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A. Murari, E. Joffrin, R. Felton, D. Mazon, L. Zabeo, R. Albanese, P. Arena,
G. Ambrosino, M. Ariola, O. Barana, M. Bruno, L. Laborde, D. Moreau,
F. Piccolo, F. Sartori, F. Crisanti, E. de la Luna, J. Sanchez
and JET EFDA contributors

# Development of Real-Time Diagnostics and Feedback Algorithms for JET in View of the Next Step

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A. Murari[1, 3], E. Joffrin[2], R. Felton[3], D. Mazon[2], L. Zabeo[3], R. Albanese[4],
P. Arena[5], G. Ambrosino[6], M. Ariola[6], O. Barana[1], M. Bruno[5], L. Laborde[2],
D. Moreau[2], F. Piccolo[3], F. Sartori[3], F. Crisanti[7], E. de la Luna[8], J. Sanchez[8]
and JET EFDA contributors*

*[1] Consorzio RFX—Associazione EURATOM ENEA per la Fusione, Corso Stati Uniti 4, I-35127, Padua, Italy*
*[2] Association EURATOM-CEA, CEA Cadarache, 13108 Saint-Paul-lez-Durance, France*
*[3] EURATOM/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
*[4] Assoc. EURATOM-ENEA-CREATE, Univ. Mediterranea RC, Loc. Feo di Vito, I-89060, RC, Italy*
*[5] Assoc. EURATOM-ENEA-CREATE, Univ. di Catania, Italy*
*[6] Assoc. EURATOM-ENEA-CREATE, Univ. Napoli Federico II, Via Claudio 21, I-80125 Napoli, Italy*
*[7] Associazone EURATOM ENEA sulla Fusione, C.R. Frascati, Italy*
*[8] Associacion EURATOM CIEMAT para Fusion, Avenida Complutense 22, E-28040 Madrid, Spain*
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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. Some of the signals now routinely provided in real time at JET are: (i) the internal inductance and the main confinement quantities obtained by calculating the Shafranov integrals from the pick-up coils with 2ms time resolution; (ii) the electron temperature profile, from electron cylotron emission every 10ms; (iii) the ion temperature and plasma toroidal velocity profiles, from charge exchange recombination spectroscopy, provided every 50ms; and (iv) the safety factor profile, derived from the inversion of the polarimetric line integrals every 2ms. With regard to feedback algorithms, new model-based controllers were developed to allow a more robust control of several plasma parameters.

With these newtools, several real-time schemes were implemented, among which the most significant is the simultaneous control of the safety factor and the plasma pressure profiles using the additional heating systems (LH, NBI, ICRH) as actuators. The control strategy adopted in this case consistsof a multi-variable model-based technique, which was implemented as a truncated singular value decomposition of an integral operator. This approach is considered essential for systems like tokamak machines, characterized by a strong mutual dependence of the various parameters and the distributed nature of the quantities, the plasma profiles, to be controlled. First encouraging results were also obtained using non-algorithmic methods like neural networks, which have been successfully applied to non-linear and ill-posed problems, for example the determination of the divertor radiated power.

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

## 1. INTRODUCTION

In the last few 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 tackled [1]. With regard to the scenarios, the ELMy H mode, in the continuous attempts to upgrade the performance 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 more and more every day on both the pressure and current profiles involved, posing non-negligible challenges to the control systems. The need to understand many unresolved issues, like the physics of ELMs or the formation and sustainment of Internal Transport Barriers (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 programme and to the more acute safety implications of a large 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 multi-variable, distributed control of profiles.

In nuclear fusion, as in any other field, the first step for 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 for identification falls mainly on plasma diagnostics. In the last few years, the main reasons 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 given by the LIDAR [3] and the interferometer, whereas the Electron Cyclotron Emission (ECE) [5] provides an electron temperature profile with a much higher time resolution than Thomson scattering. Active Charge Exchange Recombination Spectroscopy (CXRS) is of course the main means of deriving real-time information, temperature and velocity profiles, of the ion fluid [6].

A series of validated codes is also routinely used to obtain derived quantities. The internal plasma inductance $l_i$ and the derived confinement parameters are calculated from the Shafranov Development of real-time diagnostics for JET 397 integrals [7]. A new shape controller, called the eXtreme Shape Controller (XSC) [8] has already been used in highly shaped configurations, whereas an optimized equilibrium code EQUINOX [9] solves the Grad–Shafranov equation, taking into account internal magnetic measurements, like polarimetry, also on a finite element mesh instead of a regular grid like EFIT [10].

These new tools have been extensively used in the past few years and they contributed significantly to the scientific programme of the entire experiment. For example, they constituted an indispensable prerequisite for some of the most ambitious feedback programmes, like the simultaneous control of current and temperature profiles. These control schemes also made extensive use of JET actuators, like toroidal, poloidal and divertor coils, gas fuelling, neutral beam Injection and Radio Frequency (ICRH) and Lower Hybrid (LH) waves.

The JET real-time system is also a good environment to test innovative computational concepts—both software, like Digital Neural Networks (DNNs) [11], and hardware, like the new chip technology of Cellular Neural/non-linear Networks (CNNs) [12]. The information and experience gathered at JET in all the years of real-time development also provides a good basis from the perspective of ITER. The JET architecture and the general approach for implementing a distributed system could be successfully translated to ITER. On the other hand, in 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 this 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, relying heavily on the new real-time diagnostics and algorithms, are described in sections 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 ATMprotocol (asynchronous transfer mode [13]). This multi-platform approach (based mainly on the standards PCI and VME) offers several advantages, with respect to the mainframe, centralized solutions, which were more popular in the past 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 and the quantity of data to be processed in next step machines, for the implementation of fully integrated control strategies. It is, therefore, strongly believed that the JET approach can be considered to be a very good reference for ITER real-time control systems.

The flexible and adaptive architecture of the JET control system allowed us to includemany 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 in table 1.

From table 1 the remarkable progress of JET diagnostics in the direction of real time, which is not nowlimited to the traditional magnetic measurements for plasma positioning and control, can clearly be seen. 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 almost all the radial extent of the plasma, for most toroidal fields. The realtime 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 a 5ms time resolution. For the LIDAR system, the real-time approach consists of fitting the backscatter echo from the plasma to pre-calculated intensities, depending on the electron density and temperature. The system processes the data in almost the same way as the inter-shot code in less than 10ms, resulting in 50 point profiles at 4Hz (due to the 250ms repetition rate of the laser). The electron cycloctron emission data allows the determination of the $\rho^*T$ profile [14]. 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 from measurements of the Faraday rotation, using the flux surface topology obtained by the pick-up coils [4]. The last few years have also witnessed remarkable progress in diagnosing ion fluid, whose temperature and velocity are now routinely provided using CXRS [6]. In particular, the toroidal velocity is considered to be particularly relevant and it could be exploited much further in the future for very interesting feedback schemes, like the control of ion ITBs.

The performances shown were obtained thanks to significant improvements both in the hardware and the software. In the last few years many diagnostics have become more reliable Development of real-time diagnostics for JET 399 and communication technology has also witnessed dramatic progress. 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 ingredients which can normally give the desired results both in terms of accuracy and time resolution.

It is also worth noting that not only is a quite comprehensive set of signals available in real time at JET but, also, some fundamental derived quantities are calculated by optimized and reliable codes. All the basic confinement quantities, obtained from the Shafranov integrals [7], and the magnetic equilibrium from the magnetic measurements (EQUINOX code) [9], which are also reported in table 1, are particularly interesting.

## 3. CONTROL OF HIGHLY SHAPED PLASMAS

As mentioned in the introduction, the main motivations 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 the presence of strong variations of $\beta_{pol}$ and/or the internal inductance $l_i$. In this framework, a new controller, called the XSC [8] was explicitly designed and tested to improve the control of these highly shaped plasmas. In JET, eight actuators, namely eight 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 eight 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 separatrix X-point and the two strike points) and calculates the ‘smallest’ currents needed to minimize the error on the ‘overall’ shape in the least square sense.

The design of the XSC for JET single-null configurations is based on a linearized plasma model approach, implemented by theCREATE-L andCREATE-NL codes [15]. These plasmamodelling tools were specifically adjusted for JET topology, taking into account both the iron core and the eddy currents induced in the passive structures.

With regard to the controller implementation, the chosen approach identifies the principal directions of the algebraic mapping between coil currents and GAPs using the Singular Value Decomposition (SVD). These principal directions can be translated into eight linear combinations of currents, which represent one linear combination of GAPs each. Such an approach allows us to solve the original multi-variable control problem using a set of separate proportional integrative derivative (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 five or six directions (out of eight) 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 in 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 1 cm on the 48 descriptors. An example of the capability of the XSC is reported in figure 1, which shows the difference (the yellow band) 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 $\beta p$, $l_i$ and also $I_p$. In general, the XSC has already been tested successfully for variations $\Delta l_i$ up to 0.5 and $\Delta\beta_p$ up to 1.5.

## 4. CONTROL OF PROFILES AND ITBS IN ADVANCED SCENARIOS

A linearization approach was adopted for the control of the current and pressure profiles as well. The long term objective of this programme consists of being able to sustain ITBs in high performance plasmas, with a large bootstrap current fraction, and possibly to reach steadystate operation (‘advanced tokamak’ programme). 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 bootstrap currents fraction and the presence of ITBs. In order to have a reasonable chance 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 linearized, model based, distributed control system was therefore adopted for the simultaneous control of the q and $\rho^*T_e$ profiles ($\rho^*T_e$ is defined as $\rho_s/L_{Te}$ , where £ls is the Larmor radius and LTe the temperature gradient length) [16].

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 the presence of ITBs. 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, five cubic splines and three piecewise-linear functions, respectively [14]. 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 of about $3\times10^{19}$ $m^{-2}$.

The determination of the steady-state responses to variations in the heating and current drive powers was obtained from the analysis of four dedicated open loop discharges [14].

In figure 2(a) the time evolution of q at the five controlled points is reported, to show how the target values, the horizontal dashed lines, are properly achieved. The controller, acting in particular on the LHCD, manages to counteract the current diffusion and maintain the desired values of q. The evolution of the $\rho^*T_e$ profile in the controlled region is reported in figure 2(b), from which it can be seen how the controller manages to force the plasma also towards this request, in parallel with the control of the current. In the case of $\rho^*T_e$ the values at only three radial positions are shown because, since the aim of the experiment is to control ITBs, the spatial region of interest is more limited (around half of the minor radius, see figure 3). In any case, as already mentioned, for both quantities the choice of the radial points is in a certain sense arbitrary, since control was exerted on the entire profiles through their development as a series of basis functions. A more intuitive representation of the relevant physical quantities is reported in figure 3 for Pulse No: 62527, in which a weak barrier was controlled in real time for a discharge with a reversed shear profile. The q and $\rho^*T_e$ profiles are plotted versus the normalized radius at three different times during the feedback phase. From the top plots it is evident how the controller manages to stop the current diffusion and maintain a reversed shear profile. At the same time, it suppresses the spontaneous internal barrier and drives a smaller, more external one in agreement with the target 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, although profile control has been demonstrated for the first time, the robustness of the approach will have to be confirmed by longer duration pulses.

The obtained stabilization 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 the future experimental programme in JET. The robustness of the controller, with regard to ELMs and strong MHD activity is also an important aspect for JET and also from an 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 advanced control algorithms, are all based on the standard approach of linearization. Moreover, to guarantee the necessary reliability, they also tend to rely on commercial technology. On the other hand, in many fields, much progress has been made recently in real-time computational concepts and hardware components and, therefore, more innovative solutions can be envisaged. In the present section, the results of some  new approaches using DNNs [11] and CNNs [12] are presented, to illustrate the potential applications of recent developments in software 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 that more than one solution is compatible with the experimental data and that the final result is highly sensitive to small variations in the inputs. 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, because of 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 multi-layer perceptron, with one layer of hidden units trained with an error back-propagation learning algorithm, was more than adequate for the task. A sigmoid was chosen for the activation function, to make the DNNs non-linear transfer functions. In addition to 28 bolometric chords, three geometrical factors (elongation, upper and lower triangularities) were also 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 ±20% intervals, centred on the total radiation calculated with the tomographic reconstruction, is more than 90%. Within an interval of ±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, the generalization capability of the DNNs should also 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 proof 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 that could, of course, be of great relevance from the ITER perspective.

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 localization 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 has a strong bearing 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 unforeseen deviations caused by eddy currents induced in the metallic structures during fast transients. Moreover, from the ITER perspective, 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 to and/or support for the magnetic reconstruction approach could lie in the use of visual information, for example, to identify the position of the strike points. From this perspective, a significant amount of work has been recently devoted to developing technology capable of providing the localization of strike points from two-dimensional 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 non-linear 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 128×128 Focal-Plane Analogue Programmable Array Processor (FPAPAP), manufactured with a 0.35μm standard digital 1P-5M CMOS Technology. The chip, identified by the acronym ACE16K, contains about four million transistors, 80% of them working in analogue mode, with relatively low power consumption (<4W, i.e. less than 1μWper transistor). The heart of the chip is an array of 128×128 identical, locally interacting, analogue processing units designed for high speed image processing tasks requiring moderate accuracy (around 8 bits).

Although ACE16K is essentially an analogue processor (computation is carried out in the analogue domain), it can be operated in a fully digital environment. For this purpose, the prototype incorporates a bank of digital-to-analogue (for input) and analogue-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 a JET CCD visible camera (KL1 diagnostic, dynamical range of 8 bits, CCD-chip with 751×582 pixels), viewing the divertor in a nearly tangential geometry, were used as input (see figure 5). The information representative of the strike point position can be obtained from the brightness of the image. To this end, the algorithm implemented in the CNN performs the skeletonization of the image, extracting the line of maximum emission (strongest signal), which is assumed to correspond to the region of the strike points. A simplified digital version of the divertor topology, as seen from the camera and obtained using the standard software package Lightwave, is also available to the chip. A simple logic ‘OR’ operation, therefore, allows translation of the line of maximum emission into physical space. With this approach, it has already been possible to determine the outer strike point position with an estimated accuracy of 1cm and a time resolution of 10ms. A typical result is reported in figure 5, showing how the CNN manages to identify the location of the strike points in the physical space of the divertor. For the inner strike point position, the approach is a bit more problematic but only as a result of the camera view, which is not optimized for this purpose.

The CNNs guarantee high speed and extreme accuracy in the detection of strong features in images, like the position of the strike points. Currently, most of the research is directed towards investigating the maximum speed of the chip. With regard to the algorithms for the identification of the strike points, the preliminary comparison of the CNN results with the estimated 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. From the reactor perspective, the main weakness of this technology lies in its low radiation hardness. Even if CMOS components are more robust than CCD, whether these two-dimensional detectors are suitable for ITER level neutron fluxes remains an open question and a potentially interesting field of research.

## CONCLUSIONS AND ITER PROSPECTS

The 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 fluids. 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 the JET programme. These new tools were an essential prerequisite for some of the most ambitious feedback programmes at JET. The implementation of the XSC is not only extremely relevant for the experimental programme in the coming years but is also a 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 profiles constitutes one of the most significant programmes on the route to the feedback control of ITBs. New and more advanced approaches, based on soft computing, were also validated. Innovative technologies are also promoted, particularly in the field of real-time imaging, which requires more advanced two-dimensional sensors for some applications. From the technological and architectural point of view, the present JET real-time control system seems, therefore, to provide much useful information not only in support of the experimental programme but also for the design of ITER.

The relatively recent but substantial experience gathered on feedback control at JET in the last fewyears allows us to assess 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. Sound interpretation of the data is essential and the information provided needs to be sufficiently close 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 [17]. Another delicate aspect of real-time diagnostics is reliability, which is not limited to the hardware and basic interpretative software, but also has to take into account possible disturbances from the environment. This means that the diagnostic must be robust enough to produce acceptable data even in the 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 all the discharge. The time constant of the measurement technique and the computational time necessary to interpret it obviously also have 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 organized in parallel architectures, enough computational power can be provided, 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 has been completely established yet. The most delicate field is certainly that of burning plasma diagnostics. The measurements of the isotopic composition, the He ash, the slowing down and lost alphas require concerted efforts to identify the most suitable concepts even for providing reliable data, let 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 $Q_{\text{thermal}}$ 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 a very high time resolution would also be necessary, to be able to follow edge fast phenomena like the ELMs. One additional category of measurements that is very problematic for ITER is the diagnostics for the divertor. The temperature, erosion and re-deposition of the divertor plates require significant development of currently available techniques. Moreover, the plasma parameters are going to be so extreme in the ITER divertor that even 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 is of course a prerequisite to tackle 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 ofwork 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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| **Physics** | **Diagnostics** | **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 |
| $\gamma$ (R) | MSE | 25 | 2 |
| LID | FIR | 8 | 2 |
| FAR | FIR | 8 | 2 |
| LCFS | XLOC | 100 | 2 |
| $\gamma$, $l_i$ | 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 | Neuronics | 1 | Analog |
| Hard Xray | Neuronics | 1 | Analog |
| Density | FIR | 1 | Analog |

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

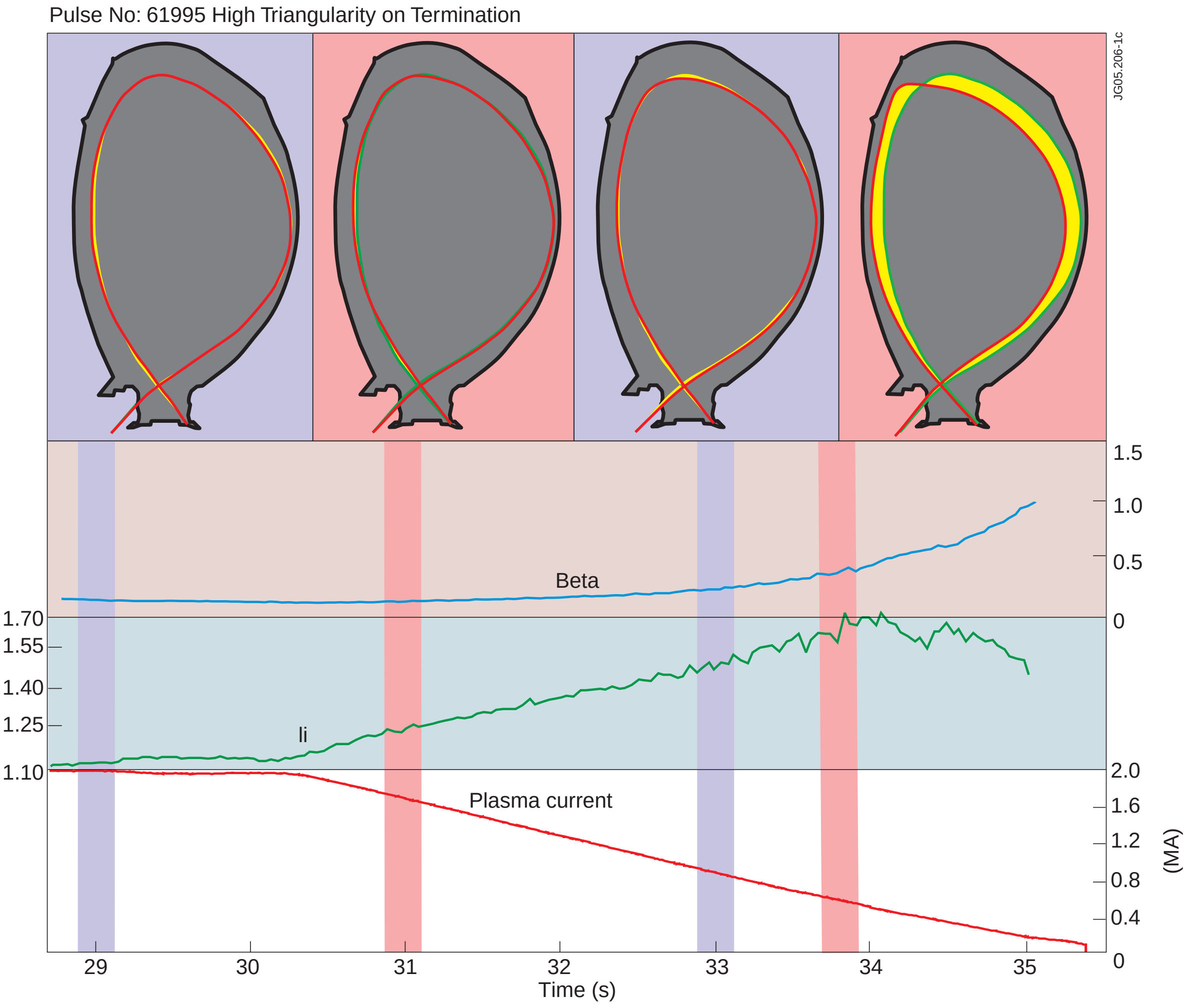

*Figure 1. Performance of the XSC in the case of very significant variations of $\beta_p$, $l_i$ and $I_p$. The yellow region indicates the distance between the target shape and the one really achieved by the controller.*

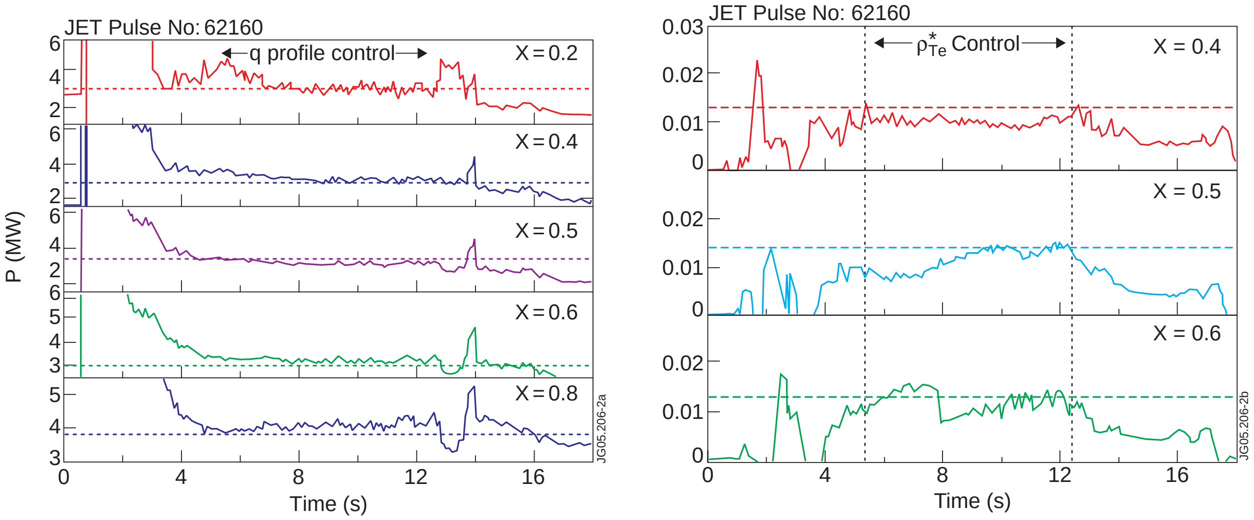

*Figure 2. Left: Time evolution of q towards the set points during the control phase at five radial positions. Right: Time evolution of $\rho^*_{Te}$ towards the set points during the control phase at three radial positions. In the various plots X is the radial position in terms of the normalized radius r/a. The horizontal dashed lines indicate the target values and the vertical dashed lines identify the period during which the feedback control is active.*

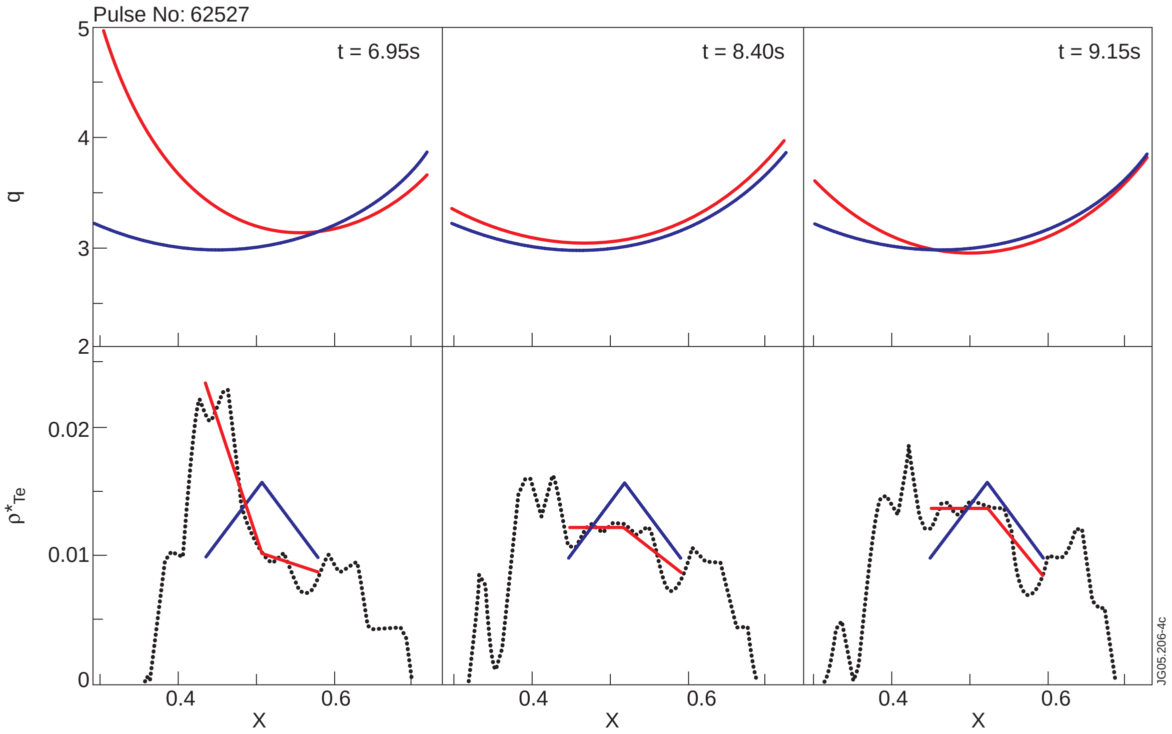

Figure 3. Control of a weak barrier in a reversed q profile discharge. X represents again the normalized radius r/a. In the top graphs the blue lines indicate the target values and the red ones the measured q profiles. In the bottom graphs the blue lines are again the target, the black ones the measured profiles and the measured profiles (in red) are expressed in terms of Galerkin coefficients, to emphasize the effectiveness of the control scheme. The controller succeeds in both counteracting the current diffusion and moving the barrier into the more external region of the plasma.

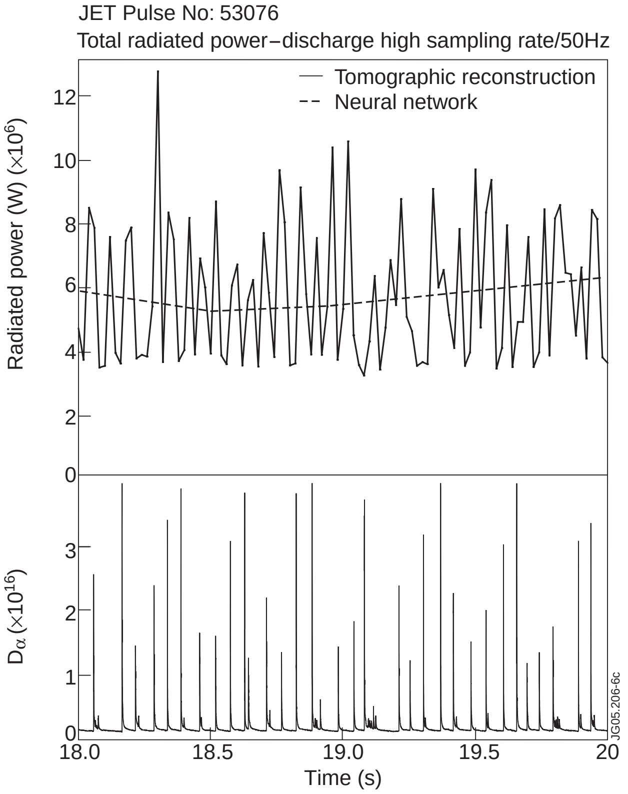

Figure 4. Top: NN estimate of the total radiated power during ELMs. Bottom: $D_\alpha$ signal.

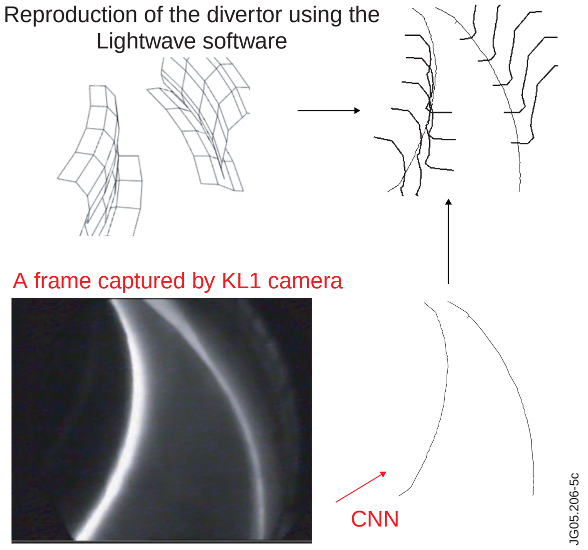

Figure 5. The approach used to determine the strike point position with the CNN.