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Lawrence Livermore National Laboratory

L.M. Divol
Centre d'Etudes Atomique, Bruyeres-le-Chatel, France

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Modeling the backscatter and transmitted light of high power smoothed beams with pF3D, a massively parallel laser plasma interaction code

R. L. Berger[a], L. M. Divol[b], S. H. Glenzer[a], D. E. Hinkel[a], R. K. Kirkwood[a], A. B. Langdon[a], J. D. Moody[a], C. H. Still[a], L. J. Suter[a], E. A. Williams[a], and P. E. Young[a]
[a]Lawrence Livermore National Laboratory, L-038, Livermore, CA 94551
[b]Centre d'Etudes Atomique, Bruyeres-le-Chatel, France

ABSTRACT

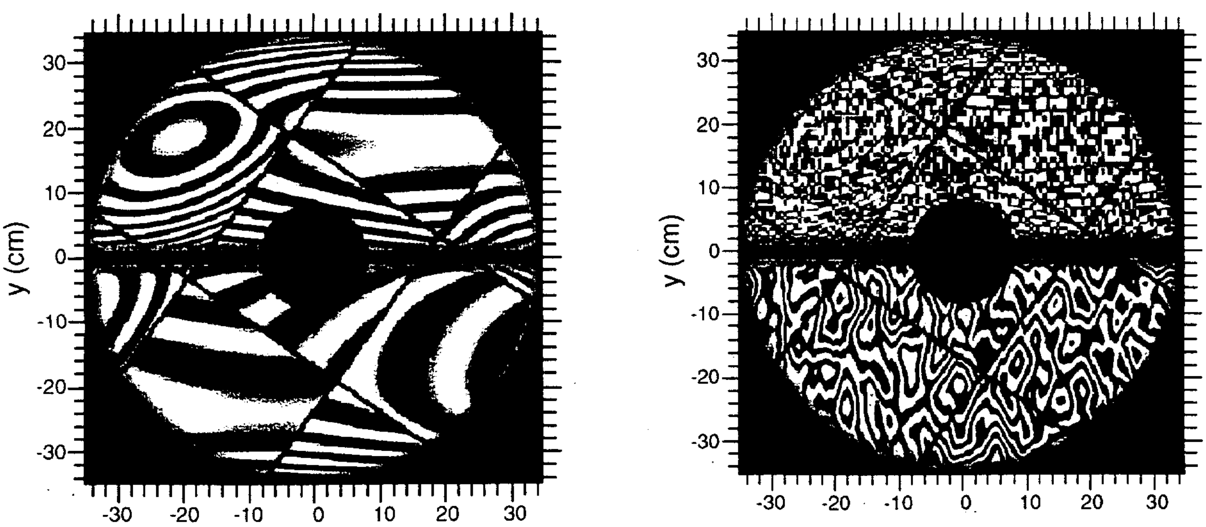
Using the three-dimensional wave propagation code, F3D{Berger et al., Phys. Fluids B 5,2243 (1993), Berger et al., Phys. Plasmas 5,4337(1998)}, and the massively parallel version pF3D, {Still et al. Phys. Plasmas 7 (2000)}, we have computed the transmitted and reflected light for laser and plasma conditions in experiments that simulated ignition hohlraum conditions. The frequency spectrum and the wavenumber spectrum of the transmitted light are calculated and used to identify the relative contributions of stimulated forward Brillouin and self-focusing in hydrocarbon-filled balloons, commonly called gasbags. The effect of beam smoothing, smoothing by spectral dispersion (SSD) and polarization smoothing (PS), on the stimulated Brillouin backscatter (SBS) from Scale-1 NOVA hohlraums was simulated with the use of nonlinear saturation models that limit the amplitude of the driven acoustic waves. Other experiments on CO_2 gasbags simultaneously measure at a range of intensities the SBS reflectivity and the Thomson scatter from the SBS-driven acoustic waves that provide a more detailed test of the modeling. These calculations also predict that the backscattered light will be very nonuniform in the nearfield (the focusing system optics) which is important for specifying the backscatter intensities to be tolerated by the National Ignition Facility laser system.

Keywords: Wave propagation, stimulated Brillouin/Raman scattering, filamentation, massively parallel, SSD, polarization smoothing

1. EXPERIMENTS AND MODELING

The advent of distributed computer facilities with hundreds of processors and gigabytes of memory per processor has made possible the modeling of the interaction of intense laser beams with plasmas in three dimensions on a physical scale of the target and for hundreds of picoseconds. Here, we present the results of F3D[i] and pF3D[ii] simulations of experimental observations of light transmitted through gasbags filled with mixtures of helium and hydrogen (HeH),[iii] of the dependence of SRS and SBS on beam smoothing from gas-filled NOVA hohlraums[iv] and gasbags[v], and the Thomson scatter from SBS-driven acoustic waves in CO_2 filled gasbags[vi]. We predict that the stimulated backscatter from NIF targets will be highly nonuniform in the nearfield which may damage the NIF final optics assembly. Because most of the light is forward or backward scattered by filamentation, Brillouin, and Raman processes within a relatively narrow cone of angles defined by the incident light, the incident and reflected light propagates within the paraxial approximation and F3D operates on scales up to millimeters and nanoseconds. All the light waves may self-focus through thermal and ponderomotive forces which produce long wavelength, slowly varying plasma density and temperature nonuniformities. On this scale, the plasma evolution is treated with a fully nonlinear, three-dimensional Eulerian hydrodynamics that includes axial and transverse spatial dependence. This nonlinear hydrodynamics also allows the self-consistent modification of the plasma flow, electron and ion temperature, and density caused by the loss of light energy and momentum in the scattering and absorption processes.

In Fig. 1, we show the phase variation of the incident laser electric field after transmission through the KDP frequency conversion crystals (Fig. 1a) and subsequently through the f/8 RPP (upper half of figure) or f/8 KPP (lower half of figure) used in the NOVA beam smoothing experiments described in this article.



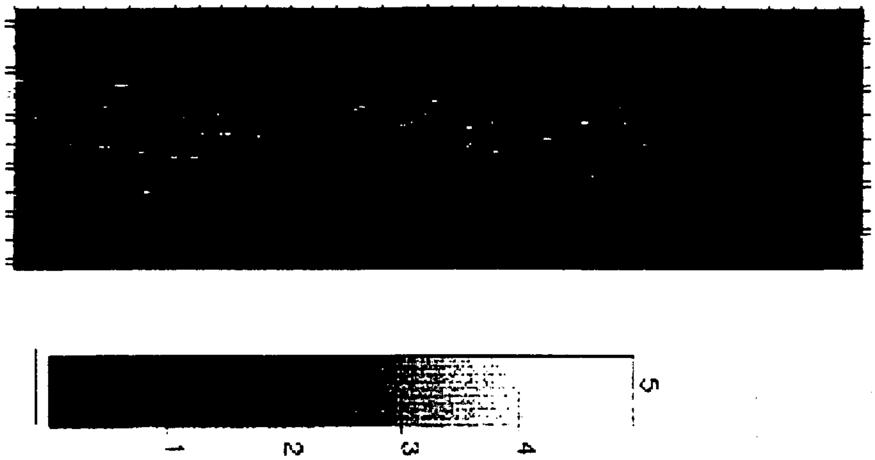


Fig. 2

With a nearfield in pF3D appropriate for the f/4 HeH gasbag experiments, the massively parallel version of F3D, the laser electric field at the target is constructed and propagated over millimeters of plasma as shown in Fig. 2, about 50 axial speckle lengths for this f/4 simulation. The plasma electron density , n_e, along the laser propagtion axis is a smooth plateau at 0.05 n_c in the central region; it drops exponentially at the edges where strong plasma flow gradients occur. Between these two regions, a "blast wave" exists which consists of a density bump that moves inwards towards the bag center at nearly the acoustic speed. Here, n_c is the critical density for 351nm light. The length of the smooth plateau region decreases with time. The electron temperature is nearly constant in space and increases slowly in time while all tens laser beams are on to a maximum of about 3 keV at 0.8-1.0ns.

Because the laser beam propagates through the entire gasbag, including the blast wave density peaks in this simulation, we can compare directly its predicted angular distribution (Fig. 3a) and its frequency spectrum (Fig. 3b) with those observed. Fig. 3a shows that 75% of the incident light remains confined within the original cone defined by the f/4 lens. The calculated angular distribution agrees well with the observed one out to the limit of the spatial resolution in this calculation. Note that finer spatial resolution perpendicular to the laser propagation direction in the plasma is required to calculate the angular distribution at larger angles in the transmitted nearfield. The calculated frequency spectrum of the transmitted light scattered

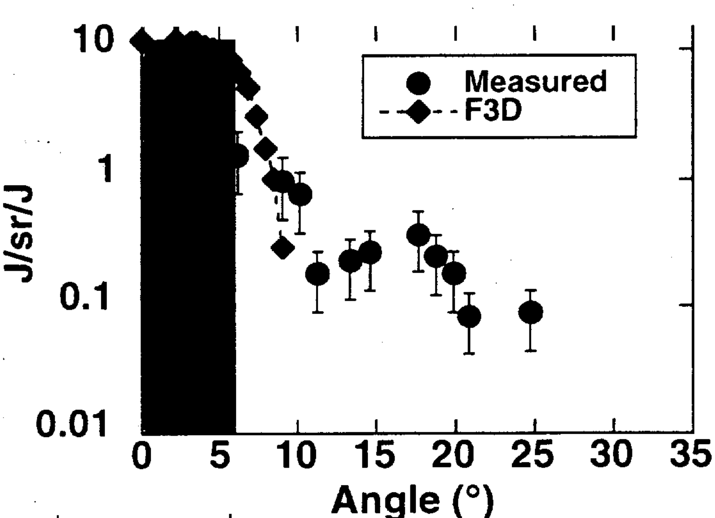


Fig. 3a

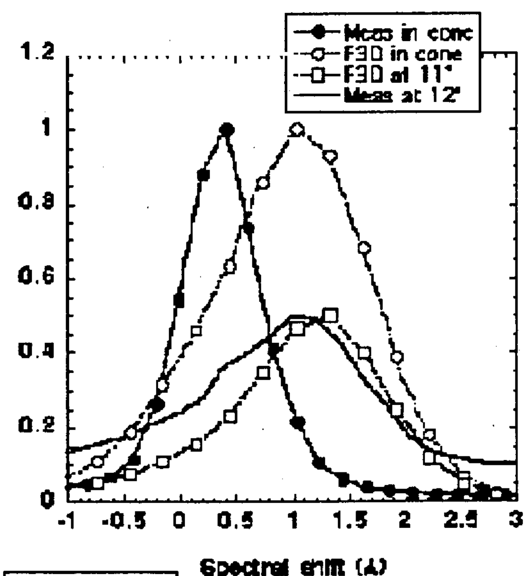


Fig. 3b

outside the incident cone angle by forward SBS is in excellent agreement with the data. Within the f/4 cone, the data has a smaller shift than the calculated shift and also a smaller shift than the light scattered outside the f/4 cone as expected by a Brillouin scattering process. We believe this difference will be resolved by including nonlocal electron transport effects in pF3D.

Laser beam hotspots, which result from the nonuniform phase in the nearfield (Fig. 1), seed filamentation and enhance the growth of SRS and SBS. In the past, we have reported results from experiments that used only SSD to control filamentation and stimulated backscatter[vii]. More recently, theoretical predictions have touted the potential of polarization smoothing to reduce SRS, SBS, and filamentation[viii,ix]. The combination of PS and SSD was predicted to be particularly effective as shown in Fig. 4a. The SRS and SBS data for 0.1 n_c gasbags at the time of peak SBS shown in Fig. 4b shows the same behavior as the simulations. Data taken at other densities, 0.07 n_c and 0.14 n_c, shows the beneficial effects of combining PS and SSD is a robust result. A recent publication showed that PS can be very effective by itself.[x]

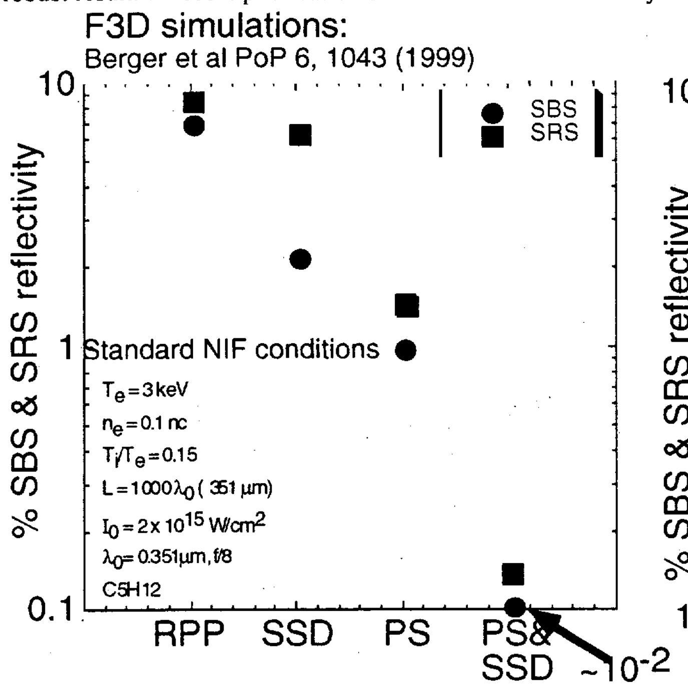


Fig 4a

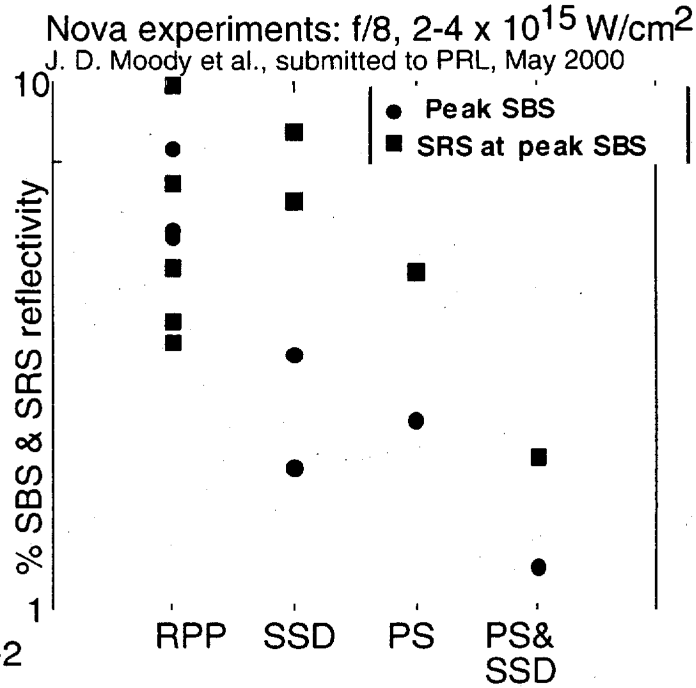
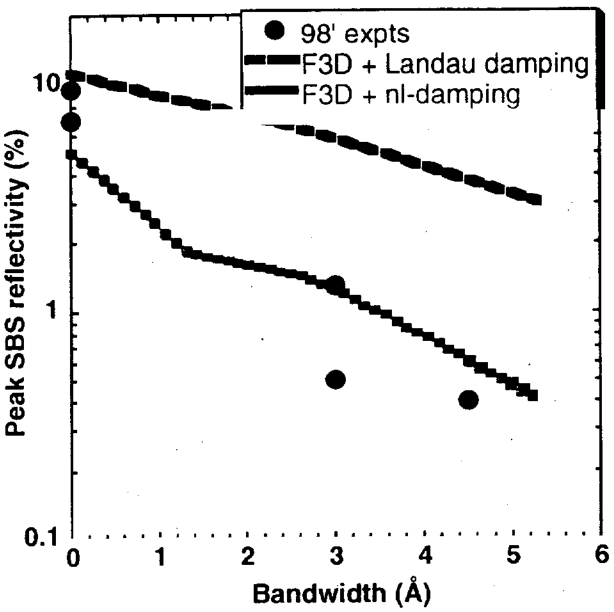
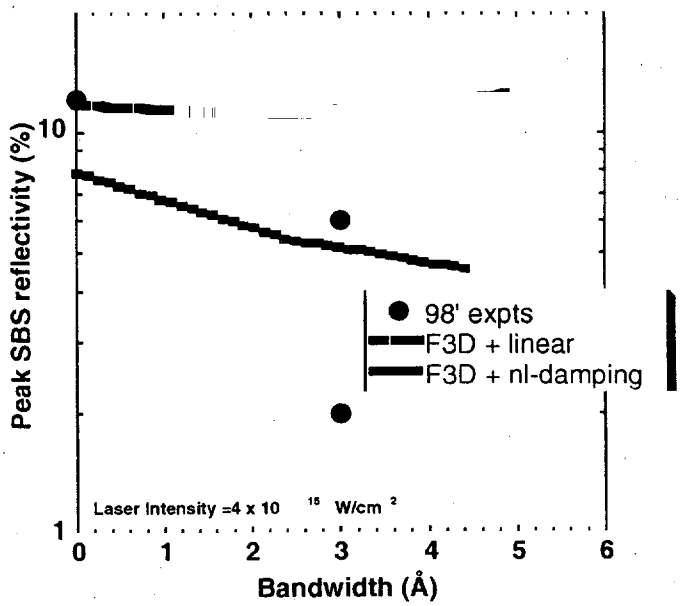


Fig 4b

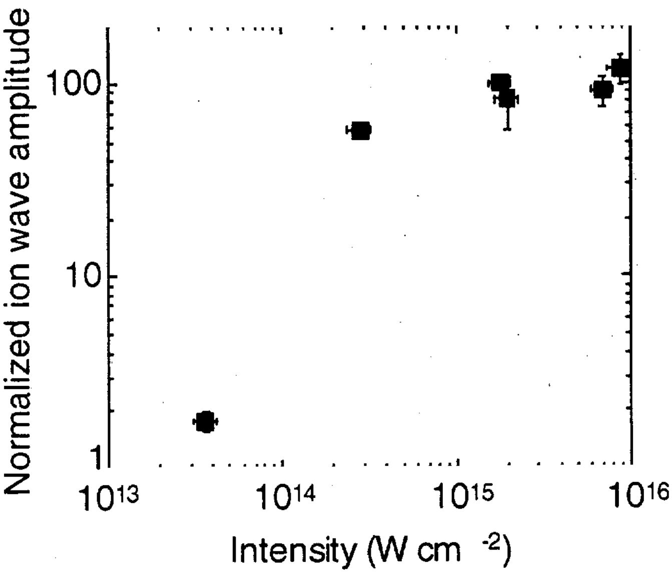
In the hydrocarbon (C_3H_8, C_5H_{12}, CH_4) and HeH filled gasbags, the acoustic waves that Brillouin scatter the light and are involved in the saturation of SRS are strongly damped ($\nu_a/\omega_a \sim 0.1$). In NIF and NOVA hohlraums, the light also interacts with high-Z gold plasma ablated from the gold container. The short wavelength ($\lambda = \lambda_0/2$) acoustic waves in gold are weakly damped by the plasma electrons, at least initially before a nonthermal tail develops by nonlinear wave-ion-particle interactions. For plasma conditions in hohlraums, extensive use is made of Lasnex simulations whose results are benchmarked by Thomson scattering, spectroscopy, and comparison of LIP-predicted spectra with observations[xi]. Using these plasma conditions, we have simulated the SBS from laser interaction with the gold plasma in NOVA scale-1 hohlraums as a function of the SSD bandwidth with and without polarization smoothing. With only linear damping of the acoustic waves, the simulations at 2 x 10^{15} W/cm^2 predict a weak dependence of the SBS reflectivity on the SSD bandwidth. The observations in Fig. 5 show a substantial reduction. However, using a nonlinear damping, whose magnitude depends on the ratio of the local acoustic wave amplitude to the threshold for two-ion-wave-decay, we find good agreement with that data. Simulations at 4 x 10^{15} W/cm^2 also show good agreement only when this nonlinear model is used.

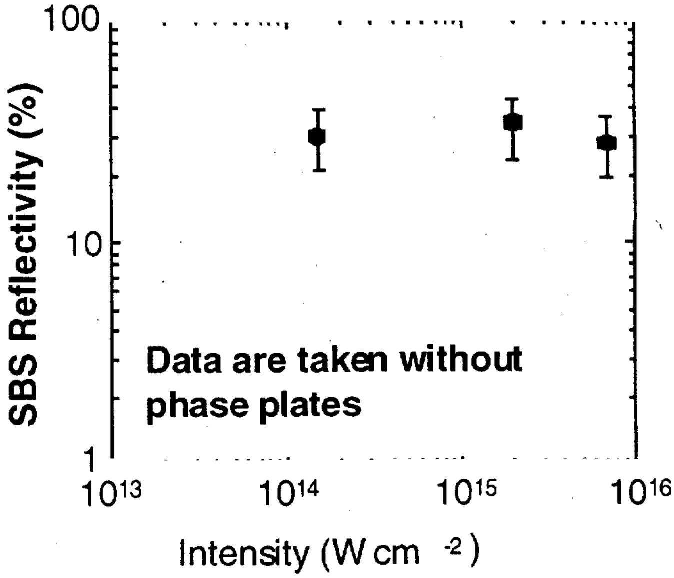




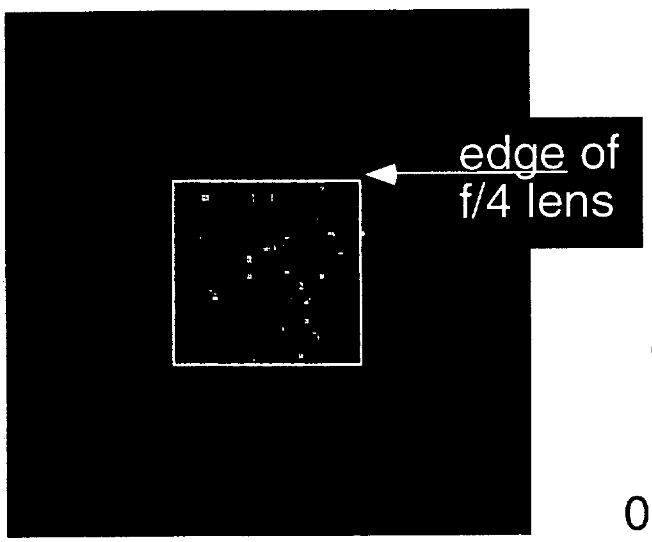
These predictions of a nonlinear limit on the amplitude of SBS-driven acoustic waves led to an experiment to observe directly the amplitude of these waves by Thomson scattering (TS) in CO_2-filled gasbags for incident intensities ranging from 5×10^{13} W/cm^2 to 8×10^{15} W/cm^2. Like gold, CO_2 acoustic waves are damped weakly by electron Landau damping. Unlike gold plasmas, the theory and experiments do not suffer from the complications of strong light absorption, X radiation effects, and the energy loss to radiation that dominates the electron energy balance calculation. Consider the geometry of the experiment where the f/4 351nm-wavelength interaction beam enters the gasbag from the right and the 263nm TS probe beam enters the bag from the left at an angle to the interaction beam of 41 degrees. The light Thomson scattered from the $2k_0$ acoustic wave that backscatters the interaction beam is observed at an angle of 97 degrees to the TS probe beam. The scattering volume is about (100 μm)^3. At the lowest interaction beam intensity, the TS signal consists of two narrow lines shifted symmetrically about the incident light which is also observed as stray light and is a convenient fiducial. The shift is consistent with the acoustic frequency for a wavenumber of $2k_0$ at a temperature of T_e =3 keV for CO2. At higher intensity, one line is enhanced as it is driven to nonthermal levels by SBS of the interaction beam. However, the dynamic range of the streaked recording is sufficient to measure the ratio of the two lines as a function of time and incident laser intensity. The TS signal peaks between 0.8-1.0ns as does the SBS backscatter of the incident light. That SBS light is a narrow line shifted to longer wavelengths by 8 Å and is consistent with scatter from a stationary plasma with no evidence of broadening from plasma flow velocity nonuniformities. This last observation is important because it constrains the modeling to look for nonlinear saturation as the limit on the SBS reflectivity and the TS signal.

In Fig. 6, we show the TS power and the SBS reflectivity as a function of the incident interaction beam intensity. The TS power in Fig 6a grows slowly above 3×10^{14} W/cm^2, remains at thermal levels for 5×10^{13} W/cm^2, and is about 100 times thermal at the highest intensity. The SBS reflectivity is about 30% between 0.8-1.0 ns and is roughly independent of incident interaction beam intensity above 3×10^{14} W/cm^2. We take these measurements as support for a model that strongly limits the amplitude of the acoustic wave above a threshold.





Finally, we discuss the possible problem that large SBS backscatter may cause for NIF even if the loss of power to the target is tolerable. In the plasma, the SBS light amplified in hotspots of the incident laser beam that are more than a coherence length apart. The SBS light from each hotspot of width $\sim f\lambda_0$ approximately fills the aperture in the nearfield. When the contributions from a large number of statistically uncorrelated SBS events are added, the result is (not surprizingly) a speckle distribution, i.e. a distribution that exponentially decreases with intensity relative to the mean intensity. The results of F3D simulations that confirm this conjecture is shown in Fig. 7.



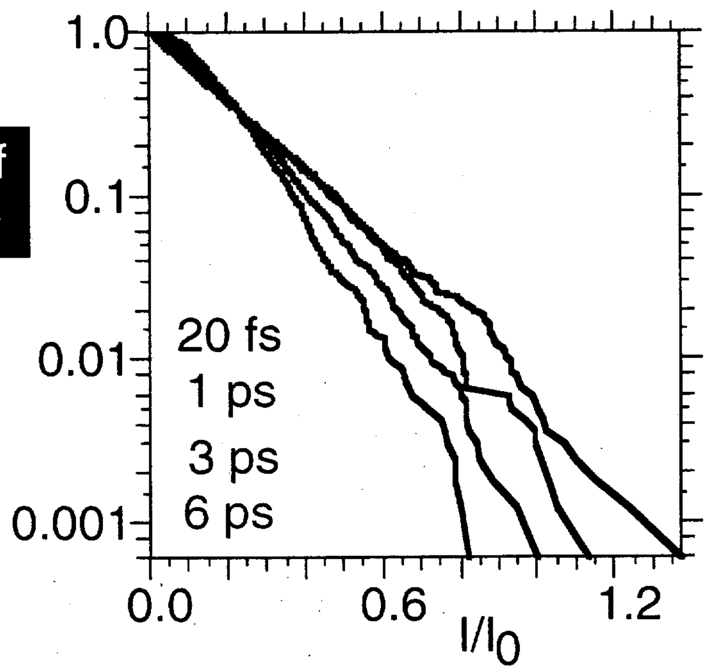


Fig. 7a

Fig 7b

In Fig. 7a, we show the speckley nature of the instantaneous backscattered light electric field intensity. In this calculation the incident light filled a square aperture uniformly in intensity but had 400 independent phase elements, fewer than will be used in NIF. Thus, the number of hotspots in the calculation of SBS is also smaller than appropriate for NIF. Nonetheless, as we show in Fig. 7b, the distribution of intensities of the reflected light in the nearfield is nearly exponential as conjectured. The amplitude of the reflected light in any one hotspot in the plasma varies in time such that the pattern of speckles in the nearfield is also time varying with a correlation time of ~ 6 ps. As a result, averaged over longer and longer times the intensity distribution of the nearfield reflected light gets smoother. In Fig. 7b, the effect of this smoothing on the intensity distribution is shown for averaging times of 20fs to 6ps. Even though the time-average intensity remains less than the incident light intensity, the fact that it is highly nonuniform may be dangerous for seeding filamentation in the optical components.

2. ACKNOWLEDGEMENTS

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