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ABSTRACT

A novel frequency modulation scheme has been developed for the multi-channel reflectometer used to measure density profiles and density fluctuations on the JET tokamak. This reflectometer normally uses slow frequency sweeping, combined with fixed-frequency operation, to measure the group delay, as well as plasma fluctuations, at 10 different microwave frequencies. The novel scheme uses continuous frequency modulation on a time-scale much faster than that of plasma fluctuations, the main aim being to make the group delay measurement more robust against plasma fluctuations. This paper discusses the theoretical background of the scheme, gives a detailed description of the system, and presents results from plasma measurements.

1. INTRODUCTION

Several different modulation schemes are employed in reflectometer systems to determine the group delay time required for electron density profile measurements [1]. The JET multi-channel reflectometer, which is able to function with the long waveguide runs needed at JET, uses slow, narrow-band sweeps of the microwave frequency in each of the channels [2]. 10 channels of the original system are currently in operation, spanning the range from 18 to 70GHz, in the O-mode. Three problems have been encountered with this approach: First, the frequency sweep is slow (6ms) in comparison to the time-scale of most turbulent and coherent plasma fluctuations. Second, the corresponding phase change is measured by fringe counters which rely on the signals being continuously present during the sweep. Third, the frequency excursion depends on the characteristics of the microwave sources and is therefore subject to small variations. These circumstances result in frequent loss of profile information, or in relatively large errors in the position of the density profiles, as well as errors in their shape, though the latter are partially corrected by making use of the phase evolution during the fixed-frequency intervals between sweeps. These limitations have degraded the performance of the instrument in measurements of both density gradients and densities near the edge, both important in the study of high-confinement (H-mode) plasmas in JET [3]. On the other hand, the existing system can perform *simultaneous* measurements of density fluctuations at 10 radial positions. Such measurements were crucial in identifying MHD modes, such as the so-called outer modes, external kink modes limiting the performance of H-mode plasmas [4, 5].

To address the problems discussed above and improve the general performance of this diagnostic, whilst retaining the advantageous aspects of the existing system, a novel scheme relying on fast frequency modulation has been developed. This paper discusses the underlying theory and technical details of this system. These will be illustrated with examples of plasma measurements.

2. THEORY

In the fast-frequency modulation (FFM) scheme, [1] the microwave sources are frequency-modulated by a stable oscillator. The time dependence of the wave launched by each source is given by

$$S(t) = A\cos(2\pi f_c t + m\sin 2\pi f_m t),$$

where f_c is the carrier frequency, f_m is the modulation frequency, and m is the modulation index. The modulation frequency of 65MHz has been chosen to be much higher than the plasma fluctuation frequencies (typically up to 1MHz), but low enough to eliminate phase ambiguity: The largest displacement within the JET cross-section is approximately 2m, corresponding to an optical path change of 4m, whereas the vacuum wavelength of the modulating signal is 4.6m; this means that any change in the phase of the modulating signal ϕ_m will be less than 2π and can be determined by a simple phase measurement with respect to a reference signal.

In the present implementation of the scheme, the modulation bandwidth, which is of the order of mf_m, is comparable to the modulation frequency, that is, the modulation index is small (m~0.4). It should be noted that in this case the scheme is similar to amplitude modulation or differential-phase schemes, in terms of the launched microwave spectrum, but is simpler to implement technically as it does not involve any modifications to the microwave components of the existing system. In the present implementation, the launched bandwidth is limited by the IF bandwidth of the microwave receiver. Nevertheless, one can in general increase this bandwidth for an FM system, by increasing the modulation index for a fixed modulation frequency. Analytical modelling [6] suggests that the robustness of the measured group delay against density fluctuations is enhanced when the launched bandwidth is such that the width of the density profile probed is much larger than the correlation length of the density fluctuations.

In comparison to the conventional scheme employing slow frequency sweeps, the present scheme uses a much higher modulation frequency (65MHz compared to ~100Hz) but a much lower modulation index (~0.4 compared to ~10^6), giving a comparable bandwidth, of the order of 100MHz. In other words, the same bandwidth is swept in a much shorter time.

In the conventional scheme, the group delay time is determined from the phase change measured over a sweep:

$$\tau_G = \frac{\Delta\phi/2\pi}{\Delta f},$$

where $\Delta\phi$ and Δf are, respectively, the changes in phase and frequency of the carrier signal over a sweep. The fringe counter used for the measurement of $\Delta\phi$ (typically several fringes) must

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[1] many authors of reflectometry articles use the term *frequency modulation* to refer to linear frequency sweeping; in this paper, the term is used in the sense usual in communications

follow the signal over the whole sweep. In the new scheme, the phase measurement is performed at the modulation frequency, which depends on the stable oscillator and not on the microwave sources. The group delay time, within one period of the modulating signal, is given by

$$\tau_G = \frac{\phi_m/2\pi}{f_m},$$

where ϕ_m is the phase of the modulating signal. Because there is no phase ambiguity, a measured phase corresponds to a single value for the group delay time, and such a measurement can in effect be performed instantaneously (subject only to averaging over enough modulation cycles to reduce the phase error). A spatial resolution of 1cm in vacuum entails a phase resolution of 1.6^o, and a stability of the group delay time in the instrumentation of 0.07ns (the group delay distortion as a function of input power can be larger, provided that this function be known).

The carrier signal is much more sensitive to profile fluctuations than the modulating ‘envelope’, by virtue of its much shorter wavelength, and can readily be used for fluctuation measurements.

Such a frequency modulation scheme can be used not only in a discrete-channel system, but also in systems employing frequency sweeping of a broadband source (such as a BWO or HTO) to probe the density profile. The maximum rate of change of frequency associated with the frequency modulation is given by

$$\dot{f}_{max} = 2\pi m f_m^2;$$

this would be of the order of 10MHz/ns, which is faster than the typical frequency rate associated with the linear sweep in such systems, of the order of 1MHz/ns.

The group delays from the 10 channels are finally used in an Abel inversion procedure to obtain the density profile. Naturally, certain assumptions have to be made about the variation of the group delay between successive channels, and also below the lowest density that is probed. The reconstruction procedure falls outside the ambit of this paper, but is discussed elsewhere (eg [1, 2]).

3. SYSTEM DESCRIPTION

To measure the group delay time, the received frequency-modulated microwave signal is down-converted to an intermediate frequency (IF) of approximately 300MHz, using the heterodyne receiver of the existing system; the modulating signal is recovered from the power-limited IF signal using a frequency discriminator; and its phase, relative to the reference signal from the master oscillator (used to modulate the transmitted signal), is measured using an IQ demodulator.

Shown in figure 1 are the microwave components and electronic instrumentation for one of the 10 channels of the reflectometer. Both transmitter and local oscillator are varactor-tuned

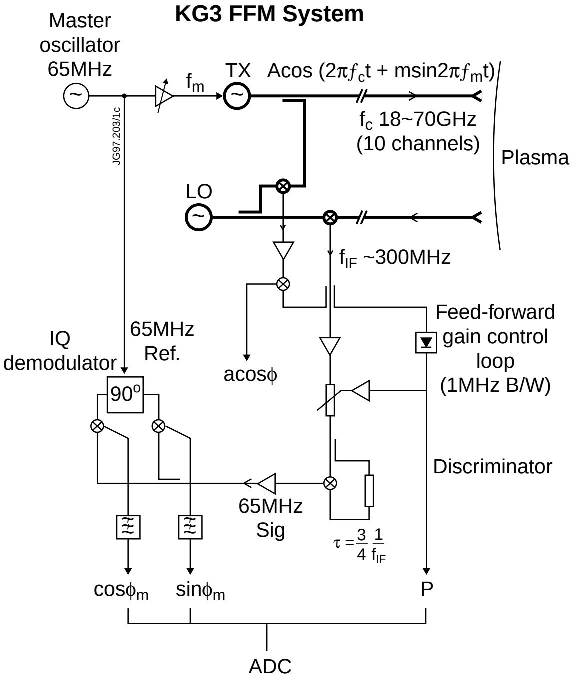

Fig.1: Schematic diagram of the microwave components (bold lines) and electronic instrumentation of the fast frequency modulation (FFM) system, for one of the 10 channels of the JET multi-channel reflectometer (KG3). (The master oscillator is common to all channels.)

Gunn oscillators. A single oscillator at 65MHz and individual amplifiers with adjustable gains and offsets are used to modulate the transmitter oscillators. Each local oscillator operates at a fixed frequency and the need for a phase-lock loop is obviated. Should the transmitter or local oscillator source drift in frequency, the resulting frequency drift of the IF signal would not affect the phase measurement at the modulation frequency; nevertheless, a slow compensating circuit (not shown) has been included to maintain a constant intermediate frequency.

The IF signal from the heterodyne receiver is limited in power by means of a feed-forward gain control loop. This uses a Schottky power detector acting through a control circuit on diode attenuators, and has its bandwidth limited to 1MHz, this being sufficient to eliminate power variations in the IF signal due to the plasma. This arrangement was chosen in preference to a limiting amplifier because of its linearity: it was expected that its group delay stability would be superior to that of a limiting amplifier (phase variations in the IF carrier are of course unimportant). A signal corresponding to the power level of the input signal is also extracted and digitized, the purpose being to apply a power-dependent correction on the measured group delay. Following this section, is a frequency discriminator which recovers the modulating signal by mixing the incoming modulated signal with a delayed version of itself. The response of this circuit to a signal of instantaneous frequency f is proportional to $\cos(2\pi f \tau_d)$, where τ_d is the delay. When the instantaneous frequency is modulated, the response of the discriminator is the modulating signal and preserves the phase of the latter. The delay must be such that the carrier is eliminated or considerably attenuated; this is achieved when the delay corresponds to an *odd* number of quarter-cycles of the carrier. The delay, provided by a 50cm coaxial line, is approximately 2.5ns or 3/4 of a cycle of a 300MHz IF signal. The frequency of the latter is adjusted to make the delay exactly 3/4 of a cycle; this maximizes the efficiency of the discriminator, because the frequency modulation is then along the steepest part of the cosine curve, about its zero-crossing point. The slow compensating circuit mentioned in the previous paragraph works by monitoring the DC component of the discriminator output, which should be zero when the IF centre frequency is at this optimal value.

Also shown in figure 1, is an ancillary circuit which generates a homodyne signal, by mixing the IF signal obtained from the plasma reflection with a corresponding IF signal obtained from the reference path of the existing system. The reference signal contains the same frequency components as the plasma signal without the broadening effect due to plasma fluctuations. The homodyne signal produced responds to the amplitude A and phase ϕ of the microwave carrier as $A\cos\phi$, and is used for density fluctuation measurements. It would have been possible, incidentally, to use in-phase/quadrature (IQ) detection to produce both $A\cos\phi$ and $A\sin\phi$ signals, and thus obtain more complete fluctuation information. This was not done in the present implementation of the scheme to reduce the complexity and cost.

The IF sections have been specifically developed for this application, the main design objectives being to obtain a large ‘limiting’ range of input power (at least 30dB); and to minimize the variation of the group delay with input power, or at least to minimize random changes in the group delay response ($<1^{o}$ at 65MHz, or <0.04ns). To minimize the group delay distortion one has to make the attenuation circuit as linear as possible, and to ensure that the discriminator mixer is at all times saturated with LO power and unsaturated in RF power. The following technique was used to assess the performance of the IF section: An amplitude modulator (mixer) driven by a function generator was used to ramp the power of a frequency-modulated IF signal by about 30dB over a time-scale of 16µs, and a fast digitizing oscilloscope (2GS/s) was used to acquire the signals at the input and output of the IF section (both limited IF signal and demodulated 65MHz signal were examined). The power of the input and output signals and the phase difference between their modulating components were then extracted using software and plotted against time. An example is shown in figure 2, which shows that whilst the IF signal was adequately limited over a range of 25dB in input power, the group delay variation over this range was around 1.3ns, or 30^{o} at the modulating frequency of 65MHz. As expected, it was found that this variation was entirely due to the limiting circuit (the demodulated signal obtained from the discriminator section exhibited the same phase variation as the modulating signal extracted by software from the limited signal). The group delay variation was repeatable and one could remove most of the effect by monitoring the input power and applying a group delay correction related to the power. A provision for doing this has been made, as described above. It is estimated that the residual error in the final measurement of the group delay is 10^{o} (at 65MHz), which

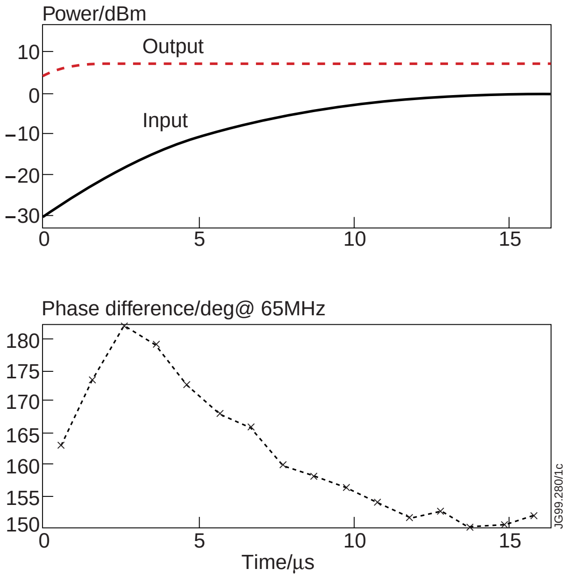

Fig.2: Assessment of IF limiter section using an input signal of increasing power: Power of input and output signals (top); and phase difference between modulating components at 65MHz (bottom), plotted against time. The phase of the modulating signal changes by 30^{o} over the limiting range of 25dB, corresponding to a group delay variation of 1.3ns.

results in an error in the equivalent displacement in vacuum of 6cm. It would have been preferable, of course, if the group delay variation were much smaller, and this might have been achieved by using resistive elements in the attenuating circuit.

Finally, an IQ (in-phase/quadrature) demodulator[2] is used to extract the phase of the recovered modulating signal centred at 65MHz. The 65MHz signal from the master oscillator is used as reference. If the oscillator is stable, there is no need for a delay line; the relevant factor here is the phase stability of the oscillator over the total propagation time of the modulating signal from the master oscillator back to the IQ demodulator (~0.7µs for the JET system). For convenience, the measured phase difference can be made zero for a signal reflected from the back wall of the vacuum vessel, by inserting an appropriate delay in the circuit, though this is not necessary. The two video signals produced by the IQ demodulator, as well as the power monitor signal from the IF section, are digitized, at a sampling rate of 5kHz, and are used to calculate the phase of the modulating signal ϕ_{m} and thence the group delay. A much higher sampling rate can be used, subject only to averaging over a large number of modulation cycles.

The IQ demodulators have also been specifically developed for this application, the main aim being to optimize the phase accuracy and resolution. Each IQ demodulator and its associated IF and video amplifiers have been implemented on a single circuit board using discrete IF components, namely broadband amplifiers, mixers and 0^{o} splitter; and a 55-90MHz, 90^{o} splitter (all from Mini-Circuits). The performance has been optimized by biasing the 90^{o} splitter (hybrid) to minimize the phase imbalance; by biasing the two detection mixers to minimize the DC offsets and amplitude imbalance; and by careful design of the video amplifiers and anti-aliasing filters. The amplitude and phase imbalances of each IQ demodulator have been measured by applying a test signal, at a frequency 1kHz below that of the 65MHz reference signal, and analysing the resulting video signals at 1kHz, which one expects to be sinusoidal signals of equal amplitudes, in exact quadrature, and with zero DC offsets. It was found that the maximum amplitude imbalance was 0.4% and the maximum phase imbalance was 1^{o}; and that both these parameters, as well as the DC offsets, were stable for each IQ detector (the variations were <0.005% for the amplitude imbalance and $<0.1^{\mathrm{o}}$ for the phase imbalance) and their effects on the calculated phase could therefore be readily removed. The corrected phase is calculated from[3]

$$\phi_{\mathrm{m,\ corr}} = \tan^{-1}\left[\frac{Q\text{-}Q_0}{I\text{-}I_0}\,\frac{1}{a} - \delta\right],$$

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[2] An IQ demodulator produces signals corresponding to $\cos\phi_{\mathrm{m}}$ and $\sin\phi_{\mathrm{m}}$ by mixing an incoming signal of phase ϕ_{m} with two reference signals in quadrature with each other, produced by a 90^{o} splitter

[3] the approximation holds for small δ

where I and Q are the raw signals; I_0 and Q_0 are the corresponding DC offsets; a is the amplitude imbalance ($a>1$ if the Q signal is larger in amplitude than the I signal); and δ is the phase imbalance in radians ($\delta>0$ if the quadrature is $<\pi/2$).

4. SIMULATIONS

The modulation and detection system described above has been simulated by a code which models, in the time domain, the imperfect electronic components of the modulation, demodulation and phase detection circuits, as well as coherent and turbulent fluctuations in the plasma. Shown in figure 3, is the temporal variation of the group delay, obtained from the simulated reflected signal, and of the power of that signal. A triangular-wave oscillation was imposed on the position of the reflection layer. It is clear that, despite the artificially introduced imperfections, the position and movement of the plasma reflection layer can be accurately reconstructed. Shown in figure 4, is the effect of a spurious reflection (10% of the incident power): such a spurious reflection can result in a distortion of the movement of the reflection layer, and also manifests itself in a modulation of the power of the demodulated signal, notwithstanding the fact that the modulated signal had its power limited; the measurement of the average position of the reflection layer, however, was not affected.

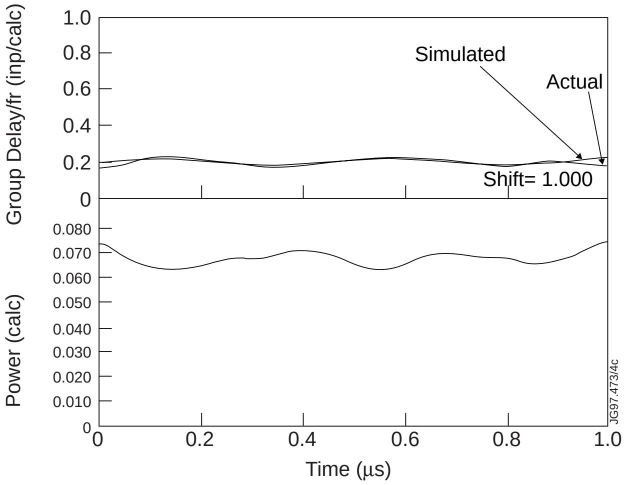

Fig.3: Temporal variation of group delay (in fringes) and power of recovered modulation signal, as determined in a simulation in which the position of the reflection layer was varied. The group delay, extracted by numerical simulation of the electronic circuit, is compared to the corresponding delay calculated directly from the position of the reflection layer. The mean position and movement are accurately reconstructed.

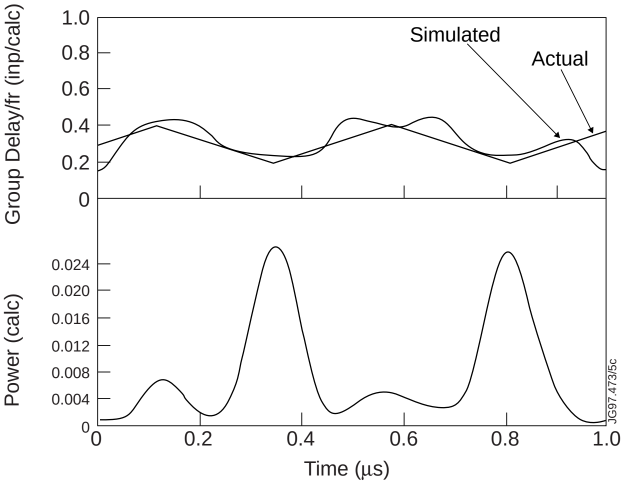

Fig.4: As figure 3, but with a spurious reflection of 10% of the launched power. The movement of the reflection layer is distorted, but the mean position is not affected; the power of the demodulated signal exhibits large fluctuations, notwithstanding the limiting of the intermediate, modulated signal.

5. MEASUREMENTS

The hardware described above has been installed and commissioned satisfactorily. Unfortunately, prolonged delays in the development and construction of the IF sections described above have meant that, at the time of writing, only two such units had been delivered and commissioned. Measurements have been limited, therefore, to only two channels of the system, and density profiles could not be obtained.

Figure 5 shows the power spectra of the launched microwave and down-converted IF signals for one of the channels of the system. Clear from these figures is the structure of the FM spectrum, with a carrier and only two sidebands (because of the low modulation index). Figure 6 shows the recovered signal at the modulation frequency of 65MHz, in the absence of plasma (reflection from the back wall of the vessel), and with plasma. The effect of plasma fluctuations in this signal is evident. It should be noted that, whilst the power at the centre frequency is attenuated (by about 4.5dB), the peak remains sharp.

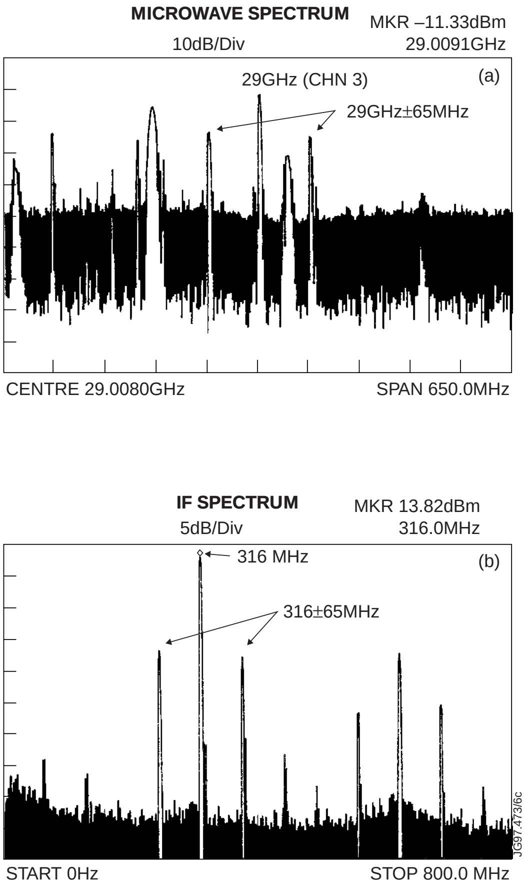

Fig.5: Power spectra of (a) launched microwave from channel 3, centred at 29.0GHz; and (b) down-converted IF signal, centred at 316MHz. The two sidebands arising from the frequency modulation are separated from the carrier by the modulating frequency of 65MHz. (The microwave spectrum includes several spurious mixing products.)

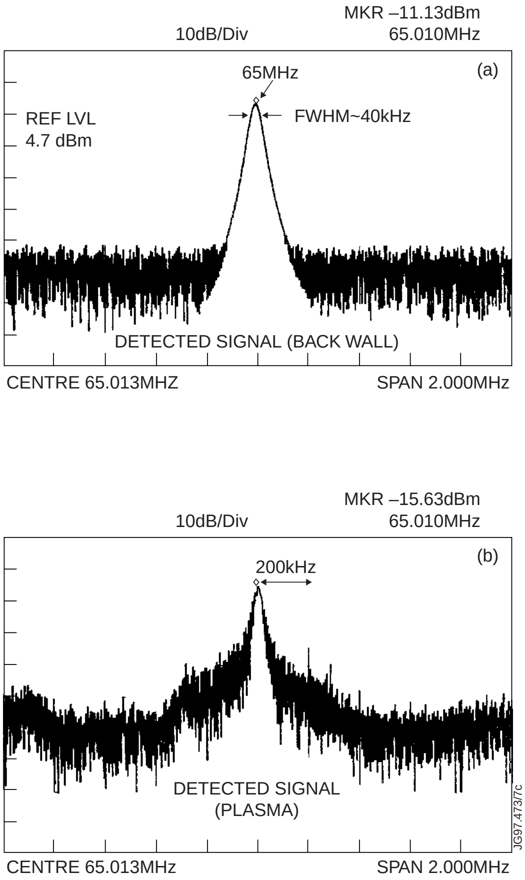

Fig.6: Power spectra of recovered modulating signal at 65MHz, obtained (a) without plasma (back wall reflection), and (b) with plasma.

Figure 7 shows the position of the reflection layer for a microwave channel corresponding to the edge of the plasma (n_e=0.4×10^{19}m^{-3}), as obtained from the measured phase of the recovered modulating signal; and the corresponding position of the plasma boundary (last closed flux surface) as obtained from a magnetic reconstruction code (XLOC). Vacuum propagation was assumed for this particular measurement, because of the proximity of the probed reflection layer to the plasma edge. In the discharge shown there was a disruption at about 19s, after which the reflection layer position is that of the back wall of the vacuum vessel, 1.82m. Indeed, it is this position that is used as a reference. In the current implementation, the reference is set using the phase measured in the so-called *dry run*, a pulse without plasma run at the beginning of each day. During the plasma phase, the measured position shows fluctuations of about 10cm amplitude. The probable cause of these is the group delay distortion resulting from the fluctuating power of the reflected signal, which has not been fully compensated for.

The same system is capable of making fluctuation measurements, as described in section 3. The video signal produced from the carrier of the frequency-modulated reflected signal was fed to a fast acquisition system used at JET for fluctuation measurements, with a sampling rate of 250kHz. Figure 8 shows this fluctuation signal, and compares it to the fluctuation signals obtained from the two adjacent channels which are operated with conventional frequency sweeping. Density fluctuations due to edge localized modes (ELMs) have been detected by all three channels.

In conclusion, fast frequency modulation has been developed and demonstrated on the JET diagnostic. It offers distinct advantages for a reflectometer system, used for both density profile and fluctuation measurements,

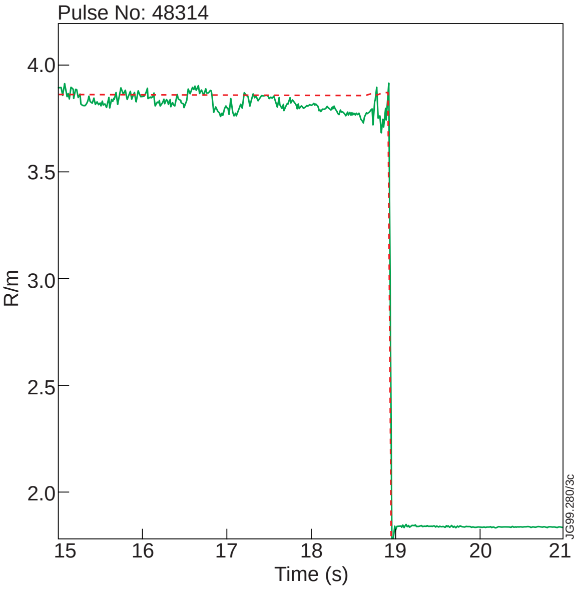

Fig.7: Radial position of reflection layer corresponding to channel 1 (18.5GHz, n_e*=0.4×10*^{19}*m*$^{-3}$*), as obtained from the measured phase of the recovered modulating signal (solid line); and corresponding position of plasma boundary from magnetic data (broken line). The position is shown in terms of the major radius. A disruption occurs at about 19s, after which the measured position is that of the vessel back wall, 1.82m.*

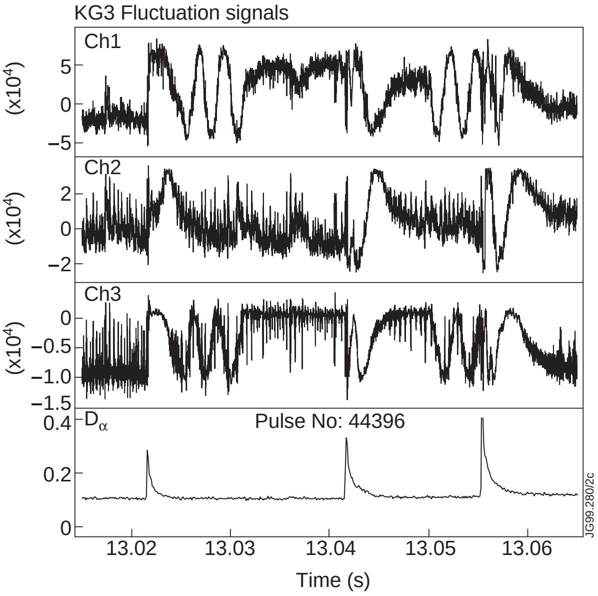

*Fig.8: Fluctuation signals (A*cosϕ*) obtained from reflectometer channels 1 (a, 18.5GHz), 2 (b, 24GHz) and 3 (c, 29GHz), showing the response to edge localized modes (ELMs); the signal from the edge* D_α *emission is also shown (d). Channel 2 uses fast FM, whereas channels 1 and 3 use conventional frequency sweeping (phase variations due to sweeps starting at 13.025s and 13.050s are clearly visible).*

namely its robustness against plasma fluctuations and its simplicity of interpretation. Its main weakness is the group delay distortion that can be introduced by the power limiting circuit, but this can be reduced or eliminated by an appropriate design.

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REFERENCES

[1] C Laviron, A J H Donné, M E Manso, and J Sanchez, Reflectometry techniques for density profile measurements on fusion plasmas *Plasma Phys. Control. Fusion* **38** 9 (1996).

[2] A C C Sips and G J Kramer, Analysis of reflectometry density profile measurements in JET *Plasma Phys. Control. Fusion* **35** 743 (1993).

[3] N Deliyanakis, D P O’Brien, B Balet, C M Greenfield, L Porte, A C C Sips, P M Stubberfield, and H Wilson, The VH-mode at JET *Plasma Phys. Control. Fusion* **36** 1159 (1994).

[4] P Smeulders, and the JET Team, Influence of MHD instabilities on JET high performance *Controlled Fusion and Plasma Physics, Proc. 22nd Eur. Conf., Bournemouth* vol 19C IV-061 (1995).

[5] P Smeulders, G D Conway, B Alper, B Balet, D V Bartlett, D Borba, N Deliyanakis, T C Hender, and O J Kwon, Characteristics of a New Class of Transport Related MHD Modes in JET H-mode Plasmas *JET Report* P(98)83, submitted to *Plasma Phys. Control. Fusion* (1998).

[6] G Vayakis, A model of the effect of Plasma Turbulence on Time Delay Measurements by Reflectometry *JET Report* P(95)76 (1995).