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Anomalous Braking and Shear Modification of Plasma Rotation in a Tokamak

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EFDA-JET work programme

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Introduction

There is evidence from different tokamaks that the onset of locked modes driven by resonant helical error fields or by spontaneous MHD activity [1], produces a dramatic *bulk* braking of the whole plasma toroidal velocity profile on short time scales. These observations are in contrast with the expected effect of an electrodynamic torque resonant at a rational surface $r=r_q$ We present a new theoretical model based on the toroidal viscous effects due to breaking of axi-symmetry caused by resonant and non-resonant helical field perturbations with (m=0,n) components. Analysis of the experimental rates of mode growth (reconnection rate) and rotation damping sheds light on the prevalent physical mechanisms.

Effect of driven reconnection on plasma rotation

In a series of JET experiments a ramp of static error field was applied with a helical component m=2, n=1 up to amplitudes $B_{2,1} \approx 6.5 \cdot 10^{-4}\,\mathrm{T}$ at q=2: the electrodynamic torque brakes the plasma rotation at the q=2 surface, and when the rotation velocity $V_\zeta(r,t)$ has been halved non-linear amplification of the initially linear driven response occurs forming an island, subsequently "locked" (Figs.1a,1b). The Charge Exchange Spectroscopy Measurements (CXSM) of Figs.(1c) give the time history of rotation at all radii and show that at mode onset (at t =18.4 s) the velocity profile is braked very quickly and uniformly across the plasma cross section, which is incompatible with a diffusive decay. The timing and the rate of the observed global braking suggest a slowing down mechanisms linked to the radial and helical structure of the magnetic perturbation that modulates the total magnetic field as $B \approx B_0\left[1-\varepsilon\cos\theta+\sum_{m,n}\hat{B}_{m,n}(\theta,\zeta)\right]$. The breaking of axisymmetry due to helical field perturbations can in fact give origin, in general, to a toroidal viscous force of the form $\left\langle \mathbf{e}_\zeta \cdot\nabla\cdot\Pi\right\rangle = \frac{2\pi^{1/2}p_i}{v_{Ti}} V_\zeta \sum_{m,n}\left\langle \frac{\mathbf{e}_\zeta\cdot\nabla B}{B}\frac{\partial\hat{B}_{m,n}}{\partial\zeta}\right\rangle \frac{q}{|m-nq|}$,that is identically zero in axisymmetry [2]. It can however be readily assessed that for modes with (m ≠ 0, n) for normal ion temperatures, this slowing down force is too weak to justify the observed rates of decay. On the contrary it can be shown that if it exists, an m=0,n component of the perturbation is $O(\varepsilon^{-1})$ and contributes effectively. The appearance of a significant m=0 magnetic perturbation is an important element of the problem and our objective here is to show that the mode coupling due to the non circular cross section of JET is the main cause. Indeed a non circular cross section, for instance an ellipse introduces m=2 harmonics that can couple with the m=2,n=1 components of the external perturbation. The problem requires consideration of the equations for tearing modes in general curvilinear coordinates, in a non circular configuration [3]. It is useful to consider a particular case where the equilibrium magnetic field and current density have the contravariant components $\sqrt{g}B_0^i = \{0, \Psi_0', F_0' + \partial\tilde{v}/\partial\theta\}$ and $\sqrt{g}J_0^i = \{0, I_{pol}', I_{tor}' + (I_{tor}'/F_0')\partial\tilde{v}/\partial\theta\}$ and define quasi-Hamada flux coordinates $(\rho = V, \vartheta = \theta + \tilde{v}(\rho,\theta)/F_0', \zeta = \phi)$, with constant Jacobian, $1/\sqrt{g}$. The poloidal and toroidal flux functions $\Psi^*(\rho,\vartheta,\zeta) = \Psi_0(\rho) + Re\sum_{m,n_s} \psi_{m,n}(\rho,t)e^{i(m\vartheta - n\zeta)}$ and $F = F_0(\rho) + Re\sum_n f_{0,n}(\rho,\zeta t)e^{-in\zeta}$ include a helical perturbation, assumed $O(\varepsilon)$, with allowance for an (m=0,n) term. The $\nabla\zeta\cdot$ projection of Faraday-Ohm law gives the equation for the evolution of the (perturbed) magnetic flux $\frac{\partial\psi}{\partial t} + \mathbf{v}\cdot\nabla_\perp\Psi^* = \frac{c\eta}{g^{\zeta\zeta}} j^\zeta$. On the rhs the ζ contravariant component j^ζ of the first order current density contains, through the metric tensor, all the information about the cross talk of the equilibrium magnetic configuration with the m,n spectrum of the perturbation:

$$j^\zeta = \frac{c}{4\pi}\frac{1}{\sqrt{g}}\left\{\frac{\partial}{\partial\rho}\left[\frac{g_{\vartheta\vartheta}}{\sqrt{g}}\frac{\partial\psi}{\partial\rho}\right] - \frac{\partial}{\partial\vartheta}\left[\frac{g_{\rho\theta}}{\sqrt{g}}\frac{\partial\psi}{\partial\rho}\right] - \frac{\partial}{\partial\rho}\left[\frac{g_{\rho\vartheta}}{\sqrt{g}}\frac{\partial\psi}{\partial\vartheta}\right] + \frac{\partial}{\partial\vartheta}\left[\frac{g_{\rho\rho}}{\sqrt{g}}\frac{\partial\psi}{\partial\vartheta}\right] + \frac{\partial}{\partial\vartheta}\left[\frac{g_{\rho\rho}}{\sqrt{g}}\frac{\partial f}{\partial\zeta}\right] - \frac{\partial}{\partial\rho}\left[\frac{g_{\rho\vartheta}}{\sqrt{g}}\frac{\partial f}{\partial\zeta}\right]\right\} \quad (1)$$

The Fourier series expansion of the Faraday-Ohm law generates through convolution products, a sequence of coupled equations for mode m,n and sidebands m ± m'. For the present work it is sufficient to obtain the coupling of the m mode with its closest side-bands m±2 from the marginal stability conditions $\nabla\zeta\cdot[\nabla\times(\mathbf{J}\times\mathbf{B})] = 0$, $\nabla\theta\cdot[\nabla\times(\mathbf{J}\times\mathbf{B})] = 0$. For a triplet of side-bands m-2, m, m+2, a system of coupled (complex) equations is obtained:

$$\Psi_0'(m - nq_s)j_{m,n}^\zeta - m\frac{\partial J_0^\zeta}{\partial\rho}\psi_{m,n} + n\frac{\partial}{\partial\rho}\left[J_0^\zeta f_{0,n}\right]\delta_{m,0} + iF_0'' j_{m,n}^\rho = 0 \quad \text{and}$$

$$\Psi_0'(m - nq_s)j_{m,n}^\vartheta - m\frac{\partial}{\partial\rho}\left[J_0^\vartheta\psi_{m,n}\right] + n\frac{\partial J_0^\zeta}{\partial\rho}f_{0,n}\delta_{m,0} + i\Psi_0'' j_{m,n}^\rho = 0 \qquad (2).$$

For m=0 since $j_{0,n}^\rho = in(c/4\pi)Y$ and $j_{0,n}^\zeta = (c/4\pi)\partial Y/\partial\rho$, $Y = \left(\frac{g_{\theta\theta}}{g}\right)_{-2}\frac{\partial\psi_{2,n}}{\partial\rho} + \left(\frac{g_{\theta\theta}}{g}\right)_0\frac{\partial\psi_{0,n}}{\partial\rho} - 2i\left(\frac{g_{\rho\theta}}{g}\right)_{-2}\psi_{2,n}$ the linear coupling between the (m=2,n) and the (m=0,n) perturbations takes a form that generalizes a previous result [3], valid for m≠0, n: $Y - (4\pi/c)\left(J_0^\zeta/F_0'\right)f_{0,n} = 0$ (4) and

$$\frac{\partial}{\partial\rho}\left[\left(\frac{g_{\zeta\zeta}}{g}\right)_0\frac{\partial f_{0,n}}{\partial\rho}\right]+\left[-n^2\left(\frac{g_{\rho\rho}}{g}\right)_0+\frac{4\pi}{cF_0'}\left(J_0'^{\theta}-\frac{J_0^{\zeta}}{F_0'}\Psi_0''\right)+\left(\frac{4\pi}{c}\frac{J_0^{\zeta}}{F_0'}\right)^2\left(\frac{g}{g_{\vartheta\vartheta}}\right)_0\right]f_{0,n}=$$
$$-\left[in\left(\frac{g_{\rho\vartheta}}{g}\right)_{-2}-\frac{4\pi J_0^{\zeta}}{cF_0'}\frac{(g_{\vartheta\vartheta})_{-2,0}}{(g_{\vartheta\vartheta})_{0,0}}\right]\frac{\partial\psi_{2,n}}{\partial\rho}-\left[2n\left(\frac{g_{\rho\rho}}{g}\right)_{-2}+2i\frac{4\pi J_0^{\zeta}}{cF_0'}\frac{(g_{\rho\vartheta})_{-2,0}}{(g_{\vartheta\vartheta})_{0,0}}\right]\psi_{2,n} \qquad (5)$$

Determining $g_{\vartheta\vartheta}$ for an elliptic cross section and the other $g_{i,k}$ from equilibrium constraints it is possible to estimate to $O(\varepsilon)$the coupling of a m=0,n perturbation induced by the elongation ratio E and E', contained in the Fourier amplitude of the $g_{i,k}$ such as $\frac{(g_{\vartheta\vartheta})_{-2,0}}{(g_{\vartheta\vartheta})_{0,0}}\cong\frac{E^2-1+2E'\rho/E}{2(1+E^2)-EE'\rho-3E'\rho/E}$. In the large aspect ratio limit the toroidal momentum balance equation in the bulk of the plasma, away from the (2,1) surface, is:$\rho_M\frac{\partial V_\zeta}{\partial t}-\frac{1}{\rho}\frac{\partial}{\partial\rho}\left[\mu_\perp\rho\frac{\partial V_\zeta}{\partial\rho}\right]+K(E,E',\psi_2(t))V_\zeta=S_\zeta/R_0$ (6); S_ζ/R_0 is the NBI momentum source sustaining the equilibrium V_ζ profile and the m=0 contribution to the non-axisymmetric toroidal viscosity is: $K(E,E',\psi_2(t))=\frac{\pi^{1/2}p_i}{R_0 v_{Ti}}\sum_{n\neq 0}\frac{1}{|n|\varepsilon^2}\left(\frac{df_{0,n}/d\rho}{B_\zeta}\right)^2$ (7)

and tends to be uniform as $f_{0,n}(\rho)\propto\rho^2$(Fig.3) and depends on E and the m=2 field perturbation *driven* by an external current ramp $I_{EFC}(t)=I_0 t$. The experimental observations suggest a self-similar evolution consistent with a factorization $V_\zeta(\rho,t)\cong V_0(\rho)\cdot y(t)$ so that from (6) one gets: $\frac{dy}{dt}+\frac{K(t)}{\rho_M}y+(y-1)\frac{S_\zeta}{R_0\rho_M V_0}=0$ (8). Up to reconnection the m=2 perturbation and its m=0 side-band grow linearly in time and therefore $K\propto t^2$. If initially stable ($|\Delta_0'|\sim 0$) after reconnection, the m=2 field grows as $\psi_2\frac{d\psi_2^{1/2}}{dt}\approx\Gamma I_0 t$ and consequently $K\propto t^{8/3}$.For $t\geq t_{rec}$ equation (8) has the solution $y(\hat{t})=e^{-\hat{t}-\frac{3\beta}{11}\hat{t}^{11/3}}\cdot\left(1+\int_0^{\hat{t}}e^{z+\frac{3\beta}{11}z^{11/3}}dz\right)$ where $\beta=\tau_\mu\hat{K}/\rho$,and $\hat{t}=(t-t_{rec})/\tau_\mu$, $\hat{K}=K(\hat{t}=1)$.The comparison of our theory with the observed braking at the q=2 surface and near the axis for JET shot 52061(Figs.4,5) is satisfactory. In conclusion the magnitude and uniformity of the braking prove the role of the m=0 n=1 mode and the agreement with the observed rotation quench rate proves that this mode is coupled by elongation to the m=2,n=1 reconnecting one.

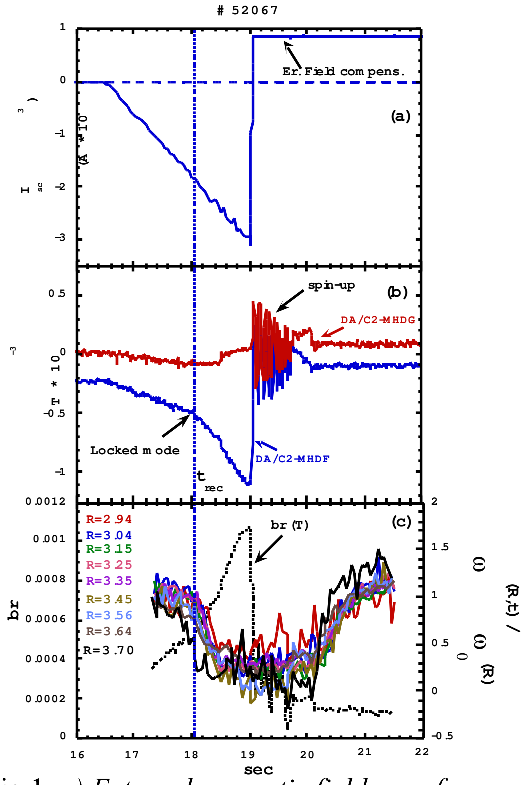

Fig.1–*a) External magnetic field waveform b)Magnetic signals showing linear and non-linear response(t=18.04 s). c) CXSM signals showing plasma rotation at different radii. At field "penetration" sudden braking is observed.*

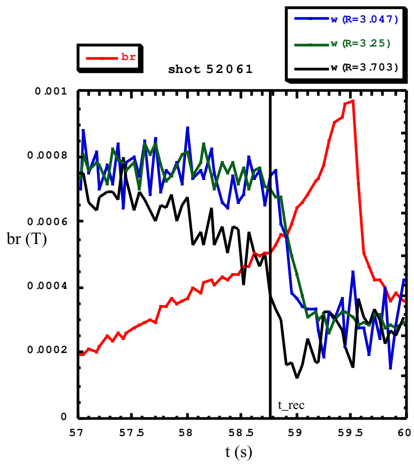

Fig.2–*a) Magnetic signal showing linear and non-linear response(shot 52061) b) CXSM signals showing plasma rotation at q=2 radius and near axis.*

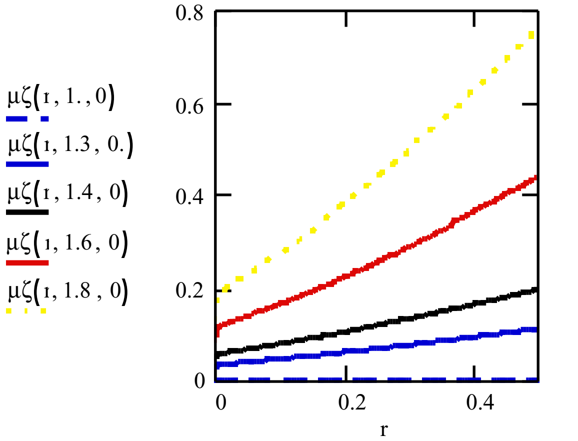

Fig.3 Radial profile of $\rho^{-2}|\partial f_{0,1}/\partial\rho|^2$ $(\propto K)$ *for elongation in the range 1<E<1.8*

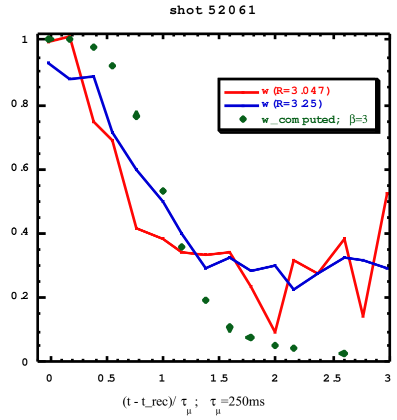

Fig.4 CXSM signals showing plasma rotation decay at q=2 radius and near axis for shot 52061. Dots are theoretical prediction from eqs. 7,8 with τ_μ*=250 ms,* β*=3.*

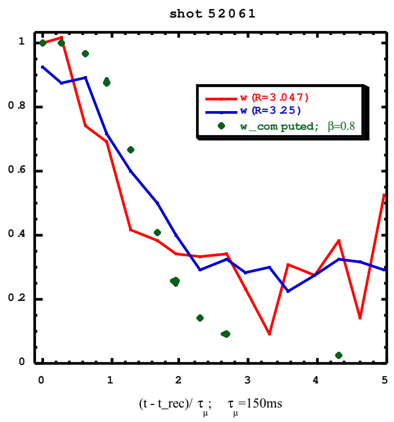

Fig.5. Same as Fig.3 with τ_μ*=150 ms,* β*=0.8*

[1]Nucl. Fus. **28**,1085 (1988); [2] Phys.of Fluids **29** 521(1986); [3] Nucl. Fus. **21**,511 (1981)