Multi-scales physics of magnetic reconnection in hot plasmas

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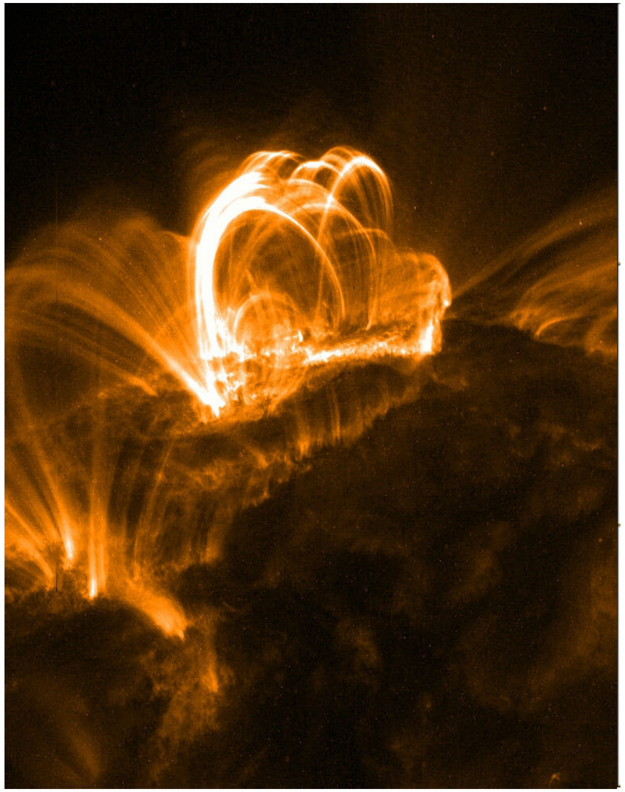
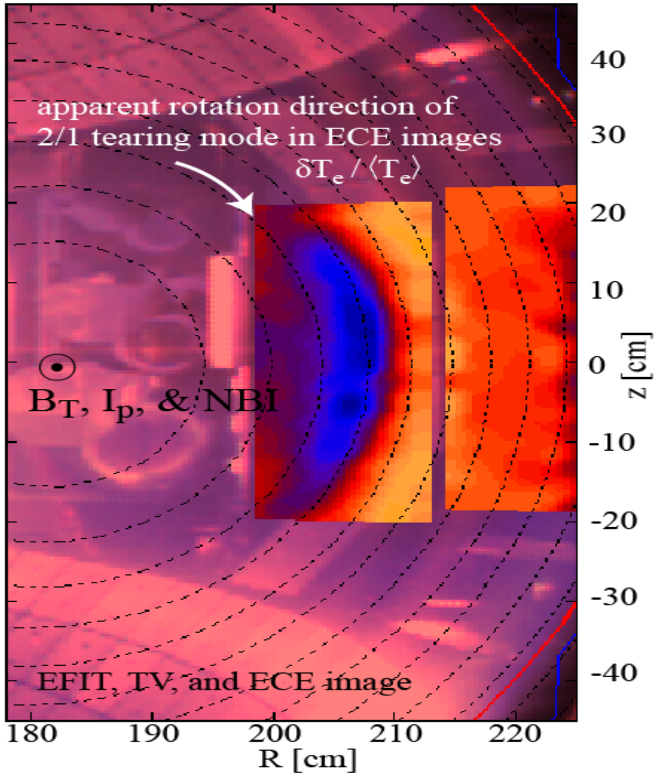
Magnetic reconnection is ubiquitous in nature

Magnetic reconnection consists of a **modification** of magnetic field **topology** and generates **magnetic island shape structures (in 2D)**.

Large magnetic island in KSTAR
[Minjun J. Choi, 2021]

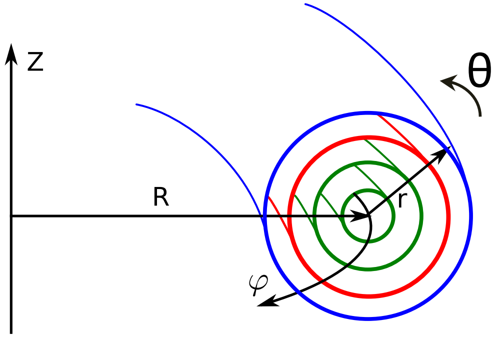




September 2005, captured in the X-ray waveband by NASA’s TRACE satellite.
[Courtesy of the University of California Berkeley, all rights reserved]

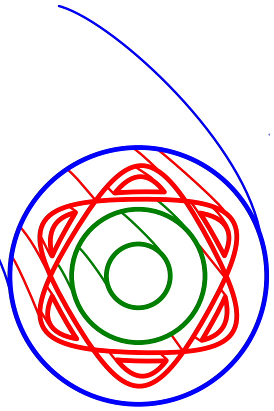
Magnetic reconnection at various scales

In fusion devices, **instabilities** lead to **magnetic island** formation **from small to large scales**.



« Tearing » instabilities:
Magnetic field lines are torn then reconnected on resonant surfaces (in red)

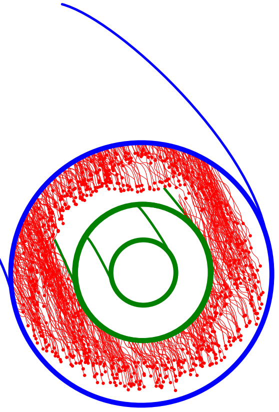
Large (few cm)
magnetic islands



[Rutherford PF 16 (1973)]

- Origin and control of large magnetic islands ?

Small (mm)
Reconnected structures



[Hazeltine et al. PF 18 (1975)]

- Impact on electron heat transport ?

Magnetic reconnection is at the heart of open issues in fusion

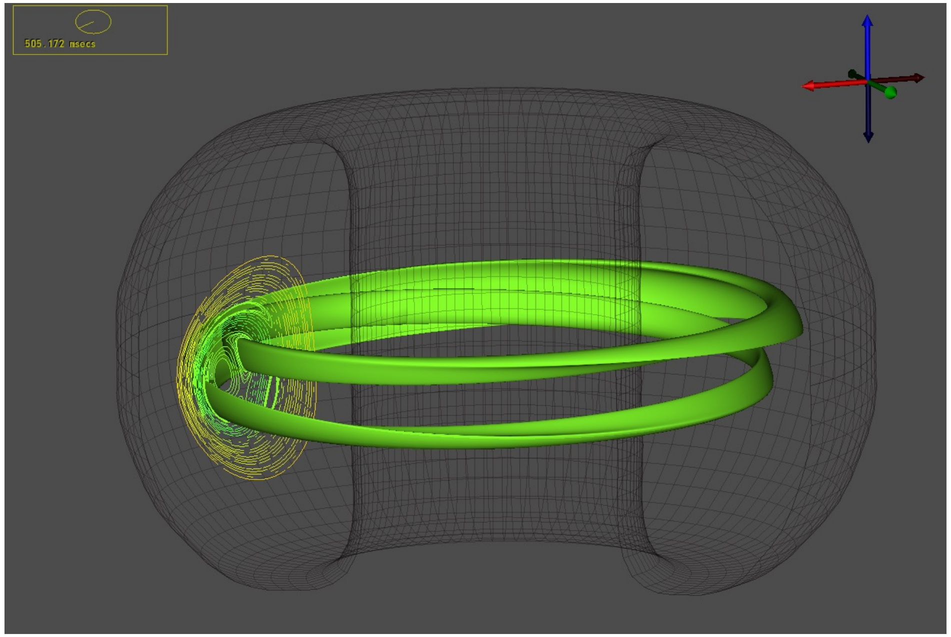
- Origin and control of large magnetic island(s) called NTM(s) **[Kong PPCF 2022]**
  EFTC Conference 2023 : I.8 E. Poli

- Micro-tearing modes is found unstable in JET pedestal **[Hatch NF 2016]**

- Magnetic reconnection is observed in sawtooth crashes **[Yu NF 2022]**

- Runaway electrons can drive magnetic reconnection **[Grasso JPCS 2022]**
  EFCT Conference 2023 : P.1.28, D. Grasso et al.

- Magnetic reconnection will play a role in compact high fields tokamaks with high β. What is the relevance for fusion applications of such configurations ?
  [Guo Nat. Comm. 2015]



NIMROD code

=> Understanding magnetic reconnection theory is crucial for many challenging issues of fusion plasmas

A brief history of Magnetic Reconnection 1/2

- Magnetic reconnection is first and foremost an **electromagnetic phenomenon** taking place in a medium in the plasma state.

- Historically: Space plasma context

During MR reconnection process, magnetic energy is converted into kinetic energy

=> Particles are locally accelerated

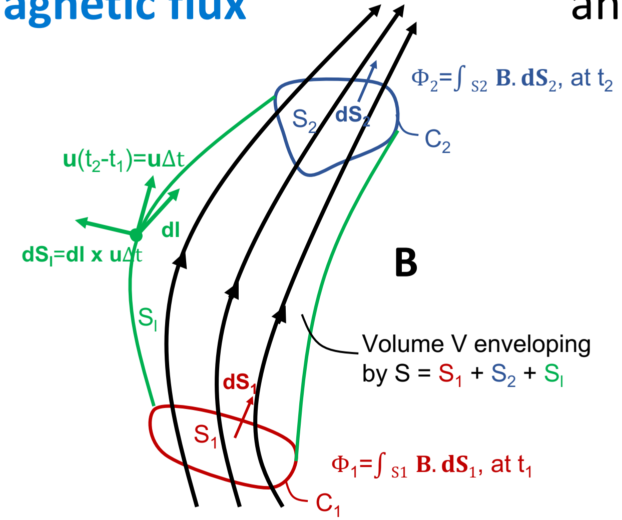
- Observed and studied since the 1940s
- First models : in a 2D fluid framework

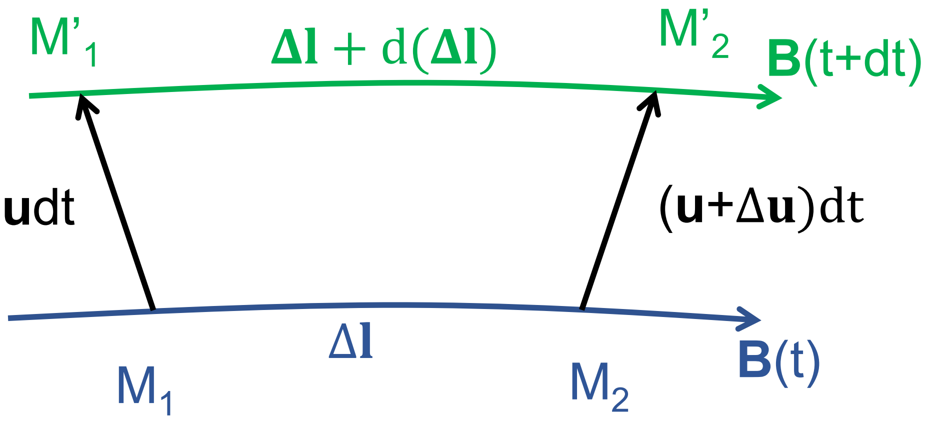
- Concept of « **magnetic field line motion** » proposed by Alfvèn in 1943

  [H. Alfvèn, Cosmical Electrodynamics, Oxford Univ. Press. 1950]

In ideal MHD, induction equation = equation of motion/transport of ***B*** in a moving (***u***) plasma $\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$

Magnetic flux and **Magnetic connectivity are conserved**:





A brief history of Magnetic Reconnection 2/2

- T.G. Cowling : Frozen-in law can be broken due to conductivity

$$\frac{\partial_1 \boldsymbol{B}}{\partial t} = \mathrm{curl}\ (\boldsymbol{v} \times \boldsymbol{B})$$

$$\frac{\partial_2 \boldsymbol{B}}{\partial t} = \frac{1}{4\pi\mu\sigma} \nabla^2 \boldsymbol{B}.$$

[T. G. Cowling, *Visitas in Astronomy*, 1955]

- In 1946, Giovanelli : on sunspost of solar flares particles are accelerated around a local ***« reversing layer »*** where ***« the magnetic field vanishes »*** . Giovanelli highlights also the imporance of the conductivity. **[R. G. Giovanelli, *Nature*, 1946]**

- Importance of the work of Dungey: **[J. W. Dungey, Phil. Mag., 1953]**

« |curlH| is very large in a small region near the neutral point. The field is not frozen into the gas in this region and the line of the force can regarded as being broken and rejoined in the way just described » **=> Magnetic reconnection is born**

- In 1958, the **resistive Sweet-Parker model** of MR highlights for the first time the physical mechanisms at play and gives a first evaluation of the characteristic time of a MR process

=> $\tau_{RM} \sim \sqrt{\tau_\eta \tau_A}$ >> first experimental evaluations in the space and fusion context!!

=> Resistivity can not explain MR in these context !!???!!!!

=> Or maybe yes… Maybe resistivity can explain the orgin of MR and then another physical mechanism can accelerate/drive the growth of reconnected structures…

Magnetic Island Life

I. **Origin :** What non ideal phenomenon breaks the magnetic field topology ?

II. **Drive :** What makes the island grow ?

III. **Saturation:** Prediction of the saturation ?

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

II. Drive : What makes the island grow ?

III. Saturation: Prediction of the saturation ?

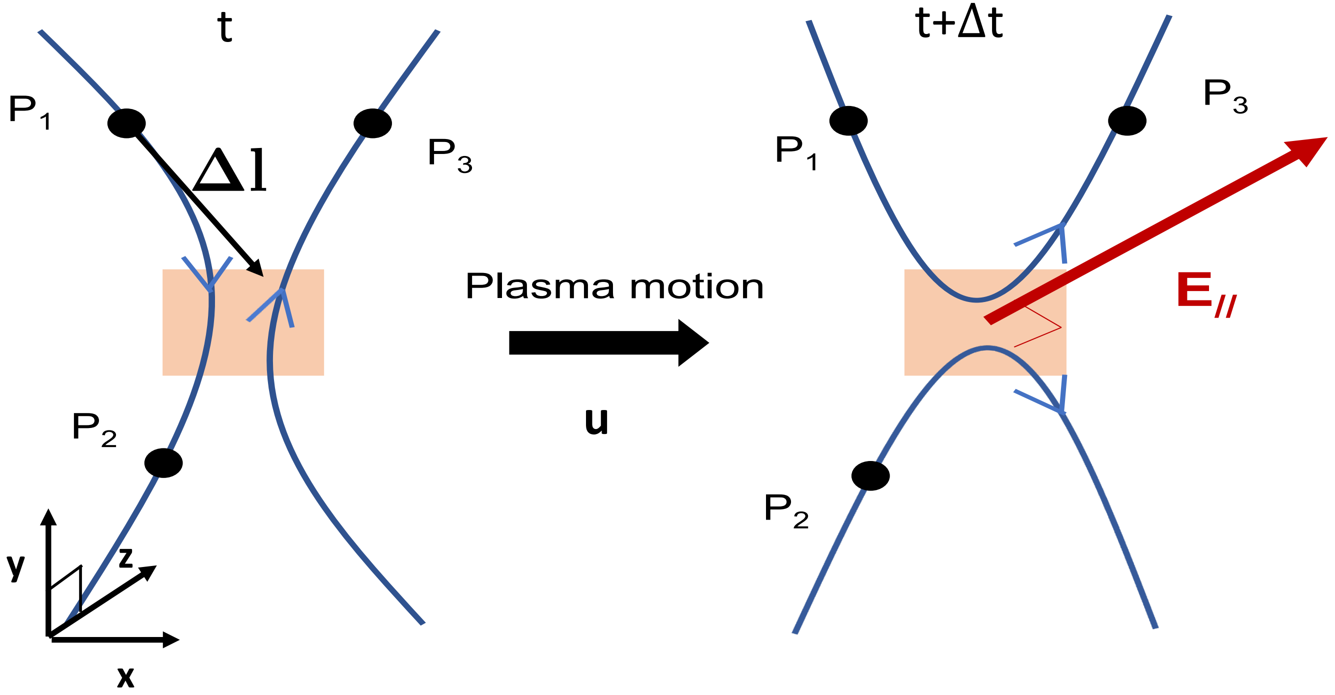
I. Physics behind magnetic reconnection

$$\mathbf{B} = \mathbf{B}_{\parallel} + \mathbf{B}_{\perp}$$

$$\mathbf{B}_{\parallel} = B_0 \mathbf{z}$$

$$\mathbf{B}_{\perp} = \delta B_x \mathbf{x} + \delta B_y \mathbf{y}$$

$$B_0 >> \delta B_x,\ \delta B_y$$



- Conservation of magnetic conectivity in MHD :

$$\frac{d}{dt}\left(\mathbf{\Delta l} \times \mathbf{B}_{\perp}\right) = \left[\nabla \times \mathbf{E}_{\parallel}^{\mathbf{NI}}\right] \times \mathbf{\Delta l}$$

=> Magnetic reconnection is the result of a local non-conservation of magnetic connectivity between two times

I. Scales competition in MHD generalized Ohm’s law

$$\mathbf{E} = \overbrace{-\mathbf{u}\times\mathbf{B}}^{\text{Ideal term}} + \overbrace{\eta\mathbf{j} + \frac{1}{n_e e}\mathbf{j}\times\mathbf{B} - \frac{1}{n_e e}\nabla p_e + \underset{\substack{\downarrow \\ \propto m_e}}{\mathbf{E}_{\mathbf{iner}}}}^{\text{Non-ideal ideal terms}} = (-\mathbf{u}+\mathbf{u}_{\mathbf{Hall}})\times\mathbf{B} + \mathbf{E}_{\parallel}^{\mathbf{NI}}$$

induction **resistivity** **Hall effect** **thermal effect** **$\propto m_e$**

L (m) >> l_η (cm, mm) $\geq$ L_{ri} (mm) > L_e

At **large scales**

=> no magnetic reconnection

Ideal MHD is valid, the magnetic field and the plasma are frozen-in together in a commun evolution and magnetic connectivity is conserved $\frac{\mathrm{d}}{\mathrm{dt}}(\boldsymbol{\Delta}\mathbf{l}\times\mathbf{B}) = \mathbf{0}$.

At **small scales**

=> magnetic reconnection leading to structures that reaches large scales

Various non-ideal phenomena can break the frozen-in law and lead to magnetic reconnection.

=> Magnetic reconnection is a multi-scales and a multi-physics problem

I. Scales competition in MHD generalized Ohm’s law

$$\mathbf{E}=\overbrace{-\mathbf{u}\times\mathbf{B}}^{\text{Ideal term}}\overbrace{+\eta\mathbf{j}+\frac{1}{n_e e}\mathbf{j}\times\mathbf{B}-\frac{1}{n_e e}\nabla p_e+\mathbf{E}_{\mathbf{iner}}}^{\text{Non-ideal ideal terms}}=(-\mathbf{u}+\mathbf{u}_{\mathbf{Hall}})\times\mathbf{B}+\mathbf{E}_{\parallel}^{\mathbf{NI}}$$

induction **resistivity** **Hall effect** **thermal effect** $\downarrow$ **∝m_e**

L (m) >> l_η(cm, mm) ≥ ρ_{ri} (mm) > d_e

Open question : Are **resistivity** or **electrons inertia** relevant to originate magnetic reconnection in fusion devices ? **Historical point of view => No!**

Sweet – Parker mechanism **(1957, 1958)** gives an estimation of the reconnection rate based on **resistive** reconnection :

$$\tau_{RM}\sim\sqrt{\tau_\eta\tau_A} \quad \text{with } \tau_A=\frac{L}{v_A},\ \tau_\eta=\frac{L^2}{\eta} \quad \text{and} \quad \tau_{RM}\sim\frac{L\tau_A}{d_e}$$

- **Center of TCV** (L ~ 0.25 m, B = 1.43 T, $\eta\sim10^{-5}\Omega\,.\,cm^{-1}$) : $\tau_{RM}^{TCV}\sim 2\ h$
- **Center of WEST** (L ~ 0.5 m, B = 3.7 T, $\eta\sim10^{-6}\Omega\,.\,cm^{-1}$) : $\tau_{RM}^{WEST}\sim 3\ days$
- **Center of JET** (L ~ 1 m, B = 3.45 T, $\eta\sim10^{-7}\Omega\,.\,cm^{-1}$) : $\tau_{RM}^{JET}\sim 115\ days$

Estimation based on reconnection due to **electron inertia** : $\tau_{RM}\sim\frac{L\tau_A}{d_e}\sim 10^{-3}s$

=> The growth of reconnected structures due to resistivity is too slow.
=> Reconnected structures due to electron inertia are too small.

I. Scales competition in MHD generalized Ohm’s law

$$\mathbf{E} = \overbrace{-\mathbf{u}\times\mathbf{B}}^{\text{Ideal term}}\overbrace{+\eta\mathbf{j}+\frac{1}{n_e e}\mathbf{j}\times\mathbf{B}-\frac{1}{n_e e}\nabla p_e+\underset{\substack{\downarrow\\ \propto m_e}}{\mathbf{E}_{\mathrm{iner}}}}^{\text{Non-ideal ideal terms}} = (-\mathbf{u}+\mathbf{u}_{\mathrm{Hall}})\times\mathbf{B}+\mathbf{E}_{\parallel}^{\mathrm{NI}}$$

induction **resistivity** **Hall effect** **thermal effect** $\propto m_e$

L (m) >> l_η (cm, mm) ≥ ρ_{ri} (mm) > d_e

Open question : Are **resistivity** or **electrons inertia** relevant to originate magnetic reconnection in fusion devices? **However**

1. Magnetic reconnection is a **multi-scales** problem and reconnection is originated in a thin non-ideal reagion

$\cancel{\tau_\eta = \frac{L^2}{\eta}}$, $\boldsymbol{\tau_\eta^{sheet} = \frac{l_\eta^2}{\eta}}$ (with $l_\eta \sim 0.01m$) **=>** **Increase of the resistive reconnection rate**

$\boldsymbol{\tau_{RM}^{TCV} \sim 10\ s}$. !!!!!, $\boldsymbol{\tau_{RM}^{WEST} \sim 2\ min}$. !!!!!, $\boldsymbol{\tau_{RM}^{JET} \sim 16\ min}$. !!!!!

2. In the Sweet-Parker model, there is no distinction between the physical mechanism breaking the Ohm’s law and the physical mechanism driving the reconnected structures.

=> In fusion devices, resitivity or electron inertia can originate magnetic reconnection. Then another physical mechanism drive the growth of resulting magnetic island(s).

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ? Conclusions

- **Resistivity (and collisions) and electron mass inertia are relevant to explain the origin of magnetic reconnection in tokamaks.**
- **Probably, another physical mechanism can drive/accelerate island(s) growth (part II).**

=> Open question : Possible kinetic mechanism breaking the frozen-in law ? Multi-scales picture of magnetic reconnection ?

II. Drive : What makes the island grow ?

III. Saturation: Impact on confinement ?

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

II. Drive : What makes the island grow ?

Small scale:

- Drive of micro-tearing mode by electronic temperature gradient

Large scale:

- ~~« Classical » tearing mode~~
- NTM (magnetic island seed is required!?)

=> Drive of large magnetic island by turbulence – TDMI mechanism (Turbulence Driven Magnetic Island)

III. Saturation: Impact on confinement ?

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

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=> Drive of large magnetic island by turbulence – TDMI mechanism
(Turbulence Driven Magnetic Island)

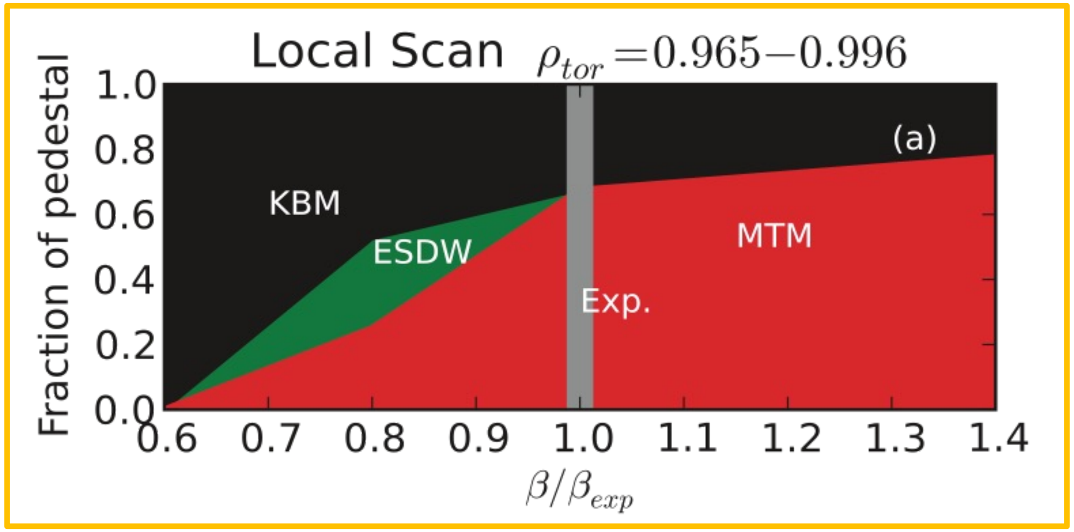
III. Saturation: Impact on confinement ?

II. Drive of Micro-Tearing Mode (MTM) in fusion devices?

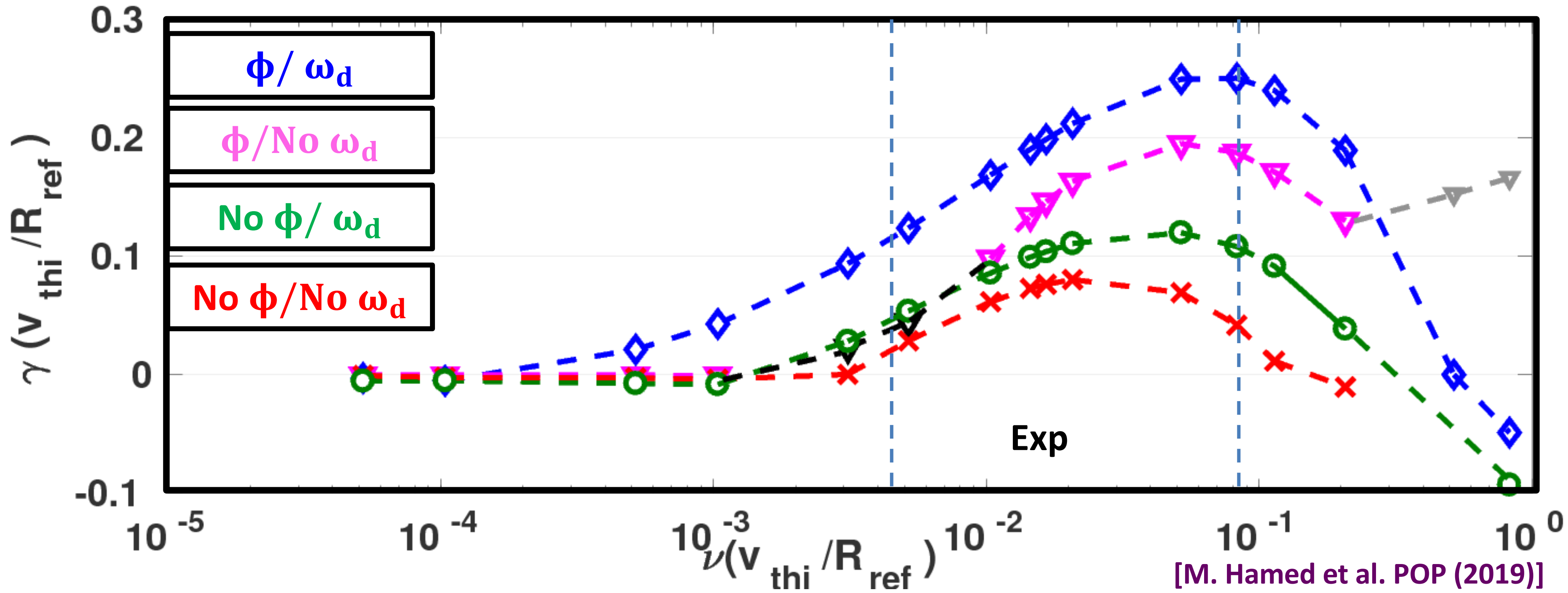
- Recent **gyrokinetic simuations** that found MTM unstable in weak collisional regime

[Applegate et al (2007)]
[Doerk et al, Guttenfelder et al (2012)]
[Dickinson et al, Predebon et al (2013)]
[Swamy et al (2014)]

MTM in pedestal JET [Hatch (2016)]



II. Destabilization of a MTM



[M. Hamed et al. POP (2019)]

- No instability without collisions => Magnetic reconnection is not allowed
- In experiences, collision frequency is large enough to allow tearing parity structures at small-scales. Then **electron temperature gradient** can drive MTM.
- **Magnetic curvature** and **electric potential fluctuations** can not destabilize MTM without collisions. However, **in presence of collisions, they enhance the MTM growth rate**.

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

II. Drive : What makes the island grow ?

Small scale:

- Drive of micro-tearing mode by electronic temperature gradient

Large scale:

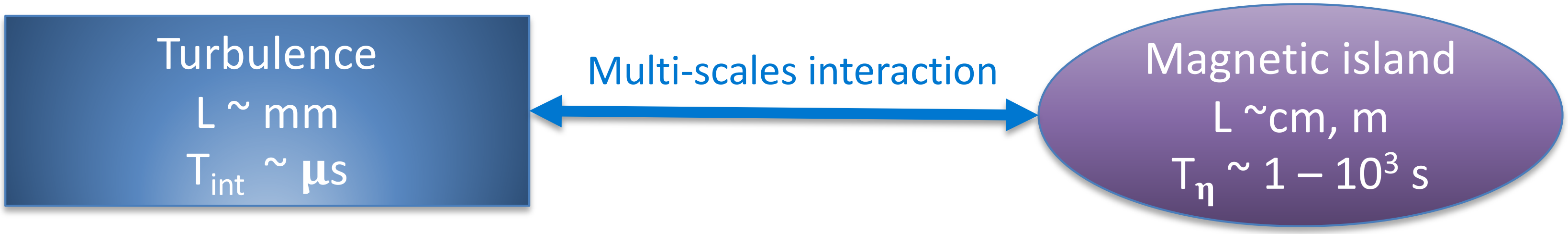
- NTM (magnetic island seed is required!?)

=> Drive of large magnetic island by turbulence – TDMI mechanism (Turbulence Driven Magnetic Island)

III. Saturation: Prediction of the saturation ?

II. Drive of large magnetic island by small-scales turbulence

- In fusion device large magnetic island cohexist with small-scales turbulence



Turbulence
L ~ mm
T_{int} ~ μs

Multi-scales interaction

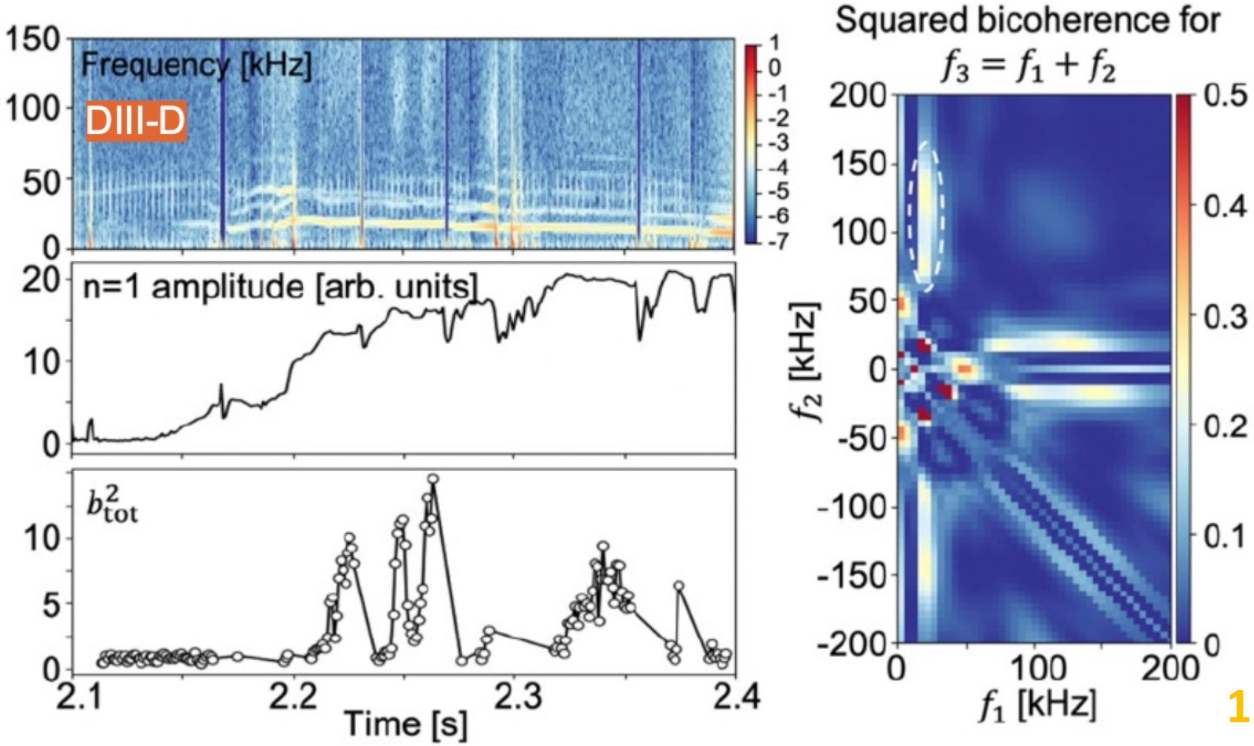
Magnetic island
L ~cm, m
$T_\eta \sim 1 - 10^3$ s

=> Can turbulence drive magnetic island (initially allowed by resistivity or electron inertia) in tokamaks? => Yes, it can!

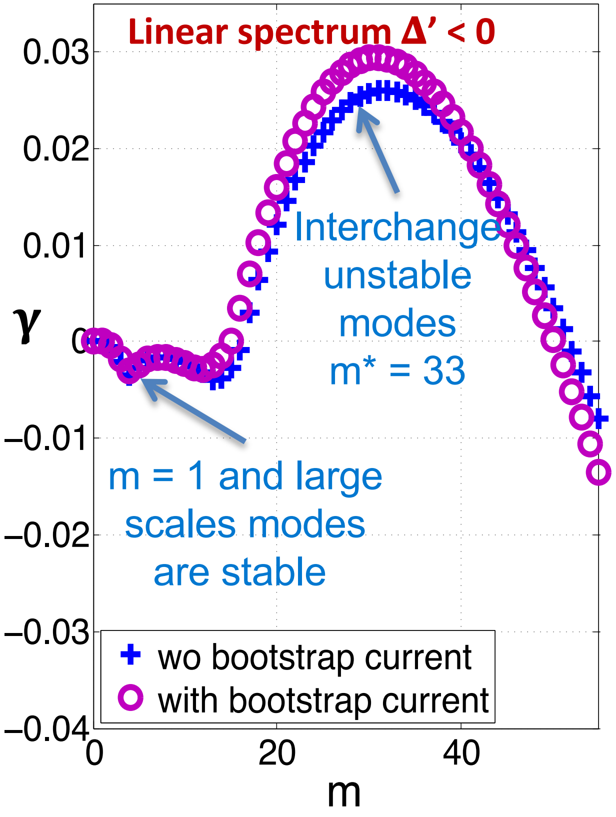
- Observations of multi-scales coupling between NTM and turbulence

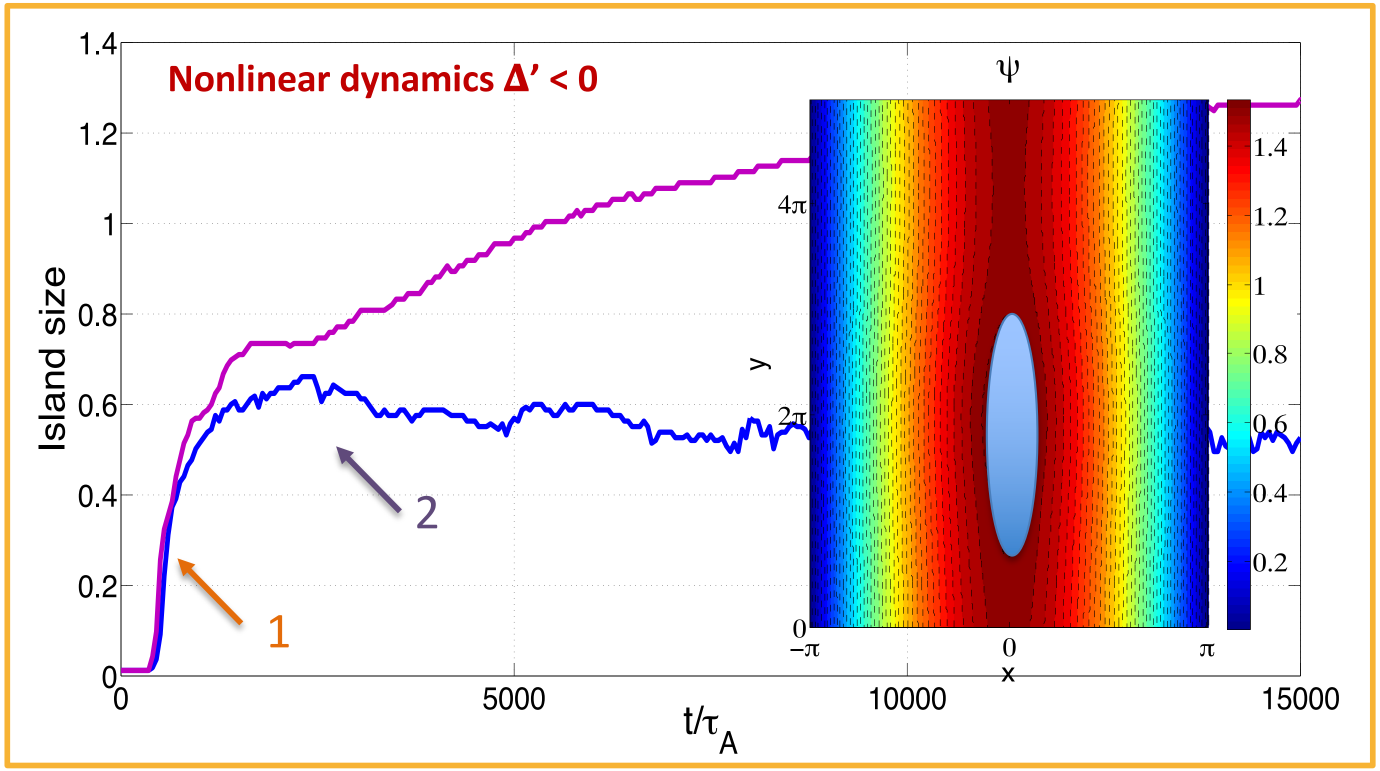
[Minjun J. Choi, Nat. Phys. 2021]

=> What is/are the possible physical mechanism(s) at play?



II. NTM growth from a 2D TDMI in MHD framework





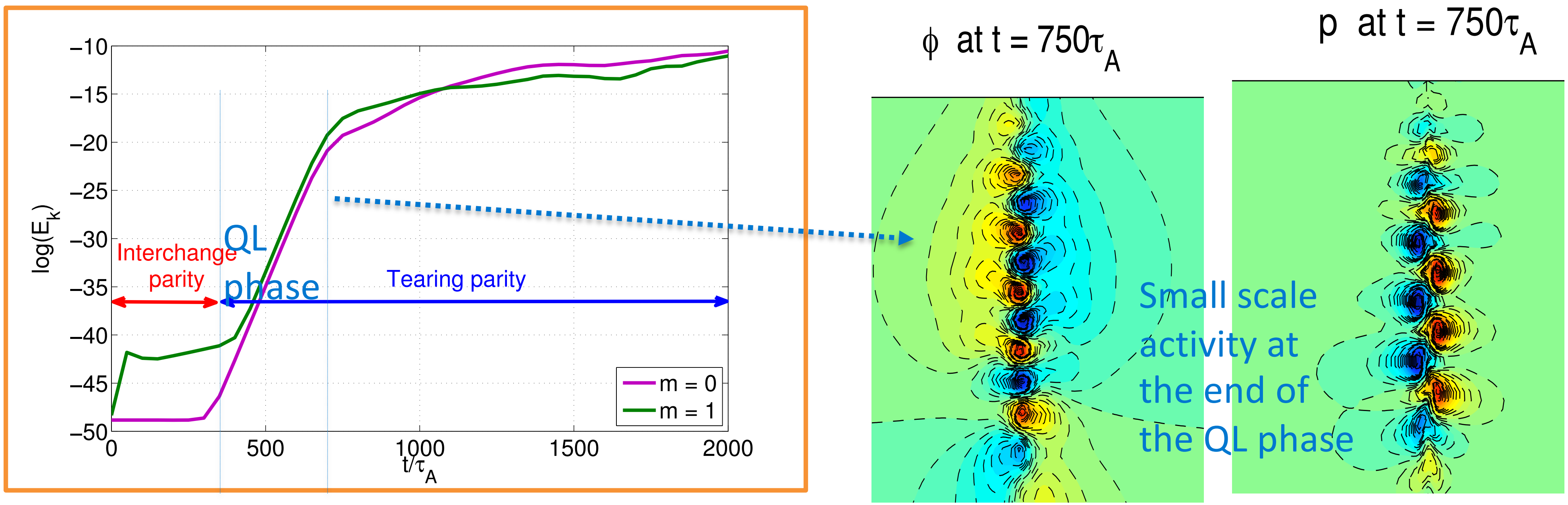
- 1 : TDMI formation

Turbulence can drive magnetic island originated by resistivity and can accelerated the growth of the island **[M. Muraglia et al., PRL (2011)]**

- 2 : NL growth of NTM

TDMI can be amplified by neoclassical effects leading to the growth of NTM. **[M. Muraglia et al, NF (2017)]**

II. Physical mechanism of 2D TDMI

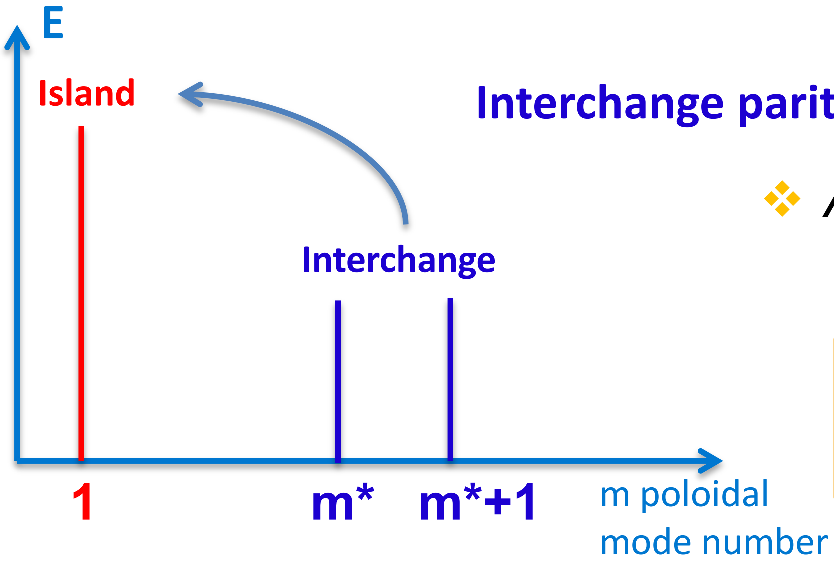


Small scale activity at the end of the QL phase

- Ohm's law projection on the mode m=1 :

$$\partial_t \psi_1 = (\partial_x \psi_{m\star})\, \phi_{m\star+1} ik \qquad + \;\dots$$

Interchange parity : Odd Even



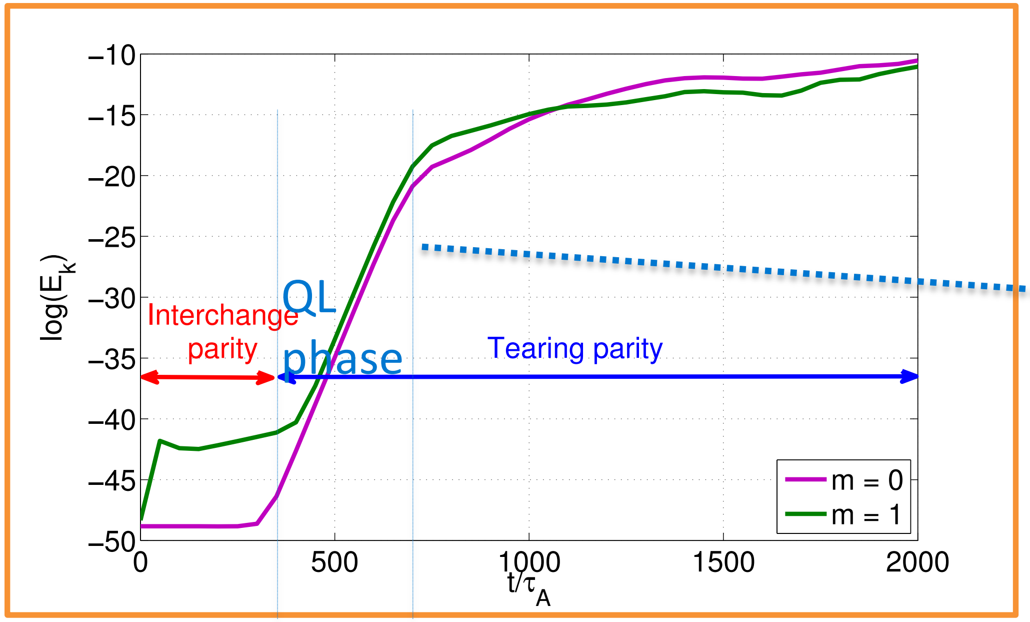
- *All the non linearities* of the model satisfy :

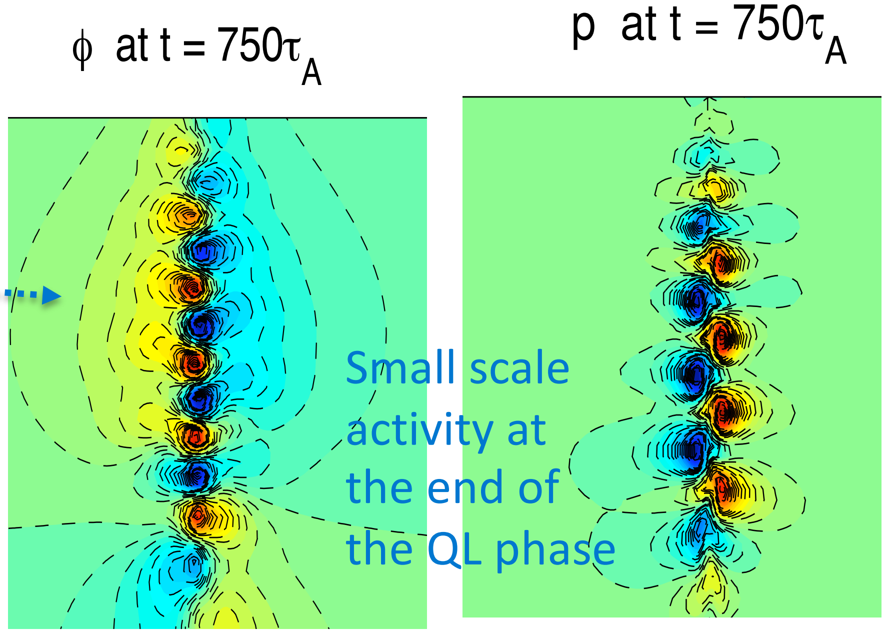
$$[\mathrm{Int}_{ss}, \mathrm{Int}_{ss}] \rightarrow \mathrm{Tear}_{ls}$$

Magnetic island generation by nonlinear beating of interchange modes

[Muraglia et al., PRL (2011) & Ishizawa, PPCF (2019)]

II. Physical mechanism of 2D TDMI



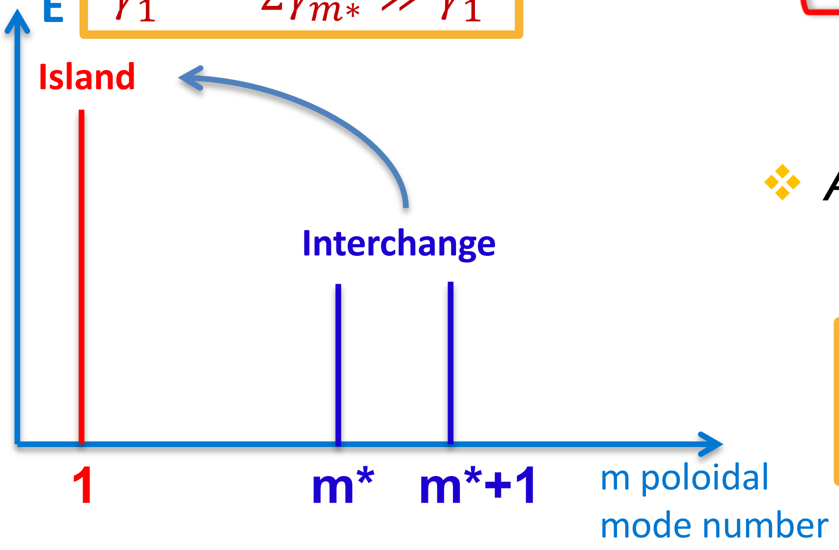


Small scale activity at the end of the QL phase

- Ohm’s law projection on the mode m=1 :

$$\partial_t\psi_1 = \underbrace{(\partial_x\psi_{m\star})\,\phi_{m\star+1}\mathrm{i}k}_{\textbf{Even => Tearing Parity}} \qquad + \quad \dots$$

$$\gamma_1^{NL} \sim 2\gamma_{m*}^{L} \gg \gamma_1^{L}$$



- *All the non linearities* of the model satisfy :

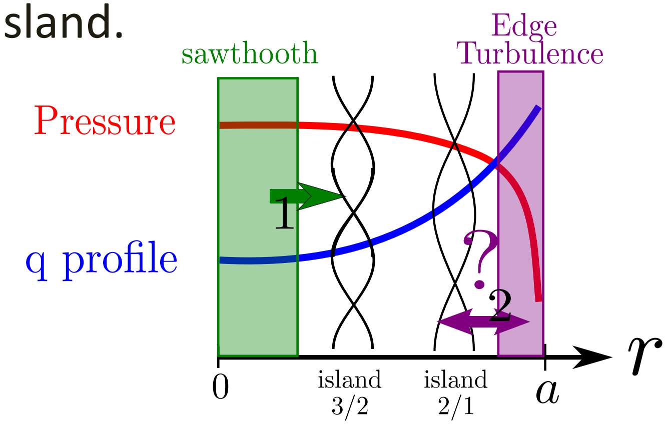
$$[\mathrm{Int}_{ss}, \mathrm{Int}_{ss}] \to \mathrm{Tear}_{ls}$$

Magnetic island generation by nonlinear beating of interchange modes

[Muraglia et al., PRL (2011) & Ishizawa, PPCF (2019)]

II. TDMI in 3D MHD cylindrical model

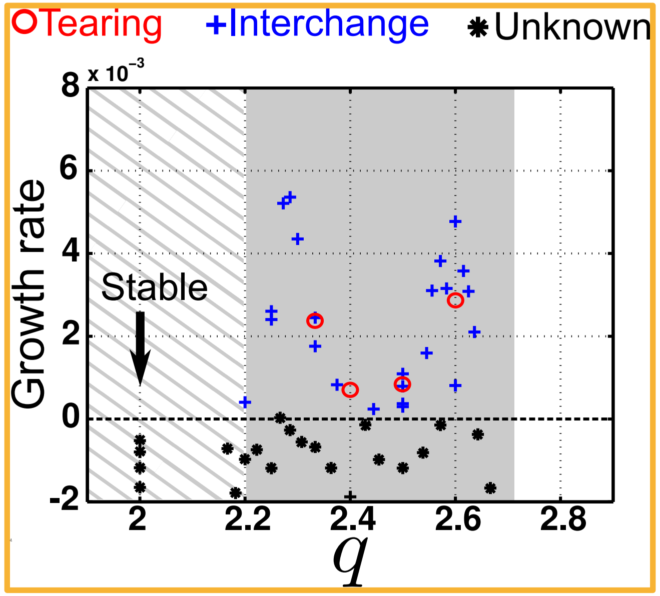
- In 2D slab geometry, turbulence and magnetic island are located around the same resonant surface **however,** in fusion devices, no systematic overlap between turbulence area and magnetic island.



Is nonlinear beating of interchange mode still efficient in 3D cylindrical model ?

- NL drive of (2, 1) magnetic island at stable location

[A. Poyé et al, POP 22 (2015)]



- Linearly

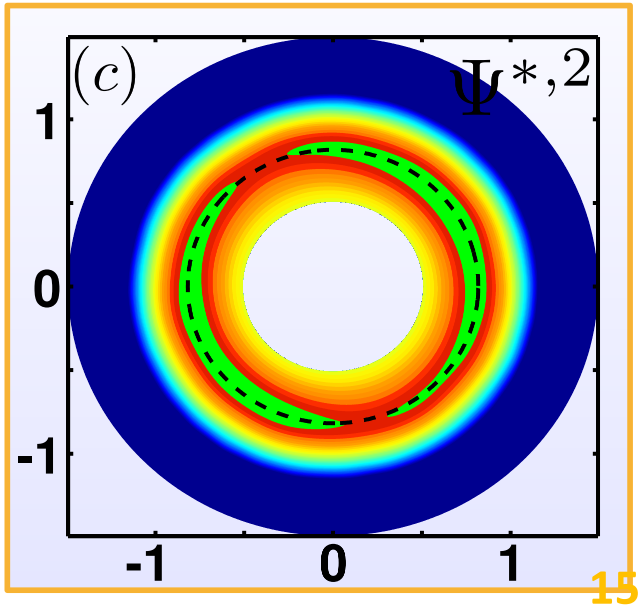
q = 2 stable

mainly interchange unstable Modes

- Nonlinearly

TDMI at q = 2

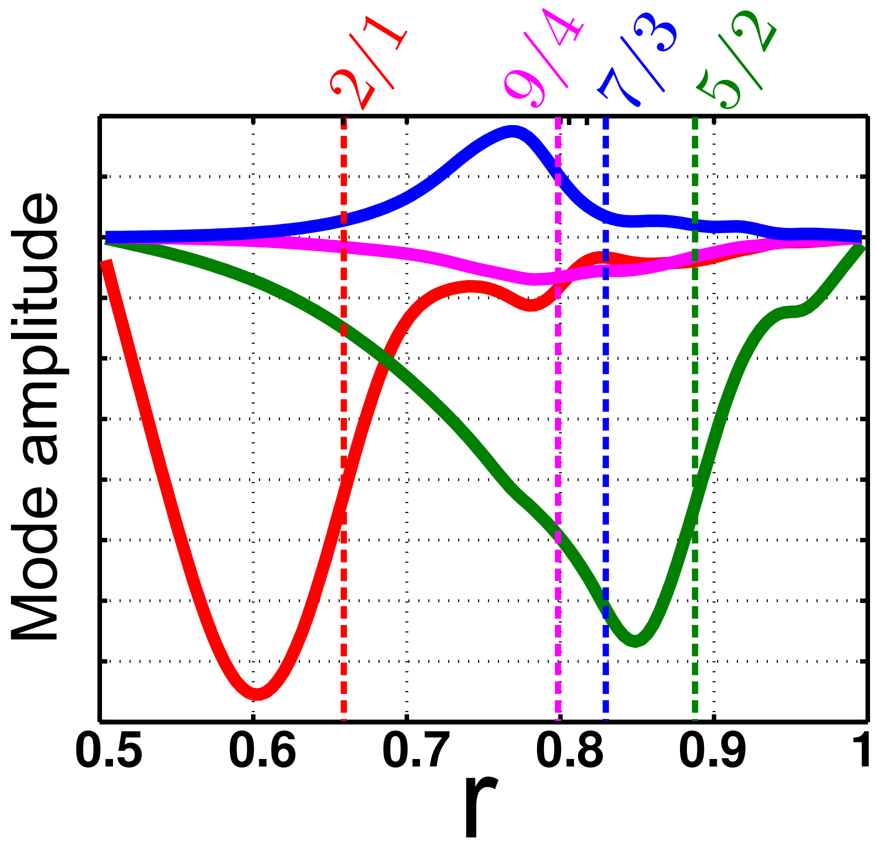
What is the physical mechanism at play ?



II. TDMI in 3D : coherent and non local beating

- The beating with turbulent modes produces with large tearing 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) at the tail of the eigen function, i.e. at q=2.

$$(7,3) - (5,2) = (2,1)$$
$$(9,4) - (7,3) = (2,1)$$



[A. Poyé et al, POP 22 (2015)]

- **3D Nonlinear coherent and nonlocal beating rules for TDMI growth :**

  1. The modes beat if they overlap.

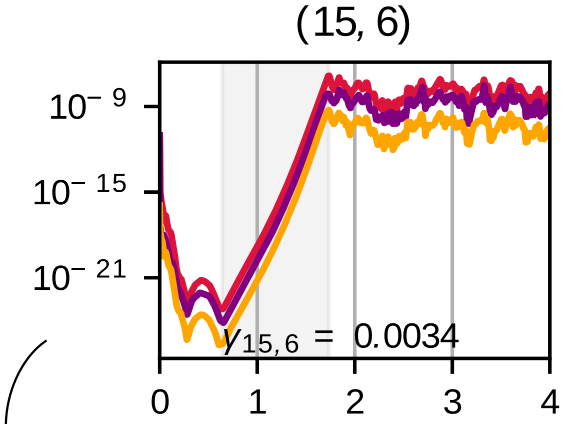
  2. The beating is effcient if the resulting mode is resonant at its birth location.

- **The (2, 1) island growth with a interchange time.**

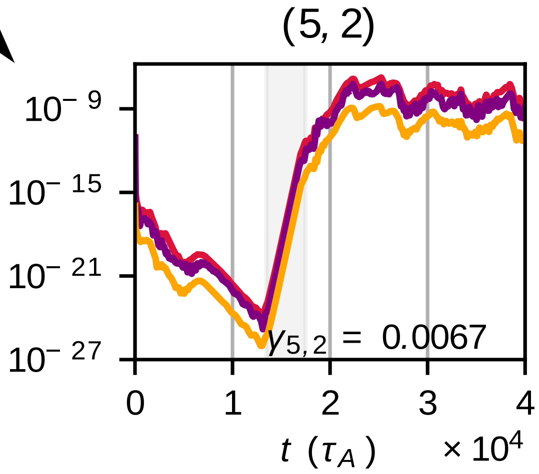
II. TDMI in 3D MHD : Impact of toroidal geometry

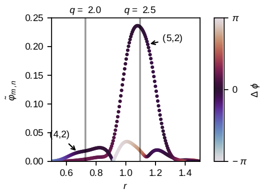
- Toroidal geometry introduce a new path toward TDMI

EFTC Conference 2023 : P.1.18, N. Dubuit et al.
[N. Dubuit et al, POP 28 (2021)]

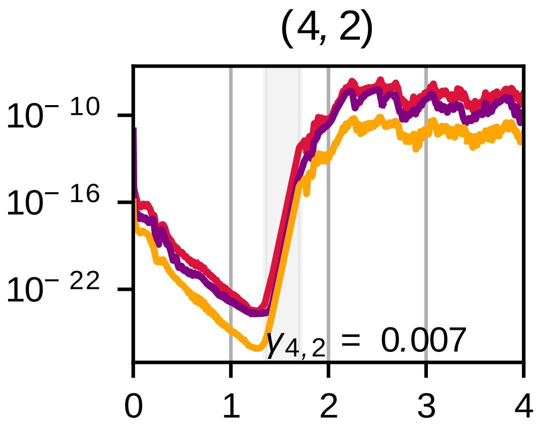


Turbulent cascade

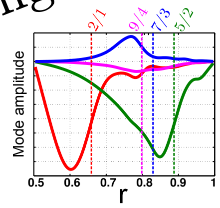


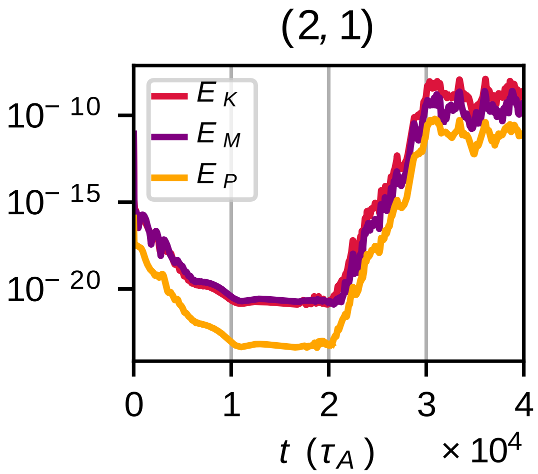


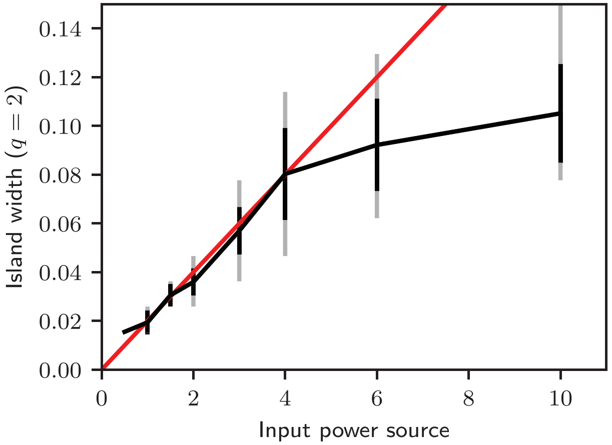
Toroidal coupling



Medium-scale mode beating





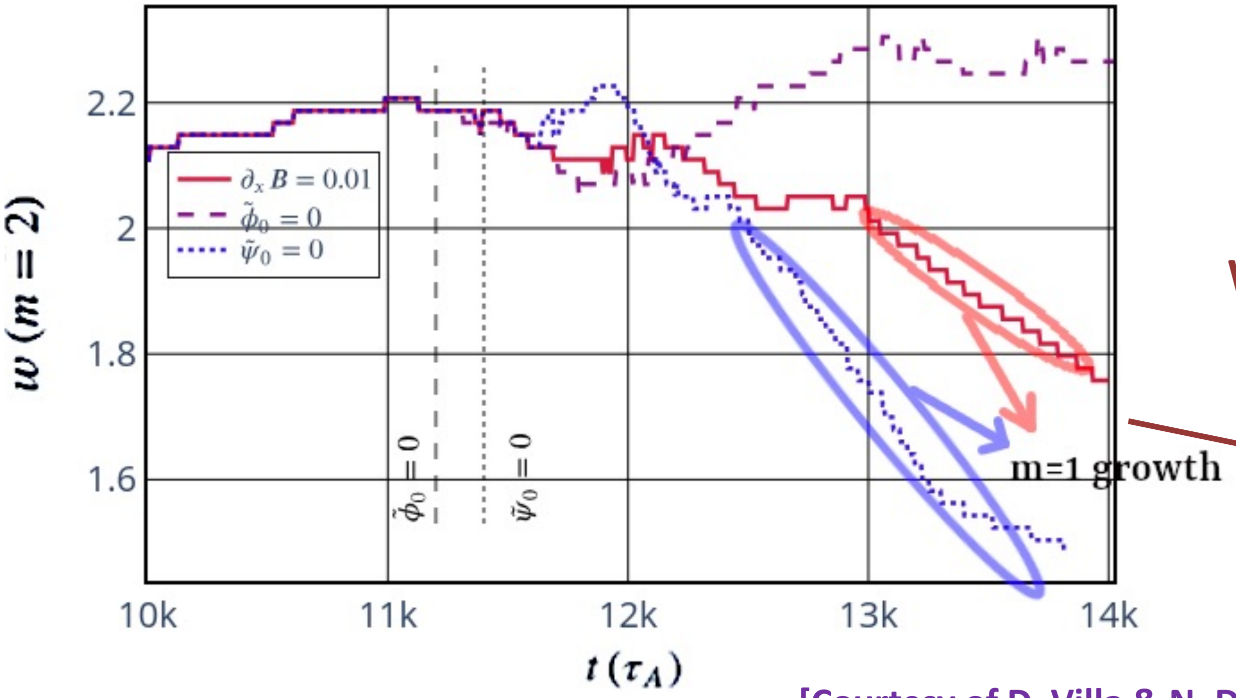


II. Interaction with Zonal Flow : New path toward TDMI

- Recent 6-fields MHD results between 2D coupling between KBM modes and zonal flows at low magnetic shear **EFTC 2023 Conference 2023: P.2.6, D. Villa & N. Dubuit et al.**

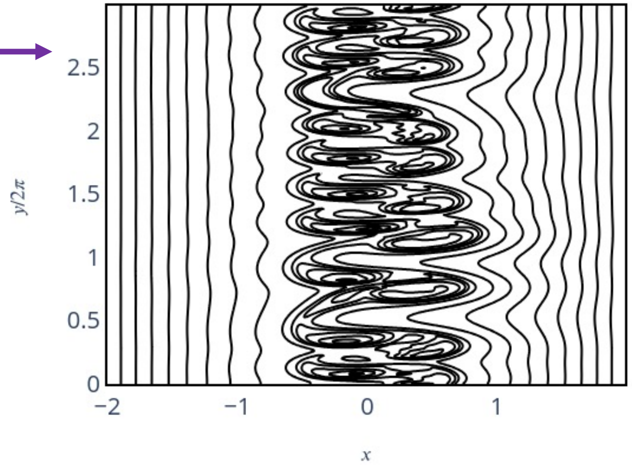
1. The KBM interchange modes get tearing parity at the begining of the nonlinear regime.

2. In presence of zonal flow, coalescence of modes towards the m = 1 scale.

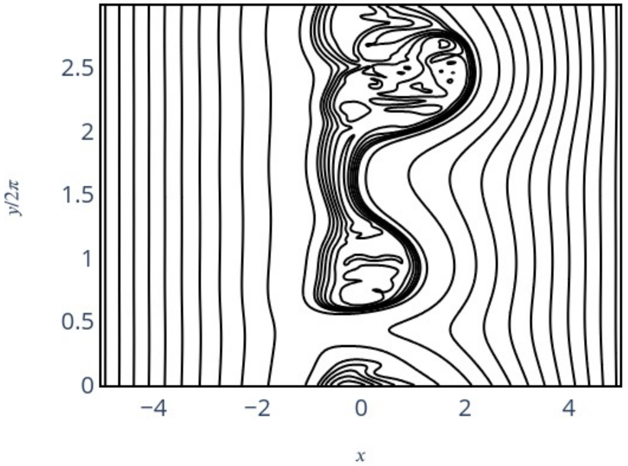


[Courtesy of D. Villa & N. Dubuit]

Before coalescence



With Zonal Flow: towards m=1 mode

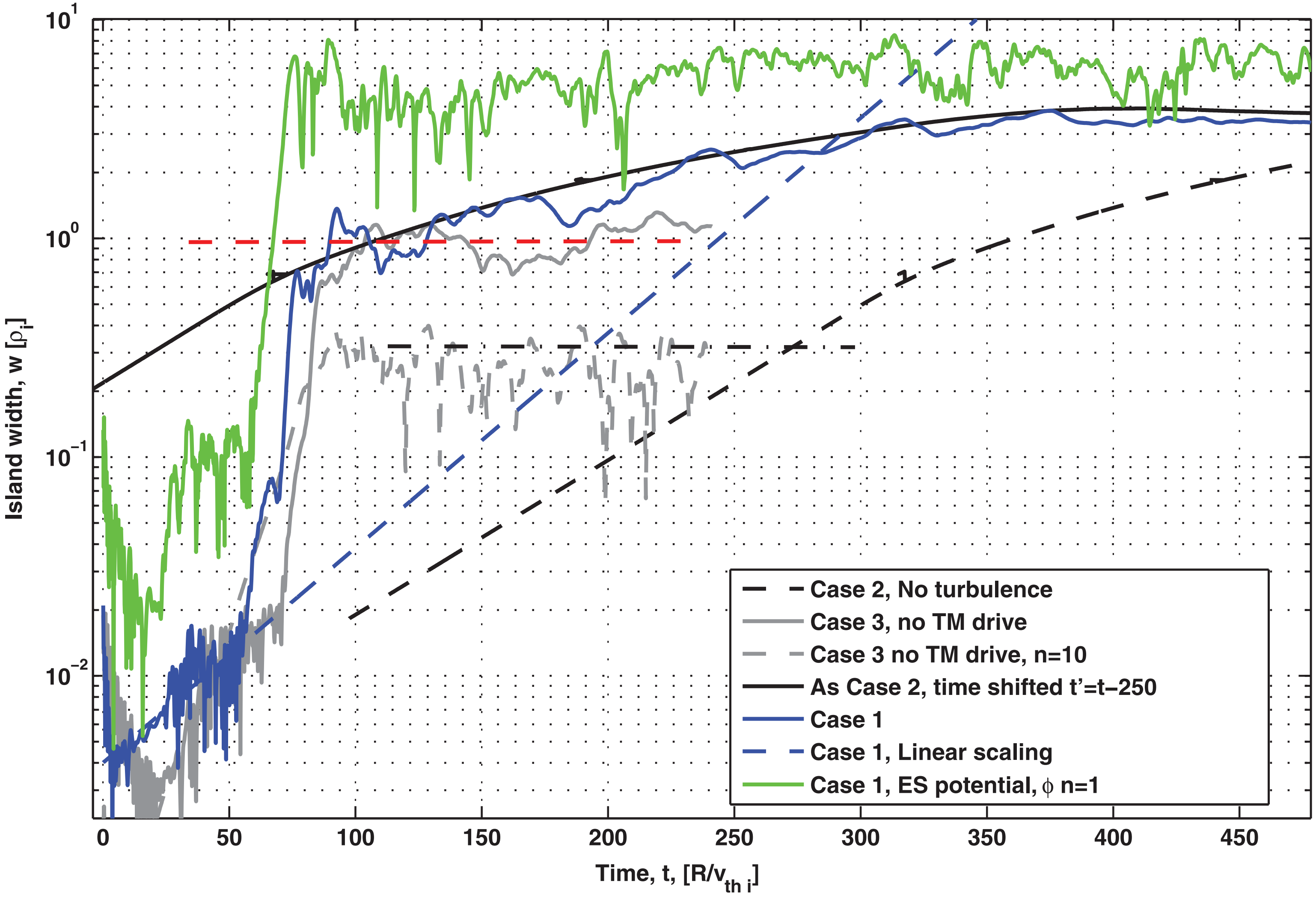


Open question : physical mechanism at play ?

II. Resilience of TDMI mechanism in GK model

- TDMI is observed in global girokinetic simulation including collisions (with GKW).

[W. Hornsby et al, PPCF (2016)]



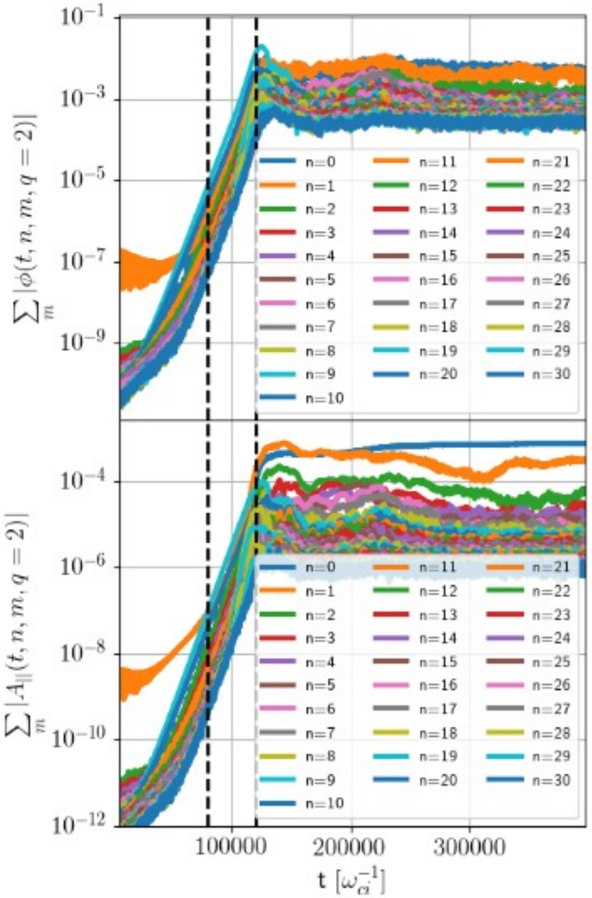
=> ITG turbulence accelerates the growth of the resistive tearing mode

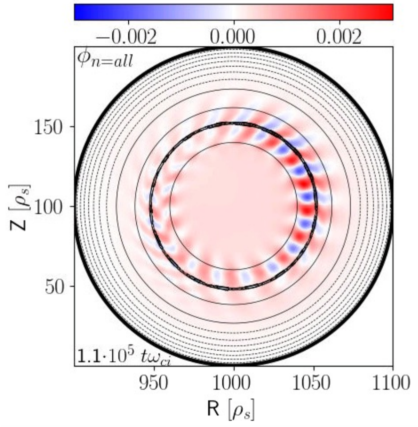
II. Collisionless TDMI driven by ITG turbulence

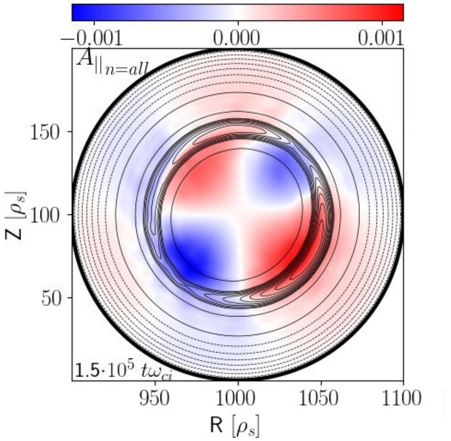
- TDMI is observed in global girokinetic simulation of collisionless tearing mode in presence of ITG turbulence (with ORB5)

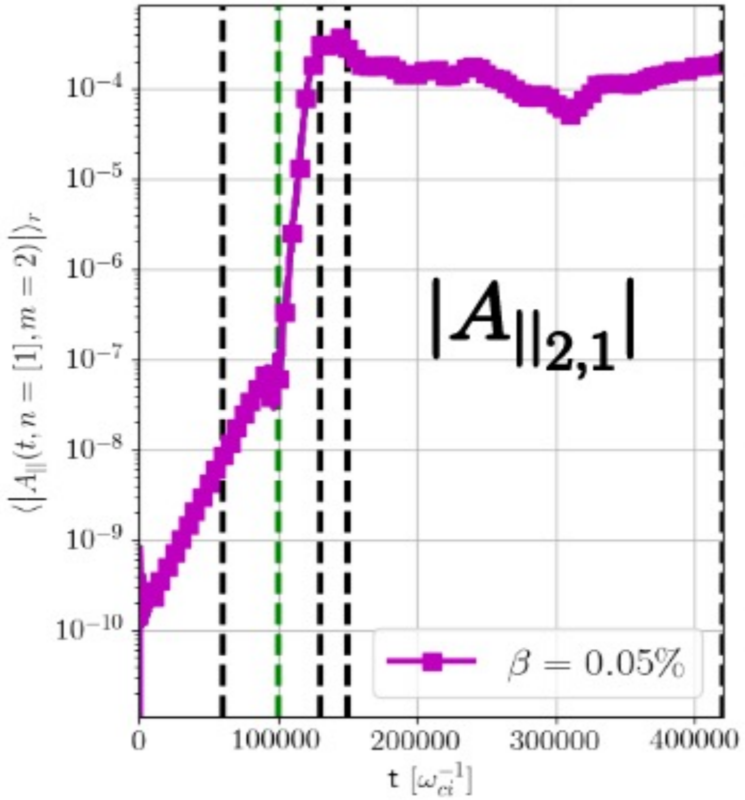
[Courtesy of F. Widmer & E. Poli]

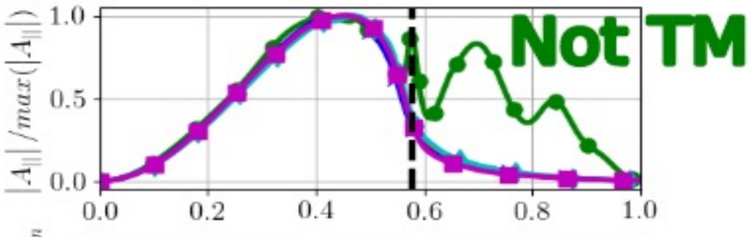
$$R_0\nabla T/T = 6,\ R_0\nabla n/n = 1,\ \beta = 0.05\%$$











=> In presence of ITG, the growth of tearing mode is accelerated.

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

II. Drive : What makes the island grow ? Conclusions

Various mechanisms in fusion devices can accelerate the growth of magnetic island (initially originated by collisions/resitivity or electron inertia):

- Electronic gradient, magnetic curvature and electric potential (for MTM at small scales)
- Turbulence (Interchange, Balooning, KBM, ITG, … ?) can drive large magnetic island TDMI
- … ?

Open question : Signatures [O. Agullo POP 2017] **and existence of TDMI ?**

III. Saturation: Prediction of the saturation ?

Magnetic Island Life

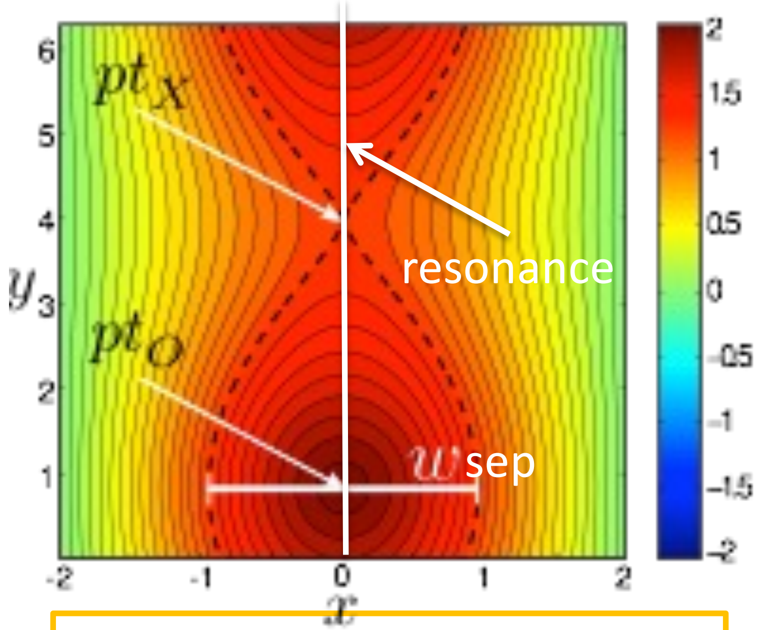
I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

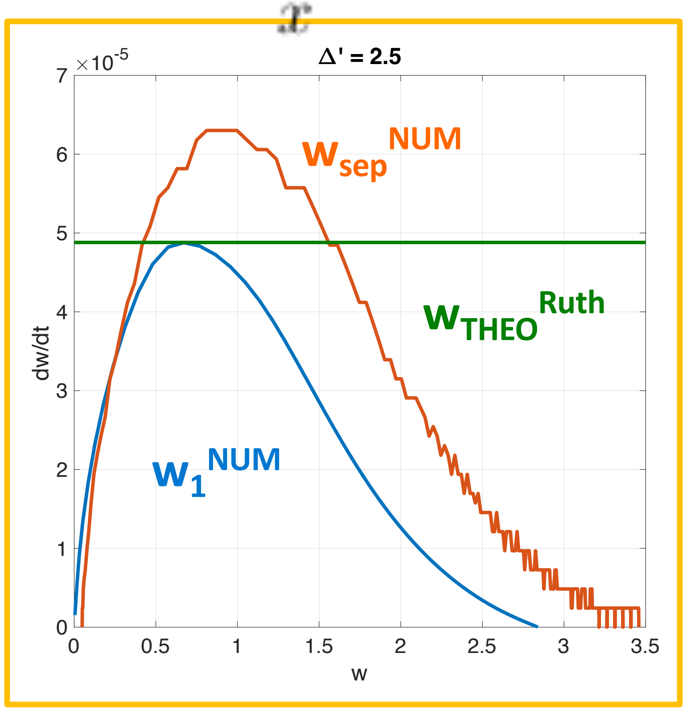
II. Drive : What makes the island grow ?

III. Saturation: Prediction of the saturation ?

- At small-scale, saturation mechanism of MTM ? Still an open question ... Investigation of the role of the electric potential in the MTM saturation mechanism **[M. Hamed et al., POP (2023)]**
- **Relevance of Rutherford model for large magnetic island and NTM**

III. History of tearing mode saturation





- **Evolution of the island size? An open question**

EFTC Conference 2023 : P.2.10, B. Momo et al.

- Evaluation of the island size/ radial witdth from poloidal mode 1 **[P.H. Rutherford POF 16 (1973)]**

$$w_{m=1} = 4\sqrt{2a\psi_1\left(x_{res}\right)}$$

- Derivation of Rutherford model from the projection of the Ohm's law on m=1 mode: **[P.H. Rutherford POF 16 (1973)]**

$$\partial_t w^{Ruth} = \partial_t w_{m=1} = 1.22\eta\Delta'$$

- Saturation of the mode m = 1 => POEM model **[Escande and Ottaviani (2004) & Militello and Porcelli (2004)]**

$$\partial_t w^{POEM} = \partial_t w_{m=1} = 1.22\eta\Delta' - 1.22\eta\frac{0.41}{a^2}w$$

1) Valid only for m = 1 and small island
2) Valid only at the resonance => 0D model

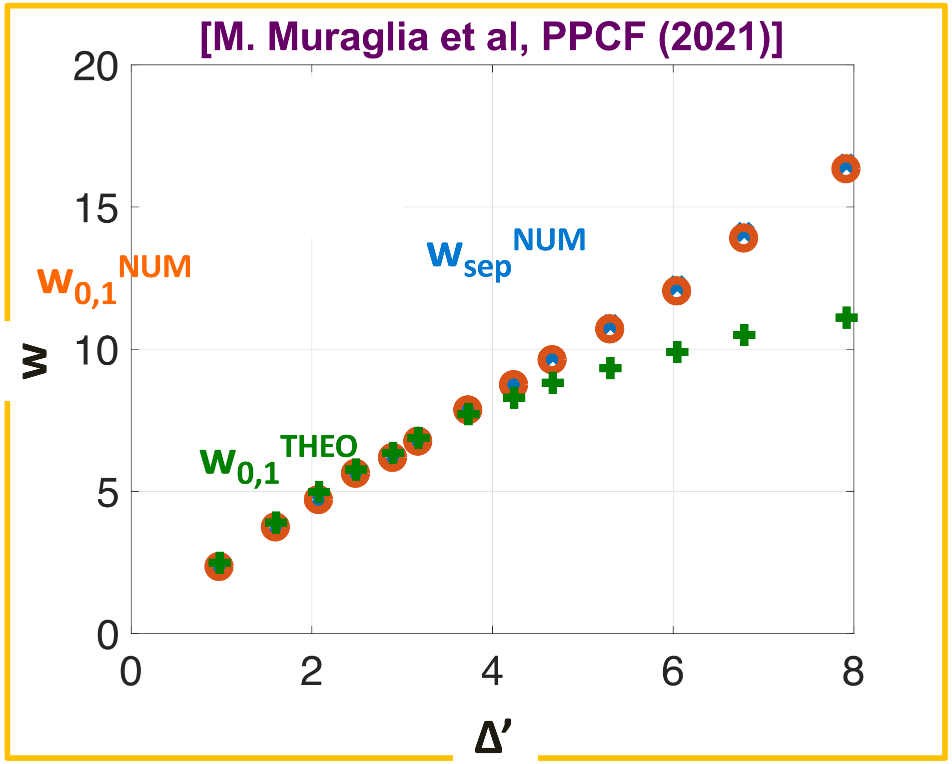
III. Systematic comparisons between theory and simulation

- **Saturation of the island taking into account modes 0 and 1**

[A. Smolyakov et al. POP 20 (2013)]

$$\partial_t w_{m=0,1} = 1.22\eta\Delta' - 1.22\eta\frac{0.41}{a^2}w \times \frac{1}{1-0.1678w^2/a^2}$$

=> Should be confronted to simulations


[M. Muraglia et al, PPCF (2021)]

=> Model fails to predict the complete dynamics

=> What's about NTM dynamics prediction by Rutherford-like models ?

III. Validity of Rutherford model for NTM

❖ **Rutherford equation for NTM does not depend on seeding mechanism**

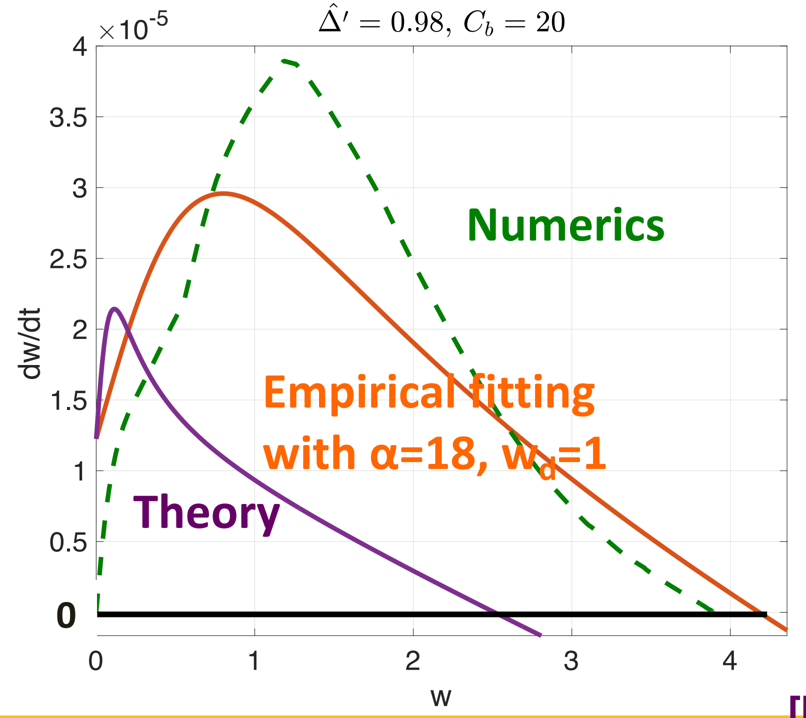
[O. Sauter et al., POP (1997)]

$$\partial_t w_1 = 1.22\eta\Delta' - 1.22\eta\frac{0.41}{a^2}w + \alpha C_b v * \frac{w}{w^2+w_d^2}$$

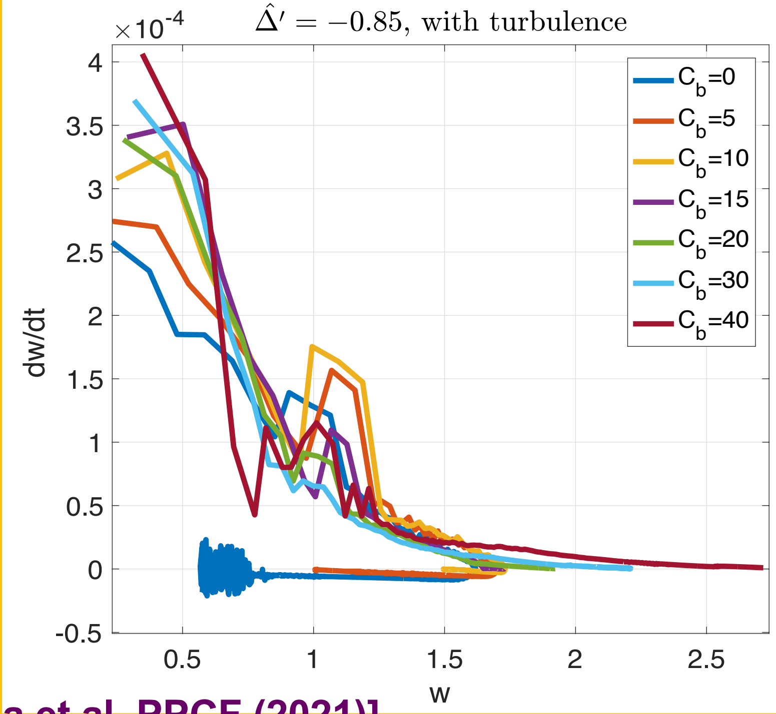
❖ Systematic comparison between theory and simulation for a NTM seeding with a tearing mode: **=>Theory fails**

❖ NTM seeding by turbulence : Rutherford-like models do not include the physics of island seeding mechanism

wo turbulence



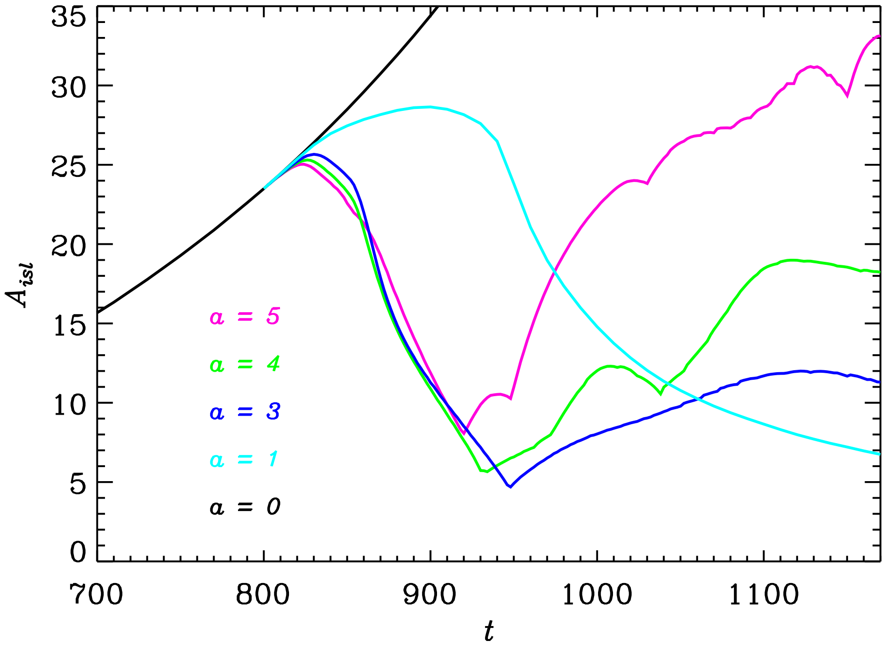
with turbulence



[M. Muraglia et al, PPCF (2021)]

III. Topological aspects are important

- Rutherford-like models have been designed in a context of 2D symmetric island taking into account current equilibrium at the resonant surface and at the X-point.



MHD model of the impact of ECCD curent injection on a tearing mode :

=> The evolution of the island depends on the balance of the total current between the 0- and X-points and not only at X-point!

[D. Borgogno, POP 14 (2014)]

- Saturation of tearing mode depends of the shape of the equilibrium magnetic field profile.

[F. Militello et al., POP 18 (2011), A. Poyé et al., POP 20 (2013), A. Poyé et al., POP 21 (2014)]

- In fusion devices magnetic reconnection processes are by nature 3D. And sometimes, multi-helicities are involved. How define the island size ?

[D. Borgogno et al., POP 12 (2005) & M. Veranda et al., NF 57 (2017)]

Magnetic Island Life

I. Origin : What non ideal phenomenon breaks the magnetic field topology ?

II. Drive : What makes the island grow ?

III. Saturation: Prediction of the saturation ? Conclusions

Although, in fusion devices Rutherford-like models are successfully used to control NTM by fitting empirically coefficients of the Rutherford equation, systematic comparisons of tearing mode saturation between models and simulations fail.

=> Open question : Rutherford models have to be improved to take into account :

- **Island seeding mechanism (like turbulence)**
- **Full harmonic pertubutation and shape of the equilibrium profile**
- **3D and multi-helicities aspects**

Also at the conference on magnetic reconnection :

P.2.9, S. Cappello
P.2.29, D. Borgogno
O.3, H. Bati
I.15, C. Granier
...

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In december, PPCF Webinar on

‘Magnetic reconnection in space and fusion plasmas: From large to small scales‘

With:

G. Cozzani (space plasma),D. Grasso (space & fusion plasmas),
M. Hamed (fusion plasma), A. Ji (space plasma), E. Poli (fusion plasma)