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Observer-based real-time control for the poloidal beta of the plasma using diamagnetic measurements in tokamak fusion reactors

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Abstract— **The constant technological advances and progresses in tokamak research constantly show up new control challenges. In this context, the control of the poloidal beta has arisen as a relevant issue. In this paper a real-time observer based on the real-time analysis of diamagnetic measurements that has been developed for the Tokamak à Configuration Variable (TCV) is presented. The algorithm proposed combine measurements of the diamagnetic loops, flux loops and magnetic probes. Afterwards, some simulations are carried out with the purpose of testing the observer. Finally, once the observer has been developed and validated through simulations, it is implemented on the TCV reactor and applied to the real-time control of poloidal beta of the plasma. The results of the experiments show the feasibility of the observer for real-time tokamak plasma control purposes.**

I. Introduction

THE current increasing sophistication of new scenarios, like advanced tokamaks with extreme shaping such as ITER-like ones, has lead to remarkable progresses in the development of more reliable and feasible real-time control of tokamak plasmas (see [1]). In this context, the need for a real-time estimation of the poloidal beta (β_p) of the plasma, which, in general, can be defined as the ratio of the plasma pressure to magnetic pressure, has emerged as a very significant issue since the measurement of this parameter is very important for tokamak operation (see [2-3]). However, considering that the poloidal beta can not be measured directly, it is necessary to use other methods to estimate its value, which has promoted an increasing interest in the development of real-time observers.

Since the early days of tokamak research, magnetic measurements have been used because many properties of tokamak plasmas can be determined using simple loops or coils of wire (see [4]). In particular, diamagnetic diagnostics have been commonly used in these devices to measure the variation of the toroidal flux induced by the plasma. From these measurements, the total diamagnetic energy content, the confinement time of the plasma and the plasma poloidal beta can be obtained (see [2], [5] and [6]).

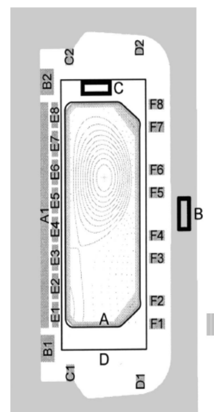

Fig. 1. A poloidal cross section of TCV showing the single (A and D) and multi (B and C) turn loops used for diamagnetic measurements. The ohmic transformer coils A1, B1, B2, C1, C2, D1 and D2 and the poloidal field shaping coils E1-E8 and F1-F8.

In particular, in this paper, the design of an observer for the poloidal beta of the plasma for the TCV is presented accompanied by some simulation and experimental results. Due to the specific characteristics of the TCV device (see [7-10]), based on its large number of magnetic measurements (see Fig.1) (see [11]) as well as on a powerful electron cyclotron resonance heating (ECRH) (see [12-14]) system that provide a flexible control of the plasma shape, it is possible to consider an algorithm based on the relation between the poloidal beta and the diamagnetic flux of the plasma (see [2-3], [5-6] and [15-20]). The scheme of the real-time observer that has been developed is shown in Fig.2. The first step of the algorithm is to obtain the diamagnetic flux in real-time through the real-time emulation of a post-processing Diamagnetic Loop (DML) tool that already exists in the TCV tokamak. In the second step the observer for the poloidal beta is developed which infers the value of the β_p from the diamagnetic flux calculated in the first step together with the values of the

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plasma current and toroidal magnetic field. Some of the most relevant parameters of the TCV required for the observer are given in Table I (see [7]).

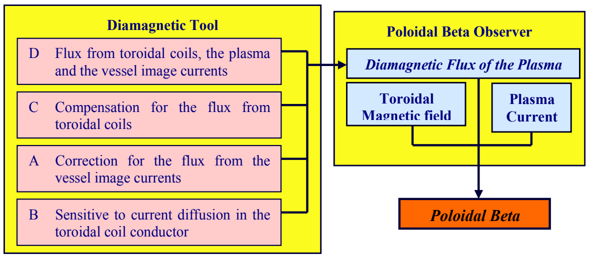

Fig. 2. Flow diagram for the Poloidal Beta observer.

TABLE I
TCV MAIN PARAMETERS

Major radius	R_0	0.90 m
Horizontal minor radius	a	0.25 m
Maximum elongation	κ	3
Maximum toroidal field	B_t	1.5 T
Plasma current	I_p	$0.1-1$ MA
ECH heating power		4.5 MW

II. DETERMINATION OF THE DIAMAGNETIC FLUX USING THE DIAMAGNETIC LOOP

A. General Description of the Diamagnetic Loop

Considering that many properties of tokamak plasmas, such as plasma current, loop voltage, plasma position and shape, stored plasma energy, current distribution and plasma instabilities, can be determined using simple loops or coils of wire, magnetic diagnostics and measurements have been used since the early days of tokamaks (see [4-5]). In particular, diamagnetic diagnostics are commonly used in tokamaks for the measurement of the variation of toroidal magnetic flux induced by the plasma (see [5] and [21]).

In general, a diamagnetic loop consists of a simple loop that links the plasma column, ideally located in a poloidal direction in order to minimize detecting the poloidal field (see [5] and [21]). Intrinsically, this loop will also pickup the toroidal magnetic flux from the toroidal field coil and any current circulating in the poloidal plane (see [19]). Since in tokamaks the plasma energy density is small compared to the energy density of the magnetic field, the toroidal flux produced by plasma pressure is a small fraction of the total toroidal flux (ϕ_T), so the change in the total toroidal magnetic flux is small ($\Delta\phi/\phi_T \approx 10^{-4}$) (see [2] and [5]). Therefore, a frequently used method of measurement is to subtract the unperturbed flux (see [5]), given by a reference signal equal to the vacuum toroidal magnetic flux measured by the same loop, in order to measure only the change in diamagnetic flux due to the plasma (ϕ_p) which makes possible to define the flux measured by the loop according to (1) (see [22]), where ϕ_{vacuum} is defined by (2) and ϕ_{Tor} represents the toroidal flux due to the toroidal field coils, ϕ_{OV} includes the contributions to the toroidal flux due to possible misalignment between ohmic field and vertical field, and the diamagnetic loop and ϕ_E represents the contribution of the toroidal field due to eddy currents on the vacuum chamber (see [17-18] and [23]).

$$\phi_p = \Delta\phi = \phi_T - \phi_{vacuum} \quad (1)$$

$$\phi_{vaccum} = \phi_{Tor} + \phi_{OV} + \phi_E \quad (2)$$

B. Emulation of the Diamagnetic Loop tool on TCV

On TCV, as well as on other magnetic confinement experimental devices, the measurement of the diamagnetic flux generated by the plasma is used to derive the plasma pressure. However, TCV particularities make the measurement more difficult: for passive stabilization of the vertical position of highly elongated plasmas, the vessel has a low electrical resistivity, leading to large image currents in the vessel. For the same reason, the plasma must also be kept close to the conducting wall, so that the in-vessel double loop method usually used to compensate for these image currents cannot be applied. Therefore, the diamagnetic diagnostic on TCV uses the signal from a single loop wound outside the vessel in combination with appropriate signal processing that accurately matches the fast component of the induced vessel current, which allows obtaining the plasma diamagnetic flux (see [7]).

The DML tool already existing on TCV, which is responsible of diamagnetic measurements, makes it possible to measure three main sources of the toroidal magnetic flux (see [7] and [24]):

1) The plasma generated diamagnetic flux, ϕ_p.
2) The flux produced by the current of the toroidal field coils, I_t.
3) The flux produced by the image current, I_v, induced in the walls of the vacuum vessel by ϕ_p and I_t.

However, this tool is based on signal post-processing which means that it is not possible to use it in real-time, as a result of this drawback, it is necessary to emulate this tool in Matlab-Simulink environment so as to integrate it into the real-time control system of the TCV.

The poloidal cross section of the TCV shown Fig.1 helps providing a better understanding of the diamagnetic diagnostic of TCV. This system is composed principally of four loops, each of these loops see different combinations of the three fluxes that contribute to the total toroidal magnetic flux (see [7]):

- Loop A is a single turn loop wound directly onto the vacuum vessel, and it is used to evaluate the vessel image currents.
- Loop B is similar to loop C, but it is sensitive to the

current diffusion in the toroidal coil conductor.

- Loop C is a multi loop coil of which area is designed so as that it catches the same flux as the loop D. This loop is used to compensate the flux from the toroidal field coils.
- Loop D measures the total toroidal flux from the toroidal field coils, the plasma and the vessel image currents.

The signal processing of the diamagnetic measurements involve combining, amplifying, integrating and filtering the signals from the loops so as to cancel the main toroidal flux sources other than the plasma diamagnetic flux. Thus, the post-processing software, of which detailed description and analysis can be found in [7], cancels the perturbations that appear as a consequence of the imperfections in the analog compensations such as those coming from the coupling with the poloidal magnetic field or flux changes due to small loop displacements under mechanical and thermal stresses in the machine.

In the method followed using this emulation all the corrections ($\phi_{corrections}$) are subtracted to the total toroidal flux according to (3).

$$\phi_p = \phi_T - \phi_{corrections} \qquad (3)$$

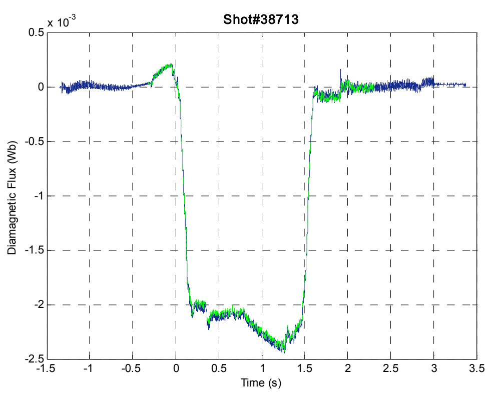

Fig. 3.a. Diamagnetic flux from the DML tool used in the TCV (blue) and from the emulation of the DML tool (green) for Shot#38713.

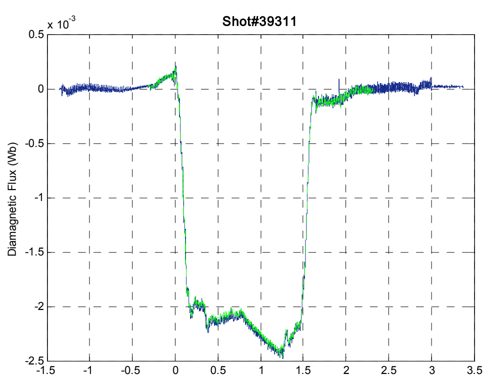

Fig. 3.b. Diamagnetic flux from the DML tool used in the TCV (blue) and from the emulation of the DML tool (green) for Shot#39311.

In the particular case of the TCV, in order to develop the abovementioned emulation of the post-processing DML tool so as it can be used in real-time in Matlab-Simulink environment, the flux corrections grouped in $\phi_{corrections}$ had to be expressed as function of quantities which are available in real-time. However, although most of the quantities involved in the calculation of these corrections and compensations can be measured in real time, some of them, more precisely some coefficients, have to be computed post-shot according to the post-processing DML tool presented in [7]. Thus, assuming that the variation of these coefficients from one shot to the next is negligible, it is possible to use their post-processed values of a previous shot in the real-time calculation of the next shot. In addition, some of the variables that are necessary for the calculation of the flux corrections had to be added to the real-time signal acquisition system of the TCV, such as most of the signals from the flux loops. In (4-10) the detailed expressions for the flux corrections applied using diamagnetic diagnostics are given as functions of the coil currents (I_{pol}), residual flux from loop C ($\phi_{resloopC}$), flux from compensation loop A (ϕ_{loopA}) and B (ϕ_{loopB}), contribution to the flux measured in flux loops ($V_{fluxloops}$) and the coefficients which have been calculated post-shot.

$$\phi_{cor1} = coef_1 \cdot \phi_{resloopC} \qquad (4)$$

$$\phi_{cor2} = coef_2 \cdot \phi^3_{resloopC} \qquad (5)$$

$$\phi_{cor3} = coef_3 \cdot \phi_{loopB} \qquad (6)$$

$$\phi_{cor4} = coef_4 \cdot \phi_{loopA} \qquad (7)$$

$$\phi_{cor5} = coef_5 \cdot \arctan\left(coef_6 \cdot \phi_{resloopC}\right) \qquad (8)$$

$$\phi_{cor6} = coef_7 \cdot I_{pol} \qquad (9)$$

$$\phi_{cor7} = coef_8 \cdot V_{fluxloops} \qquad (10)$$

In order to show the good performance and accuracy of the developed DML tool emulation, the simulation results obtained for the diamagnetic flux calculated with the achieved DML tool in Matlab-Simulink environment are compared with the results given by the post-shot DML tool. As it can be observed in Fig.3.a and Fig.3.b for two typical discharges taken as examples, the diamagnetic fluxes obtained with both methods are almost the same. A more detailed comparison between the simulation results is presented in Fig.4, where the relation between both fluxes has been obtained normalising the post-shot DML tool given flux with respect to the value provided by the emulated DML tool. According to Fig.4, the difference between both values is of about 1-2% in the flat-top phase of the plasma, which leads to considerate that the developed tool for real-time purposes, for which the control system of the TCV deals with the noise effects, is equivalent to the post-shot DML tool.

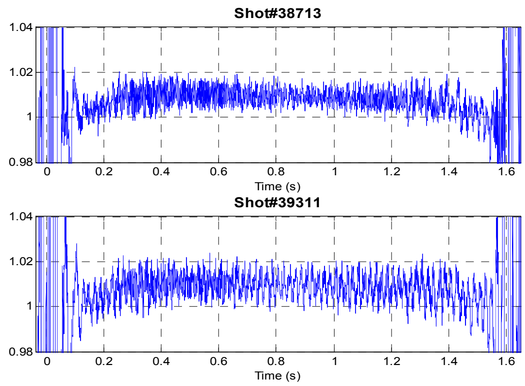

Fig. 4. Ratio of the emulaion of the DMLtool with respect to the DMLtool.

III. Observer for the Poloidal Beta

In general, the poloidal beta can be defined as the ratio of the plasma pressure to magnetic pressure using (11) where $\langle p \rangle$ is the volume average pressure of the plasma and B_{pa} given by (2) is the average poloidal field where I_p denotes the plasma current and Γ is the poloidal circumference of the plasma surface (see [25]).

$$\beta_p = \frac{\langle p \rangle}{\left(B_{pa}^2 / 2\mu_0\right)} \tag{11}$$

$$B_{pa} = \frac{\mu_0 I_p}{\Gamma} \tag{12}$$

In a tokamak configuration, the plasma is kept in equilibrium by poloidal magnetic fields. The relationship between β_p and ϕ_p may be determined using the equilibrium relation given in its simplified form (13), where μ_0 is the vacuum magnetic permeability, B_t is the toroidal magnetic field and I_p is the plasma current which can be measured with a Rogowski coil (see [7]). In practice, the plasma diamagnetism is measured, so as to obtain the plasma poloidal beta using (14) (see [2], [6], [16-17], [21] and [24]).

$$\phi_p = \left(\frac{\mu_0^2 I_p^2}{8\pi B_t}\right)\left(1 - \beta_p\right) \tag{13}$$

$$\beta_p = 1 - \frac{8\pi B_t}{\mu_0^2 I_p^2}\phi_p \tag{14}$$

In order to achieve the real-time observer it is necessary to design previously the offline version of the observer with the purpose of testing its reliability and accuracy before integrating it in the real-time control system that already exists in the TCV (see [11]). With this purpose, the β_p will be obtained using the ϕ_p given by the DML emulation tool, which is directly introduced in the state vector of the control system of the TCV.

A. Simulation Results for the Poloidal Beta Observer

In this section, the results for the offline version of the beta observer developed according to (14) in the Matlab-Simulink environment are presented and analyzed. In order to design this observer, once the diamagnetic flux produced by the plasma was obtained from the DML tool, it is necessary to obtain the plasma current and the toroidal magnetic field. Contrary to the signals required for DML tool analysis, these two quantities can be obtained from already existing measurements on TCV which are connected and accessible from the control system. More precisely, the plasma current is obtained directly from measurements while the toroidal magnetic field is calculated by (15), where I_{tor} represents the measurement of the toroidal current and R_0 is the major radius.

$$B_t = \frac{\mu_0 I_{tor}}{2\pi R_0} \tag{15}$$

With the purpose of testing the feasibility and the correctness of the developed observer, the simulation results obtained for the poloidal beta with the proposed observer are compared with the values of this parameter computed by the equilibrium reconstruction code LIUQE (see [26]). LIUQE

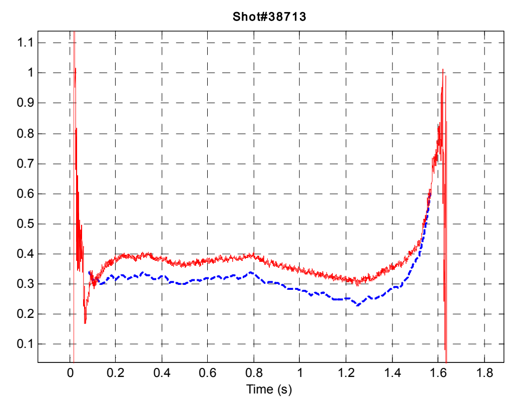

Fig. 5. Poloidal beta given by the LIUQE code (dashed line) and that obtained with the offline version of the observer (solid line) for Shot#38713.

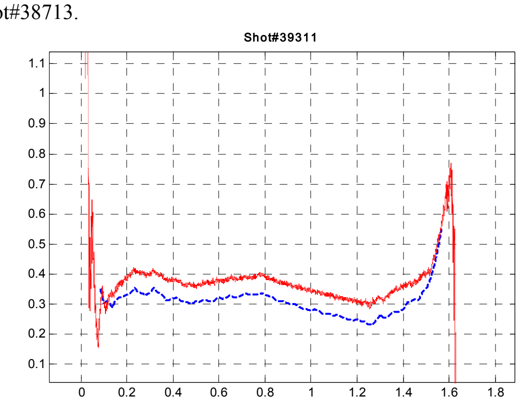

Fig. 6. Poloidal beta given by the LIUQE code (dashed line) and that obtained with the offline version of the observer (solid line) for Shot#39311.

is a free boundary Magnetohydrodynamic (MHD) equilibrium reconstruction code which solves the Grad-Shafranov equation, which can be expressed by (16) where $p(\Psi)$ and $f(\Psi)$ are two arbitrary functions dependent on the poloidal flux function Ψ associated with the pressure and the poloidal current density and the operator Δ^* has the form expressed in (17) (see [15] and [27-28]), in such a way as to minimize the difference between experimental measurements and the corresponding reconstructed quantities (see [26]).

$$\Delta^*\Psi = -\mu_0 R^2 \frac{dp(\Psi)}{d\Psi} - f(\Psi)\frac{df(\Psi)}{d\Psi} \qquad (16)$$

$$\Delta^* = R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial}{\partial R}\right) + \frac{\partial^2}{\partial z^2} \qquad (17)$$

With the purpose of studying and analyzing the features of the designed observers the data stored from the same experiments that have been considered as examples in Section II.B have been used. For both examples, the simulation results obtained from the offline version of the poloidal beta observer are compared with the values computed by the LIUQE code (see Fig.5 and Fig.6). Comparing the difference between the values of the poloidal beta as shown in Fig.7, it can be deduced that the difference between them is of about 15-25% which, for our final target of its application to real-time control can be considered as acceptable, assuming the confidence margins offered by the DML tool (see [7]).

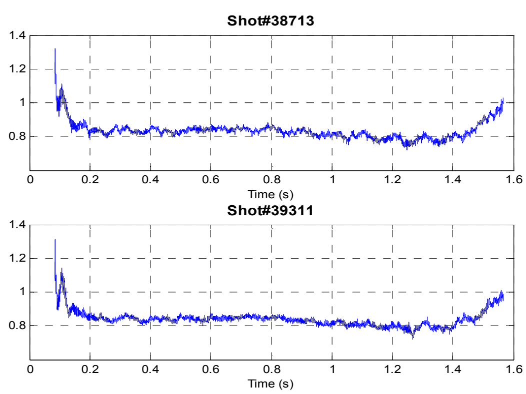

Fig. 7. Ratio of the Poloidal beta from LIUQE with respect to that obtained with the beta observer.

IV. Experimental Results for Poloidal Beta Control in Real-Time

Once the accuracy of the offline version of the poloidal beta observer presented in Section III was tested by means of simulations, some experiments were carried out in order to show the feasibility and to emphasize the practicability and functionality for real-time control purposes of the achieved observer. This section is devoted to the study and analysis of these real-time experiments developed for beta feedback control using Electron Cyclotron Heating (ECH) Power.

In these experiments a Proportional Integral (PI) controller is applied to reduce the error between the reference beta and the observed beta so that the beta value is controlled using the Gyrotron 1 power as actuator. For the design of the PI controller a simple model which related the poloidal beta of the plasma with the ECH Power defined by (18) was developed, where $[k_1 \quad k_2]$ represents the gains with respect to each of the independent gyrotron that contribute to the ECH Power, which is represented by $[P_{ECH1} \quad P_{ECH2}]^T$ in (18), and τ is the energy confinement time of about 2 ms. In order to improve the tuning of the PI parameters the step response of the system was analyzed.

$$\beta_p = \frac{1}{\tau s + 1}[k_1 \quad k_2]\begin{bmatrix} P_{ECH1} \\ P_{ECH2} \end{bmatrix} \qquad (18)$$

Once all the required parameters were obtained offline, the DML emulation and poloidal beta observer together with the PI controller were introduced in the real-time control system of the TCV to carry out the experiments. For the experiments just one of the gyrotrons was activated with a step power signal and the target was to maintain the poloidal beta of the plasma at a constant value even when the gyrotron power was growing up. This objective implies that it appears an opposite power in the other gyrotron (see Fig.8) in order to maintain the poloidal beta constant as it

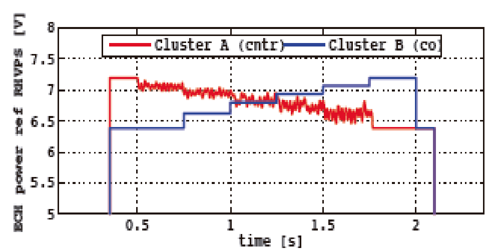

Fig. 8. Experimental results for beta control. ECH gyrotron power for Shot#39566.

Fig. 9. Experimental results for beta control. Poloidal beta reference (doted line), value from the real-time observer (solid line) and from LIUQE reconstruction (dashed line) for Shot#39566.

may be observed in Fig.9. Therefore, it can be concluded that the real-time poloidal beta observer in this experiment works correctly and makes it possible to calculate and control this parameter in real-time. This observer also makes it possible to study and analyze the effect of variations in other parameters of the plasma on the evolution of the poloidal beta.

V. CONCLUSIONS

The latest advances in tokamak research have pointed out the need to study new control problems related to the plasma in tokamaks. In this sense, the measurement of the poloidal beta of the plasma has arisen as a very relevant issue in tokamak control since from this parameter it is possible to study, analyze and obtain other significant parameters of the plasma such as the confinement time, the internal inductance, etc. Considering that this parameter can not be measured directly, the development of real-time observers with the purpose of obtaining its value has emerged as an interesting research area.

The observer for the poloidal beta presented in this work is based on the equilibrium relationship between the beta value and the diamagnetic flux of the plasma which implies the real-time analysis of DML diagnostics. The algorithm applied combines measurements from the diamagnetic loops, flux loops and magnetic probes to obtain the poloidal beta of the plasma. Once the validity of the offline version of the observer was tested by means of simulations the real-time observer was implemented in the TCV so that its feasibility for control purposes could be studied through experiments.

Finally, according to the simulation and experimental results presented in this work it can be stated that the developed real-time observer for the poloidal beta of plasmas provides a reliable and accurate value of this parameter, which is of high relevance for tokamak control. The feasibility and good performance of this observer provides new and interesting opportunities for the development of real-time controllers not only for the poloidal beta but also for many other parameters of the plasma in tokamaks which are related to it.

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