First density profile measurements using frequency modulation of the continuous wave reflectometry on JET[a)]

L. Meneses,[1,2] L. Cupido,[1,2] A. Sirinelli,[1,3] M. E. Manso,[1,2] and JET-EFDA Contributors[1,b),c)]
[1]*JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, United Kingdom*
[2]*Associação EURATOM / IST, Instituto de Plasmas e Fusão Nuclear, 1049-001 Lisbon, Portugal*
[3]*Laboratoire de Physique et Technologie des Plasmas, CNRS-École Polytechnique, Palaiseau, France*

(Presented 14 May 2008; received 9 May 2008; accepted 18 July 2008; published online 31 October 2008)

We present the main design options and implementation of an *X*-mode reflectometer developed and successfully installed at JET using an innovative approach. It aims to prove the viability of measuring density profiles with high spatial and temporal resolution using broadband reflectometry operating in long and complex transmission lines. It probes the plasma with magnetic fields between 2.4 and 3.0 T using the *V* band [$\sim(0-1.4)\times 10^{19}\ \mathrm{m}^{-3}$]. The first experimental results show the high sensitivity of the diagnostic when measuring changes in the plasma density profile occurring ITER relevant regimes, such as ELMy *H*-modes. The successful demonstration of this concept motivated the upgrade of the JET frequency modulation of the continuous wave (FMCW) reflectometry diagnostic, to probe both the edge and core. This new system is essential to prove the viability of using the FMCW reflectometry technique to probe the plasma in next step devices, such as ITER, since they share the same waveguide complexity. © *2008 American Institute of Physics.*
[DOI: 10.1063/1.2972134]

I. INTRODUCTION

A prototype of a broadband reflectometer diagnostic was developed for JET (Ref. 1) with two main objectives: (i) to probe the electronic density profile at the plasma edge which is not measured with Thompson scattering (ii) and to demonstrate the viability of profile reflectometry with large and complex waveguide connections. To meet these requirements a new design was proposed using frequency modulation of the continuous wave (FMCW), coherence detection, and very short probing times ($\leq 20\ \mu$s). To access the plasma, the millimeter wave access, oversized waveguide cluster, is employed and the coupling made with the existing optical combiners.[2] This setup imposes the sharing of waveguides with the existing microwave diagnostics[3] (operating in *W* band).

To overcome the expected losses both in the quasioptical setup (waveguides and combiners) and in the plasma, a very sensitive detection scheme was implemented employing a superheterodyne detection with quadrature detection.

A delay line was introduced in the reference signal to reduce the effect of the oscillator phase noise on the coherence of the detected signal. This delay is similar to the one introduced by the waveguide runs. The use of fast oscillator, with high intrinsic noise, required to realize fast probing measurements reduced maximum delay between reference and reflected signals to less than 10 m.

In this system we use a linear FMCW (LFM) (Ref. 4) scheme, with direct frequency conversion of the reflected chirp and bistatic antenna arrangement. With this setup, the intermediate frequency (IF) is generated by mixing the reflected signal with a replica of the transmitted chirp, and its value is related to the time delay between these signals. In Eq. (1), B represents the LFM bandwidth (22 GHz) and $T(\leq 20\ \mu\mathrm{s})$ is the chirp duration.

$$IF = (\tau_{\mathrm{wg}} + \tau_{\mathrm{plasma}} - \tau_{\mathrm{delay\ line}})B/T, \tag{1}$$

with τ_{wg} and $\tau_{\mathrm{delay\ line}}$, the delay in the waveguides (≈ 80 m) and in the external delay line (263 ns), producing a fixed IF and τ_{plasma} the delay inside the plasma, generating the density profile dependent component.

The accuracy of the measurements is directly related to the stability of the fix component of the IF (measured with a calibration mirror). Two major sources of errors in the IF are identified: (i) the quality of the LFM (ii) and the coherence length of the frequency source[5] (the propagation distance from an electromagnetic wave source to a point where the emitted waves maintain some degree of coherence).

The quality of the chirp linearization was guaranteed with the use of a tuning function representing the voltage controlled oscillator (VCO) dynamic nonlinearity. These data are produced with the fringe signal generated by a frequency discriminator that reproduces the instantaneous frequency of the VCO. This is a common technique used in FMCW radars to improve the range resolution.[6]

[a)]Contributed paper, published as part of the Proceedings of the 17th Topical Conference on High-Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 2008.
[b)]For a full listing of names and affiliations of the JET-EFDA Contributors, see A. T. Macrander, Rev. Sci. Instrum. **79**, 10F701 (2008).
[c)]See the Appendix of M.L.Watkins *et al.*, Fusion Energy 2006 (Proceedings of the 21st International Conference, Chengdu, 2006) IAEA, (2006).

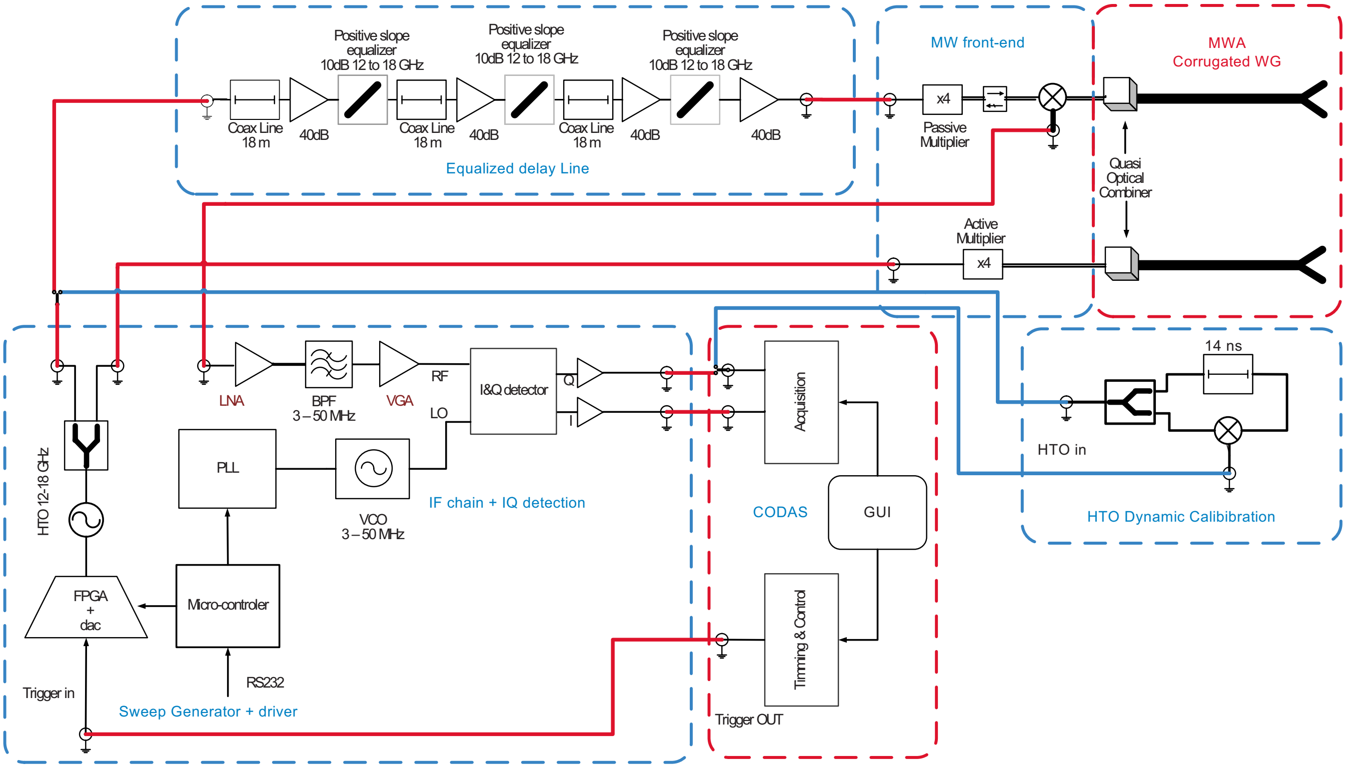

FIG. 1. (Color online) Schematic of the new FMCW reflectometer, operating in V band.

In this work we present the adopted design solution in Sec. II. The first experimental results obtained in H-mode regimes with edge localized modes (ELMs) are depicted in Sec. III and some conclusions about the system performance and measuring capability are shown in Sec. IV.

II. SYSTEM DESIGN

In this system, a FMCW with LFM scheme[7] is employed with a double frequency conversion to achieve the required sensitivity (been able to detect signals smaller than −60 dB m). The considerable propagation delay in the waveguides (>267 ns) is exploited together with the reference delay (263 ns delay line) to generate the IF in the first frequency conversion (5–50 MHz band), followed by an amplification and filter chain before the signal is detected by a quadrature detector.

In Fig. 1 the new design is presented and four blocks can be identified: (i) the equalized delay line (EDL); (ii) the microwave front ends, (iii) the FM chirp generator plus signal detection; and a calibration setup (iv) introduced to characterize the VCO dynamic response to the fast changes in the tuning voltage.

The equalized delay line uses three Ku band sections with 18 m of coaxial cable (RG402), a 10 dB positive equalizer (developed in Instituto Superior Técnico-Lisbon), and one amplifier with a 40 dB gain to compensate the loses in the coaxial cable. An extra amplifier is used at the end of the third stage to compensate the accumulated loses. With this

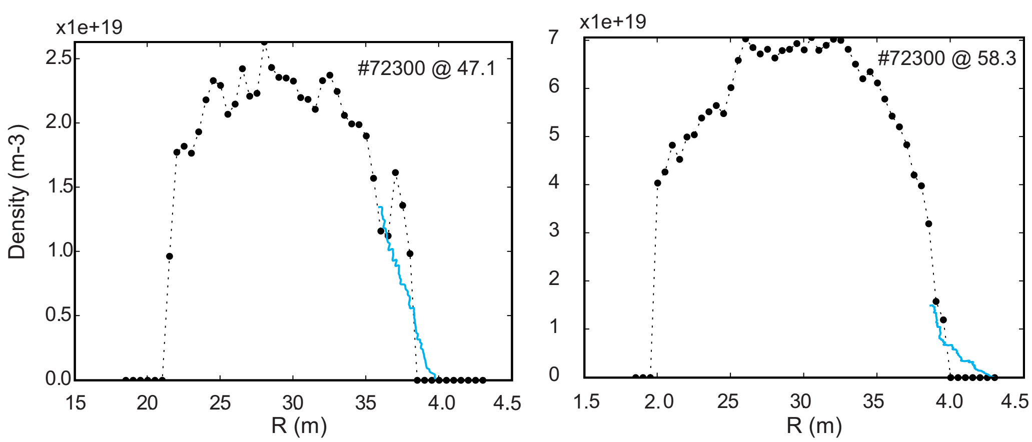

FIG. 2. (Color online) Comparison of the density profiles obtained from FMCW reflectometry and the LIDAR Thomas Scattering diagnostic.

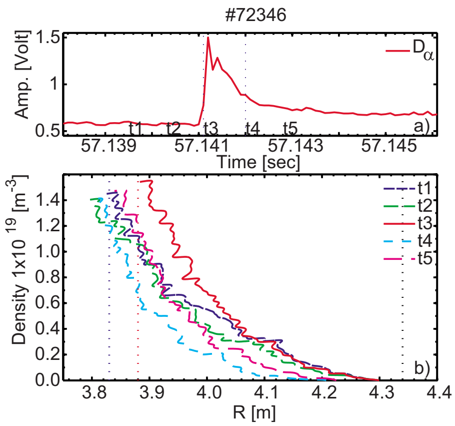

FIG. 3. (Color online) Density evolution during the onset of an ELM, showing profiles acquired with 800 μs separation before (t_1, t_2), during (t_3) and after the ELM (t_4, t_5). A shift toward the antenna is observed in t_3 with a later recovering to its prior position.

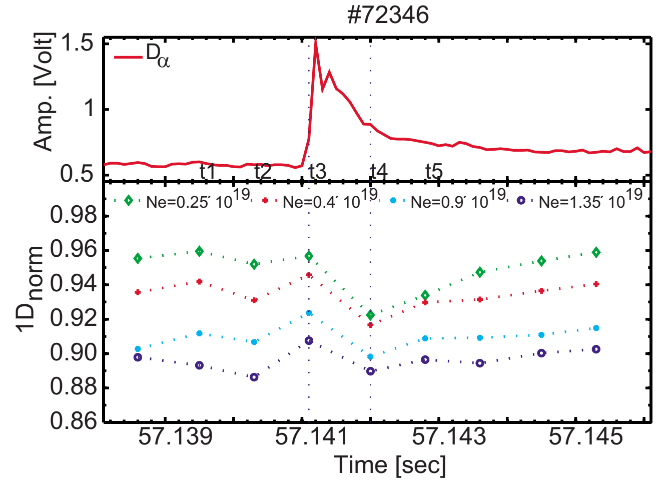

FIG. 4. (Color online) The evolution of four density layers along a 4 ms period is depicted, and a change in the gradient is observed during the onset of ELM.

setup we could guarantee less than 3 dB ripple across the Ku band. For a 13 dBm input power level the output power is 10 dBm, giving a total amplification gain of 120 dB.

The microwave front ends, consisting of frequency multipliers and the front-end mixer, are connected to the quasioptical combiner[3] without the use of fundamental waveguide. With this setup the power losses in the frequency probing band are reduced. The front ends are connected to the probing and reference sources through low loss coaxial cable, and all the losses reduced since they are produced in the Ku band. In this band power amplifiers are available at a lower cost. On the other hand, this arrangement also simplified the installation and maintenance.

The FM chirp generator consists of a field programmable gate array (FPGA) and a fast digital to analog converter controlled by a microcontroller. The tuning waveform, to produce the chirp with the desired linear chirp, is loaded to the FPGA memory through the controller. This waveform is calculated from the beat frequency fringes, and is generated in the frequency discriminator. The dynamic calibration, employed to characterize the VCO, needs to be performed at the selected chirp duration (5–20 μs) since the VCO nonlinearity, as well as the exact frequency band, may change with the sweep duration.

The IF is filtered from 5 to 50 MHz, using low and high pass filters and amplified with a variable gain, from 50 to 80 dB. The amplifier gain control can be remotely adjusted by the microprocessor. The microprocessor with the control program also controls the detector reference frequency synthesizer.

A quadrature detection with a synthesized tuned reference oscillator is used do detect the reflected signal. This synthesized reference acts like an adjustable delay with each frequency corresponding to a fix delay, allowing the optimization of the acquired signal to the frequency band of the analog to digital converter.

To achieve this, a frequency discriminator (14 ns) is used, with the output signal representing the VCO instantaneous frequency variation. This signal is then processed in a software to generate an analytic signal from which the instantaneous frequency values are calculated using the incremental phase variation, the start frequency, and the discriminator internal delay τ_{disc},

$$f_n = f_{n-1} + (\varphi_n - \varphi_{n-1})/(2\pi\tau_{\text{disc}}). \quad (2)$$

A nonlinear tuning curve, representing the VCO nonlinearity, must be calculated for each chirp durations to produce a linear chirp for plasma measurements.

III. EXPERIMENTAL RESULTS

Profile measurements with the FMCW reflectometer are being performed in 20 μs. The data acquisition system that acquires the raw data used to produce the results presented was limited to 51 profiles per shot, limited by the channel memory. A new acquisition system has been installed and the number of profiles greatly increasing, allowing a better time resolution of fast events occurring in the plasma.

The capability of the reflectometer to measure density profiles both in *L*- and *H*-mode regimes is shown in Fig. 2 where the reflectometer density profiles are compared to profiles obtained with the Thompson scattering diagnostic. The profile measurements were performed for shot No. 72300 with repetition rates of 100 ms. A good agreement in shape and position in both *L* and *H* plasmas can be observed.

The capability of the reflectometer to resolve the time evolution of the density profile during fast events occurring at the plasma edge, such as ELMs, is evident in Fig. 3 where the evolution of the density profile, in shot No. 72346, is presented at different phases of an ELM, marked in the $D\alpha$ signal. The measurements in this shot were performed with a profile repetition rate of 800 μs. The time evolution of the position of several density layers, for shot No. 72346, is depicted in Fig. 4, using a normalized distance to the antenna, obtained with the antenna position D_{ant} and the cutoff position D_{ne},

$$D_{\text{norm}} = \{1 - [(D_{\text{ant}} - D_{\text{ne}})/D_{\text{ant}}]\}. \quad (3)$$

A temporal evolution of the different layers is found to be consistent with the evolution of the $D\alpha$ signal. At the onset of the ELM, at $t=t_3$, the plasma is shifted toward the antenna and collapsing for $t=t_4$, recovering afterward at time instants. Profile modifications between t_3 and t_4 cannot be resolved due to insufficient plasma measurements. To resolve this faster repetition rate should be used.

IV. CONCLUSIONS

The installation of the prototype broadband reflectometer at JET proved the viability of broadband FMCW reflectometry in large size fusion devices with long and intricate transmission lines (40 m and nine bends each) and connections (five diagnostic channels sharing one waveguide). The use of EDL, reduce the need of employing a reference delay in waveguide.

A full heterodyne solution with a frequency upconversion scheme can be adopted, to overcome amplitude modulation and phase modulation conversion noise in the front-end mixer, however this represents an increase in system complexity.

The experimental results obtained, although limited, in number of measurement per shot by the data acquisition system revealed the good quality of the density profiles obtained both in *L*- and *H*-mode regimes. Profile changes occurring at the edge, due to fast events such as ELMS, can be tracked.

ACKNOWLEDGMENTS

This work was partly carried out in the frame of the Contract of Association between the European Atomic Energy Community and Instituto Superior Técnico (IST) and of the Contract of Associated Laboratory between Fundação para a Ciência e Tecnologia (FCT) and IST. The content of the publication is the sole responsibility of the authors and it does not necessarily represent the views of the Commission of the European Union or FCT or their services.

The author would like to thank the fruitful discussions held many of its colleagues at JET EFDA team.

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