EUROFUSION WPJET1-PR(16) 15179

P Carvalho et al.

A group delay based algorithm for inversion of electron density profiles from FMCW reflectometry at JET

Preprint of Paper to be submitted for publication in 21st Topical Conference on High Temperature Plasma Diagnostics 2016

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

A group delay based algorithm for inversion of electron density profiles from FMCW reflectometry at JET[a)]

P.J. Carvalho,[1 b)] L. Meneses,[1] B. Gonçalves,[1] and JET contributors[c)]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing above are provided by the Editorial Office)

At the Joint European Torus (JET), a reflectometer system operating with Frequency Modulated - Continuous Wave, probes the plasma both in O and X-Mode propagation (known as KG10), capable of producing high temporal and spatial resolution electron density profiles (<1cm, >= 15μs [1]).
This work provides an algorithm used for X-Mode propagation, based on the spectrogram of the raw data, with some post-processing analysis capable of avoiding most harmonics and other undesired effects present in the data, while delivering the high spatial resolution expected of the system.
The O-Mode bands are processed by the same algorithm allowing for an extension of the profile, under certain conditions of the plasma.
Some results are shown where this algorithm is compared with an independent diagnostic, the High Resolution Thomson Scattering system, capable of a spatial resolution of 8 – 16 mm [2]. The new algorithm has been tested successfully for several JET pulses, under different scenarios, and has shown its strengths in both spatial resolution and robustness to undesired disturbances to the raw data.

I. INTRODUCTION

Frequency Modulated – Continuous Wave (FM-CW) reflectometry is a common diagnostic for obtaining plasma density profiles in tokamaks[3-7]. Microwaves can propagate in two modes: O-Mode, in which the launched wave's electric field propagates parallel to the tokamak's magnetic field; and X-Mode, where they are perpendicular. At JET, of both these modes, only X-Mode is currently used to determine density profiles. JET's FM-CW reflectometry system is composed of 4 bands in X-Mode (Q, V, W and D, 40 – 135GHz) and 2 bands in O-Mode (V and W, 49 – 1311GHz)[1]. Each of the bands performs a sweep over the probing frequencies in 10 μs and can start a new sweep every 15 μs. Data is acquired at 200 MSPS, yielding 2000 points per sweep and it can acquire up to 100,000 sweeps per pulse.

Building on previous work to improve the detection of the first fringe[8], this paper describes the implementation of an algorithm that reconstructs the electron density profile from FM-CW reflectometry data at JET, by using the power time-frequency distribution (spectrogram) of the data for obtaining the group delay[9].

II. SPECTROGRAM ALGORITHM

The group delay (τ_g - plasma echo) information can be easily extracted by spectral analysis of the detected signal. A sliding Fast Fourier Transform (FFT) analysis (spectrogram) is used to estimate the evolution of the beat frequency, f_b, along the frequency chirp. This frequency is proportional to τ_g:

$$f_b(t) = df_p/dt\, \tau_g(t) \quad (1)$$

[a)]Contributed paper published as part of the Proceedings of the 21th Topical Conference on High-Temperature Plasma Diagnostics, Madison, Wisconsin, June, 2016.

[b)]pedro.carvalho@ipfn.tecnico.ulisboa.pt

c)See appendix of F. Romanelli et al. Proceedings of the 25[th] IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

Since the plasma is probed with a linear chirp, each data slice corresponds to a different probing area of the plasma.

The spectrograms used in this work are calculated from windows of 64 points, with a step of 2 points.

The evolution of the beat frequency observed in the spectrogram does not always follow a coherent path, some spurious frequencies are also present in the probed signal inducing strong perturbations on the temporal evolution of τ_g and, as a result, in the estimated density profile.

Some of the spurious signals are found to be:

1) Turbulent events crossing the antennas in a time interval much shorter than the sweep;

2) Fluctuations responsible for scattering of the reflected wave; and

3) Multiple reflections.

The algorithm that extracts the τ_g from the spectrogram developed for this work aims to mitigate these effects and provide a clean τ_g representative of the unperturbed plasma, from which to obtain the electron density profile.

A. Group Delay Extraction

Most of the strategies devised for this work stem from visual analysis of the spectrograms, with a few considerations from the expected physical events.

From the first fringe, F0 up to 1.3·F0, where the Scrape-off Layer (SOL) is expected, the maximum of the FFT is taken for each probing frequency. This part of the signal often falls below 60GHz, a spectral region for which the wave-guides were not optimized, rendering it difficult to analyze, but it has been empirically found that no special processing is required.

From 1.3·F0 to 1.75·F0, usually the pedestal region for H-mode plasmas or LFS profile for ohmic plasmas, a linear fit is performed on the maximum peaks for the next 1.5GHz and another for the previously determined 10GHz. Based on the gradients, the program can infer the type of plasma scenario and proceed accordingly. For probing frequencies above 1.75·F0, the pedestal top is expected to be present, thus relaxing the threshold for allowing upward jumps.

A series of conditions are determined to decide on taking one of the smaller peaks available, but close to the previous, instead of the maximum peak: (1) The previous peak's beat frequency is expected to belong to the plasma pedestal region and there's a large difference between the present peak and the previous, 1.2 times the standard allowed threshold, or the slope of the previous part is negative and the present probing frequency lies beyond the expected one where to find the pedestal top; (2) The present peak is more than 2 points above the previous one and more than one peak is available, there must be more than 2 of them or, if only two are available, they must be sufficiently far apart, and, if the peak is far from the previous: (a) The beat frequency from the next 1.5GHz is going downward, but the previous was horizontal and the maximum of this next part is greater than the maximum of the previous (this happens when a jump is present and then the correct trend is resumed); (b) Or both the previous and next parts have a horizontal trend, while the maximum peak is away from the previous, but there is a small peak very close to the previous; (c) Or either the previous trend is downward or the next trend is downward and the maximum peak is presenting a large jump in beat frequency and there's a peak very close to the previous; (d) Or the previous trend is horizontal, but the next isn't and there's a peak very close to the previous; (e) Both the previous and next trends are horizontal and the present FFT's probing frequency is below the suspected pedestal top.

The above cases cover regions where the detection has jumped, but most likely shouldn't. This happens when harmonics are present in the signal and their intensity overcomes that of the actual signal.

Other effects must also be taken into account and corrected appropriately: (1) When the previous and the next trends are both positive and less than 8 peaks are present, then (a) If the standard deviation of the next portion of the beat frequency is above 30 MHz, the signal is too erratic to be trustworthy, so it just takes the maximum peak; (b) If the standard deviation is below that value, and if the difference between the current maximum and the previous is not larger than 2 times the standard allowed threshold, it takes the peak closer to the expected location of the peak, given the previous trend. (2) When the previous trend is horizontal, but the next is positive, the peak closer to the two lines is chosen; (3) When the previous and the next trends are positive, the peak closer to both lines is chosen if it is close to the previous location; (4) When the previous trend is horizontal, but the next one is negative and the present maximum is above the previous by more than the standard allowed threshold, take the peaks close to the previous peak and pick the one with the highest power; (5) When too many (> 8) small peaks are present and very few (< 2) large peaks, take those which have a power down to 10 units below the maximum and choose the closest to the previous peak.

After all cases viewed previously are parsed, a second check is performed on a few other possibilities: (1) When the previous part of τ_g is horizontal and the present probing frequency is below the expected pedestal top, one or more gaussian fits are performed on the FFT as an attempt to find a dominant peak. If the fit only returns small gaussians or a very broad one, choose the peak that's closer to the previous; (2) When the next part is seen as horizontal, but the maximum peak has a beat frequency lower than the previous peak, then choose the median of the next 1.5GHz; (3) When the probing frequency is below the expected pedestal top and the maximum peak is either above the previous value by twice the normal threshold, or below it by 1.2 times it, two cases arise: (a) If the previous part is ascending, but the maximum peak is below the previous, choose the peak closest to the previous, but above it; (b) If both the previous and next parts are descending, choose the peak closer to the two lines. (4) When the maximum peak's beat frequency is closer to the previous, but still greater than the standard threshold, choose the closer of the large peaks, if there are more than 1 of these; or the closer of all peaks; (5) For a maximum peak frequency close to the previous, but going down, when the previous tendency is ascending, choose the peak with a power similar to the previous, out of all the peaks with a beat frequency above the previous; (6) If no large peaks are available, the trend of the previous 3GHz of signal is calculated (a) If this trend is ascending, the expected beat frequency is determined and the small peaks closer to this expected value is chosen; (b) If it's not ascending, and there's a peak within open point of the previous, take the previous as the present; if all peaks are away from the previous, choose the closest one. (7) When there are large peaks present and the maximum is far from the previous (above the previous value by twice the normal threshold, or below it by 1.2 times), ignores the peaks and chooses the previous location.

B. Reference Calibration

Since the waveguides, optical boxes and cables used by this diagnostic were not designed to handle frequencies below 60GHz, strong dispersion happens in the bands that fall below 80GHz[1]. The different lengths of waveguides also provide different beat frequency references. This can be corrected by taking the measurement of a reflection at the vacuum vessel high-field-side wall, before every pulse, and thus produce the required calibration which must be applied to every sweep. Once calibrated, all bands are joined in one array and, where bands overlap, the band with the least standard deviation in the overlap region is used, thus providing the full τ_g.

C. Last Reflection

During extraction of the beat frequency from the spectrogram, the power at the beat frequency is also stored to be used as the main discriminant in the determination of the last probing frequency for which there is a meaningful reflection. A simple threshold was empirically determined, below which it is assumed that the reflection is lost. If the reflection is lost for more than 1.4GHz for the X-bands, or 5GHz for the O-bands, then that marks the last frequency.

The moving standard deviation of τ_g is used as a secondary discriminant. A threshold is imposed, above which it is considered that the reflection is lost and τ_g represents only random noise. If random noise is found for more than 0.7GHz for both modes, the last frequency is determined.

The lowest of these two candidates at last frequencies is selected and the group delay end is determined.

D. Outlier Removal

On occasion, there are sections where a local maximum is expected, but it becomes absent from the signal. In this work, after the group delay extraction, an extra step is taken to eliminate strange effects such as these and others called outliers.

The first 15GHz, the SOL, are first analyzed to keep them above the value at F0+15GHz, as is expected to always happen for the X-band. If the average value of τ_g in this interval is below that value, then it gets replaced by an evolution of τ_g working from the last point to the first, where each point becomes the previous plus the average differential, times the differential's sign at that location. This keeps this part of τ_g behaving similarly to the signal extracted from the spectrogram, while remaining somewhat near the last value.

O-band processing skips this step, because the initial τ_g is supposed to be ascending. A median filter is applied to eliminate single point outliers, using a 3-point window.

For the first half of the sweep, upward jumps in τ_g of more than 1.55ns are replaced by the median of the previous 0.2GHz of τ_g, and downward jumps of more than 2.25ns are replaced by the median of the previous 3GHz.

For the part of the pulse after the first 15GHz, wherever a jump like that described in the previous paragraph happens, a few trends are considered to check if the group delay resumes any of them: (1) Horizontal line from the last point before the jump; must resume within the next 4GHz; (2) Horizontal line from the average of the last 5 points; must resume within the next 4GHz; (3) Line fit to the previous 5 points, starting at the location provided by the fit; must resume within the next 2GHz; (4) Line fit to the previous 5GHz, starting at the location provided by the fit; must resume within the next 2GHz; (5) Line fit to the previous 10GHz, starting at the location provided by the fit; must resume within the next 2GHz; (6) Line fit to the previous 10GHz, starting at last point before the jump; must resume within the next 2GHz.

The fit that resumes to the most points is chosen and all the points up to the first where the fit resumes the previous trend are replaced by the fit's. As a means of preventing a few remaining outliers, the group delay is smoothed with a 7 point window.

III. PROFILE RECONSTRUCTIONS

From the group delay, the electron density profiles were calculated using Mazucatto's algorithm[10] and the required magnetic field profile was provided by the FLUSH library[11].

Figure 1 shows a sweep from a standard H-mode plasma, with 16MW of NBI power and at an instant in between ELMs. In Fig. 1(a), the spectrogram presents some of the difficulties faced by the algorithm that extracts the beat frequency: apparent harmonics in the signal. These "harmonics" can become more intense than the actual expected signal and, in a few cases, such as this figure's, the expected signal falls in intensity to near-noise levels. The method presented in this work is able to follow the underlying pedestal reflection, even if it is apparently not there.

Figure 1(b) presents, in black, the equivalent O-mode group delay for the density profile determined using the X-mode signals, also in black in Fig. 1(c). The green line presents the contribution from the O-mode signals with the initial part, $f_p <$ 50GHz, given by the X-mode profile. The green line in Fig. 1(c) is the profile reconstructed from this complete O-mode group delay and it is found to be in good agreement with HRTS.

Many more examples could be provided, but this one shows how this method can reconstruct the electron density profile from FM-CW reflectometry, while providing a good spatial resolution and robustness against fast transient perturbations.

IV. DISCUSSION

This paper has presented the implementation of a novel method to process the raw data from JET's FM-CW reflectometry diagnostic to provide reliable density profiles, continuing previous work on the improvement of the detection of the first fringe and extending it to include the available O-mode bands.
This method has shown to be resilient to various forms of damage in the signals, providing an electron density profile with high spatial resolution. Certain features of the profile, which were difficult to resolve with HRTS, become clearly visible.

Acknowledgments This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. IST activities also received financial support from Fundação para a Ciência e Tecnologia through project Pest-OE/SADG/LA0010/2013. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1]A. Sirinelli et al, Rev. Sci. Instrum. **81**, 10D939 (2010).
[2]L. Frassinetti et al, Rev. Sci. Instrum. **83**, 0135067 (2012).
[3]M. Manso et al, Plas. Phys. Cont. Fus. **40**, 747 (1998).
[4]Z. Chongyang et al, Plas. Sci. Tech. **15**, 857 (2013).
[5]W. L. Zhong et al, Rev. Sci. Instrum. **85**, 013507 (2014).
[6]G.Wang et al, Rev. Sci. Instrum. **74**, 1525 (2003).
[7]C. Laviron et al, Plas. Phys. Cont. Fus. **38**, 905 (1996).
[8]P. J. Carvalho et al, ECPD2015 proceedings, 151 (2015).
[9]J. Santos et al, IRW3 proceedings, **55** (1997).
[10]E. Mazzucato, Rev. Sci. Instrum, **69**, 2201 (1998).
[11]S. Pamela et al, "Flush user's guide" (2013).

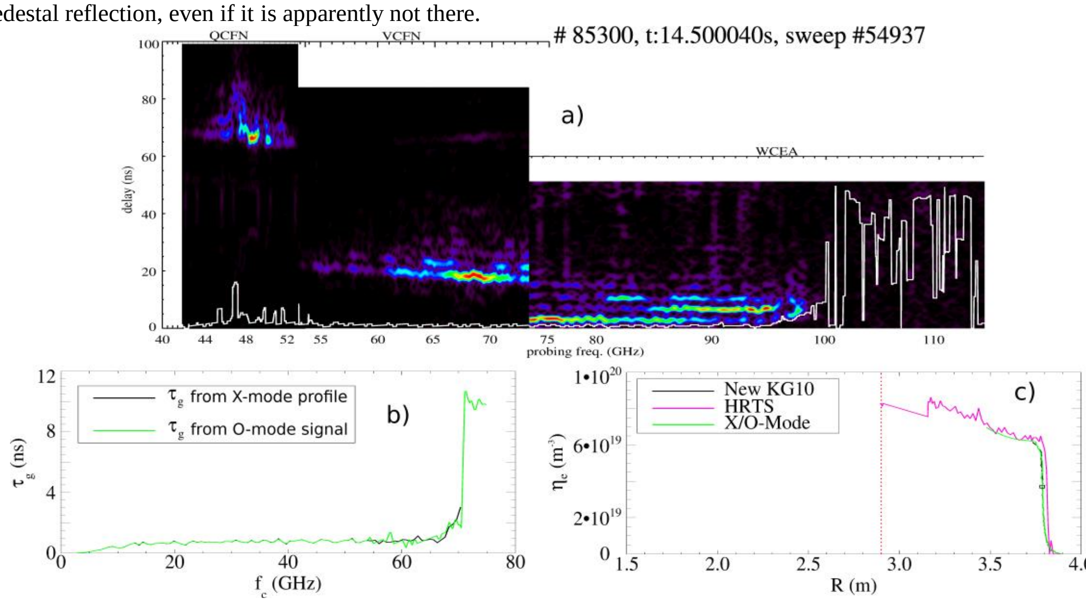

Figure 1- a) Spectrograms for the X-mode bands and the extracted group delay. b) O-mode □g calculated from X-mode profile and the □g extended with O-mode data. c) The electron density profiles from X-mode alone, X and O-mode bands and HRTS.