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Development of Real Time Diagnostics and Feedback Algorithms for JET in view of the Next Step

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Abstract.

Real time control of many plasma parameters will be an essential aspect in the development of reliable high performance operation of Next Step Tokamaks. The main prerequisites for any feedback scheme are the precise real-time determination of the quantities to be controlled, requiring top quality and highly reliable diagnostics, and the availability of robust control algorithms.

A new set of real time diagnostics was recently implemented on JET to prove the feasibility of determining, with high accuracy and time resolution, the most important plasma quantities. With regard to feedback algorithms, new model-based controllers were developed to allow a more robust control of several plasma parameters. Both diagnostics and algorithms were successfully used in several experiments, ranging from H-mode plasmas to configuration with ITBs.

Since elaboration of computationally heavy measurements is often required, significant attention was devoted to non-algorithmic methods like Digital or Cellular Neural/Nonlinear Networks.

The real time hardware and software adopted architectures are also described with particular attention to their relevance to ITER.

1. Introduction

In the last years, the fusion community has witnessed a significant proliferation in the number of real time control experiments. This is due to a variety of reasons, among which the most important are the increased sophistication of the scenarios and the advanced physical issues attacked [1]. With regard to the scenarios, the Elmy H mode, in the continuous attempts to increase the performances moving closer to the Greenwald limit, requires high elongations and triangularity, with the related difficulties in terms of stability of the plasma column. The so-called advanced scenarios, in their turn, rely every day more on involved profiles of both pressure and current, posing not negligible challenges to the control systems. The need to understand many unresolved issues, like the physics of ELMs or the formation and sustainment of ITBs, also contributes to the variety of requests for sophisticated feedback schemes. In JET the demand for more advanced real time control is particularly felt due to the extremely wide scope of its research program and to the more acute safety implications of a big device [2]. As a consequence a broad range of different feedback schemes has been recently developed covering a wide range of tasks from simple event driven actions to multivariable, distributed control of profiles.

In Nuclear Fusion, as in any other field, the first step for a successful feedback is the proper identification of the system to be controlled. This means that the relevant parameters of the system must be measured with adequate accuracy, reliability and speed. In the case of Tokamak plasmas, the responsibility of the identification falls mainly on plasma diagnostics. In the last years, the main drive behind the success of JET feedback control experiments were the major improvements in the number and reliability of the measurements [3]. The signals available in real time at JET now cover all relevant parameters, ranging from the magnetic configuration to the kinetic quantities. In addition to the traditional plasma shape obtained from the pick-up coils and the flux loops, the q profile is derived from the Faraday rotation measurements [4]. Both the electron and the ion fluid are diagnosed. The electron density profile is provided by the LIDAR [3] and the interferometer, whereas the ECE [5] guarantees an electron temperature profile with much higher time resolution than the Thomson Scattering. Active Charge exchange Recombination Spectroscopy (CXRS) is of course the main system to derive real time information, temperature and velocity profiles, of the ion fluid [6].

A series of validated codes are also routinely used to obtain derived quantities. The internal plasma inductance l_i and the derived confinement parameters are calculated from the Shafranov integrals [7]. A new shape controller, called extreme Shape Controller (XSC) [8] has already been used in highly shaped configurations, whereas an optimised equilibrium code EQUINOX [9] solves the Grad-Shafranov equation, taking into account also internal magnetic measurements, like polarimetry, on a finite element mesh instead of a regular grid like EFIT.

These new tools were extensively used in the last years and they contributed

significantly to the scientific program of the entire experiment. For example they constituted an indispensable prerequisite for some of the most ambitious feedback programs, like the simultaneous control of current and density profiles. These control schemes made extensive use also of JET actuators, which toroidal, poloidal and divertor coils, gas fuelling, neutral beam injection and Radio Frequency (ICRH) and Lower Hybrid (LH) waves.

JET real-time system is also a good environment to test innovative computational concepts, both software, like Digital Neural Networks (DNN) [10], and hardware, like the new chip technology of Cellular Neural/Nonlinear Networks (CNN) [11]. The information and experience matured at JET in years of real time developments provides also a good basis in the perspective of ITER. JET architecture and general approach, implementing a distributed system, could be successfully translated to ITER. On the other hand, on the route to the next step, the validation of new measurement techniques for some physical quantities of reactor relevance is still required.

With regard to the structure of the paper, the architecture of JET real time control and the main diagnostics and codes available in real time are reported in section 2. Some of the most recent and interesting feedback experiments, heavily relying on the new real time diagnostics and algorithms, are described in section 3 and 4. More advanced approaches, still under development, for real time elaboration of diagnostic data, involving soft computing and hardware neural Networks, are the subject of section 5. The main problems to be faced in developing diagnostic concepts for ITER are reviewed in section 6.

2. Architecture of JET real time control system and diagnostics

JET real time control implements a distributed system, with many independent stations, communicating via an ATM protocol [12]. This multi-platform approach (PCI, VME etc) offers several advantages, with respect to the mainframe, centralised solutions, which were more popular in the past also in the field of Nuclear Fusion. One of the main characteristics of the present architecture is its great flexibility, which is essential in such a fast evolving field, with diagnostics and feedback algorithms being continuously added or upgraded. The potential of the adopted solution to implement parallel computing is also a very important feature, which is not to be neglected given the fast time response of many plasma phenomena to be controlled and the quantity of data to be processed in next step machines. It is therefore strongly believed that JET approach should be considered a very good reference for ITER real time control system.

The flexible and adaptive architecture of JET control system has allowed including many new diagnostics in the real time project in a very efficient way. Now the vast majority of the most relevant measurements, from the equilibrium to the confinement parameters, are routinely available in real time [3]. Also kinetic and profile quantities are provided with more than satisfactory time and space resolution, as can be seen from the summary table 1.

Table 1. Main real time signals and derived quantities routinely available in real time at JET

Physics	Diagnostic	Size	Cycle (ms)
T_e (R)	ECE	48(96)	5
ITB_e (R)	EXE	48	5
T_e (R)	LIDAR	50	250
N_e (R)	LIDAR	50	250
T_i (R)	CX	14	50
V_{rot} (R)	CX	14	50
ITB_i (R)	CX	14	50
γ (R)	MSE	25	2
LID	FIR	8	2
FAR	FIR	8	2
LCFS	XLOC	100	2
β, l_i	Confinement	20	2
Flux	EQX	100	25
$q(r/a)$	FIR / XLOC	10	2
$q(r/a)$	MSE / EQX	10	25
$ITB_e(r/a)$	ECE / EQX	10	25
$ITB_i(r/a)$	CX / EQX	10	25
Radn	Bolometer	48	5
Impy	VUV	8	20
Impy	Vis.	16	20
ELM	Vis.	3*3	100
H:D:T	Vis.	4*3	20
T_i core	X-ray	8	20
Ipla	Magnetics	1	Analog
MHD n=1	Magnetics	1	Analog
MHD n=2	Magnetics	1	Analog
RNT	Neutronics	1	Analog
Hard Xray	Neutronics	1	Analog
Density	FIR	1	Analog

From table 1 it is very apparent the remarkable progress of JET diagnostics in the direction of the real time, which is now not limited to the traditional magnetic measurements for plasma positioning and control. The electron fluid is nowadays quite well diagnosed, since the temperature is given by the ECE and the density can be obtained from both the interferometer and the LIDAR Thomson Scattering. The ECE radiometer comprises 96 tuned heterodyne microwave receivers covering the much of the radial extent of the plasma, for most toroidal fields. The real time algorithm acquires the 96 signals and, after proper filtering, applies calibration constants derived from comparison with the absolute-reading ECE Michelson Fourier Interferometer, providing profiles with 5ms time resolution. For the LIDAR system, the real time approach consists of fitting to pre-calculated intensities, depending on electron density and temperature, the backscatter echo from the plasma. The system processes the data

in the almost same way as the inter-shot code in less than $10ms$, resulting in 50 point profiles at $4Hz$ (due to the repetition rate of the laser $250ms$). The electron cyclotron emission data allows in its turn the determination of the ρ^*T profile [13]. On the basis of the electron density, obtained by inversion of the interferometric measurements, the safety factor profile can also be calculated in real time, using the flux surface topology obtained by the pick up coils [4]. The last years have also witnessed a remarkable progress in diagnosing the ion fluid, whose temperature and velocity are now routinely provided using Charge Exchange Recombination Spectroscopy [6]. In particular the toroidal velocity is considered particularly relevant and it could be exploited much further in the future for very interesting feedback schemes, like the control of ion ITBs.

The shown performances have been obtained thanks to significant improvements both in the hardware and the software. In the last years many diagnostics have become more reliable and communication technologies has also witnessed dramatic steps forward. From the point of view of data analysis, providing a quantity in real time mainly implies very often a critical revision of the off-line algorithms, to find a trade off between accuracy and time resolution. Proper approximations, linearization of quantities and adoption of robust fitting routines, together with careful software engineering, are the main ingredient, which normally can grant the desired results, both in terms of accuracy and time resolution.

It is also worth noting that not only a quite comprehensive set of signals is available in real time at JET but also some fundamental derived quantities are calculated, by optimised and reliable codes. Particularly interesting are all the basic confinement quantities, obtained from the Shafranov integrals [7], and the magnetic equilibrium from the magnetic measurements (EQUINOX code) [9], as again reported in table 1. In the case of these codes, a reasonable compromise between the accuracy of the derived quantities and the computational efforts is again an essential ingredient of a successful strategy for providing satisfactory and reliable information. This was already achieved in the case of EQUINOX making use only of the external coils and now the attention is concentrating on finalising the version of the code capable of accommodating also the internal measurements (polarimetry and MSE).

3. Control of highly shaped plasmas

As mentioned in the introduction, the main drives behind the development of real time diagnostics at JET are the requirements of the scenarios and the advanced physics. Recently the research on the Elmy H mode has moved in the direction of producing plasmas with increased elongation and triangularity. These strongly shaped configurations are quite vulnerable to significant deformations of the shape in presence of strong variations of β_{pol} and/or the internal inductance l_i . In this framework, a new controller, called the eXtreme Shape Controller (XSC) [8] was explicitly designed at tested to improve the control of these highly shaped plasmas. In JET 8 actuators, namely 8 Poloidal Coils, are available to control the plasma shape, which is described in

terms of a set of geometrical descriptors (GAPs). These GAPs are the distance of the last closed flux surface from the first wall along predefined directions. They are obtained from the magnetic measurements of fields, fluxes and flux differences by standard analysis methods. The previous shape controller (SC) was conceived to perform the feedback control on each of the 8 actuators by using as inputs to the system either the currents flowing into the Poloidal Circuits (current control) or a limited number of the actual measured GAPs (GAP Control). The new XSC receives the errors on 38 indicators of the plasma shape (32 GAPs plus the two coordinates of the X and the two strike points) and calculates the "smallest" currents needed to minimize the error on the "overall" shape in a least square sense.

The design of the XSC for JET single-null configurations is based on a linearised plasma model approach, implemented by the CREATE-L and CREATE-NL codes [14]. These plasma-modeling tools were specifically adjusted for JET topology, taking into account both the iron core and the eddy currents induced in the passive structures.

#61995. High Triangularity on Termination

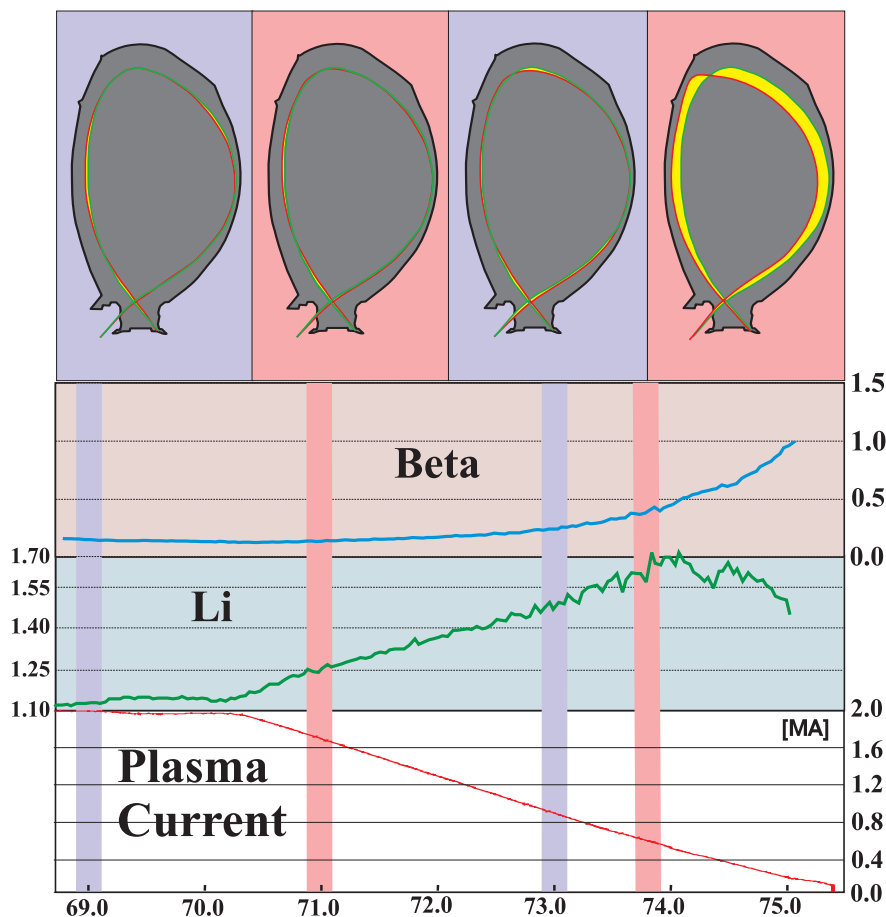


Figure 1. Performance of the XSC in the case of very significant variations of β_p , l_i and I_p . The yellow region indicates the distance between the target shape and the one really achieved by the controller

With regard to the controller implementation, the chosen approach identifies the principal directions of the algebraic mapping between coil currents and geometrical descriptors using the singular value decomposition (SVD). These principal directions can be translated into 8 linear combinations of currents, which represent one linear combination of geometrical descriptors each. Such an approach allows solving the original multivariable control problem using a set of separate PID controllers. To alleviate the burden on the actuators, the SVD orders the principal directions as a function of the current to shape sensitivity and normally only the first 5 or 6 directions (out of 8) are used. The control algorithm is optimized to obtain the most efficient distribution of the control currents, compromising between the effort of the actuators and the tracking error on the plasma shape.

As a consequence of this different approach, the XSC manages to achieve the desired shape with typically an average error of about 1cm on the 48 descriptors. An example of the capability of the XSC is reported in figure 1, which shows the difference between the desired and obtained shape for a quite extreme situation at the end of a JET discharge. The controller manages to keep the shape more or less constant even in the presence of large variations of β_p , l_i and also I_p . In general the XSC has already been tested successfully for variations Δl_i up to 0.5 and $\Delta\beta_p$ up to 1.5.

4. Control of profiles and ITBs in advanced scenarios

A linearisation approach has been adopted also for the control of the current and pressure profiles. The long term objective of this program consists of being able to sustain internal transport barriers (ITB) in high performance plasmas, with a large bootstrap current fraction and possibly to reach steady state operation ('advanced tokamak' program). In the case of these "advanced tokamak scenarios", the challenges to the control become particularly severe because the non-linear coupling between the pressure and current profiles is particularly involved, given the relevant fraction of bootstrap currents and the presence of ITBs. In order to have reasonable chances of success the plasma must be controlled on the time scale of both the current diffusion and the thermal evolution. Moreover, the adopted approach must preserve the distributed nature of the problem, because accurate control of the profiles must be achieved in order to properly influence the barriers. A linearised, model based, distributed control system was therefore adopted for the simultaneous control of the q and ρ^*T profiles [15].

The objective of the experiments reported in this paper consisted of demonstrating for the first time the feasibility of simultaneous combined control of the current and electron pressure profiles in presence of internal transport barriers. This was obtained with the distributed-parameter version of the theoretical method, in which the spatial current and pressure profiles were described by a suitable set of basis functions, 5 cubic splines and 3 piecewise-linear functions, respectively [13]. The designed multiple-input-multiple-output (MIMO) controller operates all the three available heating and current drive actuators (NBI, LHCD and ICRF) during the high power phase of the

discharge. The chosen scenario was a typical reversed shear configuration obtained with 2.5MW LHCD in the preheat phase during which the plasma current was ramped up to 1.7MA, at a line integrated plasma density about $3 \times 10^{19} m^{-2}$. The determination of the steady-state responses to variations of the heating and current drive powers was obtained from the analysis of four dedicated open loop discharges [13].

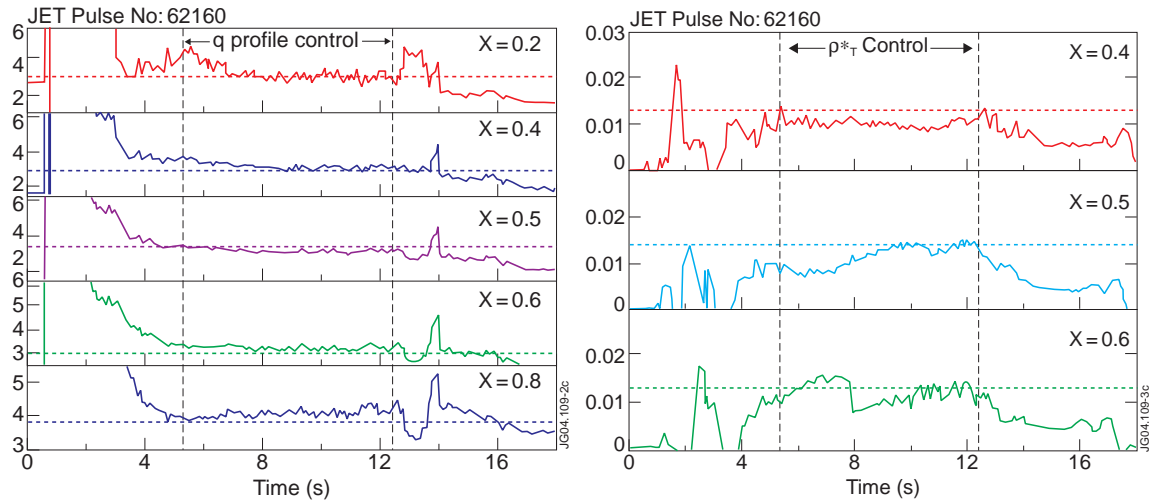


Figure 2. Time evolution of q toward the set points during the control phase. Right: Time evolution of ρ^*T toward the set points during the control phase

In figure 2a the time evolution of q at the five controlled points is reported, to show how the target values are properly achieved. The evolution of the ρ^*T profile in the controlled region is reported in figure 2b, from which it can be seen how the controller manages to force the plasma also toward this request, in parallel with the control of the current. A more intuitive representation of the relevant physical quantities is reported in figure 3 for the shot number 62527, in which a weak barrier was controlled in real time with a reversed shear profile. It must be mentioned that the control was achieved on time scales much shorter than the local resistive time, mainly due to the limitations of the actuators. So, even the profile control was demonstrated for the first time, the robustness of the approach will have to be confirmed by longer duration pulses.

The obtained stabilisation of a barrier for almost the entire shot and with two different q profiles is a very interesting result, which could have various applications in JET future experimental program. The robustness of the controller, with regard to ELMs and strong MHD activity is also an important aspect for JET and in ITER perspective.

5. Advanced computational techniques and technologies for real time control

The feedback schemes illustrated in the previous examples, even if they make use of sophisticated diagnostics and advance control algorithm, are all based on the

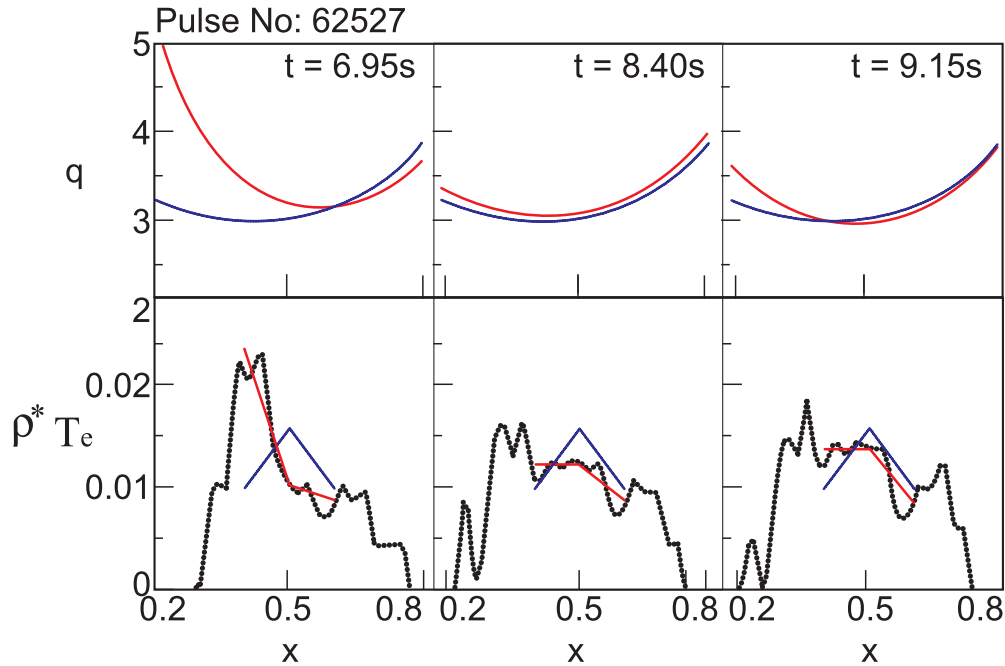


Figure 3. Control of a weak barrier in a reversed q profile discharge. The controller succeeds in both counteracting the current diffusion and moving the barrier in the more external region of the plasma

standard approach of linearisation. Moreover, to guarantee the necessary reliability, they also tend to rely on commercial technology. On the other hand, in many fields a lot of progress has been recently made in real time computational concepts and components and therefore more innovative solutions can be envisaged. In the present section, results of some new approaches using Digital Neural Networks (DNN) [10] and Cellular Neural/Nonlinear Networks (CNN) [11] are presented, to illustrate the potential applications of recent software developments and hardware technologies. These innovative computational approaches were applied to particularly difficult problems like tomographic reconstructions and fast image processing.

From the point of view of data analysis, tomographic reconstructions are considered a quite difficult issue in tokamak plasmas. In general tomographic inversions are ill posed problems, in the sense the more than one solution is compatible with the experimental data and this difficulty is strongly aggravated by the poor accessibility of fusion machines. Moreover, given the topology of the emission in JET, the relation between the total radiated power and the line-integrated measurements is a non-linear one. Therefore, due also to the computational complexity of the task, in order to obtain the total radiated power and the power emitted in the divertor in real time, it was decided to try specifically designed DNNs and train them using the total emitted power derived from the tomographic reconstructions. A multilayer perceptron, with one layer of hidden units trained with an error back-propagation learning algorithm, resulted more than adequate to the task. For the activation function a sigmoid was chosen, to make the DNNs nonlinear transfer functions. In addition to 28 bolometric

chords also three geometrical factors (elongation, upper and lower triangularities) were included in the set of inputs. The training set included about 2700 patterns for the divertor configuration and 250 patterns for the limiter configuration. The percentage of the DNN estimates that fall in the $\pm 20\%$ intervals, centered on the total radiation calculated with the tomographic reconstruction, is more than 90%. Within an interval of $\pm 10\%$ with respect to the tomographic inversion, which is a value comparable with the error bars of the method, fall almost 85% of the DNN estimates and comparable results are obtained for the evaluation of the radiation emitted in the divertor region.

In addition to the accuracy, also the generalization capability of the DNNs should be emphasized. As shown in figure 4, the designed DNN is capable of following the evolution of the total radiated power during ELMs, even if ELMs were not included in its training set. This constitutes a quantitative prove of the more general, even if qualitative result, i.e. that DNNs perform better than other possible linear methods particularly in the case of unusual and unforeseen situations, a fact which of course could be of great relevance in the perspective of ITER.

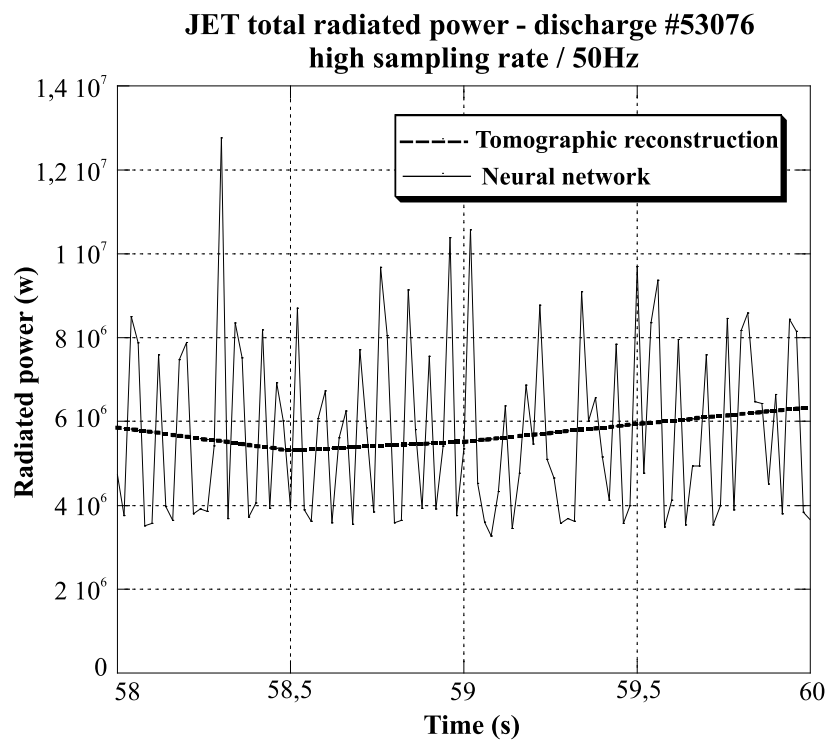


Figure 4. NN estimate of the total radiated power during ELMs

In current-generation tokamaks, the plasma shape is of primary importance not only for protection and control but also for achieving better fusion performance. The accurate localisation of the strike points on the divertor plates is essential to estimate the power load on the protection tiles, which affects the recycling properties of the configuration and bears strong consequences on operation safety. For many years, at JET the magnetic reconstruction of the separatrix done by the XLOC code has provided quite accurate and robust results. On the other hand, a known weakness of the magnetic

information is its vulnerability to non-contemplated deviations caused by eddy currents induced in the metallic structures by fast transients. Moreover, in the perspective of ITER, the long pulse mode of operation raises several questions about the stability of the magnetic measurements, which have not been tackled yet.

A possible alternative and/or support to the magnetic reconstruction approach could reside in the use of visual information, for example to identify the position of the strike points. In this perspective significant amount of work has been recently devoted to developing a technology capable of providing the localisation of the strike points from 2D sensors with adequate time resolution. Indeed one of the main difficulties of image processing for these applications is typically the need to obtain the required output on a millisecond time scale to follow fast phenomena like the ELMs. To meet these requirements, great attention has been devoted to the CNN technology. CNNs are two dimensional arrays of simple, identical, locally interconnected nonlinear dynamic circuits, called cells. These cells are arranged in a rectangular grid where each cell interacts with its nearest neighbours. In this way the CNN can implement suitable fast algorithms for image processing. The version of the chip tested at JET is a new generation 128x128 Focal-Plane Analog Programmable Array Processor (FPAPAP). Manufactured in a $0.35\mu\text{m}$ standard digital 1P-5M CMOS Technology. The chip, identified by the acronym ACE16K, contains about four millions transistors, 80% of them working in analog mode, with relatively low power consumption ($< 4W$, i.e. less than $1\mu W$ per transistor). The heart of the chip is an array of 128x128 identical, locally interacting, analog processing units designed for high speed image processing tasks requiring moderate accuracy (around 8bits).

Although ACE16K is essentially an analog processor (computation is carried out in the analog domain), it can be operated in a fully digital environment. For this purpose, the prototype incorporates a bank of Digital-to-Analog (for input) and Analog-to-Digital (for output) converters at the images I/O port. ACE16K is conceived for two alternative modes of operation. First, in applications where the images to be processed are directly acquired by the optical input module of the chip, and second, as a conventional image co-processor working in parallel with a digital hosting system that provides and receives the images in electrical form. This second operational mode is the only one tested so far at JET. The images of JET CCD visible camera (KL1 diagnostic, dynamical range of 8 bits, CCD-chip with 751x582 pixels), viewing the divertor in a nearly tangential geometry, were used as input (see fig.5). The information representative of the Strike point position can be derived by the brightness of the image. A suitable algorithm has been devised to extract the co-ordinates of the strike points from the camera images. A typical result is reported in figure 5.

The CNNs guarantee high speed and extreme accuracy in the detection of strong features in images, like the position of the strike points. The prospects of the image processing to capture the strike points look very promising. At the moment the main research is in the direction of investigating the maximum speed of the chip. With regard to the algorithms for the identification of the strike points, the preliminary comparison

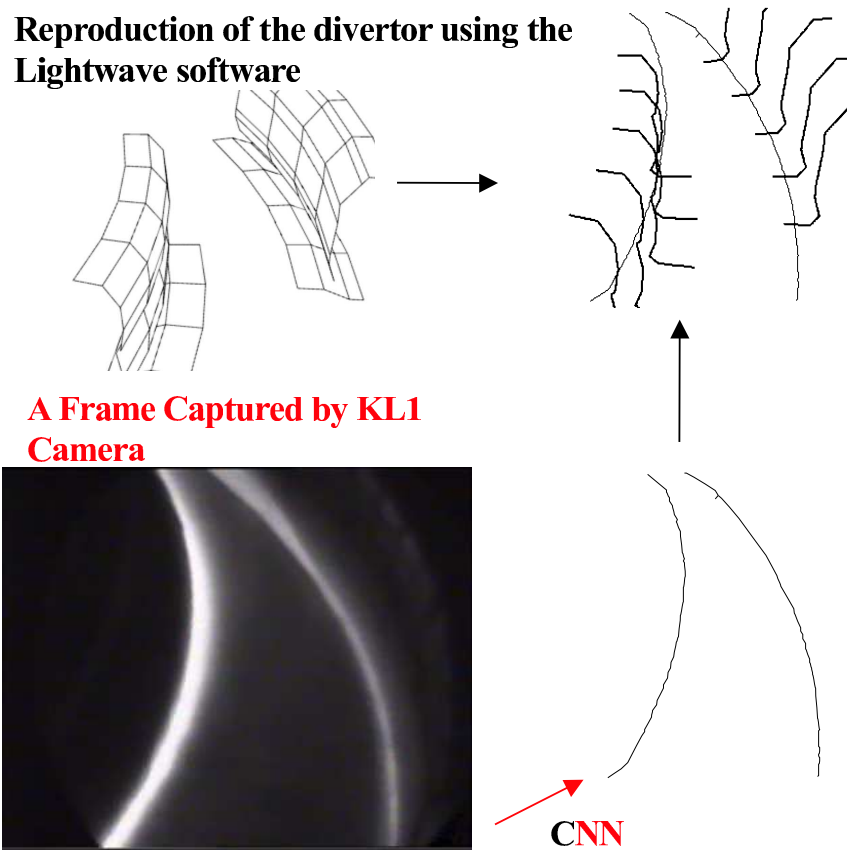


Figure 5. The approach used to determine the strike point position with the CNN

of the CNN results with the estimated of XLOC based on the magnetic measurements is more than satisfactory. The application of the same approach to infrared cameras, instead of the usual CCD for the visible, is also considered relatively straightforward, since the pixels of these sensors are normally read with CMOS circuits. In the reactor perspective, the main weakness of this technology resides in its low radiation hardness. Even if CMOS components are more robust than CCD the qualification of these 2D detectors for neutron fluxes of ITER level remains an open question and potentially an interesting field of research.

6. Conclusions and ITER prospects

JET real time control system nowadays includes a wide set of diagnostics, covering the magnetic configuration, the current profile and the main kinetic parameters of the electron and ion fluid. These measurements are complemented by other relevant tools, which provide derived quantities of major interest like the plasma position, shape and topology. The implemented multi-platform architecture, based on industry transmission standards, combines the desired flexibility with the robustness required by JET program. These new tools were an essential prerequisite of some of the most ambitious feedback

program at JET. The implementation of the XSC is not only extremely relevant for the next years experimental program but was also an unique opportunity to test ITER control techniques of the shape, based on calculating the plasma response models directly from equilibrium codes. The simultaneous control of the current and pressure profile constitutes one of the most significant programs on the route to the feedback control of ITBs. New and more advanced approached, based on soft computing, were also validated. Innovative technologies are also promoted, particularly in the field of real time imaging, which requires more advanced 2D sensors for some applications. From the technological and architectural point of view, the present JET real time control system seems therefore to provide a lot of useful information not only in support of the experimental program but also for the design of ITER.

The relatively recent but substantial experience gathered on feedback control at JET in the last years allows assessing which are the main requirements the diagnostics have to fulfil in general to become good candidates for real time. In order to use the measurement of a certain physical quantity in real time, an established method to measure it must be available. A sound interpretation of the data is essential and the information provided needs to be sufficiently closed to the plasma parameter to be controlled. In this respect, a good example of a difficult diagnostic to interpret is the MSE, if this measurement is to be used to control the q profile. Since the MSE is a local measurement whereas the definition of q is an average over a flux surface, delicate calculations are needed to derive the correct information for the control from the direct measurements [16]. Another delicate aspect of real time diagnostics is reliability, which is not limited to the hardware and basic interpretative software but has also to take into account possible disturbances from the environment. This means that the diagnostic must be robust enough to produce acceptable data even in case of major and unforeseen variations of the plasma parameters or the mode of operation (ELMs, limiter and divertor configurations etc). The calibration of the diagnostic is also a significant issue. An established procedure is necessary, which does not need to be carried out necessarily in real time but must be stable enough to guarantee meaningful outputs at least for the all discharge. The time constant of the measurement technique and the computational time necessary to interpret it have obviously also to be compatible with the plasma phenomena to be controlled. Given the rate of development of computers, it is very likely that in the perspective of ITER silicon technology, particularly if organised in parallel architectures, will be able to provide enough computational power even in the case of the most demanding diagnostics. On the other hand, for some essential parameters of interest for ITER physics and operation, no measurement technique is completely established yet. The most delicate field is certainly the one of burning plasma diagnostics. The measurements of the isotopic composition, the He ash, the slowing down and lost alphas require very significant efforts to identify the most suitable concepts even for providing reliable data, letting alone the real time aspects. In the case of neutrons, even if quite sound approaches have been tested at JET for the determination of the total yield, already available in real time, high-resolution spectrometry is still a

controversial issue. More work is certainly required in particular to identify solutions, which could provide basic information, like the yield of thermal neutrons, with the potential of providing $Q_{thermal}$ in real time. Other weaknesses of present day Tokamak diagnostics are certainly the measurement of the current density and temperature at the edge. For these quantities also a very high time resolution would be necessary, to be able to follow edge fast phenomena like the ELMs. One additional category of measurements very problematic for ITER are the diagnostics for the divertor. The temperature, erosion and redeposition of the divertor plates require significant developments of present techniques. Moreover the plasma parameters are going to be so extreme in ITER divertor that also the basic measurements of electron density and temperature are believed to be very difficult in that environment. In all these fields the identification of reliable methods are of course a prerequisite to attack the issue of providing the measurements in real time.

It must also be kept in mind that in ITER, a global control system, using all or almost all the available actuators (coils, gas injection, coolant, additional heating, tritium etc.), could become indispensable. In this respect, a lot of work remains to be done not only to significantly develop actuators and sensors, particularly in the direction of an increased reliability, but also in devising and testing "integrated" approaches, of both adequate complexity and realistic robustness.

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