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Investigation of compatibility of low activation ferritic steel with high performance plasma by full covering of inside vacuum vessel wall on JFT-2M

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Abstract

Low activation ferritic steel plates were installed in the JFT-2M tokamak to fully cover the inside wall of the vacuum vessel (ferritic inside wall; FIW) as a simulation of the blanket wall of the fusion demonstration reactor. After the physics and engineering design concerns with the ripple reduction, the electro-magnetic force and so on, FIW was installed with a tolerance of a few mm. The ripple reduction was confirmed from the detailed measurement. Tokamak discharges were obtained without changing control system, as predicted theoretically. The reduction of ripple loss of fast ions was clearly demonstrated by both experiments and calculations. Compatibility of FIW with high normalized beta plasma up to 3.3 was demonstrated at relatively far wall position. Preliminary investigation showed that the slowdown of the growth rate occurred with closer wall position, which presumably corresponds to wall stabilization effect.

1. Introduction

The low activation ferritic steel is a leading candidate structural material for a blanket of a fusion demonstration reactor [1] and the characteristics have been widely studied. However, its ferromagnetic property could affect plasma production, control, confinement, stability and so on. In addition, one might fear impurity release from the ferritic steel because it is easily oxidized in air [2]. Thus, compatibility of the ferritic steel with the plasma is one of the critical issues for applying this material to the reactor. Another motivation to use ferromagnetic material in fusion devices is for reduction of the toroidal field ripple [3]. The calculations for ITER has shown that the heat load due to the ripple loss can damage the first wall material in the case of

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negative-shear steady operation [4], and the ripple reduction with ferromagnetic material is planned [5]. Experimental clarification of the ripple reduction with the ferritic steel was needed. In the HT-2 tokamak, the compatibility with ohmic heating discharges was demonstrated with ferritic steel plates inside the vacuum vessel (VV) [6]. To investigate the compatibility with higher performance plasmas and the effect of the ripple reduction, the 'Advanced Material Tokamak Experiment' (AMTEX) is being performed in JFT-2M ($R = 1.31$ m, $a = 0.3$ m, $B_T \leqslant 2.2$ T). The low activation ferritic steel F82H (8%Cr–2%W–0.2%V–0.06%Ta–Fe) [7] is selected as the ferritic material for AMTEX. It saturates in typical magnetic field of JFT-2M (0.8 T $\leqslant B \leqslant$ 2.2 T) at the saturation magnetization (M_s) of $\sim$2 T. The specific permeability depends on the magnetic field as $(1 + M_s/B_T)$, corresponding to 2–3 for JFT-2M. The AMTEX program has been conducted in 3 steps. In the first stage, the reduction of the fast ion loss was well demonstrated with the installation of the ferritic plates outside the vacuum vessel [8,9]. In the 2nd stage, the ferritic plates of thickness 7 mm were installed along the whole toroidal circumference in the low field side above and below the horizontal ports [10]. They covered $\sim$20% of the inside area of the vacuum vessel. No adverse effects of ferritic steel on the plasma operation and stability were observed at least for the normalized beta up to 2.8 [10]. With these encouraging results, we have entered the 3rd stage of AMTEX, where the inside wall of the vacuum vessel is fully covered with the ferritic steel [11–13].

In section 2, the technical and physical issues in design and installation of FIW are briefly shown. Experimental results related to plasma control, ripple loss, and plasma stability are shown in Sections 3–5, respectively.

2. Design and installation of ferritic inside wall (FIW)

In the demo-reactor, the blanket will be installed to fully surround the plasma. To simulate this situation, the vacuum vessel wall of JFT-2M was fully covered with the ferritic steel plates as shown in Fig. 1 (called the ferritic inside wall; FIW). In addition, the toroidal field ripple was reduced by adjusting thickness distribution with three thicknesses (6, 8, and 10.5 mm). The ripple amplitude is designed to be decreased to $\sim$1/4 of that without FIW [14]. After the installation, precise magnetic field measurements were carried out with the newly developed magnetic measurement devise [15]. Installation was measured by the newly developed 3D magnetic field measurement device. Experimental results clearly indicated that the designed ripple reduction was realized.

There were several technical issues in the installation of the ferritic steel. One is the electro-magnetic force. The electro-magnetic force during the current disruption

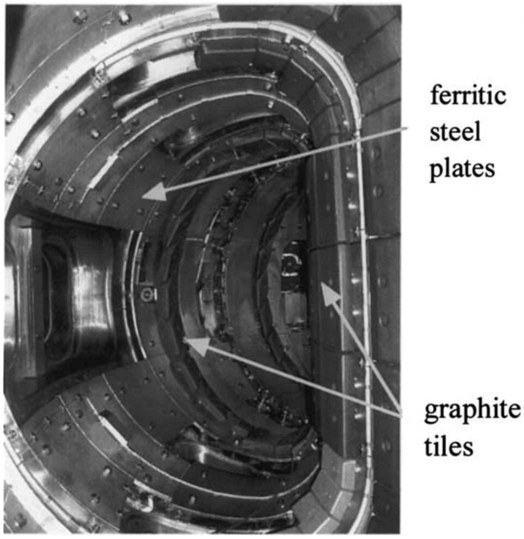

Fig. 1. Inside view of vacuum vessel of JFT-2M after the installation of the ferritic inside wall; FIW.

was calculated including ferromagnetic effects [16]. The force related to ferromagnetism was comparable to that related to the eddy current. The plates (typically, 400 mm $\times$ 500 mm $\times$ 10 mm t) was fixed by M12 bolts with a typical span of $\sim$200 mm. Oxidation of the ferritic steel during exposure to air might be a critical issue for the application though it had been demonstrated that the outgas rate is sufficiently low for tokamak devices ($\sim 10^{-8}$ Pa m^3/s m^2) with pre-baking at 350 °C and in situ baking at 250 °C [17]. It took $\sim$6 months for the installation. Tokamak experiments were carried out for a year, during which short air vent was carried out 2 times. Throughout these works, little oxidation was observed and the base pressure remained at about the same level as that before the installation of FIW. Methods to install in-vessel components such as magnetic sensors and graphite limiters are also issues because the ferritic steel becomes embrittled by the heat load during welding. Support structure without welding was employed for the installation of graphite limiters. The tapped hole was made in the ferritic plates and the support of the graphite limiter was screwed in it. As for the small objects such as magnetic sensors, they were spot welded to FIW. No damage related to the spot-welding was observed for the experiment of a year [16].

3. Plasma production and control

To evaluate the effects of FIW on the plasma control, the magnetic field caused by the FIW was calculated with the equilibrium code including the effect of ferritic

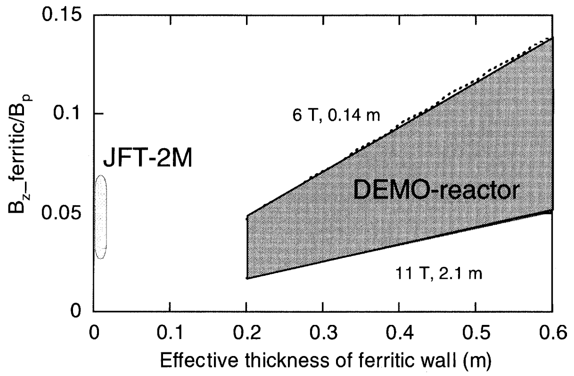

Fig. 2. Evaluation of the magnetic field from the ferritic wall normalized to poloidal field. The effect of the ferritic wall on plasma control is comparable between JFT-2M and demo-reactor.

steel. The stray field from FIW forms vertical field [11]. In the case of typical configuration in JFT-2M, it weakens the vertical field by ~10%. This effect could be easily canceled by increasing the vertical field coil current. As predicted from the calculations, tokamak discharges were obtained without a marked change in the plasma control system. Increases in the vertical field coil current by ~10% compared to the value without FIW have been observed, which is consistent with calculated results. To extrapolate this effect to the demo-reactors, simple indicator has been employed, assuming that all the magnetization in the ferritic steel is strayed uniformly inside the vacuum vessel, namely, $B_{z\text{-ferritic}} \sim (\mu_s - 1)B_p d/a = M_s B_p d/aB_T$, where B_p is poloidal field, d is thickness of ferritic steel, a is plasma minor radius, and B_T is toroidal field. Fig. 2 shows the results, assuming that 6 T $< B_T <$ 11 T, and 1.4 m $< a <$ 2.1 m. The relative intensity depends on the thickness of the blanket wall. The ratio is comparable to that on JFT-2M when the thickness is less than 0.6 m. It means that the effect of the ferritic steel on demo-reactor is comparable to that on JFT-2M.

Effect of this field on magnetic sensors is also an important issue. The flux function Ψ becomes steeper inside the FIW as shown in Fig. 3, showing the radial distribution of Ψ at equatorial plane for typical limiter discharge. The major radius of the separatrix without considering the ferritic effects is estimated ~2 cm smaller than the real one. The separatrix position estimated by the soft X-ray array agrees well with the equilibrium without considering the ferritic effect within the space resolution of ~3 cm.

4. Ripple loss measurement

The heat load onto the first wall due to the ripple loss of fast ions was monitored by an infrared TV system

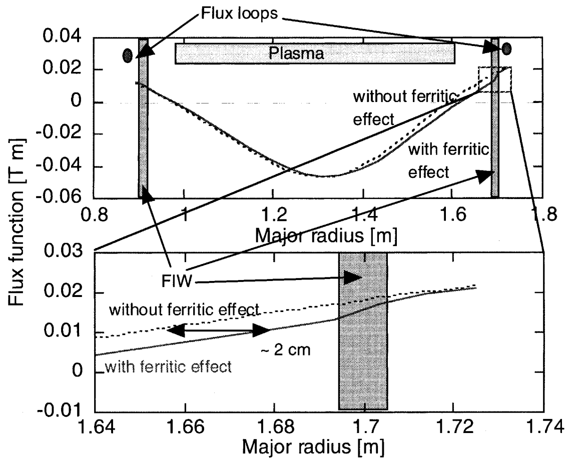

Fig. 3. Radial distribution of Flux function for typical limiter discharge. Dotted line shows the results without considering ferritic wall, indicating inward shift of ~2 cm of the plasma position compared to the case with ferritic effect.

(IRTV), which had been reported previously [18]. In the cases of typical condition, the maximum heat flux due to the ripple trapped loss decreased from 0.26 MW/m^2 (w/o ferritic steel) to less than 0.01 MW/m^2 (with FIW) [11,12]. However, this is not a general results because the magnetic field structure with FIW shows non-axisymmetric feature due to limited installation area of FIW. For the calculation, fully three dimensional magnetic field Orbit-Following Monte-Carlo (F3D OFMC) code was developed including the three dimensional complex structure of the toroidal field ripple and the non-axisymmetric first wall geometry [12]. The calculated results agree well with the experimental one. From the F3D OFMC calculation, the total loss of fast ions decreased from 19% (w/o ferritic steel) to 6% (with FIW) in the above mentioned configuration. Thus the reduction of the ripple losses by FIW was successfully demonstrated.

5. Compatibility of FIW with high-normalized beta plasma

High-normalized beta (β_N) plasma of $\beta_N = 3.5$–5.5 is required for a commercially attractive fusion reactor. To achieve such high β_N plasma, the wall stabilization effect must be utilized with close wall position to the plasma, where the low activation material should be employed. Thus, the compatibility of ferritic wall with high-normalized beta plasma is one of the critical issues for the application. Before this work, the maximum β_N in JFT-2M had been ~2.5, which was limited by the heating power and/or impurity accumulation. After the impurity reduction by boronization and adjustment of operation scenario, we have found an attractive new operation regime, with which an internal transport barrier (ITB) can be produced with keeping steady state H-mode edge [11,13]. The β_N has increased up to 3.3, which is almost same as ideal no-wall limit ($\sim$4 li; li is internal inductance). These results are import as the demonstration of compatibility of such FIW with high-normalized beta plasma up to 3.3 [11,13].

To estimate the contribution of wall stabilizing effect in attaining such high β_N Plasmas, beta limit was calculated by ERATO-J code [19]. Fig. 4 shows the beta limit due to the ideal kink-ballooning mode as a function of the position of the ideal wall (d) normalized to the plasma minor radius (a). The stability depends on pressure peaking factor, which has not been measured in JFT-2M. The pressure peaking factor was assumed to be $p(0)/\langle p\rangle = 2.3$ where $p(0)$ and $\langle p\rangle$ are the on-axis and volume-averaged pressure. The beta limit increases rapidly when d/a is less than 1.3. Experimental data are plotted for standard configuration and outward shifted one as also indicated in Fig. 4. Because of the significant increase in radiation loss power, the d/a is limited at 1.5 in the 2002 campaign, at which the wall effect is not significant. The experiments with closer wall position, by removing some graphite limiters, are planned in early 2004.

The growth rate of the instability was measured by B_θ probes (8 and 12 probes in toroidal and poloidal direction, respectively). The growth rate clearly decreased when the wall is located at $d/a \sim 1.5$ compared to the case of $d/a \sim 1.7$. It is presumably corresponds to wall

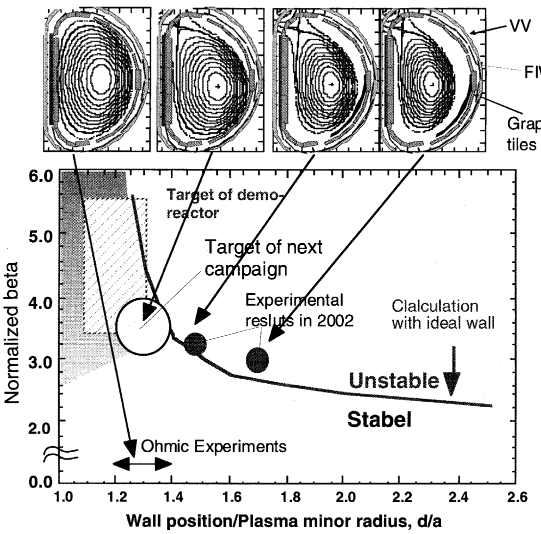

Fig. 4. Calculated (by ERATO-J code) and experimental beta limit against wall position. The limit of the normalized beta increases significantly when the wall position is nearer than $d/a \sim 1.3$.

stabilization effect, which is similar behavior with resistive wall without ferromagnetism. For preliminary analysis of the wall stabilization effect with closer wall position ($d/a \sim 1.2$), full volume plasma with only ohmic heating was investigated. The plasma current increased continuously and the magnetic behavior before the disruption of safety factor $\sim$2 was investigated. The results also showed that the growth rate is much smaller in near wall case, suggesting wall stabilization effect.

6. Summary

Ferritic steel plates were installed in the JFT-2M tokamak to fully cover the inside wall of the vacuum vessel (ferritic inside wall; FIW) as a simulation of the blanket wall of the fusion demonstration reactor. The reduction of toroidal field ripple was conducted by varying thickness distribution of FIW. The ripple distribution after the installation was measured by the newly developed 3D magnetic field measurement device. Experimental results clearly indicated that the designed ripple reduction was realized.

Tokamak discharges were obtained without changing control system, as predicted theoretically. Simple calculations indicated that the effect of the ferrtic blanket on plasma control in the demo-reactor is almost comparable to that on JFT-2M.

The ripple loss of fast ions was clearly decreased by FIW. The calculation code was developed including the three dimensional complex structure of the toroidal field ripple and the non-axisymmetric first wall geometry. The calculated results agreed well with the experimental measurements.

Compatibility of FIW with high-normalized beta plasma up to 3.3 was demonstrated at relatively far wall position (wall position normalized to plasma minor radius; $d/a \sim 1.7$). Experiments with closer wall position are planned in early 2004. Preliminary investigation showed that the slowdown of the growth rate occurred with closer wall position ($d/a \sim 1.5$ for high beta and $d/a \sim 1.2$ for low beta), which presumably corresponds to wall stabilization effect similar to the resistive wall without ferromagnetism.

Thus, encouraging results are obtained for using the ferritic steels in the demo-reactor.

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