Stabilization of the Line-Tied Resistive Wall Mode by a Rotating Conducting Wall

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Introduction and Device Description

The Resistive Wall Mode (RWM) is a performance-limiting instability which is excited when stabilizing eddy currents in a conducting wall ohmically dissipate, allowing the RWM to grow on the time scale of the wall's resistive diffusion ($\tau_w = \mu_0 \sigma_w r_w \delta_w$, where σ_w, r_w and δ_w are the wall conductivity, radius, and thickness). It is known that plasma rotation is able to stabilize the RWM as lab-frame eddy currents are inductively regenerated by the moving plasma. Analagously, theory suggests [2, 3] that differentially rotating conducting walls can stabilize the RWM, as the mode will always be rotating in the frame of one of the two walls. Stabilization by physically moving conductors is of interest both due to the physical analogy to an infinite set of active coils and due to the predicted robustness of stabilization once the mechanical challenge has been overcome.

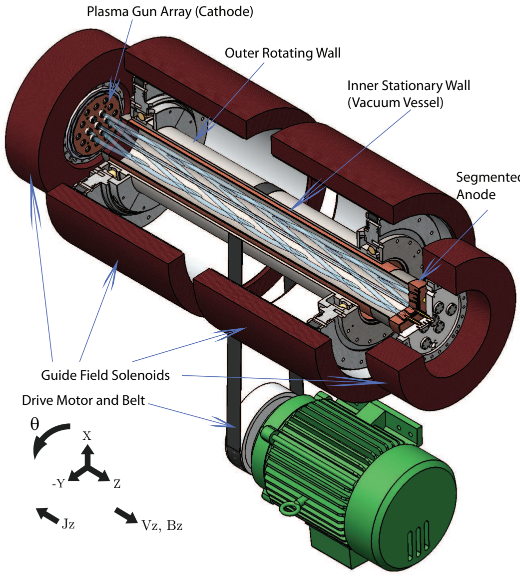

Figure 1: The Rotating Wall Machine [1] experimental geometry. A uniform 500 G guide field (B_z) is applied by four external solenoids and is twisted by up to 7 kA of plasma current (I_p). Plasmas are generated by an array of 7 washer-stabilized hollow cathode plasma guns which source both plasma and current when electrostatically biased with respect to the anode. Probes measure plasma to be dense ($n_e \approx 10^{20}$ m^{-3}) and cold ($T_e \approx 3$ eV). Plasmas are shown as discrete flux-ropes though measurements indicate that a fully merged axisymmetric profile is achieved by 1/3rd of the distance to the anode.

Experiments are performed on the Rotating Wall Machine [1], a 1.2 m long by 16 cm diameter screw-pinch shown in Fig. 1, with $\tau_w = 7$ ms. A linear experiment is used as this topologically allows solid cylinders to completely surround the plasma, while a torus would require a flowing liquid metal. The non-dimensional parameter of interest for RWM stabilization is the magnetic Reynolds number inside the rotating wall ($R_m = \Omega_w \tau_w$) which sets the ratio of advection to diffusion in the magnetic induction equation. Experiments here described are conducted up to $R_m = 5$, which corresponds to rotation at 260 km/h.

RWM Stabilization by Plasma Rotation and Wall Locking by m=1 Error Field

Large radial electric fields have been previously measured in the device [1] indicating that azimuthal ExB flows are present. This ExB flow profile is found to be both axially and radially sheared, with strongest flows near the cathode and in the mid-radius of the device while the equipotential at the anode surface necessarily requires this flow to vanish. MHD modes born in the plasma frame are thought to take an eigenfunction-weighted average of this flow to set the global mode frequency (ω) [4], which is kHz scale for the experiment. Modes at this frequency are found to be insensitive to wall rotation as $\omega \gg \Omega_w$, thus in order to study the effect of the rotating wall on RWM stability, this instrinsic rotation must first be reduced so that locked modes ($\omega \approx \Omega_w$) are studied.

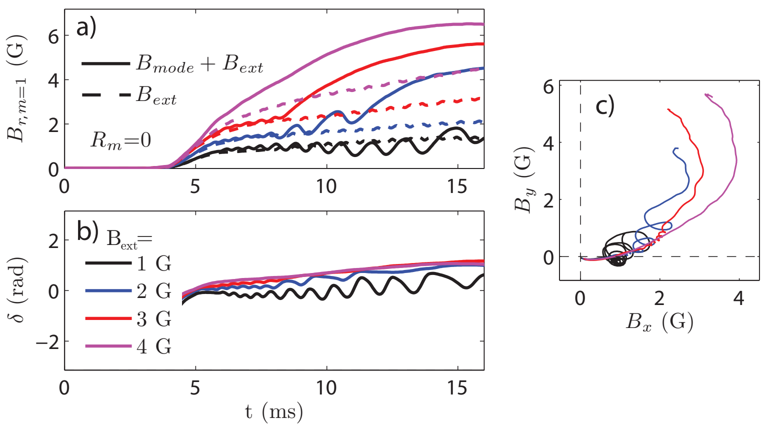

Figure 2: Time-traces of amplitude (a), phase (b), and hodogram (c) of the m = 1 component of B_r with different applied m=1 field strengths (B_{ext}). The transition from a rotating external kink (XK) to a locked RWM is clearly visible. For weak or no applied B_{ext} the mode does not lock, while intermediate cases show a slowing down phase before mode locking occurs, and for sufficiently large B_{ext} the mode is born-locked. Traces display both the applied B_{ext}, characterized by an LR penetration time (dotted line in a) as well as the XK/RWM instability (deviation from dotted line). For all cases mode growth is not observed to be characterized by a growing exponential solution, as expected by a linear theory.

An m = 1 (vertical) error field (B_{ext}) is found to slow the intrinsic plasma rotation allowing the RWM to lock and grow beyond B_{ext}, as shown in Fig. 2. B_{ext} is present at plasma formation and forces the resulting equilibrium to be centered off-axis, damping azimuthal rotation by breaking axisymmetry in a manner analagous to poloidal flow damping in the torus. As shown, a critical B_{ext} = 1.5 G is necessary to lock the mode, although this value varies with the underlying equilibrium. Hodograms (Fig. 2c) clearly illustrate the greatly reduced ω once locking occurs. Mode locking is observed to be abrupt, especially at larger B_{ext}. Growth rates of the locked modes are inconsistent with exponential growth due to the non-linearity of the locking transition. For $B_{ext} > 3$ G, no ω is seen and the observed signal immediately deviates from B_{ext}, a regime which is termed born-locked.

RWM Stabilization by Wall Rotation

Stabilization of the RWM at large R_m is clearly demonstrated for discharges which lock during the discharge lifetime, as shown in Fig. 3. Increasing R_m both reduces the observed $B_{r,m=1}$ non-linear growth rate from the B_{ext} baseline and imparts a real frequency (ω) to the locked mode, as predicted by theory [3]. For the largest R_m, the equilibrium itself couples to Ω_w, and the offset introduced by B_{ext} rotates despite being applied by a lab-frame coil. High R_m stabilization thus maintains $|B_{r,m=1}| \approx |B_{ext}|$ though $\vec{B}_{r,m=1} \neq \vec{B}_{ext}$.

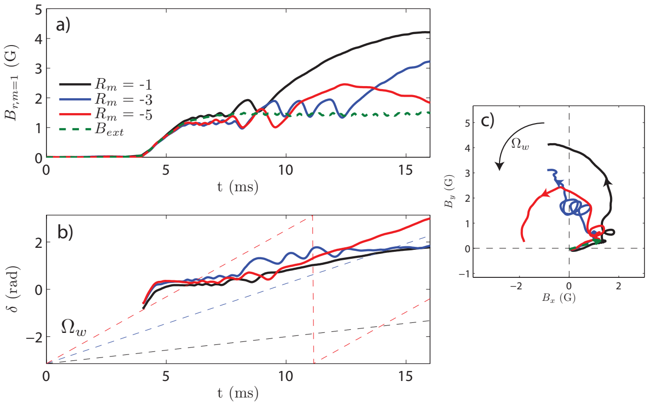

Figure 3: Time-traces of (a) amplitude, (b) phase, (c) hodogram of the m = 1 component of B_r at different wall rotation rates (R_m), illustrating the coupling of the RWM to the rotating wall and subsequent mode stabilization. A uniform locking field (B_{ext}) has been applied to the plasma at each rotation rate. At large R_m, results illustrate strong coupling of RWM to the wall and subsequently increased ω. The magnitude remains near B_{ext} for stabilized discharges. Dotted lines in b) indicate the rate of wall rotation.

The ability of the locked mode to rotate is found to be asymmetric in $\hat{\Omega}_w$, as shown in Fig. 4 for born-locked modes ($\hat{\Omega}_w$ is defined as the initial ExB rotation direction $\hat{\omega}_0$). For $\hat{\Omega}_w = -\hat{\omega}_0$ the stabilized RWM is found to rotate at $\approx \Omega_w$ (locks to rotating wall) while for $\hat{\Omega}_w = \hat{\omega}_0$ the mode locks to the static wall (vacuum vessel) and $\omega \approx 0$, though reduction in the growth rate and mode amplitude is seen in both directions. For 0 R_m discharges, a very slow rotation in the $-\hat{\omega}_0$ direction is observed (shown in Fig. 4c). Ω_w coaligned with this locked mode intrinsic rotation would thus be expected to more easily yield RWMs locked to the rotating wall.

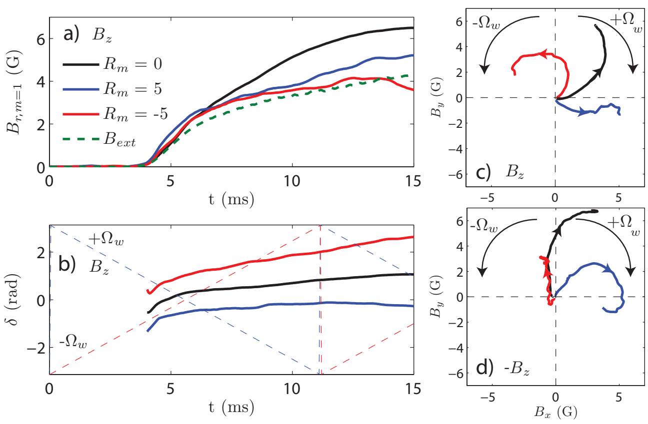

Figure 4: Coupling of the RWM to the wall is found to be asymmetric in $\hat{\Omega}_w$. Though a) indicates that both directions are stabilizing, the plasma is seen to lock to the rotating wall for $\hat{\Omega}_w = -\hat{\omega}_0$ and lock to the static wall if $\hat{\Omega}_w = -\hat{\omega}_0$. c) Illustrates a small intrinsic rotation to the 0 R_m locked mode which is counter to ω_0, and this intrinsic rotation is likely responsible for the observed asymmetry. d) Indicates that under B_z reversal (ω_0 reversal), the asymmetry in $\hat{\Omega}_w$ reverses as well. Dotted lines in b) indicate the rate and direction of wall rotation.

Extension of RWM Stability Window by Wall Rotation

Fig. 5 illustrates that $R_m > 0$ operation increases the window of RWM-stable operation, as predicted by theory [3]. Experiments are done at constant B_z and B_{ext}, such that RWM onset is found to occur at higher I_p (lower edge safety factor q_a) as compared to slow or no wall rotation. This demonstration is only possible for born-locked modes (largest amplitude traces of Fig. 2) as fast mode rotation and locking thresholds are easily confused for RWM onset conditions, though the subtraction of B_{ext} is necessitated (dotted lines in Fig. 5a,b). For $R_m = -5$ operation, extrapolation of ΔB_r indicates that q_{crit} is lowered by ≈ 0.3 from slow rotation, corresponding to a $\approx 25\%$ increase in I_p (ΔI_p in Fig. 5b) while maintaining stability to the RWM. Theory predicts that the RWM should be unstable at $q_a = 1$ for $R_m = 0$, and $q_a = 0.8$ for $R_m = 5$. The observed change (Δq) is within measurement error of the theoretical prediction though the observed transition is found to occur at higher q than predicted. However, the difficulty in defining the plasma edge (and subsequent q_a value) in combination with the coarseness of the $q(r)$ measurement suggests these discrepancies may be within measurement error.

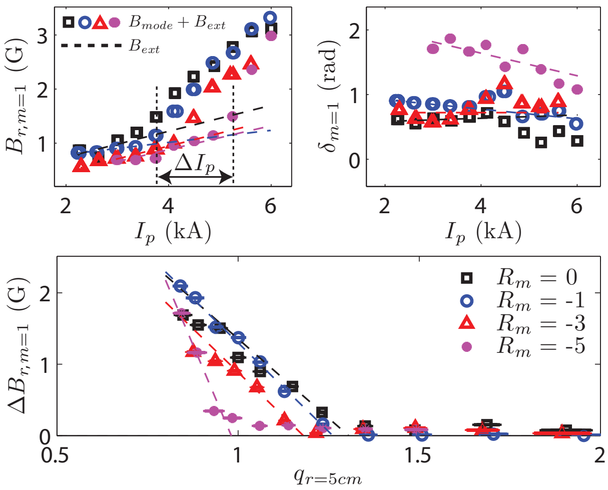

Figure 5: Extension of the RWM stability window is shown by increased I_p (lowered q) required for RWM onset. a) The obserbed m = 1 amplitude is composed of both the mode signal (B_{mode}) and the locking error field (B_{ext}) for born locked modes. Subtraction of B_{ext} (dotted lines in a,b) reveals mode onset at approximately $q_{r=5cm} = 1.3$, somewhat above that predicted by theory (shown in c). At higher R_m, onset is shown to occur at lower values of $q_{r=5cm}$ (higher I_p). For $R_m = -5$ operation, I_p was able to be increased by $\approx 25\%$ while maintaining RWM-stable operation (ΔI_p in a). Precision in this measurement is limited by extrapolations to the onset q_{crit}, the coarseness of the $q(r)$ measurement, and by phase scatter in the R_m=-5 case due to RWM rotation.

References

[1] Paz-Soldan, C., Bergerson, W. F., Brookhart, M. I., Hannum, D. A., Kendrick, R., Fiksel, G., and Forest, C. B. *Review of Scientific Instruments* **81**(12), 123503 (2010).

[2] Gimblett, C. G. *Plasma Physics and Controlled Fusion* **31**(14), 2183–2186 (1989).

[3] Hegna, C. C. *Physics of Plasmas* **11**(9), 4230–4238 (2004).

[4] Paz-Soldan, C., Brookhart, M. I., Clinch, A. J., Hannum, D. A., and Forest, C. B. *Physics of Plasmas* **18**(5), 052114 (2011).