EFDA–JET–CP(10)07/07

F.G. Rimini, F. Crisanti, R. Albanese, G. Ambrosino, M. Ariola, G. Artaserse,
T. Bellizio, V. Coccorese, G. De Tommasi, P. De Vriese, P.J. Lomas,
F. Maviglia, A. Neto, I. Nunes, A. Pironti, G. Ramogida, F. Sartori,
S.R. Shaw, M. Tsalas, R. Vitelli, L. Zabeo
and JET EFDA contributors

First Plasma Operation of the Enhanced JET Vertical Stabilisation System

First Plasma Operation of the Enhanced JET Vertical Stabilisation System

F.G. Rimini[1,2], F. Crisanti[3], R. Albanese[4], G. Ambrosino[4], M. Ariola[4], G. Artaserse[4],
T. Bellizio[4], V. Coccorese[1,4], G. De Tommasi[4], P. De Vriese[5], P.J. Lomas[6],
F. Maviglia[4], A. Neto[7], I. Nunes[1,7], A. Pironti[4], G. Ramogida[3], F. Sartori[8],
S.R. Shaw[6], M. Tsalas[1,9], R. Vitelli[4], L. Zabeo[10]
and JET EFDA contributors*

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

[1]EFDA Close Support Unit, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[2]European Commission, B-1049 Brussels, Belgium
[3]ENEA Fus, EURATOM Assoc, 00040 Frascati, Italy
[4]Association Euratom-ENEA-CREATE, Univ. Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy
[5]FOM Institute for Plasma Physics, Rijnhuizen, Association EURATOM-FOM
[6]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[7]Associação Euratom-IST, Instituto de Plasmas e Fusão Nuclear, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[8]Fusion for Energy, 08019 Barcelona, Spain
[9]NCSR Demokritos, Association EURATOM Hellenic Republic, Agia Paraskevi Attikis, Greece
[10]ITER, St. Paul-Lez-Durance, 13108, France
** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the
26th Symposium on Fusion Technology (SOFT), Porto, Portugal
27th September 2010 - 1st October 2010

ABSTRACT

A project dedicated to the enhancement of the JET Vertical Stabilization system was launched in 2006, including an upgrade of the Power Supply of the Radial Field Amplifier, of hardware and software of the VS control system. The main aim was to double the JET capability in stabilising high current plasmas when subject to perturbations, in particular large Edge Localised Modes. We present here the results of first plasma operation with the new Enhanced Radial Field Amplifier and its data acquisition and control system, focussing on the benefits of an approach based on phased commissioning, modelling and offline algorithm validation.

1. INTRODUCTION

Experiments carried out in present day large and medium sized tokamaks in support of ITER have indicated that the magnetic configuration, and in particular an elongated poloidal cross-section with magnetic X-point, is one of the main parameters determining the plasma confinement and performance in the H-mode regime. Since such elongated plasmas are vertically unstable, with a growth rate depending on the equilibrium details and the surrounding conducting structures, position control on fast timescales is an essential component of real-time magnetic control in today's tokamaks. An analysis of the JET Vertical Stabilisation (VS) system highlighted its limitations in controlling high current plasmas when subject to perturbations, in particular large Edge Localised Modes (ELMs) [1], and the risks for machine integrity if vertical control is lost resulting in a Vertical Displacement Event (VDE). The situation could worsen after the planned increase of the JET Neutral Beam heating power to 35 MW, potentially increasing the likelihood of large ELMs. A major enhancement project was, therefore, initiated in 2006, comprising an upgrade of the Power Supply of the Radial Field Amplifier (RFA) and a complete overhaul of hardware and software of the VS control system, Plasma Control Upgrade (PCU) [2]. In this paper we discuss briefly the main elements composing the Project, before we present the main results of the first plasma operation with the JET upgraded VS system.

2. OVERVIEW OF THE JET VS SYSTEM UPGRADE

The radial field necessary for the vertical stabilisation of JET plasmas is generated by a dedicated set of poloidal field coils, denoted as P2R and P3R, supplied by the old Fast Radial Field Amplifier (FRFA) [3], based on Gate Turn-Off thyristors (GTO) and composed of four units rated 2.5kA/2.5kV, typically configured to deliver 10kV/2.5kA. The design of a new amplifier was influenced by theoretical and modelling analysis of typical JET VDEs. Since control of a vertically unstable plasma following a perturbation depends both on the speed of the amplifier in producing the desired current in the coils, i.e. on the applied voltage, and on the available current the solution chosen for the new Enhanced Radial Field Amplifier (ERFA) has been an upgrade of about 20% of the output voltage to ±12kV, in four units rated ±3kV, and a doubling of the current capability to ± 5kA. An additional improvement in the system performance could be obtained, as will be discussed in more details later, by decreasing the inductance of the Radial Field Coils. ERFA is based on Insulated-Gate Bipolar Transistors as the main power device, with response time better than 100μs [4]. ERFA was delivered to JET in early 2009, tested on dummy loads [5], and ready, on schedule, for plasma commissioning by the summer of 2009.

Together with the ERFA amplifier, the JET VS system has been equipped with a new digital real-time controller, VS5, whose design has been guided by the requirements of speed, reliability and robustness against interrupts during communications (table I). VS5 is based on Advanced Telecommunication Computing Architecture (ATCA®) hardware. In addition to its characteristics of high availability, the redundancy scheme of the ATCA® architecture provides an additional safety in case of cards failure, while allowing for continuous operation and easy maintenance, both of which are essential features for real-time control systems in future tokamak reactors. The central controller is driven by an Intel Quad-core CPU. Data is acquired via 6 ATCA-MIMO-ISOL cards [6], for a total of 192 channels, at 2 Msamples/s. PCI-Express is used as communication protocol between the boards, thus ensuring low latency, <2μs, between data acquisition boards and the central controller.

The choice of ATCA® based hardware and the increase in data acquisition, coupled with powerful multi-core CPU technology, have enabled the realisation of an innovative, powerful, reliable, low latency, low jitter, 20 kHz system for the upgraded JET VS control, expanding the range of features available for the scientific experiments and easing debugging and testing. The basis of the system is the Multi-threaded Application Real-Time executor (MARTe) framework, developed as a lightweight multi-platform support, specifically optimised for Real-Time applications and supporting both multi-threaded and/or multi-processor applications. Two loops are at the core of the JET Vertical Stability control: one, proportional, guaranteeing zero plasma vertical velocity and another, proportional-integral, responsible for maintaining the Radial Field Current to a desired value [7]. Combining platform independence with a modular structure, the VS5 software architecture has provided significant advantages in the debugging and testing phases of the new system, giving the possibility to check and validate the whole real-time code, including both the control algorithm and the communication interfaces, against a computational model of the plant based on detailed plasma linearized models. This has allowed extensive offline testing, intrinsically safe and saving precious experimental time.

The new VS5 system was fully installed by the beginning of 2009. Initially it was run, in open loop, in parallel to the old system. Once the new hardware and software had demonstrated sufficient robustness during continuous open loop operation, the loop was closed on the new system in progressively more demanding conditions. Starting from very short time periods in the relative safety of quiescent plasmas at low current, the new system was tested in a large variety of plasma scenarios and, eventually, with ELM induced vertical perturbations of increasing size. Thus all the essential features of VS control were commissioned in advance of the installation of the new Radial Filed amplifier and the integrated commissioning of ERFA+VS5 was decoupled from the pure tests of the new controller, thereby considerably simplifying some of the subsequent tasks.

The relative small impact on the JET scientific exploitation of commissioning such a delicate and essential tokamak control system is a demonstration of the high value of offline tests not only of the various hardware components but also of the end-to-end controller chain.

3. ERFA/VS5 INTEGRATED PLASMA COMMISSIONING

Following the installation and connection of ERFA to the JET Radial Field coils, a campaign of plasma experiments was dedicated to the basic commissioning of ERFA, the exploration of the operating range of ERFA/V5 and the overall physics optimisation of the new JET VS system. In addition to the task of reestablishing plasma basic control modes, in particular control of the breakdown phase and transitions between the different equilibria in a pulse, time was dedicated to assessing ERFA/VS5 response to controlled and spontaneous perturbations and characterizing the specific behaviour of the new controller via the test of a variety of vertical velocity estimators, so-called observers, and the tuning of the controller parameters.

3.1. RESPONSE TO CONTROLLED PERTURBATIONS

Numerical simulations with a plasma magnetic linear model [8] suggested that an additional gain, up to 20% but dependent on the instability growth rate, could be obtained in the stabilisation margin by operating ERFA on a lower inductance load. The inductance of the Radial Field circuit was, thus, changed by configuring the connection to the P2R/P3R coils with a variable number of turns. The "standard" configuration, characterised by 72 turns, is the reference with inductance of ~ 20mH. As alternatives, tests with and without plasmas were carried out with a "reduced" configuration, 56 turns and inductance ~ 12 mH, as well as an "asymmetric" configuration, 46 turns and ~ 11 mH inductance [9]. This latter configuration, produced by connecting preferentially the turns in the coils situated at the top of the vessel, is interesting because it concentrates the induced field at the top of the machine avoiding use of the bottom turns screened by the presence of the divertor structure. In each of the radial turns configurations a similar sequence of tests was repeated, starting from closed loop plasmaless pulses, progressing to quiescent plasmas and culminating in a "live" test in large ELM scenarios. A detailed study of the effect of the different inductance configurations for the Radial Field coils has, also, been carried out on the basis of ERFA/VS5 response to controlled perturbations in as wide a range of equilibria as possible, thus covering a large range of vertical instability growth rates ($\gamma \sim 100 - 1400 s^{-1}$) and exploring the effect of parameters like plasma-wall clearance. The controlled perturbations were provided by so called "vertical kicks", i.e. an open loop maximum voltage pulse of varying length, either upwards or downwards, followed by closed loop recovery (fig.1).

The response to ERFA kicks was compared in terms of time needed to stop the plasma after the kick (Δt_{v0}), ERFA current needed to stop the plasma (ΔI_{ERFA}) and vertical excursion during the kick and recovery ($\Delta z_{(k\&r)}$). "Quality" indexes are also considered, taking into account the maximum value of $I_p^* \Delta z_{(k\&r)}$ compatible with ERFA current, including a positive current bias, and maximum voltage constraints: Q_5kA = $I_p^* \Delta z_{(k\&r)}$ *5/(ΔI_{ERFA}) and Q_12kV = I_p* $\Delta z_{(k\&r)}$ * $\Delta_{tk,max}/\Delta_{tk}$ where Δ_{tk} is the kick duration and $\Delta_{tk,max}$ is the maximum recoverable kick for the specific configuration, linked to the configuration's growth rate by $\exp(\gamma\Delta_{tk,max}) = 2$. In order to remain within the constraints of both maximum current and voltage, a combined quality factor is considered, defined as Q = min(Q_5kA,Q_12kV), where the minimum is taken for the same kick duration.

The dataset of kicks, in the different equilibria and radial turns configurations, has been analysed both by statistical means and by simulations of a limited number of representative pulses. The result is a better performance in terms of the average quality factor Q at high growth rate, $\geq 200s^{-1}$, for the reduced and asymmetric options, while no obvious difference is seen at lower growth rates (fig.2). The statistical analysis has, also, shown a significant reduction of the recovery time and the vertical excursion during recovery for the configurations at reduced inductance. It is interesting to note here that in the asymmetric turns configuration a significant radial movement has been observed, up to 2cm for a 25cm kick driven vertical displacement. This could cause problems in controlling the plasma-wall distance during rapid vertical perturbations, like ELMs.

As part of the modelling effort in preparation for the ERFA/VS5 commissioning phase, particular attention was given to developing more realistic simulations of the interaction of ELMs with the vertical stabilisation system. ELMs are considered as disturbances applied to the plasma linear modes [8, 9] and their size is quantified by the drop of plasma stored energy at the ELM crash, ΔW. Simulations covered a range of ELMs from relatively small, with energy drop in the range of a few hundreds kJ, up to very large with energy drop ~1-2MJ. Guided by these simulations, the experimental test of the ERFA/VS5 response to realistic ELM-driven perturbations started in relatively safe low plasma current and toroidal field plasmas, 2MA/ 2.2T, and small ELMs, $\Delta W \leq 0.3$ MJ. The final step in the ERFA/VS5 commissioning has been the assessment of its behaviour in H-mode scenarios with large ELMs, concentrating on plasmas at high triangularity, which produced the largest ELMs with $\Delta W \geq 1$ MJ (fig.3). The new ERFA/VS5 system behaved impeccably in these challenging ELMs conditions, even though the VS5 controller parameters had not been fully optimised by the time these experiments were carried out.

A statistical analysis of the response to ELMs has been carried out on the full database from small to large ELMs. Because the disturbance of the ELM itself induces, in the plasma, other and more complex effects than those caused by the simpler vertical kicks, this analysis is not as clean as in the controlled perturbations database. However, as the results for a medium-high growth rate equilibria suggest (fig. 4), the reduced turns option provide some benefit in terms of decreased recovery time with respect to the standard turns, at the expense of an expected increase of ERFA current swing. The ERFA current swing remains, however, well within the safe operation limits of the new amplifier even for the largest ELMs, $\Delta W_{dia} \geq 1$MJ, explored in the commissioning phase.

3.3 VS5 OPTIMAL OBSERVER AND CONTROLLER STUDIES

Activities focussed on characterizing the specific behaviour of the new controller have also been carried out, namely the test of a variety of observers and the tuning of the controller parameters. The development of a new observer has been undertaken in response to a study of the impact of the installation of the all-metal ITER-Like Wall [10] on the magnetic measurements used by VS and the expected filtering of the response of the measurement coils located behind the upper dump-plate [11]. The aim of the new vertical speed estimator, called OBS05, has been to find a compromise among the requirements of removing the filtered contribution of two discrete coils located behind the dump plate, while having the same sensitivity as the old observer, denoted as ZPDIP, with quiescent plasmas and the same dynamic response as ZPDIP to the Radial Field Amplifier voltage, so as to maintain the closedloop stability. The new combination of magnetic signals amply satisfies the design requirements and has, since, become the default for normal scientific JET operation.

The two loops, controlling the vertical speed estimator and the ERFA current, are implemented in VS5 via an adaptive mechanism which varies the propotional velocity gain according to the amplifier switching frequency and the plasma growth rate [12]. A small re-tuning of the vertical stabilization controller parameters has been made necessary by the replacement of the FRFA amplifier with ERFA, as well as by the change of the number of turns in the Radial Field circuit.

Explorations of an alternative current gain adaptation mechanism have, also, been carried out to improve the ERFA current control after an ELM. With this controller, PCU-1, on detection of an ELM, through the rapid variation of the velocity estimator, the current gain is decreased for a fixed time interval, thus minimising the ERFA current peak on this fast timescale. The current gain is, subsequently, increased during the slower timescale of recovery from an ELM perturbation so as to reduce the ERFA current settling time and minimise low frequency excursions. The PCU-1 current gain adaptation mechanism has been tested in a number of experimental discharges during the ERFA commissioning, and the effectiveness of the approach during ELM phases has been proved, although only in plasmas with relatively small ELMs, $\Delta W \sim 0.4$MJ (Fig.5), in good agreement with model based simulations.

CONCLUSIONS

The integrated plasma commissioning of ERFA and its upgraded control system VS5 has been carried out in a very short period of only 4 experimental weeks. In quiescent plasmas ERFA/VS5 was successfully tested up to extreme cases, in elongated configurations with estimated growth rates up to about 1400 s-1. This constitutes a significant improvement with respect to the stabilizing capability of the previous amplifier FRFA and VS controller, which barely reached $\gamma \leq 1000$ s-1.

The analysis of the database of ERFA/VS5 response to controlled perturbations and ELMs indicated that, amongst the three Radial Field configurations tested, the reduced turns option would provide the best overall response for medium to high growth rate plasmas, $\gamma \geq 180\text{-}200\text{s}^{-1}$. For low growth rate plasmas, the reduced turns configuration can, also, be more beneficial than the standard option when combined with operation of ERFA with a 2.5kA DC bias, allowing for larger current excursion. The asymmetric turns option, although giving as good if not marginally better performance than th reduced configuration, has been discarded due to the non-negligible induced radial movement and because of the possibility of high inter-turn transient voltage, very close to the maximum admissible value for the Radial Field coils insulation. Following the choice of Radial Field configuration and the development of a new observer OBS05, relevant for future operation in the JET ITER-like Wall environment, the VS5 controller parameters have been optimised. Thus the new Vertical Stabilisation system was successfully used for the rest of the 2009 scientific JET campaign, which included further experiments with large ELMs and ELMy Hmode operation at plasma current up to 4.5MA.

The response to large ELMs has been analysed to extrapolate, using the same model employed to prepare the experiments, to operation at higher plasma current with even larger ELMs and assess if the new system does meet its design objectives. Starting from two cases at different values of growth rate, the experimental data have, first, been reproduced, and then the ELM size has been artificially increased up to the point where the closed-loop model indicates that stabilisation would not be possible anymore. In both cases the simulations indicate that the original target of the ERFA/PCU upgrade, i.e. doubling the recovery capability up to $\Delta W = 2MJ$ at 4MA, is amply met. In fact, the model suggests that ELMs well in excess of 5MJ could be recovered at growth rate $\gamma \geq 200s^{-1}$, while at lower γ the capability could be up to ~ 8MJ with the ERFA current bias. The PCU Project, together with the ERFA upgrade, has delivered to JET a significantly improved Vertical Stabilisation system more than capable to meet the future challenges of operation in highly elongated plasmas with large perturbations to the vertical stability.

The PCU project and the integrated ERFA/VS5 commissioning have provided a full size test of application of model-based approach to design and implementation of an essential subsystem in a tokamak environment. The extensive use of predictive simulations has proved to be a very powerful method, which could be extended to ITER for the design of both the vertical stabilization and the current and shape controller. The collection of an extensive and well diagnosed database of plasma response to ELMs in plasmas with varying vertical instability growth rate can provide the ideal testbed for simulation models and allow significant progress on the estimation of the perturbations that the ITER vertical and shape controllers will be faced with. Finally, the use of the upgraded data acquisition capabilities provided by VS5 will be useful in identifying and quantifying the modelling errors in prediction of the response of the in-vessel magnetic sensors due to their proximity to the passive structures and the presence of in-vessel conductors.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the invaluable support of the JET Power Supplies and CODAS Teams. This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. H. Zohm, Plasma Physics andControlled Fusion **38**, 1996, 105–28.

[2]. F. Sartori et al., Fusion Engineering Design, vol. **83**, no. 2–3, pp. 202–206, Apr. 2008

[3]. P.L. Mondino et al., Fusion Technology 1992, Elsevier, 1993, pp. 907-911

[4]. D.Ganuza et al., Fusion Engineering Design, Vol **84** (Part A), 2009, pp 810-814

[5]. S.R. Shaw et al., this conference

[6]. A. Batista, A. Neto, M. Correia, A. Fernandes, B. Carvalho, J. Fortunato et al., Nuclear Science, IEEE Transactions on, vol. **57**, no. 2, pp. 583 –588, April 2010.

[7]. T. Bellizio et al, IEEE Transactions on Plasma Science, accepted for publication, May 2010, doi: 10.1109/TPS.2010.2053721

[8]. R. Albanese and F. Villone, Nuclear Fusion **38**(5), 1998, pp. 723-738

[9]. R. Albanese et al., this conference

[10]. J. Paméla, G.F. Matthews, V. Philipps, R. Kamendje et al., Journal of Nuclear Materials **363–365** (2007) 1–11

[11]. R. Albanese et al., accepted for publication in Fusion Science and Technology

[12]. M. Lennholm et al., in Proc. 17th SOFE Conf., vol. 1, San Diego, CA, 1997, pp. 539–542.L. Spitzer, Jr., Physics of Fully Ionized Gases (Interscience Publishers, New York, 1959) p. 20.

	VS New	**VS5**
Architecture	VME DSP RT PowerPC	4 x Core CPU
Bus	VME + C40 comms	ATCA® (Pci Express)
Processor	4 × 20MHz (C40)	4 × 3GHz (Intel®)
Input	24 channels × 12 bits – 1MHz	192 channels × 18 bits – 2MHz
Output	1	6
Language	ASM + C	C++
JET sync. err.	300µs	< 1µs

Table 1: main features of the old (VS) and new (VS5) systems

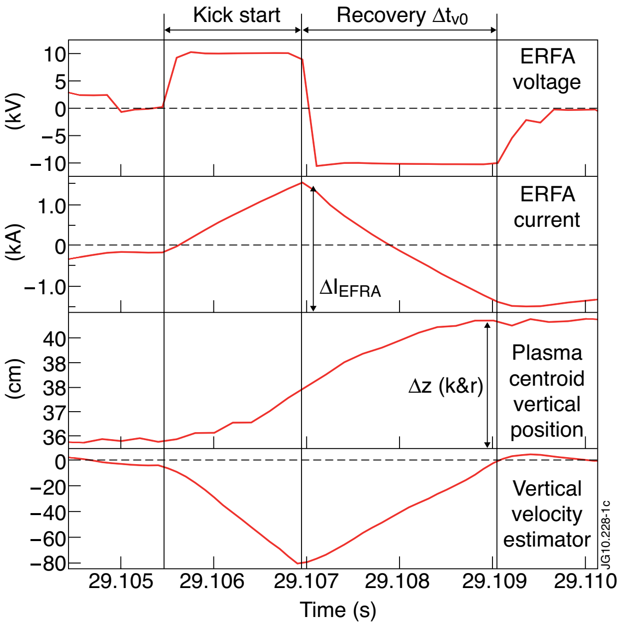

Figure 1: Time evolution of plasma and ERFA parameters during an upwards vertical kick

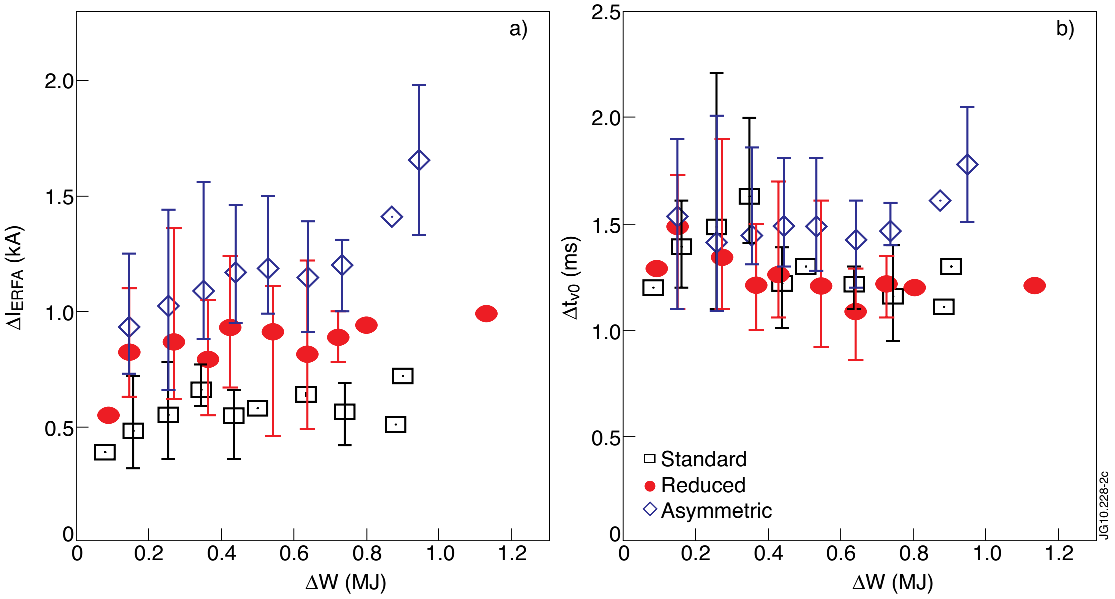

Figure 2: Quality factor Q = min(Q_5kA,Q_12kV) versus kick duration. Data for a) low and b) high growth rate equilibria. Vertical bars indicate the scatter for a given kick duration.

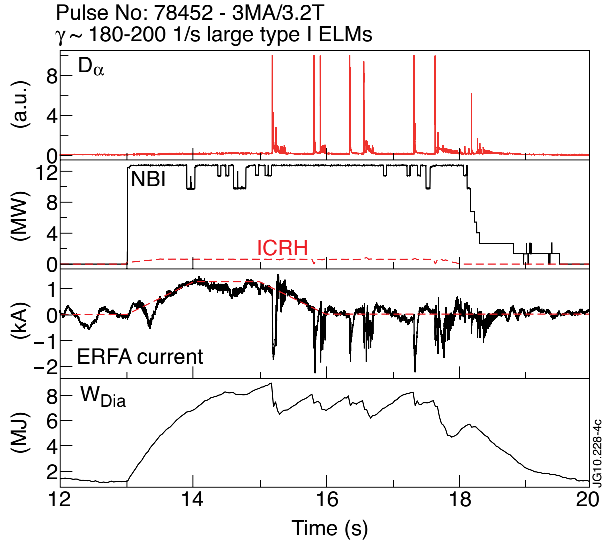

Figure 3: Giant type I ELMs with the reduced turns option for an equilibrium with γ~180-200s^{-1}

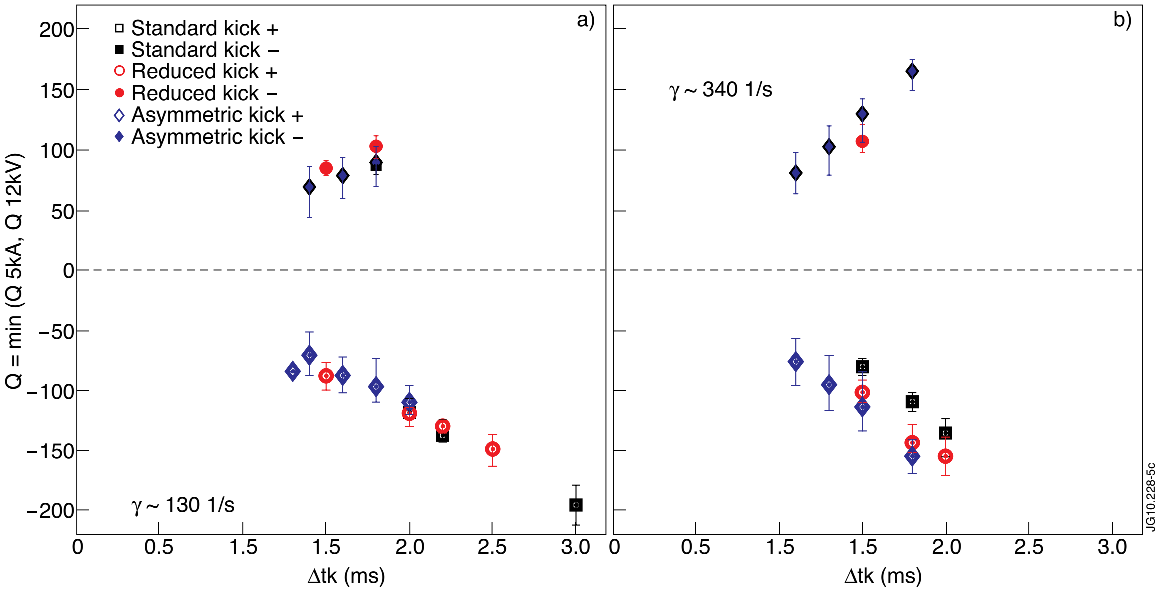

Figure 4: ERFA current swing and recovery time versus ELM energy loss (MJ) for an equilibrium with γ~180-200s^{-1}

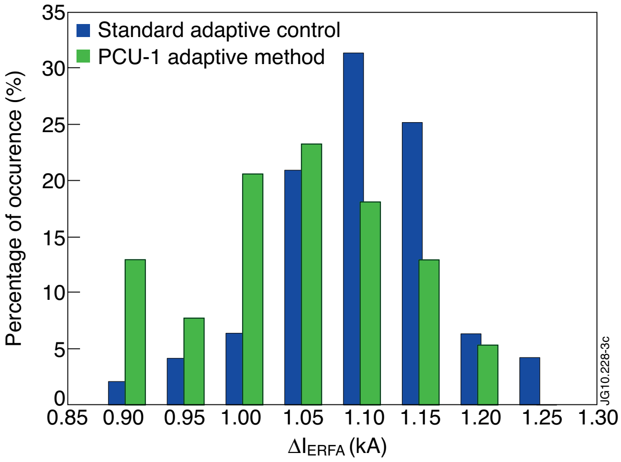

Figure 5: Current excursions after an ELM without (blue) and with (green) PCU-1 for a series of comparable ELMs.