Second-Harmonic Light from the Interaction of a Nanosecond CO_2 Laser Pulse with the Plasma Produced from Polyethylene Sheet

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A 4-J, 10.6-μm, pulsed (2 nsec), CO_2 laser has produced small amounts (4×10^{-7} of incident fundamental) of second-harmonic back emission (5.3 μm) with a definite threshold at about 1 J. Any three-halves frequency emission (7.07 μm) is at least 50 times fainter than the second harmonic. This is consistent with theoretical concepts.

We report here what we believe to be the first observation of the second harmonic (5.3 μm) of a 10.6-μm, short-pulse (2-nsec full width at half-maximum) transverse-excitation-atmosphere (TEA) CO_2 laser interacting with its target plasma. While several laboratories[1-3] have reported second-harmonic emission due to plasma effects using more powerful 1.06-μm lasers, our result is of interest for the possible use of the much more efficient CO_2 lasers in the thermonuclear fusion program. Our observations are a direct evidence of nonlinear effects probably related to the anomalous absorption required for efficient use of laser energy for fusion.

The experimental setup is shown in Fig. 1. The backscattered emission was collected with the same parabolic mirror used to focus the laser beam, and diverted with a sodium chloride beam splitter. A 1-m grating spectrograph was used in combination with a 2-mm-thick sapphire flat to improve the system rejection at 10.6 μm. A mercury–cadmium-telluride detector was used and its output was recorded with a Tektronix 7904 oscilloscope, giving a combined risetime of 1.5 nsec. The laser beam at axis was about 5 cm diam and had 95% of its energy within 2.2 mrad divergence. This beam was focused on 150-μm-thick polyethylene film with an off-axis parabolic mirror equivalent to $f/2$ optics. The damage diameter of the focal spot was 250 μm, in agreement with the diffraction limit, and at 4 J gave a power density of about 3×10^{12} W/cm^2. The laser was developed by a group[4] at the Canadian Centre de Recherche pour la Défense à Valcartier (C.R.D.V.), and the experiment was a collaboration between the Institut National de la Recherche Scientifique (INRS)–Energie and C.R.D.V.

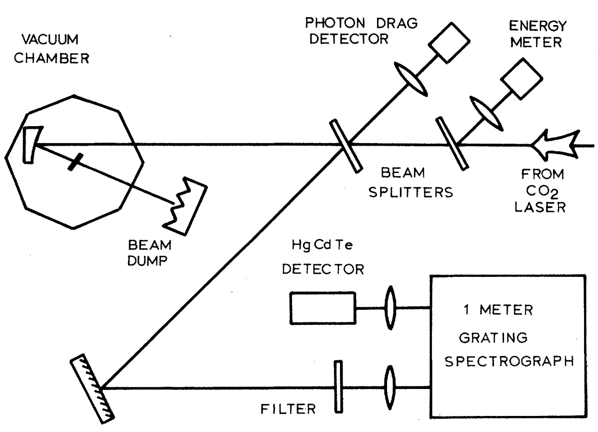

FIG. 1. Experiment arrangement for back-emitted light.

Although the maximum focused laser power density is the quantity of interest in the theory, we present the results versus laser energy. This is because analysis of the photon-drag-detector results from the center of the unfocused beam shows significant changes in beam energy distribution and some change in duration (2.2 to 1.8 nsec) as the beam energy is reduced. (This reduction is accomplished by increasing the concentration of propylene in a cell placed after the mode-locked oscillator). Hence we have cited only the power density at the highest energy.

The total second-harmonic emission back through the incident optical system is plotted in Fig. 2 versus incident laser energy for 25 individual shots. Within our time-response limitations the second-harmonic pulse seemed somewhat shorter than the fundamental. Threshold behavior is evident at roughly 1 J. This laser does not, at the moment, give us high enough energy (say up to 10 J) to determine whether there is a transition to power-law behavior, which is typically square law for normal second-harmonic nonlinearities or might be the 1.48-power law observed by Basov *et al.*[5] The maximum second-harmonic signal is 4×10^{-6} of the backscatter fun-

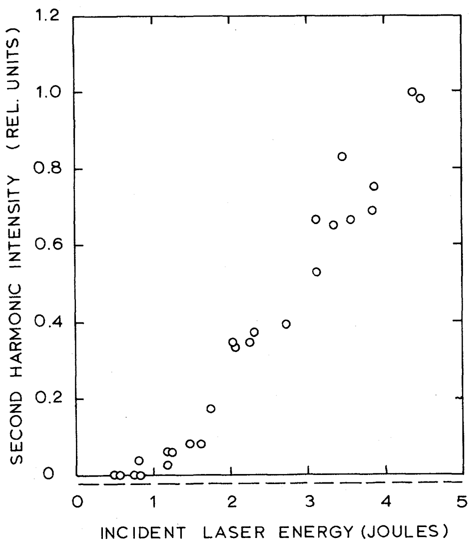

FIG. 2. Second-harmonic intensity above noise versus incident laser energy. The zero noise level is represented by the dashed line.

damental or 4×10^{-7} of the total incident energy.

Given the necessarily coarse spectral resolution ($\Delta\lambda\sim10$ nm) used for the faint second harmonic, and given the calibration uncertainties at 5.3 μm, we can make no real statement about shift or spread of the second harmonic.

Bobin *et al.*[1] (BDMV) and Lee *et al.*[2] (LGGM), using the 1.06-μm lasers, report back emission at $\frac{3}{2}$ laser frequency typically larger (e.g., 3 to 5 times) than the back-emitted second harmonic. LGGM give the magnitude of the second harmonic signal[2] as 5×10^{-4} relative to incident energy. In our case, however, we can distinguish no $\frac{3}{2}$ frequency (7.07-μm) emission, which means it is at most $\frac{1}{50}$ of the second harmonic or 8×10^{-8} of the fundamental.

We infer that while at maximum power we are clearly above threshold for second-harmonic generation, we are probably below some inferred threshold for the three-halves harmonic, while BDMV and LGGM are evidently well above both thresholds, since stronger emissions are seen at the second and three-halves harmonics in their experiments. In the absence of reliable temperature values for the bulk electrons in the critical-density region, one can only guess at temperatures to use in calculations of power thresholds for instabilities of interest. Nonetheless some progress can be made by comparing the parameters for the experiments with the two kinds of lasers. For the same temperature at the critical-density region, the threshold values for the decay and/or purely growing instabilities for different wavelengths are related roughly by the cube of the wavelength, so for equal temperatures the CO_2-laser power-density threshold is lower by a factor of 1000 than that for the 1.06-μm lasers.

Now, since the flux from the LGGM experiment ($\sim10^{16}$ W/cm^2) is 3000 times higher than ours, *for equal temperatures* it would seem that both experiments stand in about the same relation to the decay and purely growing instability thresholds. However, because of the higher flux in the LGGM experiment, their temperatures are certainly much higher than ours. Higher temperatures lower the thresholds by a factor of about the temperature ratio to the one-half power, because of the change in the Coulomb collision frequency, multiplied by the temperature. Hence the high-power glass-laser experiments are further above threshold because their plasmas are hotter.

It should be pointed out that these results are of interest not only because they show nonlinear effects with a relatively efficient CO_2 laser, but also because the critical-electron-density region (10^{19} electron/cm^3) can be optically diagnosed[6] independently, a feat practically impossible at the higher density characteristic of 1.06-μm lasers (10^{21} electron/cm^3).

In any collaboration between two totally separate organizations the successful collaborators owe a debt of gratitude to the people who make it work administratively, in this case A. Lemay, director of C.R.D.V., and B. C. Gregory, Director of INRS-Energie. In addition, at C.R.D.V., our thanks are due to M. Gravel and B. Grek for being very cooperative in sharing the laser and smoothing out the details of the collaboration, to J. L. Lachambre, P. Lavigne, and F. Rheault who, having built the laser, were more than generous in lending components and giving advice, and, finally, to C. Trepanier who actually ran the laser for us and played a vital role in the day-to-day operations. Also H. L. Buijs of the Centre de Recherche sur les Atomes et Molécules, University Laval, allowed us to raid his infrared components and gave invaluable advice. Finally our own research assistants and technicians A. Thibaudeau, J. G. Vallée, and J. Gauthier played the crucial part in making the whole experiment work.

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Current Filamentation in Parallel-Field Turbulent Plasmas*

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An electromagnetic instability leading to filamentation of the current flowing along a magnetic field in a highly resistive plasma is investigated. The instability provides a possible explanation of the discrepancy that exists between turbulent-heating experiments and numerical simulations of the electrostatic parallel-field current-driven instability.

Turbulent-heating experiments with the current flowing along an external magnetic field have proven to be effective plasma-heating mechanisms producing large increases in the initial plasma temperature.[1] The anomalous resistivity observed in such experiments is generally believed to be due to Debye-scale ion-acoustic turbulence. On the other hand, computer simulations of the electrostatic parallel-field current-driven instability show rather modest heating.[2] In parallel-field simulations with either constant drift velocity $u_\parallel = -j_\parallel/ne$ or constant $u_\parallel/v_e$, where v_e is the time-dependent electron thermal speed, the current-driven instability is quenched after several heating periods from the reshaping of the electron distribution function such that the imposed current is carried and $\partial(\int d^2v_\perp f_e)/\partial v_\parallel \simeq 0$ in the resonant region $v_\parallel = \omega_k/k_\parallel$. The early quenching is prevented, however, if a substantial component of the current flows across the magnetic field. In fact in the cross-field-current-case numerical simulations have shown strong electron heating and no rapid instability switch-off.[2]

In this Letter we propose an electromagnetic instability to bridge the discrepancy between the experimental results and the electrostatic simulations. This instability is due to a sufficiently strong dependence of the resistivity $\eta = m_e\nu/ne^2$ (ν is the effective collision frequency) on the temperature, that is $d\eta/dT < 0$ as observed in the simulations, which leads to current filamentation. The effect of the growing current filaments is to produce a local charge separation which leads to cross-field acceleration of the electrons and the implied turbulent heating shown by computer simulations.

In the theory we assume a well-developed state of electrostatic microturbulence with $\omega_{ci} \ll \nu \ll \omega_{ce}$, and a strong dependence of ν on temperature T_e and drift velocity u. We consider the geometry of parallel-field ($\vec{E}_0 \parallel \vec{B}_0$) turbulent-heating experiments of a radius r_0 in the slab approximation. During stationary, or slowly varying compared to ν^{-1}, periods of the background evolution such as during the collisional current penetration at the rate $\nu(c/\omega_{pe}r_0)^2 \ll \nu$, we study the stability of the system to high-frequency dynamics ($\omega > \omega_{ci}$) on intermediate space scales $k^{-1} \sim c/\omega_{pe}$ assumed small compared to r_0 and large compared to the Debye length $\lambda_D = v_e/\omega_{pe}$. The electron dynamics on these time and space scales is given adequately by the fluid equations containing the turbulent collision frequency $\nu = \nu(T_e, j) \ll \omega_{ce}$, ω_{pe} due to the Debye-scale electrostatic turbulence.

For equilibrium in the uniform, stationary state