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INTERFEROMETRIC MEASUREMENTS OF PLASMA DENSITY IN HIGH- β PLASMAS

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SUMMARY

In a plasma, the refractive index is primarily a function of electron density and this is the main plasma parameter determined by the various measurements of the phase changes induced in an electromagnetic wave, in the optical region, as a result of its traversal of the plasma. Two interferometry methods, holographic interferometry and coupled-cavity laser interferometry, for measuring the plasma electron density are discussed in this section. In the application of holography to plasma interferometry, the hologram enables one to store complete phase and amplitude information about a plane light wave passing through a plasma region. A laser beam is divided into a scene beam directed through the plasma and a reference beam passing outside the plasma. A double exposure, one without plasma and one with plasma in the scene beam, results in a holographic interferogram which can be reconstructed in white light. The resulting phase shift or fringe pattern corresponds to the integral of the plasma electron density over the path length through the plasma region.

The coupled-cavity laser interferometer technique is particularly applicable to the measurement of pulsed plasma densities. This technique is based on the fact that if a small fraction of a gas laser's output radiation is reflected into the laser with an external mirror, the intensity of the laser output is modulated. These amplitude or intensity modulations are produced by changes in the laser gain. A rotating corner mirror or an oscillating mirror can be used to produce a continuous feedback modulation of the interferometer which produces a continuous background fringe pattern. The presence of plasma in the outer cavity causes an additional change which results in a phase shift of the regular period of the background fringe pattern. The integral of the plasma density along the line of sight can be evaluated by comparison of the time history of the fringes obtained with and without plasma.

1. INTRODUCTION

The propagation of electromagnetic waves, whose frequencies are in the optical or near optical spectral band, through plasmas result in a weak interaction between the wave and the plasma which is manifested primarily in a slightly altered propagation velocity of the wave. The ratio of the phase velocity in vacuum to that in the plasma is called the refractive index. In a plasma, the refractive index is primarily a function of electron density and this is the main plasma parameter determined by the various measurements of the phase changes induced in a wavefront as a result of its traversal of the plasma. Jahoda and Sawyer[1] have reviewed the optical refractivity of plasmas and associated measurements of plasma parameters. Two applications of interferometry methods, holographic interferometry and coupled-cavity laser interferometry, to the measurement of the plasma electron density are discussed in this section. These methods are applicable to plasmas with density-path length products between 10^{15} and 10^{19} cm⁻².

2. HOLOGRAPHIC INTERFEROMETRY

The method of recording interferograms using double exposure holography is different in detail from a conventional Mach-Zehnder interferometer, but the final interferogram is identical in its appearance and interpretation. In holographic interferometry an overlay or double exposure of two very fine scale interferograms made sequentially produce a coarser fringe pattern, Moiré' beats, which delineate contours of constant phase change between the two exposures, e.g., with and without plasma. The details of each individual fine scale interferogram is not important, since only the constancy of the pattern, aside from the deliberate changes which are the object of the measurement, is required. The excellent coherence of laser sources, which produce the fine scale fringes of high order number, is the key ingredient in holographic interferometry.

2.1 Holography

A comprehensive treatment of holography has been given by Smith[2] and by Goodman[3]. A hologram exposure of an object results from a "scene" beam reaching the hologram plane (photographic plate) by reflection from the object and a reference beam which originates in the same source and reaches the hologram plane by a path that circumvents the object. The amplitudes of both beams are assumed constant, the phase of the scene beam is an unspecified function of position, while the phase of the reference beam is linearly proportional to the hologram coordinate. The greater the temporal and spatial coherence of the laser the less restrictive, respectively, the requirements on path equality of the two beams and on the accurate point-for-point overlay of the two wavefronts at the photographic plate. These are the same requirements as encountered in Mach-Zehnder interferometry. However, because the mean angle between the two beams is generally several degrees the fringe structure is very fine. This fine scale intensity modulation on the photographic plate produced by conventional interference results in the construction of a single hologram and is to be distinguished from the gross interference pattern due to the beating together of two similar holograms produced by two consecutive exposures which result in holographic interferograms.

The recorded photographic density is linearly proportional to the intensity for variations small compared to the constant background of the reference beam which is large relative to the scene beam. When the hologram is reconstructed by illuminating it with a

ne beam the transmitted amplitude is proportional to the original subject waveform deflected by a linear phase term of the form $e^{-i\alpha x}$, analogous to ordinary grating deflection to first order, in the direction θ . Thus an observer looking through the hologram toward the reconstruction beam sees a virtual image of the original scene angularly separated from the reconstruction direction. There is another term in the negative θ direction which duplicates the original subject phase distribution except for reversal in sign. This is equivalent to the original wavefront traveling with reversed sign in time and thereby converging to a real image in front of the plate. Since the absolute sign of the phase is of no concern, either the real or virtual reconstructions can be used according to convenience.

In practice a great deal of latitude in relative beam intensities and processing procedure is permissible, particularly in interferometric applications for which only the relative differences between two exposures are of primary interest. The most restrictive requirements in making a hologram are those on source coherence and detector resolution. For the former, even giant pulse ruby lasers without special mode selection are adequate if the reference and scene beams are kept equal in length to within a few centimeters, and if a small pinhole is used to improve spatial coherence. Since the pinhole decreases the energy density reaching the film plane it is often desirable to use a faster emulsion than the ultra-high resolution Kodak 649 emulsion often used in CW holography. A better speed with only a slight decrease in resolution is obtained from Agfa-Gevaert 8E75 and 10E75 plates.

2.2 Plasma Interferometry

The application of holography to interferometry of plasmas has been reviewed by Heflinger, Wuerker, and Brooks[4], by Jahoda and Sawyer[1], and by Jahoda and Siemon[5]. The refractive index of a fully ionized plasma is dominated by the electron refractivity,

$$n = (1 - \omega_p^2/\omega^2)^{1/2}, \quad (1)$$

where $\omega = 2\pi c/\lambda$ is the angular frequency of the illumination with wavelength λ , and $\omega_p = (4\pi n_e e^2/m)^{1/2}$ the plasma frequency, is given in terms of the electron mass m , and plasma electron density n_e . In an interferogram of a plasma for which $\omega_p/\omega \ll 1$, the fringe displacement in units of fringes, p , is given by

$$p = \frac{1}{\lambda} \int_0^L (n-1) dl = \frac{2.17 \times 10^{-22}}{\lambda} \int_0^L n_e dl, \quad (2)$$

where n_e is the electron density in cm^{-3} and dl is the element of path length through the plasma of length L in cm. Conventional or holographic interferometers using an expanded beam pulsed laser source thus give the line-integrated spatial electron density distribution with a time resolution determined by the laser pulse duration. The holographic method has the advantages of experimental simplicity and flexibility associated primarily with the comparisons of two wavefronts separated in time rather than space. The applicability of interferometry to various plasma regimes can be determined from eq. (2). Assuming that fringe

shifts between 0.1 and 30 fringes are detectable, at the ruby laser wavelength ($\lambda = 6943 \text{ \AA}$) this encompasses density-path length products between 3×10^{16} and $1 \times 10^{19} \text{ cm}^{-2}$.

If two sequential hologram exposures are made on the same photographic emulsion, the wavefront amplitude and phase structure of the scene beam from both is recorded. When the double exposure hologram is reconstructed, the wavefields of the two exposures are reproduced simultaneously. The reconstructions are coherent since they originate in a common source and two images will interfere with each other according to the phase differences between the two exposures. The result is analogous to a conventional interferogram. However, the wavefronts being compared originally existed at different times rather than, as in a conventional interferometer, existing simultaneously and requiring first a spatial separation and subsequent recombination. Since these wavefronts traverse a common path (aside from the difference purposely introduced between exposures, e.g., plasma) the experimental requirements are greatly simplified. In holographic interferometry there do not exist the needs of conventional interferometry for precise alignment to achieve recombination of the beams and for extremely high quality optical flats to prevent phase differences between the beams other than those one desires to measure in the plasma. Windows and transparent walls with curvature in the plasma vessel are often sufficient.

2.3 Background Fringe Pattern

The double exposure holographic interferogram described so far is actually the analog of the conventional interferometer adjusted for a uniform field, the case sometimes called the infinite fringe spacing. This adjustment is not generally desirable because it is not possible to detect phase disturbances small compared to a full fringe. Usually, the conventional interferometer is adjusted for a straight line fringe background by introducing a slight angle between the recombined beams with a small tilt of at least one mirror or beam splitter. In the holographic case the background fringes are easily produced by purposely making a linear phase change between exposures. This is readily done either with a hollow wedge inserted in the optical path of the scene beam whose filling gas is changed between exposures or by a mechanical motion of one mirror between exposures. The mirror tilting is easily accomplished in a reproducible and remote way by electrically heating a piece of nichrome wire arranged as a compression spring in the mirror mount. The background fringes also minimize spurious phase shifts introduced by relative motions between various components that have occurred during the time between the two exposures.

2.4 Diffuse Hologram

The method most nearly analogous to the diffuse reflection holography of opaque objects interposes a ground glass diffuser in the scene beam before it passes through the plasma as discussed by Jahoda et al., in references [1] and [5]. Each single diffuser point then illuminates, through the plasma, every point of the photographic plate. If the diffused light is weak relative to the collimated reference beam, the interference between different scattering points are of second order and the resulting fine scale interference structure can be thought of as an overlay of Fresnel zone plates, one for each independent scattering point of the diffuser. The resulting spatially jumbled exposure pattern on the photographic plate can then be unscrambled by reconstruction with collimated, monochromatic light, with each Fresnel zone plate acting as a lens having both real and virtual foci at fixed spatial

locations according to the effective center and scale length of the ring structure on the developed plates. Double exposure destroys the interference structure selectively for those locations where there is a phase change of an odd multiple of π between exposures, giving the equivalent of conventional fringes in the reconstructed image of the diffuser. If the geometry permits viewing at sufficiently different angles the diffuse holographic method allows some inference about the depth dimension. In this case it is essential to restrict the viewing angle for any given direction in the reconstruction to prevent complete smearing of fringes due to overlapping views.

In practice the range of directions over which a plasma can be viewed is often limited by the vessel and coil configuration to such an extent that it is preferred to give up the three-dimensional inference possibility in favor of the experimental advantages gained by placing the diffuser between the plasma and photographic plate. This arrangement allows the reconstruction to be done with relatively large solid angles without washing out the fringe structure and the proper scene beam exposure of the photographic plate can be achieved by selecting the distance between the diffuser and plate on the basis of the finite energy in the laser pulse and the reference beam intensity.

2.5 Image Hologram

By removing the diffuser in the scene beam entirely, the collimated laser beam projects the scene onto the photographic plate with a one-to-one correspondence between scene and plate. The fringes are not localized in space but appear on the hologram itself when it is viewed at glancing angle in incoherent non-monochromatic light. Again, two exposures are made, with and without plasma. This is similar to the old technique of overlaying two interferograms and observing the Moire' beats. In this case the dark fringes are just the Moire' beats produced where the fine scale grating of one exposure is out of phase with the grating structure of the other exposure.

The image hologram technique has several advantages. By removing the diffuser one eliminates the familiar speckle pattern associated with coherent light on a diffuse surface, and thereby significantly increases the spatial resolution when the Moire' fringe pattern becomes dense due to relatively large refractivity changes between exposures. The spatial coherence requirements on the laser source are further reduced since the scene and reference beams overlap on the recording plates such that corresponding regions recombine. Although an optical system is used for high quality, bright reconstruction, the fringe structure is localized on the photographic plate and can generally be seen at a glancing angle in ambient illumination rather than requiring a laser and locating the correct image plane in space.

A nondiffuse, image hologram arrangement, as used on the Scylla IV, 3-m θ -pinch by Siemon et al.[7], is shown schematically in Fig. 1. A ruby laser produces about 0.1 J in a 20-ns pulse in a TEM_{00} beam 2-mm in diameter. The most important component is a carefully selected ruby which is free of optical inhomogeneities. This helps the laser to meet the basic holography requirements of spatial and temporal coherence. The 2-mm pinhole aperture in the laser cavity increases the gain for lasing in the TEM_{00} mode relative to the gain for any higher mode because of diffraction. The spatial coherence, which is provided by the ruby quality and internal pinhole, appears to be more important than coherence length.

The beam splitter divides the laser beam into the scene and reference beams. Lenses L1 and L2 expand the scene beam to fill the discharge tube cross section. In addition to reflecting the scene beam onto the hologram plane, the 45° mirror is tilted by electrically heating a compressed nichrome resistance wire between the double holographic exposures to provide a very reproducible method of introducing background fringes. Lens L4 images plane A onto A', the photographic plate at the hologram plane. The purpose of Lens L4 is to minimize the effects of refraction due to plasma density gradients. Refractive bending effects of the plasma tend to degrade the fringes in the region of the plasma boundary. It is necessary to use care in selecting and arranging components to uniformly illuminate the plasma region and to relay the illumination to the hologram.

The reference beam is expanded by diffraction to about 1 cm when it reaches lens L3 where it is further expanded onto the hologram plane. The focal length of L3 and the optical arrangement of lenses and mirrors are chosen so that the overlapping scene beam and reference beam appear nearly the same on the hologram plane. A typical angular separation of the two beams arriving at the hologram is about 5°. The exposure for image holograms is usually best when the scene and reference beams are of equal intensity. For diffuse holograms it is best to make the ratio of reference to scene beam about 10:1. The total exposure for image holograms has a large range of over two orders of magnitude. Kodak neutral density filters are convenient to adjust the beam intensity.

2.6 Reconstruction

Diffuse holograms require monochromatic light for reconstruction. It is usually convenient to reconstruct with He-Ne laser light in which case the geometry is not necessarily the same in formation and reconstruction. The image location must be determined.

Image holograms can be reconstructed with white light. If the scene and reference beams were plane waves the hologram is a simple plane-ruled transmission grating. The procedure consists of imaging the hologram onto film using diffracted light for illumination.

2.7 Holographic Interferograms

The holographic interferogram provides a two-dimensional contour map of

$$N(x,y) = \int n_e(x,y,z) dz \quad , \quad (3)$$

where as in eq. (2) the contours are in units of fringes. The simplest derived quantity is the total number of electrons in the field of view obtained by integrating over the area. This number can be obtained with no knowledge of how n_e varies with z . End-on holographic interferometry has been used extensively on linear magnetic fusion devices such as the θ pinch to determine the time history of the plasma column particle inventory, peak density, radius, and, in conjunction with the excluded flux measurement, the plasma beta and total temperature. Figure 2 shows a typical near-peak field time interferogram and corresponding fringe shift or density profile of the Scylla IV-P, 5-m plasma column obtained with a 30-ns pulsed holographic ruby laser interferometer by McKenna et al.[8]. The entire 8.8-cm diameter of the discharge tube was illuminated by the interferometer laser light. The fringe pattern on each interferogram is digitized and reduced with a computer. Refractive bending of the

interferometer laser light: in the radial plasma density gradients can complicate the interpretation of the interferograms as discussed by Jahoda and Siemon[5]. In general the maximum effect due to refractive bending typically amounts to about 1.5 fringes.

The plasma particle containment time τ be obtained from analysis of a sequence of interferograms. The time history of the plasma column electron inventory, N_e , can be determined from the interferometric density profiles, $f(r)$,

$$N_e = 3.24 \times 10^{17} \int_0^b f(r) 2\pi r dr, \quad (4)$$

which is independent of z . Figure 3 shows the total electron inventory for the Scylla IV-P 5-m, θ -pinch plasma[8].

The plasma beta on axis, β_A , can be determined from the interferometric density profiles, $f(r)$, and the excluded flux radius[9], r_ϕ , by numerically integrating the exact equation

$$\pi r_\phi^2 = \int_0^b [1 - \sqrt{1 - [f(r)/p]\beta_A}] 2\pi r dr, \quad (5)$$

where b is the tube radius and p is the peak number of fringes. The peak plasma density, n_A , can be determined from the expression

$$n_A = 3.24 \times 10^{17} p/L \text{ (cm}^{-3}\text{)} \quad (6)$$

provided the path length L is known. With values determined for β_A and n_A , a total plasma temperature can be obtained from pressure balance

$$k (T_e + T_i) = \frac{B_{z0}^2}{8\pi} \frac{\beta_A}{n_A}. \quad (7)$$

3. COUPLED-CAVITY INTERFEROMETRY

Coupled-cavity interferometry is based on the discovery, by King and Steward[10], that if a fraction of a gas laser's output radiation is reflected back into the laser by an external mirror, the intensity of the laser output is modulated. These intensity or amplitude modulations are produced by changes in the laser gain which are dependent on the phase of the feedback light. The initial application of the coupled-cavity interferometer to plasma density measurements was by Ashby and Jephcott[11]. The application of coupled-cavity interferometry to plasma measurements has been reviewed by Jahoda and Sawyer[1].

3.1 Experimental Arrangement of Coupled-Cavity Interferometer for Plasma Applications

The gas laser interferometer arrangement with a rotating corner reflecting mirror, M_3 , is shown schematically in Fig. 4. The laser's output beam is passed through the plasma region to be measured and is reflected by mirror M_3 back through the plasma and into the laser. The amplitude modulation of the laser results due to an effective variable reflectivity of the

laser mirror M_2 . Both mirrors M_2 and M_3 reflect light into the laser cavity. Owing to the double pass of the light through the cavity, successive complete cycles of intensity variation, fringes, are produced as the length of the external cavity changes by one-half wavelength increments. When mirror M_3 is put into uniform motion toward or away from the laser, it produces a uniform frequency modulation of the laser output. This increases the sensitivity to plasma density variation by about an order of magnitude. When a plasma of length l is produced in the cavity, the refractivity of the electrons produces a phase shift in the uniform modulation of the laser output.

The fringe shift gives the integral of the plasma electron density, n_e , over the plasma path length L ,

$$\int n_e dl = 1.1 \times 10^{13} p / \lambda \quad (8)$$

At the He-Ne gas laser infrared wavelength, $\lambda = 3.39 \mu$, the lower limit on the resolvable fringe shifts, p , is about 1/40 fringe and the upper limit is the order of 30 fringes. Therefore, the coupled-cavity interferometer is useful for plasmas with integrated densities along the path length in the range of 10^{15} to 10^{18} electrons/cm².

3.2 Coupled-Cavity Plasma Applications

The coupled-cavity interferometer technique is directly suitable for pulsed plasmas where time variation of the plasma density can be followed along a single line of sight. The spatial resolution is equal to the laser beam width which is typically the order of 1 to 2 mm. As the plasma is produced, its increasing electron density effectively decreases the laser cavity length which modulates the laser output. The modulated laser output is detected by the appropriate photo detector for the laser wavelength being used. Figure 5 shows an oscillogram of typical data from a coupled-cavity interferometer. The lower trace shows the uniformly modulated signal taken a few microseconds before a plasma was produced in the laser path. The presence of plasma changes the regular fringe spacing due to the rotating mirror. The rotating mirror system also provides the sense of the plasma density change, according to whether the period of oscillation is increased or decreased by the plasma effect for a given direction of the moving mirror. In Fig. 5 the mirror was moving toward the plasma, so a shortening of the period indicates increasing density.

The peak density on axis can be obtained by combining this interferometer result with luminosity profile data. Assuming a Gaussian profile yields

$$\int n dl = 2 \int_0^{\infty} n_0 e^{-(r/a)^2} dr = \sqrt{\pi} n_0 a \quad (9)$$

and using eq. (8) gives the peak density on axis, n_0 ,

$$n_0 = 6.3 \times 10^{12} \frac{p}{\lambda a} \quad (10)$$

where a is the plasma radius determined from the Gaussian fit to the luminosity profile data[12]. The low density limit can be further extended by combining the rotating mirror technique for measuring fractional fringes with multiple passes through the plasma. A further increase in sensitivity can be made by attaching mirror M_3 , Fig. 4, to an audio speaker coil and oscillating it sinusoidally at a frequency of about 2 kHz to give a change in path length in the external cavity of about 0.1λ as shown by Thomas [13]. Herold and Jahoda[14] have measured fringe shifts as small as 10^{-3} fringe with a CO_2 laser when the mirror was oscillated through 0.01 wavelength. With the additional gain in sensitivity due to the $10-\mu$ CO_2 laser wavelength, 10^{-3} fringe corresponds to an integrated density of 1.1×10^{13} electrons/cm².

REFERENCES

1. JAHODA, F.C., SAWYER, G.A., in "Methods of Experimental Physics", Vol. 9B, p. 1, Academic Press, Inc., New York (1971).
2. SMITH, HOWARD M., "Principles of Holography", Wiley Interscience, New York (1969).
3. GOODMAN, JOSEPH W., "Introduction to Fourier Optics," McGraw Hill, New York (1968).
4. BEFLINGER, L.C., WUERKER, R.F., BROOKS, R.E., J. Appl. Phys. 37, 642 (1966).
5. JAHODA, F.C., SIEMON, R.E., Los Alamos Scientific Laboratory Report, LA-5058-MS (1972).
6. JAHODA, F.C., JEFFRIES, R.A., SAWYER, G.A., Appl. Optics 6, 1407 (1967).
7. GRIBBLE, R.F., QUINN, W.E., SIEMON, R.E., Phys. Fluids 14, 2042 (1971).
8. COMMISSO, R.J., EKDAHL, C.A., FREESE, K.B., GRIBBLE, R.F., McKENNA, K.F., MILLER, G, SIEMON, R.E., in Los Alamos Scientific Laboratory Annual (1977) Report, LA-7474-PR (1978).
9. QUINN, W.E., "Measurements of Plasma Beta and Energy Line Density, These Proceedings.
10. KING, P.G.R., STEWARD, G.J., New Scientist 17, 180 (1963).
11. ASHBY, D.E.T.F., JEPHCOTT, D.F., Appl. Phys. Letters 3, 13 (1963).
12. QUINN, W.E., "Measurement of Plasma Beta in High- β Fusion Experiments," These Proceedings.
13. THOMAS, K.S., Phys. Fluids 11, 1125 (1968).
14. HEROLD, H., JAHODA, F.C., Rev. Sci. Instr. 40, 145 (1969).

FIGURE CAPTIONS

- Fig. 1. Schematic arrangement for recording nondiffuse, image holograms. (Courtesy of Dr. R.E. Siemon, Los Alamos Scientific Laboratory.)
- Fig. 2. End-on interferogram and corresponding reduced fringe shift or density profile. (Ref. [3]).
- Fig. 3. Time history of the central plasma column electron inventory (Ref. [8]).
- Fig. 4. Schematic arrangement of coupled-cavity interferometer applied to a θ -pinch plasma. The rotating mirror introduces continuously varying phase in the feedback path. (Courtesy Drs. F.C. Jahoda and R. Kristal, Los Alamos Scientific Laboratory).
- Fig. 5. Oscilloscope trace showing the modulated signal from coupled-cavity interferometer with rotating mirror. Upper trace: with plasma. Lower trace: without plasma. (Courtesy Drs. F.C. Jahoda and R. Kristal, Los Alamos Scientific Laboratory.)

COUPLED-CAVITY INTERFEROMETER DATA
WITH MOVING MIRROR