Controlled Dynamics of Magnetic Islands in neo-viscous regime

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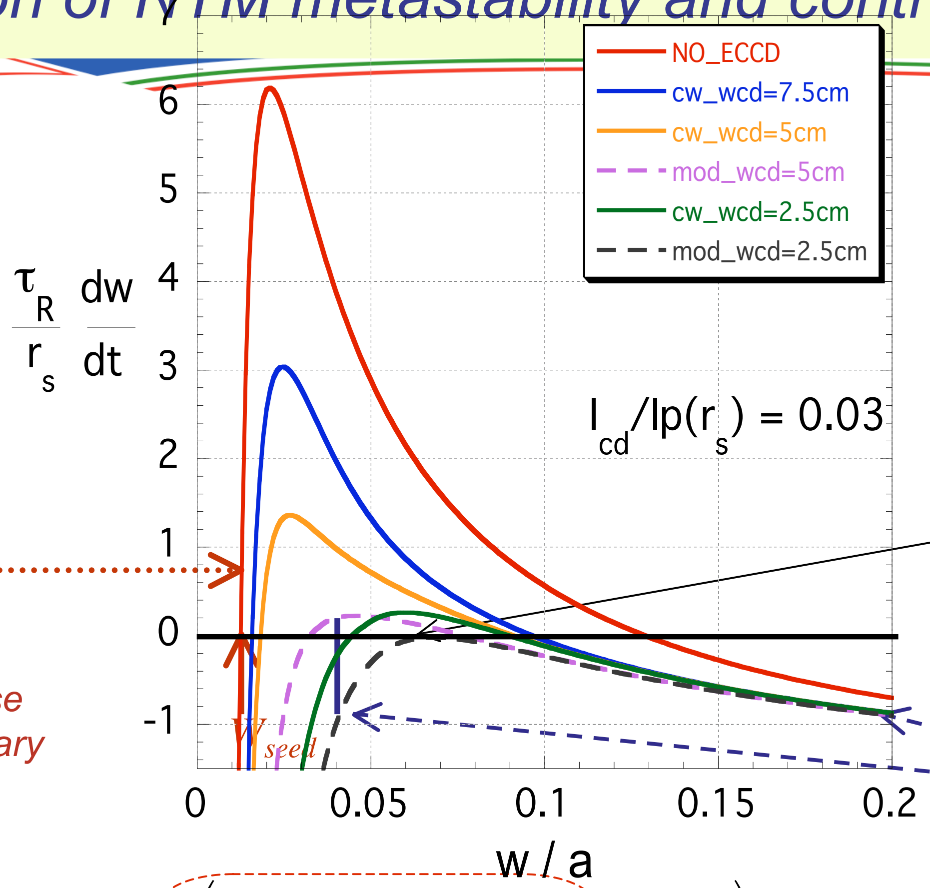
Outline

- NTM control issues: control of growing islands by ECCD
- Magnetic island break toroidal symmetry and cause a neoclassical toroidal viscosity (NTV)
- Island natural rotation determined by NTV
- Neoviscous (NTV) effect on ion polarization current stabilizing/ destabilizing mechanism
- Unavoidable viscous stress deformation of islands affects ECCD helical efficiency

Discussion of NTM metastability and control issues



β_{cr} NTM excitation

β_{mar} suppression

Hysteresis!

Early control of seed island:
less power

Frequency-phase tracking necessary

Squeezing a saturated island:
maximum RF power required

$$\frac{\tau_R}{r_s}\frac{dW}{dt} = r_s\Delta'_0 + \beta_p\left(\frac{\varepsilon^{1/2}}{s}\frac{r_s}{W_c}\frac{W/W_c}{1+\left(W/W_c\right)^2} - r_s\Delta'_{pol}\right) + r_s\Delta'_{EC}$$

Δ'_{boot}

$$\boxed{\Delta'_{EC} = \frac{8q\delta_{EC}}{\pi W^2}\,\eta\!\left(\frac{W}{\delta_{EC}}\right)\left(\frac{J_{EC}(t)}{J_{boot}}\right)}$$

$$\boxed{\Delta'_{pol} \approx g\,\frac{\varpi\left(\varpi-\omega_{*i}\right)}{\omega_{*e}^2}\left(\frac{L_s}{L_n}\right)^2\frac{\rho_{i\theta}^2}{W^3}}$$

RF power deposition on ***q=m/n*** *surface required*

Non axisymmetric viscous effects on NTMs

- Magnetic islands break axisymmetry and lead to toroidal viscosity, W dependent (NTV), $\left\langle \mathbf{B}_t \cdot \nabla \cdot \underline{\underline{\Pi}}_{//} \right\rangle \approx \mathrm{mnV}_\phi \dfrac{\partial \mathrm{B}}{\partial \phi}$ relevant in the ν and $1/\nu$ regimes [1-6]
- In turn this NTV viscous force contributes to determine the "natural" island frequency from the condition of vanishing torque [1,2]:

$$\frac{c}{4}\tilde{\psi}_s \Delta'_s = \int dx \int_{\xi_-}^{\xi_+} d\xi J_{//} \sin\xi = \left(\frac{L_s}{k_\theta \tilde{\psi}_s}\right) \int d\Psi^* \int_{\xi_-}^{\xi_+} d\xi \nabla_{//} J_{//} = 0$$

- Non axisymmetric viscous force (NTV), is relevant when comparable with perpendicular viscous force in the // momentum balance [7].
- It follows that *the range of regime parameter* $s=\omega_E/(\nu_i/\varepsilon^{0.5})$ *can be mapped onto a W range above a critical (bifurcation) width*

*[1] K.C.Shaing,PoP **12**,4728,(2003)*
*[2] Smolyakov, Lazzaro et al PPCF **43**, 1661, (2001)*
*[3] Sugama Nishimura, Phys.of Plasmas **9**,4637 (2002)*
*[4]Shaing, Hirshman, Callen PoF **29**,521,(1986),*
*[5]Smolyakov & Lazzaro PoP 1995,Lazzaro, Zanca PoP **10**,2399 (2003)*
*[6] Zhu, Sabbagh et al PRL **96** 225002 (2006), Cole et al PRL 2007*
*[7] Konovalov, Mikhailovski et al PPCF **44**, L51 (2002)*

Reminder of Neoclassical Parallel Force Balances

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Surface averaged parallel momentum and heat force balance

$$\left\langle \mathbf{B}\cdot\nabla\cdot\underline{\underline{\Pi}}_{\alpha}\right\rangle = \left\langle \mathbf{B}\cdot\mathbf{F}_{1,\alpha}\right\rangle + e_{\alpha}n_{\alpha}\left\langle \mathbf{B}\cdot\mathbf{E}\right\rangle \qquad (\alpha = e,i)$$

$$\left\langle \mathbf{B}\cdot\nabla\cdot\underline{\underline{\Theta}}_{\alpha}\right\rangle = \left\langle \mathbf{B}\cdot\mathbf{F}_{2,\alpha}\right\rangle$$

viscous *friction* *Ohmic*

$$\left\langle \mathbf{B}\cdot\nabla\cdot\underline{\underline{\Pi}}_{\alpha}\right\rangle = \left\langle B^2\right\rangle \underline{\underline{\mu}}_{1,j,\alpha}\cdot u_{\theta,j,\alpha}$$

$$\left\langle \mathbf{B}\cdot\nabla\cdot\underline{\underline{\Theta}}_{\alpha}\right\rangle = \left\langle B^2\right\rangle \underline{\underline{\mu}}_{2,j,\alpha}\cdot u_{\theta,j,\alpha}$$

viscous forces

$$u_{\theta 1,\alpha} \equiv \left\langle \mathbf{u}_{\alpha}\cdot\nabla\theta\right\rangle / \left\langle \mathbf{B}\cdot\nabla B\right\rangle$$

$$u_{\theta 2,\alpha} \equiv \frac{2}{5p_{\alpha}}\left\langle \mathbf{q}_{\alpha}\cdot\nabla\theta\right\rangle / \left\langle \mathbf{B}\cdot\nabla B\right\rangle$$

poloidal fluid & heat flows

Kinetic theory provides the viscosity and friction coefficients [3]

The radial force balance equation relates the flows within a surface to gradients of flux surface quantities (driving forces

$$\left\langle B^2\right\rangle u_{\theta 1,\alpha} = u_{//1,\alpha} + \left(\frac{2\pi R B_t}{\Psi'}\right)\left(\frac{p'_{\alpha}}{e_{\alpha}n_{\alpha}} + \Phi'\right)$$

$$\left\langle B^2\right\rangle u_{\theta 2\alpha} = u_{//12\alpha} + \left(\frac{2\pi R B_t}{\Psi'}\right)\left(\frac{T'_{\alpha}}{e_{\alpha}}\right)$$

θ *flows* $=$ // *flows* $+$ *thermodinamic forces* as

[3] Sugama Nishimura, PoP **9**,4637 (2002)

Determination of island frequency from condition of vanishing torque on island in NTV regime

[1,2]

$$\frac{c}{4}\tilde{\psi}_s\Delta'_s = \int dx \int_{\xi_-}^{\xi_+} d\xi J_{//}\sin\xi = \left(\frac{L_s}{k_\theta\tilde{\psi}_s}\right)\int d\Psi^* \int_{\xi_-}^{\xi_+} d\xi \nabla_{//}J_{//} = 0$$

$$\frac{c}{4}\tilde{\psi}_s\Delta'_{s,neo} \propto \begin{cases} Shaing: & \propto \int_{\tilde{\psi}_s}^{-\infty} d\Psi^* \int \frac{d\xi}{\sqrt{g}}\frac{\partial}{\partial\Psi^*}\left(\sqrt{g}\,p_\perp^{(\lambda)}\frac{B\times\nabla\xi\cdot\nabla\Psi^*}{B_0^2}\frac{\partial \ln B/B_0}{\partial\xi}\right) \qquad p_{//} << p_\perp \\ Lazzaro: & \propto \int_{\tilde{\psi}_s}^{-\infty} d\Psi^* \int d\xi \left(\frac{1}{\sqrt{g}}\frac{\partial}{\partial\Psi^*}[\sqrt{g}(p_{//}-p_\perp)^{(\lambda)}\frac{\mathbf{B}\times\nabla_\perp B\cdot\nabla\Psi^*}{B}]\right) \approx \int_{\tilde{\psi}_s}^{-\infty} d\Psi^* \int d\xi \left(\frac{1}{\sqrt{g}}\frac{\partial}{\partial\Psi^*}[\sqrt{g}(\mathbf{B}\cdot\nabla\cdot\underline{\underline{\Pi}})^{(\lambda)}\frac{\mathbf{B}\times\nabla_\perp B\cdot\nabla\Psi^*}{B}]\right) \end{cases}$$

$$\left(\frac{\partial}{\partial x}\left(\ln\frac{B}{B_0}\right) \approx \frac{W}{R_0} \equiv \varepsilon_W\right)$$

$$\Rightarrow \boxed{\left\{\mathbf{B}\cdot\nabla\cdot\underline{\underline{\Pi}}_{//}\right\}_{island}^{(\lambda)} = 0 \quad \Leftrightarrow \quad \mu_1^{(\lambda)}u_\theta + \mu_2^{(\lambda)}\frac{2q_\theta}{5p} = 0}$$

Equivalence to vanishing of neoclassical viscous force [3]

$considering \quad also \quad \langle \mathbf{B}\cdot\nabla\cdot\underline{\underline{\Theta}}\rangle = \langle BF_{2a}\rangle \quad u_\theta \quad is \quad determined$

$$u_{\theta,a}^{(\lambda)} \cong -\frac{\mu_{2a}^{(\lambda)}(l_{22}^{a,(\lambda)}/n_a m_a)}{\left|\mu_{1a}^{(\lambda)}\mu_{3a}^{(\lambda)} - \left(\mu_{2a}^{(\lambda)}\right)^2\right|^{0.5} + \mu_{2a}^{(\lambda)}(l_{22}^{a,(\lambda)}/n_a m_a)}\frac{\omega_{*Ta}R}{B} \equiv \frac{\langle Bu_{//}\rangle}{\langle B^2\rangle} + \frac{R}{B}\left[\frac{c\Phi'}{B} + \frac{cp'_a}{eZm_{ai}B}\right]$$

$(\mu_{i,a}^{(\lambda)} \quad and \quad l_{ij}^{a,(\lambda)} \quad coefficients\ from \quad kin. \quad theory \quad in \quad NTV \quad reg.;a = e,i)$

NTV coefficients depend on W and collisional regime (λ) [1]

$in \quad plasma \quad frame \quad u_{//} = 0$

$$\boxed{\varpi \equiv \omega - \omega_E = -\omega_{pa} - \frac{\mu_{2a}^{(\lambda)}(l_{22}^{a,(\lambda)}/n_a m_a)}{\left|\mu_{1a}^{(\lambda)}\mu_{3a}^{(\lambda)} - \left(\mu_{2a}^{(\lambda)}\right)^2\right|^{0.5} + \mu_{2a}^{(\lambda)}(l_{22}^{a,(\lambda)}/n_a m_a)}\omega_{*Ta}}$$

to be compared with Shaing's [1]

The electric field for a rotating island is a function of island frequency

*[1] K.C.Shaing,PoP **12**,4728,(2003)*
*[2] Smolyakov, Lazzaro et al PPCF **43**, 1661, (2001)*
*[3] Fitzpatrick, Waelbroeck,PoP **12** 082510 (2005)*

Neoclassical enhancement of polarization effects

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The MHD quasi neutrality constraint includes neoclassical contributions

$$\nabla \cdot \mathbf{J} = 0 \quad \Leftrightarrow \nabla_{//} \mathrm{J}_{//} = \mathrm{J}_{//} \frac{\nabla \mathrm{B}}{\mathrm{B}} - \nabla \cdot \mathbf{J}_{\perp}$$

$$\nabla \cdot \mathbf{J}_{\perp} \cong \nabla \cdot \left(\frac{\mathbf{B}}{\mathrm{B}^2} \times \left(\rho_{\mathrm{m}} \frac{\mathrm{d}\mathbf{v}}{\mathrm{dt}} + \nabla \cdot \underline{\underline{\Pi}} \right) \right) = \nabla \cdot \mathbf{J}_{\mathrm{pol}} + \nabla \cdot \mathbf{J}_{\mathrm{neo}}$$

Also the neoclassical contribution has the nature of a polarization current [7]

$$\boxed{\nabla \cdot \left(\frac{c}{enB^2} \mathbf{B} \times \nabla \cdot \underline{\underline{\Pi}} \right) \cong -\frac{c}{B_\theta} \frac{\partial}{\partial r} \left(\mathbf{b} \cdot \nabla \cdot \underline{\underline{\Pi}} \right) = \frac{c\rho_m}{B_\theta} \mathbf{b} \cdot \left(\frac{d\mathbf{v}}{dt} \right)}$$

The (Rutherford type) island evolution equation gains another term

$$g \frac{\tau_R}{r_s^2} \frac{dw}{dt} = \ldots - \frac{D_{neo}(\omega)}{w^3}$$

NTV (non axisymmetric) effects vary nonlinearly the frequency and therefore D_{neo} in different collisional regimes

NTV effects on island stability

- *Conjecture on NTV effect on ion polarization current (ipc):*
- *As island evolves W dependent NTV tends to adjust natural frequency (in absence of ext. torque) to preserve the zero torque condition and asymptotically cancel the polarization effect*
- ***Interpretation:*** $$\frac{c}{4}\tilde{\psi}_s \Delta'_{pol} = \int dx \int_{\xi_-}^{\xi_+} d\xi J_{//} \cos\xi$$
-
- depends on an integral over the island width of the **ipc** which is also related to the // neoclassical viscous force [8,9]
- $$J_{//}^{nc} - \left\langle J_{//}^{nc} \right\rangle = \int \frac{dl}{B} \nabla \cdot \left(\frac{c}{B} \mathbf{b} \times \nabla \cdot \underline{\underline{\Pi}} \right) = -\int \frac{dl}{B} \frac{c}{B_\theta} \frac{\partial}{\partial r} \left(\mathbf{b} \cdot \nabla \cdot \underline{\underline{\Pi}} \right)$$
-
- Shaing's formula of island frequency is applied to investigate [1] a possible asymptotic "healing" of polarization effects
- An alternative derivation (slightly different from [1]) shows the logical link

*[1] K.C.Shaing,PoP **12**,4728,(2003)*
*[8] Smolyakov & Lazzaro PoP **11**,4353 (2004)*
[9]Hegna MHD Control Workshop,PPPL, Nov. 22, 2004

Island width and NTV viscosity

Extending the arguments of Konovalov et al PPCF **44**, L51 (2002)

$$\boxed{0 \approx \mu_{\perp i}\frac{\partial^2 V_{//i}}{\partial x^2} + \mu_t\left(V_{//i} - V_{//i0}\right)}$$

Steady state mom. balance Konovalov et al

$$\mu_{\perp i} \approx \chi_{\perp i} \approx \frac{\rho_i^2}{\omega_{ti}}; \qquad \mu_t \approx \frac{q^2\omega_{ti}}{\nu_{*i}}\frac{1}{1+\left(\frac{\omega_E}{\nu_i/\varepsilon}\right)^2}\left(\frac{W}{r_s}\right)^2$$

Shaing-Callen interp. tor. Viscosity [10]

$$\boxed{\Rightarrow \frac{\rho_i^2}{W^2} \leftrightarrow \frac{q^2}{\nu_{*i}}\frac{1}{1+\left(\frac{\omega_E}{\nu_i/\varepsilon}\right)^2}\left(\frac{W}{r_s}\right)^2}$$

Condition for NTV relevance

$$W_\rho^2 = \left(\frac{s_E\rho_i r_s}{q}\right), \quad s_E = \frac{\omega_E}{\sqrt{\varepsilon}\omega_{ti}}, \quad s = \frac{s_E}{\nu_{*i}}$$

Mapping of collisionality onto W range

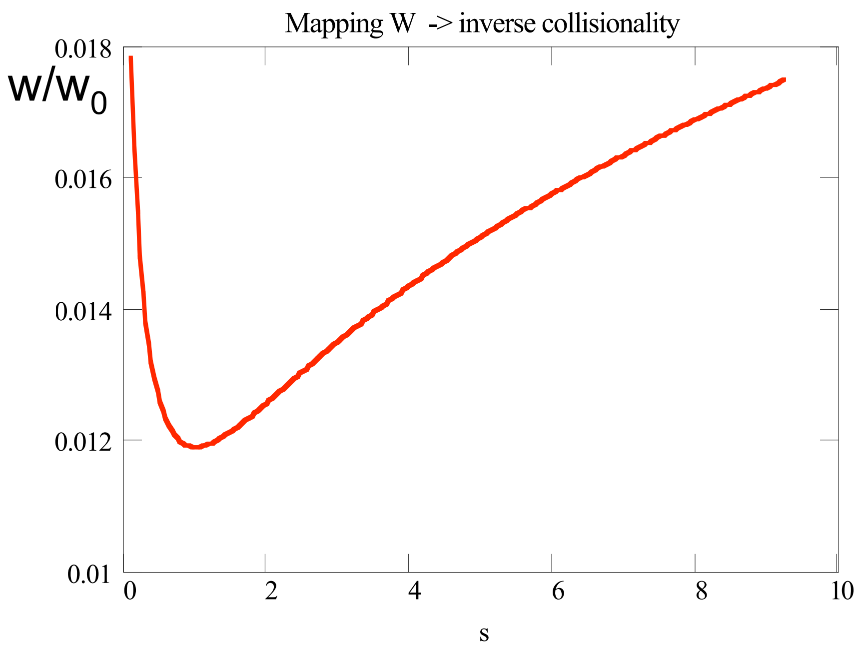
$$\left(\frac{W}{W_\rho}\right)^4 = \nu_{*i}\left(1+\left(\frac{\omega_E}{\nu_i/\varepsilon}\right)^2\right) = s_E\left(\frac{s_E}{\nu_{*i}} + \frac{\nu_{*i}}{s_E}\right) = s_E\left(s+\frac{1}{s}\right) \rightarrow \begin{cases} s_E s = \left(s_E\right)^2/\nu_{*i} & s>1 \quad (\nu\ regime) \\ s_E/s = \nu_{*i} & s<1<1/\nu_{*i} \quad (1/\nu\ regime) \end{cases}$$

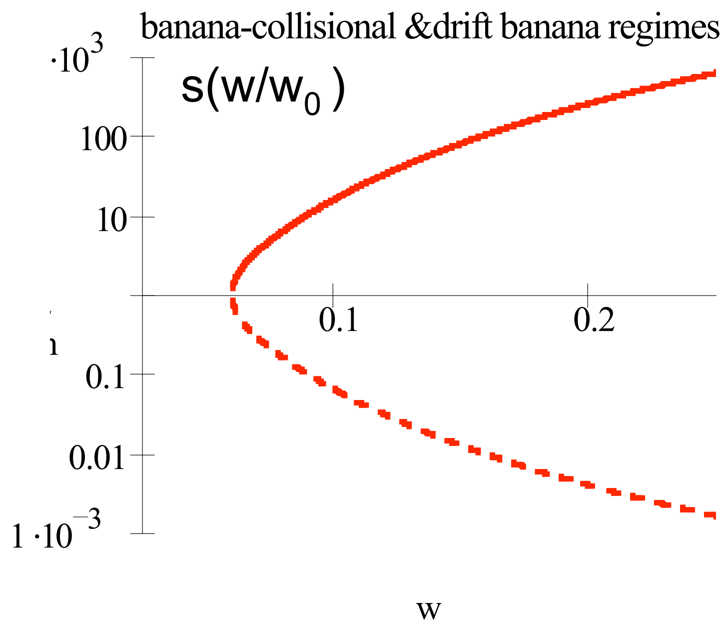
Far into the collisionless or collisional regimes we **get a mapping of the regime parameter** $s = \frac{\omega_E}{\nu_i/\varepsilon}$ **onto W⁴**,

[10] Callen IMM meeting, Atlanta 19/3/2003

Mapping of collisionality onto W range:

- As island evolves the NTV changes and a certain range of collisionality is spanned
- Island rotation is modified to maintain the "zero torque" condition
- The mapping of the ν and 1/ν regimes onto w is a (fold) bifurcation





$w_0 \sim w_{threshold} << w_{sat}$!!

$w_{NTV}=2^{0.25}\, w_0$

Test of NTV effect on ion polarization current: ν and 1/ν collisionality regimes

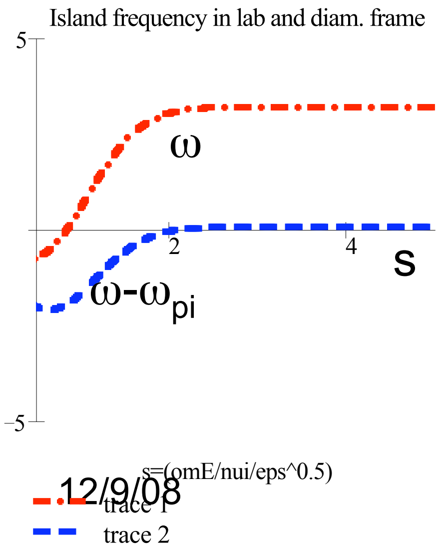
Shaing's NTV island frequency expression in varying collisional regimes

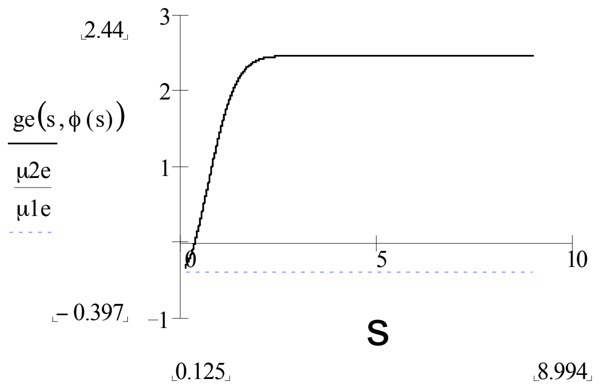
$$\varpi = -\left(\omega_{*pi} + g^{(i)}\omega_{*Ti}\right)\frac{(1+s^2)}{1+\left(\dfrac{\omega_{*pi} + g^{(i)}\omega_{*Ti}}{\omega_{*pe} + g^{(e)}\omega_{*Te}}\right)s^2}$$

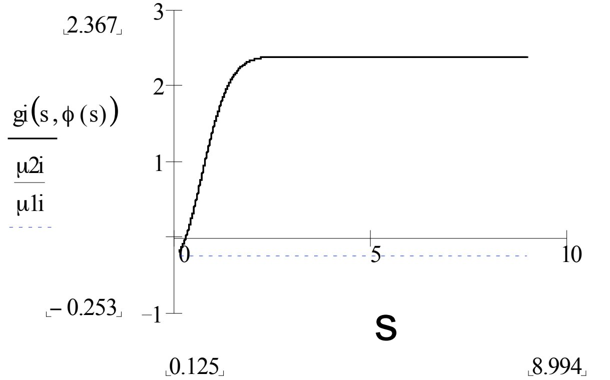
$$\begin{cases} s \ll 1 & 1/\nu \quad regime \\ s \gg 1 & \nu \ regime \end{cases}$$

$$g^{(\alpha)} = \left(\frac{\mu_{2\alpha}}{\mu_{1\alpha}}\right)\left(s^2\left(\frac{\varpi}{\omega_E}\right)^2 + \left(\frac{\mu_{1\alpha}}{\lambda_{1\alpha}}\right)G\right)\left(s^2\left(\frac{\varpi}{\omega_E}\right)^2 + \left(\frac{\mu_{2\alpha}}{\lambda_{2\alpha}}\right)G\right)^{-1} \qquad G \propto (W/r_s)^2$$

Dependence of island frequency on regime parameter $s = \omega_E/(\nu_i/\varepsilon^{1.5})$



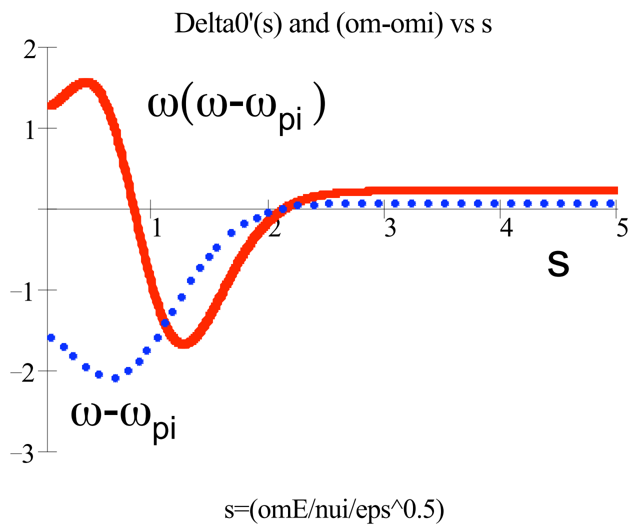


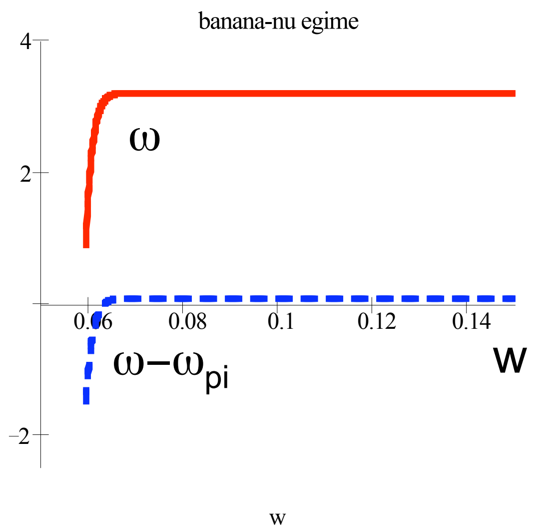


NTV effect on ion polarization current

Dependence of ion polar. term on collisional regime with Shaing's frequency formula

$$\Delta'_{pol} \propto \frac{a_3}{W^3}\frac{\varpi\left(\varpi - \omega_{*pi}\right)}{\omega_{*e}^2}$$

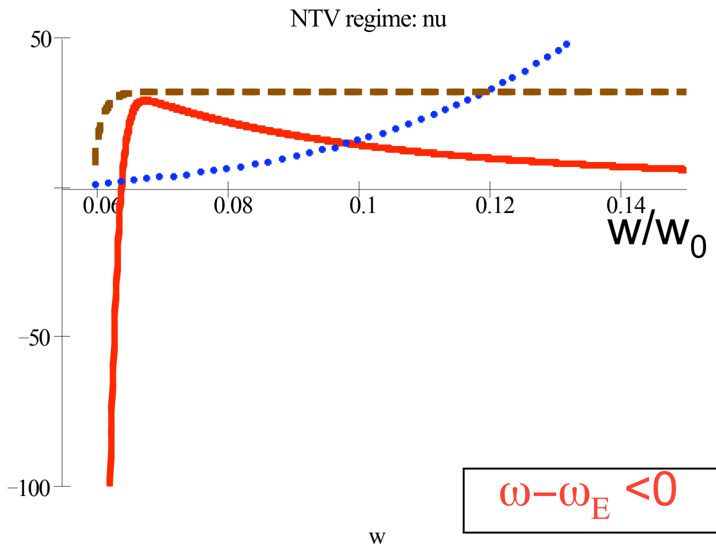




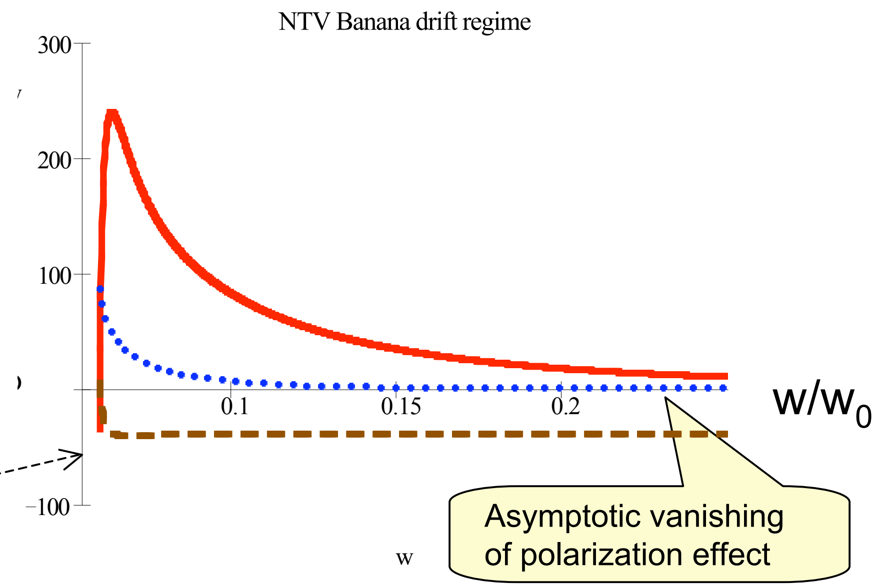
Ion polarization term can apparently switch from stabilizing to destabilizing

Test of NTV effect on ion polarization current

In ν regime the ion polarization term is stabilizing just for $w < w_{NTV}$, but may trigger the mode onset, as frequency settles to NTV zero torque condition



$\omega-\omega_E < 0$



Ion polarization term seems always destabilizing in $1/\nu$ regime !!
Eventually polarization effect vanishes, as $\omega-\omega_E \sim\omega_{*pi}$

The present conclusion however depends on the plasma test parameters chosen

Control of island dynamics by ECCD even more necessary!

Other consequences of a significant viscosity (NTV) for control by ECCD

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- *A consequence of a sheared viscous stress is deformation of magnetic islands in helical phase and amplitude*
- *Effects on the dynamics of NTM are described by an extended Rutherford model*
- *Island deformation affects the control strategy by ECCD varying the helical non-inductive current efficiency*

Island deformation by sheared viscous stress/1

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NO sheared viscous stress

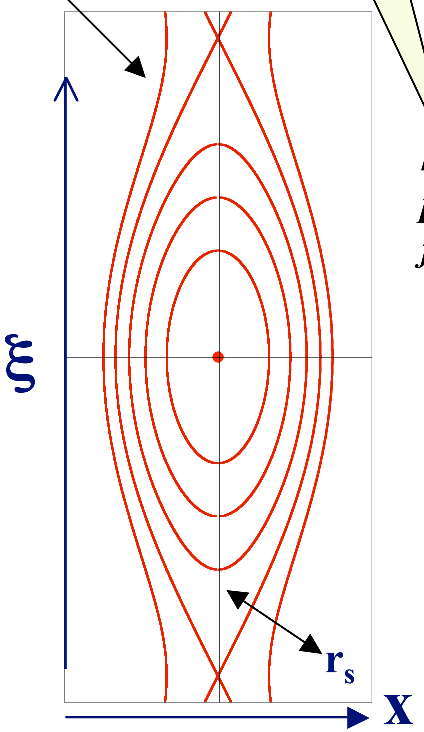
Helically Symmetric island

with sheared iscous stress

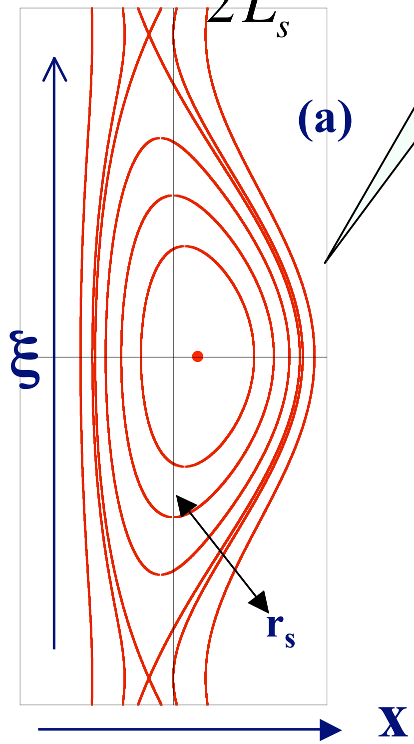
***A sheared flow trough Viscous Force* introduces:**
(a) amplitude correction, (b) sheared phase

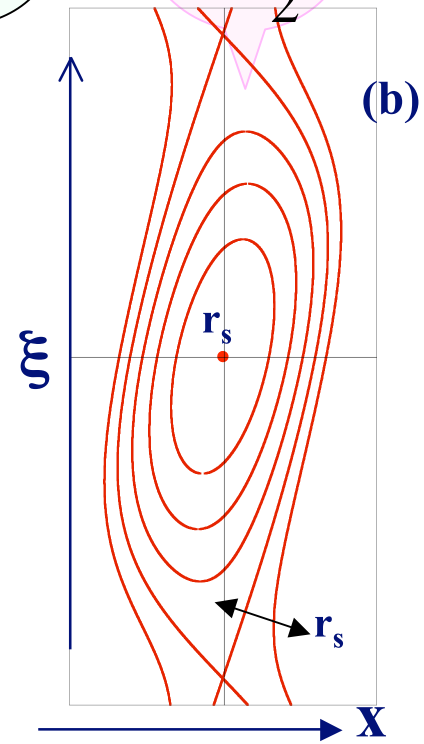
$$\Psi = -x^2 \frac{B_\phi}{2L_s} + \tilde{\psi}_s \cos\xi$$

helical perturbed flux



$$\Psi = -x^2 \frac{B_\phi}{2L_s} + \tilde{\psi}_s \left(1 + \frac{\Delta'_c}{2} x\right) \cos\left(\xi - \frac{\Delta'_s}{2} x\right)$$





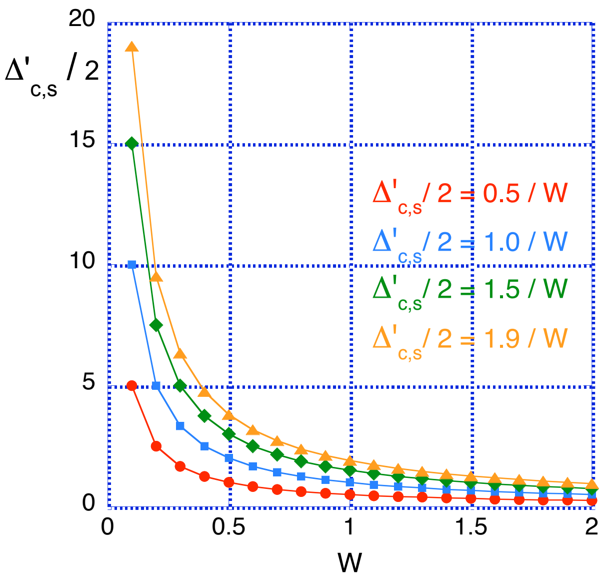
Island deformation by sheared viscous stress

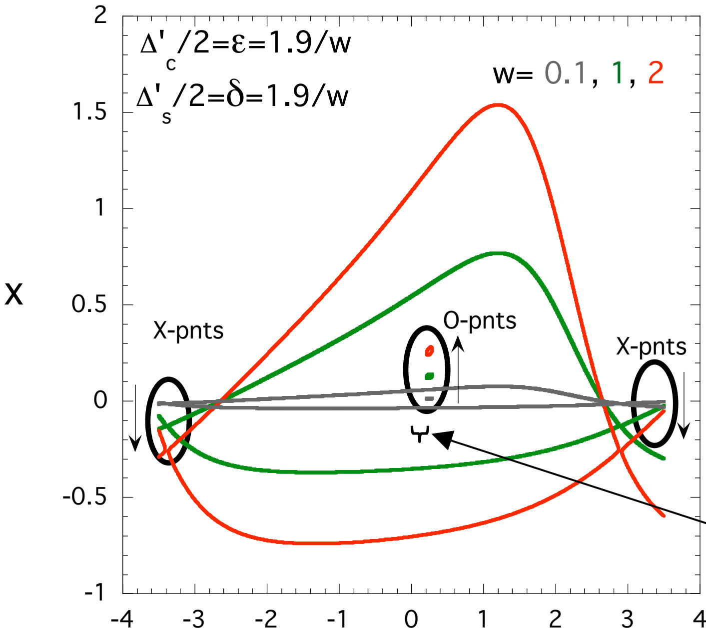
Deformed Magnetic Island Geometry

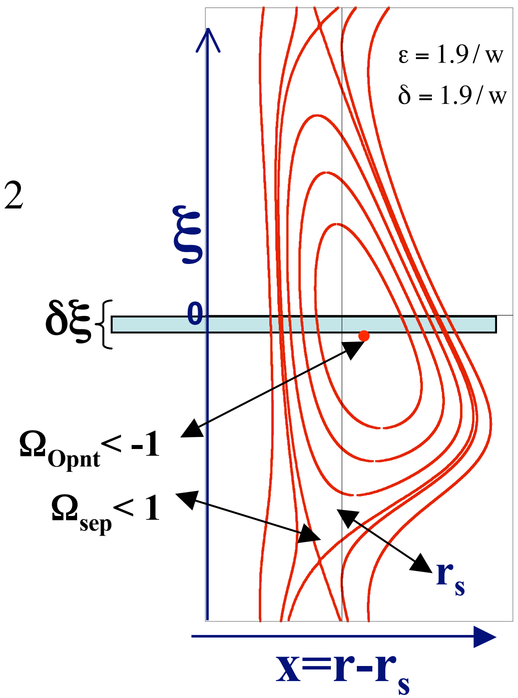
$$-\frac{\Psi(x,\xi)}{\tilde{\psi}_s} = \Omega(x,\xi) = 8\frac{x^2}{W^2} - \big(1+\underbrace{\varepsilon x}_{<1}\big)\cos\big(\xi - \underbrace{\delta x}_{<1}\big)$$

$$W = 4\sqrt{L_s \tilde{\psi}_s / B_\phi}$$

$$\varepsilon = \Delta'_c / 2, \ \delta = \Delta'_s / 2$$







$x_{opnt} \approx \varepsilon\, w^2/16$

dephasing $= \delta\xi \approx \delta x_{opnt}$

$\delta\xi \approx 12°$

Island deformation by sheared viscous stress /3

In summary:

- **Two free parameters $\varepsilon=\Delta'_c/2<1$ and $\delta=\Delta'_s/2<1$ characterize the island deformation**

- **The island contours (neglecting terms $\propto x^3$) in the (x,ξ) plane are given by:**

$$\boxed{x_{\pm}(\Omega,\xi)=\frac{W}{4Q}\left[S\pm R\right]}$$

with $P=\varepsilon W/4<1, D=\delta W/4<1$ and

$$\begin{cases} Q=1+D^2\cos\xi-2PD\sin\xi \\ R=\sqrt{\left[P\cos\xi+D\sin\xi\right]^2+2Q\left[\Omega+\cos\xi\right]} \\ S=\left[P\cos\xi+D\sin\xi\right] \end{cases}$$

- **The separatrices Ω_{sep} (last closed surfaces) and the X-point location are expressed by :**

$$\boxed{\Omega_{sep\varepsilon}=1-P^2/2\le 1 \quad \text{and} \quad x_{sep\varepsilon}=-PW/4} \Rightarrow \quad \varepsilon\neq 0,\ \delta=0$$

$$\boxed{\Omega_{sep}<\Omega_{sep\varepsilon} \quad \text{and} \quad x_{sep}<x_{sep\varepsilon}} \quad \Rightarrow \quad \varepsilon\neq 0,\ \delta\neq 0$$

Extended Rutherford model for deformed islands / 1

- ***Geometric deformation is included in the 2 integral operators*** entering the calculation of the nonlinear evolution of the reconnected flux $\partial\tilde{\psi}_s/\partial t$

- ***Angular averaging operator***

$$<f>=\frac{\oint d\xi\, f/\partial\Omega/\partial x/2\pi}{\oint d\xi/\partial\Omega/\partial x/2\pi}$$

- ***Spatial averaging operator across the island***

$$[\ldots]=r_s\int_{-\infty}^{+\infty}dx\oint d\xi = r_s\frac{W}{4}\int_{-1}^{\infty}d\Omega\int_{-\xi_\Omega}^{+\xi_\Omega}d\xi\,\frac{(\ldots)}{\partial\Omega/\partial x}$$

$$\partial\Omega/\partial x=\pm\frac{4}{W}\sqrt{[P\cos\xi+D\sin\xi]^2+2Q[\Omega+\cos\xi]}=\pm\frac{4}{W}R$$

⇒ island asymmetry modifies growth time scale

$$r_s\frac{W}{4}\frac{\partial\psi_s}{\partial t}\underbrace{\left[\int_{-1}^{\infty}d\Omega\int_{-\xi_\Omega}^{+\xi_\Omega}d\xi\,\frac{<(1+0.5\Delta'_c x)\cos(\xi-0.5\Delta'_s x)>\cos\xi}{2\pi\quad\partial\Omega/\partial x}\right]}$$

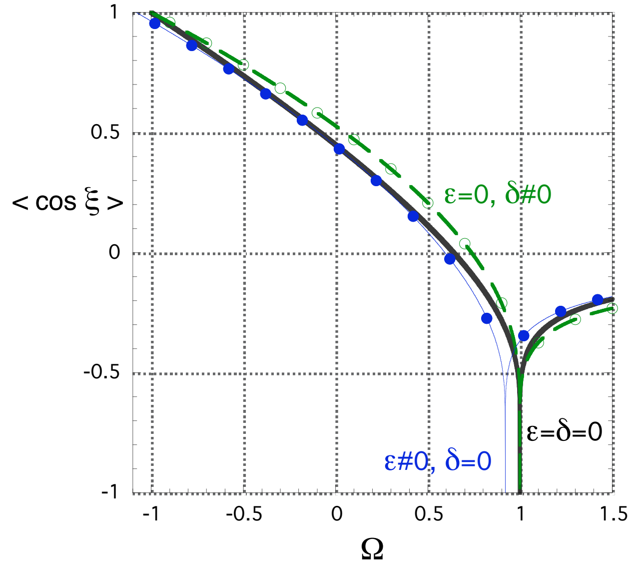
$= g_1(\Delta'_c,\Delta'_s)$ inertial coefficient

Extended Rutherford model for deformed islands / 2

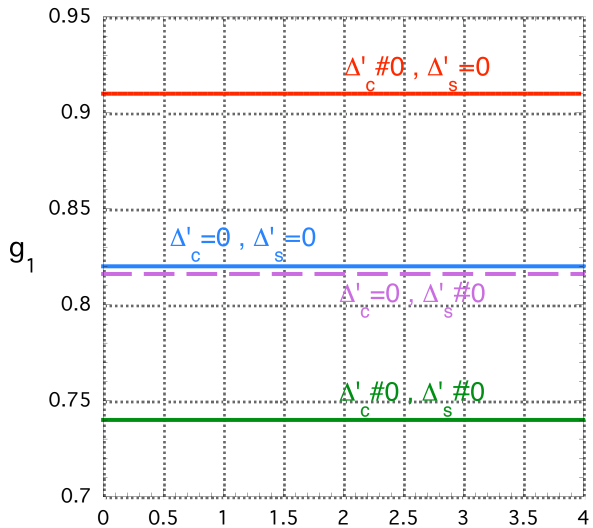
EFFECTS of $\partial\Omega/\partial x$ on the $<\cos\xi>$:

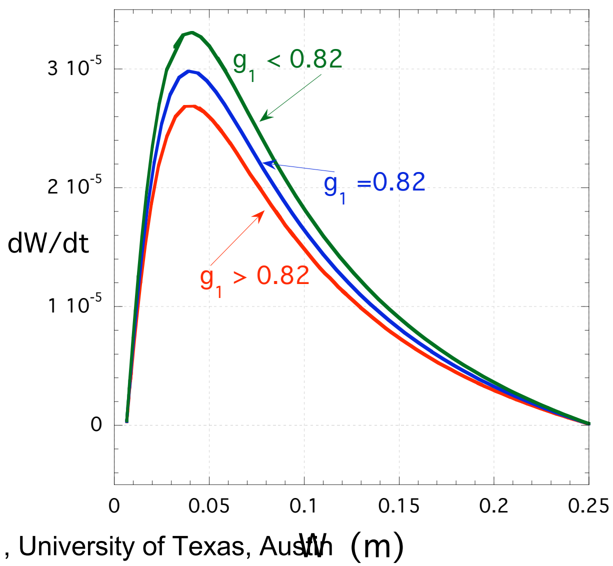
weak dependence on P & D $\Rightarrow$

neglected in most cases



EFFECTS on the time scale coefficient:





Extended Rutherford model for deformed islands / 3

A ***new generalization of Rutherford*** equation for NTMs evolution is proposed ***including new inertial coefficient g_1 and the noninductive term Δ'_{EC}*** associated to electron cyclotron waves external heat source ***as function of*** (Δ'_c, Δ'_s) :

$$\boxed{g_1(\Delta'_c, \Delta'_s)} \frac{\tau_R}{r_s} \frac{dW}{dt} =$$

$$r_s \Delta'_0 + \beta_p r_s \left(\Delta'_{BS} - \Delta'_{GGJ} - \Delta'_{pol} \right) - r_s \Delta'_w - \boxed{r_s \Delta'_{EC} \eta_{hel}(\Delta'_c, \Delta'_s)}$$

We concentrate our attention on Δ'_{EC} **testing its sensitivity to the island deformation**

We consider a well focussed EC beam depositing power and driving current in a plasma volume defined by the radial depth of power absorption and by a toroidal and poloidal window $\Pi(\xi, \xi_0, \Delta\xi)$ ***with*** *$\Delta\xi = 2\pi$* ***(=> CW injection):*** *dephasing in ξ and misalignment in x can occur*

Extended Rutherford model for deformed islands / 4

- *The function* η_{hel} (Δ'_c, Δ'_s) gives the *helical efficiency of the current drive*

$$\eta_{hel}\left(W/\delta_{CD},\Delta'_c,\Delta'_s\right)=\frac{\int_{-1}^{\infty} d\Omega \int_{-\xi_\Omega}^{+\xi_\Omega} d\xi \frac{<J_{CD}>}{\partial\Omega/\partial x}\cos\xi}{\int_{-1}^{\infty} d\Omega \int d\xi \frac{<J_{CD}>}{\partial\Omega/\partial x}} \quad ; \quad <J_{CD}>=\frac{\int_{-\xi_\Omega}^{+\xi_\Omega} d\xi \frac{J_{CD}}{2\pi\,\partial\Omega/\partial x}}{\int_{-\xi_\Omega}^{+\xi_\Omega} \frac{d\xi}{2\pi\,\partial\Omega/\partial x}} \quad ;$$

$$J_{CD} = J_0 \exp(-((x(\Omega,\xi)-x_0)/\delta_{CD})^2)\Pi(\xi,\xi_0,\Delta\xi)$$

- *Non-inductive EC current* parallel to field lines replacing the reduced bootstrap *can control the island growth*
- ***Inspection of the optimal efficiency*** η_{hel} *, comparing symm. and asymmetric islands, can lead to alternative response for the control strategy*

Helical efficiency of deformed islands with SPATIAL misalignment

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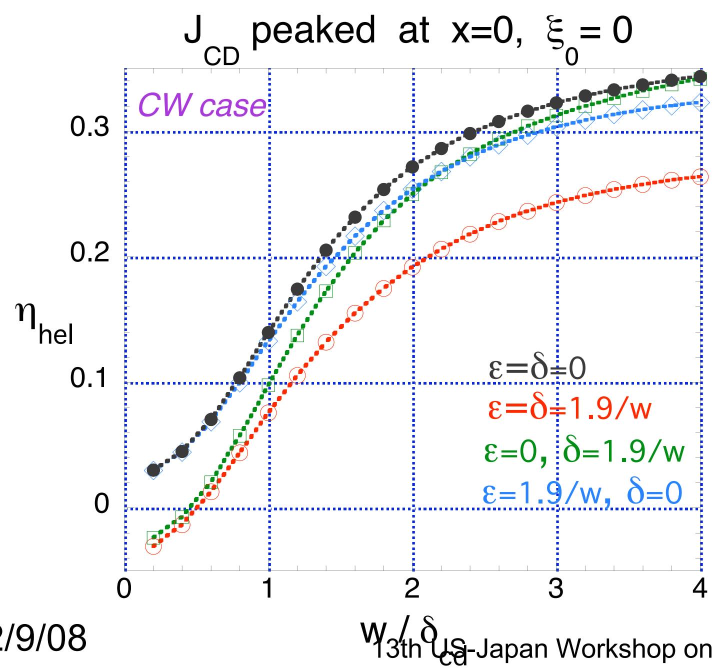
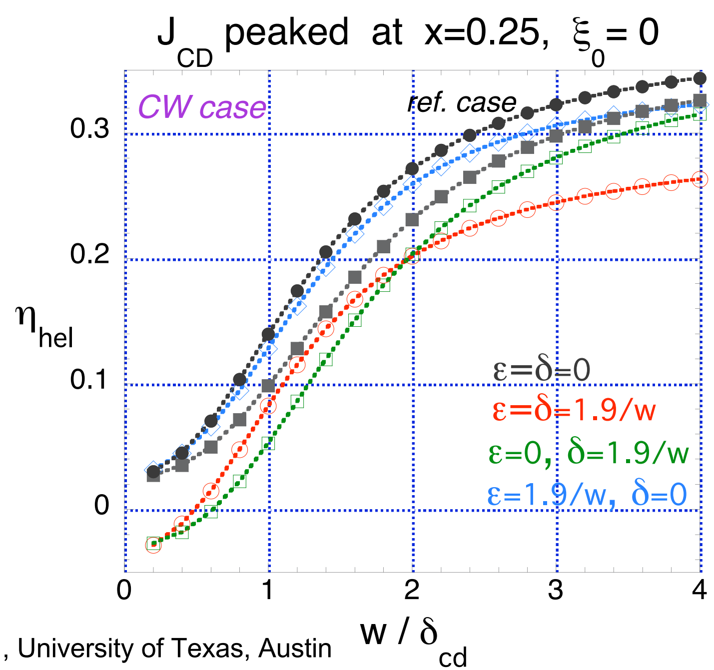
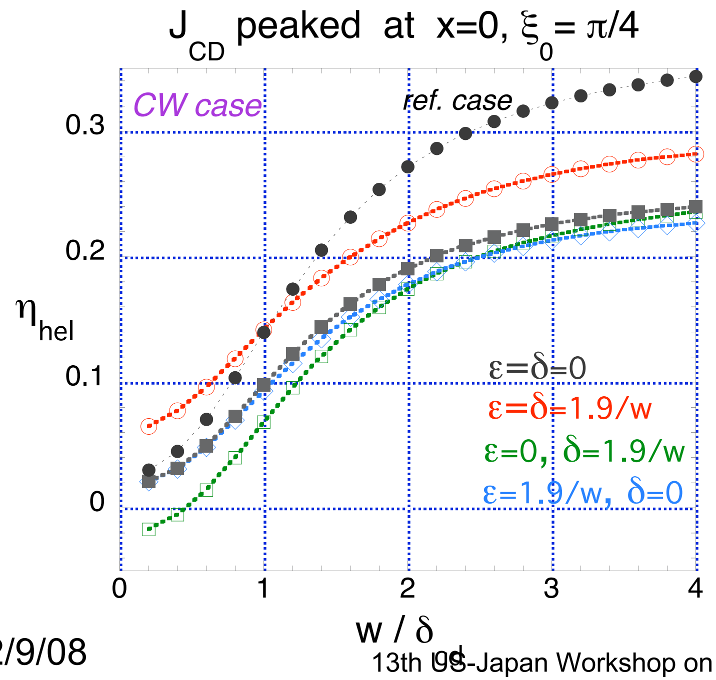
- ***Maximum*** *(and similar) η_{hel} is found for deposition centered on/around the O-point of both symm. and asymm. ($\varepsilon \neq 0$, $\delta=0$) islands with ECCD inside the range $0<W<\delta_{CD}/2$.*
  The efficiency is reduced up to 70% for dephased islands ($\varepsilon=0$ and $\delta \neq 0$, $\varepsilon \neq 0$ and $\delta\neq0$) and can be slightly negative for $W<<\delta_{CD}$ leading to destabilizing conditions.

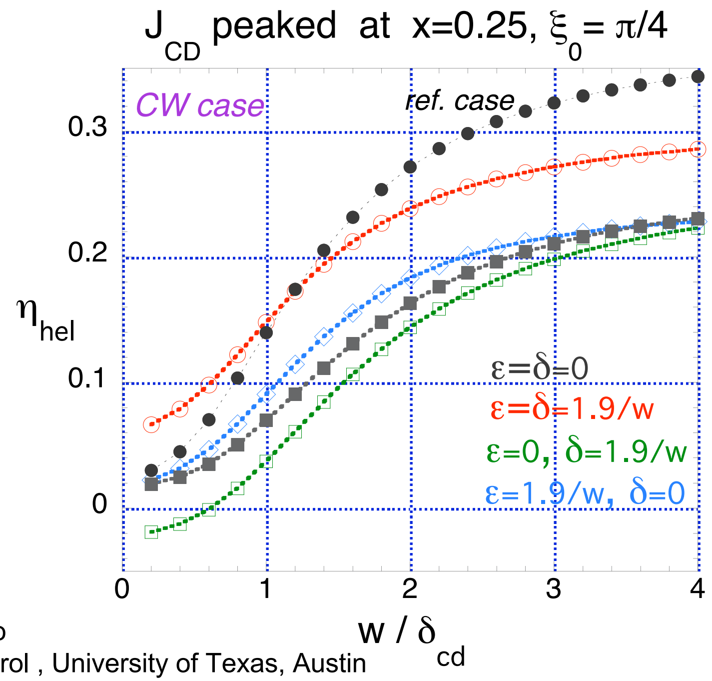




Helical efficiency of deformed islands with PHASE misalignment

- *A phase shift of $\xi_0=\pi/4$ associates the **best efficiency** (maximum at $W<\delta_{CD}$) to islands deformed in amplitude and phase ($\varepsilon\neq0,\delta\neq0$) with deposition at their O-point. The difference of efficiency between these islands and the symmetric one can reach 70%.*
- *The phase shift only ($\varepsilon=0, \delta\neq0$) can lead again to **destabilization.***





NTM stability study in the phase space / 1
- with SPATIAL misalignment -

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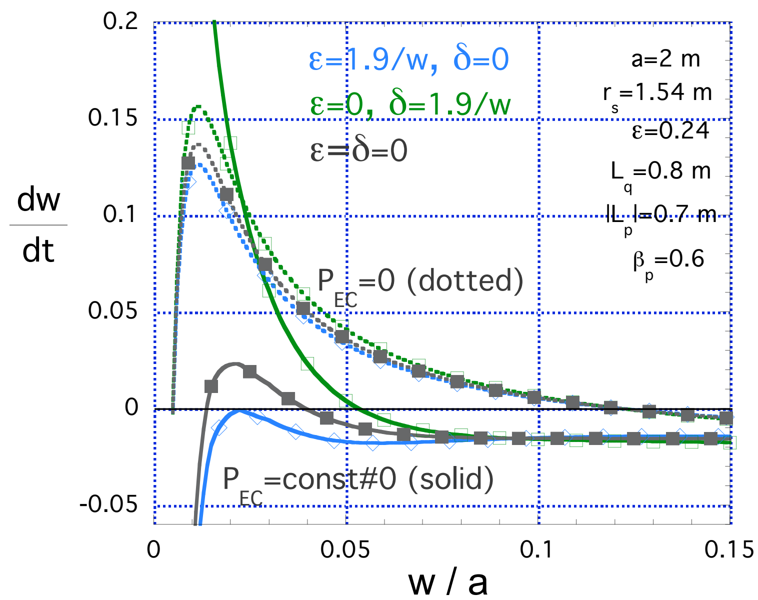
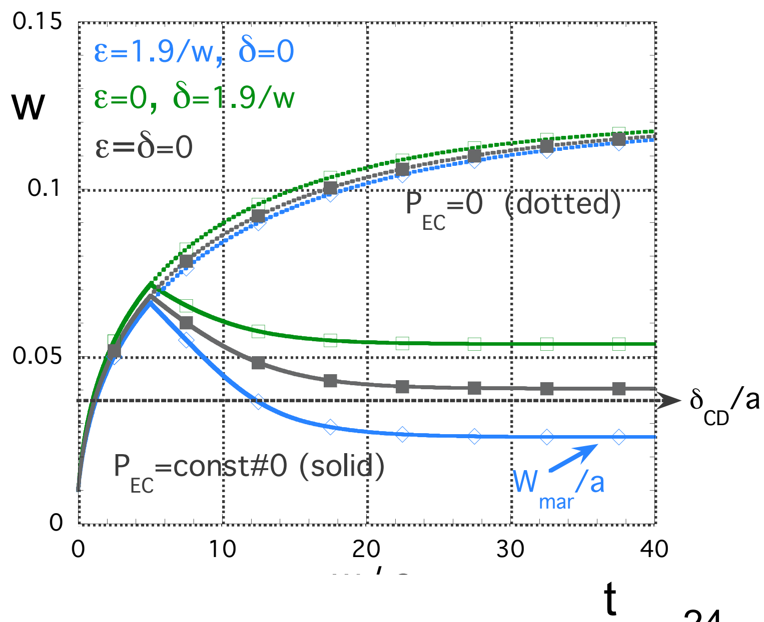
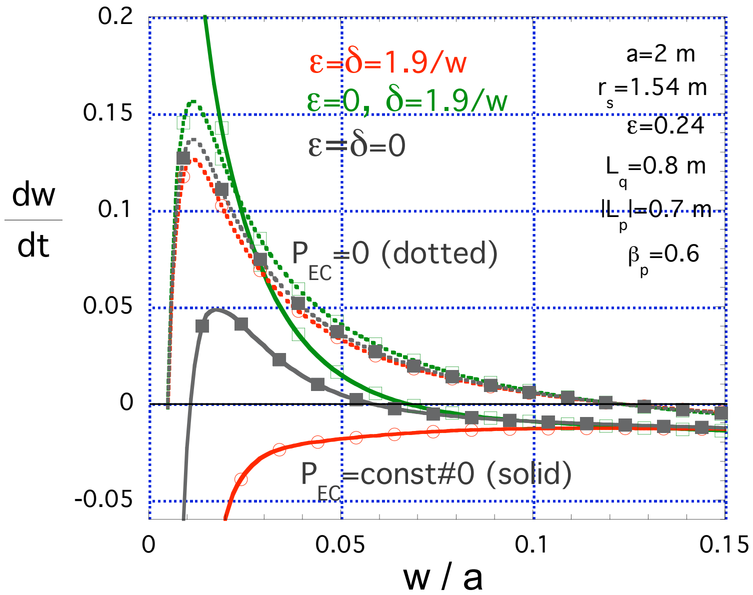
- The NTM stability can be discussed inspecting the phase-space plane and corresponding island evolution plot.
- The critical widths at dW/dt=0 are **not affected by deformations** due to the constraint $\varepsilon W<1$=constant and $\delta W<1$=constant
- The EC absorbed power economy to quench an unstable mode at the marginal stability width **is linked to the island shape**

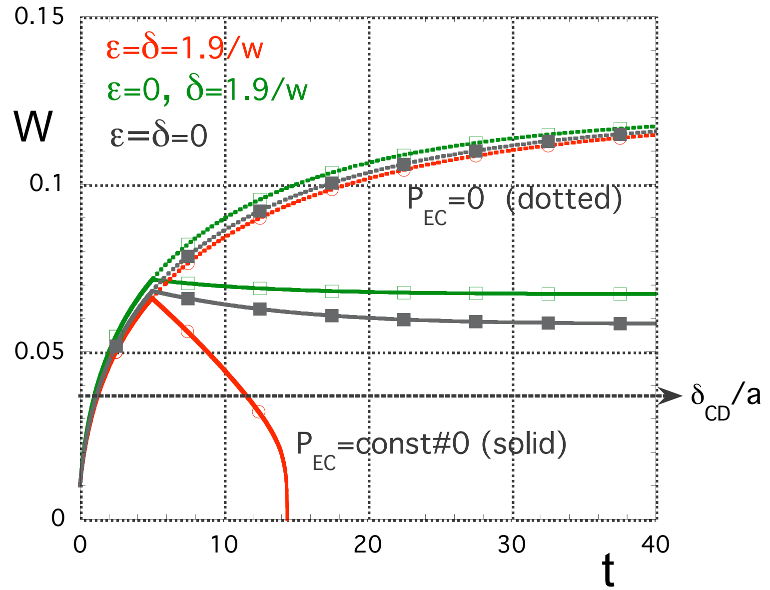




NTM stability study in the phase space /2
- with Phase misalignment -

- *For ECCD peaked at O_{point} of **islands asymmetric** in amplitude and phase and misaligned by $\xi_0=\pi/4$, the best efficiency of this island contour allows to suppress the mode, while the **symmetric and dephased ones**, using the same EC power, cannot reduce the width W below the current profile width δ_{CD}*





Conclusions

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- **The key question** of this study was to investigate the general viscous stress and NTV effects on the evolution of NTMs *within the scope of an ECCD application for control.*

- **It has been found that the role of NTV** on the island frequency has consequences on the ion polarisation current physics

An update of Rutherford equation is proposed, to describe the dynamics of deformed islands controlled by ECCD

- **Basic criteria** for the EC power economy strategy have been discussed in terms of the ECCD helical current efficiency for deformed islands.

THE END