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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE - SUISSE

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ABSTRACT

The mode structures in an optically pumped D_2O far infrared ring laser and a corresponding linear resonator have been compared. While single mode operation can be obtained over the whole useful pressure range in the ring structure, this is only possible at pressures greater than 8 Torr in the linear resonator case.

A numerical model predicts quite well the pulse shape, pressure dependence and influence of the resonator quality in the ring cavity.

INTRODUCTION

In many applications of pulsed optically pumped far infrared (FIR) lasers, spectral purity and stability of the emission frequency are very important.

Recently the first single-shot ion temperature measurements have been reported in a tokamak, obtained from the analysis of collectively scattered radiation from an optically-pumped far infrared D_2O laser [1]. The maximum precision of 20% achieved in these measurements was mainly limited by the signal-to-noise ratio and hence detector sensitivity and laser power. However, the uncertainty of the laser emission frequency was also partly responsible for the size of the error bars in this experiment. Although pumped with a single mode CO_2 laser, the far infrared laser usually emitted 2 to 4 longitudinal modes.

A large variety of mode selection techniques for different lasers have been developed over the years. Many of them can also be applied to high-power optically pumped far infrared lasers. However, they usually require the introduction of lossy elements into the resonator, resulting in a considerable reduction of output power.

In linear resonators the growth of subsidiary modes is encouraged by spatial hole burning due to the formation of a standing wave pattern. This can be avoided in ring resonators were counterpropagating travelling waves are produced. We investigated and compared the mode structure of linear and ring resonators as function of D_2O vapour pressure, pump pulse shape and reflectivity of the optical elements. In a ring resonator of 2m optical path length, single mode operation is obtained over a large pressure range.

APPARATUS

Figure 1 shows the experimental arrangement used for these experiments. The CO_2 laser system consists of a hybrid-TEA laser oscillator (LO), tuned to the 9R(22) line, followed by a preamplifier (PA) in a double-pass configuration and a single pass main amplifier (MA). In the oscillator the gain is provided by the TEA module (LM) whereas line selection is achieved by the grating (G). An aperture (A_1) is used for transverse mode selection and single longitudinal mode operation is achieved with the low pressure section (~ 15Torr), (LP). Under typical operating conditions, the laser delivers 30J in a single-mode pulse of up to 1μs duration. Through a KCl window the pulse enters a 50 cm diameter metal tube which contains either a linear or a ring resonator structure for the far infrared. The latter is formed by metallic grids and a mirror. The tube is filled with a few Torr of D_2O vapour which emits at the wavelength of 385μm. The radiation emitted from the resonator is analysed in a Faraday Cage (FC) by means of Schottky diodes in video mode or by pyroelectric energy meters (Laser Precision, model RjP 735 RF). The fraction of infrared radiation reflected from either of the two surfaces of the KCl entrance window is recorded with an energy monitor (Gen-Tec, ED-500) and a photon drag detector (Rofin LTD, model 7415).

MEASUREMENTS

1. *Mode structure in a linear resonator*

If the output of the D_2O oscillator is recorded with a fast detector like a Schottky diode, the presence of more than one resonator mode manifests itself by a beat signal. The pulse form is modulated with the intermode frequency $\Delta\nu = c/2L$, where L is the resonator length. We show in Fig. 2 (upper trace) a typical single mode (left hand side) and multimode (right hand side) FIR pulse shape. Both were obtained in a linear cavity (L = 1m) consisting of two metallic grids of reflectivities R=84% (pump input side) and

90% (output coupler). The vapour pressure was 9 Torr in the single mode case (Fig. 2a) and 2 Torr in the multimode case (Fig. 2b). The pump pulse (Fig. 2, lower trace) was single mode in both cases. It is generally observed that single mode operation can only be achieved at high pressure (>8Torr) and with a single mode pump pulse.

At first sight it seems surprising that single mode output is more readily obtained at high pressure. Over the pressure range considered, the gain profile is pressure broadened and hence larger at higher pressures. Usually the wider the gain profile, the more likely it is to observe two or more modes developing. This is in contradiction to our observation. The explanation resides in the saturation behaviour and in the fact that the position of the gain peak can shift significantly under the influence of saturating pump or FIR intensities. Hence established modes at a particular frequency see a reduced gain when the gain peak moves away to a different frequency range due to the continuously varying laser intensities during the pulse, whereas other modes are now able to grow. At lower pressures saturating intensities are easily reached. At high pressures this is not usually the case and hence the gain profiles are much more stable. The increasing width of the gain profile is not so important, since mode competition effects in optically pumped systems are quite pronounced due to the mutual coupling of different modes via the pump field. Hence a strong mode can easily suppress neighboring weaker ones.

2. Mode structure in a ring resonator

In a triangular ring resonator (see Fig.1) with a round-trip distance of 2m, consisting of two grids with 75% reflectivity (G1) and 4% to 96% reflectivity (G2) we managed to obtain single mode operation over the whole useful pressure range from 1 to 9 Torr. Again, the pump pulse has to be single mode to achieve this. Two examples are shown below for pressures of 3 Torr and 8 Torr, see Fig. 3.

We have also observed that single mode operation can be obtained for a large range of output coupler reflectivities (4% to 96%). Figure 8 shows some examples.

3. The output energy of the FIR laser as a function of gas pressure

The output energy of the FIR laser is proportional to the number of molecules in the active medium. Hence a decrease is to be expected for low pressure. At high pressure collisional effects destroy the population inversion and broaden the gain profile which results again in a decrease of output energy. Optimum performance is expected at some intermediate pressure. This is observed in Fig. 4 which shows the measured output energy as a function of gas pressure for the case of a linear resonator and a ring resonator in forward and backward direction (with respect to the direction of the pump beam).

Comparing the output in backward and forward direction we note, that the energies in forward direction are more than twice as large. For the two propagation directions the maximum is also obtained for a different pressure. This can be explained by the pump dynamics. When the pump pulse starts to penetrate into the FIR resonator, for example, radiation in forward direction is immediately produced and amplified, whereas in backward direction full gain is only available after a completed loop of the pump pulse.

We note that the total output energy in forward and backward direction is about the same as the output energy of the linear resonator. This means that single mode operation over the whole pressure range can be obtained in a ring resonator without a reduction in output energy.

4. The FIR laser pulse shape of a ring resonator as function of gas pressure and resonator quality

The basic properties of an optically pumped D_2O laser, characterized by a three-level system interacting with a FIR and a pump field (Fig. 5), are well understood [2,3,4,5]. In such a system the two photon Raman process plays an important role, as well as the usual two-step laser process. The gain is a function of pump intensity, FIR intensity, and pump frequency offset. Assuming a steady-state level population, the FIR gain for given pump conditions can be calculated. Since both pump and FIR intensities are functions of time, a dynamic simulation model is necessary to investigate a high power pulsed D_2O laser.

We used a numerical rate equation code [6] to simulate our D_2O ring resonator laser. The two photon process, the bottleneck effect, and the decrease in pump intensity due to absorption are all taken into account. Although this code has been developed for a linear resonator, it does not include the spatial hole burning effect which is important in this type of cavity. Predicting the performance of a ring resonator should therefore yield even better results.

We show below (Fig. 6) the measured and simulated pulse duration as a function of resonator quality and gas pressure. The general trends are quite well reproduced by the code. Basically we observe a considerable pulse lengthening with high quality resonators and a slight pressure dependence.

The pulse length shows a linear dependence with respect to the pump pulse duration, Fig. 7.

The FIR pulse shape is quite accurately predicted by the code as can be seen by comparing the Figs 8 and 9. For these computations the measured CO_2 pulse shape has been digitized and is used by the code as input. Please note that in Fig. 8, the intensity of each curve has been rescaled in order to make it comparable to the numerical results.

Under certain conditions we have also observed pulse shapes with two peaks, experimentally and numerically, Fig.10. This effect has been discussed extensively in [2,7,8]. It is basically due to saturation effects and the shifting of the gain profile in frequency due to the pump and FIR intensity induced Stark effects. Mode competition and interaction effects are also important in all cases where single-mode operation is not observed.

CONCLUDING REMARKS

It has been observed that single mode operation in an optically pumped D_2O laser can be achieved much more easily in a ring resonator, for comparable output energies. In a linear resonator single mode operation is usually only obtained at high pressure (> 8Torr), whereas this can be achieved over the whole useful pressure range in the ring cavity.

A rate equation code based on an optically-pumped three-level system including appropriate relaxation mechanisms is quite adequate to describe the ring laser. It cannot, however, predict the mode structure (single or multimode operation) of the far infrared laser. Work is currently in progress to study this with a code which is capable to describe mode interaction phenomena.

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FIGURE CAPTIONS

Fig. 1 : Configuration of the experimental system:

LO :	Hybrid-TEA CO_2 Laser Oscillator	G:	Grating
LP :	Low Pressure Section	$A_{1,2}$:	Apertures
LM :	TEA Laser Module	$G_{1,2}$:	Metallic Grids
PA :	CO_2 Pre-Amplifier	D_1-D_4 :	Pulse Shape or Energy Detectors
MA :	CO_2 Main Amplifier		
FIRL:	D_2O FIR Laser	GC:	SF_6 absorption cell to suppress parasitic oscillation
FC :	Faraday Cage		
OC:	ZnSe output coupler R=75%, r=5m		

Fig. 2 : A typical single and multimode pulse shape in the linear cavity
(a) Single FIR mode at 9 Torr; (b) Multimode FIR at 2 Torr. (Top trace is pump pulse shape; bottom trace is FIR laser pulse shape. The time scales are 0.5 μs/div.)

Fig. 3 : Two typical single mode FIR pulse shapes in a ring cavity
a) 8 Torr D_2O pressure (0.5μs/div.);
b) 3 Torr D_2O pressure (0.5μs/div.).
The bottom trace is the CO_2 pump pulse shape.

Fig.4 : FIR laser energy as a function of D_2O vapour pressure :
1) output energy of linear resonator (L=1m);
2) output energy of ring resonator in forward direction;
3) output energy of ring resonator in backward direction (ring resonator round trip distance : 2m).

Fig. 5 : Schematic energy level diagram of an optically pumped D_2O laser :
1) Two-step laser process;
2) Two photon Raman process.
N_i are population densities and τ_v, τ_j the vibrational and rotational relaxation time constants, respectively .

Fig.6 : FIR ring resonator pulse length as a function of D_2O pressure and output coupler reflectivity R. (R = 10%, 22%, 43%, 67%, 90% for the curves 1 to 5)
(a) experimental results,
(b) numerical results.

Fig. 7 : Measured D_2O laser pulse duration as a function of the pump pulse duration.

Fig. 8 : Measured single mode FIR pulse shapes in a ring resonator (forward direction) for different output coupler reflectivities R, (p=3Torr).
1) R=10%, 2) R=22%, 3) R=67% (different intensity scales used).

Fig. 9 : FIR pulse shapes obtained from the numerical simulation code for the conditions of Fig. 8. (curves numbered as in Fig. 8)

Fig.10 : D_2O FIR laser pulse shapes with two peaks :
(a) experimental; bottom trace : CO_2 (0.5μs/div)
(b) numerical

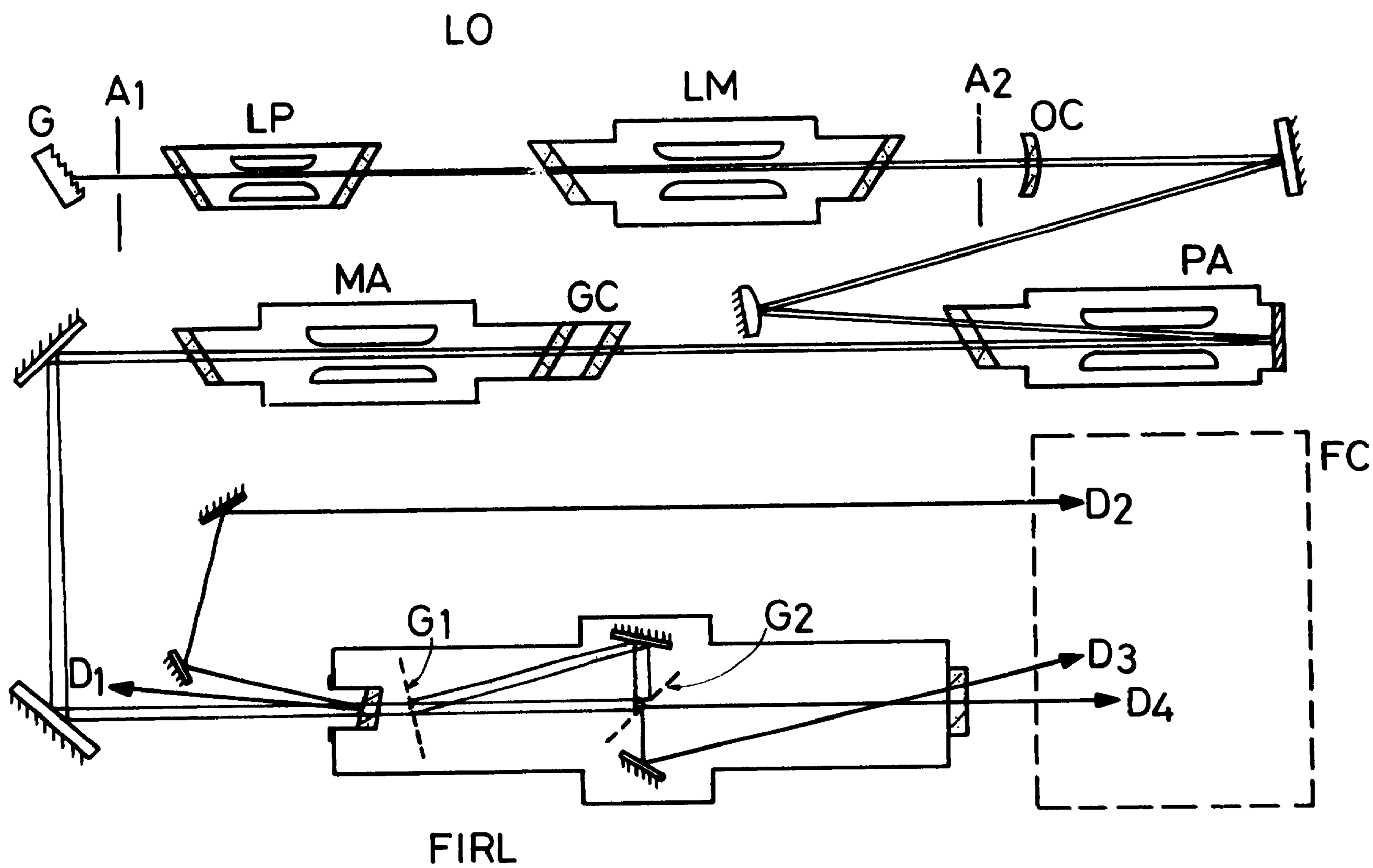
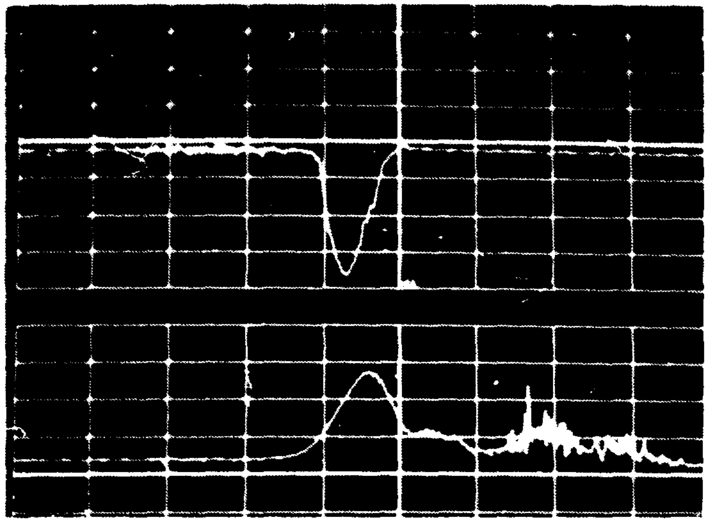


Fig. 1



a)

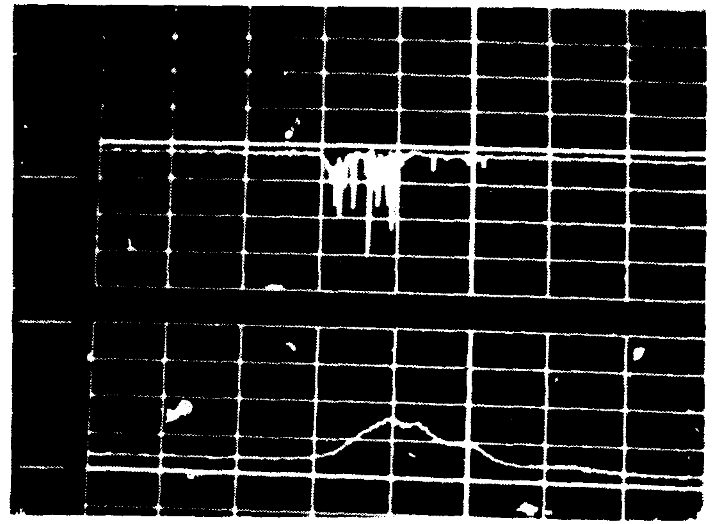


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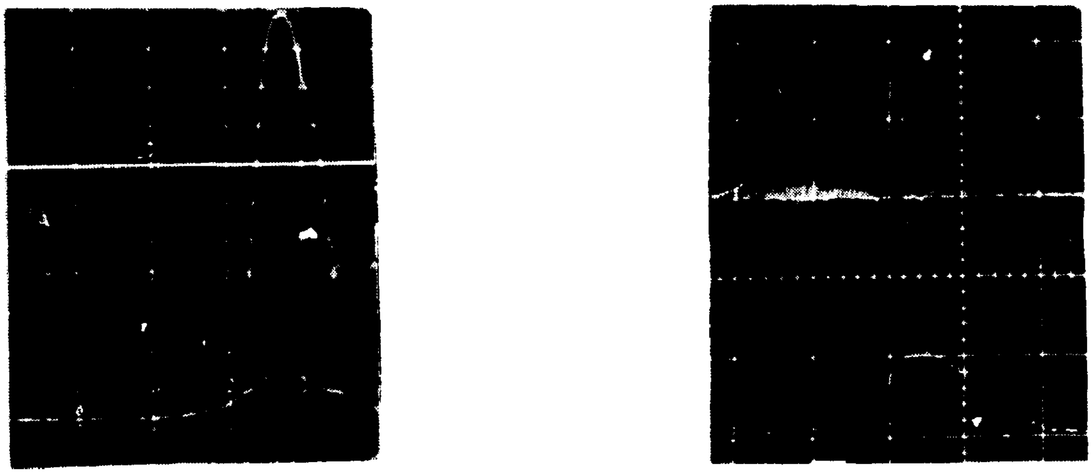
Fig. 2



a)

b)

Fig. 3

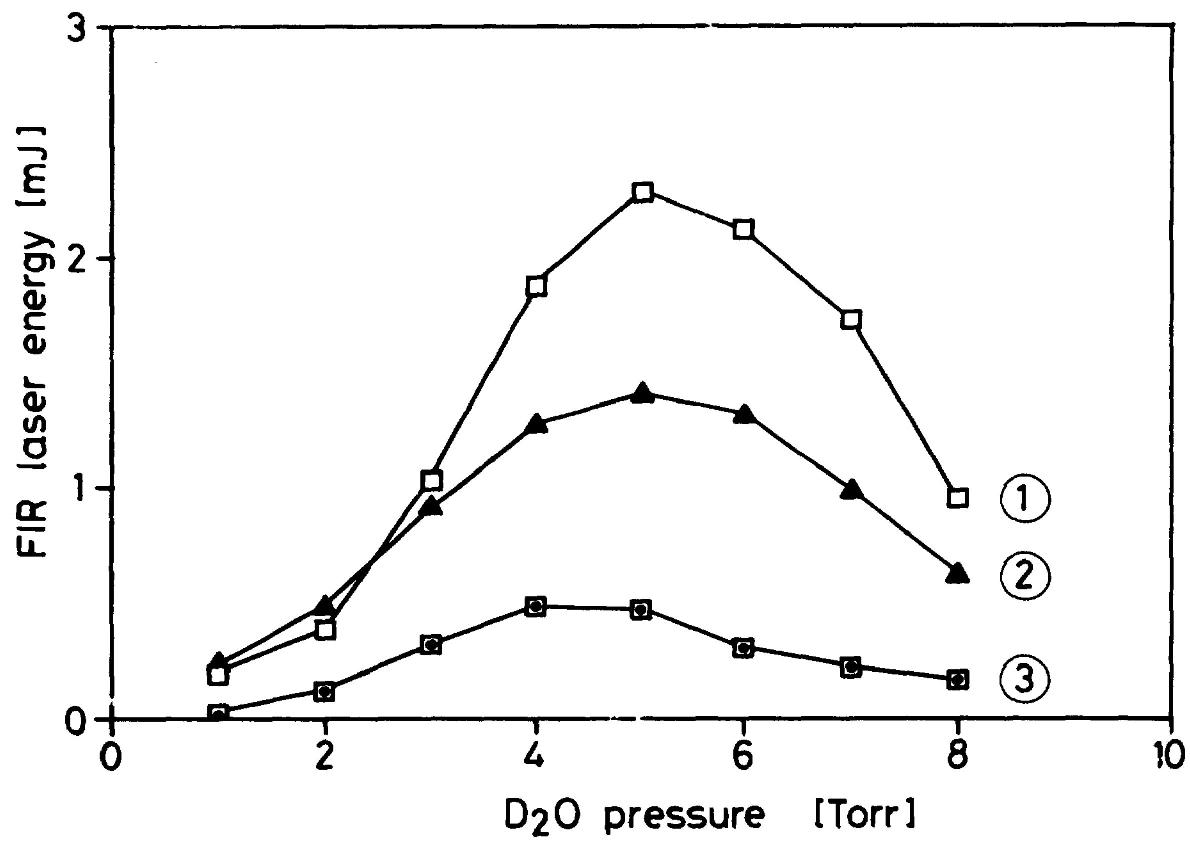


Fig. 4

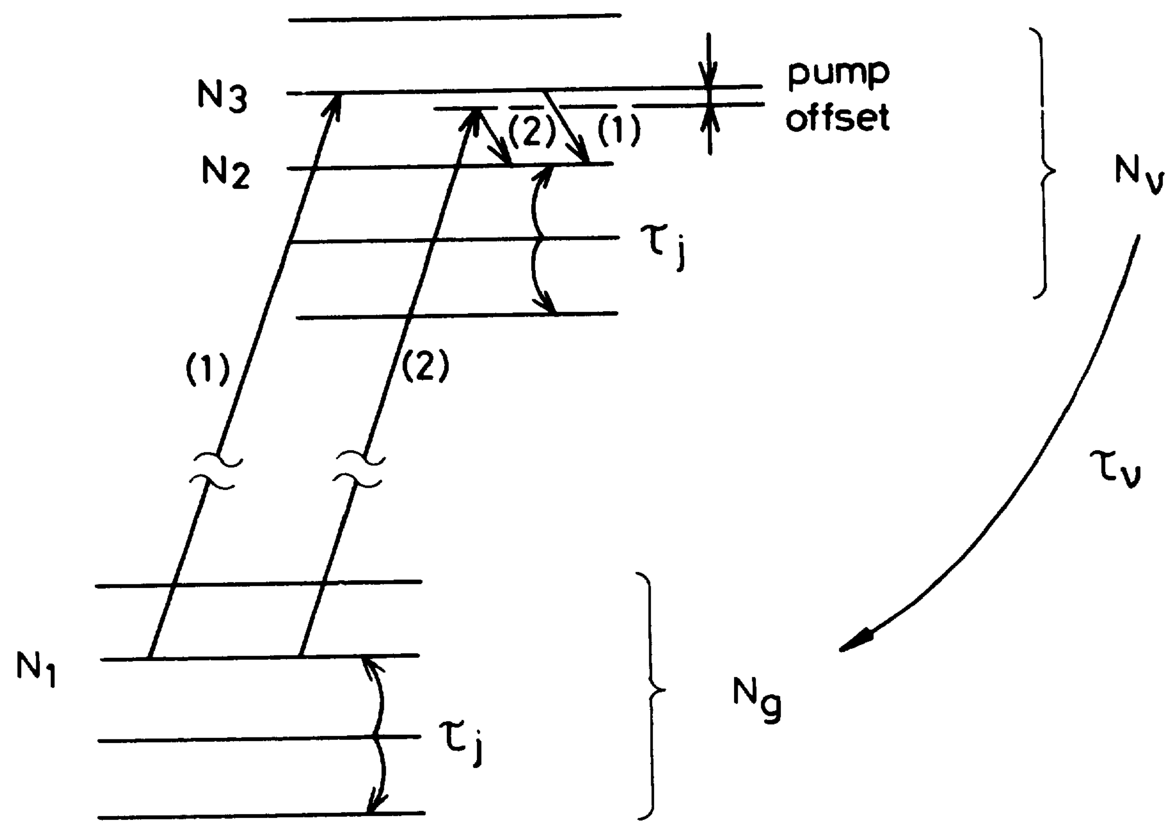


Fig. 5

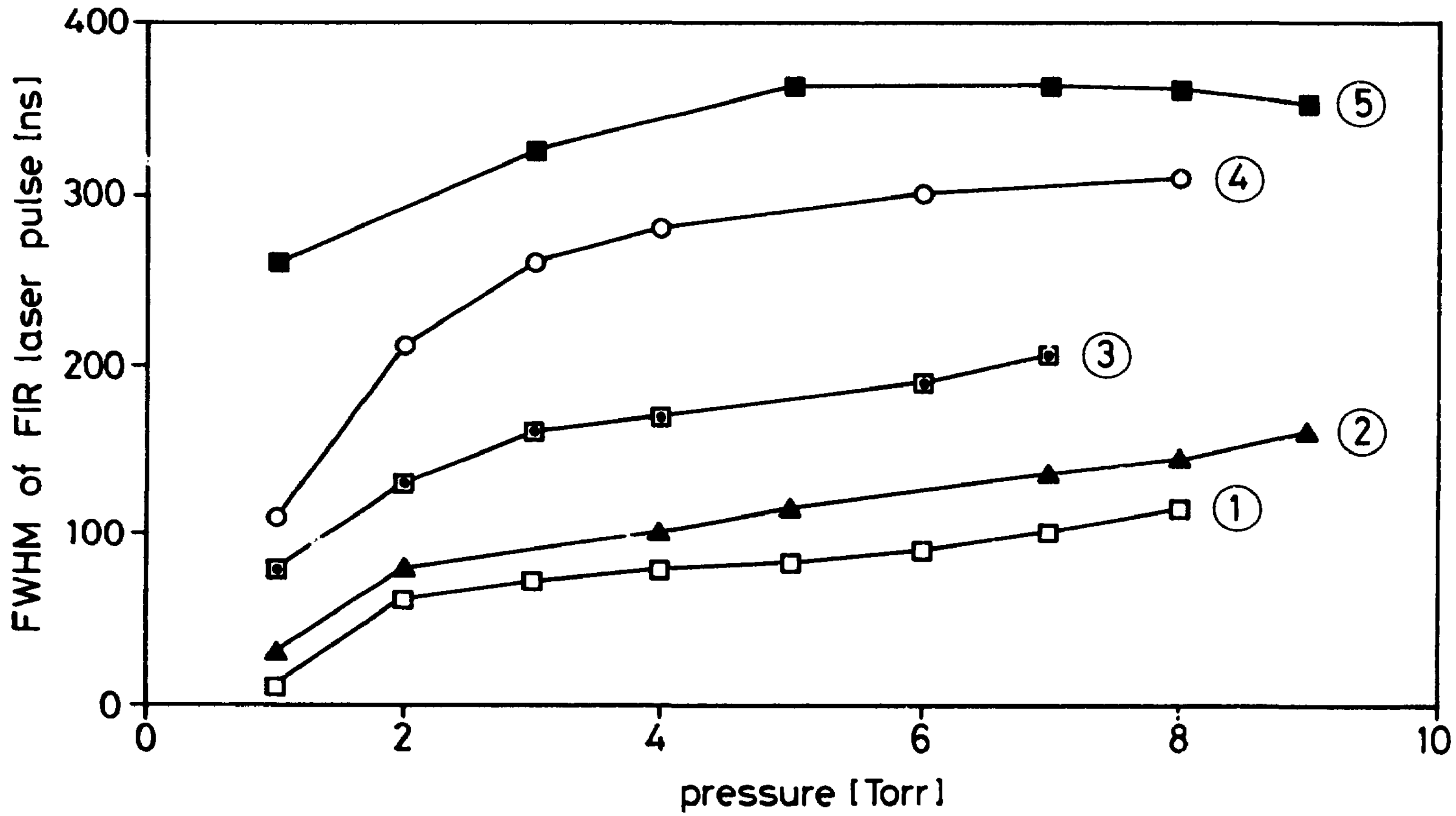

FWHM of FIR laser pulse [ns]
400
300
200
100
0
0
2
4
6
8
10
pressure [Torr]
1
2
3
4
5

Fig. 6

a)

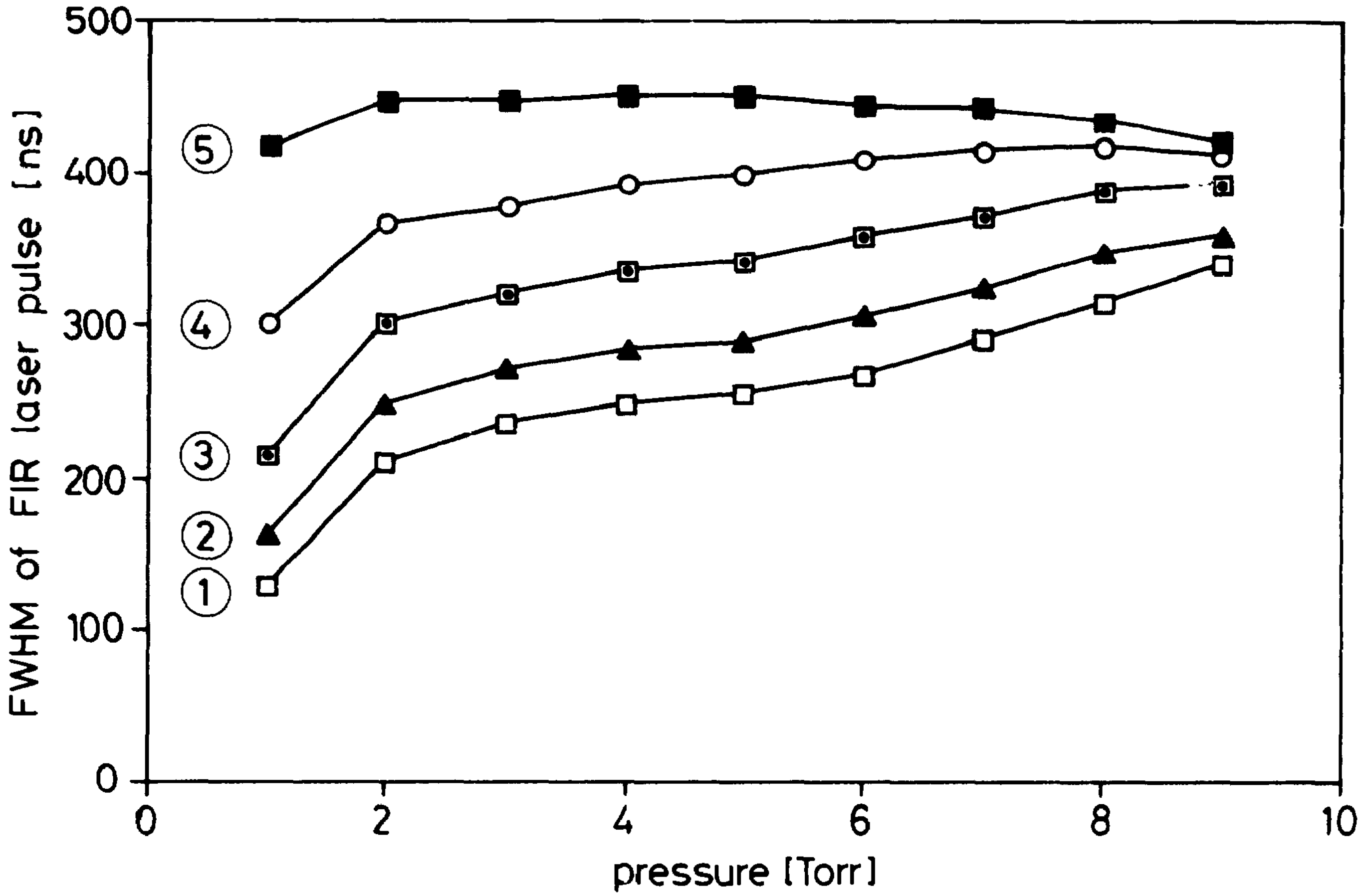
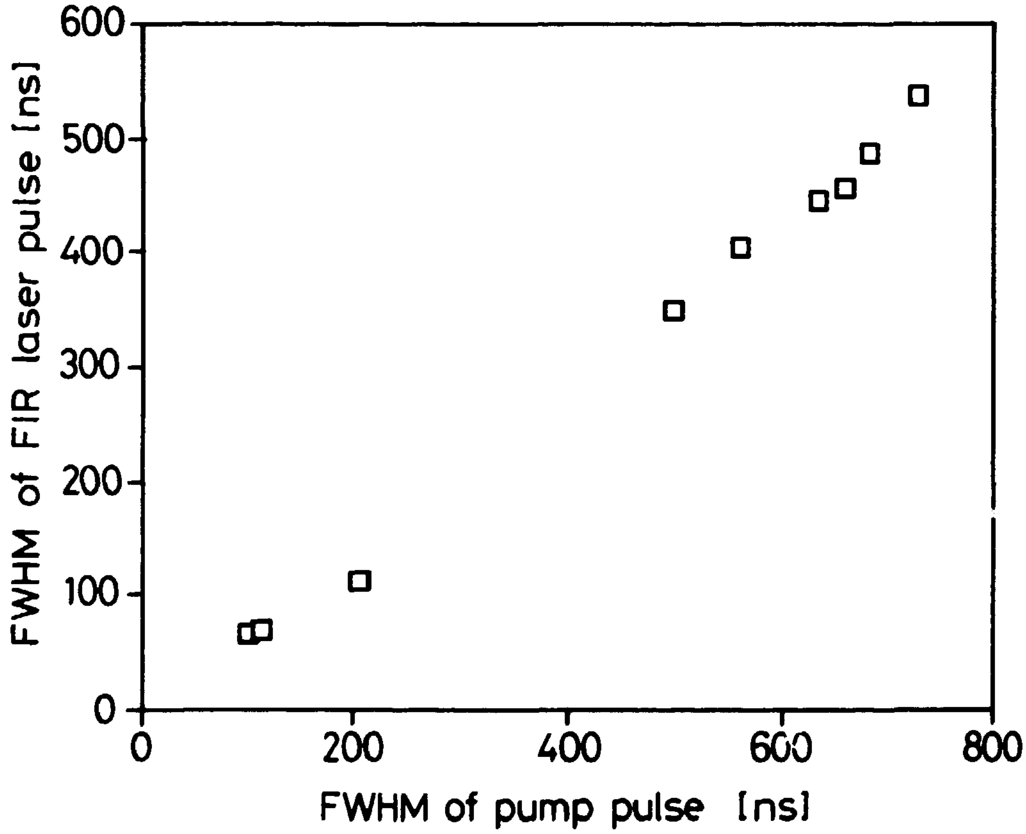

500
400
300
200
100
0
FWHM of FIR laser pulse [ns]
0
2
4
6
8
10
pressure [Torr]
5
4
3
2
1

Fig. 6



600
500
400
300
200
100
0
FWHM of FIR laser pulse [ns]
0
200
400
600
800
FWHM of pump pulse [ns]

Fig. 7

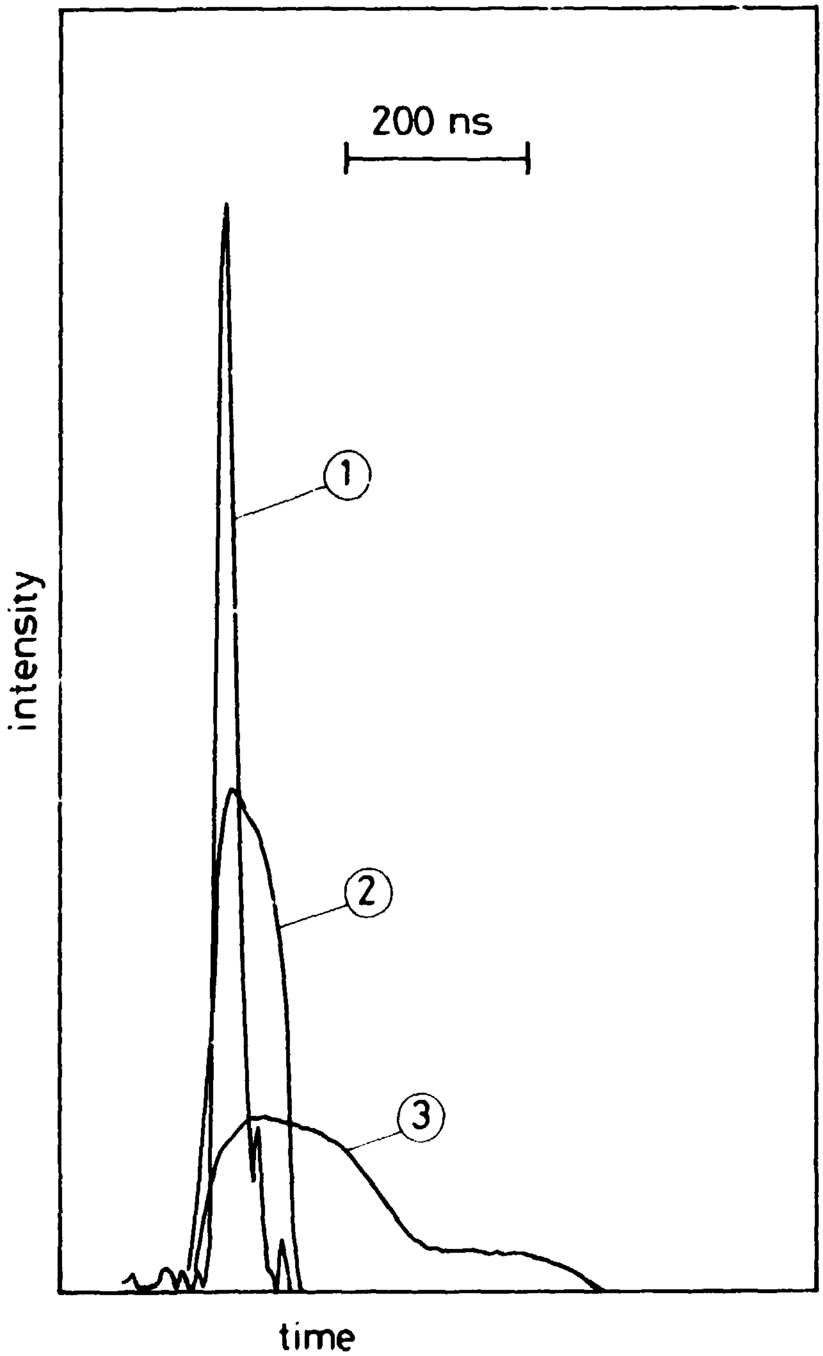


Fig. 8

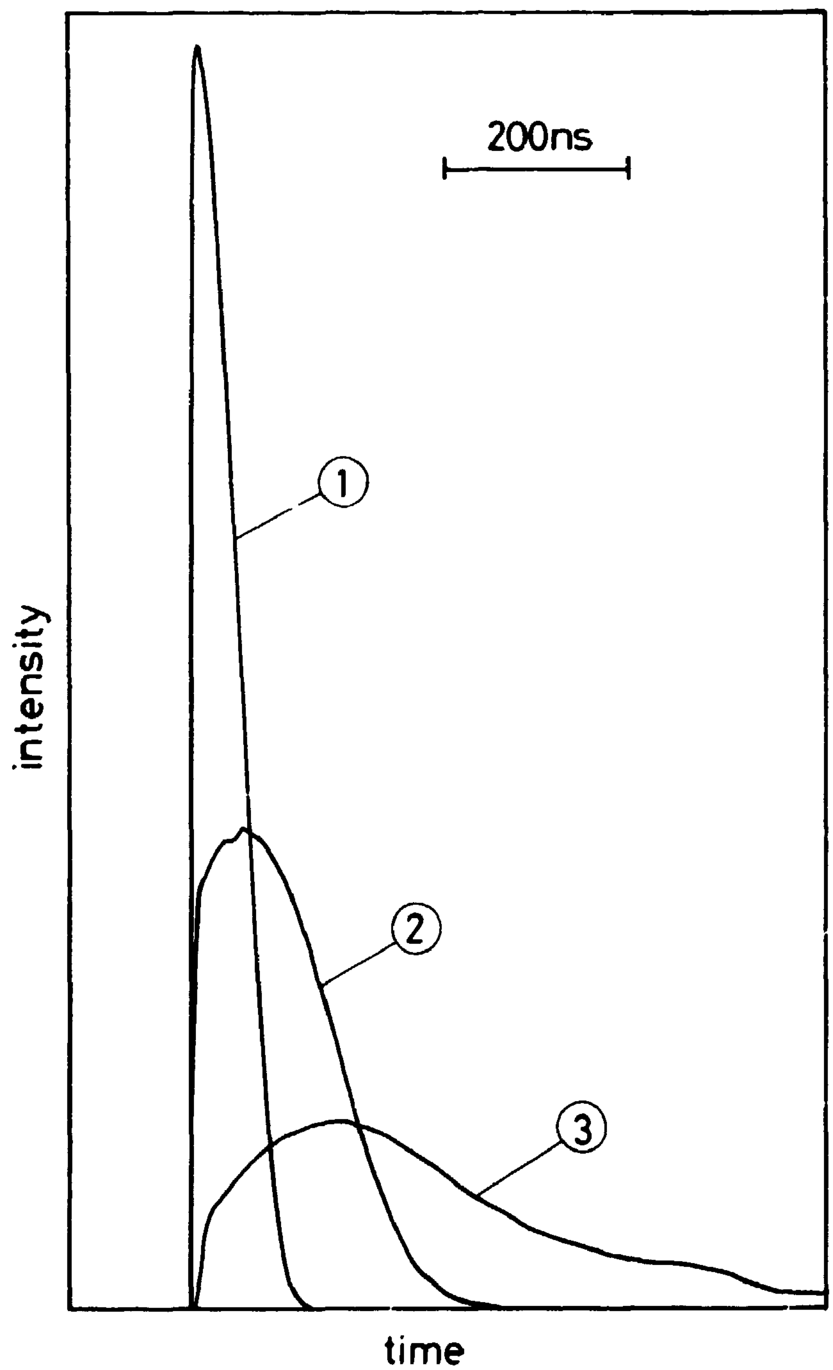


Fig. 9

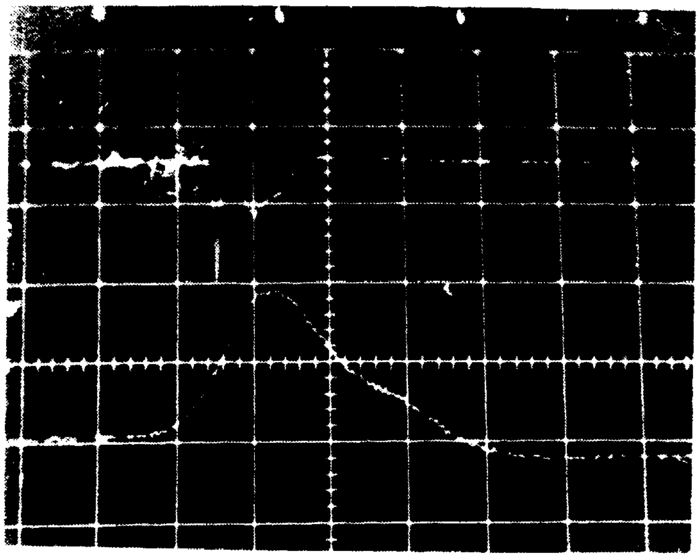


Fig. 10

a)

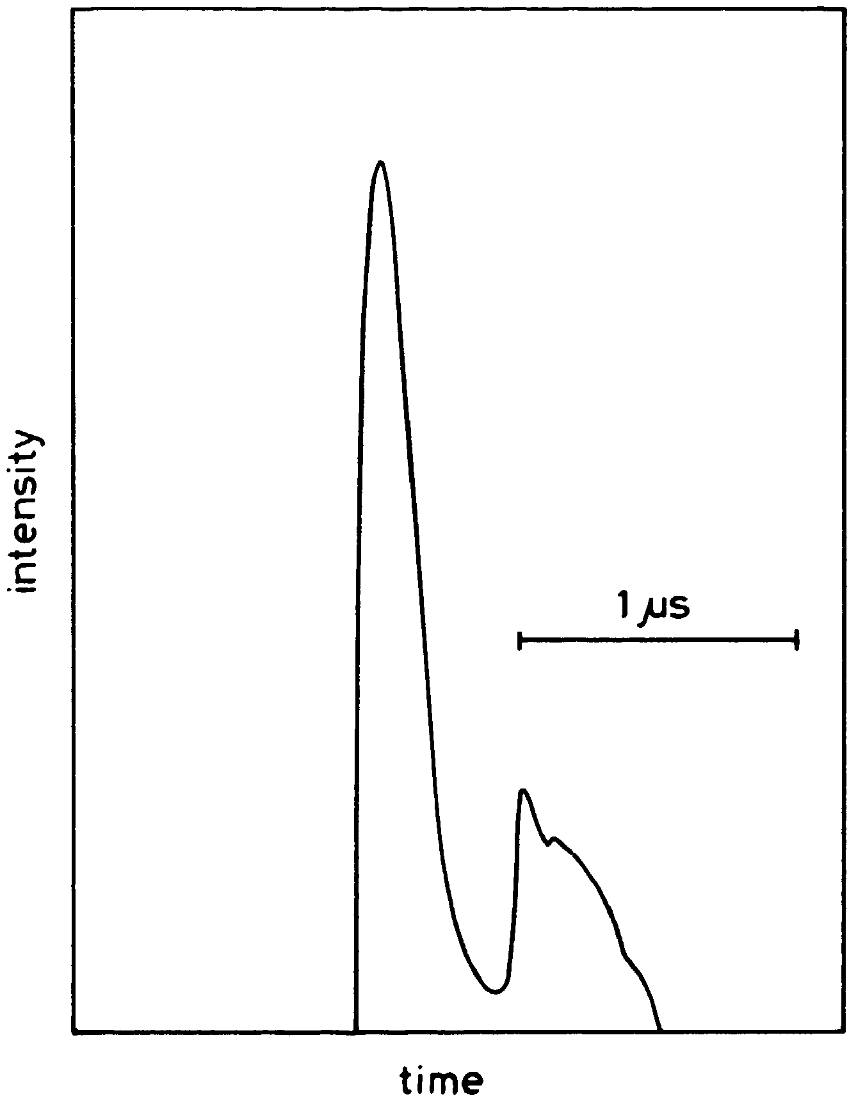


Fig. 1C

b)