U.S.P. Wokshop

Interaction between magnetic islands and turbulence

Sao-Paulo wokshop, November 15th, 2015

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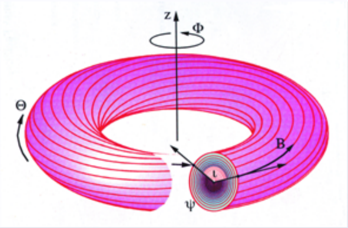
PIIM
Physique des Interactions
Ioniques et Moléculaires

cnrs
dépasser les frontières

Outline

A biased picture of a Tokamak



Tokamak

Magnetic field variation

hot core and cool walls

Current gradient

MagnetoHydroDynamics instabilities (cm~ m) /NTMs

Disruption (sudden stop)

Damages on devices

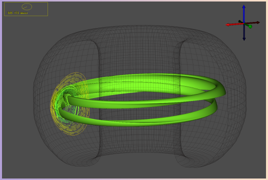
n, T, P gradient

Microscopic instabilities (µm~ mm)

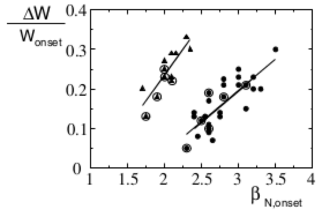
Turbulence

Confinement loss

Impact of NTMs, the magnetic islands in high β tokamak regimes



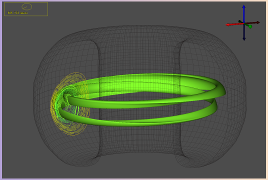
[S. Gunter et al, Phys. Rev. Lett. 87 (2001)]



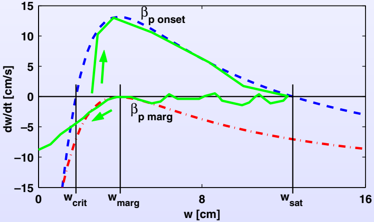
Reduction in energy confinement $\Delta W/W$ due to (3,2) NTMs on ASDEX Upgrade (same results in JET)

- Degradation of the energy confinement $\propto w$ and/or $\propto \beta = \frac{\text{pressure}}{\text{magnetic energy}}$
- Existence of unexpected high confinement regimes at high $\beta_N \gtrsim 2.3$, call FIR-NTM regimes

Origin of NTMs, the magnetic islands in high β tokamak regimes



[T.C. Hender et al, Nuc. Fusion 47 (2007)]

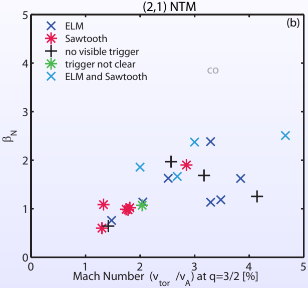


Sketch of the time evolution of the island size w of an island (power-ramp down experiment).

- When $w > w_{cri}$, Seed islands $\Rightarrow$ Radially extended islands or NTMs
- NTMs should be metastable in ITER: $\beta \gg \beta_{marg}$ [R.J. Buttery et al, 20th IAEA Conference, (2004)]

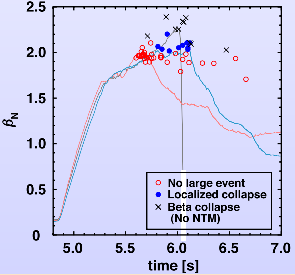
Origin of seed islands ($w \lesssim w_{cri}$)

[S. Fietz et al,41st EPS Conf. on Plasma Physics (2014)]



Trigger Mechanisms of (2,1) NTMs in normalised (β, $v_{toroidal}$) space in ASDEX Upgrade Tokamak

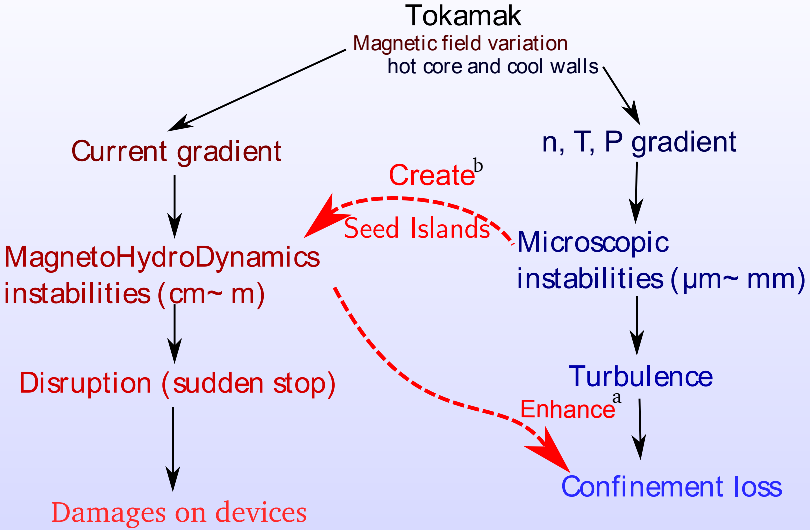
[A. Isayama et al,Plasma and Fusion Research 8 (2013)]



Onset of (2,1) NTMs in high β_p discharges in JT60U Tokamak.

In about 80% of the discharges, (2,1) NTM appear from a small amplitude without any noticeable triggering event

A biased picture of a Tokamak



Tokamak

Magnetic field variation

hot core and cool walls

Current gradient

n, T, P gradient

Create[b]

Seed Islands

MagnetoHydroDynamics instabilities (cm~ m)

Microscopic instabilities (μm~ mm)

Disruption (sudden stop)

Turbulence

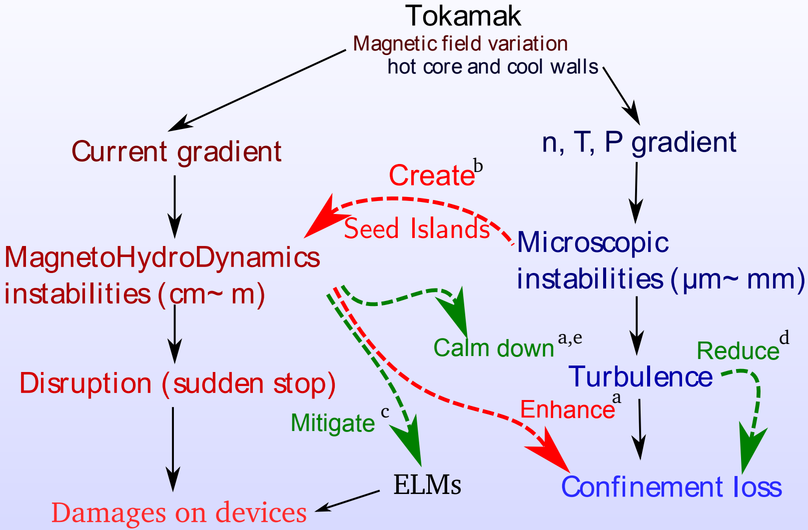
Enhance[a]

Confinement loss

Damages on devices

a Hornsby, et al, Phys. Plasmas 17 (092301), 2010
b Muraglia, et al, Phys. Rew. Lett. 107 (095003), 2011
b Ishizawa and N. Nakajima 17 (072308), 2010

A biased picture of a Tokamak



Tokamak

Magnetic field variation

hot core and cool walls

Current gradient

n, T, P gradient

Create[b]

Seed Islands

MagnetoHydroDynamics instabilities (cm~ m)

Microscopic instabilities (μm~ mm)

Calm down[a,e]

Reduce[d]

Turbulence

Disruption (sudden stop)

Mitigate[c]

Enhance[a]

ELMs

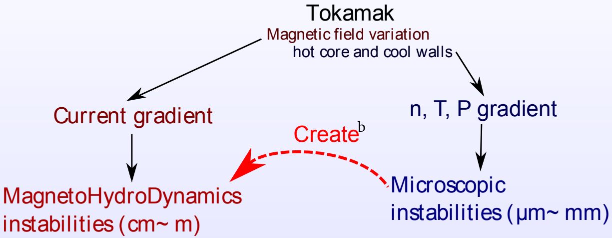
Damages on devices

Confinement loss

a Hornsby, et al, Phys. Plasmas 17 (092301), 2010
b Muraglia, et al, Phys. Rew. Lett. 107 (095003), 2011
b Ishizawa and N. Nakajima 17 (072308), 2010

c Evans, et al, Phys. Rev. Lett. 92 (235003), 2003
d Inagaki, et al, Phys. Rev. Lett. 92 (055002), 2004
e Waelbroeck, Nuc. Fus. 49 (104025), 2009

Turbulence driven magnetic islands (TDMI)?



Tokamak

Magnetic field variation

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Current gradient

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Create[b]

MagnetoHydroDynamics instabilities (cm~ m)

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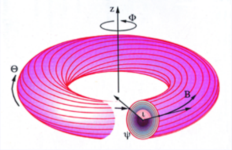
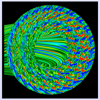
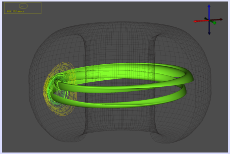


Equilibrium ⟹



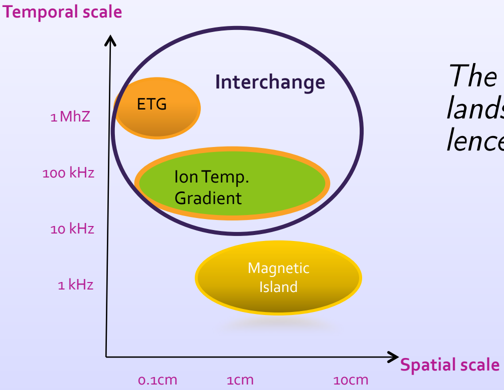
Micro turbulence ⟹



Turb. Driv. Magn. Island

A multi-scale problem

- TEM, ETG and ITG turbulences can give rise to a significant turbulent transport in the core of tokamaks. They are in essence interchange modes with an instability threshold, including drift waves. [X. Garbet et al,PPCF 46 (2004)]

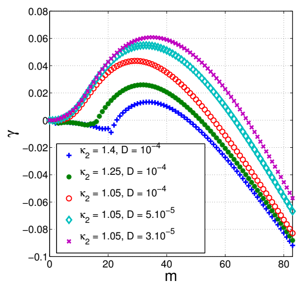


The interaction of magnetic islands with interchange turbulence is a multi-scale problem

A numerical investigation using a minimal fluid model:
Generation of seed islands by interchange turbulence ?

Numerical set-up:
a bath of interchange modes at small scales

- Reduced MHD equations for electrostatic potential ϕ, pressure p and magnetic flux ψ
- Model includes both resistive Interchange and Tearing Mode in 2D slab geometry



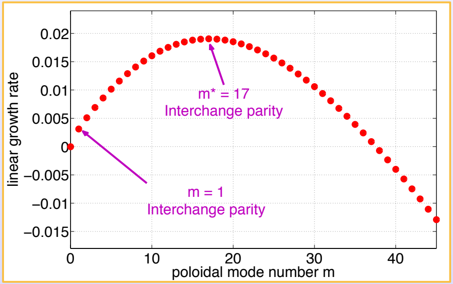
Discussed results are not sensitive to the specific shapes of the spectra

m is the poloidal mode number
γ is the growth rate of the instability

- Linear spectra are stable with respect with tearing instability (No current driven instability can generate an island: $\Delta' < 0$)

Numerical set-up: a bath of interchange modes at small scales

- Reduced MHD equations for electrostatic potential ϕ, pressure p and magnetic flux ψ
- Model includes both resistive Interchange and Tearing Mode in 2D slab geometry



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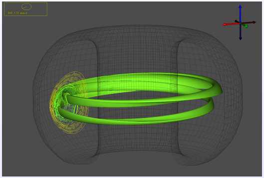
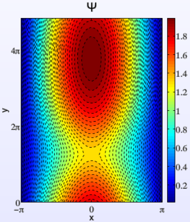
2D slab model

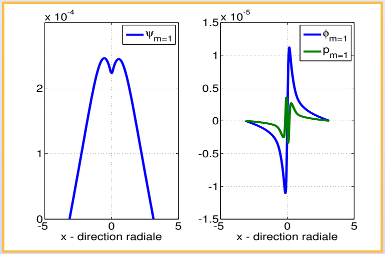
Nature of the instabilities and parity of the modes



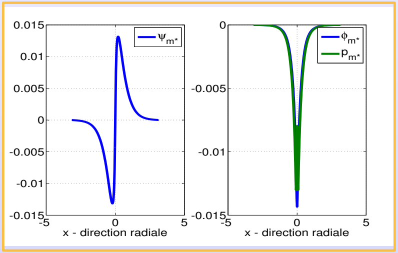
1 single helicity

$$\Longrightarrow \frac{m}{n} = \frac{2}{1}$$





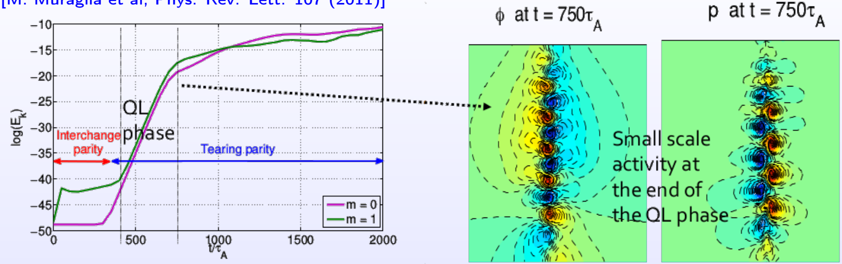
Tearing mode



Interchange mode

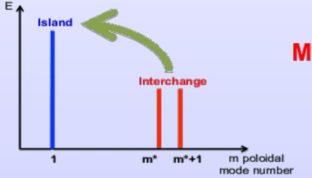
Origine of the seed TDMI

[M. Muraglia et al, Phys. Rev. Lett. 107 (2011)]



Small scale activity at the end of the QL phase

- Sym. breaking: large scale modes switch from interchange to tearing structure
- *All the non linearities* of the model satisfy $[\mathrm{Int}_{ss}, \mathrm{Int}_{ss}] \rightarrow \mathrm{Tear}_{ls}$



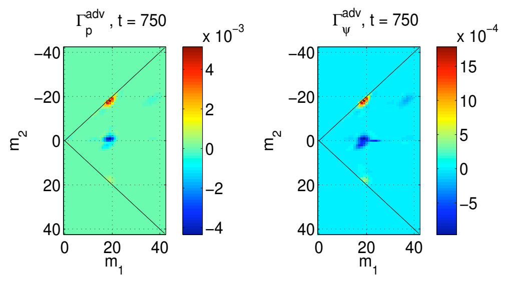
Magnetic island generation by nonlinear beating of interchange modes

- Quadrupole flow structure at large scales

Energy transferts in the QL phase: Beating of modes

- Bispectra analysis $\Gamma(m_1, m_2)$ for the pressure, vorticity $\omega = \Delta\phi$ and magnetic flux equations allows to characterize the multi-scale interaction dynamics:

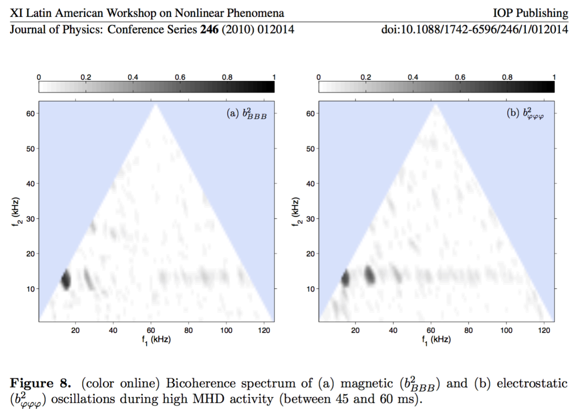
$$\frac{dE_p}{dt}(m) = \text{linear} + \sum_{m=m_1+m_2} \Gamma_p^{\text{adv}}(m_1, m_2) + \Gamma_p^{\rho_*}(m_1, m_2)$$



- In the quasi-linear phase, NL energy transfert occurs from interchange scales to MHD scales
  $(m_1, m_2) = (m_* \pm 1, m_*)$
  $1 = |m_1 + m_2|$

Energy transferts in TCABR: Electrostatic turbulence with high MHD activity

[Z. O. Guimaraer-Filho et al, Journal of Physics: Conf. Series 246 (2010)]

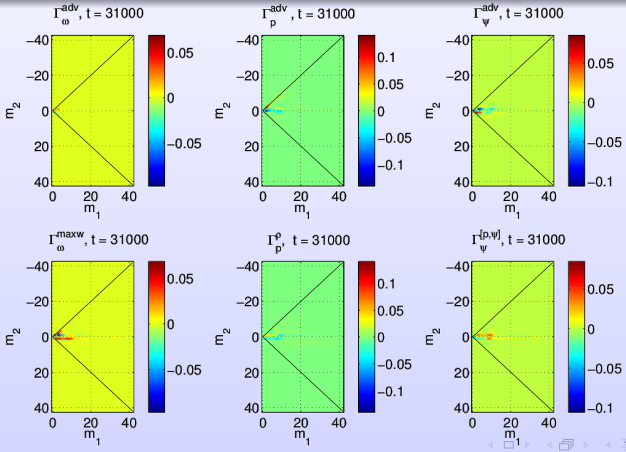


XI Latin American Workshop on Nonlinear Phenomena IOP Publishing
Journal of Physics: Conference Series **246** (2010) 012014 doi:10.1088/1742-6596/246/1/012014

Figure 8. (color online) Bicoherence spectrum of (a) magnetic (b^2_{BBB}) and (b) electrostatic ($b^2_{\varphi\varphi\varphi}$) oscillations during high MHD activity (between 45 and 60 ms).

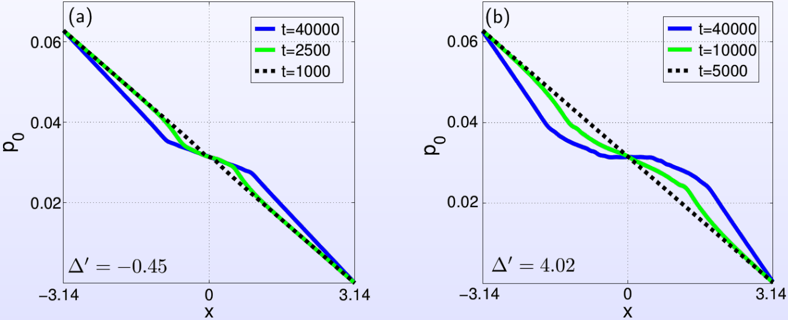
Energy transferts in the Non Linear regime:

- Pile up of energy at MHD scale through bracket $[\phi, p]$
- Intermittent release of MHD energy through spectral cascade $m \rightarrow m + 1$ (like in TCABR tokamak [Z. O. Guimaraer-Filho et al, Journal of Physics: Conf. Series 246 (2010)])



A signature of TDMI: Pressure profile exhibits a partial flattening

Pressure profiles at different times: [O. Agullo et al, Phys. Plasma 21 (2014)]



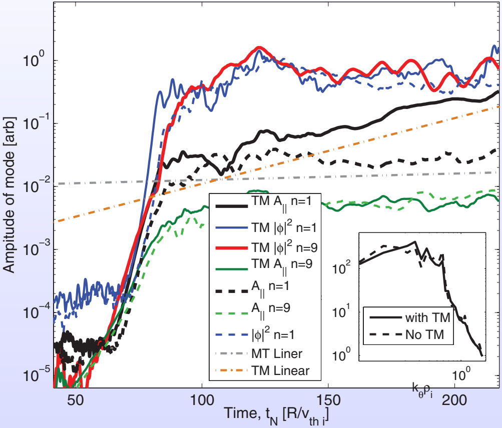
TDMI

Tearing driven island

- Partial flattening of both density and T_e, in conditions where it should not be partial (Fitzpatrick criterium), have been already observed [P.C. De Vries et al, Nuc. Fusion 37 (1997)]
- Only a source localized inside the island can induce it: Ohmic? Turbulence?...

2D slab reduced MHD: a too simple model?

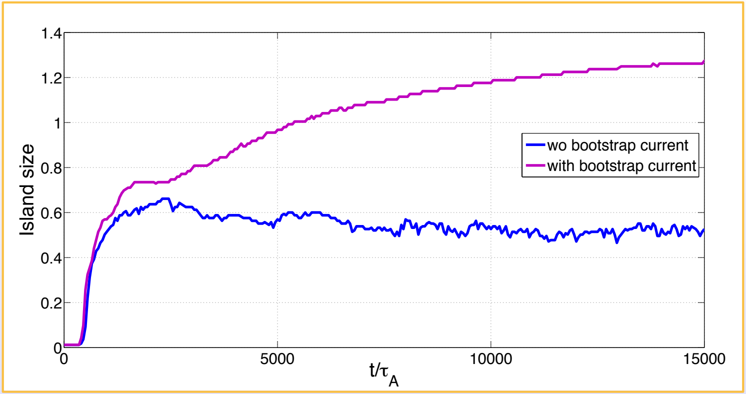
Recent results on electromagnetic gyrokinetic turbulence and island:



[W. A. Hornsby et al, Plasma Phys. Control. Fusion 57 (2015)]

- Presence of a QL phase with mode beating
- Generation of Turbulence Driven Magnetic islands
- Parity/Mode structure breaking still at play

Non linear amplification of TDMI by the bootstrap current

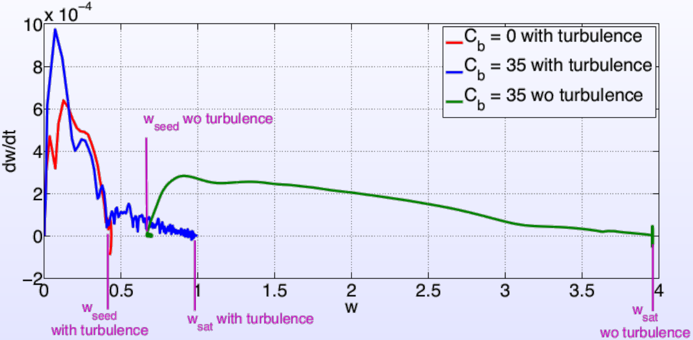


◆ **Self-consistent generation of NTM from TDMI**

1. TDMI formation => **Seeding regime**
2. NL growth of NTM => **Amplification (by bootstrap current) regime**

Non linear amplification of TDMI by the bootstrap current

[M. Muraglia et al, to be submitted]

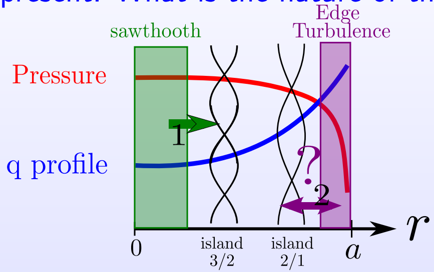


- $C_b \neq 0$ means bootstrap current is included in the dynamics
- TDMI are amplified by the bootstrap current
- Turbulence impacts on the NTM's size induced by the seed TDMI:
  - The wide belief $w \gtrapprox w_{\text{cri}} \Longrightarrow$ Large NTM is not always true.
  - When $w_{\text{TDMI, no bootstrap}} < w_{\text{cri}}$, this is false.

  (to be clarified, including in 3D context)

Oversimplified picture in a multi-helicity context

Magnetic island area do not cover the whole area where turbulence is present. What is the nature of the interaction?



1 M.F.F Nave, et al. Nuc. Fus. 43 (2003)
2 A. Isayama, et al. Plasma and Fusion Research 8 (2013)

1. Remote influence of the turbulence on magnetic islands ?
2. Can edge turbulence affects the growth of magnetic island in weak or weakly reverse shear scenarii such as projected in ITER ?
3. To which extent the size of TDMIs is large enough to generate NTMs : $w_{\mathrm{TDMI}} \gtrapprox w_{\mathrm{cri}}$?

Model: Interchange turbulence and coupling with MHD fluctuations

Reduce MHD, 3D, cylindrical geometry and curvature:

$$\begin{aligned} \partial_t\tilde{\psi} &= \nabla_{\parallel}\tilde{\phi} - \nabla_{\parallel}\left(P_{eq} + \tilde{p}\right) + \eta\tilde{j} \\ \partial_t\tilde{\omega} + \left\{\tilde{\phi}, \tilde{\omega}\right\} &= \nabla_{\parallel}\left(J_{eq} + \tilde{j}\right) - \frac{\kappa_1}{r}\partial_\theta\tilde{p} + \nu\triangle_{\perp}\tilde{\omega} \\ \partial_t\tilde{p} &= \left\{P_{eq} + \tilde{p}, \tilde{\phi}\right\} + \rho^{*2}\left\{\Psi_{eq} + \tilde{\psi}, J_{eq} + \tilde{j}\right\} + \chi_{\perp}\triangle_{\perp}\tilde{p} \end{aligned}$$

A simple model including interchange and Tearing instabilities.

$$\nabla_{\parallel}A = \left\{\Psi_{eq} + \tilde{\psi}, A_{eq} + \tilde{a}\right\} - \partial_z\tilde{a}$$

$$\{a, b\} = \frac{1}{r}\left(\partial_r a\partial_\theta b - \partial_r b\partial_\theta a\right)$$

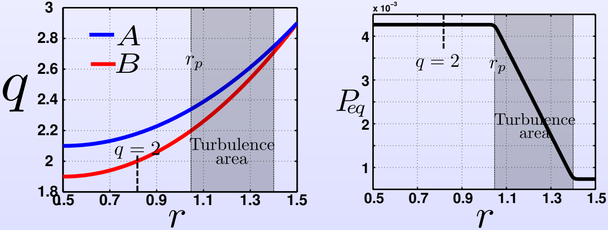
We restrict the study to cases where lowest order rational surfaces are tearing stable. Only `resistive` instabilities are allowed.

Numerical set-up : two simple situations

1. Edge turbulence level is controlled through pressure equilibrium gradient and dissipative parameters.
2. Inner zone is stable with respect to both interchange and tearing instabilities.

Case A : **without** $q = 2$.

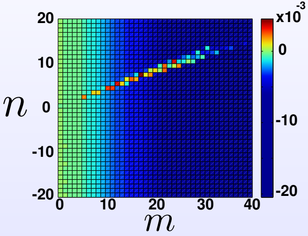
Case B : **with** $q = 2$.



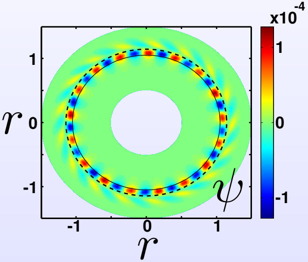
- Is the stable zone impacted by edge turbulence whether it includes low order rationnal surface (here $q = 2$) or not? How?
- Do we have have spreading of turbulence and generation of magnetic islands in stable inner area ?

Numerical set-up : Linear stage

Instability growth rates:

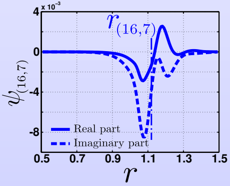


The most unstable mode is in the edge area with $m \gg 1$.

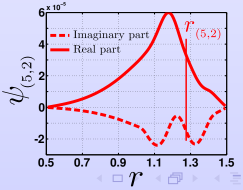


Nature of the instability and parity of the eigen function are linked:

Interchange

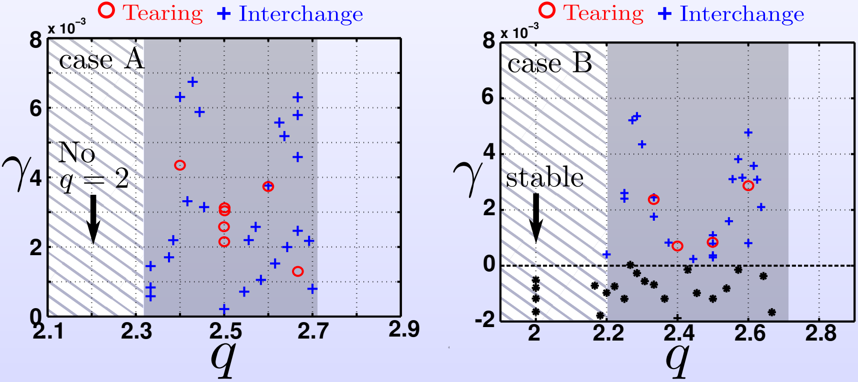


Tearing mode

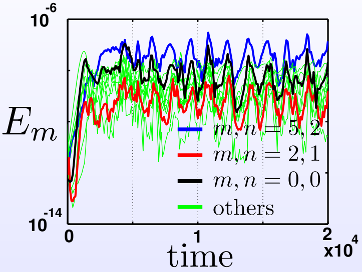


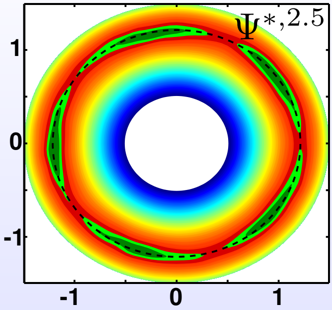
Numerical set-up: Linear stage

We identify the instabilities and their radial locations:



Non linear evolution: Case A ***without*** $q = 2$

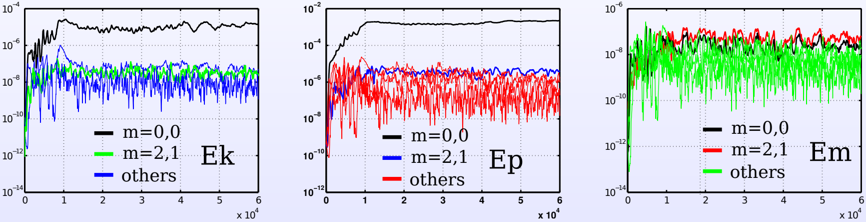




We recover the 2D result: the turbulence generates a magnetic island.

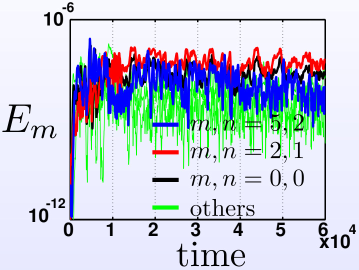
- The dominant mode, in non-linear phase, belongs to the lowest available rational surface available in the turbulent area: $q = 2.5$. Energy transfer analysis show that the generated $(5, 2)$ island is mainly produced and maintained by linearly unstable interchange modes, through nonlinear coupling.

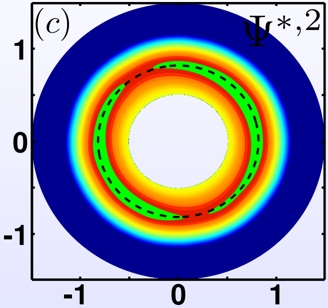
Non linear evolution: Case B *with* $q = 2$



- Generation of a zonal flow localized in turbulent zone and important unlocalized pressure profile modifications
- After a transcient NL phase, (2,1) magnetic fluctuations dominate the spectrum

Non linear evolution: Case B *with* $q = 2$





- The dominant mode, in non-linear phase, is located at the lowest rational surface aviable in the whole box : $q = 2$. It is in the quiet/stable zone and produces a magnetic island $(2, 1)$.
- No more (5,2) island in the edge turbulence region

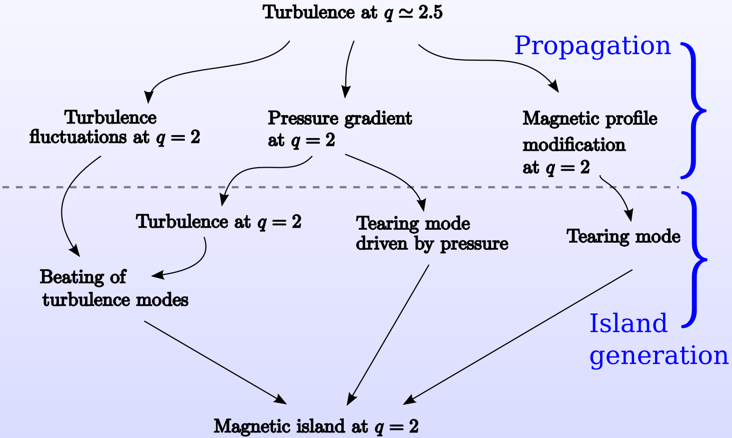
How this $(2, 1)$ island can be generated in the quiet zone ?

Island generation: Possible mechanisms ?

separatricemovie.mpg

The magnetic island has different shapes during the time evolution.

Island generation: Possible mechanisms ?



Turbulence at $q \simeq 2.5$

Propagation

Turbulence fluctuations at $q = 2$

Pressure gradient at $q = 2$

Magnetic profile modification at $q = 2$

Turbulence at $q = 2$

Tearing mode driven by pressure

Tearing mode

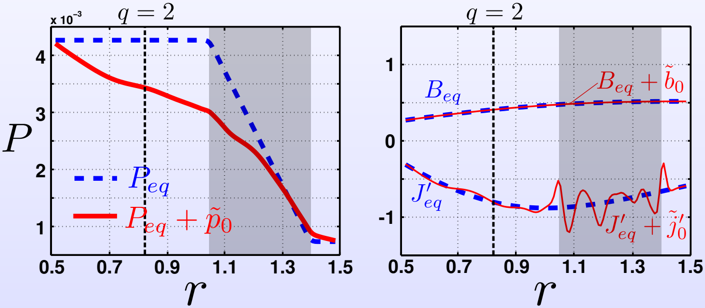
Beating of turbulence modes

Island generation

Magnetic island at $q = 2$

Does profile modifications destabilise the system ?

The profile evolutions are slow compared with the characteristic time γ^{*-1} of interchange instability. The non-linear profiles can be seen as successive new equilibria in that context.

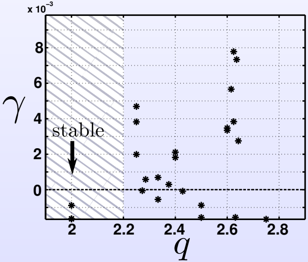


The pressure profile is modified at $q = 2$.
The current is weakly modifed only in turbulence area.

Stability of such profiles with respect to interchange and tearing instabilities ?

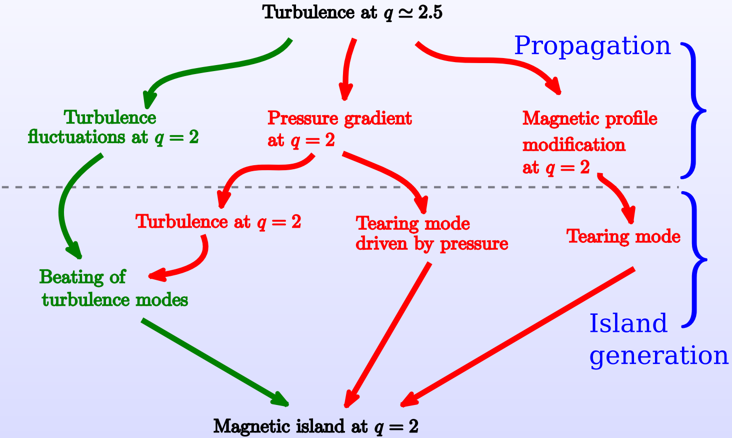
Does profile modifications destabilize the system ?

Growth rates are computed by means of linear simulations using the modified asymptotic equilibrium profile:



The profile modifications do not generate instabilities at $q = 2$, neither tearing, nor interchange.

Non linear evolution: Possibles mechanisms ?



Turbulence at $q \simeq 2.5$

Propagation

Turbulence fluctuations at $q = 2$

Pressure gradient at $q = 2$

Magnetic profile modification at $q = 2$

Turbulence at $q = 2$

Tearing mode driven by pressure

Tearing mode

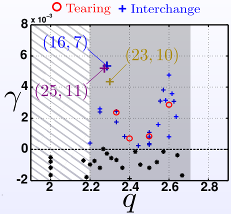
Beating of turbulence modes

Island generation

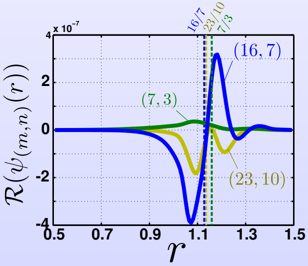
Magnetic island at $q = 2$

Non linear evolution : Beating of dominant unstable modes

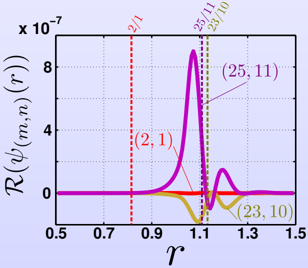
1. The modes beat if they overlap.
2. The beating is efficient if the resulting mode is resonant at its birth location.



$(23,10)+(16,7)=(7,3)$. Rules are satisfied, the $(7,3)$ is generated.



$(25,11)+(23,10)=(2,1)$. Rules are not satified, the $(2,1)$ is not generated at its resonance.



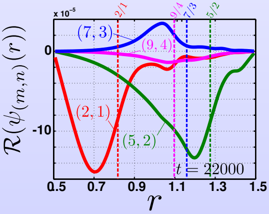
Then, how to explain the growth of the mode (2,1) ?

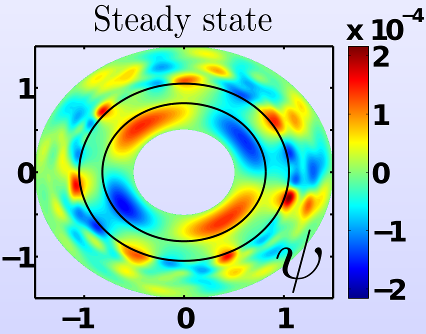
Non linear evolution : coherent and delocalised beating

- The beating mecanisms produces modes with large radial structure $(5, 2)$, $(7, 3)$ and $(9, 4)$ in the QL phase and remains efficient in the whole NL phase.
- The beating of such modes generates $(2, 1)$ but only at the tail of the eigen function, at $q = 2$.

$$(9, 4) + (7, 3) = (2, 1)$$

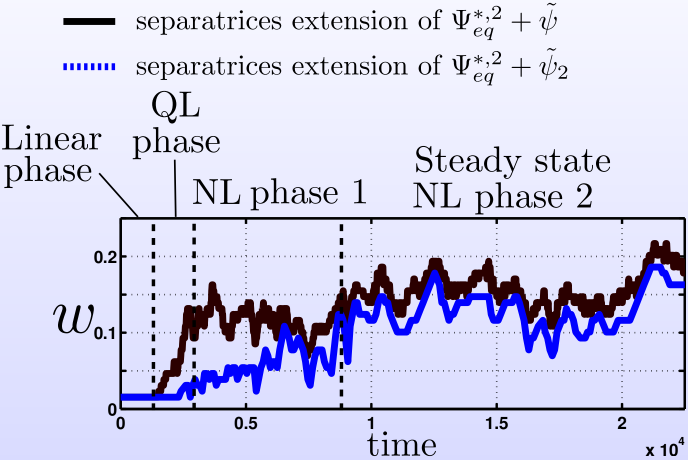
$$(7, 3) + (5, 2) = (2, 1)$$





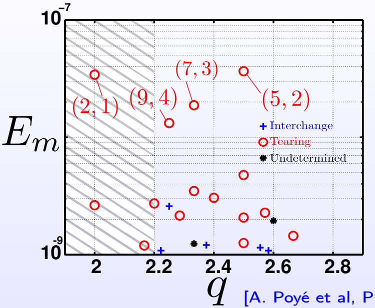
Turbulence driven island width evolution

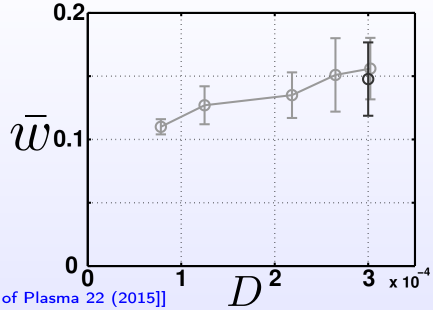
[A. Poyé et al, Phys. of Plasma 22 (2015)]



Slow and linear growth of the mode $(2, 1)$ during the Non Linear phase. $\dot{\overline{w}}_{2,1} =$ constant (but not Rutherford !)

TDMI island widths





[A. Poyé et al, Phys. of Plasma 22 (2015)]

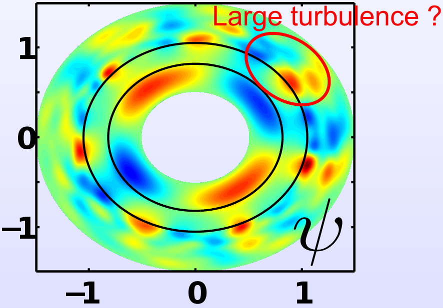
- $(2,1)$ magnetic energy saturation levels $\approx$ energy fluctuations of turbulent modes
- $\bar{w}$ weakly depend on the anomalous transport coefficient

$$D(\hat{\rho}, \chi_\perp, \eta, \dots) = \sum_{m,n}^{\gamma_{m,n}>0} \frac{\gamma_{m,n}}{k_m^2}$$

- Extrapolation to realistic values ($D \ll 10^{-4}$) gives $\bar{w}_{\text{TDMI}}/a \gtrapprox 1.5\%$, (remote turbulence contribution)

$\approx$ of the order of magnitude of the expected ITER critical size w_{cri}

An improved fluid model



Can we have magnetic islands of width much larger than turbulent eddies?

Model with Zonal Flow (ZF)

Gyrokinetic simulations have shown that turbulence can generate strong zonal flow and no inverse cascade/coalescence of turbulent eddies[1].

We inject those mechanisms in MHD equations by introducing an anomalous viscosity ν_{00}, much smaller than ν, at the largest scale. The goal is to inhibit the generation of large scale turbulent eddies by amplifying the zonal flow.

$$\partial_t \tilde{\psi} = \nabla_{\parallel} \tilde{\phi} - \nabla_{\parallel} \left(P_{eq} + \tilde{p} \right) + \eta \tilde{j}$$

$$\partial_t \tilde{\omega} + \left\{ \tilde{\phi}, \tilde{\omega} \right\} = \nabla_{\parallel} \left(J_{eq} + \tilde{j} \right) - \frac{\kappa_1}{r} \partial_\theta \tilde{p} + \nu \triangle_{\perp} \tilde{\omega} + \left(\nu_{00} - \nu \right) \triangle_{\perp} \tilde{\omega}_{00}$$

$$\partial_t \tilde{p} = \left\{ P_{eq} + \tilde{p}, \tilde{\phi} \right\} + \rho^{*2} \left\{ \Psi_{eq} + \tilde{\psi}, J_{eq} + \tilde{j} \right\} + \chi_{\perp} \triangle_{\perp} \tilde{p}$$

Tearing Mode, interchange, zonal flows.

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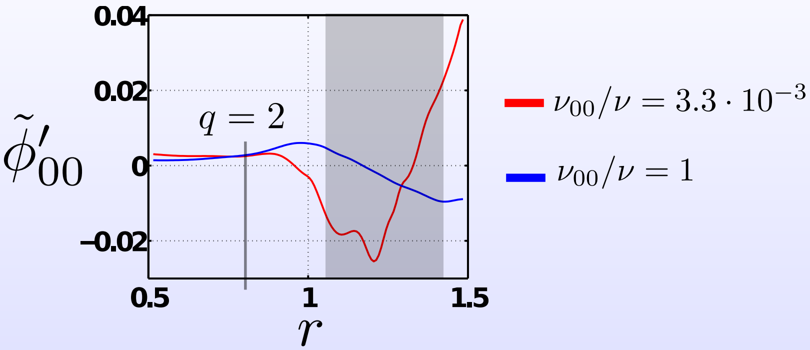
[1] Z. Lin et al, Science, 281 1835 (1998)

Impact of ν_{00} on the ZF



Strong shear flow for case $\nu_{00}/\nu = 3.3 \cdot 10^{-3}$.

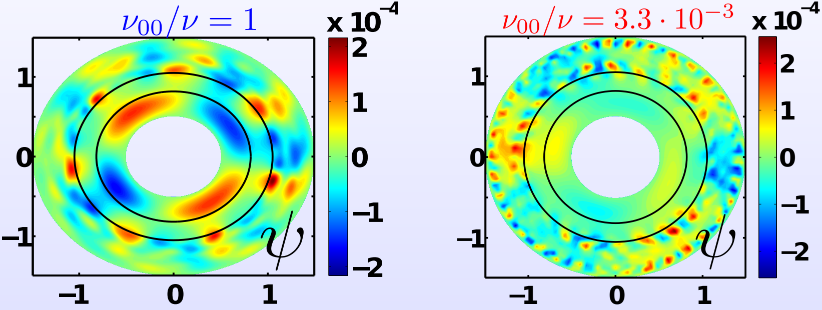
Weak shear flows for case $\nu_{00}/\nu = 1$.

Effect of the ZF on the turbulence

psi_ZF_movie.mpg

The zonal flow break the large structure of turbulence.

Effect of the ZF on the turbulence



$\nu_{00}/\nu = 1$

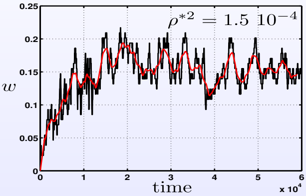
$\nu_{00}/\nu = 3.3 \cdot 10^{-3}$

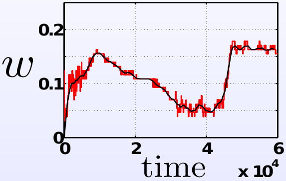
Zonal flow reduces turbulent eddy sizes

Island is still generated.

Effect of the ZF on the magnetic island

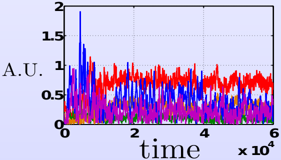
$\nu_{00}/\nu = 1.$ $\nu_{00}/\nu = 3.3 \cdot 10^{-3}.$

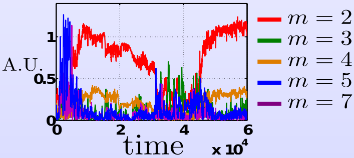




The ZF calms the island short-term fluctuations.

$$X(k, \Psi_{ptX}) = FFT(x(y, \Psi_{ptX}))$$





The ZF can destabilize but the maximal island size is the same.
Intermittent predator-prey behavior?

Behavior similar to FIR-NTM regimes . . .

Conclusions 1

- Interchange can drive seed TDMIs and NTMs. Mechanisms and limitations have been discussed.
- TDMI island sizes are possibly compatible with the required size to seed NTMs, including in ITER
- The ZF kills island width fluctuations on turb. time scales but can irregularly stabilize islands. A link with FIR-NTM? A predator-prey mechanism?

- With ZF, TDMI are noticeably larger than turbulent eddies
- The role of the toroidal geometry, the spreading of the turbulence, kinetic mechanisms remain to

Conclusions 2

- MHD, Island and Turbulence activities started in 2008, 3 PhD students, 2 postdoctoral positions (not only interaction between islands and turbulence)
- A parallel code AMON has been developped to face the multiscale character of the subject
- Basic fluid models are endangered in the hot magnetized plasma communauty, but we think they can still help to open up some problems
- Meso-scale physics (between MHD and Turbulent scales, including kinetic aspects) should received an enhanced attention, both theoretically and experimentally, because MHD does not ignore that turbulence is present and conversely.

Thank you for your attention

Conclusions 3: some details

- In the vicinity of a low order rationnal resonant surface, interchange instabilities can drive seed TDMIs and NTMs.
- TDMIs: Beating, NL generation of radially extended modes are key mechanisms. Spreading of turbulence?
- The mean island width weakly depends on the anomalous diffusion coefficient, which caracterizes interchange energy source.
- The island energy contents is of the order of dominant turbulent magnetic fluctuations in the absence of ZF
- The ZF mitigates island width fluctuation levels on turbulent time scales but it shows an irregular, possibly intermittent, behavior on larger time scales. A predator-prey mechanism? A link with FIR-NTM?
- Resulting island widths appear to be possibly noticeably larger than turbulent eddies and potentially comparable to the require critical size for the growth of NTM. Impact of the toroidal geometry?

Numerical parameters

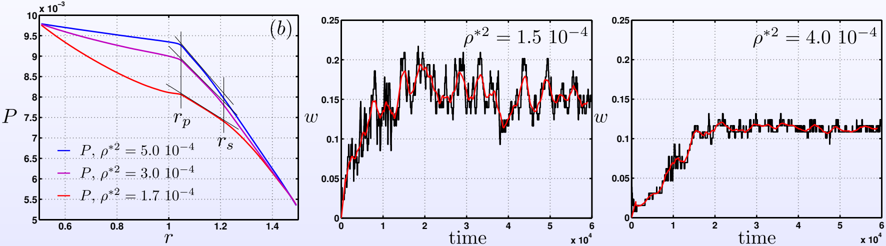
Fixed parameters

Numerical parameters : $N_X = 128$, $N_Y = 128$, $N_Z = 64$, $dt = 0.01\tau_A$.
Diffusive parameters : $\eta = 1 \cdot 10^{-4}$, $\nu = 3 \cdot 10^{-5}$, $\chi_\perp = 1 \cdot 10^{-5}$.
Equilibrium parameters : $\kappa_1 = 0.1$, $v^* = P'_{eq} = -0.01$, $q_{max} = 2.9$, $r \in [0.5, 1.5]$.

Scanning parameters

Setting the turbulence level : $\rho^{*2} \in \left[1.5 \cdot 10^{-4}, 4 \cdot 10^{-4}\right]$.
Setting the presence of $q = 2$: $q_{min} = 1.9$ or $q_{min} = 2.1$

Turbulence driven island width evolution

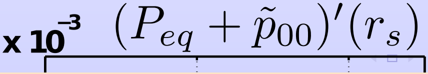


- Turbulence affects strongly mean pressure profile:

$$D = \sum_{m,n}^{\gamma_{m,n}>0} \frac{\gamma_{m,n}}{k_m^2} \text{ with } \frac{dD}{d\rho^\star} < 0$$

Island size and fluctuations decrease with $\rho^\star$ and depend on various parameters controlling interchange instability

Evolution of the pressure gradient at r_s:



Why the island $(5, 2)$ is vanishing ?

1. The turbulence develop on $r > r_p$ (edge zone).
2. Beating of dominant interchange localized modes generate large radial structure mode: they reach $r = r_2$.
3. Such mode beat themselve and generate the mode $(2, 1)$.
4. The mode $(9, 4)$, $(7, 3)$ have a feed back from $(2, 1)$: they have comparable energy to $(5, 2)$.
5. The density of rationnal surface mode amplitude are too high to let the islands $(9, 4)$, $(7, 3)$ and $(5, 2)$ distinctly appear.