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Holographic Plasma Diagnostics

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Holographic Plasma Diagnostics*

by

F. C. Jahoda

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HOLOGRAPHIC PLASMA DIAGNOSTICS

by

F. C. Jahoda

ABSTRACT

The uses of holography in plasma diagnostics are reviewed. Holographic interferometry is the most significant technique.

The essence of holography is the simultaneous storage of both the amplitude and phase of an optical electromagnetic field in a manner that permits the reconstruction of these aspects of the field at arbitrary later times. Hence, there is also a recreation of those observable effects of the field that depend on amplitude and phase and not, for instance, on polarization or wavelength. The most spectacular of these effects is the three-dimensional quality complete with parallax that has so quickly made holography popular.

The special requirement in making this practicable is a source of coherent light. However, a plasma emits, of course, only incoherent light and is generally a very weak scatterer and absorber of optical radiation so that it hardly influences the amplitude of coherent light propagating through it. Since amplitude or intensity modulation is, however, required for direct observation of any object (or hologram reconstruction), one cannot observe a plasma directly in full three-dimensional holographic splendor.

Nevertheless, a plasma having a refractivity different from unity, does alter the phase of radiation propagating through it, and these phase changes can be recorded holographically, and then analyzed. It is my purpose to show that this seemingly indirect procedure can have considerable advantages.

Figure 1 is intended for quick review of some fundamentals. In making a hologram, two beams derived from the same coherent source impinge on a

Fig. 1. Schematic for making hologram (left) and reconstructing real and virtual image (right).

photographic plate - one, the reference beam which has been sent around the object to be recorded and the other the scene beam, reflected from, or in the case of plasma, transmitted by, the object. After development of the plate and removal of the object, when the hologram is illuminated by a reconstruction beam, looking through it one sees a virtual image of the object. In addition, there is also a real image in front of the hologram. Figure 2 tries to explain this. The intensity at the coordinate x of the photographic plate is the absolute square of the sum of the amplitudes of the reference beam taken as a plane wave incident at angle θ and the scene beam of arbitrary amplitude and phase. Because of the coherence of the source, the time average of the cross-product terms does not reduce to zero. The greater the coherence, the greater the tolerance in the mismatch of the temporal and spatial overlap of the two beams at the plate.

The density of the developed plate is I^Y where Y is the slope of the H-D curve characteristic of the emulsion and processing procedure. When in

$$\begin{aligned} \text{Ampl.} &= A_0 e^{-i\alpha x} + A(x) e^{i\phi(x)} \\ \text{ref. beam} & \quad \text{scattered beam} \\ \text{For } x &= \frac{\lambda}{\theta}, \alpha x = 2\pi \quad \therefore \alpha = \frac{2\pi\theta}{\lambda} \\ I &= (\text{Ampl.})^2 = A_0^2 + A(x)^2 + A_0 A(x) e^{i[\phi(x) + \alpha x]} + A_0 A(x) e^{-i[\phi(x) + \alpha x]} \\ D &= I^Y \\ \text{Amplitude Transmission } T(x) &\propto \frac{1}{D^{1/2}} = [I(x)]^{-\frac{Y}{2}} \\ \text{and for } A_0 &\gg A(x) \end{aligned}$$

$$T(x) \propto 2A_0^2 - YA(x)^2 - YA_0 A(x) e^{i[\phi(x) + \alpha x]} - YA_0 A(x) e^{-i[\phi(x) + \alpha x]}$$

Fig. 2. Analytic formulation of holographic imaging.

reconstruction, a plane wave illuminates this plate its amplitude transmission will be proportional to $D^{-\frac{1}{2}}$, for which the first few terms in the expansion appear in the last line. Note that the third term has exactly the form of the original object beam, multiplied only by an attenuation factor and a linear phase term. Just as the equivalent term in the analytic formulation for the action of a prism or a grating, the linear phase term causes a deviation of the information-bearing term in a direction θ , and physically separates it from the remaining terms.

Looking through the hologram, then, as through a window, when it is illuminated by a reconstruction beam from the rear, one sees offset at the angle θ a virtual image in the original object location. There is another term in the negative θ direction which duplicates the original amplitude and phase distribution at the photographic plate except for reversal of sign in the phase. This is equivalent to the same wave travelling backwards in time, and in reconstruction this leads also to a convergent wave focusing to a real image in front of the plate. Since the absolute sign of the phase is never of concern, either the real or virtual reconstructions can be used according to convenience. In the case of an object which, like a plasma, is viewed in transmission there are two different options which I would like to distinguish clearly (Fig. 3). In both cases the scene beam, which originates in the coherent source, will be a plane or spherical wave with some uniform phase structure that is modulated

Fig. 3. a) Diffuse illumination of hologram plate. b) Collimated illumination of hologram plate.

by the plasma that it traverses. In case 1 it then illuminates a diffuser, every point of which becomes a secondary source which illuminates all points of the hologram. After a single exposure, reconstruction of any small portion of the hologram will reproduce the entire diffuser. By the same token the reconstruction is extremely insensitive to scratches or other artifacts in the developed plate. However, the diffuser adds its own very random phase distribution to the phase information existing in the beam to its left, and so the phases existing prior to the diffuser cannot be extracted in the reconstruction. In case 2, without diffuser, to a geometrical optics approximation, there is a one-to-one correspondence between any ray through the plasma and position on the hologram plate. In this case the reconstruction will have the phase distribution imparted to the beam by the plasma, though degraded somewhat by the extra window that the hologram substrate and emulsion itself constitutes. Any portion not illuminated by the reference beam will be lost in the reconstruction. Within these limitations, however, the beam propagating to the right in the reconstruction, long after the plasma is gone, can be used to analyze the phase distribution imparted to the original scene beam by the plasma, in any way that the original beam itself might have been used. The primary advantage, of course, is that instead of the original occurring just once as a transient pulse, the reconstructed beam can be CW and available for all time while the diagnostics are adjusted and optimized or changed from one type of

measurement to the next. I shall return to this case later.

The most significant plasma application up to now, however, of proven utility and really very simple, is holographic interferometry, and for this, while either of these cases can be used, having the diffuser present is more advantageous. Consider a second exposure of the same hologram emulsion before the plate is processed, with a small phase change in the scene. The diffuser again adds its random phase distribution in the space to its right, but it is of course the same randomness as on the first exposure. The net result can be thought of as two independent holograms which, when simultaneously reconstructed, will interfere with each other, the differences in phase which result in an interference pattern being due only to the phase differences caused by the change. The same thing is put analytically in Fig. 4. Considering only one cross-product term is sufficient since, as we have seen, it becomes spatially separated from all the other terms. The second exposure adds another intensity term, where the reference beam has been taken to have the same amplitude and phase, and the scene beam the same amplitude as on the first exposure but with a different phase. Combining the two terms by expressing the new phase as the old phase plus the difference, one gets again the same reconstructed wavefront as from a single exposure, except that the amplitude is now modulated by a term depending on the phase differences between exposures, and these phase differences will be rendered visible as intensity variations or fringes superposed on the scene. (Note that while every hologram is a fine-scale interferograph between the scene and reference beam, I am here and from now on referring only to the gross scale interferographs produced by consecutive exposures, both of which individually involve two beams.) The net result is analogous to a conventional interferograph, only in this case the test beam and the comparison beam are separated in time rather than in space. Though the resulting interferographs give the same information with the same

$$A_0 A(x) \exp[i\alpha x + i\phi(x)] + A_0 A(x) \exp[i\alpha x + i\phi'(x)] = A_0 A(x) \exp[i\alpha x + i\phi(x)] \{1 + \exp[i\Delta\phi(x)]\}$$

where $\phi'(x) = \phi(x) + \Delta\phi(x)$.

Fig. 4. Analytic formulation of image term for double exposure.

sensitivity (one full fringe or phase shift of 2π at the ruby wavelength results from an electron density of $3 \times 10^{17} \text{ cm}^{-2}$), this is a very significant difference. Optical interferometers are very delicate instruments, which need very precise alignment and very high quality optics, and, in order to span a given plasma device, they often need to be very large as well. Also, the windows of the plasma vessel must be of the highest optical quality, precisely to avoid phase distortions in the one beam which cannot be duplicated in the comparison beam. In the holographic method, only the crudest kind of alignment is needed, and, since the two beams being compared traverse precisely the same path, all optical elements can be quite crude. Whatever their effects on the beam stays constant between the exposures, and we sense as fringes only the differences. If the vacuum vessel itself is transparent, that will do for the window despite any curvature.

Actually, for what I have described so far, the holographic interferograph corresponds to the case of the interferometer adjusted for a uniform field, the so-called infinite fringe case, which is not generally desirable because this arrangement is not sensitive to phase disturbances small compared to a full fringe. Generally in the conventional interferometer there is a straight-line fringe background due to a slight angle between the recombined beams caused by a slight tilt of at least one element from strict parallelism with the others. In the holographic case, this is very easily simulated by purposely making a comparable phase change between exposures. This is most readily done with a hollow wedge inserted in the optical path of the scene beam and changing the filling gas between exposures. Figure 5 perhaps clarifies this. These are reproductions of the real image locations in the reconstructions of double exposure holograms where for one exposure a jet of SF_6 gas was turned on. On the right there was also a gas exchange in a glass wedge covering not quite the whole field of view. On the left one can measure phase differences only to the nearest multiple of π , while on the right precise measurements can be made of each fringe displacement. Incidentally, it also shows the ability to see fringes through the glass tube walls.

At long last, let me turn now to the application of this method to a real plasma. Figure 6

Fig. 5. Holographic interferograms of gas jet with (right) and without (left) background wedge.

shows a schematic of the arrangement on the plasma gun installation of Marshall and Henins. The plasma is located in the center of a 4-ft diameter vacuum tank, which with associated pumps, valves, and electrical leads fills most of the available space. This apparatus could not readily have been spanned by a conventional interferometer. The light source is a giant pulse ruby laser. To minimize temporal coherence requirements, the scene and reference beam path are made equal lengths with a meter stick to a couple of centimeters accuracy and not to within a few wavelengths. A 1/64-in. external pinhole wastes most of the light but gives sufficient spatial coherence to make high quality holograms. The scene beam expanded to cover the 8-in. windows (also an extreme dimension for conventional interferometry) passes through the wedge, then the plasma region, is again focussed down to pass through a stop which prevents most of the plasma self-luminosity from getting through and fogging the film, and strikes the diffuser. The auxiliary lens which images the plasma location on the diffuser is useful in counteracting the refractive bending effects of the plasma, which otherwise would somewhat degrade the

Fig. 6. Schematic of experimental arrangement.

interference fringes. Two exposures are made that can be separated in time by a minute or two, one without plasma present and one with, and with the gas in the wedge having been changed from, for instance, air to helium.

The first case I will show you is a variant of the coaxial gun configuration called Snowplow, in which there is a single cylindrical electrode inserted through the end of the vacuum chamber with an insulator separating it from the wall. There is a static D_2 gas filling, and gas breakdown occurs first across the insulator between the end of the electrode and the tank wall. The current sheath then propagates down the electrode and collapses off the end forming a plasma focus. Figure 7 shows holographic interferograms for three different times at two different filling pressures. The top frames are just before the sheath leaves the end of the electrode; in the center frames one can see the disturbance in the region of the plasma focus, and finally on the bottom pictures, a disturbance ahead of the front, which has been called the bubble by Butler and Morse, who have given a theoretical description, in close correspondence with various experimental

Fig. 7. Snowplow discharge in deuterium. a-c: $P = 450$ mtorr; d-f: $P = 1100$ mtorr.

diagnostics, elsewhere at this meeting.

You may have noticed the slight slant in the background fringes which differs on every frame, each of which represents a different discharge. This is due to some uncontrolled motions between the two exposures which add a small linear phase change to the background purposely introduced by the wedge. Figure 8 shows a double exposure under typical conditions without either plasma or change of gas in the wedge. By itself this background would be intolerable, the fringe spacing and direction being wholly random, but added in to the much larger gas wedge effect it is of no consequence, being equivalent to a slight drift in adjustment of a conventional interferometer. While this may seem like a minor point, in practice it means that these interferograms can be obtained in the environment of a plasma laboratory without any attempt at vibration damping of any component.

Figure 9 shows a time sequence in front of the muzzle of a coaxial gun, in this case with argon gas pulsed in by a fast valve. The slightly protruding center electrode is quite apparent, the outer electrode diameter is just about the chord which cuts the field of view on the left. The early turbulence, with increasing focusing on the center line at later times is quite typical.

There is another advantage of great potential significance that holographic interferometry can have over the conventional technique. If the diffuser is placed in the scene beam before it traverses the plasma instead of after, then the plasma

Fig. 8. Spurious background fringes due to random motions between exposures.

Fig. 9. Time sequence of coaxial gun pulsed with argon gas.

will be illuminated over a whole range of angles and the holographic recording will give the various fringe distributions characteristic of each different direction in the playback. Any one view is necessarily the line integral of density in that direction, but if the geometry permits viewing sufficiently different angles it should be possible to deduce something about the depth dimension.

I wish to turn back now to the case of a single holograph exposure without diffuser, in which in the reconstruction, as already stated, the collimated beam with the plasma's phase modulation superposed is directly available. Whether holographic recording in this case is advantageous will depend on the individual situation. For the ultimate in sensitivity in, say, a schlieren system, I have already mentioned that the hologram substrate itself will add a source of noise. Furthermore, since schlieren pictures are (1) harder to evaluate quantitatively than interferographs, and (2) lead to density gradients rather than density, I think they have often been made only because it was experimentally less demanding than interferometry. Since holography inverts the relative ease quite decidedly in favor of interferometry, there will also be less reason to produce schlieren pictures. Nonetheless, measuring the density gradients is complementary rather than redundant to a density measurement and will have merit in certain cases. Holography will then be particularly useful if ultimate sensitivity is not required and if the continued availability of the

information-bearing beam permits simpler quantitative evaluation by virtue of variable adjustments, i.e., methods that can ordinarily be used in steady state situations but not for transient events.

One such method is the use of moiré plates. Two plates having equispaced parallel rulings are placed in the reconstructed wavefront some distance apart and the moiré fringe spacing selected by relative rotation of plates. An angular deviation in any part of the field sufficient to displace the shadow projection of a particular ruling on the first plate by one period of the rulings on the second plate results in a local shift of the moiré pattern by one fringe. This gives a considerable magnification effect, which is displayed on a screen or photographic film, after first selecting with lens and pinhole one of the many orders produced by these coarse gratings. The parameters by which the sensitivity can be adjusted are the separation distance between the plates and the spacing of the rulings themselves. This is illustrated in Fig. 10 which shows various reconstructions all from a single hologram, again of a gas jet, and differing only in moiré plate adjustment. The amount of fringe deviation is proportional both to the spacing between the rulings and the distance between the plates. Figure 11 shows variation in fringe spacing but constant deviation as measured in fringe units as the relative rotation between the plates is altered. With this method it is reasonable to measure angular deviations down to 10^{-4} radians or $5 \times 10^{17} \text{ cm}^{-3}$ for the product of density gradient $\times$ path length.

Figure 12 shows this method applied to a transient plasma. Here we are looking axially at a 1-m-long rather cold theta-pinch plasma. Neither the

Fig. 10. Reconstructions from a single hologram of gas jet, varying a) ruling spacing, b) separation distance of moiré plates.

Fig. 11. Same hologram as Fig. 10, reconstructed with varying relative orientations of moiré plates.

end windows nor the filters were of good schlieren quality, so the moiré fringes in the no-plasma case are already somewhat distorted. The same distortions can be recognized in the plasma case, and the plasma stands out clearly in addition. The constant slope in the core region means constant second derivative or approximate parabolic density variation with radius. A holographic interferograph of this plasma source is shown for comparison. I have already indicated that I think this is preferable unless special requirements make the schlieren desirable.

I should have entitled this talk, "Some Holographic Plasma Diagnostics," because I have discussed only two types of measurements in fair detail. One can also make use of the fact that a hologram

INTERFEROGRAPH:

SCHLIEREN-MOIRÉ:

Fig. 12. Schlieren-moiré hologram reconstruction of 1-m long theta-pinch (bottom) compared with holographic interferogram (top).

can accurately reproduce the relative brightnesses of different portions of a field to measure, for instance, Faraday rotation with spatial resolution. A group at Leningrad under Zaidel has made temperature determinations of a laser spark plasma this way by measuring the absorption of the coherent laser light in the presence of high but incoherent self-luminosity at the same wavelength.

The development of coherent light holography has stimulated renewed work on wavefront reconstruction starting with incoherent light, and three-dimensional display of transient plasmas in their own light may sometime become feasible.

I am currently interested in extending the sensitivity of holographic interferometry. Since the real and virtual images are of opposite phase polarity, if they are made to interfere with each other, the phase differences are doubled. Since a hologram is a kind of grating, there can be higher order images, generally neglected, in which the

phase content is multiplied by the order number. Figure 13 is a preliminary result, again of a gas jet source, single exposure, in which beating the real and virtual first order images together, one gets, lower left, fringes with twice the usual sensitivity, and beating the real and virtual second orders, lower right, four times the conventional sensitivity. The scratch marks are intended to help indicate twice the amount of fringe displacement on the right. The trouble which makes this unpractical so far is shown on top, where in the absence of an object, one cannot get a good straight line fringe background because the degree of collimation of the two images is not quite the same.

I hope that the account of more speculative and less-developed ideas in the latter part of my talk will not have erased the impression I wanted to create earlier that holographic interferometry, in particular, can really simplify now the instrumentation problem for anyone who could utilize the conventional technique.

Fig. 13. Interference of second-order real and virtual images (lower right), first order real and virtual images (lower left) of hologram with gas jet as object. Interference of real and virtual images for hologram without gas jet object (top).