2.D Three-Halves Harmonic Spectra and Self-Focusing in Laser Plasmas

We have recently reported on the spectral characteristics and the generation mechanisms for the harmonic radiation emitted from laser-produced plasmas.[1] We noted on that occasion that the observed asymmetric splitting of the $3\omega_0/2$ spectra from UV-laser plasmas (Fig. 16) could not be explained on the basis of a planar plasma-expansion model. In the preceding article of this review, the theoretical basis has been laid for the two-plasmon decay instability (TPD) inside filaments formed by the incident laser in the plasma corona. In this article we present some experimental data recently obtained on thin plastic targets irradiated at 351 nm at intensities of up to 10^{15} W/cm^2 on the UV irradiation facility, GDL.

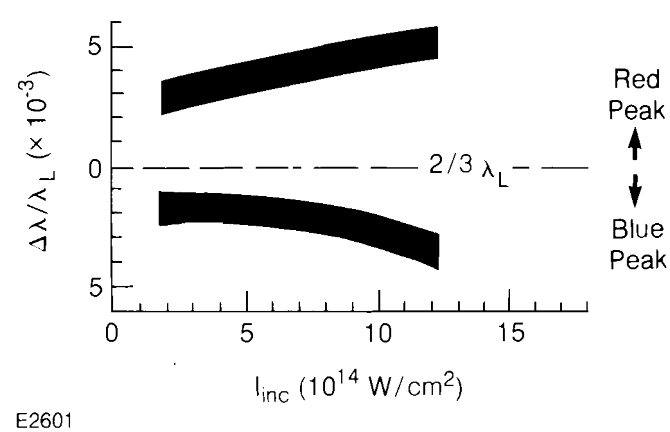

Fig. 16
Intensity dependence of the spectral splitting of the $3\omega_0/2$ radiation emitted from planar UV plasmas. We note the strong asymmetry of the splitting which cannot be modeled by conventional theory applied to planar targets. The data were taken with 0.5 ns at λ_L = 351 nm. Irradiated spot radius ranged from 50 μm to 200 μm. The targets were thick CH foils.

The existence of the filamentation of the incident laser light in the corona of laser plasmas has been known for some time. Experiments employing visible shadowgraphy have revealed evidence for filamentation under certain irradiation conditions.[2] At LLE, we do not have any direct evidence of filamentation. Indirect evidence for filamentation exists in some of the single-beam, planar target experiments conducted with the GDL laser. Furthermore, there is some evidence that nonlinear interaction mechanisms such as the two-plasmon decay (TPD) instability, observed in these one-beam experiments, occurs predominantly in filaments. In this article we present some spectroscopic data related to the preceding theoretical article on TPD inside filaments.

In experiments on thin plastic foils, irradiated in GDL with a single UV beam, we have observed the $3\omega_0/2$ spectra around 234 nm in several different angular directions: in backscattering through the focusing lens, at 45°, and in forward scattering at 135° with respect to the incident light (45° with respect to the forward direction). A schematic layout of the experiments and typical spectra are shown in Fig. 17. The intent of these experiments was to show that the forward-scattered $3\omega_0/2$ spectra consist of only a single, blue-shifted component, as predicted by conventional theory for the scattering of incident photons from the higher-frequency plasmons produced by the TPD instability. In marked contrast to these predictions, our experiments on thin plastic foil showed forward-scattered $3\omega_0/2$ spectra consisting of a single, slightly red-shifted component (Fig. 17). Furthermore, the observed red-shift of the forward-scattered spectra was roughly equal to the shift of the blue component of the backscattered spectra at either 0° or 45°. The backscattered red component, in contrast, exhibited shifts which were two to three times larger. This asymmetry is, of course, exactly the same as that shown in Fig. 16 for thick targets, which could not be explained by conventional theory in Ref. 1. In the thin-target experiments, however, we noted a clear decrease of the intensity of the blue backscatter component relative to the red one.

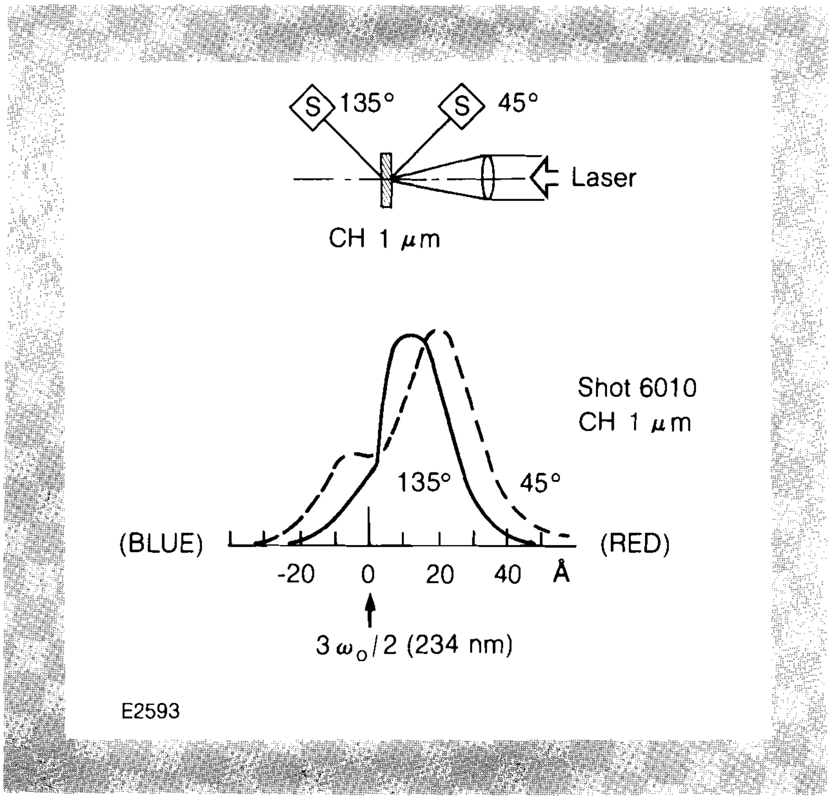

Fig. 17
Schematic of the experimental layout and typical $3\omega_0/2$ spectra observed in forward and backscattering from thin (1-μm to 2-μm) plastic targets irradiated at 10^{15} W/cm^2 at λ_L = 351 nm and t_L = 0.5 ns. The slightly red-shifted, forward-scattered light is in accordance with the filamentation model.

This surprising experimental result finds a satisfactory answer in the framework of filamentation, as treated in the preceding article of this review. In this theory, a red forward-scattered $3\omega_0/2$ component was predicted if the angle of observation was not too close to the forward direction. In fact the cut-off angle for observing this component depends on the density of the background plasma through which the filament propagates and at which the TPD occurs inside the filament. Figure 18 is a rough estimate of this cut-off angle (ϕ) as a function of the background density. Ignoring non-planar-background plasma effects or distorted filament trajectories, we could use experimental

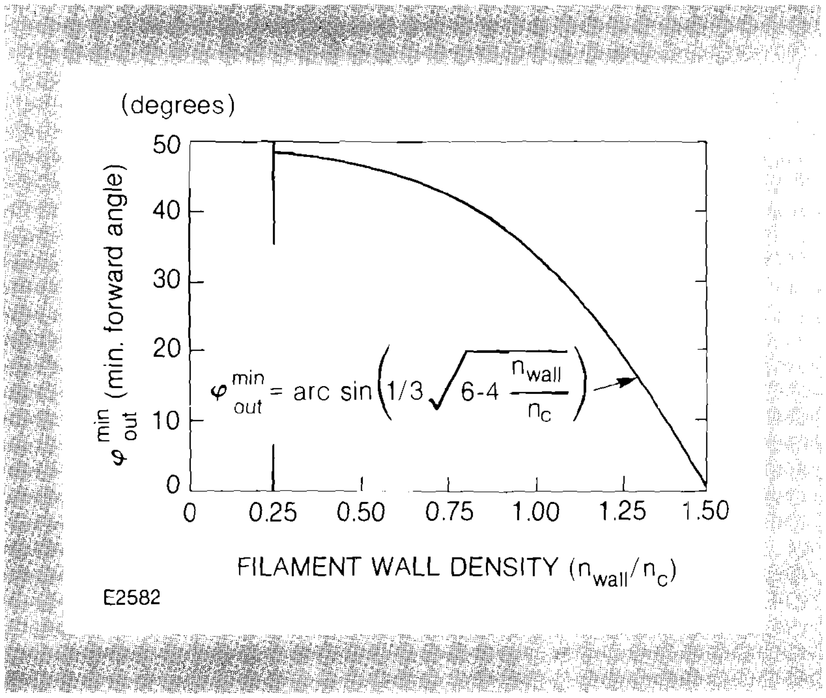

Fig. 18
Estimate of the minimum forward-scattering angle at which a red-shifted $3\omega_0/2$ component may be observed. The abscissa is the maximum background electron density through which the filament penetrated and at which the two-plasmon decay instability occurred inside the filament. The equation for ϕ^{min}_{out} contains phase-matching conditions for the $3\omega_0/2$ generation as well as refraction effects in the background plasma.

measurements of the cut-off angle as indication for the maximum background density through which the filaments penetrated. Conversely, observation of the change from red- to blue-shifted forward-scattered $3\omega_0/2$ radiation as a function of angle would constitute significant evidence for filamentation and the occurrence of TPD inside these filaments.

Although we have not yet investigated the $3\omega_0/2$ spectra in direct forward scattering there exists experimental data taken at 30° with respect to the forward direction from Shiva, planar, thin-foil IR irradiation experiments at the Lawrence Livermore National Laboratory.[3] A scaled version of these data is shown in Fig. 19 along with one of our forward-scattering spectra observed at 45° to the forward direction. Although the experimental conditions were far from identical, we note that the Shiva data show approximately the same blue shift from the center ($3\omega_0/2$) frequency as the red shift for our data. This is predicted by the theory developed in the preceding article. Furthermore, the shifts for the red backscatter components are also in close agreement with the predictions.

Additional indirect evidence for the occurrence of TPD inside filaments has been observed in the angular distribution of the $\omega_0/2$ radiation emitted by our UV-laser plasmas. Figure 20 shows typical polar plots of this emission which usually consists of two lobes, one pointed along the target normal, the other one directed toward the incident laser (focusing lens). The former is the typical emission pattern expected for planar plasma blow-off in which all light generated at its own critical density is emitted normal to the target as a consequence of Snell's law. We propose that self-focusing of the laser light inside the plasma is responsible for the second component. Radiation at $\omega_0/2$ generated inside the filament and directed roughly

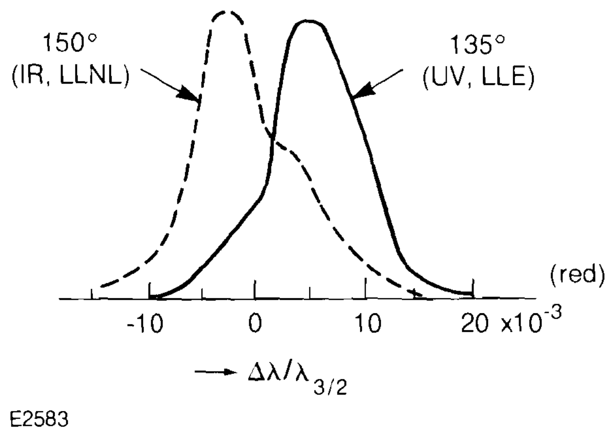

Fig. 19
Spectra obtained for the $3\omega_0/2$, forward-scattered light at 135° (45° with respect to the forward direction) for the UV (LLE) data, and 150° (30° with respect to forward direction) for the IR (LLNL) data. From our analysis we conclude that ϕ_{out}^{min} for the observation of red forward-scattered $3\omega_0/2$ radiation lies below 45° for the UV data and above 30° for the IR data.

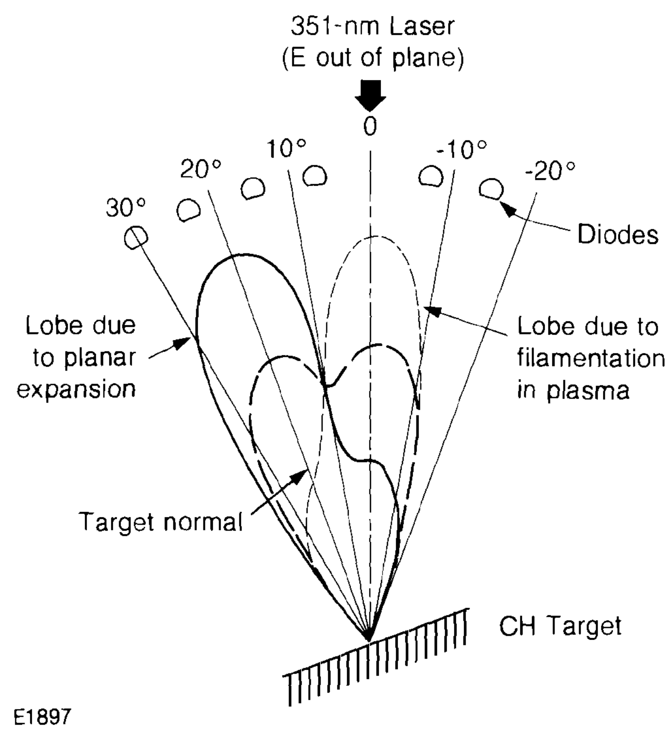

Fig. 20
Angular distribution of the scattered $\omega_0/2$ radiation from UV-laser plasmas. We note two lobes, one corresponding to the expected planar plasma blow-off, the other one due to filamentation of the incident laser light inside the plasma corona.

along the filament axis could then be guided out of the plasma without effectively seeing the overall planar-target plasma expansion. In general, we have observed that this emission pattern has a stronger self-focusing lobe for longer irradiation pulses as indicated in Fig. 20.

In short, we have presented experimental $3\omega_0/2$-harmonic spectra from planar, single-beam, UV-laser plasmas which are well explained by the predictions, based on the TPD instability, made in the preceding article of this review. Since these experimental measurements cannot be explained on the basis of conventional planar-plasma blow-off, we believe that our data strongly suggest that TPD occurs, perhaps predominantly, inside filaments formed by the incident laser. Additional evidence has been found in the angular emission pattern of the $\omega_0/2$ radiation emitted from the same plasmas.

REFERENCES

1. LLE Review **14**.
2. O. Willi, P. T. Rumsby, and Z. Kiu, Sixth Workshop on Laser Interaction with Plasma, Monterey, CA, 1982.
3. R. E. Turner *et al.*, Lawrence Livermore National Laboratory Report UCRL-86420, 1981.