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Resistive Wall Modes and Plasma Rotation in DIII-D

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The stabilization of the resistive wall mode (RWM) by toroidal plasma rotation has been demonstrated in neutral beam heated DIII-D discharges for values of β up to 70% above the no-wall stability limit [1]. The stabilizing effect of plasma rotation is explained by assuming some dissipation, which is caused by the rapid plasma flow through a perturbed magnetic field [2]. Sufficient plasma rotation is predicted to extend the operating regime of tokamaks from the conventional no-wall β limit up to the ideal wall β limit. While plasma rotation has a stabilizing effect on the RWM, a finite amplitude RWM also increases the drag on the plasma, which leads to a non-linear interaction between the RWM and the plasma rotation. A good understanding of the underlying dissipation mechanism is crucial for reliable predictions of the plasma rotation which will be required for wall-stabilization in a burning-plasma experiment. In order to measure the stabilizing effect of plasma rotation on the RWM the technique of active MHD spectroscopy, which was previously applied to MHD modes at frequencies above 10 kHz [3], is extended to frequencies of a few Hz.

Interaction Between a Resistive Wall Mode and an External Magnetic Field

The interaction of the RWM with external magnetic fields according to several single-mode models [4,5] can be described by a system model for the evolution of the perturbed field at the wall B_w,

$$\left(\gamma\tau_w^* - \gamma_0\tau_w^*\right)B_w = M_{wc}^* I_c \quad , \tag{1}$$

where γ is the growth rate of the RWM and γ_0 its growth rate in the absence of currents in any perturbing external coils, I_c. Dissipation in a rotating plasma causes γ_0 to become a complex number. In the absence of plasma, $\gamma_0\tau_w^* = -1$, where τ_w^* is the characteristic resistive wall time of the mode. An effective mutual inductance M_w^* describes the coupling between the coils and the field at the wall and depends on the geometry and mode structure.

The RWM stability is probed by applying an external resonant field, which can be amplified by a marginally stable mode [6]. The amplitude of the resonant field amplification (RFA) A_{RFA} is defined as the ratio of plasma response and the applied field in vacuum, $A_{RFA} = (B_w - B_{w,vac})/B_{w,vac}$. A sinusoidal, rotating external field with an angular frequency ω_{ext} is applied to excite the mode. After an initial transient phase all quantities oscillate with the externally imposed frequency and Eq. (1) yields,

$$A_{RFA} = \frac{1+\gamma_0\tau_w^*}{i\,\omega_{ext}\tau_w^* - \gamma_0\tau_w^*} \quad . \tag{2}$$

Active MHD Spectroscopy on the Marginally Stable RWM

In DIII-D two sets of non-axisymmetric coils are used to generate an external field with a large overlap with the RWM mode structure. Two toroidal arrays of six internal coils located above and below the outboard midplane (I-coils) [7] were recently added to an array of six external coils (C-coils). The plasma response is detected with complete toroidal arrays of B_r and B_p sensors, located above, on and below the outboard midplane, Fig. 1. The frequency dependent mutual inductance M^*_{wc} is determined in vacuum shots and is used to calculate the vacuum field $B_{w,vac}$.

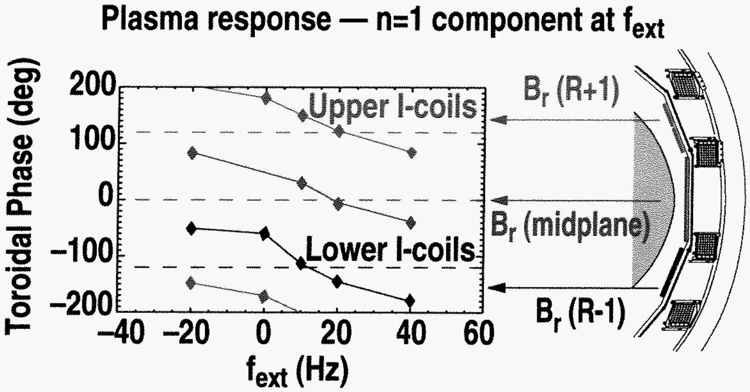

Fig. 1. Toroidal phase of the n=1 plasma response to external fields at various frequencies measured with several saddle loop arrays. The typical RWM mode structure remains rigid, independent of the applied frequency.

The external field is applied in an ELMy H-mode discharge with q_{min} above 1. Tangential neutral beam injection raises the plasma pressure above the estimated no-wall limit of β_N~1.8 and provides a momentum source. Correction of the intrinsic error field maintains the rotation above the critical frequency required for rotational stabilization [1]. The n=1 component of the magnetic measurements of the plasma response is extracted using Fourier transforms in time and space. The toroidal phase of the plasma response is determined with respect to the phase of the external field (at the midplane). The phase difference between the upper and lower saddle loop arrays of approx. 260°, which is typical for an RWM in such a plasma, is independent of the applied frequency, Fig. 1.

The measured frequency dependence of A_{RFA} at two values of β is compared to the prediction Eq. (2). Amplitude and phase, both, can be well fitted to the predicted form, Fig. 2. The measurements show in particular a maximum amplification occurring for an external frequency, which is a fraction of the inverse wall time, and a clear preference of one toroidal direction relative to the plasma rotation. According to Eq. (2) the frequency with the largest response corresponds to the natural rotation frequency of the RWM. The non-zero phase shift at the resonance frequency can be caused by the up-down asymmetry of the single-null plasma. The good fit strongly supports the applicability of a single-mode model and allows for a measurement of the RWM stability parameter γ_0.

Active measurements at zero frequency have been used to systematically probe the RWM stability as a function of β. The measured amplitude and phase of the resonant field amplification and its damping rate after the external field is switched off are fitted to a single mode model [4] yielding the β-dependence of the complex growth rate γ_0 [8]. It is found that the damping of the mode becomes weaker and approaches marginal stability as β increases above the no-wall β limit, Fig. 3(a). The rotation frequency varies less significantly with β and is typically a fraction of the inverse wall time, Fig. 3(b).

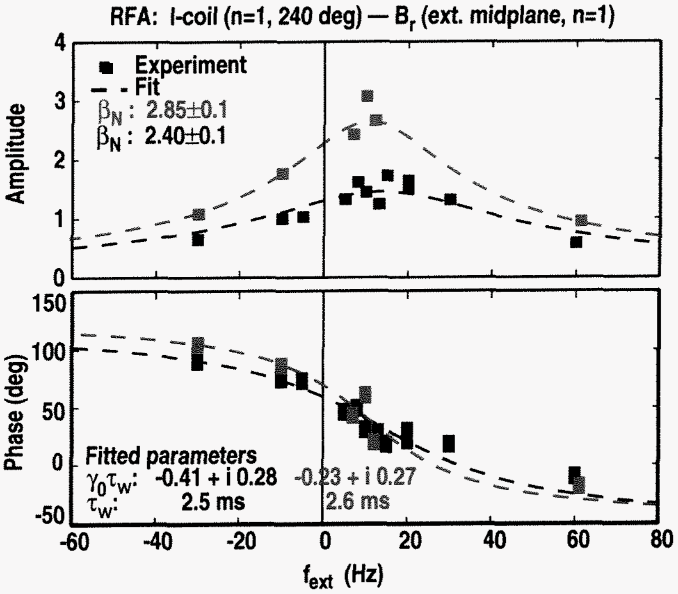

Fig. 2: Resonant field amplification measured for various applied external frequencies and at two values of β. The experimental data is in good agreement with the predicted frequency dependence Eq. (2). The fit of the measurements to the predicted frequency dependence yields γ_0 and τ_w.

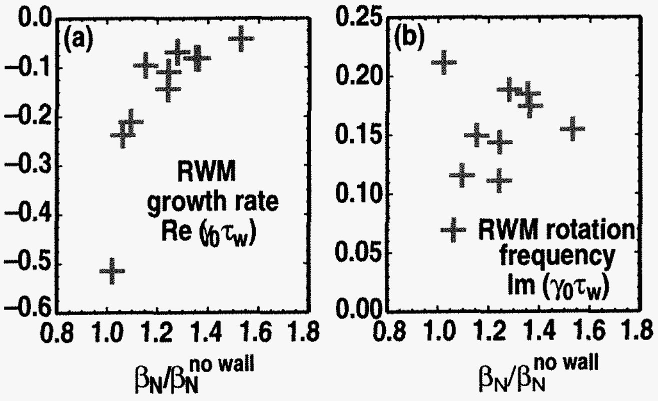

Fig. 3. The RWM stability is probed with n=1 pulses with the C–coil at zero frequency and at various values of β above the no-wall β-limit. The measured amplitude, phase and damping rate of the plasma response is fitted to a single mode model yielding a measurement of the β-dependence of γ_0.

Drag of a Finite Amplitude RWM

A finite amplitude RWM exerts an additional drag on the plasma. This drag can be sufficiently large that resonant field amplification of machine intrinsic error fields slows the plasma below the critical rotation required for rotational stabilization leading to a β collapse.

The use of external fields in order to excite a finite amplitude RWM allows for a controlled slowing-down of the plasma rotation, Fig. 4. The rotation decays uniformly across the entire profile and does not reveal any local effects, Fig. 4(c). A non-resonant effect could be the enhanced neoclassical toroidal "ripple" viscosity caused by the non-axisymmetric perturbed magnetic field δB [9]. The evolution of the rotation frequency f is described by,

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_M} - C\cdot\delta B^2 f \quad . \qquad (3)$$

An estimate of the drag coefficient C [10] is used to compare the experimental rotation decay to predictions. In discharges where external non-axisymmetric magnetic fields do not cause any RFA the perturbed field δB is well known. The observed C typically exceeds the predicted value of C by a factor of 5. In discharge 109922, Fig. 4, where β is well above the no-wall stability limit, an applied external field amplifies a marginally stable RWM. The fit of the rotation decay measured at mid-radius to the predicted evolution Eq. (3) using the $B_{p,w}$ measurement of the plasma response at the wall yields $C^* = (\delta B/\delta B_{p,w})^2 \bullet C$ Fig. 4(b). In order to obtain the same agreement between the observed rotation decay and the

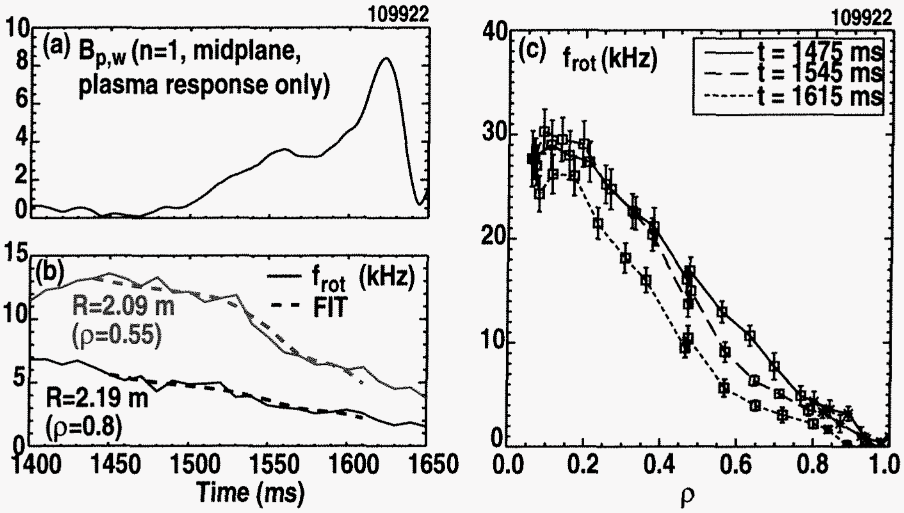

Fig. 4. (a) In a discharge above the no-wall limit (β_N=2.6~4ℓ_i) and q_{min}>2 a finite amplitude RWM is excited starting at t=1500 ms. (b) The rotation decay is fitted to Eq. (3). With τ_M = 70 ms the fit yields $C^* = 1.4\ s^{-1}G^{-2}$ for the chord at ρ = 0.55 and $C^* = 1.1\ s^{-1}\ G^{-2}$ for the chord at ρ = 0.8. (c) The rotation decays across the entire profile.

predictions (including the factor of 5) the magnetic perturbation inside the plasma has to be approx. 10 times larger than the measured perturbation amplitude at the wall. Measurements of the ion temperature perturbation caused by RFA in another discharge indicate that the amplitude of the internal magnetic perturbation is indeed of the order of 10. The enhanced neoclassical toroidal viscosity is, therefore, a promising candidate to explain the momentum dissipation associated with a finite amplitude RWM.

Concluding Remarks

Active MHD spectroscopy at low frequencies has been used to probe the stability of the RWM which is stabilized by plasma rotation. The plasma response to applied external fields is rigid and consistent with single-mode models. This increases our confidence in the applicability of these models for measurements of the stability as well as for predictions of feedback performance. Active measurements have also been used to investigate the additional drag caused by a finite amplitude RWM, suggesting that neoclassical toroidal "ripple" viscosity could be the momentum dissipation mechanism.

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