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# Using Magnetic Diagnostics to Extrapolate Operational Limits in Elongated Tokamak Plasmas

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(Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

**ABSTRACT**

Tokamaks are the most promising approach for nuclear fusion on earth. They are toroidal machines where the plasma is heated in a ring-shaped vessel and kept away from the vessel by applied magnetic fields. To achieve high performance in tokamaks, plasmas with elongated poloidal cross-section are needed. Such elongated plasmas are vertically unstable, hence position control on a fast time scale is clearly an essential feature of all machines. In this context the Plasma Control Upgrade (PCU) project was aimed at increasing the capabilities of the Vertical Stabilization (VS) of the JET tokamak. This paper introduces the new JET VS system and focuses on how the flexibility of this real-time system has been exploited to enlarge its operational limits in terms of maximum controllable disturbance. Moreover, the experiments recently carried out at JET are presented.

## 1. INTRODUCTION

One of the main challenges in a modern tokamak device [1] [1] is to operate with very highly elongated plasma in presence of large perturbations, i.e. large Edge Localized Modes (ELMs) [3]. In this context, the Plasma Control Upgrade (PCU) project [4] was aimed at increasing the capabilities of the Vertical Stabilization (VS) system at the JET tokamak [5] (see Fig.1), in particular to recover from large ELM perturbations, when operating with highly elongated plasmas, characterized by large vertical instability growth rates.

In this paper, after providing a brief introduction to the PCU project, we focus our attention on the performance of the new VS system in terms of the maximum controllable ELM frequency and energy. In particular, we focus the attention on how the flexibility of this real-time system has been exploited to enlarge the system operational limits.

The paper is structured as follows: a brief description of the PCU project is given in the next section. Afterwards, hardware and software architectures of the JET VS system are described in Section III. ELM physics and their effects on VS system are briefly introduced in Section IV. Section V presents the limits of the new VS system in terms of plasma configurations and diamagnetic energy drop during a phase of MHD instability.

## 2. THE PCU PROJECT

The main objectives of the PCU project are hereafter summarized:
- the conceptual design of the new power supply, namely Enhanced Radial Field Amplifier (ERFA[6]), for the radial field circuit, to assess the system performance for different choices of the maximum amplifier voltage and current;
- the assessment of the best choice for the turns setup of the poloidal field coils used for vertical stabilization;
- the design of the new VS control algorithm, to optimize the controller parameters for the different operative scenarios provided by the physicists;
- the enhancement of the software and hardware architecture for the control and data acquisition system [7].

1

In particular, the new ATCA based hardware provided access to state of the art technology and processing power, enabling the simultaneous acquisition of almost 200 channels at 2MHz driven by the new multi-core CPU technology.

Taking advantage of the capability of the new hardware architecture, a set of closed loop simulations and experiments have been performed to assess the optimal parameters of the VS system defining its limits in terms of plasma configurations and diamagnetic energy drop during a phase of MHD instability.

## 3. VERTICAL STABILIZATION SYSTEM AT JET

In this section we present the new VS system recently deployed at the JET tokamak. In particular, Section III-A introduces the new plasma velocity estimation that has been adopted within the PCU project. The software and hardware architecture of the VS system are introduced in Section III-B, while in section III-C the closed-loop simulator that has been used to test and validate the VS behaviour is described.

In most modern tokamaks, the plasma has a poloidal crosssection that is vertically elongated, *D*-shaped, and hence vertically unstable. In JET, the combined action of the iron polar expansions and the various shaping coils produce a magnetic field structure that is designed to stretch and shape the plasma, allowing both better filling of the vacuum chamber and obtaining better fusion performance.

Since elongated plasmas are vertically unstable, if no corrective action is taken, in a fraction of a second the hot gas column moves vertically until it reaches the vessel protecting tiles. The plasma then rapidly shrinks and eventually disruptsdischarging all its energy to the machine structures imparting large impulsive forces.

As shown in Fig.2 the VS controller is manly composed of three parts. The velocity loop removes the plasma unstable pole, the current loop keeps the ERFA current close to a reference value and operates on a lower time scale and the adaptive controller slowly changes the controller parameters so that to make VS able adapt to large variations in system parameters.

Since the plasma vertical velocity cannot be directly measured, an estimator is required. Such an estimator computes plasma vertical velocity starting from a set of magnetic measurements. The main requirement of the VS system is to stabilize the system, and the task of keeping the plasma in its nominal configuration is left to a shape control system that operates on a longer time scale (more details can be found in [5] [5]).

The VS system uses 32 magnetic measurements, coming from sets located in four different octants (Figs. 3-4), each including 18 internal discrete coils (tangential field sensors), situated inside the vacuum vessel and 14 saddle loops, namely CX1, …, CX18, SX1, …, SX14 where X = 1, 3, 5, 7 depending on the octant. These diagnostics were originally utilized to estimate the vertical plasma velocity by means of the following relationships:

$$\frac{dI_p}{dt} = \frac{1}{\mu} \oint \frac{dB_t}{dt} \, ds \approx \sum_{k=1}^{Nmag} w_{0k} \approx m_k \tag{1}$$

2

$$\frac{d(Z_pI_p)}{dt} = \frac{1}{\mu} \oint \left[ Z\,\frac{dB_t}{dt} - R\log\left(\frac{R}{R_0}\right)\frac{dB_n}{dt} \right] ds \approx$$

$$\approx \sum_{k=1}^{Nmag} w_k \approx m_k \tag{2}$$

where $I_p$ is the plasma current, $Z_p$ the vertical position of its centroid, $R$ and $Z$ are the radial and vertical coordinates, respectively, $R_0$ is the major radius of the chamber, $N_{mag}=32$, while $B_t$ and $B_n$ are the tangential and normal components of magnetic flux density, respectively.

Using the $N_{mag}$ magnetic measurements $mk$ of time derivatives of magnetic fields, the line integrals (1)-(2) can be approximated as linear combinations of these signals with suitable weights $w_{0k}$ and $w_k$. After the introduction of the divertor coils D1-D4 and the installation of MK2 conducting structure inside the vessel, the magnetic measurements coming from magnetic field sensors placed on the lower part of the machine are not only behind currents flowing inside the vessel, but also significantly affected by the noise of the amplifier. The pick-up coils in the lower region were then discarded, and the remaining weights were readjusted. The resulting combination provides a rough estimate of (2) at slowly varying plasma current, denoted as ZPDIP, which is obviously inaccurate. Nonetheless, the VS system successfully works with feedback on ZPDIP, which is an output correlated to the unstable mode.

### 3.1. AN ALTERNATIVE VERTICAL VELOCITY ESTIMATOR

This subsection describes an alternative controlled variable that has been designed to increase the performance of the VS system during the H mode phase. The design of the new vertical velocity estimator has been performed thanks to the new ATCA-based hardware that permits to simultaneously acquire almost 200 channels at 2MHz.

The standard VS controlled variable used during JET operation use only the first nine pick-up coils (Fig.3) placed on the upper part of the machine.

In the future, a full replacement of JET first wall materials is planned, with beryllium in the main wall and tungsten in the divertor region [8]. This has a potential impact on the diagnostics and control of JET vertical stabilization system, because the shielding effect might become dramatic for the sensors placed behind the dump plates (CX05 and CX06).

A new VS controlled variable OBS05 has been designed so as to avoid the contribution of the magnetic signals coming from the sensors placed behind the dump plates and have scarce sensitivity to ELMs and fast plasma movements that are not expected to excite the unstable mode, e.g. radial motion.

Thus, the OBS05 weights were selected by imposing the following constraints:
- zero weights for the sensors placed behind the dump plates (CX05 and CX06) to avoid a shielding effect;
- zero weights for the sensors located in the lower part of the vessel (from CX10 to CX18), i.e. the same weights as ZPDIP, thus avoiding the shielding effect of divertor conductors and having low sensitivity to divertor kicks;
- same weights as ZPDIP for the saddle fluxes SX01 to SX14.

Moreover, OBS05 weights were selected so as to the same response as ZPDIP to the ERFA voltage in all normal operating conditions and Vertical Displacement Events (VDEs). Thus, it was not necessary to redesign the controller algorithm.

Finally, to improve the capabilities of the VS system, attention was paid so as to get a better response to an ELM and be less sensitive to the divertor switching power supply noise at 300Hz [9].

### 3.2. SOFTWARE AND HARDWARE ARCHITECTURE

The new VS control system is based on the Multi threaded Application Real-Time executor (MARTe [7]). This system represents the first *MARTe based* control system that has been successfully developed and deployed at JET. Within the MARTe environment, the end users are required to define and implement algorithms inside a well defined software block named *Generic Application Module* (GAM), which is executed by the real-time scheduler. The JET VS system has been implemented by using MARTe under the Real Time Application Interface (RTAI)/Linux operating system [10]. Thanks to this choice it has been possible to exploit the multiprocessor ATCA based hardware architecture [11]. A functional block diagram of the overall VS system software architecture is shown in Fig. 5. The different modules are synthetically described following:

- *ATCA-ADC:* manages the inputs to the VS cubicle from other JET subsystems that are acquired via ADCs;
- Signal Processing GAM (SPGAM): computes the reference waveforms for the control loops;
- *Observer GAM*: computes up to ten different estimations of the plasma vertical velocity;
- *Controller GAM*: allows to fix all the controller parameters, contains four different control algorithms, and computes the voltage reference to the power supply;
- *Scheduler GAM*: allows scheduling the experiment because every JET discharge is logically divided into a number of *time windows*. In each time window, all control algorithms receive all the plasma velocity estimations;
- *Vertical Amplifier Manager GAM* (VAMGAM): is based on the signals received from the *Scheduler GAM* and can also perform several additional functions;
- *Divertor Amplifiers Manager GAM* (DAMGAM): sends the voltage requests to the divertor power supplies.

As for the computational delay introduced by the software, all the modules are executed within 50μ*s*. The exact time at which the reference is sent to the amplifier varies accordingly to the enabled features in the different parts of the experiment, but it is always bounded by the 50μ*s* figure. The synchronization mechanism guarantees that the software is always ready and waiting for a new set of samples, with an error in the order of the hundreds of nanoseconds.

### C. VS SIMULATOR

Thanks to the modularity of MARTe framework by adding different modules it is possible to implement a complete closed-loop simulator that allows studying the VS behaviour. In particular

as shown in Fig.5 the three GAMs depicted in yellow have been specifically developed to simulate the plant. The state–space model GAM allows to simulate the plant behaviour by receiving the voltage applied by ERFA as input, and produces the estimation of the plasma vertical velocity and the amplifier current as output. The state–space can be provided by using the CREATE–L [12]. Additional inputs that are not modified by the closed–loop are simulated with a GAM able to generate waveforms. The third module simulates hysteretic characteristic of ERFA and adds some noise to simulate a real acquired signal. This simulator has been very useful during the VS software commissioning and to asses the VS parameters. In Section V is described how this simulator has been useful to study the operational limits of the VS system.

## 4. EDGE LOCALIZED MODES AND THEIR EFFECTS ON VERTICAL STABILIZATION SYSTEM

Edge Localized Modes (ELMs) are very strong localized MHD plasma instabilities. They manifest themselves as strong magnetic perturbations associated with a burst of D-alpha radiation and a loss of particles and energy from the plasma periphery. The phenomenon is roughly periodic with an intensity which is inversely proportional to the period. Energy pulses of more than 1 MJ can be discharged by the plasma at a rate of about 1Hz. This phenomenon is to some degree understood, but the lack of accurate measurements means that the exact details of what happens to the plasma are not known.

The following classification of ELMs is now standard:

- *Type I ELMs*: the D-alpha radiation shows large isolated bursts and, therefore, Type I ELMs are also called 'large' or even''giant' ELMs. Ideal MHD models can be used to explain the instability, which is driven by a combination of edge pressure and current.', and as the heating power is increased, the ELM repetition frequency also increases. The degradation of the plasma confinement is smaller than with other ELM types.
- *Type II ELMs*: these are observed only in stronglyshaped plasmas, i.e. with high elongation and triangularity of plasma cross-section. Also the plasma density needs to be rather high. The magnitude of the ELM bursts is lower and the frequency is higher than that of type I ELMs, while the confinement stays almost as good. Type II ELMs are often called 'grassy' ELMs.
- *Type III ELMs*: the bursts are small and frequent. Therefore, another name for type III ELMs is 'small' ELMs. The ELMs repetition frequency is found to decrease with the increasing heating power.

Because an ELM event is a variation of internal pressure and a perturbation of the magnetic field it is related to a variation of poloidal beta and internal inductance:

$$\beta = \frac{4}{R\mu_0 I_p^2} \int p dV \qquad li = \frac{4}{R\mu_0 I_p} \int \frac{B_p^2}{2\mu_0} \, dV$$

Moreover an ELM event is characterized by a loss of the diamagnetic energy that is strictly related

to a variation of poloidal beta and the relationship is given by [13]:

$$\Delta W = \frac{3}{8}\ \mu_0 R_0 I_p^2 \Delta\beta$$

Because the perturbation affects the magnetic fields creating a strong variation in the plasma speed measurement, the VS sees an ELM as a rapid increase of plasma speed followed by a rapid inversion and a slower decay. This causes the firing of ERFA and a resulting vertical excursion of the plasma, in some cases associated with loss of control.

For these reason it is very important to characterize the behaviour of the VS system in term of type I ELMs. Moreover because an ELM event is a fast phenomena, a fast acquisition of the magnetic signals is needed.

## 5. OPERATIONAL LIMITS OF THE VERTICAL STABILIZATION SYSTEM

This section describes the analysis and the experimental tests carried out to study the behaviour of the VS system when it is stressed by type I ELM. The first subsection provides a brief introduction of the analysis, while the second subsection describes the experimental behaviour of the system and reports a discussion on the main results.

### 5.1. SIMULATION ANALYSIS

As mentioned earlier an ELM event creates a strong variation in the plasma speed measurement. From the viewpoint of the VS system an ELM event, being a variation of poloidal beta and internal inductance, can be schematized as a disturbance for the system. In particular, by using CREATE-L model, a representation of the plant behaviour is given in the state space form. A characterization of ELMs by means of poloidal beta and internal inductance variations has been carried out via simulation. In particular the identification has been performed by using both experimental magnetic signals and CREATE-L model. As shown in Fig.7, two different identification procedures have been adopted to indentify the time derivative of poloidal beta and internal inductance, both multiplied for the plasma current:

- *Unconstraint procedure ($d(\beta I_p)_u/dt$, $d(l_i I_p)_u/dt$):* identified so as to fit both ZPDIP and Obs05 experimental data in simulations with the CREATE-L model giving VERFA, $d(\beta I_p)_u/dt$, $d(liIp)u/dt$ in input;
- *Constraint procedure ($d(\beta I_p)_c/dt$, $d(l_i I_p)_c/dt$):* obtained as linear combinations of *n=2* and drift compensated VS pickup coil signals 1 to 9, so as to fit $d(\beta I_p)_u/dt$, $d(l_i I_p)_u/dt$ so as to remove the drift of $\beta I_p$ and $l_i I_p$.

By considering the identified quantities as disturbances for the system the closed loop simulations have been performed by using MARTe simulator (described in Section III.C). In particular, as shown in Fig. 8 the input of the system are the amplifier voltage VERFA and the identified quantities, instead the output are the amplifier current IERFA and the estimation of the vertical velocity ZPDIP. Thanks to these simulations it has been possible to find the maximum controllable ELM by

multiplying the disturbances for a factor a Since the poloidal beta and internal inductance variations are strictly related to a loss of diamagnetic energy, with this simulations we are able to find the maximum controllable ELM from the VS system in term of maximum diamagnetic energy loss.

## 5.2. RESULTS AND EXPERIMENTAL TESTS

The controlled variable OBS05 was finally tested during the H-mode phase. The behaviour of OBS05 was better than ZPDIP. This is demonstrated by the experimental data collected in the ELMy phases of Pulse No: 78666. The average excursion of ERFA current was about 40% less in Pulse No: 78666 before 16.5 s, i.e., when OBS05 is the feedback variable (Fig. 9). The new controlled variable OBS05 was successfully tested in JET experimental campaigns on a variety of plasma scenarios and was then used as preferred VS controlled variable.

As for the performance of VS system in the presence of big ELMs, the following points have been assessed.

The tolerable $\beta$ drop ($\Delta\beta$) scales with $1/I_p$, whereas the tolerable energy drop ($\beta W \propto \Delta\beta \leq I_p^2$) scales with $I_p$. ELM transients are characterized by fast dynamics (hundreds of μs) followed by a slow $\beta$ drop (tens of ms).

In Pulse No: 78452 with $I_p=3MA$, and a relatively high growth rate of the vertical instability ($\gamma=200\ s^{-1}$), the VS system tolerated a considerable energy drop ($|\Delta W|>1.5MJ$) with an excursion of the ERFA current ($|\Delta I_{ERFA}| = 2.5kA$) well below its operational limit. Simple extrapolations based on scaling laws and more accurate simulations based on the CREATE-L model (Fig.10) show that the tolerable energy drop for a 4 MA plasma would have been well beyond 2MJ, with a dramatic improvement with respect to the previous VS system with the old radial field amplifier FRFA.

## CONCLUSIONS

Thanks to the new ATCA based hardware a simultaneous acquisition of almost 200 channels at 2MHz is enabled, making possible to compute compensated magnetic measurement reducing the effect of high frequency noise.

The modularity of real-time the software architecture of the Vertical Stabilization allows us to implement a closed loop test-bench where the plasma behaviour is simulated with a state-space model given by CREATE-L code.

The high resolution and the reduction of the noise of the experimental signals allows us to study an alternative estimator of the vertical velocity that guarantee a lower current excursion during an ELM phase.

A characterization of the operational limit in term of maximum controllable ELM and energy has been carried out. The results show that after the enhancement of the VS system and of the vertical field amplifier the maximum tolerable energy drop increases when compared to the old system.

## ACKNOWLEDGMENT

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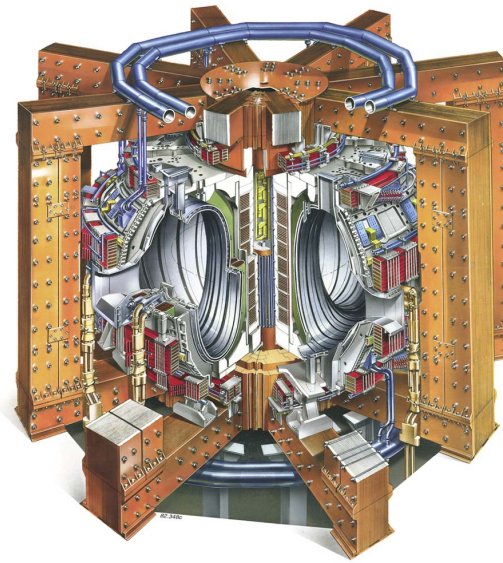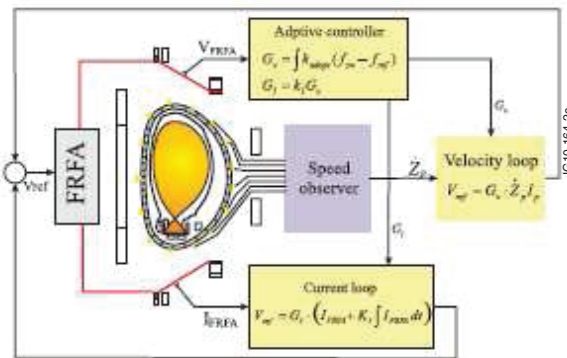
*Figure 1: 3D view of the JET tokamak.*



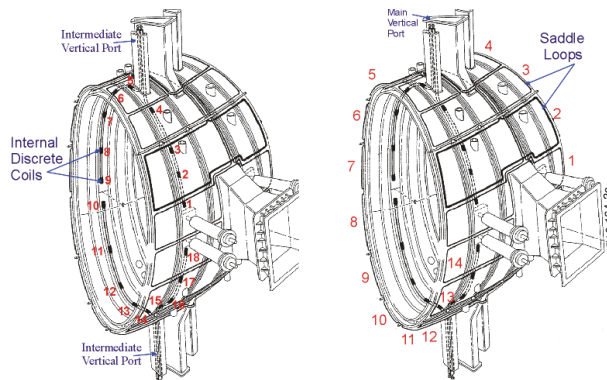*Figure 2: VS controller block diagram.*



*Figure 3: Poloidal cross sections with the location of the pick-up coils (left) and saddle loops (right).*
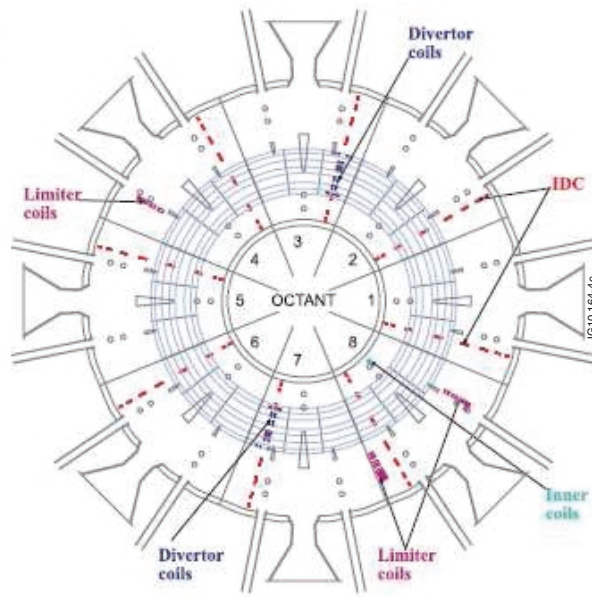
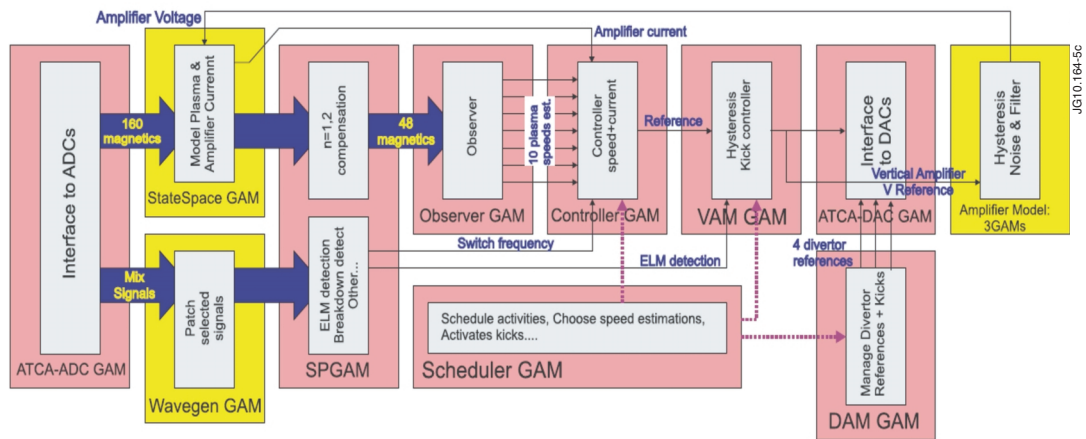*Figure 4: Top view of the JET tokamak with the toroidal locations of coil sets.*



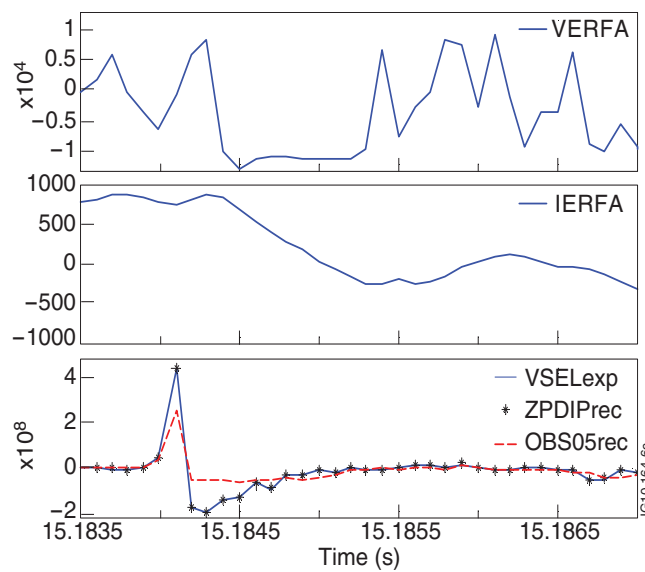*Figure 5: Block diagram of the VS software architecture*



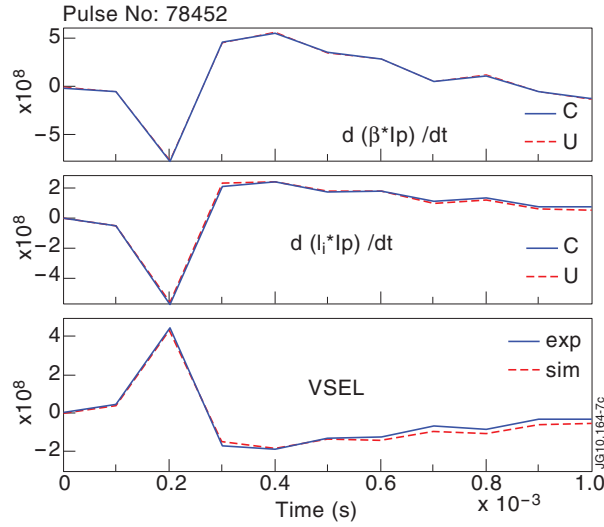*Figure 6: Effect of an ELM event on the VS parameters.*

**Pulse No: 78452**

x10⁸ ... d (β*Ip) /dt — C, U

x10⁸ ... d (lᵢ*Ip) /dt — C, U

x10⁸ ... VSEL — exp, sim

Time (s) x 10⁻³

JG10.164-7c

*Figure 7: Different procedures (constraint end unconstraint) for the identification of the disturbances: poloidal beta and internal inductance. The third plot shows the comparison between the experimental and the simulated vertical velocity estimation that is used as feedback.*
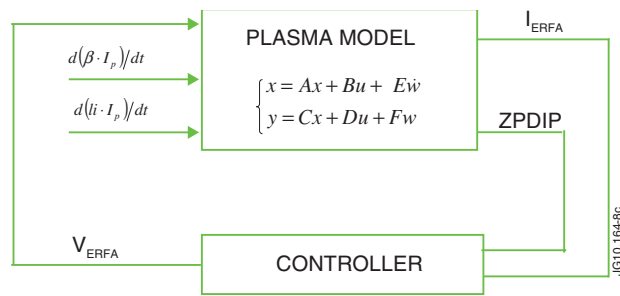
$d(\beta \cdot I_p)/dt$

$d(li \cdot I_p)/dt$

PLASMA MODEL

$$\begin{cases} \dot{x} = Ax + Bu + E\dot{w} \\ y = Cx + Du + Fw \end{cases}$$

$I_{ERFA}$

ZPDIP

$V_{ERFA}$

CONTROLLER

JG10.164-8c

*Figure 8: Closed loop simplified scheme*

**Pulse No: 78666**

$D_\alpha$ (s⁻¹cm−2 sr⁻¹)

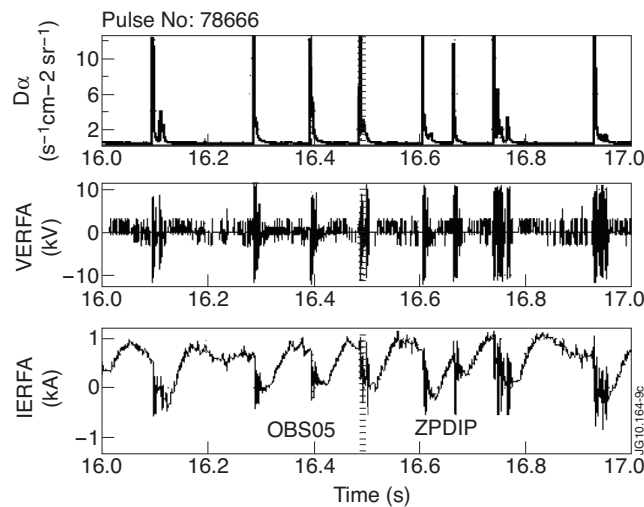VERFA (kV)

IERFA (kA)

OBS05   ZPDIP

Time (s)

JG10.164-9c

*Figure 9: Experimental tests of OBS05 in closed loop in Pulse No: 78666 before 16.5s: $D_\alpha$, radial field amplifier voltage and controlled variables. With OBS05 the stability is preserved and the radial field circuit current excursion is considerably smaller.*
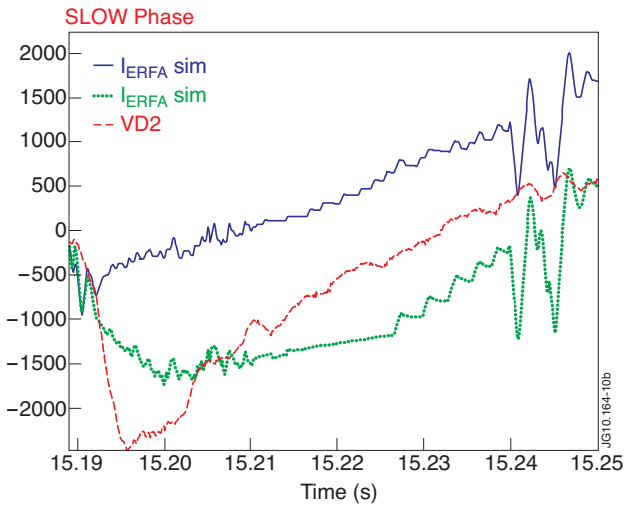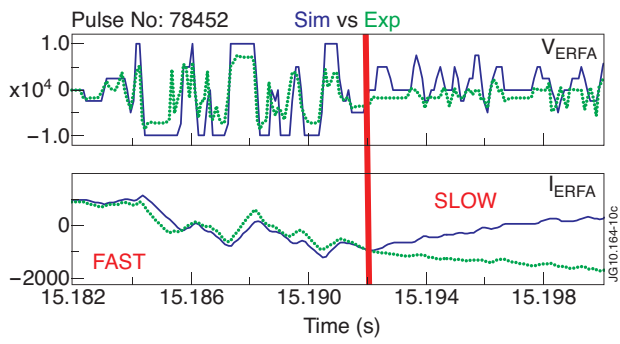
11

*Figure 10: ERFA current and voltage during an ELM in Pulse No: 78452: simulation versus experiment. (a) The agreement is fairly good in the fast phase where the action of shape controller can be neglected. On the contrary during the slow phase there is a strong action of the shape controller. (b) is the zoom of the slow phase and the red line is the divertor coil voltages requested by the shape controller.*