Fusion Engineering and Design 129 (2018) 152–157

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Model-based plasma vertical stabilization and position control at EAST

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ARTICLE INFO

Keywords:
Model-based control design
Plasma magnetic control in tokamak
Plasma vertical stabilization

ABSTRACT

This paper deals with the model-based approach that has been adopted to design the plasma magnetic control at the EAST tokamak. Such a design approach, which is based on a linear model for the response of the plasma and of the surrounding coils, has been successfully applied in 2016 to design an alternative solution for the plasma vertical stabilization, the plasma centroid position control, and the controller of the currents in the poloidal field circuits. After an introduction to the linear model for the plasma/circuits response, the proposed control algorithms are presented together with the preliminary results obtained during the 2016 experimental campaign at EAST. A brief description of the ongoing and future design activities is also given.

1. Introduction

A model-based approach for the design of plasma magnetic control at the EAST tokamak has been proposed in [1]. The control architecture presented in that paper includes a multi-input-multi-output (MIMO) system for integrated plasma shape and flux expansion control, whose final aim is to control advanced magnetic configurations at the EAST, such as *quasi*-snowflake [2]. The approach proposed in [1], which exploits the plasma linear models derived from the CREATE magnetic equilibrium codes [3,4], has been successfully adopted in 2016 to design alternative algorithms for both the vertical stabilization (VS) system [5] and the plasma centroid position control system. Furthermore, first results have been obtained with a model-based MIMO controller for the currents in the poloidal field (PF) circuits.

This work shows the effectiveness of the proposed approach by presenting the experimental results obtained during the 2016 experimental campaign at EAST. In particular, the paper is structured as follows: the next section briefly introduces the linear model of the plasma/circuit response exploited for the design. Section 3 describes the proposed algorithms for the VS system and the plasma centroid position control. The results obtained in 2016 with these two controllers are discussed in Section 4, while Section 5 deals with the ongoing design activities, briefly presenting the preliminary results obtained with the PF current MIMO controller, and the future plans.

Before concluding this section, it is worth to remark that, although the cost of setting-up a reliable suite of modeling tools is not negligible (both in terms of time and effort), a model-based approach is essential to reduce the time needed to test, validate and commission new control algorithms, as it will be briefly recalled also in Section 4, while other relevant examples on existing tokamak devices can be found in [6–8]. Moreover, the availability of *engineering-oriented* models is essential not only for control system design, but it can also support the design and commissioning of the magnetic diagnostic [9], as well as to run intershot simulations aimed at optimizing the controller parameters [10].

Note: In this paper we will often refer to the architecture of the magnetic control system within the EAST PCS. The interested readers can find more information about this architecture in [11,5].

2. Plasma modeling for plasma magnetic control

This section briefly introduces the linear model for the response of the plasma and of the surrounding conductive structures that is automatically generated by the CREATE nonlinear magnetic equilibrium codes [3,4]. These modeling tools have been successfully used to design magnetic control systems, for example at JET [12], and are currently used to perform preliminary studies and code benchmarking for JT-60SA [13], ITER [14].

From the magnetic control point of view, a plasma equilibrium is specified in terms of nominal values of the plasma current I_p, of the currents in the PF circuits and, for a given *shape* of the plasma internal profiles (e.g., *bell* shaped profiles, by the nominal values of both the poloidal beta β_p and the internal inductance l_i. Around a given

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https://doi.org/10.1016/j.fusengdes.2018.02.020
Received 30 May 2017; Received in revised form 30 January 2018; Accepted 5 February 2018

equilibrium, the plasma linearized model for the EAST tokamak can be specified in the standard state space form as

$$\dot{x}(t) = \mathrm{A}\,\mathrm{x}(t) + \mathrm{B}\,\mathrm{u}(t) \tag{1a}$$

$$y(t) = \mathrm{C}\,\mathrm{x}(t), \tag{1b}$$

where

- $x = (\delta I_{\mathrm{PF}} \quad \delta I_{\mathrm{IC}} \quad \delta I_{\mathrm{eddy}} \quad \delta I_p)^T$ is the vector of the variations of the current in the 12 superconductive PF circuits, in the copper in-vessel coils (IC), in the passive structures, and of the plasma current;
- $u = (V_{\mathrm{PF}} \quad V_{\mathrm{IC}})^T$ is the vector of the voltages applied to the superconductive PF circuits and to the IC;
- y is the output vector, that includes all the controlled variables (e.g., both the radial and horizontal position of the plasma centroid, the plasma shape descriptors, etc.).

Note that in (1) only control inputs have been considered, i.e., the voltage applied to the active coils. However, the linear model (1) may include also the disturbance exogenous inputs, which coincide with the variation of β_p and l_i, as far as magnetic control in concerned.

Both CREATE nonlinear equilibrium codes and the linear model (1) are available in the Matlab/Simulink® environment. A *validation campaign* of these modeling tools started in 2015 using EAST experimental data, including both open-loop validations (aimed at the development of advanced magnetic configurations [2]), and closed-loop ones. In order to perform the latter, the magnetic control algorithms implemented within the EAST Plasma Control System (PCS, [11,15]) were back-engineered in order to have them available in the Simulink® environment.

3. Plasma stabilization and position control at east

This section briefly describes the algorithms for plasma VS and centroid position control which have been designed exploiting the plasma model (1).

3.1. ITER-like vertical stabilization

The solution for plasma vertical stabilization described in this paper was originally proposed for the ITER tokamak in [16]. A block diagram of the *ITER-like* VS deployed at EAST is shown in Fig. 1; the correspondent control algorithm is given by

$$V_{\mathrm{IC_{ref}}}(s) = \frac{1 + s\tau_1}{1 + s\tau_2}\left(K_v \bar{I}_{p_{\mathrm{ref}}} \frac{s}{1 + s\tau_z} Z_p(s) + K_{\mathrm{IC}} I_{\mathrm{IC}}(s)\right), \tag{2}$$

where $\bar{I}_{p_{\mathrm{ref}}}$ is the nominal value for the plasma current at each time instant, and the control parameters are the speed gain K_v (which is scaled by $I_{p_{\mathrm{ref}}}$), the current gain K_{IC}, and the time constants of the lead compensator τ_1 and τ_2 ($\tau_1 > \tau_2$).

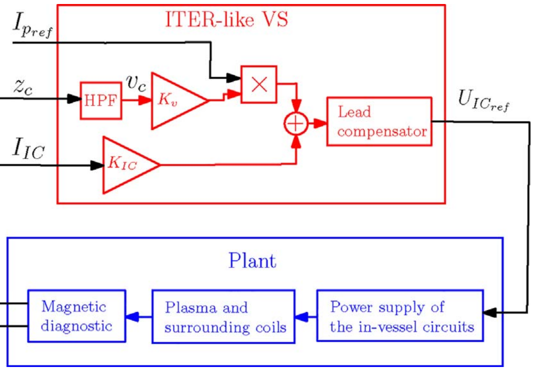

Fig. 1. Block diagram of the ITER-like VS for the EAST tokamak.

The control algorithm (2) decouples the VS from the plasma shape control, while the algorithms previously implemented to stabilize the EAST plasma exhibit a strong coupling with plasma shape control system. Indeed, in [5] it has been shown that in the commonly used setup of the EAST PCS, both the VS and the plasma shape controller contribute to the plasma vertical stabilization, that is the VS alone is not stabilizing the plasma. Hence, in this setup, the two systems act on z_p, although the solution of the vertical stabilization problem simply requires to control to zero the vertical speed, leaving the control of the vertical position to the plasma position and shape controller. As a consequence, the VS algorithms previously implemented within the EAST PCS prevent the deployment of advanced MIMO plasma shape control schemes, such as the ones proposed in [1]; indeed, such MIMO controllers rely on the decoupling with the VS system.

By exploiting the linear model 3 it was possible to prove that, due to a 550 μs delay introduced by the IC power supply, and to the typical values for the growth rate at EAST, the plasma could be vertically stabilized using a single-input-single-output (SISO) controller that takes as input the vertical speed v_p, only if the vertical position z_p is also fed back (more details can be found in [5,17]). It follows that, in order to stabilize EAST with a SISO loop on v_p, the integral action is required; hence the PIDs on v_p previously used at EAST for VS are strongly coupled with the plasma shape control system. The *ITER-like* control algorithm specified in (2) is a multi-input-single-output (MISO) loop, that does not feed back z_p, allowing to achieve the desired decoupling. For more details the interested reader is referred to [17], where the *parity-interlacing-property* (PIP, [18]) is exploited to show that, given the properties of the EAST plant and plasmas, it is not possible to achieve vertical stabilization with a SISO control system without feeding back also z_p. Furthermore, in [17], the PIP is exploited again to show how the feedback on I_{IC} *adds* a second unstable pole to the open loop transfer function that, eventually, permits to stabilize the plasma adding another feedback just on v_p. It should be noticed that the nominal plant could also be stabilized without the need of the lead compensator, which has been added in order to increase the robustness of the overall closed loop system.

3.2. Control of the plasma centroid position

Once the alternative approach to VS described in the previous section was successfully commissioned, it was possible to tune the plasma centroid position control system. Indeed, gains of the PIDs previously used to control both the horizontal (r_p) and vertical position (z_p) of the plasma centroid were experimentally *optimized* in order to deal with a different VS. By exploiting the linear model (1), and by explicitly taking into account the VS described in Section 3.1, the following steps have been followed to redesign the gains of both the r_p and z_p PIDs

1. exploiting (1), the MIMO closed-loop system obtained is computed by closing both the *ITER-like* VS and the controller of the currents in the PF coils (see also [11] or [5] for more detailed description of the architecture of magnetic control system within the EAST PCS). Note that first-order systems with delay are included when performing this step in order to model the PF power supplies;
2. a SISO transfer functions between the controller request and the controlled variable (either r_p or z_p) is computed; note that the r_p and z_p control problems are treated as SISO by distributing the controller request among the PF circuits using the same weights used by the original PIDs;
3. the PIDs are tuned offline exploiting the SISO model obtained at step 2;
4. closed-loop simulation are performed in order to assess the performance.

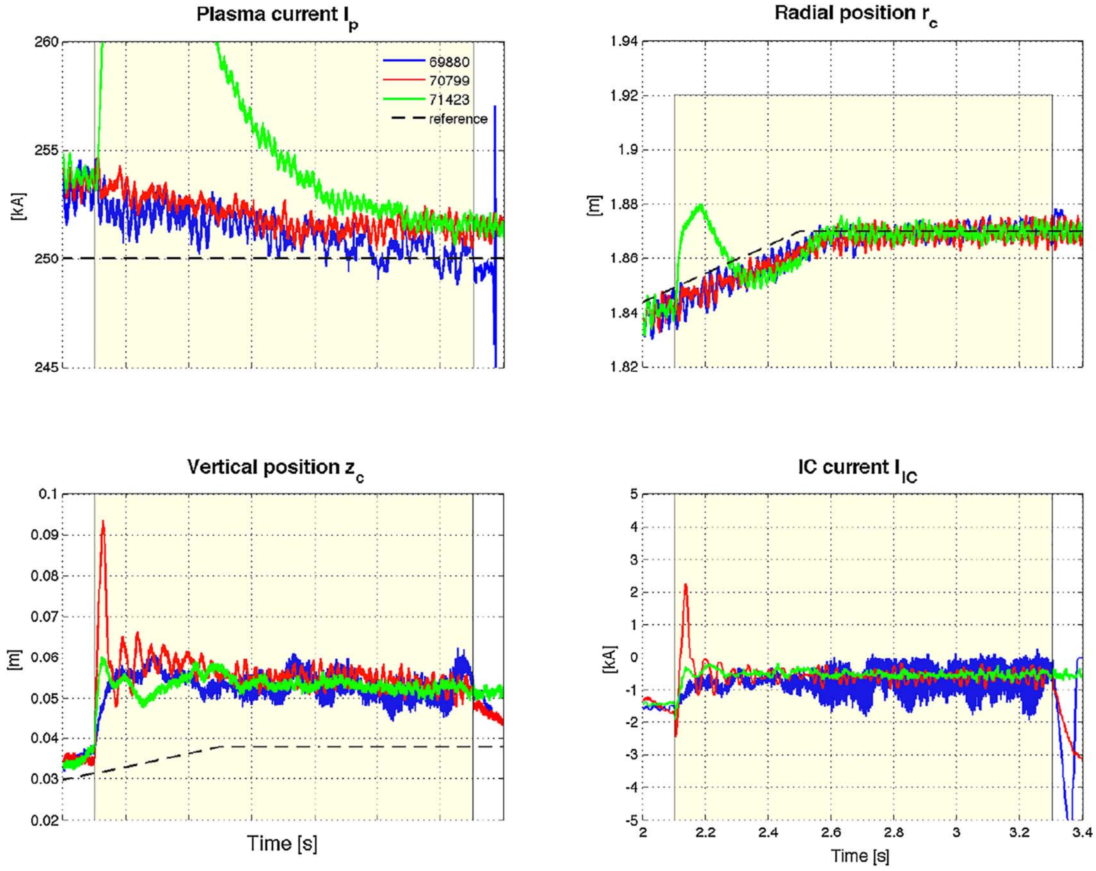

Fig. 2. Comparison between the EAST pulse #69880, which was the first one where the *ITER-like* VS was enabled for more than 1 s (from $t = 2.1$ s to $t = 3.3$ s), and the pulses #70799 and #71423, during which the VS controller gains were finely tuned exploiting to the model.

4. Preliminary experimental results

In this section the first experimental results obtained are presented in order to show the effectiveness of the proposed control algorithms.

Fig. 2 compares the time traces of I_p, r_p, z_p, and I_{IC} for the EAST pulses #69880, #70799, and #71423. Pulse #69880 was the first one where the *ITER-like* VS was enabled for more than 1 s, from $t = 2.1$ s to $t = 3.3$ s. In pulse #70799 the VS controller gains were tuned exploiting the model (1), in order to reduce the maximum absolute value of the current requested in IC. Indeed, if the absolute value of the current in IC exceeds a given threshold, the power supply is tripped and the discharge is shut down. Further fine tuning was made for pulse #71423, in order to increase the stability margins, and hence to reduce the oscillatory behaviour. Note that, during pulse #71423 a fictitious disturbance was also induced on the plasma current by a bump on the correspondent control loop. This bump was generated by the reset of the integral action in the I_p control loop, at $t = 2.1$ s. Such a reset induces a temporary increase of the control error on I_p, which is recovered once the integral action is *charged*. The overall behaviour, from the point of view of both the VS and the plasma centroid control loops, is equivalent to a step disturbance to be rejected. It should be also noticed that, during the three considered pulses, only I_p and r_p were controlled, while z_p was left uncontrolled. This was made on purpose in order to confirm that the ITER-like VS stabilizes the plasma by controlling $\dot{z}_p$ and I_{IC}, without the need to feed back the vertical position z_p.

Fig. 3 reports the time traces of I_p, r_p, z_p, and I_{IC} during the EAST pulse #70800, when the PIDs for the centroid position control were tuned according to the procedure described in Section 3.2, and these two loops were enabled in the time windows from $t = 2.1$ s to $t = 3.3$ s, when also the *ITER-like* VS was enabled. Note that, similarly to pulse #71423, also during pulse #70800 a fictitious disturbance was induced on the plasma current by a bump on the correspondent control loop.

As conclusion of this section, it should be mentioned that the effort needed to validate the linear model (1) on the EAST experiment was not negligible. A rough estimation of such an effort indicates approximatively the equivalent of 6 months of offline activities for an expert in plasma magnetic modelling and control, and about 20 dedicated pulses. The offline activities were mainly aimed at obtaining the required level of reliability in order to enable model-based control design. To this aim, one of the key steps was to reproduce experimental also by means of closed loop simulations. Hence it was required also to back engineering the existing plasma magnetic control in the Matlab/Simulink® environment, which turned out to be a time consuming task.

However, once the reliability of the model was assessed, the deployment of a new control law, such as the re-tuning of the PIDs for centroid position control, succeeded at the first try, minimizing the impact on the experimental activities.

5. Ongoing activities

Exploiting the model-based design approach described in the previous sections, the following two main activities are envisaged for the next future

1. The improvement of the decoupling among the PF circuits, by replacing the SISO PIDs currently adopted at EAST for the control of the currents in the PF circuits (see [11]), with a MIMO controller whose design is based on a plasmaless model (see [13,Section 4.4] for more details about the adopted design approach). A simulation that compares the behaviour of the EAST SISO PIDs with the proposed MIMO is reported in Fig. 4, where the improvement in the decoupling of the PF circuits is shown. Moreover, Fig. 5 shows the

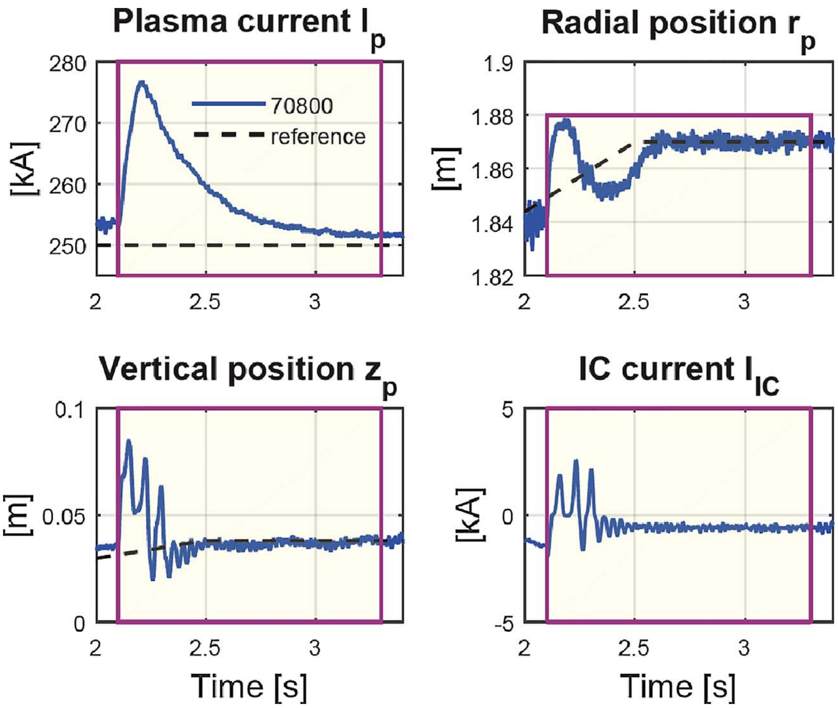

Fig. 3. Time traces for the EAST pulse #70800, during which both the *ITER-like* VS and the model-based centroid position control (whose design procedure is described in Section 3.2) were enabled from $t = 2.1$ s to $t = 3.3$ s. A fictitious disturbance was induced on the plasma current by a bump on the correspondent control loop.

preliminary results experimentally obtained with the MIMO approach during one plasmaless discharge. Only the currents in the two circuits PF1 and PF2 are shown, however it is possible to note that the simulated and experimental results are in good agreement, and that the desired decoupling is achieved. Indeed, taking into account the measurement noise, the experimental current in PF2 is practically zero, while the current in PF1 is varying; the same behaviour was observed also on the other circuits.

2. The deployment of the MIMO plasma shape controller proposed in [1], aimed at controlling advanced magnetic configurations such as the upper quasi-snowflake configuration recently achieved at EAST. Note that the performance of the MIMO plasma shape controller proposed in [1] relies on a good decoupling between the PFC circuits.

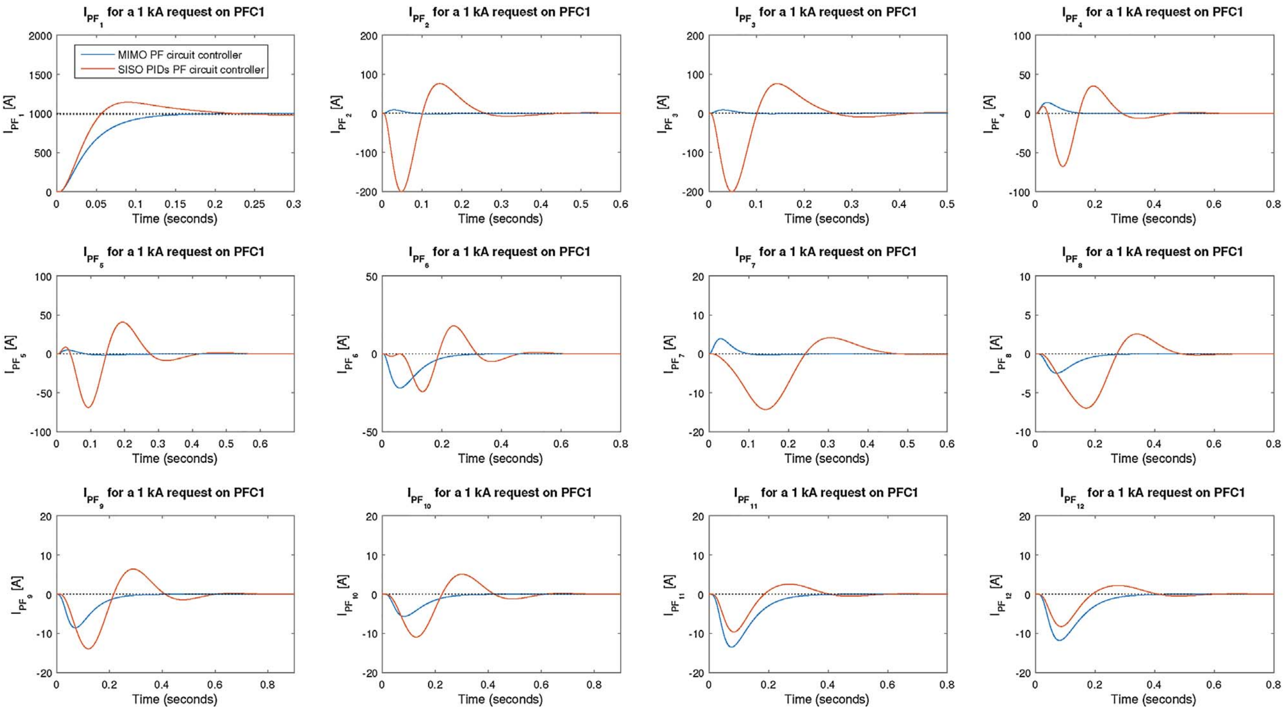

Fig. 4. Simulation showing the comparison between a MIMO PF current controller designed exploiting a model-based approach, and the PF current controller based on SISO PIDs, currently used at EAST.

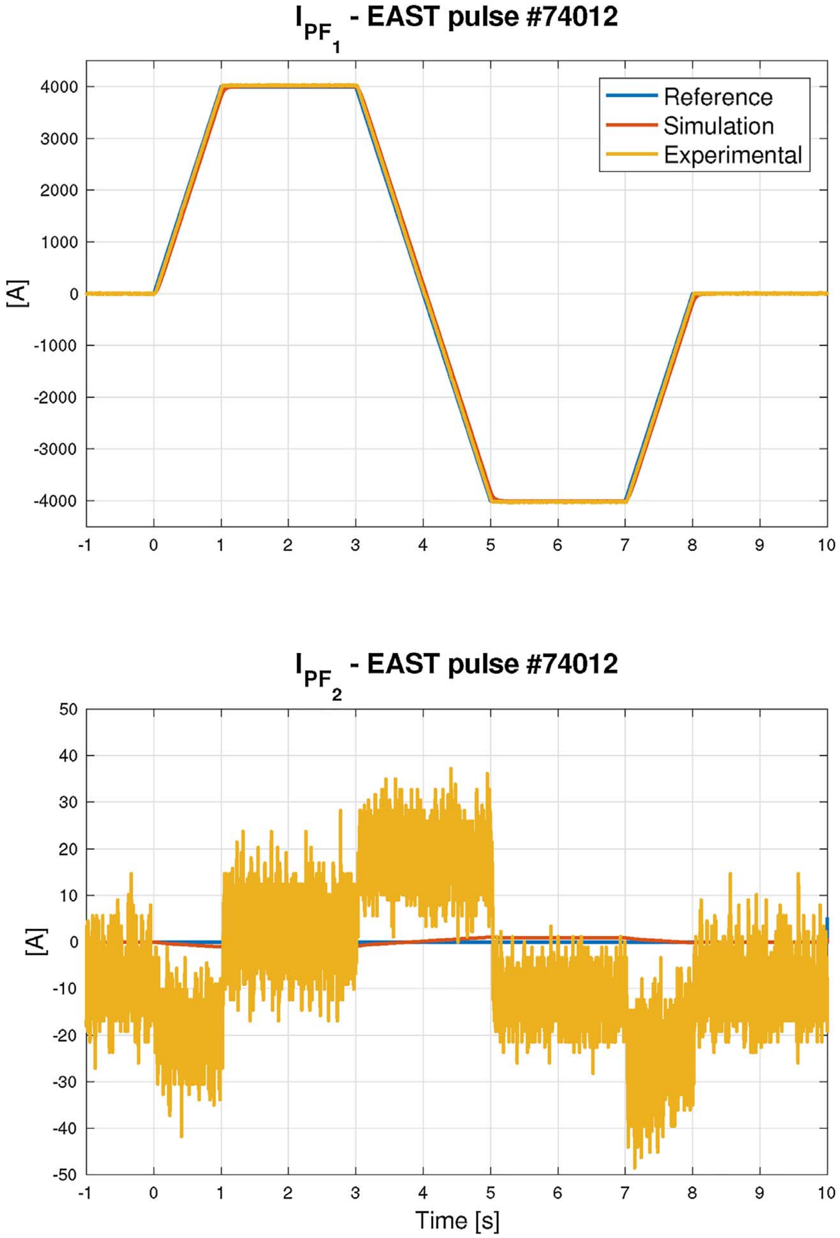

Fig. 5. Comparison between the simulated and the experimental values for the currents in both the PF1 and PF2 circuits for the EAST pulse #74012. Note that, taking into account the measurement noise, the experimental current in PF2 is practically zero.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement no. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The CREATE team would like to thank Dr. Giuseppe Calabró, Dr. Flavio Crisanti for the opportunity to work with the ASIPP colleagues.

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