ROTATION EFFECTS ON ERROR FIELD LOCKED MODES, MODELLING AND SCALING LAW PREDICTIONS

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Introduction.

It is highly desirable to eliminate the “error field” modes, induced by external non-axisymmetric magnetic perturbing fields that can deteriorate plasma performance and often lead to disruptions. The basic mechanism for error field modes is the non-linear response to externally driven magnetic reconnection at rational-q surfaces, which is opposed by plasma rotation. The systematic JET experiments presented here widen the previous data base collected on Compass-D, DIII-D and JET [1,2] and re-assess the *conventional* empirical scaling of the threshold of the field penetration with the main plasma equilibrium parameters $b_{pen}/B \propto n^{a_n} B^{a_B} \omega_0^{\eta}$ (1), including as a novel feature the plasma toroidal rotation frequency ω_0.

Experimental observations, theoretical modelling and scaling

The JET experiments were performed in plasmas with NBI momentum injection, operating at constant q_{95}~3.5 with the toroidal field B in the range 1 to 3 T, and with densities in the range 1.4 – 3.3 10^{19} m^{-3} in a Single Null separatrix configuration. A ramp of static error field was applied with a helical component m=2, n=1 up to amplitudes $b_{2,1} \approx 6.5 \cdot 10^{-4}\,T$ at q=2: the electrodynamic torque brakes the plasma rotation at the q=2 surface, and when the angular rotation frequency ω_0 has been reduced to a critical value, non-linear amplification of the initially linear driven response occurs forming a “locked” island (Fig.1). When the external field is switched off and the natural error field is suitably compensated, the locked mode may spin up in the e- or i- drift direction because of viscous restitution of momentum by the rest of the plasma .The typical action and response pattern shown by the experiment (Fig.1)and theory (Fig.2) agrees with the concept of an electrodynamic torque localized around the q=2 surface. When the e.m. torque has reduced the local rotation frequency at least to one half the mode is amplified non-linearly. For the shots at constant P_{NBI} multiple regression on the data leads to the scaling $b_{pen}/B \propto n^{0.973\pm0.05}B^{-1.207\pm0.06}$ in line with that found previously on JET [2] in absence of rotation. With NBI momentum injection the frequency is found to scale as

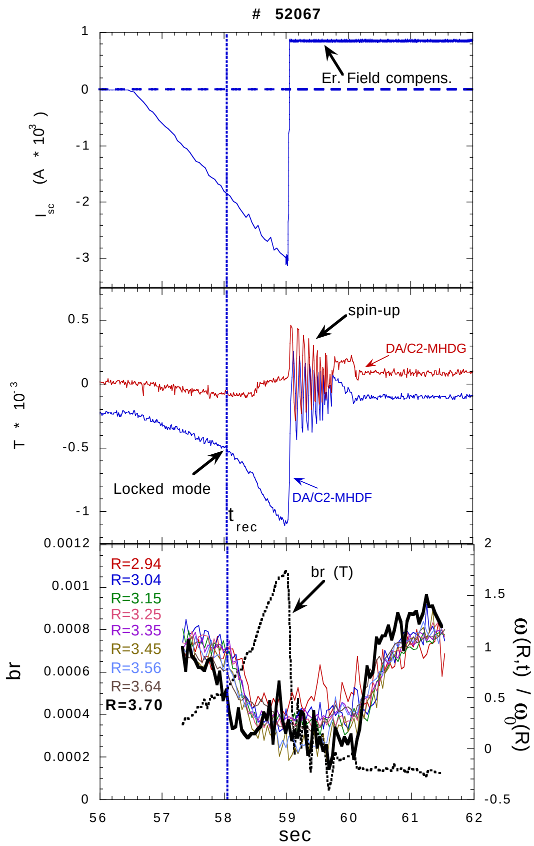

Fig.1–a) Typical external magnetic field waveform; at end of ramp compensation of natural error field allows mode spin-up in e- or i-drift directions.
b) Magnetic signals showing linear and non-linear response (t=58.04 s).
c)Charge Exchange Spectroscopy signals showing plasma rotation at different radii. At field "penetration" sudden braking occurs.

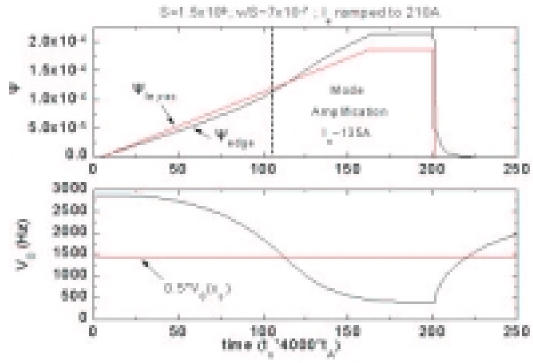

Fig.2–Theoretical RMHD model of driven reconnection of the helical flux ψ in presence of toroidal rotation. Non-linear mode amplification occurs when $V_\zeta = V_{\zeta 0}/2$

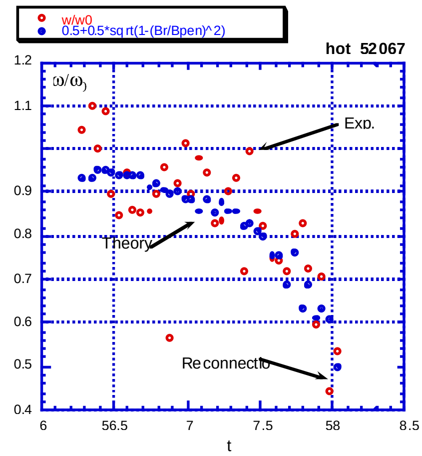

Fig.3–Braking of plasma toroidal rotation (charge exchange diagnostic) at the q=2 surface. Penetration occur s when $V_\zeta = V_{\zeta 0}/2$

$\omega_0 \propto B^{0.567}(P_{NBI}/n)^{0.637}$ close to previous JET results [3]. In the visco-resistive regime $\omega_0 << \omega_I \cong \tau_V^{1/3}\tau_R^{-2/3}\tau_H^{-2/3}$,the expected dependence on frequency is linear [4,5] and the best fit of the data with this assumption is $b_{pen}/B \propto n^{0.55\pm0.03}B^{-1.25\pm0.03}\omega_0$ Fig.(7). However a much better data fitting is given by $b_{pen}/B \propto n^{0.583\pm0.02}B^{-1.274\pm0.02}\omega_0^{0.5}$ (Fig.8). This non-linear scaling with ω_0 is consistent with the scaling in the ideal viscous regime [4] with $\omega_0 > \omega_I$, implying that the effective (anomalous) viscous time should have values of the order of $\tau_V \approx \tau_R^2\tau_H^2\omega_0^3 \le 10^{-2}$ s. A value of $\tau_V \approx 10^{-2}$ s is in reasonable agreement with the damping of the oscillations in the spin-up phase (Fig.1). In dimensionless parameters the scaling of

Fig.8 is $b_{pen}/B \propto \beta^{0.02}\nu_*^{0.25}\rho_*^{0.9}$. A full RMHD problem for the m=2,n=1 mode, solved with boundary conditions that include an external helical current I_E and assuming constant n, predicts that the non-linear amplification ("penetration") of the helical flux $Re[\psi(r)e^{i(m\theta-nz/R)}]$ occurs when $V_\zeta = V_{\zeta 0}/2$. In Fig.2 and 5 the qualitative agreement of the model with the experiment is shown, but Figs.1,4 show that in the experiment the expected

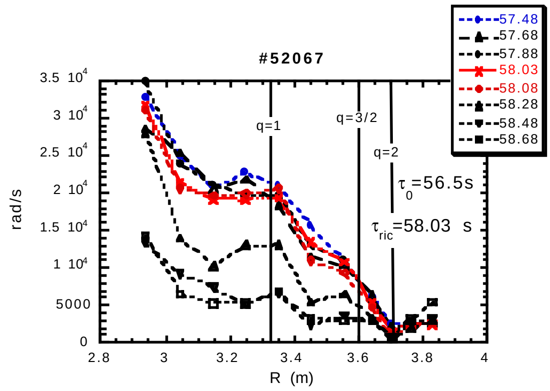

Fig.4–Experimental plasma toroidal velocity evolution:the e.m. torque localization at q=2 surface and global braking are evident.

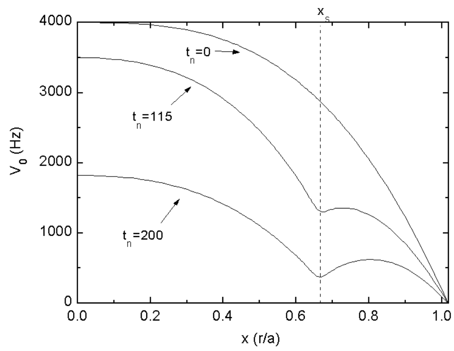

Fig.5–Theoretical model of plasma toroidal velocity evolution in presence of viscosity.

condition on the variation of rotation $\Delta\omega(r) \cong \text{const.}$ for $0 < r < r_{q=2}$ [4] is not met and the velocity profile $V_\zeta(r,t)=\omega(r,t)R$ drops everywhere self-similarly, which is incompatible with a viscous decay. The velocity profile appears not clearly affected by mode coupling but the scaling of the observed braking rate suggest that the rotation damping can be described by $d\left[V_\zeta(r,t)/V_0(r)\right]/dt = -|b_\theta/B_0|^2 \nu_{\zeta 0} V_\zeta(r,t)/V_0(r)$ by some mechanism depending on $|b_\theta|^2$. A possible *conjecture* is that the helical modes destroy axisymmetry, perturbing the modulus of the magnetic field over a considerable range $L \approx \psi_s/\psi' > W$ *away* from the rational surface: $B \approx B_0\left[1-\varepsilon\cos\theta + \left(B_{\theta 0}/B_0^2\right)\sum_\pm\left(|b_{\theta,c}^{m,n}|\cos(m\theta \pm nz/R) + |b_{\theta,s}^{m,n}|\sin(m\theta \pm nz/R)\right)\right]$.

This could give rise to a toroidal neoclassical viscous force of the type [5,6] $\langle F_\zeta\rangle = \langle \vec{e}_\zeta \cdot \nabla \cdot \overleftrightarrow{\Pi}_{//}\rangle \cong \left(|b_\theta|^2/B_0^2\right)\left(n_i T_i/\omega_t\right)\left(\sqrt{\pi}\Gamma(3)n/2R\right)(\varepsilon/q)^2\left(n V_\zeta/R\right)$; then the damping of V_ζ would due to a mechanism of magnetic pumping but quantitatively the braking rate may be too low. With high conductivity σ a strong braking is provided more likely by the force contribution $\langle j_r b_{\theta r}\rangle$, with $\langle j_r\rangle = 0$, giving a rate $\nu_\zeta \cong \left(\sigma/n_i m_i c^2\right)|b_\theta^2|$. The theoretical RMHD model that includes a damping $\propto |b_\theta^2| V_\zeta$ compares qualitatively well (Fig.9) with the experiment (Fig.4). Thus several, but not all, aspects of the observed non-linear response agree with standard theory [4,5], but the interpretation of the sudden fast braking of the

whole plasma rotation profile [3] associated with the locked mode amplification is still open.
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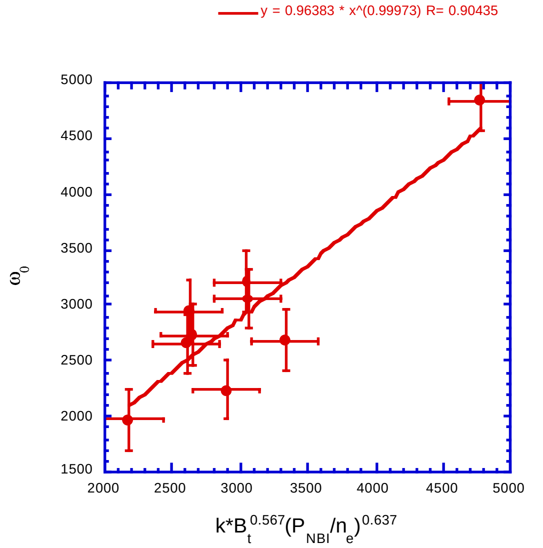

Fig.6-Power law scaling of the rotation frequency with n and B

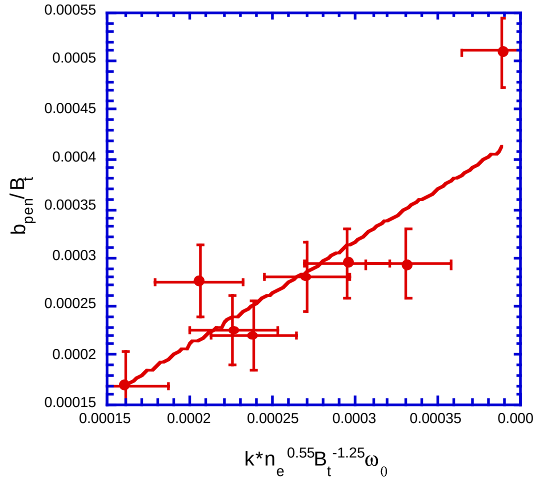

Fig.7- Scaling of the normalised penetration threshold vs power law ~ $n^{1/2}B^{-5/4}\omega$

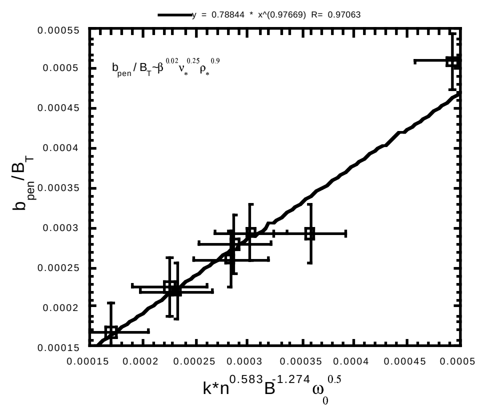

Fig.8-Scaling of the normalised penetration threshold vs power law ~ $n^{7/12}B^{-13/10}\omega^{1/2}$

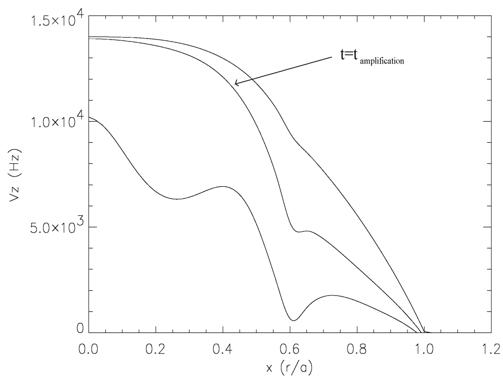

Fig.9–Theoretical model of plasma toroidal velocity evolution in presence of a braking effect $\propto |b_\theta|^2 V_\zeta$

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