EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)02/24

E. Lazzaro, T.C. Hender and P. Zanca

Anomalous Braking and Shear Modification of Plasma Rotation in a Tokamak

Anomalous Braking and Shear Modification of Plasma Rotation in a Tokamak

E.Lazzaro[1], T.C.Hender[2], P.Zanca[3]
and contributors to the EFDA-JET work programme*

[1]IFP CNR, Assoc. EURATOM-ENEA-CNR per la Fusione, Via Cozzi 53, Milan, Italy
[2]EURATOM/UKAEA Fusion Assoc., Culham Science Centre, Abingdon OX14 3DB, UK
[3]Consorzio RFX, Associazione Euratom-ENEA sulla Fusione C.so Stati Uniti 4 Padova Italy
**See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Proceedings of the 29th EPS Conference, (Montreux, Switzerland 17-21 June 2002)

Anomalous Braking and Shear Modification of Plasma Rotation in a Tokamak

E.Lazzaro[1], T.C.Hender[2], P.Zanca[3] and contributors to the
EFDA-JET work programme

[1]*IFP CNR, Assoc. EURATOM-ENEA-CNR per la Fusione, Via Cozzi 53, Milan, Italy*
[2] *EURATOM/UKAEA Fusion Assoc., Culham Science Centre, Abingdon OX14 3DB, UK*
[3]*Consorzio RFX, Associazione Euratom-ENEA sulla Fusion eC.so Stati Uniti 4 Padova Italy*

Introduction

There is evidence from different tokamaks that the onset of locked modes driven by resonant helical error fields or linked to spontaneous MHD activity [1], produces a dramatic *bulk* braking of plasma toroidal velocity that leads to a self-similar quench of the whole 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 $B_{2,1} \approx 6.5\ 10^{-4}\,\mathrm{T}$ 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 reduced to a critical value, non-linear amplification of the initially linear driven response occurs forming an island, subsequently “locked” (Figs.1a,1b) [1].The Charge Exchange Spectroscopy Measurements (CXSM) of Figs.(1c,2) 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 $B \approx B_0 \left[1 - \varepsilon \cos\theta + \sum_{m,n} \tilde{B}_{m,n}(\theta,\zeta) \right]$.The breaking of axisymmetry due to resonant and non-resonant helical field perturbations can in fact give origin, in general, to a toroidal viscous force of the form $\langle \mathbf{e}_\zeta \quad \Pi \rangle = \frac{2\pi^{1/2} p_i}{v_{Ti}} V_\zeta \sum_{m,n} \left\langle \frac{\mathbf{e}_\zeta \quad B}{B} \frac{\partial \tilde{B}_{m,n}}{\partial \zeta} \right\rangle \frac{q}{|m - nq|}$,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 account for 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 $\mathcal{O}(\varepsilon^{-1})$ 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[3]. Indeed a non circular cross section, for instance an ellipse introduces m=2 n=1 harmonics that can couple with the m=2,n=1 components of the external perturbation. The problem requires necessary to reconsider the equations for tearing modes in general curvilinear coordinates, in a non circular configuration described parametrically by $R = R_0 - \Delta(\rho) + \rho\cos\alpha$, $Z = E(\rho)\rho\sin\alpha$. In flux coordinates (ρ,θ,ζ), where $\theta = 2\pi\int_0^\alpha dt/\sqrt{g g_{\zeta\zeta}} \Big/ \oint dt/\sqrt{g g_{\zeta\zeta}}$, the magnetic field is $\mathbf{B} = F' \nabla\rho\times\nabla\theta - \nabla\Psi^*\times\nabla\zeta$ and the velocity field is $\mathbf{v} = V_{0\zeta}\nabla\zeta + \nabla\Phi\times\nabla\zeta$, where the poloidal magnetic flux $\Psi^*(\rho,\theta,\zeta) = \Psi_0(\rho) + \sum_{m,n_s} \mathcal{Re}\,\psi_{m,n}(\rho,t)e^{i(m\theta - n\zeta)}$ describes an axisymmetric equilibrium term with superimposed a helical perturbation presently considered $\mathcal{O}(\varepsilon)$. The projection along $\nabla\zeta$ of Faraday-Ohm law gives the equation for the evolution of the (perturbed) magnetic flux $\frac{\partial\psi}{\partial t} + \mathbf{v}\cdot\nabla\Psi^* = \frac{c\eta}{g^{\zeta\zeta}} j^\zeta$ On the rhs the ζ contravariant component j^ζ of the first order current density contains indeed, through the metric tensor, all the information about the cross talk of the equilibrium magnetic configuration with the m,n spectrum of the perturbation:

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

The Fourier series expansion of the Faraday-Ohm law generates through the required 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 sidebands m±2 from the tearing mode marginal stability condition $\nabla\zeta\cdot\left[\nabla\times(\mathbf{J}\times\mathbf{B})\right] = 0$. For a triplet of sidebands m-2,m,m+2, the latter becomes

$$\frac{\partial\Psi_0}{\partial\rho}(m - nq_s)j^\zeta_{m,n} + \sum_{m'=-2,0,2}\left[m' J^\zeta_{0,m'}\frac{\partial\psi_{m-m',n}}{\partial\rho} - (m-m')\psi_{m-m',n}\frac{\partial J^\zeta_{0,m'}}{\partial\rho}\right] = 0 \qquad (2)$$

where the geometric coupling of the different harmonics is contained in the Fourier amplitude of the current. Sorting out the real and imaginary parts of the complex equation (2) the linear coupling between the (m=2,n) and the (m=0,n) perturbations can be obtained in the form:

$$\mathcal{Re}\left(j^\zeta_{0,n}\right) = \frac{c}{4\pi}\left\{\frac{\partial}{\partial\rho}\mathcal{Re}[(g^{\zeta\zeta}g^{\rho\rho})^*_2\frac{\partial\psi_2}{\partial\rho}] + \frac{\partial}{\partial\rho}[(g^{\zeta\zeta}g^{\rho\rho})_0\frac{\partial\psi_0}{\partial\rho}] - 2\frac{\partial}{\partial\rho}\mathcal{Im}[\left(g^{\zeta\zeta}g^{\rho\theta}\right)^*_2\psi_2]\right\} = 0 \qquad (3)$$

Extracting explicitly the real quantities in (3) and integrating once one gets the linear coupling relation of the type $\frac{\partial \psi_0}{\partial \rho} = -\frac{(g^{\zeta\zeta} g^{\rho\rho})_2}{(g^{\zeta\zeta} g^{\rho\rho})_0}\frac{\partial \psi_2}{\partial \rho} - 2\frac{(g^{\zeta\zeta} g^{\rho\theta})_2}{(g^{\zeta\zeta} g^{\rho\rho})_0}\psi_2$ (4) where $(g^{\zeta\zeta} g^{ik})_m$ are the Fourier coefficients of the corresponding metric coefficients With the chosen representation of elliptic equilibrium surfaces relation (4) to $O(\varepsilon)$ is

$$\frac{\partial \psi_0}{\partial \rho} = -\left\{ \frac{E^2 - 1 + 2E'\rho/E}{2(1+E^2) - EE'\rho - 3E'\rho/E}\frac{\partial \psi_2}{\partial \rho} - 2\frac{E^2 - 1 + E'\rho/E + E'\rho^2}{\left(2(1+E^2) - EE'\rho - 3E'\rho/E\right)\rho}\psi_2 \right\} \qquad (5)$$

where it is apparent that mode coupling is induced by the elongation ratio E and its shear. For simplicity we consider now in the large aspect ratio limit the toroidal momentum balance equation $\rho_M \frac{\partial V_\zeta}{\partial t} - \frac{1}{\rho}\frac{\partial}{\partial \rho}\left[\mu\, \rho \frac{\partial V_\zeta}{\partial \rho}\right] + K(E, E', \psi_2(t))V_\zeta = S_\zeta / R_0$ (6) in the bulk of the plasma, away from the (2,1) resonant surface; S_ζ / R_0 is the NBI momentum source that sustains the equilibrium rotation profile and

$$K(E, E', \psi_2(t))\ V_\zeta = \frac{\pi^{1/2} p_i}{R_0 v_{Ti}} V_\zeta \sum_{n\neq 0}\frac{1}{|n|\varepsilon^2}\left(\frac{d\psi^{0,n}/d\rho}{B_\zeta}\right)^2 \equiv \left\langle e_\zeta \qquad \Pi \right\rangle_{m=0} \qquad (7)$$

is the m=0 contribution to the non axisymmetric toroidal viscosity,that depends (through (5)) on E (Fig.3) 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 $V_\zeta(\rho, t) \quad V_0(\rho)\ y(t)$ so that from (6) one gets: $\frac{dy}{dt} + \frac{K(t)}{\rho} y + (y-1)\frac{S_\varphi}{R_0 \rho V_0} = 0$ (8)

Up to reconnection the m=2 perturbation and its m=0 sideband grow linearly in time and therefore $K \quad t^2$.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 $K \quad t^{8/3}$.For $t \geq t_{rec}$ equation (8) has a solution of the type $y(\hat{t}) = e^{-\hat{t} - \frac{3\beta}{11}\hat{t}^{11/3}}\left(1 + \int_0^{\hat{t}} e^{z + \frac{3\beta}{11}z^{11/3}} dz\right)$ where $\hat{t} = (t - t_{rec})/\tau_\mu$, $\beta = \tau_\mu \hat{K}/\rho$ and $\hat{K} = K(\hat{t} = 1)$.

Figs (4,5) show the satisfactory comparison of the observed rate of braking oat the q=2 surface and near the axis for JET shot 52061 with our theoretical prediction. In conclusion the agreement with the observed rate of global quench of the plasma toroidal rotation validates the mechanism associated with the non-resonant m=0 component of the perturbation coupled by elongation E to the m=2,n=1 reconnecting one. This global braking may deteriorate confinement as it flattens the shear of $V_\theta^{EXB} = V_\zeta B_\theta / B + \frac{c}{en_i ZB}\left[p' - 1.17 n_i T_i'\right]$, whereas a localized torque could be beneficial.

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

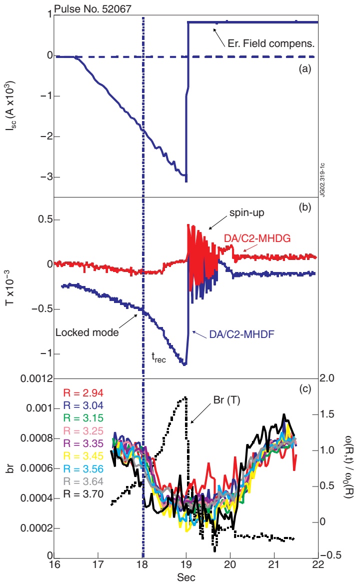

Fig.1–a) External magnetic field waveform b)Magnetic signals showing linear and non-linear response(t=18.04 s). c) CXSM signals showing plasma rotation at different radii. At field "penetration" sudden braking is observed.

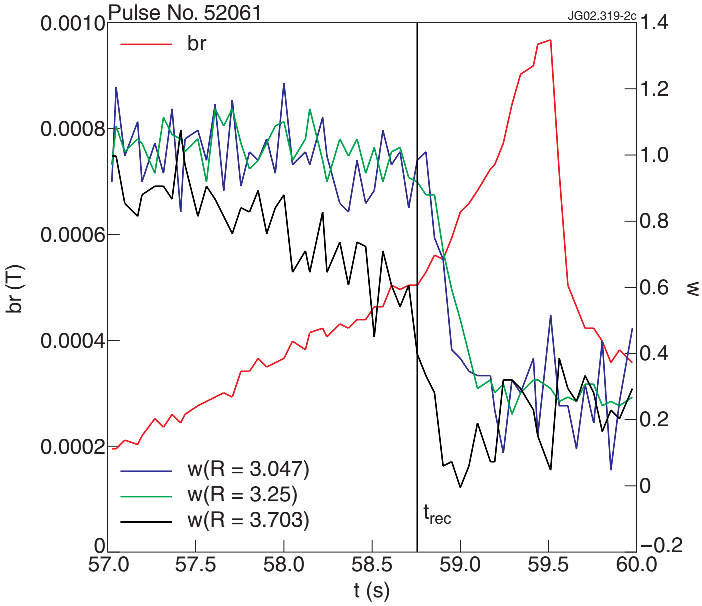

Fig.2–a) Magnetic signal showing linear and non-linear response (Pulse No: 52061) b) CXSM signals showing plasma rotation at q = 2 radius and near axis.

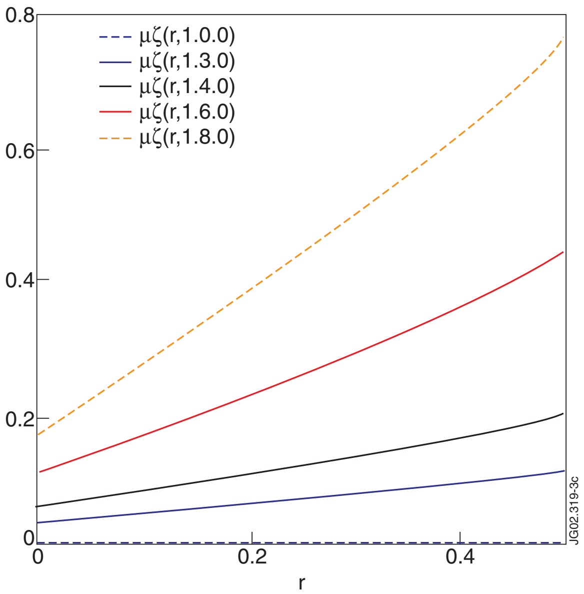

Fig.3 Radial profile of $\rho^{-2} \mid \partial f_{0,1} / \partial \rho \mid^2$ *for elongation in the range 1<E<1.8*

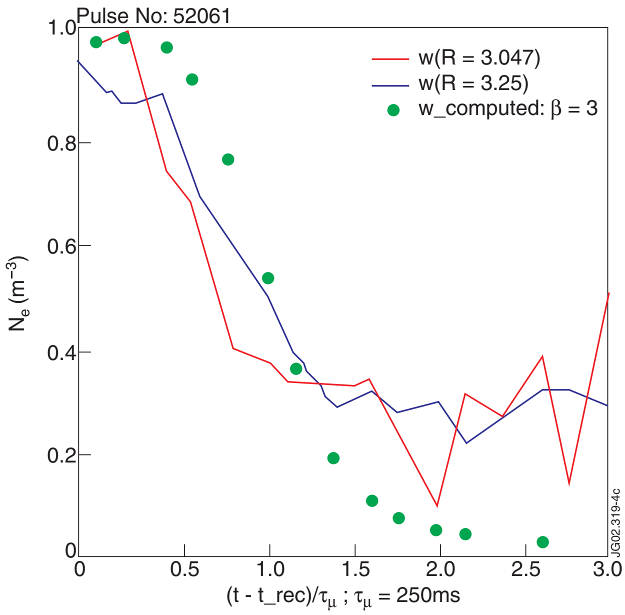

Fig.4–CXSM signals showing plasma rotation decay at q = 2 radius and near axis for Pulse 52061. Dots are theoretical prediction from eqs. 7,8 with) τμ=250 ms, β = 3

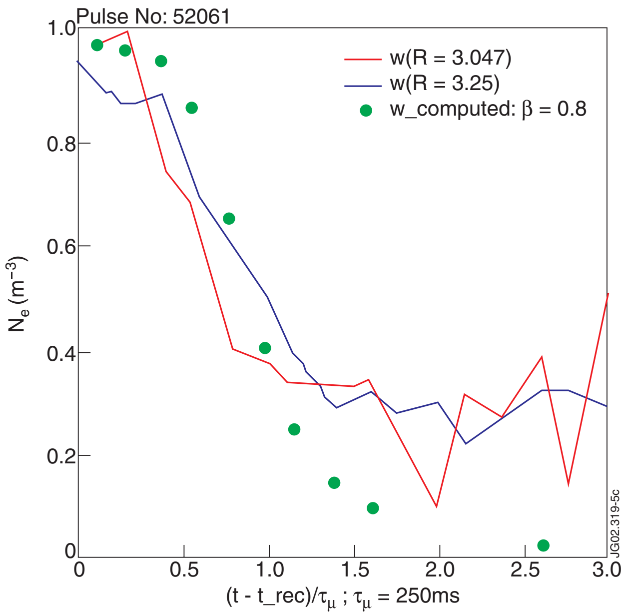

Fig.5. Same as Fig.3with) τμ=150 ms, β=0.8