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A TWO-WAVE LENGTH HeNe LASER INTERFEROMETER

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E. H. A. Granneman*

ABSTRACT

This paper presents an interferometer set-up in which two wavelengths are used simultaneously. This enables one to determine separately the phase shifts caused by changes in plasma density and by mechanical vibrations of the interferometer structure.

1. *The BETA II Interferometer:*

At present the plasma density in the BETA II field reserved plasma ring is measured by means of a HeNe laser interferometer operating at a wavelength of 0.6328 μm. This system consists of the usual combination of a test leg going through the plasma and a reference leg outside the plasma (see figure 1). The system is double pass, which enhances the sensitivity by a factor of two. By giving the reference and test legs the same length, the spot size of both beams at the point of recombination is the same. The horizontal and vertical dimensions are roughly 3.0 and 2.5 m, respectively. The laser and all the optical components are mounted inside a rigid, closed structure made of an epoxy fiberglass laminated sheet (G-10). This structure is connected to the machine through a number of vibrationally isolated mounts placed underneath the horizontal bar of the system.

The fringe pattern registered by the detectors is made up of two components. The first is a slowly varying one caused by vibrations present in the interferometer structure, the most important one being the bending motion of the two legs (4-7 Hz). The second contribution to the phase shift, of course, is that caused by density variations in the plasma. The slow phase shift variations, i.e. those generated by pass length changes are fed into a feed back system driving a speaker carrying the reference leg retroreflecting mirror. In that way the optical path length can be kept constant, independent of mechanical vibrations in the system. The speaker can be driven such that

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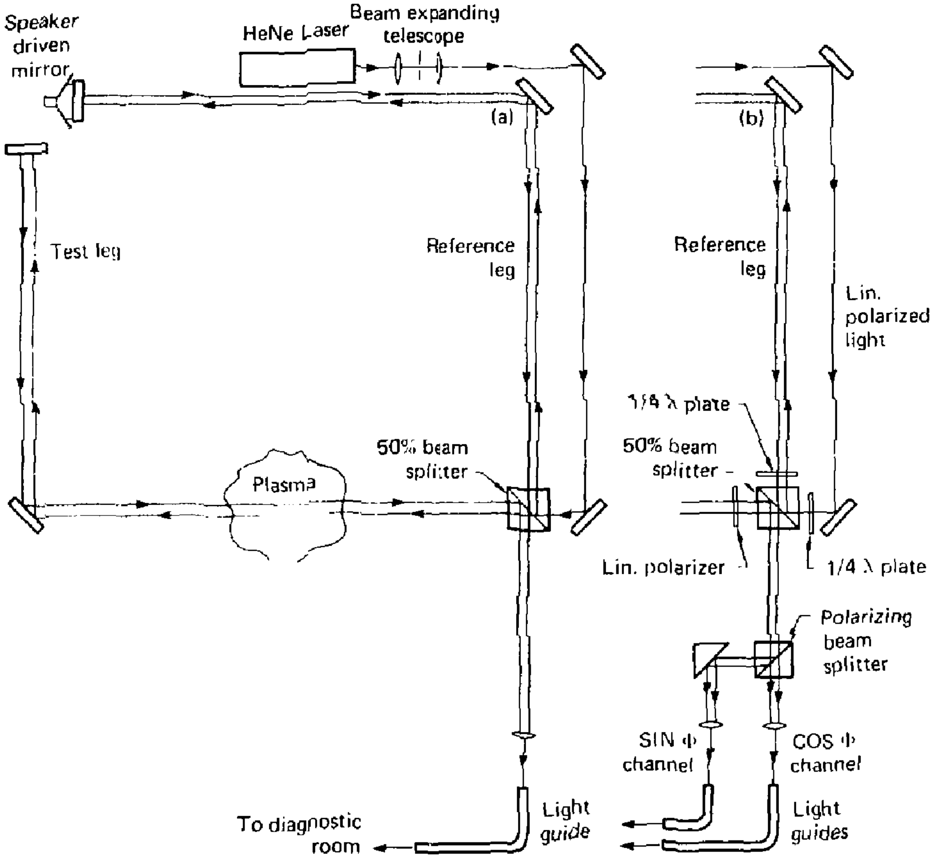


FIG. 1. The (one-wavelength) interferometer as used on the BETA II experiment. (a) One channel system; (b) quadrature system (sin Φ, cos Φ).

for slow variations, a constant phase difference of $\pi/2$ is maintained between reference and test beams. Hence the sensitivity ($\equiv$ signal variation per unit density change) of the system is maximum at the moment of plasma injection. This is advantageous when the system is operated in a single channel mode (at low enough densities, see next paragraphs).

Phase shifts of the order of 5×10^{-2} fringe can easily be detected; depending on the experimental parameters, maximum phase shifts corresponding with 0.2 - 1.5 fringes are commonly measured. Since ambiguities in the interpretation of the signals arise once the phase shift (Φ) exceeds a quarter of a fringe, two detection channels are in use registrating signals proportional to sin ϕ and cos ϕ, respectively (for details, see 1) .

Since in the present experiment plasma is present during approximately 400 - 800 μsec, whereas, the mechanical vibrations cause phase shifts of the order of 0.05 fringe/ msec, it is possible to correct for this latter contribution by measuring the "background" phase before and after the shot and interpolate during the shot. However, in the next stage of field reversed plasma ring experiments neutral beam heating of the compact torus is planned. This extends the lifetime of the plasma to possibly the 10 - 20 msec range. It is clear that the "background" phase shift caused by mechanical vibrations can no longer be determined through a simple interpolation procedure but has to be measured in some way. This can be done by means of an interferometer operating at two different wavelengths. Baker and Lee[2] have described such a system for the Doublet III tokamak; they use two different lasers, a HeNe laser (0.6328 μm) and a CO_2 laser (10.6 μm). The set-up described in this paper uses two wavelengths emitted by one (HeNe) laser. Also the optical lay-out is markedly different.

2. The Two-Wavelength Interferometer:

In case of a single pass interferometer the phase variation $\Delta\phi_p$ caused by a change in plasma densitiy is given by:

$$\Delta\phi_p = \frac{e^2\lambda}{4\pi\varepsilon_0 \, mc^2} \int n_e \, dl$$

in which e and m are the electron charge and mass, respectively. c is the speed of light, λ the laser wavelength and ε_0 the permittivity of the space. $\int n_e \, dl$ is the electron density (n_e) integrated along the line of sight.

If we write $N_L = n_e \, dl \; (m^{-2})$ for the single pass line density then for a double pass interferometer:

$$\Delta\Phi_p = 5.62 \times 10^{-15} \lambda N_L = \alpha\lambda N_L \tag{1}$$

The phase variation $\Delta\Phi_m$ caused by a relative mechanical displacement Δx between reference and test leg can be written as:

$$\Delta\Phi_m = \frac{2\pi\cdot\Delta x}{\lambda} \tag{2}$$

Since for different wavelengths, $\Delta\Phi_p$ and $\Delta\Phi_m$ are different functions of N_L and Δx an interferometer operating at two different wavelengths simultaneously makes it possible to determine $\Delta\Phi_p$ and $\Delta\Phi_m$ separately. If we call the total phase shift $\Delta\Phi_t$ we can compute $\Delta\Phi_{t1}$, and $\Delta\Phi_{t2}$ for two different wavelengths λ_1, and λ_2, respectively.

$$\Delta\Phi_{t1} = \Delta\Phi_{p1} + \Delta\Phi_{m1} = \alpha\lambda_1 N_L + \frac{2\pi\cdot\Delta x}{\lambda_1}$$

$$\Delta\Phi_{t2} = \Delta\Phi_{p2} + \Delta\Phi_{m2} = \alpha\lambda_2 N_L + \frac{2\pi\cdot\Delta x}{\lambda_2}$$

$\Delta\Phi_{t1}$ and $\Delta\Phi_{t2}$ are the experimentally determined quantities; N_L and Δx can be deduced according to:

$$N_L = \frac{\Delta\Phi_{t1}\cdot\lambda_1 - \Delta\Phi_{t2}\cdot\lambda_2}{\alpha \quad \lambda_1^2 - \lambda_2^2} \tag{3}$$

$$\Delta x = \frac{\Delta\Phi_{t1}\cdot\lambda_2 - \Delta\Phi_{t2}\cdot\lambda_1}{2\pi \quad \lambda_2/\lambda_1 - \lambda_1/\lambda_2} \tag{4}$$

A good candidate for a laser supplying two wavelengths simultaneously is the HeNe laser. It emits the following three wavelengths: 0.6328 μm, 1.152 μm and 3.391 μm. A HeNe laser with powers ≳10mW and optics optimized for the red line (0.6328 μm) will emit approximately 20% of the total power in the two other lines. One with optics optimized for one of the infrared lines usually has 30% of the power in the other IR line.[3] In principle it is possible to order laser output optics such that approximately equal powers in the desired lines are emitted. The total power required for convenient operation depends strongly on the total number of optical components present in the system. A

15mW (linearly polarized) HeNe laser probably is sufficient for most applications.

In case the combined effect of $\Delta\Phi_p$ and $\Delta\Phi_m$ is such that for neither of the two wavelengths the fringe limit is reached during the shot ($\Delta\Phi_{t1,2} < \pi/2$) the interpretation of the signal is always unambiguous and a system like the one shown in figure 2^a suffices. However, generally this will not be the case and a quadrature system for at least one-wavelength and probably for both wavelengths is necessary. A quadrature system for one of the two wavelengths is easy to accomodate (figure 2^b); it is essentially the same as that for a one-wavelength system (figure 1^b). The laser light has to be linearly polarized; the $1/4\lambda$ plate converts this into circularly polarized light. The linear polarizer in the plasma leg makes the light linearly polarized again (at a loss of a factor of two in intensity). The polarizing beam splitter, which ideally should be placed at an angle of 45^o with respect to the polarization vector of the linearly polarized beam now yields two beams with fringe patterns $\pi/2$ out of phase.

Since the mirrors, beam splitters and windows introduce additional, spurious, phase shifts, a correction wave plate is usually necessary to tune this phase difference to exactly $\pi/2$. (For instance a $1/4\lambda$ plate above the 50% beam splitter has shown to be sufficient; alternately one can place a $1/2\lambda$ plate adjacent to the $1/4\lambda$ plate located in the incoming beam.[4]) The orientation of the optical axis of these correction plates with respect to the light polarization direction has to be determined experimentally.

To make a quadrature system for both wavelengths is obviously more complicated. Some of the optical components can be choosen such that the required function is independent of wavelength. E.g. for the linear polarizers and the polarizing beam splitters Glan-Thompson or similar type prisms can be used.[5] Useful optical elements to consider are Magnesium Fluoride or Lithium Niobate Rochon (or Wollaston) polarizing beam splitters since these in principle split the beam directly into the four desired components.[5] Note further that by ordering a $1/4\lambda$ plate for 3.164 μm one obtains an exact $1/4\lambda$ plate for 0.6328 μm ($\equiv 5/4\lambda$) and one for 3.391 μm within 7%.

The spurious phase shifts caused by mirrors, beam splitters and other optical components being different for both wavelengths, one probably wants to utilize two correction wave plates at least one of which influences one wavelength exclusively. It might therefore be necessary to split the beam up

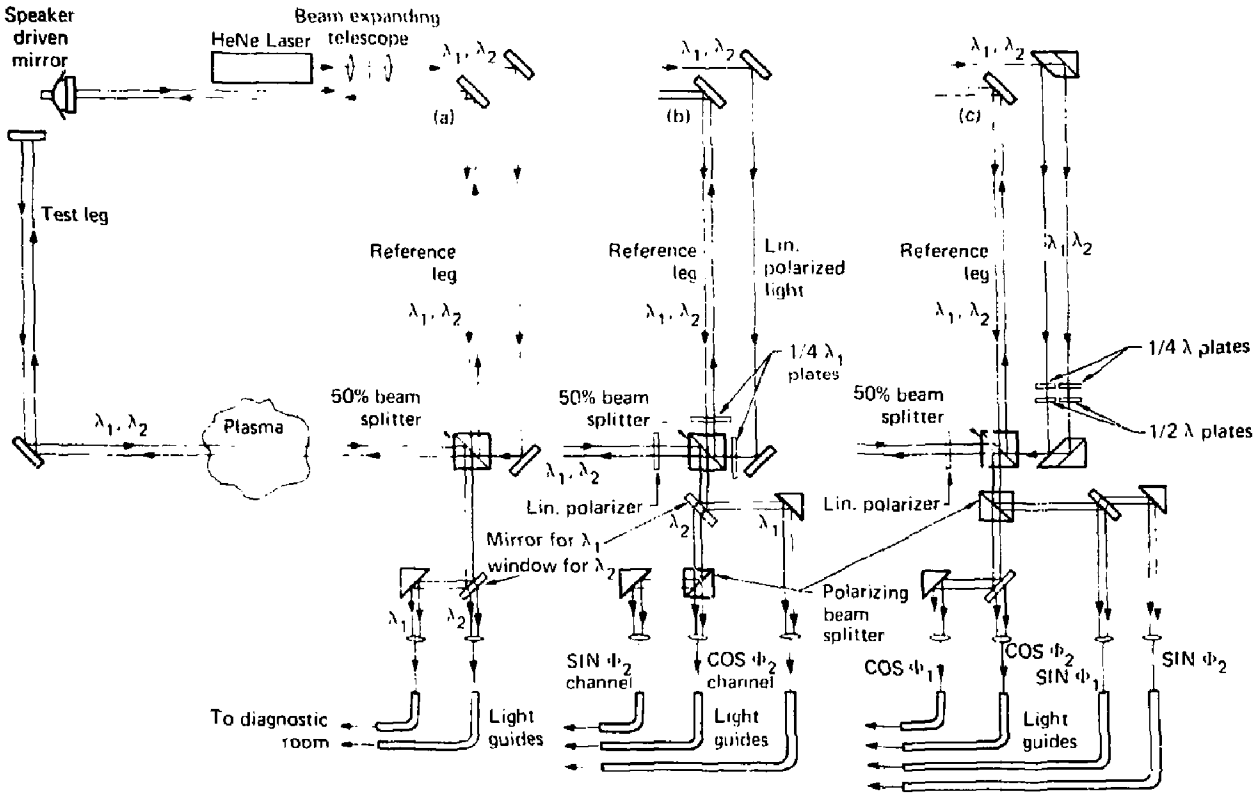


FIG. 2. The proposed two-wavelength interferometer. (a) A single channel system for both wavelengths; (b) a quadrature system is applied for one wavelength; (c) a quadrature system for both wavelengths.

locally (see figure 2[c]). It should be noted that the phase difference between the two fringe patterns (at one wavelength) does not have to be exactly $\pi/2$ to remove the ambiguity in the interpretation. Any phase difference suffices in principle; however, only a $\pi/2$ phase shift yields a simple mathematical relation between the phase Φ_t and the two recorded signals V_{sin} and V_{cos}: $\Phi_t = \arctan (V_{sin}/V_{cos})$.

The following numbers give an idea about the magnitude of the various phase shifts involved: At the wavelengths 0.6328, 1.152 and 3.391 μm a full fringe (2π) phase shift is obtained for plasma line densities (n_e dl) equal to: 1.76×10^{17}, 9.67×10^{16} and 3.28×10^{16} cm^{-2}, respectively. Figure 3 shows phase variations caused by mechanical vibrations of the legs of the existing BETA II interferometer. Figure 3[a] was recorded when the interferometer was mounted on two rubber blocks which were placed on the wooden structure surrounding the experiment. In figure 3[b] the interferometer was placed on an optical table which was vibrationally isolated from the wooden structure through four NRC "air cushion" mounts.[6]

Finally figure 4 gives examples of "experimental" signals obtained for characteristic plasma densities and mechanical motion. The plasma line density is assumed to increase linearly during 10 μs to maximum values of 10^{16} and 10^{17} cm^{-2}. After that it decays exponentially with a time constant of 10 ms. As typical mechanical motion a sinusoidal vibration with a

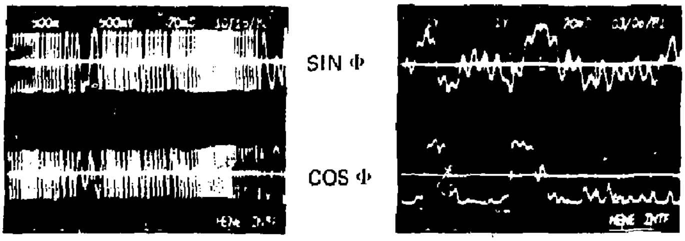


FIG. 3. The "background" fringe pattern caused by mechanical vibrations present in the interferometer structure. (a) The interferometer is mounted on two rubber blocks placed on the wooden support structure of the BETA II experiment; (b) the interferometer is mechanically isolated from the machine through four NRC vibration isolation mounts.

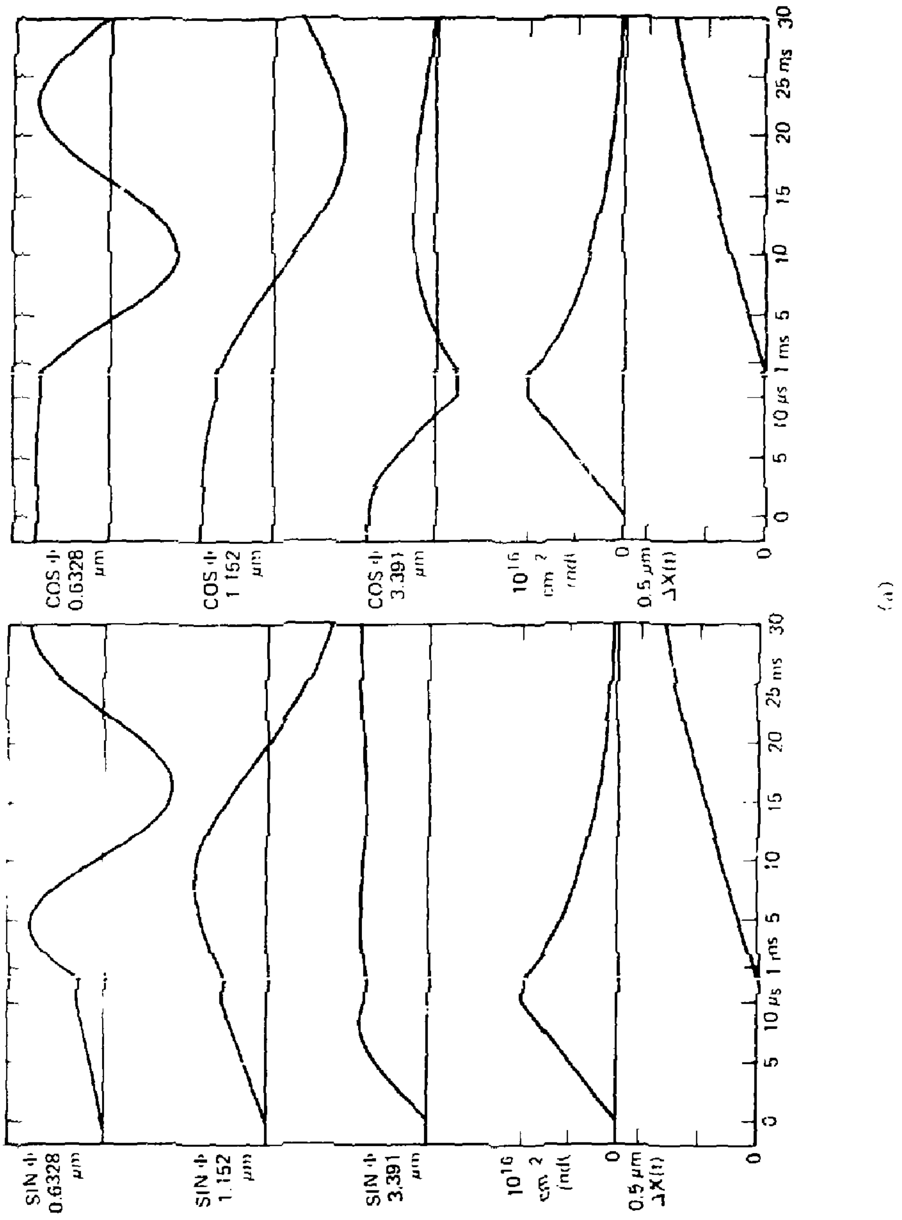
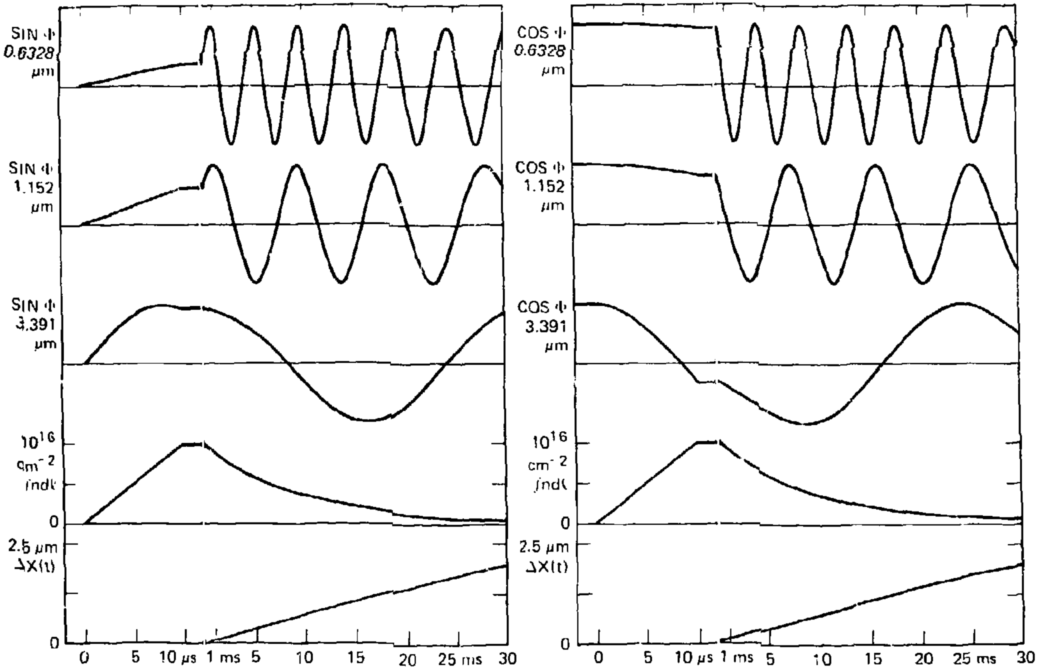


FIG. 4. Typical fringe patterns obtained for the three *HeNe* laser wavelengths for *a number of* characteristic cases. In all cases the plasma density increases linearly during 10 μs; after that it decays exponentially with a time constant of 10 ms. The mechanical vibration is assumed to be sinusoidal with *a frequency of 5 Hz*. *a*,b: Maximum density 10^{16} cm^{-3}; c,d: maximum density 10^{17} cm^{-3}; a,c: amplitude mechanical vibration 1 μm (peak-peak); b,d: amplitude mechanical vibration 5 μm (peak-peak).


SIN Φ 0.6328 μm
SIN Φ 1.152 μm
SIN Φ 3.391 μm
10^{16} cm^{-2} ∫ndℓ
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2.5 μm ΔX(t)
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5
10 μs
1 ms
5
10
15
20
25 ms
30
COS Φ 0.6328 μm
COS Φ 1.152 μm
COS Φ 3.391 μm
10^{16} cm^{-2} ∫ndℓ
0
2.5 μm ΔX(t)
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5
10
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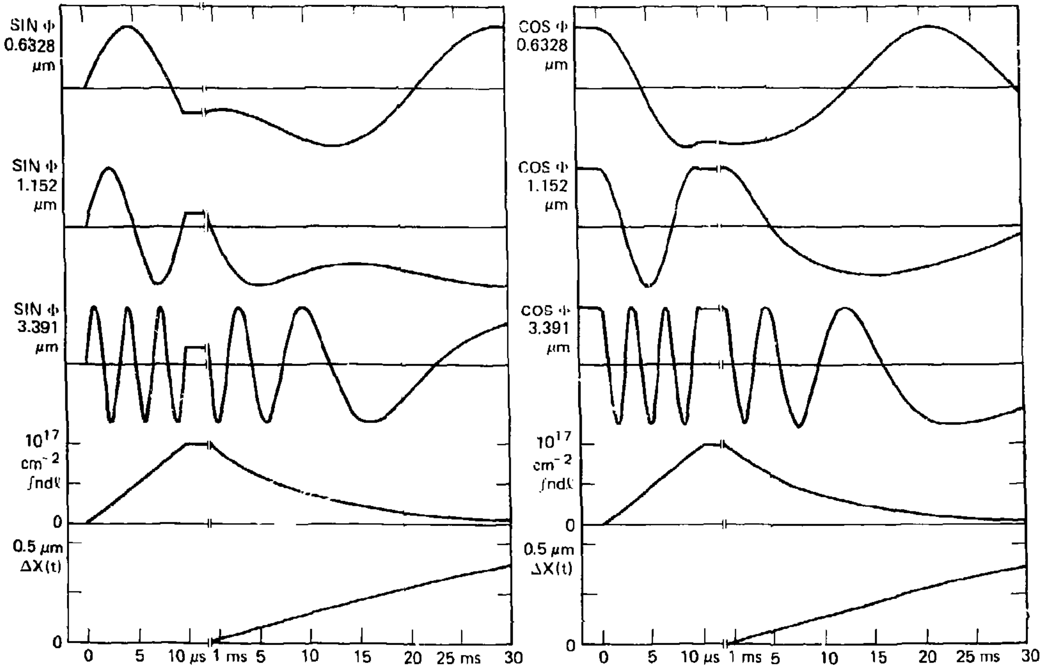
25 ms
30

(b)


SIN Φ
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COS Φ
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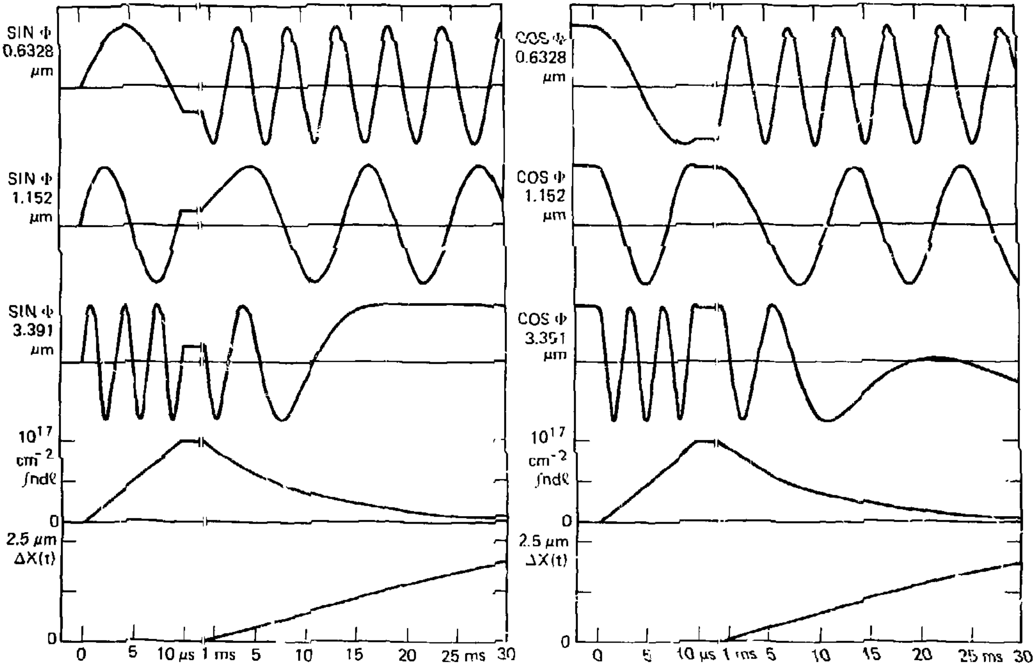
(c)


SIN Φ
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0
2.5 μm
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(d)

frequency of 5 Hz is assumed. It starts at t=0 and has maximum excursions of 1 and 5 μm. From these figures it is clear that the phase shifts induced by the plasma and by mechanical motion can be deduced from the total phase shifts measured at two different wavelengths.

3. References

1. Lawrence Livermore National Laboratory Mirror Fusion Quarterly report, July-September 1980, UCAR-10060-80-3, to be published.
2. D. R. Baker and S. T. Lee, Rev. Sci. Instr. 49, 919 (1978).
3. Spectra Physics, Mountain View, California, private communication.
4. C. J. Buchenauer and A. R. Jacobson, Rev. Sci. Instr. 48, 769 (1977).
5. Karl Lambrecht Co., Bulletin No. P-78 (Chicago, Ill., 1978).
6. Newport Research Co. 1980-81 Catalog (Fountain Valley, California).