Real Time ECE-MIRNOV cross-correlations by dual phase lock-in technique in FTU

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Cross-correlations between magnetic (Mirnov) and electronic temperature (ECE) fluctuations are a widely used tool to locate the instantaneous O-point position of magnetic islands. These quantities, when calculated in the time domain as in Real Time (RT) application, can suffer of errors due to the phase difference between the two diagnostic signals. Phase differences can change along the time, since they depend on acquisition systems as well as on the coil position and the (m,n) mode order numbers. The procedure already implemented in the RT controller under development for FTU is being upgraded to avoid this problem by making use of the dual phase lock-in technique (DPT). The comparison between the old and the new procedure and their results on data acquired in RT is here presented.

Introduction

The automatic controller under development for FTU [1], which is devoted to suppress and/or to mitigate (Neoclassical) Tearing Modes instabilities by injection of EC power, requires precise RT measurements of the magnetic island position (R_{Isl}). In fact, the efficiency of such control action depends on the distance between the R_{Isl} and the EC power deposition locus [2]. Several procedures, based on the analysis of ECE fluctuations, have been developed in past years to measure R_{Isl} in RT [3, 4, 5, 6] along the ECE line of sight. The current procedure [7] (SPT, Single Phase Technique) of the RT FTU controller cross-correlates the Electronic Temperature ($T_e(t)$) fluctuations measured by a 12 channels ECE-polychromator [8] with one signal ($B'(t)=dB/dt$) coming from magnetic diagnostics as Mirnov (or pick-up) coils in order to filter out fluctuations not related with (N)TM activities. ECE-Mirnov cross-correlations shall provide information both on the instability presence and on its location. SPT code is composed of two stages. The first one is devoted to evaluate the profile $\{E_i(t)\}_{i=1\ldots12}$ of signed amplitudes of thermal fluctuations coherent with magnetic by the following calculations:

$$E_i(t) = \langle T_{e,i}, B'\rangle(t)/\left|B'\right|(t) \qquad \text{[eV]} \qquad (1)$$

[*] See the appendix of Buratti P. et al, 2012, Overview of FTU results 24th IAEA Fusion Energy Conf. (San Diego, USA) OV/P-01

Where brackets mean the following operation between two signals s_1 and s_2:

$$\langle s_1, s_2\rangle(t) = (s_1 \cdot s_2) * h(t); \qquad |s|(t) = \mathrm{sqrt}(\langle s, s\rangle(t)); \tag{2}$$

h(t) is the impulse response of a single order low-pass filter, and ∗ is the usual convolution product. The second stage detects the presence of the island O-point between adjacent channels i^{th} and $(i+1)^{th}$ when $E_i * E_{i+1} < 0$ and $|E_i| + |E_{i+1}|$ is higher than a given threshold (A_{Th}); R_{Isl} is evaluated by linear interpolation as the major radius R where the fluctuations amplitude is 0. A_{Th} should be as low as possible to allow early detection of smaller Islands, but also high enough to discriminate noise effects. A phase difference between $T_e(t)$ and B'(t) will result in a reduction of the signal to noise (S/N) ratio and in the underestimate of the actual fluctuations amplitudes. Different Mirnov spatial positions, different (m,n) order numbers of the mode and different fluctuation frequency (because ECE and Mirnov are acquired by different acquisition systems) will cause phase differences that can change along a discharge. Use of the dual phase lock-in technique (DPT) [6,9] removes the sensitivity to phase differences because it allows evaluating both amplitude and phase of T_e fluctuations related with B' fluctuations. DPT implementation on the RT FTU controller is described in the next section, while the comparison between the results provided by SPT and DPT on data acquired by the RT system during the last FTU campaign is presented in the third section.

Implementation of dual phase lock-in technique

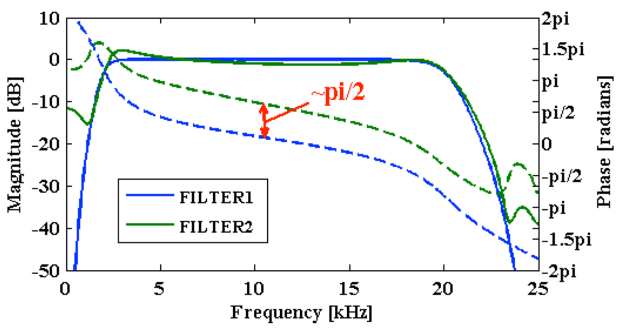

Figure 1. Magnitude (solid lines) and Phase (dashed lines) of the first (blues lines) filter and the second (green lines) filter. First filter is a 8^{th} order IIR Butterworth band pass, while the second is a 6^{th} order IIR band pass filter.

The $\{E_i\}$ coefficients are evaluated (eq.1) after digital filtering of B' and T_e signals. Present implementation of the DPT is based on the use of two filters that should ideally have the same Magnitude response but with Phase responses differing of 90°. First filter (FILTER1, blue lines in Figure 1) is an Infinite Impulse Response (IIR) 8^{th} order Butterworth filter (2kHz to 20kHz). The second filter (FILTER2, green lines in Figure 1) has been designed as an IIR 6^{th} order filter by applying numerical methods in order to fit the ideal requirements described above.

Figure 2 shows the usage of this couple of filters. $T_e(t)$ are filtered by FILTER1, while B'(t) is doubled and filtered by both FILTER1 and FILTER2 providing two reference signals, one "in phase", and the other "in quadrature".

Each reference signal is used to calculate two sets of cross-correlation coefficients (eq.1): first set $\{E^C_i\}$ is obtained using the "in phase" reference while the other $\{E^S_i\}$ using the "in quadrature" one. The resulting amplitude and phase estimates are:

$$E_{amp,i}^2 = E^{C\,2}_i + E^{S\,2}_i; \qquad E_{phase,i} = -\mathrm{atan}(E^S_i/E^C_i); \qquad (4)$$

Due to the non-ideality of the second filter, the E^S_i coefficient is evaluated after applying an orthonormalization procedure. Island detection between two ECE channels occurs if:

$$E_{amp,i} + E_{amp,i+1} > A_{Th};$$

$$DPh_i = |\, E_{phase,i+1} - E_{phase,i} \,| > Ph_{Th}; \qquad (5)$$

Island position R_{Isl} is evaluated by linear interpolation.

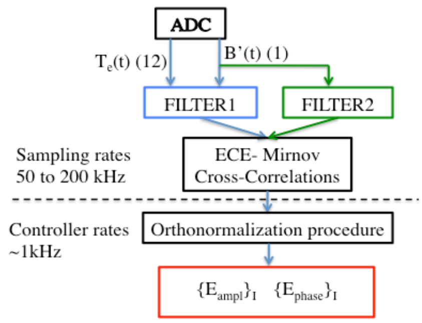

Figure 2. Block scheme of the procedure. ECE channels (T_e) are filtered by the first filter, while Mirnov (B') channel is doubled and then filtered by both filters, producing a couple of reference signals that are both cross-correlated with T_e. Amplitude and phase of T_e fluctuations are then evaluated from two cross-correlation coefficients for each channel (eq.4).

Comparison between DPT and SPT results

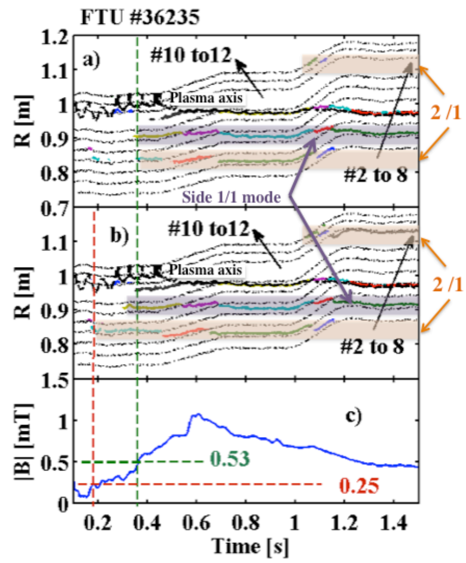

Figure 3. FTU discharge #36235. a) R_{Isl} evaluated by using SPT; b) R_{Isl} by DPT. Colored lines refer to R_{Isl} evaluated between different couples of adjacent ECE channels; black dashed lines to ECE channels positions; and black line to plasma axis position. c) Amplitude of magnetic fluctuations. DPT detects the MHD activity about 200ms before than SPT. Data acquired by the RT system.

FTU discharge #36235 (I_P=360kA) has been performed by ramping toroidal magnetic field B_T from 5 to 6T (t=0.4 to 1.2s). q profile varies along the discharge and ECE channels move across the equatorial plane. A (2/1) TM appears in the early phase and lasts until the discharge ends. SPT procedure performed good detection and tracking of R_{Isl} in RT (figure 3a), but off-line elaboration showed that the relative phases between T_e and B' signals were of about 60°/-120° (Figure 4b), then introducing an error of about 50% on the amplitude estimates. In Figure 3, the comparison by the results provided by SPT (a) and by DPT (b) is shown (A_{Th}=20eV in both cases). DPT starts detecting MHD activity about 200ms before than SPT, corresponding to smaller magnetic fluctuations amplitude (Figure 3c). Position of ECE channels (2 to 8 and 10 to 12) (black dashed lines) and an estimate of the plasma axis position (black line) are shown in Figure 3 a) and b); colored lines refer to Islands detected between different pairs of adjacent ECE channels. Orange shadings in Figures 3 and 4 highlight the position where symmetrical pi-jumps due to the 2/1 TM appear, while the grey one highlights the presence of a not symmetric (with respect to the plasma axis) pi-jump likely due to a side 1/1 mode [10].

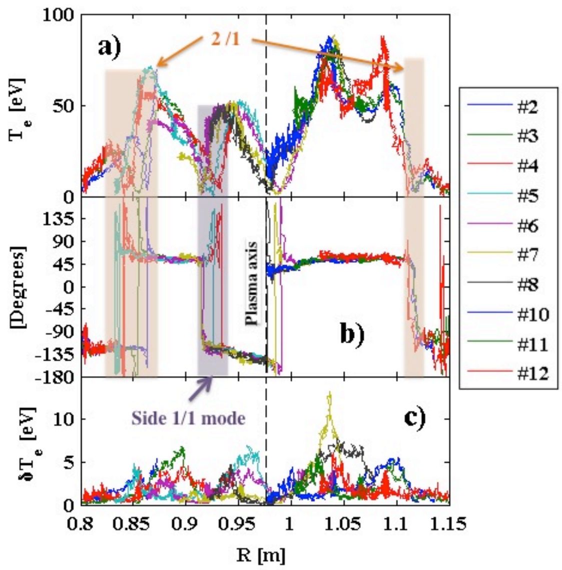

Figure 4. $\{E_{ampl}\}_i$ (a) and $\{E_{phase}\}_i$ (b) profiles (see eq.4) versus the FTU major radius R. Average errors on amplitude estimates (c) evaluated by using a set of 12 Mirnov coils.

In Figure 4, radial profiles of $\{E_{amp}\}_i$ (a) and $\{E_{phase}\}_i$ (b) estimates are shown, by plotting the time estimates versus the ECE channel positions in the time interval t=(0.4; 1.2s) while B_T was varying from 5 to 6T. A set of 12 Mirnov coils placed at different angular positions were acquired in RT. Typical errors on $\{E_{ampl}\}_i$ are assessed by evaluating the standard deviation of the amplitude estimate along the set of coils (Figure 4c). Due to the ramping B_T, errors are assessed at different positions of the ECE channels with respect to the Island O-point and the plasma axis. The expected error is evaluated averaging along the time and it results less than 2eV (8%) for each channel. Similar analysis, performed on the $\{DPh\}_i$ estimates, shows typical errors of less than 5°.

Conclusions

Use of dual phase lock-in technique considerably improve the ECE-Mirnov cross-correlations, performing estimates of $\{E_{ampl}\}_i$ and of the $\{DPh\}_i$ with errors below 2eV (8%) and 5° independently on the angular position of the Mirnov coil used for calculations. This also allows better and earlier Island detections. Further upgrades are still under study in order to use the additional information on $\{E_{phase}\}_i$ to discriminate the contributions on $\{E_{amp}\}_i$ due to different modes, or to improve sensitivity of the algorythm.

References:

1. E. Alessi, et Al., Nuclear Instruments & Methods In Physics Research A (2013), http://dx.doi.org/10.1016/j.nima.2012.12.003
2. R.J. La Haye et Al., Nucl. Fusion, **49**, 2009, 045005
3. Isayama A. et Al., Nucl. Fusion, **43**, 2003, 1272
4. J.Berrino et Al., Nucl. Fusion, **45**, 2005, 1350
5. Y.S.Park, Plasma Phys. Control. Fusion, **48**, 2006, 1447
6. M. Reich et Al., Fus. Sci. Tech., **61**, 2012, 309
7. E. Alessi et Al., Proc. Of EC17, EPJ Web of Conferences, **32**, 2012, 02105
8. O.Tudisco et Al., Rev. Sci. Instrum., **67**, 1996, 3108
9. Y. Shi, Rev. Sci. Instrum., **77**, 2006, 036111
10. P.Buratti, This Conference