DE LA RECHERCHE À L'INDUSTRIE

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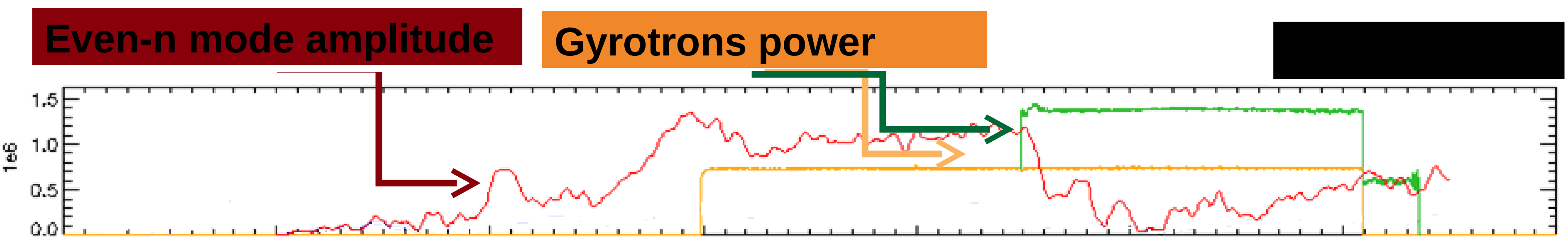
Motivation of this study



[Reich'13]

Motivation of this study : status of modeling

Modeling RF stabilization : geometry & RF structure

- Cylindrical geometry, reduced MHD *(no toroidal stabilization [GGJ'75])*
  - ECRH [Kurita'94]
  - ECCD stabilization with dynamic equation for fast electrons [Yu'00]
- Toroidal geometry :
  - ECCD stabilization but instantaneous 3D RF current [Popov'02]
  - ECCD stabilization via equilibrium modification only [Jenkins'10]

In this work:

► **First 3D full-MHD simulations in a torus of island stabilization.**

► **First comparison with theoretical RF stabilization efficiency ηRF**

OUTLINE

The Rutherford model: a tool for validation

Modeling ECCD-driven current density evolution

Full MHD Simulations of ECCD impact on tearing modes: comparison with Rutherford model

Beyond the Rutherford model

The Rutherford framework: a tool for validation

- The island size dynamics can be studied in the framework of a 0D model: the M odified Rutherford Equation (MRE) [Rutherford'73] (W=w/a)

$$0.82\tau_R \frac{\mathrm{d}W}{\mathrm{d}t} = a\Delta'(W) + \Delta_{RF}$$

- The ECCD-driven current contribution ΔRF [Hegna'97]

$$\Delta_{RF} = -\frac{D_{RF}}{W^2}\eta_{RF} \quad \text{with} \quad D_{RF} = \frac{16}{\pi}\frac{q}{xs}\frac{\mu_0 R_0 I_{RF}}{a^2 B_0}$$

(It also has an effect on equilibrium Δ'-term)

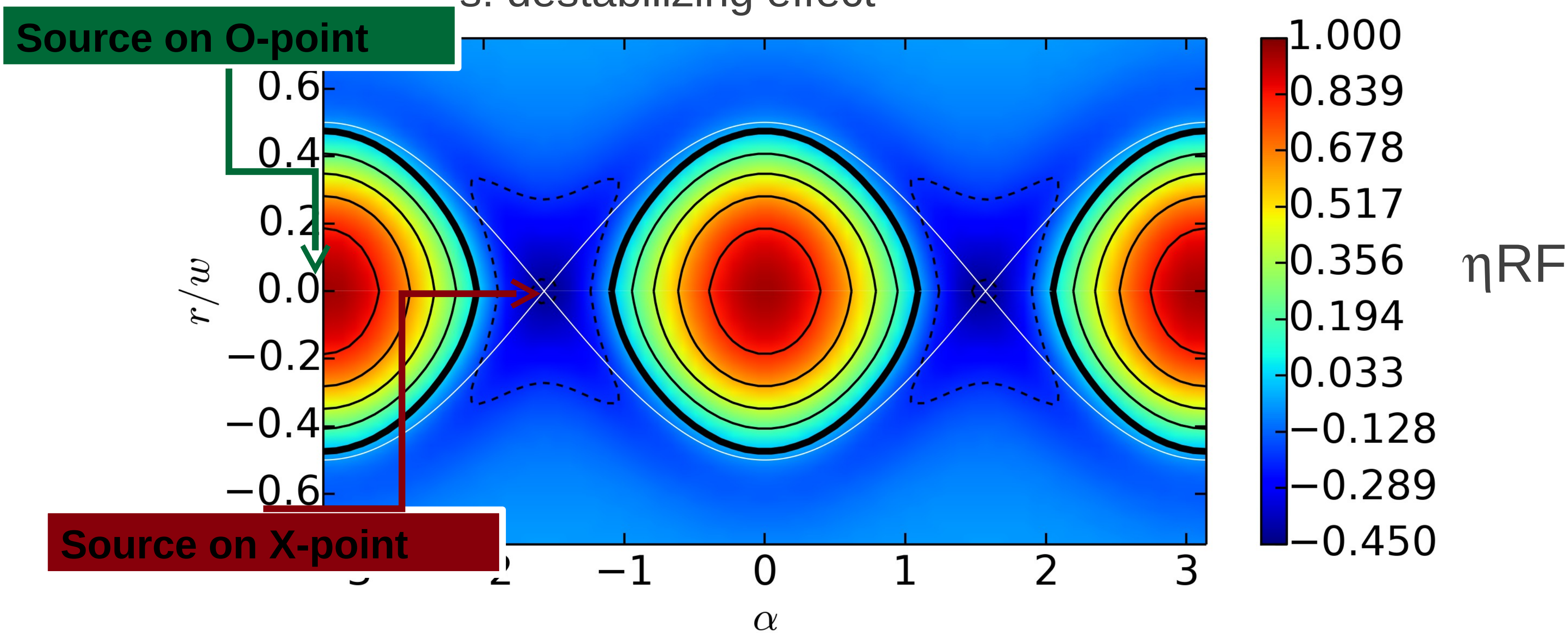
- η**RF** is the **efficiency**, and describes how well the current is driven inside the i sland O-Point

$$\eta_{RF} = \frac{\int \mathrm{d}\Omega \int \frac{\mathrm{d}\alpha}{2\pi} \cos(m\alpha) \langle J_{RF} \rangle}{\int \mathrm{d}\Omega \int \frac{\mathrm{d}\alpha}{2\pi} \langle J_{RF} \rangle}$$

$$\alpha = \theta - \frac{n}{m}\phi$$

η_{RF} is the key parameter to define control efficiency

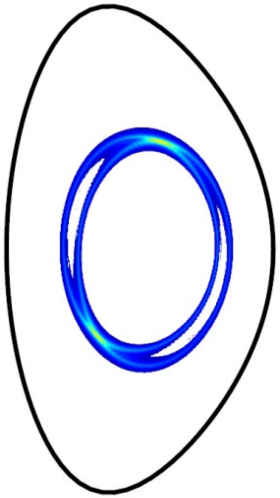
- η_{RF} depends on source shape, source width and source position
- Positive values : stabilizing effect
- Negative values: destabilizing effect



Map of the efficiency for a (2,1)-island, for a fixed-size source

Modeling ECCD-driven current density evolution

ECCD-driven current density evolution



- ECCD current deposition evolves over time :
  - Current rises on a collisional timescale
  - Current propagates along magnetic field lines:

    3D configuration, evolves over time

=> Need for an equation describing the dynamics of the current s
e.

- Fast electrons are convected along field lines [Westerhof'14]

Convection

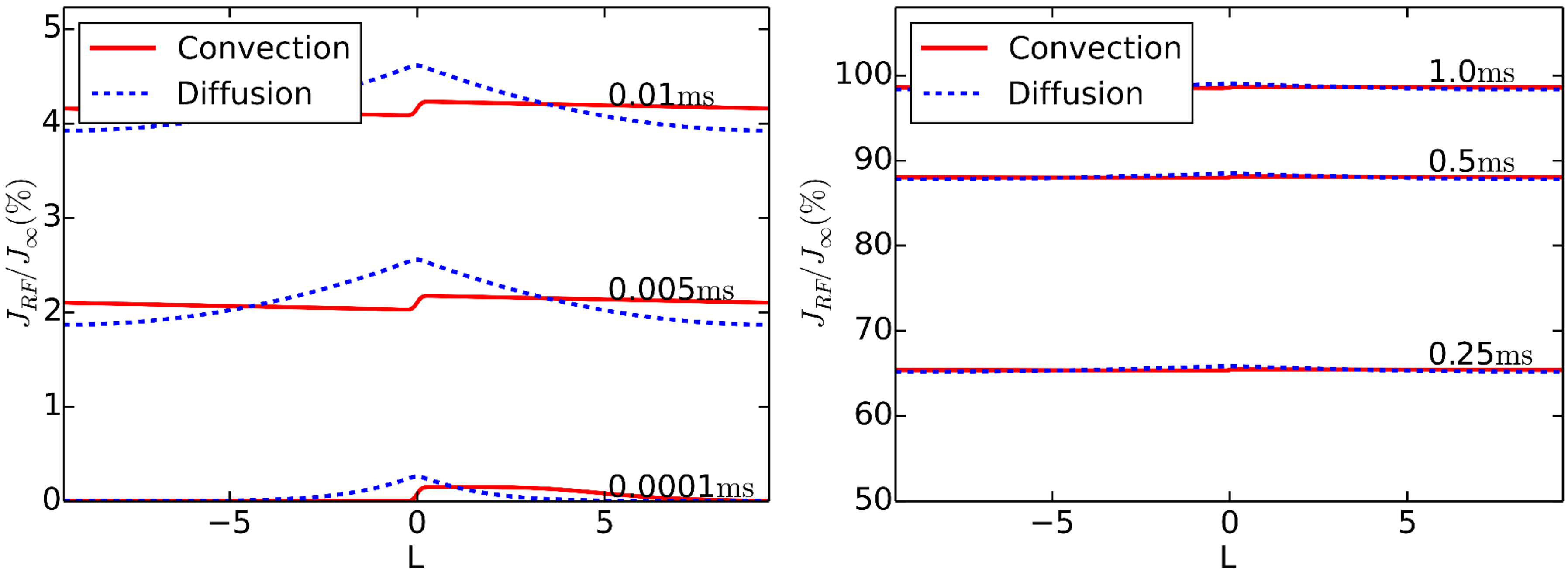
$$\frac{\partial J_{RF}}{\partial t} = \nu\left(J_{RF}^{S} - J_{RF}\right) + \chi_{\perp}\nabla_{\perp}^{2} J_{RF} + \boxed{v_{||}\nabla_{||} J_{RF}}$$

- However, advection is difficult to handle numerically… A diffusive model can be used, similar to [Yu'00]

Diffusion

$$\frac{\partial J_{RF}}{\partial t} = \nu\left(J_{RF}^{S} - J_{RF}\right) + \chi_{\perp}\nabla_{\perp}^{2} J_{RF} + \boxed{\chi_{||}\nabla_{||}^{2} J_{RF}}$$

Comparison of the two models



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Full MHD Simulations of ECCD impact on tearing modes: comparison with Rutherford model

MODELING TOOL: The XTOR-2F Code

- XTOR-2F : 3D full-MHD code. Fully implicit numerical scheme. Use of finite differences for radial coordinate, and spectral method (fourier) for both poloidal and toroidal coordinates. [Lütjens'10]

$$(\partial_t + \mathbf{V}\cdot\nabla)\, n_i + n_i \nabla\cdot\mathbf{V} + \nabla\cdot\Gamma_{turb} = S$$

$$n_i m_i (\partial_t \mathbf{V} + \mathbf{V}\cdot\nabla\mathbf{V}) - \mathbf{J}\times\mathbf{B} + \nabla p = \nu\nabla^2\mathbf{V}$$

$$\mathbf{E} + \mathbf{V}\times\mathbf{B} - \eta\left(\mathbf{J} - \mathbf{J_{CD}} - J_{RF}\frac{\mathbf{B}}{|\mathbf{B}|}\right) = 0$$

$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$

$$(\partial_t + \mathbf{V}\cdot\nabla)\, p + \Gamma p \nabla\cdot\mathbf{V} = \frac{2}{3}\{H - \nabla\cdot\mathbf{q}^{\chi}\}$$

$$\frac{\partial J_{RF}}{\partial t} - \chi_{\perp}^{RF}\nabla^2 J_{RF} - \chi_{||}^{RF}\nabla_{||}^2 J_{RF} = \nu_f (J_s - J_{RF})$$

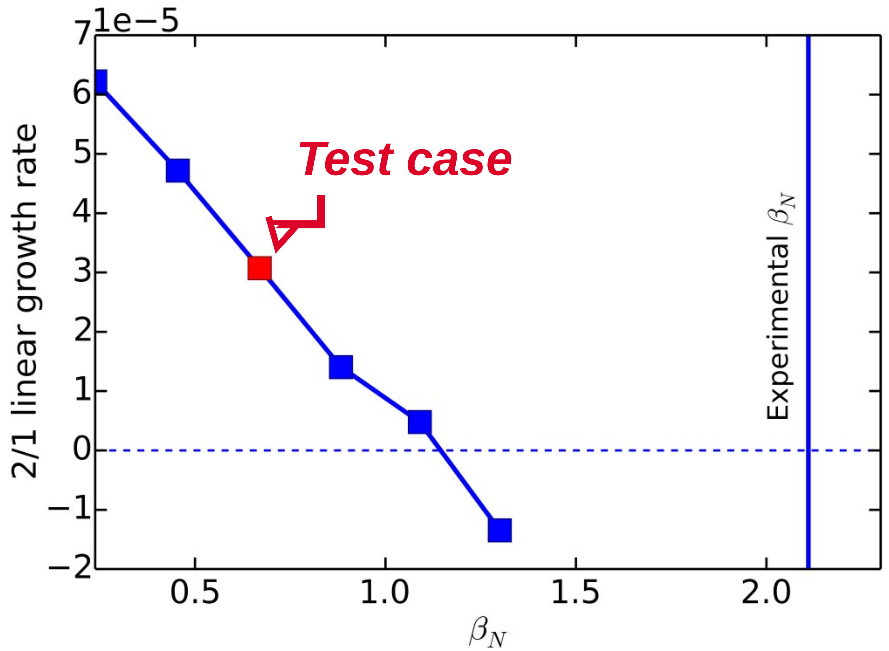
RF source

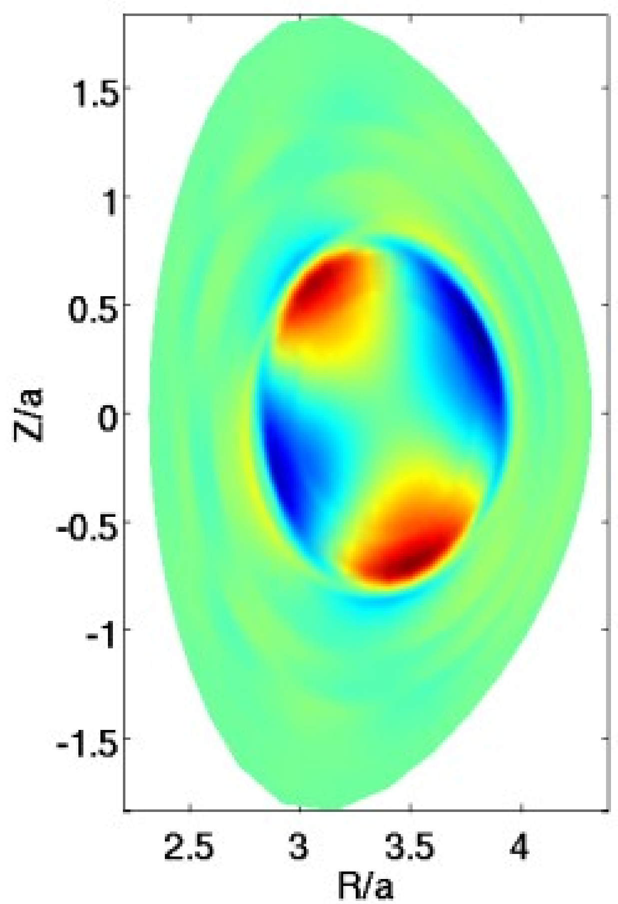
Equilibrium Used for the simulations

- AUG-Like equilibrium, issued from shot #29682 (Up-down symmetry for simplicity)

- Pressure profile reduced so as to deal with linearly unstable tearing modes

  Tearing stable at experimental βN



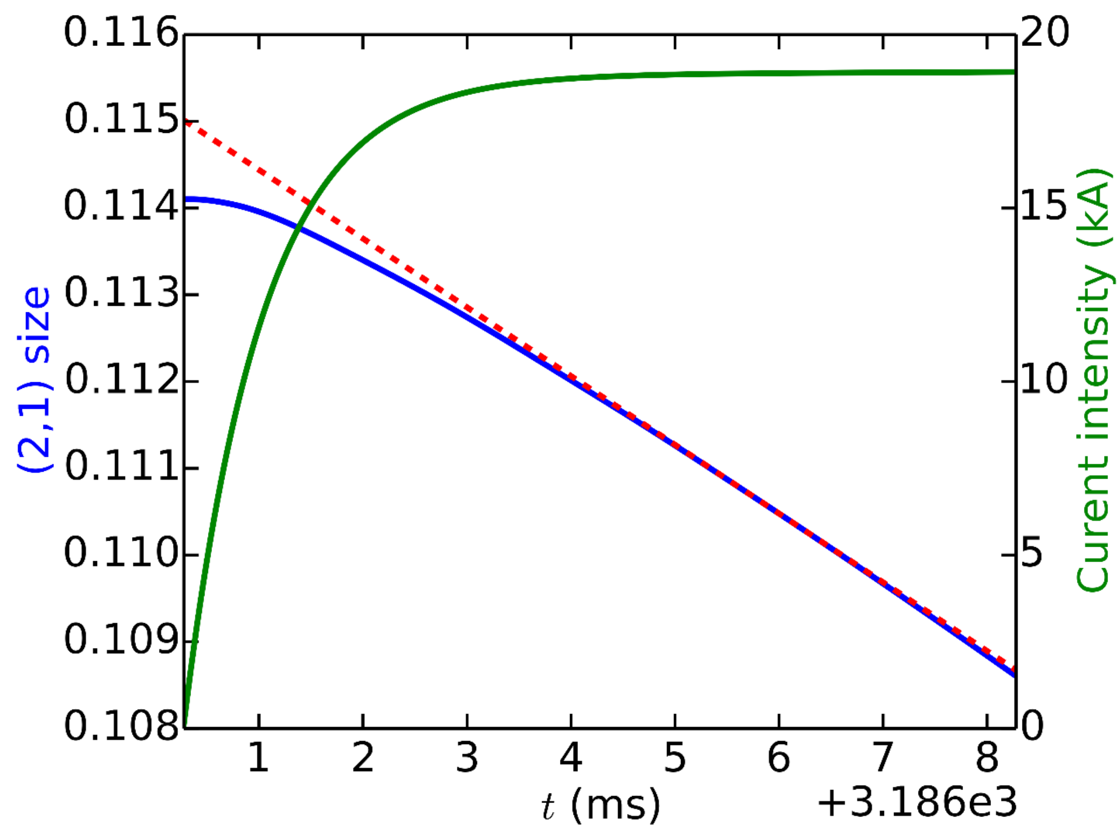


Pressure perturbation induced by the 2/1-mode at saturation.

Methodology

- At the very beginning of the c ontrol :

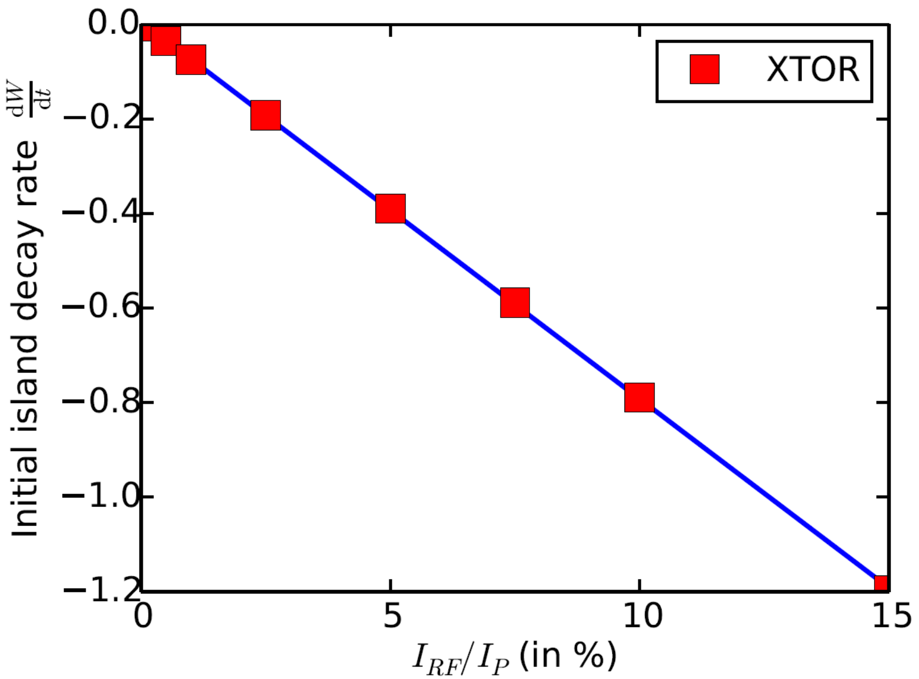
$$\left.\frac{dW}{dt}\right|_{t=0^+} \propto -\frac{D_{RF}}{W_{sat}^2}\eta_{RF}(W_{sat})$$

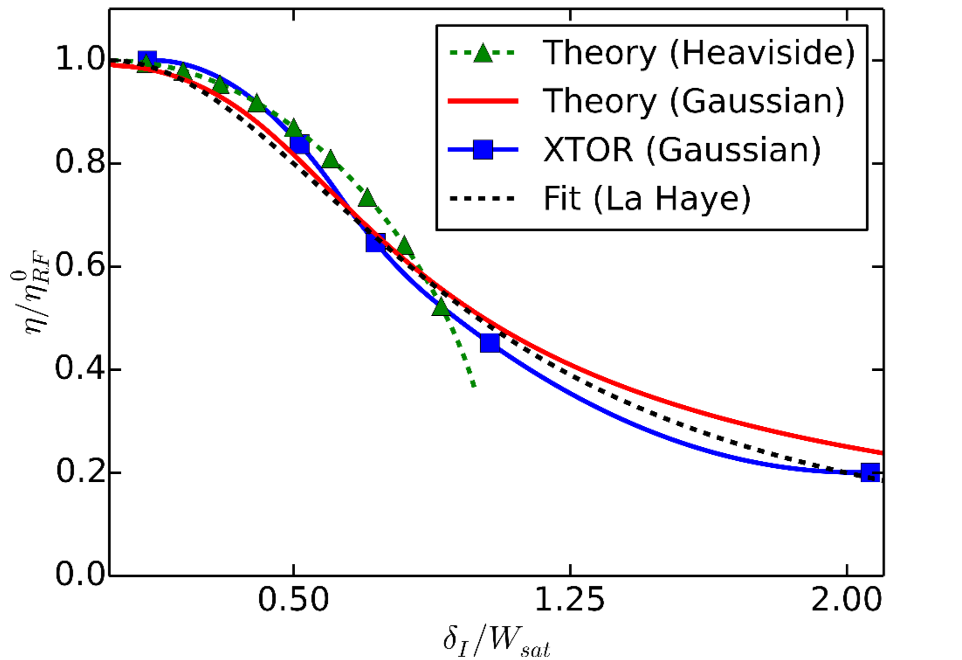


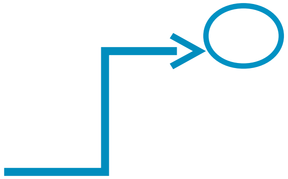
- Relative comparison of XTOR results and analytical model : We **rescale the computed ef ficiency so that for narrow s ource, its value is 1.**

- We observe that the dynamics is **about ten times slower** than predicted by the analytical model. Investigation in progress.

Source intensity and width impacts

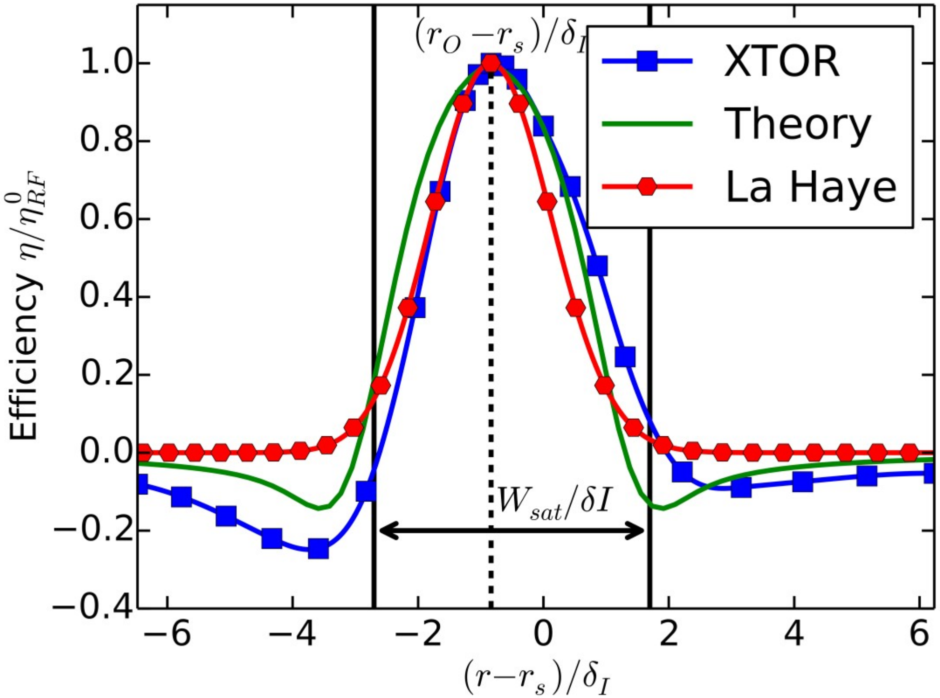


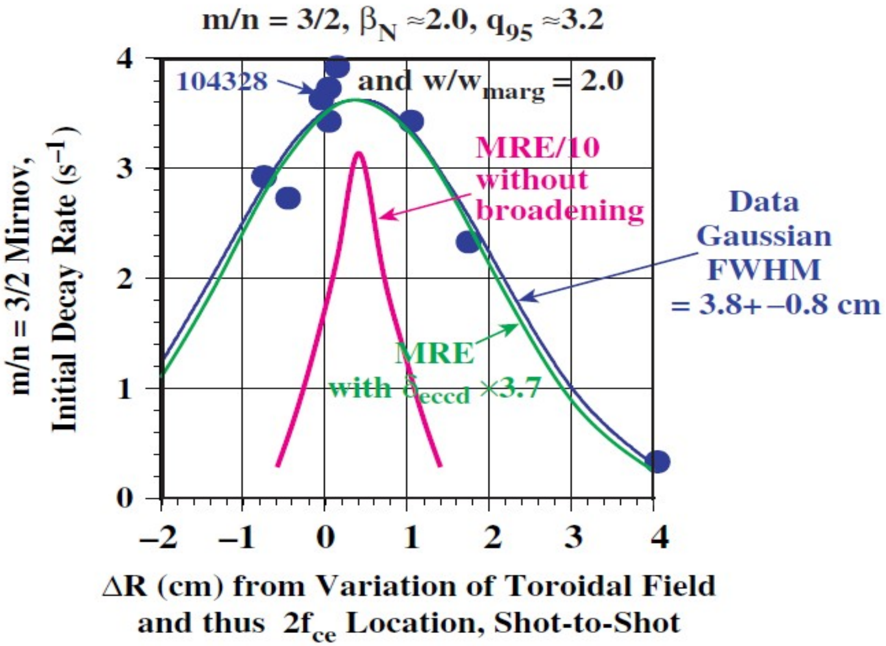




Width of RF source

Impact of misalignment





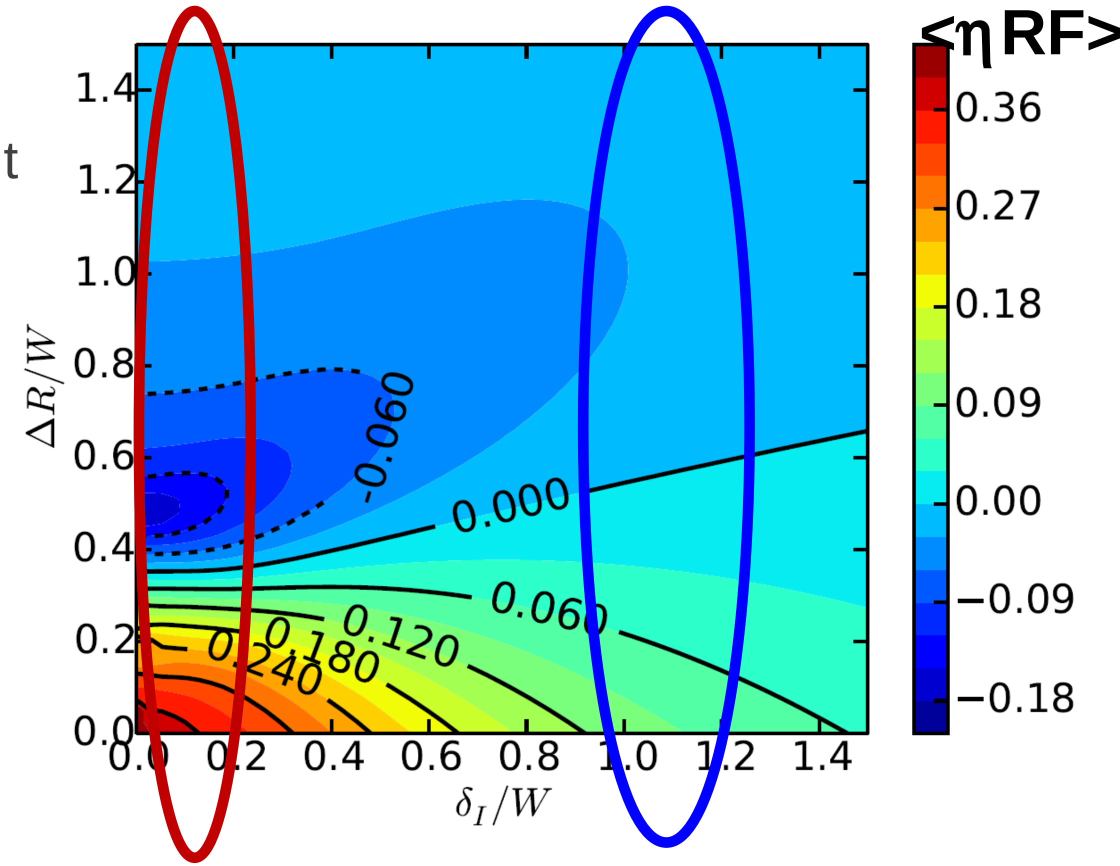
R.J. La Haye *et al* Nucl. Fusion **48** (2008) 054004

Combined effect of source wiDth and misalignment

- Combined effect misalignment and source width :

  - **Narrow source** : better efficiency but worse sensitivity to misalignment

  - **Broad source** : lower efficiency but lower sensitivity to misalignment

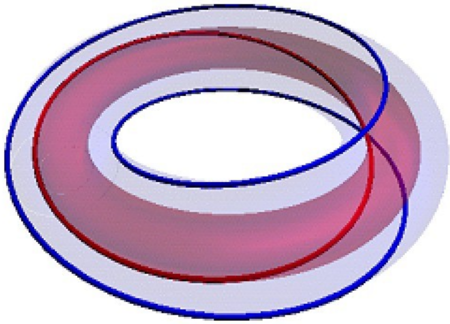


[Computed from analytical model with a gaussian RF source]

Island response to the 3D RF source: Beyond the rutherford model

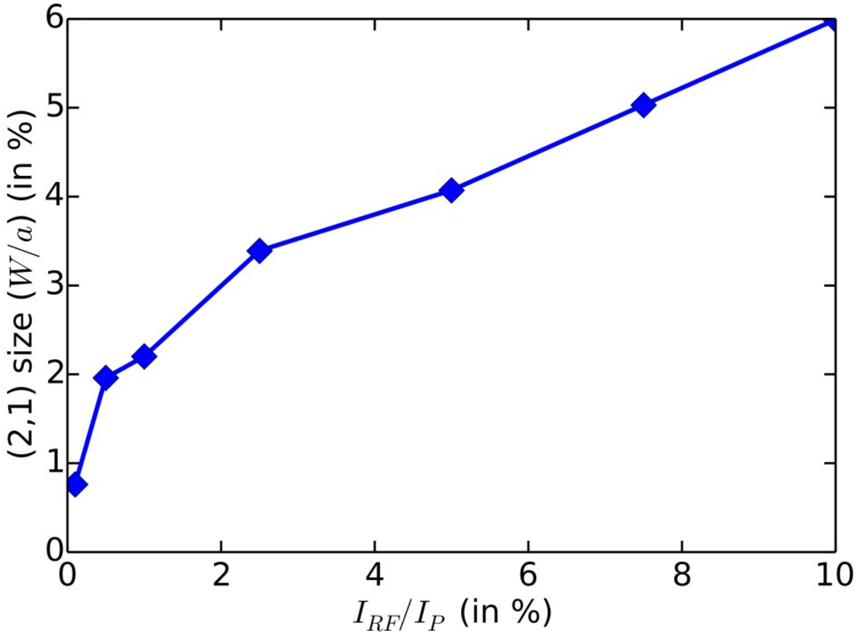
Island response by phase adjustment

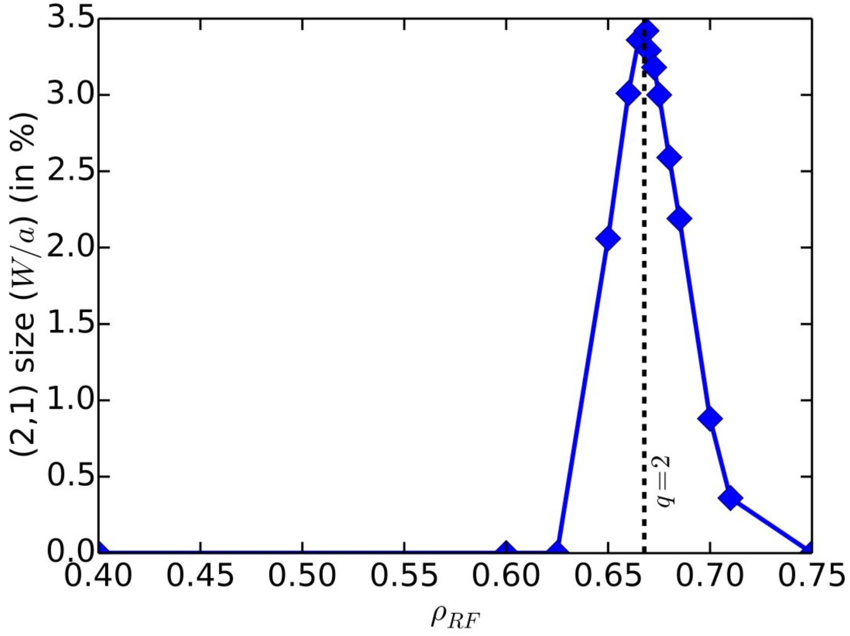
- When using a 3D current source term, plasma response will try to incr ease island size :
  - By forming an X-point at the co-current RF source location due t o the current filament created by the source.



  - In case of a pre-existing island, for a source term localized on a O-Point, the island flips: **X-Points and O-Points will exchange their positions.**

Mode Onset by ECCD

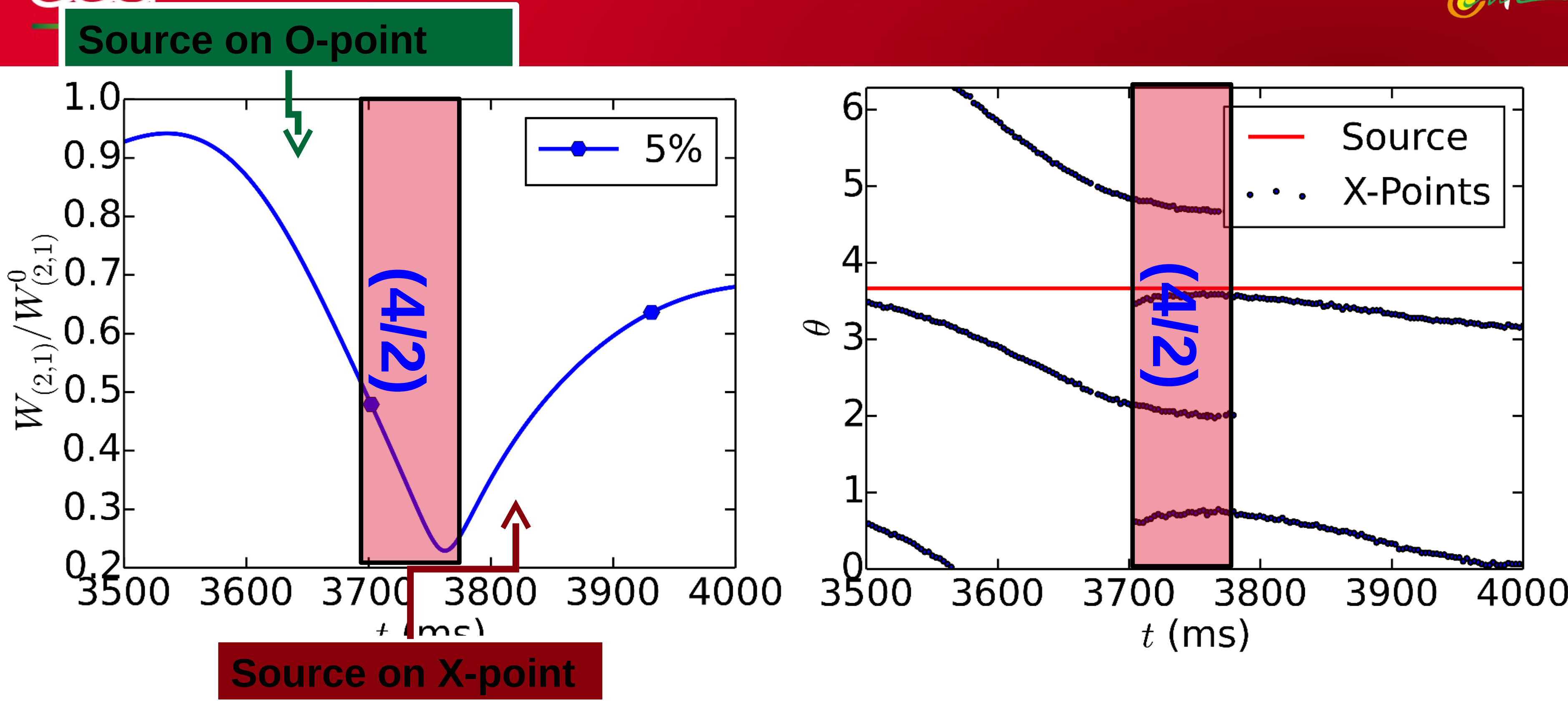




- Driving current precisely on a rational surface (without island) creates a current filament, hence an island.
  - Co-current: X-Point is created at the position of the current deposition.
  - Contra-current: O-Point

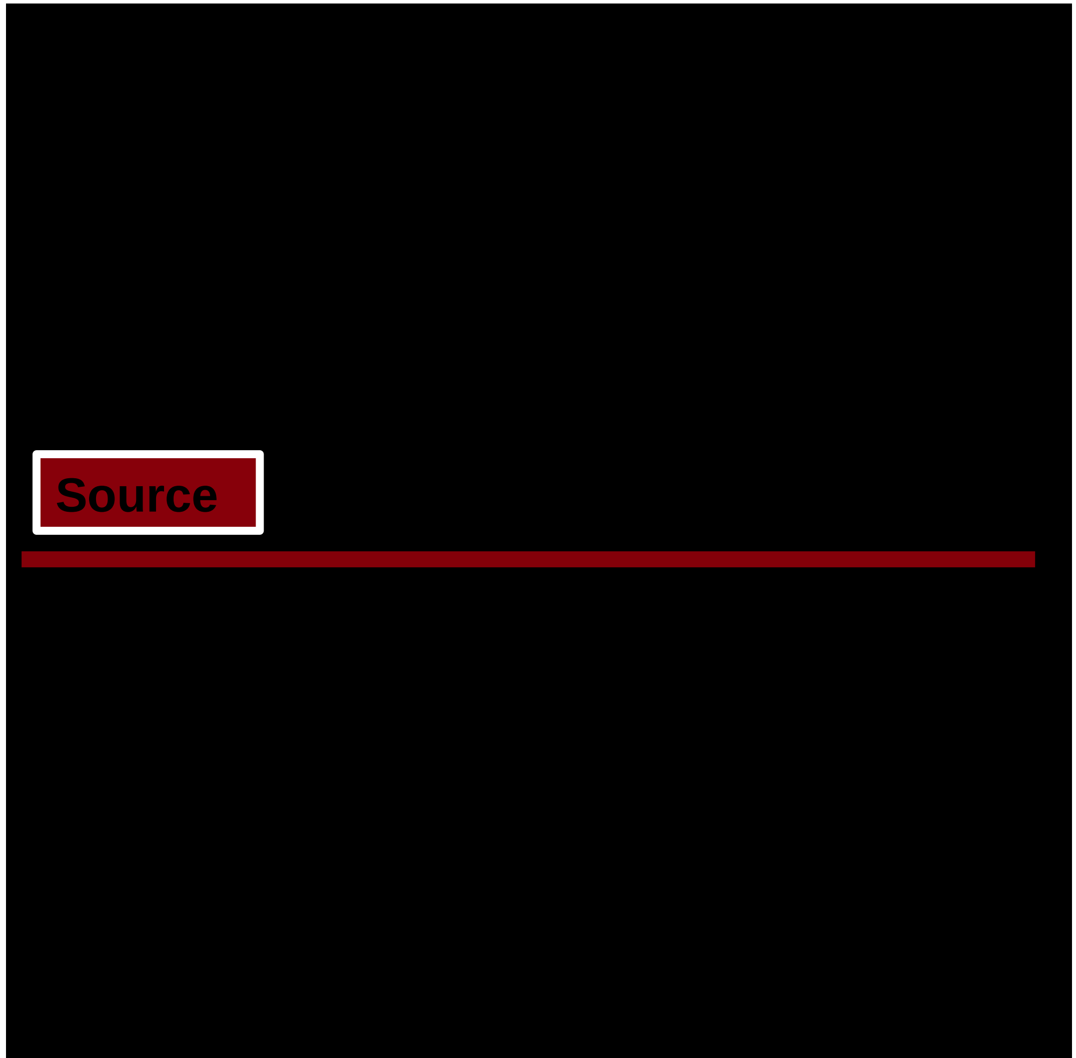
- Allowed misalignment to actually form an island: ~5%
- Even large values of injected current lead to **relatively small islands.**

The Flip Instability [Borgogno'12]

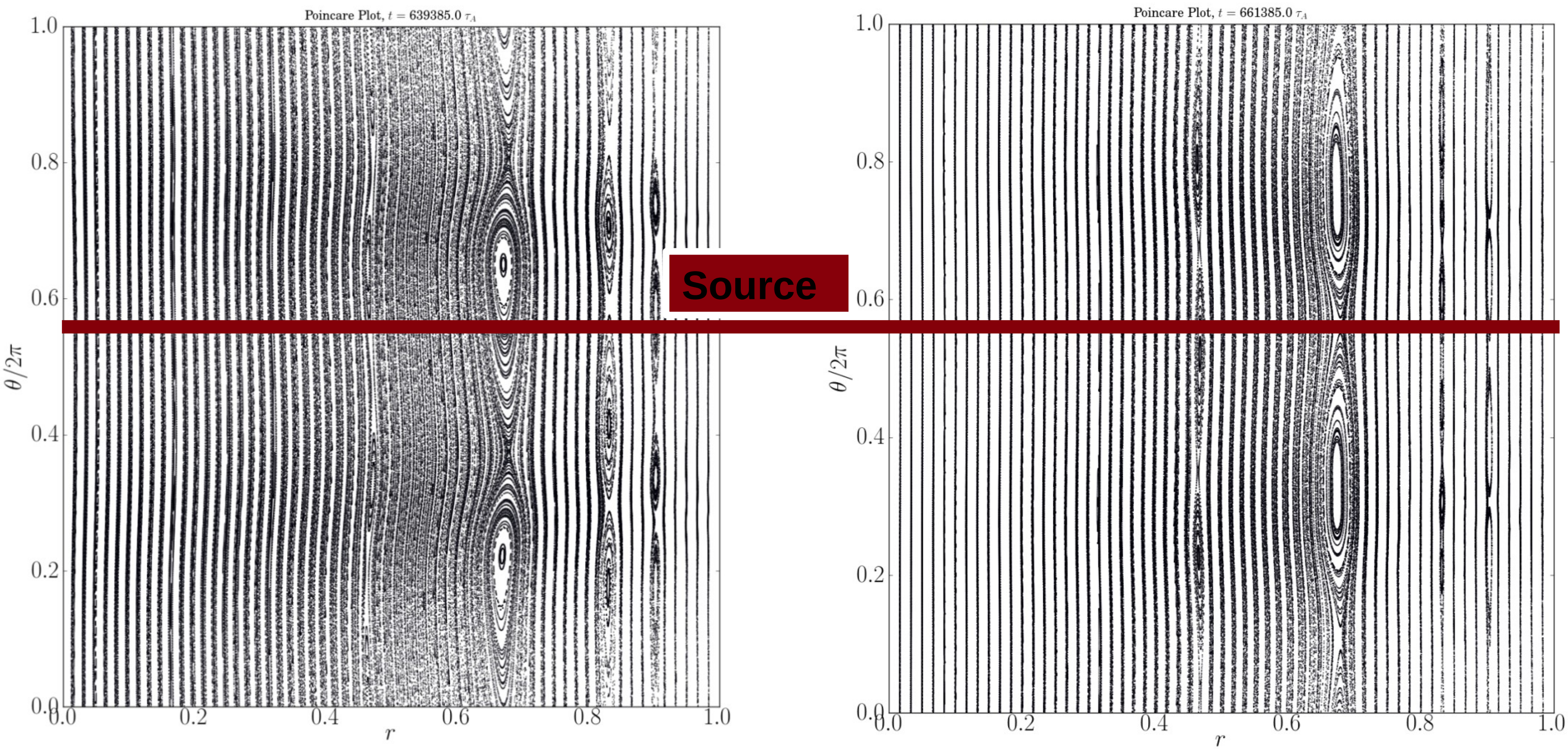


- Natural rotation of the island is slow (no momentum source, no diamagnetic effects).
- Island structure changes : (2,1) (4,2) (2,1) with phase-change
- Island locks on a position where the source is on close to an X-Point : Flip Instability

The Flip Instability [Borgogno'12]



The Flip Instability [Borgogno'12]



Before the flip

After the flip

Conclusion

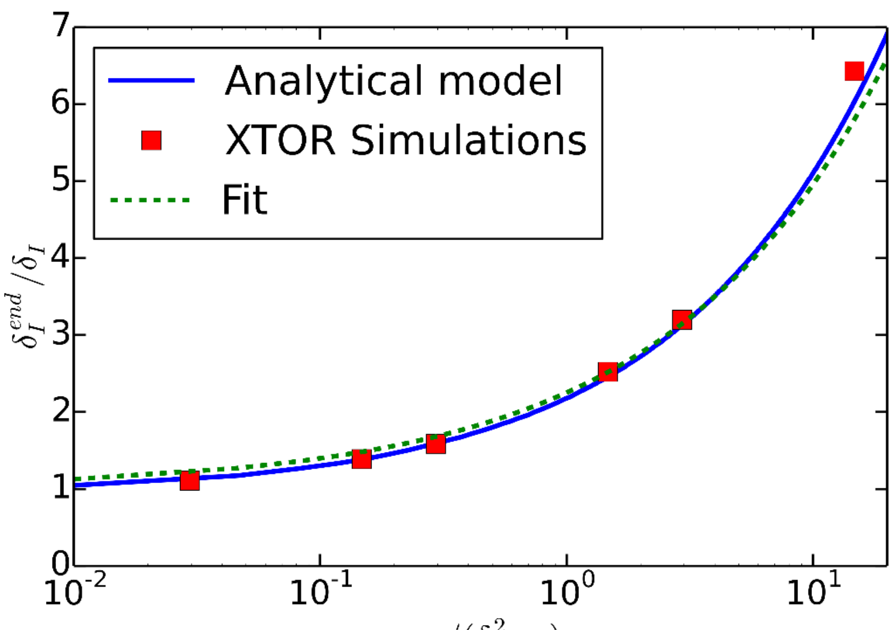
First principle simulations of magnetic island stabilization

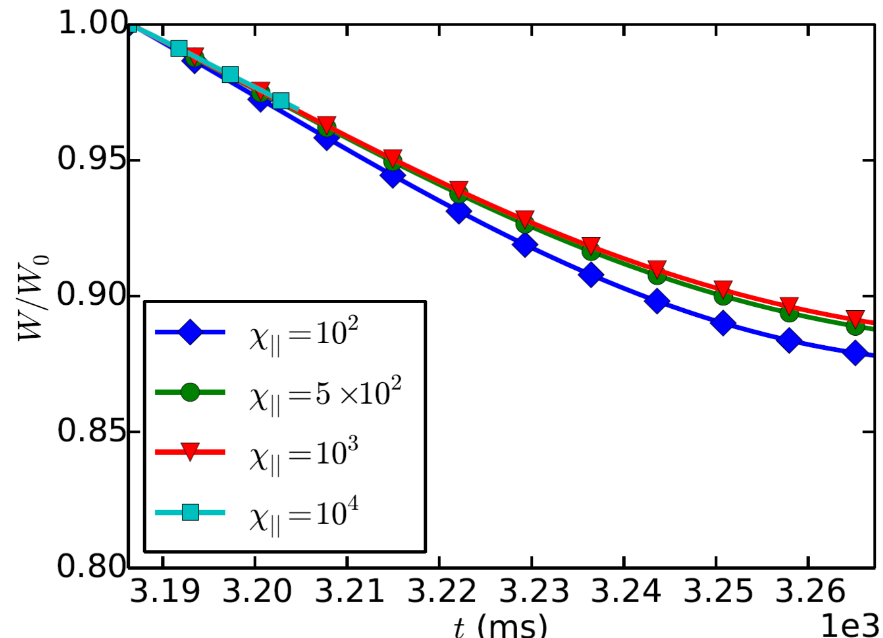
- First benchmark of a full MHD code vs analytical model for island stabilization by ECCD

- Expected effects of deposition width and misalignment are recovered, good relative agreement with Hegna's model.

  Dynamics obtained with the code is however slower, needs to be understood.

Additional Slides


Analytical model
XTOR Simulations
Fit
δ_I^{end}/δ_I
$\chi_{||}/(\delta_I^2 \nu_f)$
0
1
2
3
4
5
6
7
10^{-2}
10^{-1}
10^{0}
10^{1}


$\chi_{||}=10^2$
$\chi_{||}=5\times10^2$
$\chi_{||}=10^3$
$\chi_{||}=10^4$
W/W_0
t (ms)
1e3
0.80
0.85
0.90
0.95
1.00
3.19
3.20
3.21
3.22
3.23
3.24
3.25
3.26