Identification of the ITER plasma equilibrium using modulation

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Introduction

Accurate knowledge of the magnetic fluxes and surfaces, which constitute the environment within which the plasma evolves, is necessary for efficient control of the plasma equilibrium. This information is foreseen to be extracted using the ITER magnetic diagnostics, which consist of magnetic probes and flux loops. This technique suffers two principal sources of error, which are the drift of the integrators (the fields and fluxes being time-integrals of the probe signals) and the appearance of radiation and thermally-induced electromotive forces in the diagnostic sensors and cables due to the harsh environment that they will have to withstand. Moreover, a third effect observed on Tore Supra consists of a slight rotation of the magnetic probes by thermo-mechanical distortion during long pulses, inducing an error in the diagnostic signals. For these reasons, an alternative drift-free method for equilibrium estimation might be needed, while keeping in mind that ideally, the ITER magnetic diagnostics design should not be modified. Such an alternative approach was first introduced in [1] on the basis of TCV simulations and subsequently tested experimentally on Tore Supra [2]. Sinusoidal modulation of the plasma position and current around an ITER operating point induces measurable finite frequency responses observed within the magnetic diagnostics. These modulated responses allow an estimation of the plasma equilibrium without resorting to time-integration of diagnostics signals. This approach is thus guaranteed to avoid the drifts and offsets that appear when using conventional electronic integrators. At the same time, the method shows a considerable tolerance to noise.

Modulation simulation

The plasma vertical position (Z_p), radial position (R_p) and current (I_p) are sinusoidally modulated around an ITER operating point in Scenario 2. Each of the modulation amplitudes are chosen to be small compared to respectively the separatrix gaps and the nominal plasma current, thus avoiding any large modifications of the equilibrium and guaranteeing a linear response of the magnetic diagnostics to the imposed sinusoidal modulations. The modulation frequencies are set to be slow and not multiples of each other. In addition, a drift is imposed to the plasma, driving the plasma's magnetic centre downward and sideways away from the operating point, and also increasing the plasma current. This drift is not linked to the modulation itself, but enables us to check whether this new approach is resistant to large equilibrium changes as well as providing data on which the self-learning method can be based. We note that the self-learning can be based on actual ITER operation during short pulses and reduced RIEMF and TIEMF conditions.

	Frequency	**Amplitude**	**Drift**
Vertical position Z_p	f_Z = 1.3943 [Hz]	3.0 [mm]	- 400 [mm]
Radial position R_p	f_R = 0.4791 [Hz]	2.5 [mm]	+ 150 [mm]
Plasma current I_p	f_I = 0.1875 [Hz]	15 [kA]	+ 650 [kA]

Table 1: Modulation frequencies and amplitudes, as well as imposed linear drifts.

Data flow

The plasma response to modulation has been simulated using DINA-CH, which also provides simulated magnetic diagnostic signals. In order to map these simulated diagnostics signals to the plasma equilibrium parameters such as position or ultimately gaps, the simulation data needs to be post-processed as follows:

(a) Divide the simulation into multiple randomly selected time-windows. The time-windows should be large enough to contain at least one period of the slowest modulation.

(b) For each time-window, determine a mean vertical position and a mean radial position.

(c) For each time-window, demodulate the plasma vertical position, radial position, the plasma current, as well as the magnetic probe signals and the flux loop signals. This is done by projecting these onto the basis functions, which are:

$$f_0 = 1$$
$$f_1 = t$$
$$f_2 = \cos(\omega_Z t) + i\sin(\omega_Z t)$$
$$f_3 = \cos(\omega_R t) + i\sin(\omega_R t)$$
$$f_4 = \cos(\omega_I t) + i\sin(\omega_I t)$$

In other words, we have

$$X = \alpha_X \cdot f_0 + \beta_X \cdot f_1 + a_X \cdot f_2 + b_X \cdot f_3 + c_X \cdot f_4 ,$$

where $X = Z_p$, R_p or I_p, α_X, β_X are real scalars and a_X, b_X, c_X are complex scalars.

Assuming that the magnetic diagnostic responses to the plasma modulation are linear enables us to demodulate them in a similar manner.

(d) Because we want to remove any linear drift or constant signal, we simply do not take into account α_X and β_X in our further description of the plasma position and current, and of the simulated diagnostics signals. Thus, to describe the demodulated plasma position and current, we define a 3x3 *ZRI*-matrix as follows:

$$ZRI = \begin{pmatrix} a_Z & b_Z & c_Z \\ a_R & b_R & c_R \\ a_I & b_I & c_I \end{pmatrix}$$

A (48+24)x3 *Signals*-matrix can be constructed in a similar manner, 48 being the number of magnetic probes and 24 the number of flux loops considered in the simulation. We thus define a *ZRI*-matrix and a *Signals*-matrix for each time-window.

(e) Construct a *Q*-matrix for each time window which links the offset-free and drift-free *ZRI*-matrix and the offset-free and drift-free *Signals*-matrix. We define:

$$Q = Signals \times ZRI^{-1}$$

(f) We now link this *Q*-matrix to Z_p and R_p, or in other words, we find a mapping *M* such that $(Z_p,R_p) = M(Q)$.. We can proceed in two different ways:

1. Assume this mapping is linear, in which case *M* is a matrix.
2. Assume this mapping is non-linear. Then, *M* is an unknown function of *Q*. In this case, it is not trivial to approximate *M*. An appropriate way to map (Z_p,R_p) and *Q* is by using Artificial Neural Networks (ANN).

The linear mapping is realized by regressing (Z_p,R_p) against the *Signals*-matrix. Such a mapping provides acceptable results when no noise is added to the diagnostic signals, but becomes rapidly sensitive to noise. The ANN mapping is realized using a Multi-Layer Perceptron with 3 hidden layers. Half of the samples are used to train the ANN and the other half is estimated from the mapping *M*. Only estimated results are displayed in Table 2.

Results

To assess the accuracy of the results obtained, we compare the estimated (Z_p,R_p) to the averaged (Z_p,R_p) for each time-window. In order to test the resilience to noise of this new approach, we artificially added white noise to the signals after having run the simulation. The level of noise added corresponds to 3 ADC counts for the magnetic probes signals and a 1 ADC count for the flux loops for a 12-bit digitalisation. Both mappings described in point **3.**(e) were tried and the results are displayed in Table 2. The linear mapping is acceptable when no noise is added to the magnetic diagnostics signals, whereas it becomes rapidly unusable as soon as noise is introduced. On the other hand, the ANN mapping remains good, even when the noise level becomes important. Indeed, the mapping error that is generated consists only of 4.5 [mm] for the plasma vertical position, 1.1 [mm] for the plasma radial position and 9.4 [kA] for the plasma current. Such a mapping ensures that accurate estimation of the equilibrium can be achieved using this technique.

	No noise	**Noise**
	Linear mapping	
Z_p	0.007 [mm]	6.3 [mm]
R_p	0.08 [mm]	68 [mm]
I_p	0.2 [kA]	170 [kA]
	ANN mapping	
Z_p	0.6 [mm]	4.5 [mm]
R_p	0.2 [mm]	1.1 [mm]
I_p	1.1 [kA]	9.4 [kA]

Table 2: Standard deviation of the plasma vertical position, radial position, and current reconstructed using a linear mapping or an ANN mapping.

Conclusion and future work

Identifying the ITER plasma equilibrium using modulation is a valid alternative to conventional use of electronic integrators. This approach does not involve any modifications of the current ITER magnetic diagnostics design. Moreover, it allows plasma equilibrium estimation without significantly modifying the plasma equilibrium. This present paper has extended the previous TCV modelling to the ITER device while using the experimental verification of the method on Tore Supra. Future work in this domain will include modulation of the 11 PF coil currents. Such an extension is expected to provide more information about the plasma than its vertical and radial position and may thus provide an even more accurate equilibrium reconstruction method**.**

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References

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