Romanian participarion at EUROfusion WPTE-SA and complementary research

Project director: Teddy Craciunescu (INFLPR)

Email: teddy.craciunescu@inflpr.ro

Partners:

- National Institute for Lasers, Plasma and Radiation Physics INFLPR Magurele, Romania
- National Research And Development Institute For Cryogenic And Isotopic Technologies, ICSI, Ramnicu Valcea, Romania

Team:

INFLPR: Teddy Craciunescu, Iulian Gabriel Miron, Dragoș Iustin Palade, Ligia Maria Pomârjanschi

ICSI: Sorin Soare, Marian Cururia

External Partners:

- CCFE, Culham Science Center, UK
- Consorzio RFX (CNR, ENEA, INFN, Universita' di Padova, Acciaierie Venete SpA), Padova, Italia
- Universitaty of Rome Tor Vergata, Italiy
- CIEMAT, Madrid, Spain

The Work Package Tokamak Exploitation (WPTE) is mainly dedicated to the operation of the EUROfusion supported tokamaks (ASDEX Upgrade, MAST-U, TCV, WEST) in an integrated scheme in view of preparing for ITER exploitation and guiding the DEMO design.

The main objective of WPTE is to provide the physics basis for ITER and DEMO operational scenarios in a Europe-wide unique integrated approach utilizing machines of different capabilities, sizes and parameters. As no single facility has the possibility to completely test ITER or DEMO scenarios, each EUROfusion facility will address, in a coordinated manner, different aspects of the operating scenarios within a specific operational range. The integration of the accumulated knowledge for prediction towards ITER and DEMO is ensured via outstanding theory and simulation. WPTE's priorities are directly related to the ITER research plan (https://wiki.euro-fusion.org/images/a/a0/Iter_rp.pdf) and the EUROfusion document defining the scientific gaps in view of DEMO: "Key DEMO Physics Uncertainties and Related Investigation Needs" (https://wiki.euro-fusion.org/images/a/ad/Demo_priorities.pdf). In Horizon Europe framework, WPTE activities are focused on the objectives of Mission 1 (Plasma Regimes of Operation) and Mission 2 (Heat Exhaust System).

As outlined in the European Fusion Roadmap, JT-60SA is a crucial facility in support of ITER and DEMO. JT-60SA will be jointly operated and enhanced by the EU and Japan. Fusion for Energy (F4E) and EUROfusion agreed together on the need to rationalize and coordinate the future exploitation of the JT-60SA device for the next funding phase, BA phase II. At the level of institutional responsibilities within Europe, F4E will maintain its focus on design, integration, construction and future enhancements, while EUROfusion will dedicate its efforts towards the joint definition and execution of the scientific programme, the contribution to the plasma operations and the exploitation of diagnostics, and the provision of scientific support to the machine and sub-systems. Among the priorities for the exploitation of JT-60SA, the avoidance and mitigation of disruptions and runaways and the design, integration, construction and future enhancements play a central role.

Project objectives:

Image-based methods for plasma diagnostic and disruption prediction

The aim of the project is to contribute to the development of image-based tools for plasma diagnostic. Image-based methods for disruption prediction will be developed considering that many disruptions are preceded by anomalies in the radiation patterns, particularly in ITER-relevant scenarios. Following the successful development and application in JET and AUG of a bolometry reconstruction method, able to provide also an evaluation of the reconstruction uncertainties, this method will be applied to the analysis of the experiments in AUG.

A new modes localization technique and its ensuing usability at AUG

An alternate method to the present experimental localization techniques is provided to be used when the latter are unavailable or unreliable. Our method is tested and planned to be validated at AUG in order to trustfully use it. An accurate mode location is a precondition for a good mode amplitude derivation therefore the calculated vs experimental amplitude match will be finally checked to validate the model. Subsequently, the corresponding error field mode amplitude will be also delivered using an upgraded theoretical model.

Modelling and numerical simulations of turbulent transport in WPTE tokamak devices

Another central aim of this project is related to the characterization of turbulent transport via test-particle numerical methods. Building on top of previous research (D.I. Palade 2023 Nucl. Fusion 63 046007, D.I. Palade – in preparation) we aim at developing code, regression models, performing numerical simulations and experimental validation for bespoke WPTE tokamak configurations. In this way, we will contribute to the understanding of the physical processes behind transport and their relation with the plasma parameters in regimes of interest.

Support of the installation of the JT-60 TS and VUV diagnostic systems

During 2024-2025 the scientific team from ICSI will participate at the testing, integration, installation and commissioning of the TS and VUV diagnostic systems for JT-60SA for which it provided the mechanical design and integration of all systems linked to the mechanics and the manufacture of all designed system integrated with the optics and detection systems.

Also, the complementary research activities aim to accomplish a set of objectives:

Time series analysis for disruption prediction

The present project aims on the development of real-time disruption predictors able to provide accurate prediction, but also capable of operating with a minimum number of signals, because in the first campaigns of new devices typically only a very limited number of diagnostics is available.

New aspects of turbulent transport based on numerical simulations and neural networks

Another aim of this project is to develop new tools of transport evaluation in tokamak devices based on neural networks while also answering open questions related to the interaction between neoclassical and turbulent transport and the influence of the sheared rotation on turbulence and transport.

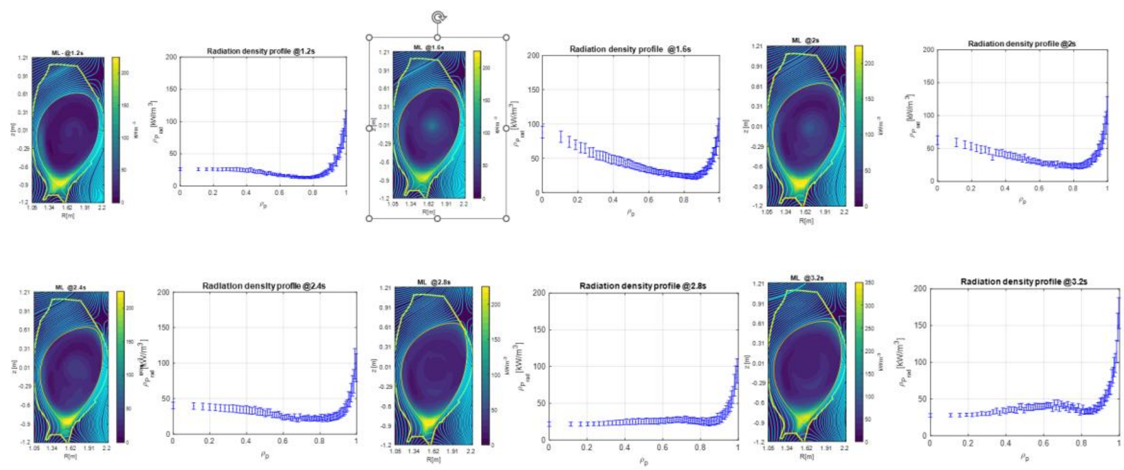
<u>Modes localization and modes locking dynamics models validation at JET</u>

A precise retrieval of the perturbations location for localized modes during JET dedicated campaigns based on a newly presented analysis is proposed, without the need for the charge exchange recombination data or the equilibrium reconstruction safety factor data. The locked modes behaviour is also to be found and checked against the experimental results by means of the mode amplitude in order to validate the model. It will be checked whether the locking is due to the associated error field through the resonant mode coupling mechanism or not.

Results:

2024-2025

- The Romanian participation at the WPTE comprises the diagnostic support for AUG experiments that are performed at ASDEX Upgrade tokamak. The bolometry Maximum Likelihood code has been used for the experiments RT-01 “Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER” and RT-02: “Physics understanding of alternatives to Type-I ELM regime”. The ML method has been also used for the design of the bolometric diagnostics for the Divertor Tokamak Test Facility (DTT, Italy).



- *Bolometry analysis for the AUG pulse #43046 and radiated profiles*

- Innovative algorithms that enhance the accuracy of the bolometry inversio processes, thereby ensuring reliable results for physics understanding, modelling, and plasma control has been developed. This work introduces new methodologies based on Physics-Informed Neural Networks (PINNs) to perform time-resolved emission tomography from bolometer data. The algorithm has been applied to reconstruct specific radiative anomalies, such as Multifaceted Asymmetric Radiation from the Edge (MARFE), core radiation, and radiative rings, at the Joint European Torus (JET). The study demonstrates that PINNs not only enhance the overall accuracy of tomographic inversions but also offer advanced capabilities like super-resolution, data projection, and self-modelling. In the same time it represents a valuable tool for the development of image-based disruption prediction methods.

- A physics-informed autoencoder (PIC-AE) is introduced to impose physical or mathematical constraints on the latent representation, allowing the discovery of fundamental dynamics and model parameters. It has been applied to edge-localized modes (ELMs) in nuclear fusion plasmas to test if ELMs follow a Lotka-Volterra model and the results indicate the need for alternative models. For causality detection, a novel autoencoder-based method has been developed to overcome limitations of traditional techniques. This new approach accurately identifies causal relationships while providing a probabilistic measure of their strength. Applied to nuclear fusion data, it has confirmed the causal influence of ion cyclotron resonance heating (ICRH) on sawtooth crashes, aligning with previous findings obtained through different methodologies and extending the analysis to the spatio-temporal domain.

- In this stage, the project team focused also on developing regression models for ion turbulent transport in WPTE devices. These models will later be tested and compared with experimental and gyrokinetic data. The present work aimed to establish the methodology for building such tools before a validation campaign. As a preparatory step, additional tests, corrections, and programming improvements were made to the in-house code T3ST, which evaluates transport coefficients in tokamak axisymmetric equilibria using synthetically generated random fields as surrogates for electrostatic turbulence. Two representative discharges, TCV (#81500) and WEST (#54178), were selected. G-EQDSK equilibrium files were extracted from the LAC and Cephelee servers and pre-processed using Wolfram Mathematica scripts developed in earlier project stages. Due to limited experimental data, turbulence in these cases was modeled with the standard ITG/TEM drift-like spectrum of T3ST, allowing the parameters $\Phi, \lambda_x, \lambda_y, \lambda_z, \tau_c, k_0$, and L_n to vary independently. Two simulation sets were performed. In the first, individual turbulence parameters were varied across relevant ranges, showing that Padé (2,2) approximants accurately capture single-parameter dependencies and reproduce known analytical trends. The second, larger series (1000 runs) explored the full 5D space $(\Phi, \lambda_x, \lambda_y, k_0, L_n)$ to fit a Padé (3,3) regression model for the transport coefficients. The model achieved global errors below 20%, with higher accuracy for diffusion than for convection. The WEST case performed better overall, likely due to its less elongated and less triangular magnetic geometry.

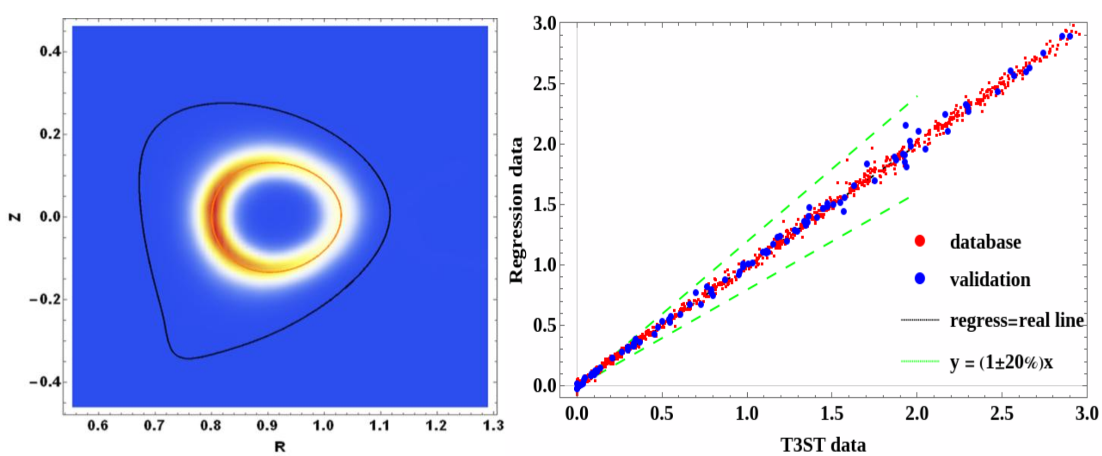


Fig. : (Left) Poloidal plane projection of the distribution of gyrocenter test-particles achieved asymptotically. Black line indicates LCFS while orange line the local flux-tube. (TCV #81500). (Right) . Regression plot comparing diffusions (left) and convections (right) obtained with the T3ST code (x axis) and the regression model (y axis) for the learning database (red) and the validation set (blue). The validity of the regression's predictions can be assessed following the $y = x$ line (black) and the $y = (100 \pm 20\%)x$ limits (green). The data is obtained for the case of WEST #54718 discharge at t=1.s and midradius dominated by ITG turbulence.

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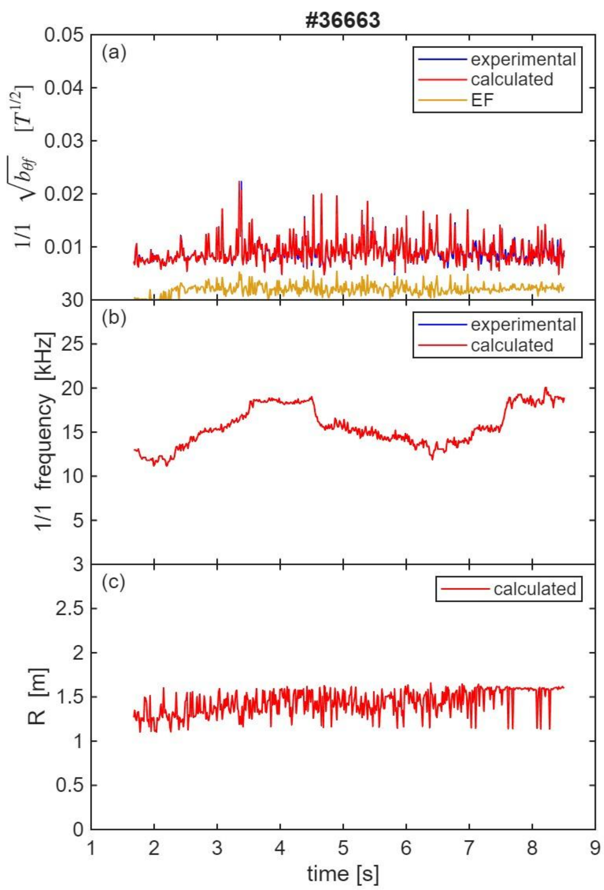
- The importance of the unit safety factor profile derivation is associated with the central 1/1 perturbation developing either as a reconnection process triggered by a less than unity magnetic axis safety factor or as a 1/1 interchange perturbation when the safety factor near the magnetic axis is slightly above 1, both flattening the central temperature and driving a restored sawtooth preventing safety factor profile afterwards. A theoretical model has been proposed in order to describe the 1/1 mode and to further derive the magnetic axis safety factor dynamic profile as an indicator of the sawtooth activity or of the onset of the magnetic flux pumping mechanism. The 1/1 corresponding error field amplitude is provided to check its influence on the central perturbation dynamics that could affect its subsequent phenomena related to the central stability of the plasma. For this aim, no matter the mode location is available or not, we being able to theoretically derive it.



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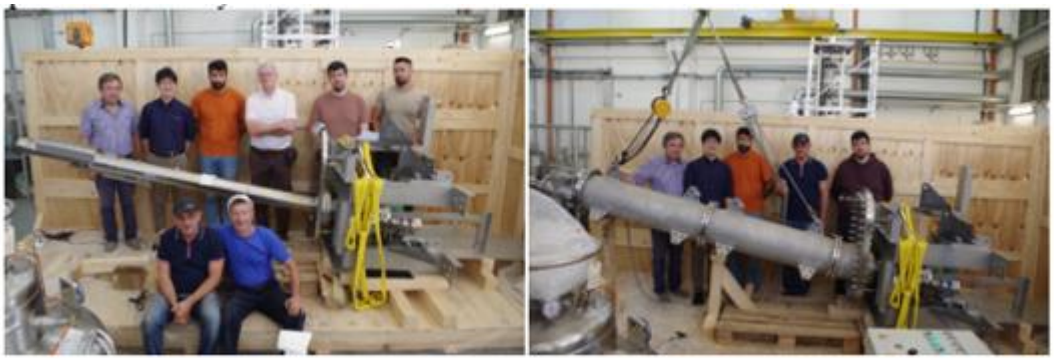
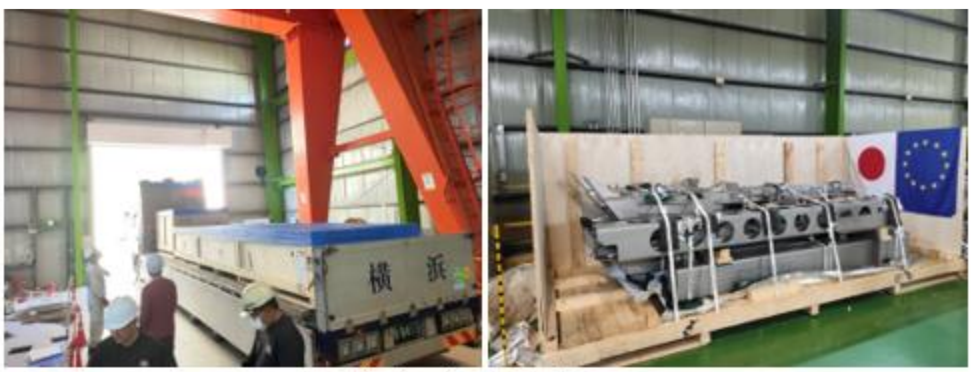
AUG 36663 1/1 mode (a) experimental vs calculated mode amplitude and corresponding error field amplitude, (b) experimental vs calculated mode frequency and (c) calculated location.

- The JT-60SA Thomson scattering system (TS) is required to measure electron temperature Te and density ne profiles and is standard diagnostic in tokamak experiments. Since YAG lasers can operate with high power and high repetition rate, a Thomson scattering system using a YAG laser (YAG Thomson system) can measure temporal evolution of Te and ne profiles during the entire discharge. The YAG Thomson system has been used in JT-60U and will also be re-employed in JT-60SA. Later it was decided to procure a new laser. Two Thomson scattering diagnostics are planned to be installed on JT60SA to measure electron temperature and density profiles across a plasma in the equatorial plane: one dedicated to the core region of the plasma (P2), another to the edge region (P1). P1 samples the edge profile with 50 spatial positions, P2 the core profile with 46 positions, corresponding to 96 fibres optic bundles and 96 polychromators. Some of the P1 channels will be used for the core measurements. This project addresses the P1 (edge region) system only. The results obtained during 2025 refer to TS & VUV spectrometer manufacturing.



The VUV system coupled to the VacChamber was packed and shipped to ENEA (arrival at ENEA, Roma on 18th of Sept. 2025).

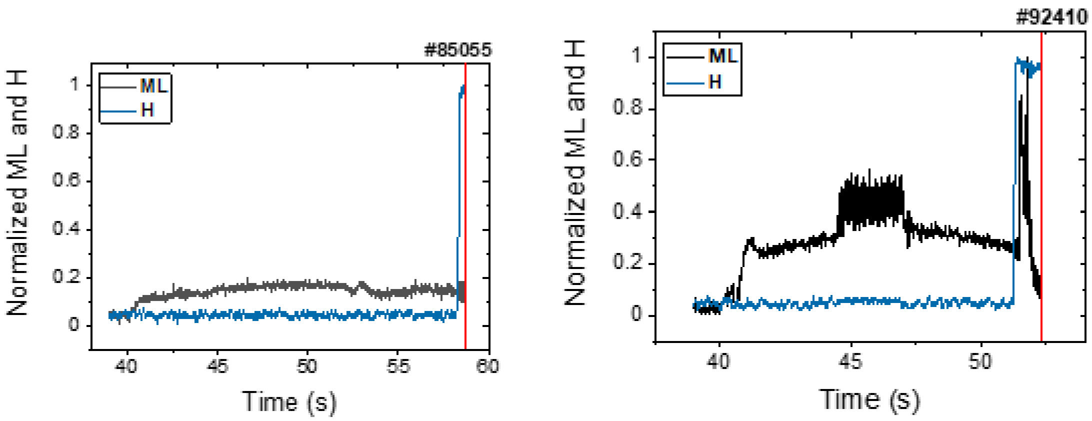


First batch at Naka, Japan

Second batch at Naka, Japan

The main results obtained in the framework of the complementary research are the followings:

- Disruptions are a potential showstopper on the route to developing a tomakak fusion reactor. Since their consequences can be more severe the larger the devices, in the next generation of machines they will have to be carefully managed from the beginning of operation. On the other hand, in new devices coming on line, the diagnostic coverage is typically limited and there will be no opportunity to collect many examples for the training of traditional machine learning classifiers. It is therefore important to develop predictors that can ideally operate satisfactorily without training and with minimal diagnostic information. A technique capable of satisfying these requirements is described in the present work. It is based on converting the time series of macroscopic basic signals, such as the plasma current or the locked mode amplitude, into a string of symbols, before quantifying the complexity of the resulting sequences with permutation entropy. The application to a large dataset of discharges of JET with a metallic wall has provided very interesting results. In addition to good statistical performances, the warning times are sufficient not only for mitigation but also for the prevention of most disruptive events. The transfer of the technique to JET with a carbon wall has also been quite encouraging and therefore it is proposed to deploy the approach in new machines such as JT-60SA and DTT.



Time evolution of the raw signals in black and the corresponding permutation entropy H in blue for some representative discharges. First two rows: plasma current I. Last two rows: locked mode amplitude ML. The vertical red line indicates the beginning of the current quench.

Overview statistics of the results obtained for the disruptive discharges of JET database with the metallic wall using the locked mode amplitude signal.

	Correct predictions %	Missed disruptions %	Early Alarms %	Tardy Alarms % False Alarms %
Symbolic dynamics	97.64	0.0	2.14	0.22 7.27
Chaos onset	96.2	2.34	1.4	0.06 6.30
Concept drift	98.6	1.17	1.4	0.20

- During 2025 the interplay between neoclassical and turbulent transport in tokamak plasmas has been studied, using the newly developed T3ST code (a Lagrangian test-particle framework), and focusing on how collisions and turbulence jointly influence particle fluxes. A central motivation of the work is to challenge two long-standing assumptions in fusion transport theory: P1: total fluxes can be obtained as the sum of independently computed neoclassical and turbulent contributions; P2: that neoclassical fluxes vanish in the absence of collisions. To analyse these propositions, we introduced a novel decomposition of the particle flux into neoclassical and turbulent subcomponents, each associated with partial transport coefficients derived from Lagrangian trajectories. Our analytical and numerical results show that P1 is formally incorrect: when both collisions and turbulence are present, a synergistic diffusion appears, approximately proportional to the product of the separate neoclassical and turbulent diffusion coefficients. This synergy enhances turbulent fluxes, while neoclassical fluxes remain largely unaffected by turbulence. In contrast, P2 holds true: the neoclassical component of transport indeed vanishes when turbulence is present but collisions are absent. Finally, we explored how magnetic equilibrium parameters such as the safety factor, magnetic shear, and major/minor radius affect turbulent transport. We found that these dependencies naturally arise from the structure of neoclassical trajectories within the Lagrangian propagator. Overall, our results reveal couplings between collisions, turbulence, and magnetic geometry, providing new physical insight and guidance for more accurate transport modelling in fusion plasmas.

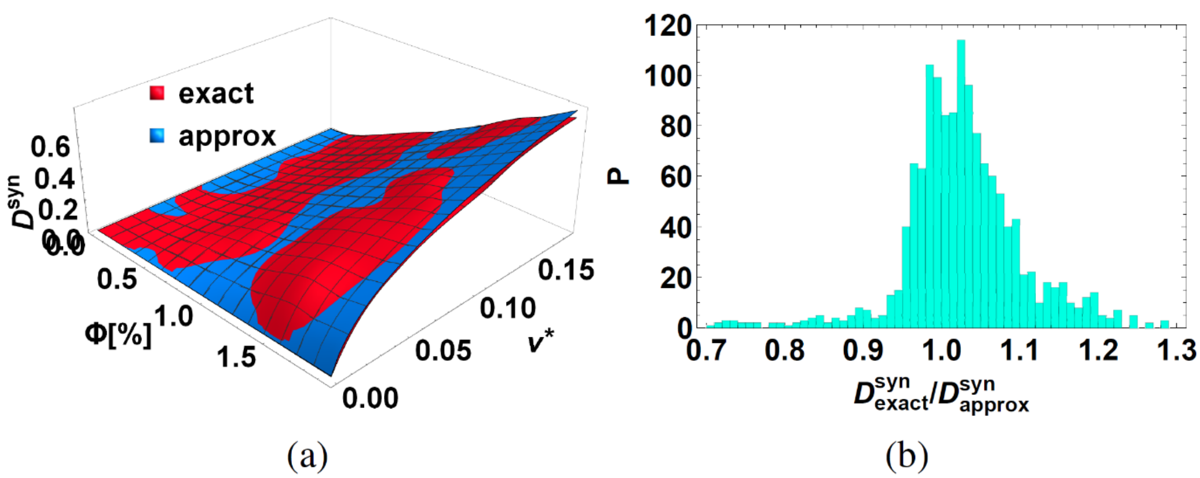
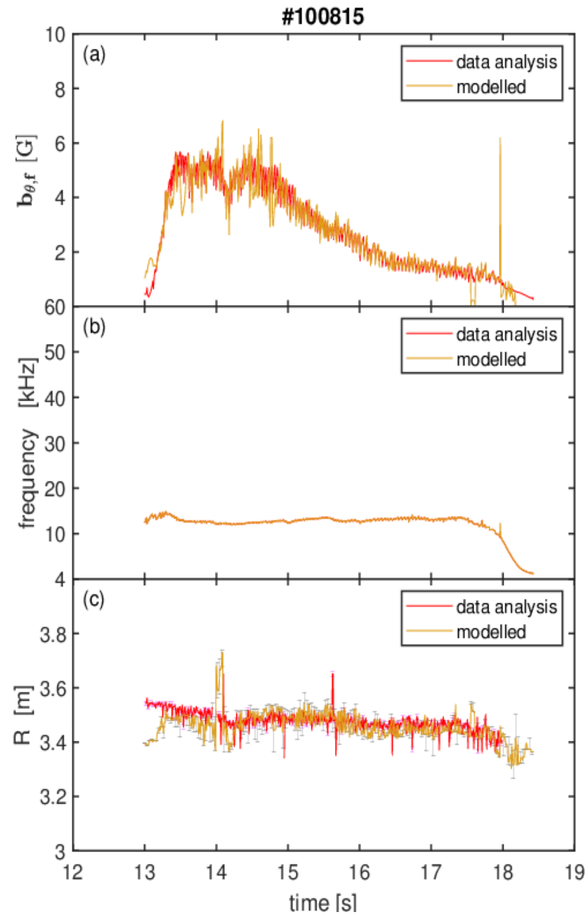


Fig. . : Exact (red) synergic diffusions D^((syn)) and their interpolating approximation (blue as functions of Φ and v^⋆ (a). Histogram of the ratio between the exact and approximate values over the 2D grid (b).

- A new method for localizing the perturbations at JET, based on knowledge of their amplitude is briefly presented. Relying on the successful testing of the perturbations model (Miron (JET Contributors) 2021 Nucl. Fusion 61 106016) against the experimental results at JET, its reversed implementation is applied to derive the location of the modes. The experimental mode amplitude plays, this time, the role of the input data with the aim of conversely obtaining the perturbations location. The calculated location accuracy is conditioned by a good theoretical retrieval of the experimental mode amplitude and frequency. Based on the chosen initial conditions, the desired location is the one associated with the best possible mentioned retrieval. Our model reliability basically ensures the derivation of the suitable location. No safety factor and plasma rotational velocity data profiles are used. The method has been extensively tested and checked in order to become a valid alternative to the usual localization techniques.



JET 100815 discharge experimental vs. calculated 2/1 mode (a) amplitude, (b) frequency and (c) location. The grey modelled location error bars are due to the HRTS data errors input. The pink experimental location error bars are the differences between the two consecutive ECE channels positions that bound the phase jump at the resonant surface.

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[12] D.I. Palade, “Non-linear transport coefficients in inhomogeneous magnetized plasmas”, International Conference on Plasma Physics and Applications (CPPA), 3 – 5 Sept. 2025, Bucharest, Romania (oral)

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