WPDTT2-CPR(17) 17481

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Preprint of Paper to be submitted for publication in Proceeding of 1st IEEE Conference on Control Technology and Applications

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.

On plasma vertical stabilization at EAST tokamak

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***Abstract*— In this paper we discuss the problem of plasma vertical stabilization at the EAST tokamak. By exploiting a plasma/circuit linearized model, we show that the plant cannot be strongly stabilized by using the in-vessel coils and a single-input-single-output controller that feeds back only the plasma vertical speed $\dot{z}_p$ (i.e. without integral action on $\dot{z}_p$). Moreover, a stable multi-input-single-output controller that stabilizes the plant without the need of feeding back the plasma vertical position is presented. The proposed solution permits to achieve stabilization of the EAST plant without coupling the vertical stabilization system with the plasma shape controller. Such decoupling is a key requirement to enable advanced design approaches for plasma shape controller.**

Keywords: tokamak control systems; plasma magnetic control; vertical stabilization system; strong stabilization.

I. INTRODUCTION

Tokamaks [15] are experimental fusion devices aimed at proving the feasibility of energy production by means of nuclear fusion reaction on Earth. In a tokamak, a plasma (a fully ionized gas) of hydrogen ions, is confined by magnetic fields and heated to temperatures of the order of several keV (i.e. tens to hundreds millions of degrees). At such high temperatures, collisions between ions can overcome the Coulomb repulsive forces, resulting in fusion reactions. Confinement of the hot plasma in tokamaks is achieved by means of several magnetic fields. In particular, a set of coils wrapped around the vacuum vessel produce the toroidal magnetic field (see Fig. 1). An additional external field is produced by a set of toroidal coils, called Poloidal Field (PF) coils. The produced poloidal magnetic field is needed to induce current into the plasma itself, and to change its shape and position. Combining the various components, the net magnetic field lines wind helically around the torus, as shown in the simplified schematic reported in Fig. 1.

Reliable and robust operations of modern tokamaks call for active control of the poloidal component of the magnetic field. The main objectives of magnetic control are the regulation of the plasma current and shape, as well as the vertical stabilization (for a complete overview of magnetic control in tokamaks, the reader is referred to the monograph [8]). In particular, the Vertical Stabilization (VS) system is essential to operate tokamaks with elongated and vertical unstable plasmas (see [10, Sec. III.A]).

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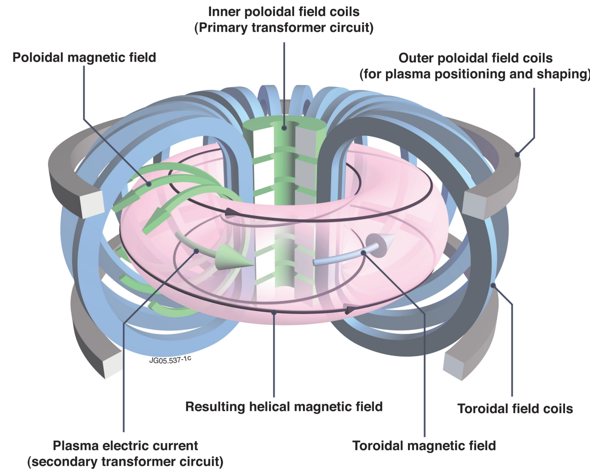

Fig. 1. Simplified scheme of a tokamak.

At EAST, the Plasma Control System (PCS) is in charge of controlling the current in the PF coils system [18], [16], and hence also to stabilize the plasma column.

The standard VS control algorithm at EAST provides a PID that feeds back the plasma vertical speed $\dot{z}_p$, and generates either a request for the voltage to be applied to a pair of in-vessel coils, or a request for the current flowing in them. However, the use of an integral action on $\dot{z}_p$ is equivalent to feeding back also the plasma vertical position z_p. This fact implies a coupling between the VS system and the plasma shape and position controller. Such a coupling prevents the independent design of the two control systems, especially when they are not well separated in the frequency domain, as in the case of the EAST tokamak.

Moreover, the use of z_p to vertically stabilize the plasma, prevents to apply advanced magnetic control approaches, such as the integrated plasma shape and flux expansion controller proposed in [2].

In order to avoid such undesired coupling, the VS system should not make use of z_p. However, it turns out that, without integral action, it is not possible to achieve vertical stabilization at EAST with a stable single-input-single-output (SISO) loop on $\dot{z}_p$. In this work, by exploiting the Parity-Interlacing-Property (PIP, [17]) and the plasma/circuits linear model generated by the CREATE magnetic equilibrium codes [1], [9] – which has been validated against the EAST experiment – we show that EAST plasmas cannot be stabilized feeding back only $\dot{z}_p$ and its derivatives, regardless to the way the in-vessel circuit is driven.

The same tools are then used to show that the EAST plasma can be vertically stabilized with the in-vessel circuit, by using an ITER-like VS system [5], [3]. The proposed controller relies on a multi-input-single-output (MISO) algorithm, that does not feed back z_p; hence it permits to achieve the desired decoupling between plasma shape control and the vertical stabilization.

The paper is structured as follows: the next section gives an overview on plasma magnetic control at EAST. In Section III, by exploiting the CREATE linear model for the response of the plasma and of the surrounding coils, we discuss in more details the problem of vertical stabilization at EAST. In particular, we show that it is not possible to stabilize the plant using a stable SISO controller – *strong stabilization* [13] – that feeds back only $\dot{z}_p$ (i.e. without integral action). In Section IV, we present a different solution that permits to stabilize the plasma, as well as to decouple plasma shape control from the VS system; some experimental results are also presented. Eventually, some conclusive remarks are given in Section V.

II. MAGNETIC CONTROL AT EAST

This section first briefly introduces the main objectives of plasma axisymmetric magnetic control. Afterwards an overview of the EAST magnetic control system is given.

A. The plasma magnetic control problem

Axisymmetric magnetic control is an essential feature to achieve and maintain the desired *operational scenario* in a tokamak device. It can be conceptually separated into three subtasks [8], [10], [14]:

- Position and shape control;
- Plasma current control;
- Vertical stabilization.

Position and shape control deals with the control of the position of the plasma column within the vacuum chamber, and of the shape of the plasma boundary. Different approaches can be adopted to deal with this problem. Control of both the horizontal and vertical position of the plasma centroid is usually used during the early phases of the plasma discharge (i.e., plasma formation and current ramp-up, [6, Section I]), relying on a feed forward action to obtain the desired plasma shape. On the other hand, during the plasma current flattop, position and shape control is achieved either adopting an *isoflux* [18] or a *plasma-wall gap* [7] approach. At EAST the former one is implemented within the PCS.

Plasma current control takes care of regulating the plasma current to the desired value; usually, this is done mainly (but not only) exploiting the coils in the central solenoid. The usual approach is to design a robust plasma current control able to work with different scenarios, independently of the desired plasma shape.

Finally, *vertical stabilization* is required to operate elongated plasmas [14].

B. EAST magnetic control system

Plasma magnetic control at EAST is achieved by driving the required currents in the PF coils system. Fig. 2 shows the poloidal cross-section of the EAST tokamak with the layout of the PF coils, including also the in-vessel copper coils IC1 and IC2. These two coils are connected in anti-series in order to form the so called IC circuit. This circuit is able to react to the plasma vertical instability on a faster time scale, if compared with the ex-vessel superconductive coils; indeed the IC circuit is used as actuator to vertically stabilize the plasma column.

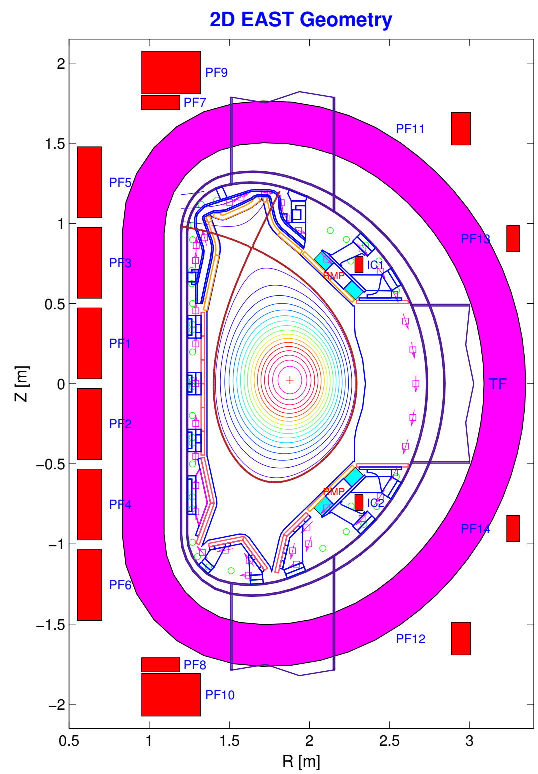

Fig. 2. EAST poloidal cross-section and layout of the PF coils system. Both the ex-vessel PF superconductive coils and the in-vessel copper coils are shown. The 14 superconductive coils (PF1-14) are connected to form 12 independent PF circuits (the couples PF7/PF9 and PF8/PF10 are connected in series). Moreover, the two in-vessel coils are connected in anti-series to form the IC circuits. In this figure, an upper single-null plasma is shown in the vacuum chamber.

The EAST magnetic control system, whose simplified block diagram is shown in Fig. 3, includes the following controllers:

- the *PF Circuit Current Controller*, that drives the currents in the superconductive ex-vessel coils;
- the *Plasma Current Controller*, that tracks the plasma current reference waveform, by generating the correspondent requests to the PFC Current Controller;
- the *Shape and Position Controller*, that tracks the shape of the plasma boundary or the position of the centroid, by generating the corespondent requests for the PFC Current Controller;
- the VS system, that drives the current in the in-vessel coil in order to vertically stabilize the plasma.

It is worth to notice that the EAST VS system can

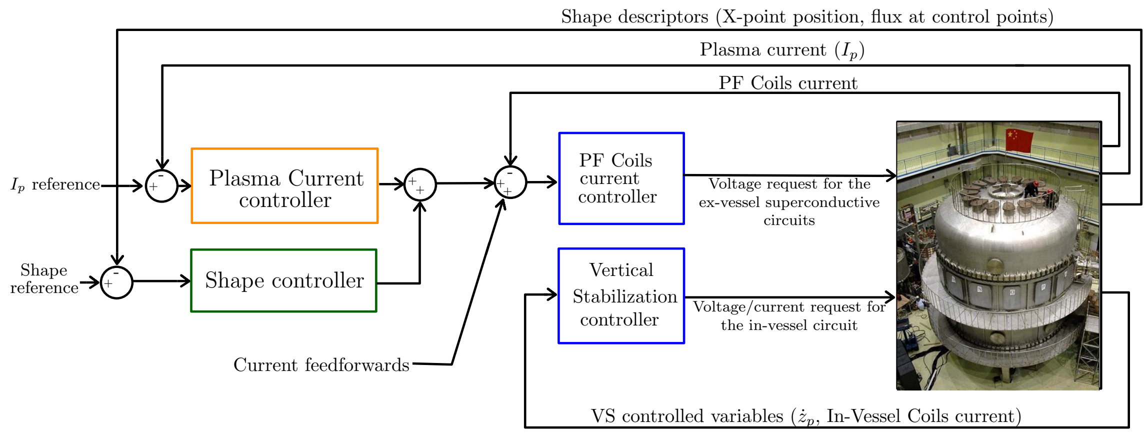

Fig. 3. Simplified block diagram of the EAST magnetic control system.

generate either a current or voltage request for the IC circuit, by accordingly setting the power supply local controller. As it will be shown in the next section, a stable controller that feeds back only the vertical speed $\dot{z}_p$, without using an integral action, cannot stabilize the plasma, regardless to the way the IC circuit is driven (voltage-driven or current-driven). Moreover, in order to achieve vertical stabilization of the plasma without having to feed back z_p, the approach based on the algorithm proposed for the ITER tokamak [5], [3] can be adopted, as it will be discussed in Section IV .

III. VERTICAL STABILIZATION AT EAST

In this section the CREATE linear model for the response of the plasma and of the surrounding coils is exploited to show that the EAST plant cannot be strongly stabilized by a SISO controller that feeds back only the plasma vertical speed $\dot{z}_p$ and its derivatives.

From the magnetic control point of view, a plasma equilibrium is specified in terms of nominal values for the plasma current $I_{p_{eq}}$, the currents in the PF circuits $I_{PF_{eq}}$, and the disturbances, i.e. the poloidal beta $\beta_{p_{eq}}$, and the internal inductance $l_{i_{eq}}$[1].

Around a given equilibrium, the behavior of the plasma and of the surrounding conductive structures can be described by the state space model

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (1a)$$
$$y(t) = Cx(t)\,, \quad (1b)$$

where:

- $x = \begin{pmatrix}\delta I_{PF} & \delta I_{eddy} & \delta I_p\end{pmatrix}^T$ is the vector of the variations of the current in the PF circuits, in the passive structures, and of the plasma current;
- u is the vector of the voltages applied to the PF circuits;
- y is the output vector, which usually includes the variations of the plasma position and shape descriptors, as well the variation of the currents in the PF circuits.

[1]The two parameters β_p and l_i measure the plasma internal distributions of pressure and current, respectively. These two parameters acts as disturbances on the plant, as far as the plasma magnetic control is concerned.

It should be noticed that, for the adopted description of the passive structures, the order of model (1) is about 180. Moreover, (1) exhibits an unstable eigenvalue, that corresponds to the plasma vertical instability.

In order to carry out the studies we are interested in this paper, the input vector in (1) will be limited to the voltage applied to the IC circuit u_{IC}, while the considered output vector will include z_p and the current i_{IC} flowing in the IC circuit, i.e. $y = \begin{pmatrix} z_p & i_{IC}\end{pmatrix}^T$. Given this choice for the plant inputs and outputs, it is possible to derive the following input-output relationship in the Laplace domain

$$Y(s) = \begin{pmatrix} Y_1(s) \\ Y_2(s)\end{pmatrix} = W_p(s)\cdot U_{IC}(s) = \begin{pmatrix} W_{p_1}(s) \\ W_{p_2}(s)\end{pmatrix}\cdot U_{IC}(s)\,, \quad (2)$$

where $U_{IC}(s)$ is the Laplace transform of the actual voltage applied to the IC circuit, $Y_1(s) = Z_p(s)$, and $Y_2(s) = I_{IC}(s)$. Furthermore, by choosing the magnetic fluxes $\psi = Lx$ as state variables, being L the inductance matrix, it can be shown that (1) can be rewritten so as to take into account also current-driven circuits. By doing such change of state variables, it is possible to derive the following linear model, which links i_{IC} to z_p

$$Z_p(s) = \widetilde{W}_p(s)\cdot I_{IC}(s)\,. \quad (3)$$

The IC power supply is modeled as

$$U_{IC}(s) = \frac{e^{-\delta_{ps}s}}{1+s\tau_{ps}}\cdot U_{IC_{ref}}(s)\,, \quad (4)$$

with $U_{IC_{ref}}(s)$ the voltage request, $\delta_{ps} = 550\ \mu$s, $\tau_{ps} = 100\ \mu$s[2]. It should be noticed that the same delay and first order response can be used to model the relationship between the current request to the IC power supply and the actual current i_{IC} that flows into the circuit.

Moreover, at EAST, the plasma vertical speed $V_p(s)$ is estimated by means of a derivative filter applied on $Y_1(s)$,

[2]The parameters in (4) have been experimentally estimated during plasmaless pulses.

TABLE I

MAIN PLASMA PARAMETERS OF THE THREE EAST EQUILIBRIA CONSIDERED IN SECTION III. THE VALUES OF THE PLASMA CURRENT AT THE EQUILIBRIUM $I_{p_{eq}}$ AND OF THE UNSTABLE POLE γ ARE ALSO REPORTED.

Equilibrium	Shape type	$\mathbf{I_{Peq}}$ [kA]	γ [s^{-1}]
46530 at $t = 3$ s	Double-null	281	137
56603 at $t = 5.5$ s	Lower single-null	235	613
60938 at $t = 6$ s	Upper single-null	374	194

TABLE II

SUMMARY OF THE REAL POLES AND ZEROS OF THE VOLTAGE-DRIVEN (VD) PLANT (6) AND OF THE CURRENT-DRIVEN (CD) PLANT (7) FOR THE EQUILIBRIA LISTED IN TABLE I.

Equilibrium	Power supply mode	γ	Real nonnegative zeros
46530	VD	137	{0,8444}
	CD	149	{0,8444}
56603	VD	613	{0,8444}
	CD	639	{0,8444}
60938	VD	194	{0,8444}
	CD	208	{0,8444}

i.e.

$$V_p(s) = \frac{s}{1+s\tau_v} \cdot Z_p(s)\,, \qquad (5)$$

with $\tau_v = 1$ ms.

It is now possible to exploit (2)–(5) to derive the model that links the plasma vertical speed $\dot{z}_p$ to the control variable. In particular, this model is given by

$$W_{VD}(s) = \frac{s}{(1+s\tau_v)(1+s\tau_{ps})} \cdot W_{p_1}(s) \cdot e^{-\delta_{ps}s}\,, \qquad (6)$$

when the IC circuit is set in voltage-driven mode, while it is

$$W_{CD}(s) = \frac{s}{(1+s\tau_v)(1+s\tau_{ps})} \cdot \widetilde{W}_p(s) \cdot e^{-\delta_{ps}s}\,, \qquad (7)$$

when in current-driven mode. For a given a plasma equilibrium, in what follow we will use the SISO models (6) and (7) in order to check strong stabilization of the EAST plasma, by applying the following PIP[3].

Theorem 1 ([17]): A linear plant $W(s)$ is strongly stabilizable *if and only if* the number of poles of $W(s)$ between any pair of real zeros in the right-half-plane (RHP) is even. ■

For the sake of brevity, in this paper we consider three equilibria, whose main plasma parameters are reported in Table I. For each of the considered equilibrium, we compute both the poles and the zeros in the RHP (including the ones on the imaginary axis), and we apply Theorem 1 to check if EAST is strongly stabilizable by a controller that does not feed back the vertical position z_p.

As a matter of fact, the EAST plant turns out to be not strongly stabilizable, either using the IC circuit in voltage-driven or current-driven mode. Indeed, since both plants (6) and (7) have one unstable pole corresponding to the vertical instability, according to PIP, this single unstable pole should never sit between two real nonnegative zeros, in order to have strong stabilizability. This never happens at EAST.

In particular, the results obtained for the equilibria reported in Table I are summarized in Table II. As anticipated, regardless to the driving mode of the IC power supply, the EAST plant cannot be strongly stabilized by feeding back just the plasma speed. This is due to the fact the there is only one unstable pole (whose value slightly changes depending on the way the IC circuit is driven) that stays between a zero in the origin, and one at $\sim$ 8444 s^{-1}. The positions of these zeros do not depend on the specific equilibrium. Indeed, the one in the origin is due to the fact that the plasma speed is the controlled variable, while the latter is due to the presence of the power supply delay. Indeed, the third order Padé approximation of the time delay in (4) gives

$$\frac{-(s-8444)(s^2-1.34\cdot 10^4 s+8.54\cdot 10^7)}{(s+8444)(s^2+1.34\cdot 10^4 s+8.54\cdot 10^7)}\,.$$

It should be noticed that the EAST plant could be strongly stabilized if also the vertical position z_p were used by the controller, i.e. if an integral action were used in a SISO controller. This is the approach usually adopted at EAST [18], [16]. However, such an approach causes a coupling between the VS system and the plasma shape and position control. Since advanced plasma shape control approaches rely on the decoupling between the VS and the plasma shape control itself, it is desirable to achieve vertical stabilization without feeding back also z_p, as it is done at the JET tokamak [12], and as it is proposed for ITER [5]. Having a stable controller is also a usual requirement for the VS.

Motivated by these needs, in the next section an ITER-like VS algorithm for the EAST tokamak is introduced, and the results achieved with this alternative approach during the 2016 experimental campaign are also presented.

IV. ITER-LIKE VERTICAL STABILIZATION

In order to solve the stabilization problem of the EAST plant with a stable controller and without controlling the plasma vertical position, the VS architecture shown in Fig. 4 was proposed in [2], and recently implemented and experimentally validated at EAST. In particular, the architecture in Fig. 4 is based on the current proposal for the VS [5], [4] of the ITER tokamak, and it consists of the following MISO controller

$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2}\left(K_v \bar{I}_{p_{ref}} \frac{s}{1+s\tau_z} Z_p(s) + K_{IC} I_{IC}(s)\right)\,, \qquad (8)$$

where $\bar{I}_{p_{ref}}$ is the nominal value for the plasma current at each time instant. The parameters of the control algorithm are

- the speed gain K_v, which is scaled by $I_{p_{ref}}$;
- the current gain K_{IC};
- the time constants of the lead compensator τ_1 and τ_2, with $\tau_1 > \tau_2$.

[3] In order to apply the PIP to either (6) or (7), the time delay is replaced with its Padé approximation.

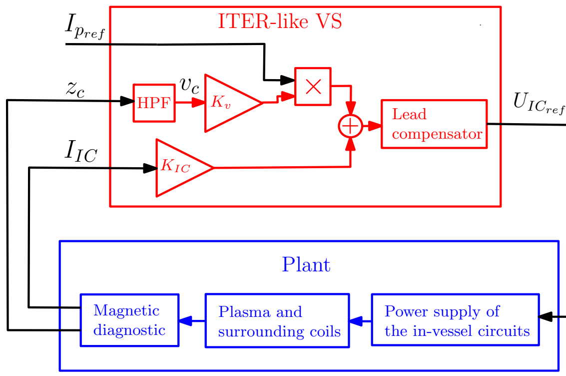

Fig. 4. Block diagram of the ITER-like VS for the EAST tokamak.

By tuning in a proper way the parameters in 8, it is possible to bring to zero the vertical speed, hence achieving stabilization, while maintaining low the current in the IC circuit (i.e., far from the saturation).

By applying again Theorem 1, it is possible to check that the proposed approach permits to strongly stabilize the EAST plant. Indeed, by letting

$$K_v = -2.15 \cdot 10^{-4}\,, \quad K_{IC} = -5.3 \cdot 10^{-2}\,, \qquad (9)$$

and by not considering the lead compensator, i.e. by setting $\tau_1 = \tau_2 = 0$, if we open the SISO loop in correspondence of $U_{IC_{ref}}$, we can apply the PIP.

As an example, if we consider the plasma equilibrium for the EAST pulse #60938, it turns out that there is only one real positive zero, which is the one at $\sim$ 8444 s^{-1}, and one unstable pole at $\sim$ 208 s^{-1}. It follows that the plant is now strongly stabilizable; indeed it can be stabilized by means of the lead compensator, which can be designed by using standard SISO techniques [11], in order to obtain the desired stability margins.

Furthermore, Theorem 1 can be exploited again to explain how strong stabilization is obtained by means of (8). Let us consider the following model that links the control variable $U_{IC}(s)$ to the current that flows in the IC circuit

$$W_{IC}(s) = \frac{I_{IC}(s)}{U_{IC}(s)} = W_{p_2}(s) \cdot \frac{e^{-\delta_{ps}s}}{1 + s\tau_{ps}}\,. \qquad (10)$$

It turns out that, by closing the controller

$$K_{IC} \cdot \frac{1 + s\tau_1}{1 + s\tau_2} \qquad (11)$$

on the $u_{IC} - i_{IC}$ channel it possible to introduce another unstable pole between the two real nonnegative zeros on the $u_{ic} - \dot{z}_p$ channel. In order to show this fact, we consider a reduced order version of the SISO transfer function for the $u_{ic} - \dot{z}_p$ channel, obtained when (11) is closed via a positive feedback on (10). In particular, a reduced model of order 10 has been obtained by means of a balanced reduction [19], i.e. by discarding the relatively small Hankel singular values of the stable parts of the considered SISO model. Fig. 5 shows the comparison between the full-order and the reduced-order models. Now, by using the reduced-order version of the SISO model for the $u_{ic} - \dot{z}_p$ channel and the third-order Padé approximation of the power supply delay, it is possible to plot the root locus shown in Fig. 6. It turns out that a second unstable pole appears between the zero in the origin and the one at $\sim$ 8444; hence the PIP assures that there exist a stable controller that stabilizes the plant. Indeed, by adding also the lead compensator

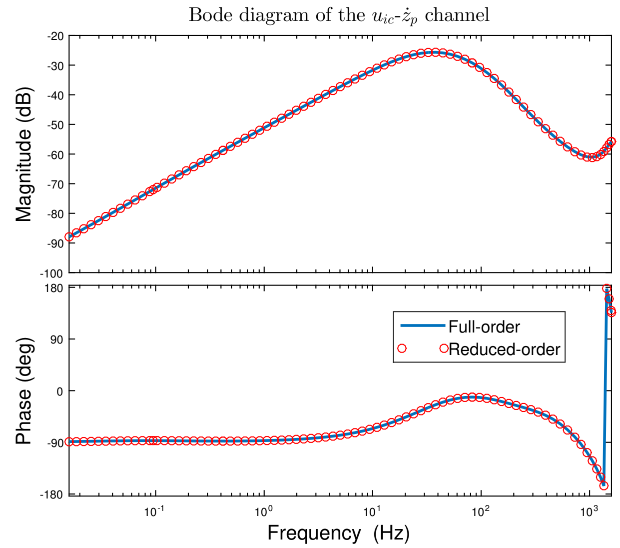

Fig. 5. Bode diagrams of the full-order and reduced-order versions of transfer function for the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed using the controller (11).

$$K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{1 + s\tau_1}{1 + s\tau_2}\,, \qquad (12)$$

on the $u_{ic} - \dot{z}_p$ channel, the root locus of Fig. 6 is modified as in Fig. 7 (where only the relevant portion of the locus is reported), which shows that the plasma can be stabilized by using (12).

The VS system (8) has been implemented within the EAST PCS and successfully tested during the 2016 experimental campaign. In particular, Fig. 8 shows the time traces of the plasma centroid position – both horizontal r_p and vertical z_p – as well as the current in the IC circuit, for the EAST pulse #71423. The controller gains were set equal to (9), while $\tau_1 = 1.7$ ms and $\tau_2 = 0.01$ ms.

This pulse was aimed at showing that the ITER-like VS (8) was able to stabilize the EAST plasma by using only the IC coils; hence only r_p was controlled in closed loop by the plasma shape controller, while z_p was left in open loop. It should be also noticed that, although z_p is not controlled by the plasma shape controller, the proposed algorithm manages to keep the IC current small (at EAST the saturation value is 9 kA). The IC current is controlled to zero (on average), if also z_p is controlled in closed loop by the plasma shape controller, as shown in Fig. 9, were the time traces for the EAST pulse #70131 are shown.

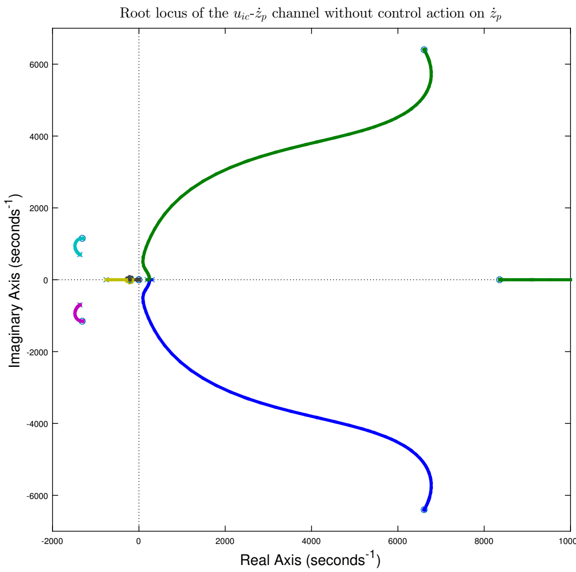

Fig. 6. Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed using the controller (11).

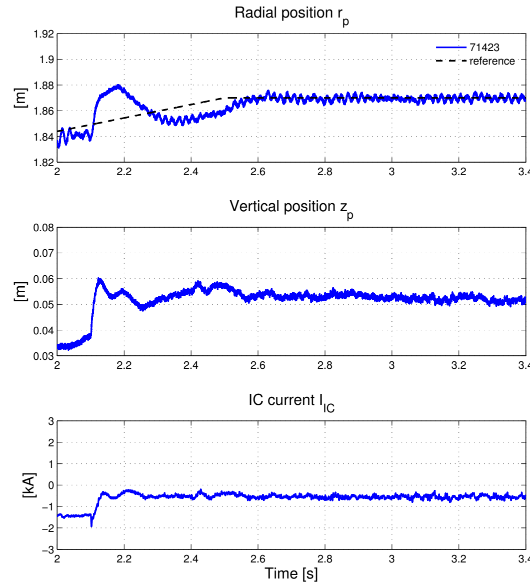

Fig. 8. Time traces of the position of the plasma centroid (r_p, z_p) and of the current in the IC circuit for the EAST pulse #71423.

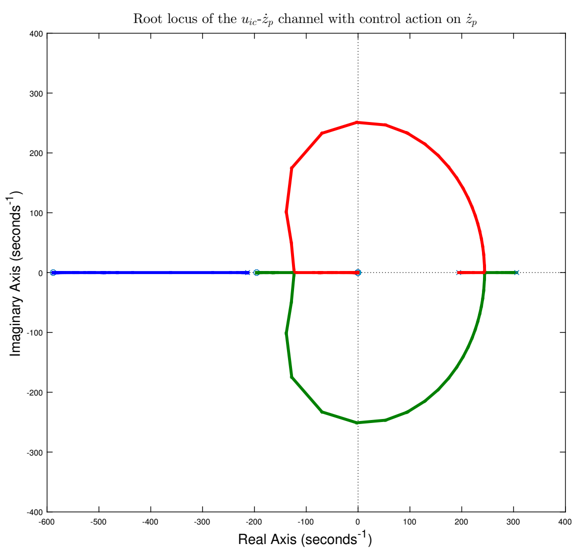

Fig. 7. Root locus of the $u_{ic} - \dot{z}_p$ channel, when the loop on the IC current is closed using the controller (11) and also the control action on $\dot{z}_p$ is included.

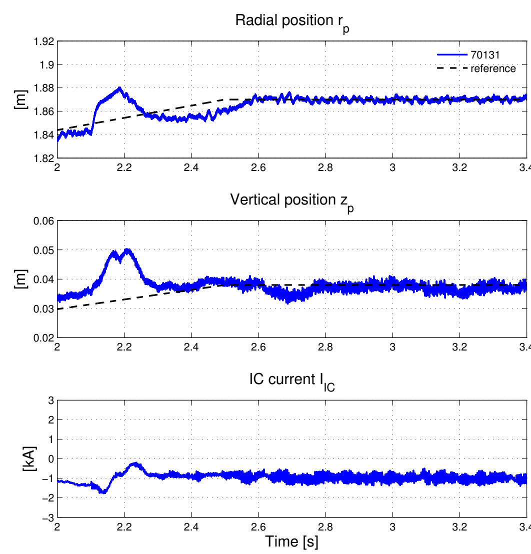

Fig. 9. Time traces of the position of the plasma centroid (r_p, z_p) and of the current in the IC circuit for the EAST pulse #70131.

V. CONCLUSIONS

In this paper the CREATE models for the plasma and the surrounding coils has been used to show that vertical stabilization cannot be achieved at EAST by means of a SISO stable controller that feeds back only the plasma speed $\dot{z}_p$. Stabilization can be achieved by a SISO controller on $\dot{z}_p$ with an integral action, i.e. by controlling also the plasma vertical position. However, this solution would couple the VS system with the plasma shape controller, preventing the deployment of advanced plasma shape control schemes that rely on such a decoupling. Motivated by this need and by the impossibility of strongly stabilizing the EAST plasma with a SISO controller on $\dot{z}_p$, a MISO vertical stabilization algorithm has been proposed a validated at EAST during the 2016 experimental campaign.

ACKNOWLEDGMENT

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.

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