Federico Fiorenza

Advanced magnetic control and reconstruction in fusion devices

Tutor: Prof. Gianmaria De Tommasi

Cycle: 38 Year: 2025

Candidate’s information

- MSc degree: Automation and Robotics Engineering
- DIETI Research group/laboratory: Plasma control group/CREATE
- PhD start date – end date: 01/01/2023 – 31/12/2025
- PNRR-NEFERTARI
- Participation to JT-60SA IC, Naka, Japan (28/10/2023-3/12/2023)
- Fusion For Energy, Barcellona, Spain (3/11/2024-31/07/2025)

Summary of study activities

- Japan International Fusion School 2024
- SIDRA PhD Summer School 2023
- Symposium on Fusion Technology 2024
- Control and Decision Conference 2024
- JT-60SA IC Analysis and Modeling workshop 2024 and 2025
- Conference on Control of Complex System 2025
- Symposium On Fusion Engineering 2025

Research area(s)

Identification and control in fusion devices

- RFX-mod2 electromagnetic modeling and control
- Real-time algorithms for plasma quantities reconstruction
- High-performance actuator sharing techniques for magnetic control in fusion devices
- Demodulation techniques in plasma diagnostics applications

Basic control theory

- Current State Opacity verification in Petri Nets
- Finite Time Stability

Research results

- Development of CARONTE code for real-time plasma boundary reconstruction
- Design of a magnetic control system for RFX-mod2 with strict input constraints
- Design of a decoupled Magnetic control system for JT60SA
- Testing of ITER magnetic reconstruction algorithms using JT-60SA experimental data
- Real-time identification and compensation of transmission line effect for ITER bolometer diagnostics
- Necessary and sufficient conditions for CSO verification in labeled and unlabeled Petri Nets
- Necessary and sufficient conditions for FTS in non-linear systems and linear descriptor systems

Research products

[IJ1]	***F. Fiorenza**, G. De Tommasi, D. Frattolillo, C. Ingesson, S. Inoue, S. Kojima, M. Mattei, Y. Miyata, A. Neto, A. Mele, A. Pironti, O. Sauter, M. Takechi, H. Urano, "Preliminary validation of ITER magnetic diagnostic algorithms by using JT-60SA magnetic measurements," Fusion Engineering and Design.*
[IJ2]	*S. Dubbioso, D. Ottaviano, **F. Fiorenza**, G. De Tommasi, N. Ferron, G. Manduchi, E. Acampora, R. Ambrosino, "Rapid prototyping of control modules for the DTT Plasma Control System," Fusion Engineering and Design.*
[IJ3]	*F. Romanelli,…,**F. Fiorenza** "Divertor Tokamak Test facility project: status of design and implementation." Nuclear Fusion 64.11 (2024): 112015*
[IJ4]	*T. Szepesi, A. Buzás, G. Cseh, G. Kocsis, Á. Kovácsik, D. Réfy, T. Szabolics, H. Homma, K. Kamiya, T. Nakano, M. Yoshida, W. Bin, G. De Tommasi, **F. Fiorenza**, D. Frattolillo, M. Iafrati, M. Mattei, A. Pironti, D. Ricci, C. Sozzi, J. Svoboda, J. Cavalier, "Analysis of the first plasmas of JT-60SA using the EDICAM visible video diagnostic", Fusion Engineering and Design.*
[IJ5]	*G. De Tommasi, L. E. di Grazia, S. Dubbioso, **F. Fiorenza**, D. Frattolillo, S. Inoue, M. Mattei, A. Pironti and H. Urano, "Control of elongated plasmas in superconductive tokamaks in the absence of in-vessel coils," Nuclear Fusion, vol. 64, no. 7, pp. 076005, July 202, (Scopus/ISI Web of Science).*

Research products

[IJ6]	*F. Basile, S. Dubbioso, G. De Tommasi,* ***F. Fiorenza*** *Verification of K-step Non-Interference for Live Bounded and Reversible Discrete Event Systems Modeled with Petri Nets, IEEE Control Systems Letters*
[IJ7]	***F. Fiorenza****, L. Capellà Negre, G. De Tommasi, A. Neto, A. Pironti, F. Sartori "IQ demodulation with real-time transmission line compensation for ITER bolometer diagnostics." Submitted to IEEE Transactions on Plasma Physics.*
[IJ8]	***F. Fiorenza,*** *S. Dubbioso, G. De Tommasi, A. Pironti "CARONTE: a Physics-Informed Extreme Learning Machine-Based Algorithm for Plasma Boundary Reconstruction in Magnetically Confined Fusion Devices." Submitted to Engineering Applications of Artificial Intelligence.*
[IJ9]	*F. Basile, G. De Tommasi, S. Dubbioso,* ***F. Fiorenza****, "On current-state opacity in bounded labeled Petri net systems," Transactions On Automatic Control, submitted.*

Research products

[IC1]	*F. Basile, G. De Tommasi, S. Dubbioso,* ***F. Fiorenza****, "An Optimization Approach to Current State Opacity Asessment," in 63rd IEEE Conference on Decision and Control (CDC'24), Milano, Italy, December 2024 (Scopus/ISI Web of Science)*
[IC2]	***F. Fiorenza****, G. De Tommasi, D. Frattolillo, C. Ingesson, S. Inoue, M. Mattei, Y. Miyata, A. Neto, A. Pironti, M. Takechi, H. Urano, "Validation ITER magnetic diagnostic algorithms using JT60SA magnetic measurements," in 33rd Symposium on Fusion Technology (SOFT'24), Dublin, Ireland, September 2024.*
[IC3]	*S. Dubbioso, D. Ottaviano,* ***F. Fiorenza****, N. Ferron, G. Manduchi, R. Ambrosino, G. De Tommasi, "Rapid prototyping of control modules for the DTT Plasma Control System," in 33rd Symposium on Fusion Technology (SOFT'24), Dublin, Ireland, September 2024.*
[IC4]	*T. Szepesi, A. Buzás, G. Cseh, G. Kocsis, Á. Kovácsik, D. I. Réfy, T. Szabolics, S. Zoletnik, H. Homma, K. Kamiya, T. Nakano, M. Yoshida, T. Wakatsuki, C. Biedermann, D. Hathiramani, M. Jakubowski, M. Krause, M. Otte, W. Bin, G. De Tommasi,* ***F. Fiorenza****, D. Frattolillo, M. Iafrati, M. Mattei, A. Pironti, D. Ricci, C. Sozzi, J. Svoboda, "Visible video diagnostics for the support of Wendelstein 7-X and JT-60SA commissioning and operation," in 33rd Symposium on Fusion Technology (SOFT'24), Dublin, Ireland, September 2024.*

Research products

[IC5]	*T. Szepesi, A. Buzás, G. Cseh, G. Kocsis, Á. Kovácsik, T. Szabolics, D. I. Réfy, H. Homma, K. Kamiya, T. Nakano, M. Yoshida, W. Bin, G. De Tommasi, **F. Fiorenza**, D. Frattolillo, M. Iafrati, M. Mattei, A. Pironti, D. Ricci, C. Sozzi, J. Svoboda, "Analysis of the first plasmas of JT-60SA using EDICAM," in 50th EPS Conference on Plasma Physics, Salamanca, Spain, July 2024.*
[IC6]	*C. Sozzi, G. De Tommasi, M. Iafrati, W. Bin, A. Buzás, L. Cordaro, L. E. DiGrazia, **F. Fiorenza**, D. Frattolillo, A. Gallo, L. Garzotti, G. Golluccio, G. Kocsis, Á. Kovácsik, L. Le Coz, P. J. Moreau, M. Mattei, L. Pigatto, A. Pironti, G. Pucella, D. I. Réfy, D. Ricci1, N. Richermoz, J. Svoboda, T. Szabolics, T. Szepesi, E. Tomasina, Y. Kazakov, L. Zani, G. Falchetto, F. Bonne, T. Bolzonella, J. Buermans, J. Cavalier, G. Cseh, S. Gerasimov, Q. Gorit, L. Figini, S. Nicollet, F. Villone, "The EUROfusion contribution to Operation 1 of JT-60SA," in 50th EPS Conference on Plasma Physics, Salamanca, Spain, July 2024.*
[IC7]	*F. Basile, S. Dubbioso, G. De Tommasi, **F. Fiorenza*** *Sequence-based Vs Observer-based Approaches to Verify Current-State Opacity: A Benchmark Case, 2025 IEEE Conference on Control Technology and Applications (CCTA),*
[IC8]	*D. Abate, M. Brombin, R. Cavazzana, **F. Fiorenza**, D. G. Lui, G. Marchiori, A. Pironti, F. Villone “A Model Predictive Control Approach for the active coil currents in the RFX-mod2 device.” Conference on Control Of Complex Systems (COSY) 2025*

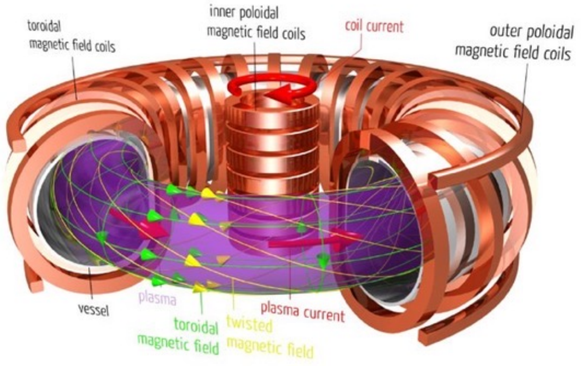
Research products

[IC9]	*F. Amato, G. De Tommasi, S. Dubbioso,* ***F. Fiorenza****, D. G. Lui "Finite-time stability and stabilization for linear time-varying descriptors systems." Conference on Control Of Complex Systems (COSY) 2025*

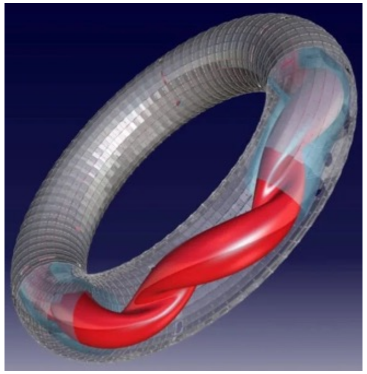
Tokamaks

- A tokamak is a toroidal device designed to confine extremely hot plasma for controlled nuclear fusion.

- Magnetic fields act as an “immaterial container,” preventing the plasma from touching the vessel walls.



Toroidal magnetic field: generated by external coils,
Poloidal magnetic field: mainly produced by the plasma current.
Together they achieve effective particle confinement

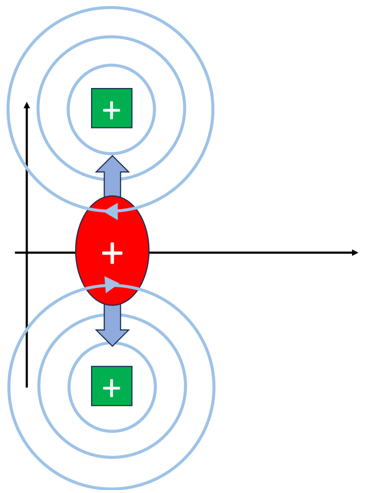


Reversed Field Pinches (RFP) as an alternative to Tokamaks

Advantages: More compact and easier to construct than Tokamaks.

Challenges: Loss of axisymmetry complicates modeling and control.

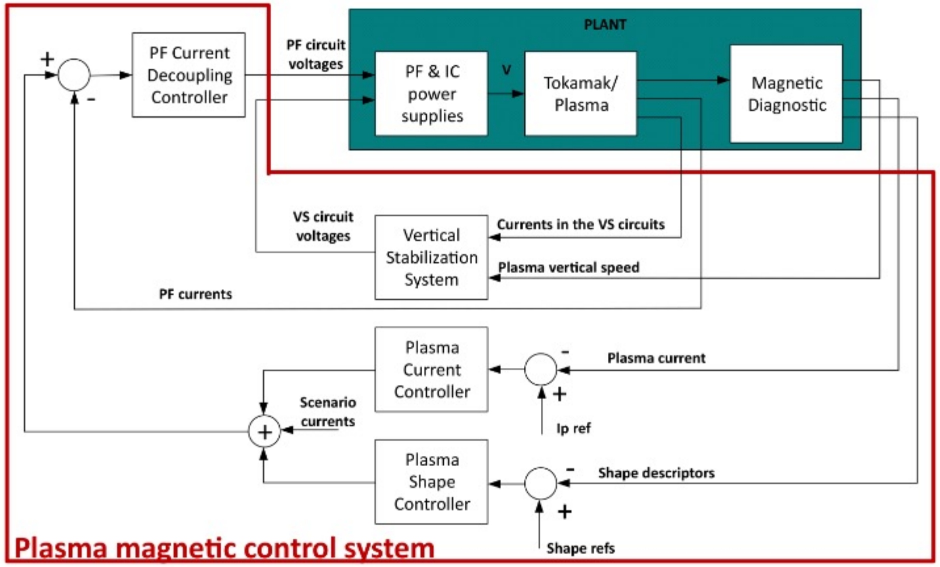
The magnetic control problem



High efficiency plasmas are usually vertically elongated.
This equilibrium configuration is unstable

An active control system is crucial to keep the plasma in place by applying corrections to the equilibrium magnetic field

The magnetic control system tackles the problem of stabilizing the plasma and tracking a desired shape and plasma current.
It relies on accurate reconstruction algorithm



The focus of the thesis is the magnetic control system and reconstruction algorithms needed to compute physical quantities to be controlled.

Model-based magnetic control design

Starting from a nonlinear lumped parameters model, the following linearized state-space model of the plasma-circuit behaviour can be obtained

$$\begin{cases} \delta\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\delta\boldsymbol{x} + \boldsymbol{B}\delta\boldsymbol{u} + \boldsymbol{E}\delta\boldsymbol{w} \\ \delta\boldsymbol{y}(t) = \boldsymbol{C}\delta\boldsymbol{x} + \boldsymbol{D}\delta\boldsymbol{u} + \boldsymbol{F}\delta\boldsymbol{w} \end{cases}$$

- $\delta\boldsymbol{x}(t) = \left[\delta\boldsymbol{I}_{PF}^{T}(t)\ \delta\boldsymbol{I}_{e}^{T}(t)\ \delta I_p\ (t)\right]^T$ is the state space vector
- $\delta\boldsymbol{u}(t) = [\delta\boldsymbol{V}_{PF}^{T}(t)\ \boldsymbol{0}^T\ 0]^T$ are the input voltage variations
- $\delta\boldsymbol{w}(t) = \left[\delta\beta_p(t)\ \delta l_i(t)\ \right]^T$ are the internal pressure and current density variations
- $\delta\boldsymbol{y}(t)$ are the output variations

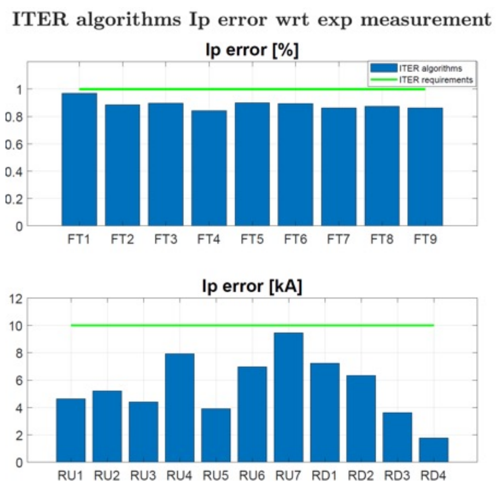
Codes like CREATE-NL/L can solve the plasma equilibrium and derive a linearized model which can be used to design controllers.

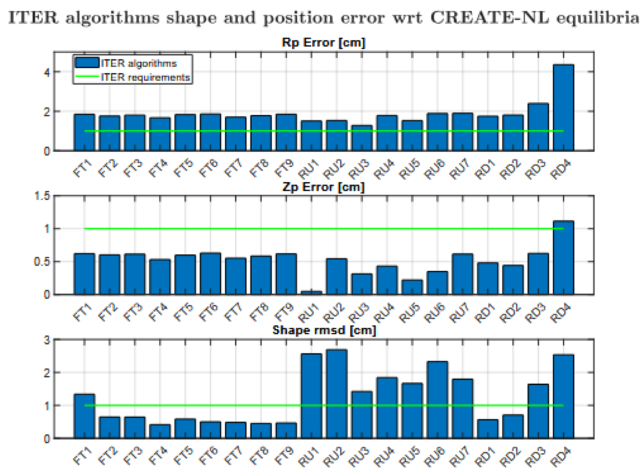
PhD Thesis Contribution – magnetic reconstruction (1/2)

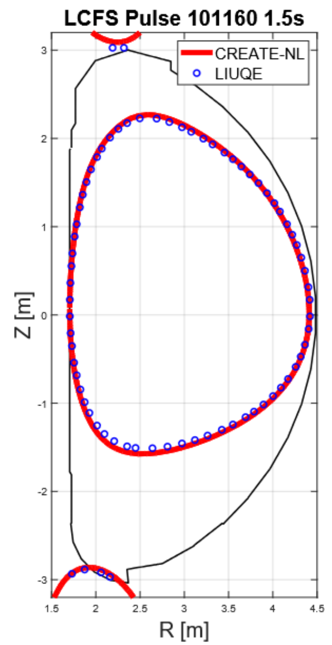
JT-60SA is currently the largest tokamak in the world and has been recently commissioned with reduced actuators capabilities and a reduced number of sensors

It's the best test-bench for the ITER magnetic diagnostic algorithms.
(Some of them developed by CREATE)

They have been evaluated taking the equilibrium computed by CREATE-NL, which is an iterative high-fidelity code, as ground truth





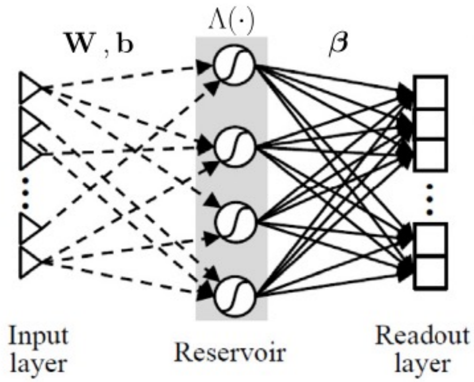


PhD Thesis Contribution – magnetic reconstruction (2/2)

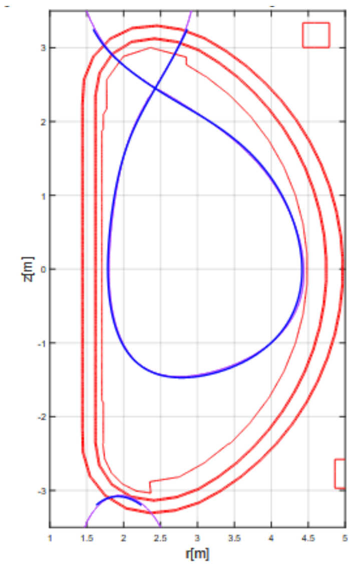
The **CARONTE** algorithm, a new NN-based plasma boundary reconstruction algorithm, is proposed.

It exploits a particular NN structure, namely the **Extreme Learning Machine** (ELM), such that the training of the weights can be made in real-time.

There is no need to train the network on a huge amount of data before.



It has been tested on CREATE-NL equilibria as well as experimental data from JT-60SA

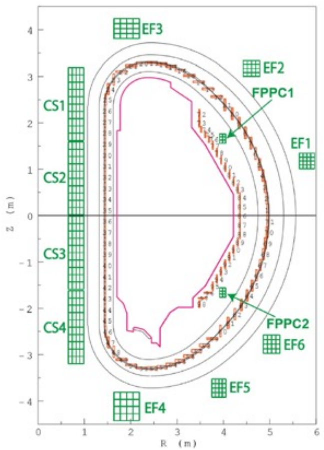


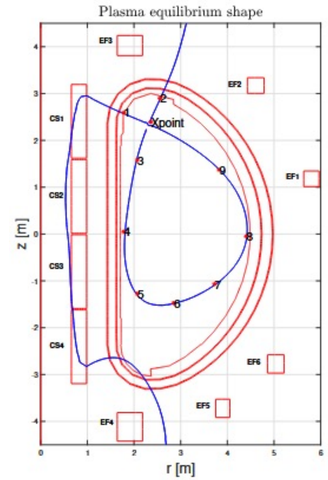
More details later…

PhD Thesis Contribution – magnetic control (1/2)

Vertical stabilization systems usually rely on **dedicated fast in-vessel coils**.
As for JT-60SA, during the initial commissioning of large superconductive tokamaks not every component is available.

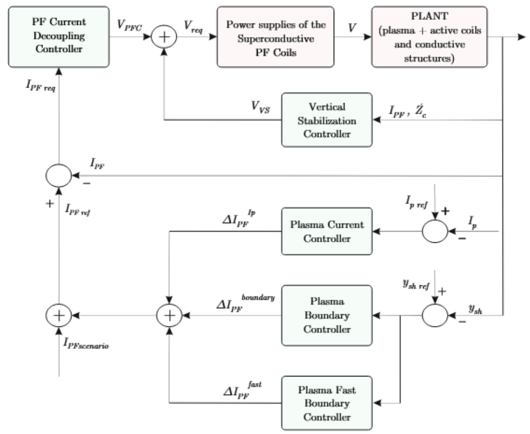
We need to stabilize elongated plasmas without in-vessel coils

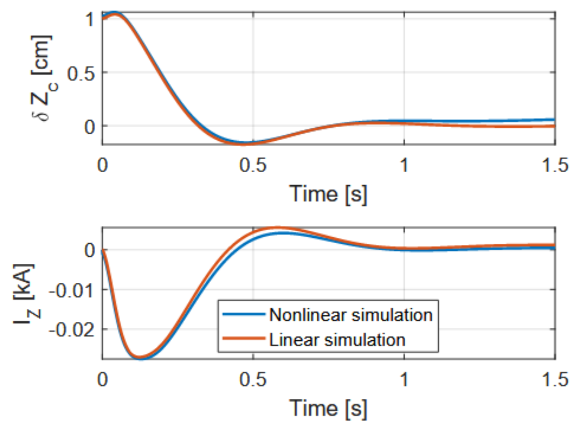




N. Cruz, et al
'Control-oriented tools for the design and validation of the JT-60SA magnetic control system'

Exploiting a plasma linearized model, an effective actuator sharing technique based on geometrical decoupling can help to stabilize elongated plasma.

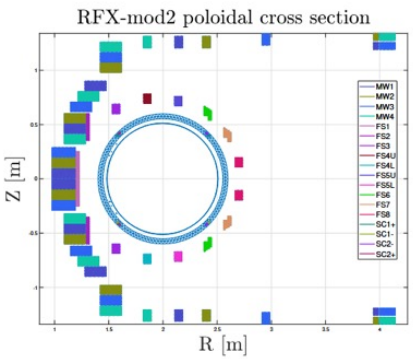


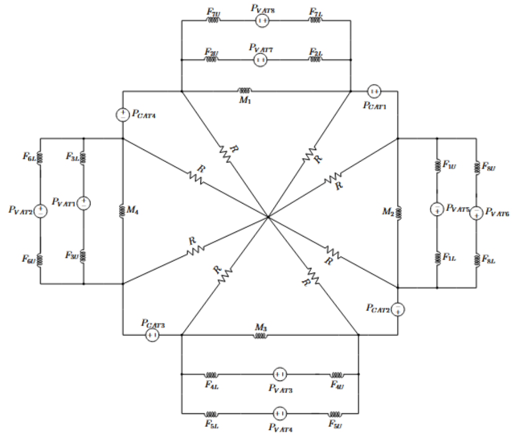


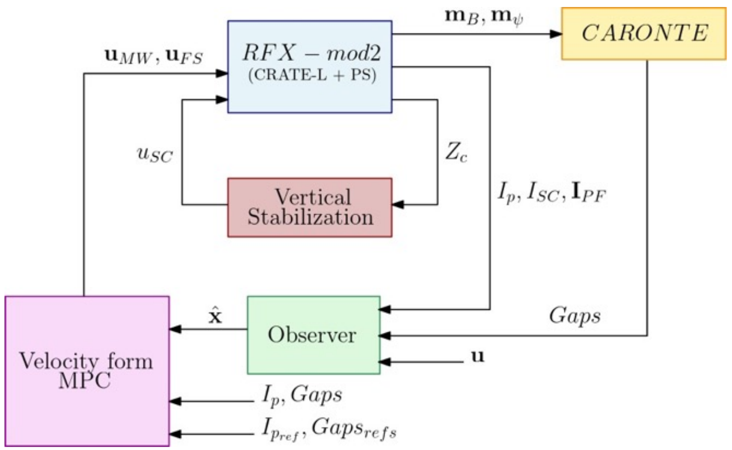
PhD Thesis Contribution – magnetic control (2/2)

RFX-mod is the largest RFP in the world and is currently being upgraded to RFX-mod2.

It can operate as tokamak as well.







Courtesy of Dr. Sara Dubbioso

The power supply system uses one-quadrant ac. - dc. converters for MW and FS circuits.
Therefore, only positive voltages can be fed as input.

We developed an MPC controller to take into account these strict constraints in the design phase.

Also, the whole system has been tested using the CARONTE reconstruction in the loop and in the MARTe real-time framework.

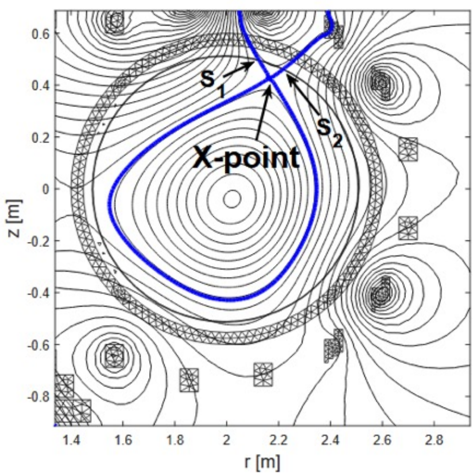
PART ONE:
MAGNETIC RECONSTRUCTION

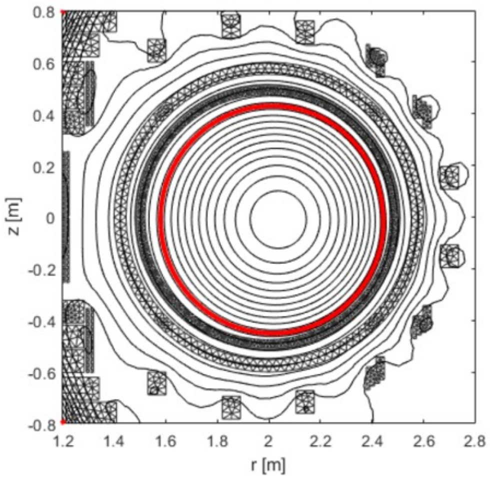
CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction

The Grad-Shafranov (GS) equation describes the behaviour of the poloidal flux function, which can be used to estimate the plasma boundary coordinates.

$$\begin{cases} \Delta^*\psi(r,z) = 0 & \textit{vacuum} \\ \Delta^*\psi(r,z) = -\mu_0 r J_p & \textit{plasma region} \\ \Delta^*\psi(r,z) = -\mu_0 r J_c & \textit{conductors} \end{cases}$$

$$\Delta^*\psi(r,z) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\psi(r,z)\right) + \frac{\partial^2}{\partial^2 z}\psi(r,z)$$





The plasma boundary is identified with the last closed flux surface.

CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction

Physics Informed Neural Networks (PINNs) can be used to solve Partial Differential Equations with initial/boundary conditions.

We propose to solve the GS equation in the vacuum $\Delta^*\psi(r,z) = 0$ using a single Physics-Informed **ELM**

The structure of an Extreme Learning Machine is the following

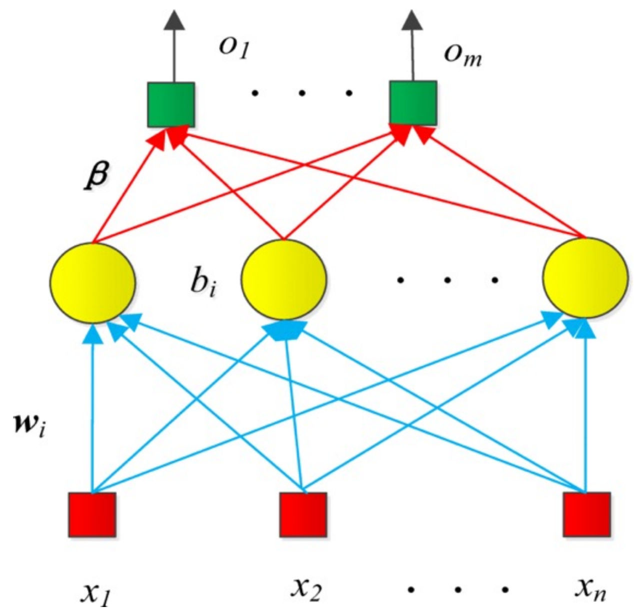
$$\psi_{ELM}(x) = \beta^T \sigma(Wx + b)$$

β is a vector of unknown weights

σ is the activation function

W and b are randomly initialised and not trained.

Extreme Learning Machines are similar to classic one-layer feedforward NNs and proved to have great generalization capabilities.



CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction

$$\Delta^* \psi(r,z) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\psi(r,z)\right) + \frac{\partial^2}{\partial^2 z}\psi(r,z) = 0$$

Using $\psi_{ELM}(x) = \beta^T \sigma(Wx + b)$ as approximation of the poloidal flux, the homogeneous GS equation is linear with respect to β.

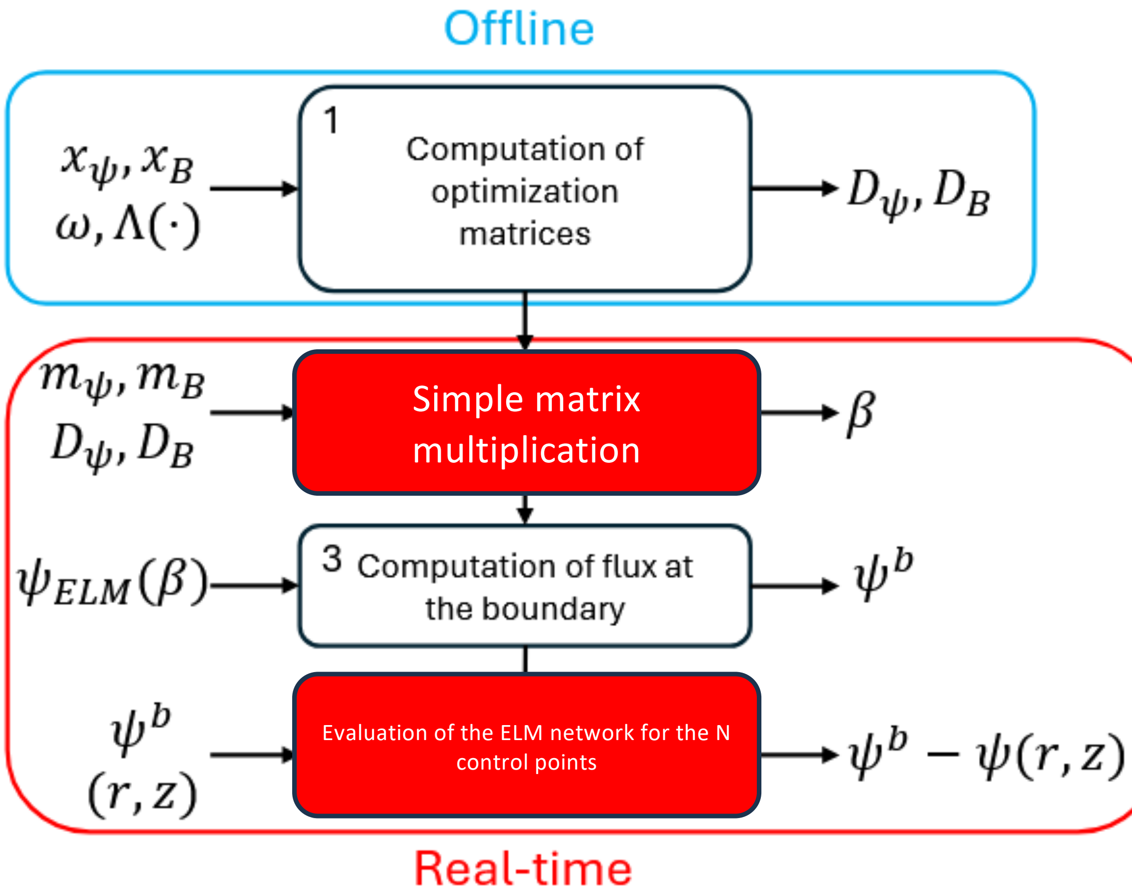
The ELM can be trained to satisfy the GS equation and match the magnetic measurements minimizing the following cost function

$$Loss(\beta) = \|\beta^T D_{GS}(x_c)\| + \left\|\beta^T \sigma\left(W x_\psi + b\right) - m_\psi\right\| + \|\beta^T D_B(x_B) - m_B\|$$

It is a quadratic function of β, standard least-squares methods are sufficient to train the ELM weights (pseudo-inverse).

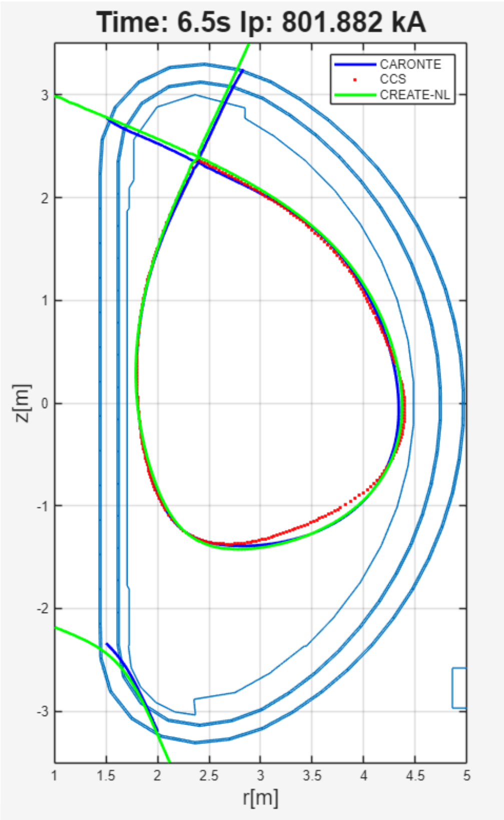
This means that the ELM can be trained in real-time!

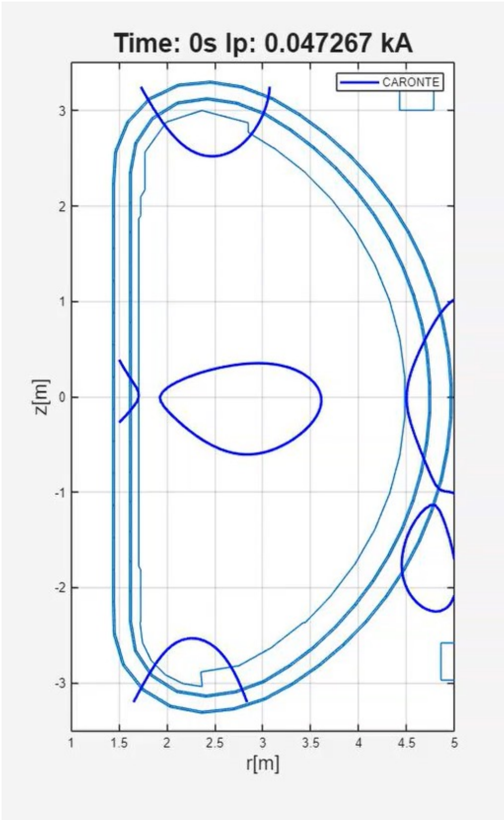
CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction



CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction

Exploiting experimental data, CARONTE has also been compared with the CCS code, which is currently used at JT-60SA.





PART TWO:
MAGNETIC CONTROL

Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

Previous Approach: Classic Linear Quadratic Gaussian (LQG) method.

Improved Design: Transition to MPC for better handling of power supply constraints.

Reference Disturbance: Voltage drop in the plasma circuit due to plasma resistance.

$$\boldsymbol{\xi}(k+1) = \begin{bmatrix} \boldsymbol{A_z} & \boldsymbol{0} \\ \boldsymbol{CA_z} & \boldsymbol{I} \end{bmatrix} \boldsymbol{\xi}(k) + \begin{bmatrix} \boldsymbol{B_{PF}} \\ \boldsymbol{CB_{PF}} \end{bmatrix} \Delta \boldsymbol{u_{PF}}(k)$$

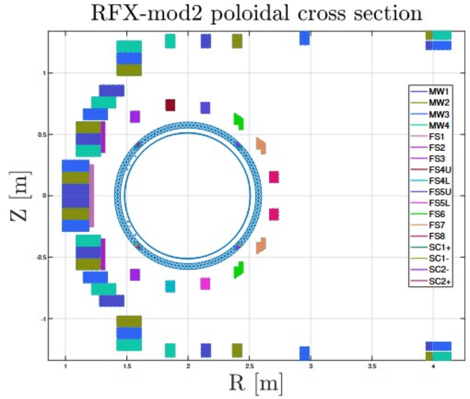
$$\boldsymbol{\xi}(k) = \begin{bmatrix} \Delta \boldsymbol{x}(k) \\ \boldsymbol{e}(k) \end{bmatrix}$$

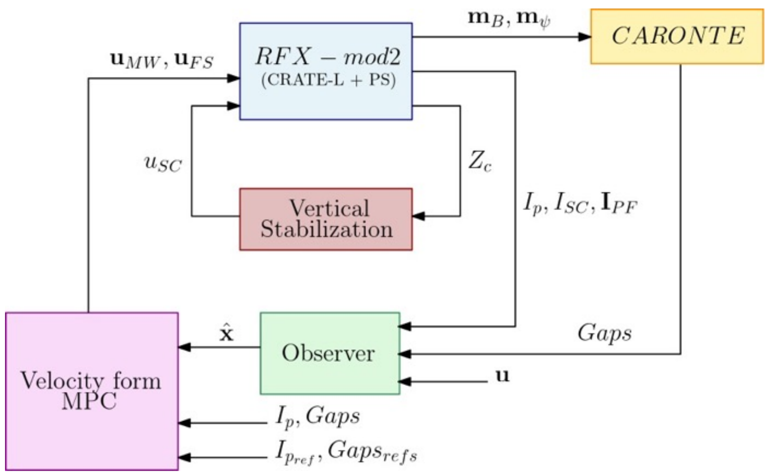
$T_s = 1$ ms

$$\min_{\{\Delta \boldsymbol{u_{PF}}\}_k} \sum_{i=0}^{T_p-1} ||\boldsymbol{e}(k+i)||_{\boldsymbol{Q}}^2 + ||\boldsymbol{\Delta u_{PF}}(k+i)||_{\boldsymbol{R}}^2$$

s.t.

$$0 \le \boldsymbol{u_{PF}} \le \boldsymbol{u_{max}}$$





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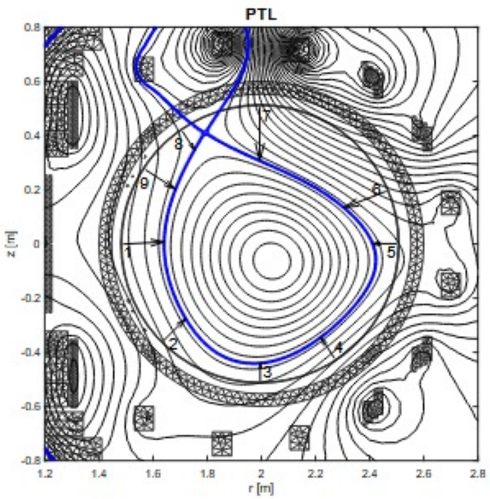
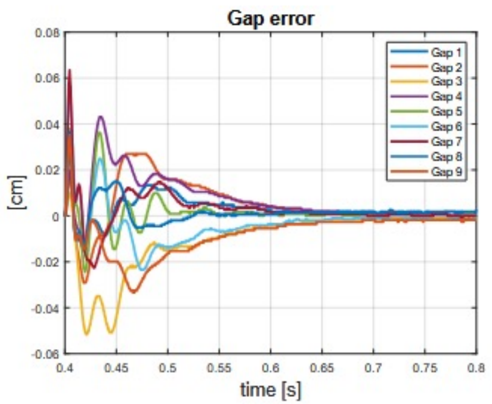
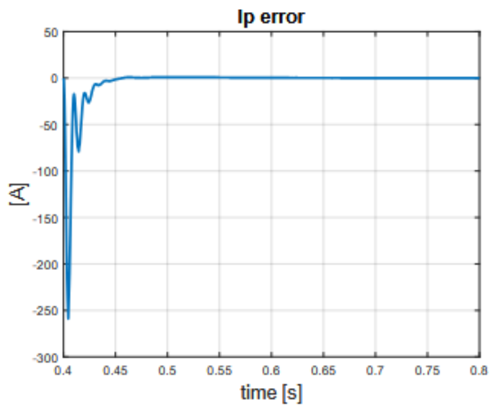
Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

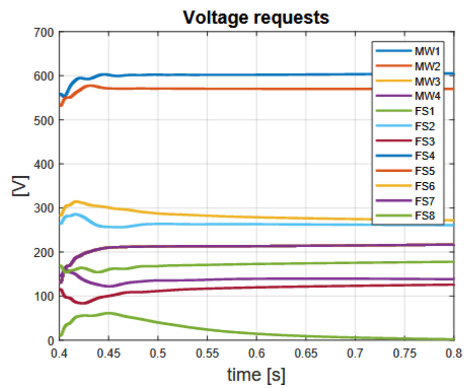


Considering 60kA plasma current equilibrium and $R_p = 10^{-7}\Omega$ (value estimated from past RFX-mod experiments) a sudden drop voltage at t = 0.4 s is considered.

The MPC is effectively controlling the plasma shape and current, while ensuring voltage limits.







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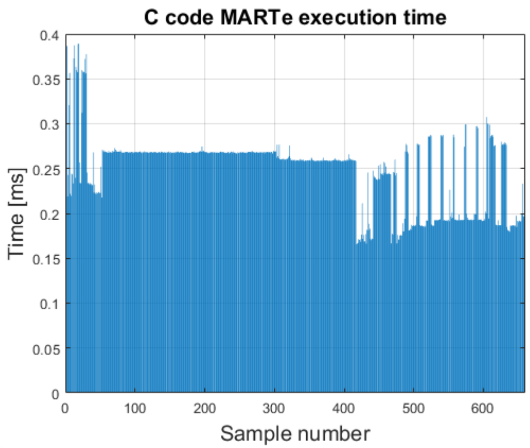
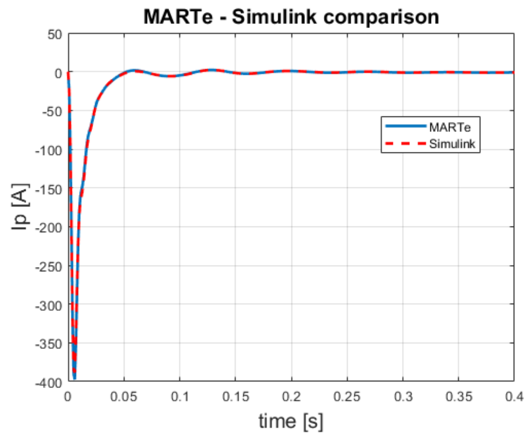
Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

To meet the 1ms requirement in real-time, several semplifications can be done:

- A reduced-order model is used for the prediction and the observer
- To reduce the degrees of freedom the voltage on the MW circuits is kept the same, this approach has proven to be effective in RFX-mod
- In the solution of the QP problem the control action can be kept constant for 2/3 steps --> **this does not mean that the system is fed with constant inputs for consecutive steps**!

With these adjustments, the generated code execution time is kept well under 1ms.
This has been tested in the MARTe real-time framework, envisaged for RFX-mod2 operations.





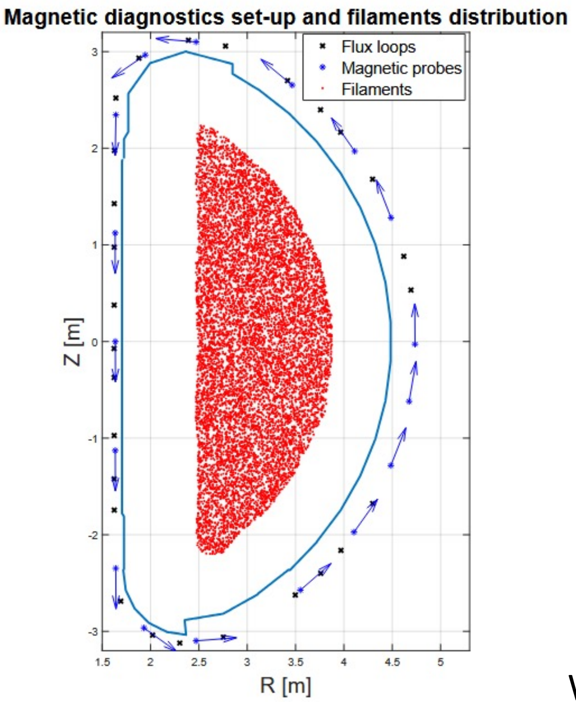
Conclusions and future work

- CARONTE exploits a NN that can be trained online, removing the extensive offline training needed for classic ML approaches. It also has proven effective on real experimental data. Experimental proposals have been made for 2026-2027.
- It should be possible to reconstruct the whole plasma equilibrium using the same approach.
- Testing of the ITER reconstruction algorithms during JT-60SA OP2 in 2026-2027.
- Testing of the proposed decoupling control system using the MECS simulator, which is the current testbench for JT-60SA control system.
- Deployment and test of the RFX-mod2 MPC control on the target real-time architecture -> 2027

Thank you for your attention!

BACK-UP SLIDES

ITER magnetic reconstruction algorithms



We place N filaments in the vacuum chamber. With an optimization problem we can compute the weigths that best predict the position and (unitary) current of each filament.

$$m_{B_t} = m_{B_t}^{I_p} + m_{B_t}^{I_a} = m_{B_t}^{I_p} + C_{I_a} I_a \qquad E \in \ker(C_{I_a})$$

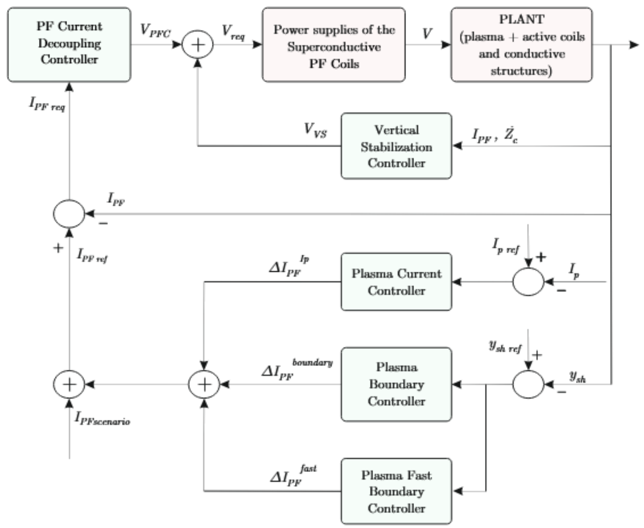
$$\min f_{I_p} = \left\| C_{I_f}^T E x_{Ip} - \mathbf{1} \right\|^2 \longrightarrow w_{I_p} = E x_{Ip}$$

$$\min f_{z_p} = \left\| C_{I_f}^T E x_{z_p} - \boldsymbol{z_f} \right\|^2 \longrightarrow w_{z_p} = E x_{zp}$$

$$\min f_{r_p} = \left\| C_{I_f}^T E x_{rp} - (\boldsymbol{r_f} - \boldsymbol{r_0})^{\mathbf{2}} \right\|^2 \longrightarrow w_{r_p} = E x_{r_p}$$

We can exploit the Green's function to let the weigths be insensitive to the active currents

Actuator sharing techniques for early-stage operations in superconductive tokamaks



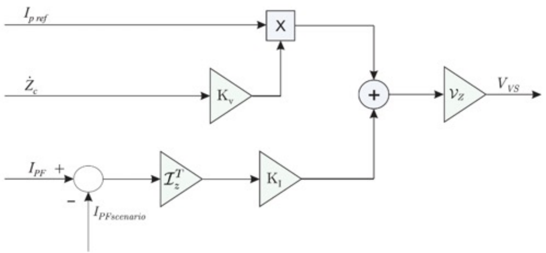
The architecture includes:

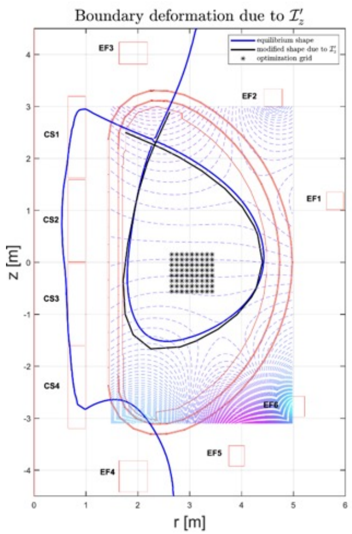
- An inner PF Current Controller
- Three outer loops that compute corrections to the nominal scenario currents:
  - Plasma Current Controller
  - Plasma Boundary Controller
  - Plasma Fast Boundary Controller (FBC)
- The VS controller is voltage-driven and shares the same actuators of the other controllers.

The VS controller stabilizes the plasma vertically, while the FBC rejects fast horizontal displacement due to the additional heating power

Actuator sharing techniques for early-stage operations in superconductive tokamaks

Vertical Stabilization controller





The direction specified by the vector I_z (which can be seen as a virtual circuit) is designed to maximize the radial field

Exploting the model a QP problem can be used to find the optimal virtual circuit

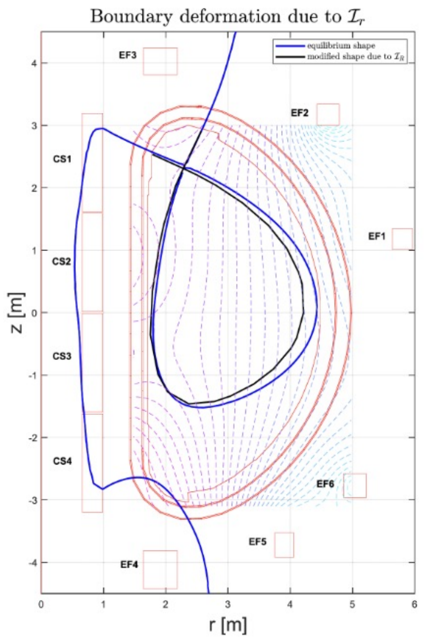
$$\min \frac{1}{2}\, \delta I_{PF} C_{B_Z}^T\, C_{B_Z} \delta I_{PF}$$

s.t.

$$C_{B_R} \delta I_{PF} \geq \overline{B_R}$$
$$\delta I_{PF}^M \geq \delta I_{PF} \geq \delta I_{PF}^m$$

Actuator sharing techniques for early-stage operations in superconductive tokamaks

Fast Boundary Controller



A similar procedure can be put in place to find a control direction I_r that induces a plasma deformation capable of counteracting the one caused by the additional heatings

$$Y_r = C_{sh} I_r$$

Is the deformation due to the unitary virtual circuit I_r.

$$\Delta I_{PF}^{FBC}(s) = -I_r K_{FBC}(s)\, Y_r^T Y_{sh}(s)$$

$K_{FBC}(s)$ can be chosen a classic PI controller

Actuator sharing techniques for early-stage operations in superconductive tokamaks

Plasma Boundary Controller

$$\Delta I_{PF}^{boundary}(s) = -K_{boundary}(s) I_r^{\perp} C_{sh}^{\dagger} Y_r^{\perp} Y_{sh}(s)$$

$Y_r^{\perp}$ is a matrix whose columns are a basis in $\ker(Y_r)$

$I_r^{\perp}$ is a matrix whose columns are a basis in $\ker(I_z)$

Decoupling with VS and FBC controllers is achieved.

$C_{sh}^{\dagger}$ can be computed using the Singular Value Decomposition

$K_{boundary}(s)$ contains a set of n_{PF} regulators to improve the dynamic response of the controller. It acts on a slower time scale wrt $K_{FBC}(s)$

Actuator sharing techniques for early-stage operations in superconductive tokamaks

Plasma Current Controller

$$\Delta I_{PF}^{I_p}(s) = -I^{\perp} I_{Ip} K_{I_p}(s)(I_{p_{ref}}(s) - I_p(s))$$

I_{Ip} is the linear combination PF currents that provide the transformer field

$I^{\perp}$ is a matrix that projects teh control effort in orthogonal directions wrt I_r and I_z

Therefore the Plasma Current Controller is decoupled from the VS and FBC controllers.

CARONTE: PINN-Based Algorithm for Real-Time Plasma Boundary Reconstruction

The (output layer) weights β are trained every time a new set of measurments are available.

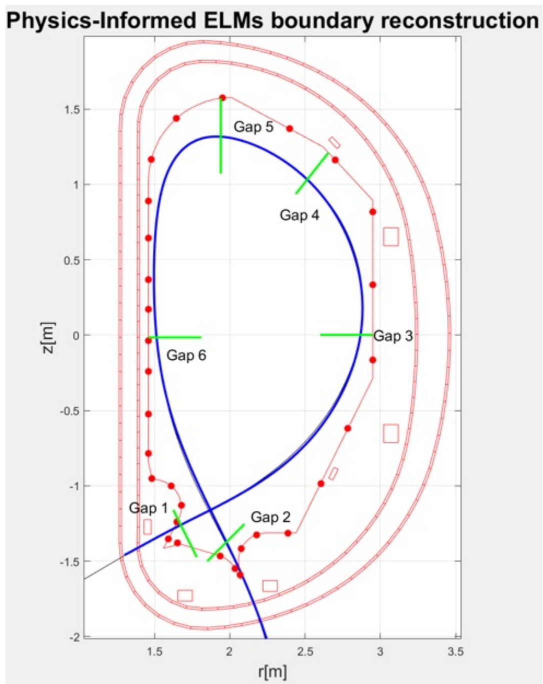
This is the only operation needed to reconstruct poloidal flux function.

Once trained, the PINN is not constrained by a grid of points.

Other real-time methods (XLOC, CCS, filamentary reconstruction,…) need to either identify the boundary locally in several regions or first identify the sources and then put togheter the contributions.

Other NN-based approach require extensive time consuming training

Gap	Error [cm]
1	0.05
2	0.46
3	0.18
4	0.18
5	0.08
6	0.05
RMSD	0.71



The red dots represent where the solution of the GS equation is set as hard constraint. The blu line is the reconstructed one. The black comes from CREATE-NL

Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

Previous Approach: Classic Linear Quadratic Gaussian (LQG) method.

Improved Design: Transition to MPC for better handling of power supply constraints.

Reference Disturbance: Voltage drop in the plasma circuit due to plasma resistance.

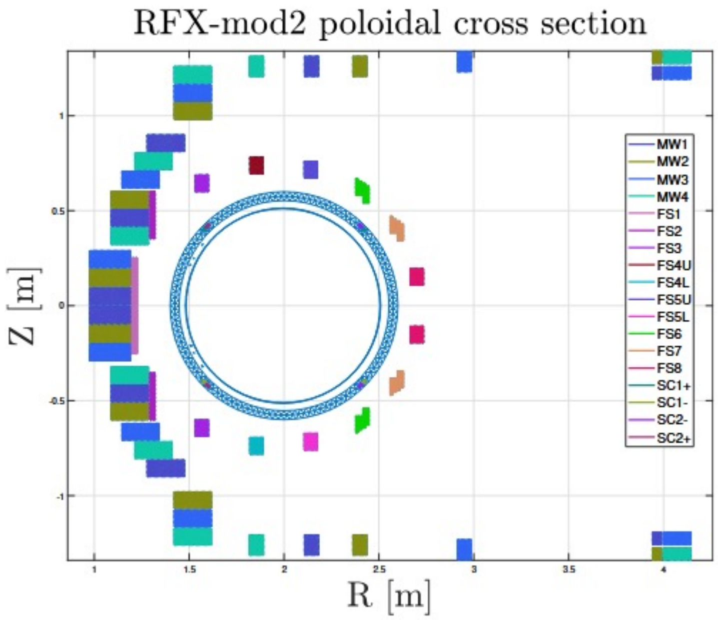
$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\left(\boldsymbol{u} + \boldsymbol{E}R_p I_p\right)$$

where: $\boldsymbol{x} = \left[\boldsymbol{I}_{MW}^T\ \boldsymbol{I}_{FS}^T\ \boldsymbol{I}_{SC}^T\ \boldsymbol{I}_{e}^T\ I_p\right]^T$

$$\boldsymbol{u} = \left[\boldsymbol{V}_{MW}^T\ \boldsymbol{V}_{FS}^T\ \boldsymbol{V}_{SC}^T\ \boldsymbol{0}^T\ 0\right]^T$$

$$\boldsymbol{E} = \left[\boldsymbol{0}^T\ \ -1\right]^T$$

$$\boldsymbol{0} \leq \boldsymbol{V}_{MW} \leq \boldsymbol{V}_{max}$$
$$\boldsymbol{0} \leq \boldsymbol{V}_{FS} \leq \boldsymbol{V}_{max}$$



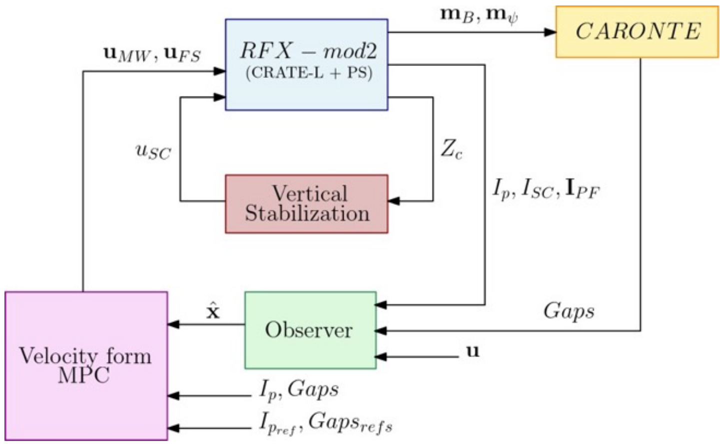
Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

The plasma is stabilized by a static feedback of the plasma vertical position

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{B_{SC}}\boldsymbol{K_{SC}}\boldsymbol{C_z})\boldsymbol{x} + [\boldsymbol{B_{MW}}\ \boldsymbol{B_{FS}}](\boldsymbol{u_{PF}} + \boldsymbol{E}R_p I_p) = \boldsymbol{A_z}\boldsymbol{x} + \boldsymbol{B_{PF}}(\boldsymbol{u_{PF}} + \boldsymbol{E}R_p I_p)$$

The MPC controller is designed on the stable system. It controls both the plasma shape and plasma current.

To cope with the constant disturbance a velocity form MPC is employed. The sampling time is set to 1 ms.



Courtesy of Dott. Sara Dubbioso

$$\boldsymbol{\xi}(k+1) = \begin{bmatrix} \boldsymbol{A_z} & \boldsymbol{0} \\ \boldsymbol{CA_z} & \boldsymbol{I} \end{bmatrix} \boldsymbol{\xi}(k) + \begin{bmatrix} \boldsymbol{B_{PF}} \\ \boldsymbol{CB_{PF}} \end{bmatrix} \Delta\boldsymbol{u_{PF}}(k)$$

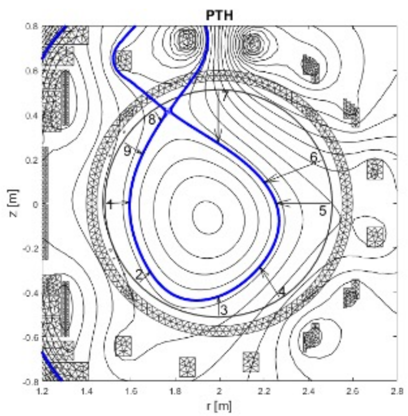
$$\boldsymbol{\xi}(k) = \begin{bmatrix} \Delta\boldsymbol{x}(k) \\ \boldsymbol{e}(k) \end{bmatrix}$$

$$\min_{\{\Delta\boldsymbol{u_{PF}}\}_k} \sum_{i=0}^{T_p-1} ||\boldsymbol{e}(k+i)||_{\boldsymbol{Q}}^2 + ||\boldsymbol{\Delta u_{PF}}(k+i)||_{\boldsymbol{R}}^2$$

s.t.

$$0 \le \boldsymbol{u_{PF}} \le \boldsymbol{u}_{max}$$

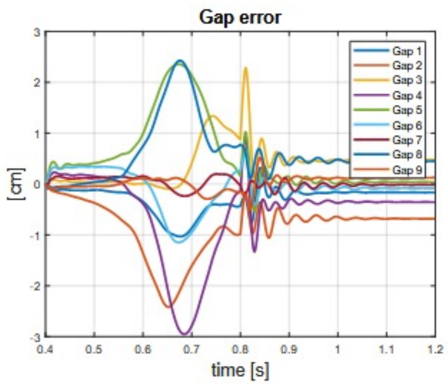
Integrated Plasma Equilibrium Control in RFX-mod2 via Model Predictive Control

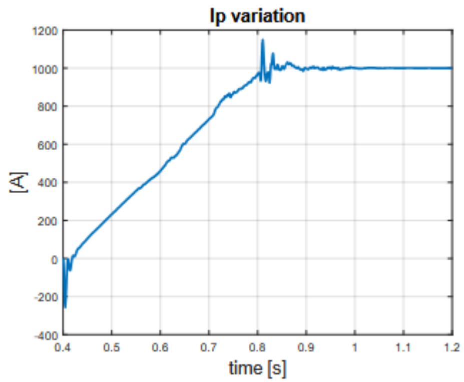


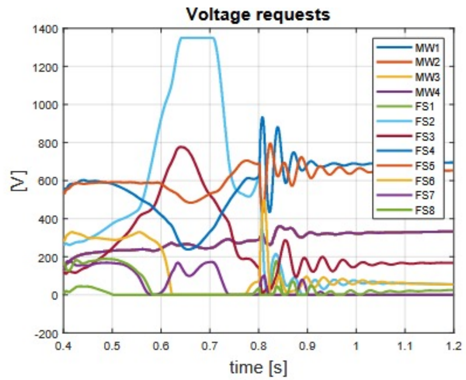
The controller robustness has been tested using a LTV model which transitions from PTL to PTH equilibrium in 0.4 s.

The simulation is not intended to be reliable but only a proof of robustness

Gap reference of several cm and 1kA current ramp successfully tracked while keeping the voltages in the feasible limits.







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