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MEASURING THE COHERENCE PROPERTIES OF LIGHT EMISSION FROM LASER-PLASMA INTERACTIONS

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Measuring Coherence Properties of Light Emission from Laser-Plasma Interactions

I. Introduction

Several detrimental instabilities can be excited when a high-intensity laser interacts with plasma.[1] The temporal evolution and spectra of the scattered light emitted by many of these instabilities are used to characterize the instabilities and to benchmark theories.[2] It has been difficult to image the emission region with sufficient resolution to make quantitative comparisons with theory. Direct measurement of the emission region would yield information on ponderomotive steepening phenomena, the true emission zone of convective instabilities, and on the saturation of absolute instabilities.

The increase in laser intensity caused by the filamentation instability is conjectured to elevate the levels of parametric instabilities found in high-energy laser-plasma interactions. Because the diameter of the filaments is very small (on the order of 10 μm), it is impossible to image the emission sites directly and either to prove or to disprove this conjecture. The research reported here examines an alternate method of measuring the emission region of scattered light from parametric instabilities. The size of the emission region may be deduced by measuring the transverse and longitudinal spatial coherence of the emitted light. This method may be applied straightforwardly to a system consisting of only one filament. Unfortunately, in a typical laser-plasma interaction, many emission sites (filaments) are present. In this situation, the coherence measurement loses all sensitivity and is meaningless. If only one emission region is present, it may be possible to measure the coherence of large regions of the plasma.

This report provides a brief background of coherence theory by defining the relevant parameters in section II. A concrete example of the effect that multiple scattering sites would have on the proposed measurement is provided in section III. The following section briefly describes experiments that might be able to demonstrate the proposed technique. The conclusion raises the issue of coherence and its effect on the expected angular distribution of scattered light from parametric instabilities.

II. Coherence Parameters

If light at one point in time or space is highly correlated with light at another point in time or space, the two emitting points are said to be coherent.[3] We make the assumption that if emission is coherent, it is created by the same driving mechanism. Therefore, if a certain coherence length is measured, it is assumed that the light is all emanating from an area of approximately that size. Light may have temporal coherence, transverse spatial coherence, or longitudinal spatial coherence.[4-9] Knowing all three quantities would be a boon for laser-plasma research. From these measurements, detailed comparisons could be made with theory to investigate saturation, threshold, and amplification mechanisms. The focus in this work is on transverse spatial coherence, to test the link between filaments and instabilities.

A direct method of determining the coherence of light is to measure the phase difference between the light at two separate points in space. If a definite phase relationship exists, the waves are correlated. It is important to remember that even thermal emission, which is considered uncorrelated, will show some coherence properties.

A brief example of the use of the complex degree of coherence function, γ_{12}^{c}, is given below in order to illustrate a method of measuring the spatial coherence.[4] Figure 1 displays the geometry of a Young's double slit experiment. Suppose that light is emitted at the left of the figure at any number or arrangement of points. The light strikes an opaque screen that has two pinholes or slits in it. The light from each point will travel through each pinhole. Let the electric fields in the pinholes be represented by the

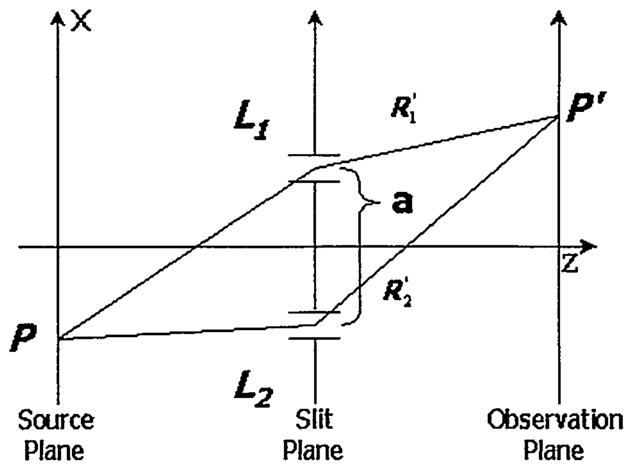

Fig. 1 Light strikes two pinholes, L_1 and L_2, separated a distance a apart. The observation point, P', is R_1' from L_1 and R_2' from L_2. Assume that the transmission of each pinhole is identical.

The difference in transit times from each pinhole to the observation point P' is called the retardation time, τ',

$$\tau' \equiv \frac{R_2' - R_1'}{c} \quad . \tag{2}$$

The total observed field is then expressed as

$$E(P',t) = E_1(t) + E_2(t-\tau') \quad . \tag{3}$$

The measured quantity, however, is the square of the electric field

$$\langle E^2 \rangle = \langle E_1(t) \rangle^2 + \langle E_2(t) \rangle^2 + 2\langle E_1(t) E_2(t-\tau') \rangle \quad . \tag{4}$$

Identifying $\langle E^2 \rangle$ as the flux density S, Eq. (4) is rewritten as

$$S = S_1 + S_2 + 2\sqrt{S_1 S_2}\,\gamma_{12}^c \quad , \tag{5}$$

where we have defined the complex degree of coherence as

$$\gamma_{12}^c \equiv \frac{\langle E_1(t) E_2^*(t-\tau') \rangle}{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle} \quad . \tag{6}$$

Of course, being complex, the mutual coherence function can be expressed as

$$\gamma_{12}^c = |\gamma_{12}^c| e^{i\phi} \quad . \tag{7}$$

The phase is determined by the frequency of the emitted light. Applying this to Eq. (5), it is apparent that the total flux density consists of a constant background (S_1+S_2) and a sinusoidal component proportional to $|\gamma_{12}^c|$. These are the well-known interference fringes. A useful quantity introduced by Michelson[10] is the fringe visibility, V, defined as

$$V \equiv \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}} \quad , \tag{8}$$

where S_{max} and S_{min} are adjacent local minima and maxima in the fringe pattern. Because the phase of γ_{12}^c varies between ±1, the fringe visibility of Eq. (5) is very simply

$$V = |\gamma_{12}^c| \quad , \tag{9}$$

if the light from each pinhole is the same, $S_1 = S_2$. Thus, a measurement of the fringe visibility is a direct measurement of the mutual coherence function. This function has a value of one for complete coherence, zero for complete incoherence, and can have any value in-between for partial coherence.

The full angular distribution of emitters may be determined by measuring the fringe visibility as a function of pinhole spacing. Suppose that the light source is described by the angular distribution

$$\imath(\theta) = S(\theta)/S_o \quad . \tag{10}$$

Here, $S(\theta)d\theta$ is the total flux density at the plane of the pinholes coming from the part of the source located between θ and $\theta + d\theta$. The total flux density is S_o. It has been shown that the visibility as a function of pinhole spacing is the Fourier transform, $I(a/\lambda)$, of the angular distribution $i(\theta)$,

$$V(a) = \left| I\left(\frac{a}{\lambda}\right) \right| \quad . \tag{11}$$

In principle, it is possible to map completely the spatial distribution of the emission region by measuring the fringe patterns created by several pairs of pinholes or slits, each pair having a different spacing.

III. Counter Example

Many filaments (emission sites) are expected in a typical laser-plasma interaction. The following example demonstrates the reason the proposed double-slit measurement will fail in a typical application. Suppose that a screen having two pinholes 100 microns apart is placed 15 cm from a laser-plasma interaction as in Fig. 1. The resulting interference pattern is observed 15 cm from the screen. Only 0.5-micron light is measured. Assume that only one single point source is present. The interference pattern, solid line in Fig. 2, is the usual double-slit interference pattern first observed by Young. Now suppose that there are N identical emitters present. Each radiates from a single point that is both physically separated and completely incoherent with the other points. These points are restricted to lie on the x-axis in Fig. 1. Figure 2 demonstrates the interference patterns from three sources that are randomly located within 100 microns of the optical axis. Obviously, the patterns do not line up. The center of the pattern from

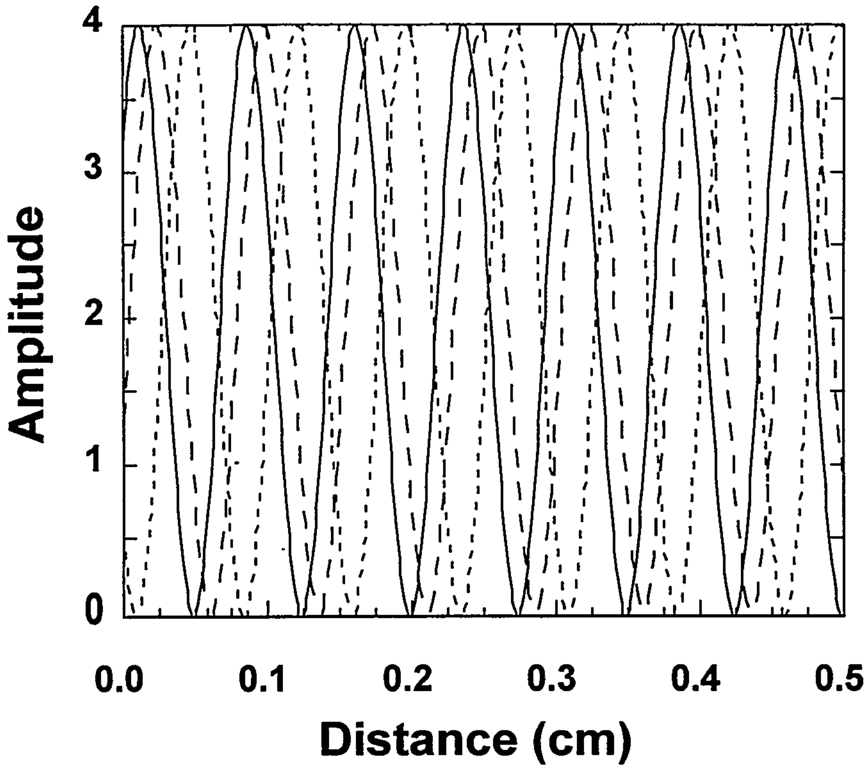

Fig. 2. The interference fringes from three emission sites, randomly located in space.

each source is located at zero phase difference ($\tau' = 0$). The magnification of this example system is one, so the center of the fringes is located the same distance from the optical axis that the source is located, but on the opposite side of the axis.

Because we assumed that each source has no correlation with any of the other sources, the observed interference pattern will be the simple incoherent sum of the N emitters. That is, γ_{12}^{c} has been assumed to be identically zero in this example. To calculate a typical fringe visibility, we assumed that there were 13 emission sites randomly located within 100 microns of the optical axis. The incoherent sum of the 13 fringe patterns (divided by 13) is displayed in Fig. 3. The visibility was only 0.06. This is low contrast, but might be measurable with heroic efforts.

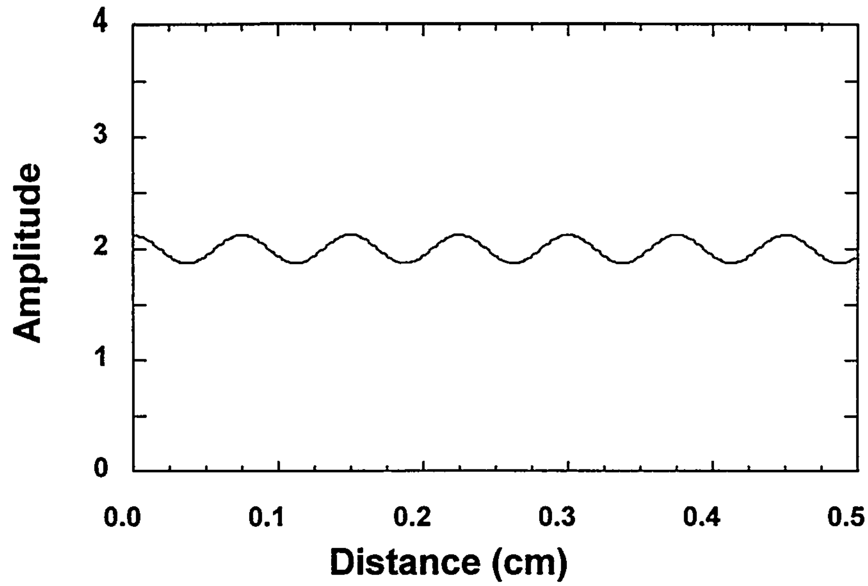

Fig. 3. The final interference pattern. The fringes from 13 sources, randomly located in space, have been summed and divided by the number of sources (13). The fringe visibility is 0.06.

The previous example illustrates one of the three limitations to this method. By design, the example had no correlated emission. The visibility, and hence the coherence function, were greater than zero. Even uncorrelated sources may have some apparent coherence. Furthermore, the value of the coherence function will depend on the extent of the source in the y-direction (out of the plane of paper in Fig. 1). The visibility of a uniform line source subtending an angular height of $\Delta\theta$ is zero when the slit spacing, a, is[4,5]

$$a = \frac{\lambda_o}{\Delta\theta} \quad , \tag{12}$$

where λ_o is the central wavelength of the light. If instead of a uniform line, the source is a uniform disk of the same angular extent, the visibility vanishes when the slit spacing is larger,

$$a = 1.22\frac{\lambda_o}{\Delta\theta} \quad . \tag{13}$$

Two dimensionality of the uniform disk source introduced a 22% difference in the visibility function.

The second limitation of this method is that the visibility varies depending on the spatial location of the sources. For the example with 13 sources, different locations of the sources, randomly chosen, produced fringe visibility ranging from 0.04 up to 0.6. Clearly, multiple emission sites confuse the measurement and render it useless.

A third limitation of this method with multiple sources present occurs if the sources have the different strengths. The complex degree of coherence, Eq. (6), is modified by including a weighted sum over the autocorrelation of each source. When more than a few sources are present, it is impossible to deconvolve the contribution from each source.

IV. Experiments Which Could Measure the Coherence of Laser-Plasma Phenomena

If the multiple emission sites of a typical laser-plasma make a coherence measurement useless, it is natural to consider situations that will lend themselves to such a measurement. The prerequisite is that the emission being measured emanates from only one region of the plasma. Under this condition, there are two issues to be considered. The first is the selection of an instability to be monitored. It may not be possible to examine every instability. The second consideration is how the plasma is created and the instability stimulated. A general guide to addressing these issues is given in the rest of the section. More detailed answers are not warranted because we are not proposing to pursue this research to the experimental stage.

There are several different possible approaches. For example, in a low-density plasma, whole-beam self-focusing may occur.[1] This is one limit of the filamentation instability where the entire laser beam acts as a single filament. The laser beam is focussed to a smaller spot and consequently, a higher intensity. This approach would be useful for studying instabilities that are spatially localized due to density-profile constraints. Some examples are ponderomotive steepening or absolute stimulated Raman scattering (SRS) at the quarter-critical density ($n_c/4$) surface. This method would also shed light on the origin of $3\omega_0/2$ emission.[2] It is generally believed that this light is produced by a mixing of the electron plasma wave (epw) produced by SRS at $n_c/4$ with incoming laser light. The slight frequency offset from $3\omega_0/2$ is thought to be caused by the epw propagating to a slightly higher or lower density where phase matching may take place.

The whole-beam self-focusing approach is less than ideal, however. Filamentation may still occur, particularly if the laser beam already has many intense "hot spots" in it. Also, there is no guarantee that the plasma is spatially uniform in either temperature or density. That is, the $n_c/4$ surface may not be localized in one location. The plasma may be "lumpy" with several, discontinuous $n_c/4$ surfaces present.

An alternative approach is to use an "exploding foil" plasma.[11-13] In these types of experiments, the target material from which the plasma is made is very thin. The density of the plasma rapidly decreases below n_c before the end of the laser pulse. The density profile along the axis of the laser beam is parabolic and is inverse parabolic in the direction perpendicular to the beam. The SRS instability has its lowest threshold at the peak density. The laser intensity may only surpass the threshold, however, in a very small area around the density peak. In the experiment of Labaune *et al.*,[13] hydrodynamic simulations showed that the SRS was limited to within a few microns of the top of the plasma and was below threshold elsewhere. Experimental measurement of the coherence volume may provide a very fine test of the hydrodynamic codes and simple threshold theory.

V. Discussion and Conclusion

Source coherence determines the angular distribution of radiated power.[14,15] For example, a thermal source has low coherence and radiates according to Lambert's law: $I(\theta) \propto \cos(\theta)$. In contrast, a laser, which is highly coherent, radiates in a very narrow beam: $I(\theta) \propto \delta(\theta)$. Thus, the angular distribution of radiant intensity may give rise to a potential means of measuring source coherence.

The coherence function Γ is defined as

$$\Gamma(|\mathbf{s}|) = \Gamma(\mathbf{r}_1, \mathbf{r}_2) = \left\langle E_i(\mathbf{r}_1) \bullet E_i^*(\mathbf{r}_2) \right\rangle \quad , \tag{14}$$

where E is the electric field and $\mathbf{s} = \mathbf{r}_2 - \mathbf{r}_1$ in the source plane. The invertion of the measured far-field radiation pattern is[16]

$$\Gamma(ks) = \int_0^1 \frac{I(p)}{gA(2-p^2)} J_0(pks) p \, dp \quad , \tag{15}$$

where $p = \sin(\theta)$, J_0 is the Bessel function, A is the area of the source, g $= 2\pi c$, and k is the wavenumber. In practice, Eq. (15) is numerically integrated for a given measured *I(p)*. Polarization of the scattered light will modify this result, and implementation of this technique may be difficult due to refraction of the scattered light in the plasma and low gain coefficients for direct forward scatter. However, the technique may be applicable to studying scattering near backscatter to perhaps an angle of 45° from backscatter.

A calculation that remains to be made is the expected coherence properties of laser-plasma instabilities. Three categories of calculations need to be examined. The first is a calculation of convective driven parametric instabilities. Recent research[17] has shown that low-gain convective instabilities are an issue for next-generation inertial-confinement fusion experiments due to the large spatial extent (large gain medium) of the plasmas. These instabilities may be expected to have large longitudinal (in the direction of propagation) spatial coherence and transverse coherence that is limited by the transverse density profiles. Absolute instabilities also need to be examined. These are expected initially to grow in small areas, spatially limited by instability detuning due to plasma density, temperature, or laser intensity variations. As these instabilities grow more intense, the gain presumably becomes large enough to drive the instability even under off-resonance conditions. A calculation of how coherence changes in time followed by experimental measurements would clarify the gain and saturation mechanisms. Effects of filamentation on both convective and absolute instability study results then need to be determined.

This study investigated using spatial coherence of emitted light from laser-plasma interactions as a measure of the size of the emission region. It is found that this method is not useful in practice due to the possible existence of multiple emission sites wthin the plasma. This diagnostic technique may be useful for plasma prepared in a special manner, namely the "exploding-foil" approach. Finally, the potential application of the angular distribution of scattered radiation to characterize the coherence of source emission is suggested, but no experimental work is proposed at this time.

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