EUROfusion

Active control of kinetic-RWMs in JT-60SA scenarios

L. Pigatto, M. Bonotto, F. Villone, T. Bolzonella

JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

CONSORZIO RFX
Ricerca Formazione Innovazione

Create

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

- Motivation and introduction
- Equilibrium and ideal kink stability
- RWM in drift-kinetic model
    - Precession and bounce resonance damping
- Coupling linear kinetic plasma response model with 3D external structures
    - Application of CarMa-D to JT-60SA
- Outlook

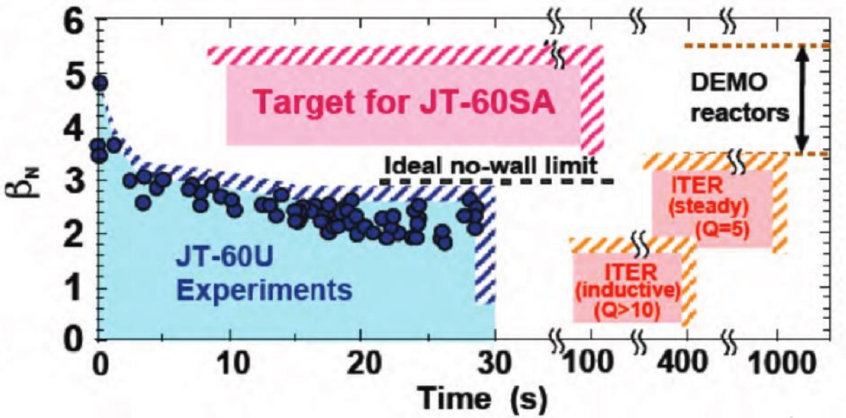
Motivation

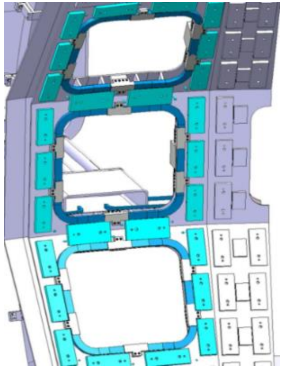
One of the main missions of JT-60SA is **demonstrating and studying steady-state high β operation**. RWM stabilization is necessary for high β operation:

- Dedicated in-vessel coils will be installed for **RWM feedback control**

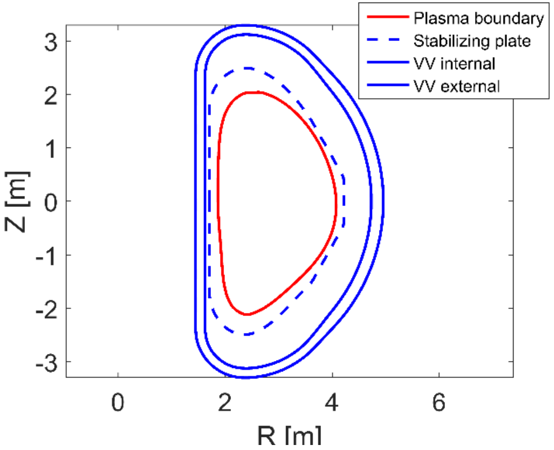
- Complementary to active control, it is required to understand the mode interaction with plasma rotation and particles: **Kinetic-RWM physics**

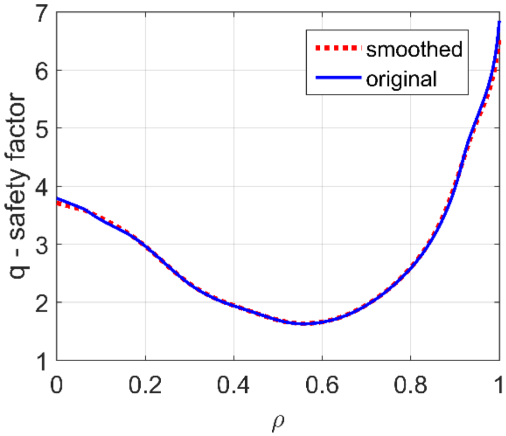
Modelling the synergy between these passive and active stabilization channels is essential for a realistic description of the phenomenon in advanced scenarios





Modeling workflow





Flat top phase of “scenario 5” with I_p=2.3 MA and B_t=1.7 T

Equilibrium is solved with CHEASE fixed boundary code, for high mesh resolution inside the plasma

Linear stability is studied with MARS-F using fluid damping models for RWMs and with MARS-K using the self-consistent drift-kinetic formulation

[L. Pigatto et al. Nucl. Fusion 59 (2019) 106028]

Codes integrated in python workflows:

- ✓ Equilibrium + stability workflow for low-n core modes
- ✓ Plasma response workflow for e.g. EFC applications
- ✓ CarMa coupling workflow for RWM modeling

Outline

- Motivation and introduction
- Equilibrium and ideal kink stability
- RWM in drift-kinetic model
    - Precession and bounce resonance damping
- Coupling linear kinetic plasma response model with 3D external structures
    - Application of CarMa-D to JT-60SA
- Outlook

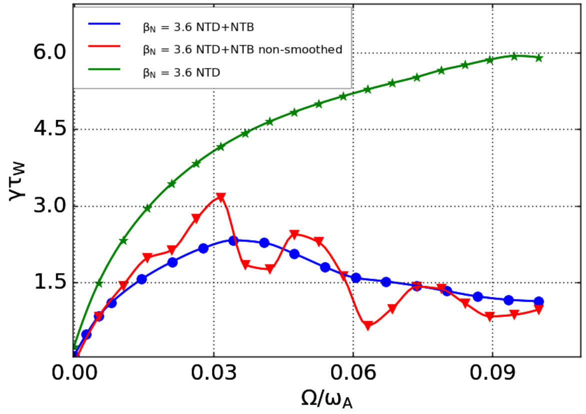
Improved modeling of kinetic-RWM

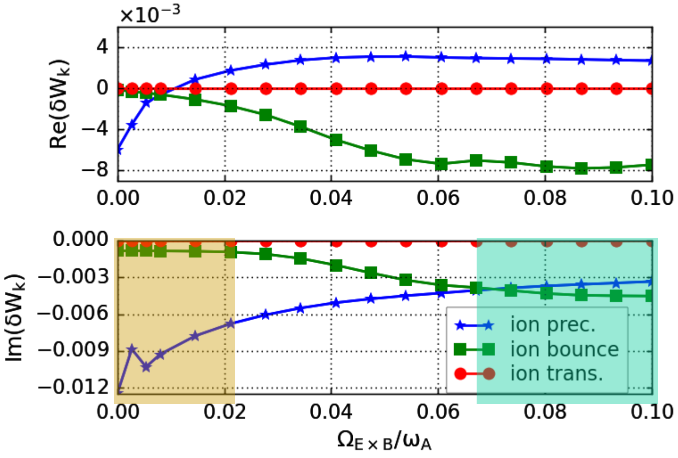
n=1,2 ideal RWMs are unstable in the fluid model

Kinetic damping **stabilizes** the n=2 mode at both low and fast toroidal flow

n=1 instability is unstable undergoes different stabilizing mechanisms:

- ☐ precession drift resonance is dominant and almost fully stabilizing at slow rotation
- ☐ bounce resonance gives a stabilizing contribution at fast rotation





Outline

- Motivation and introduction
- Equilibrium and ideal kink stability
- RWM in drift-kinetic model
  - Precession and bounce resonance damping
- Coupling linear kinetic plasma response model with 3D external structures
  - Application of CarMa-D to JT-60SA
- Outlook

CarMa-D application

Progress in coupling RWM unstable plasma response with 3D conductors

- CarMa code

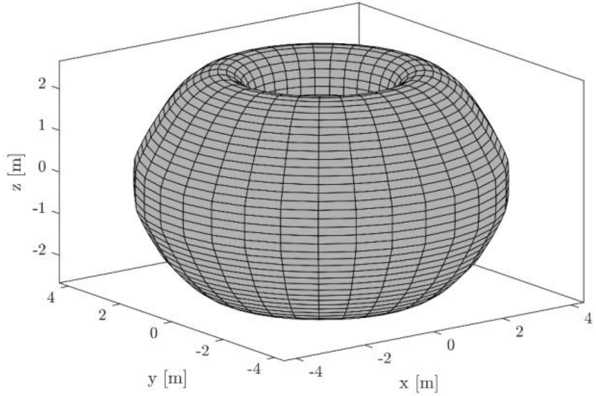
[Portone, A., et al (2008) *Plasma Physics and Controlled Fusion*, *50*(8), 085004.]

- CarMa-D approach of frequency interpolation

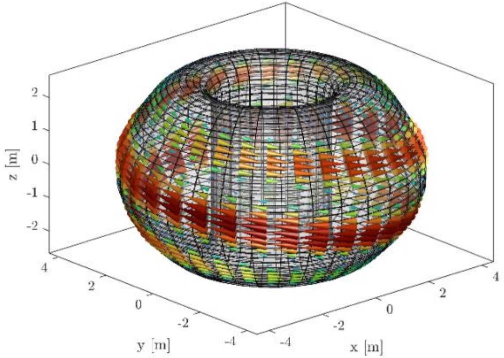
[Bonotto, M., et al (2020) *Plasma Physics and Controlled Fusion*, *62*(4), 045016.]

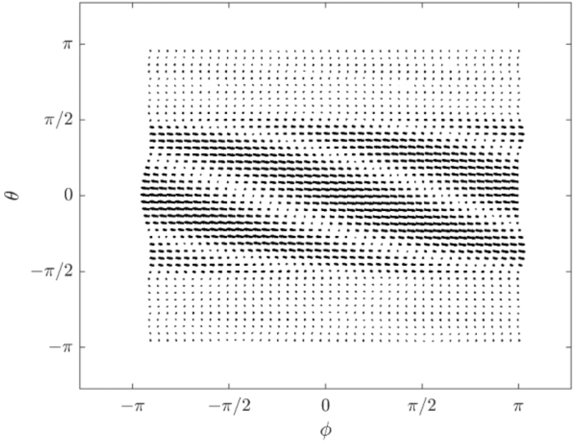
The CarMa-D coupling uses response matrices for fixed toroidal rotation (on axis $\frac{\Omega_0}{\omega_A} = 8\%$ i.e. relatively fast)

- Consistency check with MARS-K with axisymmetric wall in stabilizing plate position
- Both arbitrary **virtual** magnetic sensors and **real layout** of RWM control sensors implemented



CarMa-D application





(m,n)=(2,1) pattern of the most unstable mode on the axi-symmetric wall

	MARS-K	CarMa-D
$\gamma[s^{-1}]$	~ 16	~ 20

Can we improve this?

Summary & outlook

- ✓ Revised plasma response calculations with smoother input profiles and optimized mesh
- ✓ n=2 found to be stabilized in the explored rotation/beta range
- ✓ CarMa-D coupling with axisymmetric wall

- ► Fully 3D passives are being considered (VV and SP)
  - Can be numerically challenging
- ► Investigating behavior of unstable mode with changing structures
  - A step back to static CarMa could be useful to check robustness
- ► Cross-check MARS-K and CarMa results with varying wall resistivity
- ► Implementation of state-space model in dynamic simulator

- ❖ The workflow is now flexible enough to make switching scenarios relatively easy

Spares

MARS-K formulation

INPUTS

2D Equilibrium
- Equilibrium field, **B**
- Equilibrium current, **J**
- Equilibrium pressure, P
- Plasma boundary

Experimental profiles
- Ion & Electron temp., T_i T_e
- Electron density, n_e
- Toroidal plasma rotation, $\mathbf{V}_0$

Model parameters
- X-point smoothing
- Resistivity model (if)
- Parallel sound wave damping coefficient, $\mathbf{K}_{||}$

PROCESS (-K)

$$(\gamma +\ in\boldsymbol{\Omega})\boldsymbol{\xi} =\ \boldsymbol{v} + (\boldsymbol{\xi}\cdot\nabla\boldsymbol{\Omega})R^2\nabla\Phi$$

$$(\gamma + in\boldsymbol{\Omega})\boldsymbol{v}$$
$$= -\nabla\cdot\boldsymbol{p} + \nabla\times\boldsymbol{Q}\ \times\boldsymbol{B} + \nabla\times\boldsymbol{B}\ \times\boldsymbol{Q}$$
$$-\rho\left[2\boldsymbol{\Omega}\nabla Z\times\boldsymbol{v} + (\boldsymbol{v}\cdot\nabla\boldsymbol{\Omega})R^2\nabla\Phi\right] \qquad -\nabla\cdot(\rho\boldsymbol{\xi})R^2\boldsymbol{\Omega}^2\nabla Z\times\nabla\Phi$$

$$(\gamma +\ in\boldsymbol{\Omega})\boldsymbol{Q} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}) + (\boldsymbol{Q}\cdot\nabla\boldsymbol{\Omega})R^2\nabla\Phi$$

$$\boldsymbol{p} = p_{\|}\widehat{\boldsymbol{b}}\widehat{\boldsymbol{b}} + p_{\perp}\left(\boldsymbol{I} - \widehat{\boldsymbol{b}}\widehat{\boldsymbol{b}}\right)$$

Liu, Y., et al, 2000, *Physics of Plasmas (1994-present),* vol. 7, no. 9, pp. 3681-3690.
Liu, Y., et al, 2014, *Physics of Plasmas (1994-present),* vol. 21, no. 5, pp. 056105.
Liu, Y., at al, 2008, *Physics of Plasmas (1994-present),* vol. 15, no. 11, pp. 112503.

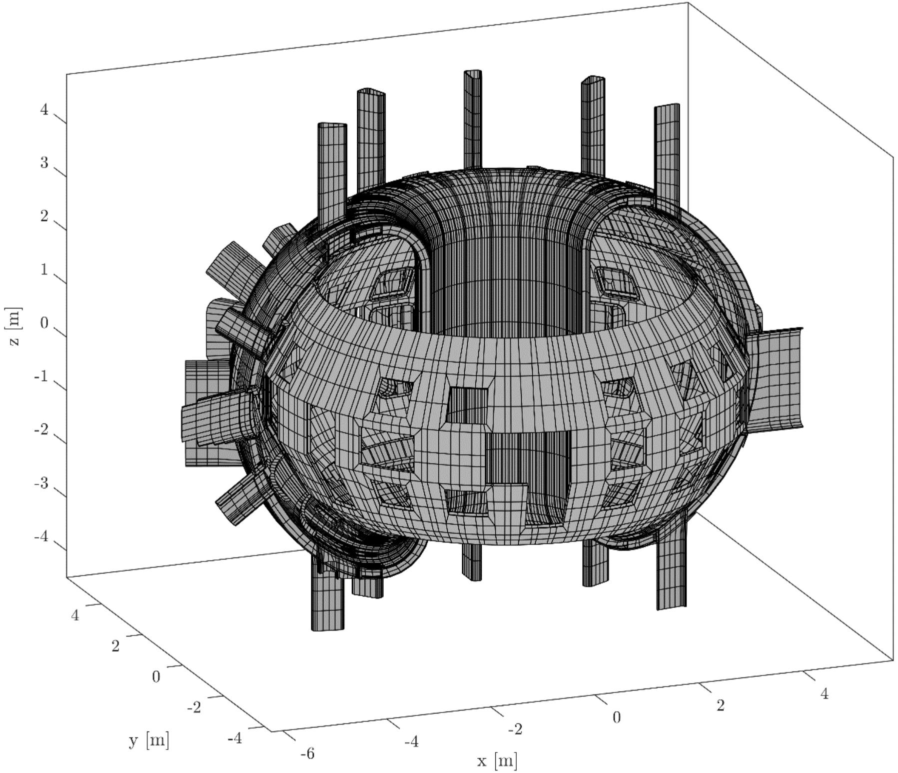
- Major radius, R
- Toroidal angle, Φ
- Plasma rot. Freq., $\boldsymbol{\Omega}$
- Parallel & perp. kinetic pressure comp., $p_{\|}$ $p_{\perp}$

OUTPUTS

Perturbed quantities:
- Plasma displacement, $\boldsymbol{\xi}$
- Perturbed velocity, $\boldsymbol{v}$
- Perturbed magnetic field, $\boldsymbol{Q}$
- Perturbed current, $\boldsymbol{j}$
- Perturbed pressure tensor, $\boldsymbol{p}$

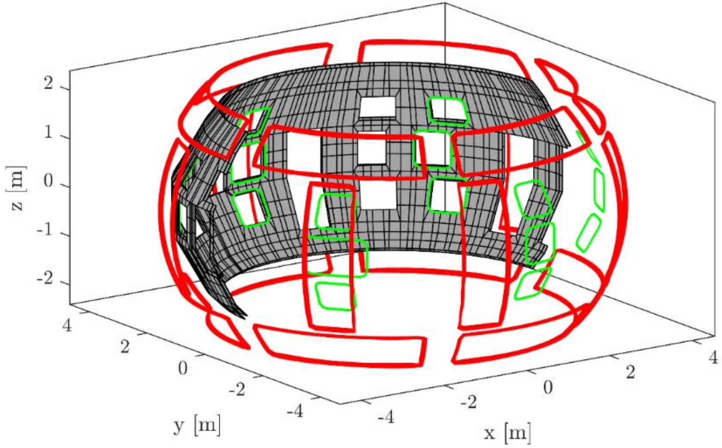
Components of the perturbed potential energy, kinetic in particular, δW_k

3D structures

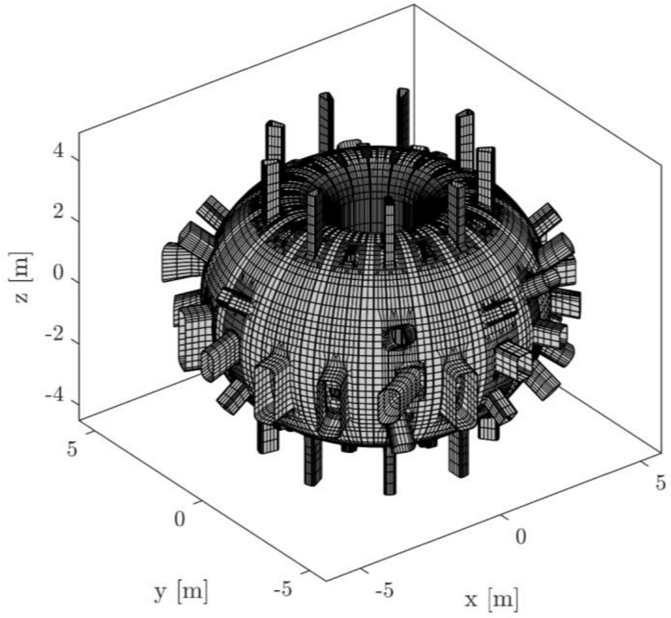


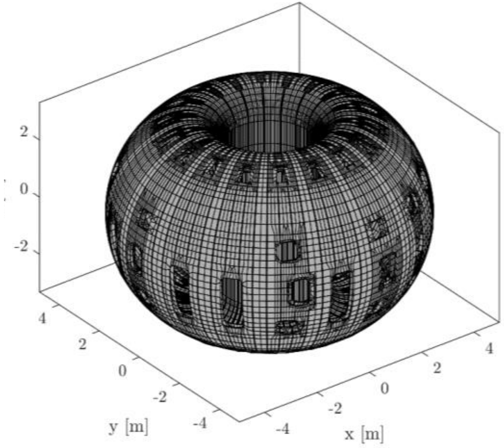
Accurate 3D geometry of:

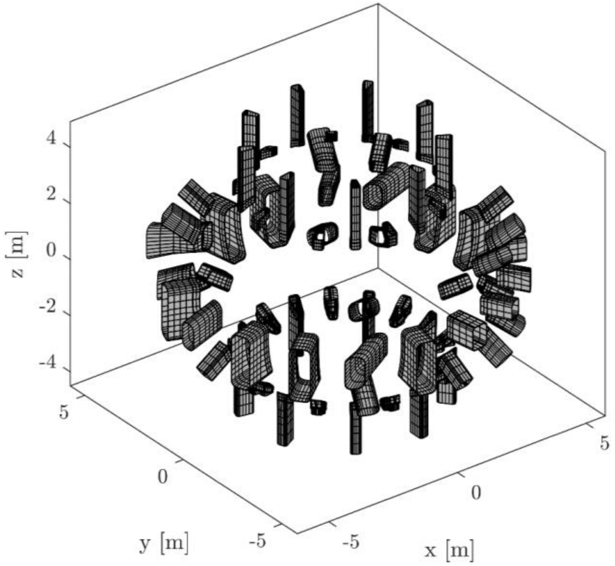
- Stabilizing plates
- Vacuum Vessel (with port extensions)
- EFCC and RWMCC



Contribution of port extensions







Feedback modeling toolbox

Flight simulator developed for JT-60SA, based on **CarMa (= MARS-F + CARIDDI)** code, allows to simulate the time evolution of the closed-loop system

- Multi-n RWM feedback
- Eigenvalue study
- Time simulations: latency, detection thresholds
- Kinetic damping through CarMa-D state-space model