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**RESEARCH PROPOSAL ON:
AMPLITUDE MODULATED REFLECTOMETRY
SYSTEM FOR THE JET DIVERTOR**

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Introduction

The reflection of microwave beams at the cutoff layer of fusion plasmas requires operation with microwaves in the millimeter range.

The usual dimension of the plasma leads to the measurement of the phase delay which the reflected beam undergoes as compared to a reference beam. Time delay measurements are not usual so far.

The relevant magnitude in density profile measurements is the differential phase shift: $d\phi/df$, typically larger than 2π . Also, the movements of the reflecting layer (due to density fluctuations) can produce fast phase oscillations larger than 2π .

As it is typical in multiradian phase measurements, the phase must be coherently tracked during the experiment to keep memory of the number of fringes. Any temporary loss of information will make impossible further tracking of the phase value (lost fringes).

This situation appears very often in microwave reflectometers: the amplitude of the reflected signal shows strong oscillations (probably due to macroscopic deviations of the beam caused by refraction) which bring the signal down to the noise level for short periods of time.

In the other hand, reduction of the phase shifts by the use of larger wavelengths is not possible in the reflectometer experiment: large wavelengths produce poor spatial resolution and, in any case, the wavelength is directly dependent on the critical density.

AM reflectometry

Amplitude Modulated reflectometry is to some extension an intermediate solution between the classical phase delay reflectometry, so far applied to small distances, and the time domain reflectometry, used for ionospheric studies and recently also proposed for fusion plasmas.

If a wave with periodical amplitude modulation is launched to the plasma, the delay time of the returning reflected beam can be easily evaluated as the phase delay of the modulation signal.

With a typical modulation frequency of 50 MHz, the 'vacuum wavelength' of the modulation signal will be 6m, then we will expect moderate phase shifts ($<2\pi$) for the usual dimensions and density gradients in plasma devices (even JET-ITER). In the other

hand the carrier can have the suitable frequency (10-200 GHz) for reflection in the plasma. The modulation frequency can be adjusted to the particular plasma dimensions.

Fundamentals

First AM experiments in reflectometry have been reported from T-10 tokamak¹ (Vershkov and Zhuravlev). The authors operated a single channel reflectometer and were able to measure the time delay of the AM signal, the interpretation of the results is not clear, since the dispersion effects, mainly depending on the local value of the density gradient where not explicitly considered.

It must be noted that the delay time of the pulse cannot be directly used for location of the reflecting layer: the AM wave is not a monochromatic beam, and since we are measuring the delay on the modulating signal, the relevant speed is the group velocity .

The resulting delay time will be quite different from that estimated by using the speed of light and the refraction index at the carrier frequency.

If a sinusoidally modulated wave is launched and reflected at the plasma, the group delay can be evaluated by analysis of the behavior of its spectral components: after some straightforward calculations we can conclude that the time delay τ_p of the modulation in the reflected signal is:

$$\tau_p = \frac{1}{2\pi} \frac{d\phi}{df} \quad [1]$$

Where ϕ is the phase delay for a given frequency f of the microwave beam. $d\phi/df$ is the relevant magnitude for the reconstruction of the density profile and is dependent on the profile shape and the distance plasma-reference plane.

The measurement of τ_p can be easily performed by phase comparison between the incoming and outgoing modulation envelopes. If τ_p is determined for a set of frequencies covering the plasma radius, the density profile can be reconstructed.

Experimental system

A generic diagram of an AM reflectometer is shown on fig. 1. The mm wave signal is modulated at approx: 50 MHz and launched to the plasma. The reflected signal is received by a second antenna. The detector diode provides the modulating 50 MHz signal, which is amplified and phase compared with the original one at the phase meter. In that case the zero phase level should be taken before the plasma start up by reflection at the opposed wall of the vacuum vessel.

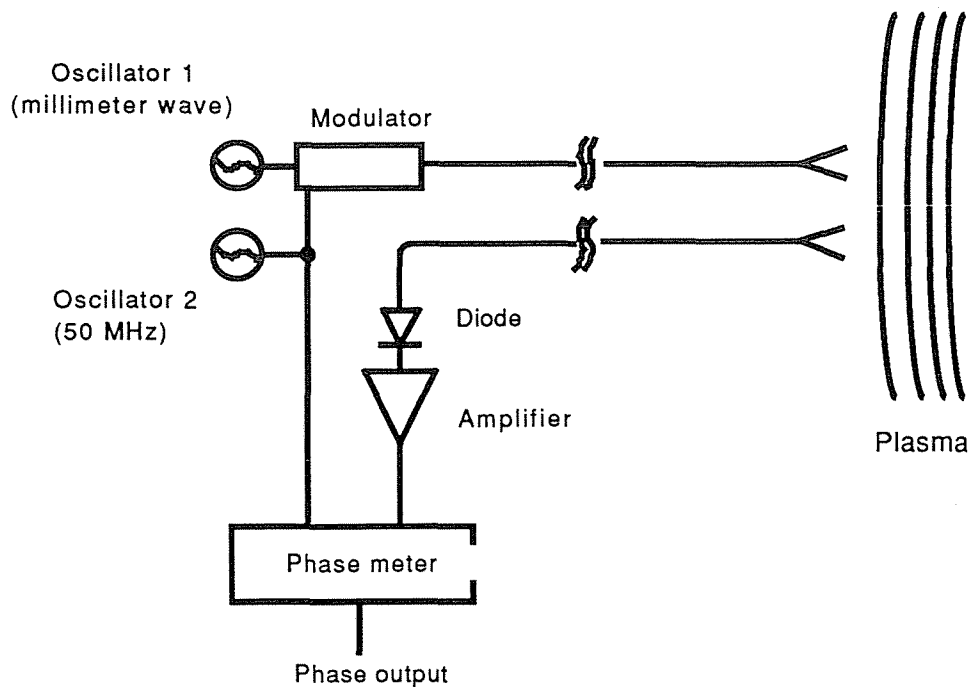


Fig. 1.- Schematic block diagram of the AM reflectometer

This simple block diagram can be expanded in different directions: heterodyne detection for higher dynamic range, comparison of the modulating phase after the modulator with that of the reflected signal at the plasma, use of several down conversion steps for lower frequency phase meters...etc. In principle both X and O mode polarizations can be used.

The system can operate in a wide range of frequencies. Since the required modulation amplitude (< 50 %) and frequency (< 50 MHz) are not high, operation over a whole microwave band could be possible with a single modulator.

The simplest modulator would be a PIN diode, they are commercially available with 1ns switching time (10%-90%) for all microwave bands up to 110 GHz (5 GHz bandwidth for the W-band). State of the art modulators will probably provide those characteristics for the higher frequencies.

The accuracy on the phase determination can be very high even in noisy environment, due to the fact that a sample of the phase delay is taken every 20ns (for 50 MHz modulation). In any case when going to a detailed design of the system the modulation frequency and amplitude can be selected to suit the accuracy requirements.

Application to JET Divertor

The expected densities for the JET divertor show a broad range of values, a very simple simulation was considered with:

Profile : parabolic-like : $n(r) = n_0 (1 - (r/a)^\alpha)^\beta$
 $n_0 < 2 \times 10^{20} \text{ m}^{-3}$
 Radius: $a = .25 \text{ m}$
 $B = 3.4 \text{ T}$ (flat for simplicity)

The relevant frequencies would lie in the ranges:

- 0 - 130 GHz O-mode
- 95-180 GHz E-mode (upper cutoff)
- 0 - 90 GHz E-mode (lower cutoff)

The O-mode will be probably the most suitable , although the E-mode can overcome the negative density gradients if the magnetic field decreases with the radius.

Fig.2 shows the differential phase delay for AM beams at different frequencies reflecting along the density profile, the delay phases are in the range of 2π , from those data the reconstruction of the density profile is a well established technique.

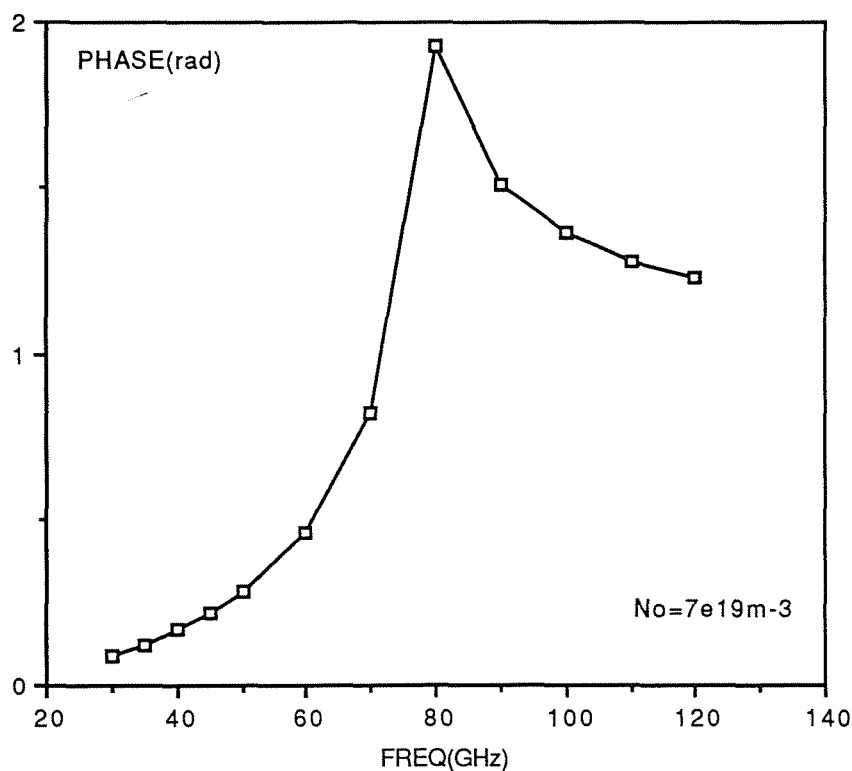


Fig.2 .- Differential phase delay for the different launched frequencies reflecting in a parabolic density profile. The modulation frequency is 50 MHz (2π differential phase delay corresponds to 20ns time delay). The frequencies reflecting at the plasma (< 80 GHz) can be easily distinguished from those reflecting at the opposed wall.

The evolution of the differential phase delay, also for different frequencies, when the central density increases is shown on fig.3. The main goal of this figure is to show the expected phase delays and also to compare the performance with the originally proposed comb reflectometer for determination of the peak density (ref), the cutoff density for each incident frequency is clearly marked by the spike on the time delay when the microwave beam switches from reflection at the opposed wall (.5 m distance) to reflection at the plasma. This effect could be used as a faster indication of the density values in addition to the standard density profile reconstruction.

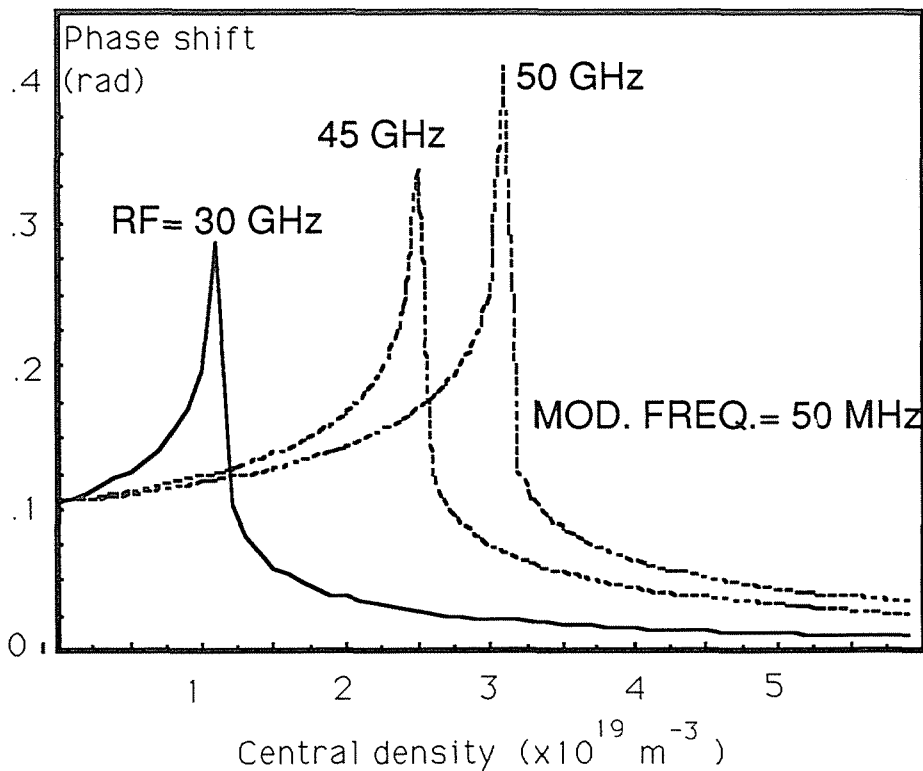


Fig.3.- Differential phase delay as a function of the central density for a parabolic profile, at different incident frequencies. The spike on the phase shift shows the cutoff density. Differential phase delay is equivalent to the time delay (2π differential phase delay corresponds to 20ns time delay for 50 MHz AM)

Discussion on the limitations of the method

A very important consideration on AM or pulse radar reflectometry is the evaluation of the possible deformation of the modulating pulse and the effect on the delay time measurement. Deformation of the pulse can arise mainly due to two effects: higher order derivatives of $\phi(f)$ and non uniform amplitude losses for the different frequency components of the pulse:

Effect of higher order derivatives:

The spectrum of a wave with sinusoidal amplitude modulation (fig.3) shows a central line and two satellite bands:

$$E \propto \sin \omega t (1 + a \cos \Omega t) \quad [2]$$

which can be written as:

$$E \propto \sin \omega t + a/2 \sin (\omega + \Omega)t + a/2 \sin (\omega - \Omega)t \quad [3]$$

after reflection at the plasma :

$$E \propto \sin (\omega t + \varphi_0) + a/2 \sin [(\omega + \Omega)t + \varphi] + a/2 \sin [(\omega - \Omega)t + \varphi'] \quad [4]$$

If we write :

$$\varphi = \varphi_0 + \Delta \quad [5]$$

$$\varphi' = \varphi_0 - \Delta' \quad [6]$$

the pulse shape is conserved if :

$$\Delta \approx \Delta' \quad [7]$$

(difference phase delay between the central frequency and the satellite bands).

$$E \propto \sin(\omega t + \varphi_0) [1 + a \cos(\Omega t + \Delta)] \quad [8]$$

now the phase delay of the modulation is Δ and the time delay:

$$\tau_p = \Delta / \Omega \quad [9]$$

which is consistent with [1]

The condition [7] can be expressed in the form:

$$(\Delta - \Delta')/\Delta \ll \Delta \quad [10]$$

which is equivalent to:

$$\frac{\partial \phi}{\partial f} \gg df \cdot \frac{\partial^2 \phi}{\partial f^2} \quad [11]$$

Due to the small df used (50 MHz) the condition [11] can be easily fulfilled for different density profiles and at the different radial positions (see Table I, II), thus no significant influence on the time delay measurements is expected due to this effect.

	Freq (GHz)	r/a (cutoff)	$\partial\phi/\partial f$ (rad/GHz)	$df (\partial^2\phi/\partial f^2)$ (rad/GHz)
$n_o = 10^{20} \text{ m}^{-3}$	30	0.94	1.22	5.82×10^{-3}
	60	0.74	5.69	1.72×10^{-2}
	80	0.45	13.3	1.83×10^{-2}
$n_o = 7 \times 10^{19} \text{ m}^{-3}$	30	0.92	1.80	2.76×10^{-3}
	50	0.74	5.61	3.12×10^{-3}
	70	0.36	16.4	1.28×10^{-2}

TABLE I
The effect of second order derivatives for different incident frequencies in the plasma.
Parabolic density profile

	Freq (GHz)	r/a (cutoff)	$\partial\phi/\partial f$ (rad/GHz)	$df (\partial^2\phi/\partial f^2)$ (rad/GHz ²)
$n_o = 10^{20} \text{ m}^{-3}$	30	0.9	1.67	8.58×10^{-4}
	60	0.75	4.53	6.72×10^{-3}
	80	0.57	9.44	4.27×10^{-2}
$n_o = 7 \times 10^{19} \text{ m}^{-3}$	30	0.88	2.10	1.46×10^{-2}
	50	0.76	4.5	4.28×10^{-3}
	70	0.51	11.8	2.82×10^{-2}

TABLE II

The effect of second order derivatives for different incident frequencies in the plasma. Density profile $n(r) = n_o (1 - (r/a)^\alpha)^\beta$, $\alpha = 4$, $\beta = 2$, $n_o = 10^{20} \text{ m}^{-3}$

Effect of non uniform losses for the different frequency components :

If one of the spectral components of the launched pulse suffers a larger fraction of losses than the others, the pulse width increases and the determination of the time delay could be incorrect. This can happen either due to the non uniform refraction in the plasma or due to the non uniform transmission of the long and complicated waveguide systems which are necessary in the large thermonuclear devices.

As in the previous case, the use of narrowband modulation minimizes the problem. In the particular case of sinusoidal AM the spectra deformation will not be dangerous provided the amplitude in the central line is always dominant (this can be guaranteed by a moderate degree of modulation - 50%-), even a complete suppression of one of the satellite bands could be overcome, in that case the pulse becomes broader but the maxima and minima keep the right phase.

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"Propuesta de investigación: reflectometría de amplitud modulada para el divertor del JET".

SANCHEZ, J.; BRAÑAS, B.; ESTRADA, T.; LUNA DE LA, E. (1992) 9 pp.; 3 figs.; 2 refs.

Uno de los problemas fundamentales que se han presentado en los últimos años en reflectometría es la necesidad de llevar un seguimiento coherente del retraso de fase: las fluctuaciones rápidas de densidad en el plasma y las fuertes variaciones que se producen en el nivel de señal reflejada dan lugar a 'saltos de franja' en la señal de fase, que constituyen un severo problema cuando estamos trabajando con desviaciones de fase mayores que 2π .

Las condiciones en el divertor del JET: geometría del plasma, acceso y largos caminos de guía sobre dimensionada hacen muy difícil las medidas de fase en el rango de onda milimétrica. La Reflectometría por Modulación de Amplitud constituye una solución intermedia entre la clásica técnica de medida de fase, aplicada a pequeñas distancias, y la reflectometría en el dominio

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del tiempo, usada para medidas en la ionosfera y recientemente propuesta para plasmas de fusion. Su principal ventaja viene dada por el hecho de que permite el uso de ondas milimetricas con retrasos de fase moderados ($\approx 2\pi$).

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Amplitude Modulated reflectometry is presented here as a tool for density profile measurements in the JET divertor plasmas.

One of the main problems which has been present in most reflectometers during the last years is the need for a coherent tracking of the phase delay: fast density fluctuations and strong modulation on the amplitude of the reflected signal usually bring to 'fringe jumps' in the phase signal, which are a big problem when the phase values are much larger than 2π .

The conditions in the JET divertor plasmas: plasma geometry, access and long oversized broadband waveguide paths makes very difficult the phase measurements at the millimeter wave range.

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