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A. Fonseca[1], A.C.A. Figueiredo[1], J. Fessey[2], L. Cupido[1], B. Alper[2], N. Cruz[1],
L. Meneses[1], A. Sirinelli[2], M.E. Manso[1], M. Walsh[2] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico,
Av Rovisco Pais, 1049-001 Lisbon, Portugal
[2]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
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ABSTRACT.
In-situ methods for the calibration of the Correlation Reflectometry (CR) Systems on the JET Tokamak are presented. These methods consists of introducing a modulation in the path length of the wave or in the control voltage of the microwave Local Oscillator (LO) in order to produce fringes at the output of the CR systems. One of these methods is implemented by introducing small changes in the waveguide path length of a few millimeters. Using this procedure, all four reflectometers could be calibrated simultaneously and their phase deviations, amplitude imbalances and DC offsets routinely corrected. In another alternative method, an external wave generator modulates the voltage input of the LO with frequencies up to 1MHz. In both methods, the same experimental assembly for the plasma discharge measurements, i.e. the same microwave systems, microwave components and waveguides, electronics and electrical connections is used. These techniques also allow system enhancements to be introduced in a controlled way and comparisons of the correlation analysis, between signals in calibration mode and during plasma discharges, to be performed straightforwardly.

1. INTRODUCTION

Fluctuations and turbulence are believed to play an important role in anomalous transport of heat and particles in magnetic fusion devices [1]. One important diagnostic that is useful to characterize transport mechanism, in order to understand and control them, is Correlation Reflectometry (CR). The basic operation of this diagnostic consists of launching two microwave beams with different frequencies into the plasma from which the turbulence correlation length, L_r, and the density fluctuation level, $\tilde{n}/n$, can be deduced [2].

The correct estimations of these quantities require a correct calibration, in phase and in frequency, of each CR system. The methods be presented here uses the same experimental assembly as used for the reflectometry measurements during a plasma discharge. The individual calibration of each system, and also the cross checking of the calibration between them, can be performed straightforwardly. These allow also to test the operationally of each system or to introduce enhancements into the systems in a controlled way.

A brief description of the experimental arrangement of the CR systems installed at JET is presented in section 2. A description of the methods used for the calibration and characterization of the CR systems, with some practical examples, are presented in Sec.3 and conclusions in Sec.4.

2. EXPERIMENTAL SETUP

At JET, the Correlation Reflectometry (CR) systems send simultaneously to the vacuum vessel several microwaves through a complex interconnection of waveguides (length of about 40m and nine bends), Quasi-Optical (QO) boxes [3], vacuum window and antennas, as previously described in literature [4]. A similar path is used to receive the microwaves reflected from the reflection layer in the plasma or the back-wall to the CR systems. The launching/receiving antennas (open corrugated waveguides with internal diameter of 31.75mm) are installed inside of the vacuum vessel at 30.2 cm and 26.8 cm, respectively, above the equatorial plane of the machine. The antennas are aligned in the vertical direction and have an angular deviation of 1.70^{o}, in the vertical plane, from the centre of the antennas mouth. The cluster of antennas for the CR is located at R~4.3m (mouth of the antenna) from the main axis of JET, at Octant 8, Sector B.

The CR systems are composed of four reflectometer systems [5,6], that have the fixed frequency channels operating at the frequencies 76GHz ,85GHz, 92GHz and 103GHz, and the correspondently configurable channels in steps of frequency range at 76-78GHz, 85-87GHz, 92-96GHz and 100-106GHz, respectively. The systems are connected to the oversized corrugated waveguides through the QO boxes [3]. Each CR channel is equipped with a quadrature phase detector. The sixteen reflectometry signals are recorded during the discharge at a sampling rate up to 2.5MHz in a VME data acquisition system (limited to 1.5 millions of samples per shot) that is localized near the system. Recently the CR signals are acquired in another data acquisition system, located more than 40 meters from the CR systems acquiring at a sampling rate of 2.0MHz, during 10 seconds of the plasma discharge.

To carry out our experiments, the mirror in the first bend of the Millimetre Waveguide Access (MWA) waveguide, near the CR systems, was replaced by a loudspeaker with metallic surface. An external function generator was used to drive the loudspeaker (modulate the metallic surface at frequencies up to ~ 5kHz) or to modulate the control voltage of the Local Oscillator (LO) with frequencies up to 1MHz.

3. METHOD FOR THE CALIBRATION OF THE CORRELATION REFLECTOMETRY SYSTEMS.

The experimental method consists on varying the path length of the wave or modulating directly in the control voltage of the Local Oscillator, in order to generate fringes of interference. This method has the advantage, over common methods, of using the same experimental assembly that is used for the reflectometry measurements during a plasma discharge.

Each CR channel is equipped with a quadrature phase detector and the signals at the output are:

$$I(t) = A_I \sin(\omega t) + A_{I,DC} \tag{1}$$

$$Q(t) = A_Q \cos(\omega t + \varphi_{Q0}) + A_{I,DC} \tag{2}$$

Theses signals have, in general, DC offset and different amplitudes or phase imbalances and must be corrected. The DC offsets, $A_{I,DC}$ and $A_{Q,DC}$ are removed from the signals by hardware before being amplified and digitalized in the Data Acquisition Systems. In the next step, the I/Q signals are normalized and it is imposed that their amplitudes must be equal, i.e. $A_I = A_Q$. Finally, I/Q signals must be in quadrature, i.e. the phase difference between them must be $\pi/2$ or $\varphi_{Q0} = 0$ in eq.

(2). The correction procedure is finished when I and Q, in a polar representation, form a circle centred on the axis (fig.1, curve (a)). If the amplitude of the I/Q signals are not equal an elongation along the xx′ axis or in the yy′ axis is observed (fig.1, curve (b)). In another case, when the signals have imbalance in phase (or an equivalent shift in time between the two signals), an elongation along the axis rotated by 45^o is observed (fig.1, curve (c)). For the construction of the curve (b) and (c), in Fig.1, there was an imbalance in amplitude of $A_Q/A_I = 0.7$ or an imbalance in phase of $\varphi_{Q0} = \pi/8$, respectively, have been assumed.

The amplitude and phase are given, respectively, by:

$$A(t) = \sqrt{I^2(t) + Q^2(t)} \tag{3}$$

$$\varphi(t) = tg^{-1}(Q(t)/I(t)) \tag{4}$$

In figs.2(a) and (b) the amplitude and phase, using the equations (3) and (4), for the three different cases shown in the fig.1 are reported.

As a practical example, was consider a wave with a frequency of 92GHz (λ~3.3 mm) sent throughout the waveguides and reflected by the back-wall before being mixed with the original wave in the reflectometer. In the first bend of the MWA waveguide, the mirror bend was replaced by a metal loudspeaker. The path of the wave has been modulated by vibrating the reflecting surface of the loudspeaker (frequency modulation of ~256Hz) together the movement of the loudspeaker. The I and Q signals, in a polar representation, obtained at the output of the CR system are shown in fig.3. In this figure, the complete circle represents the movement of the mirror (for a displacement of ~ 6.6mm or approximately two wavelengths) and the arc represents the oscillation due to the loudspeaker (~1.2 rad), i.e. when the loudspeaker stays in a fixed position.

The unwrapped phase is presented in fig.4. In this case, the movement of the loudspeaker produces a change in the phase of about 4p radians or an equivalent displacement of two wavelengths (~6.6 mm). During the time interval, that the loudspeaker is in a fixed position (for example, from t=0.63s to t=0.80s), the changes in the phase are produced only by the vibration of loudspeaker surface. The vibration of the reflecting surface produces a change in phase of ~1.2 radians, which corresponds a displacement of the reflecting surface of ~0.6mm.

With this method both fixed and variable frequency channels can be calibrated in phase simultaneously. Also, for the others CR systems, which operate at different frequencies, the method gives approximately the same results. By this way, the cross-checking between the systems can be performed.

Finally, another alternative method consists of using an external wave generator to modulate the voltage at the input of the LO of the variable channel (with frequencies of modulation up to 1MHz). In this method it appears that the maximum amplitude in the phase is independent of the frequency of the modulation of the LO (the voltage applied to the LO was 20mV peak-to-peak). In figure 5 it is presented the unwrapped phase at the output of the variable channel at 92.4GHz, modulated with a frequency of 500kHz, corresponding to a variation in phase of ~10.2 radians.

Applying the same voltage and changing the frequency of modulation, between 20 kHz up to 1 MHz, it has been observed that the maximum phase changes remains approximately equal for all cases. The beat frequency, proportional to the rate of phase with time, has the same value as the frequency of the signal generator.

The coherence between the fixed and variable channel, at different frequency separations, is estimated using standard cross-correlation analyses techniques [7]. A user-friendly program installed at JET permits the analysis of the CR data in a straightforwardly way [8]. Independent of frequency separation between the fixed and variable channel, the normalized coherence for the conditions of calibration is almost one, as expected.

The methods presented were tested and it was concluded that the simplest methods to implement and use consistently are the vibration of the loudspeaker surface and the modulation of the L.O.. The first method is easy to install and to operate before the beginning of each plasma discharge and also produces enough phase variation that permits to make the correct calibration of both CR channels. The second method has the advantage that can be checked the phase linearity, for the full range of signal frequency, but has the advantage that can only used for the variable channel.

CONCLUSIONS

The methods presented permit to perform the in-situ calibration of the Correlation Reflectometry systems simultaneously and also gives the possibility to cross check the results between the systems. These methods permit also to identify easily malfunctioning of the systems, and allow us to introduce in a controlled way enhancements into the CR systems. The phase variation produced by the vibrations of the loudspeaker surface is an appropriate way to make the calibrations of the CR systems simultaneously.

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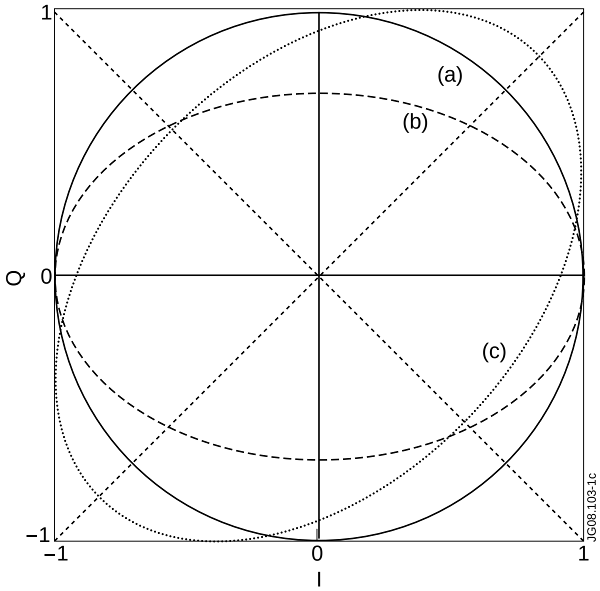

Figure 1: Polar representation of I and Q signals for three different cases: (a) the signals are calibrated in amplitude and phase (continues line); (b) the signals are in phase but imbalanced in amplitude (dash line); and (c) the signals have the same amplitude but are imbalanced in phase (dot line).

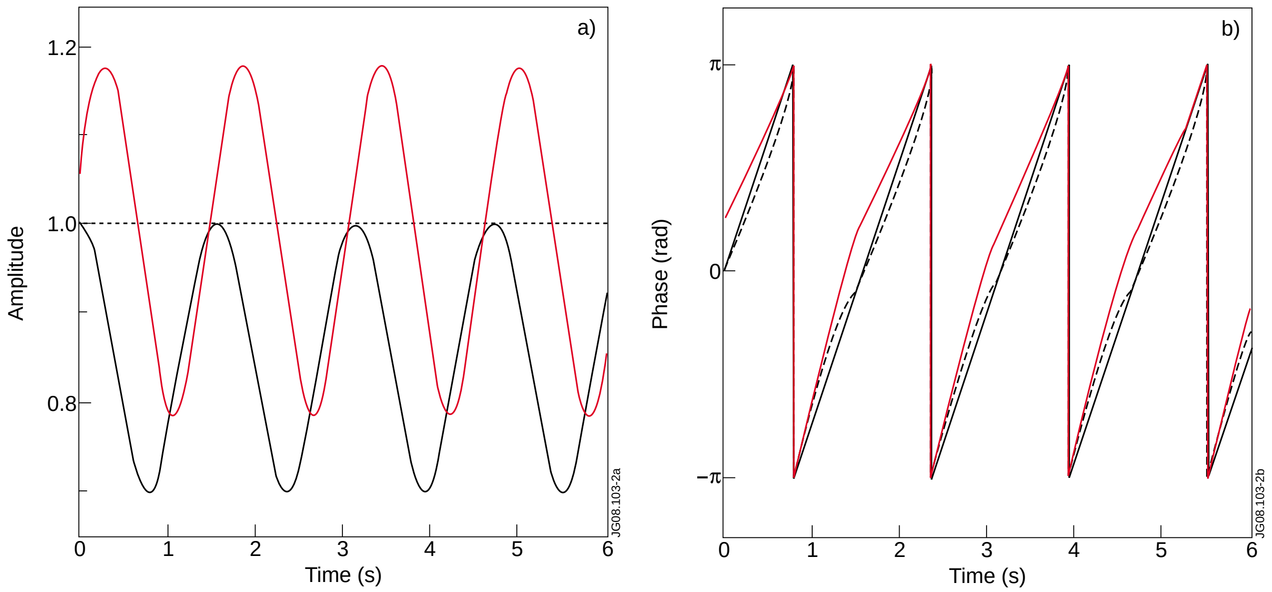

Figure 2: Amplitude (a) and phase (b) for the three cases exposed in the fig.1.

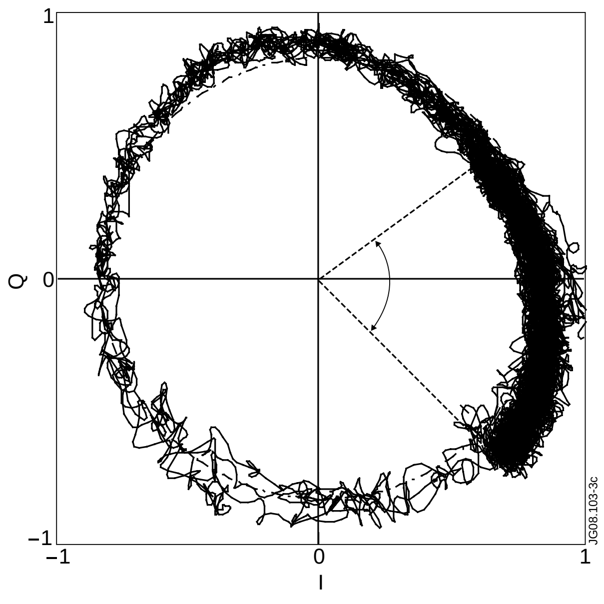

Figure 3: Polar representation of the I and Q signals due to the movement of the loudspeaker together with the vibration of its surface at ~256Hz.

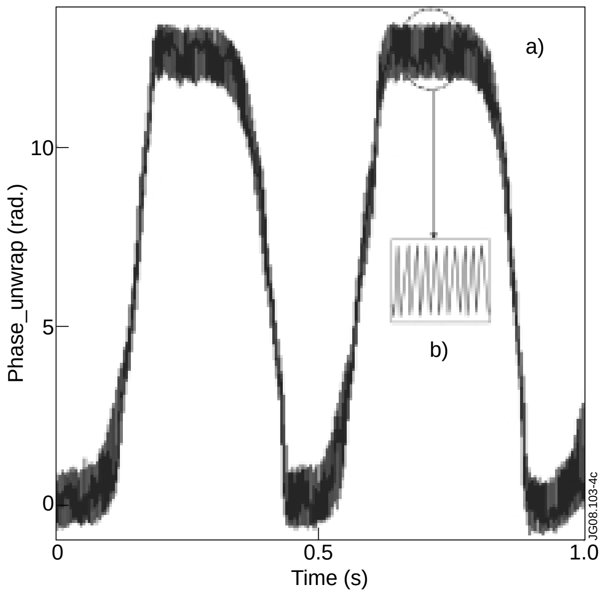

Figure 4: The unwrapped phase illustrates the movement of the loudspeaker together the oscillations of its surface (a blow up of the phase changes generated by the vibration of loudspeaker surface is shown in insert (b)). The frequency of CR channel used here was 92GHz.

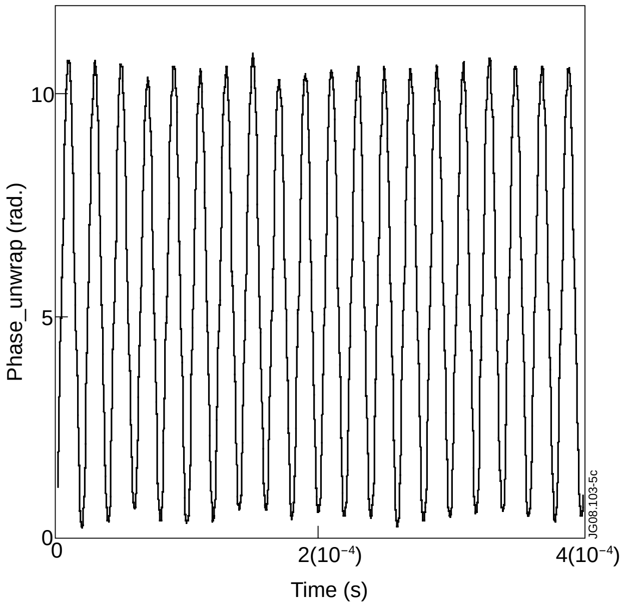

Figure 5: Phase evolution obtained from the signals of the 92.4GHz, variable channel, modulated in the voltage control of the LO with a frequency of 500kHz.