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New Information Processing Methods for Control in Fusion

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.

Magnetic confinement fusion devices are very integrated systems, difficult to access for measurement, and therefore they pose particular challenges to identification and to the prediction of undesired events. With regard to system identification, Bayesian statistics is a very promising methodology, which provides for the first time a sound way to include physical information about the diagnostics in the evaluation of the error bars. In a prototypical application, a Bayesian statistical approach determines the magnetic topology without any assumption on the equilibrium and provides clear confidence intervals on all the derived quantities. This technique, which complements another more traditional approach based on the Grad-Shafranov equation, can be implemented to provide results about every few milliseconds and therefore it can be envisaged to exploit for feedback purposes. Some phenomena in the evolution of Tokamak plasmas, like disruptions, are too dangerous and prohibitively difficult to control. For these cases avoidance is the best alternative and therefore specific classifiers have been trained and optimised to predict the occurrence of disruptions. The success rates of these predictors, mainly based on Support Vector Machines, are very often of the order or higher than 90%. The generalisation capability of the method has been confirmed by applying the same predictor to new campaigns without retraining. The success rate remains very high (above 80%) even 12 campaigns after the last one used for training.

1. THE DATA ANALYSIS PROBLEM IN THE CONTEXT OF FEEDBACK CONTROL IN NUCLEAR FUSION

All open systems, from unicellular living beings to complex societies, have to preserve their internal organization by processing matter and energy in order to delay the inevitable heat death. Their internal structure, indispensable to survival, can be successfully maintained only thanks to sophisticated information processing and carefully programmed interventions on the surrounding physical world. High temperature plasmas, relevant for nuclear fusion research, are complex, open systems which have to be pushed very far from equilibrium conditions to achieve the required performance in terms of energy production. They present practically all the problems typical of open systems: they need adequate supply of energy and matter, their internal transformation processes have to be carefully regulated and adequate mechanisms to eliminate the wastes are required. In the typical language of Tokamak physics, these are the issues related to fuelling and additional heating, confinement regime optimization, heat loads and He ash.

Controlling open systems of the complexity of nuclear plasmas presents several challenges, which can be basically classified into two categories: a) difficulties inherent in the control strategies; b) difficulties pertaining to the complex data processing and distribution.

With regards to the first topic, the main specific aspect of Tokamak operation, which has a strong impact on the control systems, is the high level of integration and interdependence between all the various aspects of the plasma and between the plasma and the surrounding machine structures. Indeed all the main aspects of fusion plasmas, which can have a strong impact on their performance as energy sources, are linked and cannot be considered separately. The plasma shape, the internal distribution of the plasma currents, the behaviour of the fast particles and impurities cannot be fixed or controlled independently. As a consequence also the machines subsystems are strongly coupled. Therefore a distributed controller, with different subsystems being controlled independently, will not be adequate. A full integrated control system, supervised by a centralized controller, will probably be necessary. In this approach, whose architecture is shown in figure 1, the centralized controller determines the control inputs for all the subsystems, taking into account the coupling among them. The design procedures require the availability of a full MIMO (Multiple Input Multiple Output) dynamic model of the overall controlled system, including the dynamic interactions among the subsystems. This solution is more complex but guarantees, at least in principle, the best performance of the overall control system.

A centralized controller becomes more necessary the more nonlinear and sophisticated are the processes to be controlled. On the other hand, in some cases, the complexity of the processes is so high and the time scales of the plasma evolution so quick that control becomes prohibitive and prevention is the only practical alternative. This applies for example to disruptions, which can be also so harmful to the integrity of the machine that their avoidance is a much more meaningful strategy than direct control of their evolution. On the other hand, disruptions are so complex phenomena that it has proven impossible so far to model them sufficiently well, to develop algorithmic solutions predicting their occurrence sufficiently early to be able to undertake reliable remedial action. Therefore various machine learning methods have been employed in the last years. With regard to the second category of issues, the data analysis and distribution, it must be realized that information processing is an essential aspect of open systems, both natural and man made. Inadequate information processing can strongly affect their performance and even endanger their survival potential. For artificial systems, in [1] it is described how in the 19th century the speed of trains in the USA had to be reduced because too many accidents tended to occur due to the inability of the telegraph to process and distribute information quickly and accurately enough. In modern, reactor grade Tokamak machines the data processing is complicated by several issues. First of all many quantities have to be properly measured and made available. Secondly the amount of information to be processed can be enormous. JET real time system includes about 30 diagnostics for a total number of more than 50 signals to be handled by an ATM network. Another important peculiar aspect of control for fusion to be kept in mind is the fact that plasmas are systems very difficult to access for measurements. A lot of crucial information is therefore derived from measurements taken outside the plasma exploiting their natural emission. The interpretation of these signals needs solving sophisticated inversion problems, which are difficult, sometimes ill-posed and can require significant computational resources.

In the largest devices like JET, and even more in the next generation of machines like ITER, the importance of control will increase significantly. The higher power input and energy content of the plasmas, together with the need to push the boundary of the parameter space to achieve better performance, will tend to increase the potential danger of the experiments. The length of the discharges will also require new approaches to the supervision of the operations, which will have to depend less on human supervision. More sophisticated but at the same time more reliable control strategies will therefore be required.

With regard to the structure of the paper, in section 2 one of the main issues of system identification for control in Tokamak plasmas is discussed: the real time determination of the magnetic topology. New methods based on Bayesian statistics and more traditional approaches, solving the Grad-Shafranov equation, are presented. In section 3, the most recent advances in disruption prediction, using a completely new approach based on Support Vector Mahines (SVM), are described.

2. REAL TIME DETERMINATION OF THE MAGNETIC TOPOLOGY

In Tokamaks, the topology of the magnetic fields inside and outside the plasma plays a fundamental role. The configuration of the fields is also one of the main aspects which tend to increase the interconnections between various phenomena. Moreover, the interpretation of the vast majority of diagnostics requires the information about the magnetic topology. On the other hand, even if the feedback control of the last closed magnetic surface is a task achieved routinely on many devices, the determination of the internal topology of the magnetic fields has proved to be a much more difficult task.

A new approach is being developed at the moment in JET to determine the configuration of the magnetic surfaces without any hypothesis on the equilibrium. It consists of a purely probabilistic approach based on Bayesian theory [2]. The plasma and the surrounding structures are modeled as a series of current beams. The current in the beams is determined by calculating the distribution with the highest probability given the measurements available. A major advantage of the method is that it provides, in addition to the solution with the highest probability, also the uncertainty intervals of the results. An example of a magnetic reconstruction at JET is shown in figure 2. Only external magnetic measurements (pickup coils) have been used for this case.

Since the problem is linear and significant efforts have been devoted to expressing the prior as a multivariate normal distribution, the posterior MAP is analytically solvable and therefore the proposed approach is particularly suited to real time applications. The computational time required to obtain the magnetic surfaces with the maximum probability is of the order of 1ms on a 2GHz laptop. For the uncertainty intervals a few tens of ms are sufficient and therefore the method is more than adequate for any control application on big devices. Another important advantage of the Bayesian method is that any required form of smoothing can be accommodated in the “a priori” probability of the Bayesian treatment. For feedback control several alternatives can be considered. Priors derived from similar previous discharges are expected to be often adequate. Also different diagnostics can be used depending on the accuracy required particularly on the estimate of the uncertainty interval. An example is provided in figure 3, where the uncertainty intervals for two different sets of diagnostic measurements are compared. In addition to the innovative method just described, a more traditional approach based on the Grad-Shafranov equation is also being pursued at JET. This approach solves the ‘Grad Shafranov’ equation assuming equilibrium between the magnetic and kinetic pressure. The magnetic reconstruction problem is formulated numerically as a least-square minimization based on available measurements with a Tikhonov regularization. In the present version of the solver called EQUINOX [3], the experimental measurements that are planned to be used for the reconstruction are the magnetic pick-up coils, the interferometric and polarimetric measurements and the Motional Stark Effect (MSE). The version of the code using only magnetic measurements has already been completely validated. A set of 130 JET discharges has been carefully prepared exactly for this purpose. This database covers almost JET whole operational space. The plasma current range covered is between 1.12 and 3.09MA, the magnetic field is between 1.68 and 3.42T, the range in triangularity is $0.06<\delta<0.51$. It is worth mentioning that also advanced scenarios like the hybrid have been included. The validation strategy consists of comparison of the EQUINOX results of global and local quantities with EFIT, the reference code at JET for magnetic reconstructions. Some of the parameters compared systematically are: plasma volume, I_p, q_{95}, q_0, li, β_p, R_x, Z_x. (in order they are: the plasma current, the safety factor at 95% of the minor radius, the safety factor on axis, the plasma internal inductance, the poloidal beta, the horizontal and vertical position of the X point). For the main parameters of the last closed flux surface, the EQUINOX estimates have been compared also with the code used at JET for boundary control: XLOC. All these tests have given very positive results. In figure 4 the time evolution of the radial position of the X point is reported, together with a statistical comparison of the distance ROG between the last closed magnetic surface and the wall in the equatorial plane. It is worth mentioning that an evaluation of the sensitivity of the code to the magnetic measurement errors has also been performed. The validation of the version of EQUINOX including internal magnetic measurements (polarimetry and MSE) is under way together with the cross validation with the Bayesian approach.

3. DISRUPTION PREDICTION

As mentioned in the first section, disruptions are very undesirable events. They strongly affect the experimental programme and they can also endanger the integrity of the machines [4]. It is also to be considered that once a disruptive event has been triggered, it can evolve very fast and therefore its control is a difficult task.. Even landing the plasma safely on the most robust parts of the vacuum vessel is a quite challenging proposition. All these considerations motivate an improvement of the predictive capability, which on present day machines is not particularly satisfactory. No algorithm is available to model the behaviour of the plasma close to the operational boundary to predict disruptions reliably.

In the past decade, several machine learning methods, like neural networks [5] and Fuzzy logic systems [6, 7], have been developed to tackle this issue. One of the main weaknesses of the predictors developed so far is their limited applicability to campaigns different to the ones they had been trained with. Recently much better results have been obtained in this respect [8] with some original applications of Support Vector Machines (SVM) [9]. SVM calculate a separating hyper-plane between to classes, disruptive and non disruptive discharges in our case, using a quadratic optimization algorithm, which maximizes the margins from the separating hyper-plane to the closest training examples. In this way, the SVM system takes into account only the examples (support vectors) placed at the margins, i.e. closest to the separation hyper-plane which renders the predictors much less sensitive to outliers. This improves the generalisation capability and the robustness of the method to distinguish between different classes of data.

From a methodological point of view, two main innovative developments have been implemented in the system for JET. First of all, a series of different predictors, based on Support Vector Machines (SVM) and trained during specific time intervals before the disruption, have been deployed in parallel. They analyse different time slices of the discharge to detect in advance the approach of a disruption. The decision whether to trigger an alarm or not is performed by a decision function, again based on SVM, on the basis of the outputs of the individual predictors. This second layer of SVM, which is the second original aspect of the developed technique, is adaptive in the sense that it can be retrained automatically with the signals of each new discharge. It is also worth mentioning that all the results reported in this paper have been obtained considering the complete evolution of the discharges. In this way, contrary to what was done in most of previous works, the predictor is applied from the beginning to the end of each discharge, including ramp up and ramp down of the plasma current, and not only to specific time intervals. Finally, the model has been trained with shots of the campaigns up to C7 and then it has been tested with discharges up to the campaign C19 with very positive performances.

The success rates and the false alarms obtained up to C19 are shown in figure 5. The decline in performance is very slow. The relatively unusual low performance in C11 can be explained in terms of the characteristics of this campaign. C11 was the campaign of the Trace Tritium Experiments, in which particular attention was devoted to avoid disruptions. Since the predictor has been optimized to minimize missed alarms at the price of more false alarms, in this campaign the extremely low number of disruptions decreases the statistical performance of the method. After C14 significant modifications have been implemented on the device, including the installation of a new bolometer system and the Error Field Correction Coils (EFCC) and therefore the rates decays mainly due to an increment of the false alarms. In any case, these results are the more important because, contrary to most previous works, in the present case the complete evolution of the considered discharges is followed from the beginning to the end, without any selection of the time slices. The applied database is also the biggest used so far at JET for real-time disruption prediction with machine learning techniques.

The performance of this new approach has also been compared with the predictor traditionally used by JET Prediction System (JPS) to terminate discharges at risk of disruption. The results are reported in figure 6 for the campaigns up to C19. The clear improvement in the success rates up to about 200 ms before the disruptions can be clearly noticed.

ACKNOWLEDGEMENTS

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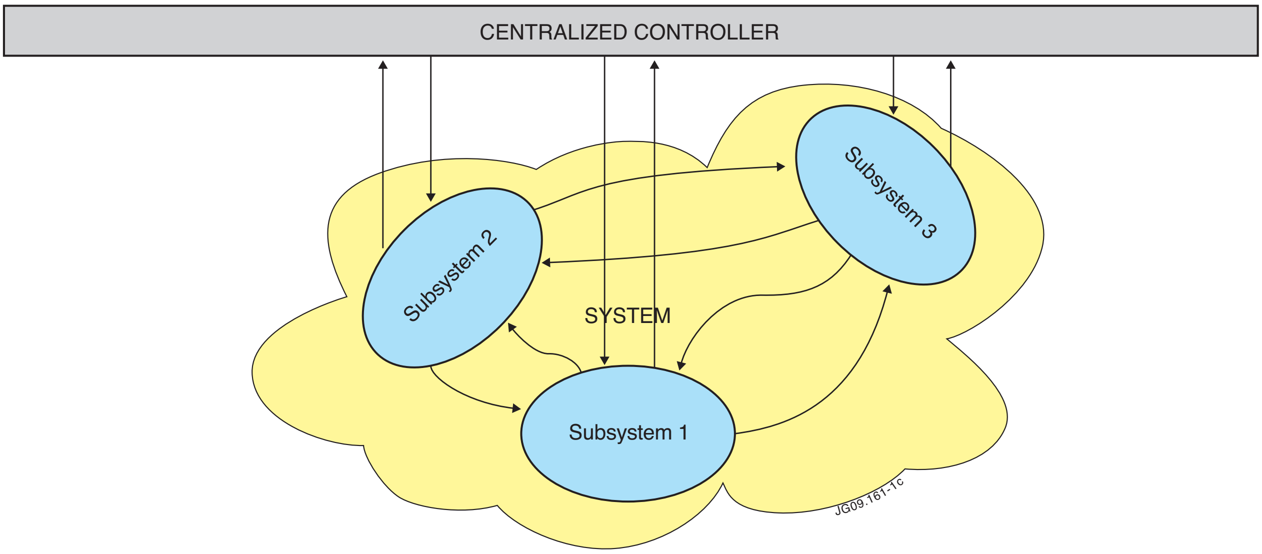

Figure 1:Pictorial view of a centrallised controller

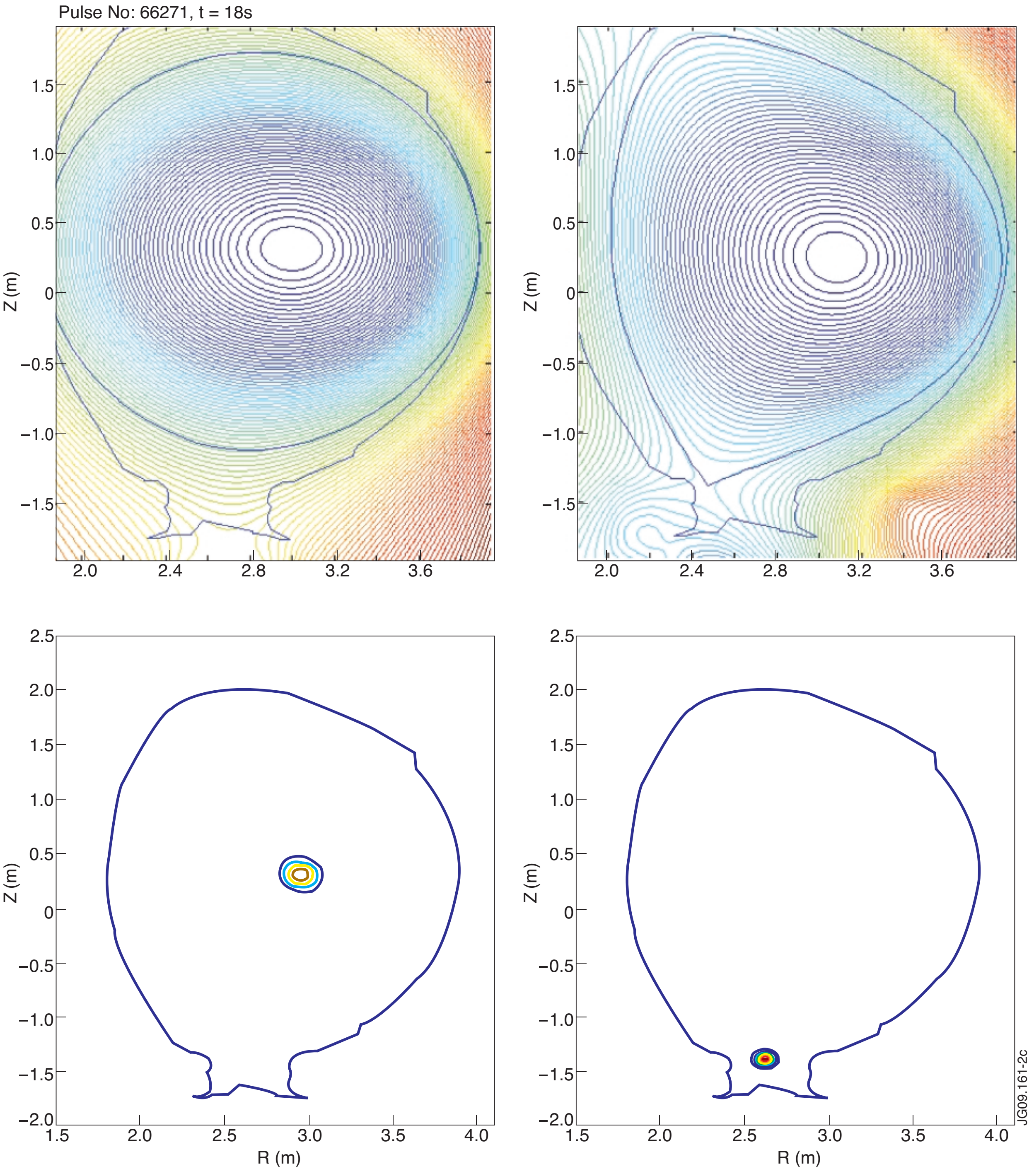

Figure 2:Top: magnetic surfaces reconstructed with the Bayesian method for a limiter (left) and X-point configuration (right). Bottom: uncertainty in two important topological parameters the position of the magnetic axis (left) and X point position (right). JET Pulse No: 66271.

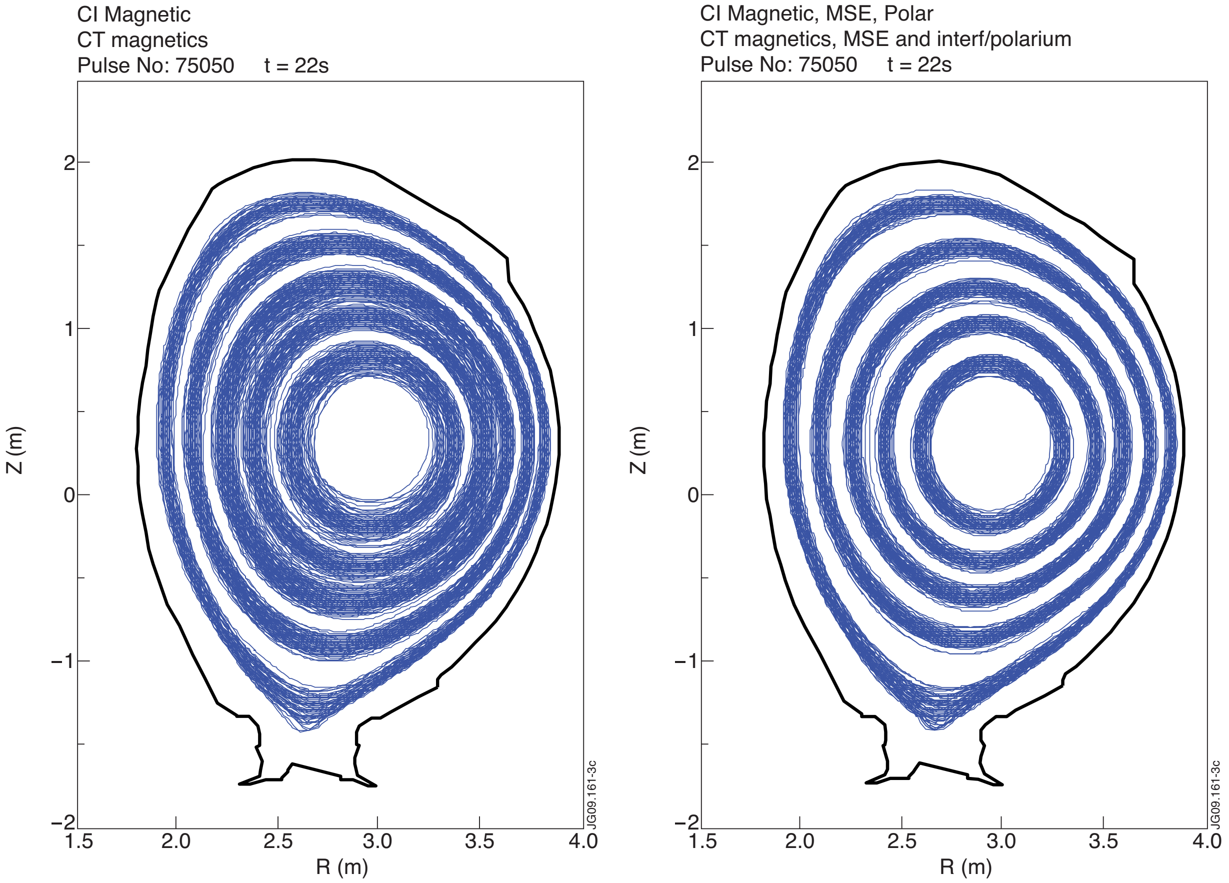

Figure 3: Reduction of the uncertainty intervals on the magnetic topology when additional diagnostics (polarimetry, MSE) are included in the analysis.

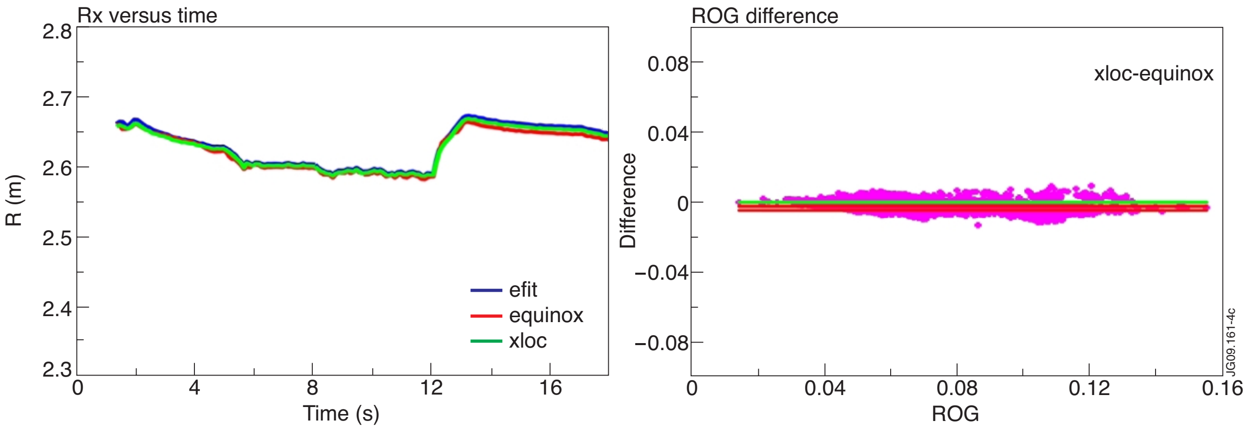

Figure 4:Validation of EQUINOX with EFIT and XLOC. Top: time evolution of the radial position of the X point. Bottom: difference between the estimates of the distance between the plasma and the first wall at the outer midplane.

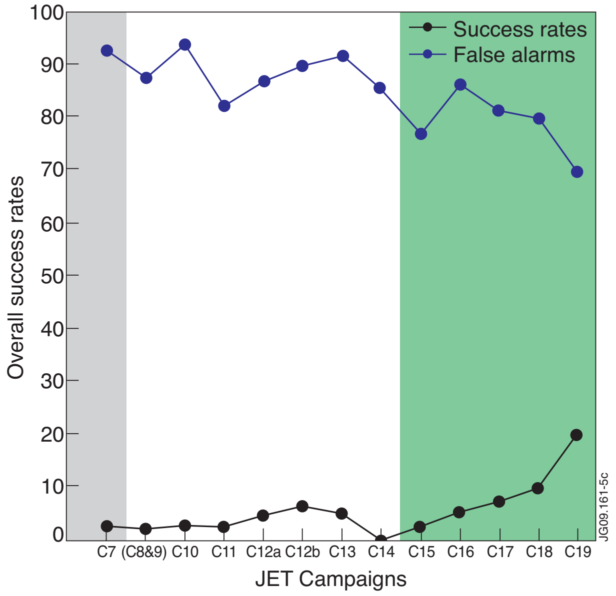

Figure 5: The success rates of the SVM predictor for the campaigns used for the training and subsequent.

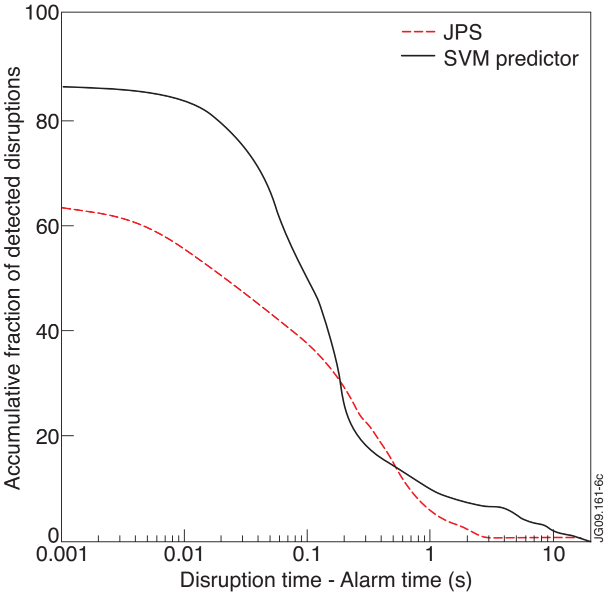

Figure 6: The success rate of the SVM predictor compared with the one traditionally used by JET Prediction System.