ELSEVIER

Journal of Nuclear Materials 307–311 (2002) 1386–1390

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Recent activities on the compatibility of the ferritic steel wall with the plasma in the JFT-2M tokamak

K. Tsuzuki *, M. Sato, H. Kawashima, N. Isei, H. Kimura, H. Ogawa, K. Miyachi, M. Yamamoto, T. Shibata

Experimental Plasma Physics Laboratory, Japan Atomic Energy Research Institute, Shirakata Shirane, Tokai-mura, Ibaraki-ken 319-1195, Japan

Abstract

The compatibility of the low activation ferritic steel with a fusion plasma has been investigated in the JFT-2M tokamak. The program consists of three stages. In the first stage, the reduction of fast ion losses was well demonstrated by ferritic steel plates (FPs) outside the vacuum vessel (VV). In the second stage, 20% of the inner surface of the VV was covered by the FPs. The plasma control, stability, and impurity release were preliminary investigated. No deteriorative effect on the plasma was observed at least in the following conditions: partial covering of 20% and the normalized beta value less than 2.8. First boronization was applied to JFT-2M leading to a remarkable decrease of the oxygen impurity. After the boronization, plasmas with the highest normalized beta in JFT-2M were obtained. Thus encouraging results were gained for this stage. In the third stage, the VV was fully covered by FPs, where the ripple reduction and the plasma stability will be investigated as a full scale testing.

1. Introduction

The low activation ferritic steel is one of the candidate materials for a demo-reactor [1]. It shows good properties for thermal and neutron irradiation compared to the conventional stainless steel [2]. However, it is ferromagnetic material, and thus, one must fear that the plasma confinement and stability might degrade due to the field error. In addition, impurity release might be problematic because the ferritic steel easily rusts in air and retained oxygen is several times larger than that of the stainless steel [3,4]. Thus, it is important to investigate the compatibility with plasmas, before applying it to a reactor. Another motivation for the use of ferritic steel is a ripple reduction. The calculation in ITER showed that the ripple losses of fast ions would be a severe problem in steady state operation [5]. It is proposed that the proper arrangement of the ferritic steel allows a reduction of the toroidal field ripple [6–9]. The use of the ferromagnetic material is planed in ITER [10]. So, the ferritic steel is rather effective to improve plasma if the compatibility with the plasma is demonstrated.

In the small tokamak, HT-2, the ferritic steel, F82H, was installed inside the vacuum vessel (VV) [11,12]. The plasma control and impurity desorption were primary investigated. The compatibility of the ferritic steel was well demonstrated for ohmic heating plasma. For the next step, the effect on the plasma confinement and stability should be investigated in a higher performance plasma, i.e. H mode condition. In the medium size tokamak JFT-2M ($R = 1.31$ m, $a = 0.31$ m, $B_T \leqslant 2.2$ T), testing of ferritic steel as wall material, advanced material tokamak experiment (AMTEX), is in progress [13–20]. The test consists of three stages, namely (1) installation of the ferritic steel plates (FPs) outside the VV, (2) partial covering of the VV wall with the FPs, and (3) full covering of the VV. Now, we finished the experiment of the second stage and are preparing the third stage.

---

* Corresponding author. Tel.: +81-29 282 5559; fax: +81-29 282 5614.

E-mail address: tsuzukik@fusion.naka.jaeri.go.jp (K. Tsuzuki).

0022-3115/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01126-1

2. Ripple reduction experiment

The FPs, F82H, were inserted between the VV and all (16) toroidal field coils (TFCs), aiming at reducing toroidal field ripple [13–19]. The main purpose of this stage is to demonstrate experimentally the reduction of fast ion losses. The form of the field ripple differs strongly from that produced by TFCs only because the magnetic field from the ferritic steel is not sinusoidal but includes higher harmonics [13,14]. The dependence on ripple profile was investigated by changing the FP thickness and the toroidal field strength [15,16]. The results show that the key parameter for the reduction of the ripple loss is a fundamental component around the shoulder part [15,16].

The un-periodicity of the FP installation due to the interference with existing ports makes the toroidal distribution more complex. The results show that the ripple loss is not sensitive to the local ripple but to the averaged ripple [17].

No deteriorative effect on plasma confinement and stability was observed. The improved confinement mode is obtained using the conventional procedure in single-null divertor configuration [15,18,19]. Thus, the ripple reduction using ferromagnetic material is well demonstrated.

3. Installation of the ferritic steel inside the vacuum vessel

The FPs were installed inside the VV to simulate the blanket wall of the reactor. The position of the ferritic steel is much closer to the plasma, and thus, the effect on the plasma stability and control is different from the first stage. In order to investigate the effects preliminarily, two sets of toroidally uniform FP's belts (F82H) of 7 mm thickness were installed, by which 20% of the VV surface was covered [16,20]. The position of the FPs and their effect are schematically illustrated in Fig. 1. The ferritic plates (FP) are magnetized in poloidal direction and generate a magnetic field as shown in the figure. The plasma control is affected because the field weakens the poloidal field and affects locally the magnetic probes, which is located on VV for plasma control. In addition, an enhancement of the MHD instability might be induced, since the behavior of the wall is different from a normal resistive wall, which is installed to stabilize the MHD instability [21]. However, if the frequency of the fluctuation is sufficiently high, an eddy current is strongly induced, reducing the effect of the ferromagnetism. As a measure of this effect, we introduce the effective permeability, $\mu_{\rm rff}$, which is defined as the volume averaged magnetization divided by the averaged external field. When the skin depth is smaller than the FP thickness, the magnetization is localized in the surface region, and thus, the $\mu_{\rm eff}$ decreases. The calculated results are shown in Fig. 2 for the case $B_{\rm T} = 1.0$ T, 5 to 10 mm thickness. The thickness of the FP (7 mm) is assigned to show diamagnetism ($\mu_{\rm eff} < 1$) for the typical fluctuation frequency of the JFT-2M($\simeq$8 kHz).

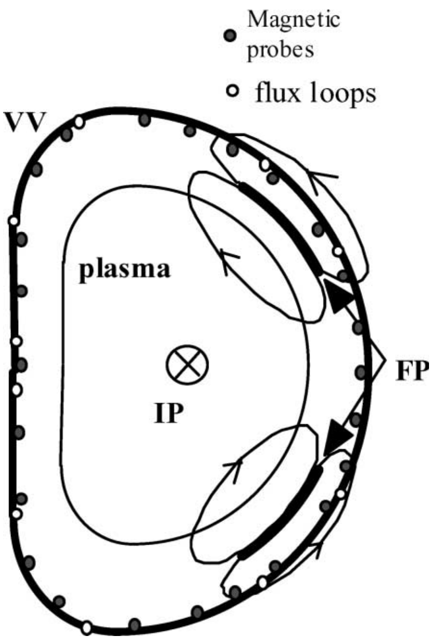

Fig. 1. Schematic cross-section of the VV. The magnetic field from the FP weakens the poloidal field and affects the magnetic sensors, which in turn affect the plasma control.

Another concern with inside FPs is the impurity release. Though it was demonstrated in HT2 [11,12] that the impurity release is not a severe problem, it may be still problematic because of an existence of the auxiliary heating and limited baking temperature of 120 °C. It should be noted that the main limiter is made of

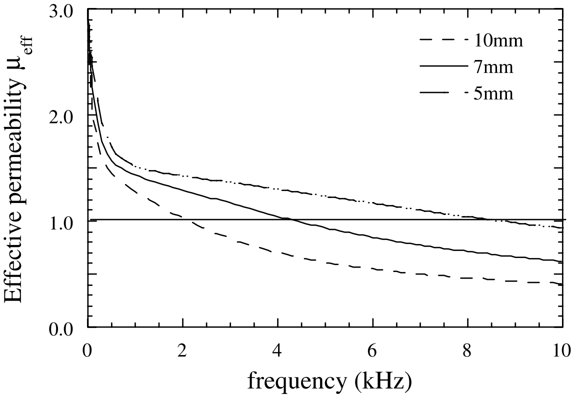

Fig. 2. Effective permeability, which is defined as volume averaged magnetization divided by the external field at $B_{\rm T} = 1.0$ T. In the case of thickness 7 mm, it shows diamagnetism for frequencies higher than 4 kHz.

graphite, and the position of the FPs is 20 mm behind the limiter. A boronization system was installed to reduce impurity desorption, and to achieve higher performance plasmas with reduced impurities. Checking the effect of the boronization was also important in the second stage.

Before the installation, the FPs were baked at 350 °C for 20 h, according to Ref. [3]. The base pressure of $\simeq 10^{-6}$ Pa (same as previous condition) was obtained after pumping, 120 °C baking and Taylor discharge cleaning. The plasma was generated using the same procedure as before. Small outward shift ($\simeq$5% of the minor radius) in the plasma position compared to the equilibrium calculation was observed, which agrees with the theoretical prediction. To check the effect of the impurity release during the plasma discharge, the total radiation losses are plotted against the line averaged electron density in Fig. 3. The losses are almost identical before and after the FPs installation, even when the neutral beam (500 kW) is injected. Thus, it is confirmed that the effect of the FPs on the plasma control and impurity desorption is negligible for the present experimental conditions.

For the study of the plasma stability, the behavior of the tearing mode was investigated. One may fear that the miss-alignment of the FPs induces low-n error fields, which enhance mode locking [22,23]. However, in the case of JFT-2M, the induced error field is much lower than the critical value for ohmically heated plasmas. The main aim of this experiment is an investigation of the wall stabilizing effect. The experimental results show that the operational range for the density became rather large, after the installation of the ferritic steel [20]. The typical frequency at the onset of the mode is 8 kHz, which is high enough to show the diamagnetisms (see Fig. 2). In the case of disruption, the slowing down of the mode frequency occurred up to 1 kHz, before disrupting. We found that, if any, some effect of FPs when the mode frequency was reduced below $\simeq$3 kHz. The corresponding value of μ_{eff} is about 2. But again, this is not a strong effect.

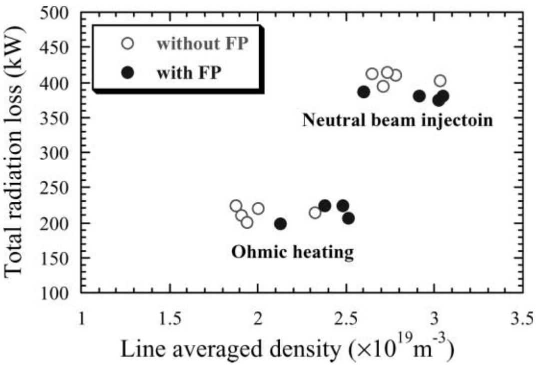

Fig. 3. Total radiation loss power against line averaged density. The power is almost identical with and without FP even when a neutral beam is injected.

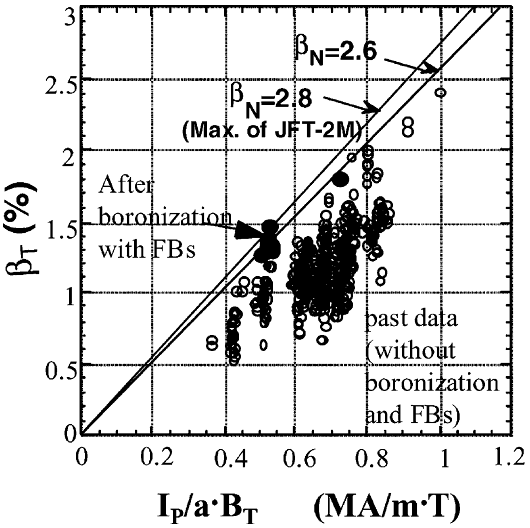

Fig. 4. Toroidal beta against I_p/aB_T, where I_p is the plasma current, a is the minor radius and B_T is the toroidal field. The slope of the data point represents the normalized beta.

After the series of the experiments, the boronization was carried out with DC glow discharge in mixture gas of 1% $B(CH_3)_3$ (tri-methyl-boron) + 99% He. It was confirmed that the boron films of $\simeq$100 nm were deposited on almost the whole inner surface of the VV. After the boronization, the total power loss by radiation was reduced to 1/3, and the oxygen ion line intensities measured by a visible spectroscopy also reduced to 1/20. The carbon line intensity also decreased slightly though the main components of the deposited film is C (the composition ratio; $B/C = 0.18$). The experiments aiming at obtaining high beta plasmas were performed after the boronization. Fig. 4 shows the toroidal beta (β_T) as a function of $I_P/(aB_T)$, where the inclination of the slope corresponds to the normalized beta, β_N. The open circles represent the data before the AMTEX program and close circles show the data after the FP installation and boron coating. The normalized beta value range up to $\simeq$2.8, which is the highest level in JFT-2M was obtained. It is of paramount importance as the demonstration of compatibility of ferritic steel with high performance plasma. Thus encouraging results were obtained for the next stage of AMTEX.

4. Preparation of full covering

The VV will be fully covered by FPs in the third stage. The aim is (1) full-scale testing as the blanket wall or the VV of the demo reactor in view of the magnetic effects and the impurity release [16], and (2) an ideal reduction of toroidal field ripple. Thickness and arrangement of FPs are determined to meet both the wall stabilization and the ripple reduction. To demonstrate the ripple reduction (from 2% to 0.3%) experimentally and to measure the error field concerning with MHD instability, a system was installed to measure the magnetic field. It is equipped with a rail, a vehicle, and magnetic sensors (three hole elements for each position to measure the *XYZ* direction). The vehicle moves in toroidal and radial direction for a whole toroidal section. The experiment before the FP installation is finished. The toroidal field ripple before the FP installation ($\simeq$2%) was clearly measured. The shift of the VV with respect to TFCs are estimated to be $\simeq$3 mm from the inhomogeneity of the magnetic field. The field error related to this shift is negligibly small. The profile of the ripple and the error field will be measured after the FP installation. As for the plasma control, it will become easier because magnetic sensors are placed between the FPs and the plasma. The part of the sensors are placed both at the plasma side and the VV side to investigate the shielding effect of the FPs. The effect on the stability and impurity release are investigated more quantitatively with a larger amount of FPs compared to the second stage.

5. Summary

The compatibility of the low activation ferritic steel with the plasma has been investigated in the JFT-2M tokamak, mainly in respect of its ferromagnetism. The reduction of fast ion losses was firstly demonstrated with the ferritic steel outside the VV. The results are important for ITER and other devices in view of compact and economical coil design. The FPs are installed inside the VV to simulate the blanket. The effect of FPs on plasma stability and control was preliminary investigated by the partial covering of 20%. The plasma was produced using almost the same procedure as before. The operational region became rather large by the inside FP. The boron coating was applied to JFT-2M for the first time. The oxygen line intensity was drastically decreased and the total radiation loss was reduced to 1/3. After the boronization, high normalized beta values up to 2.8 were obtained, which is the highest level for JFT-2M. Thus, encouraging results were obtained in the second stage of AMTEX. We are now installing FPs for full covering of VV. The effect on stability will be investigated more quantitatively with a larger amount of FPs compared to the second stage.

Acknowledgements

The authors are indebted to Mr J. Yagyu, Mr T. Arai of JAERI and Dr N. Noda and A. Sagara of National Institute for Fusion Science for valuable discussions and experiments concerning the boron coating system. The authors are also indebted to Dr T. Abe and Y. Kosaku of JAERI for discussions and experiments of vacuum properties of the FPs. The authors also appreciate Mitsubishi Heavy Industries, Ltd. and Hitachi Corporation for their effort on engineering designs of the FP installation. The authors appreciate Dr H. Kishimoto, Dr S. Matsuda, Dr A. Kitsunezaki, Dr M. Shimizu, Dr H. Ninomiya and Dr M. Kuriyama of JAERI for their continuous encouragement and support.

References

[1] Y. Seki, M. Kikuchi, T. Ando, Y. Ohara, S. Nishino, M. Seki, T. Takizuka, K. Tani, T. Ozeki, K. Koizumi, Y. Matsuda, M. Azumi, A. Oikawa, H. Madarame, T. Mizogushi, F. Iida, Y. Ozawa, S. Mori, S. Yamazaki, T. Kobayashi, S. Hirata, J. Adachi, B. Ikeda, Y. Suzuki, N. Ueda, T. Kagayama, M. Maeda, M. Asahara, K. Konishi, N. Yokogawa, K. Shinya, A. Ozaki, H. Takase, S. Kobayashi, Proceedings of International Conference on Plasma Physics and Controlled Nuclear Fusion Research IAEA, Vienna, 3 (1990) 473.

[2] A. Hishinuma, A. Kohyama, R.L. Klueh, D.S. Gelles, W. Dietz, K. Ehrlich, J. Nucl. Mater. 258–263 (1998) 193.

[3] K. Odaka, O. Sato, M. Ohtsuka, T. Abe, S. Hara, H. Takatsu, M. Enoeda, J. Plasma Fus. Res. 73 (1997) 1001, in Japanese.

[4] T. Hino, Y. Hirohata, Y. Yamauchi, S. Sengoku, 18th IAEA Fusion Energy Conference, CN-77/FTP1/08, Sorrento, 2000.

[5] K. Tobita, H. Harano, T. Nishitani, T. Fujita, K. Tani, T. Oikawa, H. Shirai, Y. Kusama, Nucl. Fus. 37 (1997) 1583.

[6] L.R. Turner, S.T. Wang, H.C. Stevens, in: Proceedings of Third Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, 1978, p. 883.

[7] M. Ricci, N. Mitchell, in: Proceedings of 15th Symposium on Fusion Technology, Utrecht, 1988, p. 1565.

[8] G.V. Sheffield, Princeton Plasma Physics Laboratory report-2876 1993.

[9] T. Nakayama, M. Abe, K. Takeuchi, Y. Miura, M. Sato, Jpn. J. Appl. Phys. 40 (2001) 3409.

[10] K. Ioki, V. Barabash, A. Cardella, F. Elio, Y. Gohar, G. Janeschitz, G. Johnson, G. Kalinin, D. Lousteau, M. Onozuka, R. Parker, G. Sannazzaro, R. Tivey, J. Nucl. Mater. 258–263 (1998) 74.

[11] T. Nakayama, M. Abe, T. Tadokoro, M. Otsuka, J. Nucl. Mater. 271&272 (1999) 491.

[12] M. Abe, T. Nakayama, K. Asano, M. Ohtsuka, J. Plasma Fus. Res. 73 (1997) 1283, in Japanese.

[13] M. Sato, Y. Miura, H. Kimura, H. Kawashima, S. Sengoku, M. Yamamoto, T. Koike, T. Shibata, T. Aiyama, M. Abe, T. Nakayama, M. Ohtsuka, M. Hasegawa, F. Sato, M. Yamane, Y. Suzuki, J. Plasma Fus. Res. 75 (1999) 741.

[14] M. Sato, Y. Miura, S. Takeji, J. Nucl. Mater. 258–263 (1998) 1253.

[15] H. Kawashima, M. Sato, K. Tsuzuki, Y. Miura, N. Isei, H. Kimura, T. Nakayama, M. Abe, D.S. Darrow, JFT-2M group, Nucl. Fus. 41 (2001) 257.

[16] H. Kimura, M. Sato, H. Kawashima, H. Kawashima, N. Isei, K. Tsuzuki, H. Ogawa, T. Ogawa, Y. Miura, M. Yamamoto, T. Shibata, T. Akiyama, K. Miyachi, JFT-2M Group, Proceedings of 21st SOFT Fusion Engineering, Design, Madrid, 2000, 56–57 (2001) 837.

[17] H. Kawashima, K. Tsuzuki, N. Isei, M. Sato, K. Shinohara, H. Kimura, Proceedings of 28th European Conference on Controlled Fusion and Plasma Physics, Madeira: EPS, 2001, p. 4.001.

[18] K. Tsuzuki, M. Sato, H. Kawashima, Y. Miura, H. Kawashima, T. Abe, K. Uehara, T. Ogawa, T. Akiyama, T. Shibata, M. Yamamoto, JFT-2M Group, J. Nucl. Mater. 283–287 (2000) 681.

[19] M. Sato, H. Kawashima, Y. Miura, K. Tsuzuki, H. Kimura, K. Uehara, T. Ogawa, N. Isei, T. Tani, T. Akiyama, T. Shibata, M. Yamamoto, T. Koike, M. Abe, T. Nakayama, Fus. Eng. Des. 51–52 (2000) 1071.

[20] N. Isei, M. Sato, K. Tsuzuki, H. Kawashima, Y. Miura, H. Kimura, JFT-2M Group, Fus. Technol. 39 (2001) 1101.

[21] ITER Physics Basis, Nucl. Fus. 39 (1999) 2260.

[22] S. Takeji, M. Mori, M. Kikuchi, H. Ninomiya, S. Jitsukawa, T. Ito, M. Kuriyama, H. Kishimoto, Proceedings of 16th IEEE/NPSS SOFE, Illinois, 1995, 1214.

[23] R.J. La Haye, R. Fitzpartrick, T.C. Hender, A.W. Morris, J.T. Scoville, T.N. Todd, Phys. Fluids B 4 (1992) 2098.