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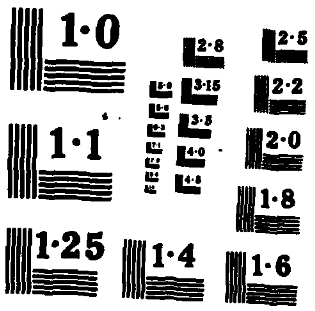
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Time Resolved Flow Velocity and Concentration Measurements Using a Travelling Thermal Lens

by

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TIME RESOLVED FLOW VELOCITY AND CONCENTRATION MEASUREMENTS USING A TRAVELLING THERMAL LENS

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ABSTRACT: The travelling thermal lens technique is a new all optical method for probing concentration and velocity patterns in flowing media. A thermal lens created by absorption of a short laser pulse moves with the flow and can be probed by a cw laser beam further downstream as a deflection signal. This technique enables optical measurements of the flow velocity component perpendicular to the probe laser at high spatial resolution. Its application requires no seeding with particulates as needed in most other optical techniques.

Velocity and concentration measurements in flows are mainly performed by intrusive methods such as Pitot-tubes or hot-wire probes.[1] In many cases this causes a significant perturbation and the measurement can also be affected by the composition of the flow. Therefore, different types of noncontact optical probes have been developed. For example, Doppler anemometry[2] has proven very valuable for probing velocity patterns. However, as they mainly rely on Lorentz-Mie scattering, flows have to be seeded with smoke or aerosols. This may not be desirable for many applications and can also lead to systematic errors due to slippage of the particles at high flow speed. Also, optical access at an angle to the seeded flow is needed. These restrictions also hold for particle image and laser speckle velocimetry.[3,4] Another optical technique recently developed provides concentration measurements by two-dimensional recording of Mie-scattering.[5-8] Coherent Raman techniques can be used to measure velocity and temperature distributions in jets[9] requiring pump and probe beams at an angle to the flow. For spectroscopic identification of gas constituents and for measuring thermal diffusivity, photothermal deflection spectroscopy (PDS)[10-18] has recently been applied successfully. In this letter we present the use of PDS as a new all optical method for both instantaneous and mean velocity and concentration measurements in flows. This technique does not require seeding of the flow and is one of the few optical techniques which measure the velocity component perpendicular to the probe beam direction. It offers high spatial resolution and also the possibility to distinguish different components by spectroscopic methods.

Our experimental scheme is shown in Fig. 1. A Q-switched CO_2 laser beam for excitation (pulse width 1 μs, energy 1-10 mJ), is tightly focused by a lens of focal length 15 cm onto a laminar flow of N_2 mixed with a small amount of water or ethanol vapor.

This vapor serves to absorb a small fraction of the infrared laser light. The absorption gives rise to the formation of a travelling thermal lens (TTL) which moves with the flow and is probed downstream by a cw laser. For probing, we use a diode laser (wavelength=780 nm, power=4 mW) because of its superior power stability as compared to a HeNe laser. The probe beam is focused (by a lens of focal length 8 cm) onto the flow. Both the position and the focusing of the excitation and probe beam can be adjusted by translation stages. The diverging probe beam is subsequently focused in one dimension by a cylindrical lens and detected by a photodiode (UDT 600, bandwidth 0-1 MHz) located either in the Gaussian wing of the probe profile (to obtain a TTL defocusing signal) or in the center (to obtain a TTL thermal lensing signal). The active area of the photodiode is $2\times 2\ \mathrm{mm}^2$, while the probe beam cross section at the diode is $0.2\times 15\ \mathrm{mm}^2$. The transient signal is stored in a Data Precision DATA 6000 waveform digitizer triggered by the CO_2 laser pulse via a 100 MHz bandwidth HgCdTe detector. Single shot or time-averaged signals can further be analyzed on a IBM personal computer.

In the present work using focused excitation and probe beams, thermal diffusion cannot be neglected as in a previous study.[13] As a starting point we therefore use the work of Jackson *et al.*,[19] who calculated the the temperature gradient $\partial T/\partial r$ in a weakly absorbing medium along a radial direction r perpendicular to the excitation beam:

$$\frac{\partial T}{\partial r} = -\frac{\alpha E_0}{2\pi D r \Delta t}\left[\exp\left(\frac{-2r^2}{w_0^2+8Dt}\right)-\exp\left(\frac{-2r^2}{w_0^2+8D(t-\Delta t)}\right)\right] \qquad (1)$$

where α is the absorption coefficient, E_0 the pulse energy, D the diffusivity, w_0 the beam radius and Δt the excitation pulse duration. If Δt is much shorter than the thermal diffusion time $t_c = w_0^2/4D$, this reduces to

$$\frac{\partial T}{\partial r} = -\frac{\alpha E_0}{2\pi D r}\frac{d}{dt}\left(\exp\left(\frac{-2r^2}{w_0^2 + 8dT}\right)\right) \tag{2}$$

which can be integrated to yield the time dependent temperature distribution

$$T = T_0 + \frac{2\alpha E_0}{\pi(w_0^2 + 8Dt)}\exp\left(\frac{-2r^2}{w_0^2 + 8Dt}\right). \tag{3}$$

This agrees with Twarowski *et al.*[20] who used a slightly different approach. In the present perpendicular observation scheme, the thermal lens created is detected as a cylindrical lens by the probe beam. A similar set-up has been used by Dovichi *et al.*[15-17] for investigations of solids and liquids under static conditions. The beam deflection ϕ is determined by the transverse refractive index gradient $\partial n/\partial r$, which is proportional to the transverse temperature gradient[19] $\Delta_\perp T$ according to

$$\phi = \frac{1}{n_0}\frac{\partial n}{\partial T}\int \Delta_\perp T(\bar{r},t)\,ds\,. \tag{4}$$

For our case shown in Fig. 1, $\Delta_\perp$ reduces to $\partial/\partial z$, and $r^2=x^2+z^2$ and $z=vt-a$, where v is the flow velocity and a is the beam separation. From this, the TTL beam deflection signal is calculated to be

$$\phi(t) = \frac{16\alpha E_0(vt-a)}{\sqrt{2\pi}\,(w_0^2 + 8Dt)^{3/2}}\exp\left[-\frac{2(vt-a)^2}{w_0^2 + 8Dt}\right]. \tag{5}$$

The TTL defocusing signal is related to the second transverse derivative of the refractive index and can be calculated using Eq. (5). While a beam deflection signal is always observed independent of the location of the probe beam focus, a first order defocusing signal can only be observed[21] if the probe focus is shifted along the probe beam direction from the intersection of the pump beam and flow. In the latter case, spatial resolution must be sacrificed and the beam offsets must be accurately known to make quantitative measurements. These effects can be observed in Fig. 2, where the detected transients for different detector arrangements and probe laser focusing conditions are shown. The disappearance of the TTL defocusing signal under the centered focusing conditions is very useful for alignment of the system. For the measurements described below the probe beam focus is always centered.

Several features of Eq. (5) should be noted. Mean velocities can easily be derived from the zero crossing of the signal at a given beam separation. This is shown in Fig. 3, which also demonstrates signal decrease and broadening in agreement with Eq. (5). By scanning the laser beams, the spatial velocity profile can be measured. This is shown in Fig. 4 for a direction perpendicular to the flow. For times $t >> t_c$, the signal shape becomes independent of the pump beam radius w_0. Non-Gaussian intensity distributions are therefore not very critical as discussed in Ref. (13). At early times (*i.e.*, $t_r << t_c$) and zero beam separation, thermal diffusion can be neglected. As a result the signal can be approximated by

$$\phi(t) = \frac{16\alpha E_0 vt}{\sqrt{2\pi}\, w_0^3} \exp\left[- \frac{2v^2t^2}{w_0^2} \right]. \tag{6}$$

The signal maximum at $t_{max} = w_0/(\sqrt{2}v)$ is calculated to be

$$\phi(t_{max}) = \frac{8\alpha E_0}{\sqrt{\pi}\, w_0^2} \tag{7}$$

which is proportional to the gas concentration but independent of v in contrast to the quasi-static case encountered in Ref. (13). This, however, imposes a restriction on the flow speed according to $t_{max} << t_c$ which yields $v >> \sqrt{8}D/w_0$. As a typical example, $D = 0.21\ cm^2/s$ (N_2 at 25°C) and $w_0 = 100\ \mu m$, and so the condition is $v >> 0.6$ m/s, which is fulfilled under our experimental conditions. Figure 4 shows the concentration profile determined under these conditions.

In addition to the determination of time averaged properties, instantaneous values for velocity and concentration can also be obtained by analyzing single shot measurements according to Eq. (5). In Fig. 5 a measured signal and the calculated best fit are shown. The flow velocity is assumed constant for the fit, and the only adjustable parameters are the instantaneous velocity $v(t_0)$, the separation $a = \int_0^{t_0} v dt$ and the signal amplitude.

In conclusion, the travelling thermal lens deflection technique is shown to be a valuable method for noncontact monitoring of mean and instantaneous velocity, density or composition distributions in flows and also mixing processes in fluids. The method is useful for a very wide range of flow speeds, requiring only short pump laser pulses at higher flow speeds.

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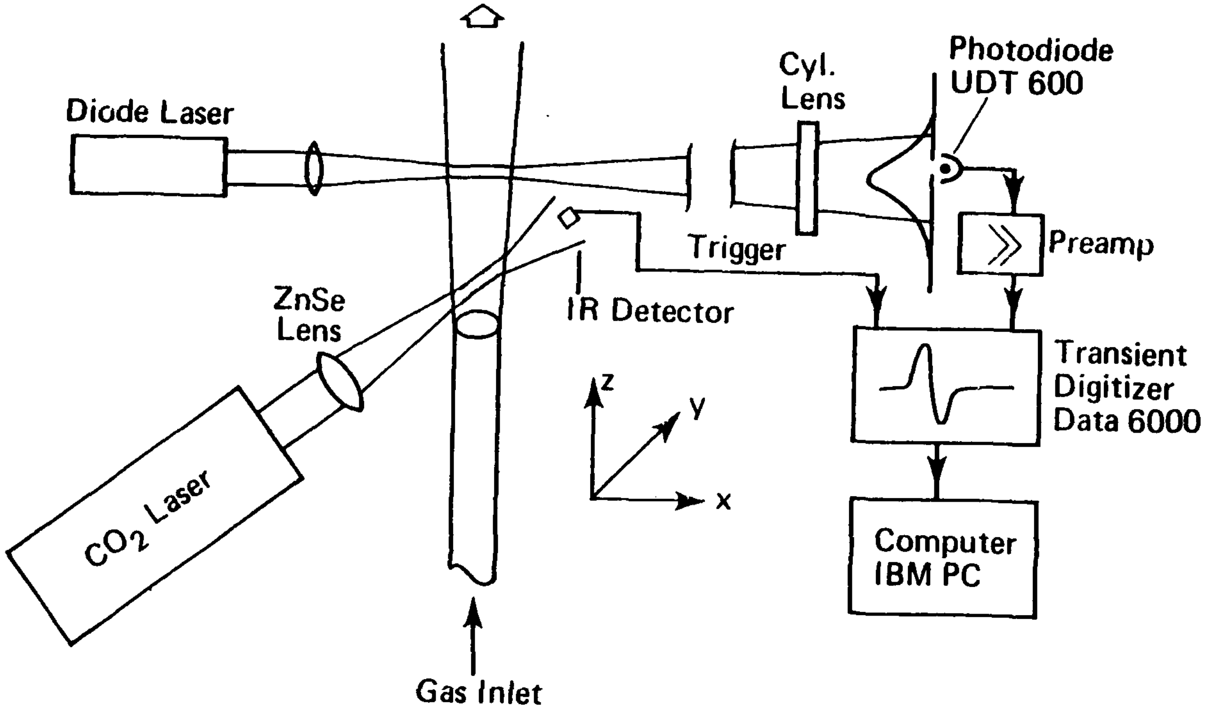

Figure 1. Experimental set-up.

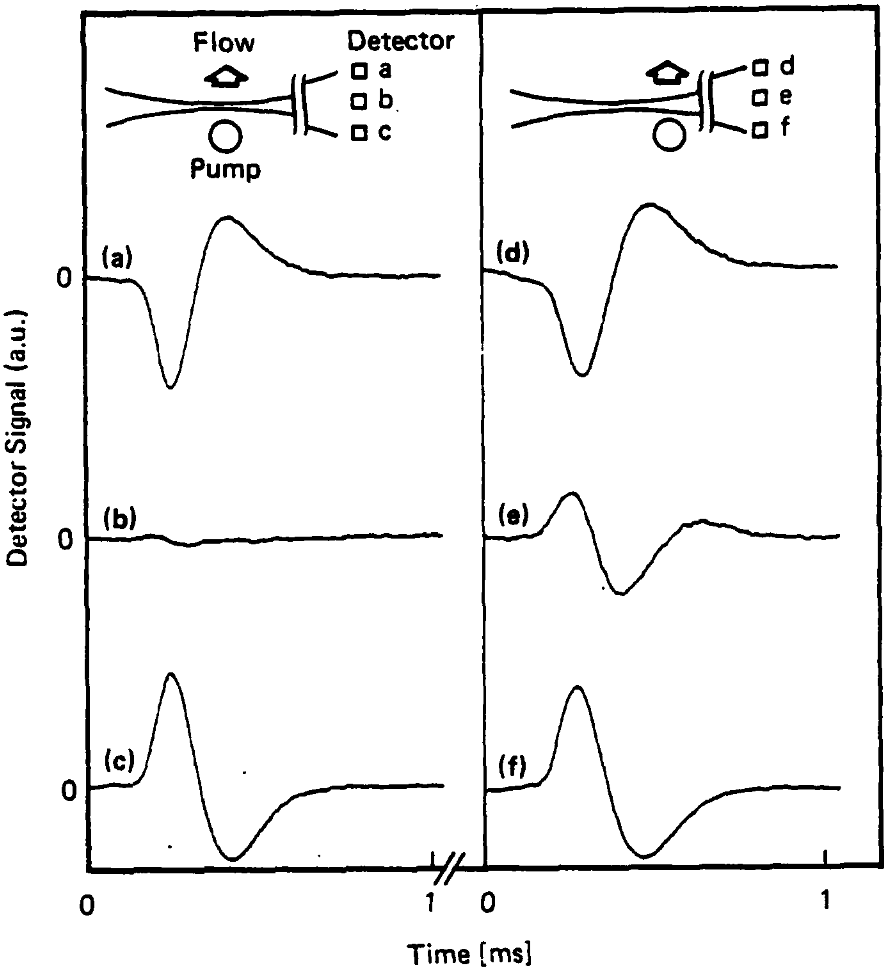

Figure 2. TTL transient signals for different conditions. From (a) to (c): probe laser focus directly above pump focus, and with detector located in the Gaussian wing of intensity, in the center and in the opposite wing, respectively, as shown in the inset. From (d) to (f): transient signals as in (a) to (c), but with probe beam focus displaced by one confocal length as shown. In (e) a TTL defocusing signal is observed. The deflection signals in (d) and (f) are distorted by second order contributions.

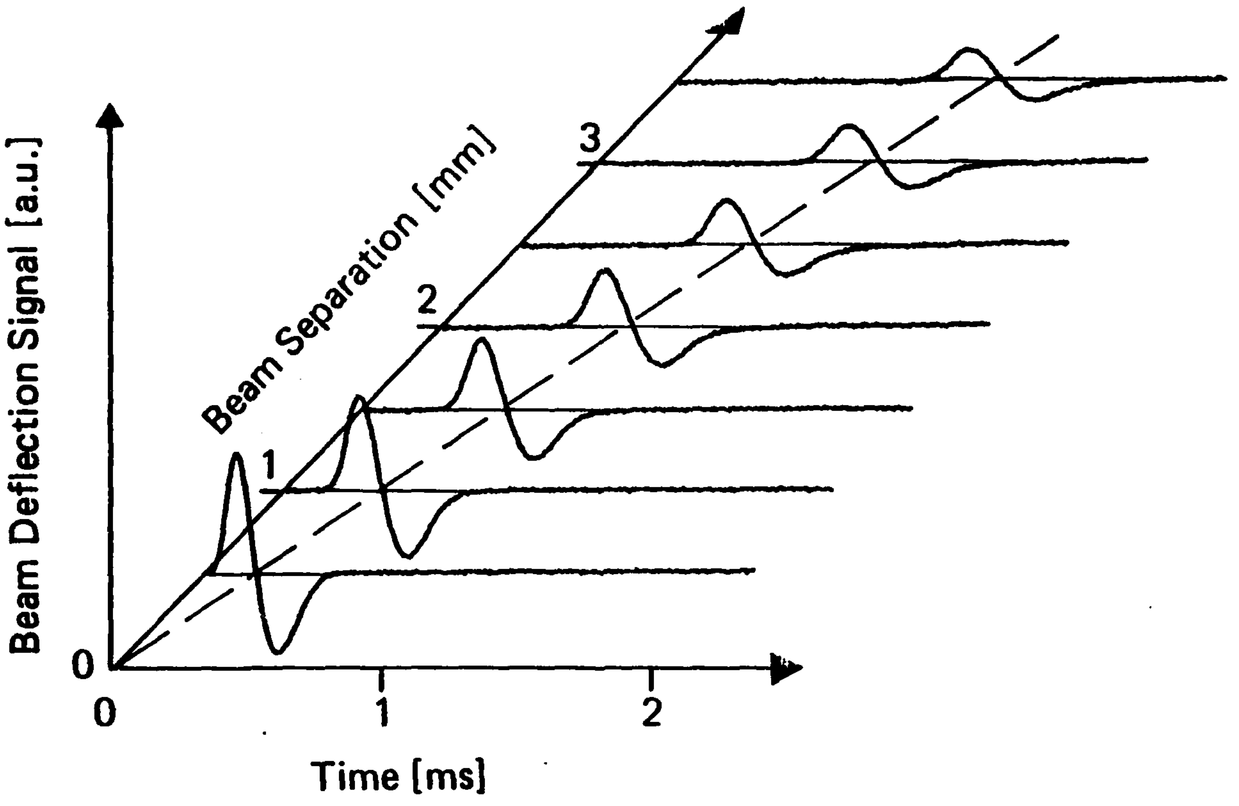

Figure 3. TTL beam deflection signals (32 shots averaged) for different separations between pump and probe beams. From the zero crossing positions, the mean velocity can be derived as v=4.24 m/s.

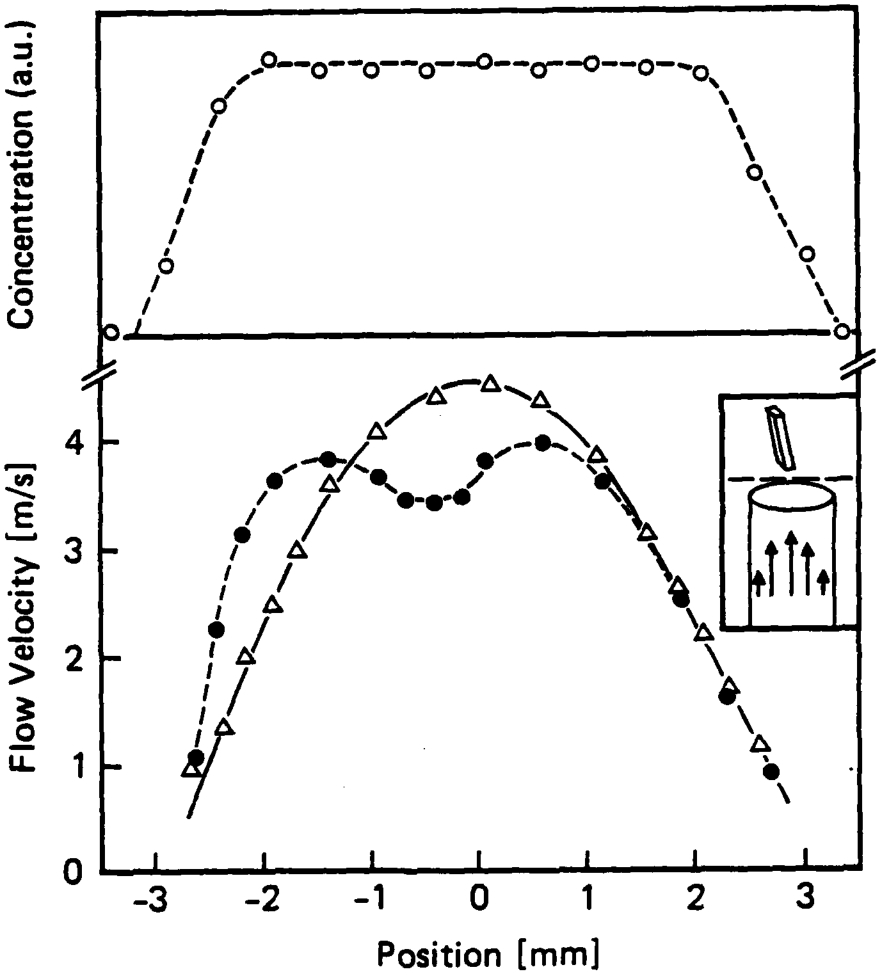

Figure 4. Velocity (symbols Δ, ●) and concentration (symbol ○) distribution of ethanol across the beam as determined from time-averaged TTL beam deflection signals along a line 1 mm from the nozzle (see the dashed line in inset). The long dashed line corresponds to a parabolic velocity fit to the data points Δ. Also shown is the measured velocity data (●) for a flow disturbed by a thin plate (0.5 mm thickness) as shown in the inset.

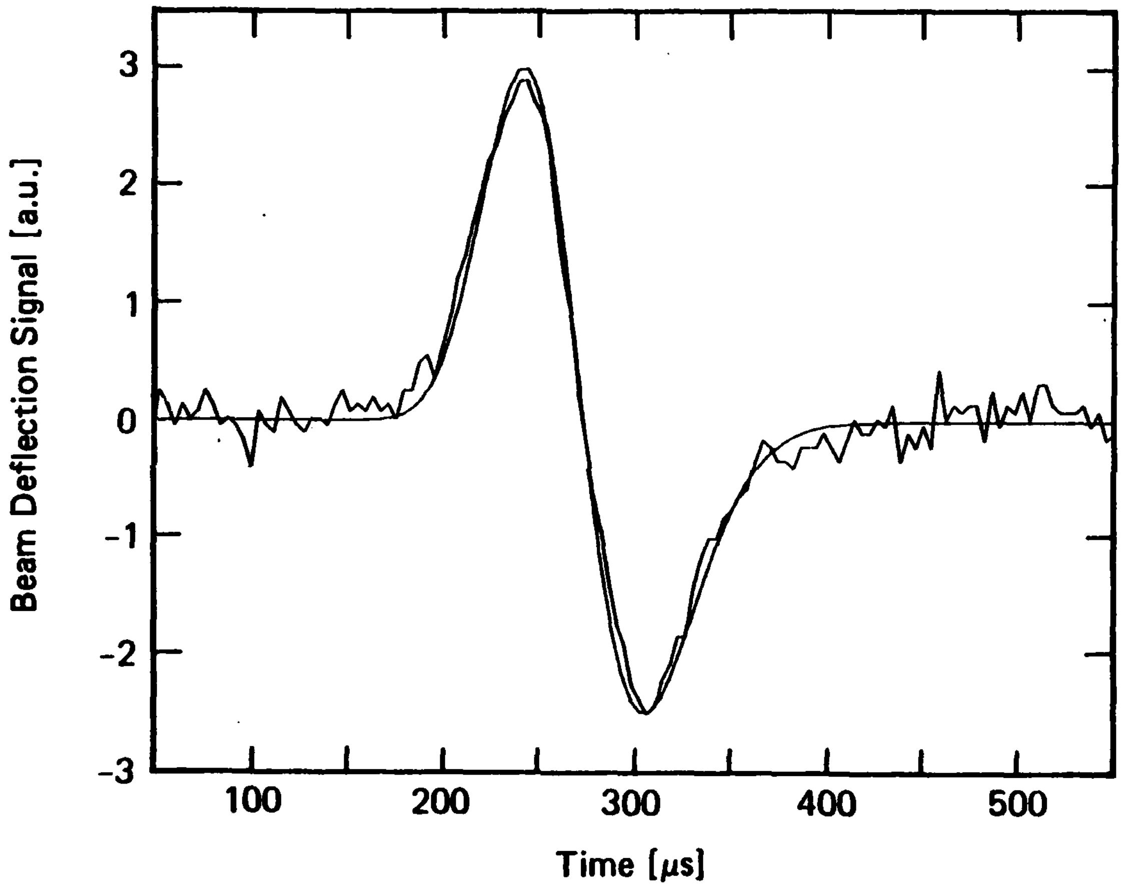

Figure 5. Single-shot TTL beam deflection signal for a beam with mean velocity v=3.18 m/s. The smooth line corresponds to the best fit according to Eq. (5) with v=3.10 m/s.