Stabilization Effects of Wall and Plasma Rotation on Resistive Wall Mode in JT-60U

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1   Introduction

Stabilization of the resistive wall mode (RWM) is one of the key issues for sustainment of high-β_N values required for economically attractive future fusion reactors. The resistive wall location and the plasma rotation are essential parameters for the stabilization of the RWM [1, 2]. The prediction of the critical plasma rotation to stabilize RWM is required for ITER.

In JT-60U tokamak, we have performed the RWM experiments focusing on the stabilization effects of the wall location and the plasma rotation. The former has been investigated using current-driven RWM in OH plasmas, the latter has been done in high-β plasmas. For a study of the plasma rotation effect, JT-60U has an advantage that the plasma rotation can be controlled widely by combination of co- and counter-tangential and perpendicular NBs. Utilizing this ability, we have tried to change only plasma rotation at constant β_N in order to purely evaluate the plasma rotation effect.

2   Wall location effect

In order to investigate the passive stabilization effect of the wall location on the RWM, we have performed plasma-wall gap scan in ohmic plasmas in the JT-60U tokamak. In OH plasma, since a current-driven external kink mode can be destabilized by decreasing the edge safety factor by I_p ramping up, the wall location effect can be clearly measured. With increasing I_p with 0.5 MA/s, the edge safety factor q_{eff}, which is q-value at about 97% of minor radius, was decreasing. Finally, when q_{eff} was below 3, a thermal collapse (not major disruption) caused by $m/n = 3/1$ instability, of which the growth time is about 10 ms, where m and n are poloidal and toroidal mode number, respectively. Note that this instability did not rotate and the plasma rotation was nearly zero. As shown in Fig. 1, the plasma-wall gap has been changed 20 cm to 40 cm, systematically. Waveforms of each discharge are shown in Fig. 2. It is found that when the plasma-wall gap was smaller, the growth times of the instabilities became longer and the plasma can survive longer.

Experimentally obtained dependence of the growth rates and wall location are shown in Fig. 3. Also, growth rates calculated by AEOLUS-FT, which is a MHD stability code that can
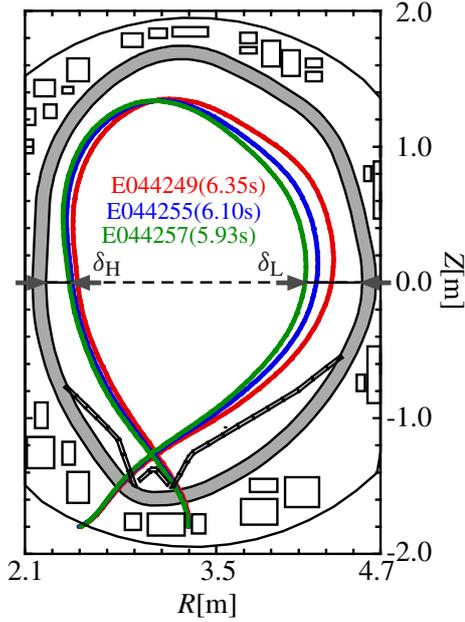
Figure 1 Separatrixes of plasma-wall gap scan experiments. δ_H and δ_L are the gaps at high and low field side, respectively.
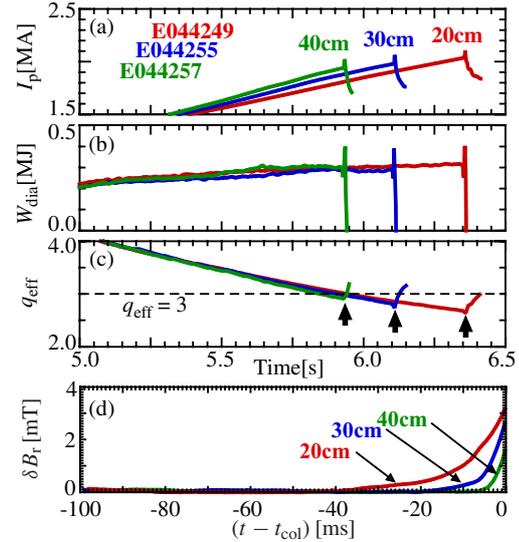

Figure 2 Comparison of three discharges with different plasma-wall gaps. (a) Plasma currents, (b) stored energies and (c) edge safety factors. (d) Radial magnetic field just before collapses, where t_{col} is the time of collapse.

take into account a resistivity of wall [3], and dispersion relations [4] are superimposed. The dispersion relation without plasma rotation and dissipation can be described as

$$\gamma^2 - \Gamma_\infty^2 \left(1 - \frac{d_c}{d}\frac{\gamma\tau_W}{\gamma\tau_W + 1}\right) = 0,$$

where γ, Γ_∞ and τ_w are the growth rate, the growth rate without wall and the skin time of the wall; d and d_c are the wall location and the critical location of ideal wall stabilization, respectively. Since these instabilities have been observed at $d \leq d_c$ where ideal MHD with ideal wall is stable, the observed instabilities are identified as the RWM. The dependence of growth rate and wall location agrees well with the dispersion relation. On JT-60U, τ_w is evaluated as about 10 ms. However, experimentally obtained growth rates are 10 times smaller than the results of AEOLUS-FT and the above dispersion relation in the $\tau_w = 10$ ms case. Further interpretation is required in order to explain this discrepancy.
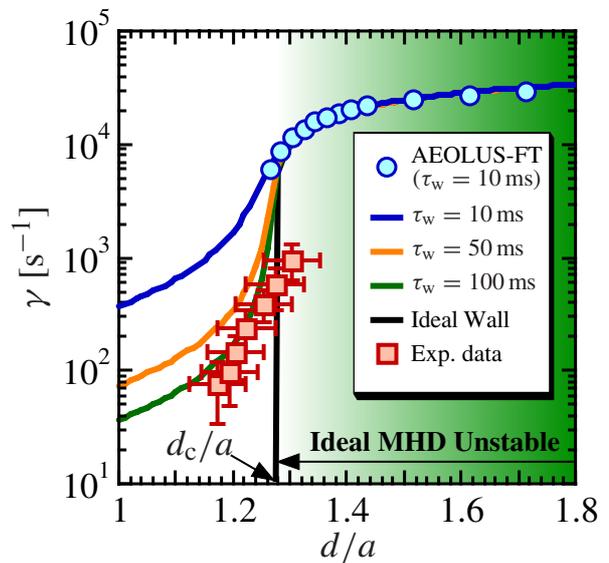

Figure 3 Dependence of experimentally obtained growth rates on wall location. Thick lines show a dispersion relation with $\tau_w = 10, 50, 100$ ms and ideal wall.

3 Plasma rotation effect

After last experimental campaign, ferritic steel tiles had been installed inside the JT-60U vacuum vessel so as to reduce a magnetic ripple that can enhance fast ion ripple loss. This makes it possible to produce a high-β plasma close to the wall.

In order to obtain the stabilization effect of the plasma rotation, experiments of high-β_N plasma, where plasma-wall gap was $d/a \simeq 1.2$, have been carried out at $B_t = 1.57$ T. As shown in Fig. 4, the plasma rotation was changed by a switching counter- to co-NB injection at 6.0 s and β_N was kept constant using a stored energy feedback control. After NB switching, plasma rotation slowly decelerated and major collapse occurred (Fig. 4(d)). Figure 5 shows enlarged waveforms just before the collapse. In this phase, β_N was kept constant at 2.8. From ideal MHD stability analysis using

Figure 4   Waveforms of high-β_N experiment. From the top, (a) plasma current and NB powers, (b) β_N and radiation power, (c) $D\alpha$ intensity, (d) toroidal plasma rotations at several positions, (e) ctr- and (f) co-NB power.

MARG2D code [5], $\beta_N \simeq 2.8$ is exceeded the no-wall β_N limit β_N^{free}. Just before the collapse, a growing of radial magnetic field, of which growth time is about 10 ms, was observed. According to toroidal and poloidal magnetic probe arrays, this instability was $n = 1$ and poloidal structure was localized at the low field side (bad curvature side). Simultaneously, β_N degradation started and finally collapse occurred. This instability was identified as $n = 1$ RWM because of slow growth time $\gamma^{-1} \sim \tau_w$ and $\beta_N > \beta_N^{\text{free}}$. Since the CXRS measurement showed ion temperature profile was almost unchanged in the phase of β_N constant, the pressure profile was also almost fixed. The q profile from MSE measurement showed the current profile was also unchanged. Therefore, it can be concluded that the RWM became unstable owing to deceleration of toroidal rotation. Figure 6 shows the profiles of toroidal rotation and q profile from MSE measurement. After switching counter- to co-NB, the rotation profiles were decelerated with almost keeping the profile. From MARG2D code, $m = 2$ component of eigenfunction is dominant. Therefore, toroidal rotation at $q = 2$ surface is thought to be effective for RWM stabilization. At just the RWM onset, toroidal rotation at $q = 2$ was around 0.5 kHz, which is equivalent to 0.5% of Alfvén velocity and 3.0% of sound wave velocity. This
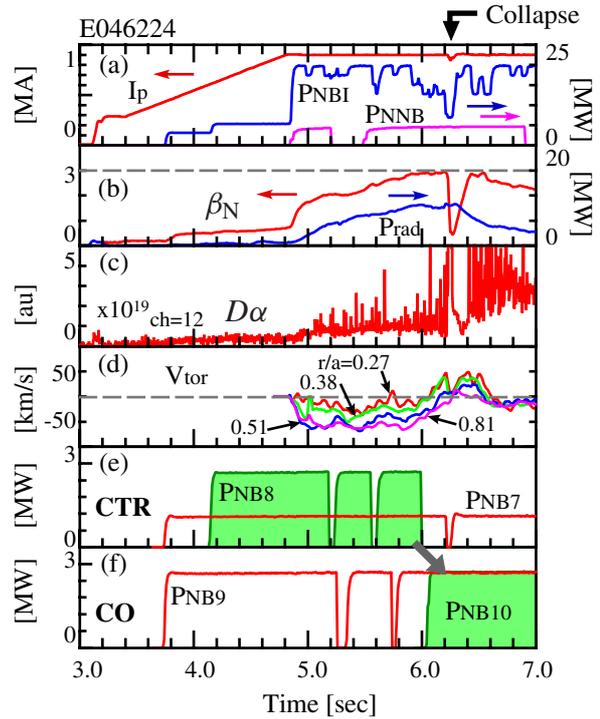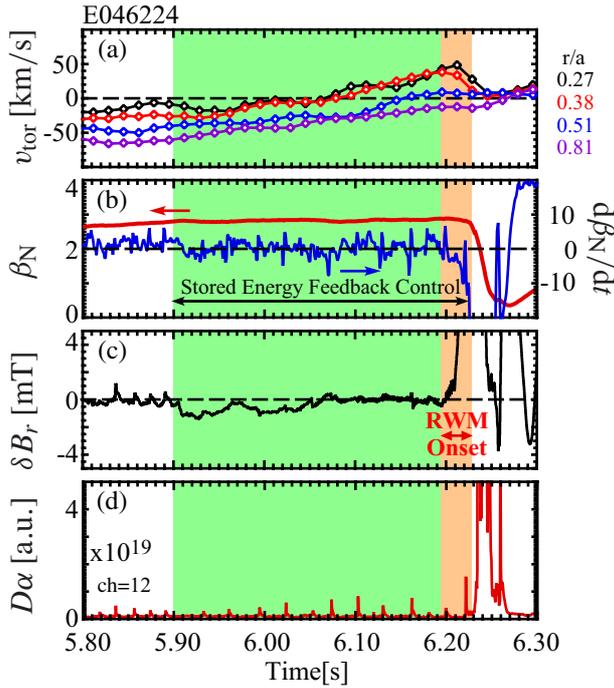
Figure 5   Enlarged waveforms of (a) toroidal plasma rotations, (b) β_N and deviation of β_N, (c) odd component of radial magnetic field and (d) $D\alpha$ intensity.
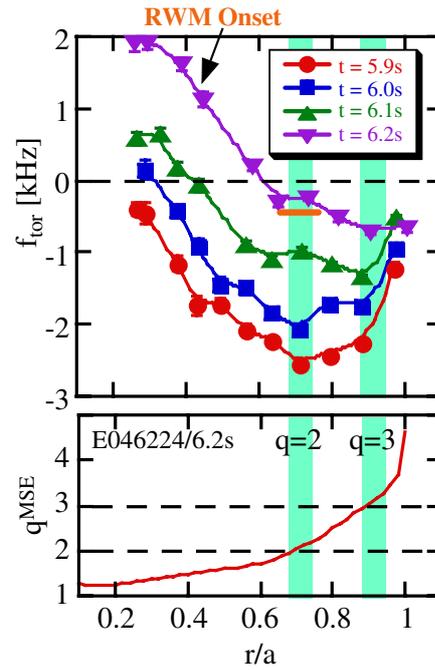
Figure 6   Profiles of toroidal plasma rotation after switching ctr- to co-NB and q profile from MSE.

plasma rotation seems to be a critical plasma rotation for RWM stabilization.

4   Conclusion

We have carried out the experiments in order to investigate the stabilization effects of wall location and plasma rotation on RWM in the JT-60U tokamak. The dependence of RWM growth rate on the wall location has been obtained, that is, the smaller plasma-wall gap makes the RWM growth stable. At high-β plasma, destabilization of the RWM due to plasma rotation deceleration has been observed. The critical plasma rotation was 0.5% of Alfvén velocity and 3.0% of sound wave velocity. We need further analysis for the critical plasma rotation for RWM stabilization.

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