# Measurement of Two Plasmon Decay Instability Development in $k$ Space of a Laser Produced Plasma and Its Relation to $\frac{3}{2}$ -Harmonic Generation

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(Received 18 August 1993)

The two plasmon decay instability in a uniform $CO_2$-laser produced plasma is studied by Thomson scattering of ruby laser radiation. Initially the instability grows as predicted by linear theory as decay plasma wave pair of expected wave vectors. During saturation unstable plasma wave activity spreads over wide regions in $k$ space extending in places beyond the Landau cutoff contour. Comparing the saturated plasma wave intensity distribution in $k$ space and measurements of the angular variation of $\frac{3}{2}$ harmonic emission confirms the mechanism in which this radiation is generated by scattering of pump photons off two plasmon decay waves.

PACS numbers: 52.25.Gj, 52.35.Fp, 52.40.Nk, 52.50.Jm

The two plasmon decay instability (TPD) in laser irradiated plasmas has been investigated in great detail over the last couple of decades and many of the theoretical and experimental studies have been reviewed recently [1]. The initial growth of this parametric process in which an electromagnetic wave decays into two plasma waves is well described by linear theory [1,2]. However, some of the most fundamental theoretical predictions still have to be experimentally verified. More recently radiation emitted at $\frac{3}{2}$ times the laser frequency ($\frac{3}{2}\omega_0$), generally considered to be a secondary signature of TPD, has received renewed attention since its spectrum can potentially provide a thermometer for the laser target plasma [3]. This would be of great importance for laser fusion studies and x-ray laser research. Unfortunately many difficulties remain in understanding the relationship between $\frac{3}{2}\omega_0$ and TPD in its saturated state. In fact the mere link between them still has to be shown experimentally. In this Letter we describe experiments which confirm some fundamental predictions and provide data which as a test bed for theoretical and numerical studies will help to gain understanding of the nonlinear saturated TPD regime and the $\frac{3}{2}\omega_0$ spectrum.

In order to gain insight into the evolution of TPD and its relation to $\frac{3}{2}\omega_0$ it is important to study the complete wave vector distribution of the decay plasma waves. In addition it is desirable to start with the simplest possible case of a homogeneous plasma. The homogeneous TPD growth rate [1]

$$\gamma \cong \frac{\mathbf{k}\cdot\mathbf{v}_0}{4}\left(\frac{(\mathbf{k}-\mathbf{k}_0)^2-k^2}{k|\mathbf{k}-\mathbf{k}_0|}\right)$$

maximizes in the $k_x,k_y$ plane of polarization of the pump ($k_x$ in $\mathbf{k}_0$ direction) on the hyperbola given by $k_y^2 = k_x(k_x-k_0)$. Here $\mathbf{k}_0$ is the incident wave vector, $\mathbf{v}_0$ is the electron quiver velocity in the incident electromagnetic field, and $\mathbf{k}$ the larger of the decay plasma wave vectors. For instability this growth has to exceed Landau damping which limits the region of unstable plasma waves in $k$ space. For conditions of interest to the present experiment ($v_0/c=0.05$ and $c/v_e=35.7$ for the electron thermal speed $v_e$) the contour in the $k_x,k_y$ plane is shown in Fig. 1 on which the TPD growth rate equals the Landau damping rate. Using the Bohm-Gross dispersion relations for the TPD waves ($\omega_{1,2}$ and $\mathbf{k}_{1,2}$) and the matching conditions $\omega_1+\omega_2=\omega_0$ and $\mathbf{k}_1+\mathbf{k}_2=\mathbf{k}_0$ one can show that the TPD plasmons in the $k_x,k_y$ plane have to be localized on a circle around $k_x=0.5k_0$ and $k_y=0$ of radius $R$ given by

$$\left(\frac{R}{k_0}\right)^2=\frac{1}{3}\left(\frac{c}{v_e}\right)^2\left(\frac{n}{n_c}\right)^{1/2}\left(\frac{1-2(n/n_c)^{1/2}}{1-n/n_c}\right)-\frac{1}{4}.$$

Here $n$ and $n_c$ are the electron and critical densities, respectively. For the mentioned conditions the circles for $n/n_c=0.235$ and 0.225 are indicated in Fig. 1 because the net growth maximizes between these values on the hyperbola. For a homogeneous plasma of given $n/n_c$ one will therefore expect TPD waves to grow at the intersections of the appropriate circle with the hyperbola in the $k_x,k_y$ plane.

Previous experimental, theoretical, and numerical code

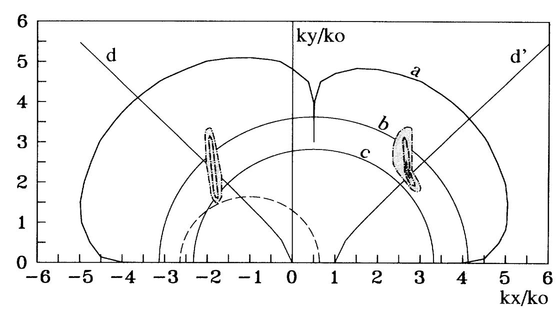



FIG. 1. $k$ plane of polarization. On contour $a$ TPD growth equals Landau damping for conditions of this experiment. At densities $n/n_c=0.225$ and 0.235 TPD waves are localized on the circles $b$ and $c$, respectively. TPD growth maximizes on the hyperbola $d$, $d'$. Plasmons generating $\frac{3}{2}\omega_0$ radiation are localized on the dashed circle around $k_x=-k_0$, $k_y=0$. The dot-dashed contours around $k_x/k_0=-2,3$; $k_y/k_0=2.5$ are those of plasma wave intensity during the first 25 ps of TPD growth.

0031-9007/93/71(18)/2915(4)$06.00

[4] studies have shown that these initial TPD daughter waves effectively couple to ion acoustic waves once their amplitudes have grown to large values approaching $\delta n/n \sim 1\%$. This leads to Langmuir turbulence and saturation of the instability [5]. Recent 2D pseudospectral simulations of an extended "Zakharov" description [5] show that in the process large amplitude plasma wave activity spreads over wide regions in the $k_x,k_y$ plane, which then permits the generation of $\frac{3}{2}\omega_0$ emission into a wide angular range [5]. It is generally accepted that $\frac{3}{2}\omega_0$ arises through scattering of pump photons from TPD plasmons [3]. The necessary matching condition $\mathbf{k}_{3/2}=k_0+\mathbf{k}$ requires that these plasmons are localized on a circle in the $k_x,k_y$ plane of radius $\frac{8}{3}{}^{1/2}k_0$ around $k_x=-k_0$, $k_y=0$ and the radius indicates the $\frac{3}{2}\omega_0$ wave vector.

The only possible method to study TPD plasmons over a wide $\mathbf{k}$ range consists in Thomson scattering of probe laser radiation of a wavelength much shorter than that of the pump [1]. In the present experiment $CO_2$ laser radiation (10.6 $\mu$m, $\sim$10 J in 2 ns) generates the plasma and acts as a pump for TPD. The radiation is focused to intensities around $0.3\times10^{14}$ W/cm$^2$ under normal incidence onto a planar and laminar $N_2$ gas jet target flowing in low pressure stabilizing He-background gas. The gas pressures are carefully adjusted to ensure the generation of a long ($\sim$1.2 mm) uniform plasma optimized for maximum TPD signatures. The Thomson scattering geometry is indicated in Fig. 2. Ruby laser radiation ($\omega_r$, single mode, 6 ns pulse) is incident at variable angles $\Theta$ against $\mathbf{k}_0$ in the plane of polarization of the pump and is astigmatically focused to a $\sim$1 cm long line which over its focal depth covers the plasma in its center. The second vertical line focus appears in a beam dump near the target chamber wall 25 cm from the plasma. A large aperture $f/2.5$ collimating mirror can be placed on either side of the beam dump to intercept scattered radiation over a wide angular range of $\Delta\Theta=18°$. The collimated scattered ruby laser radiation, proportional in intensity to that of the plasma waves, is directed out of the target chamber, passed through a 10 nm band pass interference filter centered at $\omega_r+\omega_0/2$, and imaged onto the entrance slit of a ps-resolution streak camera. The recorded streak images which also display a fiducial of the probe intensity are digitized and analyzed on a computer. By imaging either the plasma or the collimator onto the slit one can probe the evolution of plasma waves both in real and in wave vector space. If the collimator is imaged one detects radiation scattered off plasma waves localized in the $k_x,k_y$ plane on an arc of radius $(\omega_r+\omega_0/2)/c$ centered at $k_x=(\omega_r/c)\cos\Theta$, $k_y=(\omega_r/c)\sin\Theta$. Target chamber windows permitted the variation of $\Theta$ in steps of 18° from 19° to 145°. Thus varying $\Theta$ and using both possible locations of the collimating mirror the complete $k_x,k_y$ plane range of interest for TPD (see Fig. 1) was investigated in a series of experiments. For a few experiments a $\lambda/2$ plate was placed into the pump beam to rotate the plane of polarization by 90°. In a separate experimental series with the scattering optics removed the angular distribution of the emitted $\frac{3}{2}\omega_0$ energy was measured by methods described previously [6].

A typical streak record in which the plasma region is imaged onto the camera slit, is shown in Fig. 3, displaying the spatial development of the TPD wave intensity. Probe light scattered from plasma waves appears uniform in intensity over a plasma length of > 1 mm, indicating a long plasma of practically constant density. In about 50 ps the TPD wave intensity saturates and subsequently oscillates at a frequency around 20 GHz which corresponds to that of ion acoustic waves of $\sim 2k_0$. The overall duration of the instability varies from experiment to experiment between 300 to 600 ps. During the periods of maximum TPD activity the plasma wave intensity appears spatially nonuniform, displaying closely spaced local maxima of resolution limited size.

Three examples of $k$ resolved streak records are dis-

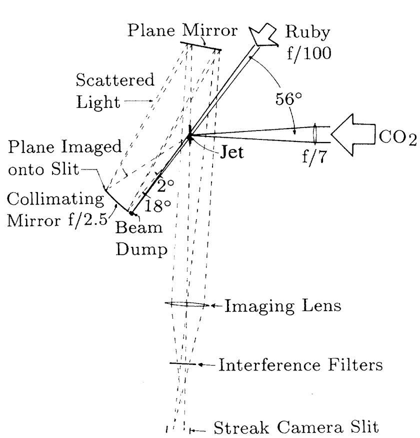



FIG. 2. The Thomson scattering geometry for one angle of probe incidence.

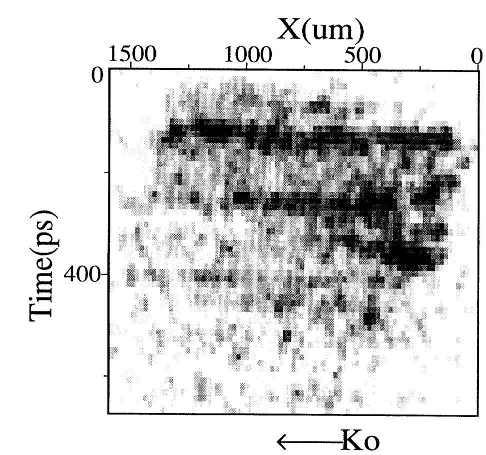



FIG. 3. Thomson scattering streak record of the spatial development of TPD wave intensity.

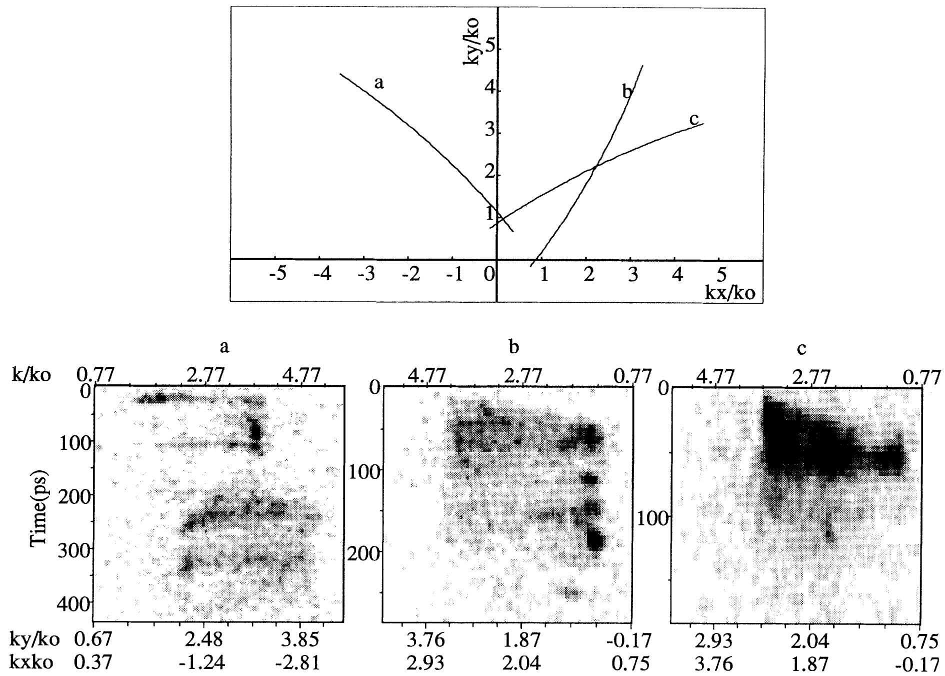



FIG. 4. Three streak records of the $k$-space development of TPD wave intensity. The individual $k$-space location of records (a), (b), and (c) is shown in the $k_x, k_y$ plane.

played in Fig. 4. The arcs in $k_x, k_y$ space for each streak are also shown on which the development of the plasma wave intensity is measured. As in the case of spatially resolved measurements the saturated wave amplitudes are seen to oscillate at ion acoustic frequencies. Once saturated the TPD amplitude displays more than one $k$ space maximum on various arcs of measurement as evident in Fig. 4(c). After normalizing the scattered intensity to that of the probe in the fiducial and after averaging over many ($>5$) experiments along a probed $k_x, k_y$ arc, the streak records from all measurements can be used to generate contour plots of TPD wave intensity in the $k_x, k_y$ plane. Integrating over the first 25 ps, when the wave amplitudes are still growing rapidly, leads to the contours shown in Fig. 1. The results clearly demonstrate the growth of a decay pair with $\mathbf{k}_1+\mathbf{k}_2=\mathbf{k}_0$ at positions predicted by linear theory if the density is adjusted for maximum growth of TPD as attempted in our experiments. To our knowledge this is the first experimental confirmation of the most fundamental basis of TPD theory. It shows that initially development of TPD is well described by linear theory and is not altered by additional wave-wave coupling processes. However, the situation changes dramatically when the instability saturates. If the scattered probe intensity is integrated over the first 100 ps the generated contours, indicated in Fig. 5, show the TPD $k$-space distribution effectively at maximum saturated intensity. Now unstable plasma waves are detected over a wide region in $k_x, k_y$ space extending out to and in places beyond the Landau cutoff contour from Fig. 1. Three regions of maximum TPD intensity, respectively, are found now in forward ($+\mathbf{k}_x$) and in backward ($-\mathbf{k}_x$) directions and their positions cannot be associated with a matching condition corresponding to $\mathbf{k}_+ + \mathbf{k}_- = \mathbf{k}_0$. Obviously the saturation process, presumably arising from coupling to ion acoustic turbulence [5], generates a wide spectrum of unstable plasma waves and affects their maximum amplitude. Large amplitude plasmons are detected at positions for which the TPD growth rate is zero, at regions of $k_x=0.5k_0$ and around $k_x=k_0$ for $k_y=0$. The latter has to be associated with the absolute stimulated Raman instability which is confirmed by experiments perpendicular to the plane of polarization. In

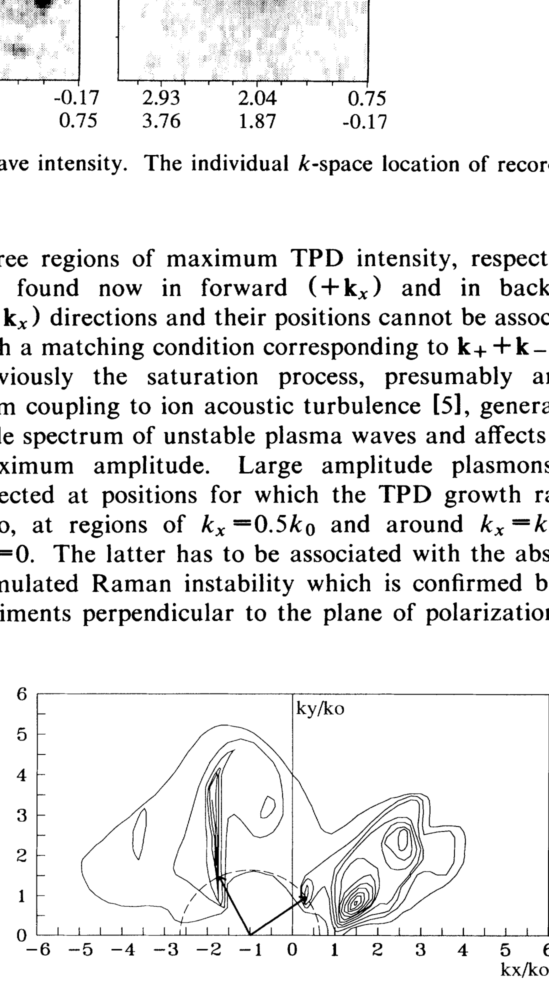



FIG. 5. Contours of the saturated TPD wave intensity in $k$ space obtained from streak records after integrating over the first 100 ps. Plasmons on the circle around $k_x=-k_0$, $k_y=0$ generate $\frac{3}{2}\omega_0$ radiation and the arrows indicate the wave vectors of this emission due to plasmons with maximum amplitude.

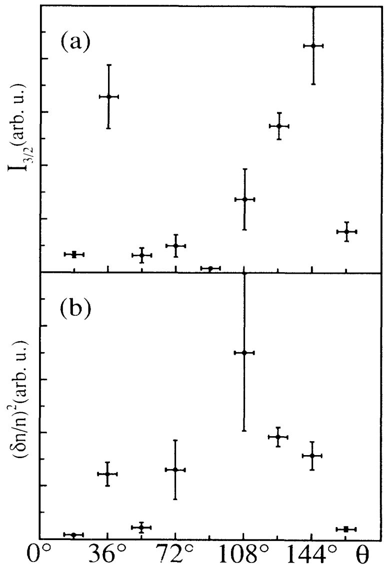



FIG. 6. Angular distribution of emitted $\frac{3}{2}\omega_0$ intensity (a) and generating plasma wave intensity (b). Points in (b) are obtained after dividing the measurements in (a) by the Thomson cross section. Horizontal error bars indicate the accepted angular range and vertical error bars the standard deviation of five or more experiments.

these experiments with the $\lambda/2$ plate in the pump beam only plasma waves with $\mathbf{k} \sim \mathbf{k}_0$ are detected.

Examining the matching circle for $\frac{3}{2}\omega_0$ generation in Fig. 5 indicates that saturated TPD plasmons can now produce $\frac{3}{2}$-harmonic emission over a wide angular range via the assumed scattering process. The measured saturated plasma wave intensity distribution on the matching circle maximizes for $\frac{3}{2}\omega_0$ emission into two angles around $\Theta = 35°$ and $\Theta = 115°$. This can be compared with measurements of the angular distribution of the $\frac{3}{2}$-harmonic emission shown in Fig. 6. If the generation mechanism indeed consists of a process in which pump photons are scattered off TPD plasmons, then the $\frac{3}{2}\omega_0$ intensity is proportional to the plasma wave intensity and the Thomson cross section $\sigma_{\mathrm{Th}}$. Dividing the values of Fig. 6(a) by $\cos^2\Theta$ ($\propto \sigma_{\mathrm{Th}}$) will therefore generate the TPD wave intensity on the matching circle shown in Fig. 6(b). At $\Theta = 90°$ the $\frac{3}{2}\omega_0$ intensity would be zero in the absence of a finite detected angular range and the TPD wave intensity becomes indeterminable. Therefore no point is shown at 90° in Fig. 6(b). The good agreement with the Thomson scattering results of Fig. 5 represents to our knowledge the first direct experimental evidence for the generation of $\frac{3}{2}$-harmonic emission by TPD plasmons via scattering of pump photons.

In conclusion, we have shown that initially the TPD instability evolves in $k$ space as predicted by linear theory. The saturation process spreads TPD activity over wide regions in $k$ space in agreement with Langmuir turbulence calculations [5]. The coupling to ion acoustic waves is indirectly suggested by the oscillation frequency of the saturated TPD intensity. Finally we have provided direct evidence for the process in which saturated TPD plasmons lead to $\frac{3}{2}\omega_0$ emission by scattering of pump photons.

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

[1] 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, New York, 1991), Vol. 2, pp. 397–408.

[2] C. S. Liu and M. N. Rosenbluth, Phys. Fluids **19**, 967 (1976); A. Simon, R. W. Short, E. A. Williams, and T. Dewadre, Phys. Fluids **26**, 3107 (1983).

[3] W. Seka, B. B. Afayan, R. Boni, L. M. Goldman, R. W. Short, K. Tanaka, and T. W. Johnston, Phys. Fluids **28**, 2570 (1985); R. E. Turner, D. W. Phillion, B. F. Lasinski, and E. M. Campbell, Phys. Fluids **27**, 511 (1984); P. E. Young, B. F. Lasinski, W. L. Kruer, E. A. Williams, K. G. Estabrook, E. M. Campbell, R. P. Drake, and H. A. Baldis, Phys. Rev. Lett. **61**, 2766 (1988); V. Aboites, T. M. Hughes, E. Goldrick, S. M. L. Sim, S. J. Karttunen, and R. G. Evans, Phys. Fluids **28**, 2555 (1985); F. Amiranoff, F. Briand, and C. Labaune, Phys. Fluids **30**, 2221 (1989).

[4] A. B. Langdon, B. F. Lasinski, and W. L. Kruer, Phys. Rev. Lett. **43**, 133 (1979); H. A. Baldis and C. J. Walsh, Phys. Rev. Lett. **47**, 1658 (1981); Phys. Fluids **26**, 3426 (1983); S. J. Karttunen, Plasma Phys. **22**, 151 (1980); J. Meyer, Phys. Fluids B **4**, 2934 (1992).

[5] D. F. DuBois, D. Russell, and H. A. Rose, in Proceedings of the 23rd Annual Anomalous Absorption Conference, Wintergreen, Virginia, Talk No. 101, 1993 (to be published).

[6] J. Meyer, Y. Zhu, and F. L. Curzon, Phys. Fluids B **1**, 650 (1989).

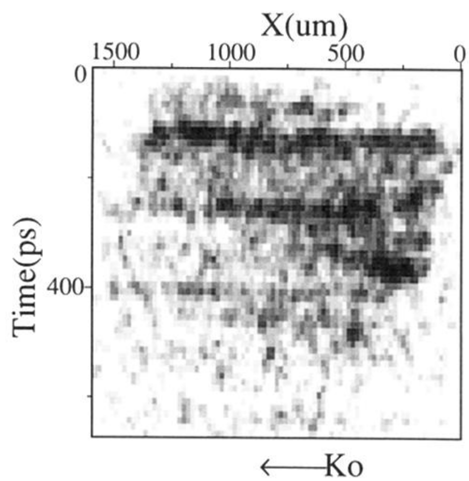
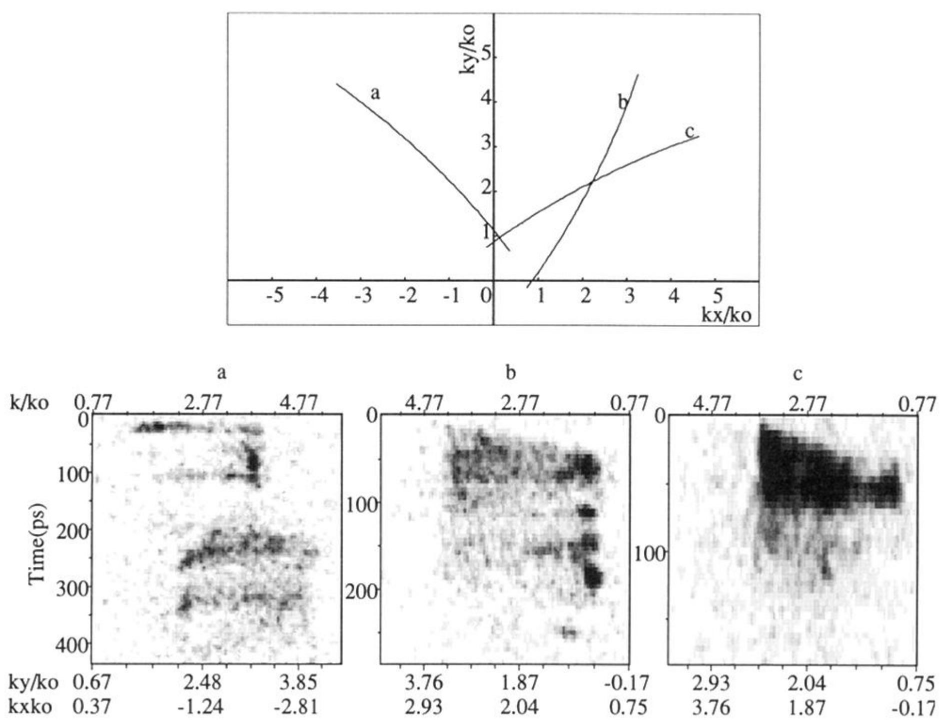



FIG. 3. Thomson scattering streak record of the spatial development of TPD wave intensity.

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