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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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ABSTRACT

The recent upgrades and the potential of the X-mode reflectometry diagnostic on JET, dedicated to measurement of the turbulence radial correlation length, are presented in this paper. The reflectometer system now consists of four independent heterodyne instruments working at different probing frequencies, which in principle enables analysis of the density fluctuations at four distinct radial regions in the plasma. A VME based computer connected to the JET database computer system is used to control all the diagnostic, in particular frequency of the tuneable sources and frequency of the fast acquisition boards. The diagnostic is fully operated by remote control. A study of the effects of type I ELMs observed at JET illustrates its potential. The main limitation comes from the low quality of the transmission lines, which leads to a strong attenuation of the signal and makes the measurements difficult especially in the plasma core. To reach higher performances, new low attenuation corrugated circular waveguides (with an expected gain of 20 dB) will be installed next summer 2004 during the JET shutdown.

1. INTRODUCTION

The X-mode radial correlation reflectometry diagnostic on JET has been recently upgraded. In addition to the existing 92-96 GHz unit supplied by ELVA-1 Ltd (St. Petersburg, Russia), three new units - two supplied by CFN (IST Lisbon, Portugal) and one on loan from PPPL (Princeton, US) - have been installed. Consequently this diagnostic is now composed of four independent heterodyne reflectometers, each one probing the plasma with 2 different millimetre waves in the Xmode polarisation, one at fixed frequency and the other one whose frequency can be swept step-by-step to allow radial correlation measurements. A new VMEbus computer architecture (the term "VME" stands for VERSA Module Eurocard, more details of which can be found in Ref. 1) controls all the diagnostic and offers flexible fast-acquisition possibilities. The main features of the diagnostic, namely the hardware characteristics of the instruments, the new control system and the acquisition capabilities, are presented in Sec. II. Some illustrative measurements are shown in Sec. III. Sec. IV is devoted to concluding remarks including a brief discussion on the main limitations of the diagnostic.

2. UPGRADE OF THE CORRELATION REFLECTOMETRY DIAGNOSTIC

A. GENERAL CHARACTERISTICS

The upgraded X-mode reflectometer diagnostic probes the JET plasma at fixed frequencies 76, 85, 92, 103 GHz and at tuneable frequencies in the range 76-78, 85-87, 92-96, 100-106 GHz respectively with the two new CFN systems, the old ELVA system and the new PPPL system. A set of 3 dB couplers are used to simultaneously connect the four instruments to the same pair of oversized wave-guides, thus inducing 6 dB losses in emission and 6 dB losses in reception for each instrument. All the probing signals and the corresponding reflected ones are respectively launched and received in two different pyramidal horn antennas separated by 25 mm poloidally around the plasma mid-plane. All four reflectometer systems are equipped with a micro-controller and I/Q detectors, although their hardware characteristics vary. In this paper we do not discuss the PPPL system, some details of which can be found in Ref. 2. A full description of the ELVA system can be found in Ref. 3 and the main characteristics of the CFN systems are presented in the next subsection. All the diagnostic is fully controlled by a new VME based system, which is described in sub-section II.C.

B. THE NEW CFN REFLECTOMETER SYSTEMS

These two systems were installed on JET in the beginning of 2002. Except for the frequencies of the sources, they are both identical (their schematic is represented in Fig. 1). The transmitted signals at both fixed frequency and tuneable frequency are generated by two Gunn oscillator sources with an output power of about 20 mW (i.e. 13 dBm). The micro-controller sets the desired value of the tuneable frequency and a Phase Lock Loop (PLL) allows the difference between the tuneable frequency and the fixed frequency to be maintained constant. The originality of these systems is that the Gunn oscillator generating the tuneable frequency signal plays the role of local oscillator (LO) to down-convert the received fixed frequency signal, and vice-versa. Thus only two microwave sources are required. Two I/Q detectors enable to get I and Q signals (i.e. $A \cos \varphi$ and $A \sin \varphi$ respectively) for both the fixed frequency and tuneable frequency channels. A low frequency source of 2.5 GHz was introduced to guarantee that the phase and amplitude unbalance of the I & Q outputs is minimum and stable. To achieve this aim, the source is used to produce LO and RF signals at frequency of 2.5 GHz as inputs to the I/Q detectors. One part of the source signal directly acts as LO whereas another part is mixed with a reference signal (obtained from the mixing of part of the two emitted signals). The resulting signal is used to convert the received signals, thus producing RF inputs to the I/Q detectors in a bandwidth of 10 MHz around 2.5 GHz. The LO and RF inputs to the I/Q detectors are then always at the frequency of 2.5 GHz, independently of the value of the tuneable frequency. This avoids necessity of a calibration procedure for the I/Q detectors.

C. THE NEW INTEGRATED CONTROL AND ACQUISITION SYSTEM

A new VME system, including a PC module, two intelligent transient recorders with Digital Signal Processors (DSP) and two fast acquisition boards, has been supplied by CFN. An http protocol allows the VME system to be controlled remotely via a 10 Mbytes/s Ethernet connection. This protocol is also used to send the acquired data to the JET database after each pulse. The VME PC controls all the reflectometer systems via RS232 connections. This computer is responsible for monitoring all the microwave systems, which are equipped with a micro controller. For instance it enables to set the intermediate frequency (IF) gains of the CFN units and to perform a remote calibration of their PLL. It also controls the multi-position switch used for the calibration procedure of the ELVA system I/Q detector (see Ref. 3). The intelligent transient recorders and part of the DSP capabilities generate the triggers required to set the tuneable frequencies as well as the clock used for the fast acquisition procedure. Two fast acquisition boards (each with 8 channels) enable I and Q signal data to be recorded from both channels at fixed and tuneable frequencies of all the four reflectometers. The memory is restricted to 1.5 million samples per channel. The sampling frequency is variable (from 100 kHz up to 2 MHz), thus affecting the maximum total time of acquisition. Up to 20 fast acquisition windows per shot and up to 20 frequency steps of the tuneable source per window can be set. All the fast acquisition windows have the same duration and the same pattern of frequency steps. The input parameters for the fast acquisition procedure, namely the number and the times of acquisition windows, the tuneable frequency tables for each system and the sampling frequency, are set from a software program running in the JET control room. A slow acquisition at sampling frequency of 200 KHz is also performed using 16 DSP channels. A real time digital signal algorithm runs over the acquired data delivering 1KHz data that aims at evaluating the Root Mean Square of the signals in the two frequency ranges 0-10 kHz and 10-250 kHz.

3. ILLUSTRATIVE RESULTS

A. PRINCIPLES OF MEASUREMENT

Reflectometry measurements are mainly affected by density fluctuations localised in the cutoff layer region (see Ref. 4). A spectral analysis of the reflectometry signals is then useful to get an idea of the density fluctuations in the vicinity of the cutoff layer. An example of a typical spectrum obtained from the 76 GHz channel signal is depicted in Fig. 2, showing the dynamic range (i.e. the S/N ratio) of the instrument. All the instruments of the reflectometry system at JET are equipped with I/Q detectors so that the complex form $a(t).\exp[j\varphi(t)]$ of the reflected signals can be computed. I/Q detection allows phase and amplitude of the reflected signal to be separately analysed. Coherence between both signals from the fixed frequency and tuneable frequency channels is sensitive to the radial separation of the respective cutoff layers and to the density fluctuation characteristics. The evaluation of the coherence can then give some information either on the radial correlation length of the density fluctuations (see Ref. 3) or on the fast changes of the density profile (as exemplified in the next subsection in the presence of ELMs).

B. EFFECTS OF ELMS

The following example illustrates the sensitivity of the 76-78 GHz reflectometer to some type I ELMs observed at JET (shot #62209). In the considered plasma scenario (B_0=2.5 T, n_e.dl=1.8×10^{20} m^{-2}), the cutoff layers for the 76-78 GHz channels are located at the plasma edge (r≈3.8-3.9 m) as shown in Fig. 3. The magnetic field profile obtained from a flux surface reconstruction (EFIT) and the density profile measured by a Lidar Thomson scattering diagnostic are used to reconstruct the radial profile of the X-mode upper cutoff frequency depicted in Fig. 3. The effects of the ELMs on the reflectometry data are illustrated in Fig. 4. Although a reduction in the amplitude of the reflected signal is noticeable during the ELMs, the main effects appear in the phase of the signal. A significant broadening of the spectrum of the signal phase and then an increase of its mean value are clearly observed during the ELMs. Correlation between cosines of the phases of both fixed frequency and tuneable frequency signals also displays a significant reduction during the ELMs. These effects on the reflectometry signals are associated with strong and fast changes of the density profile induced by the ELMs. Further analysis of these reflectometry data is required to get a better quantitative interpretation of the ELMs effects (which is not the aim of this paper).

4. CONCLUDING REMARKS

The X-mode polarisation and the frequencies of the probing waves were chosen to study the advanced scenarios developed at high magnetic field. The consequence of this choice is that measurements are not possible for a too low applied magnetic field (typically lower than 1.7 T). In such conditions, the probing waves may be reflected by the inner wall and not by the plasma (no cutoff layer) or may be absorbed if their frequencies equal the second harmonic of the electronic cyclotron frequency. However, the main drawback of the diagnostic is presently the bad quality of the transmission lines (composed mainly of about 60 m of oversized rectangular wave-guides). The total losses in the entire signal path are estimated at around 60 dB. Consequently, the parasitic signals coming from the leaks between the fixed frequency and tuneable frequency channels (“cross-talk”) dominates the plasma signal (strongly attenuated in the transmission lines). This “cross-talk” (especially strong in the 76-78 GHz and 85-87 GHz systems) induces in the signal some parasitic offset and fluctuations which interfere with the plasma contribution. Then the S/N ratio can be low, especially when the probing wave is reflected in the core plasma region, thus making the measurements difficult. This is a limitation to study the turbulence behaviour in the plasma core, which is an important topic at JET for the development of advanced scenarios with improved confinement regimes. Further upgrade will be carried out during the 2004 JET shutdown with the installation of new low attenuation corrugated circular wave-guides (with an expected gain of 20 dB). This should significantly improve the quality of the measurements in the next campaigns in 2005 and then provide a better understanding of the turbulence behaviour in the advanced scenarios studied at JET.

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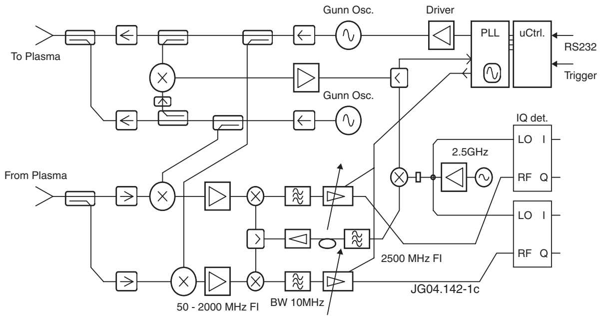

FIG.1: Schematic of the 76-78 GHz and 85-87 GHz systems

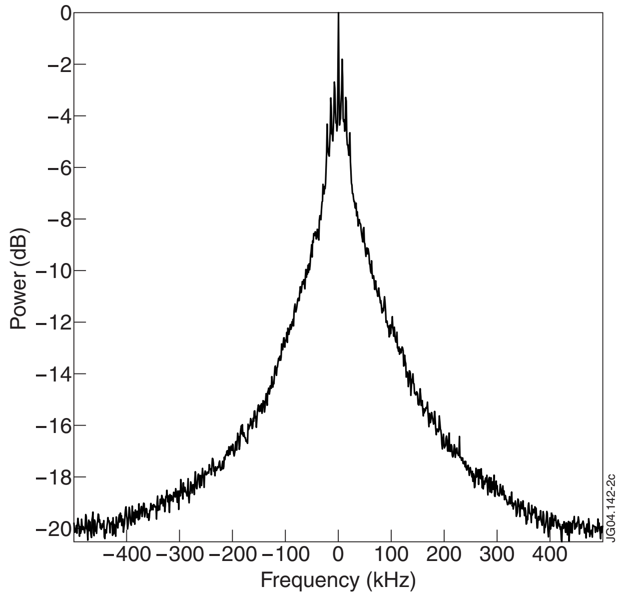

FIG.2: Typical power spectrum of complex signal a(t).exp[jφ(t)] from the 76 GHz channel

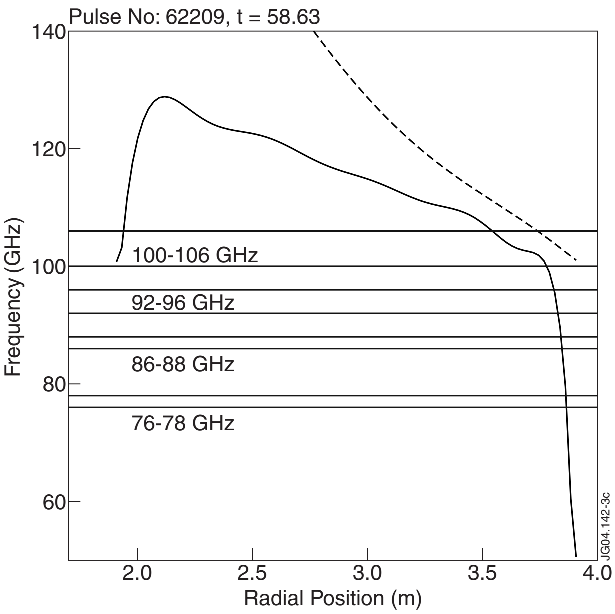

FIG.3: Radial profile of the X-mode upper cutoff frequency (full line) showing the localisation of the cutoff layers for the different channels. The radial profile of the 2nd harmonic of the electronic cyclotron frequency (dotted line) also illustrates a possible absorption of the probing waves for the 100-106 GHz system

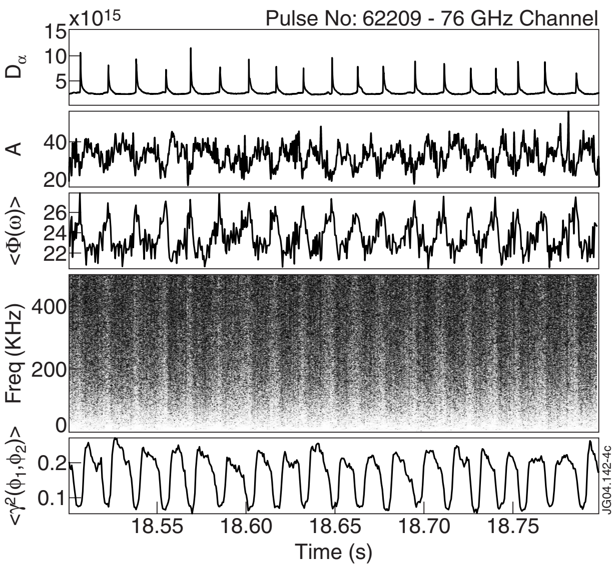

FIG.4: Results from the 76-78 GHz system during type I ELMs. From the top to the bottom: (1) D_α emission signal, (2) amplitude of the 76 GHz reflected signal, (3) mean value of the spectrum of the 76 GHz signal phase, (4) spectrogram of the 76 GHz signal phase, (5) frequency averaged coherence γ^2 between phase cosines of 76 GHz and 76.9 GHz reflected signals.