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*Columbia University, New York, New York.
†EURATOM/UKAEA Fusion Association, Culham, United Kingdom.
‡Oak Ridge National Laboratory, Oak Ridge, Tennessee.
$^{\Delta}$Max-Planck-Institut für Plasmaphysik, Garching, Germany.

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

H. Reimerdes[1], J. Bialek[1], M. Bigi[2], A.M. Garofalo[1], R.J. Groebner[3], M.P. Gryaznevich[2],
T.C. Hender[2], D.F. Howell[2], G.L. Jackson[3], R.J. La Haye[3], G.A. Navratil[1], M. Okabayashi[4],
S.D. Pinches[5], J.T. Scoville[3], E.J. Strait[3], the DIII-D team and JET EFDA contributors*
[1] *Columbia University, New York, New York, USA*
[2]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*
[3]*General Atomics, San Diego, California, USA*
[4]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*
[5]*Max-Planck-Institut für Plasmaphysik, Garching, Germany*

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 rotation required for RWM stability, $\Omega_{\rm crit}$, 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 $\Omega_{\rm crit}$, and thereby improves the capability to extrapolate to future devices including ITER.

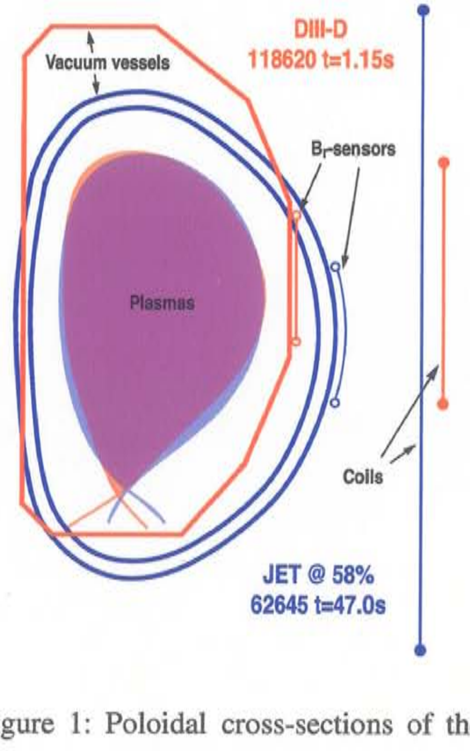

Figure 1: Poloidal cross-sections of the DIII-D (red) and JET (blue) experiments.

Similarity experiment

In DIII-D (major radius $R_0^{\rm D3D} = 1.69\,{\rm m}$) and JET ($R_0^{\rm JET} = 2.96\,{\rm m}$) 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, $\beta_{\rm no-wall}$ [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 and pressure profiles has been developed in DIII-D. Ideal MHD stability calculations for the DIII-D equilibrium yield $\beta_{\rm N,no-wall}^{\rm D3D}/\ell_i \approx 2.8$, which is approximately 15% lower than the no-wall limit in the JET

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

plasma. Here ℓ_i is the plasma internal inductance. While the ideal wall limit $\beta_{\mathrm{N,ideal}}$ in DIII-D exceeds $\beta_{\mathrm{N,no-wall}}$ 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 (EFCC) in JET. At high β the resulting n=1 error fields lead to an enhanced drag and the plasma slows until its rotation is no longer sufficient to stabilize the ideal kink mode. The onset of the n=1 RWM is seen in magnetic measurements marking the time of marginal stability, where charge exchange recombination (CER) spectroscopy using $\mathrm{C}^{\mathrm{VI+}}$ yields a measurement of Ω_{crit}. Since previous experiments suggested a strong dependence of Ω_{crit} on q_{95} [3, 4], the value of q_{95} is varied. It is found that Ω_{crit} evaluated at the q=2 surface and normalized with the inverse of the local Alfvén time,

$$\tau_{\mathrm{A}} = R_0 \frac{\sqrt{\mu_0 n_e m_i}}{B_0}\,, \tag{1}$$

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

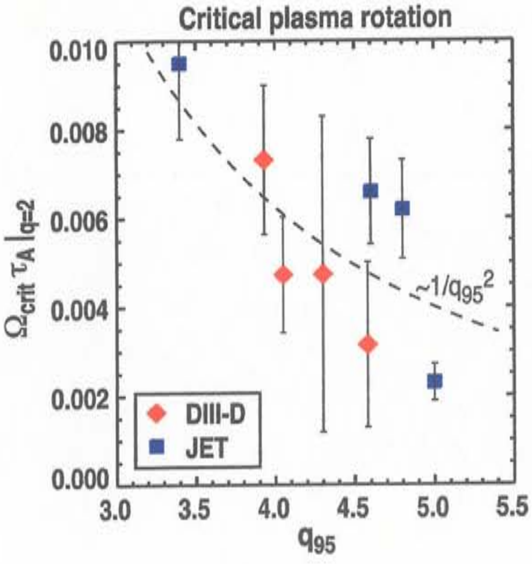

Figure 2: q_{95}-dependence of the normalized critical plasma rotation at q=2 in DIII-D (red) and JET (blue). The error bars are based on an estimated uncertainty of q of ±3%.

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, $B^{\rm plas}$, which arises from the direct coupling between sensors and coils, $B^{\rm plas}$ is measured at the nodes of the applied field. The resonant field amplification (RFA) is defined as the ratio of $B^{\rm plas}$ and externally applied field $B^{\rm ext}$,

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

The RFA amplitude strongly depends on the geometry of the applied field and of the plasma response and on the location of the magnetic sensors. In both devices the RFA is seen to increase significantly once β is close to or above $\beta_{\rm no-wall}$. While the RFA in JET is measured at constant $\Omega_{\rm rot}\tau_{\rm A}|_{q=2} \approx 0.012$, the rotation in DIII-D varies. In addition to the β-dependence, the DIII-D measurements also yield an increase of the plasma response with decreasing rotation consistent with larger amplification closer to marginal stability. In order to compare the measurements in DIII-D and JET a linear correction is used to map the DIII-D data to $\Omega_{\rm rot}\tau_{\rm A}|_{q=2} = 0.012$. The different radial positions of the magnetic sensors can be accounted for by mapping 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 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,

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

results in quantitative agreement (see Fig. 3).

Conclusion

The comparison of $\Omega_{\rm crit}$ 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

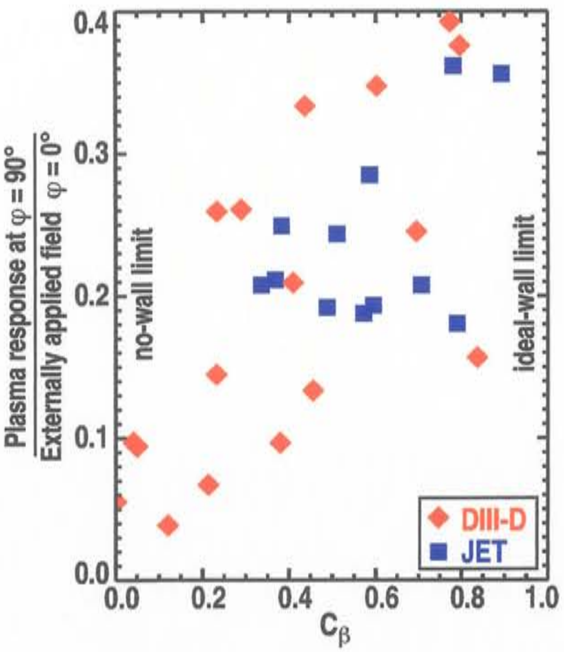

Figure 3: β-dependence of the RFA measured at the node of the applied n=1 field and extrapolated to the plasma boundary in DIII-D (red) and JET (blue).

critical rotation with the inverse Alfvén time holds for ITER. The measurements also confirm a significant dependence of Ω_{crit} on the q-profile, notably 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, 6]. The quantitative agreement also extends to the RFA in DIII-D and JET. In a single mode model, which accurately describes the dynamic behavior of a stable RWM [4], the RFA is directly related to the growth rate of the RWM, $\gamma_0\tau_W$. This confirms that the RWM damping is determined by the ideal MHD stability characteristics of the plasma including C_β and the normalized toroidal plasma rotation $\Omega_{\mathrm{rot}}\tau_A$. 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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