal desorption spectroscopy (TDS). Samples for this analysis were prepared in the laboratory (1.7 keV D^+ beam) and JFT-2M. The ferritic steel panels in JFT-2M were exposed to charge exchange neutral, lost fast ions and so on (see 'Experimental set-up'). The ion irradiation experiments in the laboratory

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were carried out in order to examine the deuterium retention of the F82H steels under this situation. The deuterium retention of the F82H was also compared with that for 316L stainless steel and graphite, which have been widely used in various fusion devices [6,7].

2. Experimental setup

The JFT-2M is a medium size tokamak (the major radius $R = 1.31$ m, minor radius $a = 0.3$ m, elongation $\kappa < 1.7$, toroidal magnetic field $B_t < 2.2$ T). Fig. 1 shows schematic drawing of the installation of ferritic steel plates in the second (a) and the third stage (b). JFT-2M has a D-shaped vacuum vessel made of stainless steel (SUS-304L). Two heating neutral beams are injected almost tangentially with major radius of 1.31 m (co- and ctr-). In the second stage (partial coverage), the ferritic steel plates (F82H) were placed at shoulder position of the outer vacuum vessel wall (about 20% of inside vacuum vessel wall). In the third stage, ferritic steel plates were placed along the vacuum vessel with a stand-off distance of 30 mm on the whole inside wall except for the diagnostic ports. Graphite guard tiles were installed on ferritic steel plates. The configuration of graphite tiles in the third stage is similar to that in the second stage, namely, they are placed continuously in the high field side, and discretely in the weak field side. Graphite limiters are also placed discretely. In this geometry, ferritic steel plates are located at 20 mm behind the limiter in the second stage and 50 mm in the third stage, respectively. Therefore, the plasma mainly interacts with graphite tiles, but weak plasma in the limiter shadow, charge exchange neutrals, and lost fast ions can interact with ferritic steel plates.

Impurity behaviors in JFT-2M plasma were observed by using the fiber-optically coupled Czerny-Turner visible spectrometer (focal length 1 m) and the flat-field VUV spectrometer (at the third stage alone). Both spectrometers view the equatorial plane from horizontal ports. A detector used in the spectrometers was an intensified multi-channel photodiode array. The time resolution of the spectrometer was >10 ms which was limited by the scan time of the detector. During these experiments, the time resolution of VUV spectrometer was set at 100 ms in order to integrate weak impurity ion lines for a long time. The total radiation losses were measured by the bolometer. The time evolution of line-averaged electron density was measured by a 2 mm μ-wave interferometer.

For the irradiation study, small samples of F82H were placed on the first wall of JFT-2M and exposed to the deuterium discharge. The total number of discharge shots was approximately 300. After plasma exposure, the amounts of retained deuterium in these samples were measured by the TDS method.

Two kinds of F82H samples were prepared for the ion irradiation experiments, one was exposed to the atmosphere for several years and the other was mechanically polished in the laboratory. For the mechanical polished sample, degassing at 500 K for 2 h was conducted in a vacuum. The sample was irradiated by deuterium ions using the ECR ion source [8]. The energy of the deuterium ion was 1.7 keV and the flux was $\sim 10^{14}$ D/cm^{2}s. The irradiation temperature was room temperature. Dependence on ion fluence was measured between 1×10^{18} and 7×10^{18} D/cm^2. After irradiation, the amount of retained deuterium was measured by the TDS method. The sample was heated from room temperature to 1073 K with a ramp rate of 0.5 K/s. The desorption rate of deuterium was quantitatively measured by using a quadrupole mass spectrometer (QMS) [9]. The retained amount of deuterium was obtained by integrating the desorption rates for

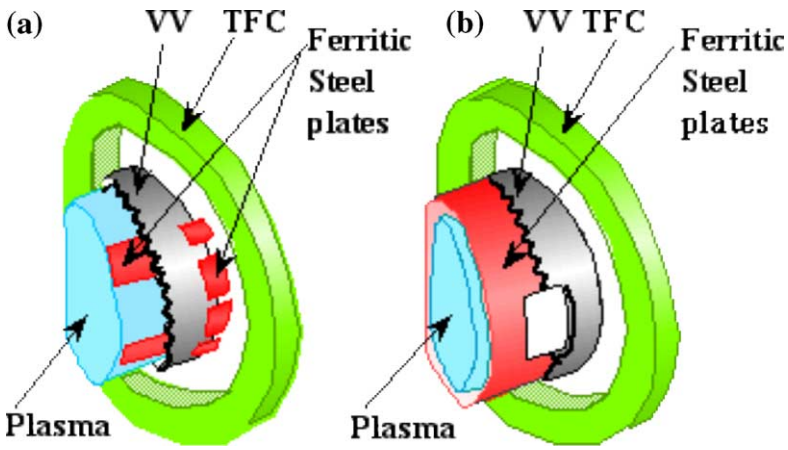

Fig. 1. Schematic drawing of the installation of ferritic steel plates in the second (a) and third stage (b). The vacuum vessel (VV) was made of staineless steel (SUS-304L).

gases containing D with respect to the heating time. The depth profile of atomic composition was also examined by Auger electron spectroscopy, AES, before and after the irradiation, in order to investigate the effects of surface impurity layers on the deuterium retention.

3. Experimental results

Wall conditioning procedures were almost the same in the 2nd and 3rd stages. First the vacuum vessel was baked at 120 °C for 3 weeks. The Taylor-type discharge cleaning (TDC) was performed during the baking for about 27 h. Finally He-GDC (TDC in 2nd stage) was performed for about 6 h at the room temperature. After the wall conditioning, stable tokamak discharges were obtained without marked difficulties in ether limiter or divertor configurations with ohmic and neutral beam (NB) heating.

Fig. 2(a) shows observed spectra of wavelengths from 370 to 377 nm in the second (dotted line) and the third stage (solid line) and Fig. 2(b) shows that from 1 to 12 nm in the third stage. In this wavelength region lower to higher ionized oxygen ion lines were observed during NBI heating. In the electron temperature range for the JFT-2M plasma ($T_{e0} \leqslant 1.5$ keV and $T_{eedge} \sim$ several 10 eV), the O II, O III and O IV lines were emitted mainly from the scrape-off layer, on the other hand, O VII and O VIII lines were emitted from the core region. From Fig. 2(a), emissions from lower ionized oxygen ion lines in the third stage were not enhanced. This result suggests that the oxygen impurity influx in the third stage was not larger than that in the second stage. In previous JFT-2M experiments [10], we could observe several iron ion lines such as Fe X, Fe XIV, Fe XV, Fe XVI, Fe XVIII, Fe XIX. Fig. 2(b) shows that emissions of those iron ion lines are under the detectable level. This result suggests that the iron impurity release from ferritic steel plates was not so serious even in the third stage.

To investigate the impurity release for wider heating power range, the total radiation loss is plotted as a function of the total input power in Fig. 3(a). The loss was almost identical in 2nd and 3rd stage during both ohmic heating and NB heating. In the cases of high heating power discharges, ELM-free H-mode was obtained, in which impurity ions such as oxygen, carbon and iron were accumulated in the core region of the plasma and highly ionized ion density increased throughout the plasma cross-section [10]. To investigate more precisely, the line-integrated intensity of impurity ion lines from the core region is plotted in Fig. 3(b) as a function of the total radiation loss in the third stage. The emissions of O VII and O VIII increased almost linearly with the radiation loss. On the other hand, emissions of carbon ion lines such as CVI and CV did not increase

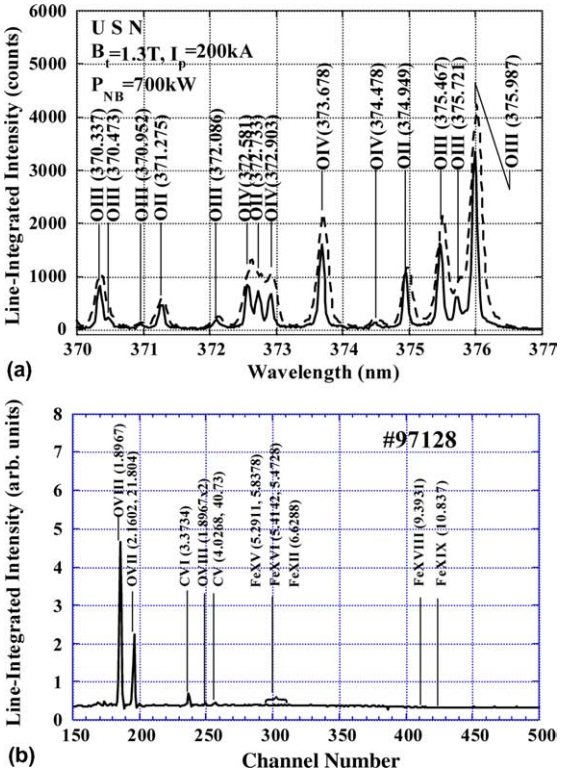

Fig. 2. Observed spectrum of wavelengths range from 370 to 377 nm (a) and from 1 to 12 nm (b). The solid line denotes third stage operation and a dotted line denotes second stage operation.

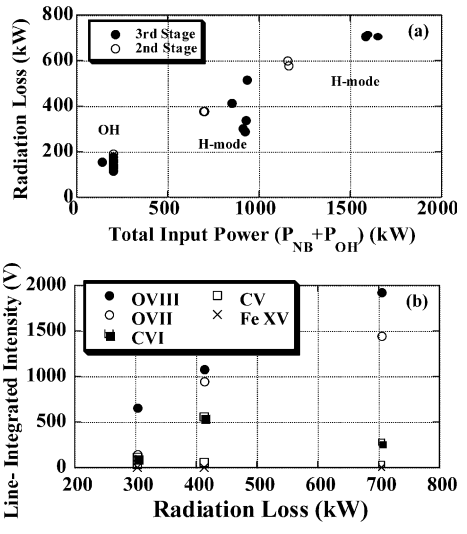

Fig. 3. (a) Total radiation loss plotted as a function of total input power in the second (open circles) and third stage (closed circles), and (b) line-integrated intensity of O VIII, O VII, C VI, C V and Fe XV plotted as a function of total radiation loss.

lineally because in the electron temperature range of JFT-2M plasmas, main carbon ion species was a fully stripped ion (C^{6+}), which does not contribute to the radiation loss. This means that the increase in the radiation loss is mainly due to the accumulation of the oxygen impurity ions. Since the radiation loss in the third stage was not increased compared with that in the second stage, it was suggested that the increase of oxygen ions in the third stage also was not enhanced compared with that in the second stage. Even in the ELM-free H-mode cases, emissions of other impurity ion lines such as iron lines were still under the detectable levels. These results suggest that ferritic steel plates have only small effects on the impurity behavior.

Fig. 4 shows the depth profiles of atomic composition for the F82H exposed to the atmosphere (a), after mechanical polishing (b) and after ion irradiation with the fluence of 7×10^{18} D/cm^2 (c). Although the surface of the sample before the ion irradiation had a metallic luster, it had a thick impurity layer containing oxygen and carbon (Fig. 4(a)). The thickness of the impurity layer was approximately 80 nm. After the ion irradiation, the thickness of the impurity layer decreased due to the ion sputtering. After the irradiation with 7×10^{18} D/cm^{12}, the thickness of the impurity layer decreased to 20 nm, which is almost the same as that after the mechanical polishing. The projected range of 1.7 keV deuterium ions in pure iron is 20 nm [7], so that implanted deuterium is trapped in the impurity layer when the fluence is low for the sample exposed to the atmosphere. When the deuterium ion fluence is high, the deuterium ion is trapped in both the impurity layer and the bulk region.

The deuterium retained in the F82H samples was mainly desorbed as HDO, D_2 and D_2O during the TDS measurement. The desorptions of HDO and D_2O indicates that deuterium was detrapped from the impurity layer and an isotope-exchange reaction with H_2O occurred at the surface. Fig. 5 shows the retained amount of deuterium versus the ion fluence. Even when the fluence was low, the retained amounts of deuterium were observed to be large. The reason is that most deuterium was trapped in the impurity layer. The retained amount for the F82H exposed to the atmosphere was larger than that for the F82H with mechanical polishing when the fluence was low. However, the retained amount became comparable to that of the F82H with mechanical polishing when the fluence was high. This was caused by the reduction of the impurity layer thickness by ion sputtering. The retained deuterium amounts of the F82H

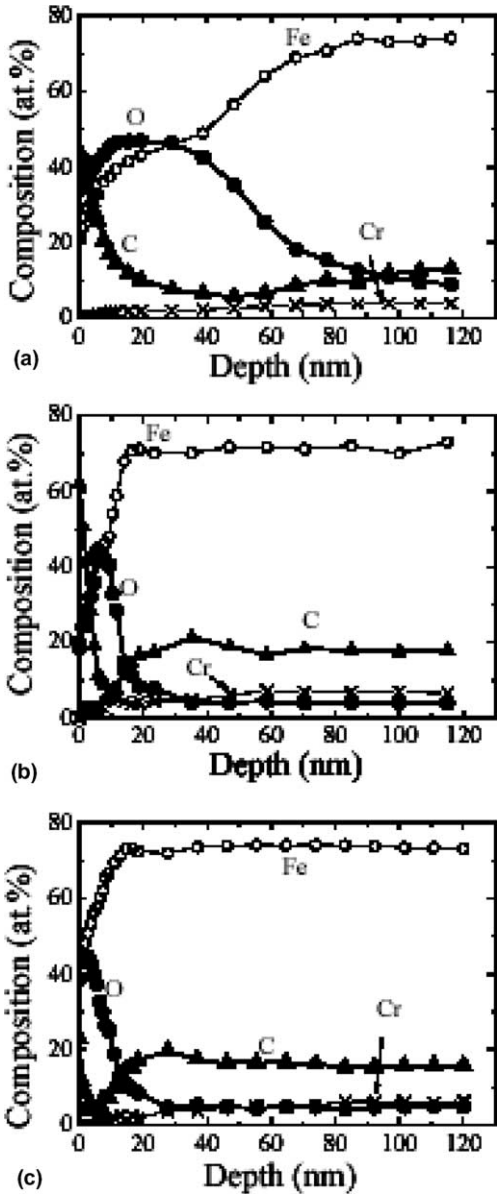

Fig. 4. Depth profiles of atomic compositions of F82H before the irradiation (a), after mechanical polishing (b) and after the irradiation with a fluence of 7×0^{18} D/cm^2 (c).

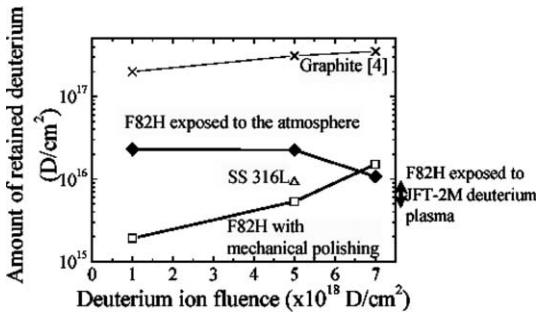

Fig. 5. Amount of retained deuterium for F82H exposed to the atmosphere, F82H with mechanical polishing, F82H exposed to JFT-2M deuterium plasma, 316L SS, and graphite.

samples exposed to the atmosphere and with mechanical polishing were comparable to that of 316L SS and one order of magnitude smaller than that of graphite [8]. Fig. 5 also shows the retained amounts of deuterium for the F82H sample exposed to the JFT-2M deuterium plasma. The retained amount of deuterium for the F82H exposed to the deuterium plasma was similar to that exposed to the deuterium ion beam in the laboratory. This result indicates that the amount of retained deuterium of the samples exposed to the JFT-2M plasma almost saturated, and also that the temperature of the samples was nearly room temperature.

4. Conclusions

Impurity release from ferritic steels and deuterium retention in the steel was studied in the JFT-2M tokamak and in the laboratory and the following results were obtained.

From the visible and VUV spectroscopic measurements, no significant enhancement of emissions of the oxygen ion lines was observed compared with the second stage results. The emissions from iron ion lines were below the detectable levels in this geometry. These results indicate that impurity release from the ferritic steel was not serious when plasma did not interact directly with the steel.

A thick impurity layer was observed on the surface of the F82H. The surface impurity layer gradually decreased with increase of deuterium ion fluence. When the fluence was 1×10^{18} D/cm^2, the retained amount of deuterium for the F82H exposed to the atmosphere was one order of magnitude larger than that of the mechanically polished F82H. As the fluence increased, the retained deuterium amount became comparable to that of the F82H with mechanical polishing. The amount of retained deuterium for the F82H was comparable to that for 316L SS and one order of magnitude smaller than for graphite. The amount of retained deuterium for the F82H exposed to JFT-2M deuterium plasma was similar to that exposed to the deuterium ion beam.

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