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Extraction of the plasma current contribution from the numerically integrated magnetic signals in ISTTOK

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Abstract: ISTTOK tokamak operates in AC mode allowing to have consecutive cycles of positive and negative plasma current. The plasma centroid position is estimated from the reconstruction of the signals obtained from a poloidal array of twelve magnetic probes. In the previous setup, this reconstruction relied on a cylindrical approximation algorithm in which the error fields generated by active coils and currents in the passive structures were not taken into account, leading to some centroid position inaccuracy. Although this approach has been able to produce flat top current AC discharges with reasonable reliability, a better solution was implemented as a preferred plasma position estimator. The signals are currently corrected subtracting the contribution from external magnetic fields following a method that relies on state-space models which use data collected from a systematic vacuum calibration procedure. Also, the plasma centroid position is estimated using a multi-filament current model. Furthermore, the recent implementation of numerical integrators in the real time ATCA based data acquisition system substantially improved the real time conditioning of the magnetic signals measurements. First results demonstrate that this new approach delivers a more reliable estimation of the plasma current centroid position with noticeable improvement on control performance, which is paramount to the success ratio of the AC plasma current switching.

Keywords: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - probes

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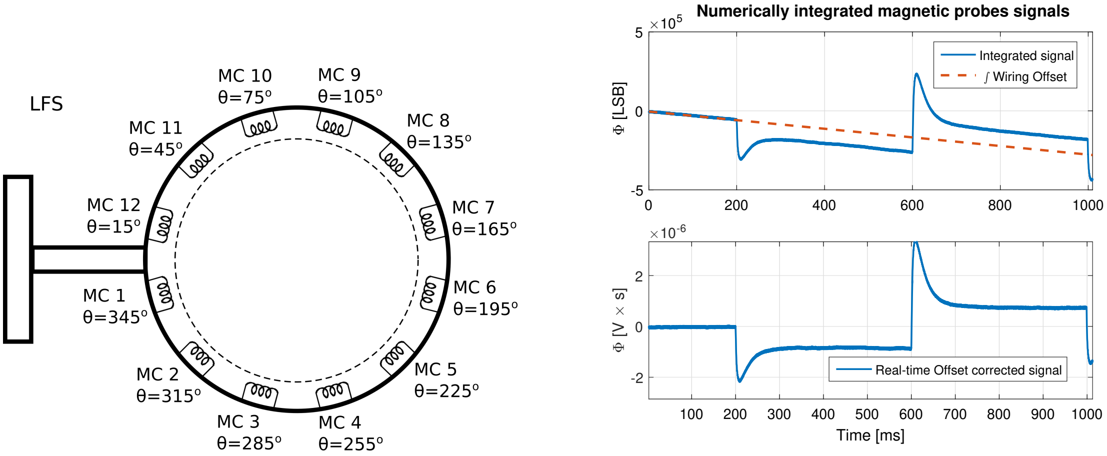
Contents

1 Introduction

ISTTOK is a large aspect ratio tokamak (IST, Lisbon, Portugal) operating for almost 30 years and which has been in constant upgrading of diagnostics, hardware acquisition system and control algorithms (major and minor plasma radius are respectively $R = 46\,cm$, $a = 8.5\,cm$). Due to the flexibility of the power supplies 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, refer to figure 1.3 in section 1.4 of reference [1]. The current inversions make it possible to achieve a much longer plasma duration in comparison to single mode operation, which is limited by the saturation of the iron core magnetization,the plasma duration is of approximately 1 s ([2, 3]). ISTTOK real-time control diagnostics and actuators implementation rely on the 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) framework, which integrates and processes the information gathered by all the diagnostics [4]. Recently implemented hardware-integrated acquisition of the magnetic probes signals at ISTTOK allowed the implementation of new real-time algorithms for an accurate reconstruction of the current centroid position. The reliable success of the plasma current inversions in AC mode demands a highly accurate plasma position control just before the reversal of the plasma current and also during its restarting, due to the delicate and inherently unstable residual plasma that lasts during the time span it takes to complete an inversion. Current centroid position reconstruction methods have been implemented before in ISTTOK based on electric probes [3] and a cylindrical approximation without correction of the external fluxes effect using analog integrators for magnetic probes signals [5, section 2]. The goal of this paper is to report the improvements in ISTTOK's general real-time operation with the use of new hardware enhancements which allowed the implementations of more complex algorithms for the reconstruction of the plasma current and centroid position.



(a) (b)

Figure 1. Figure 1a: set of 12 magnetic probes for the reconstruction of the plasma centroid position located along the poloidal direction at ISTTOK. Figure 1b: real-time subtraction from the integrated WO is performed on every MARTe cycle for each magnetic probe.

2 Real-time correction of magnetic probe signals

ISTTOK has a set of 12 magnetic probes positioned along the poloidal direction (figure 1a). The probes are connected to a carrier board where each channel is connected to a plugged-in ADC module. These modules are connected digitally to a XILINX Virtex-4 FPGA (Field-programmable gate array) which performs the necessary digital signal processing. Magnetic probes measurements are affected by the appearance of Wiring Offset (WO) that may be originated either inside the module or in the external wiring, connectors and soldered parts, mainly due to uncompensated thermocouple effects, external interference or radiation effects [6]. In the first graph from figure 1b it is possible to observe the integrated WO summed to the probe signal. Recent software implementations make possible to estimate the value of the integrated WO on each channel prior to the tokamak discharge in order to subtract on each MARTe cycle (100 μs) its contribution. The second graph in figure 1b shows the real-time signal without the effect from the WO.Even tough offset removal is a common feature in processing magnetic data it is remarkable the flexibility ISTTOK gives by allowing the calculation of the offset prior to each discharge. In contrast with other experiments where the offsets do not tent to change and have to be calibrate one single time, due to the physical conditions in ISTTOK the offset values are in constant change and so they should be calculate on real-time prior to every discharge.

ISTTOK Poloidal Field (PF) coils are connected to three independently feedback controlled power supplies for the purpose of generating plasma current and also to control vertically and horizontally its centroid position. Figure 2 shows the location of the PF coils. The primary PF coils, in white color, generate ohmic heating for the creation of plasma current and an additional vertical field. In figure 2 is shown 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. In yellow is depicted the vertical PF coils and in green the horizontal PF coils, both controlled by PID (Proportional-Integral-Derivative) algorithms in order to follow a centroid position set point [7].

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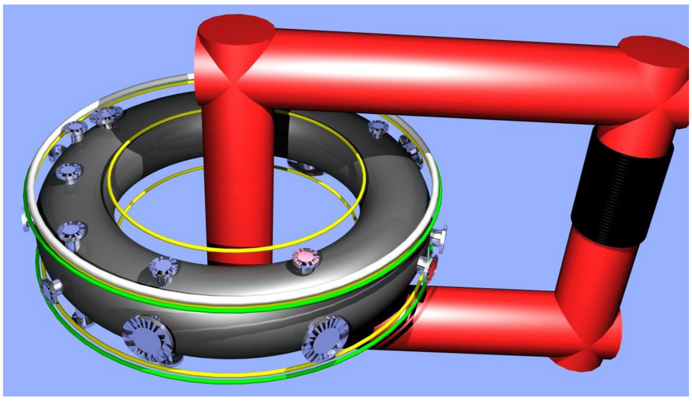


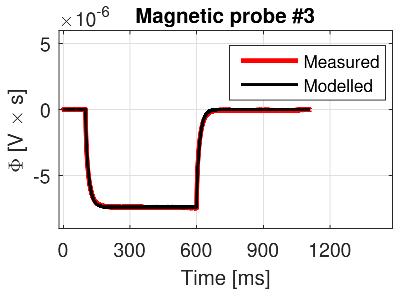
Figure 2. 3D scheme of the ISTTOK PF coils, vacuum chamber with ports, iron core and the former central solenoid (black color). Primary coils (white color) and horizontal coils (green color) are formed by 2 coils each one and located on the upper and lower LFS (Low Field Side) of tokamak. Vertical coils (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). Figure 26 in section 1.5 of ref. [5].

Performing plasma-less discharges in ISTTOK by applying different step functions waveforms in the PF coils currents, data-driven discrete state-space models were obtained in order to determine the contribution to the probes signals from passive-structures eddy currents and PF coils fluxes at any instant. Due to the linear dynamics of the PF coils and the simplicity for implementing the state-space equations on top of MARTe framework it was decided to use state-space models for the reconstruction of external contributions [8, section 2]. The modelling process was done using the *System Identification Toolbox* from MATLAB [9]. Each magnetic probe possess a set of three state-space models associated to the magnetic contribution from the vertical, horizontal and primary PF coils. The extraction of magnetic measurements related only with the plasma are used to calculate and accurate reconstruction of the centroid position, this will be addressed in the next section.

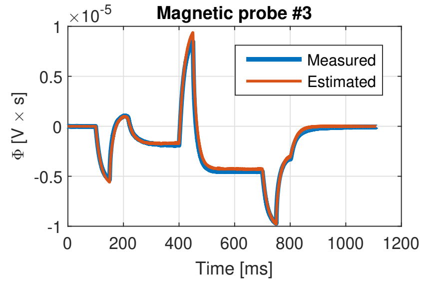
Figure 3a and 3b show the results obtained in one of the magnetic probes during the modelling process and the accuracy of the models for estimating the effect of plasma-less fluxes during a discharge. The signals shown in figure 3a were used as source information for calculating the state-space models while the figure 3b depicts the accuracy of the applied models in a vacuum discharge.

3 Plasma centroid position reconstruction

The procedures described in section 2 allowed for the cleaning of the signals and for the compensation of the effect of the external fluxes in the measurements. In this section it is described the method for obtaining a vertical and horizontal centroid position in ISTTOK using the processed signals described in the past section. The plasma centroid position is a geometrical center for the current distribution. In [10] and [11] the current centroid is evaluated by substituting the plasma with a small number of arbitrary filaments in arbitrary fixed positions since the reconstruction is not sensitive to these parameters. These filaments are used to approximate the effect of the plasma current distribution on the magnetic measurements; hence each of them is assumed to carry a certain amount of current. It should be noted that the individual filamentary current values obtained with



(a)



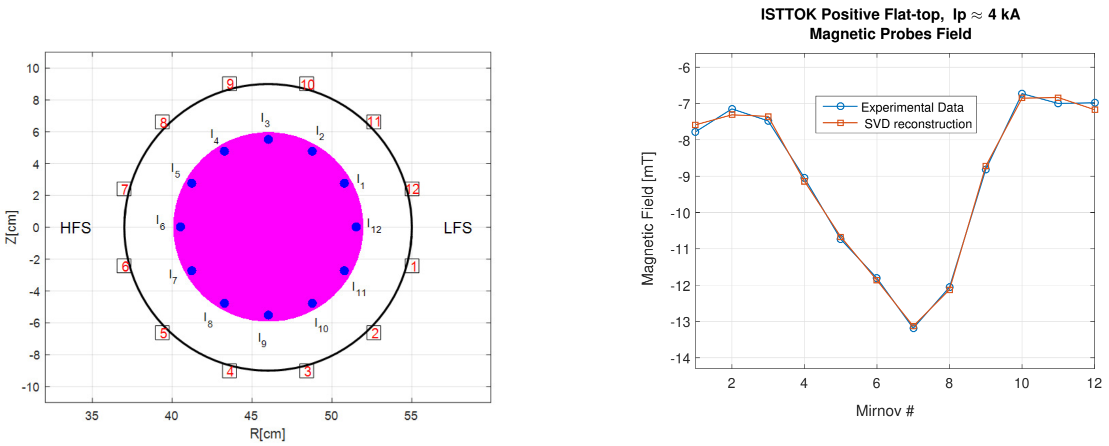
(b)

Figure 3. Figure 3a Response of the integrated and offset corrected signal in shot #44480 from magnetic probe #3 (red) used for obtaining data-driven models of the external fluxes. Reconstruction of the experimental signal through the data-driven model is shown in black. Figure 3b Response of the magnetic probe #3 (orange) to a plasma-less discharge (shot #44632) with different current waveforms in the PF coils. Post-process reconstruction of the signal probe using the models already obtained is shown in orange.

this approach possess no physical meaning, while the total current, and the centroid position (r_0, z_0) correspond to the actual current and position of the centroid.

The following work reconstructs a multi-filament model using the corrected magnetic measurements as input. This approach follows the guideline described in [12, section 3]. The method is based on the fact that an optimal solution based on toroidal harmonics is typically close to the MHD equilibrium calculation for the centroid position [12, section 3]. ISTTOK does not possess a Grad-Shafranov solver since it has a very limited set of magnetic field and flux probes and due to the cycle time on MARTe, it is necessary to select a method such as a multi-filament model for a reliable centroid reconstruction. The first step consists in the generation of matrixes that are used to estimate the filamentary currents on real-time. The setup of the current filaments was designed by setting the number of filaments and their distance from the centre of the chamber. The values of the currents flowing in each filament were determined by inverting a discretized version of the Biot Savart's equation: $\vec{dB} = \frac{\mu_0}{4\pi}\frac{I\vec{dl}\times\hat{r}}{r^2}$. The numerical inversion is done by computing the pseudo-inverse matrix through Singular Value Decomposition (SVD), resulting in $i_{p,f} = M^{\dagger}_{fp} f_p$ where f_p is the magnetic probes measurements data vector, $i_{p,f}$ are the filamentary currents best fitting the measurements and $M^{\dagger}_{fp}$ is the pseudoinverse of the fixed matrix whose ij-element gives the contribution to the measurement i of a unitary current in the filament j. The definitive geometry for ISTTOK has 12 degrees of freedom, as there are 12 static filaments at the distance of 5.5 cm from the centre of the chamber. Figure 4a shows the geometry which was chosen after empiric analysis of the measurements optimization and comparison of the plasma current with the sum of the filaments.

Afterwards it is possible to evaluate the results by comparing the magnetic measurements with the ones obtained using the filamentary currents, as in figure 4b; another estimation of the results is the total current in the filaments, which is approximately equal to the total current calculated by the sum from the magnetic probes measurements (Ampere's Law) as shown in figure 5. Finally, is possible to reconstruct the position of the current centroid with a weighted average of the 12



(a) (b)

Figure 4. Figure 4a: ISTTOK Poloidal Cross Section with depiction of the radial and poloidal positions of the selected filaments for the plasma modelling and the magnetic probes. Figure 4b: comparison between magnetic probes measurements (blue line) and reconstructed values (orange line) during a plasma current positive Flat-top.

filaments currents as in eqs. (3.1) where μ is the respective filament number.

$$r_0 = \sqrt{\frac{\sum_{k=1}^{\mu} i_{p,f_k}\, r_{p,f_k}^2}{\sum_{k=1}^{\mu} i_{p,f_k}}} \tag{3.1a}$$

$$z_0 = \frac{\sum_{k=1}^{\mu} i_{p,f_k}\, z_{p,f_k}}{\sum_{k=1}^{\mu} i_{p,f_k}} \tag{3.1b}$$

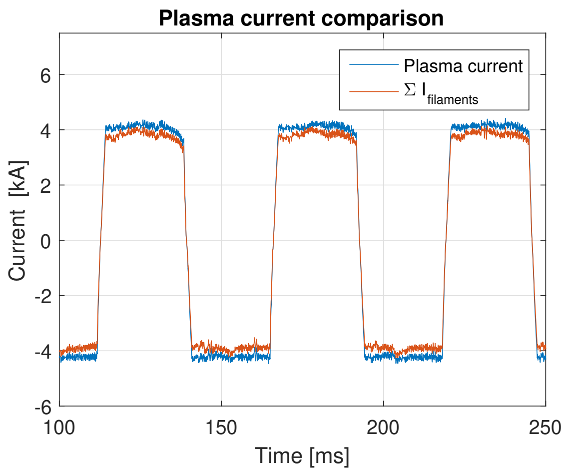


Figure 5. Comparison between the plasma current signal computed with Ampere's law and with the filamentary currents sum.

4 Real-time MARTe implementation

Real-Time control in ISTTOK relies on the execution of Generic Application Modules (GAM) executed on MARTe [13]. Algorithms for the subtraction of the magnetic contributions of the PF coils from the magnetic probes signals and for the reconstruction of the current centroid position were implemented in C++ language in an specific ISTTOK GAM.

4.1 Poloidal magnetic external contributions subtraction

Figure 6 compares the time response in one of the magnetic probes to the one reconstructed by the state-space models. During this plasma-less discharge positive and negative current step functions waveforms were applied at different starting times on the PF coils. In figure 7 are shown the signals related to the external fluxes subtraction on real-time from a magnetic probe signal during a plasma current flat-top.

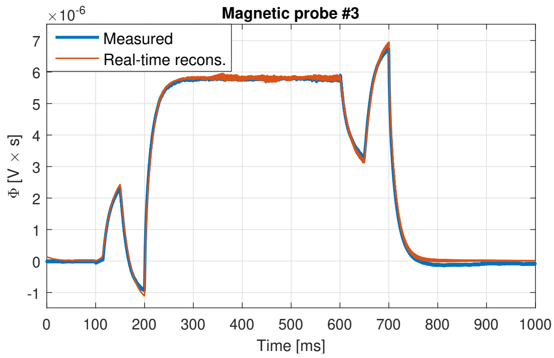


Figure 6. Real-Time reconstruction of the external fluxes contribution to the magnetic probes.

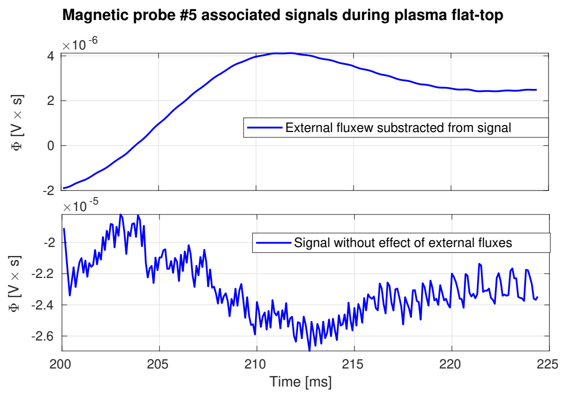


Figure 7. Real-Time reconstruction during a plasma flat-top of the external fluxes and its subtraction from the magnetic probe signal.

4.2 Plasma current and centroid position reconstruction

In addition to the centroid position, the plasma current is also estimated in ISTTOK from the magnetic probes measurements and programmed on top of MARTe as a discretization of Ampere's law (see eqs. (4.1))

$$\oint_S B \cdot dl = \mu_0 \, I_{\text{plasma}} \,, \tag{4.1a}$$

$$\frac{2\pi r_{\text{probe}}}{N} \sum_{N=1}^{N=12} B_{\text{probes}_i} = \mu_0 \, I_{\text{plasma}} \,. \tag{4.1b}$$

Figure 8 depicts a comparison between the plasma current contribution to the magnetic Probe # 1 and the reconstruction of it through the relation $f_p = M_{fp} \, i_{p,f}$. Figure 9 shows the horizontal and vertical positions and plasma current waveforms calculated on real-time during an AC discharge. Due to the actual controller settings in the tokamak the radial position takes more time to reach the set point than the vertical position whose response is faster. Currently ISTTOK current centroid position reconstruction on real-time is performed based on the multi-filamentary model described on the previous section. In figure 9 is possible to compare plasma current and position from two discharges. In the first one the control signals are based on a centroid position reconstructed by Langmuir probes and in the second discharge the centroid position is computed by the multi-filament model using magnetic probes. It is possible to observe successful inversions of plasma current when the centroid is computed by the multi-filament model in comparison with the absence of plasma current inversions when computing the centroid using the Langmuir probe signals. The plasma current inversion success percentage using algorithm reconstruction assisted by Langmuir probes in ISTTOK is ~ 80% and assisted by magnetic probes is ~ 99.8%.

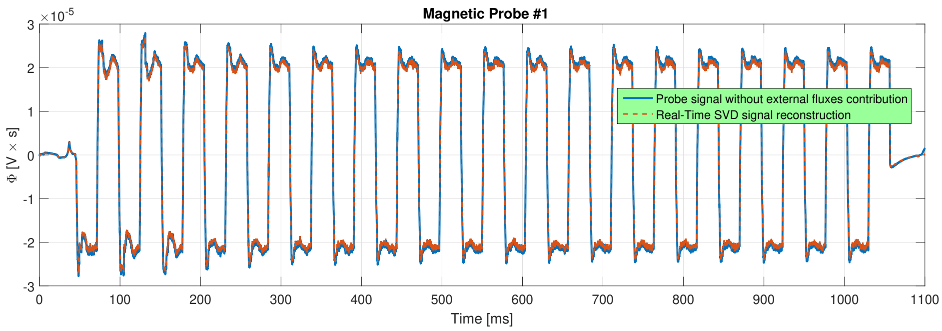


Figure 8. Comparison of the magnetic probe # 1 signal without the contribution of the external fluxes and its real-Time SVD reconstruction over the course of an AC Plasma discharge.

5 Conclusions

During this work, a comprehensive analysis and processing of the ISTTOK magnetic diagnostics was done in order to obtain a reliable reconstruction of the centroid position. With the presented corrections on the numerically hardware integrated magnetic signals in ISTTOK, it is now possible to reliably control the plasma position while varying key parameters, such as plasma current and toroidal field, these results may be presented in a future work.

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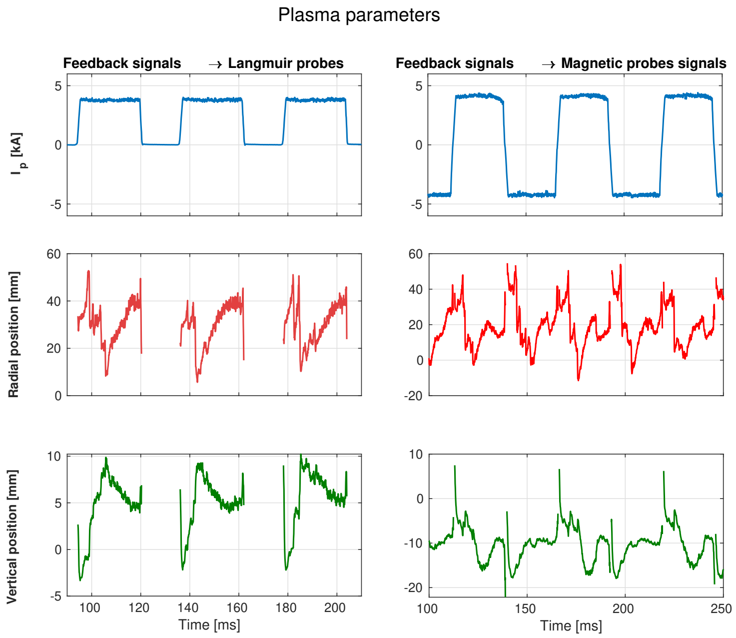

Figure 9. Real-time reconstruction of the vertical and horizontal current centroid position and plasma current assisted by the magnetic probes signal acquisition and post-processing of two plasma discharges. Left column shows the resulting signals when the discharge control feedback is performed using Langmuir probes and right column shows when using Magnetic probes signals. Negative plasma cycles are lost when using Langmuir probes signals.

Acknowledgments

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