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ABSTRACT:
This paper describes the procedure adopted for the selection of an alternative controlled variable to be used for the vertical stabilization of elongated plasmas in the JET Tokamak in the framework of the Plasma Control Upgrade (PCU) activities. The PCU enhancement project, aimed at increasing the capabilities of the Vertical Stabilization (VS) system, explored the possibility of having a valid alternative to the controlled variable ZPDIP used for several years. This study was mainly aimed at improving the VS capabilities by reducing the effect of Edge Localized Modes (ELMs) on the vertical position estimator. An additional motivation was the need of operating JET in future campaigns with the new ITER-Like Wall (ILW), which is expected to significantly shield some magnetic diagnostics. The alternative controlled variable was also planned to play the role of back-up solution in case of troubles with the standard one after the modifications of the radial field circuit. The selection was made paying particular attention to robustness, reliability, and reduced impact on the ongoing experimental campaigns. The new controlled variable, denoted as OBS05, was successfully tested in JET on a variety of plasma scenarios and became the new vertical velocity estimator for VS system.

1. INTRODUCTION

The most promising device for magnetic confinement is the Tokamak [1], a toroidal machine where the plasma is heated in a ring-shaped vessel and kept away from the vessel walls by applied magnetic fields (Fig. 1). To achieve high performance in tokamaks, plasmas with elongated poloidal cross-section are needed. Since such elongated plasmas are vertically unstable, position control on a fast time scale is clearly an essential feature of all machines.

The Plasma Control Upgrade (PCU) [2] project aimed at increasing the capabilities of the Vertical Stabilization (VS) system to recover from large Edge Localised Mode (ELM) perturbations, in particular for the case of plasmas with high elongation, i.e. plasmas with large instability growth rates [3].

The main aims of the PCU project were:

- the design of the new power supply for the radial field circuit, to assess the system performance for different choices of the maximum amplifier voltage and current [4] and then procure and install the "Enhanced Radial Field Amplifier" (ERFA) [5];
- the assessment of the best choice for the turns setup of the poloidal field coils used for vertical stabilization;
- the design of the new VS control algorithm, to optimize the controller parameters for the different operative scenarios provided by the physicists;
- the enhancement of the hardware architecture to get all the magnetic measurements (V5) available with low latency to a modern powerful processor [6].

The VS is one of the most critical systems at the JET Tokamak, since uncontrolled vertical instabilities may be responsible of large mechanical loads on the vacuum vessel. It is responsible for guaranteeing a zero average vertical velocity of the plasma while at the same time trying to keep the average radial field current to a reference value [7]. The stabilisation is obtained by using a velocity and a current control loop. Since the vertical velocity of the plasma cannot be directly measured, an estimator is required capable of translating the magnetic signals into vertical velocity. The main requirement of the VS system is to stabilize the system, and the task of keeping the plasma in its nominal configuration is left to a shape control system that operates on a longer time scale.

The VS system uses 32 magnetic measurements, coming from sets located in four different octant (Fig.2), each including 18 internal discrete tangential field sensors, situated inside the vacuum vessel and 14 saddle loops (namely CX1, ...,CX18, SX1, ...,SX14 where X = 1,3,5,7 depending on the octant), originally utilized to estimate the vertical plasma velocity by means of the following relationships [8]:

$$\frac{dI_P}{dt} = \frac{1}{\mu} \oint \frac{dI_t}{dt}\, ds \approx \sum_{k=1}^{N_{mag}} w_{0k}\, m_k \tag{1}$$

$$\frac{d(Z_P I_P)}{dt} = \frac{1}{\mu} \oint \left[Z \frac{dB_t}{dt} - R \log\left(\frac{R}{R_0}\right) \frac{dB_n}{dt} \right] ds \approx \sum_{k=1}^{N_{mag}} w_k\, m_k \tag{2}$$

where I_P is the plasma current, Z_P the vertical position of its centroid, R the radial coordinate, Z the vertical coordinate, R_0 the major radius of the chamber, t the time, B_t and B_n the tangential and normal component of magnetic flux density, respectively.

With a finite number, , of magnetic measurements, m_k, of time derivatives of magnetic fields, line integrals (1)-(2) can be approximated as linear combinations of these signals with suitable weights w_{0k}*'s* and w_k*'s*. After the introduction of the divertor coils D1-4 and the installation of MK2 conducting structure inside the vessel (Fig.1b), the magnetic measurements coming from magnetic field sensors placed on the lower part of the machine are not only behind currents flowing inside the vessel but also significantly affected by the noise of the amplifier. The pick-up coils in the lower region were then discarded, and the remaining weights were readjusted. The resulting combination provides a rough estimate of (2) at slowly varying plasma current, denoted as ZPDIP, which is obviously inaccurate. Nonetheless, the VS system successfully works with feedback on ZPDIP, which is an output correlated to the unstable mode.

In principle, additional magnetic measurements located at different positions in the poloidal plane RZ might be used for VS diagnostics. However, these additional in-vessel sensors are located at only two toroidal locations and it is not possible therefore to compensate for non-axisymmetric n = 2 plasma perturbations.

Attempts at VS control have been done at JET using nonmagnetic measurements, e.g. soft X-rays. The so-called full current moment method was also tested. However, there was a prejudice that these techniques would not be reliable enough for routine operation or would deal with ELMs and therefore the idea was not followed up beyond the first test [9].

A major goal of the PCU enhancement project was to determine whether a better vertical velocity estimator could be designed compared to the semi-empirical ZPDIP used for many years. This study was mainly aimed at improving the VS capabilities by reducing the effect of Edge Localized Modes (ELMs) on the vertical position estimator. An additional motivation was the need of operating JET in future campaigns with the new ITER-Like Wall (ILW), which is expected to significantly shield some magnetic diagnostics. The alternative controlled variable was also planned to play the role of back-up solution in case of troubles with the standard one after the modifications of the radial field circuit. The selection was made paying particular attention to robustness, reliability, and reduced time allotted for dedicated tests so as to limit the impact on the ongoing experimental campaigns. The new controlled variable, denoted as OBS05, was successfully tested in JET on a variety of plasma scenarios and became the new vertical velocity estimator for VS system.

This paper presents the study that led to the implementation of the new controlled variable OBS05, selected using the technique presented in [10], paying attention to the following aspects: i) improvement of the procedure taking into account the range of frequencies of interest and using upgraded response model and experimental acquisition system; ii) reduction of the impact of in-vessel currents; iii) choice of a set of weights usable for a wide range of plasma configurations.

Section 2 discusses the effects of the dump plates on the magnetic sensors. Section 3 describes the procedure used for the selection of the weights. Section 4 illustrates the experimental results. Finally, Section 5 reports the main conclusions.

2. EFFECTS OF DUMP PLATES ON MAGNETIC SENSORS

The standard VS controlled variable used during JET operation use only the first nine pick-up coils (Fig.2), placed on the higher part of the machine.

A closer analysis shows that the INCONEL dump plate structure of the first wall in JET placed on the top of the machine has a shielding effect with an electromagnetic time constant of about 1ms.

Internal discrete coils C105 and C106 are placed behind the INCONEL dump plate structures. Fig. 3 shows the response of the magnetic sensors, which measure the time derivative of the flux density, to a voltage step applied to the external radial field circuits. For magnetic sensor C104, which is not behind the plate, the time behaviour is completely different in the two cases with and without the plasma. On the other hand, internal discrete coil C105 does not see the movement of the plasma for about 350 ms. Moreover, a 2D analysis carried out by using the CREATE-L perturbed equilibrium approach [11] confirms the effect of the dump plate structure on pick-up coil #5. Figure 3 shows the time response of internal discrete coils #4 and #5 to a voltage step applied to the radial field circuit. The motion of the plasma, which is perceived immediately by other diagnostics, affects the time behaviour of coil #5 only after about 350μs, in which the time behaviour is similar to a plasmaless pulse since the signal is mostly dominated by the field trapped between vessel and dump plate.

In the future a full replacement of JET first wall materials is planned, with beryllium in the main wall and tungsten in the divertor region [12]. This has a potential impact on the diagnostics and control of JET vertical stabilization system. The effect of the new tiles in the divertor region on pick up coils in the divertor could be significant for shape control. However, for reason given earlier, these are not used for vertical stabilization and therefore need not be considered further. The limiter tiles are rather small, and attached to the existing INCONEL beams. In addition to the INCONEL support structure of the dump plates considered above, the beryllium tiles are mounted on new thick INCONEL carriers. Even where there are no beryllium tiles the original INCONEL support structure is protected by new thick INCONEL plates. The beryllium tiles, about 40mm thick, will form two rails, but they will be castellated, hence an equivalent thickness of 20mm can be assumed (Fig.4). The electromagnetic time constant of a dump plate with the beryllium tiles has been estimated to be about 7 ms by CARIDDI [13]. In principle, there is cause for concern, as the vertical stabilization system has to work on a time scale much faster than 1 ms. Thus, a new VS controlled variable might be needed with the new ILW.

3. SELECTION OF THE VS CONTROLLED VARIABLE

The new VS controlled variable OBS05 should avoid the contribution of the magnetic signals coming from the sensors placed behind the dump plates and have scarce sensitivity to ELMs (edge localised modes) [14] and fast plasma movements that are not expected to excite the unstable mode, e.g. radial motion.

To minimize the impact on JET operation, it was decided to keep the same frequency response as the standard VS controlled variable ZPDIP so as to avoid redesign of the controller algorithm and gains.

The requirement that the response to the radial field circuit of OBS05 is the same as ZPDIP was then imposed via pseudo-inversion of experimental and/or simulated data in the time or frequency domain. The design procedure utilized to define the weights of OBS05 is similar to the technique presented in [10]. The controlled variable CREATE_A proposed in [10] was mainly aimed at verifying the design procedure and addressed the reduction of the influence of the ELMs for a particular plasma configuration. In contrast, the weights of OBS05 were selected so as to be usable for a wide range of plasma configurations, taking into account the range of frequencies of interest, using upgraded response model and experimental acquisition system, and reducing the impact of in-vessel currents.

3.1 MODELS AND EXPERIMENTAL DATA

The design procedure of the new VS controlled variable makes use of linearized response models and experimental data. The linearized CREATE-L plasma response model provides the response of the 128 magnetic signals (32 from each octant) to various inputs and as shown in Fig.5 the agreement between simulations and experimental data is good and adequate for the present study [10].

The linearized model is in some cases preferred to the use of experimental data because it is available for any configuration of plasma, the frequency domain analysis is straightforward and it is possible to split the different contributions acting on the plasma. The disadvantages when using the linearized model are the modelling errors, whereas the limitation of the experimental data is that they are available at a sufficiently high sampling rate only for experimental discharges carried out after the upgrade of the data acquisition system V5 (from Pulse No: 76278). The modelling errors are essentially due to the equivalent axisymmetric approximation of 3D conducting structures and to the uncertainties in the plasma current profile parameters.

Taking account of the above merits and limitations, both experimental data and linear models were used for the present study.

The linearized CREATE-L model was used especially for frequency analyses, whereas the experimental data were utilized in the time domain.

3.2 REQUIREMENTS

The procedure illustrated in [10] requires the alternative controlled variable to have the same response as ZPDIP to the ERFA voltage, so as to maintain the closed-loop stability. This is not strictly necessary, since different transfer functions can be compatible with a suitable control scheme. However, this requirement was imposed for OBS05, because it was extremely useful to avoid redesign of the control system architecture and adaptive selection of the control gains.

The shielding effect expected by the ILW is significant only on the in-vessel pick-up coils. In addition, the possible improvements of the behaviour of the controlled variable are expected immediately after the occurrence of an ELM, i.e., on the fast time scale (about 1 ms) in which only the in-vessel pick-up coils are affected. For these reasons, it was decided to take the same weights as ZPDIP for the saddle fluxes, which are shielded by the eddy currents in the vessel.

A thorough analysis of the CREATE_A behaviour showed that:

- CREATE_A has not the same response as ZPDIP at the frequencies of interest for a wide set of plasma configurations (Fig.6);
- CREATE_A has nonzero weights (Fig.7a) for the sensors located in the lower part of the vessel, so it is very sensitive to a voltage kick applied to the divertor coils (Fig.7b), which is a capability of the new VS software [6].

Thus, the OBS05 weights (Fig.7a) were selected by imposing the following constraints:

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

Moreover OBS05 should show behaviour as close as possible to ZPDIP:

- for a quiescent plasma, so as to have the same response as ZPDIP to the ERFA voltage when excited by ERFA amplifier (Fig.8a);

- during a Vertical Displacement Event (VDE), so as to have the same sensitivity to the unstable mode (Fig.8b).
- during plasma current ramp up and ramp down phase (Fig.8c);
- during H-L transition (Fig.8d).

Finally, to improve the capabilities of the VS system, OBS05 should have a better response to an ELM and be less sensitive to the divertor switching power supply noise at 300Hz [10]. As shown in Fig.9a, the sign of ZPDIP is positive for a time interval $\Delta\tau \approx 300$ms and then negative for much longer, thus giving rise to an equivalent delay of $\Delta\tau_{eq} \approx 2\Delta\tau$ in the stabilizing action. Fig.9b shows the 300Hz noise due to the power amplifiers feeding the in-vessel coils in a plasmaless pulse when the ERFA voltage is zero. Therefore the weights of OBS05 should be selected so as to eliminate or at least reduce:

- the initial spike with the wrong sign shown by ZPDIP (Fig.9a).
- the divertor switching power supply noise at 300Hz in plasmaless pulses (Fig.9b).

3.3 DESIGN PROCEDURE AND EXPECTED PERFORMANCE

Due to the above constraints, the unknown weights are only seven. The determination of these weights was made paying particular attention at the typical VS operating frequencies. To this purpose, the experimental data of Pulse No: 78398 with a 1.5MA quiescent plasma having a growth rate of about 300 s^{-1} were extremely useful. This particular pulse was in fact aimed at estimating the phase margin and the crossover frequency of the VS stabilization loop [15].

It was then decided to maintain the closed-loop stability by imposing the time behaviour of OBS05 to match that of ZPDIP in the time interval from 26.03s to 26.08s of Pulse No: 78398 (Fig.10), in which plasma oscillations at the frequency of about 400Hz were deliberately excited. The weights were selected via pseudoinversion taking into account only the first two singular values, as the ratio between the third and the first one did not exceed 12%. The five independent combinations of weights obtained with the remaining singular values, were reserved as extra degrees of freedom to be used to match the dynamic response to ERFA voltage in other conditions as well as the additional requirements. However, this turned out to be unnecessary.

As shown in Figs. 6-8 in terms of dynamic response to voltage inputs applied to the radial field circuit and to divertor coils, there is a very good agreement between OBS05 and ZPDIP not only in pulse #78398 (Fig. 10), but also for a variety of configurations, scenarios, and conditions.

In particular Fig. 8b shows that the difference between OBS05 and ZPDIP is within 7% till 26.02, when the plasma displacement is more than 40 cm; the sensitivity to the unstable mode has also been tested on the linearized models of Fig. 6 and the discrepancy between ZPDIP and OBS05 was within ±5%.

In addition, Fig.9a shows that after an ELM the positive spike of OBS05 is smaller than ZPDIP and that OBS05 is also less sensitive to the 300Hz power amplifier noise. Consequently a lower excursion of ERFA current was expected when using OBS05 instead of ZPDIP, even if there is probably room for further optimization after a better understanding of the electromagnetic effects of an ELM on the VS system.

The time behaviours illustrated in Figs.7-10 were of course reconstructed offline. The software of the new JET VS system allows online acquisition of different combinations of magnetic signals. After selection of the OBS05 weights, the online OBS05 signal was then acquired and compared to ZPDIP, which was still used as feedback variable, so as to test the validity of procedure (Fig. 11) and the correct implementation in the control system of JET, before closing the loop on OBS05.

4. EXPERIMENTAL RESULTS

The alternative VS controlled variable OBS05 was then successfully tested in feedback during several VS experiments in JET. To minimize the impact on JET operation and to avoid dangerous disruptions, OBS05 was initially tested during ramp down at low plasma current (Fig.12).

Afterwards, OBS05 was successfully tested for one second in the quiescent low beta current flat-top phase of a 1 MA discharge. The signals coming from OBS05 and ZPDIP were nearly coincident also using OBS05 as controlled variable.

The controlled variable OBS05 was finally tested during the H-mode phase. As expected from the analysis of giant ELMs (Fig. 9a), the behaviour of OBS05 was better than ZPDIP. This is demonstrated by the experimental data collected in the ELMy phases of Pulse No's: 78665 and 78666. The average excursion of ERFA current was about 40% less in Pulse No: 78665 after 16.5s, i.e., when OBS05 replaced ZPDIP as feedback variable (Fig.13a). This was confirmed in pulse Pulse No: 78666 (Fig. 13b), an experiment with the same scenario as Pulse No: 78665, with the only difference that after 16.5s ZPDIP replaces OBS05.

Indeed OBS05 was experimentally tested in a variety of scenarios and conditions: Fig.14 shows different pulses where OBS05 was the controlled variable for the VS system and ZPDIP was in open loop. All these experimental results confirm the predictions obtained using the modelling approach.

After these validation tests, in the remaining part of the JET experimental campaign OBS05 was used as preferred VS controlled variable.

CONCLUSIONS

The alternative controlled variable OBS05 has been proposed and successfully tested on the vertical stabilization system of JET.

This study was mainly aimed at improving the VS capabilities by reducing the effect of Edge Localized Modes (ELMs) on the vertical position estimator. An additional motivation was the need of operating JET in future campaigns with the new ITER-Like Wall (ILW), which is expected to significantly shield some magnetic diagnostics. The alternative controlled variable was also planned to play the role of back-up solution in case of troubles with the standard one after the modifications of the radial field circuit.

The selection was made paying particular attention to robustness and reliability.

The new controlled variable OBS05 was successfully tested in JET experimental campaign on a variety of plasma scenarios and was then used as preferred VS controlled variable. To minimize the impact on the ongoing experimental campaign, OBS05 was required to reproduce the same behaviour as ZPDIP in most normal operation conditions, whilst reducing the sensitivity to the initial phases of ELMs, so as to avoid modification of VS controller architecture and gains.

The behaviour of OBS05 was better than ZPDIP in the ELMy phases of some pulses, yielding a significant reduction (about 40%) of the excursion of ERFA current.

The selection of the weights was made via singular value decomposition exploiting experimental data and tested on both additional experimental data and simulations based on linearized plasma response models. The independent combinations of weights corresponding to the discarded singular values can be used as extra degrees of freedom for further optimization of the closed loop response.

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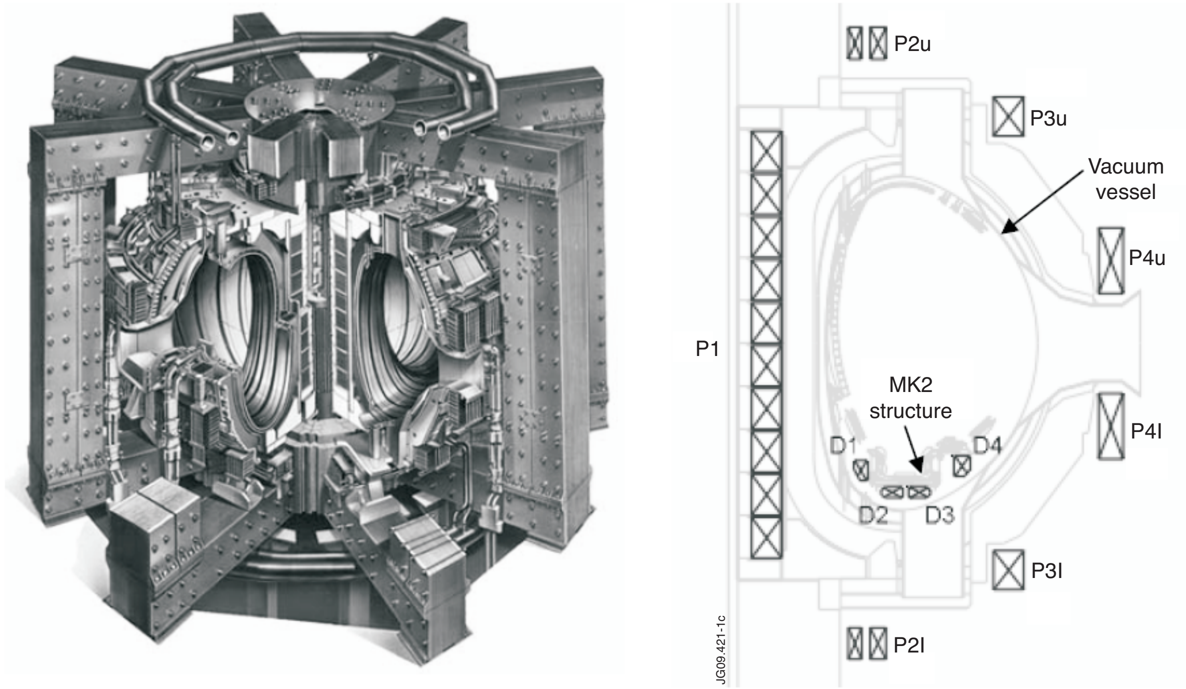

Figure 1: The JET Tokamak: a) 3D view; b) poloidal cross section (EFDA-JET images).

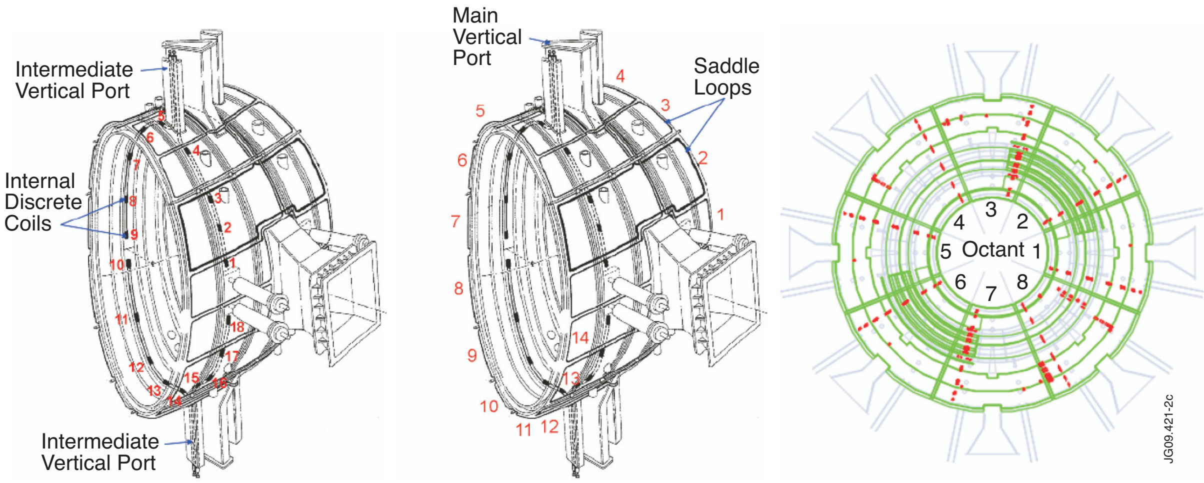

Figure 2: The JET Tokamak: locations of pick up coils and saddle loops used for the vertical speed estimation, available in octants 1, 3, 5 and 7 (EFDA-JET images).

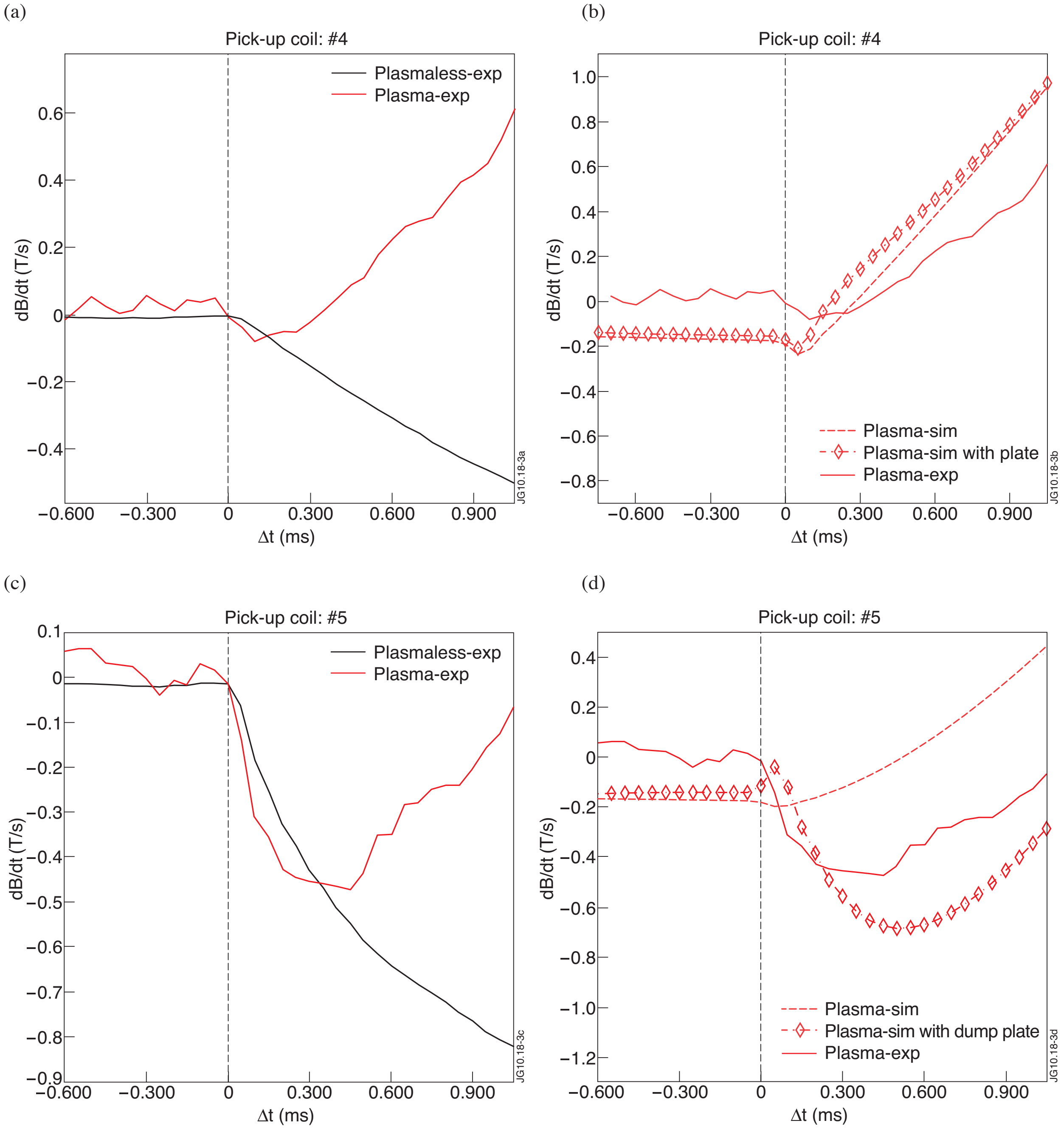

Figure 3: Response of internal discrete coils #4 and #5 to a voltage step applied to the radial field circuit at $\Delta\tau = 0$ ms, showing the effect of the INCONEL dump plate structure: a) coil #4 signal in a plasmaless pulse; b) coil #4 signal in a plasma pulse; c) coil #5 signal in a plasmaless pulse; d) coil #5 signal in a plasma pulse. The motion of the plasma, which is perceived immediately by other diagnostics, affects the time behaviour of coil #5 (behind the structure) only after about 350 ms, in which the time behaviour is similar to a plasmaless pulse. This is confirmed by numerical simulations. The experimental data refer to plasmaless Pulse No: 76241, in which $\Delta\tau = t$-38.1141s, and to the 2MA plasma Pulse No: 76196, in which $\Delta\tau = t$-18.3280s.

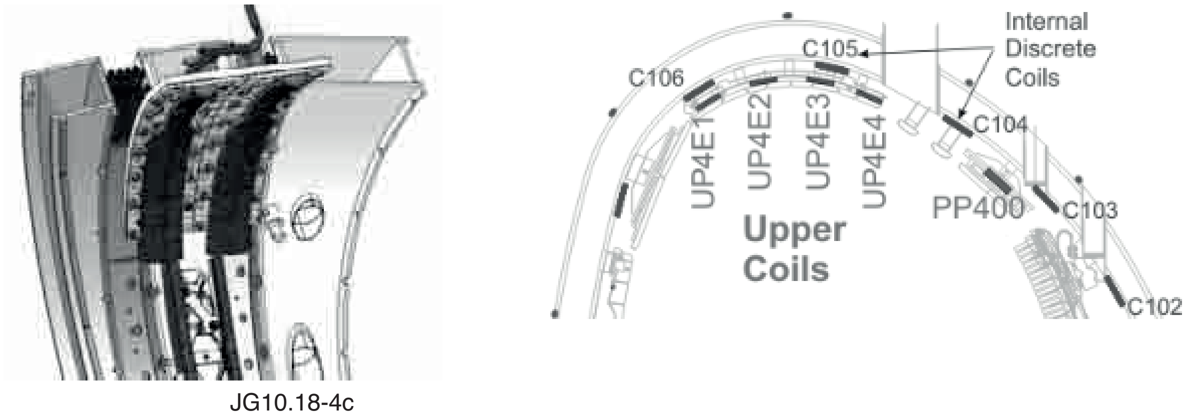

Figure 4: Dump plates and beryllium tiles to be installed at JET (left) and position of the discrete coils used by the vertical stabilization system (right). Internal discrete coils C105 and C106 are behind the existing dump plate.

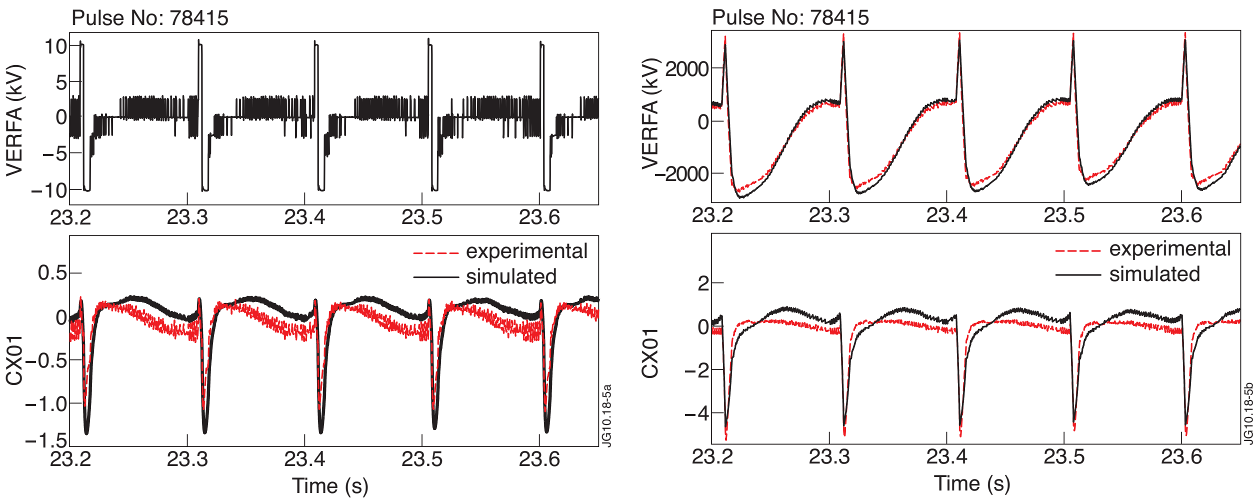

Figure 5: Time response of coil signals (T/s) and ERFA current to ERFA voltage in Pulse No: 78415: comparison between simulations with the CREATE-L model and experimental data.

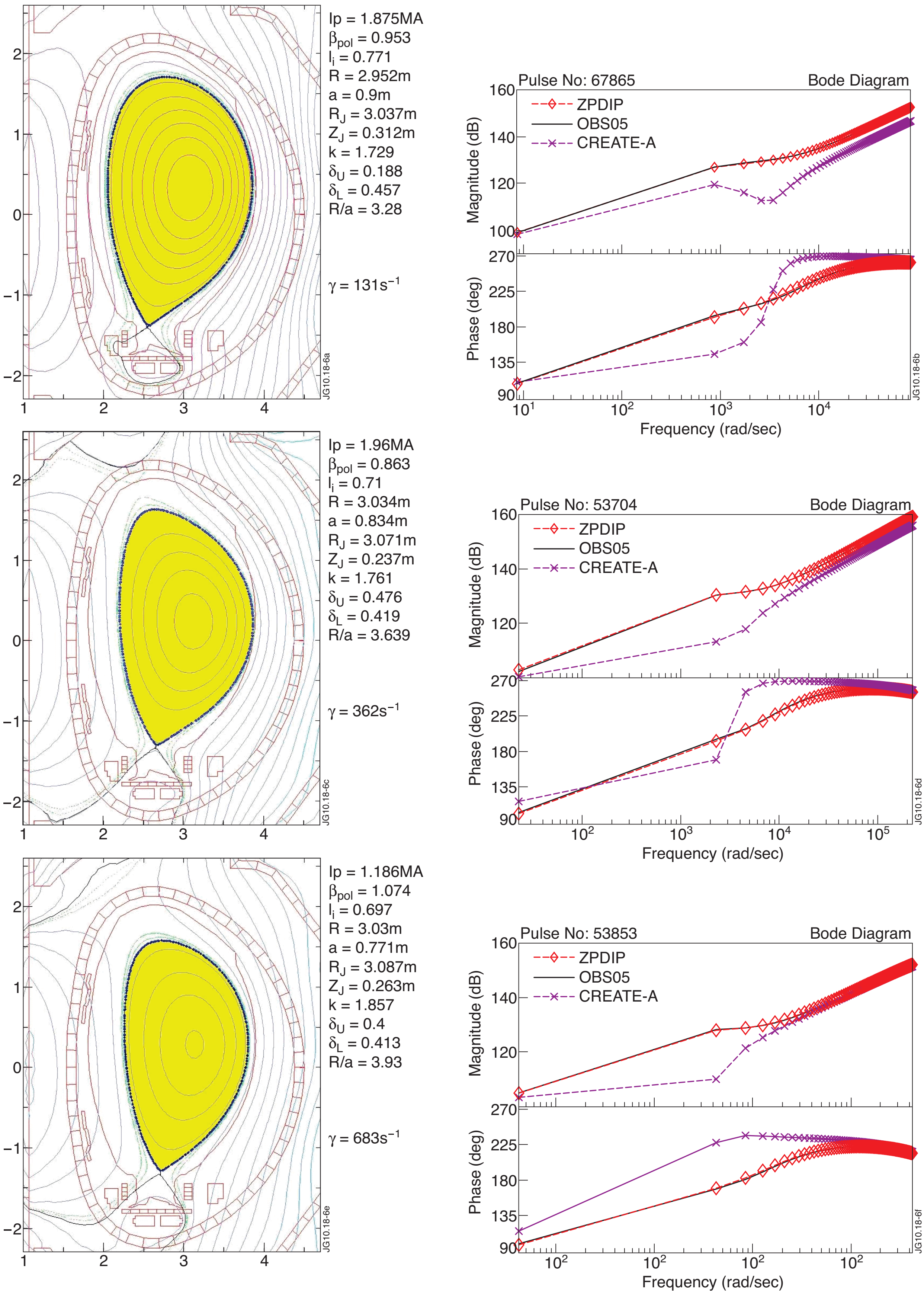

Figure 6: Bode plots: frequency response of ZPDIP, OBS05 and CREATE_A to VERFA for various configurations with different growth rates of the vertical instability: a) Pulse No: 67865 @ 8.490s, $\gamma = 131s^{-1}$; b) Pulse No: 53704 @ 22.840s, $\gamma = 362s^{-1}$; c) Pulse No: 53853 @ 30.080s, $\gamma = 683\ s^{-1}$.

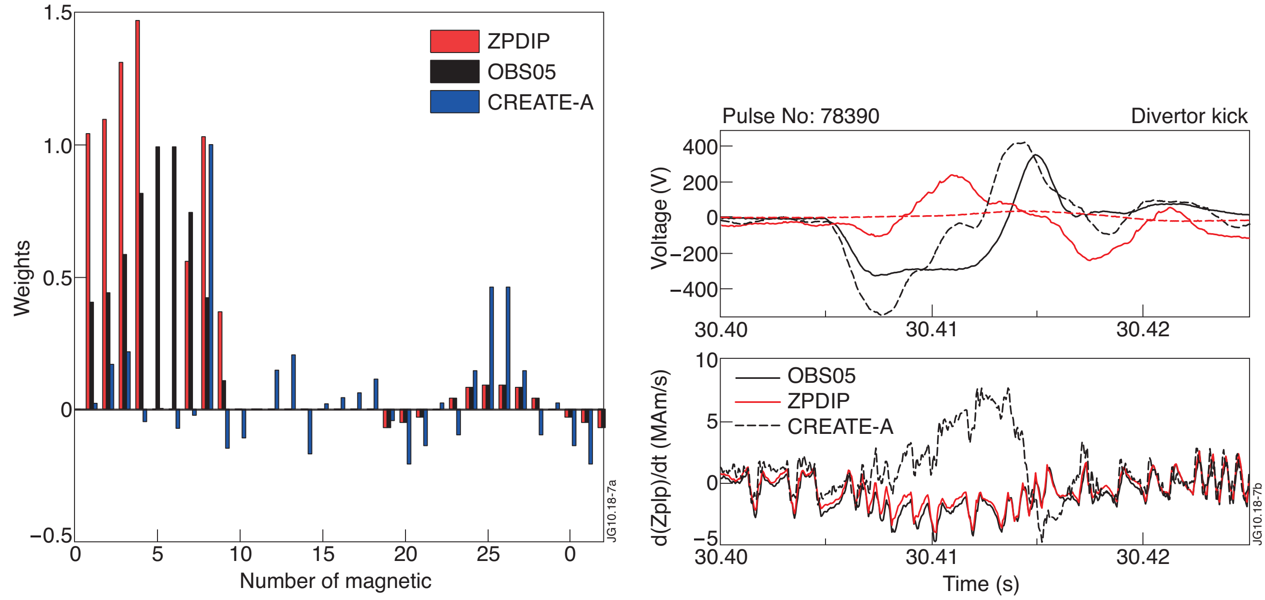

Figure 7: Comparison between ZPDIP, OBS05 and CREATE_A: a) weights applied to the signals coming from the 18 pick-up coils and the 14 saddle loops; b) response to divertor coil amplifier voltage inputs in Pulse No: 78390, in which the VS control loop was closed on ZPDIP.

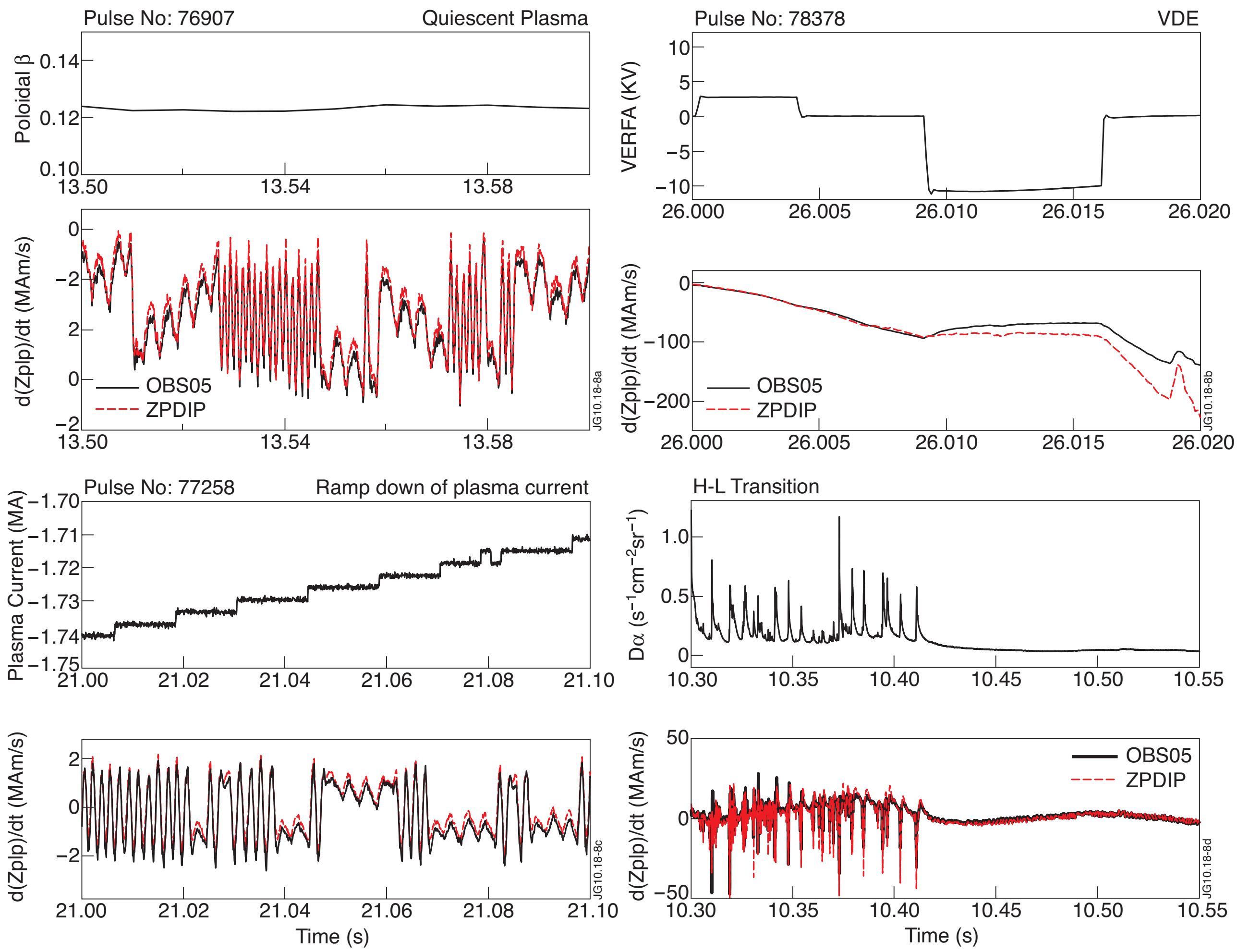

Figure 8: Comparison between OBS05 (black) and ZPDIP (red) in conditions where the requirements asked for similar behaviours: a) quiescent plasma - Pulse No: 76907; b) vertical displacement event - Pulse No: 78378; c) ramp down of plasma current - Pulse No: 77258; d) H-L transition - Pulse No: 76907. In all cases ZPDIP was the controlled variable; e) Plasmaless Pulse No: 76241.

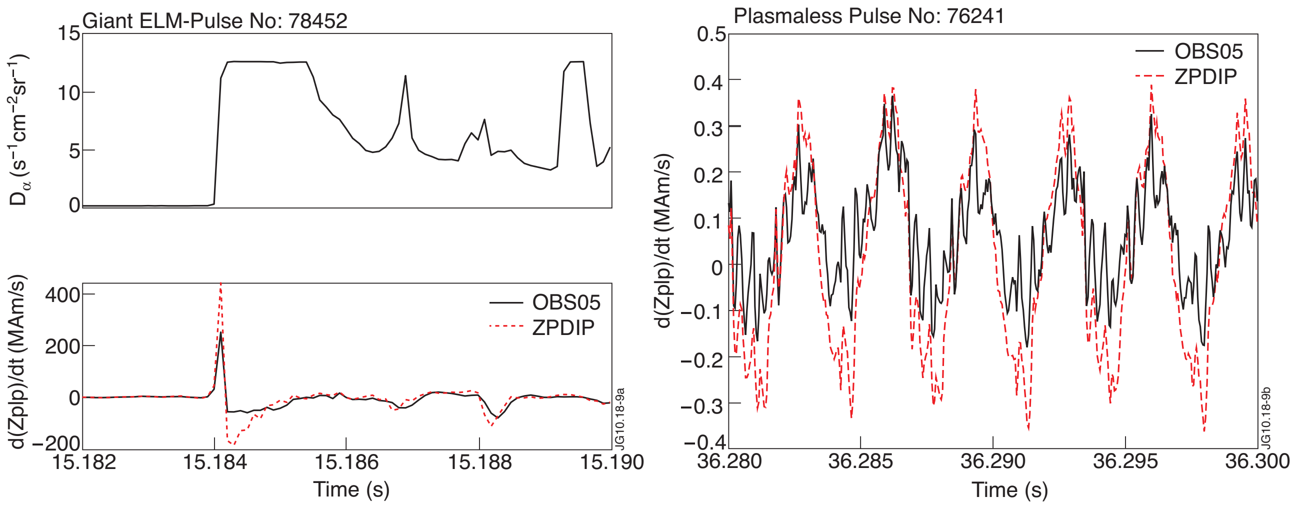

Figure 9. Different response of OBS05 and ZPDIP: a) to a giant ELM in Pulse No: 78452 (the upper plot shows the D_α emission); to 300 Hz power amplifier noise in plasmaless Pulse No: 76241.

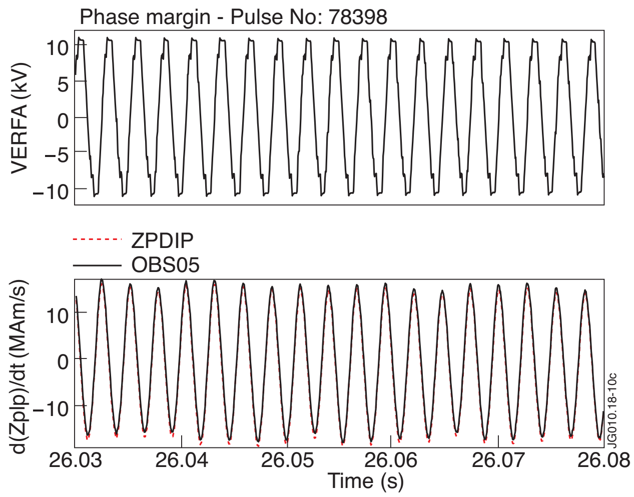

Figure 10: Phase margin experiment, JET Pulse No: 78398: OBS05 and ZPDIP show a similar behaviour as requested by the design procedure at the frequency of about 370Hz.

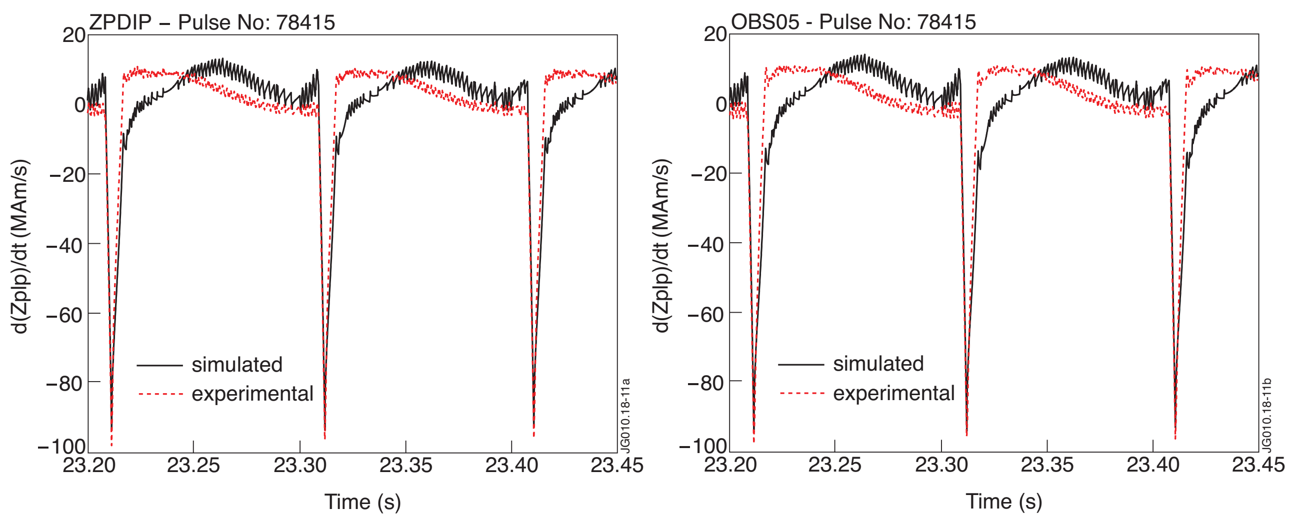

Figure 11: Response to radial field circuit voltage inputs: comparison between simulations and experimental values of ZPDIP and OBS05 in kick and recovery tests of Pulse No: 78415. The values are obtained as linear combination of magnetic signals.

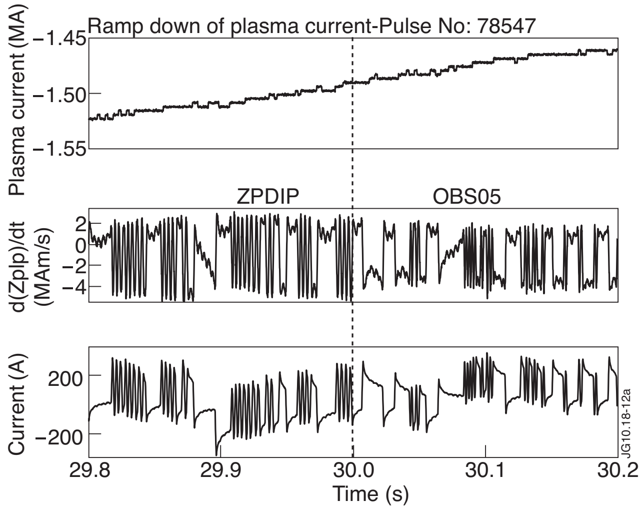

Figure 12: Experimental test of OBS05 in closed loop during ramp down (Pulse No: 78547).

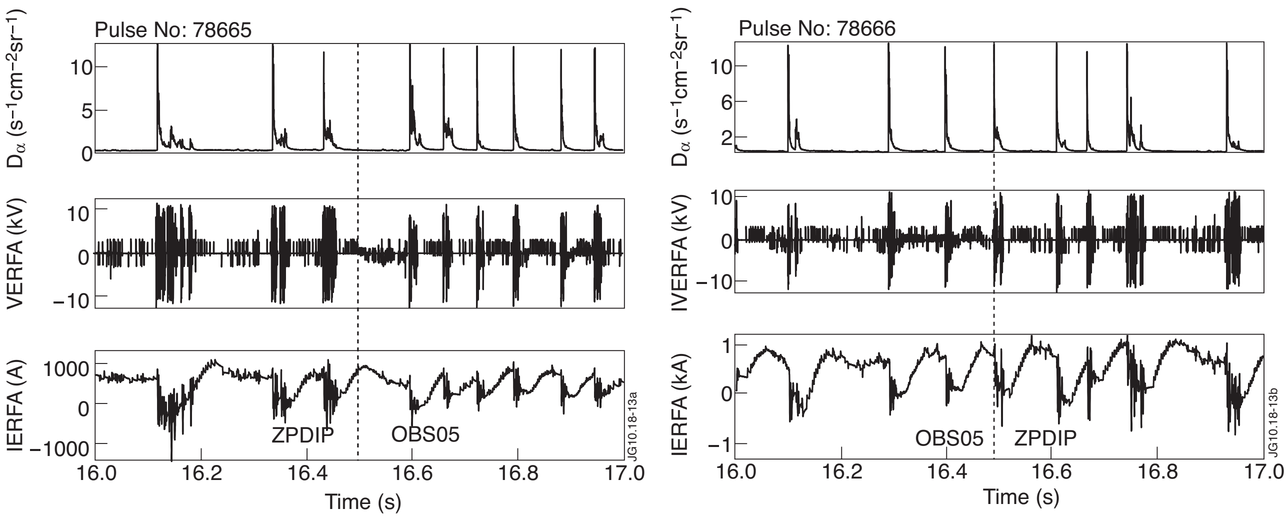

Figure 13: Experimental tests of OBS05 in closed loop in Pulse No: 78665 after 16.5s and in Pulse No: 78666 before 16.5s: D_α, radial field amplifier voltage and controlled variables. With OBS05 the stability is preserved and the radial field circuit current excursion is considerably smaller.

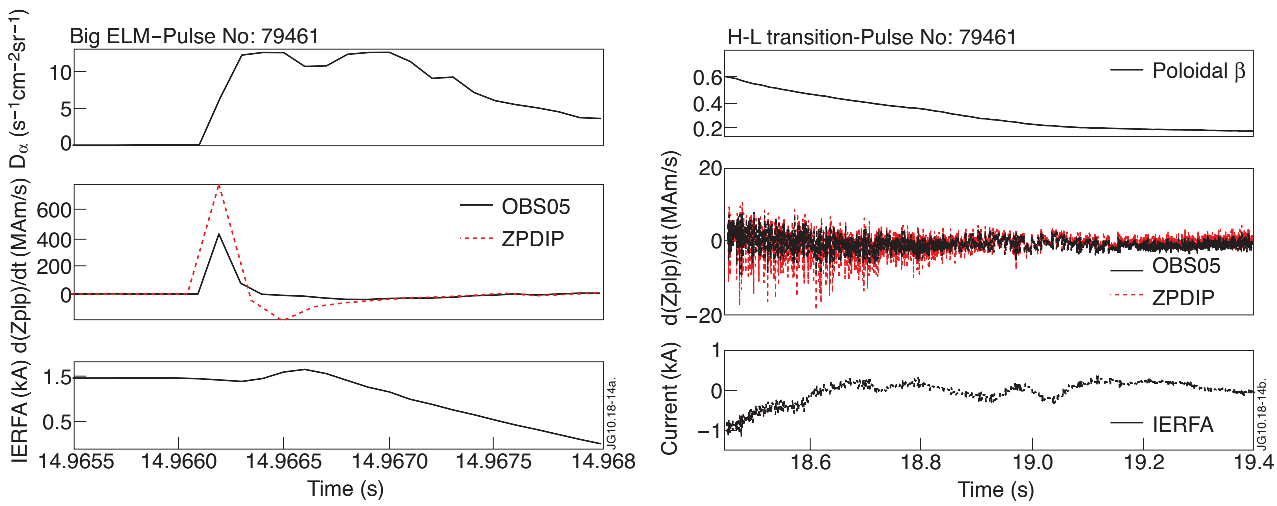

Figure 14: Experimental test of OBS05 in closed loop in Pulse No: 79461: a) ELMy phase; b) H-L transition.