Contribution ID: **1304** Type: **Regular Poster**

Machine learning method for prediction and detection of plasma confinement states and ELM activity

Friday, 14 May 2021 18:25 (20 minutes)

The typical fusion plasma confinement states in tokamaks include low (L) confinement, high (H) confinement and the dithering (D) state which implies intermittent switching from the L- to the H- confinement modes. The H- mode manifests itself by self-organization of a region inside the poloidal separatrix where the transport coefficients are reduced by up to an order of magnitude compared to the L-mode and by formation of the plasma pressure pedestal. The large pressure gradients most likely drive the MHD instabilities, known as peeling-ballooning modes, which cause the appearance of ELMs. The ELMs intermittently release particles and energy from the edge of the plasma limiting the pressure gradient, thus limiting the temperature of the plasma core and the performance of the device. In addition the impulsive energy and particle flux released during ELM bursts may cause serious damage to the internal walls and divertors. Hence, prediction of mode transitions and ELM dynamics is essential for the proper functioning of the fusion devices. Usually, post-experimental analysis reveals the frequency of ELMs occurrence and other relevant features of the confinement changes. In our previous work 1, based on the experimental results, we have shown that Type-I ELMs occur as the result of stochastic bifurcations similar to the first order phase transitions and that their occurrence may be detected by zero-crossing function of the ion-saturation current in this case. The zero-crossing function indicates the number of equilibria and the stochastic bifurcation is recognized as the change in the number of stable equilibria. In Fig. 1 we show the behavior of the invariant zero-crossing function for the L-, dithering L/H mode and the ELMs dominated H-mode of the ion saturation current of the MAST device. The two stable equilibria in the H-mode suggest that ELMs, which dominate the dynamics of this particular confinement regime, represent stochastic bifurcations between two stable states. The appearance of the second stable equilibrium may be detected at its inception so that the pdf may be regarded as precursors of the confinement changes.

We have recently developed a mathematical and computational framework for determination of the wavelet basis optimally suited for the analysis of a dynamical system under study which quantitatively determines the level of self-organization in the system [2]. Applications of the method to fusion plasmas [3], revealed its versatility in evaluation of confinement configuration effects on the formation of different patterns and large-scale structures, in the detection of quantitative changes in the dynamics and in distinct self-organization features of different confinement modes. The method is based on the Hidden Markov model of wavelet coefficients and we have shown that the probability density functions (pdf's) of the wavelet coefficients are predictive states in the sense that they may be used for prediction purposes.

Additional improvements of the method are made to make it a non-supervised machine learning framework with the adaptability features that make it compatible for combination with the convolutional neural networks. Furthermore, we show here that the wavelet coefficients pdf's have the same behavior as the zero-crossing functions albeit more sensitive to the subtle changes in the dynamics making them ideal for prediction purposes. This feature is reflected in the temporal domain through the characteristic tree structure of the wavelet coefficients. We demonstrate the efficiency of the method on experimental data in detecting and predicting confinement changes, ELM occurrences and in making a distinction between ELMs and the dithering regime. In order to further illustrate the predictive abilities of the method we apply it to the two theoretical models of confinement changes.

The Sugama-Horton [4] model for the L-H mode transitions consists of three differential equations which describe temporal evolution of the main quantities, namely potential energy contained in the pressure gradient, the turbulent kinetic energy and the background shear flow energy. The Sugama-Horton model has some advantageous features which make it a favorable model to compare with the experimental data. First, the model covers the possibility of L-H transition as either the 1st order phase transition (explosive bifurcation) or as the 2nd order phase transition (continuous bifurcation) depending on the shear flow damping. Second, for certain parameter set values the ELM behavior occurs due to the loss of stability of the H-mode stationary state which bifurcates to the limit cycle characterized by periodic relaxation oscillations similar to those observed in the ELM state. A characteristic feature of the model is the use of the potential energy production, given by the energy input to the peripheral region, as an external parameter. We show that the model shows chaotic behavior for a subset of parameter region, a feature of the model not noticed by the authors, which is important for understanding ELM behavior. The chaotic temporal behavior is more appropriate for describing the ELM dynamics however in order to adapt to the realistic parameter range relevant for ELM occurrences we add stochastic term (noise) to one of the equations (case 1) and to each of the three equations (case 2).

The case 1 leads to better agreement overall and this change enables the actualization of the stochastic bifurcations of the explosive (catastrophic) type within the model. As in the case of experimental time series, the method successfully predicts ELM dynamics and L-H confinement transitions. We also show how the method precisely detects the bifurcations in the original, deterministic model, and in the modified, stochastic model.
The second model is based on the work [5], which also consists of three differential equations, however the main quantities are now the average spectral intensity, characteristic velocity of the shear flow and the average density gradient. Again we show that for certain parameter regime this model exhibits very rich bifurcation scenarios including chaotic solutions (not seen nor discussed by the authors) and we adapt the equations in the same manner as in the case of the Sugama-Horton model in order to generate stochastic bifurcations of catastrophic type. The machine learning method based on quantification of self-organization again shows efficient predictive features confirming its effectiveness for detection and prediction of confinement changes and ELM dynamics.
The two modified models of L-H transitions and ELM activity show very good compliance with the experimental data and it remains an interesting issue to explore more of their features in contrast to the perturbed Hamiltonian models and the proposed methods of ELMs control with 3D magnetic perturbations. The wavelet based machine learning method may be used for prediction purposes on other types of diagnostic data, such as photodiode signals, interferometer signals and diamagnetic loop signals, and it may be readily adapted to be used in conjunction with the convolutional neural networks.

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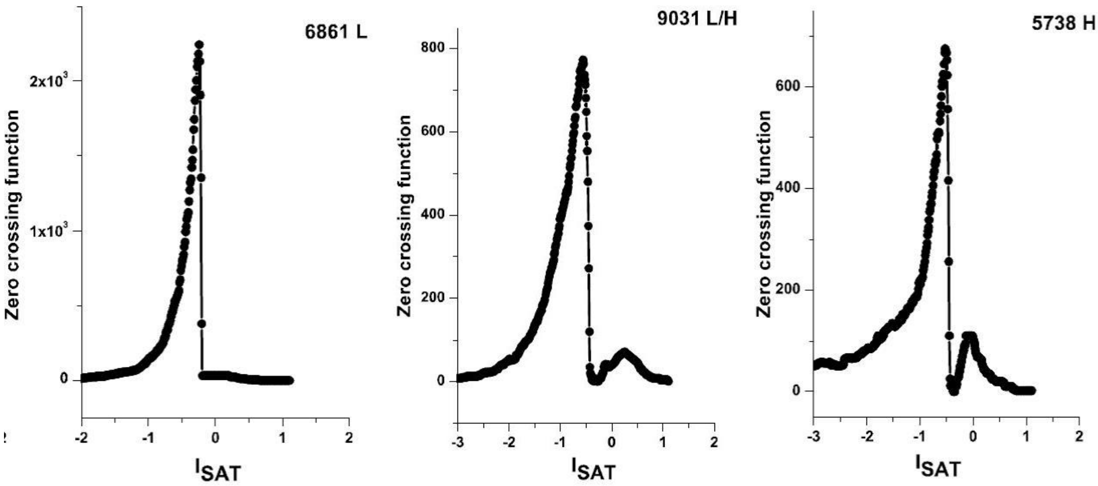

Figure 1: Zero-crossing function of three different confinement regimes indicated in the figure t

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Session Classification: P8 Posters 8

Track Classification: Magnetic Fusion Theory and Modelling