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

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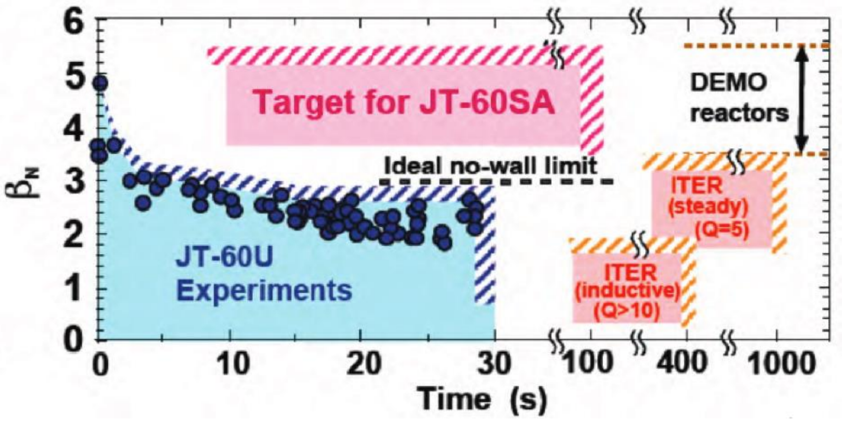
Outline

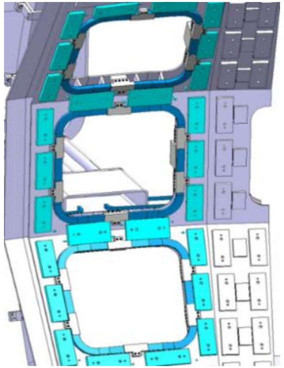
- Motivation and introduction
- Equilibrium and ideal kink stability
- RWM in drift-kinetic model
    - Precession and bounce resonance damping
- Coupling linear kinetic plasma response model with 3D external structures
    - Application of CarMa-D to JT-60SA
- Outlook

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**

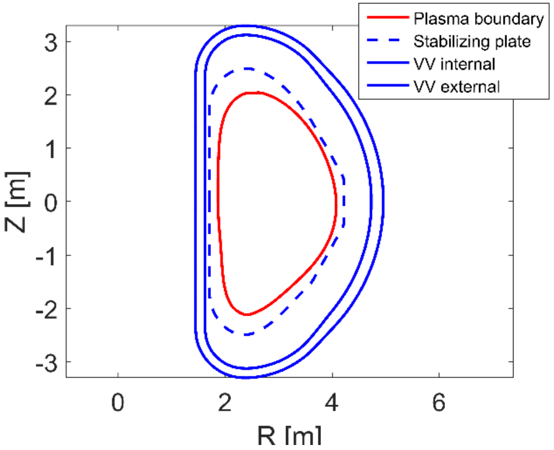


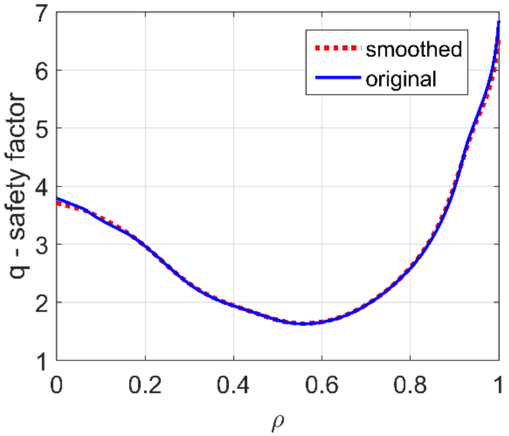


Modelling the synergy between these passive and active stabilization channels is essential for a realistic description of the phenomenon in advanced scenarios

Physics and models are relevant for all scenarios aiming at high β (# 4.*, 5)

Modeling workflow





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

- **Lower input power for flat-top $\beta_N \cong 3.6$**

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

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Improved modeling of kinetic-RWM

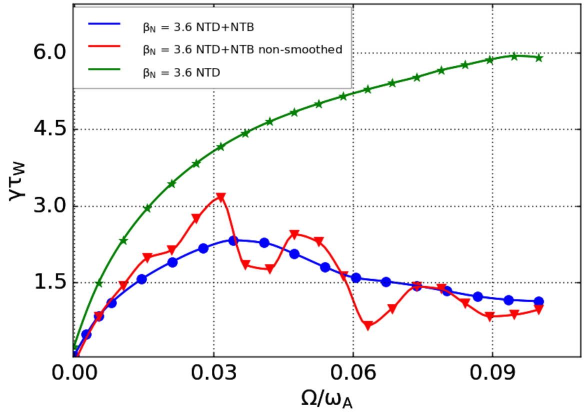
n=1,2 ideal RWMs are unstable in the fluid model

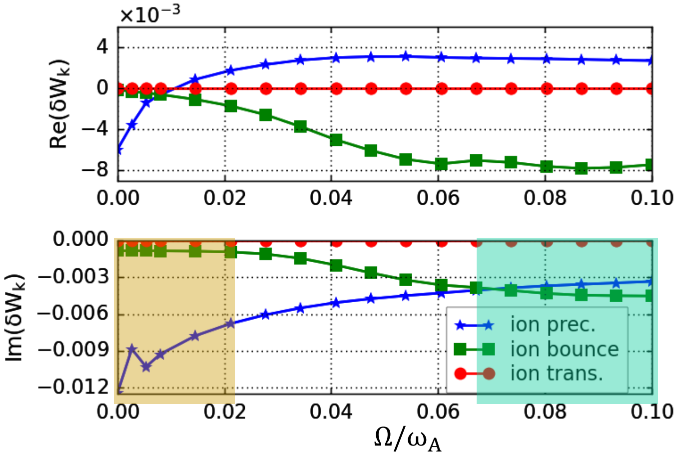
Kinetic damping **stabilizes the n=2** mode at both low and fast toroidal flow, **n=1 is unstable**

Two resonances for thermal particles:

- ☐ precession drift resonance is dominant and almost fully stabilizing at slow rotation (JT-60U exp.)
- ☐ bounce resonance gives a stabilizing contribution at fast rotation

Fast ions not accounted for (non-trivial distribution and implementation)





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CarMa-D application

Progress in coupling RWM unstable plasma response with 3D conductors

- CarMa code

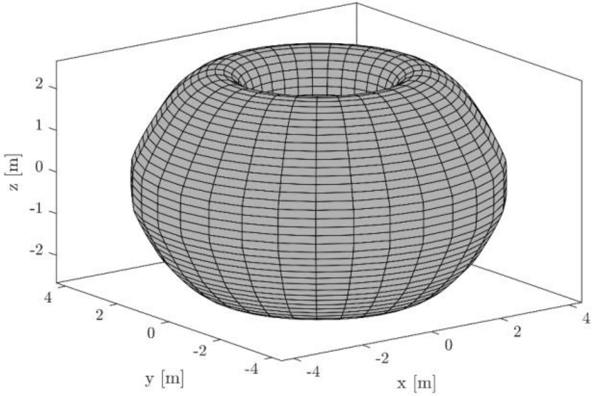
[Portone, A., et al (2008) *Plasma Physics and Controlled Fusion*, *50*(8), 085004.]

- CarMa-D approach: frequency interpolation

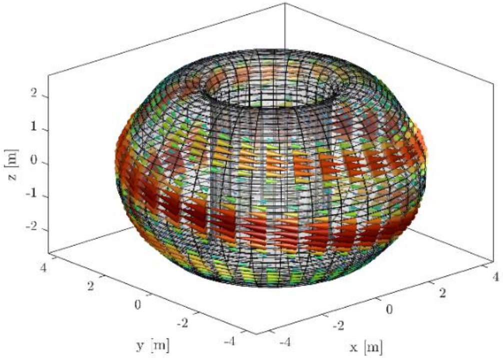
[Bonotto, M., et al (2020) *Plasma Physics and Controlled Fusion*, *62*(4), 045016.]

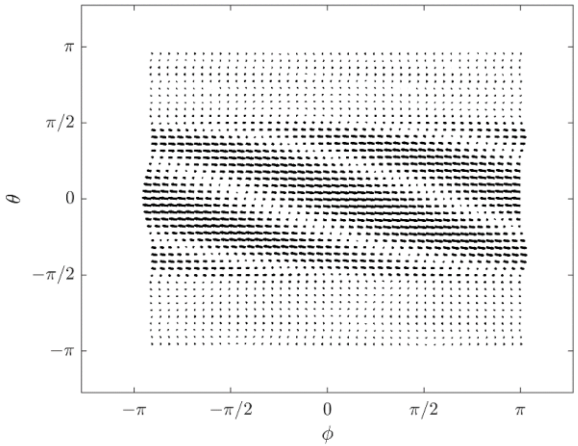
The CarMa-D coupling uses response matrices for fixed toroidal rotation (on axis $\frac{\Omega_0}{\omega_A} = 8\%$ i.e. relatively fast)

- 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

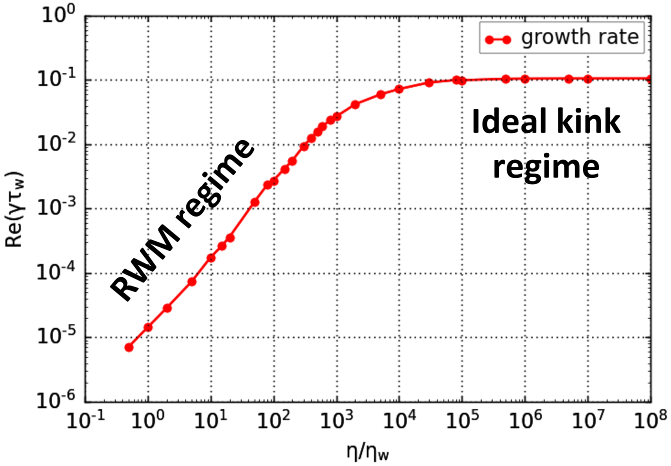




(m,n)=(2,1) pattern of the most unstable mode on the axi-symmetric wall

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

Can we improve this?



CarMa-D can reproduce this dynamic

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)

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

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

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

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

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.

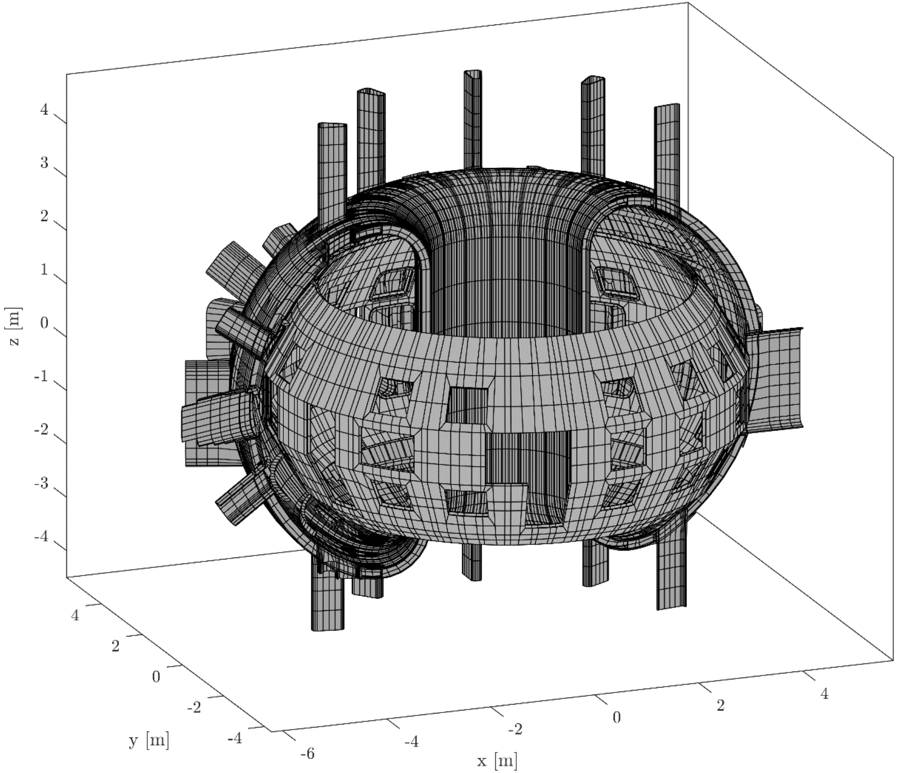
Major radius, R
Toroidal angle, Φ
Plasma rot. Freq., $\boldsymbol{\Omega}$
Parallel & perp. kinetic pressure comp., $p_{\parallel}$ $p_{\perp}$

OUTPUTS

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

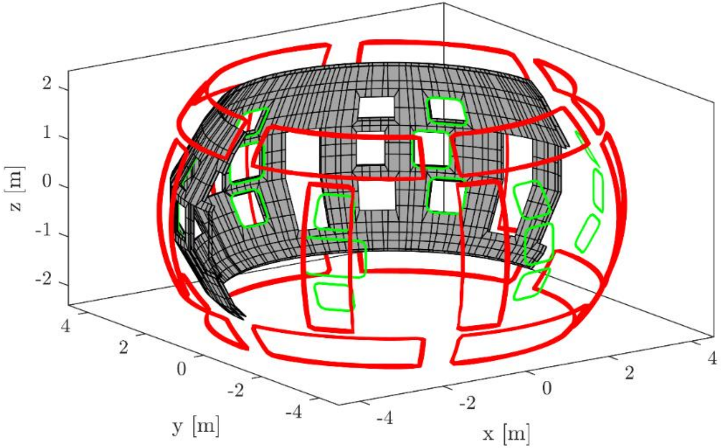
Components of the perturbed potential energy, kinetic in particular, δW_k

3D structures

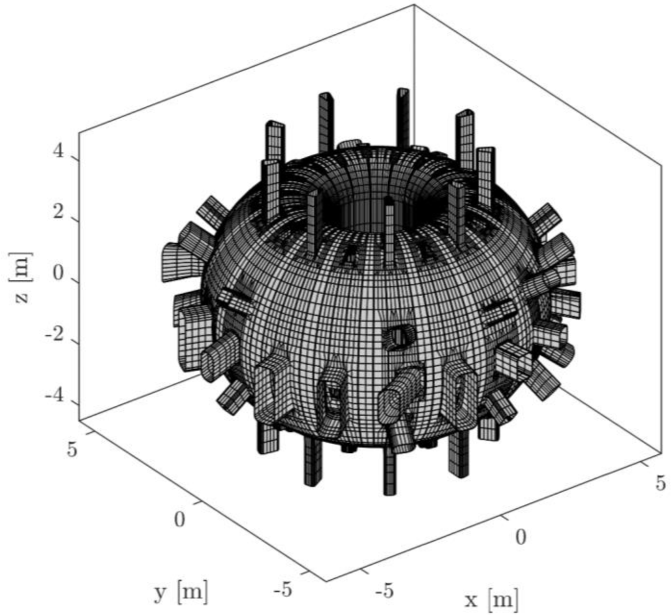


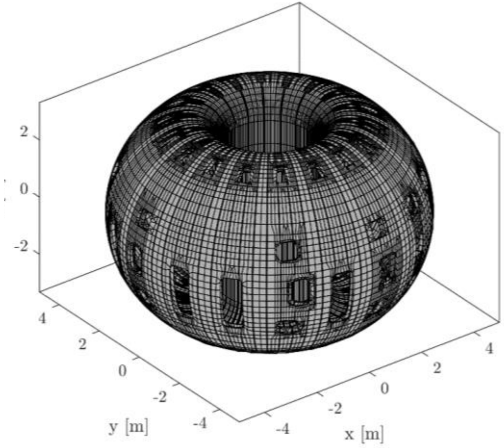
Accurate 3D geometry of:

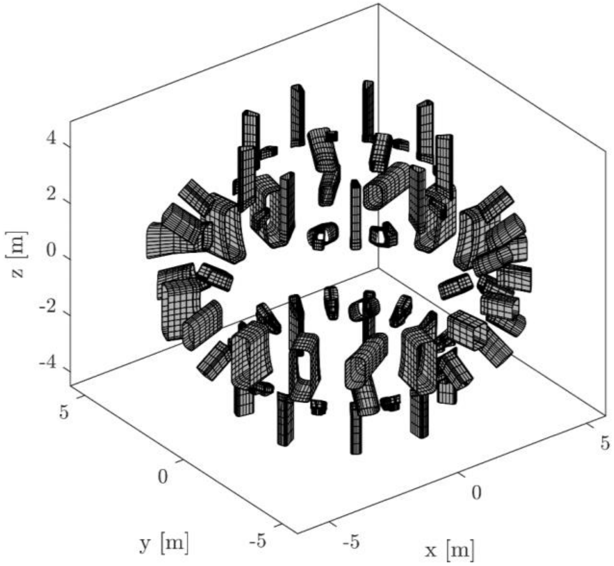
- Stabilizing plates
- Vacuum Vessel (with port extensions)
- EFCC and RWMCC



Contribution of port extensions



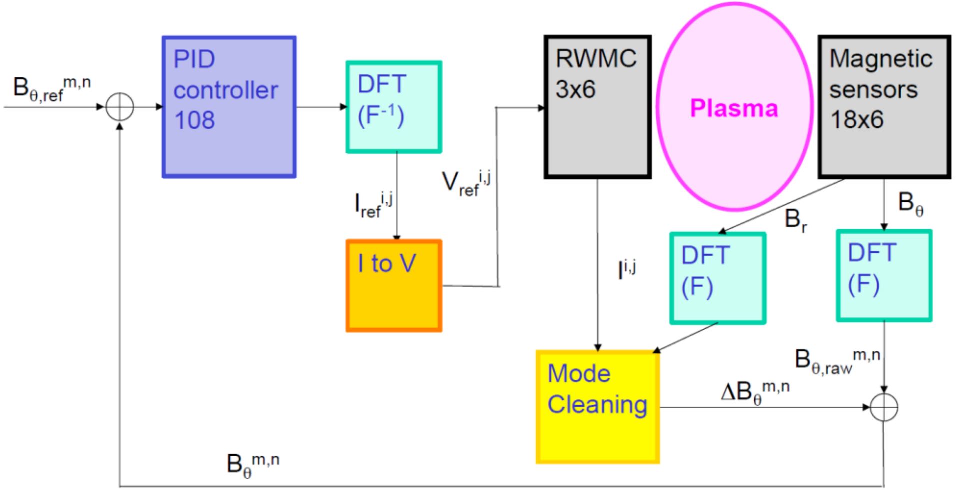




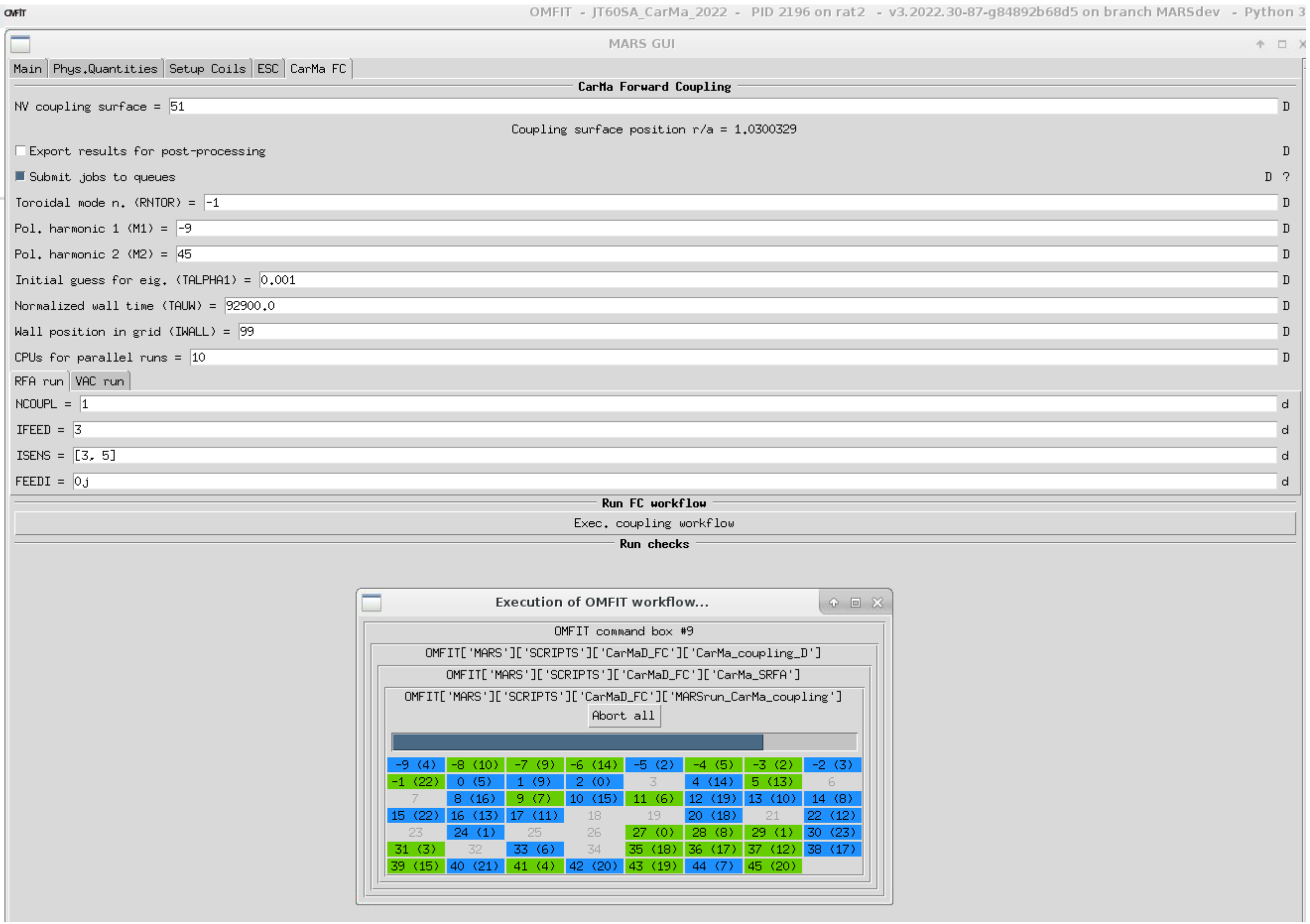
Feedback modeling toolbox

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



Tools for CarMa workflow



NV coupling surface = 51

Coupling surface position r/a = 1.0300329

☐ Export results for post-processing

☑ Submit jobs to queues

Toroidal mode n. (RNTOR) = -1

Pol. harmonic 1 (M1) = -9

Pol. harmonic 2 (M2) = 45

Initial guess for eig. (TALPHA1) = 0.001

Normalized wall time (TAUW) = 92900.0

Wall position in grid (IWALL) = 99

CPUs for parallel runs = 10

NCOUPL = 1

IFEED = 3

ISENS = [3, 5]

FEEDI = 0j

OMFIT command box #9

OMFIT['MARS']['SCRIPTS']['CarMaD_FC']['CarMa_coupling_D']

OMFIT['MARS']['SCRIPTS']['CarMaD_FC']['CarMa_SRFA']

OMFIT['MARS']['SCRIPTS']['CarMaD_FC']['MARSrun_CarMa_coupling']

-9 (4)	-8 (10)	-7 (9)	-6 (14)	-5 (2)	-4 (5)	-3 (2)	-2 (3)
-1 (22)	0 (5)	1 (9)	2 (0)	3	4 (14)	5 (13)	6
7	8 (16)	9 (7)	10 (15)	11 (6)	12 (19)	13 (10)	14 (8)
15 (22)	16 (13)	17 (11)	18	19	20 (18)	21	22 (12)
23	24 (1)	25	26	27 (0)	28 (8)	29 (1)	30 (23)
31 (3)	32	33 (6)	34	35 (18)	36 (17)	37 (12)	38 (17)
39 (15)	40 (21)	41 (4)	42 (20)	43 (19)	44 (7)	45 (20)	

- Equilibrium <-> CHEASE
- MARS-F templates with few variables to set up
- Parallel execution of plasma response runs for all boundary conditions
- Post processing