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Active MHD Spectroscopy on the Resistive Wall Mode in DIII-D and JET

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I. Introduction

Active MHD spectroscopy measures the macroscopic plasma stability, while the plasma remains stable. The stability is probed by applying magnetic fields, which largely overlap with the structure of a mode. If the mode is only weakly damped, it amplifies the resonant component of the applied field, a phenomenon referred to as resonant field amplification (RFA) [1]. This measurement technique is well suited to analyze the stability of the resistive wall mode (RWM) in high-beta plasmas above the no-wall stability limit, where rapid toroidal plasma rotation in the order of a few percent of the Alfvén velocity is sufficient to stabilize the $n=1$ RWM [2]. Active MHD spectroscopy allows for a quantitative test of models of the underlying dissipative process, which is required for a reliable extrapolation of the stabilizing effect of plasma rotation in future experiments. We present recent measurements on the DIII-D and JET tokamaks, where non-axisymmetric control coils are used to apply a rotating or oscillating $n=1$ magnetic field at various frequencies. In both experiments the spectrum of the plasma response can be described by a single mode model and yields a measurement of the RWM damping rate and the mode rotation frequency.

II. Resonant Field Amplification Spectrum

At the applied low frequencies, $\omega_{\rm ext}\tau_{\rm w} \le 1$, with $\tau_{\rm w}$ being the characteristic resistive decay time of wall currents induced by the mode, it is necessary to take into account the eddy currents in the wall. Assuming a single marginally stable mode, the interaction of the perturbed radial field at the wall $B_{\rm s}$ and externally applied magnetic fields can be described by [3],

$$\tau_{\rm w}\,\frac{dB_{\rm s}}{dt} - \gamma_0\,\tau_{\rm w}\,B_{\rm s} = M^*_{\rm sc}\,I_{\rm c} \quad , \tag{1}$$

where γ_0 is the (complex) growth rate of the RWM in the absence of currents in any perturbing external coils, $I_{\rm c}$. Note, that $\gamma_0\tau_{\rm w} = -1$ describes the case without a plasma. The effective mutual inductance $M^*_{\rm sc}$ determines the resonant component of the magnetic field due to coil currents $I_{\rm c}$ at a sensor *s*. It has been shown that Eq. (1), which has originally been derived for slab geometry, also holds for general toroidal geometry [4].

If the currents in external coils are phased to generate a rotating magnetic field $I_c(t) = \hat{I}_c\, e^{i\omega_{ext}t}$ all quantities will eventually oscillate with the externally imposed frequency $\omega_{\rm ext}$. The plasma response $B_{\rm s}^{\rm plas}$ is obtained by subtracting the externally applied field including the corresponding eddy currents in the wall from the total perturbed field, $B_{\rm s}^{\rm plas} = B_{\rm s} - B_{\rm s}^{\rm ext}$. With $B_{\rm s}^{\rm ext}$ obtained by setting $\gamma_0 = -\tau_{\rm w}^{-1}$, Eq. (1) yields,

$$B_{\rm s}^{\rm plas}(t) = \frac{\gamma_0\,\tau_{\rm w}+1}{\left(i\omega_{\rm ext}\,\tau_{\rm w}-\gamma_0\,\tau_{\rm w}\right)\left(i\omega_{\rm ext}\,\tau_{\rm w}+1\right)}\cdot M_{\rm sc}^{*}\,\hat{I}_c\, e^{i\omega_{ext}t} \quad . \qquad (2)$$

III. Measured RFA Spectrum

In recent DIII-D and JET experiments internal or external coils are used to apply a rotating or oscillating $n=1$ magnetic field. In both experiments the spectrum of the plasma response is measured as the perturbed magnetic field at the wall.

A. DIII-D

Internal coils are used to apply a rotating $n=1$ magnetic field. The direct coupling of the control coils to the sensors is measured in vacuum shots. For frequencies below 100 Hz the measured vacuum field at the wall is well described by $B_{\rm s}^{\rm ext}\,(\omega_{\rm ext}) \propto I_{\rm c}/(1+i\omega_{\rm ext}\,\tau_{\rm w})$. Since the magnetic field of the coils has a similar spatial structure as the RWM, the fit of the measurements yields the estimate for the characteristic wall time of the n=1 kink mode of $\tau_{\rm w}$ ~ 2.5 ms. The plasma response measured with toroidal arrays of saddle loops at several poloidal locations has the characteristic structure of the RWM in DIII-D [5]. The plasma response peaks when the externally applied field rotates in the direction of the plasma rotation. The frequency dependence of its amplitude, Fig. 1(a), and phase, Fig. 1(b), measured at two values of β above the no-wall stability limit, is well described by Eq. (2).

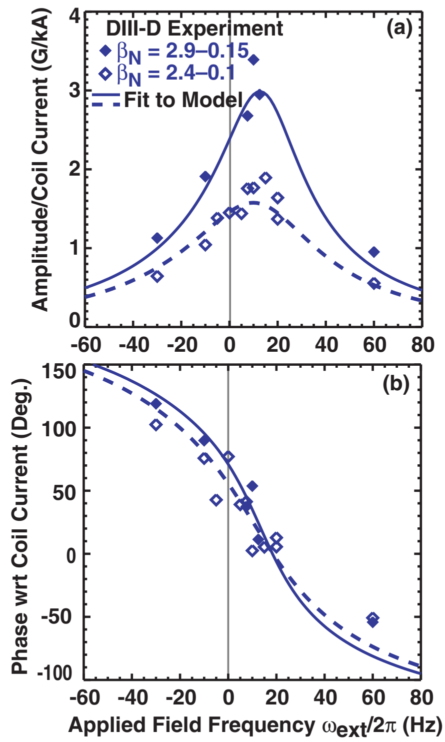

Fig. 1. Measurements of the amplitude (a) and phase shift (b) of the plasma response to an externally applied rotating field in DIII-D. The fit to Eq. (2) yields $M_{\rm sc}^{*}$ = 1.1 G/kA, γ_0 = (–157 + i80)s^{-1} at $\beta_{\rm N}$ = 2.4 and γ_0 = (–111 + i73)s^{-1} at $\beta_{\rm N}$ = 2.9.

B. JET

In JET, plasmas above the no-wall stability limit are obtained by operating at a low toroidal field ($B_{\rm T}$ =1.4 T) with high heating power ($P_{\rm NBI} \le 20$ MW, $P_{\rm ICRH} \le 5$ MW). The stability is probed using oscillating currents in a pair of external coils in the midplane, which generate a standing wave with a dominant $n=1$ component. The coil currents and, hence, the plasma response have positive and negative frequency components,

$$B_s^{\mathrm{plas}}(t) = \frac{1}{2}\,\hat{B}_s^{plas}(\omega_{\mathrm{ext}})e^{i\omega_{ext}t} + \frac{1}{2}\,\hat{B}_s^{plas}(-\omega_{\mathrm{ext}})e^{-i\omega_{ext}t} \quad . \tag{3}$$

where $B_s^{\mathrm{plas}} = \hat{B}_s^{plas}(\omega_{\mathrm{ext}})e^{i\omega_{ext}t}$ is given by Eq. (2). The response is detected with two toroidally opposed midplane saddle loop pairs located at the node and anti-node of the externally applied field. The direct coupling of the antenna coil to the sensor pair at the anti-node of 30 G/kA is approximately 30 times larger than the plasma response leading to a significant uncertainty of the B_s^{plas} measurement. The sensor pair at the node, shifted by 90 degrees in the toroidal direction, does not directly couple to the external coils and only detects the plasma response. An estimate of the characteristic decay time of $n=1$ wall currents in JET of $\tau_w \approx 5$ ms is obtained from square wave pulses with internal coils. The B_s^{plas} measurements at the node together with the 0 Hz measurement at the anti-node, where the vacuum coupling is sufficiently well known, are compared to the predicted frequency dependence Eq. (3). The fit of the experiment to the prediction results in reasonably good agreement, Fig. 2.

The good agreement between the measurements in DIII-D, Fig. 1, and JET, Fig. 2, strongly supports the single mode approach to describe the interaction between externally applied magnetic fields and a marginally stable plasma. The fit yields the damping rate and the rotation frequency of the RWM in the absence of external currents, which can be directly compared to predictions using the MARS code [6]. The fit also yields the effective mutual inductance M_{sc}^*.

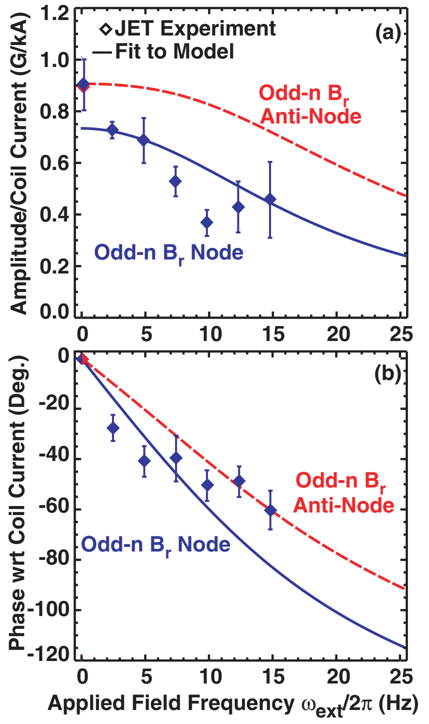

Fig. 2. Amplitude (a) and phase shift (b) of the plasma response to an externally applied standing wave in JET at β_N = 3.4. The fit to Eq. (3) yields γ_0 = $(-100+\ i35)\mathrm{s}^{-1}$ and M_{sc}^* = 1.2 G/kA.

IV. Continuous Stability Measurement

Once M_{sc}^* is known, the measurement of the plasma response at a single frequency is sufficient to determine the RWM stability allowing for a continuous measurement of ideal MHD stability. An example of such a measurement using a low amplitude externally applied field with $\omega_{ext}/2\pi$ = 20 Hz during a DIII-D discharge, where β was increased up to an RWM onset, is shown in Fig. 3.

A preliminary comparison of the RWM stability measurements and MARS [6] using a flat plasma rotation profile, a generic equilibrium and the sound wave dissipation model [7] ($\kappa_{||} = 0.5$) has been carried out. To compare the RWM growth rates, the gain in β between the no-wall and ideal wall stability limit $C_\beta = (\beta - \beta_{\text{no-wall}})/(\beta_{\text{ideal}} - \beta_{\text{no-wall}})$ is used as the stability parameter. While the observed damping rate is in qualitative agreement with the predicted damping rate for a plasma rotation of 2% of the Alfvén velocity, in Fig. 3(a), the observed natural rotation frequency is an order of magnitude lower than the predictions, in Fig. 3(b).

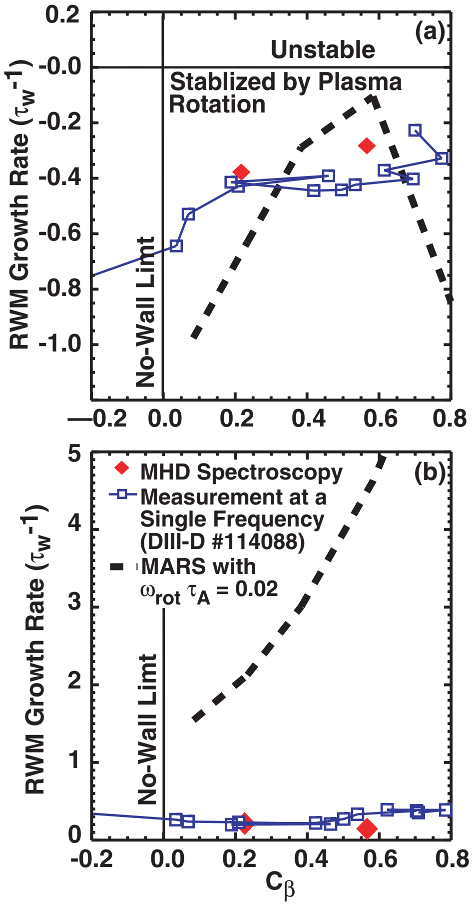

Fig. 3. Comparison of the measured growth rate (a) and mode rotation frequency (b) derived from the fit of the spectrum (diamonds) and from a continuous 20 Hz wave (squares) with MARS predictions (dashed line).

V. Summary and Discussion

Active MHD spectroscopy of the RWM has been successfully applied in rapidly rotating DIII-D and JET plasmas above the no-wall ideal MHD stability limit. The frequency dependence of the plasma response to externally applied fields is in good agreement with predictions for a single marginally stable RWM yielding a measurement of the damping rate and the mode rotation frequency. Measurements in DIII-D and JET, normalized on the respective wall times, are of comparable magnitude. While the observed damping rate of the RWM in DIII-D is in qualitative agreement with predictions using the sound wave damping model, the observed natural rotation frequency is an order of magnitude too low, indicating that further theoretical and experimental work is needed before results can be extrapolated with confidence to future experiments.

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