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SCATTERING OF CO_2 LASER LIGHT FROM A COLLISIONLESS SHOCK

by

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A B S T R A C T

We describe measurements of the scattering of CO_2 laser radiation by long wavelength ($k\lambda_D \sim 0.1$) turbulent density fluctuations within a collisionless shock. The spectrum of the scattered radiation is shifted in wavelength from that of the incident laser beam demonstrating genuine scattering rather than enhanced stray light. The observed level of fluctuations is a hundred times thermal but a thousand times lower than that to be expected from an extrapolation of the Kadomtsev spectrum observed previously for $k\lambda_D \sim 1$.

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We describe measurements of the scattering of CO_2 laser radiation by turbulent density fluctuations within a steady state, low Alfven Mach Number ($M_A \sim 2.5$) perpendicular collisionless shock[1].

The shock is produced by the radial compression, in a linear z-pinch[1], of an initial low β hydrogen plasma ($n_{e1} = 6.4 \times 10^{20}$ m^{-3}, $T_{el} = 1.2$ eV) containing an axial magnetic field ($B_{z1} = 0.12$ T). The observed electron heating ($T_{e2} \sim 45$ eV) within the shock of width $L_s = 1.4$ mm implies an effective resistivity $\eta^* \sim 100\ \eta_s$ (η_s = Spitzer value) and an effective collision frequency $\nu^* \sim 3$ GHz. The azimuthal current within the shock corresponds to an electron drift velocity which exceeds the ion sound speed and theory [2] predicts current driven ion wave turbulence with $\eta^* > \eta_s$.

Previous measurements [3,4] of this turbulence, obtained by scattering ruby laser light, show a supra-thermal (x 200) level of density fluctuation with $k\lambda_D \sim 1$. The frequency spectrum $S_k(\omega)$ (from $S(\omega,\underline{k}) = \langle\ \delta n_e^2\ (\omega,\underline{k})\rangle/n_e$ for constant $\underline{k}$) is shifted in a direction corresponding to wave propagation in the direction of the electron drift and by an amount corresponding to the ion wave frequency for mean shock conditions. For a limited range of k ($0.6 < k\lambda_D < 1.0$) the wave number spectrum, $S(\underline{k}) = \int S(\omega,\underline{k})d\omega$ fits the form of the theoretical ion wave turbulence spectrum derived by Kadomtsev [5], ie $S(k) \propto k^{-3}\ \ell n\ (1/k\lambda_D)$.

In the present experiment we have extended the above study of S(k) to smaller k by using the long wavelength ($\lambda_i = 10.6\ \mu m$) radiation of a CO_2 laser.

EXPERIMENTAL ARRANGEMENT: The beam from a TEA laser of the Rogowskii electrode type [6] (10 MW, 50 nsec, P20 transition) passes through the discharge region in the rz plane at an angle $\zeta = 5^o$ to the shock and is focused to a diameter of 8mm in the midplane at a radius r = 90 mm. Measurements are confined to a single forward scattering angle (7.8^o) corresponding to a wave vector, $\underline{k} = \underline{k}_s - \underline{k}_i$, with mean $k = 8 \times 10^4\ m^{-1}$ and directed approximately in the azimuthal direction (see Fig. 1). The scattered radiation is detected with a Cd-Hg-Te photovoltaic detector (sensitive area = $4.4 \times 10^{-8}\ m^2$, rise time $\tau \sim 1$ nsec) operating at liquid nitrogen temperature. The frequency spectrum of the scattered radiation is measured using a pressure scanned germanium Fabry-Perot interferometer with free spectral range 11.2 Å and finesse 15.

The timing of the laser pulse is monitored with a photon drag detector and the arrival of the shock at the scattering volume by an electric probe slightly displaced from the scattering volume. The shock transit time past a point is 6 nsec and this has to coincide with the 50 nsec laser pulse.

RESULTS WITHOUT SPECTRAL RESOLUTION: In Fig. 2 we plot the peak detector signal, without spectral resolution, against the relative timing between the laser pulse and the arrival of the shock in the region of the laser beam viewed by the detector. A large detector signal occurs when the shock and laser beam are coincident at the scattering volume. The timing interval over which the signal is detected, $\delta t \sim 80$ nsec, approximately corresponds to the transit time of the shock through the region of laser beam viewed by the detecting optics.

We must also consider the possibility that this signal is enhanced stray radiation resulting from deflection of the incident beam in the refractive index gradient in the shock wave. For an electron density gradient dn_e/dr a ray propagating in the z direction is deflected through an angle

$$\alpha = \frac{e^2 \mu_0 \lambda_i^2}{8\pi^2 m_e} \int \frac{dn_e}{dr} \, dz \quad \text{rads.}$$

For our shock conditions $\alpha = 6 \times 10^{-4}$ rads which corresponds to a movement of the beam of 0.3 mm at the laser beam exit port. We have deliberately misaligned the incident beam over larger distances without increasing the stray radiation. Thus we can neglect deflection effects.

RESULT WITH SPECTRAL RESOLUTION: The resolution of the Fabry-Perot and detection system is 0.9Å as measured using the narrow line from low pressure (260 mtorr) operation of the laser. The scattering experiments however are performed with the laser at atmospheric pressure for which the measured halfwidth of the laser line was 1.9Å.

Fig 3 shows spectrally resolved detector signals obtained from shots with the timing in the interval δt of Fig. 2. The stray radiation spectrum, obtained from shots with the timing outside this interval is the same as the spectrum of the incident laser radiation measured before and after the run. The spectrum of the scattered radiation within δt, obtained by subtracting the measured stray radiation level, shows a shift to shorter wavelength $\Delta\lambda = 1.0$Å.

We must consider the possibility that a frequency shift of the stray radiation might arise from the time varying path length of the beam in the plasma. This results from the motion of the shock and the difference of refractive index across the shock. For our shock parameters this would produce a shift to shorter wavelength of only 0.05Å. This fact, together with the absence of any enhanced stray radiation anyway, leads to the conclusion that we observe genuine scattered radiation with a shifted wavelength.

In addition to the shift arising from the propagation of the fluctuations there is a further Doppler shift due to the small but finite component of $\underline{k}$ in the direction of plasma motion., (see Fig 1) and this shift is to longer wavelength. The magnitude of this shift depends on the position, within the shock, from which the strongest scattering occurs and can take a value from zero for the front of the shock to 0.6Å for the rear. As we do not know this position, we can only say that the corrected shift is in range 1.0 to 1.6Å and the corresponding range of fluctuation frequencies in the plasma are 1.7 to 2.7 GHz. This range overlaps the range of ion wave frequencies, with the appropriate k, within the shock ie 0.84 GHz at the front to 5.0 GHz at the rear.

The half width of the scattered spectrum (2.5Å) is only marginally larger than that of the incident beam (1.9Å). However from this upper limit on $\delta\lambda$ we can put a lower limit on the mode lifetime of the scattering wave $\tau = \lambda_i^2 / c\,\delta\lambda$ 1.5 nsec. This should be compared with a value $\tau \sim 0.3$ nsec found at higher k, and hence higher ω, using ruby light. An increase in τ at lower ω is consistent with the nonlinear theory of both ion wave scattering on ions and wave decay[7] because $\tau \propto 1/\omega$ for both.

LEVEL OF FLUCTUATIONS: The ratio of the scattered to incident laser power is a measure of S(k), $P_s/P_i = G\,\ell\,\Omega\,n_e\,\sigma_T\,S(k)$ where ℓ is length of laser beam viewed by the detector, Ω is the solid angle, σ_T is the Thomson cross-section and G is a geometrical factor arising from the fact that the detector does not view the full diameter of the laser beam. There is no simple method of absolutely calibrating the overall system at CO_2 laser wavelength. Rayleigh scattering, which is so useful at the ruby laser wavelength, is not feasible because the cross section $\sigma_R \propto \lambda^{-4}$. Our calculation of S(k) relies on knowing accurately all the other elements of the above equation. The input power P_i was measured using a photon drag detector to obtain the time dependence of the power and a calibrated calorimeter to obtain the pulse energy. We calibrated the detector by expanding a laser pulse of known power to a large cross section with a diverging lens and scanning the power distribution with the detector. The result agreed with the manufacturers figure.

We calculate the average S(k) over the shock width to be 185, i.e. an enhancement of ~ 260 above the thermal level [8]. This is about three orders of magnitude below that to be expected from an extrapolation of the Kadomtsev spectrum measured at $\underset{\sim}{k} \lambda_D \sim 1$. We consider three possible reasons for such a deviation:

(1) Collisional Damping: Ion-ion collisions with $\omega_{ii} = 1.6$ GHz will damp the observed waves with $\omega \sim 2$ GHz.

(2) Non-steady State: In the theory of Kadomtsev [5], energy diffuses from high to low k. Tsytovich [7] has derived a time scale for this diffusion which, for our conditions, would not allow the establishment of a steady state within the transitory shock.

(3) Angular Diffusion: Tsytovich [7] suggests that wave decay, made possible by the finite correlation time of the waves, is the dominant

non-linear process. He shows that this also has a Kadomtsev form and that the time scale for diffusion to low k, $\tau_d \sim 0.2$ nsec, is significantly shorter than the shock transit time. However for $\omega < \omega^* = 3m_e^{\frac{1}{2}} m_i^{-\frac{1}{2}} \omega_{pi}$ angular scattering of the waves becomes important and the level of turbulence will be lower than the Kadomtsev form. For our conditions $\omega^* \sim 3.3$ GHz. Consequently $\omega < \omega^*$ and we can expect such an effect.

CONCLUSIONS: We have described the first clear demonstration of the scattering of CO_2 radiation from a pulsed plasma. In previous scattering experiments [9,10] the observed signal was not spectrally resolved and hence the possibility of stray light could not be excluded with certainty. Our measured fluctuation level is three orders of magnitude lower than that predicated by an extrapolation of the Kadomtsev spectrum observed at high k. This disagrees with the result of Kornherr et al [9] who, for a high β collisionless shock, found the Kadomtsev form of spectrum to extend to low k.

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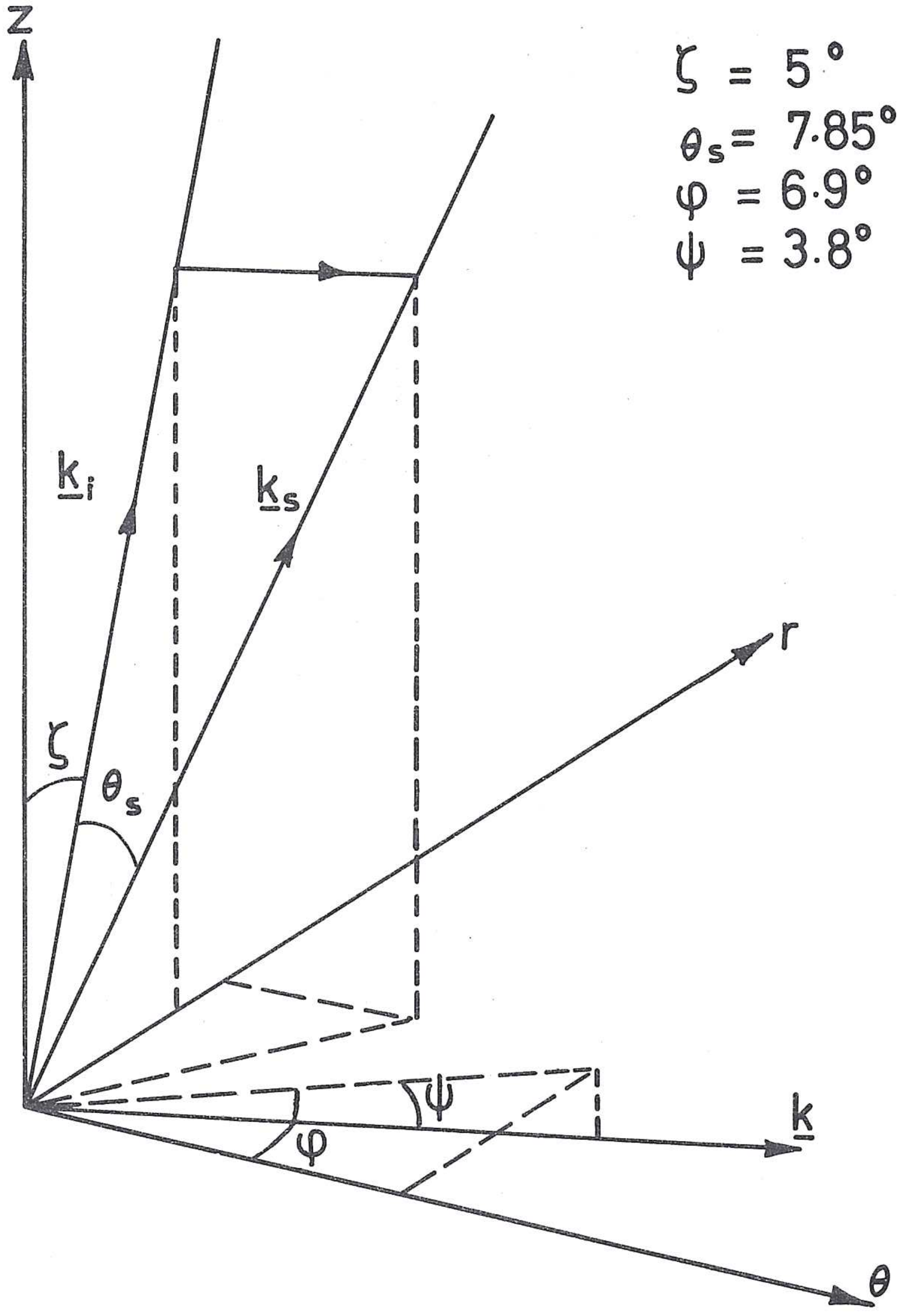

Fig. 1 Scattering geometry

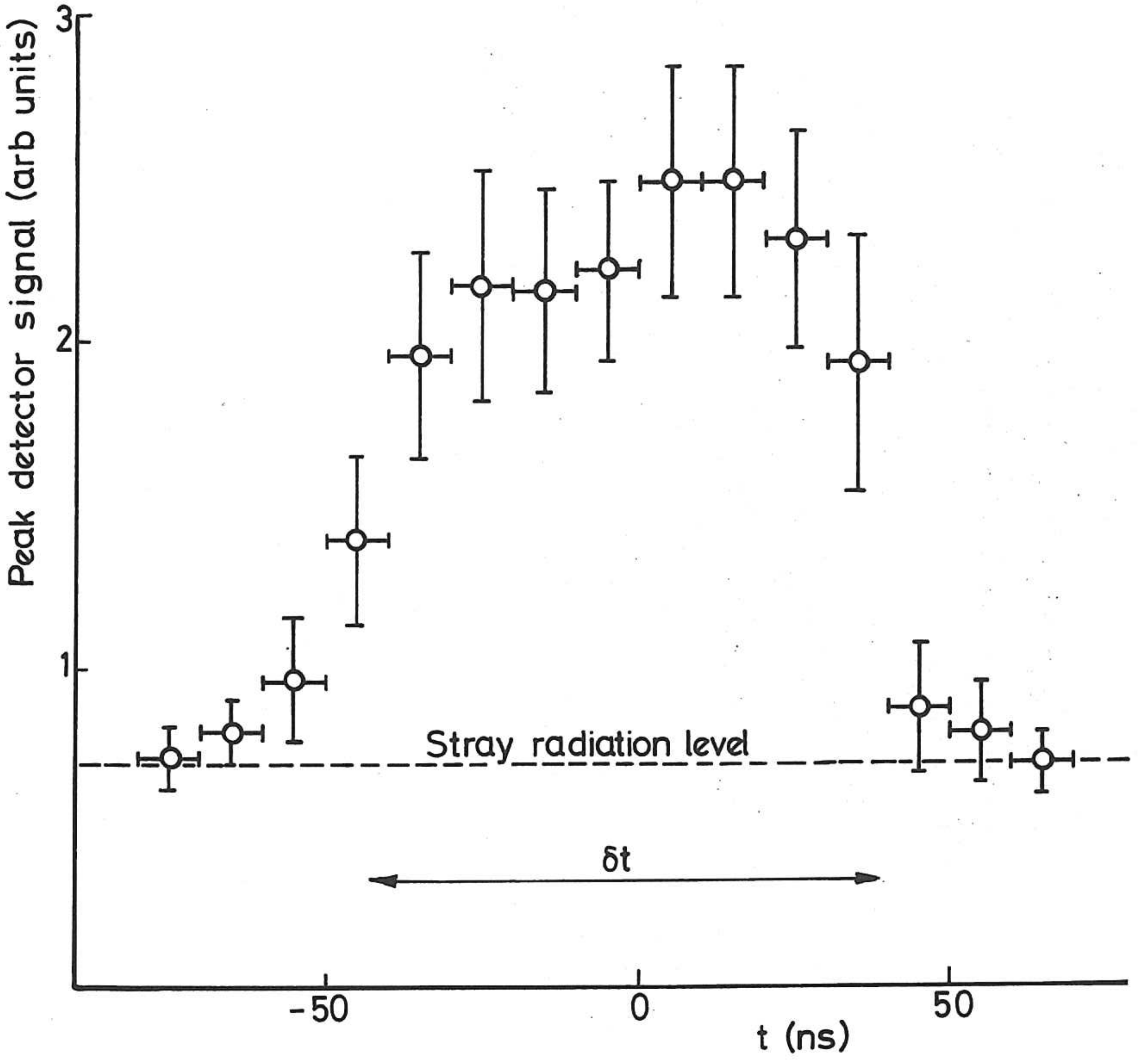

Fig. 2 Peak detector signal as a function of shock-laser timing

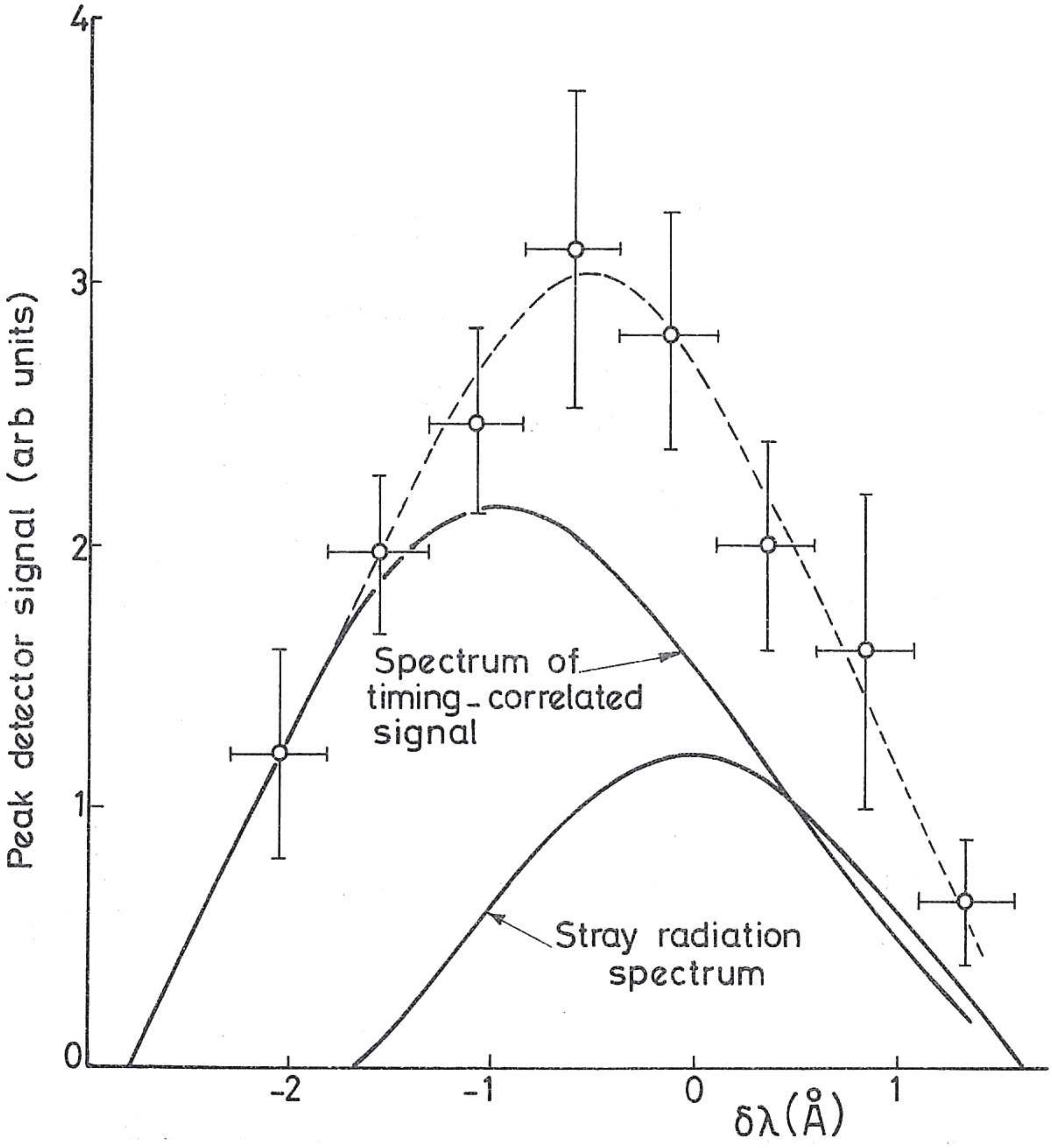

Fig. 3 Spectral resolution of scattered radiation signal