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L. Meneses, L. Cupido, A.A. Ferreira, S. Hacquin, M. Manso
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and JET EFDA contributors*

[1]*Associação EURATOM/IST, Centro de Fusão Nuclear, Instituto Superior Técnico,
Av. Rovisco Pais*1, 1049-001 Lisboa, Portugal
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**ABSTRACT.**
New transmission lines and antennas recently installed at JET under the EFDA enhancement project "Millimeter Wave Access (MWA)" meet the performance requirements of broadband reflectometry for density profile measurements. Using the new access a fast swept Frequency Modulation Continuous Wave (FMCW) [1, 2, 3, 4] using coherent detection of the reflected signal, was developed to probe the mid-plane plasma in the X-mode polarization in the 50-75GHz frequency range, aiming at measuring the edge density profile in the JET advanced scenarios with axis magnetic field of 2.4T. This paper describes the operating principles of the new system and presents some preliminary results obtained with it.

Special attention is given to the fact that this swept reflectometer is capable of operating on bi-static antenna arrangements over long waveguides, by using a local generated reference, as these will be the operating conditions considered adequate for ITER reflectometer.

## 1. INTRODUCTION

Reflectometry measures the phase deviation between the launched wave and the one reflected at a certain plasma density [2]. At JET the plasma shape and operational conditions, imposes the use of a sweep frequency reflectometer, using the higher X-mode cut-off polarization to probe the Scrape Of Layer (SOL) and plasma edge regions, where the fast sweep rate capability of this reflectometer and it high spatial resolution (less than 1cm) are potentially useful. This diagnostic will operate with magnetic field from 1.75 to 2.4T, covering densities up to $2.35\times10^{-19}$ $m^{-3}$.

The installation of four new corrugated transmission lines with very low loss and wide bandwidth (50–150GHz) obviate the transmission loss problems of the previous waveguide setup (estimated 50dB round trip).

We will present the preliminary studies of the spatial resolution evaluation and the diagnostic performance with high plasma temperature plasma conditions on sec. II, system description with some test results on sec. III, and conclusions on sec. IV.

## 2. PRELIMINARY STUDIES

To access the performance of the diagnostic installed, the spatial resolution and power balance were evaluated. Some ray-tracing simulations were carried out using typical JET parameter with ray-tracing simulations and considering the diagnostic installation setup. The spatial resolution was estimated taking into account the antenna radiation pattern, and the plasma shape and position in these simulations. The uncertainty on the cut-off position is given by [1]

$$\Delta r_c = 1.5 \left(\frac{c}{2p\,f}\right)^{2/3} \left[\frac{dN_x^2(f, r_c)}{df}\right],$$

where, f is the probing frequency and Nx (f, $r_c$) the refractive index of the plasma (which is function of the density profile $n_e(r)$, magnetic field B(r), and probing frequency).

For a typical mode density profile of JET , L-mode plasma, this uncertainty wasfound to be on the order of magnitude of 0.5cm.

However a good estimation of expected spatial resolution measurements requires taking into account the antenna radiation pattern. This was done with 2D ray-tracing computations using JET plasma parameters and geometry. As illustrated in Fig.1 the spatial resolution was estimated to about 0.7cm in the case of typical JET L-mode plasma.

The influence of the misalignment between the plasma and the antennas on the spatial resolution was also assessed. As shown in Fig.2 a statistical study over 2004 JET discharges points out that the spatial resolution is expected to be better than 1cm in almost all plasma scenarios.

Taking into account the measured losses in the circular corrugated waveguides and antennas (4 dB in each run) and the coupling arrangement, to couple 5 systems onto 1 waveguide (8 dB per run) and the assuming the losses in the plasma are about 20dB the total reflected power from the plasma edge in estimated to be around −45dBm.

## 3. SYSTEM DESCRIPTION

This new diagnostic was designed to operate with a sweep rate of up to 10μs. The waveguides transmission losses 4dB per run, are mainly due to the vacuum double window. This long path between the diagnostic hall and the vessel (≈40m) constrains the design of the diagnostic since the phase deviation introduced needs to be compensated (about 270ns delay) (see Fig.3 for a detailed scheme).

The diagnostic will share the same central pair of waveguides [5] already used by four W band correlation reflectometers [6] using quasi optic coupling [7]. Coupling five systems onto a single waveguide introduces an additional loss of 8B per run.

We have decided to perform the correction of the waveguide delay on the frequency domain instead of the time domain normally used34, because it is more flexible and on the other hand uses just one oscillator, this simplifies the microwave circuit of the diagnostic. In order to implement a flexible, easy to use and reliable diagnostic we have decided to develop a diagnostic that could be calibrated, adjusted and operated using a computer connected to the diagnostic via a serial port (RS232). This proved to be a powerful toll during the diagnostic tests and calibration since it is easy to change the operation parameters without changing the test or calibration setup.

A microcontroller card (infineon C515 based) interfaces the user with the diagnostic, and it software, controls all the electronic modules, i.e., Intermediate Frequency (IF) gain, IF band filter, reference frequency, microwave Voltage Controlled Oscillator (VCO) frequency calibration and sweep rate.

The system uses a novel VCO drive module, FPGA[(a)] based (Altera-Cyclone I) with the capability of linear frequency sweep and flexible sweep rates. It is trigger controlled and generates a frequency sweep per input trigger. All frequency calibration parameters are stored in the microcontroller and sent to the driver module after configuring the frequency limits and sweep duration. The computed sweep tables are locally stored inside the FPGA (Field Programable Gate Array) RAM and ready do drive a DAC (Digital to Analog Converter) after a trigger event.

At sweep duration less than 30μs we may still need to add a software frequency calibration prior to profile evaluation as the VCO have some post tuning drift that affects its reaction to the applied tuning voltage. The linear sweep is illustrated in Fig.4.

The microwave oscillator, a 12−18GHz Hiperabrupt varactor Tuned Oscillator (HTO), is used both to generate the plasma signal and the Local Oscillator (LO). The probing plasma frequency 48−72GHz is obtained with a frequency multipliers chain delivering about 9dBm output power.

In order to increase the quality of the detected signal it was decide to use a balance mixer (with about 7dB conversion loss) as the front end converter, the LO signal is also obtained the same HTO avoiding the use of an extra VCO.

The resulting IF frequency is therefore proportional to the total delay between the LO arm of the mixer and the reflected signal and the frequency probing scan, this can be written:

$$\tau = \frac{1}{2\pi\,\delta f}\frac{\delta\varphi}{\delta f} \quad \text{and} \quad f_b = \frac{\delta f}{\delta t}$$

where $\tau$ is the delay, $\delta\varphi$ is the phase deviation, $\delta f$ is the frequency deviation, $f_b$ the fringe frequency, $\frac{\delta f}{\delta t}$ sweep rate.

The IF frequency is amplified and filtered before reaching the quadrature (IQ) detection. At this stage the plasma signal is filtered and amplified to about 0dBm. The amplifier chain dynamic range is 75dB in addition to a programmable gain exceeding 45dB.

The IF filter section has 4 sections of 200MHz covering DC to 650MHz selected according to the programmed sweep rate.

A reference calibration is performed in the IQ detection section, to remove the effect of the long waveguides by adjusting the reference frequency in order to set the I and Q signals frequency to one corresponding to the plasma distance (1 to 4MHZ at 1GHz/μs and plasma edge at 20−30cm).

The ability to perform the reference adjustment accurately with flexibility is achieved a with new a synthesized VCO module, controlled via the microcontroller.

In this diagnostic the IF frequency $f_b$, is given by:

$$\frac{\delta f}{\delta t} = 1GHz/1\mu s \text{ and } \tau = \tau_{wg} + \tau_v + \tau_p \text{ where } \tau_{wg} + \tau_v \approx 270ns$$
$$f_b = 270MHz + (\tau_p + \tau_v) \times 1GHz/\mu s$$

The reference frequency ref IQ needs to be set to 270MHz in order to remove the waveguide delay contribution. This frequency could also be adjusted in order to place the reference at any point beyond the plasma limiter (50cm in front of the antennae), the quadrature reference frequency precision is represented in Fig.5.

The I and Q phase difference was evaluated using the acquired I and Q signals obtained using an external frequency generator as IF signal. The error in the phase is less than $6^{o}$ in the 50 to 550MHz band as depicted in Fig.6

**CONCLUSIONS**

From the laboratorial tests performed we could conclude that the diagnostic behaves according to the initial target specifications. The IF and detection sections were not test using the actual parameters, since the IF frequency is dependent of waveguide length therefore further tests at JET are needed to evaluate some of the options made during this design.

The usage of an electronic reference instead of a physical one (waveguide or cable delay line) is an important breakthrough in the design of future diagnostics as it adds flexibility to the reference position.

**ACKNOWLEDGMENTS**

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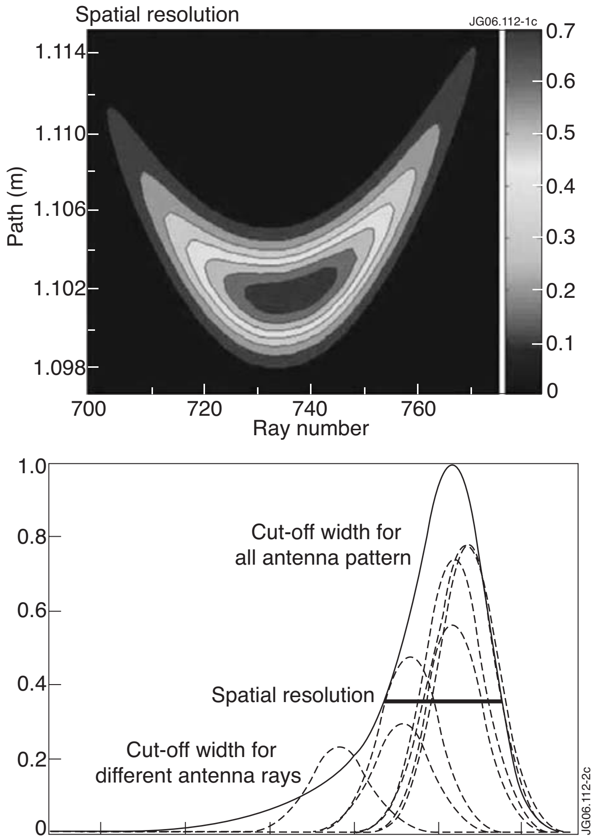


*Figure 1: Radiation patter effect on spatial resolution*

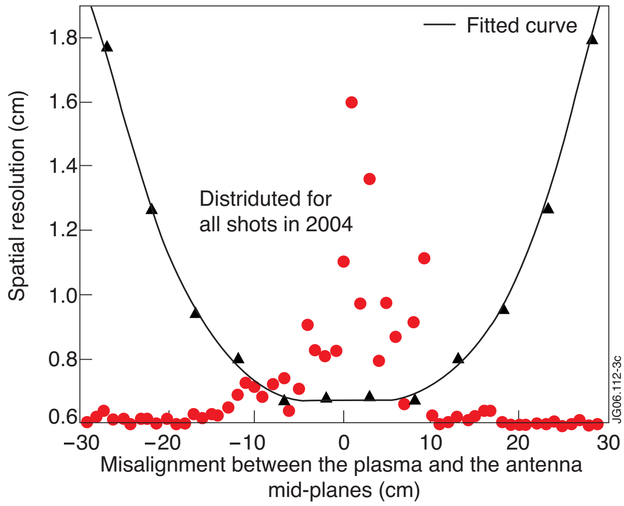


*Figure 2: Antenna misalignment effect on spatial resolution*

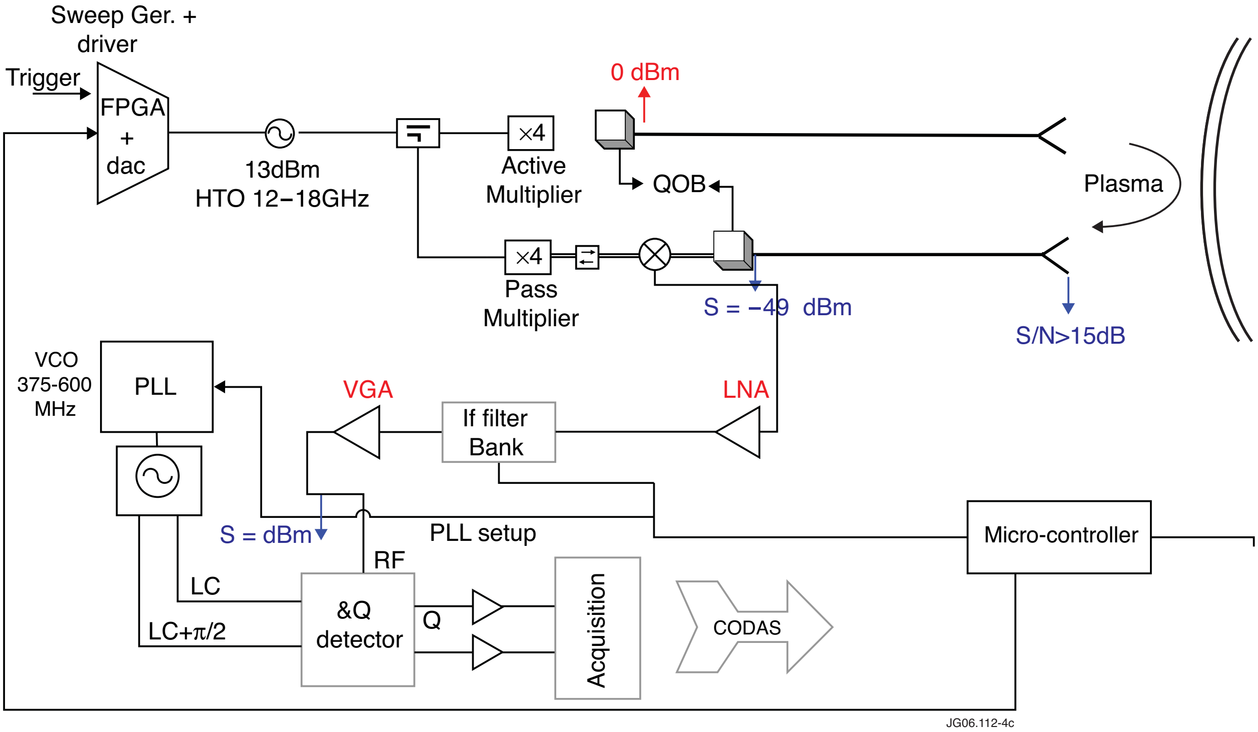


*Figure 3: Schematic design*

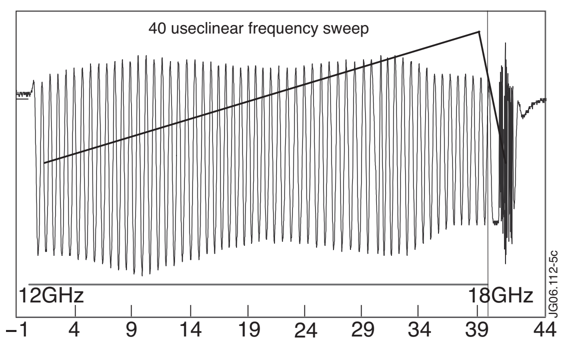


*Figure 4: Linear frequency sweep 40μs*

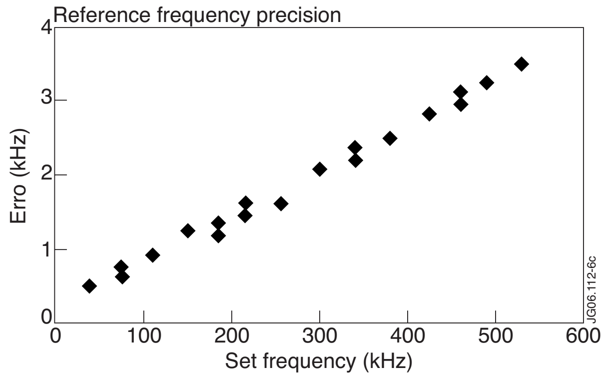


*Figure 5: Quadrature reference precision*

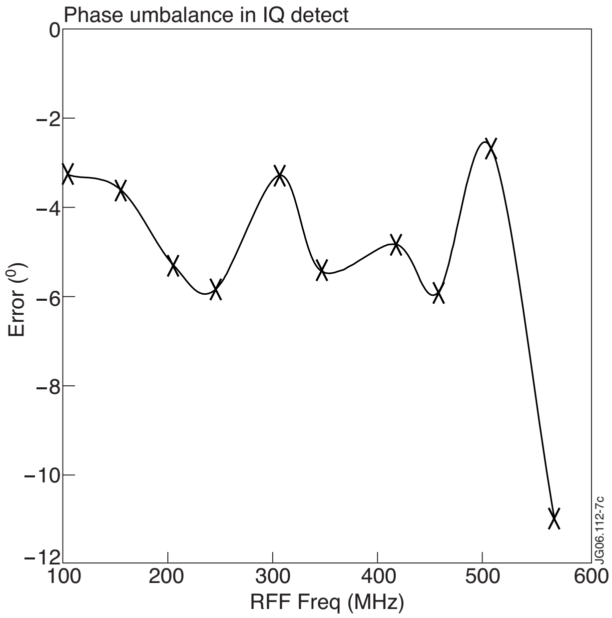


*Figure 6: Quadrature detection phase error*