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Motivation of this study

Even-n mode amplitude  Gyrotrons power

[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 $\eta_{RF}$
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
Introduction: rutherford approach

The Rutherford framework: a tool for validation

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

\[
0.82 \tau_R \frac{dW}{dt} = a \Delta'(W) + \Delta_{RF}
\]

The ECCD-driven current contribution \(\Delta_{RF}\) [Hegna’97]

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

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

\(\eta_{RF}\) is the efficiency, and describes how well the current is driven inside the island O-Point

\[
\eta_{RF} = \frac{\int d\Omega \int \frac{d\alpha}{2\pi} \cos(m\alpha) \langle J_{RF} \rangle}{\int d\Omega \int \frac{d\alpha}{2\pi} \langle J_{RF} \rangle} \quad \alpha = \theta - \frac{n}{m} \phi
\]
\( \eta_{RF} \) 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

- Source on O-point
- Source on X-point

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 source.

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

$$\frac{\partial J_{RF}}{\partial t} = \nu \left( J^{S}_{RF} - J_{RF} \right) + \chi \nabla_{\perp}^{2} J_{RF} + \nabla_{\parallel} J_{RF}$$

Convection

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

$$\frac{\partial J_{RF}}{\partial t} = \nu \left( J^{S}_{RF} - J_{RF} \right) + \chi \nabla_{\perp}^{2} J_{RF} + \nabla_{\parallel}^{2} J_{RF}$$

Diffusion
Comparison of the two models

Convection
Diffusion

$J_{RF}/J_\infty(\%)$ vs $L$

$0.01\text{ms}$
$0.005\text{ms}$
$0.0001\text{ms}$

$100\%$
$90\%$
$80\%$

$0.5\text{ms}$
$0.25\text{ms}$

$50\%$
$40\%$
$30\%$
$20\%$
$10\%$
$0\%$
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]

\[
\begin{align*}
(\partial_t + \mathbf{V} \cdot \nabla) n_i + n_i \nabla \cdot \mathbf{V} + \nabla \cdot \Gamma_{turb} &= S \\
 n_i m_i (\partial_t \mathbf{V} + \mathbf{V} \cdot \nabla \mathbf{V}) - \mathbf{J} \times \mathbf{B} + \nabla p &= \nu \nabla^2 \mathbf{V} \\
 \mathbf{E} + \mathbf{V} \times \mathbf{B} - \eta \left( \mathbf{J} - \mathbf{J}_{CD} - \frac{J_{RF}}{\mathbf{B}} \right) &= 0
\end{align*}
\]

\[
\begin{align*}
\partial_t \mathbf{B} &= -\nabla \times \mathbf{E} \\
(\partial_t + \mathbf{V} \cdot \nabla) \rho + \Gamma p \nabla \cdot \mathbf{V} &= \frac{2}{3} \{\mathbf{H} - \nabla \cdot \mathbf{q}^x\}
\end{align*}
\]

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

  \textit{Tearing stable at experimental } \beta_N \textit{ at saturation.}

\textbf{Test case}

Pressure perturbation induced by the 2/1-mode at saturation.
At the very beginning of the control:

\[
\frac{dW}{dt} \bigg|_{t=0^+} \propto -\frac{D_{RF}}{W_{sat}^2} \eta_{RF}(W_{sat})
\]

Relative comparison of XTOR results and analytical model:

We rescale the computed efficiency so that for narrow source, 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

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Combined effect of source width and misalignment:

- **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
When using a 3D current source term, plasma response will try to increase island size:

- By forming an X-point at the co-current RF source location due to 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.**
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.
Natural rotation of the island is slow (no momentum source, no diamagnetic effects).

Island structure changes: \((2,1) \rightarrow (4,2) \rightarrow (2,1)\) 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]

Before the flip

After the flip
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