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BRILLOUIN SCATTER IN A HYDRODYNAMIC SIMULATION*

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ABSTRACT

A numerical method for modeling stimulated Brillouin scatter (SBS) in a hydrodynamic simulation code is discussed. Preliminary results using the model show that scattering is reduced as shorter wavelengths are used and for spherical symmetry that ion heating by SBS is not significant since the ions cool by expansion.

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Experiments[1,2] have demonstrated that stimulated Brillouin scatter (SBS) can reflect large amounts of laser light and therefore prevent efficient energy coupling between the laser and its target. Scattering instabilities are more important for larger targets and longer pulse lengths because they occur in the underdense plasma which grows as the target size and pulse length do. To model these targets accurately one must take into account the scattering instabilities.

In this paper our new model of SBS for computer simulations on fluid time scales is described. The limitations of the model are discussed and a few preliminary results are given. We find that SBS losses are reduced by going to shorter wavelength light and that ion heating by SBS is not a significant affect as the heat is quickly dissipated by expansion.

Our model is based on Kruer's[2] non-linear analysis of Brillouin scatter. We fit the data from a one-dimensional, kinetic, relativistic, electromagnetic simulation code, OREMP,[3] to an adaptation of the Brillouin scaling[2] which is made independent of zoning (eq. 1). See Fig. 1.

$$\text{reflection} = 1\text{-exp-}\left\{\frac{A[(v_0/v_t)^2(n/n_c)^y(\ell/\lambda_0)]}{(\omega_i/\omega_r)[1+(3T_i/ZT_e)][1-n/n_c]^{1/2}}\right\} = 1-e^{-q} \qquad (1)$$

where ω_r/ω_0 = ion acoustic frequency/laser frequency = kc_s/ω_0, c_s = sound speed = $\left\{(ZT_e + 3T_i)/[m_i(1 + k^2\lambda_D)]\right\}^{1/2}$, k = ion acoustic wave number = $2(\omega_0/c)(1 - n/n_c)^{1/2}$, ω_i = ion Landau damping (see Figs. 2 and 3). ℓ = zone length, v_o = $eE(\text{position})/(m_e\omega_o)$ = electron peak oscillatory velocity in the electric field (E) of the laser light of angular frequency ω_o. e/m_e = electron charge to mass ratio, λ_o = laser vacuum wavelength. I = laser vacuum intensity in W/cm^2, $v_t = T_e/m_e$, n/n_c = electron density/critical density, λ_d = electron Debye length, m_i = ion mass, T_e = electron temperature and T_i = ion temperature. This form is reasonably good only for $v_o/v_t \lesssim 1$ and consequently the code has a non-linear statement to describe wave saturation. We have found that the non-linear limiter plays an important role in the scattering for typical targets and is simply reflection $\lesssim .17\ n/n_c$ reflection per λ_o. The development on the non-linear model and the interpretation and fitting of the results of kinetic simulations in the saturated regime are still in progress.

Eq. 1 is fitted to a large number of kinetic simulations which studied Brillouin backscatter as a function of the parameters between limits $.3 < v_o/v_t < 2.$, $10 < L/\lambda_o < 127$, $.05 < n/n_c < .7$, $1 <$ *initial* $T_e/T_i < 30$, $\omega_r t < 10$. *A best fit for eq. 1 to the* simulation data for $.3 < n/n_c < .7$ was $y = 1$, $A = .04$. However, some experimentation was done with $y = 2,3$ and $A = .08, .12$ respectively. This will be discussed later.

Kruer's more complete form showed a region of exponential increase with q for low q and a region of pump depletion limit at high q and consequently was zoning dependent if fitted to each zone. Eq. 1 assumes that the Brillouin is always in a pump depletion limit which is not always strictly correct, but has the advantage that it is reasonably independent of zoning and is suited to density and temperature gradients. At each timestep, for each zone from vacuum to critical. starting with the edge that the laser first strikes, light is reflected according to eq. 1. The ions are then heated according to the Manley-Rowe relations $\Delta T_i/\Delta t$ = reflection $(\omega_r/\omega_0)[I/(\ell n_i)]$ and the intensity in the next zone away from the light is decreased by the fraction of light reflected by the previous zone.[4] The ion heating increases the ion Landau damping which in turn decreases the reflection on the next timestep.[4] Light momentum also acts on the plasma.

In general we have found that this model errs on the side of reflecting more light than is experimentally observed or inferred. There are many reasons which may explain the difference. We are modeling complex plasma phenomena with a few macroscopic variables. A list of these reasons, or alternatively a list of present and future considerations of our model is as follows: (1) Brillouin heats up the ions[2,4] on each reflection and there can be multiple reflections.[4,6] The model does not yet follow each multiple reflection but does follow Brillouin of the light reflected from critical. Our model does not calculate the inverse bremsstrahlung absorption of the scattered light as it propagates back out of the target. This absorption could be quite important in some targets (e.g. high-Z targets). (2) Most of the heated ions are accelerated up to higher densities so that they are in position and velocity space to do the most damping. Since the ion-ion equilibration time is generally not small, this effect is significant.[5] The model does not specifically include this although there is a parameter to mock this up artificially by a multipler on T_i used in the ω_i/ω_r calculation. (3) Kinetic simulations revealed that for densities less than .25 n_c that the Compton instability (another word for Raman below the resonant density) heats in a surprisingly vigorous fashion and thus lowers q by increasing v_t. If one includes the Compton heating and the swelling term, OREMP runs are consistent with the theory[2] with y = 1, otherwise y's of 2 to 3 are needed to fit the kinetic simulation data. Since Compton occurs at plasma densities lower than those in the region of traditional absorption by inverse bremsstrahlung, resonant absorption, and instabilities and also lower than the densities at which Brillouin is most potent, then it and quarter critical instabilities might become the dominant absorption mechanism[7] for reactor pulse lengths. We are working on a Compton model. (4) Brillouin is a convective instability. For q small, the reflection grows exponentially[2] rather than the pump depletion limit $1 - e^{-q}$. Using $y \gtrsim 2$ allows one to more accurately fit this limit. Effects[5-16] are not presently included in the code. (5) The ion acoustic instability[8,9] transfers energy from the electron drift to the ion kinetic energy. We are considering Manheimer's ion heating model.[8] (6) Ion-ion streaming instabilities between ion species of different Zm_e/M_i [9,10] may produce ion heating. (7) Brillouin increases greatly[6] in the region where the relative velocity between critical and that region is Mach $(1 - n/n_c)^{1/2}$. For long density gradients, other plasma effects that may also become important are the (8) $2\omega_p$ and (9) Raman back and side scatter[11] which can heat electrons to suprathermal temperatures, and (10) filamentation which can concentrate the light so that when it reaches critical (as well as quarter critical). the high intensity can heat electrons to higher temperatures than would otherwise occur. For filamentation to dominate[11,14] Brillouin back and sidecatter, $ZT_e/T_i \lesssim 1$. (11) There is experimental evidence that the density profile undergoes relaxation oscillations that occur on both fast[12] and slow[13] time scales. Some of these may be due to the flow through critical becoming sub and supersonic,[12] laser hot spots, surface instabilities, magnetic fields or other effects yet unknown. Even in the short time and space scales of the kinetic simulations, there are very large oscillations in the Poynting vector of the reflected and transmitted light. At times much more light is reflected than is transmitted since light undergoes multiple reflections even in an entirely underdense plasma. (12) Density gradient thresholds[15] are not included, but are being seriously considered. (13) Velocity gradient effects were found to be small. (14) The kinetic simulations were limited to times of 10 ion acoustic periods. (15) Ion-ion collisions ν_{ii} can reduce damping for $\nu_{ii} > \omega_r$ and are not yet included nor is (16) sidescatter.

Our preliminary results on the scaling of SBS and light absorption with laser wavelengths showed a definite trend of reduced scattering and increased absorption as the laser wavelength is decreased from 1 μm to 1/4 μm falling off more sharply near 1/4 μm. See. Fig. 4.

For spherical expansion where $c_s\tau \gtrsim r$ or slab illumination where $c_s\tau \gtrsim D$ the strong ion heating by SBS does not limit reflection as ion expansion dissipates the ion heating quite efficiently. For example, if the energy deposited into ion waves is assumed to heat all ions and to be carried away as rapidly as possible, i.e. free streaming, the following energy balance equation is obtained.[2]

$$\text{(reflection)} \quad I \; \frac{\omega_r}{\omega_o} \; = \; n_i T_i v_i \qquad (2)$$

where v_i is the ion thermal speed. For $I = 10^{14}$ W/cm^2, $n_i = Zn_e = Z \cdot 10^{21}$ cm^{-3}, $T_e = 2$ keV. $A = 200$, $Z = 50$, equation (2) gives $T_i = 10$ keV. In a calculation with these conditions, the ion temperature was hottest in the critical zone with $T_i \sim 7$ keV. The ion temperature dropped sharply away from the critical surface becoming half of the maximum T_i in 100 μm. The density scale length at this time was ~ 100 μm. In the 100 psec preceding the peak of the pulse .04 of a joule was deposited to the ions through SBS. In that same time .03 of a joule of ion energy went to hydrodynamic expansion. Consequently, we find the non-linear saturation of the ion waves to be the dominant limiting mechanism on reflection.

In conclusion, we have implemented a stimulated Brillouin scatter model in our hydrodynamic code. This model has yielded some interesting results, but it is still under development.

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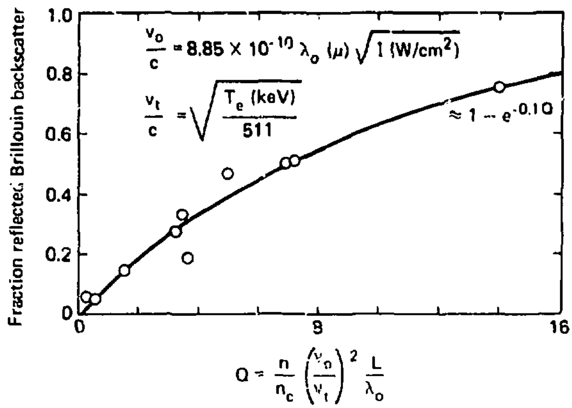
FIGURE CAPTIONS

Fig. 1 Fraction reflected by SBS vs q fitted to the data from kinetic simulations, the points shown.

Fig. 2 Our fit of $\frac{\omega_i}{\omega_r}$ vs $k\lambda_D$ for various temperature ratios.

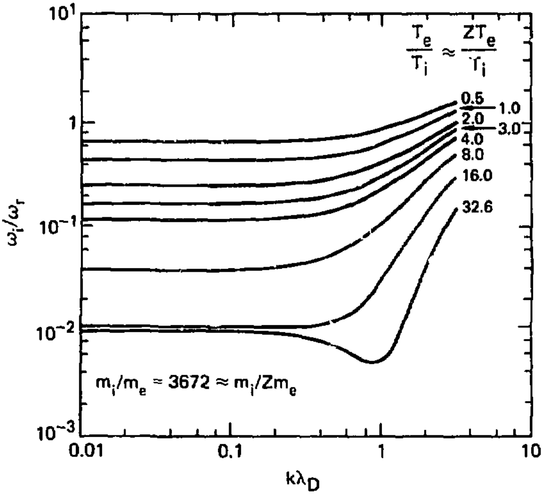
Fig. 3 Our fit of $\frac{\omega_i}{\omega_r}$ vs temperature ratio for various mass ratios.

Fig. 4 Reflection due to the Brillouin instability as determined by the code. The 1.06 μm, y = 2 point is fit to experimental data. However, the trends are more correct than the absolute numbers. We have not made an exhaustive parameter study, but 1 nsec simulations on gold at intensities 5×10^{14} and 10^{14} show even more dramatic increase in absorption with uv light as does glass with lower intensity.



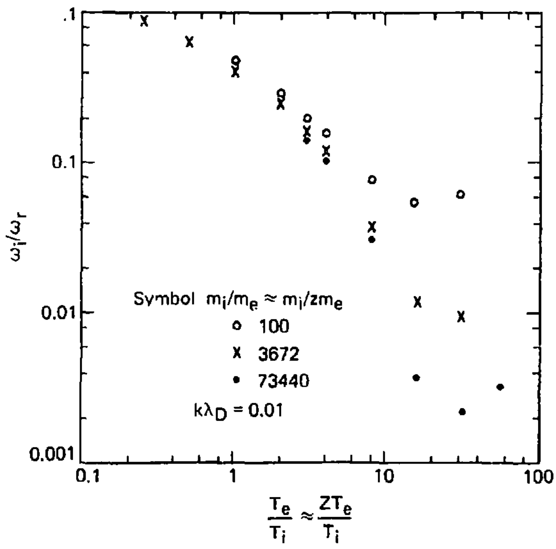
Fraction reflected Brillouin backscatter
1.0
0.8
0.6
0.4
0.2
0
0
8
16
$\frac{v_o}{c} = 8.85 \times 10^{-10} \lambda_o (\mu) \sqrt{I\ (\mathrm{W/cm^2})}$
$\frac{v_t}{c} = \sqrt{\frac{T_e\ (\mathrm{keV})}{511}}$
$\approx 1 - e^{-0.1Q}$
$Q = \frac{n}{n_c} \left(\frac{v_o}{v_t}\right)^2 \frac{L}{\lambda_o}$

Fig. 1



10^1
1
10^{-1}
10^{-2}
10^{-3}
ω_i/ω_r
0.01
0.1
1
10
$k\lambda_D$
$\frac{T_e}{T_i} \approx \frac{ZT_e}{T_i}$
0.5
1.0
2.0
3.0
4.0
8.0
16.0
32.6
$m_i/m_e = 3672 \approx m_i/Zm_e$

Fig. 2



.1
0.1
0.01
0.001
0.1
1
10
100
ω_i/ω_r
Symbol $m_i/m_e \approx m_i/zm_e$
o 100
x 3672
• 73440
$k\lambda_D = 0.01$
$\frac{T_e}{T_i} \approx \frac{ZT_e}{T_i}$

Fig. 3

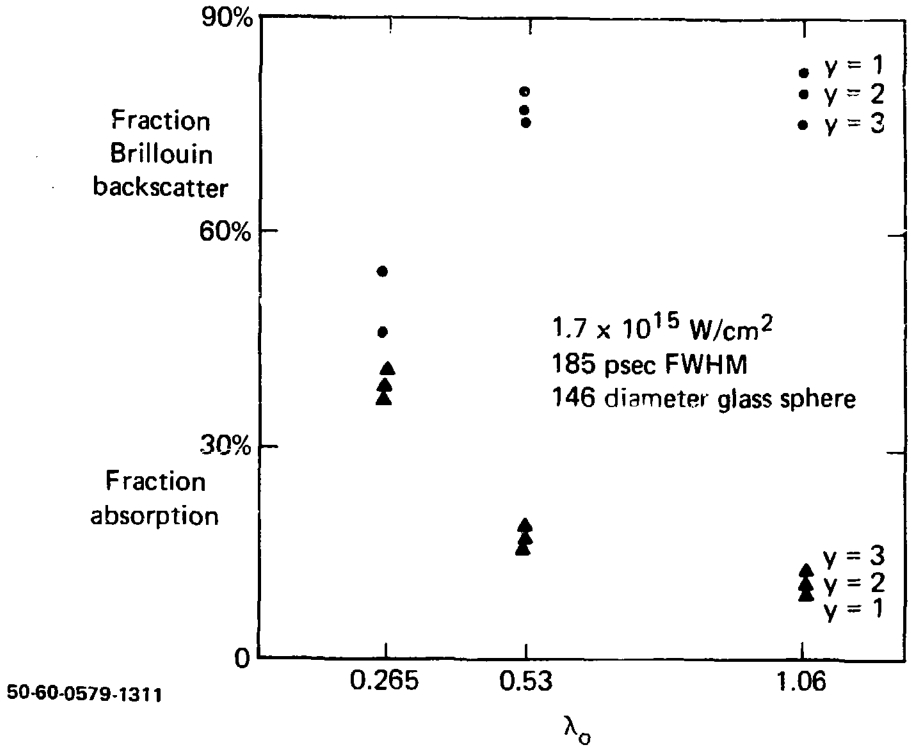

90%
60%
30%
0
Fraction
Brillouin
backscatter
Fraction
absorption
γ = 1
γ = 2
γ = 3
1.7 x 10^15 W/cm^2
185 psec FWHM
146 diameter glass sphere
γ = 3
γ = 2
γ = 1
0.265
0.53
1.06
λo
50-60-0579-1311

Fig. 4