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A Novel Fast Frequency Modulation Scheme for the JET Multi-Channel Reflectometer

N Deliyanakis

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,

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1. INTRODUCTION

Several different modulation schemes are employed in reflectometer systems to determine the group delay time required for density profile measurements (Laviron *et al*, 1996). The JET multi-channel reflectometer uses slow, narrow-band sweeps of the microwave frequency in each of the channels (Sips and Kramer, 1993). 10 channels of the original system are currently in operation, spanning the range from 18 to 70GHz, in the O-mode. Three problems are associated with this approach: First, the frequency sweep is slow (6ms) in comparison to the time-scale of most plasma fluctuations, whether turbulent or coherent. Second, the corresponding phase change is measured by fringe counters which rely on the signals being continuously present during the sweep. Third, the exact frequency excursion depends on the characteristics of the microwave sources. 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 are significant in measurements of edge density gradients and densities, both important in the study of high-confinement (H-mode) plasmas in JET (Deliyanakis *et al*, 1994). On the other hand, the present system can perform *simultaneous* measurements of density fluctuations at 10 radial positions; such measurements were crucial in identifying the so-called outer modes, external kink modes limiting the performance of H-mode plasmas (Smeulders *et al*, 1995). The present system is also able to function in conjunction with the long waveguide runs needed at JET.

To eliminate the problems discussed above and improve the general performance of this diagnostic, whilst retaining the advantageous aspects of the present system, a novel scheme relying on fast frequency modulation has been designed and is being implemented. This paper discusses the underlying theory and technical aspects of this novel system. These will be illustrated with examples of preliminary measurements.

2. Theory

In the fast-frequency modulation (FFM) scheme,‡ the microwave sources are frequency-modulated by a stable oscillator at 65MHz. The time dependence of the wave launched by each source is given by

$$S(t) = A\cos(2\pi f_{\mathrm{c}}t + m\sin 2\pi f_{\mathrm{m}}t), \tag{1}$$

where f_{c} is the carrier frequency and f_{m} is the modulation frequency, and m is the modulation index. The modulation bandwidth is comparable to the modulation frequency, that is, the modulation index is small. It should be noted that this scheme is similar, in terms of the launched microwave spectrum, to amplitude modulation or differential-phase schemes, but is simpler to implement technically as it does not involve any modifications to the microwave components of the existing system. In the present scheme, the bandwidth of the launched microwave power is limited by the IF bandwidth. In general, however, one can increase this bandwidth for an FM system, by increasing the modulation index for a fixed modulation frequency. Some models (Vayakis, 1995) suggest that the robustness of the measured group delay against density fluctuations is enhanced when the bandwidth exceeds the correlation bandwidth of the fluctuations.

The modulation frequency 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 wavelength of the modulating signal is 4.6m). The phase measurement is now performed at the modulation frequency, which depends on the stable oscillator and not on the microwave sources. The group delay time is given by

$$\tau_{\mathrm{G}} = \frac{\phi_{\mathrm{m}}/2\pi}{f_{\mathrm{m}}}, \tag{2}$$

within one period of the modulating signal, for a phase ϕ_{m} between 0 and 2π. 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. A spatial resolution of 1cm in vacuum entails a phase resolution (and stability of the corresponding group delay time in the instrumentation) of 1.6°.

3. Technical aspects

To measure the group delay time, the received microwave signal is down-converted to an intermediate frequency (IF) of approximately 300MHz, using the heterodyne receiver

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

of the exisiting system; the modulating signal is recovered from the limited IF signal using a frequency discriminator; and its phase, relative to the reference signal from the master oscillator, 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 Gunn oscillators. A single oscillator at 65MHz and indidual, variable-gain amplifiers are used to modulate the transmitter oscillators. The local oscillator operates at a fixed frequency and the need for a phase-lock loop is obviated. Should the transmitter or local oscillator sources drift in frequency, the resulting drift in frequency 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 controlling a PIN-diode attenuator, and has its bandwidth limited to 1MHz, this being sufficient to eliminate power variations in the IF signal due to the plasma. This arrangement is preferable to a limiting amplifier, because of its linearity and group delay stability (phase variations in the IF signal are of course unimportant). 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 delay is such that the carrier is eliminated or considerably attenuated). Finally, an IQ (in-phase/quadrature) demodulator is used to extract the phase information from 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 two video signals produced by the IQ demodulator are digitized, at 5kHz and 250kHz, and are used for the calculation of the group delay. The group delays from the 10 channels are then 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.

Also shown in figure 1, is a secondary circuit which generates a homodyne signal, by mixing the IF signal originating in the plasma with a corresponding signal from the reference waveguide of the existing system. This homodyne signal, which clearly responds to the phase and amplitude of the microwave carrier, is used for density fluctuation measurements.

The frequency discriminator and IQ demodulator have both been specifically developed for this application, the main design object being to optimize the group delay stability of the discriminator and the phase resolution of the IQ demodulator. The latter has been optimized by careful design of the video amplifiers, and by biasing the 90° hybrid and the two mixers of the circuit.

4. Simulations

The modulation system described above has been simulated by a code which models, in the time domain, both coherent and turbulent fluctuations in the plasma, and the imperfect electronic components of the modulation and detection circuits. Shown in figures 2 and 3, are the power and phase spectra of the detected modulating signal generated, respectively, in the absence of plasma, and from a plasma with coherent fluctuations, resulting in fluctuations in both the phase and amplitude of the reflected signal. Shown in figure 4, are the temporal variations of the group delay, obtained from the phase of the detected signal, and of the power of the latter. 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 5, 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 detected signal.

5. Preliminary measurements

The hardware described above has been installed and commissioned satisfactorily, with the exception of the discriminator circuits (these include the gain-control loop); the latter have been developed but not delivered. Preliminary experiments were carried out using a commercially obtained limiting amplifier in the place of the gain-control loop. Figure 6 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 7 shows the recovered signals 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. Finally, figure 8 shows the equivalent vacuum displacement of the reflection layer as obtained from the measured phase of the recovered modulating signal, and the corresponding movement of the plasma boundary (LCFS) as obtained from a magnetic reconstruction code (XLOC). Whilst the measured phase clearly exhibits the movement of the plasma, the latter is grossly overestimated (by a factor of about 15). This serious difficulty has been attributed to the limiting amplifier used, and has led to the design of the gain-control loop described above. Two further solutions to this problem will be considered, should this approach fail. First, the limiting process may be eliminated; the simulation shows that good resolution in position can be obtained even in the presence of large power variations. Second, amplitude modulation can be implemented instead of frequency modulation, with relatively few changes to the existing system (PIN modulators would have to be included in the four microwave bands of the instrument).

References

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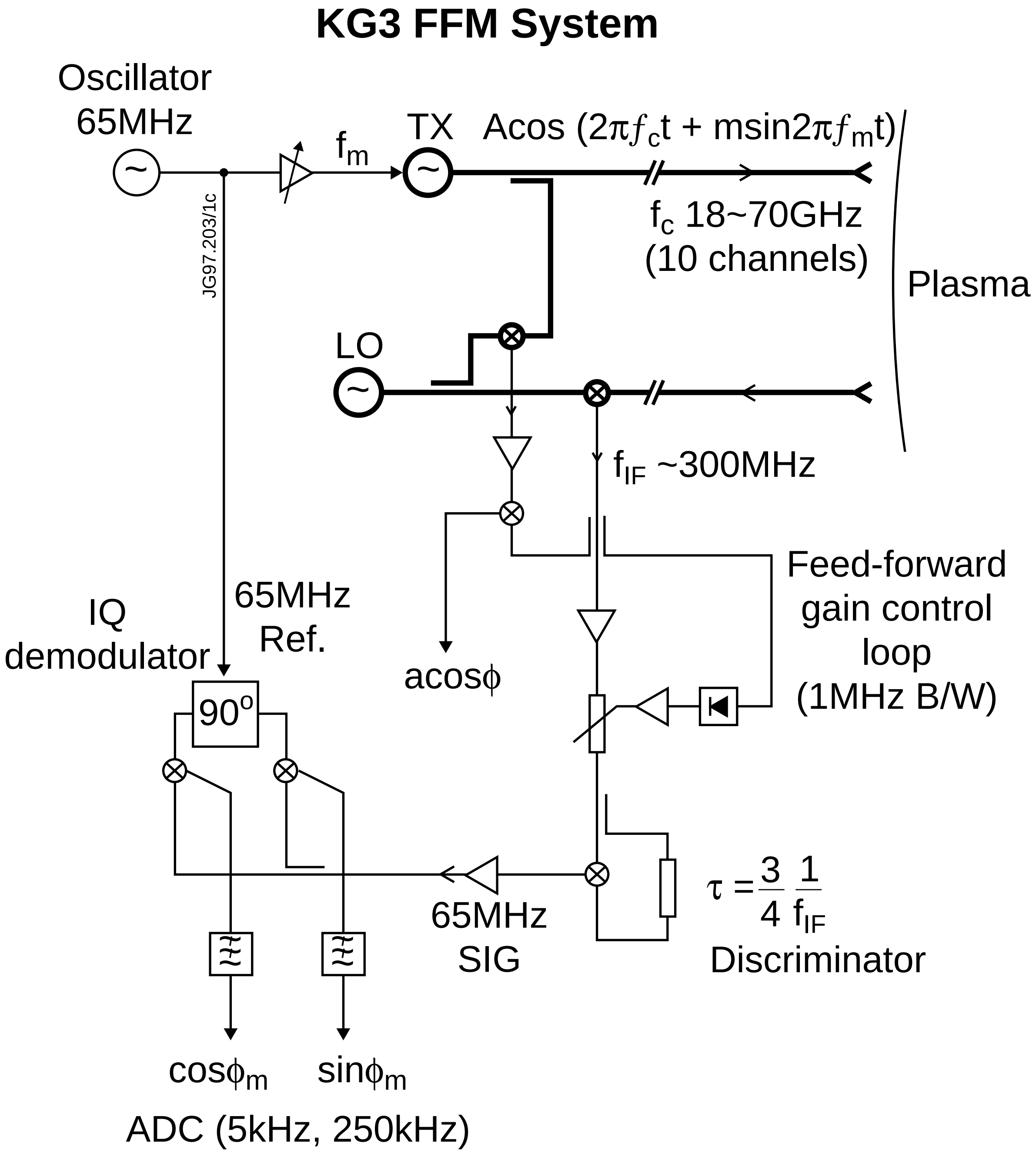

Figure 1. Schematic diagram of the microwave components (bold lines) and electronic instrumentation of the fast frequency modulation (FFM) system, for one of the 10 channels of the JET reflectometer (KG3).

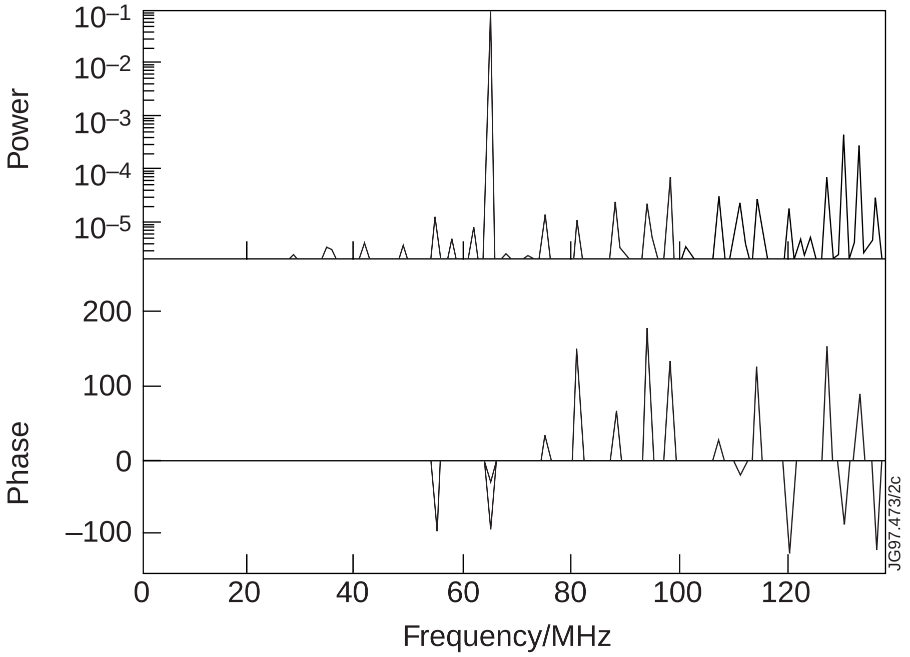

Figure 2. Power and phase spectra of recovered modulation signal at 65MHz, as simulated in the absence of plasma.

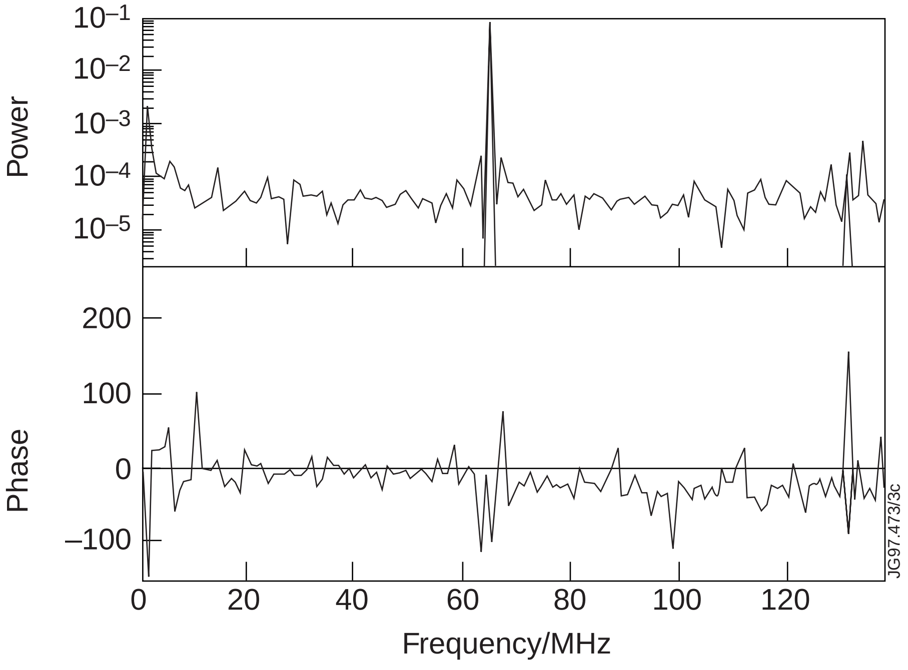

Figure 3. Power and phase spectra of recovered modulation signal at 65MHz, as simulated for a plasma with coherent fluctuations at 2MHz.

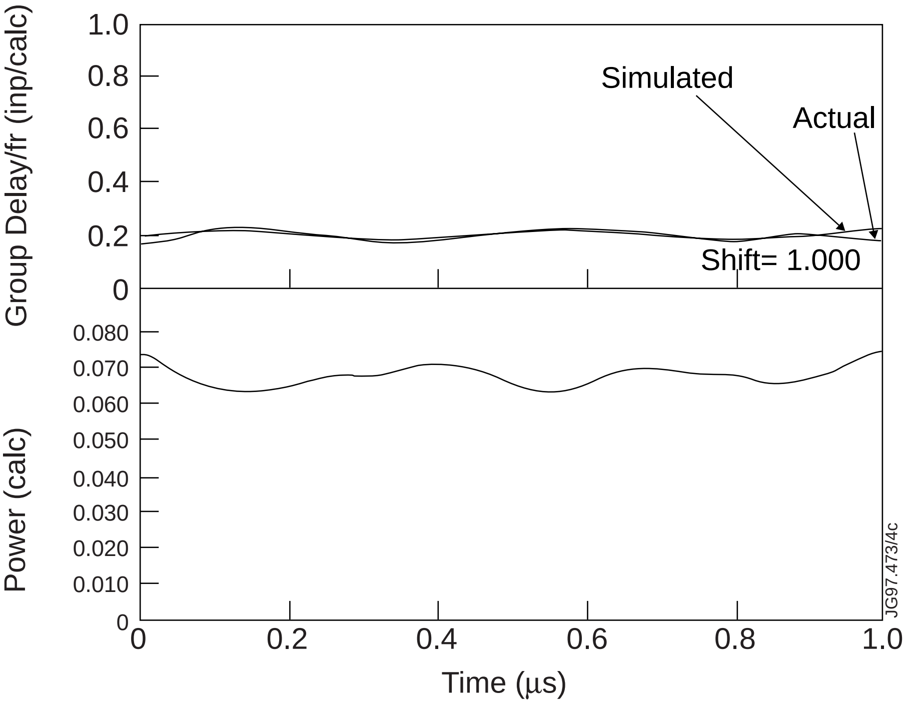

Figure 4. Temporal variation of group delay (in fringes) and power of recovered modulation signal, as determineed by simulated IQ demodulation. Th group delay is compared to the corresponding delay calculated directly from the position of the reflection layer. The meean position and movement are accurately reconstructed.

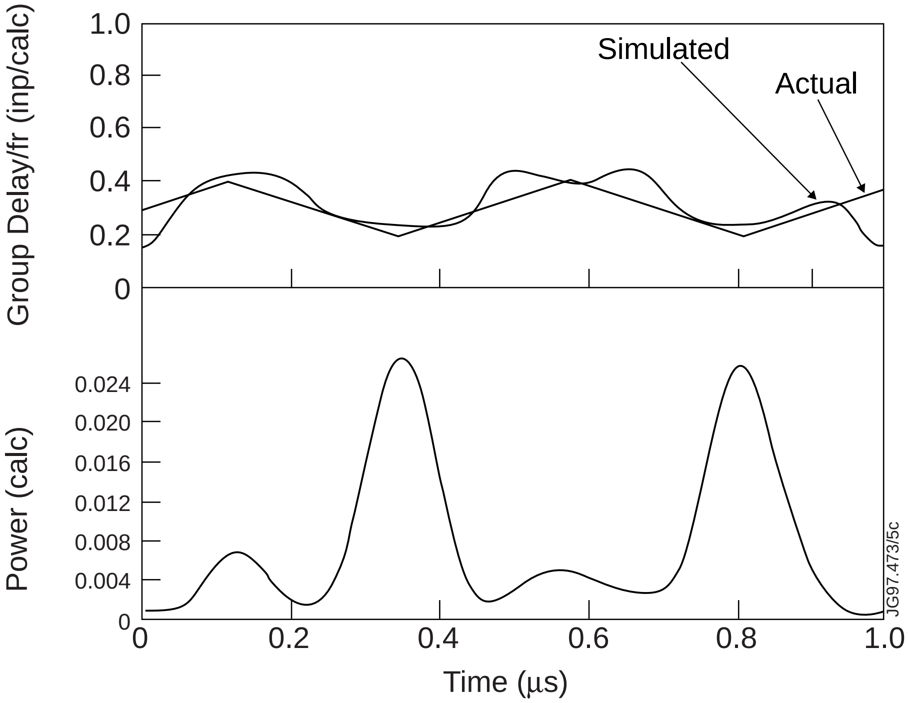

Figure 5. As figure 4, but with a spurious reflection of 10% of the launched power. The movement of the reflection layer is distorted, but the mean position is not affected; the power of the detected signal is strongly modulated.

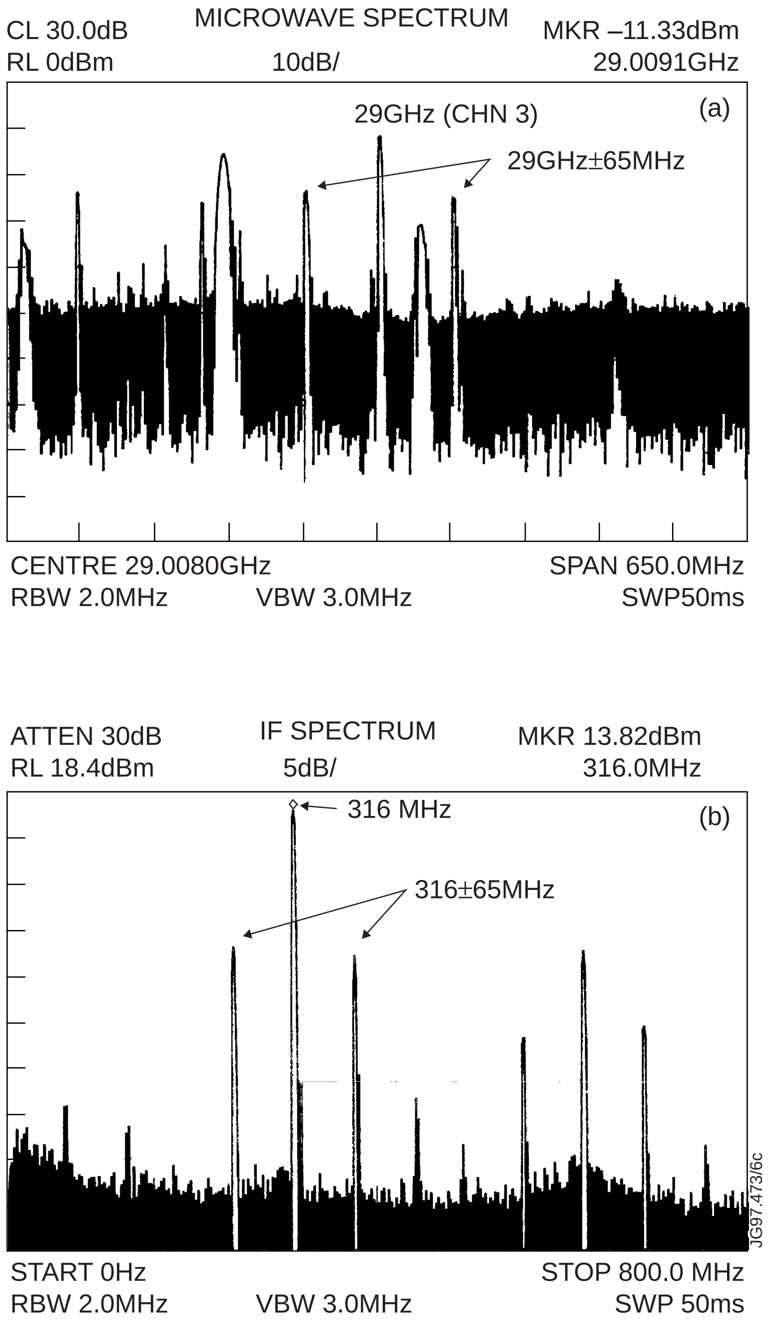

Figure 6. Power spectra of (a) launched micrrowave from channel 3, centred at 29.0GHz; and (b) down-converted IF signal centred at 316MHz. The two sidebands arising from the frequency modulation are separarted from the carrier by the modulating frequency of 65MHz. (The wider peaks in the microwave spectrum correspond to spuripus mixing products) .

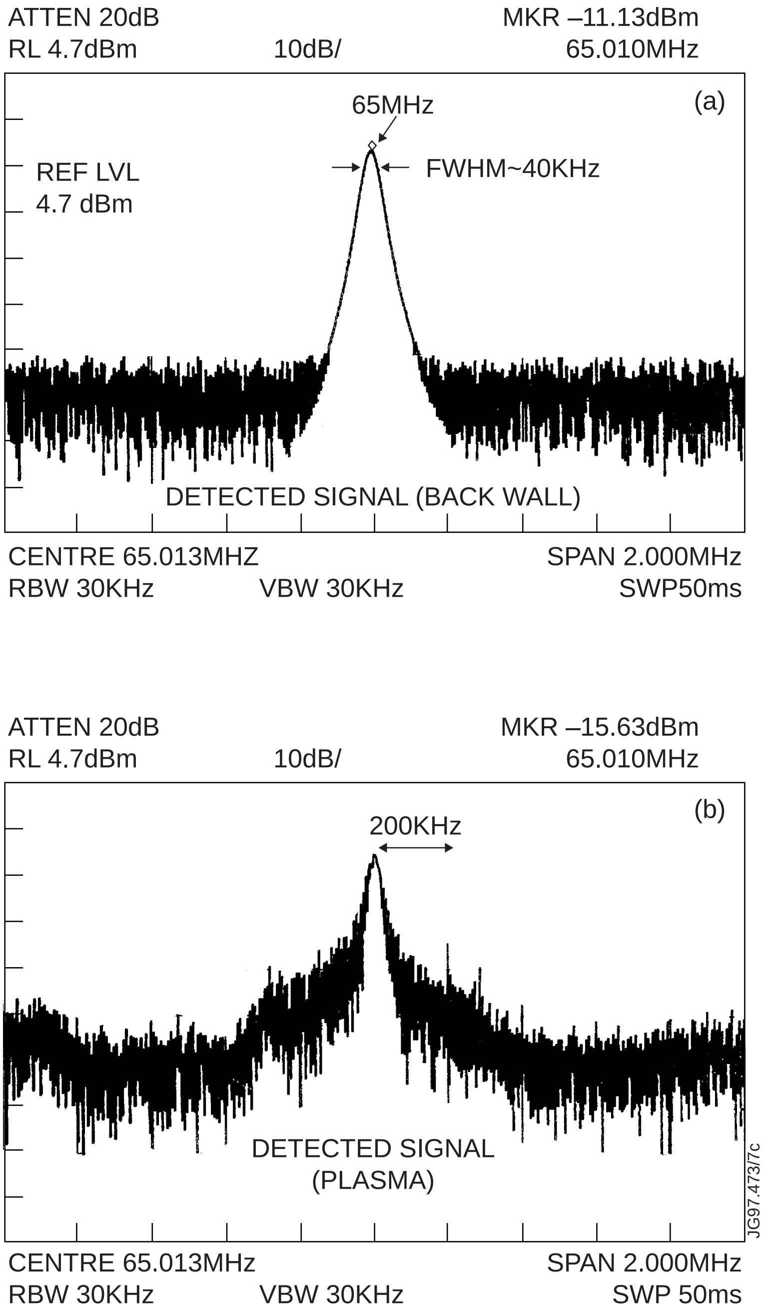

Figure 7. Power spectra of recovered modulating signal at 65MHz, obtained (a) without plasma (back wall reflection), and (b) with plasma.

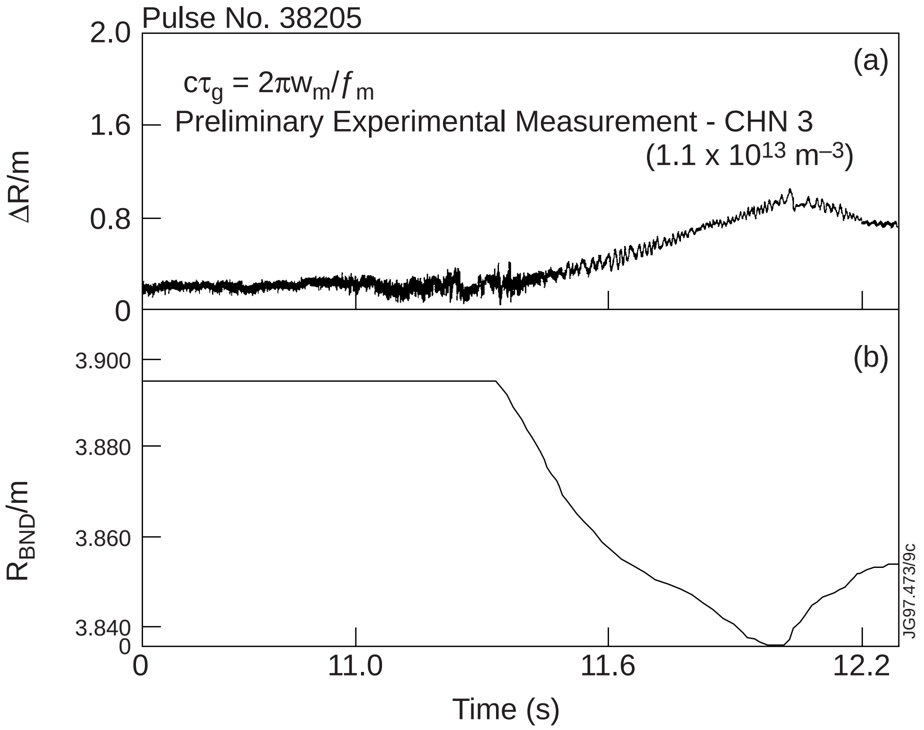

Figure 8. (a) Equivalent vacuum displacement of reflection layer corresponding to channel 3 (29.0GHz), as obtained from the measured phase of the recovered modulating signal (b) Corresponding movement of plasma boundary from magnetic data.