Romanian participarion at EUROfusion WPAC and complementary research

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WPAC contributes to the implementation of the European Roadmap, in which theory and simulation play a strong role, it is crucial to further bring together the accumulated knowledge and expertise in these fields under a highly focused Theory, Simulation, Verification and Validation (TSVV) programme. The development in these areas are key enablers that must be retained within the programme to advance our understanding and predictive capabilities. They will underpin the production of a high-quality suite of "EUROfusionstandard" software (building on the research software) to model data from EUROfusion facilities and to reliably extrapolate to future devices.

Project objectives:

<u>Numerical Simulations of Disruption Current Spike generated by the Wall Touching Kink Mode</u>

Disruptions represent an unacceptable instability in the next step tokamaks. They can cause substantial damage to the in-vessel component of the machines, which are in contact with the plasma. The Wall Touching Kink Mode (WTKM) - a nonlinear MHD instability - leads to a dramatic quench of the plasma current within ms: very energetic electrons are created (runaway electrons) and finally a global loss of confinement happens, i.e. a major disruption. The WTKM are frequently excited during the Vertical Displacement Event (VDE) and cause big sideways forces on the vacuum vessel. Deep understanding of the disruption phenomenon became now the highest priority topic in tokamak plasma physics. Understanding that in disruptions the sharing of electric current between the plasma and the wall plays an important role in plasma dynamics, we have developed a wall model that covers both eddy currents, excited inductively, and source/sink currents due to current sharing between the plasma and the wall [5 - 7]. The tokamak disruption simulations require a realistic model of the conducting structures around the plasma, referred here for simplicity as a "wall". A proper representation of its 3D structure (ribs, limiters, penetrations, gaps) is absolutely essential. In our numerical codes for source-sink-eddy currents calculation [5] we have included rib-like wall elements and have determined the matching conditions at joint of a rib-like wall element with the toroidal wall surface. The variational principle for source-sink-eddy currents in a thin wall with a rib-like wall element has been deduced [8]. Although it is the best prototype for ITER, the JET tokamak has a distinct element, namely the iron core which can affect the stability of the plasma. As a consequence of the high non-linear dependence of the magneto-hydrodynamic solutions on the iron permeability μFe in JET, we have taken into account the influence of ferromagnetic components in the equations of the surface currents developed in the vessel structures during WTKMs by reviewing the equations to be solved in order to simulate the influence of the ferromagnetic components in VDEs and equilibrium stability calculations [9]. Finally, via this project we intend to create the first numerical model implementing the physics of the WTKM as the driver of tokamak disruptions.

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Potential leading edge effect in in plasma energy deposition to material surfaces during disruptions triggered by Vertical Displacement Events (VDE) in tokamak

The understanding of plasma disruptions in tokamaks and predictions of their effects require realistic simulations of electric currents excited in 3D vessel structures during the Vertical Displacement Events (VDE) and by the plasma Wall Touching Kink Modes (WTKM) instabilities. These instabilities cause big sideways forces on the vacuum vessel which are difficult to confront in large tokamaks like ITER or DEMO. Understanding that in disruptions the sharing of electric current between the plasma and the wall plays an important role in plasma dynamics, we have developed a wall model that covers both eddy currents, excited inductively, and so source/sink currents due to current sharing between the plasma and the wall [1-3]. Considering for MHD simulations the TMHD (Tokamak MHD) model [4] we have to consider adaptive grids which are aligned with the 3-D ergodic magnetic field lines, so-called Reference Magnetic Coordinates (RMC) [5]. Due to the fact that during fast VDE disruptions, the plasma acquires a contact with the plasma facing material surfaces (e.g., protective plates in ITER), the instability generates the edge Hiro currents [6] which from the free plasma surface enter the "wall" surface mostly through the contour of the wetting zone. This creates the scenario when the leading edge effect with concentrated power deposition at the edges of the plates and potential destruction of the edges. This effect could be considered by as an important cause of wall melting in JET and as a cause the formation of runaway electrons.

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Bayesian ensemble algorithms for the decomposition of times series generated by tokamak diagnostics

Modelling of certain diagnostic signals as a combination of quasi-periodic elements of the time series, trends and change-points would be useful for the subsequent analysis of various phenomena like macroscopic charge-and-fire instabilities such as ELMs or sawteeth, slow drifts of the discharge properties and performances due to impurity accumulation or current diffusion. This project aims to use a Bayesian ensemble approach to model the decomposition of time series which quantifies the relative usefulness of individual possible decomposition models, leveraging all the models via Bayesian model averaging. This approach has in principle the advantage to alleviate model misspecification, address algorithmic uncertainty, and reduce over-fitting. A promising development is to further use the developed methodology to train advanced machine learning tools for online application.

Results:

2024-2025

- The WTKMs are frequently excited during the VDEs and lead to big sideways forces on the vacuum vessel which are difficult to confront in large tokamaks. As the key basis for our plasma disruption modelling, we have considered the understanding of how currents flow to the plasma facing surfaces during plasma disruptions. We realized that the galvanic plasma-wall contact is critical in disruptions, and that the reproduction of 3D structure of the wall is important. Thus, we have developed a wall model that covers both eddy currents, excited inductively, and source/sink currents due to current sharing between the plasma and the wall. To obtain the space and time distribution of the surface currents, we have developed a weak formulation form (variational formulation) and have minimized the correspondent energy functionals in a Finite Element approach. We realized that the major player in plasma-wall interactions are the currents flowing between the plasma and the wall. As an example of currents sharing between plasma and the wall in VDE we have considered: (a) surface currents as the currents at the plasma boundary generated by free boundary MHD instabilities; (b) eddy currents in the wall, excited by perturbed magnetic field, which is screened by the plasma surface currents: (c) Hiro currents as the negative component of the surface currents shared between plasma and the wall (opposite to the plasma current I_{pl}); (d) Evans current as the positive component of the surface currents potentially shared between plasma and the wall (same direction as I_{pl}); (e) halo currents as the positive diffused currents to the tile surface from outside the last closed magnetic surface. In conclusion: We developed a Wall-Touching-Kink-Mode model for explanation of the negative voltage spike in tokamak disruptions. We mention that the financial support for this project was 1.0 PM and the research work presented here has been developed together with our colleague L.E. Zakharov from LiWFusion, Princeton, NJ 08543, USA, without financial support for him.

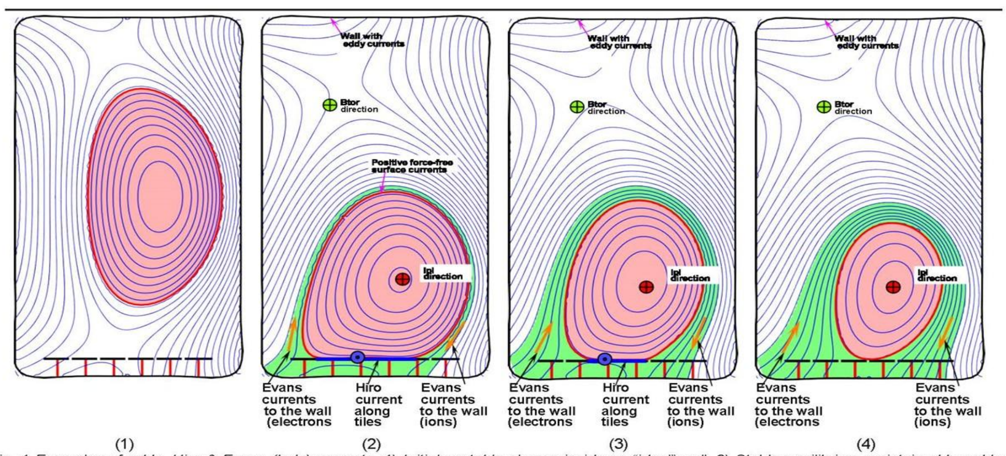


Fig. 1 Examples of eddy, Hiro & Evans (halo) currents. 1) Initial unstable plasma inside an "ideal" wall. 2) Stable equilibrium maintained by eddy currents in the wall and Hiro currents along tiles (JET case). 3) Reduced plasma maintained by eddy, Hiro, and Evans (halo) currents in the halo zone driven by loop voltage. 4) Shrunken plasma maintained by eddy and Evans currents. It is to note that: eddy and Hiro currents are inductively driven electrons, and Evans are source-limited ion-currents.

- Starting from the fact that on JET disruptions were capable of melting the plasma facing beryllium tiles, and similar wall damage in ITER should be assessed, in this project we had to consider two important disruption effects in both mitigated and non-mitigated disruptions in JET and ITER: (a) excitation of vertical disruption during the current quench (i.e., abnormal plasma current ramp down) and (b) potential leading edge effect in power deposition to the in-vessel tiles during disruptions related to the wetting zone of plasma and plasma facing surfaces. For this we had to determine: - the geometry of the wetting zone as well as the power deposition to edges of the protective plates in ITER and - the limitations on current decay rate given the geometry of vessel structure and characteristics of feedback stabilization systems. For this task, due to the fact that a conventional MHD model cannot solve numerical problems related to extreme plasma anisotropy and negligible mass we had to use the new mathematical model, called Tokamak MHD (TMHD) formulated for disruptions simulation as a replacement of conventional MHD (a model reported in our previous Complementary Project 2024: ,,Applying a new model, called Tokamak MHD (TMHD) instead of the conventional MHD model, in order to solve the old problem of the Courant time step limitation"). We had to upgrade the existing 2D VDE code the wall geometries of JET and ITER in order to perform simulation of VDE and to develop a 3D extended version of the simulation code of VDE.

- The vast majority of signals generated by tokamak diagnostics are in the form of time series. Consequently dealing with time-indexed data is a major task, to be tackled daily by both experimentalists and analysts. Decomposing a time series in terms of seasonal components, trends, change-points and noise is therefore a crucial activity, per se and as a preliminary step to further investigations. In the present work, the Bayesian ensemble approach to model decomposition of time series, originally developed for remote sensing of the earth, is applied to various global measurements routinely available in tokamak devices. Among the competitive advantages of the methodology, particularly relevant are its holistic view of the data and the independence from the details of the statistical algorithms and models. The potential of the technique, implemented by the BEAST code, has been assessed with both synthetic signals and experimental data. The approach proves to be very reliable in modelling trends and determining the time locations of abrupt changes even of strongly oscillatory components, such as ELMs and sawteeth. Deployment to assess small drifts confirms the lack of stationarity in tokamak high performance discharges. The difficulties of modelling the details of the sawteeth and irregular ELMs indicate the need to improve the method to deal with seasonal components of complex harmonic content and/or varying frequency. However, the available routines are already very effective in determining the times changes in the ELM regimes and could be refined for real time deployment.

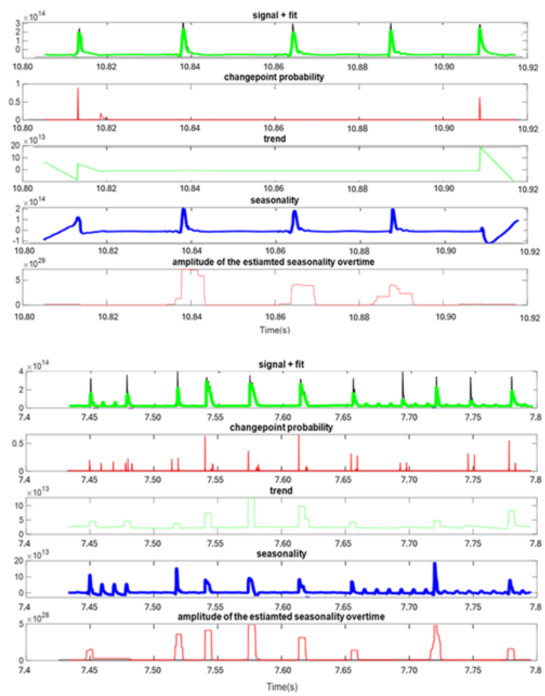
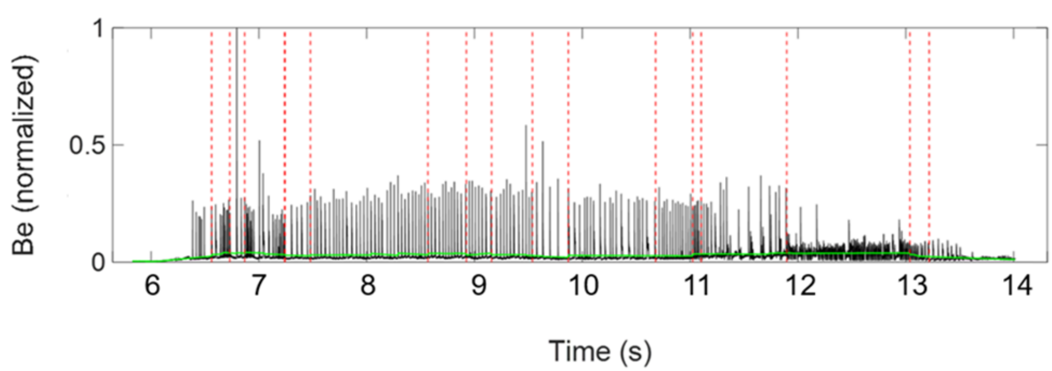


Fig.9. Bayesian decomposition of the Be signal of JET discharge #94871.



The seasonality component for JET discharge #94871, in which the oscillations of the ELMs are almost exactly periodic for several quite long time intervals. However the ELM frequency and behaviour vary quite abruptly depending on the phase of the pulse. The BEAST algorithm manages to identify the time location of these abrupt changes quite accurately. A different choice of the threshold would allow detecting also smaller variations in the ELM regimes at about 7s and 11.3 s.

Publications:

Papers

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