1 μ s broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements

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a) For a list of team members, see Appendix of H. Zohm et al., *Nucl. Fusion* 55 (10), 104010 (2015)

b) For a list of team members, see Appendix in *Fusion Science and Technology*, 56(3), pp. 1453–1454(2009)

c) For a list of team members, see "H. Meyer et al, Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in *Nuclear Fusion*"

Introduction

Frequency swept reflectometry has reached the symbolic value of 1 μ s sweeping time with a dead time as short as 0.25 μ s in between sweeps [1], this performance has been made possible due to an improved control of the ramp voltage driving the frequency source. In parallel, the memory depth of the 1 Gs/s acquisition system has been upgraded and can provide up to 200 000 density profiles during a plasma discharge. Additionally, improvements regarding the trigger delay determination for the acquisition, which needs to be precisely set and the frequency sweep linearity required by this ultra-fast technique along with the stability of the ramp voltage driving the VCOs, have been made. While this diagnostic is traditionally dedicated to the density profile measurement, such a fast sweeping rate can also provide a study of fast plasma events and turbulence with unprecedented time and radial resolution from the edge to the core and thus compete with the fixed frequency systems. Taking the opportunity and the upgrade period of the Tore Supra tokamak to the WEST project, experimental results were obtained on ASDEX Upgrade plasmas and are presented to demonstrate the performances of the diagnostic.

Experiment and results

Fast frequency sweeps are achieved using an arbitrary waveform generator which provide the ramp voltage driving the VCO (Voltage Controlled Oscillator) with the help of a voltage

amplifier since the frequency sources generally require up to 20 V while fast generators provide nowadays about 1 or 2 V (Fig. 1).

Figure 1 : Schematic of the swept frequency setup (left) with an illustrated calibration curve between the driving voltage and the launched frequency (right).

The calibration of the frequency source, $F=f(V)$ (illustrated on figure 1), is achieved by changing the frequency step by step. However, it does not reflect correctly the time dynamic of the sweep as the sweep time decreases [2]. The frequency departure can be determined using a dynamic calibration setup, which consists in comparing continuous and repetitive fast sweeps with a fixed frequency synthesizer through a balanced mixer (Fig. 2). The recorded signal indicates when the swept signal reaches the synthesizer frequency within the bandpass filter (100 ± 20 MHz).

Figure 2 : setup of the dynamic frequency calibration of the VCO (left) and the detected I.Q. signal which provides the frequency departure from stepped frequency calibration to ultrafast 1 μs frequency sweeping (right).

This operation is performed for several synthesizer frequencies to provide the frequency corrections achieved by a post processing treatment during the signal analysis (Fig. 3).

Figure 3 : Frequency departure from stepped calibration for two sweeping speeds determined for 8 synthesizer frequencies (x label represents the frequency determined from static calibration).

Moreover, it is important to record correctly the reflected signal taking into account the delay due to the wave propagation along the cables, microwave components, waveguides and so on. In order to determine this delay, we apply a square impulse voltage to the VCO, instead of a ramp, provoking an impulse response of the detected signal (Fig. 4). The measured delay of 110 ns cannot be neglected anymore for such short 1 μs signal and is taken into account for the signal acquisition by setting a post trigger. This method provides a determination of a post trigger with an uncertainty of about 2 ns.

Figure 4 : Measurement of the trigger delay need to be set on the acquisition to catch precisely the start of the signal by using a square voltage onto the VCO to provoke a clear and sharp impulse response of the system.

The performance achieved by our sweeping reflectometer, in term of stability and reproducibility can be evaluated by looking at the recorded signal from a reflecting mirror (Fig. 5). The frequency dispersion of the signals is about 40 MHz (estimated on the V-band reflectometer). It corresponds to roughly less than a millimeter of relative radial plasma precision.

Figure 5 : 500 recorded reflected V-band signals onto a mirror plate illustrate the sweep stability and repeatability.

One can retrieve a temporal signal from a fast repetitive at a rate of 800 kHz ($1.25 \mu\text{s}$) for each of the swept frequencies. Such an ultrafast swept system approaches the sampling rate of fixed frequency hopping systems [3, 4] with however less dynamic sensitivity but with a remarkable radial resolution considering that each signal (V and W-bands) is digitized with 1000 points equivalent a to 2000 fixed frequency reflectometers. It has to be noted that such high sampling rate enlarges the frequency bandwidth thus reducing the aliasing effect into the frequency spectra as the turbulence amplitude strongly decreases beyond 400 kHz. Finally, it provides a very high radial evolution of the turbulent spectrum and can open perspectives for novel turbulence studies [5] cf. fig.6 which shows (a) higher temporal resolution density profiles, and (b) simultaneous fluctuation spectrogram vs radius.

Figure 6 : Density profile reconstruction of an ASDEX Upgrade plasma during an L-H transition for a sweep time of $1 \mu\text{s}$ with a dead time of $0.25 \mu\text{s}$ (left). Radial evolution of the turbulent frequency spectrum at the rate of 800 kHz (right).

References

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