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Exploitation of Modularity in the JET Tokamak Vertical Stabilization System

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Abstract— **The Vertical Stabilization system of the JET tokamak has been recently upgraded. This new system enables a more sensitive control of the plasma geometry and can withstand larger perturbations, enabling scientists to push the plasma performance to its limits without risking a severe control loss, which might endanger the machine integrity. The project was successfully delivered in the course of 2010. This paper briefly introduces the new JET Vertical Stabilization design, discussing how its modular architecture enabled the system to provide different experimental features in several operational environments. Furthermore, some of the major achievements of the commissioning activity and of the regular operation during the last experimental campaign are presented.**

Keywords: Tokamak control, vertical stabilization system.

I. INTRODUCTION

The research in the nuclear fusion field aims at providing a complementary source for alternative energy. In particular, tokamak devices have been proved to be suitable devices to achieve magnetic confinement of plasma [1].

In a tokamak reactor, plasma is formed into a vacuum chamber (the *vessel*), and several magnetic fields are applied to confine the plasma. The dominant one, the toroidal magnetic field, is generated by a set of coils named Toroidal Field coils. However, a plasma placed in such a field cannot come to an equilibrium force balance [2]. For this reason an additional magnetic field component should be added to confine the plasma. In the tokamak configuration this difficulty is overcome by passing a toroidal current through the plasma itself.

The combined (toroidal and poloidal) magnetic field is helical. Another component is added to the plasma generated poloidal field by means of the Poloidal Field (PF) coils (see Fig. 1). This additional component is used to both achieve the desired plasma configuration and to control the plasma shape and position.

The need of achieving always better performance in present and future tokamak devices, has leveraged plasma control importance in tokamak engineering (see the special issues [3] and [4], and the recent book [5]).

In order to increase the energy confinement time, which is a vital criterion for realizing sustained fusion, modern tokamak designs favor vertically elongated plasmas shapes. The downside is that these configurations are vertically unstable [6], requiring an active feedback system, called Vertical Stabilization (VS) system.

The VS system of the Joint European Torus (JET, [7]) has been recently upgraded [8]. The new system enables more sensitive control of the plasma geometry and can withstand larger perturbations, e.g., larger Edge Localized Modes (ELMs, [9]). It also enables scientists to push the plasma performance to its limits without risking a severe control loss, which might endanger the machine integrity.

Plasma disruptions are characterized by an abrupt termination of the plasma current and a consequent transferring of high heat loads into the plasma facing components. The system upgrade became necessary as JET prepares for experiments with its new ITER-Like-Wall (ILW, [10]), where the number of disruptions must be kept to an absolute minimum, since these may lead to the melting of the beryllium surface. The system's response time was improved by increasing the amplifier's maximum voltage and current, while the hardware was replaced to increase the signal to noise ratio. Processing capabilities have also been increased to two gigaflops, giving the possibility to implement more complex control algorithms. In particular the system was upgraded giving the option of easily implementing different control algorithms which can be applied to the different phases of the plasma discharge [11].

This paper presents the system architecture of the new JET VS and discusses the first results attained during the last experimental campaign. It is structured as follows: Section II gives an overview of the JET magnetic control infrastructure, while Section III focuses on the particular control features of the new JET VS. Afterwards, the major achievements of the commissioning activity and some results regarding the regular operation of the new VS system are presented in Section IV. Eventually some conclusive remarks are given.

II. THE JET MAGNETIC CONTROL SYSTEM

In this section a brief overview of the JET magnetic control system is given. For more details the reader can refer to [12].

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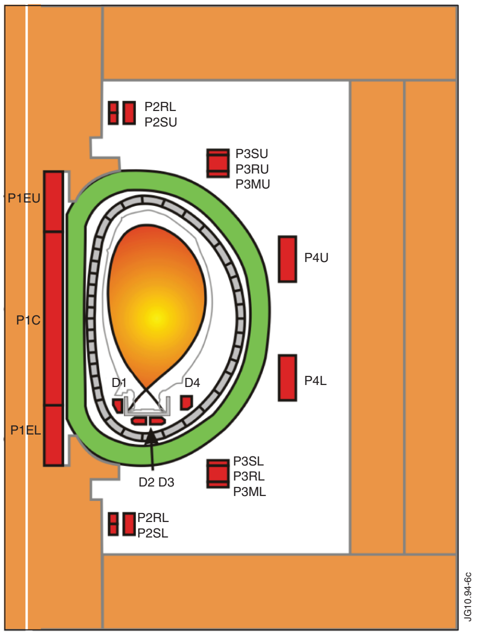

Fig. 1. The JET poloidal field coils system. The radial field circuit, termed RFA, connects the P2RU, P3RU, P2RL, and P3RL, and is used by the VS system. The *P1* circuit includes the elements of the central solenoid P1EU, P1C, P1EL, as well as P3MU and P3ML. The series circuit of P4U and P4L is named *P4*, while the circuit that creates an imbalance current between the two coils is referred to as *IMB*. *SHA* is made of the series circuit of P2SU, P3SU, P2SL, and P3SL. The central part of the central solenoid contains an additional circuit named *PFX*. Finally the four divertor coils (*D1* to *D4*) are driven separately each by one power supply.

In a tokamak device the magnetic control system is in charge of controlling the position and the shape of the plasma column inside the vacuum vessel. When dealing with this problem the three-dimensional plasma is typically considered axisymmetric, and normally divided in three axisymmetric magnetic control problems:

- vertical stabilization;
- plasma shape control;
- plasma current control.

On almost all the existing machines, a frequency separation approach is adopted to solve the plasma magnetic control problem. Following this approach, first the plasma is vertically stabilized on the fastest time scale possible, given passive structures and actuators. Afterward, the current and shape controller is designed on the basis of the stable system obtained considering the presence of the vertical stabilization controller. In particular, for the JET tokamak, the time constant of the unstable mode is ~ 2 ms, while the settling time of the shape controller is about 0.7 s.

Fig. 1 shows a poloidal cross-section of the JET tokamak where the PF coils are shown as red squares. These coils are linked together into 10 circuits driven by independent power supplies, named *P1*, *P4*, *IMB*, *SHA*, *PFX*, *D1*, *D2*, *D3*, *D4* and RFA.

These circuits are the actuators used to control the plasma current, shape, and position. In particular, the *P1* circuit enables both the plasma inductive formation and the control of the plasma current. Furthermore, eight PF circuits[1] are controlled either by the JET Shape Controller (SC, [12]) or by the eXtreme Shape Controller (XSC, [13]) to perform both plasma current and shape control. The current in the RFA circuit is driven by the VS system.

As shown in Fig. 2, the VS controls both the plasma velocity and the current in the RFA circuit. Indeed, the implemented control law provides a proportional action on plasma velocity and a proportional-integral action on the actuator current, that is

$$U_{RFA_{ref}}(t) = G_v(t)\dot{z}_p(t) + G_I(t)\big(I_{RFA_{ref}}(t) - I_{RFA}(t)\big) + \frac{G_I(t)}{T_I}\int_0^t \Big(I_{RFA_{ref}}(\tau) - I_{RFA}(\tau)\Big)d\tau\,,$$

where $U_{RFA_{ref}}(t)$ is the voltage reference for the power supply, while $I_{RFA_{ref}}(t)$ and $I_{RFA}(t)$ are the reference and the measurement of the current in the RFA circuit, respectively. Since one of the VS controller objectives is to keep the current in the actuator small, typically $I_{RFA_{ref}}(t)$ is set either equal to zero or to a bias value.

It is worth to notice that the structure of the JET VS system is kept as simple as possible. Indeed, this *simplicity* is strongly recommended in the fusion community, as the controller parameters typically need to be tuned during the experiments, in order to achieve better fusion performance. It readily follows that the lower the number of controller parameters, the more effective the tuning procedure to be performed by the scientists during the experiment. For this reason the VS gains $G_v(t)$ and $G_I(t)$ are adjusted during the discharge according to the variations of a number of plant parameters, such as the plasma vertical instability growth rate, power supply switching frequency, its temperature, and the value of the current in the actuator [12].

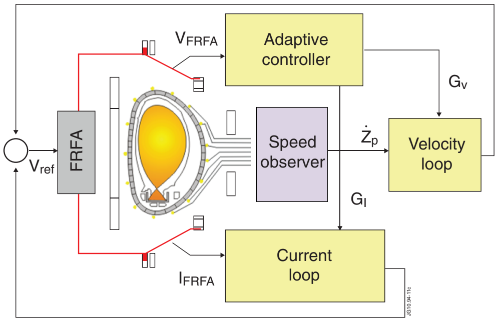

Fig. 2. The JET VS system block diagram.

Furthermore, in the scenarios with highly elongated plasmas in presence of large ELM perturbations, it is envisaged that the JET VS system could potentially use different estimations of the plasma vertical velocity, as well as different adaptive algorithms for the controller gains, in order to optimize the system behavior. It turns out that the adoption of a flexible and modular software architecture is mandatory for the VS implementation. Indeed, the old VS system [14],

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[1] Namely *P4*, *IMB*, *SHA*, *PFX*, *D1*, *D2*, *D3*, and *D4*.

based on four Texas Instruments DSPs (TMS320C40), was not flexible enough to satisfy the requirements. Indeed, the DSPs did not have any standard operating system, all the algorithms were carefully developed and optimized in order to meet the stringent cycle time requirements (50 μs) and to enable some of the required experimental features.

In order to take into account all the functional requirements, the new VS system has been developed exploiting the flexibility of the MARTe framework and of the Real Time Application Interface (RTAI)/Linux operating system [15]. Thanks to this choice it has been possible to exploit the multi-processor ATCA[2] based hardware architecture [16].

III. MAIN FEATURES OF THE NEW VS CONTROLLER AT JET

The main features that have been introduced in the JET VS after the enhancement are described in this section.

Fig. 3 shows a functional block diagram of the VS architecture where only the main signals are reported. The main modules are:

- the *Observer*;
- the *VS Control Algorithms*;
- the *Vertical Amplifier Manager* (VAM);

Furthermore the *Scheduler* sends scheduling signals to the modules listed above, while the *Signal Processing* Module computes the signals commonly used by the other modules.

A. Observer Module

The architecture of the new JET VS system has been conceived to operate in advanced plasma scenarios, where different estimations of the plasma vertical velocity must be available in order to optimize system performance.

If reliable models were available, rather than the plasma velocity, the plasma unstable mode could be used the control control variable. Indeed, the unstable mode would be the more effective variable to be controlled to minimize the vertical displacement in presence of disturbances.

For these reason, the *Observer Module* has been designed as a *container* of up to ten different observers. Each of these observers implements a dynamic state space model, giving the possibility of computing different estimations of the unstable mode to be used in different phases of the experiment.

Moreover, each observer receives as input a set of measurements and the resulting outputs can be used as inputs for other observers, in a daisy chain design, enabling the possible reuse and optimization of some calculations.

As a special case, when only the feed-through matrix D of the observer is specified, an observer can be used as a *plasma velocity estimator*, i.e., it computes an estimation of $\dot{z}_p$ as a linear combination of the magnetic field measurements. In particular, this is the currently adopted setup at JET, while the possibility of performing an estimation of the unstable mode via a dynamic observer is envisaged for the next experimental campaigns.

B. Controller Module

As for the Observer Module, the *Controller Module* has been conceived as a container of up to four different control algorithms which are available during the whole pulse. Thanks to this choice, it is possible to meet the requirements in terms of disturbances rejection and thermal losses in the RFA circuit, by selecting the *optimal* controller in each phase of the pulse. Furthermore this architectural choice permits to safely validate new control algorithms on the plant by running them in open–loop during the experiments.

There are a number of inputs that are common to all the control algorithms (i.e., the Observer outputs and the current in the RFA coil). Moreover, each algorithm can have its own input signals. The selection of the plasma vertical velocity to be used for the control is made on the basis of the scheduling signal provided by the *Scheduler*.

The control blocks can implement any linear or nonlinear control algorithm, provided that the computational effort is achievable. However each control algorithm must satisfy two basic requirements:

- control of the plasma vertical velocity or unstable mode, in order to achieve vertical stabilization;
- control the current in the RFA circuit, in order to avoid current saturation and to reduce the thermal losses in the coil.

C. Vertical Amplifier Manager

The *VAM* module selects the desired controller output, on the basis of the scheduling signals provided by the *Scheduler*. Before sending it to the RFA, the selected voltage request could be further processed.

The *Kicks* module is the most innovative component of the *VAM*, and allows to apply voltage pulses of a given time length and amplitude to the coil used for vertical stabilization. These voltage kicks vertically move the plasma, and are used to trigger Vertical Displacement Events (VDEs), to perform halo currents studies [17], and for ELM pacing experiments [18].

It implements all the various types of kicks, by varying the voltage pulse lengths and amplitude, which can be specified by using the VS graphical user interface.

A *kick logic* is specified by using a *kick waveform* and a *kick type*. The former describes the voltage waveform to be applied by the kick module, while the latter decides when to apply the waveform itself. More details can be found in [11].

IV. EXPERIMENTAL RESULTS

This section starts by presenting the required profiling results that asserted the safe deployment of the new control system software, followed by the commissioning and experimental results.

A. Profiling

One of the most important characteristics of any control system is that the execution of its algorithms is bounded to a well defined time period. This requirement is particular important in the VS system, since the number of operations

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[2] Advanced Telecommunication Computing Architecture.

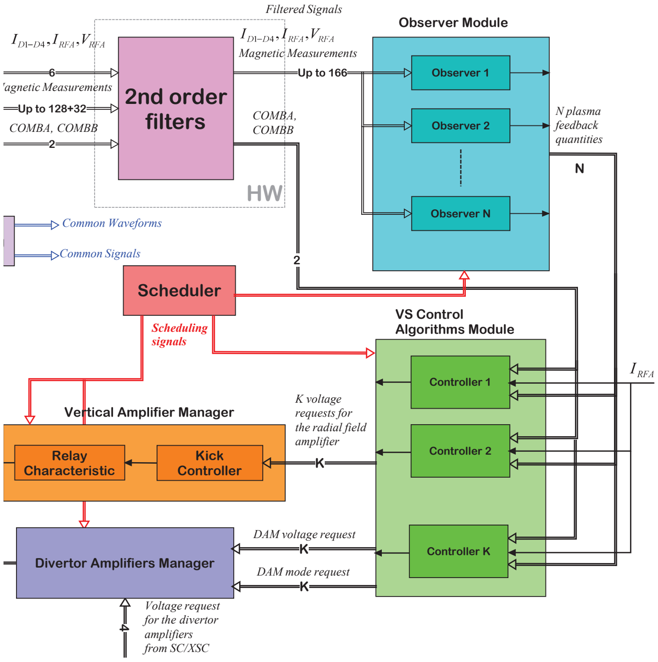

Fig. 3. Internal architecture of the new JET Vertical Stabilization system.

performed in a control cycle varies with the number of features enabled in a given time window.

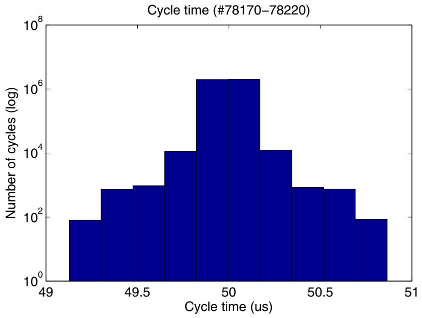

Fig. 4. Cycle time measurements. The jitter is always bounded to 1 μs and no cycles were ever lost.

Even in the worst case conditions, where all the modules have all their control and experimental features enabled, the system coped and managed to execute and synchronize with the next control cycle with-in the prescribed 50 μs value. These results are highlighted in Figs. 4 and 5, showing profiling data from 50 commissioning pulses, accounting for more than 500 s of experimental time. The former demonstrates the accuracy of the synchronization mechanism, while the latter gives a good estimate of the processing power still available for the implementation of new modules, or algorithms, in the present system. In this histogram, the results are calculated as the ration between the execution time of all modules in the control chain and 50 μs.

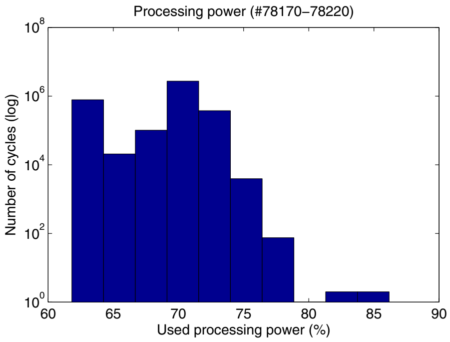

Fig. 5. Amount of time consumed to execute all the modules in a 50 μs control cycle, expressed as a percentage of this value. Even in the worst case scenario there is still some processing power available if further calculations or modules are ever to be required.

B. *Observer*

As discussed before, a new plasma velocity observer had to be designed in order to take into account the field modifications imposed by the new wall. The way the observer software module was designed allowed to compare in the same pulse, albeit in open-loop, up to ten plasma observers in parallel. On the other side, the usage of a simulator, together with linear plasma models [19], provided excellent estimations of the expected behavior in the presence of fast disturbances [20], leading to the release of a new plasma velocity estimation named *OBS05*.

The first part of the experimental activity consisted in demonstrating that *OBS05* had the same response of the old estimation of plasma velocity during normal operation, so that no modifications to the controller algorithm parameters

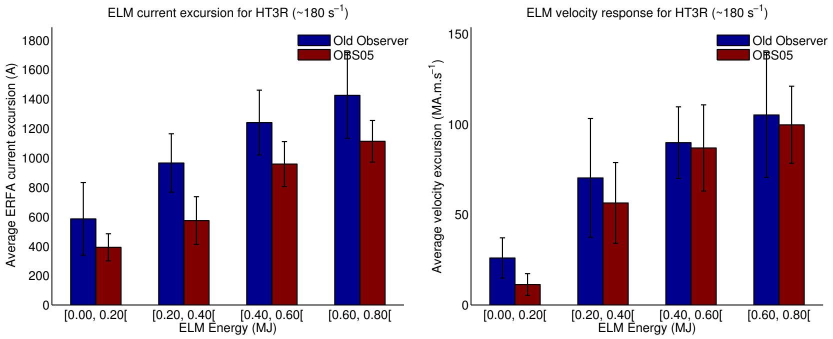

Fig. 6. Comparison between the old VS observer and *OBS05* in the response to ELMs. It can be seen that on average the new *OBS05* observer outputs, for the same ELM energy, has a smaller variation, resulting in a smaller current excursion in the power supply.

were required. In Fig. 6 it is shown that, for the same ELM energy, the new *OBS05* has a smaller plasma velocity variation, enhancing the controller response which requires a small current excursion to the *Enhanced Radial Field Amplifier* (ERFA).

C. Turns optimization

One of the design outcomes of a modeling task, was that the overall system response could greatly benefit (up to 20 %) by operating with a lower inductance on the radial field circuit, which can be changed by configuring the number of turns dedicated to the radial field circuit on the P2U, P3U, P2L and P3L coils. A large number of experimental sessions was designed and prepared to assess the turns options specified in Table I. The main objective was to study the system reaction to disturbances, in particular ELMs, against different plasma configurations. As the ELM energy and event time is difficult to predict and greatly depends on the experimental conditions, it was decided to start by comparing the different turns options using VS kicks, of different time lengths and voltage. This allowed the development of a database with more than 1600 kicks, for a large set of different plasma configurations, characterized by different plasma geometries and vertical instability growth rates. The considered figures of merit were the time interval and the ERFA current required to return the plasma vertical velocity back to zero.

TABLE I

TESTED INDUCTANCE VALUES ON THE RADIAL FIELD CIRCUIT.

Turns (P2U-P3U-P2L-P3L)	Name	Inductance
16-20-16-20	Standard	20 mH
8-20-8-20	Reduced	12 mH
16-20-8-2	Asymmetric	10 mH

For each plasma pulse, usually, one or two different plasma configurations were tested against a battery of kicks. The majority of the kicks were periodic with a frequency ranging between 5 and 20 Hz. The kick size, defined as the length of the kick multiplied by the kick voltage, varied between 3 and 36 Wb. Negative and positive kicks, which trigger a plasma movement in opposite directions, were also analyzed separately.

Figs. 7 and 8, show the recovery time and current when different plasma velocities are considered for a configuration with vertical instability growth rate $\sim 280\ s^{-1}$. As expected, the amount of current required to recover from the kick increases proportionally to the velocity displacement and for negative kicks there is a large discrepancy for the amount of current required for the asymmetric turns, which require up to more 1 kA for the same velocity. The recovery time for positive kicks, clearly benefits from the reduced or asymmetric options. For negative kicks, there was only valid data available for the reduced and asymmetric turns, where the latter provides a faster response, usually with a smaller current excursion. It was also observed that when using the asymmetric turns option, both kicks and ELMs also generated a non-negligible horizontal movement. The same results were also true in other plasma configurations [21], with different vertical instability growth rates, so that the reduced turns option was eventually chosen as the new official option for the VS system.

D. Regular operation

Once the ERFA commissioning phase was terminated, the system was released as the new official vertical stabilization system and successfully run for more than 1500 plasma pulses during several weeks of operation. As shown in Fig. 9, the new vertical stabilization has demonstrated the capability of handling large ELMs ($>$ 1 MJ) at high plasma currents ($>$ 3 MA). As the culmination of the C27 campaign, JET was operated for the first time since 1997, at a plasma current of 4.5 MA, with ITER relevant scenarios, confirming one of the project's major milestones.

CONCLUSIONS

The robustness of the JET vertical stabilization system is vital for a safe operation of the experiment. At the same time, the system is expected to provide advanced experimental features, enabling the exploitation of new scientific problems and the adaption to different experimental regimes. In order to safely allow both modes of operation to co-exist, the new VS was designed using a modular and decoupled architecture. In particular an *Observer Module* enables the

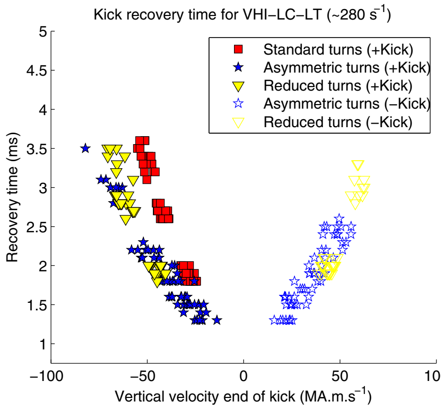

Fig. 7. Results for a high plasma vertical instability growth rate. The reduced and asymmetric turns allow for a considerable reduction of recovery time.

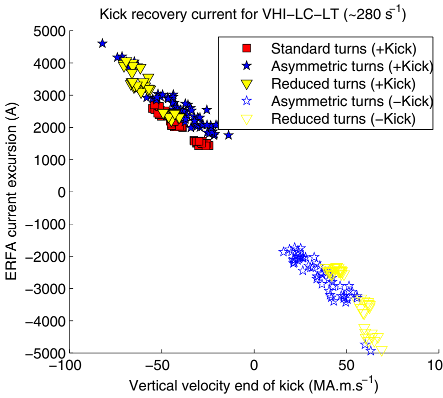

Fig. 8. The faster recovery time of the reduced turns option is made at the expense of using more ERFA current.

production of several plasma velocity estimations, which can later be used either as an input to a controller or as part of a open-loop tuning process. Being able to switch the behavior of the single modules accordingly to the discharge phase, enables to test new features in safer plasma operational modes and to use special controller parameters when required.

Decoupling the operational control properties, from the advanced experimental requirements (e.g. kicks), greatly eased the process of commissioning of each of the functional requirements.

Eventually, since its installation the new JET VS successfully controlled more than 1500 plasma pulses, with an extremely low failure rate (no natural VDEs or control failures during ELMs ever observed).

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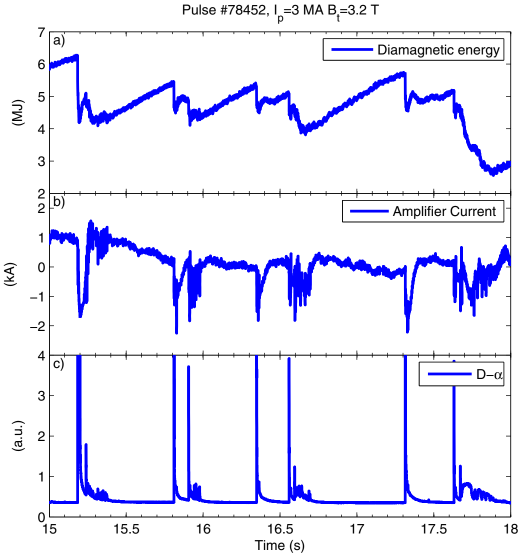

Fig. 9. Operation with large ELMs (> 1 MJ) at high plasma currents (> 3 MA) in the HT3R plasma configuration (vertical instability growth rate of $\sim 180\ s^{-1}$). The system coped very well with these large disturbances (observable by abrupt variations in the presented D-alpha signal), enabling the safe testing and operation of new plasma scenarios..

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