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Exploitation of Modularity in the JET Tokamak Vertical Stabilization System

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A. Neto[1], R. Albanese[2], G. Ambrosino[2], M. Ariola[3], G. Artaserse[4], A.J.N. Batista[1], B. Carvalho[1], F. Crisanti[4], G. De Tommasi[2], H. Fernandes[1], P.J. Lomas[5], F. Maviglia[6], A. Pironti[2], F. Rimini[5], F. Sartori[7], L. Zabeo[8]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associação EURATOM-IST, Instituto de Plasmas e Fusão Nuclear Laboratório Associado, Instituto Superior Técnico, Universidade Técnica de Lisboa, 1049-001, Lisboa, Portugal.
[2]Associazione EURATOM-ENEA-CREATE Università degli Studi di Napoli Federico II, Via Claudio 21, 80125, Napoli, Italy.
[3]Associazione EURATOM-ENEA-CREATE Universit`a degli Studi di Napoli Parthenope, Centro Direzionale di Napoli, Isola C4, 80143 Napoli, Italy.
[4]Associazione EURATOM-ENEA, Frascati, Italy.
[5]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[6]Associazione EURATOM-ENEA-CREATE, Via Claudio 21, 80125, Napoli, Italy.
[7]Fusion for Energy, 08019 Barcelona, Spain.
[8]ITER-IO, St. Paul-Lez-Durance, 13108, France.
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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 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 2009. This paper 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 2008/2009 experimental campaigns are presented.

1. 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 the most promising devices to achieve magnetic confinement of plasma [1].

In a tokamak reactor, plasma is formed in 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 poloidal 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 achieve the desired plasma configuration, defined by a shape and a position.

The need for 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 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 a Vertical Stabilization (VS) system.

Different solutions have been proposed for plasma vertical stabilization in tokamaks: simple SISO controllers [7,8], optimal linear-quadratic control [9], predictive control [10], nonlinear adaptive control [11], and robust control [12,13]. In [14] an anti-windup synthesis is proposed to allow operation of the vertical controller in the presence of saturation. Furthermore, thermal constraints limiting the current into the actuator have been considered in [15].

The VS system of the Joint European Torus (JET) [16] has been recently upgraded [17]. The new system enables more sensitive control of the plasma geometry and can withstand larger perturbations, e.g., larger Edge Localized Modes (ELMs [18]. It also enables 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), [19,20], 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 [21], while the hardware was replaced to increase the signal to noise ratio. Processing capabilities have also been increased to two gigaflops [22], 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 [23].

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 2 gives an overview of the JET magnetic control infrastructure, while Section 3 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 4. Finally some concluding remarks are given.

2. OVERVIEW OF 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 [24] and [25].

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 (i.e. no dependence in the toroidal angle), and normally divided in three axisymmetric magnetic control problems:

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

On almost all 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 ~2ms, while the settling time of the shape controller is about 0.7s.

Figure 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), [24] or by the eXtreme Shape Controller (XSC), [26] to perform both plasma current and shape control. The current in the RFA circuit is driven by the VS system.

The block diagram of the JET magnetic control system is shown in Fig.2. The Current controller is designed to control the current in each PF circuit. In particular, it receives as inputs:

- the feed-forward currents $I_{FF}(\cdot)$ (also called scenario currents), i.e., the PF currents needed to achieve the target reference in terms of plasma current and shape;
- the control currents computed by either the SC or the XSC, i.e., the current requests generated to counteract the disturbances.

Based on the current control errors, the Current controller evaluates the voltages to be applied to the plant, i.e. the voltages applied by the power supplies to the PF coils. The design of this feedback system is usually done on the basis of a plasma-less model, in which the current control is used such a way that in dry discharges (i.e., discharges without plasma) the current references are tracked with a certain accuracy (more details can be found in [24]).

Note that both VS and SC generate voltage requests. Indeed in the case of VS, a current controller may introduce an unacceptable delay, limiting the system performance. The SC usually is not affected by the delay introduced by the current controller, since it reacts on a slower time scale with respect to the VS.

As shown in Fig.3, 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

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

where $U_{RFAref}(t)$ is the voltage reference for the power supply, while $I_{RFAref}(t)$ 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 IRFAref (t) is set either equal to zero or to a bias value. The voltage output from the radial field amplifier is quantized to a set of nine values, which can vary in 3kV steps from −12kV to 12kV, with an hysteresis scheme implemented.

It is worth noticing 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

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

typically need to be tuned during the experiments, in order to achieve better fusion performance. Also 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 [24].

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 (Lennholm et al., 1997), 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 [27, 28] and of the Real Time Application Interface (RTAI)/Linux operating system [29]. Thanks to this choice it has been possible to exploit the multi-processor ATCA[2] based hardware architecture [30].

3. MAIN FEATURES OF THE NEW VERSUS CONTROLLER AT JET

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

Figure 4 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);
- the Divertor Amplifiers Manager (DAM).

Furthermore the Scheduler sends scheduling signals to all the modules listed above, while the Signal Processing Module computes all the signals commonly used by the other modules. The Scheduler is driven by pre-programmed time window settings and by external events, such as an early plasma termination due to an unforeseen fault in an essential system.

3.1. 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

[2] *Advanced Telecommunication Computing Architecture.*

be used as 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 reasons, 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 (see Fig.5).

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.

3.2. 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 disturbance rejection and thermal losses in the RFA circuit, by selecting the optimal controller in each phase of the pulse. Furthermore this architectural choice permits safe validation of 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.

In the current version of the JET VS system the plasma velocity regulator is a proportional controller and a proportional-integral regulator is used for the current in the RFA circuit. Different adaption algorithms for the controller gains are available as will be shown in Section 4.

3.3. VERTICAL AMPLIFIER MANAGER

The VAM module, depicted in Fig. 6, 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 by the following components: the Dither module, the Delay module, the Kicks module and the Relay Characteristic.

3.3.1. Dither

The Dither component adds a sawtooth waveform to the selected voltage request. This feature is used to reduce the effect of voltage quantization.

3.3.2. Delay

The Delay module is used to delay the voltage request by a given number of time samples. The resulting delay introduced in the system is used to estimate the stability margins [31] during dedicated tests.

3.3.3. Kicks

In recent experiments, voltage pulses of a given time length and amplitude have been be applied to the coil used for vertical stabilization. These voltage kicks patterns can be executed at a pre-defined time, repeated at a given frequency or as a response to an experimental event (e.g. amplifier current saturation). Kicks vertically move the plasma, and are used to trigger Vertical Displacement Events (VDEs), to perform halo currents studies [32], and for ELM pacing experiments [33].

The Kicks module is the most innovative component of the VAM. 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 [23].

3.3.4. Relay Characteristic

The Relay Characteristic module implements the same variable hysteresis logic of the power supply ensuring that the correct voltage is applied by the amplifier even in presence of noise or not perfectly calibrated DACs.

3.4. DIVERTOR AMPLIFIERS MANAGER

The DAM is a module created in order to let the VS system act on the divertor coils, which are normally controlled by either the SC or the XSC. In particular the the DAM allows the user to perform kicks using the divertor coils.

4. EXPERIMENTAL RESULTS

Before connecting the new power supply, called Enhanced Radial Field Amplifier (ERFA) [21], to the vertical stabilization circuit, a large number of commissioning procedures had to be executed in order to guarantee the expected behavior and to formally accept the amplifier from the industry.

In parallel to this activity, the new hardware, software framework, plasma observers and controller parameters, were also commissioned and tuned against a great variety of scenarios.
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.

4.1. 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 performed in a control cycle varies with the number of features enabled in a given time window. 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 50μs value. These results are highlighted in Figs. 7 and 8, showing profiling data from 50 commissioning pulses, accounting for more than 500s 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 ratio between the execution time of all modules in the control chain and 50μs. The processing unit is based on a standard ATX motherboard and a multi- core x86 processor, so that it can be upgraded to a faster version if more processing power is ever to be required.

4.2. OBSERVER

A new plasma velocity observer had to be designed in order to take into account the field modifications imposed by the new wall, as it is expected that some of the magnetic signals used by the previous velocity estimator are going to be affected by the new all metal wall [34]. The way the observer software module was designed allowed comparison in the same pulse, albeit in open-loop, of up to ten plasma observers in parallel. On the other hand, the usage of a simulator, together with linear plasma models [35, 36], provided excellent estimations of the expected behavior in the presence of fast disturbances [37], leading to the release of a new plasma velocity estimation named OBS05.

The first part of the experimental activity consisted of demonstrating that OBS05 had the same response as the old estimation of plasma velocity during normal operation, so that no modifications to the controller algorithm parameters were required. In Fig. 9 it is shown that, for the same ELM energy range, the new OBS05 outputs a smaller plasma velocity variation, enhancing the controller response which requires a smaller ERFA current excursion.

4.3. ADAPTIVE CURRENT GAIN

In case of vertical displacement, the operation of the VS adaptive control scheme with high current gains has the major advantage of greatly reducing the amount of time required by ERFA to return to zero current. Furthermore, it also plays an important role in the reduction of low frequency oscillations that arise either due to the interaction with the shape controller system or from a fast reaction to an external disturbance (usually ELMs). Unfortunately high current gains also increase the ERFA current peak during the response to a disturbance, making the system operate near the power supply current limits.

In order to overcome this problem, a controller named PCU1 allows the current gain $G_I(t)$ to be adapted against the experimental conditions. High current gains, in respect to the normal values of the VS standard controller, are used during the normal operation of the system. When the voltage requested by the controller is greater than a configurable threshold, the presence of a disturbance is assumed and the gain is reduced to a lower value during a configurable time period.

As depicted in Fig. 10, it was shown that the average ERFA current excursion after an ELM was improved when PCU1 was used. Extrapolating from modeling results, and comparing with the experimental data, it is expected to have up a 10 % improvement on the ERFA current excursion for large size ELMs (> 1MJ), even if for higher energy ELMs more experimental data is required in order to improve the statistical results. It should also be noticed that this controller was tested in well defined time windows of the experiment, taking advantage of the controller time window switching mechanism.

4.4. 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 1. 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.

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 20Hz. The kick size, defined as the length of the kick multiplied by the kick voltage, varied between 3 and 36Wb. Negative and positive kicks, which trigger a plasma movement in opposite directions, were also analyzed separately.

Figures 11 and 12, show the recovery time and current when different plasma velocities are considered for a configuration with vertical instability growth rate ~280 s^{-1}. As expected, the amount of current required to recover from the kick increases proportionally to the velocity displacement.

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 [38], with different vertical instability growth rates, so that the reduced turns option was eventually chosen as the new default option for the VS system.

4.5. REGULAR OPERATION

Once the ERFA commissioning phase was terminated, the new VS system was released as the new official vertical stabilization system and successfully run for more than 1500 plasma pulses during several weeks of operation. It always guaranteed the required 50 μs control cycle time and permitted at the same time to explore a large set of experimental features, providing a very good combination between scientific and technological development. As shown in Fig.13, the new vertical stabilization has also demonstrated the capability of handling large ELMs (> 1MJ) at high plasma currents (>3MA). As the culmination of the C27 campaign, JET was operated for the first time since 1997, at a plasma current of 4.5MA, with ITER relevant scenarios, confirming one of the project's major milestones.

CONCLUSIONS

The robustness of the JET vertical stabilization system is vital for 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 production of several plasma velocity estimations, which can later be used either as an input to a controller or as part of an open-loop tuning process. Being able to switch the behavior of the single modules according to the discharge phases enables the testing of new features in safer plasma operational modes and to use special controller parameters when required.

Finally, 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. During the radial field turns optimization, being able to configure the vertical stabilization kicks for more than 20 plasma pulses, before each session and to later fine tune the settings against the session evolution, was extremely important for the success of the commissioning activity. The functional separation between all the modules enabled the experts to provide the required configurations, sometimes within a very short period of time, having the confidence that these would not impact on the operational parts of the vertical stabilization system. During the commissioning period, some of the experiments required more than 15 vertical stabilization time windows, each with its own controller, controller gains and settings, feedback variable, ERFA kick and divertor kick configuration.

Since its installation, the VS system has successfully controlled more than 1500 plasma pulses, with an extremely low failure rate (no natural VDEs or control failures during ELMs ever observed). An extremely important requirement, as without a robust vertical stabilization system, the JET operation and the actual machine safety can be put in jeopardy.

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

Table 1: Tested inductance values on the radial field circuit.

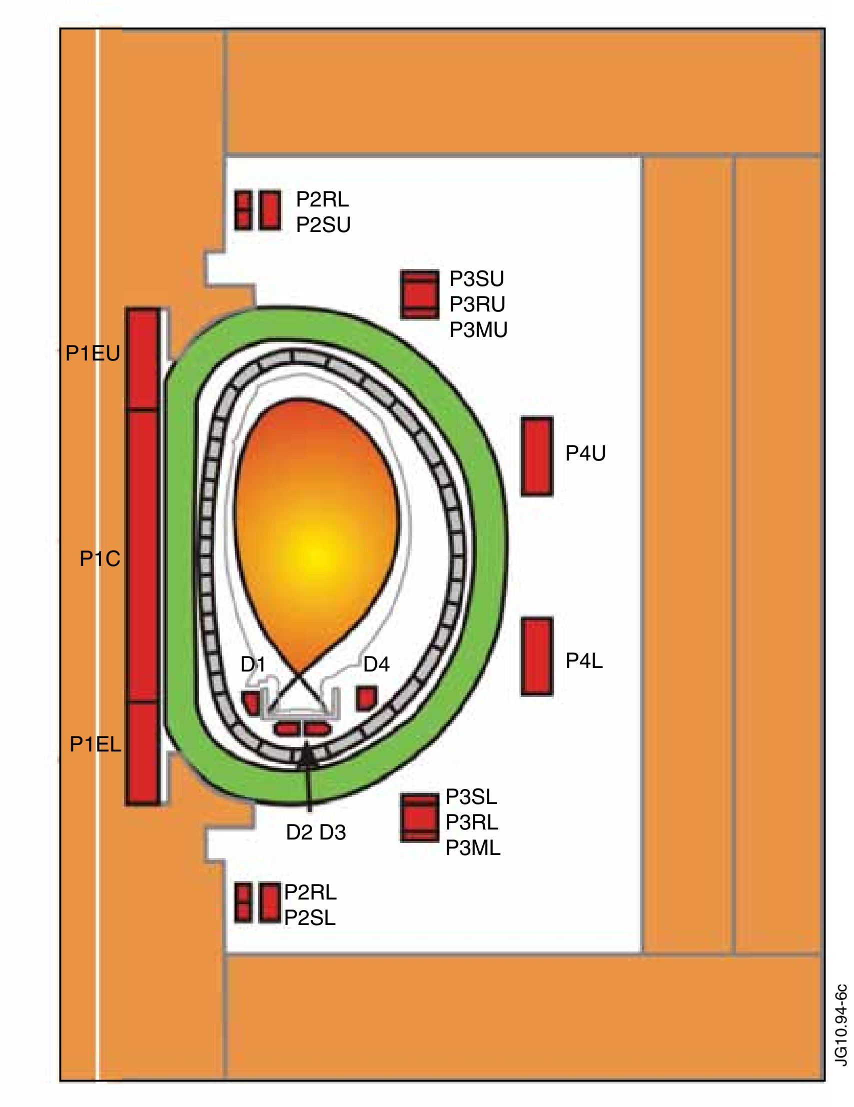

Figure 1: The JET poloidal field coils system. The radial field circuit, termed RFA, connects the P2RU, P3RU, P2RL, and P3RL, and is used by the VS system. The P1 circuit includes the elements of the central solenoid P1EU, P1C, P1EL, as well as P3MU and P3ML. The series circuit of P4U and P4L is named 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.

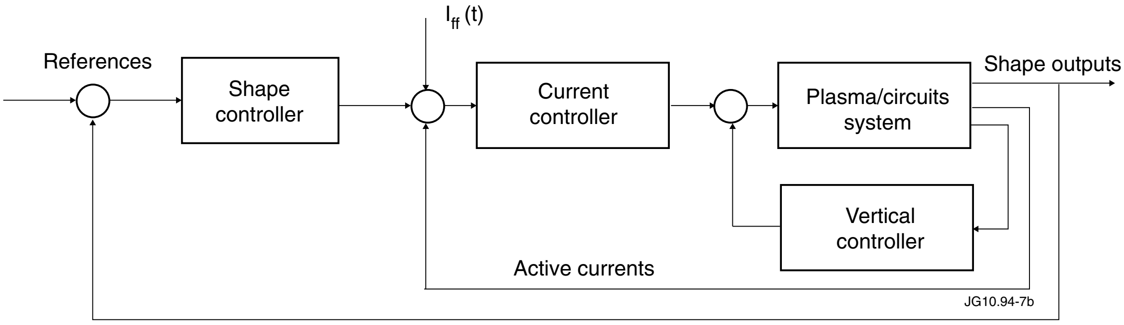

Figure 2: Architecture of the JET magnetic control system, where the VS system has a dedicated control system.

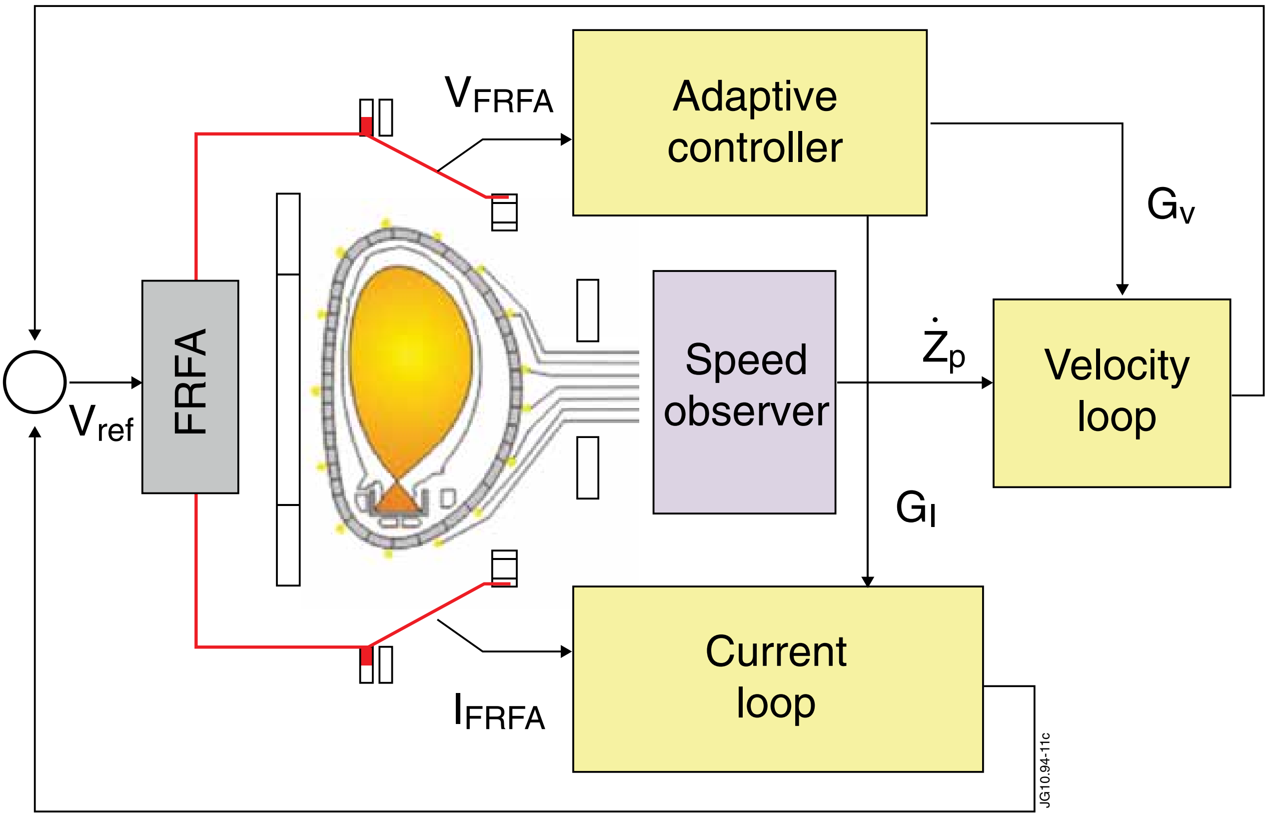

Figure 3: The JET VS system block diagram. The voltage request to the amplifier is the sum of the output of two control loops, where the gains are adjusted in real-time against variations of a number of plant parameters.

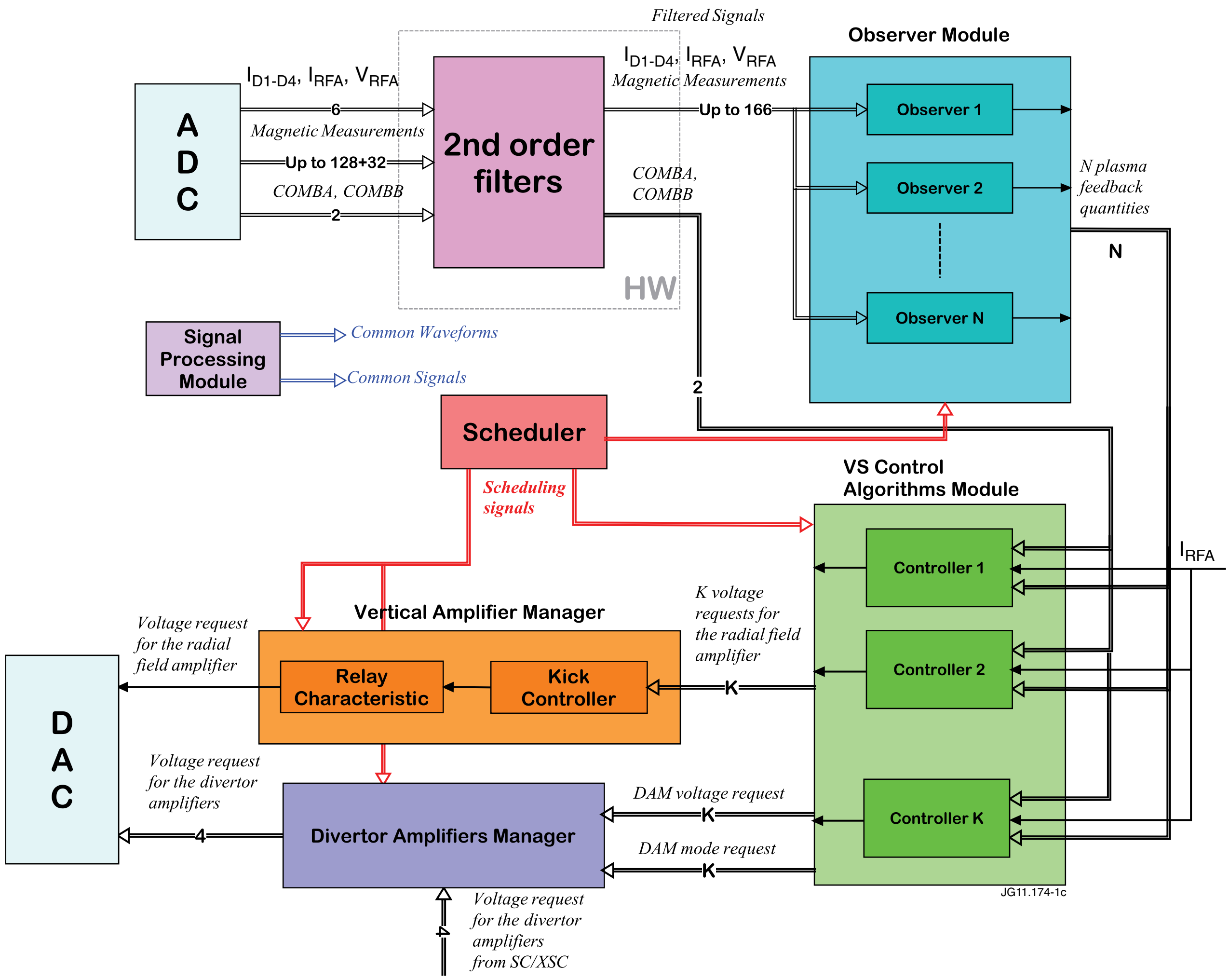

Figure 4: Internal architecture of the new JET Vertical Stabilization system. The functional behavior of the system was divided in several processing blocks, where the vertical amplifier and divertor amplifier managers are mostly tailored at the experimental exploitation of the system.

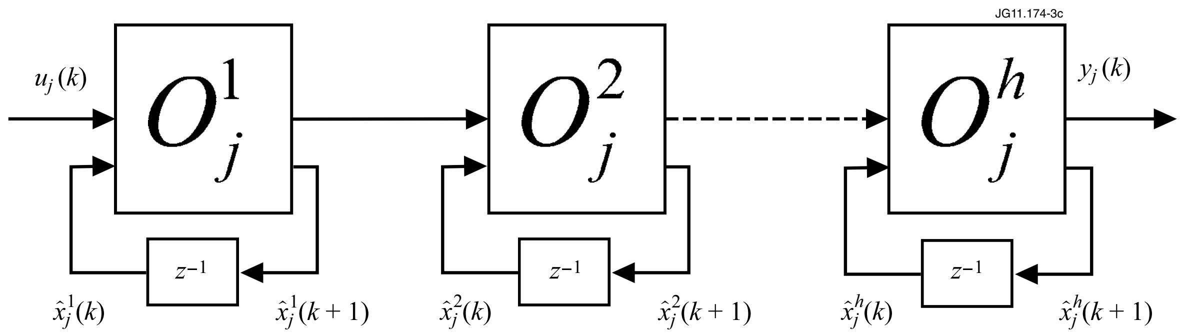

Figure 5: Implementation of the n-th observer as a series connection of h blocks.

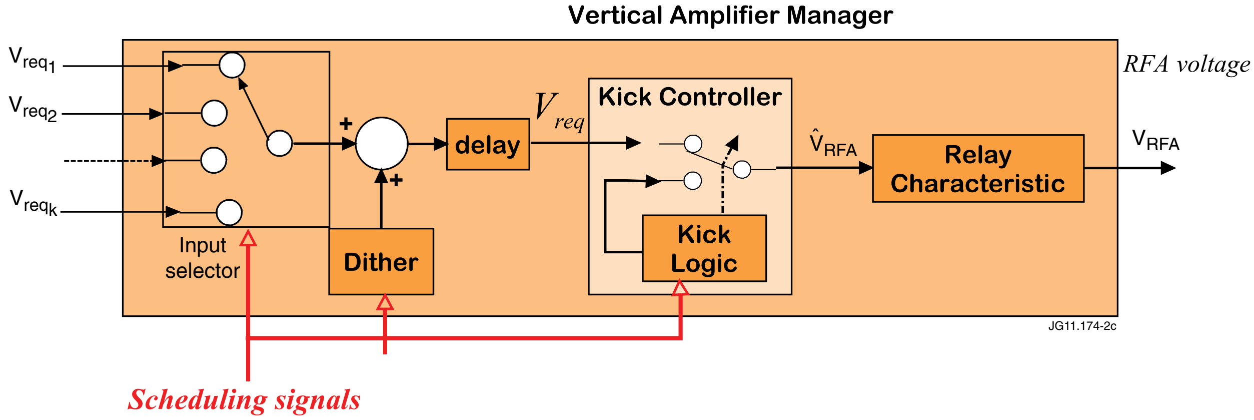

Figure 6: Internal structure of the Vertical Amplifier Manager module. It is capable of adding a dither signal and of applying a delay to the control voltage. The kick controller is responsible for the production of kick patterns, followed by the hysteresis module. These features are enabled using scheduling signals.

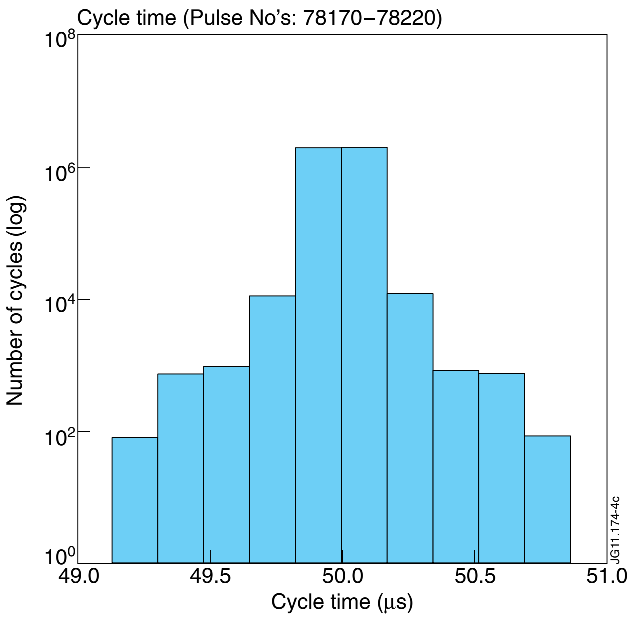

Figure 7: Cycle time measurements. The jitter is always bounded to 1 µs and no cycles were ever lost.

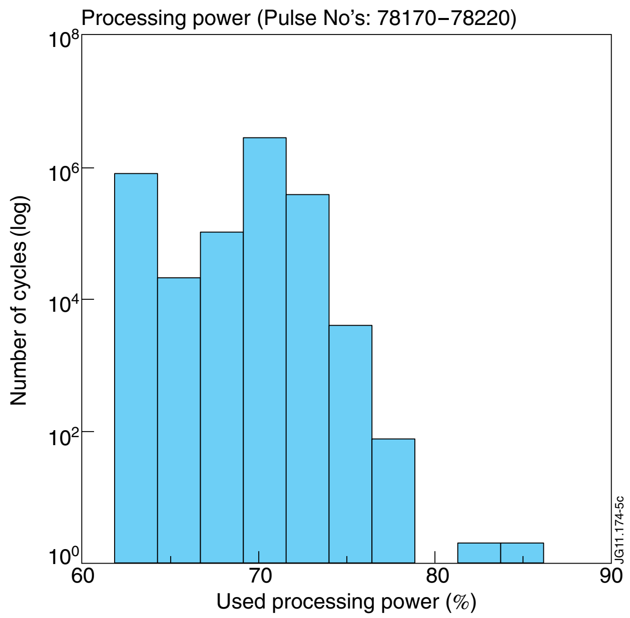

Figure 8: Amount of time consumed to execute all the modules in a 50 µs control cycle, expressed as a percentage of this value. Even in the worst case scenario there is still some processing power available if further calculations or modules are ever to be required.

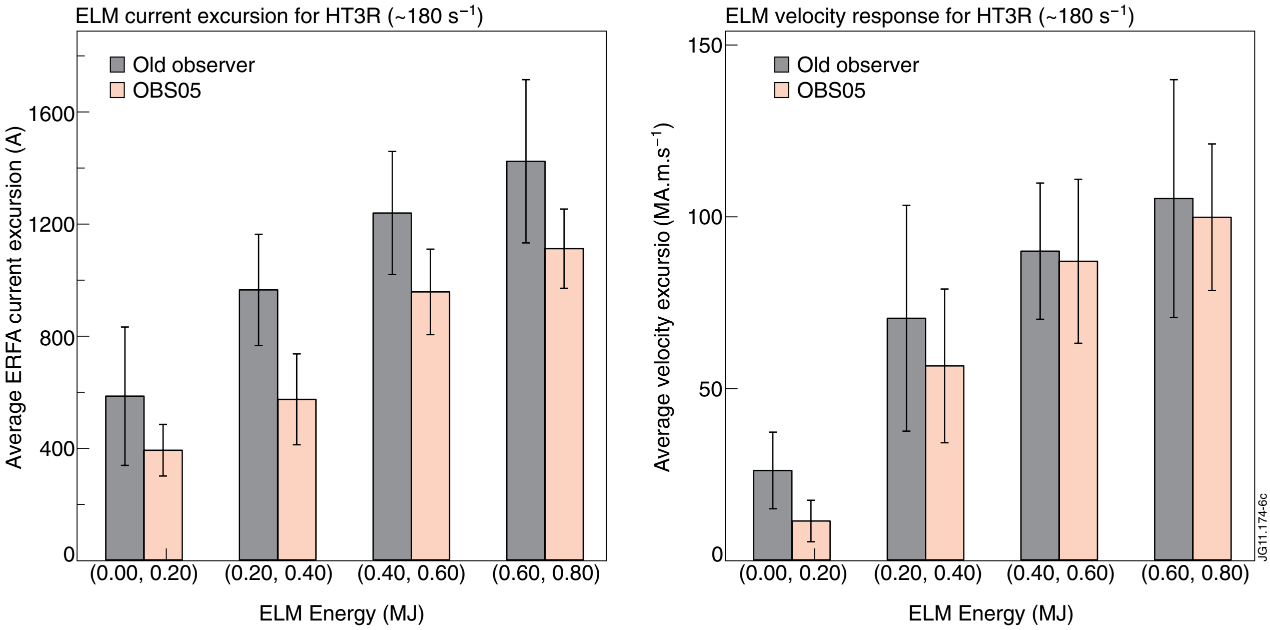

Figure 9: Comparison between the old VS observer and OBS05 in the response to ELMs. It can be seen that on average the new OBS05 observer outputs, for the same ELM energy, a smaller velocity variation, resulting in a smaller current excursion in the power supply.

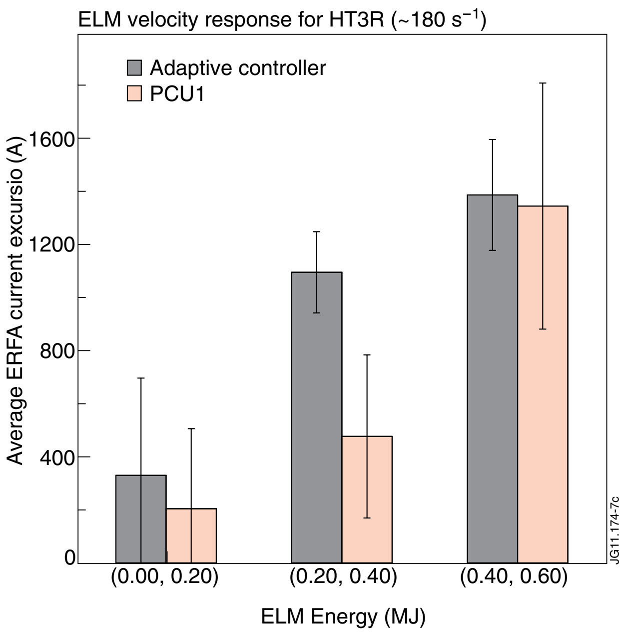

Figure 10: PCU1 controller tests in the presence of ELMs for the plasma configuration HT3R, which has a vertical instability growth rate of ~180 s^{-1}. On average, the ERFA current excursion was improved by the usage of the new PCU1 controller.

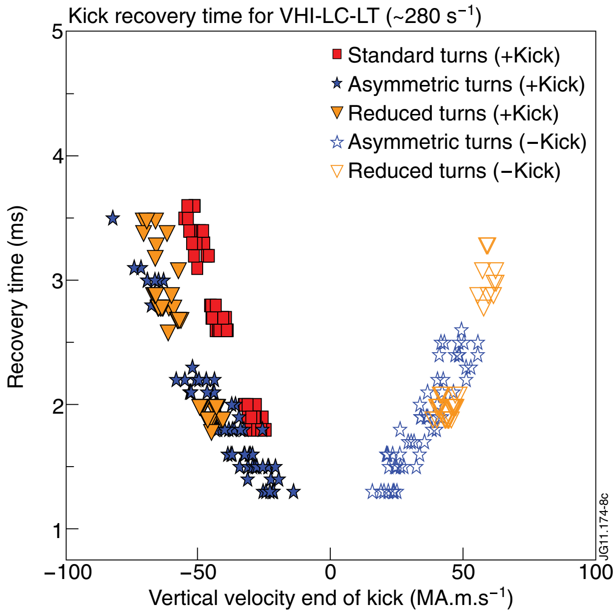

Figure 11: Results for a high plasma vertical instability growth rate. The reduced and asymmetric turns allow for a considerable reduction of recovery time.

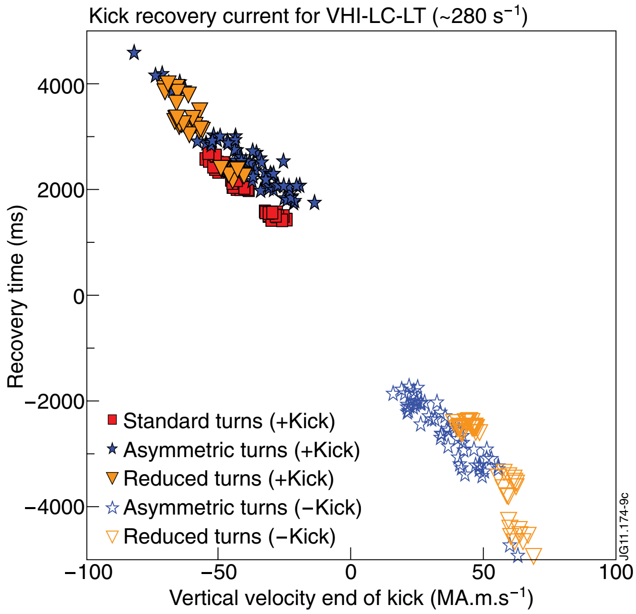

Figure 12: The faster recovery time of the reduced turns option is made at the expense of using more ERFA current.

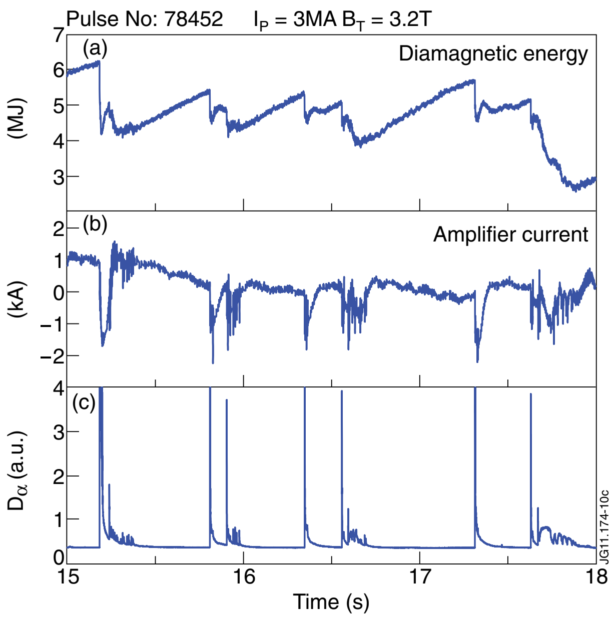

Figure 13: Operation with large ELMs (> 1 MJ) at high plasma currents (>3MA) in the HT3R plasma configuration (vertical instability growth rate of ~180 s^{-1}). The system coped very well with these large disturbances (observable by abrupt variations in the presented D-alpha signal and quantified by the amount of energy drop in the diamagnetic energy measurement), enabling the safe testing and operation of new plasma scenarios.