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ABSTRACT.

In advanced tokamak operation the ultimate performance limit is set by Resistive Wall Modes (RWMs). The nature of the plasma damping term governing RWM stability is not unambiguously established. A model based on ion Landau damping represented through a parallel viscosity term has been used extensively, but recently a more accurate ‘kinetic’ model, based on drift-kinetic theory, has been implemented in the MARS-F stability code. The damping of stable RWMs may be determined experimentally by measuring the response to n = 1 helical magnetic perturbations from coils external to the plasma, under conditions where rotational stabilisation suppresses RWM growth - in JET, saddle coil systems both internal and external to the vacuum vessel are available for such studies. The Resonant Field Amplification (RFA) has been measured for both DC and AC applied magnetic perturbations. RFA is observed in JET as β increases, particularly beyond the no-wall limit, and good agreement with MARS-F is found for either the kinetic damping model or for strong ion Landau damping. The occurrence of a critical flow velocity below which the RWM becomes unstable can also be compared with modelling. Magnetic braking is used to slow the plasma until a naturally unstable mode occurs. Comparison of the critical velocity with MARS-F modelling again shows reasonable agreement with the kinetic damping model or strong ion Landau damping. The results presented provide a very important experimental validation of RWM damping models, allowing for extrapolation to ITER, where it is found that the observed strong damping leads to a requirement for a flow of ~2 to 3% of the Alfvén velocity at the plasma centre to stabilise RWMs.

1. INTRODUCTION

In advanced tokamak operating scenarios, such as those foreseen for ITER and compatible with the steady-state operation of a power plant, the ultimate performance limit is set by Resistive Wall Modes (RWMs) [1]. The RWM is a kink mode whose growth rate is largely governed by the tokamak wall time but whose stability is related to damping arising from relative rotation between the plasma and the slowly rotating wall mode. The nature of this damping term is not unambiguously established. A model based on ion Landau damping [2] has been used extensively. In this model the force that damps the (m,n) Fourier component of the perturbed toroidal motion of the plasma is represented as a parallel viscosity term, $F_{damp} = -\kappa_{||}|/k_{||}v_{th,i}|\ \rho v_{||}$. Where, $k_{||} = (m/q - n)/R$ is the parallel wave number, $v_{th,i}$ is the ion thermal velocity, r is the mass density, $v_{||}$ the perturbed parallel velocity of the plasma and $\kappa_{||}$ is a constant whose value may be empirically determined by fitting to experimental results. Recently a more accurate ‘kinetic’ model [3], based on drift-kinetic theory has been implemented in the MARS-F stability code [4] to predict the forces acting on the displacements perpendicular to the magnetic field; it is important to note that this kinetic model has no free fitting parameters. A range of other damping models and mechanisms have been proposed, e.g. [5,6,7]. Since predictions of plasma rotation and RWM feedback system requirements for ITER and power plants depend quantitatively on the damping, experimental validation of the RWM damping mechanism is very important.

In this paper 3 methods for determining the RWM damping term experimentally are described:-

- Measurements of Resonant Field Amplification (RFA) of a DC ‘error field’, applied using non-axisymmetric coils external to the plasma. RFA is predicted to increase rapidly as β exceeds the no wall β-limit [5,8].
- Measurement of the RFA as a function of frequency from applied AC error fields
- Determination of the critical plasma velocity below which the RWM becomes intrinsically unstable [9]

The first 2 are a form of MHD spectroscopy in which the stability of stable RWMs is probed using externally applied error fields. For each of the 3 methods the experimental results are compared with MARS-F stability code calculations, allowing the damping model which best describes the data to be determined. In the following sections results from these 3 methods for determining the RWM plasma damping are described.

2. PLASMA RESPONSE TO DC APPLIED FIELDS

By measuring the response to $n = 1$ helical magnetic perturbations from coils external to the plasma, the damping of stable RWMs may be measured. This MHD spectroscopy technique has been successfully applied on the DIII-D tokamak [10]. On JET, saddle coil systems both internal and external to the vacuum vessel were available for studying the RFA arising from driven RWMs. To study RFA in JET, discharges with low l_i (~0.7) are used to give a relatively low ideal β-limit. This is achieved by heating, with Lower Hybrid (LH) and then Neutral Beam Injection (NBI), early in the current rise phase to inhibit current penetration (Fig.1). The RFA is measured by applying square wave pulses of dominantly $n = 1$ fields, showing increased amplification as β rises towards the ideal limit (see Fig.1).

In some of these discharges $m = 2$, $n = 1$ Neo-classical Tearing Modes (NTMs) are found. This is interpreted as the ideal with-wall limit being approached and the NTM being destabilised [11]. Averaged over several discharges with 2/1 NTMs occurring at ~7s, shows a threshold for the NTMs of β_N~4.3l_i; the ideal with-wall limit can be assumed very close to this threshold. MARS-F code calculations indicate that the no-wall ideal $n = 1$ β-limit is β_N~4.3l_i; this is further supported by measurements of the critical velocity for RWM destabilisation (see Critical Velocity Section and Fig.6 in particular below).

The measured RFA amplification [which is defined as RFA = $[B_r\text{-}B_r(vac)]/B_r(vac)$ and measured using radial flux loops near the outboard mid-plane of the tokamak] has been compared with calculations using the MARS-F MHD stability code [4] (see Fig.2). Both the ion Landau and the kinetic damping model, mentioned above, have been implemented in the MARS-F code. It is found that either strong damping ($\kappa_{||} = 1.5$) or the kinetic model are in reasonable agreement though somewhat above the average of the RFA data. The kinetic model is expected to lead to strong damping because even when the flow is strongly subsonic, since there will be regions close to resonant surfaces where the parallel phase velocity in the plasma frame is large enough to resonate with thermal particles giving rise to strong local damping. The RFA has also been measured using the external Error Field Correction Coils (EFCCs) on JET and equivalently good agreement between the data and the kinetic damping model is found.

3. PLASMA RESPONSE TO AC APPLIED FIELDS

Low frequency AC fields have been applied using both the internal saddle coils and external error field correction coils on JET. In order to match the data from vacuum AC shots, a model with 2 shells is used in the MARS-F code. The first shell corresponds to the JET vacuum vessel (r/a~1.3) and the second to a thin shell placed at r/a~ 1.7 (a is the plasma minor radius), with poloidal gap covering about 10% of the total poloidal circumference, and with the wall time 10 times larger than the JET wall time. The resistivity in the poloidal gap is 100 times larger than the other region. Although not directly based on any machine structure, but rather chosen to give a best fit to the vacuum data, this second shell does correspond approximately with the location of the mechanical support structure in JET. The fit achieved with this double shell model to vacuum data from the internal and external coils is shown in

Based on the vacuum model the calculated frequency response of the amplitude and phase is compared with data for pulses with β_N~3.4 in Fig.4, for the case of the external EFCCs. In this case a standing (as opposed to a travelling) wave is applied by the external coils and the calculated results are based on the kinetic model implemented in the MARS-F code. The data shown are measured by an $n = 1$ combination of midplane radial field pick-up coils, that are not coupled in vacuum to the EFCC pair that is used. The agreement with the MARS-F code is reasonable, with at least part of the minor discrepancies being clearly due to the variation of β_N over the data set. Similar results are obtained with AC fields applied to the internal saddle coils and so overall the AC results further support the applicability of the kinetic model implemented in MARS-F.

4. CRITICAL VELOCITY FOR RWM DESTABILISATION

The occurrence of a critical flow velocity below which the RWM becomes unstable can also be compared with modelling. In JET the flow velocities due NBI injection are fairly high (~1% of $V_{Alfvén}$ at q = 2) while the predicted critical velocity for RWMs ~0.5% of $V_{Alfvén}$ (depending on q_{95}). A ~30% reduction of plasma velocity was achieved by substituting ~4MW of NBI with Ion Cyclotron Resonance Heating (ICRH). Further reduction of the velocity however required magnetic braking using the error field coils. Employing this technique an intrinsically unstable mode is found to grow below a critical velocity (Fig.5), leading to severe confinement degradation, and at lower q_{95} (~3) to disruptions. There seems to be a threshold in β_N below which the magnetic braking is not effective (Fig.6), which is interpreted as β_N being below the no-wall β-limit. It should be noted that there is no 2/1 NTM observed in these cases and so the observed braking is not due to a large NTM locking to the wall. The mode which grows due to the magnetic braking has not been unambiguouslyidentified as an RWM. A key RWM signature of a slow rotating growing mode is absent, since the large applied error field causes a locked mode at all times. The results seem consistent with an RWM being destabilised, and are tentatively interpreted as such here; but further studies are needed to confirm this.

This critical velocity for mode destabilisation has also been compared with MARS-F code predictions (Fig.7) and again the strong ion Landau damping ($\kappa_{||}$>1) model, or the kinetic damping model, are found to agree best with data. These results also highlight the importance of good error field correction at high β to avoid strong RFA, and the ensuing magnetic braking and RWM destabilisation.

These results (Fig.7) are at relatively high-*q*. It is found that the critical velocity for RWM stabilisation scales approximately as $1/q_{95}$ as expected from theory [13]. This partly explains the higher wcr values reported on DIII-D [12], though it seems that wall geometry and other factors are also playing a role [13].

SUMMARY

The results presented provide a very important experimental validation of RWM damping models. For JET either strong ion Landau damping or the kinetic model give a consistent account of the data; though it should be noted that the kinetic model involves no free parameters and so can unambiguously be applied to make predictions. For ITER it is found that the observed strong damping leads to a requirement for a flow of ~2 to 3% of $V_{\text{Alfvén}}$ at the plasma centre to stabilise the RWM [1]. It is marginal whether the flow velocity in ITER will reach such values indicating that an active RWM control system will be a prudent option.

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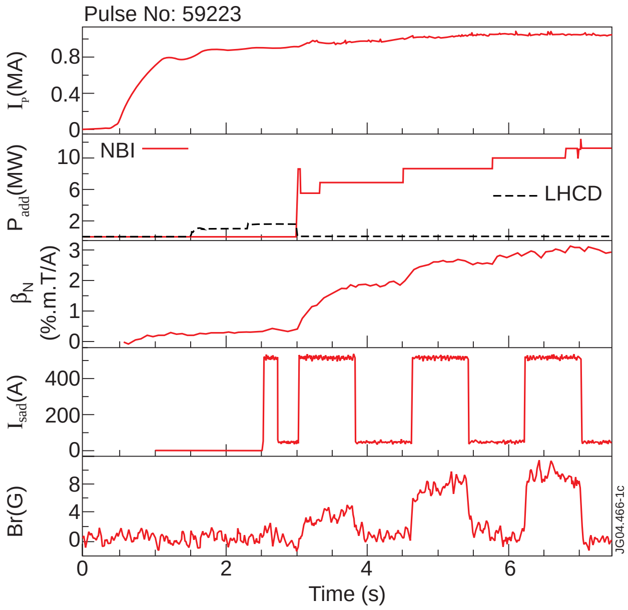

Figure 1: 500A square wave n=1 fields are applied with internal coils. Odd-n radial field (B_r) measured using a coil combination that has no direct vacuum pick-up shows increased amplification as β_N rises towards ideal limit

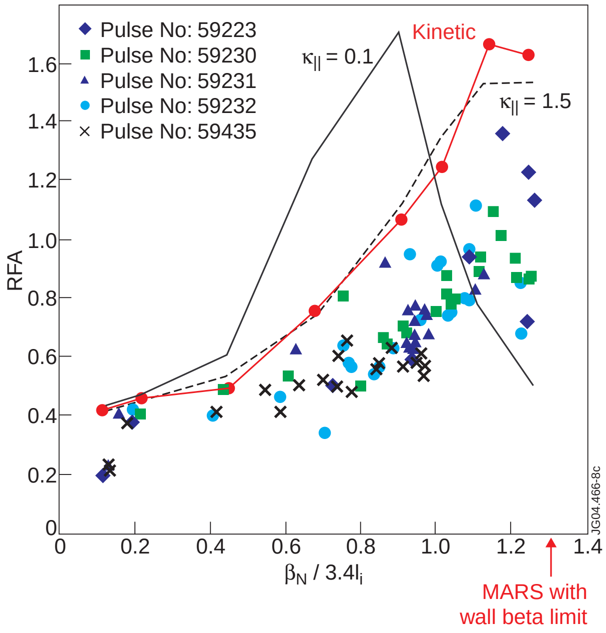

Figure 2: RFA measured with mid-plane B_r coils arising from fields applied using the internal error field coils. β_N is normalised with respect to the approximate no-wall limit, 3.4li. Each symbol type represents a different pulse. The curves show the predictions of various damping models in the MARS-F code – either the 'kinetic' model or strong parallel damping are in reasonable agreement

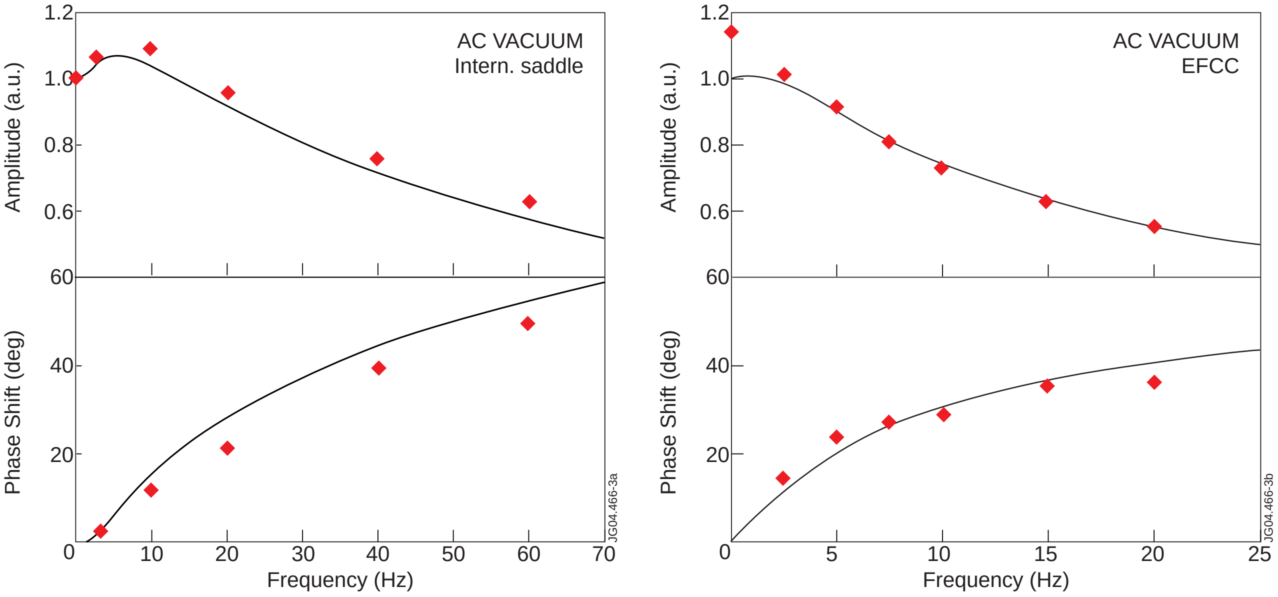

Figure 3: Comparison of vacuum AC data from the internal saddle coils and EFCCs with MARS-F code modelling. The phase shift is temporal and defined relative to the phase of the applied saddle coil current. Data is from an n=1 combination of mid-plane radial field coils, with a phase such that there is no vacuum coupling to the internal saddle coils or the EFCCs that are powered.

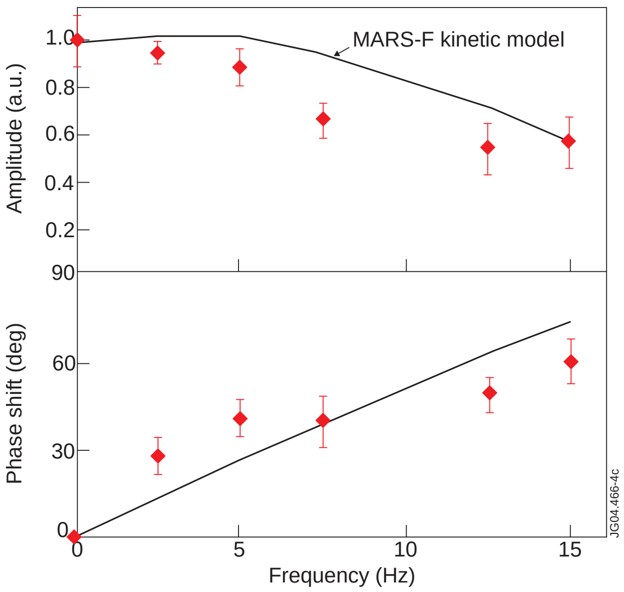

Figure 4: Amplitude and phase variation of the $n = 1$ radial field for β_N in the range 3.45±0.15. The phase is a temporal shift measured relative to the applied current in the EFCCs. The red points are data with the errors bars being the one standard deviation spread and the solid lines are from MARSF code simulations employing the kinetic model

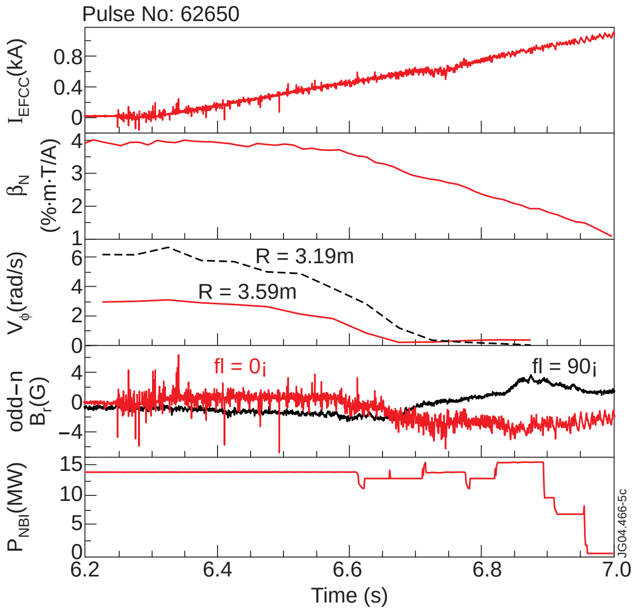

Figure 5: q_{95} = 3.2 pulse in which application of an applied field with the EFCCs, leads to mode-locking as seen on the plasma velocity (V_ϕ) and the quadrature pair of odd-n B_r signals (with direct vacuum pickup from the EFCCs eliminated). As the locked mode develops the confinement is severely degraded as evidenced by the decline in β_N. Shortly beyond the time shown a disruption occurs.

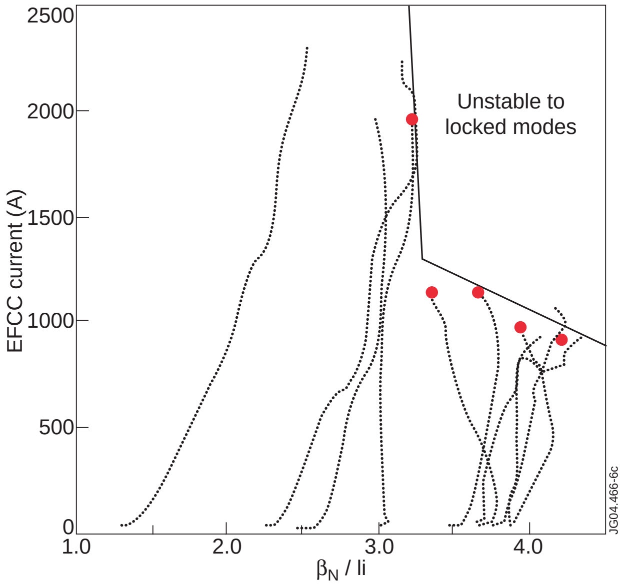

Figure 6: The black dots show discharge trajectories for pulses where the EFCCs are applied. Those trajectories which end with a red dot experience rapid magnetic braking and form an RWM at that point. It can be seen that there is a sharp threshold at β_N/li~3.3, below which magnetic braking is not observed for the available range of EFCC current.

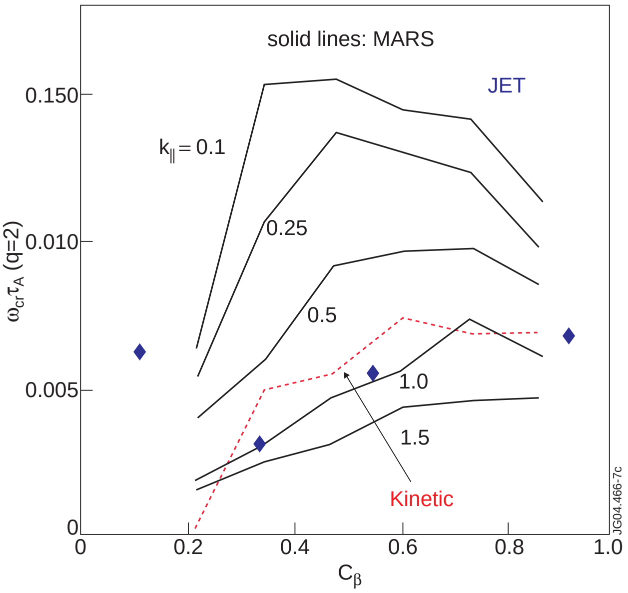

Figure 7: Comparison of computed critical velocity at $q = 2$ normalised to the Alfvén velocity versus C_β, with data (diamonds) which has q_{95} = 4.5 to 5.0. Here $C_\beta = (\beta_N - \beta_N(\text{no wall}))/(\beta_N(\text{with wall}) - \beta_N(\text{no wall}))$. Results are shown from MARS with various parallel damping and for the kinetic model.