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# Implementation of a high-speed multichannel data acquisition system for magnetic diagnostics and plasma centroid position control in ISTTOK

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**ABSTRACT** In tokamak and other fusion devices, magnetic control is the main tool that allows to regulate the plasma current, position and shape; it is in charge of actuating the desired plasma current waveform, steering the plasma position to a given set point and maintain the plasma shape close to a prescribed plasma equilibrium. This work describes the application of several physics concepts and computational tools in order to obtain a novel optimal controller for the plasma centroid position, which has been implemented and tested in the real-time plasma control system at the ISTTOK tokamak. A key point for the development of the new control system was the installation of a recently upgraded hardware, that numerically integrates in real-time the magnetic probes signals.

**INDEX TERMS** Real-time control, plasma current, plasma current centroid position, magnetic probe, poloidal field coils, numerical integration.

## I. INTRODUCTION

Tokamaks [1] are experimental devices used in nuclear fusion research, in which a hot (from tens to hundreds of millions of degrees) Hydrogen plasma (H/D/T in different isotopic mixtures) is confined in a toroidal (i.e. doughnut-shaped) vacuum chamber by strong magnetic fields. Currently, tokamaks are considered the most promising concept to achieve energy production through nuclear fusion reactions.

In tokamaks, a number of dedicated control systems are used to regulate and maintain the performance of the plasma, and to protect the device itself. Such systems are crucial to achieve stable and sustained fusion reactions, and are in charge of controlling a wide range of plasma parameters [2]. Among these systems, plasma magnetic control [3]–[5] is devoted to actuating the currents in the so-called *Poloidal Field Coils* (PFC), i.e. a set of windings (often made of superconductive materials in modern reactors) that are used to generate the magnetic fields needed to confine the plasma and regulate quantities such as the total plasma current, the current centroid position and the plasma shape (defined on

the basis of the magnetic field topology as the last closed magnetic flux surface which is completely inside the vacuum chamber - see for example [6]). In addition, this system is also used to stabilize the  $n = 0$  plasma vertical instability [7], [8].

The practical implementation of any of the control systems of a tokamak, including the magnetic one, involves a combination of reliable sensors, fast actuators and specific control algorithms. In particular, as direct sensing is infeasible for fusion plasmas, dedicated techniques are often needed to reconstruct the quantities of interest from indirect measurements [9]–[11].

In this paper, we discuss the implementation of the diagnostic and control system for the plasma current centroid position in the ISTTOK tokamak [12]. ISTTOK is a circular cross-section research tokamak operated at the Instituto Superior Técnico, Lisbon. It has a major radius of 46 cm and minor radius of 8.5 cm, with a nominal toroidal field of 0.3 – 0.6 T which can reach a maximum of 2.8 T. ISTTOK has an iron-core transformer and a graphite limiter, and it has

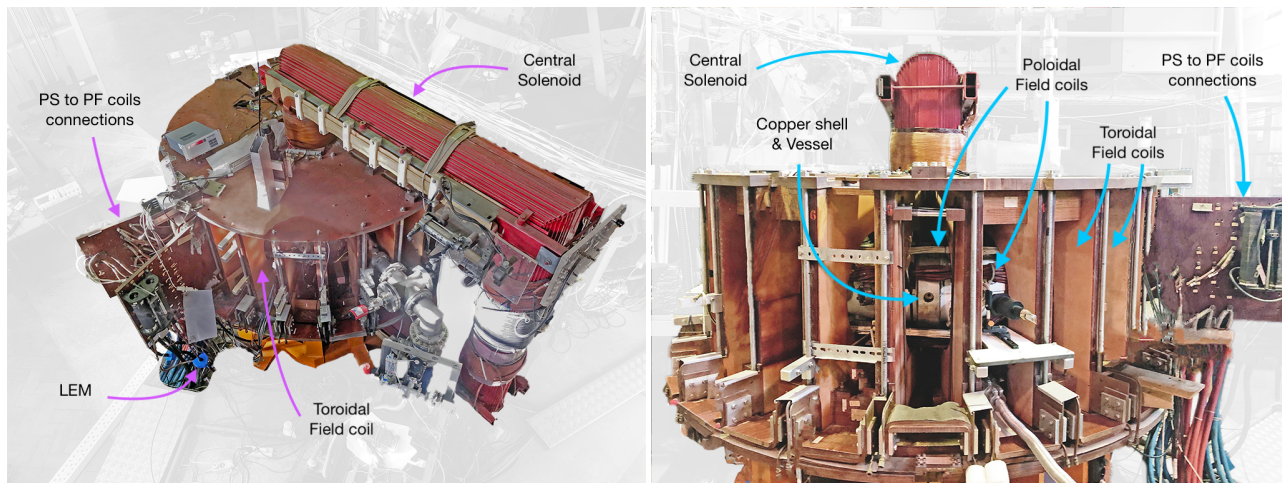


FIGURE 1: Left: ISTTOK top view, the main elements are indicated with magenta lines. Right: frontal view, the main components considered in this article are indicated with blue lines.

the peculiarity of being capable of operating in both Direct and Alternate Current, with a maximum plasma current of 7 kA.

The real-time integration of diagnostic signals enabled a reliable reconstruction of the plasma current centroid position. The availability of these real-time data for the plasma position facilitated the implementation of novel and more accurate control techniques.

The rest of the paper is structured as follows. The ISTTOK magnetic configuration is first introduced in Section II, followed by the hardware implementations in Section III, and the real-time software integration in Section IV. Section V presents the real-time position control results, while Section VI discusses the obtained results.

## II. ISTTOK TOKAMAK

Many ISTTOK components, such as the vacuum systems, the PFCs, and the power supply for the toroidal magnetic coils, as well as its diagnostics and control&data acquisition system, were locally designed and built at the Instituto Superior Técnico, Lisbon. Figure 1 shows a top and a frontal view of the ISTTOK tokamak. The main elements are indicated in the figure.

### A. ISTTOK AC PLASMA CURRENT

ISTTOK main characteristic is that, thanks to the flexibility of the power supplies and their relatively low electrical time constants, it is possible to perform AC discharges which allow the fast reversal of the plasma current while maintaining a finite plasma density between consecutive flat tops [13]. During the AC discharges, the toroidal field  $B_\phi$  is kept unchanged, but the plasma inversion result in a reversal in the generated poloidal which requires in turn a change of sign of the equilibrium vertical field required to achieve the desired toroidal force balance. ISTTOK's dwell time in between two cycles is adjustable, but normally chosen equal to  $\sim 1$  ms.

### B. DIAGNOSTICS AND ACTUATORS

ISTTOK integrates a set of different diagnostics to retrieve important plasma parameters, including Langmuir probes, interferometry, tomography, and magnetic probes [14]. In particular, ISTTOK has a set of 12 poloidally distributed magnetic field probes (*Mirnov coils*), as shown in figure 2. Three-dimensional computer models of the pick-up coils and of their graphite mounting are shown in figure 3.

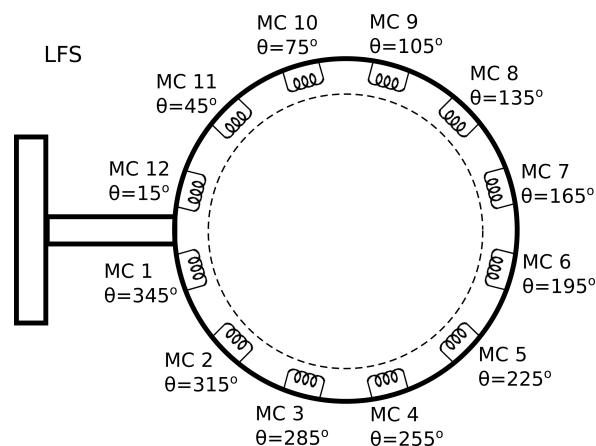


FIGURE 2: Set of 12 poloidal magnetic field probes for the reconstruction of the plasma centroid position at ISTTOK, with the corresponding poloidal angles. The Low-Field Side is indicated as LFS.

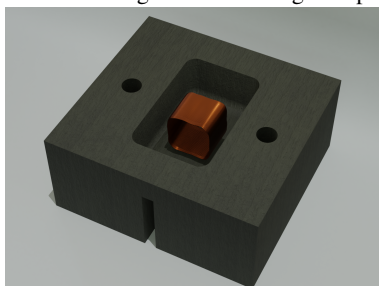
Figure 4a shows the vessel side port, where the magnetic probes are placed and the probes acquisition cables, along with some of the PFCs cables in orange and white. Magnetic probes are capable of picking up the induced voltage due to Faraday's law

$$\varepsilon = -N \frac{d\Phi_P}{dt},$$

where  $\Phi_P$  is the total poloidal magnetic flux generated by the plasma, the PF-Coils and the passive elements and enclosed



(a) 3D model of a single ISTTOK magnetic probe coil.



(b) 3D model of one graphite box which conforms the plasma facing limiter and contains a magnetic probe inside. Each probe is capsuled inside a graphite box, cut horizontally to avoid eddy-currents.

FIGURE 3: ISTTOK magnetic probes.

by the probe cross-section. The relatively small cross-section of the Mirnov coils allows to assume that the magnetic field remains approximately constant over the probe volume.

### C. POLOIDAL FIELD COILS

ISTTOK's Poloidal Field (PF) coils are connected to three independently feedback-controlled power supplies, for the purpose of generating plasma current and of controlling the plasma current centroid's vertical and horizontal position. Figure 6 depicts, on the right side of the iron core, an old central solenoid which used to be responsible for plasma current generation; this element is currently disconnected, and has been replaced by another one on the limb of the transformer. The primary PFCs, in white color, generate Ohmic heating for the creation of plasma current and an additional vertical field. The vertical PFCs are shown in yellow, while the horizontal PFCs are in green. These groups of coils are controlled by different control algorithms in order to follow a centroid position set point [15]. The poloidal field geometries generated by these three independent circuits are shown in figure 5.

Figures 4a and 4b show the cables from the PFCs arranged in sets of orange (Vertical and Horizontal PFCs) and white cables (Ohmic Heating coils).

From the pictures in figure 4 it is clear that due to strong space constraints and a vacuum vessel with a multitude of diagnostics ports, especially the vertical and horizontal PFCs

(orange cables) are not uniformly arranged, toroidally not very axisymmetric and they seem to have a general negative offset in the vertical coordinate. In addition, there is no exact knowledge of how the internal vertical coils have moved during the years, and these uncertainties presented relevant difficulties while attempting to adjust a numerical, physics-based ISTTOK model. This motivates the need for the model identification procedure discussed in section V-B.

### III. ISTTOK HARDWARE

The implementation of ISTTOK's real-time control diagnostics and actuators relies on a recently upgraded hardware based on the Advanced Telecommunications Computing Architecture (ATCA). The real-time control system is programmed on top of the Multi-threaded Application Real-Time executor (MARTe) software framework [16], which collects and processes the information gathered by all the diagnostics [17]. A recently implemented, hardware-integrated, magnetic probes signals acquisition system allowed the implementation of new real-time algorithms for an accurate reconstruction of the current centroid position on ISTTOK.

#### A. ATCA-MIMO-ISOL BOARDS

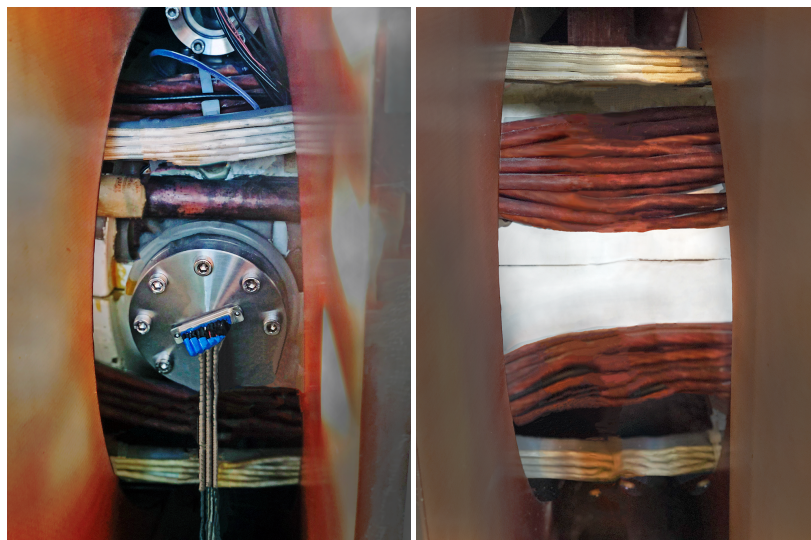
The ATCA carrier board is an IPFN-developed board [18] complying with the ATCA standard specification, highly modularized, and with an optional Rear Transition Module (RTM) for extended connectivity. The carrier board can hold up to 32 analog input channels, each connected to a plugged-in ADC module. All modules are connected digitally to a XILINX Virtex-4 FPGA, which performs necessary digital signal processing and includes a PCI Express Endpoint providing the data interface to the ATCA switch board. The latest version of the ATCA-MIMO-ISOL boards built at IPFN were initially developed for the magnetic acquisition in the stellarator W7-X [19], and they were then tested for use in the ISTTOK device. A picture of the ATCA board is shown in figure 7.

The phase modulated (chopper) ADC module [18] was designed targeting the digital integration of signals generated by magnetic coils, over periods of time larger than one hour. This ADC module is composed by a Signal Condition block with a passive filter attenuator and an active differential amplifier, the ADC block (18-bit resolution, fixed 2MSPS (Mega samples per second)), a DC-DC converter and a galvanic isolation coupler (ILS711-S1) and finally the digital interface to the FPGA in the ATCA carrier Board. The FPGA also provides the clock signals for the DC-DC converter, the chopper and ADC clocks and receives the serial ADC data and clock signals.

### IV. REAL-TIME INTEGRATION SOFTWARE

To recover the magnetic field magnitude from inductive probe signals, an integrating component is needed. However, typical electronic integrator circuits always suffer from voltage offsets present in the components and wiring. Even





(a) Magnetic probes, which are connected to the ATCA acquisition boards. In addition, the PFCs and copper shell are also visible in the image. (b) Close-up of the PFCs, with the white cables corresponding to the primary coils and the orange cables representing the vertical and horizontal coils.

FIGURE 4: ISTTOK close up side views.

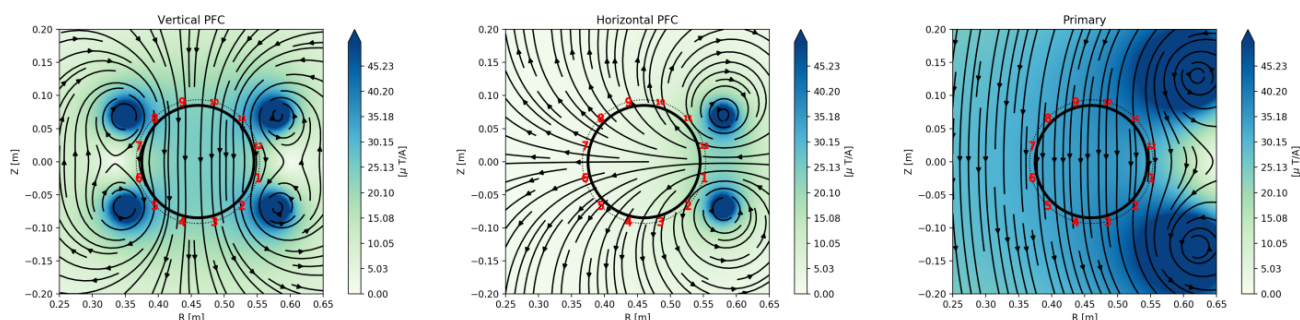


FIGURE 5: Magnetic field generated by the active coil circuits on their nominal positions. Mirnov coils are represented by their sequential numbers (in red) over the dashed line. The black circle represents the limiter.

very low offsets integrated during a long period of time may appear as a noticeable drift of the integrated signals [20] and eventually saturate their outputs. The solution chosen for this integrator design, previously demonstrated in a four channel prototype in PXI format [19], was to modulate signals with a phase inverter (chopper), which reverses periodically the input signal before active amplification (multiplies the signal by 1 and then by -1), filtering and sampling in the ADC, as shown in figure 8. The switching frequency is programmable and made synchronous with the sampling ADC 2Mhz clock, as both are generated in the same FPGA. By applying the signal inversion before any electronic amplification, and reconstructing the digital equivalent of the signal after the digitalization, the average of the Electronics Offset (EO) (i.e. the voltage offset introduced downstream of the chopper converter due to chopper charge transfers and the amplification of the ADC input, see fig. 8) is expected to be almost zero

in the integration process if its value is steady enough over at least two inversion periods. In addition, a second offset also appears before the chopper, i.e. the Wiring Offset (WO) which may be generated upstream of the DC-DC converter either inside the module or in the external wiring, connectors and soldered parts, mainly due to uncompensated thermocouple effects, external interference or radiation effects (see again fig. 8). Unfortunately, the WO is not averaged by the chopping method, since it goes across two signal reversions, and is typically much lower than either both EO or the ADC resolution. From figure 8 the integration process can be inferred. Let's say the upcoming signal from the probe is  $s(t)$ , the sampled value is  $V_{ADC}[n]$

$$V_{ADC}[n] = (s(nT_s) + WO) \cdot Ph_{chop}(nT_s) + EO, \quad (1)$$

where  $t = nT_s$ ,  $T_s$  is the ADC sampling period, and  $Ph_{chop}$  is the phase signal of the chopper (1 or -1). Assuming



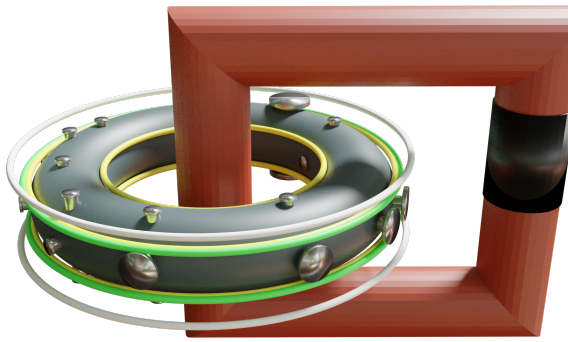


FIGURE 6: 3D model of the ISTTOK PFCs, vacuum chamber with ports, iron core and the former central solenoid (black color). Primary coils (white color) and horizontal coils (green color) are formed by 2 coils each, and are located on the upper and lower LFS (Low Field Side) of tokamak. Vertical coils (yellow color) are formed by 4 coils, 2 are located on the upper and lower LFS and 2 in the upper and lower HFS (High Field Side).

$s(nT_s) \approx n[T]$  and  $Ph_{chop}(nT_s) \approx Ph_{chop}[n]$ , the phase reconstructed signal from the magnetic probe can thus be approximated from the discrete samples using

$$s[n] \approx (V_{ADC} - EO) \cdot Ph_{chop}[n] - WO. \quad (2)$$

Assuming the ADC sampling frequency is sufficiently higher with respect to the double of the the signal bandwidth, the integral of the magnetic fluxes picked up by the Mirnov coils can be approximated by the expression

$$\Phi(t = nT_s) = \int_0^{t=nT_s} s(t)dt \approx \sum_0^N ((V_{ADC}[n] - EO) \cdot Ph_{chop}[n]) - nT_s \cdot Wo. \quad (3)$$

Hence, to approximate the integral of the signals acquired from the magnetic diagnostics, the EO-corrected  $V_{ADC}$  summation is computed in the FPGA and then sent to the MARTe database via PCI-express.

Even though WO removal is a common feature in processing magnetic data, the solution implemented at ISTTOK gives a remarkable flexibility in allowing the calculation of the offset prior to each discharge. This is in contrast with other experiments, where the offset correction is fixed and calibrated one sigle time. Due to the physical conditions in ISTTOK, which do not include a good isolation of the instrumentation for minimizing electromagnetic noise and temperature impact, the offset drift values are in constant change and so they should be calculated prior to every discharge. Figure 9 shows the WO fluctuation in the magnetic probe # 10 in 2019, it is possible to see that in most of the shots the changing percentage is in the order of  $\pm 30\%$ . Figure 10 shows the WO values and percentage changes for a less number of shots on the magnetic probe #10, this shot numbers correspond to data acquisitions where the WO

had the smallest changes, from these figures is possible to conclude that a real-time algorithm is needed to calculate the WO on each probe prior to a plasma discharge.

Even though the probes signals before the discharge starts are not stored in the experiment database, the WO of each probe can be computed several seconds before the start of the discharge. The WO value obtained is then subtracted in real-time at every MARTe iteration once the discharge starts from the actual probe signals. In figure 11, the integrated WO summed to the probe signal is shown.

## V. ISTTOK REAL-TIME PLASMA POSITION CONTROL

The real-time measurements of the plasma current and centroid position is used in the implementation of a feedback control loop for these quantities. The reconstruction from these signals is widely addressed in the previous work presented in [14]. The controller design, on the other hand, is based on a state-space model that links the PF currents to the quantities of interest; such model is obtained through a data-driven procedure, discussed in section V-B.

In practice, the control of the plasma current centroid position is then achieved by means of several programming blocks working together, also known in MARTe as General Application Modules (GAMs). A block diagram of the control loop architecture is shown in figure 12. The control cycle starts with the acquisition of the signals from the magnetic probes. These signals are processed in the "Magnetics" GAM, where the radial and vertical centroid position are computed for every MARTe cycle. Then, the "Controller" GAM selects the controller to be used for the centroid position based on the data selected in the "Discharge Configurator" GUI, which is configured by the tokamak operator before the start of the discharge; the control inputs are computed either by the "PID" (Proportional-Integral-Derivative) GAM or the "LQR" (Linear-Quadratic Regulator) GAM, discussed later in this section. These inputs are sent back to the "Controller" GAM, which provides them as control signals to the PFCs power supplies.

Since the ISTTOK tokamak is operated in AC mode, during the transition from negative to positive (or opposite) plasma current the reconstruction of the centroid position is inhibited, as it gives non-valid results. During the transitions, which last  $\approx 1ms$ , a pre-programmed, open-loop configuration of the PFCs currents is used, which means that there is a constant switching from automatic to manual control in between plasma cycles. The switching process between controllers may produce jumps at the plant inputs: this is known as the *bumpless transfer* problem [21, Chapter 8]. To minimize these jumps, the control signal at the manual-to-automatic switching instant should be made as close as possible to the value it assumed during manual mode [22].

### A. PID CONTROL IMPLEMENTATION

Early tokamaks often employed sets of PFCs that were symmetrically placed with respect to the tokamak equatorial plane, in order to guarantee mutually independent vertical

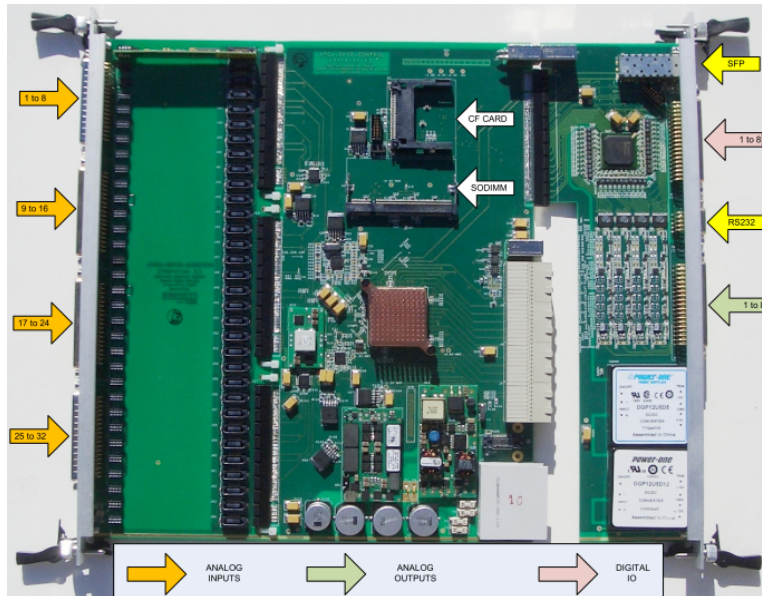


FIGURE 7: General view of the ATCA-MIMO-ISOL carrier board, including on the right side an original IPFN RTM board joined through an edge connector.

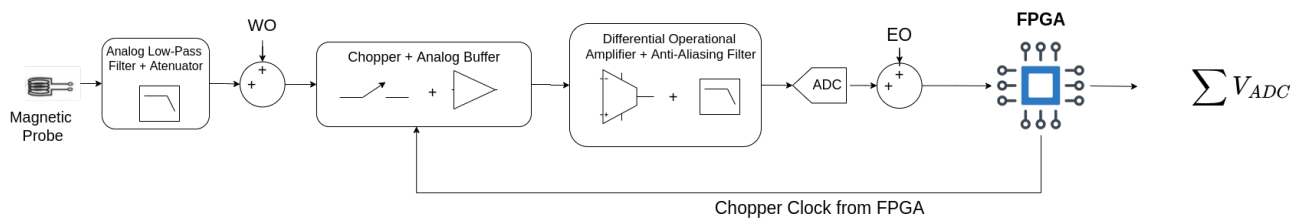


FIGURE 8: ADC module diagram depicting the influence of the WO and EO offsets and the instrumentation since the magnetic probes signal it is acquired until its integration in the FPGA.

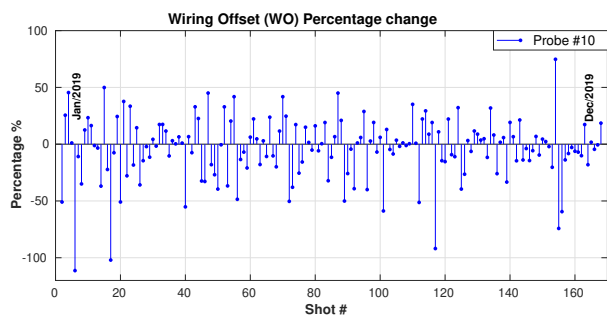


FIGURE 9: WO percentage change in the magnetic probe # 10 in 2019 using data from approximately 180 shots distributed during the entire year.

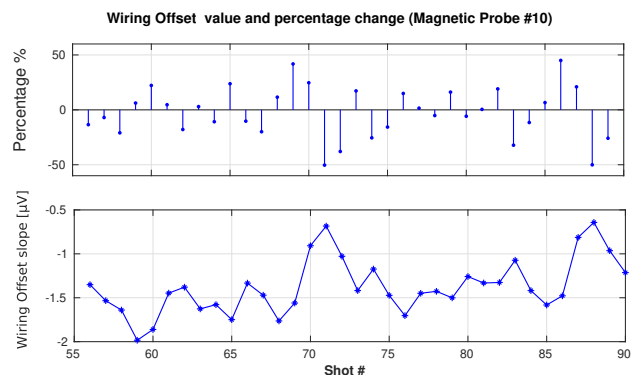


FIGURE 10: WO and percentage change in the magnetic probe #4 throughout 45 shots in ISTTOK.

and horizontal movement of the plasma [3, Chapter 1]. For many years, ISTTOK plasma position control strategy was driven by the principle that an external vertical field generates an horizontal force and an horizontal external field generates a vertical force due to the Lorentz force law. This in turn led to the implementation of two separate SISO (Single-Input Single-Output) controllers for the vertical and radial

centroid position. The "PID" GAM in figure 12 implements the same algorithm in the MARTE framework: it has two PID controllers with pre-configured gains, an anti-windup

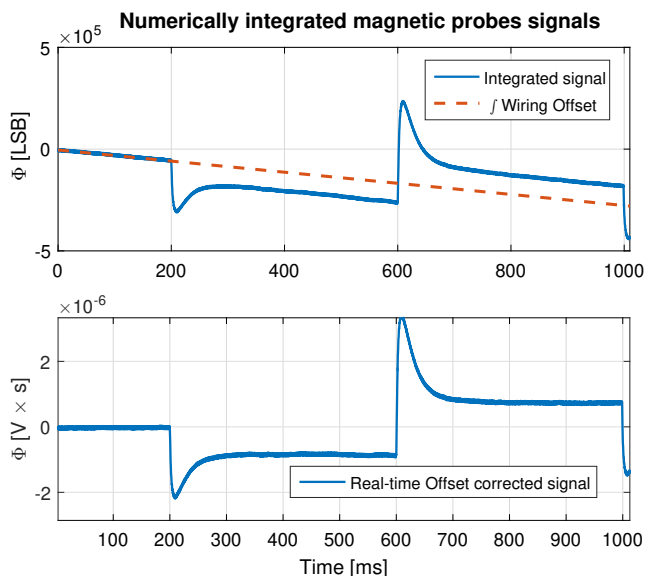


FIGURE 11: Real-time subtraction of the integrated WO for drift compensation is performed on every MARTe cycle throughout the shot and for each magnetic probe.

system<sup>1</sup> and a bumpless transfer mechanism, obtained by adjusting the integral action when the saturation limits are reached and/or when the transition from manual to automatic control takes place [24, Chapter 3], [22].

### B. DATA-DRIVEN STATE-SPACE MODEL RETRIEVING

This original SISO logic has been upgraded to a MIMO one, which relies on a data-driven model of the plasma behaviour. This model is discussed in this section.

As it was discussed in section II-C, obtaining an accurate physics-based electromagnetic model (either axisymmetrical or 3D) for the ISTTOK plasma response is a hard task, due to the large uncertainties in the machine geometry and parameters. Early efforts in finding a theoretical model for ISTTOK magnetic control were performed during the last years. However, since ISTTOK PFCs are not axially symmetric and apparently their actual positions have been shift from the original ones, despite the efforts a working theoretical model was never successfully obtained. For this reason, finding an alternative path to implement a model-based magnetic control in the ISTTOK real-time MARTe system became necessary. In particular, in order to design the plasma position controller, data-driven models of the plasma response were obtained from past discharges data by means of Matlab's *System Identification Toolbox* [25]. These models are in the form of  $2 \times 2$  MIMO systems, with the Vertical and

<sup>1</sup>The saturation of actuators or major set point changes are some of the most frequent non-linearities in control applications, which can cause instabilities in the system. The undesired interplay of these events with the integral action of a PID controller is called *windup* [23]. It typically produces undesired overshoots resulting from overreaction of the integrator block of a PID controller [21, Chapter 1], and must hence be compensated for.

Horizontal PF circuits currents as inputs and the vertical and radial plasma current centroid coordinates as outputs.

When trying to join data sets of signals coming from positive and negative plasma current discharges, the models started to loose consistency, showing from early stages that the two discharge phases needed to be modeled separately. Hence, one state-space model was obtained for discharges where  $I_p > 0$ , and another for discharges where  $I_p < 0$ . This matter probably originates from the fact that a tokamak is not completely axisymmetric in reality. This is particularly true for ISTTOK, which happens to have very non-axisymmetric PFCs which can produce a different overall topology of the poloidal magnetic field in the tokamak for the  $I_p < 0$  and  $I_p < -0$  cases. Figures 13 and 14 show the comparison between the database centroid position signals and their reconstruction using the estimated state-space models. It is worth to remark that these are validation plots, i.e. the reconstructed centroid position was not used as modeling data. Differences in the transients of the signals might originate from differences in the initial states between systems.

Since a tokamak is an intrinsically nonlinear system, the modeling process was done using data sets in which the centroid position was located in a prescribed region, in order to approximate the estimated model to an equilibrium region where a linear approximation is valid. Local linearized models are typically evaluated in a set of operating points that capture the key modes of operation. Linear controllers like PID or LQR are then synthesized for the obtained linear system, ensuring that some relevant performance specifications are met in the vicinity of the operating point in question [26]. The optimal number of states computationally retrieved was found to be 10. The input and output vectors for the identified models are defined as  $u^T = [I_{vert}, I_{hor}]$  and  $y^T = [R, z]$  respectively.

### C. KALMAN FILTER IMPLEMENTATION

In order to reconstruct the state vector  $x$ , two Kalman filters were also implemented, one for the model related to positive plasma current and another for the negative current one. The Kalman filter matrices were obtained based on noise estimates obtained from ISTTOK experimental data, calculating the co-variance matrices from the signal vectors [27]. Figures 15b and 15a correspond to the real-time Kalman filter reconstruction of the vertical and radial plasma centroid position and its comparison with the multi-filament reconstructed position computed by the "Magnetics" GAM.

### D. MULTIPLE-INPUT MULTIPLE-OUTPUT CONTROL IMPLEMENTATION

The full-state estimate from the Kalman filter is generally used in conjunction with the full-state feedback control law from LQR, resulting in the optimal, sensor-based linear-quadratic Gaussian (LQG) controller [28, Chapter 8]. Under this principle, the real-time reconstructed states are multiplied by the control LQR gain  $K$  in order to steer the



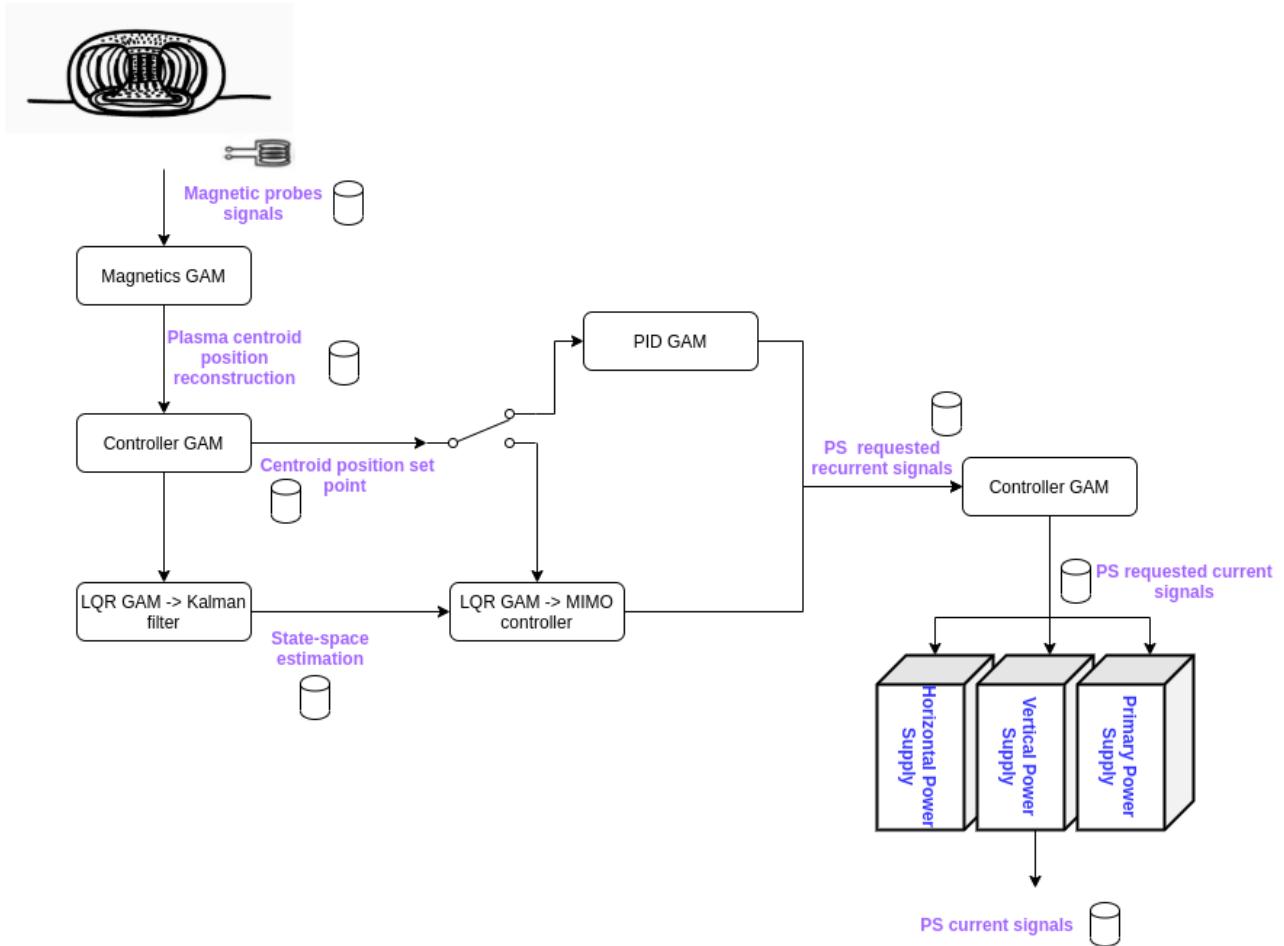


FIGURE 12: ISTTOK MARTe overall plasma position control scheme.

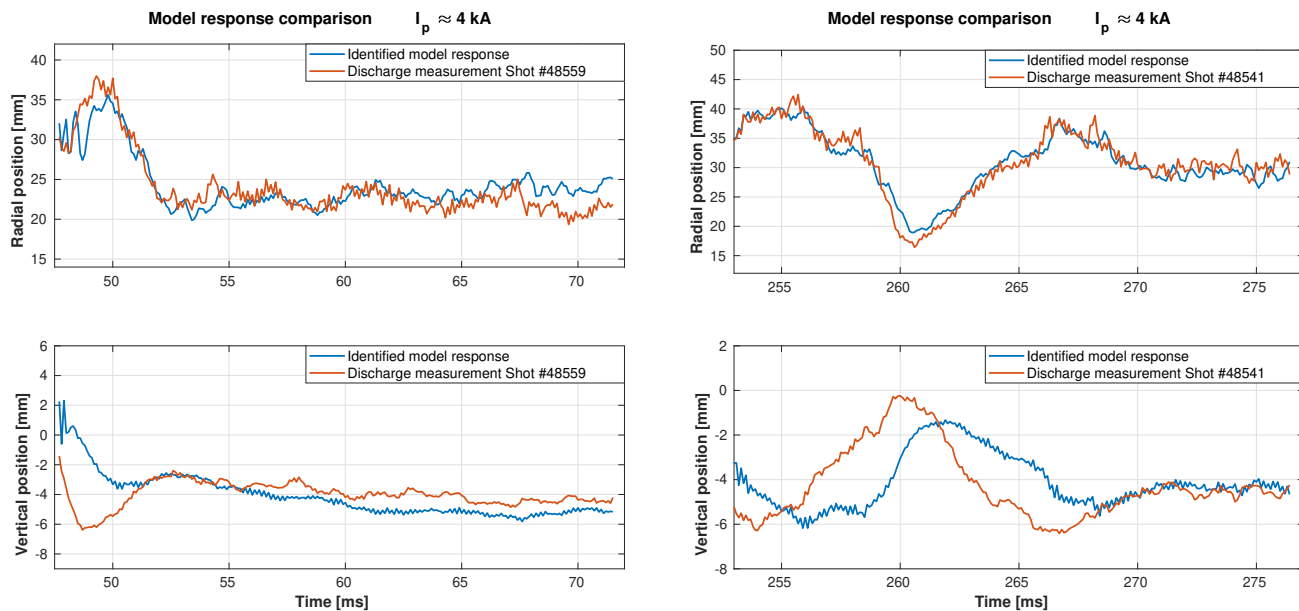
vertical and radial plasma centroid position towards a desired set point; this process is computed in the "LQR" GAM. The weight matrices for the discrete LQR controller were empirically tuned in order to have a balance between a fast response and the input energy demand. However, several algorithms for a non-empirical calculation of the LQR matrices exist, some of which propose a tuning based on experimental data with a gain matrix that can be iteratively updated [29, Chapter 9], [30].

## VI. PLASMA CURRENT CENTROID POSITION CONTROL RESULTS

In the following plots, the control performance in terms of vertical and horizontal plasma centroid coordinates is compared for the cases where these quantities are controlled by a set of 2 PID's and by a single LQR MIMO controller, and for different pre-programmed set points. The inputs response, i.e. vertical and horizontal PFCs currents, are also shown and compared in the considered cases. In the figures, the discharges are referred to as *Shot#* followed by the ISTTOK's database discharge number. Since it is not mathematically possible to determine the initial conditions of the states, they must be steered to the MIMO controller region of attraction.

This is achieved by controlling the centroid position with the PIDs at the beginning of the discharge, while the Kalman filter converges to the actual value of the state vector. For this reason, the discharges marked as LQG control start with PID controllers and then switch to LQG at  $t \sim 1 \text{ ms}$  for positive  $I_p$  plasmas and at  $t \sim 3.5 \text{ ms}$  for negative  $I_p$  ones (the switching instants can be configured by the user). Switching between two controllers in parallel yields a control substitution which causes bumps in the response; bumpless transfer schemes can be modified in order to smooth the phasing-in of a new controller to supplement or replace an existing control at the plant, e.g. as described in [26].

Figures 16a and 16b show the time traces of the vertical and horizontal plasma centroid position for two different scenarios. Figure 16a shows the plots corresponding to a plasma discharge where  $I_p \approx -4 \text{ kA}$ ; the green vertical line marks the switching point from PID to LQG control. The vertical position time trace shows a non-minimum phase system behavior for the MIMO LQG control, while this behaviour is absent for the PID case. It is possible that this behavior originates from a delay that was introduced as a numerical artifact during the data-driven identification pro-



(a) Comparison between the identified model response and the real-time centroid position reconstruction. Shot #48559

(b) Comparison between the identified model response and the real-time centroid position reconstruction. Shot #48541

FIGURE 13: Model response for two different  $I_p \approx 4$  kA discharges.

cess<sup>2</sup>. Figure 16b corresponds to a plasma discharge where  $I_p \approx 4$  kA; since the PID controlled part of the discharge is very short in this case, the switching point is not marked. The position set points are shown as black dashed lines in both figures.

Figure 16 indicates that the LQG controller has significantly improved performance when  $I_p$  is positive. However, in the case of a negative  $I_p$ , the LQG controller's performance is comparable to the PIDs on the radial position channel, although with a slightly shorter settling time. Instead, it is slower than the PIDs on the vertical position channel but both attain the setpoint with practically no error in a shorter time.

For both considered cases, i.e.  $I_p \approx \pm 4$  kA, a noticeable smaller current request from the vertical and horizontal PFCs power supplies can be appreciated in the LQG case, which implies less power is required by the system with the updated controller.

## VII. CONCLUSIONS

This article provides a comprehensive account of the recent advancements made to the plasma current centroid position control system of the ISTTOK tokamak. In addition to describing the new and improved hardware and software components used to implement this control system, the article also delves into the technical details and specifications of

<sup>2</sup>Open-loop and closed-loop models for  $I_p \approx -4$  kA have a zero far from the unitary circumference in the transfer function  $H_2(z)$  map which links the vertical centroid position  $z$  and the vertical PFCs current  $I_{vert}$ , this might have generated an initial inverse response in the vertical centroid position.

these components. By providing a detailed account of the control system's architecture, the article aims to provide insights into the underlying principles and mechanisms of the ISTTOK plasma centroid position control. An *ad-hoc* offset compensation mechanism has been implemented to take into account the AC plasma current in the ISTTOK device, and a data-driven model identification was performed in order to identify the plasma centroid position response to variations in the PF currents. A novel MIMO LQG controller was designed and tested, and a comparison with the results obtained resorting to the pre-existing PID control logic shows that comparable or better performance can be obtained with a reduced energy consumption from the PFCs power supplies.

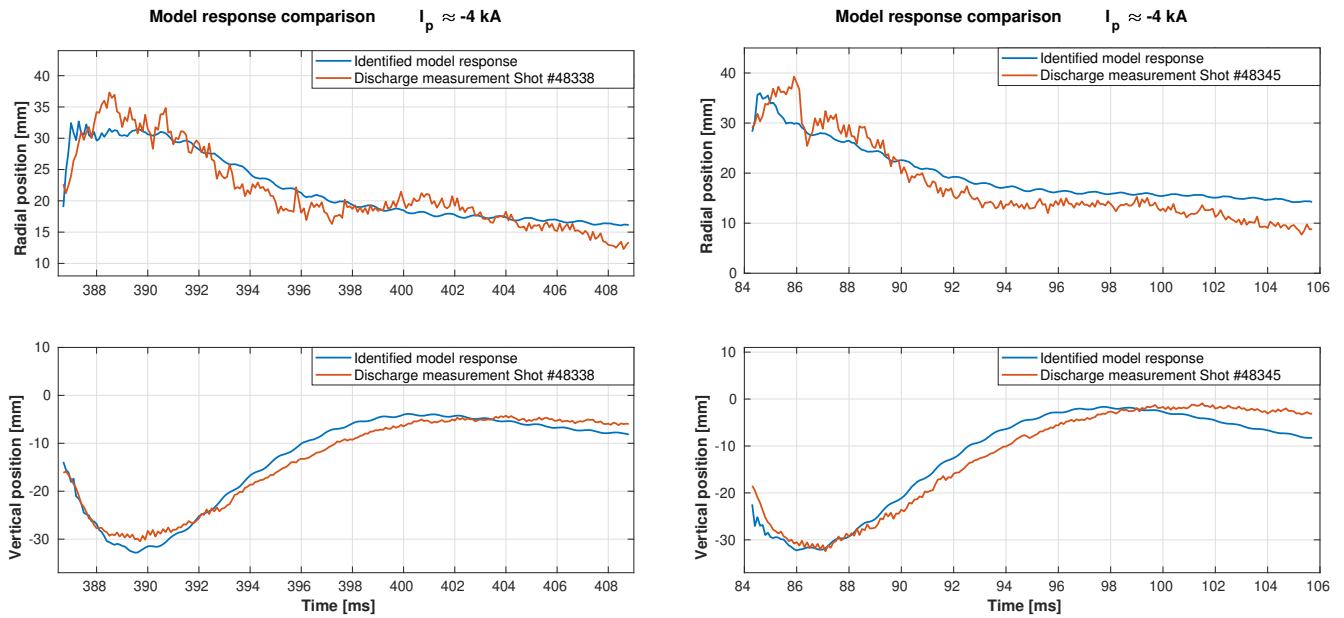
## ACKNOWLEDGMENTS

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The work of Adriano Mele has been supported by the Italian Ministry for University and Research (MUR) under the European Social Fund REACT EU - PON Ricerca e Innovazione 2014-2020 (D.M. 1062/2021).

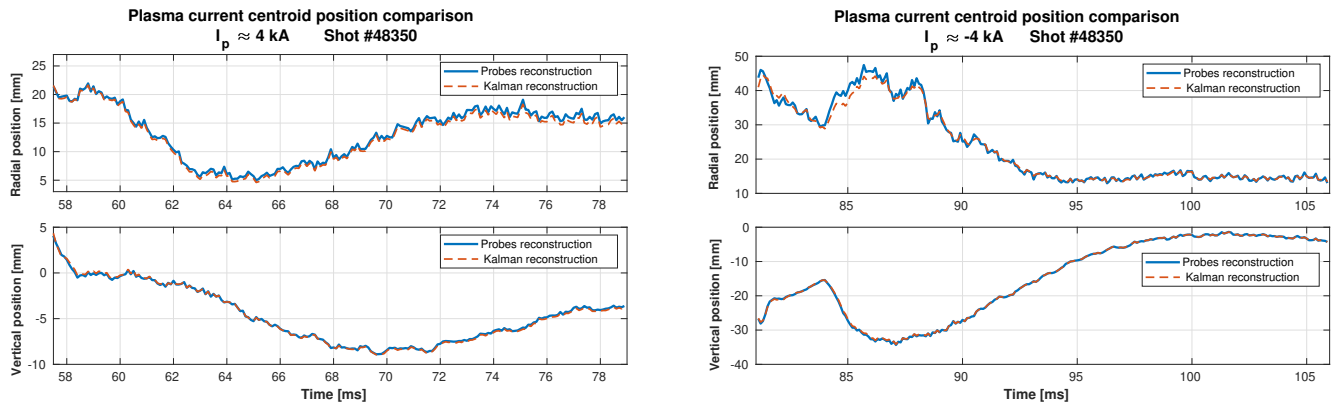
The work of Adriano Mele and Doménica Corona was also partially supported by the Italian Ministry for University and Research (MUR) under the Young Independent Research Group (YIRG) project SOLEMIO (D.M. 737/2021).

This work of Nuno Cruz has been carried out within the



(a) Comparison between the identified model response and the real-time centroid position reconstruction. Shot #48338 (b) Comparison between the identified model response and the real-time centroid position reconstruction. Shot #48345

FIGURE 14: Model response for two  $I_p \approx -4$  kA discharges.



(a) Real-time Kalman filter retrieved centroid position compared against the multi-filament reconstruction time trace for  $I_p > 0$ . (b) Real-time Kalman filter retrieved centroid position compared against the multi-filament reconstruction time trace for  $I_p < 0$

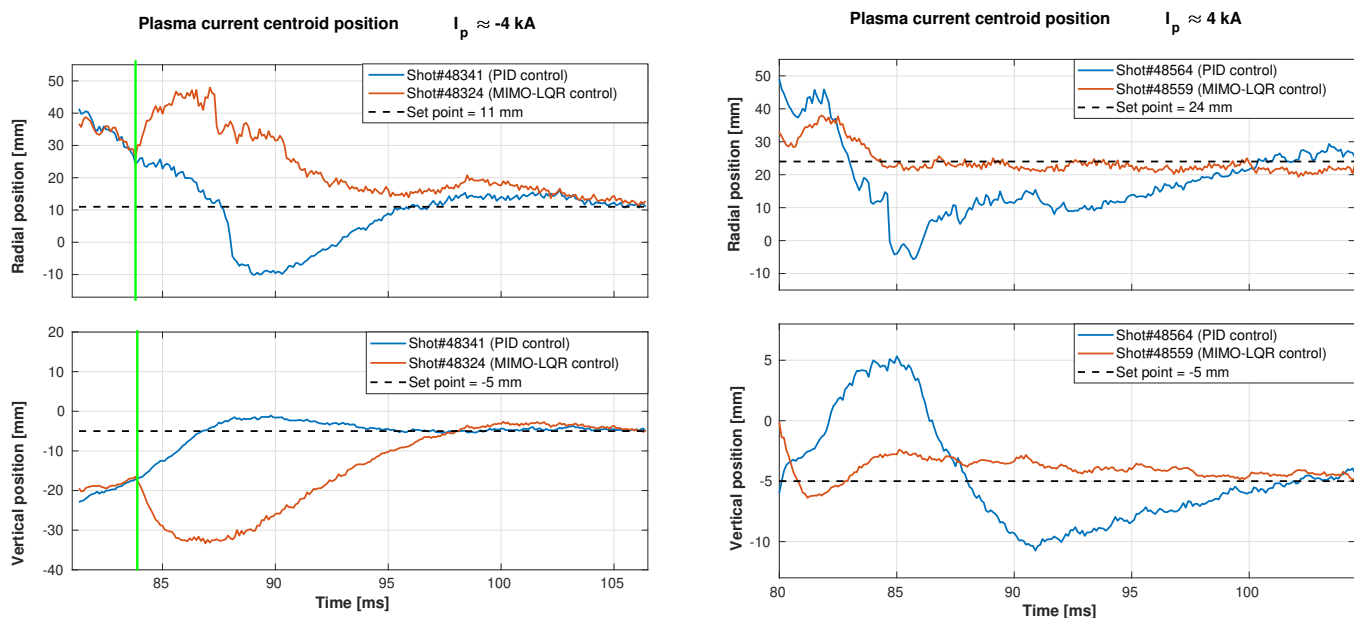
FIGURE 15: Comparison of the Kalman-filtered centroid position with the multi-filament reconstruction.

framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. IPFN activities received financial support from “Fundação para a Ciência e Tecnologia” through projects UID/FIS/50010/2019, UIDB/50010/2020 and UIDP/50010/2020.

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(a)  $I_p \approx 4$  kA. Blue time trace corresponds to a PID feedback control and orange time trace to a LQR feedback control, the dashed black line shows the programmed set point. The green vertical line marks the time instant at which the discharge Shot#48324 switches from PID to LQR control.

(b)  $I_p \approx 4$  kA. Blue time trace corresponds to a PID feedback control and orange time trace to a LQR feedback control, the dashed black line shows the programmed set point.

FIGURE 16: Horizontal and vertical plasma centroid positions.

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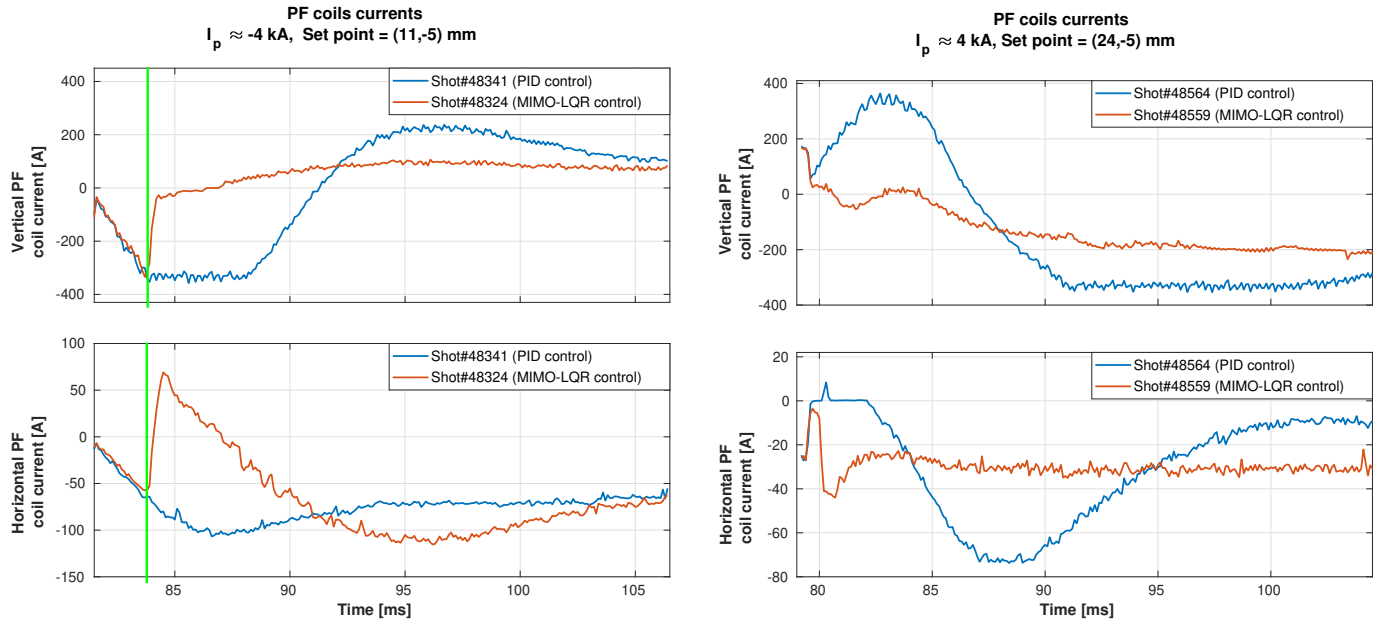
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(b)  $I_p \approx 4$  kA. Blue time trace corresponds to a PID feedback control and orange time trace to a LQR feedback control.

FIGURE 17: Vertical and Horizontal PFCs currents

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for plasma vertical stabilization for TCV, and magnetic control tools for JT-60SA.

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of more than 25 master students and seven PhD students. Since 1999 he developed a remote controlled laboratory presently hosting more than 20 experiments on-line some of them dispersed all over the world. Related to that he taught courses for high school teachers. He is a member of the Portuguese Physics Society and has been his treasurer. Presently is member IUPAP's Commission on Physics for Development and Chairs the General Assembly of the Physics Union of Portuguese-speaking countries. He had a role in a few international institutions (e.g. Scientific Investigator in a CRP-IAEA project, Fusion for Energy member of the Technical Advisor Panel, SC member of the Fusion-DC Erasmus mundus). At IST he had served in several administrative boards such as president of the post-graduate students Union, member of the University General Assembly, vice-president of the Physics department and faculty deputy director.

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Wendelstein 7-X (Greifswald, Germany) fusion experiments.

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