Three-Halves-Harmonic Radiation from Long-Scale-Length Plasmas Revisited

Introduction

Starting with the very early experiments relating to laser fusion, observations have shown a characteristic spectral emission near the 3/2 harmonic of the irradiating laser wavelength.[1] For simplicity we will name this emission "3/2 self-emission" to distinguish it from similar spectral features that may be induced by a separate probe beam. This spectral signature was immediately recognized as being related to the underlying two-plasmon-decay[2–5] (TPD) instability near quarter critical density. The detailed generation mechanism for this emission is, however, still a subject of considerable controversy and active research. This article represents another attempt to explain the detailed origin of this emission and its consequences for diagnostic applications. These conclusions can be succinctly summarized as follows: (1) The observed threshold for this 3/2 emission is not a good indicator of the threshold of the underlying TPD instability; (2) the absence of 3/2 emission is not a reliable indicator of the absence of the TPD instability; and (3) the value of the spectral features as a temperature diagnostic is very limited at best.

These conclusions are contrary to the majority of published work.[6–9] On the other hand, LLE's position on this subject has been one of caution for quite some time,[10,11] clearly de-emphasizing the diagnostic value of this signature. More recently, Meyer and Zhu[12] reported on Thomson scattering experiments on CO_2-laser-plasma interactions that showed broadening of the k-vector spectrum of TPD plasma waves well above threshold. Their conclusions are essentially similar to ours, although they did not discuss the detailed 3/2-harmonic spectra and their relevance to shorter wave interaction physics.

The continued interest in the TPD instability lies primarily in its potential for generating energetic electrons,[13] which could prove detrimental for laser fusion. The energetic electrons are produced as a consequence of the large-amplitude plasma waves generated by the TPD instability. The threshold of the TPD instability is a few times 10^{13} W/cm^2 for typical laser-fusion applications.[11] In long-scale-length plasmas this instability is apparently not influenced significantly by current laser-beam-smoothing schemes, such as smoothing by spectral dispersion (SSD).[11] Contrary results were obtained in experiments with induced spatially incoherent[14] (ISI) beams. However, these experiments were single-beam, solid-target experiments with short density scale lengths and may therefore lead to different interaction results.

Experimental Setup and Data

The experiments were carried out on the 24-beam OMEGA UV (351-nm) laser system using eight beams to explode mass-limited targets (6-μm-thick, 600-μm-diameter CH targets). Another set of eight beams was delayed by 0.6 ns and maintained the electron temperature at $\geq$1 keV over periods of ~1 ns. An additional interaction beam was then incident on the plasma perpendicular to the original target surface and could be timed within a few nanoseconds of the heating beams. All beams were outfitted with distributed phase plates (DPP) for increased average irradiation uniformity (ignoring the high-frequency DPP speckle pattern). The plasma produced in this way has been carefully characterized[15] and modeled using the two-dimensional hydrodynamic code *SAGE*.

Streaked 3/2-harmonic spectra were taken primarily in the backscatter direction at ~30° with respect to the interaction beam. Details of these and other data have been reported in Ref. 11. Here we would like to discuss in more detail the 3/2 self-emission, which was only perfunctorily dealt with in Ref. 11.

In Fig. 57.12 we have reproduced two typical streaked spectra. The upper streak was taken with secondary heating beams, while the lower streak was taken without secondaries. The weak signal around 1 ns is due to the primary heating beams and is of no interest in this discussion. The typical, split 3/2 emission of interest is located between 1.4 and 2.1 ns in this figure. The temporal pulse shape of the secondary heating beams is shown superposed in the upper half. (The primary heating beams have the same pulse width and peak at 1 ns but are not shown in this figure.) The dotted line superposed on

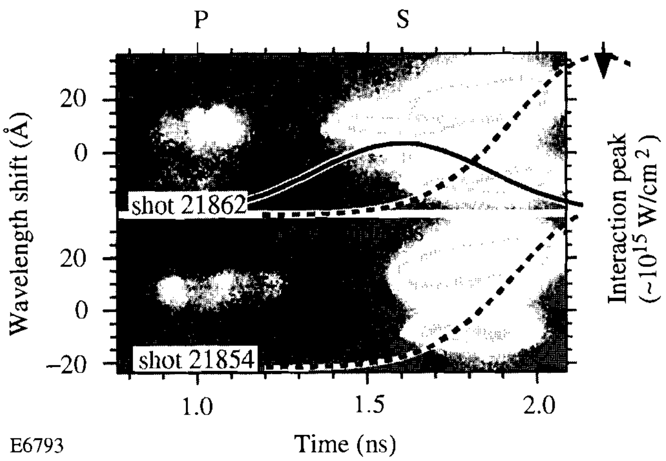

Figure 57.12
Streaked, 3/2-harmonic self-emission spectra from long-scale-length laser plasmas. Upper streak: spectrum in the presence of primary (P), secondary (S), and interaction (I) beams timed at t = 1 ns, 1.6 ns, and 2.2 ns, respectively. The intensities of the individual primary and secondary beams are ~5 to 6 × 10^{13} W/cm^2; that of the interaction beams is ~10^{15} W/cm^2. Lower streak: same as above but without secondary heating beams.

both streaks represents the normalized interaction beam intensity, which peaks at 2.2 ns. Note that the two curves are not drawn to scale; the on-target peak intensity of the interaction beam is ~10^{15} W/cm^2, while the peak intensity of each of the secondary (and primary) beams lies around 5–6 × 10^{13} W/cm^2.

There is one obvious difference between the two streaks shown in Fig. 57.12. The upper trace contains an additional spectral component that starts at ~1.4 ns, well before the onset of the main 3/2 emission, and exhibits a smaller frequency shift relative to $3\omega_0/2$. This component has been discussed in detail in Ref. 11, where it was tentatively identified as due to Thomson scattering off TPD plasmons excited by one particular secondary heating beam. In this case the interaction beam plays only the role of a Thomson probe. Separate experiments have since verified this identification. This Thomson-scattering feature is thus a very sensitive diagnostic for the TPD threshold. The threshold was found to be ~2–3 × 10^{13} W/cm^2 for the following plasma conditions near $n_c/4 : T_e \approx 1$ keV, density scale length $L_n \approx 250$ μm, λ_L = 351 nm. The theoretical TPD threshold[4] is given by

$$I_{th}^{2\omega_p} \approx 5.2\times 10^{15} T_{keV} / \left(L_{n,\mu m} \lambda_{\mu m} \right)$$

$$\approx 6\times 10^{13}\ W/cm^2 .$$

This intensity is ~2–3 times higher than the experimental threshold but is consistent with the intensity distribution of a typical DPP speckle pattern in which ~60% of the energy is found at intensities above the peak of the smooth Airy envelope. The latter is the generally accepted nominal beam intensity, but significant energy content is found right up to ~3 times the nominal peak intensity.

By contrast, the main 3/2-harmonic, self-emission feature exhibits larger frequency splitting (~18-Å red shift and ~12-Å blue shift) and has a threshold of a few 10^{14} W/cm^2 (see Fig. 57.12). This threshold is 5–10 times higher than the TPD threshold determined above. Thus the 3/2 self-emission threshold is not a good measure of the TPD threshold nor is the absence of 3/2 self-emission proof that the TPD instability is not excited. Here we make the usual assumption that all 3/2 emission is due to some form of Thomson scattering involving incident photons of the interaction beam and plasmons of frequency close to $\omega_0/2$, which are in some way related to the TPD instability. The problem with this assumption is the difficulty of satisfying the required phase-matching conditions.

Interpretation of Data

Reference 11 pointed out that the frequency splitting of the self-emission spectra is consistent with Thomson scattering of the interaction beam off TPD plasmons near the Landau cutoff. However, the phase-matching conditions for this scattering process are not easily satisfied, as will be discussed below. In addition, the theoretically predicted, maximum TPD growth occurs closer to $n_c/4$ with correspondingly smaller frequency splitting between the plasma waves, yet we find no evidence of these plasmons in the 3/2-harmonic self-emission spectra. However, it should be kept in mind that the growth rates drop off only very slowly with decreasing electron density.[4]

In Fig. 57.13 the TPD decay diagram is shown in k-vector space with $k_{\parallel}$ aligned with the density gradient prevailing in the interaction region. All TPD decay triangles terminating on a given horizontal line result in plasma waves with the same frequencies, $\omega_0/2 \pm \Delta\omega$. The TPD growth rate has its maximum along the hyperbola shown in the graph and drops to zero near the Landau cutoff, and also for $k_{\perp} = 0$. The growth rate[4] decreases quite slowly as one moves away from the hyperbola of maximum growth, as is also shown in Fig. 57.13 ($\gamma \approx 0.6\,\gamma_{max}$ at edge of shaded area).

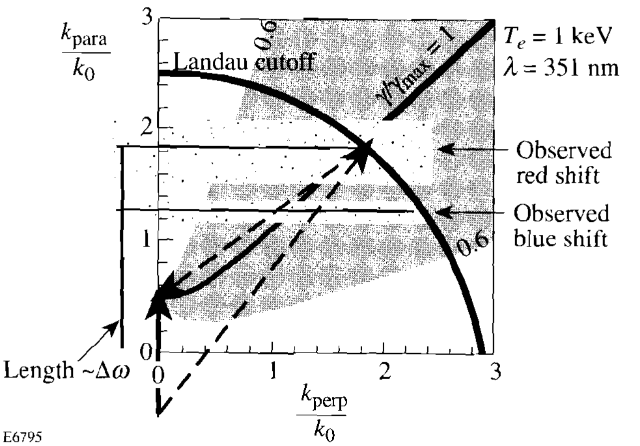

Figure 57.13
Two-plasmon decay diagram in k-space with $k_{\parallel}$ aligned parallel to incident beam and local density gradient. The Landau cutoff is given by $k\lambda_D = 0.3$. The frequency shifts of the two TPD daughter waves are proportional to the ordinate of the apex of the decay triangle as shown. The shaded areas correspond to the observed shifts for the red and blue components of the 3/2-harmonic self-emission.

The upper, stippled, horizontal area indicates the range of 3/2-harmonic red shifts seen in the experiments. The observed blue shifts are smaller and correspond to the lower stippled area as though the two 3/2-harmonic features originated from different decays. This difficulty can be removed as follows: First we assume that the primary TPD decays occur near the Landau cutoff and close to the maximum growth rate hyperbola. Second, to approach the phase-matching conditions for Thomson scattering involving an incident photon (wave vector k_0) and a "blue" plasmon, we must invoke a secondary electron plasma wave (EPW) decay of the "blue," i.e., longer k-vector plasmon. This results in a reduced blue-shifted secondary plasmon whose direction is parallel to that required for phase matching for Thomson scattering (see lower half of Fig. 57.14). The blue shift of this plasmon from $\omega_0/2$ also corresponds closely to that observed for the blue 3/2-harmonic feature as was already pointed out in Ref. 11. This kind of secondary decay process has been variously invoked experimentally[16,17] and theoretically[18] but was usually combined with propagation of plasmons in the density gradient. However, the importance of a threshold of these secondary decays has not been recognized.

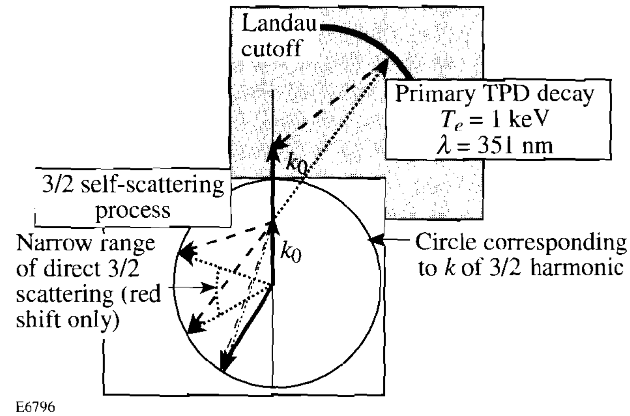

Figure 57.14
k-vector diagrams of the primary TPD decay and the secondary Thomson scattering process leading to 3/2-harmonic self-emission. The upper part of the figure shows the primary TPD decay, while the circle in the lower part represents the locus of the 3/2-harmonic em wave generated by summing an incident photon (k_0) with a plasmon. With the exception of a small range of "red" plasmons giving rise to near-90°-sidescattering, 3/2-harmonic radiation, all plasmons participating in the Thomson-scattering process must first undergo a secondary electron plasma wave decay for the "blue" plasmons or must be scattered by appropriate ion waves ("red" plasmons).

Invoking the secondary EPW decay has a number of interesting consequences: (1) It explains the higher threshold for the 3/2 self-emission compared to the TPD threshold since the plasma waves have to build up to where their intensity exceeds the threshold of the EPW decay instability. (2) The EPW decay growth rate is proportional to k and thus maximizes near the Landau cutoff. This could explain why the dominant 3/2 emission reflects TPD decays just below the Landau cutoff density. Furthermore, the decay process, while peaking in back direction, is not restricted to exact backscattering. It can thus generate the plasma waves with the proper direction for phase matching to Thomson scattering as discussed above (see Fig. 57.14). (3) Once the EPW decay instability is above threshold, ubiquitous ion waves are produced, which has been variously reported in PIC code simulations[19,20] and in experiments on 3/2-harmonic generation.[21,22]

Direct experimental evidence for the TPD instability near the Landau cutoff is shown in Fig. 57.15. The scattering configuration for this streaked spectrum is indicated at the top of the figure. One of the secondary beams was selected as the "interaction beam" while the nominal interaction beam was delayed to peak 1 ns later as indicated in the figure. The very strong Thomson signal exhibits exactly the predicted shift and is only visible in the presence of the secondary beam acting as interaction beam. (Note that the polarization was chosen to optimize this signal and that experimental constraints forced us to probe TPD decays below the maximum growth rate hyperbola. The exact decay triangle probed was located in the lower stippled area (see Fig. 57.13) and very near the Landau cutoff.

The spectral splitting of the 3/2-harmonic self-emission is of very dubious diagnostic value for estimating the coronal temperature. The above model for generating this 3/2 self-emission involves two competing effects: the spectral splitting increases with temperature for any given plasmon k-vector length $\left(\Delta\omega \sim k^2 T_e\right)$, but this effect is counterbalanced by the k-vector cutoff set by Landau damping:

$$\left(k_{\text{cutoff}} \sim 1/\lambda_D \sim T_e^{-1/2}\right).$$

Thus, one would not expect any significant temperature dependence of the 3/2 spectral splitting, which corresponds well to most of our observations. The lower streaked spectrum in Fig. 57.12 is a notable exception: here, the intense interaction beam is incident on a very cold plasma (no secondary heating beams), and very strong heating (and filamentation) is expected.

Conclusions

In this article we propose a new interpretation of the ubiquitous 3/2-harmonic emission from laser-produced plasmas. This emission is a consequence of the strongly driven TPD instability whose plasma waves (daughter waves) undergo secondary electron plasma wave decays above a certain threshold. The plasma waves produced in this process can then be Thomson scattered using again photons of the interaction beam. The resulting spectral shifts are in accord with experimental observations. On the other hand, the 3/2 self-emission threshold reflects the threshold of the EPW decay instability rather than that of the primary TPD instability. While the existence of the 3/2-harmonic emission is always associated with the TPD instability, its absence is not conclusive proof for the absence of the TPD instability. Within the framework of this model the 3/2 self-emission spectra are not a useful temperature diagnostic.

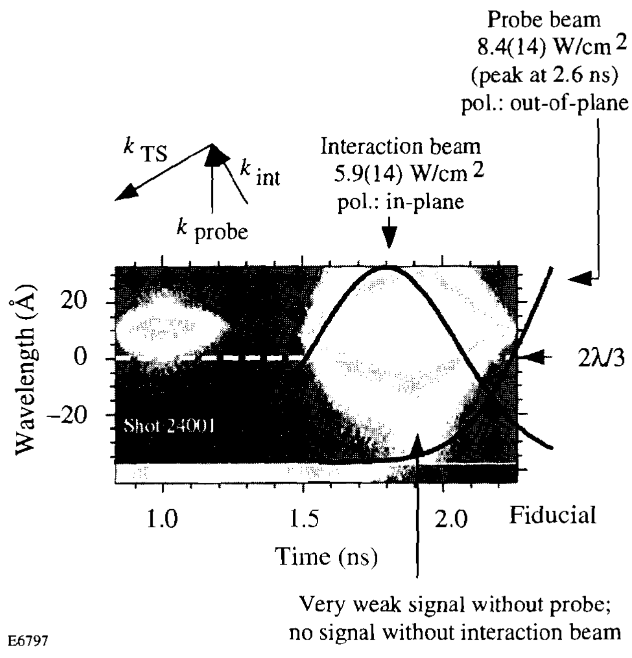

Figure 57.15
Direct evidence of TPD decay near the Landau cutoff using Thomson scattering. The TPD decay was driven by a particular secondary beam focused to ~6×10^{14} W/cm^2 (averaged over the DPP speckle pattern). The Thomson probe beam was delayed to peak at 2.6 ns to avoid any accidental 3/2-harmonic generation from the probe beam itself.

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REFERENCES

1. J. L. Bobin *et al.*, Phys. Rev. Lett. **30**, 594 (1973); P. Lee *et al.*, Appl. Phys. Lett. **24**, 406 (1974); H. C. Pant *et al.*, Opt. Commun. **16**, 396 (1976).
2. C. S. Liu and M. N. Rosenbluth, Phys. Fluids **19**, 967 (1976).
3. A. Simon, R. W. Short, E. A. Williams, and T. Dewandre, Phys. Fluids **26**, 3107 (1983).
4. W. L. Kruer, The *Physics of Laser Plasma Interactions* (Addison-Wesley Publ. Co., Redwood City, CA, 1988), pp. 81 ff.
5. H. A. Baldis, E. M. Campbell, and W. L. Kruer, *Handbook of Plasma Physics,* edited by N. M. Rosenbluth and R. Z. Sagdeev (Elsevier Science, Amsterdam, 1991), Vol. 3, pp. 397–408.
6. A. I. Avrov *et al.*, Sov. Phys. JETP **45**, 507 (1977); V. Yu. Bychenkov *et al.*, Beitr. Plasma Phys. **23**, 331 (1983); R. L. Berger and L. V. Powers, Phys. Fluids **28**, 2895 (1985).
7. J. Meyer, Y. Zhu, and F. L. Curzon, Phys. Fluids B **1**, 650 (1989).
8. P. E. Young *et al.*, Phys. Rev. Lett. **61**, 2766 (1988).
9. P. E. Young *et al.*, Phys. Fluids B **2**, 1228 (1990).
10. W. Seka, B. B. Afeyan, R. Boni, L. M. Goldman, R. W. Short, K. Tanaka, and T. W. Johnston, Phys. Fluids **28**, 2570 (1985).
11. W. Seka, R. E. Bahr, R. W. Short, A. Simon, R. S. Craxton, D. S. Montgomery, and A. E. Rubenchik, Phys. Fluids B **4**, 2232 (1992).
12. J. Meyer and Y. Zhu, Phys. Rev. Lett. **71**, 2915 (1993).
13. N. A. Ebrahim *et al.*, Phys. Rev. Lett. **45**, 1179 (1980); D. W. Phillion *et al.*, Phys. Rev. Lett. **49**, 1405 (1982); D. M. Villeneuve, R. L. Keck, B. B. Afeyan, W. Seka, and E. A. Williams, Phys. Fluids **27**, 721 (1984); R. L. Keck, L. M. Goldman, M. C. Richardson, W. Seka, and K. Tanaka, Phys. Fluids **27**, 2762 (1984).
14. T. A. Peyser *et al.*, Phys. Fluids B **3**, 1479 (1991).
15. W. Seka, R. S. Craxton, R. E. Bahr, D. L. Brown, D. K. Bradley, P. A. Jaanimagi, B. Yaakobi, and R. Epstein, Phys. Fluids B **4**, 432 (1992).
16. F. Amiranoff, F. Brian, and C. Labaune, Phys. Fluids **30**, 2221 (1987).
17. A similar secondary decay process was proposed for the strongly driven parametric decay instability by K. Tanaka, W. Seka, L. M. Goldman, M. C. Richardson, R. W. Short, J. M. Soures, and E. A. Williams, Phys. Fluids **27**, 2187 (1984).
18. H. C. Barr and G. A. Gardner, in the *1984 International Conference on Plasma Physics,* edited by M. Q. Tran and M. L. Sawley (Ecole Polytechnique, Lausanne, 1984), Vol II, p. 265; S. J. Karttunen, Laser and Particle Beams **3**, 157 (1985).
19. A. B. Langdon, B. F. Lasinski, and W. L. Kruer, Phys. Rev. Lett. **43**, 133 (1979).
20. D. F. DuBois and H. A. Rose, Bull. Phys. Soc. Am. **38**, 1913 (1993), paper 2Q 6.
21. P. E. Young *et al.*, Phys. Rev. Lett. **61**, 2766 (1988).
22. D. M. Villeneuve, H. A. Baldis, and C. J. Walsh, Phys. Fluids **28**, 1454 (1985); H. A. Baldis and C. J. Walsh, Phys. Scr. **T2/2** (1982); H. A. Baldis and C. J. Walsh, Phys. Rev. Lett. **47**, 1658 (1981).