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Role of anomalous transport in onset and evolution of neoclassical tearing modes

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OUTLINE:

- What is the Neoclassical Tearing Mode
- Mechanisms providing β-threshold of NTM
- Cross island heat transport influence on bootstrap drive and magnetic curvature effect.
- Correction to transport threshold due to ion perpendicular viscosity effect on the bootstrap drive of NTM
- Transport modifications to the polarization current effect
- Summary and discussion

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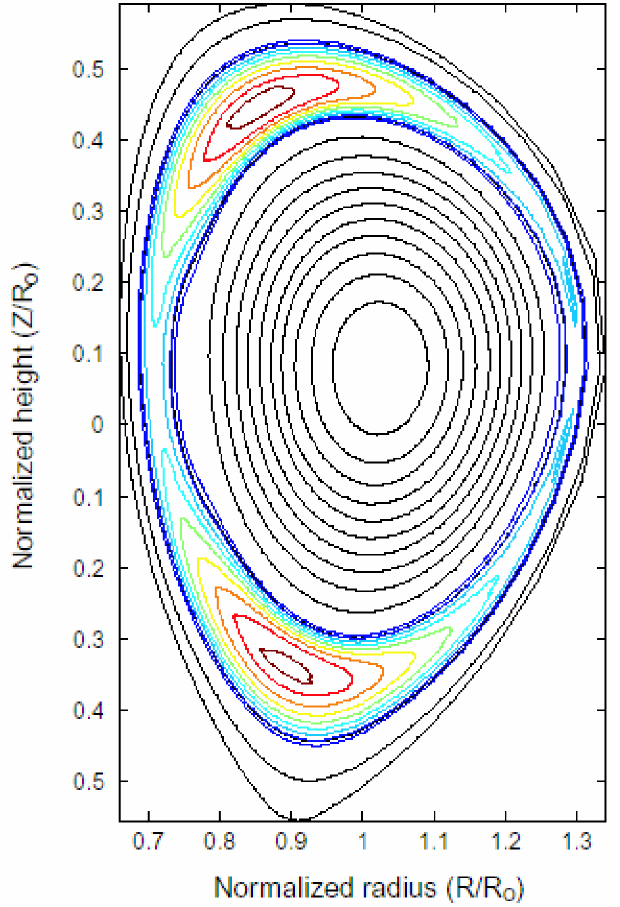
Why NTMs are of concern



NTMs are one of principal obstacles in attaining reactor relevant regimes

- appear well below ideal limit $\beta_{N\_NTM} << \beta_{N\_ideal}$
- degrade confinement (soft limit)
- limit ultimate β ⟹ $P_{fusion} \sim \beta^2 B^4$

  (shrink operation domain & rise $, overall ⇩)
- at worst result in disruption (hard limit)

NTMs should be AVOIDED or SUPPRESSED

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Evolution of the magnetic island width – 1. classical Rutherford equation

perturbation, $\tilde{\psi}\cos\xi, \quad \xi = m\theta - n\varsigma - \omega t$

forms magnetic island $W = 4\left(q_s R\tilde{\psi}/B_o s\right)^{1/2}$

island flux surface label $\Omega = 8x^2/W^2 - \cos\xi$

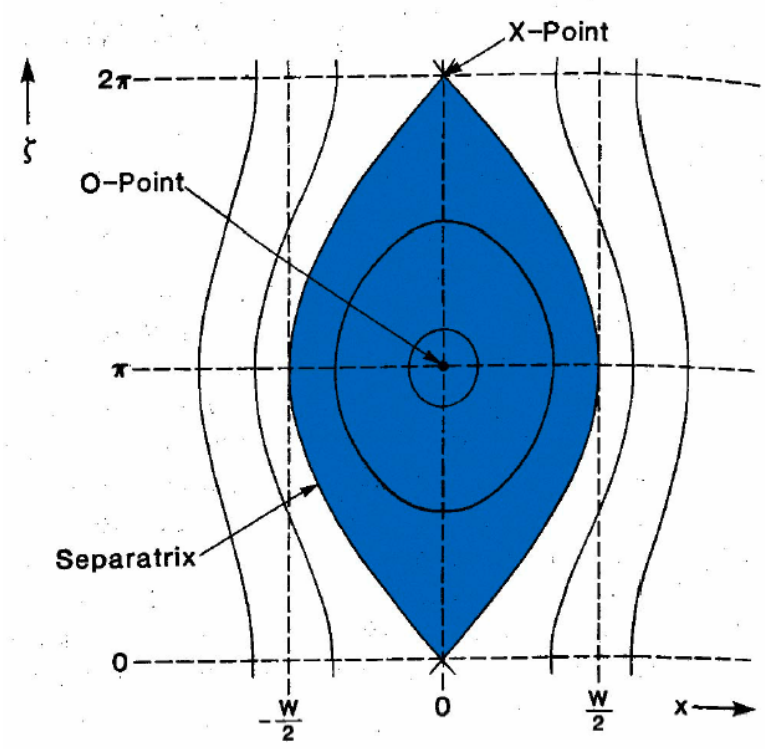
inside the island $-1 < \Omega < 1$

Ampere law $\Delta'\tilde{\psi} = 2\mu_0 R\int_{-\infty}^{\infty} dx \oint d\xi J_{\parallel}\cos\xi$

Rutherford-1973 :

induced current $J_{\parallel} = J_{\parallel}(\Omega) = \frac{1}{\eta}\frac{\partial\tilde{\psi}}{\partial t}\langle\cos\xi\rangle$

Island width evolution: (Rutherford equation)



$$0.41\tau_r\frac{dW}{dt} = r_s^2\Delta'$$

For fast parallel transport the **pressure is flattened inside the island**

Evolution of the neoclassical island – 2. modified Rutherford equation

Bootstrap is removed from inside the island, $J_{bs} \sim \frac{dp}{dr}$ whilst remains outside.

$$J_{\parallel}(\Omega) = \frac{1}{\eta}\frac{\partial \tilde{\psi}}{\partial t}\langle \cos\xi \rangle + \frac{1}{\eta n e B}\langle \mathbf{B}\cdot\nabla\cdot\pi_{\parallel e}\rangle \quad = \quad \text{Inductive + Bootstrap}$$

Particle drift across the magnetic surfaces provides
curvature and polarization drift contributions into NTM dynamics

Curvature — Polarization drift

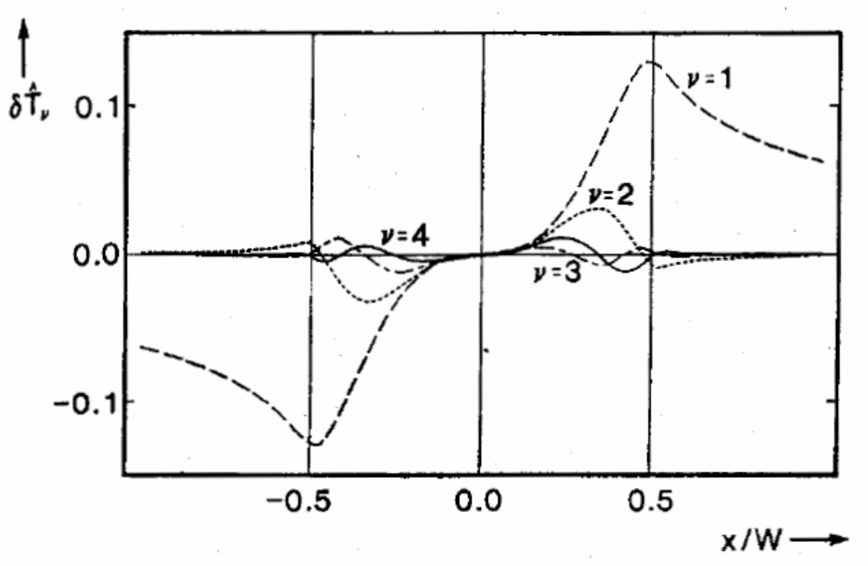
$$\mathbf{B}\cdot\nabla\frac{J_{\parallel}}{B} = -\nabla\cdot\frac{\mathbf{B}\times\nabla p}{B^2} - \nabla\cdot\frac{\mathbf{B}}{B^2}\times\left(\rho\frac{d\mathbf{V}}{dt} + \nabla\cdot\boldsymbol{\pi}\right)$$

All new contributions are sensitive to transport phenomena:
($\tilde{T}_{e,i}(r)$, $\tilde{n}_e(r)$, $\tilde{\mathbf{V}}(r)$ to be determined)

Temperature perturbations associated with magnetic islands -1

First analysis for finite parallel thermal conductivity Fitzpatrick-1995 (MHD-Braginskii) and Gorelenkov et al -1996 (Drift kinetic)

Heat balance is $\nabla \cdot \mathbf{q} = \chi_{\|}\nabla_{\|}^{2}T + \chi_{\perp}\nabla_{\perp}^{2}T = 0$ $W_c \sim \left(\chi_{\perp}/\chi_{\|}\right)^{1/4}$



(Fitzpatrick – 95)

- $W >> W_c$ - temperature is **flattened**

$T = T(\Omega = 1)$;

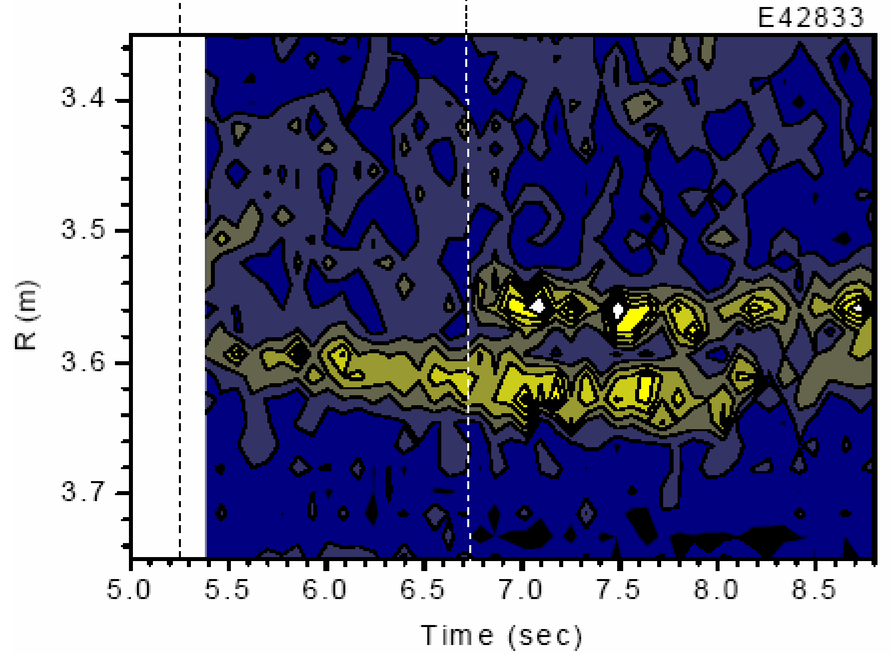
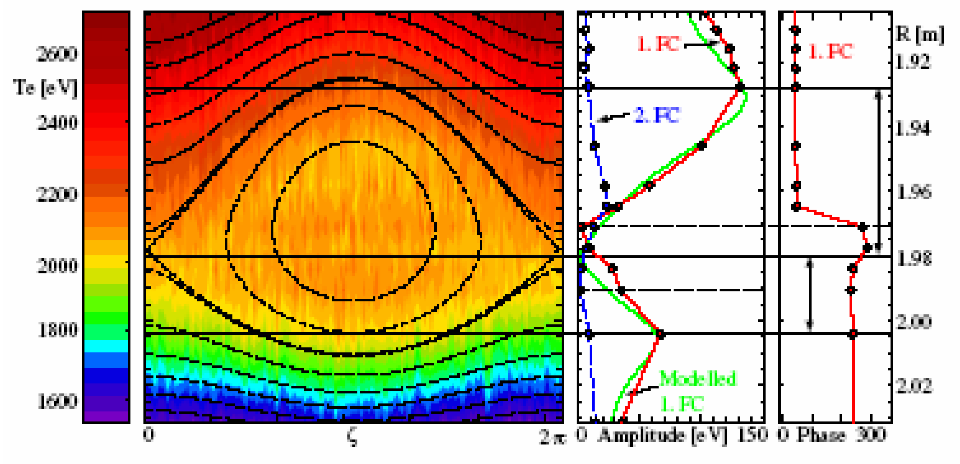
$\delta T(x,\xi) = \sum_{\nu} T_{\nu}(x)\cos\nu\xi$;

$$\Delta_{bs} \sim \frac{1}{W}$$

- $W \le W_c$ - there is **no flattening**,

$T = f(x)\cos\xi$; $\Delta_{bs} \sim \frac{W}{W_c^2}$

Temperature perturbations associated with magnetic islands -2

	
NTM evolution from ECE measurements in JT-60U (Nagasaki et al. 2004)	Simulated and ECE detected structure of $\tilde{T}_e(r)$ in AUG (Meskat et al 2001)

Fitzpatrick model vs. experiment: 1) $\chi_\perp$ should be anomalously high;

2) heat flux limit for $\chi_\parallel = \chi_{sp} \Big/ \sqrt{1 + \left(3.16 V_e / \nu_{e,i} L_c\right)^2}$

Anomalous transport affects NTM threshold

$$\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s\Delta' + \beta_p\left[\frac{r_s C_{bs}}{w}\times\frac{w^2}{w^2+w_*^2} + \frac{r_s C_{mw}}{w}\times\frac{w}{w+w_{*mw}} \pm g\frac{C_{pol}}{w^3}\right] + \Delta_{EC}$$

Conventional tearing ***Bootstrap Drive*** ***Magnetic curvature*** ***Polarization drift***

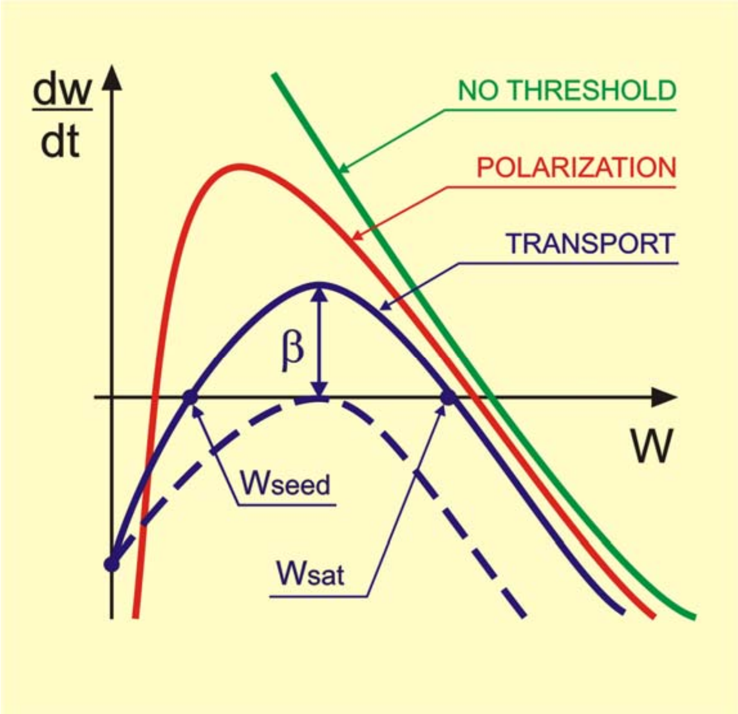
Transport threshold

$$\beta^{\chi}_{p,m\arg} \propto W_* \frac{\Delta'}{\sqrt{\varepsilon}}\cdot\frac{L_p}{L_q}$$

Anomalous transport

Polarization drift

$$\beta^{poll.curr.}_{p,m\arg} \propto -\Delta'\rho_{pi}\sqrt{g\frac{L_p}{L_q\varepsilon^{3/2}}}$$



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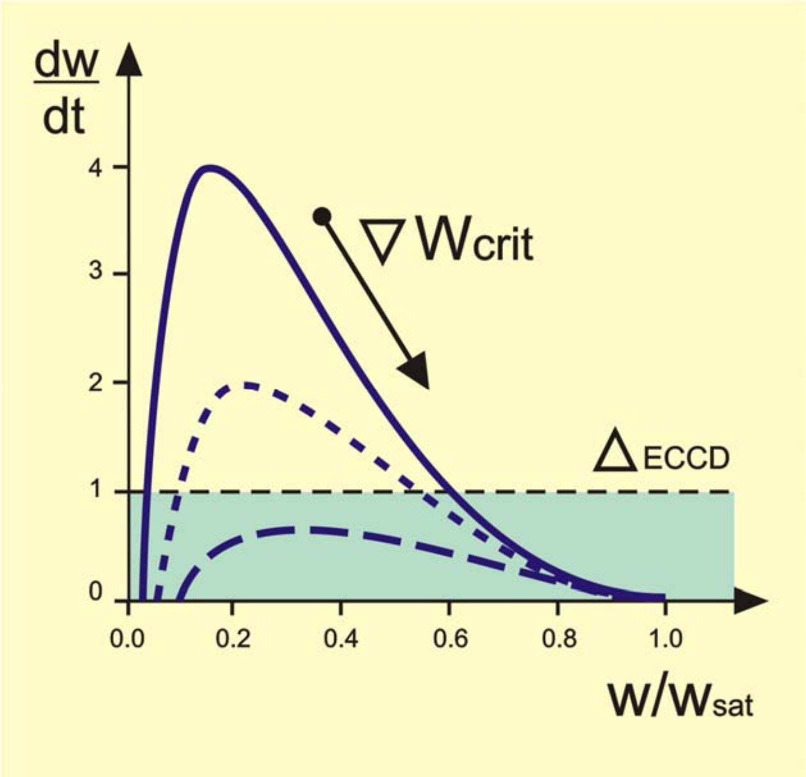
Finite parallel heat transport effect on NTM evolution / suppression



Adding non-resonant helical perturbation rise effective value of $\chi_{\perp eff}$ (Yu et al 2000):

$$\hat{\mathbf{b}} = \mathbf{b} + b_{ext\_r}\mathbf{x}$$

$$\nabla_{\parallel} = \mathbf{b}\cdot\nabla + b_{ext\_r}\frac{\partial}{\partial x}$$

$$\chi_{\perp} \to \chi_{\perp}^{eff} = \chi_{\perp} + \chi_{\parallel}\left\langle b_{ext\_r}^{2}\right\rangle_{\theta}$$

$B_{ext\_r}/B_0 \approx 10^{-4}$ suppress NTM

Rise of W_* facilitate ECCD suppression

Possible way to suppress NTM by externally applied nonresonant helical perturbation

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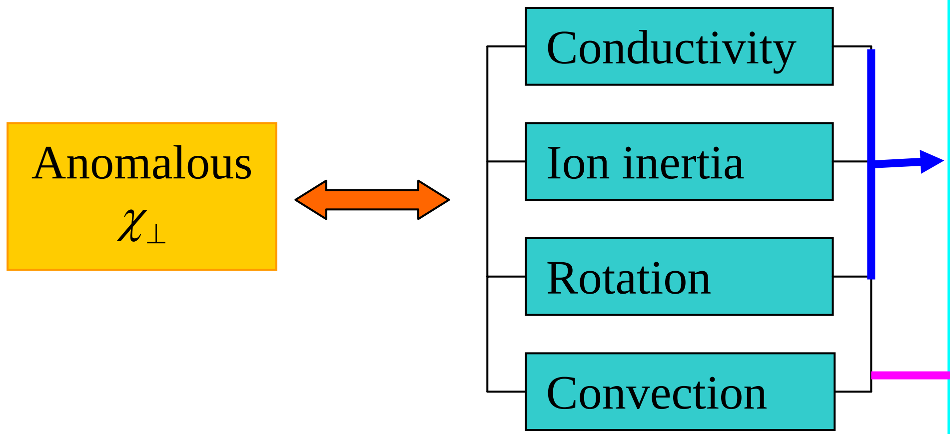
Transport threshold model of NTM

$\beta^{\chi}_{p,m\,\mathrm{arg}} \propto W_*$, W_* depends on the transport model used: $W_* \propto \left(\chi_\perp / \chi_\parallel\right)^{1/4}$

$\chi_\perp = \chi_\perp^{gB} \propto T^{3/2}/B^2$; $\chi_\parallel = \chi_{Spitzer}$ $\qquad \beta^{\chi}_{p,m\,\mathrm{arg}} \propto \rho^*_{pi}\sqrt{\nu^*_{ii}}$

Anomalous cross-island heat transport competes with series of parallel transport mechanisms in forming perturbed temperature profile:



$$\frac{3}{2} n \frac{dT}{dt} + \rho c_s^2 \nabla_\parallel V_\parallel = -n\left(\chi_\parallel \nabla_\parallel^2 + \chi_\perp \nabla_\perp^2\right)T$$

$$V_\parallel \nabla_\parallel f - \chi_\perp \frac{\partial^2 f}{\partial x^2} = 0$$

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Varieties of the heat transport mechanisms

Model	Basic equations	Characteristic island width [Mikhailovskii 2005]
Collisional[1] (Fitzpatrick 95)	$\nabla \cdot \mathbf{q} = 0, \qquad \mathbf{q} = -n_0\left(\chi_\parallel \mathbf{b}\nabla_\parallel + \chi_\perp \nabla_\perp\right)T$	$W_{col} = 2^{3/2}\left(\frac{L_s^2 \chi_\perp}{k_y^2 \chi_\parallel}\right)^{1/4}$
Rotational[3] (Konovalov 2002)	$n_0 \frac{d_0 T}{dt} = -\frac{2}{3}\nabla \cdot \mathbf{q}_\perp$	$W_{rot} = \left(\frac{128\sqrt{2}}{3\pi}\frac{\chi_\perp}{\omega}\right)^{1/2}$
Inertial[4] (Mikhailovskii 2003)	$\rho_0 c_{is}^2 \nabla_\parallel V_\parallel = -\frac{2}{3}\nabla \cdot \mathbf{q}_\perp, \quad \rho_0 \frac{d_0 V_\parallel}{dt} = -n_0 \nabla_\parallel T$	$W_{inert} = \left(\frac{128\sqrt{2}\pi}{3}\frac{\omega L_s^2 \chi_\perp}{k_y^2 c_{is}^2}\right)^{1/4}$
Convective[5] (Mikhailovskii 2003)	$\nabla_\parallel q_\parallel - \frac{3}{2}\chi_\perp \frac{\partial^2 p}{\partial x^2} = 0$, $\frac{5}{M}\nabla_\parallel (pT) - \chi_\perp \frac{\partial^2 q_\parallel}{\partial x^2} = 0$	$W_{conv} = \left(\frac{2^{11/2}\chi_\perp L_s}{c_s k_y}\right)^{1/3}$

Bootstrap drive and curvature effect for series of heat transport mechanisms

1) Partial contributions from temperature and density gradients

$$\Delta_{bs} = \sum_{A=n,T_e,T_i} a_{bs,A} \frac{W}{W^2 + W_{bs,A}^2}, \qquad \Delta_{mw} = \sum_{A=n,T_e,T_i} a_{mw,A} \frac{1}{W + W_{mw,A}}.$$

(Curvature effect weakening – Lutjens et al 2001)

2) characteristic island widths $W_{bs,A}$ and $W_{mw,A}$ are determined by the combination of transport mechanisms

$$\frac{1}{W_{bs,A}^2} = \sum_k \frac{1}{W_{bs,A,k}^2}, \qquad \frac{1}{W_{mw,A}} = \sum_k \frac{1}{W_{mw,A,k}}.$$

3) "Effective" critical island width is determined by the fastest of parallel transports

Perturbed T_e and T_i are formed due to different transport mechanisms

Electrons		Ions	
Convective	***Collisional***	**Inertial**	***rotational***
Convection is dominant $W_* \propto \chi_\perp^{1/3}$ **Collisional** (heat flux limit for $\chi_\parallel$) $W_* \propto \chi_\perp^{1/4}$		**Ion transport mechanisms are frequency dependent** For $\omega \approx \omega_*$, and $W_{\min} \approx \Delta_{orbit}$ **Inertial** for $W/W_{\min} > \varepsilon^{-1/2}$. $W_* \propto (\omega\chi_\perp)^{1/4}$ **Rotational** for $1 < W/W_{\min} < \varepsilon^{-1/2}$. $W_* \propto (\chi_\perp/\omega)^{1/2}$	

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Taking into account partial contributions from electron and ion temperatures

Bootstrap drive (high aspect ratio limit, neglecting ∇n effect)

$$\Delta_{bs} = 3.89 \frac{\varepsilon^{1/2} r_s}{s} \left[0.40 \cdot \frac{\beta_{pe}}{L_{Te}} \cdot \frac{W}{\left(W^2 + W^2_{crit,e}\right)} - 0.17 \cdot \frac{\beta_{pi}}{L_{Ti}} \cdot \frac{W}{\left(W^2 + W^2_{crit,i}\right)} \right]$$

Magnetic well (curvature) effect

$$\Delta_{mw} = -3.16 \frac{\varepsilon^2 r_s}{s^2} \left(1 - \frac{1}{q^2}\right) \left[\frac{\beta_{pe}}{L_{Te}\left(W + W_{mw,e}\right)} + \frac{\beta_{pi}}{L_{Ti}\left(W + W_{mw,i}\right)} \right]$$

Relative role of the magnetic well effect rises at small island limit:

Δ_{bs} is weakened (∇T_i effect) and drops faster at $W \le W_{crit}$,

thus $\left(-\Delta_{mw}\right) > \Delta_{bs}$ gives **NTM suppression**

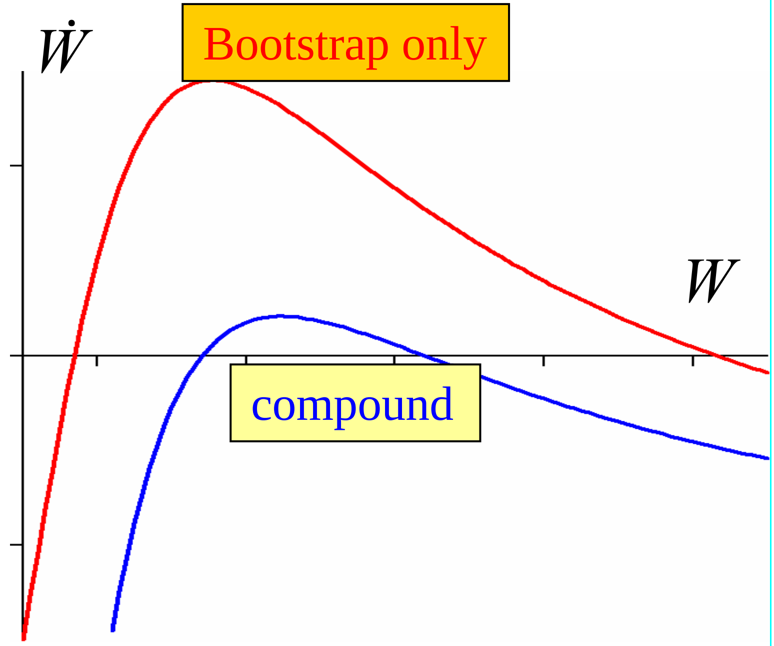
For collisional mechanism NTM suppressed at $W < W^{comp} \approx 29 \varepsilon^{3/2} W_{col}$.

Generalized transport threshold model

- **The relative role of MW effect rises** at small island limit. (Full suppression instead of reduction at $W \approx W_*$)

- **Compound = Bootstrap+MW+transport** gives more favorable predictions for NTM stability

- Scaling for $\beta_{p,m\arg}$ should be modified : $\beta_{p,m\arg} \neq \beta_{p,m\arg}\left(\rho^*_{p,i}, \nu^*_{ii}\right) \Rightarrow \beta_{p,m\arg}\left(\chi_{\perp,ei}, \omega, \cdots\right)$



Perpendicular ion viscosity effect on the bootstrap drive of NTM

In the presence of ion perpendicular viscosity [Konovalov 2002] $\tilde{J}_{bs} = \tilde{J}^{e}_{bs} + \tilde{J}^{i}_{bs} + \tilde{J}^{E}_{bs}$

Electron part $\tilde{J}^{e}_{bs}$ **does not change**,

Ion contribution $\tilde{J}^{i}_{bs}$ **is reduced** by $W^2 \big/ \left(W^2 + W_\mu^2\right)$, where $W_\mu = \left(\mu_{\perp i} \big/ \varepsilon^{1/2} \nu_i\right)^{1/2}$

New component due to perturbed electrical field **appears**:

$$\tilde{J}^{E}_{bs} = -\frac{2.46\varepsilon^{1/2} c e n_0 \tilde{E}_x}{B_\theta} \cdot \frac{W_\mu^2}{W^2 + W_\mu^2} \qquad \Delta_{bs,E} = -3.79 \frac{\varepsilon^{1/2} r_s}{sW} \frac{\beta_{pe}}{L_{p_e}} \frac{W_\mu^2}{\left(W^2 + W_\mu^2\right)} \frac{\omega}{\omega_{p_e}}$$

For islands, rotating in the ion diamagnetic drift direction viscousity can cancel threshold

Simple estimations of the viscosity effect on bootstrap drive

Typical initial island $W_{seed} \approx \rho_b < W_\mu$:

- $\mu_\perp \approx \chi_\perp \approx \chi_{\perp g-Bohm} \approx \rho_i^2 V_{Ti} / qR$

Then $W_\mu \approx \rho_i^2 / \varepsilon^2 \nu_i^{*1/2}$, where $\nu_i^* \equiv \nu_i qR / \varepsilon^{3/2} V_{Ti} < 1$ (in banana regime)

- $W_\mu / \rho_b \approx \left(q\varepsilon^{3/2} \nu_i^{*1/2}\right)^{-1} >> 1$

Perpendicular viscosity is *a priory* important

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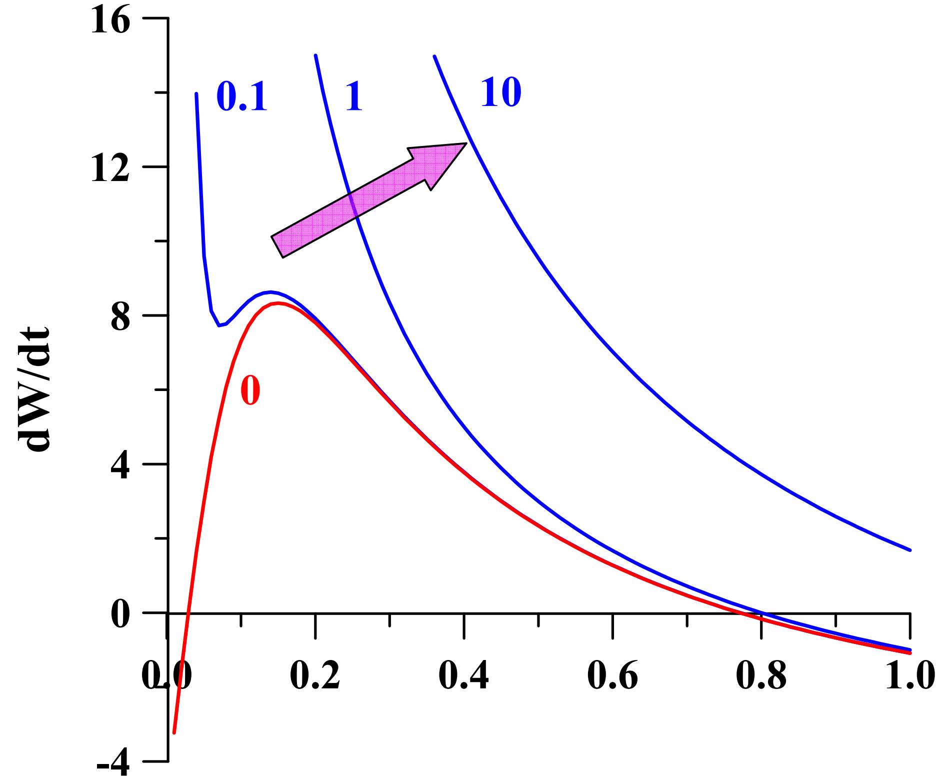
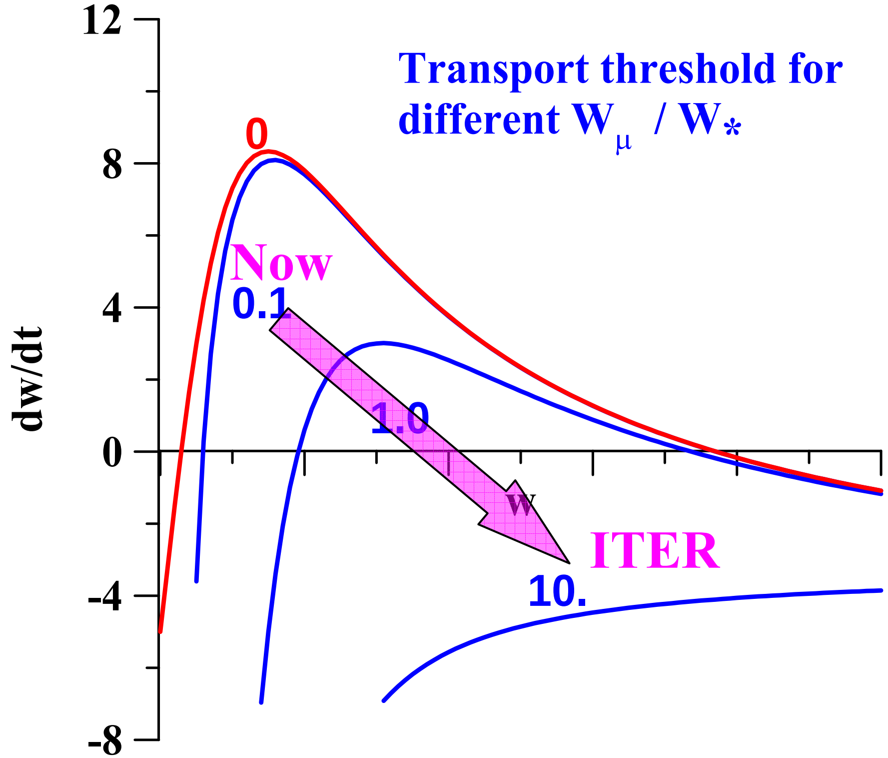
Relative role of viscous effect rises with plasma temperature



$$W_* \approx \left(\frac{\chi_\perp L_s}{V_{Te} k_y} \right)^{1/3}, \qquad W_\mu \big/ W_* \sim T^{5/3}$$



For island rotating with frequency of $\omega = \omega_{*,e}$ viscous bootstrap is stabilizing

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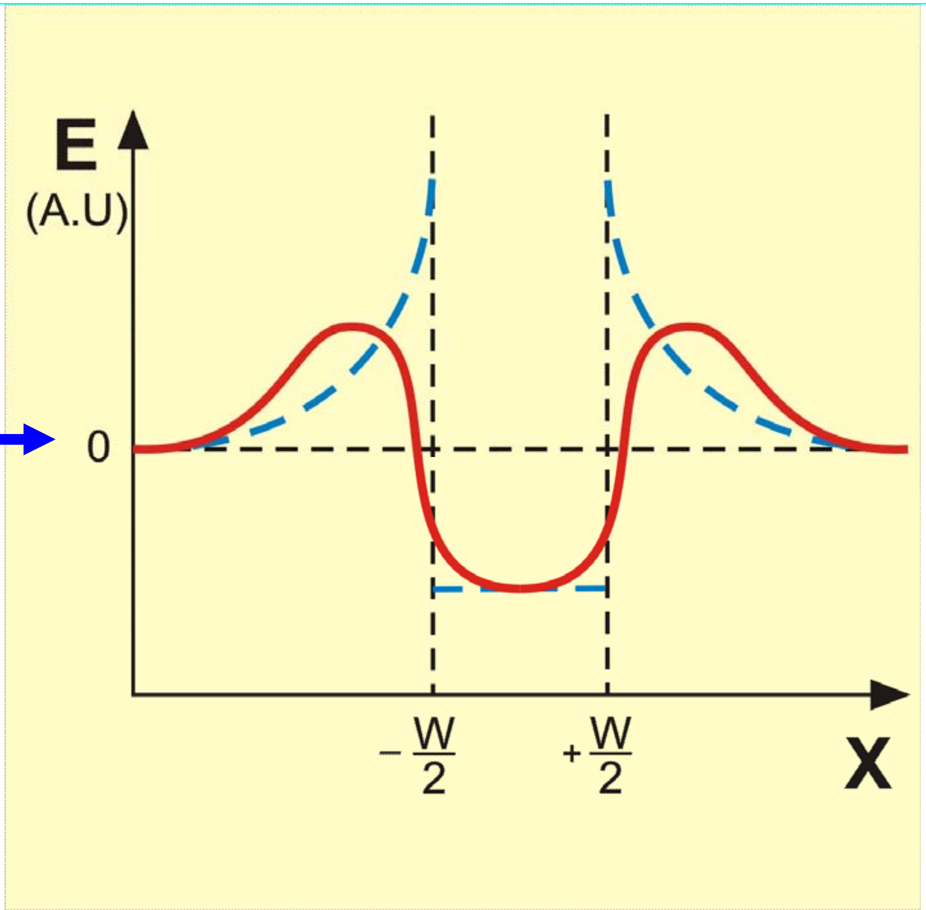
Standard polarization current threshold model can not give quantitative predictions of NTM stability

Drawbacks:

- Δ_p changes sign with change of the island rotation direction, but always referred as stabilizing [Mikhailovskii review 2003]
- Amplitude depends on the perturbed flow velocity profile [Connor et al 2001] It drastically decreases when realistic perturbed velocity profile is considered [Konovalov 2001] $\Delta_p = \alpha_{pol} \Delta_{pol}^{analytic}$, $\alpha_{pol} \leq 0.1$



Perpendicular viscosity modifies (removes!) collisionality dependence of the polarization threshold

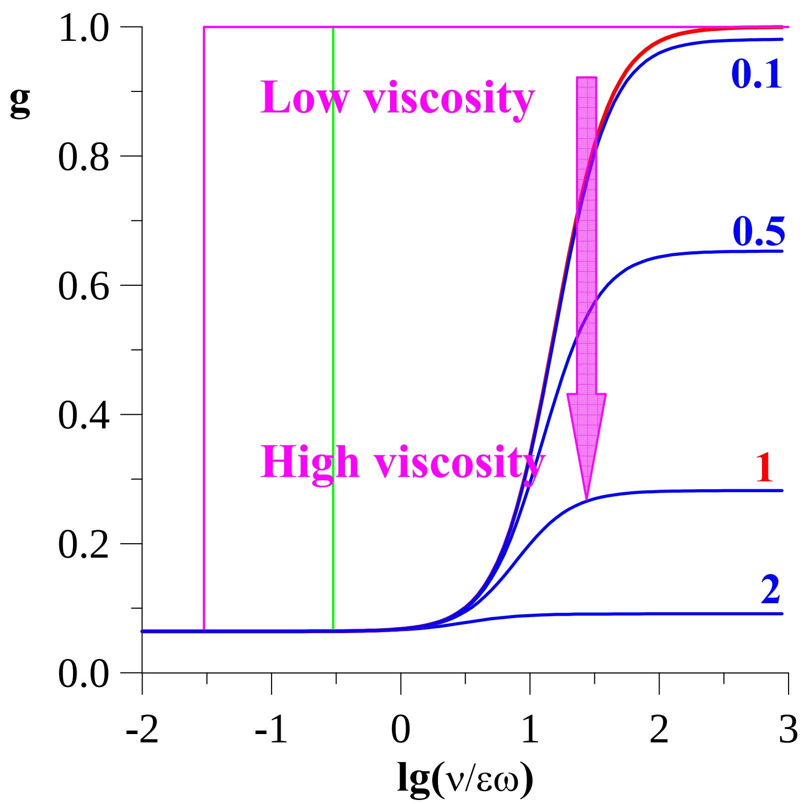
- Low collisionality limit gives smallness

$$g \to \varepsilon^{3/2}$$

Amplitude and collisionality:

$$\Delta_p = g\alpha_{pol}\Delta_{pol}^{analytic} \to 0.01\Delta_{pol}^{analytic}$$

Standard polarization current effect is important at extremely small (hardly detectable) island width.



Function g for different ratios of W_μ / W

Summary

What we know (what can be used in NTM simulations)

- **Partial contributions from electrons are of principal importance**
  - they enter in a different way into modified Rutherfor equation
  - perturbed electron and ion temperature profiles are determined by the different transport mechanisms.

- **Dominant mechanisms competitive to the cross-island heat**
  - parallel heat convection for electrons,
  - parallel plasma inertia for ions

- **In the small island limit $\Delta_{bs} \approx \Delta_{mw}$ generalized transport threshold model**
  - gives more favorable predictions for NTM stability
  - modifies scaling law for β_{onset}.

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Discussion - 1

What we understand (what to be included in the next step NTM modeling)

- Equation for island rotation frequency is necessary

- Ion transport and perpendicular viscosity provide $\beta_{onset}(\rho_*, \nu) \rightarrow \beta_{onset}(\rho_*, \nu, \omega, \ldots)$

- Viscous contribution to bootstrap drive in the small island limit
  - Can be of the order of "standard" bootstrap drive $\Delta_{bs,E} \approx \Delta_{bs}$
  - destabilizing for the island rotating in the ion diamagnetic drift direction
  - can cancel out transport threshold of the NTM onset.

- Polarization current effect seems to be too weak, but we still need it or an alternative effects (Smolyakov-Lazzaro 2004) to compensate viscous bootstrap

Discussion - 2

On the standard transport threshold model:

Electrons: Establishment of $\tilde{T}_e(r)$ and $\tilde{J}_{bs,e}$ contribution to the NTM evolution are more or less understood

Ions: Finite orbit width effect [Poli et al 2002] $\tilde{J}_{bs,i} \to 0$ for $W \geq \Delta_{banana}$

Density: $W_{d,n} \sim 4W_{d,e}$ [Fitzpatrick – 95], i.e $\Delta_{bs,n}$ is strongly suppressed.

Further analysis is necessary: particle transport should be considered with strict requirement of quasineutrality, sound wave dominated parallel transport etc..

Local values of $\chi_\perp$, $\mu_\perp$. Selfconsistent modification of

- heat transport [Connor 2001, Zabiego 2002],
- viscosity and island rotation [Shaing – 2004]

Conclusions

➢ **Theory needs further development**

There must be much more to the theoretical understanding of the NTM onset and evolution, where transport phenomena play the key role.

➢ **Experimental study is far ahead at the present**

- NTM avoidance by plasma current profile (JT-60U, JET, AUG, DIII-D, …) and seed island size (JET, AUG, …) controls
- Suppression (JT-60U, JET, AUG, DIII-D, …) or avoidance with use of preventive ECCD (JT-60U)
- High performance regimes with moderate NTM (FIR regime in AUG)

Overall, experiments guided by semi-qualitative theory show optimistic perspectives for reactor relevant plasmas.

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Acknowledgements

The authors would like to express their appreciation to JAERI and Kurchatov Institute for providing this opportunity of Russia-Japan cooperation. This work was supported by JAERI fellowship program (S.V. Konovalov) and JAERI invitation program of foreign researchers (A.B. Mikhailovskii).

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