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Resistive wall mode stability in high beta plasmas in DIII-D and JET

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Introduction

A quantitative comparison of resistive wall mode (RWM) stability in rotating high-β plasmas has been carried out in both the DIII-D and the JET tokamaks. The stability is studied by measuring the critical plasma rotation required for RWM stability, Ω_{crit}, and by probing the plasma with externally applied resonant, n=1 magnetic fields. Such a comparison tests the understanding of the stabilizing effect of plasma rotation at high β [1] and, in particular, the scaling of Ω_{crit}, and thereby improves the capability to extrapolate to future devices including ITER.

Similarity experiment

In DIII-D (major radius $R_{D3D} = 1.69\,m$) and JET ($R_{JET} = 2.96\,m$) the toroidal plasma rotation induced by tangential neutral beam heating can be sufficiently high to access the wall stabilized regime above the no-wall stability limit, $\beta_{no-wall}$ [2, 3]. In order to compare the RWM stability in both devices a target plasma with the JET shape (see Fig. 1) and similar safety factor ($q_{min} \approx 1.5$, $q_{95} \approx 4-5$) and pressure profiles has been developed in DIII-D. Ideal MHD stability calculations yield $\beta_{N,no-wall}/\ell_i \approx 2.8$ for the no-wall limit in DIII-D, which is approximately 15% lower than

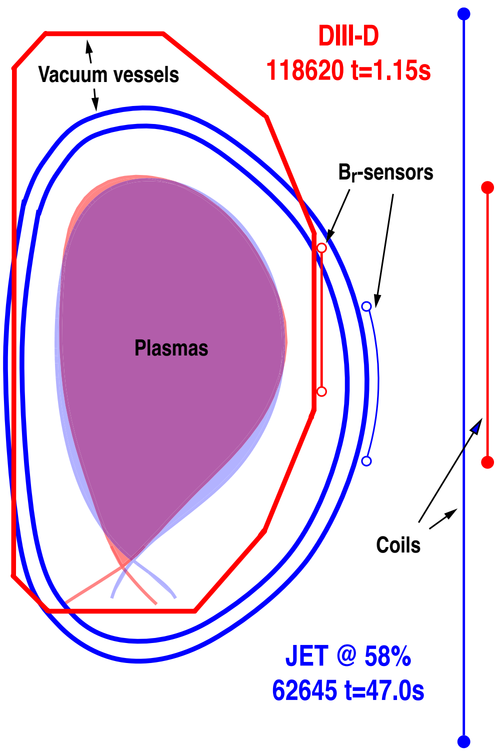

Figure 1: Poloidal cross-sections of the DIII-D (red) and JET (blue) experiments.

*See J.Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004).

the no-wall limit in the JET plasma. Here ℓ_i is the plasma internal inductance. While the ideal wall limit $\beta_{\rm N,ideal}$ in DIII-D exceeds $\beta_{\rm N,no-wall}$ by 60%, the greater wall distance in JET reduces this gain to 30%. The comparison provides plasmas with the same no-wall ideal MHD stability properties but different sizes and wall properties.

Critical plasma rotation for RWM stabilization

The plasma rotation can be controlled by varying the magnitude of the n=1 error field with non-axisymmetric control coils shown in Fig. 1. The rotation is reduced by decreasing the n=1 error field correction applied with the C-coil in DIII-D and by applying an n=1 error field with the error field correction coil in JET. At high β the resulting n=1 error field leads to an enhanced drag and the plasma slows until its rotation is no longer sufficient to stabilize the RWM. The onset of the n=1 RWM, which is generally the least stable mode, is seen in magnetic measurements marking the time of marginal stability, where charge exchange recombination (CER) spectroscopy using C^{6+} yields a measurement of $\Omega_{\rm crit}$. Since previous experiments suggested a strong dependence of $\Omega_{\rm crit}$ on q_{95} [3, 4], the value of q_{95} is varied. It is found that $\Omega_{\rm crit}$ evaluated at the q=2 surface and normalized with the inverse Alfvén time does well in connecting DIII-D and JET within the uncertainty of the measured values (see Fig. 2). Here, the Alfvén time is defined by,

$$\tau_{\rm A} = R_0 \frac{\sqrt{\mu_0 n_e m_i}}{B_0} , \quad (1)$$

where R_0 and B_0 are the major radius and magnetic field on the magnetic axis, m_i the ion mass and n_e the local electron density. The main uncertainty of the $\Omega_{\rm crit}\tau_{\rm A}|_{q=2}$ measurement arises from the uncertainty of the location of the q=2 surface. For q_{95}=4.5 both experiments yield $\Omega_{\rm crit}\tau_{\rm A}|_{q=2} \approx 0.005$. In DIII-D a stronger rotation profile peaking leads to somewhat higher central values of $\Omega_{\rm crit}\tau_{\rm A}$ than in JET. Both experiments clearly show the decrease of $\Omega_{\rm crit}\tau_{\rm A}$ with increasing q_{95} and are consistent with a $1/q_{95}^2$ dependence of $\Omega_{\rm crit}\tau_{\rm A}$, which has been predicted by the MARS-F code using a kinetic damping model [5].

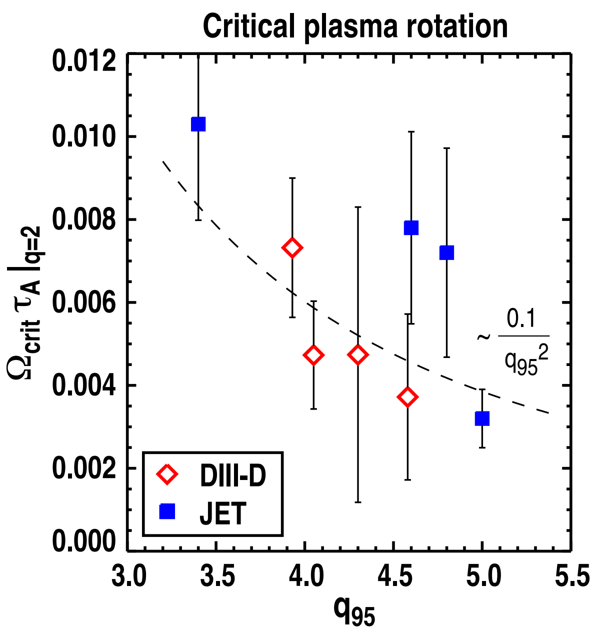

Figure 2: q_{95}-dependence of the normalized critical plasma rotation at q=2 in DIII-D (red) and JET (blue). The error bars result from the CER error and an estimated uncertainty in q of ±3% in DIII-D and ±7% in JET.

Resonant amplification of a weakly damped RWM

A RWM that is stabilized by plasma rotation is only weakly damped, and can be excited with externally applied resonant fields. In the cross-machine comparison the RWM stability is probed by applying n=1 pulses using pairs of external non-axisymmetric control coils with similar geometry in both devices, shown in Fig. 1. The pulses are long with respect to characteristic eddy current decay times, τ_W, and result in a static plasma response, which is then measured with radial field probes located close to the vacuum vessels, also shown in Fig. 1. In order to reduce the uncertainty in the measurement of the plasma response, B^{plas}, which arises from the direct coupling between sensors and coils, B^{plas} is measured at the nodes of the applied field. The resonant field amplification (RFA) is defined as the ratio of B^{plas} and externally applied field B^{ext} ,

$$\text{RFA} = \frac{B^{\text{plas}}}{B^{\text{ext}}} \ . \tag{2}$$

In both devices the RFA is seen to increase significantly once β is close to or above $\beta_{\text{no-wall}}$. In addition to the β-dependence, the DIII-D measurements also yield an increase of the RFA with decreasing rotation consistent with larger amplification closer to marginal stability. The rotation dependence is removed by using a linear correction to map the DIII-D data to $\Omega_{\text{rot}}\tau_A|_{q=2} = 0.012$, which is comparable to the values in JET ranging from 0.01 to 0.02. The RFA measurement strongly depends on the geometry of the applied field and of the plasma response and on the location of the magnetic sensors. The geometry of the applied fields in DIII-D and JET is similar, but the different radial positions of the magnetic sensors have to be accounted for by extrapolating the externally applied field and the plasma response to the plasma boundary. While the externally applied field decreases from the sensor to the plasma, the plasma response decreases from the plasma to the sensor. In a cylindrical approximation, assuming an effective poloidal mode number at the outboard midplane of

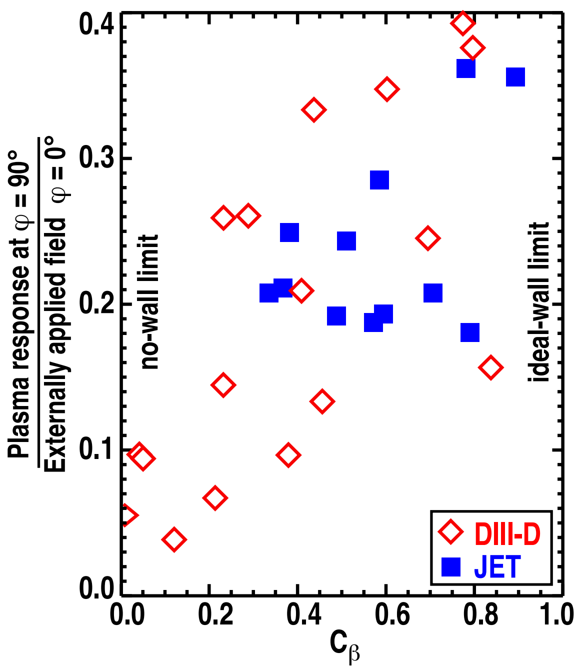

Figure 3: β-dependence of the RFA measured at the node of the applied n=1 field and extrapolated to the plasma boundary in DIII-D (red) and JET (blue).

m=2, the RFA at the DIII-D plasma boundary is 3.8 times larger than at the DIII-D sensors whereas the RFA at the JET boundary is 8.4 times larger than at the JET sensors. Evaluating the RFA at the plasma boundary in plasmas with the same normalized plasma rotation and at the same β, normalized to the difference between the no-wall limit and ideal-wall limit,

$$C_\beta = \frac{\beta - \beta_{\text{no-wall}}}{\beta_{\text{ideal-wall}} - \beta_{\text{no-wall}}} \tag{3}$$

results in quantitative agreement (see Fig. 3).

Conclusion

The comparison of Ω_{crit} in DIII-D and JET, which differ by a factor of 1.75 in linear dimensions, yields quantitative agreement and increases our confidence that the scaling of the critical rotation with the inverse Alfvén time holds for ITER. The measurements also confirm a significant dependence of Ω_{crit} on the q-profile, in particular a decrease of Ω_{crit} with increasing q_{95}. Note, that the increase of the minimum q above 2 in the ITER-AT scenario is expected to increase the plasma rotation required for stability [4]. The quantitative agreement also extends to the RFA in DIII-D and JET. Since the RFA is thought to be directly related to the growth rate of the RWM, $\gamma\tau_W$ [2, 4], the quantitative agreement indicates that the RWM stability is determined by the matched quantities, notably C_β and $\Omega_{\text{rot}}\tau_A$. However, the analysis of the RFA measurements, in particular the cylindrical approximation of the geometry, has introduced a significant uncertainty in the comparison. The observations are consistent with a model where the stabilization of the RWM is provided by the fast bulk plasma rotation relative to the quasi-static magnetic perturbation of the mode. The geometry of the wall sets the ultimate, ideal-wall β-limit, whereas the conductivity of the wall prevents the mode from rotating with the bulk plasma and sets the damping or growth rate of the mode.

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