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Modification of EXB Shear near Rational Surfaces in Response to Magnetic Driven Reconnection due to Mode Coupling or External Fields

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1 – Introduction

The onset of Internal Transport Barriers (ITBs) characterized by the rapid appearance of sharp temperature gradients is often associated with rational surfaces q=m/n, where it is conjectured that the magnetic island structure modifies the electrostatic potential profile, varying thereby the shear of the plasma electric drift velocity in the poloidal direction $V_\theta^{EXB} \equiv cE^r/B$. An *accepted* criterion for reduction of the typical scale length of turbulence (and consequent reduction of convective transport) is that the E×B velocity shear $V_\theta'^{EXB} \geq \gamma$, where γ _is the typical growth rate of turbulence [1]. We investigate whether a magnetic island, possibly driven by external perturbations, can modify locally, near q=m/n, in a sufficient and favorable way $V_\theta^{EXB} \equiv \frac{cE^r}{B} = V_\zeta \frac{B_\theta}{B} + \frac{c}{en_i ZB}\left[\frac{\partial p}{\partial r} - K_1 n_i \frac{B_T^2}{B^2}\frac{\partial T_i}{\partial r}\right]$. The perturbation forcing reconnection could be provided by mechanisms of mode coupling, possibly involving outer kink-modes with m>3 [2]. JET experiments of externally driven reconnection have been done with saddle coils on a plasma with rotation impressed by 5-8 MW NBI. Localized direct power deposition to the electron component was provided by mode conversion of ICRH waves. Experimental evidence shows that reconnection is strongly hindered by plasma rotation and generally *insufficient* to produce the required E×B shear perturbation, while naturally occurring ITBs, "anchored" to the q=2 surface are indeed associated with edge MHD signals. The typical waveforms of the applied saddle coils current and MHD locked mode response in JET are shown in Fig.1. The ρ^* criterion for ITB onset is shown in Figs 2 and 3, evidencing that for driven reconnection (Fig2, Shot 58320) no ITB appears, in contrast with a spontaneous ITB case (Fig.3 Shot 58315).

2. Theoretical Interpretation

The expectation that an ITB is formed when an external field creates an island can be based on the assumption that the helical perturbation produces an axisymmetric electrodynamic torque localized at the q=m/n surface. The effect on V_θ^{EXB} is then expected via the braking-acceleration effect on V_ϕ and V_θ, that are also affected by the anomalous perpendicular viscosity and the neoclassical damping. Here it is shown that these mechanisms are crucial in explaining the observations.

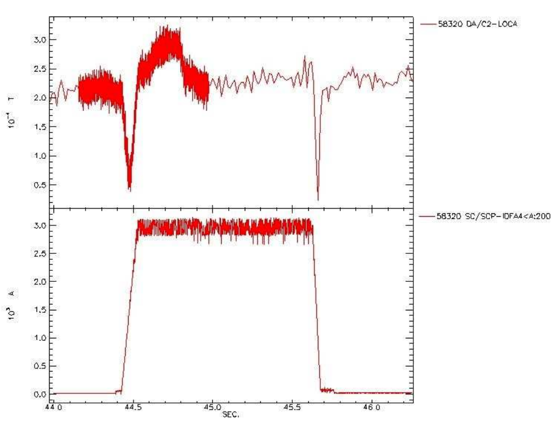

Fig.1- Lower trace is waveform of saddle coils in JET shot 58320; Upper trace is Locked mode signal showing reconnection at t=44.5

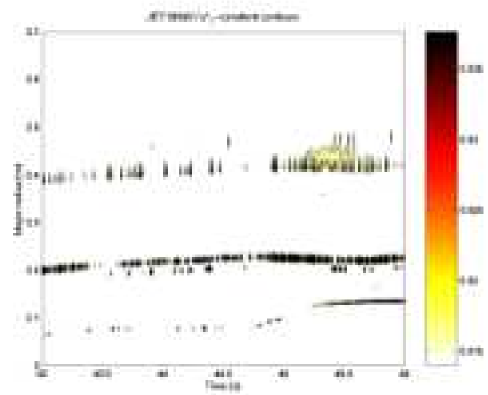

Fig.2- ITB criterion in terms of ρ*: lack of increase at t=44.5 shows that no ITB has appeared at island formation for shot 58320*

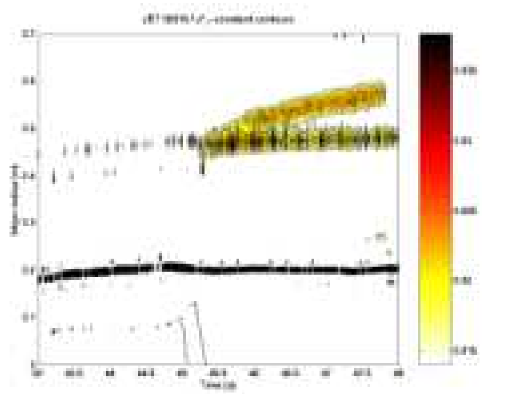

Fig.3-ITB criterion in terms of ρ*: increase at t=45.3 shows that a spontaneous ITB has appeared in shot 58315*

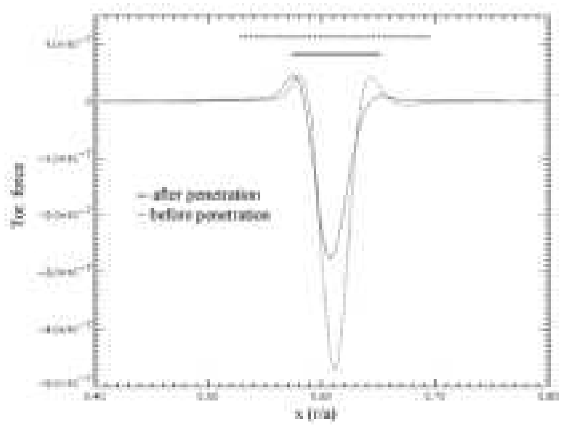

Fig.4-Calculated profile of local braking torque at the island region just before and after nonlinear mode amplification

From Maxwell and momentum balance equations a RMHD system of equations for the space and time evolution of the magnetic flux perturbations $\tilde{\psi}(r,t)\exp(im\theta - nz/R)$ and velocity stream function $\tilde{u}(r,t)\exp(im\theta - nz/R)$ has been written in large R/a limit including the evolution of the background toroidal and poloidal velocity fields. The magnetic field is written as $\mathbf{B} = g\nabla\Psi \times \mathbf{e}_h + B_z\mathbf{e}_z$, with $g^{-1} = 1 + (nr/mR)^2$ and $\mathbf{e}_h = \mathbf{e}_z + \mathbf{e}_\theta (nr/mR)$

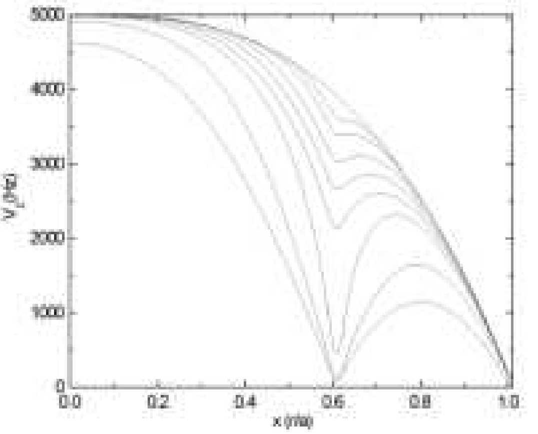

*Fig.5-Calculated profile of Vz with localized braking force at low viscosity (S=8.3*10^5, γ=0.05)*

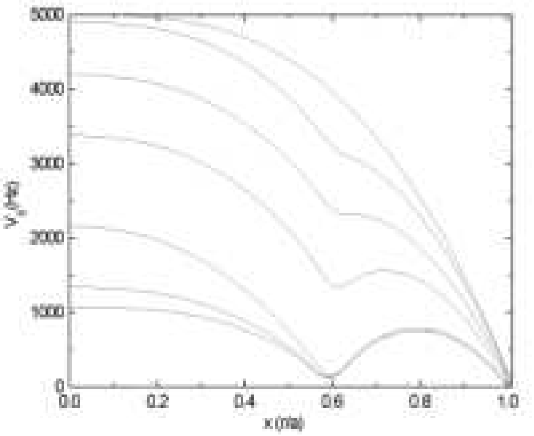

*Fig.6-Calculated profile of Vz with localized braking force, at high viscosity; The local shear does not increase (S=8.3*10^5,γ=5)*

and the equations for the background velocity components are

$$\rho\frac{\partial V_{z0}}{\partial t} = \nabla\cdot\mu_\perp^{Anom}\nabla\left(V_{z0} - V_{z0}\big|_{t=0}\right) + \frac{n}{2\mu_0 R}\mathrm{Im}\left(\tilde{\psi}^*\nabla_\perp^2\tilde{\psi}\right) - \frac{\rho n}{2R}\mathrm{Im}\left(\tilde{u}^*\nabla_\perp^2\tilde{u}\right)$$

and

$$\rho\frac{\partial V_{\theta 0}}{\partial t} = \nabla\cdot\mu_\perp^{Anom}\nabla\left(V_{\theta 0} - V_{\theta 0}\big|_{t=0}\right) - \frac{m}{2\mu_0 r}\mathrm{Im}\left(\tilde{\psi}^*\nabla_\perp^2\tilde{\psi}\right) + \frac{\rho m}{2r}\mathrm{Im}\left(\tilde{u}^*\nabla_\perp^2\tilde{u}\right) - \hat{\mu}_{neo}\left(V_{\theta 0} - V_{\theta 0}\big|_{t=0}\right)$$

with standard notation for the coefficients. For a given Lundquist number $S=\tau_\eta/\tau_A$ the calculations show (Fig.4) that the relative width δ/W of the region where the e.m. force is applied shrinks as the island grows, so that the effect of perpendicular (anomalous) viscosity on the velocity profile V_ϕ prevails. Indeed, Fig. 5 shows that for low Prandtl number $\gamma=\tau_\eta/\tau_\mu$ ~0.05 the gradient of V_ϕ may be large in the reconnection region, but for values γ~5 the region of decay of the velocity increases (Fig.6), leading to a flattening of the gradient that is detrimental for the ITB onset. The numerical results can be understood also on the basis of simple analytical considerations on the mechanism of field penetration and torque transfer in conditions of driven reconnection. The general response function of flux reconnecting at rational surfaces ,due to external perturbations Ψ_V and in presence of a differential rotation $\delta\Omega = RV_\phi - \omega_{coil}$ between the plasma and the perturbation, shows a shielding effect that depends on the physics of the reconnecting layer: $\psi_s = \Psi_V \dfrac{2m/r_s(-\Delta'_{mode})}{1+\Delta'_{layer}(\delta\Omega)/(-\Delta'_{mode})}$, where

$\Delta'_{layer}, \Delta'_{mode}$ are the tearing stability indices relative to the inner layer and the outer solution (with no island) respectively. In the visco-resistive regime, when $\delta\Omega < \tau_A^{-2/3}\tau_\eta^{-2/3}\tau_\mu^{1/3}$, one has $\psi_s = \dfrac{2m/|r_s\Delta'_{mode}|\Psi_V}{1+i\delta\Omega\tau_{rec}}$, and the layer of reconnection, $\delta_{layer} = r_s\tau_A^{1/3}\tau_\eta^{-1/6}\tau_\mu^{-1/6}$, depends on the local layer parameters. In this regime a large differential rotation reduces in magnitude the reconnected flux and therefore reduces the local torque on the plasma. On the contrary, for higher Prandtl number the visco-ideal regime is entered, the reconnected flux is now

$$\psi_s = \frac{2m\Psi_V}{|r_s\Delta'_{mode}|}\frac{|\delta\Omega\tau_{rec}|^{1/4}}{\left(|\delta\Omega\tau_{rec}|^{1/4}+\cos\frac{7\pi}{8}\right)\pm i\sin\frac{7\pi}{8}}$$

and the reconnection layer actually *increases with the differential rotation* $\delta_{layer} = r_s|\Delta\Omega|^{1/4}\left(\tau_A^2/\tau_\mu\right)^{1/4}$. Using the linear asymptotic form of the magnetic flux perturbation in the reconnecting layer the total averaged electrodynamical torque affecting the (toroidal) component of velocity can be expressed as $T_\phi^{m,n} = -K\,\mathrm{Im}\left(r\tilde{\psi}^*_{m,n}\tilde{\psi}'_{m,n}\right)\Big|_{r_s-\delta_{layer}/2}^{r_s+\delta_{layer}/2} \cong -Kr_s|\psi_s|^2\,\mathrm{Im}\left(\Delta'_{layer}\right)$, with K a constant, yielding

$$T_\phi^{m,n} = -K\frac{|\Psi_V|^2}{|\Delta'_{mode}|}\frac{|\delta\Omega\tau_{rec}|^{1/4}\sin(7\pi/8)}{1+2|\delta\Omega\tau_{rec}|^{1/4}\cos(7\pi/8)+|\delta\Omega\tau_{rec}|^{1/2}}.$$

Since this torque will be distributed over δ_{layer}, it is then clear that in this regime the gradient of the E×B poloidal velocity is expected to be reduced by a large differential rotation as $\left|(cE_r/B)'\right| \propto |V_\phi - V_\phi(t=0)|/\delta_{layer} \propto \Delta V_\phi/\delta\Omega^{1/4}$. Large differential rotation prevents field penetration (braking torque) in <u>low viscosity</u> regimes, or broadens the braking region at <u>high viscosity</u>. Therefore viscosity opposes the formation of large V_ϕ shear near rational surfaces. From the present observations on JET it should be concluded that in ITB experiments at relatively high temperature near the electron banana regime and high plasma rotation (due to NBI) a visco-ideal regime was entered, unfavorable for onset of ITBs.

References

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