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Ripple reduction and surface coating tests with ferritic steel on JFT-2M

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Abstract

Applicability of the low-activation ferritic steel (F82H), which is one of the candidate materials for next generation fusion devices, has been tested in JFT-2M. Ferritic steel boards (FB) were installed between toroidal field coils (TFC) and the vacuum vessel at all toroidal sections. The experiment and the calculation show that the ripple amplitude decreases from 2.2% to 1.1% by the FB installation at $R = 1.6$ m. The ripple reduction results in the reduction of fast ion loss and in the shift of the ripple loss to the outer region. No undesirable effect to the energy confinement and the plasma control was observed. The FB will be installed inside the vacuum vessel in the near future. In preparation, surface coating tests, mainly concerning with an in situ boron coating, are carried out. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The first wall of next generation fusion devices will suffer more severe heat and neutron flux than in current devices, and thus, new materials have to be employed. Low-activation ferritic steels are under development because of the good properties regarding neutron irradiation [1]. They are considered as the candidate material for the DEMO reactor, and the characteristics have widely been studied [2,3].

An important feature of ferritic steels is their ferromagnetism. The effect of the ferromagnetism on the plasma control and confinement is not well understood because ferromagnetic materials have not been used in fusion devices to avoid the error field. Thus, the compatibility of ferritic steels with the plasma has to be checked. In small tokamak, HT-2, the plasma production and its control with ferritic steels are well demonstrated [4]. For the next step, the compatibility with the plasma in improved confinement mode should be checked in medium-size devices.

In addition, it has been proposed that ferritic steels can be utilized to reduce toroidal field ripple [5–7]. In the presence of toroidal field ripples, fast ions with $v_{//}/v \sim 0$ (velocity component parallel to the magnetic field ~ 0) are trapped at the ripple and lost due to the grad-B drift, in some conditions. The calculation in the case of negative shear operation in ITER [8] shows that 25% of the fast alpha particles are lost due to ripples. In this case, the heat flux exceeds 4 MW/m^2, and the first wall suffers severe damage. Thus, ripple reduction is a critical issue for steady-state operation in ITER, where application of ferritic steels is planned [9]. Experimental data are required to show the actual effect of ripple reduction.

In JFT-2M tokamak, advanced material tokamak experiment (AMTEX) tests are performed [10–12] to show the compatibility of ferritic steels with the improved confinement plasma with reduced toroidal ripple. The test consists of three stages, namely, (1) ripple reduction test, where ferritic steel boards (FB) are placed outside the vacuum vessel and the effect of the ripple reduction is tested, (2) preliminary testing for compatibility with plasma, where the FBs are planned to cover partly the inside of the vacuum vessel to test the plasma wall interaction and the effect on the plasma control,

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and (3) testing for compatibility with the plasma, where the vacuum vessel wall will be made of ferritic steel. The ripple reduction test (1) is presently being carried out. Here, the first results of stage (1) and the preparation experiments for stages (2) and (3) are presented.

2. Arrangement of ferritic steel and reduction of magnetic field ripple

The low-activation ferritic steel, F82H [1], is employed in this experiment. The FBs are placed between the vacuum vessel and the toroidal field coils (TFC) in all toroidal sections ($N = 16$) for poroidal angle of −65° to +65° (outer part) [11,12]. They decrease the magnetic field under the TFC (except inside the FB) and increase it between the TFCs, hence, the magnetic field is flattened. However, if the FB is too thick, the ripple is over-canceled and the higher mode is induced. The diffusion coefficient is proportional to $n^{9/4}\delta^{3/2}$ (n: toroidal mode number, δ: ripple amplitude) for the banana drift particles, with high energy in low collisional regime [13,14]. So, the higher mode has to be carefully reduced.

To optimize the FB arrangement, calculations of the magnetic field have been carried out [10,11]. The arrangement is aimed at reducing both the fundamental and the higher modes. The optimum thickness of the FB depends on the toroidal field. For the adjustment, the number of FB (8 mm thick each) is changed from 0 to 8 elements. Typical number of FB elements is 6 and 8 optimized for 1.3 and 2.2 T, respectively. The thickness is changed not only for optimization but also to induce higher or lower modes to check the effects of those modes. The FB setup optimized for 1.3 T (e.g., 6 elements; total ∼50 mm thick) is mainly investigated up to now.

Before and after the FB installation, the magnetic field was measured to show the ripple reduction experimentally and to cross-check the calculations. Two sets of magnetic probe arrays were used for the measurement. They were placed at $R = 1.6$ m, $z = 0$ m and $R = 1.55$ m, $z = 0.2$ m, respectively. Each probe contains six sets of pick-up coils, each for three directions: toroidal; radial; vertical. They were distributed from just under the TFC to the middle point between TFCs.

The radial magnetic field, B_r, was used as a measure of the ripple amplitude because it is proportional to the ripple amplitude in the ideal case and contains relatively smaller error. Fig. 1 shows the distribution of B_r at $R = 1.6$ m, $z = 0$ m. The calculation showed that the FB installation reduces the ripple amplitude from 2.2% to 1.1% in this port section. Correspondingly, the calculated B_r was reduced by almost half. Direct measurements of B_r did not agree well with the calculation, mainly because the toroidal field, which is two orders of magnitude higher than B_r, affects the measurements due to a misalignment of the probes. Here, the calculation and measurement before the FB installation is assumed to be correct except for the small misalignment of ∼0.5°, and the measurement after the installation is calibrated with the results. The calibrated results are plotted in Fig. 1, showing good agreement with the calculated results. Thus, we conclude that the ripple amplitude is reduced by almost half by the FB installation.

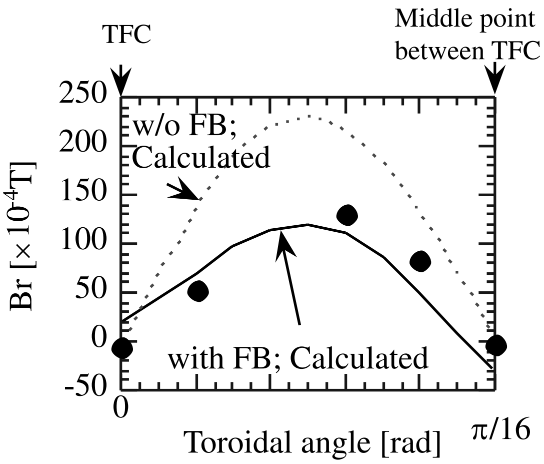

Fig. 1. Distribution of radial magnetic field Br, before and after the FB installation.

3. Effect of FB on plasma performance

To monitor the fast ion losses, an infrared TV (IRTV) system has been installed. Fast hydrogen ions are supplied by neutral beam injection (NBI) with its primary energy of 36 keV (tangential CO injection). The injection power is about 540 kW. The plasma parameters are scanned as follows: $B_t = 1.3$ to 2.2 T; $I_p = 100$ to 280 kA; $n_e = 1.5$ to 3.0×10^{19} m^{-3}.

When the NBI was injected, a hot area was observed around the middle point between the TFCs in both cases with and without the FB. It was observed only for the direction of the ion grad-B drift. The dependence on B_t, and I_p (q dependence) was consistent with simple theoretical prediction. Therefore, the hot area is considered to be a contribution of the ripple loss.

The temperature increase is attributed not only by the ripple loss, but also by other loss mechanisms such as the radiation. We assume that the other losses are independent to the direction of the magnetic field. Then, the change in the temperature profile with the change of the magnetic field direction is considered to be the ripple loss. Fig. 2 shows the radial profile of the temperature increase due to the ripple loss in the case of the full volume limiter discharge (the position of the outermost magnetic surface, $R_{out} = 1.6$ m). The peak temperature

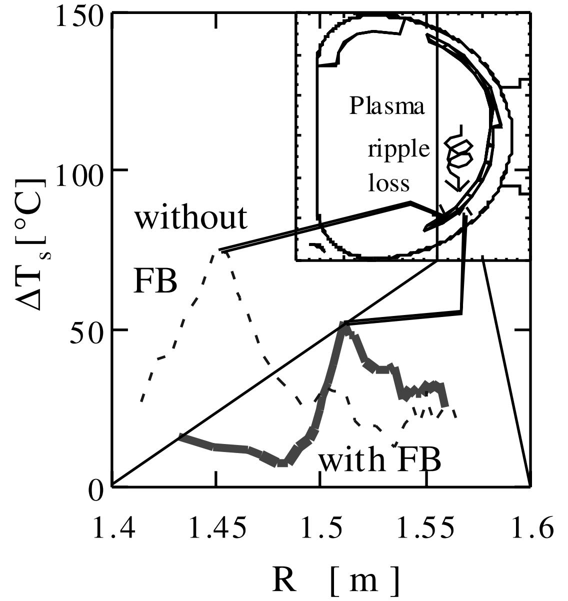

Fig. 2. Radial distribution of temperature increase before and after FB installation. The cross-sectional view of the JFT-2M is also shown in this figure to show the relative position of the ripple loss part to the plasma.

decreased from 75°C to 50°C and the radial peak position shifted to the outer region by about 6 cm by the FB installation. The decrease of the peak temperature directly shows the reduction of the ripple loss. To estimate the total power of the loss, the temperature increase was integrated. The result showed that the loss became almost half by the FB installation. The shift of the temperature is also attributed to the ripple reduction. The region at which the ripple loss may occur is distributed around the outer edge of the plasma, where both the ripple amplitude, δ, and the safety factor, q, are high. The region becomes narrower by the ripple reduction, resulting in the outer shift of the ripple loss region. From these results, we conclude that the FB is effective to reduce the ripple trapped fast ion loss.

Another way to reduce the ripple loss is an inward shift of the plasma because the ripple amplitude becomes smaller with smaller R. The plasma position was scanned from R_{out} of 1.60 to 1.54 m. Fig. 3 shows the temperature profile, estimated by the same way as in Fig. 2. The peak temperature decreased from 50°C to 35°C by the inward shift of 6 cm. Since the ripple amplitude is reduced by the FB, the ripple loss could be significantly decreased with smaller shift. In other words, the plasma of the same ripple loss could be obtained with the smaller TFC by utilizing the FB. This is favorable for design feature for ITER and other large devices, in view of the cost reduction.

As for the plasma operation with the FB, there was almost no effect on the control. To check the effect of the FB on plasma confinement, the energy confinement time τ_E was calculated with various I_p, and B_t, and these are plotted against ITER-89P scaling [15] in Fig. 4. Closed and open circles show the data with and without FB, respectively. The confinement time agrees well with the scaling law, and the FB installation does not appear to affect the τ_E. Since the beam injection angle is ~38° to the magnetic axis, the fast ion loss may not affect the global energy performance. In the case of a single null divertor operation, a H-mode was observed after the installation of the FB without special effort. Therefore, we conclude that the FB installation did not degrade the plasma confinement.

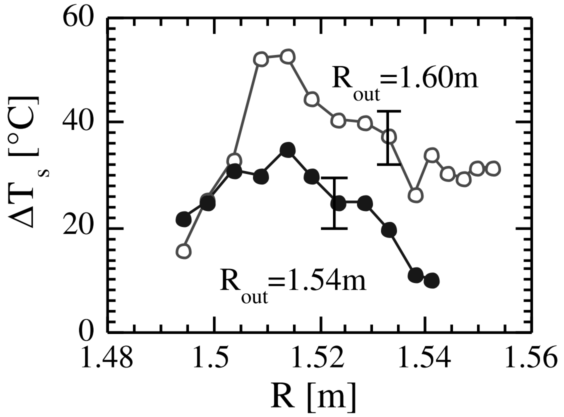

Fig. 3. Radial distribution of temperature increase around ripple loss part. The plasma position is shifted from $R = 1.60$ to 1.54 m.

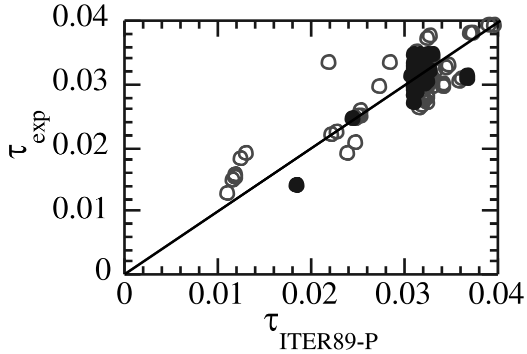

Fig. 4. Energy confinement time against ITER-89P scaling law. Open and close circles show the data without and with FB, respectively.

4. Surface coating tests

As described in Section 1, the FB will be installed inside the vacuum vessel in stage (2). In stage (3), the vacuum vessel wall will be made of the ferritic steel. In such cases, the impurity desorption from the ferritic steel will be a problem. It may oxidize in the air. The retained gas species are much larger in the ferritic steel than in the stainless steel [3]. Although the out gas from well-treated F82H is not so bad [16], the retained gas species might desorb under the plasma irradiation. Therefore, the surface treatment will be needed. For oxidation protection and modification of plasma wall interaction, coatings of SiC, TiN, Cr, and B_4C are tested. Good coating films have been obtained in all cases. In addition, in situ coating of a boron film is planned. To check the compatibility of the pre-coated films or the FB itself with boron, a boron coating test was carried out. Small test stand (PPT) at National Institute for Fusion Science was used for the test. The boron films were deposited on the samples by glow discharges in mixture gas of $95\%\mathrm{He}+5\%\mathrm{B_2H_6}$. The films on SiC and TiN easily peeled off. Films on the Cr coating and the FB itself were hardly peeled off and prevented oxidation till now (5 month). Thus, the candidate of the coating material at present is either the Cr coating or the FB itself.

5. Summary

Low-activation FBs made of F82H have been installed in JFT-2M tokamak to investigate the effect of ferromagnetism on plasma performance. The ferritic boards were placed between toroidal field coil and the vacuum vessel. The arrangement was aimed at reducing the toroidal field ripple of both fundamental and higher modes. The magnetic field measurements and the calculation confirmed the ripple was reduced from 2.2% to 1.1% at $R = 1.6$ m.

The ripple trapped fast ion loss was monitored by the increase in wall temperature, measured by IRTV. It clearly decreased with the FB insertion, and the ripple part shifted to the outer region of the plasma. No degradation was observed in plasma control and confinement. These results show the promising feature of the FB, in view of the ripple reduction.

Surface coating tests were carried out in preparation for the installation of the FB inside the vacuum vessel. A good coating was obtained for Cr, TiN, B_4C, and SiC. A boron coating test was carried out to check the compatibility of the pre-coated films with the in situ boron coating. A good boron film was obtained only on the FB and Cr-coated FB.

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