Feedback of a neoclassical tearing mode on drift wave - Zonal Flow turbulence

M. Leconte[1], PH. Diamond[1,2] and Dong-Keun Oh[1]

[1]WCI Center for Fusion Theory
NFRI, Korea

[2]CMTFO and CASS
UCSD, USA

Acknowledgements: A. Ishizawa, Kaijun Zao, K. Miki

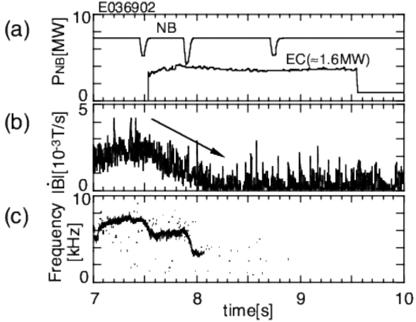
NFRI National Fusion Research Institute

WCI Center for Fusion Theory

Outline

General Intro

- predicting Neoclassical Tearing Mode onset critical to ITER
- What is the role of microturbulence and Zonal Flows?



onset & control of an NTM on JT60U [**Isayama PPCF 2000]**

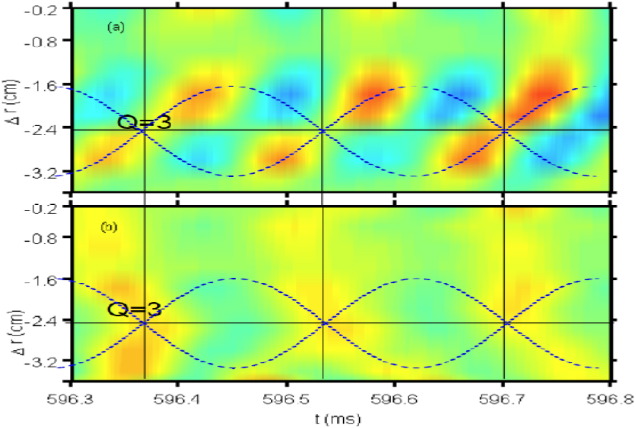
- What sets the threshold island width?
    - Effect of turbulence on the bootstrap-current ?
    - Effect of island on turbulence drive & ZFs ?
  - ad-hoc heat diffusivity $\chi_\perp$ in island $\leftrightarrow$ turbulence
  - turbulence-ZF sets threshold island width

- neoclassical picture: trapped particles: $\searrow \nabla p$
  $\hookrightarrow$ bootstrap current
- **But** turbulence plays crucial role : $\searrow \nabla p \rightarrow$ affects island
  Note: ZFs are very strong near the island separatrix
  'polarization current' issue : not adressed here

Evidence for turbulence role in island evolution

- Evidence of turbulence role in island dynamics (HL-2A)

K. Zao APTWG'13



- island **modulates** turbulence
- m=0,n=0 mode (ZF) couples to the 3:1 vortex flow

Neoclassical Tearing Mode: Basic Mecanism
Qu & Callen '85, Carrera '86

- associated to bootstrap current:

Ohm's law

$$\delta j_{\|} = \delta j_{\|}^{\text{induct}} - D_{\|} \nabla_{\|} (\delta\phi - \delta n) + \sqrt{\epsilon} \frac{\partial}{\partial x} \delta p$$

- due to neoclassical damping of electron flow & enhanced by trapped-electrons (trapped-fraction $\sqrt{\epsilon}$)
- island growth and saturation if $\Delta' < 0$ [**Carrera '86**] temperature flattened by island → modified Rutherford Eq:

$$\frac{dW}{dt} = \Delta' + \Delta_{bs}(W)$$

- $\Delta_{bs}(W) \sim \dfrac{\beta_p}{W}$, for large W, with β_p : poloidal beta

What sets the threshold island width?

- **Key point**: competition between:
- parallel heat transport along tilted field lines
  v.s. $\perp$ heat transport across flux surfaces
- **[Fitzpatrick 1995]**

island growth if: $W \gg W_{turb0} = \left[\frac{\chi_{turb}}{\chi_{\parallel}} \frac{L_s^2}{k_y^2}\right]^{1/4}$, with χ_{turb} : ad-hoc

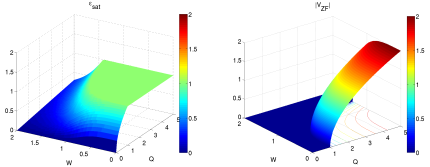
- **but**
  - χ_{turb} **self-consistently** determined @ constant power Q
    $\hookrightarrow$ threshold island width $=$ power threshold (onset β_p)
  - χ_{turb} is affected via:
    i) self-regulation by ZFs i.e. ZF $\nearrow$: turb. $\searrow$
    ii) depletion of turbulence drive i.e. $\nabla T_e \searrow$: turb. $\searrow$
    iii) island-induced ZF damping i.e. ZF $\searrow$: turb. $\nearrow$
    $\hookrightarrow \chi_{turb} = \chi_{turb}(W, Q)$

Marginal stability of NTM coupled to marginal stability of DW-ZF → extended onset criterion

- parallel transport v.s. $\perp$ transport (including effect of island)
- marginal stability ($d/dt = 0$) of DW-ZF predator-prey model perturbed by island
  $\hookrightarrow$turbulence energy ϵ (and ZF energy V_{ZF}) as function of heat flux Q and island-width W
- inject in marginally stable Rutherford equation (below)
  $\hookrightarrow$ **extended criterion** for island growth:

$$\text{island growth if:} \quad \frac{QW}{W^2 + W_{turb0}^2 \sqrt{\epsilon(W,Q)/\epsilon_0}} - |\Delta'| \geq 0$$

Marginally stable turbulence/ZF energy v.s. heat flux Q



and island-width W

0D model: predator-prey model with NTM coupling

Equations

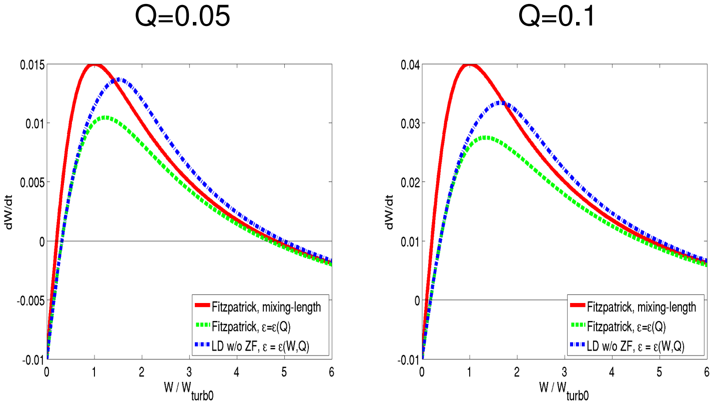
$$\frac{d\epsilon}{dt} = \frac{Q\epsilon}{W_{turb0}^4[\epsilon/\epsilon_0] + W^4} - \alpha\epsilon v_{ZF}^2 - \gamma_{NL}\epsilon^2$$

$$\frac{dv_{ZF}^2}{dt} = \alpha\epsilon v_{ZF}^2 - \left[1 + \frac{\mu_{MHD}}{\mu} W^4\right] \mu v_{ZF}^2, \text{with} \quad (\mu_{MHD} W^4/\mu) \ll 1$$

$$\frac{dW}{dt} = -|\Delta'| + \frac{QW}{W_{turb0}^2\sqrt{\epsilon/\epsilon_0} + W^2}$$

- with fixed heat flux $Q \leftrightarrow \beta_p$
- ϵ: DW turbulence energy
- v_{ZF}^2: Zonal Flow energy
- W: island-chain width
- α: DW-ZF coupling parameter
- $\mu \sim \nu_{ii}$: ZF neoclassical friction
- turb. driven by electron temperature gradient (TEM, ETG...)

Model curve dW/dt v.s. W (analytic) w/o ZFs



- modifications of **NTM onset** / no effect on **NTM saturation**
- no ZFs: threshold island **larger** than Fitzpatrick threshold.
- self-consistent model curve with Zonal Flows not tractable analytically (co-dimension 2 bifurcation)
  $\hookrightarrow$ numerical evaluation

At marginal stability $dW/dt = 0, d\epsilon/dt = 0, dV_{ZF}^2/dt = 0$

case	turb. energy	threshold island
w/o ZF	$\epsilon = \epsilon_1(W,Q) \sim \sqrt{W^8 + 4Q/\gamma_{NL}} - W^4$	graphically
with ZF	ϵ set by ZFs and W	using 0D code

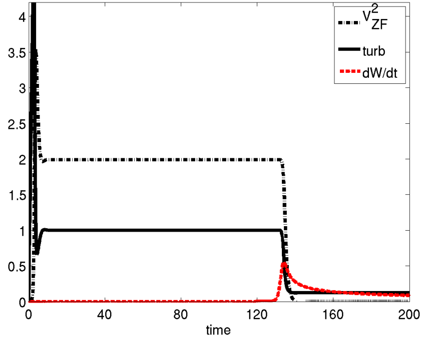
- With ZFs, turbulence at marginal stability exhibits a threshold in Q **and** W

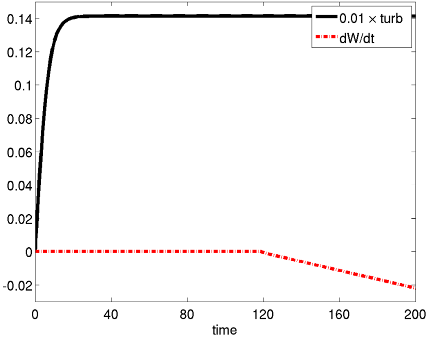
$$\epsilon = \epsilon_1(W,Q) - [\epsilon_1(W,Q) - \epsilon_2]H(\epsilon_1(W,Q)/\epsilon_2 - 1))$$

- codimension-2 threshold represented by Heaviside function

$$H(\epsilon_1(W,Q)/\epsilon_2 - 1))$$

Numerical Results: Dynamics & stability of 0D model





with Zonal Flows: unstable

- turb. regulated by ZFs: seed-island **succeeds** in flattening T_e profile: turb ↘ thus ZFs ↘

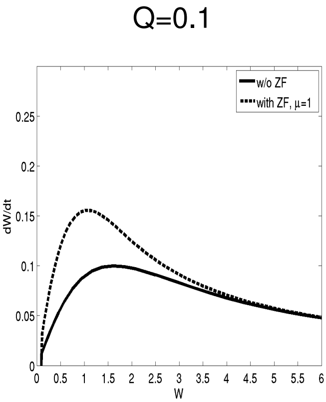
Note 1: ZFs destabilize NTMs

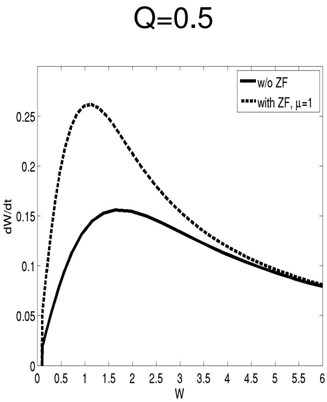
w/o Zonal Flows: stable

- turb. regulated by self-damping: seed-island **cannot** flatten T_e profile

Note 2: NTM seed-island modifies the DW-ZF dynamics

Zonal Flow impact on model curve $dW/dt = f(W)$ [numerical]





- modifications of **NTM onset** / no effect on NTM saturation
- with ZFs: threshold island & β_{onset} **smaller** than w/o ZFs.
- note that larger dW/dt corresponds to **smaller** β_{onset}

1D model: predator-prey model with NTM coupling

$$\begin{aligned}
\frac{\partial I}{\partial t} &= \left[-\frac{\partial T_e}{\partial x} + \left.\frac{\partial T_e}{\partial x}\right|_c\right] I - \alpha I v_{ZF}^2 + \frac{\partial}{\partial x}\left[I \frac{\partial I}{\partial x}\right] \\
\frac{\partial v_{ZF}^2}{\partial t} &= \alpha I v_{ZF}^2 - \left[1 + \frac{\mu_{MHD}(x, W)}{\mu} W^4\right] \mu v_{ZF}^2 \\
\frac{dW}{dt} &= -|\Delta'| - \frac{c_1}{W} \left.\frac{\partial T_e}{\partial x}\right|_{sep}
\end{aligned}$$

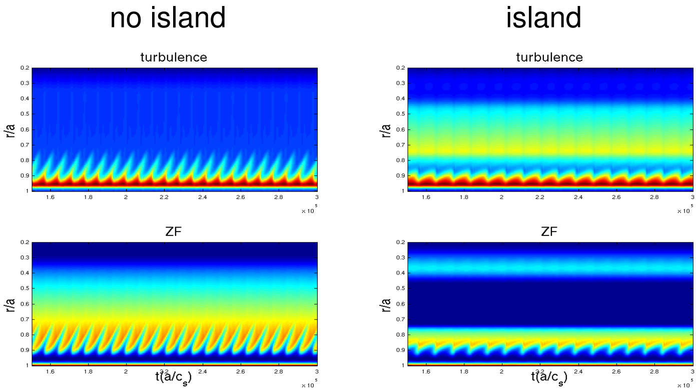
- with Cst heat flux (heat source), based on *Miki et al.* PoP '12

$$\frac{\partial T_e}{\partial t} = \frac{\partial}{\partial x}\left[\chi_{QL} I \frac{\partial T_e}{\partial x}\right] + S_{heat}$$

- island-induced T_e flattening not implemented yet (in 1D)
- cannot address threshold physics → **saturation physics**

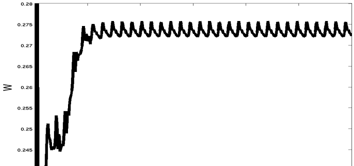
- I: DW turbulence intensity
- v_{ZF}^2: Zonal Flow intensity

NTM saturation physics: negative feedback on ZFs



- T_e flattening not implemented: → ZFs ↘ and turbulence ↗ in island region

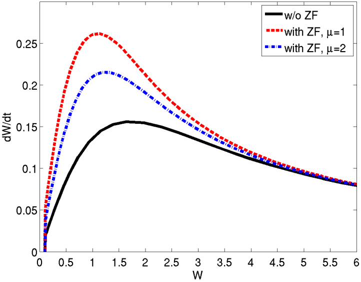
- island-width is modulated:



Predictions of the 0D NTM Predator-Prey model

- Threshold island-width

Fitzpatrick ‘95	our model with ZFs
$W \geq W_{turb0} \sim \epsilon_0^{1/4} \chi_{\parallel}^{-1/4}$	$W \geq W_{turb} \sim \mu^{1/4} \chi_{\parallel}^{-1/4}$
with turb. energy ϵ_0 ad-hoc	with
$\chi_{\parallel} \sim \nu_{ei}^{-1}$	$\mu \sim \nu_{ii}$



Model curve dW/dt v.s. W for different ZF damping μ

- ZFs **destabilize** NTM
- neoclassical ZF damping: **stabilizes** NTM

predictions: scaling with

- ion-ion collision freq.: ν_{ii}: suggests collisionality scan

Discussion

- Threshold island-width predicted to depend on ZF damping
  - predicts threshold island: $\nearrow$ with neo ZF damping
  - $\searrow$ with island-induced ZF damping
- key-points:
  - Zonal Flows regulate turbulence $\rightarrow$ smaller threshold-island
  - depletion of turbulence-drive due to T_e flattening
- open question: turbulence spreading into the island?
- prediction of island-width modulation by the DW-ZF limit-cycle $\leftrightarrow$ LCO in (ϵ, V_{ZF}, W) space
  experimental evidence? (K. Zhao unpublished)
  expression for the DW-ZF-island LCO frequency?
  without island: $\omega_{LCO} \sim \sqrt{Q\mu}$

Summary and conclusions

- Feedback of island on Zonal Flows
- $\searrow$ threshold island-width @low collisionality
- key-point:
  $\hookrightarrow$ ZFs regulate turbulence, cross-field transport $\searrow$
- prediction of island-width modulation by the DW-ZF limit-cycle

- Open Questions
  - Back-reaction of Zonal Flows on island:
    polarization current?
    Coherent ZFs v.s. random ZFs?
    flow direction @ resonance surface?
    (associated to screening/amplif.)
  - island effect on turbulence-driven toroidal rotation?
    (Toroidal Zonal Flows)