Compatibility of Reduced Activation Ferritic Steel Wall with High Performance Plasma on JFT-2M

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Abstract. In JFT-2M (R=1.31 m, a≤0.35 m, k≤1.7, B_{t0}≤2.2T), applicability of reduced activation ferritic steel to a fusion demonstration reactor has been demonstrated mainly concerning with ferromagnetic effect on plasma production, control, stability, and confinement. As a progress of previous IAEA conference (Lyon, 2002), the compatibility of closer ferritic wall with high-normalized beta plasma has been mainly investigated because the demo-reactor will utilize wall stabilization effect. Due to modifications of operation scenario and limiter configuration, the region showing good compatibility was extended for closer wall position (wall position normalized to the plasma minor radius; r_{wall}/a~1.3) and higher normalized beta (β_N~4). Reduction of growth rate of the instability was also observed in the close wall case, which presumably corresponds to wall stabilization effect, similar to resistive wall without ferromagnetism. Behavior of low beta tearing mode and L/H transition power were also investigated, showing no adverse effect related to ferromagnetism.

1. Introduction

Reduced activation ferritic steel is a leading candidate material for a blanket of a fusion demonstration reactor (DEMO) [1] due to low radioactivity and good thermal properties, and the characteristics have widely been studied. However, its ferromagnetic property could affect plasma production, control confinement, stability and so on. In addition, impurity release from the ferritic steel could be the problem because it easily oxidized in the air and retention of oxygen is larger than that of the stainless steel [2]. Thus, compatibility of the ferritic steel with 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] as planned in ITER [4]. Experimental clarification of the ripple reduction was also important. Thus, Advanced material tokamak experiment (AMTEX) has been performed in medium size tokamak, JFT-2M (R=1.31m, a=0.3m, B_T≤2.2T) by 3 steps in order to investigate the compatibility of the ferritic steel with high performance plasma and the effect of the ripple reduction [5-9]. The reduced activation ferritic steel F82H (8%Cr-2%W-0.2%V-0.06%Ta-Fe) [10] is selected as the ferritic material for AMTEX. It saturates in typical magnetic field of JFT-2M (0.8 T ≤ B ≤ 2.2 T) at the saturation magnetization (M_s) of ~ 2 T. The specific permeability depends on the magnetic field as ($1+M_s/B_T$), corresponding to 2~4 for JFT-2M. In the previous IAEA conference, results of the 3rd stage (full covering ferritic inside wall; FIW) was mainly presented showing no adverse effect of the ferritic steel wall on plasma production, control stability, confinement, and impurity release at relatively far wall position (wall position normalized to plasma minor radius; r_{wall}/a~1.6, where the values at outer mid-plane was employed for both r_{wall} and a) [5]. The compatibility with high normalized plasma of β_N ~3 was demonstrated by utilizing new operation region where both internal transport barrier and steady H-mode edge (high Recycling Steady H-mode; HRS) were formed [5,6]. However, this result is not sufficient to demonstrate the compatibility with DEMO because the commercially attractive demo-reactor require wall stabilization effect at closer wall position; $r_{wall}/a < 1.3$ to obtain high normalized beta plasma of β_N :3.5 ~ 5.5. As a progress of previous studies, the compatibility of closer ferritic wall with higher normalized beta plasma has been mainly investigated in this work and the results are presented from section 2 to section 4. In section 5, effect of the ferromagnetism on equilibrium calculation, which is one of the key diagnostic tools of this study, is discussed. The effect of the ferritic wall on the tearing mode and H –mode transition was also investigated and the results are shown in section 6 and 7, respectively.

2. Modification of JFT-2M

During the previous experimental series, geometrical limit of r_{wall}/a was ~1.3 due to the existence of graphite guard limiters, which were located at 7 cm from the surface of the ferritic inside wall. Practical limit was larger because outer gap of a few cm is required to reduce impurity release and to obtain improved confinement plasmas [11]. Therefore it was difficult to obtain the plasma configuration, which is relevant to demo-reactor ($r_{wall}/a<1.3$). To improve this situation, part of the graphite limiters were removed, by which additional space of 2 cm was acquired. The geometrical limit became ~ 1.2. Some of the in-vessel components near to the plasma were also removed to prevent impurity release. In addition to these modifications, in-situ conditioning such as boron coating and glow discharge cleaning were intensively employed. Figure 1 shows the total radiation loss during full power neutral beam (NB) injection (~1.6 MW) against the normalized wall position before (open circles) and after (close circles) above modifications. Before the modification, the radiation increased almost linearly. The maximum beta was limited less than 3 and it decreased with decreasing wall distance mainly due to the impurity release. After the modification, the radiation was almost constant down to r_{wall} /a~1.35. So, the dependence of plasma stability on wall position is investigated apart from the impurity release.

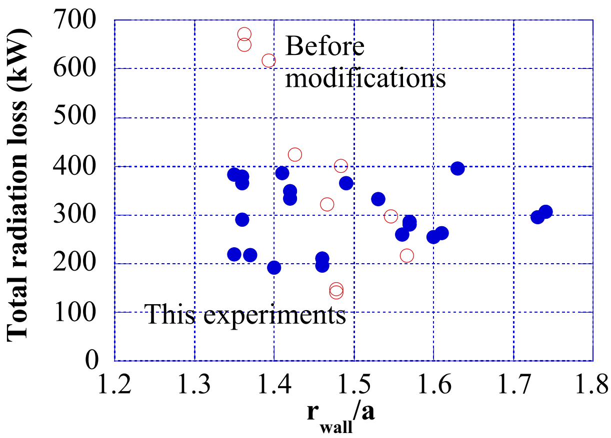

Fig.1 Total radiation loss against normalized wall position, where r_{wall} and a denote minor radius of wall and plasma at outer mid-plane,respectively.

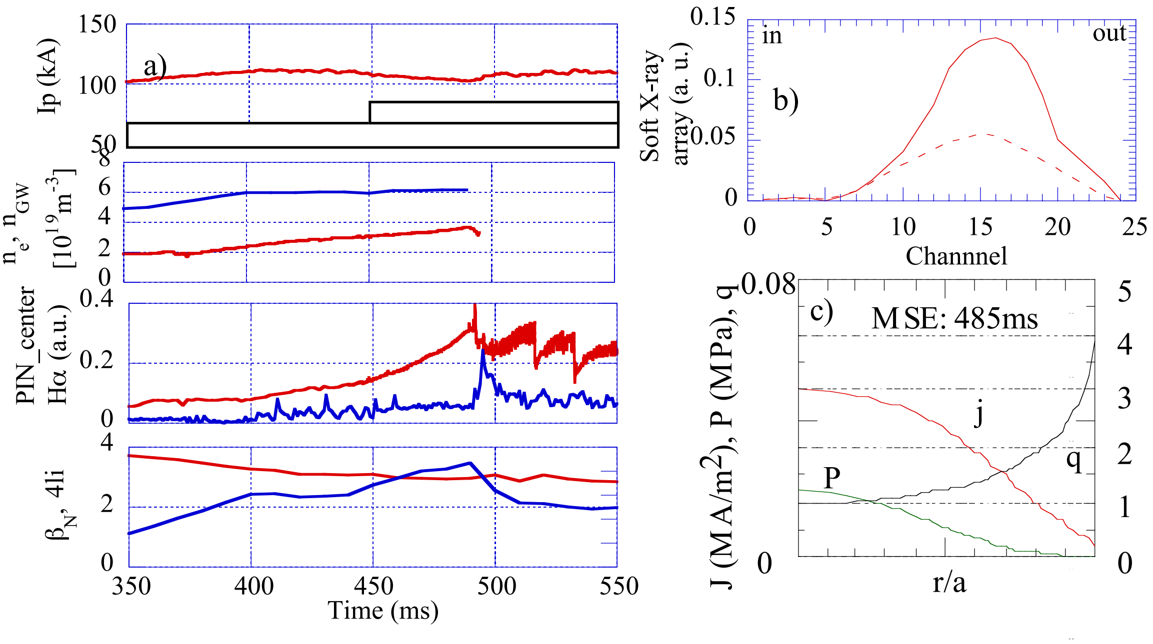

Fig.2 a) Typical wave form of plasma parameters, b)soft Xray profile and c) Profile of safety factor (q), current (j) and pressure (p).

3. Operation Scenario

Improvement of the maximum normalized beta up to DEMO's region (β_N>3.5) was also important issue for this study. Basically, operation region with both internal transport barrier and steady H-mode edge (high Recycling Steady H-mode; HRS) [5,6,12] was utilized. Since the heating power is limited, the typical toroidal field was decreased from 1.0 T to 0.8 T to obtain higher beta plasmas. In addition, the electron density was carefully scanned because it had been reported that the H-mode characteristics are strongly affected by the electron density [6,12]. The waveforms of one of the optimized scenario are shown in Fig. 2. During the ramp up phase of the plasma current, neutral beam of co-direction (co-NB) was injected (350 ms ~). The electron density increased to n_e/n_{GW}~0.5 during co-injection phase, where n_{GW} is Greenwald density. Transition to HRS H-mode occurred just after the injection of ctr-NB (450 ms ~). Then sharp increase in soft X-ray from center occurred and normalized beta increased. The collapse occurred at ~ 500 ms, n_e/n_{GW} ~ 0.6,and b_N ~3.5~4 li. Radial profile of soft X-ray emission is shown in Fig 2(b), before (440 ms) and after (480 ms) ctr-NB injection. They clearly peaked after the ctr-NB injection. The radial profile of safety factor and plasma current, estimated with motional Stark effect (MSE) is shown in Fig. 2(c) after the ctr-NB injection. The profile changes normal shear to weak shear by the ctr-NB injection.

4. Dependence on wall position

Plasma position was scanned with keeping the conditions in section 3 in order to investigate the effect of the ferritic wall on such high normalized beta plasmas. Figure 3 shows the normalized beta just before the collapse against the normalized wall position (r_{wall}/a) for all effective shots. The data, which were obtained before previous IAEA conference are also shown in the figure. Due to the improvement of the operation scenario and the hardware as described in section 2 and 3, the operational region was extended to β_N~4, r_{wall}/a ~ 1.3. Thus, the compatibility of the ferritic steel wall with DEMO relevant high normalized beta plasma

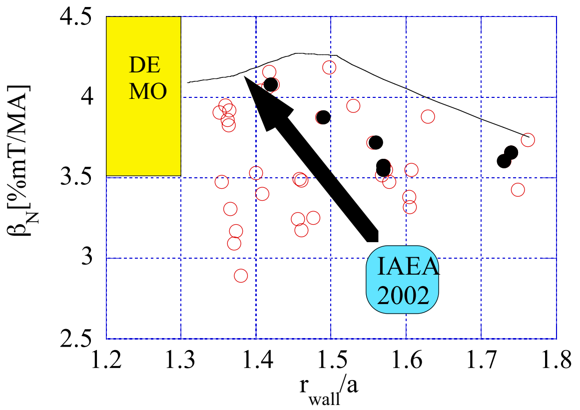

Fig. 3. Normalized beta against normalized wall position for all effective shots. Close circles show data set with similar condition for analysis of wall effect.

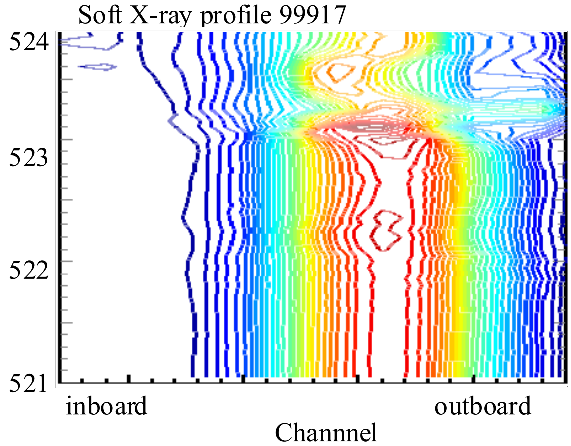

Fig. 4.Contour plot of soft X-ray profile before the collapse. Shift of the profile was observed, which is the typical behavior of the high beta collapse at n_e/n_{GW}~0.6.

was demonstrated. It should be noted that the absolute value of beta contain some ambiguity, but relative value is reliable as discussed in section 5.

Scattering of the data is probably attributed by the difference in pressure and temperature profile, caused by the difference in the electron density, the wall condition and so on. To investigate the wall effect, discharges with similar condition should be carefully chosen. The series of the experimental data plotted by close circles in Fig. 3 is mainly discussed.

They are taken on same day with keeping radiation level at ~ 300 kW during full power NB injection. The waveform of electron density is similar to Fig.2 namely, n_e/n_{GW}~0.5 for co-injection phase and collapse occurs at n_e/n_{GW}~0.6. Other parameters related to plasma stability are summarized in TABLE 1. The parameters are almost reproducible. Another important feature is the behavior of soft X-ray profiles before the collapse. In this series, sharp shift of the profile was observed as shown in Fig. 4, which is clearly different from the behavior of tearing mode disruption. These data suggests that the target plasmas and mechanism of the collapse are almost reproducible and only the wall position was scanned. Figure 5 shows time evolution of the normalized beta. The waveforms are almost identical before 480 ms. The closer configuration results in longer discharge time, and thus, the higher normalized beta. It might correspond to the wall stabilization effect. Clear difference was observed in magnetic probe signal. In both cases, n=1 mode (where n is toroidal mode number) was observed, which was measured by toroidally distributed 8 B_θ probes at outer mid-plane. The position of the locking is reproducible, which means that the

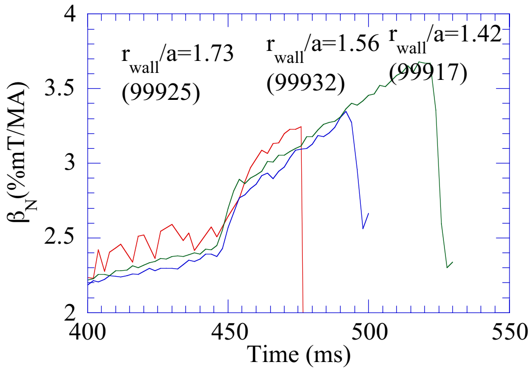

Fig. 4. Time evolution of Normalized beta fot different wall position.

TABLE 1 : COMPARISON OF PLASMA PATAMETERS

	99925	99932	99917
r_{wall}/a	1.73	1.56	1.42
R_{axis} (m)	1.35	1.38	1.39
n_e/n_{GW}	0.56	0.66	0.62
li	0.67	0.74	0.74
q_{95}	3.0	3.0	3.0
P_{rad} (kW)	300	260	330
H_α (a.u.)	0.90	0.75	0.88

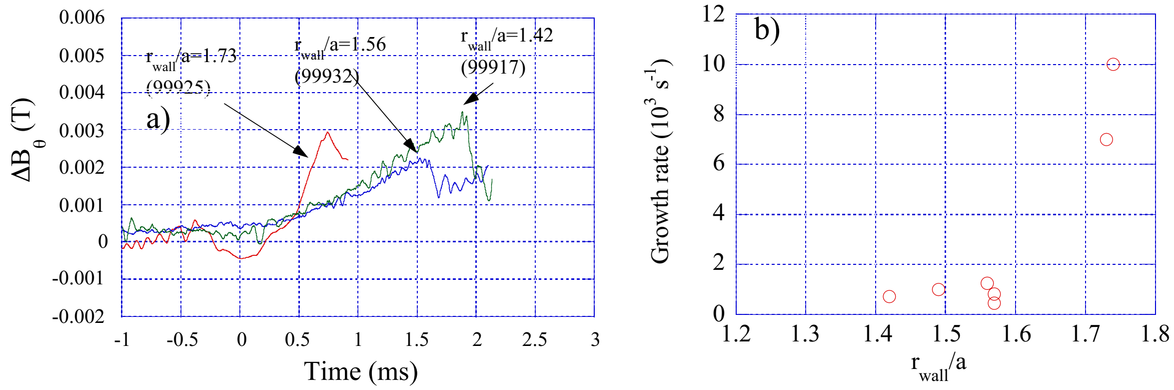

Fig 6 Time evolution of magnetic probe signal. Growth rate was estimated and plotted in (b)

locking is related to external error field. In order to compare growth rate, the difference of probe signal of toroidally opposite location is plotted in Fig. 6(a) for typical 3 cases. The growth rate was estimated from this curve and summarized in Fig. 6 (b) as a function of r_{wall}/a. The growth rate is smaller with closer wall position. Similar to the resistive wall without ferromagnetism, reduction of the growth rate from Alven time scale to wall time constant (a few ms) was observed with ferritic wall. Thus, it is concluded that the ferromagnetic wall shows similar behavior as normal resistive wall and the adverse effect related to ferromagnetism was not observed at least in this experimental condition. It should be noted that the thickness of the ferritic steel in this experiment (~10 mm) is much smaller than that of DEMO, but the normalized effect is expected to be comparable because of the larger minor radius and toroidal field for DEMO.

5. Equilibrium Calculation

Equilibrium code is one of the key diagnostic tools in this work because both normalized beta and distance from the plasma are estimated by the code. In JFT-2M, 24 B_θ probes on surface of the ferritic steels and 8 flux loops on vacuum vessel are used for the calculation. The calculated results might contain systematic error because the magnetic sensors are affected by the ferritic steel wall. Calculation code including ferromagnetic wall have been developed to investigate this effect. Figure 7 shows relation of the sepratrix position estimated by equilibrium code with and without including ferromagnetic effect. The line in the figure

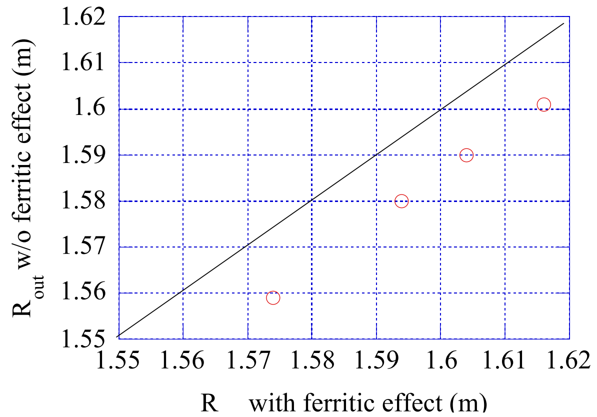

Fig.7. Relation of Outer separatrix (R_{out}) with and without considering ferromagnetic effect.

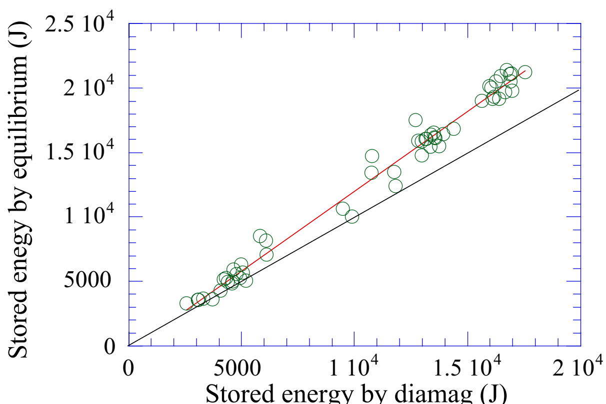

Fig. 8. Relation of stored energy estimated by equilibrium code and diamagnetic loop.

corresponds to inclement =1. The results including ferromagnetic effect is ~1.5 cm larger than that without considering ferromagnetic effect in every case. The shift corresponds to several % of plasma minor radius. This calculation was carried out for B_T=0.8 T case (high beta experiments). The effect is smaller when the magnetic field is higher. This is also consistent with experimental results using the 2 step electrostatic probes [13] and soft X-ray array. The effect on the normalized beta was also investigated. The effect is limited within a few %. In addition, linear relation was obtained between equilibrium code and diamagnetic measurement as shown in Fig. 8. The stored energy estimated from the equilibrium code is 20% larger than that estimated from diamagnetic signal. The absolute value of the beta value has some ambiguity. However, the relative value seems to be reliable and this ambiguity do not change conclusion of this work.

6. Low beta tearing mode

Effect of the ferritic wall on low beta tearing mode is also important issue because it might restrict start up of tokamak discharge. It was afraid that the misalignment of the ferritic steel wall could enhance the error field, and thus, the locked mode. The error field was calculated for most extreme case; namely, all ferritic wall is shifted in same direction by maximum 40 mm. The estimated error field was Br21/Bt~1×10^{-5} for the possible shift of several mm. This is an order of magnitude smaller than the critical value [14], which had been estimated by the experiments with external coils [15].

Another important effect of the ferromagnetic wall is wall stabilization effect. The calculation code with ferromagnetic wall was newly developed [16] for this study. The tearing mode stability parameter Δ’ was calculated for plasma with parabolic profile and the results are shown in Fig. 9(a). The wall shows stabilizing effect only when the resonance layer is very near to the wall. The ferromagnetism de-stabilize the tearing mode but the effect is much smaller than that of the conducting wall. To compare this results with the experiment, resonance layer (q=2 surface) was scanned from r/a=0.3 to 0.97 by increasing plasma current continuously. The tearing mode stability parameter Δ’ was calculated for the experimental data and plotted in Fig. 9(b). The results showed that the Δ’ in this configuration was almost the same as no-wall case, even when the resonance layer is located near to the wall. So, it was concluded that the effect of ferromagnetic wall on the tearing mode is negligibly small in JFT-2M. These calculations are consistent with the experimental results related to the tearing mode, in which, no adverse effects of ferritic wall was observed.

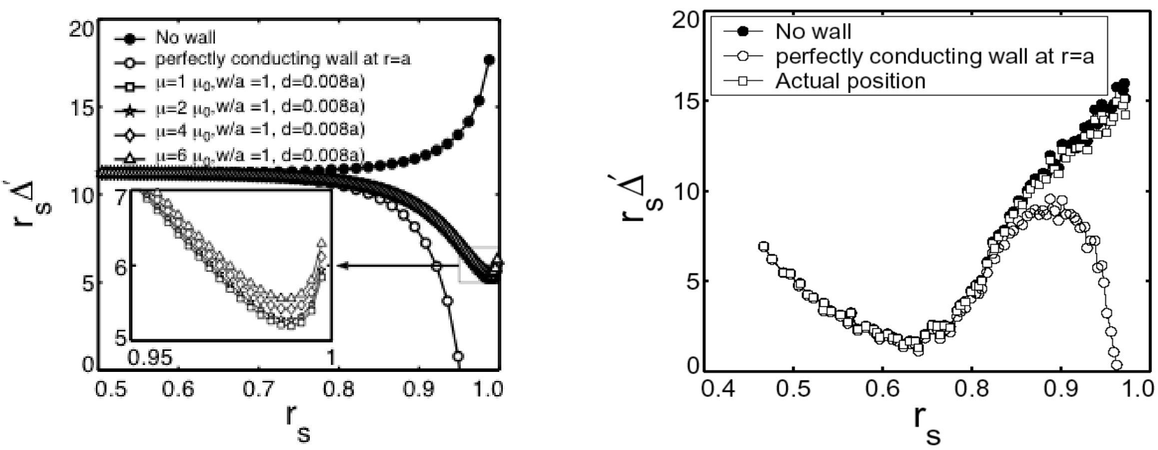

Fig. 9. Tearing mode stability parameter estimated by newly developed calculation code for a) asummed profile, and b) experimental data [16].

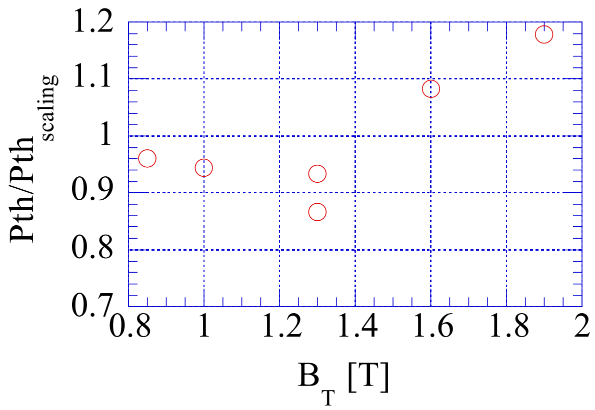

Fig.10.Dependence of the H-mode threshold power on toroidal field.

7. H-mode

When the toroidal field is decreased, the ripple amplitude and the specific permeability varied from 1.2% to 0.5% and 3.5 to 2, respectively. To investigate such magnetic effect on the L/H transition, the threshold power (P_{th}) was measured for 0.85T < B_T<1.9T. The measured P_{th} agreed with scaling law by 15% as shown in Fig. 10. It means that degradation of P_{th} was not observed for this magnetic field range.

8. Summary

The compatibility of the ferritic steel wall with plasma has been investigated mainly for operation regime of high normalized beta and close wall position, which is relevant to the commercially attractive fusion reactor. Due to modifications of operation scenario and limiter configuration, the region showing good compatibility was extended for closer wall position (wall position normalized to the plasma minor radius; r_{wall}/a~1.3) and higher normalized beta (β_N~4). Reduction of growth rate of the instability was also observed in the close wall case, which might corresponds to the wall stabilizing effect.

Effect of the ferromagnetism on equilibrium calculation was investigated. The calculated results showed that the effect of the ferritic wall on separatrix position was limited by ~ 1 cm. The it is consistent with probe measurements. Effect on the beta value was also investigated. The effect of the ferromagnetism on beta value was less than a fer %.

For low beta tearing mode, the calculation code was developed to evaluate stability parameter D' with ferromagnetic wall. The results shows that the wall is not effective for JFT-2M condition. The low toroidal number error field related to miss-alignment of the ferritic wall is estimated to be $Br21/B_T$~$1x10^{-5}$, which is an order of magnitude smaller than the critical value.

The threshold power for H mode transition was measured for wide range of toroidal field. Though the ripple amplitude and the specific permeability varied from 1.2% to 0.5% and 3.5 to 2, respectively, the power agree wall with scaling low.

Acknowledgement

The authors appreciate Prof. K. Kawahata of National Institute for Fusion Science (NIFS) and Prof. S. Okajima of Chubu university for adjustment of FIR. They thank to Prof. K. Ida of NIFS for measurement of CXRS. They appreciate Dr. M. Azumi of JAERI for development of equilibrium code with ferritic steel. The authors are indebted to Dr. H. Kishimoto, Dr. S. Matsuda, Dr. H. Ninomiya, Dr. M. Kuriyama, Dr. M. Kikuchi and Dr. N. Hosogane of JAERI for their continuous encouragement and support.

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