Control system optimization techniques for real-time applications in fusion plasmas: the RFX-mod experience

L. Pigatto[a,b], **M. Baruzzo**[a], **P.Bettini**[a,b], **T. Bolzonella**[a], **G. Manduchi**[a], **G. Marchiori**[a]

*a. **Consorzio RFX** (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA) Corso Stati Uniti, 4 35127 Padova – Italy*
b. Università degli Studi di Padova, Padova, Italy

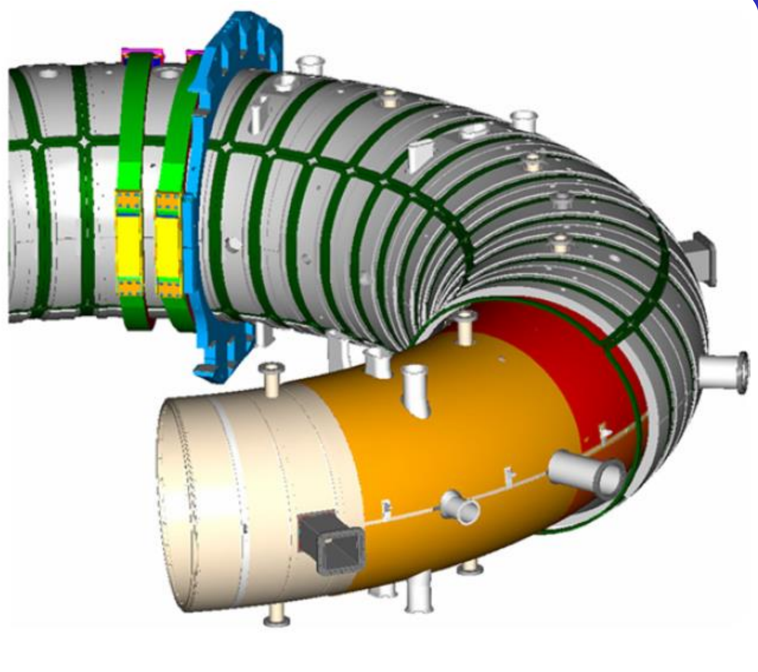
Corresponding author: leonardo.pigatto@igi.cnr.it

CONSORZIO RFX
Ricerca Formazione Innovazione

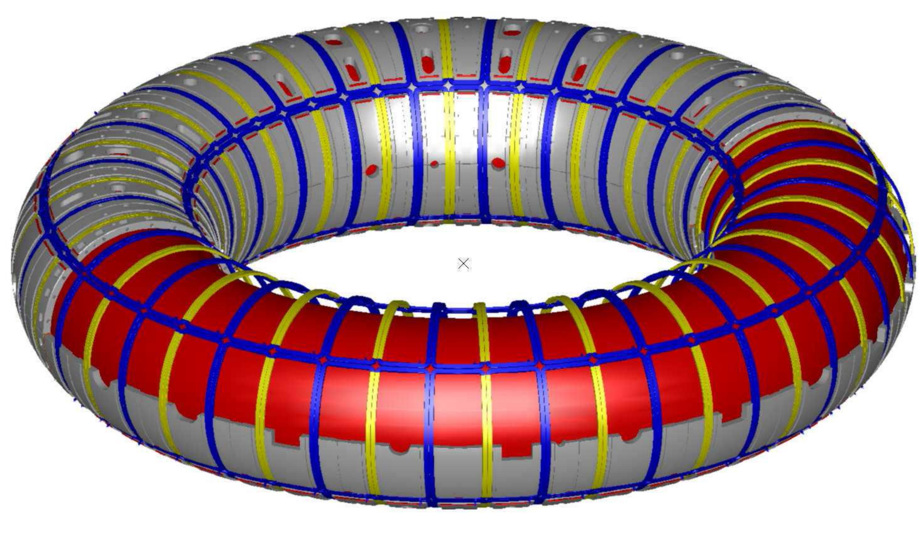
20th IEEE – NPSS REAL TIME CONFERENCE
6-10 June, Padova, Italy

RFX-mod is a medium size (R=2m, a=0.459m) device capable of confining plasmas in both **Tokamak** and **Reversed Field Pinch** magnetic configurations. It is equipped with an advanced feedback system for field error and MHD control [1]. **192 active saddle coils** (independently fed) entirely cover the outer surface of the resistive shell and play as actuators with **192 saddle sensors**.

In order to improve the effectiveness of the active control system and assess the external action on a given plasma, optimization of the produced magnetic fields is sought. This work shows examples of simple techniques that can be applied real time for performance improvement.



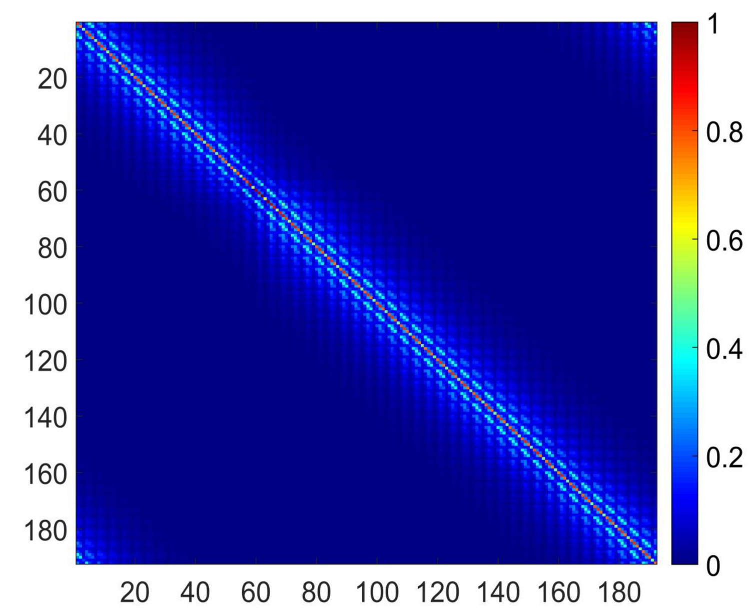
Layout of the RFX-mod control coils and passive structures. Copper shell appears in orange and saddle coils in green.



View of the RFX-mod torus in which a so-called 'supercoil' configuration is shown: saddle coils are coupled to form bigger actuators, covering in this case the whole surface of the torus

Saddle coils can be software reconfigured to create different geometries [2]

- Each active coil can be fed a maximum current of 400 A, providing a DC radial field of 46 mT at the vacuum vessel surface
- Highly flexible control system, working in a bi-dimensional Fourier space characterized by the poloidal (m) and toroidal (n) mode numbers, allows to switch on or off each single coil
- Performance improvement pursued through harmonic distortion minimization (i.e. reduction of spurious harmonics) or adapting to real experimental conditions



Experimental decoupling matrix calculated for ω = 10 Hz

Improving the performance of the control system is a task that can be tackled by using the coupling terms between actuators and sensors. Given the presence of passive structures in between, these coupling terms are frequency dependent.

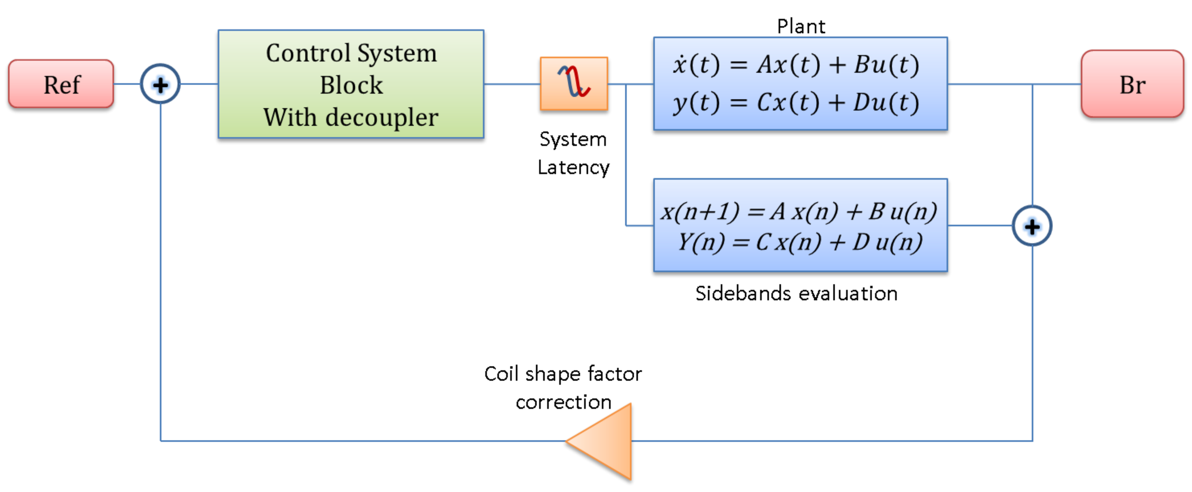
Mutual coupling matrices have been calculated from experimental data (currents and magnetic fluxes) for a given set of frequencies, during dedicated vacuum shots

$$\frac{\overline{\Phi_i}(\omega)}{\overline{I_k}(\omega)} = \dot{M}_{ik}(\omega)$$

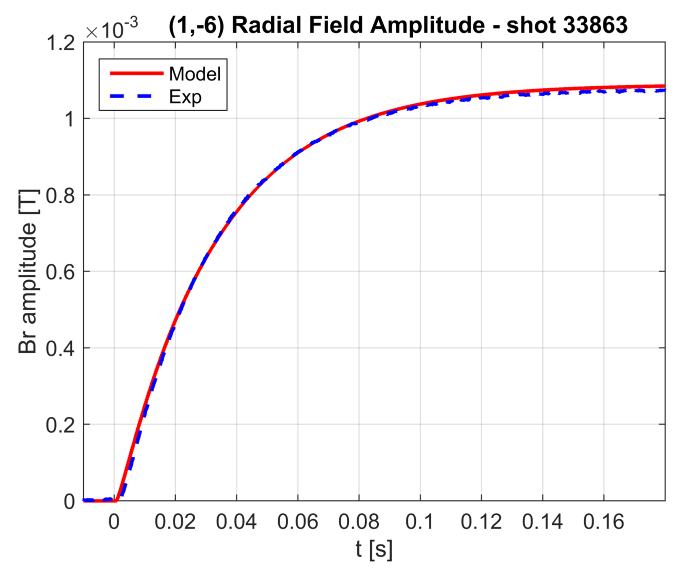
Decoupling matrices are obtained from coupling terms and used in experiments and simulations to **recombine input currents** as to achieve an optimized output.

A **dynamical simulator** [3] has been implemented based on an input current plant model obtained through the CarMa code [4]. Decoupling matrices are also obtained from model transfer function:

$$K(\omega) = [C(j\omega - A)^{-1}B + D]$$



Closed Loop diagram of the simulation toolbox



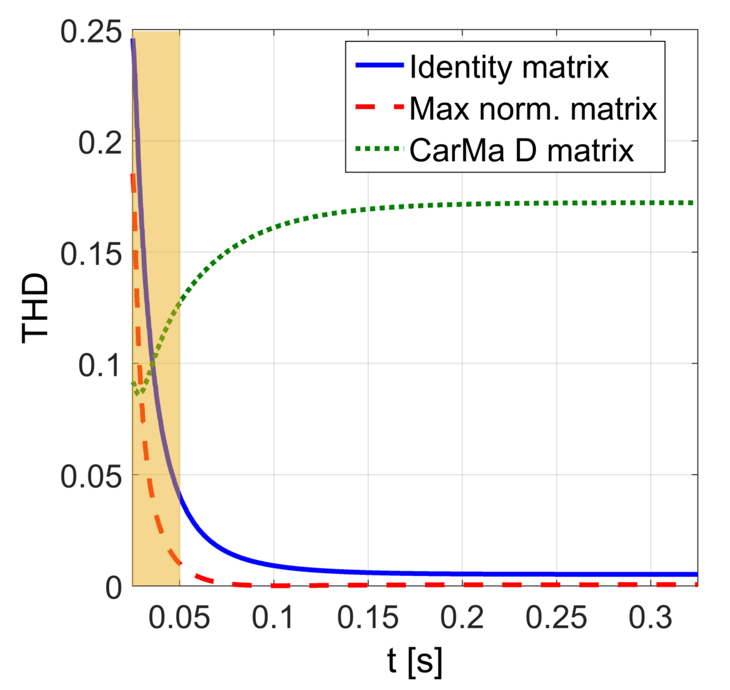
Experimental and model time evolution of m=1, n=-6 harmonic component of the radial field

The **vacuum model** has been tested and validated against experimental data.

Real vacuum experimental setup is reliably reproduced by the simulation tools, that can be therefore applied in a predictive way.

A first test of two decoupling matrices is made using Total Harmonic Distortion to assess the effect in reducing spurious harmonics.

The ω=0 experimental case is represented in comparison with the infinite frequency limit from the CarMa model.

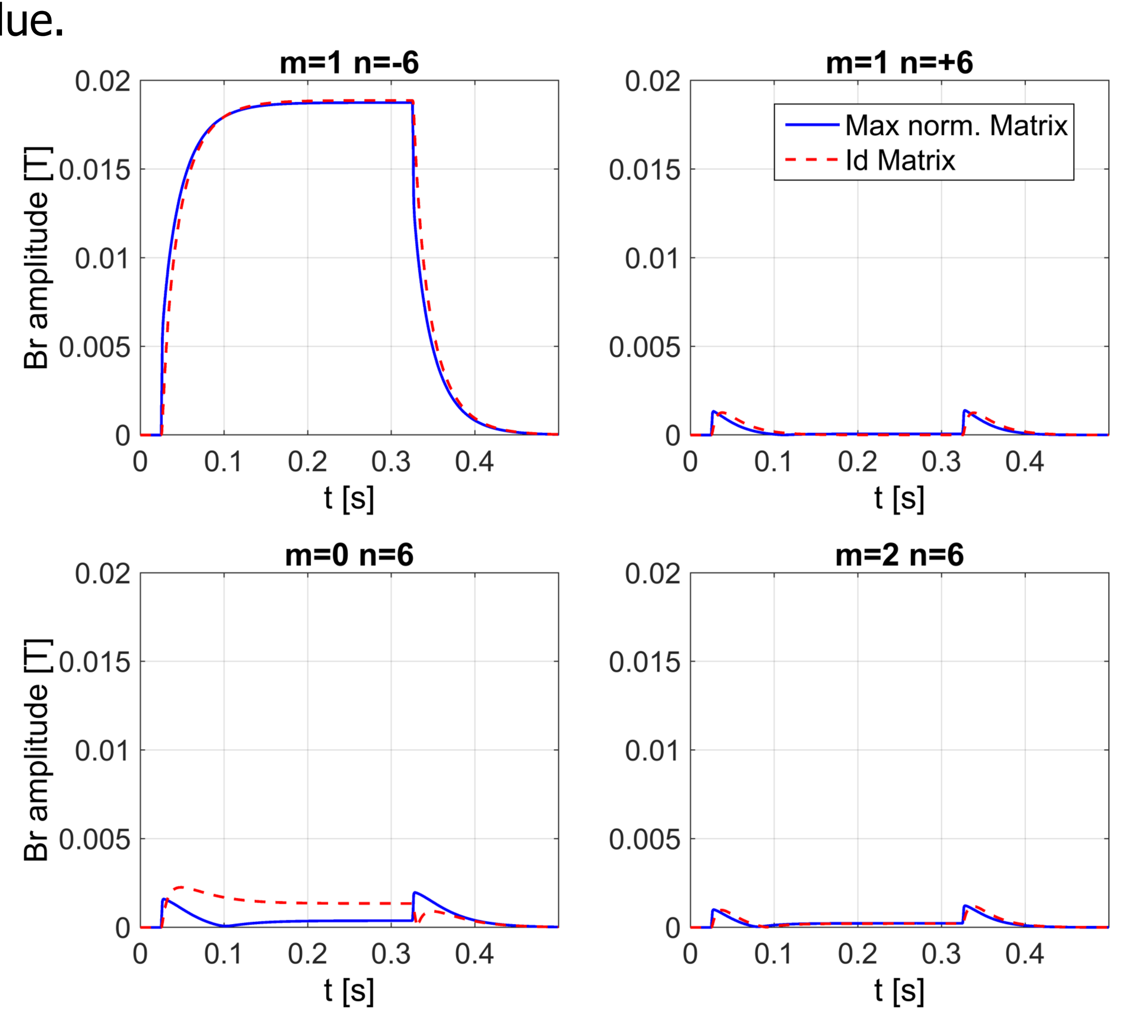


Total harmonic distortion from simulations with D matrix, ω = 0 Hz matrix and identity matrix

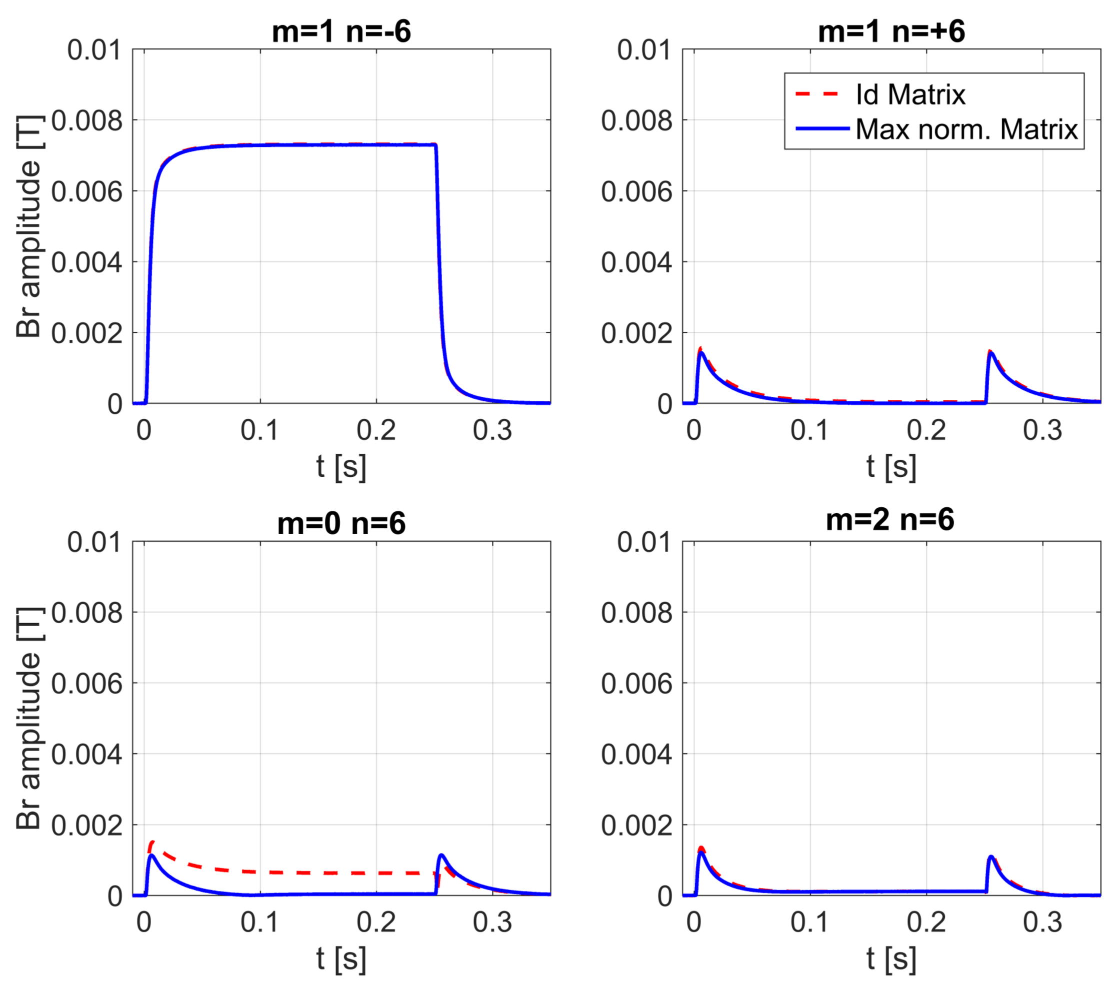
A decoupling matrix calculated from the CarMa model for ω = 0 Hz has been applied in both simulations and dedicated experiments, in which a sample magnetic perturbation is requested to the active system.

The **open-loop** generation of a step-like (1,-6) perturbation has been tested with and without decoupling. The reduction of the m=0 component can be noticed, leading to the sought improvement of the harmonic content.

The same has been seen with different frequencies and matrices, the best results being obtained normalizing each matrix to its maximum value.



Poloidal harmonics produced for (m = 1; n = -6) reference. Step-like perturbation with no decoupling (dashed red) and with CarMa ω = 0 Hz matrix applied (solid blue)

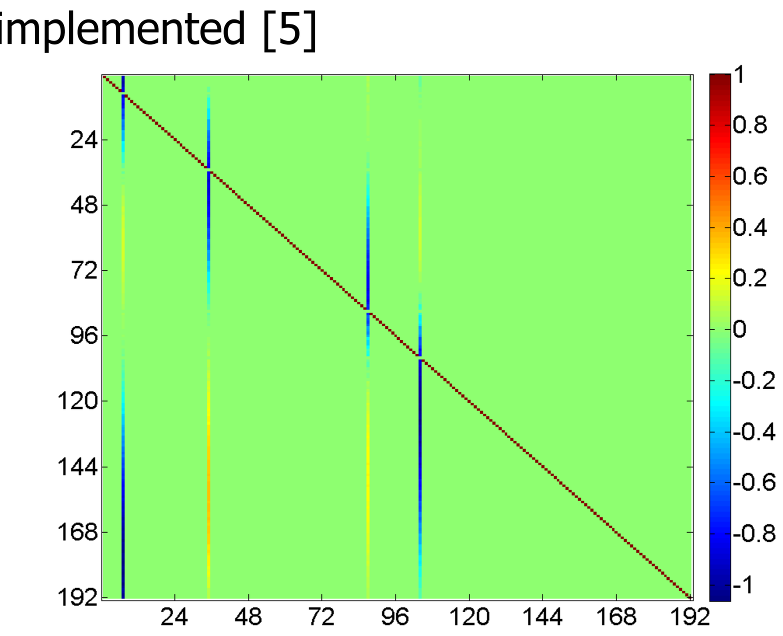


Step-like (m = 1; n = -6) perturbation generated in a closed-loop with purely proportional gain on the requested harmonic only. Comparison between shots 27294 and 27295.

A **closed-loop** application example allows to appreciate the same result as in the open-loop case, with the applied matrix being calculated from experimental data.

Furthermore, the very good superposition of the requested n=-6 component in the two cases leads to the conclusion that the implementation of a decoupling matrix has a negligible affect on the applied gains.

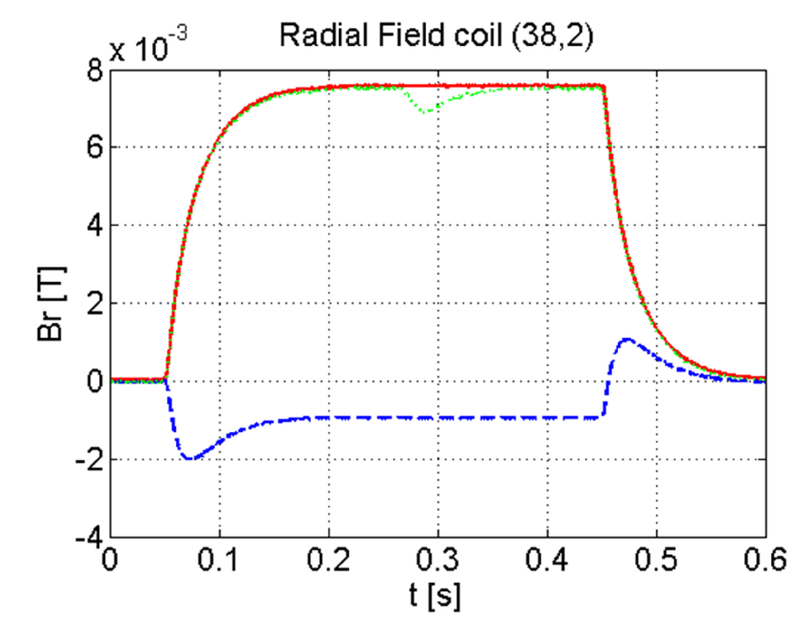
A **missing actuator compensation** strategy based on a static matrix has been developed and implemented [5]



Compensation matrix for four actuators disabled

Recombination of the current references to compensate for missing saddle coils.

$$B_r = S^{-1}KI_r = S^{-1}\hat{K}\hat{I}_r \quad\Rightarrow\quad \hat{I}_r = pinv(\hat{K})K\,I_r$$



One coil compensation example: radial field measured in position (38,2). Working coil (red) compared to disabled (blue) and compensated (green).

Conclusions

A range of simple and real-time applicable strategies for the assessment and optimization of the RFX-mod active system output magnetic field has been developed and tested. Starting from the acknowledgement that such a field contains spurious components given by geometrical characteristics and discreteness of the active system. Full dynamic simulations and vacuum experiments have been presented to show the effects of such simple optimization methods, which have been implemented and used during routine experimental sessions.

References

[1] P. Sonato et al, Fusion Eng. Des. 66-68, 161 (2003)
[2] M. Baruzzo et al, Nucl. Fusion 52, 103001 (2012)
[3] G. Marchiori et al, Nucl. Fusion 52, 023020 (2012)
[4] R. Albanese et al, IEEE Trans. on Mag. 44, 1654 (2008)
[5] L. Pigatto et al, Fusion Eng. Des., 96-97, 690–693 (2015)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053 and from the Italian MIUR under PRIN grant 2010SPS9B3. The views and opinions expressed herein do not necessarily reflect those of the European Commission