Neoclassical Effects in the Theory of Magnetic Islands: Neoclassical Tearing Modes and more

A. Smolyakov

University of Saskatchewan, Saskatoon, Canada,

also at CEA Cadarache, France

IAEA Technical Meeting on Theory of Plasmas Instabilities: Transport, Stability and their Interaction, 2-4 Mar, 2005, Trieste, Italy

Acknowledgements/Contributors:

J.D. Callen, U Wisconsin
J. Connor, UKAEA
R. Fitzpatrick, IFS, UT
X. Garbet, CAE Cadarache
E. Lazzaro, IFP, CNR
A.B. Mikhailovskii, Kurchatov Institute
M. Ottaviani, CAE Cadarache
P.H. Rebut, JET
A. Samain, CAE Cadarache
B. Scott, IPP
K.C. Shaing, U Wisconsin
F. Waelbroeck, IFS,UT
H. Wilson, UKAEA
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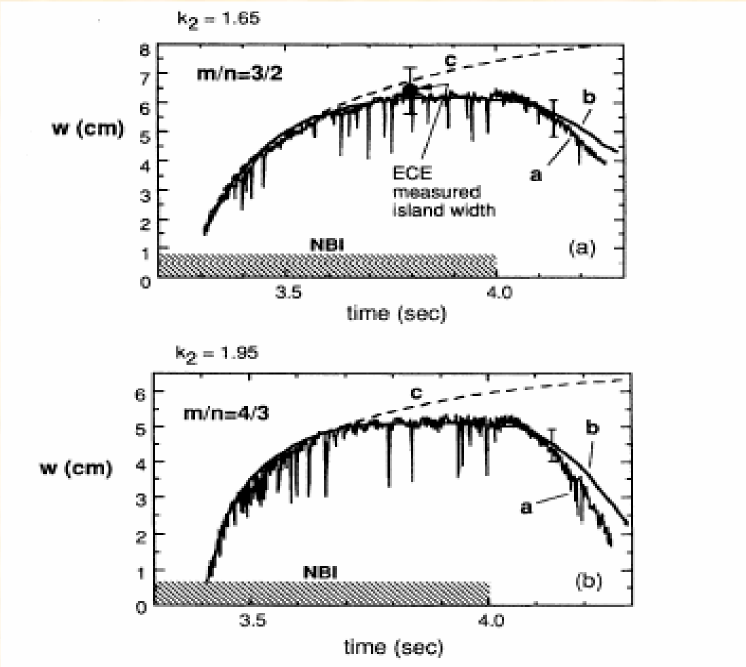
Neoclassical Magnetic Islands

- Neoclassical modes in TFTR, Z. Chang et al. PRL 74, 4663 (1995)



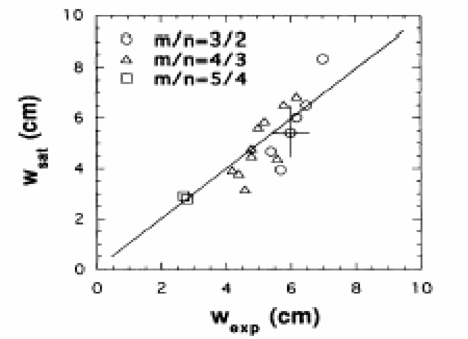


FIG. 4. Theory-experiment comparison of saturated magnetic island width. The w_{exp} is from Eq. (5). The w_{sat} is from Eq. (4). A constant $k_2 = 1.7$ has been used for all discharges.

Saturation for

$$\Delta < 0$$

$$w_{sat} \sim \beta / \Delta'$$

$$\tau_R \frac{\partial w}{\partial t} = \Delta' + \frac{\beta}{w}$$

$$w \sim (\beta t / \tau_R)^{1/2}$$

Rutherford growth

$$w \sim \Delta' t / \tau_R$$

Bootstrap growth

Beta dependence signatures are critical for NTM identification

Outline

- Basic island evolution -- extended Rutherford equation
- Finite pressure drive: Bootstrap current
- Stabilization mechanisms:
    - Removal of pressure flattening due to finite heat conductivity
    - Polarization current
- Other neoclassical effects
    - Neoclassical coupling of transverse and longitudinal flows
    - Enhanced polarization current due to neoclassical flow damping
- New stabilization mechanism due to parallel dynamics and neoclassical coupling
    - Ion sound effects
- Island rotation frequency

Basics of Nonlinear Magnetic Islands Theory

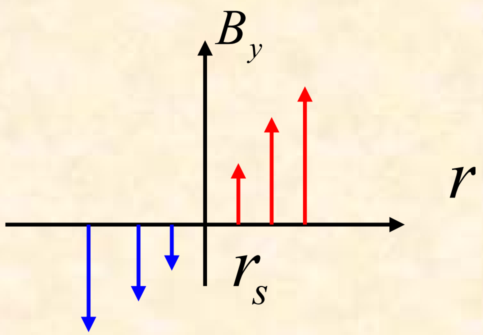
- Effective helical flux function for the rotating island

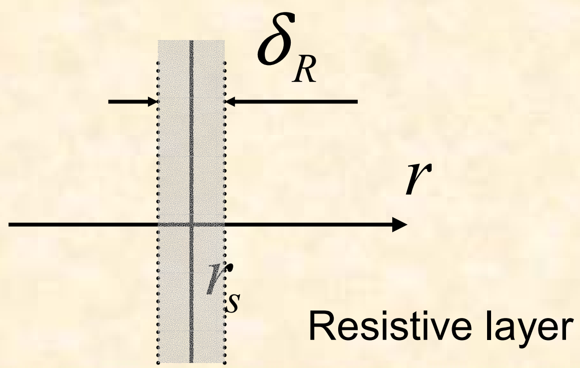
$$\psi(x,t) = -\frac{x^2}{2L_s}B_0 + \widetilde{\psi}(t)\cos\xi.$$

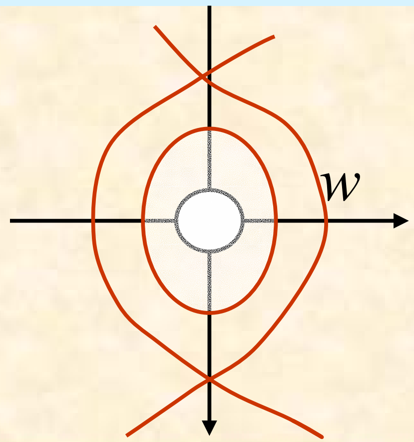
$x = r - r_s$ is the distance from the rational surface, $L_s = qR/S$ is the shear length, $S = q'r_s/q$, and the helical coordinate $\xi = m\widehat{\theta} - \int^t \omega(t')dt'$, $\widehat{\theta} = \theta - \zeta/q_s$. Magnetic island with half-width $w^2 = 4L_s\widetilde{\psi}/B_0$.

- Rutherford regime: $w > \delta_R$. Typical values: $\delta_R < 0.3$ cm for $S = 10^5 - 10^8$, $w \simeq 1$ cm

- Constant ψ approximation. Single helicity







Motivation

- Neoclassical Tearing Modes (NTM) are often observed in the ideal MHD stable ($\Delta' < 0$) plasmas – seriously degrade tokamak performance (10-50 %, loss of H-mode and disruptions)

- Modes are driven by finite pressure effects: bootstrap current associated with the perturbation of plasma pressure near/inside the magnetic island –neoclassical effect $\longrightarrow$ NTM

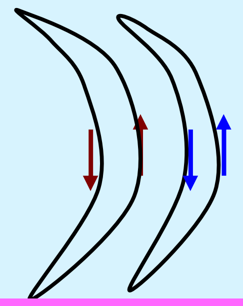
- Experimental data seem to suggest that at a small island width the destabilizing effect of the bootstrap current is reduced by some other effect(s) $\longrightarrow$ Threshold (*Sauter et al. PoP 4, 1654 (1997)*)
  Plasma is metastable with respect to NTM $\longrightarrow$ Trigger mechanism, seed island

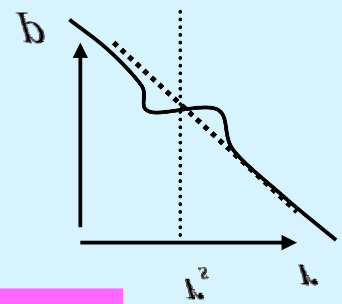
Stabilization/driving mechanisms?

Bootstrap Current Drive

- Pressure driven current due to friction between trapped and untrapped particles

$$J_{\parallel} = \sqrt{\epsilon}\frac{c}{B_\theta}\frac{dp}{dr}$$





Loss of the bootstrap current around the island

Diamagnetic banana current +friction effects

- Generalized Ohm law

$$0 = -en\left(-\nabla\phi - \frac{1}{c}\frac{\partial\psi}{\partial t}\right) - \mathrm{b}\cdot\nabla p_e - \mathrm{b}\cdot\nabla\cdot\Pi_e + enJ_{\parallel}/\sigma$$

Bootstrap current

$$\mathrm{b}\cdot\nabla\cdot\Pi_e = n_e n\mu_e V_{\theta e}$$

$$V_{\theta e} = -\frac{c}{enB_0}\frac{\partial}{\partial r}(p_e + p_i) + \frac{B_\theta}{B_0}(V_{ze} - V_{zi}]$$

Constant on magnetic surface

$$J_b = \langle J_b \rangle \qquad \nabla_{//} J_b = 0$$

Extended Rutherford Equation–Basic Evolution Equation

- The nonlinear equations for the evolution of the magnetic island follow from the matching conditions obtained by integration of the Ampere's law, $4\pi J_{\|}/c = \nabla_{\perp}^2 \psi$, across the nonlinear region

$$\int_{-\pi}^{\pi} d(m\theta) \int_{-\infty}^{\infty} dx J_{\|} \cos\xi = \frac{c}{4} \triangle_c' \tilde{\psi}$$

- Rutherford equation

Qu, Callen 1985

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle_c'}{4} + \sqrt{\epsilon} \frac{\beta_\theta}{S w} + \ldots$$

$$J_{\|} = \frac{\sigma}{c} \frac{\partial \psi}{\partial t} + \sqrt{\epsilon} \frac{c}{B_\theta} \frac{dp}{dr}$$

- Transition to the linear limit $w \rightarrow 0$?

  All m mode numbers are unstable? Does not happens in the experiments: most often m/n=3/2, 4/3, 5/4. $\rightarrow$

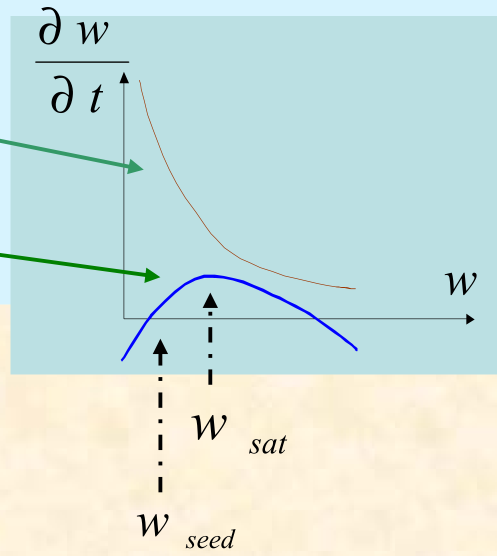
  Threshold mechanism?

Neoclassical Tearing Modes are metastable – Thresholds

- Modification of the bootstrap current for small island width (finite parallel heat conductivity)

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle'_c}{4} + \sqrt{\epsilon}\frac{\beta_\theta}{Sw} \qquad \textit{No threshold}$$

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle'_c}{4} + \sqrt{\epsilon}\frac{\beta_\theta}{S}\frac{w}{w_c^2 + w^2} \qquad \textit{Threshold}$$



- Polarization current threshold

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle'_c}{4} + \sqrt{\epsilon}\frac{\beta_\theta}{S}\frac{w}{w_c^2 + w^2} - \alpha\beta_\theta\frac{1}{w^3}$$

w

- Magnetic field curvature (Glasser-Green-Johnson) effect is also stabilizing. Usually is small but can be important for small aspect ratio (MAST, *R.J. Buttery et al., PRL 88, 125005-1 (2202), H.Lutjens, J-F Luciani, and X. Garbet, POP 8, 4267 (2002)*).

$$\triangle'_{GGJ} = g_{GGJ}\frac{D_R}{\sqrt{w_c^2 + w^2}}$$

Drift/Inertial, Neoclassical, Curvature, etc Effects

- Quasineutrality equation

$$\nabla_{\parallel} J_{\parallel} + \nabla_{\perp} \cdot \mathbf{J}_{\perp} = 0$$

$$J_{\parallel} = \nabla^{-1} \nabla_{\perp} \cdot \mathbf{J}_{\perp}$$

- Perpendicular current

$$\mathbf{J}_{\perp} = \frac{c}{B} \mathbf{b} \times \nabla p + \frac{c m_i n_0}{B} \mathbf{b} \times \frac{d_0}{dt} \mathbf{V} + \frac{c}{B} \mathbf{b} \times \nabla \cdot \Pi$$

Diamagnetic current

Glasser-Green Johson

Inertia, polarization current

Neoclassical viscosity, enhanced polarization

Polarization Current Effects

- Polarization current

$$J_{\|} = \nabla^{-1}\nabla_{\perp} \cdot \mathrm{J}_{\perp} \qquad \mathrm{J}_{\perp} = \frac{c m_i n_0}{B} \mathrm{b} \times \frac{d_0}{dt} \mathrm{V}$$

- Rutherford equation

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle_c'}{4} + \sqrt{\epsilon} \frac{\beta_\theta}{S w} + g \frac{\beta_\theta}{w} \left(\frac{\rho_s}{w}\right)^2 \frac{\omega(\omega - \omega_{*i})}{\omega_{*e}^2}$$

Bootstrap current drive

Polarization current

Neoclassically Enhanced Polarization Current

Coupling of the transverse and longitudinal flows/Neoclassical flow damping

- Current closure equation

$$\nabla_{\parallel} J_{\parallel} + \nabla_{\perp} \cdot \left(\frac{c m_i n_0}{B} \mathrm{b} \times \frac{d_0}{dt} \mathrm{V} \right) + \nabla \cdot \left(\frac{c}{B} \mathrm{b} \times \nabla \cdot \Pi \right) = 0$$

$$\Pi_{\parallel} = \frac{3}{2} \pi_{\parallel} \left(\mathrm{bb} - \frac{1}{3} \mathrm{I} \right) \qquad \frac{3}{2} \pi_{\parallel} = p_{\perp} - p_{\parallel}$$

- Neoclassical current

$$\nabla \cdot \mathrm{J}_{nc} \equiv \nabla \cdot \left(\frac{c}{B^2} \mathrm{B} \times \nabla \cdot \Pi \right) = \frac{c}{B_\theta} \frac{\partial}{\partial x} \langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle$$

- Divergence of the transverse current is related to the component of the parallel force

$$m_i n_0 \frac{d}{dt} V_{\parallel} = -\nabla_{\parallel} p - \langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle_{\theta}$$

$$\nabla \cdot \mathrm{J}_{nc} = \frac{c}{B_\theta} m_i n_0 \frac{\partial}{\partial x} \frac{d_0}{dt} V_{\parallel} + \frac{c}{B_\theta} \frac{\partial}{\partial x} \nabla_{\parallel} p$$

Parallel ion dynamics effects

Enhanced inertia, replaces the standard polarization current

Neoclassical Flow Damping

- Neoclassical force

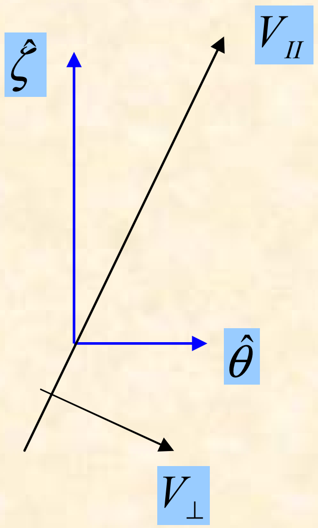
$$\langle \mathrm{b}\cdot\nabla\cdot\Pi\rangle = -\frac{3\,\varepsilon}{2\,q}\left\langle \pi_{\|}\frac{1}{r_s}\frac{\partial}{\partial\theta}\nabla_{\perp}\ln B\right\rangle = m_i n_0 \chi_\theta V_\theta$$

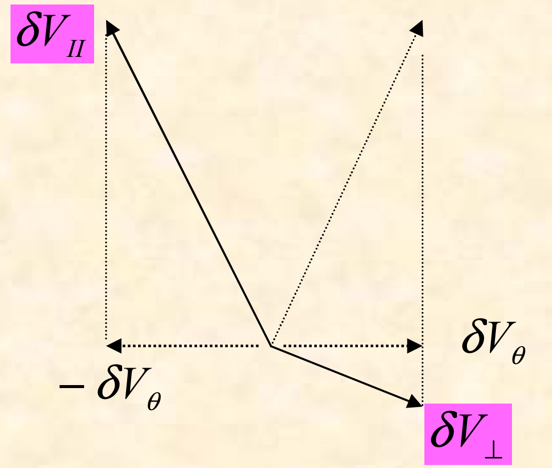
$$\chi_\theta = \frac{q^2}{\varepsilon^{1/2}}\left(\frac{d_0}{dt}+\frac{\nu_i}{\varepsilon}\right) \qquad V_\theta = V_y + \frac{\varepsilon}{q}V_{\|} \qquad V_y = \frac{c}{B_0}\frac{\partial\phi}{\partial x}$$

Resulting equation for the parallel flow velocity is

$$\frac{d_0}{dt}V_{\|} = -q\varepsilon^{1/2}\left(\frac{d_0}{dt}+\frac{\nu_i}{\varepsilon}\right)\left(V_y+\frac{\varepsilon}{q}V_{\|}\right) - \frac{1}{m_i n_0}\nabla_{\|}p$$

Neoclassical inertia enhancement





Neoclassical Flow Damping II

- Large collisional frequency: $\nu_i/\varepsilon \gg d_0/dt$

$$V_\parallel^{(0)} = -\frac{q}{\varepsilon} V_y$$

$$\frac{d_0}{dt} V_\parallel^{(0)} = -q\varepsilon^{1/2} \frac{d_0}{dt} V_y - \varepsilon^{1/2} \nu_i V_\parallel^{(1)} - \frac{1}{m_i n_0} \nabla_\parallel p$$

$$\langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle = q\varepsilon^{1/2} \frac{d_0}{dt} V_y + \varepsilon^{1/2} \nu_i V_\parallel^{(1)}$$

Neoclassical polarization

- Low collisional frequency: $\nu_i/\varepsilon \ll d_0/dt$

  Zero order

$$\frac{d_0}{dt} V_\parallel^{(0)} = -q\varepsilon^{1/2} \frac{d_0}{dt} V_y$$

$$V_\parallel^{(0)} = -q\varepsilon^{1/2} V_y$$

$$\langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle = q\varepsilon^{1/2} \frac{d_0}{dt} V_y + q \frac{\nu_i}{\varepsilon^{1/2}} V_y$$

Neoclassically Enhanced Polarization Current II

- Neoclassical current

$$\nabla \cdot \mathrm{J}_{nc} = \frac{c}{B_\theta} m_i n_0 \frac{\partial}{\partial x}\frac{d_0}{dt} V_\parallel + \frac{c}{B_\theta}\frac{\partial}{\partial x}\nabla_\parallel p$$

- From the radial momentum balance

$$V_\parallel \simeq V_\zeta = V_\theta \frac{B_\zeta}{B_\theta} + \frac{c}{e n_0 B_\theta} E_r - \frac{c}{B\theta}\frac{\partial p}{\partial r} \qquad V_\theta = k\frac{cT'}{eB}$$

- Extended Rutherford equation

$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle_c'}{4} + \sqrt{\epsilon}\frac{\beta_\theta}{S w} + g\frac{\beta_\theta}{w}\left(\frac{\rho_s}{w}\right)^2 \frac{\omega(\omega - \omega_{*i})}{\omega_{*e}^2} + g_{neo}\frac{\beta_\theta}{w}\left(\frac{\rho_s}{w}\right)^2 \frac{\omega(\omega - k\omega_{*i})}{\omega_{*e}^2} + ?$$

standard inertia

Neoclassically enhanced inertia

$$g_{neo} = \left\{ \begin{array}{lll} q^2/\epsilon^2 & \nu_i \gg \epsilon\omega & Smolyakov\ \ et\ \ al., PoP\ 2,\ 1581\ \ (1995) \\ q^2/\sqrt{\epsilon} & \nu_i \ll \epsilon\omega & Wilson\ \ et\ \ al.\ PoP\ 3,\ \ 248\ (1996) \end{array} \right\}$$

$g_{\ neo}$ depends on collisionality regime and may have further dependence on frequency, Mikhailovskii PPCF 2001

Neoclassically Enhanced Polarization Current

Coupling of the transverse and longitudinal flows/Neoclassical flow damping

- Current closure equation

$$\nabla_{\|} J_{\|} + \nabla_{\perp} \cdot \left(\frac{c m_i n_0}{B} \mathrm{b} \times \frac{d_0}{dt} \mathrm{V} \right) + \nabla \cdot \left(\frac{c}{B} \mathrm{b} \times \nabla \cdot \Pi \right) = 0$$

$$\Pi_{\|} = \frac{3}{2} \pi_{\|} \left(\mathrm{bb} - \frac{1}{3} \mathrm{I} \right) \qquad \frac{3}{2} \pi_{\|} = p_{\perp} - p_{\|}$$

- Neoclassical current

$$\nabla \cdot \mathrm{J}_{nc} \equiv \nabla \cdot \left(\frac{c}{B^2} \mathrm{B} \times \nabla \cdot \Pi \right) = \frac{c}{B_\theta} \frac{\partial}{\partial x} \langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle$$

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$$m_i n_0 \frac{d}{dt} V_{\|} = -\nabla_{\|} p - \langle \mathrm{b} \cdot \nabla \cdot \Pi \rangle_\theta$$

$$\nabla \cdot \mathrm{J}_{nc} = \frac{c}{B_\theta} m_i n_0 \frac{\partial}{\partial x} \frac{d_0}{dt} V_{\|} + \frac{c}{B_\theta} \frac{\partial}{\partial x} \nabla_{\|} p$$

Parallel ion dynamics effects

Enhanced inertia, replaces the standard polarization current

Finite Ion Orbits

- Cold ions case: $T_e \gg T_i$. Plasma pressure is $p \simeq T_e n_e$, and the electron density is determined from the quasineutrality condition $n_e = n_i$ so that $p = T_e n_i$. The ion density is not a function of magnetic flux surface due to the ion inertial drift off the surface

$$n_i = \frac{c^2}{v_A^2}\frac{1}{4\pi e}\nabla_\perp^2 \phi = n_0 \rho_s^2 \nabla_\perp^2 \frac{e\phi}{T_e}$$

$p = p(\psi) \to \nabla_{//} p = 0$

$\rho_i \to 0$

For finite ρ_i

$n \neq n(\psi)$

- Extended Rutherford equation

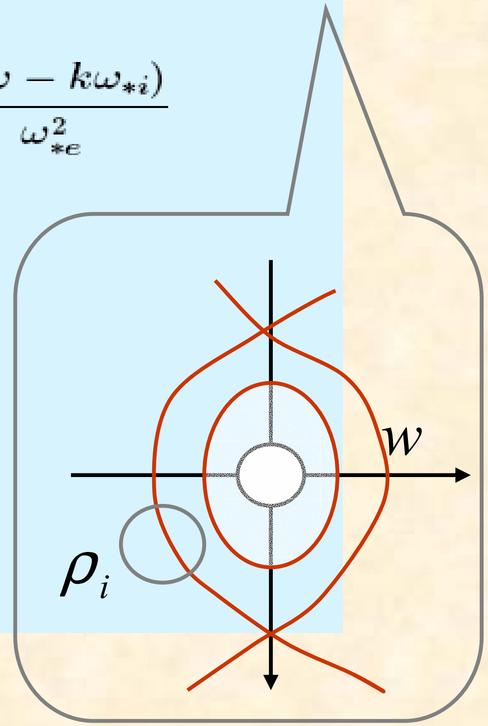
$$\tau_R \frac{\partial w}{\partial t} = \frac{\triangle_c'}{4} + \sqrt{\epsilon}\frac{\beta_\theta}{Sw} + g_1 \frac{\beta_\theta}{w}\left(\frac{\rho_s}{w}\right)^2 \frac{\omega(\omega - \omega_{*i})}{\omega_{*e}^2} + g_{neo}\frac{\beta_\theta}{w}\left(\frac{\rho_s}{w}\right)^2 \frac{\omega(\omega - k\omega_{*i})}{\omega_{*e}^2}$$

$$+ g_2 \frac{\beta_\theta}{w}\frac{\rho_s^2}{w^2}\frac{\omega}{\omega_*} \qquad g_{neo} = \begin{cases} q^2/\epsilon^2 & \nu_i \gg \epsilon\omega \\ q^2/\sqrt{\epsilon} & \nu_i \ll \epsilon\omega \end{cases}$$

- Finite banana width

$$n_b = n_0 \rho_s^2 \frac{q^2}{\epsilon}\sqrt{\epsilon}\nabla_\perp^2 \frac{e\phi}{T_e}$$

$$g_2 \sim 1 \to g_2 \sim \frac{q^2}{\sqrt{\epsilon}}$$



Finite orbit effect provides threshold of the same order as polarization current !

Effect of a Finite Heat Conductivity Along the Magnetic Field

- Finite parallel heat conductivity results in the variations of plasma pressure along the perturbed magnetic surface

$$p \neq p(\psi) \qquad \nabla_{\parallel} p \neq 0$$

$$w_c^4 = \frac{\chi_\perp}{\chi_\parallel}\frac{L_s^2}{k_\theta^2}$$

bootstrap drive is reduced,

Fitzpatrick PoP 2, 895 (1995)

Ware pinch contributes to stabilization

- Pressure gradient across the magnetic island is partially restored

$$\tau_R \frac{\partial w}{\partial t} = \frac{\Delta_c'}{4} + c_1\sqrt{\epsilon}\frac{\beta_\theta}{S}\frac{w}{w_c^2 + w^2} - c_2\frac{\beta_\theta}{Sw}\frac{(w/w_c)^2}{1+(w/w_c)^6}$$

- At the threshold Ware pinch term is comparable or larger than the standard bootstrap current (driving) term!

Ion Sound Effects

- Ion sound effects are known to stabilize drift-tearing modes in linear regimes *Bussac et al. PRL 40, 1500 (1978)*. There are indications that these are also stabilizing nonlinearly, however may be destabilizing for large ω_*, *M. Ottaviani, et al., PRL 93 (2004)*

- Basic equations

$$-enE_\parallel - T_e \nabla_\parallel n = 0.$$

$$\frac{d_0}{dt}\left(n_i - n_0\rho_s^2\nabla_\perp^2\frac{e\phi}{T_e}\right) + \nabla_\parallel\left(n_0 V_{\parallel i}\right) = 0 \qquad -\frac{c^2}{4\pi v_A^2}\frac{d_0}{dt}\nabla_\perp^2\phi + \nabla_\parallel J_\parallel = 0.$$

$$\frac{d_0}{dt}n_e + \nabla_\parallel\left(n_0 V_{\parallel e}\right) = 0$$

$$n_0 m_i \frac{d_0}{dt}V_\parallel = -T\nabla_\parallel n.$$

- Coupling of the Alfven and ion sound modes

$$\left(k_\parallel^2 v_A^2 - \omega^2\right)\left(1 - \frac{k_\parallel^2 v_s^2}{\omega^2}\right) + k_\parallel^2 v_A^2 k_\perp^2 \rho_s^2 = 0$$

Stabilizing ion sound, but ω_*

- Extended Rutherford equation taking into account the ion sound effects, *Smolyakov et al., PPCF, 46 (2004)*

$$\Delta' + \frac{g_1}{w^3}\frac{\omega^2 L_s^2}{k_\theta^2 v_A^2} - \frac{g_2}{w}\frac{c_s^2}{v_A^2} = 0$$

- Caveat: ω_* dependence has been omitted!

$$1 \sim \frac{k_{//}{}^2 c_s{}^2}{\omega^2} \qquad k_{//} = -k_\theta w / L_s$$

- Coupling of the Alfven and ion sound modes

$$\left(k_\parallel^2 v_A^2 - \omega^2\right)\left(1 - \frac{k_\parallel^2 v_s^2}{\omega^2}\right) + k_\parallel^2 v_A^2 k_\perp^2 \rho_s^2 = 0$$

Stabilization Mechanisms

- Ion polarization current (*Smolyakov, Sov J Pl Phys. 15, 667 (1989), PoP 2 1581 (1995); Wilson et al. 3, 248 (1996); Waelbroeck & Fitzpatrick PRL 78, 1703 (1997), Connor et al. PoP 8, 2835 (2001), Mikhailovskii &Co. 2000,...*

- Removal of pressure flattening due to finite $\chi_{\parallel}/\chi_{\perp}$, (*Fitzpatrick PoP 2, 825 (1995); Gorelenkov, Zakharov PoP 3, 3379 (1996)*)

- Other stabilizing neoclassical effects/ion sound effects?

Island Rotation Frequency

- Island rotation is determined by dissipation
  - minimum dissipation principle

Dissipation:

- Classical collisions: resistivity and heat conductivity
- Collisionless (Landau damping)
- Perpendicular diffusion density/energy: classical/anomalous
- Perpendicular anomalous viscosity
- Neoclassical flow damping/symmetry breaking

Classical dissipation: parallel resistivity and heat conductivity

$$\frac{\partial E}{\partial t} = -Q \equiv \int dx d\xi \left(\frac{1}{\sigma} J_{II} - \frac{1}{e} \nabla_{II} T \right) J_{II}$$

$$\left(\nabla_{II} T\right)^0 = 0 \qquad \left(\nabla_{II} T\right)^1 = \frac{1}{\chi_{II}} (\ldots)$$

$$Q \sim \left(\omega - \omega_{*e}\right)\left(\omega - \omega_{*i}\right)^2 \left(\omega - \omega_{*e}\left(1 - \eta_e / \eta_{cr}\right)\right)$$

Smolyakov, Sov J Pl Phys 1989

Connor et al; PoP, 2001

$$\eta_{cr} = \frac{1 + (1+\alpha)^2 \sigma T / e^2 \chi_{II}}{3(1+\alpha)\sigma T / 2e^2 \chi_{II}}$$

$$\eta_e = \partial \ln T_e / \partial \ln n$$

Classical dissipation: parallel resistivity and heat conductivity

$$\frac{\partial E}{\partial t} = -Q \equiv \int dx d\xi \left(\frac{1}{\sigma} J_{II} - \frac{1}{e} \nabla_{II} T \right) J_{II}$$

$$\int dx d\xi J^{c}{}_{II} \cos\xi = \Delta' \tilde{\psi}$$

$$\int dx d\xi J^{s}{}_{II} \sin\xi = \Delta_s' \tilde{\psi}$$

$$(\nabla_{II} T)^0 = 0 \qquad (\nabla_{II} T)^1 = \frac{1}{\chi_{II}} (\ldots)$$

Δ_s' is due to the coupling to external perturbations/wall; otherwise =0

$$Q \sim (\omega - \omega_{*e})(\omega - \omega_{*i})^2 (\omega - \omega_{*e}(1 - \eta_e / \eta_{cr}))$$

$$\omega = \omega_{*e}(1 - \eta_e / \eta_{cr})$$

Smolyakov, Sov J Pl Phys 1989

Connor et al; PoP, 2001

$$\eta_{cr} = \frac{1 + (1+\alpha)^2 \sigma T / e^2 \chi_{II}}{3(1+\alpha)\sigma T / 2e^2 \chi_{II}}$$

$$\eta_e = \partial \ln T_e / \partial \ln n$$

Collisional dissipation in toroidal plasma: mainly collisions at the passing/trapped boundary

$$\omega = \omega_{*e}\left(1+\eta_e/4\right)$$

$$\frac{\nu_e}{\varepsilon\omega} < 1$$

Weakly collisional regime, electron dissipation, Wilson et al, 1996

$$\omega = \omega_{*e}\left(1+0.3\eta_e\right)$$

$$\omega = \omega_{*i}$$

$$\frac{\nu_e}{\varepsilon\omega} < 1$$

Mikhailovski, Kuvshinov, PPR, 1998

$$\omega = \omega_{*e}\left(1+2.43\eta_e\right)$$

$$\omega = \omega_{*i}$$

$$\frac{\nu_e}{\varepsilon\omega} < \left(\frac{m_i}{m_e}\right)^{1/6}$$

Ion dissipation is important for larger collisionality

$$\omega = \omega_{*i}\left(1+0.389\eta_i\right)$$

$$\omega = \omega_{*i}$$

$$\frac{\nu_e}{\varepsilon\omega} > \left(\frac{m_i}{m_e}\right)^{1/6}$$

Neoclassical magnetic damping

Drift waves emission

Anomalous viscosity

Symmetry breaking, neoclassical losses in 3D

Summary

Variety of mechanisms affect the island stability:

neoclassical/bootstrap, polarization/inertial drifts, magnetic field curvature/plasma pressure, parallel heat conductivity, banana orbits, ion-sound effects, …

Each of these has to be carefully evaluated

Critical issues:

Island rotation frequency?

Nonlinear trigger/excitation mechanism

"Cooperative effects" of the error field and neoclassical/bootstrap drive?