The New JET Vertical Stabilization System with the Enhanced Radial Field Amplifier and its Relevance for ITER

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Abstract. This paper describes the experimental activities carried out at JET for the integrated commissioning of the new enhanced radial field amplifier (ERFA) and the upgraded Vertical Stability control system. This commissioning was part of the JET enhancement project Plasma Control Upgrade (PCU). The main aim of the commissioning was not only the pure test of these new components but also the optimisation of their performance on plasmas. This activity was based on the so-called model-based approach for the current, position and shape controller, which seems the most viable solution for ITER and future devices. The electromagnetic simulation models of the interaction between the plasma and the surrounding conductors was used for the design of the control system with a very limited activity of tuning of the large number of controller parameters during the experiments and a reduced risk of plasma disruptions. One of the crucial issues was the determination of the most promising option amongst three different radial field turn configurations of the radial field circuit. A significant experimental time has also been allocated to the exploration of plasma scenarios with a large variety of edge localized modes (ELMs). Many activities carried out at JET during this commissioning can be regarded as ITER relevant, and can therefore give significant indications for ITER controller design and any possible satellite experiment (like JT60-SA and FAST): assessment of controllers and power amplifiers designed using the model based approach; usage of in-vessel coils on the time scale of vertical stabilization; characterization of plasma response to the ELMs; response of magnetic diagnostics on the time scale of vertical stabilization.

1. Introduction

Accurate electromagnetic simulation models of the interaction between the plasma and the surrounding active and passive structures are required for the operation of ITER and future fusion devices. These simulation models make it possible to design the vertical stabilization system and the current and shape controller basing only on the model itself [1]. The model based approach for the controller design gives significant advantages. First of all, it is possible to take into account during the design phase of many constraints (e.g. maximum currents, maximum tolerable displacements, etc.) and of the performance targets (e.g. maximum disturbances that the control system can reject, time needed to recover from

* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

disturbances, etc.) that are requested in the experiments. In general, the more demanding the performance are, the more accurate the model describing the interactions between the plasma and the metallic external structures should be. The controllers are designed as a whole, in general their structure is quite complex, and they are specified in terms of tens or even hundreds of parameters. These controllers have multiple inputs and multiple outputs since they control at the same time various parameters in an integrated way. Almost no tuning is requested during the experimental activity and this is a great advantage since typically a limited amount of experimental time is allotted for this task. Moreover, especially when the tuning regards the vertical stabilization, there are serious risks of disruptions, which are therefore limited by the adoption of the model-based controllers. Finally, the controllers are typically designed in a so-called “robust” fashion, so as to work in various, though not too different, plasma configurations; this brings to an enlargement of the operational space of the device. Therefore, for all these reasons, the model-based approach for the current, position and shape controller seems the most viable solution for future devices.

As a relevant example of model-based approach, this paper reports on the experimental activities carried out in JET for the integrated commissioning [2] of the new enhanced radial field amplifier (ERFA) [3] and the upgraded Vertical Stability control system [4]. This commissioning was part of a more general enhancement project called Plasma Control Upgrade (PCU) [5]. The main aim of the commissioning was not only the pure test of these new components but also the optimisation of their performance on plasmas. Therefore, in the framework of the commissioning, various other activities were carried out, such as the choice of a new combination of magnetic measures, called “vertical observer”, to control the plasma vertical speed and the optimization of the gains of the controllers. Finally, as a by-product of the commissioning activity, the tests carried out during the experimental campaigns have given several hints for ITER controller design and any possible satellite experiments (like JT60-SA and FAST).

The paper is structured are follows: in Section 2 the tests carried out for the commissioning of the JET amplifier are described; Section 3 is devoted to the activities conducted during the experiments to improve the plasma performance. Finally Section 4 describes the lesson learnt for ITER. Some conclusions are drawn in Section 5.

2. Commissioning of the JET radial field amplifier

The design of a new radial field amplifier at JET was motivated by theoretical and modelling analysis of typical JET vertical displacement events (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 30% of the output voltage to ± 12 kV, in four units rated ±3 kV, and a doubling of the current capability to ± 5 kA. 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.

The new VS5 system was fully installed by the beginning of 2009. 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.

The commissioning started with plasmaless pulses so as to test the validity of the design choices and the correct installation of hardware and software. Then the tests on the plasma started with a set of configurations with increasing values of plasma current, instability growth rate, and diamagnetic energy. ERFA/V5 has been successfully tested in quiescent plasmas up to extreme cases, in slim and extreme-slim configurations, with estimated growth rates up to about 1400 s^{-1}. This constitutes a significant improvement with respect to the previous vertical system stabilizing capability which only reached $\gamma \leq 1000\ s^{-1}$.

One of the crucial issues of this commissioning activity was the determination of the most promising option amongst the *standard* (16-20-16-20), *reduced* (8-20-8-20) and *asymmetric* (16-20-8-2) radial field turns configurations. For this purpose, the performance of the vertical controller has been assessed, in each radial turn configuration, on the basis of its response to controlled perturbations in as wide a range of configurations as possible. These controlled perturbations consisted of steps of the voltages in the vertical or divertor coils, named *kicks*, typically with the vertical stabilization circuit switched off. The exploitation of kick technique is essential to fully explore the system capability in response to controlled/reproducible perturbations as safely and time-efficiently as possible. However, since controlled perturbations such as kicks cannot fully represent the most common vertical disturbance in JET plasmas, the edge localized modes (ELMs) [6], a significant experimental time has been allocated to the exploration of plasma scenarios with a large variety of ELMs. Eventually tests with big ELMs (more than 1MJ) were carried out at high plasma current (3 MA) showing the reliability of the full system that worked far from its maximum capability (Fig. 1).

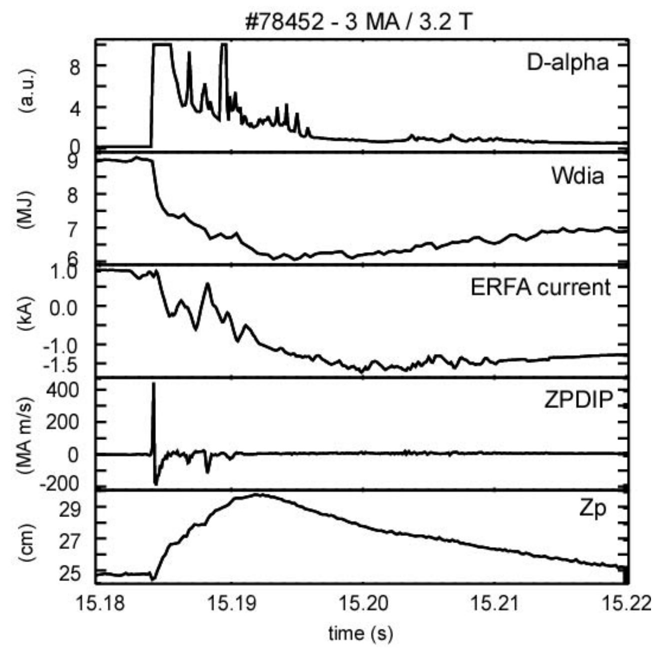


FIG. 1. Test with a large ELM with a Ip=3 MA plasma in JET pulse #78452: WDIA is the diamagnetic energy, Zp is the vertical plasma position, IERFA is the ERFA current, ZPDIP is the estimate of the time derivative of ZpIp.

The choice of the optimal turn was essentially done on the basis of the response to kicks, since they are reproducible and directly comparable. The response to ERFA kicks was compared (see Fig. 2) in terms of:

- time needed to stop the plasma after the kick (Δt)
- ERFA current needed to stop the plasma (ΔI)

In addition, the turns options have also been compared in terms of a "quality" index defined as the maximum value of Ip*Δz (kick & recovery) compatible with ERFA current, including a positive current bias, and voltage constraints.

This analysis has shown that for medium-high growth rate plasmas the best response was in the reduced 8-20-8-20 case, while the asymmetric 16-20-8-2 option gave performance only slightly worse than the reduced symmetric option. It has also been noticed that in the asymmetric option the radial movements of the plasma, in response to a vertical kick or an ELM, are significantly larger than in the symmetric case. Moreover, the asymmetric choice could potentially be a risk for the Radial Field coils insulation because of its higher inter-turn voltage, very close to the maximum admissible value.

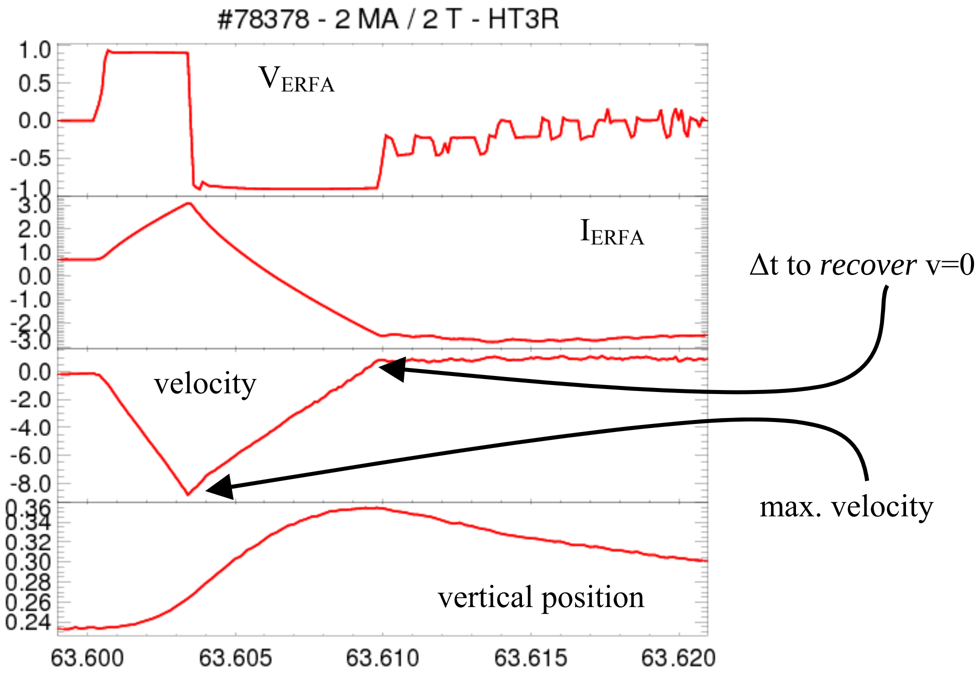


FIG. 2. Criteria used for the determination of the optimal turn option

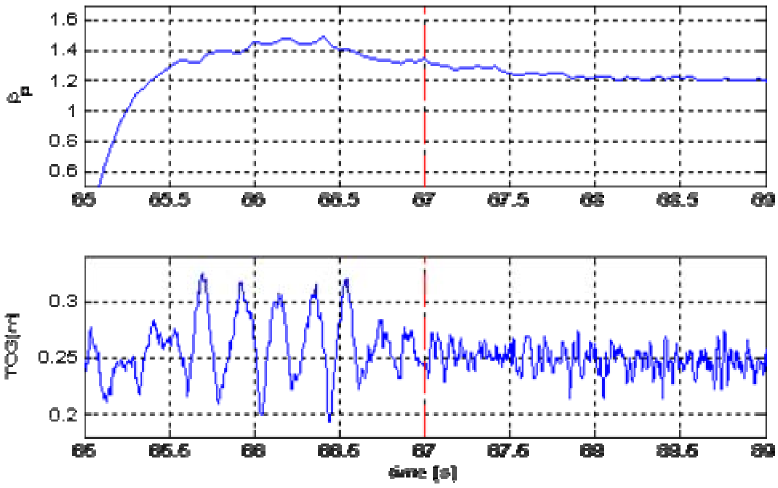
3. Improvement of plasma performance

Besides the commissioning, the activities focused also on characterizing the specific behaviour of the new controller, namely the test of a variety of observers and the tuning of the controller parameters.

For what concerns the new controller, the activities have been essentially focused on the following aspects:

- tuning of the controller parameters with the new amplifier and for the different turn options;
- testing of innovative controller features;
- reduction of the interaction between shape control and vertical stabilization systems, which in some cases yielded undesired oscillations.

The simulations led to understanding the mechanisms behind the undesirable plasma vertical low frequency (5-10 Hz) oscillations as well as predicting their amplitude and frequency. The predictions showed that the oscillations can be reduced by increasing the value of the current gain of the VS system. This fact was validated in the experiments as shown in Fig. 3, thus confirming the reliability of the model-based approach to design the position and shape control, without resorting to any tuning during the experiments.



(40 s to be subtracted from time values)

FIG. 3. Experimental behaviour of TOG (top gap) in pulse #74756 when changing the current gain from 5000 to 10000; the amplitude of the oscillations increases at higher poloidal beta; when increasing the current gain the amplitude of the oscillations decreases while the frequency becomes higher.

Particular attention was devoted to the selection of the linear combination of the magnetic measurements which gives an estimate of the plasma centroid vertical speed, tuned so as to minimize its sensitivity to ELMs and fast plasma movements, but retaining the controllability of the plasma.

The development of a new observer has been undertaken in response to a study of the impact of the installation of the ITER-Like Wall on the magnetic measurements used by VS and the consequent significant filtering of the response of the coils located behind the upper dump-plate. The main requirement of the new vertical speed estimator is to avoid the contribution of the magnetic signals coming from the sensors placed behind dump plates and to have scarce sensitivity to ELMs and fast plasma movements.

To minimize the impact on JET operation, it was decided to keep the same structure of the estimator and retain the same controller parameters. Therefore, the new observer should have the same response as ZPD-IP to the ERFA voltage, so as to maintain the closed-loop stability. In particular the same behaviour as ZPD-IP has been imposed:

- for a quiescent plasma, so as to have the same response as ZPDIP to the ERFA voltage when excited by ERFA in the time domain;
- during a VDE, so as to have the same sensitivity to the unstable mode.

The requirements to guarantee the same behaviour as ZPDIP are therefore imposed via pseudo-inversion of experimental and/or simulated data in the time domain.

This new combination of magnetic signals, called Obs05 (see Fig. 4), satisfies the design requirements; moreover with the new choice of the controlled variable the ERFA current excursions are reduced of about 40% with respect to ZPDIP. The new controlled variable has, since, become the default for normal S/T JET operation [7].

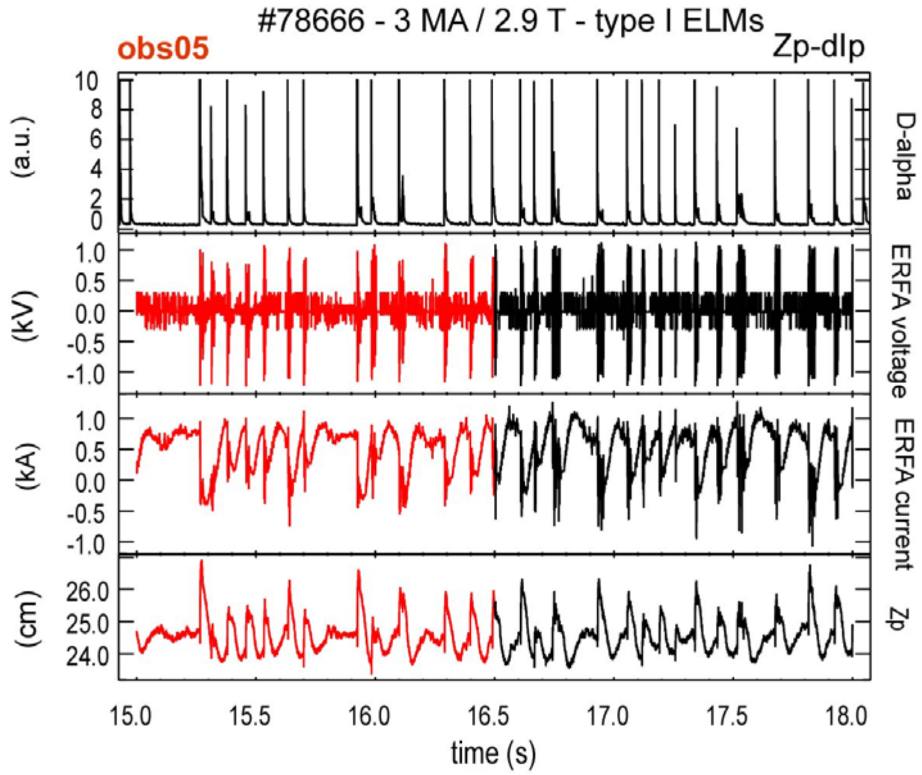


FIG. 4. Comparison between new (Obs05) and standard (ZpdIp) vertical observer

4. Relevance for ITER

Many activities carried out at JET during this commissioning can be regarded as ITER relevant, and can therefore give significant indications for ITER controller design and any possible satellite experiment (like JT60-SA and FAST).

4.1. Model-based approach for the controller design

As already discussed, this commissioning has been an example of the powerfulness of the model-based approach for the design of the current, position and shape control. The first step for this approach is the availability of a model describing the electromagnetic interactions between the plasma and the metallic structure which must be reliable. Therefore these models need to be validated against experimental data, which they must be able not only to reproduce but also to predict. On the other hand, since these models are the starting point for the design of the controller, their complexity needs to be kept as low as possible. As a consequence the models most commonly used are linearized models with a number of state variables which does not usually exceed 2 or 3 hundreds. The models include simplified schemes of the power supplies and of the diagnostic systems.

One of the problems arising in the modelling activity is the fact that due to the proximity to the passive structures and the presence of in-vessel conductors, the prediction of the response of the in-vessel magnetic sensors and the identification of plasma position and speed are not as accurate as on the time scale of the shape control. The comparison between the predictions and the signals provided by the upgraded data acquisition system V5 [8] can be used to quantify the modelling errors. This is helpful for ITER, where the eddy currents play a significant role for on-line plasma identification, vertical stabilization and shape control. Model predictions and experimental V5 data allowed to satisfy all design requirements for the new controlled variable Obs05, which was successfully tested without any further adjustments (Fig. 4).

The results of the commissioning activity have clearly shown that the separate design of the vertical controller on one side and of the shape controller on the other can give rise to undesired coupling between the control systems. As a consequence two possible approaches can be followed: either the controller is designed all together, or the shape controller is designed after the vertical controller, but taking into account the modifications of the plasma behaviour due to the vertical stabilization system. The commissioning phase has also clearly shown that the coils placed inside the vessel (the divertor coils at JET) because of the absence of the shielding effect of the vessel, might be very useful for the vertical stabilization. Unfortunately, at JET the in-vessel coils cannot be fully exploited for vertical stabilization, since the power supply response is on the time scale of about 5 ms. However, the data collected during the tests made at JET with divertor kicks are also relevant for ITER since in ITER the usage of "in-vessel" coils is envisaged for the plasma vertical stabilization.

4.2. Definition of disturbances

One of the problems that need to be faced when coping with the design of a vertical and shape controller is to define which kind of disturbances should be counteracted during plasma operation. This list of disturbances becomes more challenging to compile when referring to a tokamak, like ITER, which has not been built yet. A possible approach is then to scale, in an appropriate way, similar disturbances occurring on operating tokamaks. ELMs are amongst the most significant disturbances foreseen during ITER operation. A large part of the ERFA commissioning has been based on the response of the plasma to "small" and "big" ELMs. This activity has given the opportunity of creating a sort of database of ELMs in various configurations. Therefore these ELMs can give indications of possible perturbations that should be counteracted in ITER by the vertical and shape controllers.

4.3. Activities for the breakdown

Due to the necessity of changing the turns of the radial field circuit, an effort was dedicated to make predictions of the static and dynamic vertical and radial field required for breakdown. The reconstructions were successfully compared with the experimental evolution of the field and passive currents estimations signals being able to follow the dynamics of the first phases of the breakdown. The flux map simulations were also in good agreement with the new fast visible video camera images [9], showing that it is possible to reliably predict and in principle optimize the region of plasma formation. This activity could be extremely useful for ITER, where the eddy current effects are significant, and in addition there is no dedicated transformer circuit, and the breakdown is to be obtained by acting simultaneously on several circuits.

5. Conclusions

The Plasma Control Upgrade project and the related enhancement of the Radial Field Amplifier aimed at providing the JET tokamak with a significant improvement in its vertical stabilisation capability in high performance conditions. Throughout its life this project relied heavily on modelling activities both to guide the design of the new VS controller and to assess regularly the expected performance of the new system. Eventually, the model-based approach was also used to influence the planning of the integrated commissioning of the system. The Plasma Control Upgrade (PCU) project and the integrated ERFA/VS5 commissioning have, thus, provided a full size test of the application of a model-based approach to design and implementation of an essential subsystem in a tokamak environment and demonstrated clearly the benefits of an approach based on phased commissioning, modelling and offline algorithm validation in terms of machine safety and optimisation of the use of experimental time.

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