The Electro-optical Effect

The fastest charged particle detectors of charged particles utilize the conversion of electric field to light, e.g. Čerenkov and transition radiation.

The electro-optical (**EO**) effect does this as well but indirectly. It has the potential for far superior temporal resolution (fs) as well as better spatial resolution.

The operating principle of EO detectors is that the polarization of laser light in an appropriate material is briefly changed by the passing particles' electric field so that the laser light which had been extinguished by a crossed polarizer appears for detection by a fast photodiode.

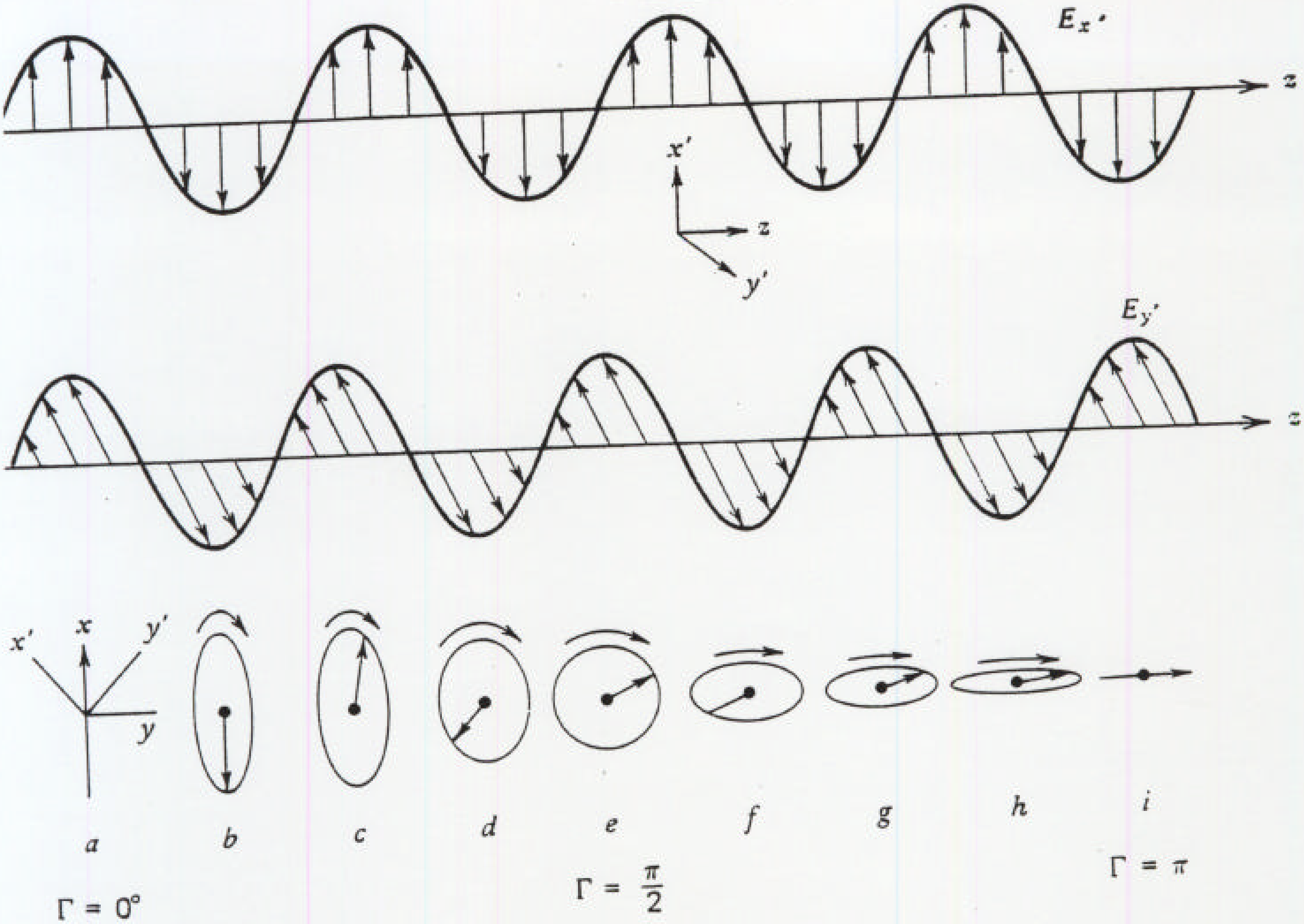
The electric field modifies the index of refraction of the material so that the index of refraction becomes birefringent, i.e. the index of refraction becomes different for different directions of polarization.

This means that one component of the laser light travels faster than an orthogonal one and a phase difference between the them arises. The light is then elliptically polarized. The ellipticity can be transformed back to a linear polarization with a quarter wave plate albeit at a somewhat different angle than the original.

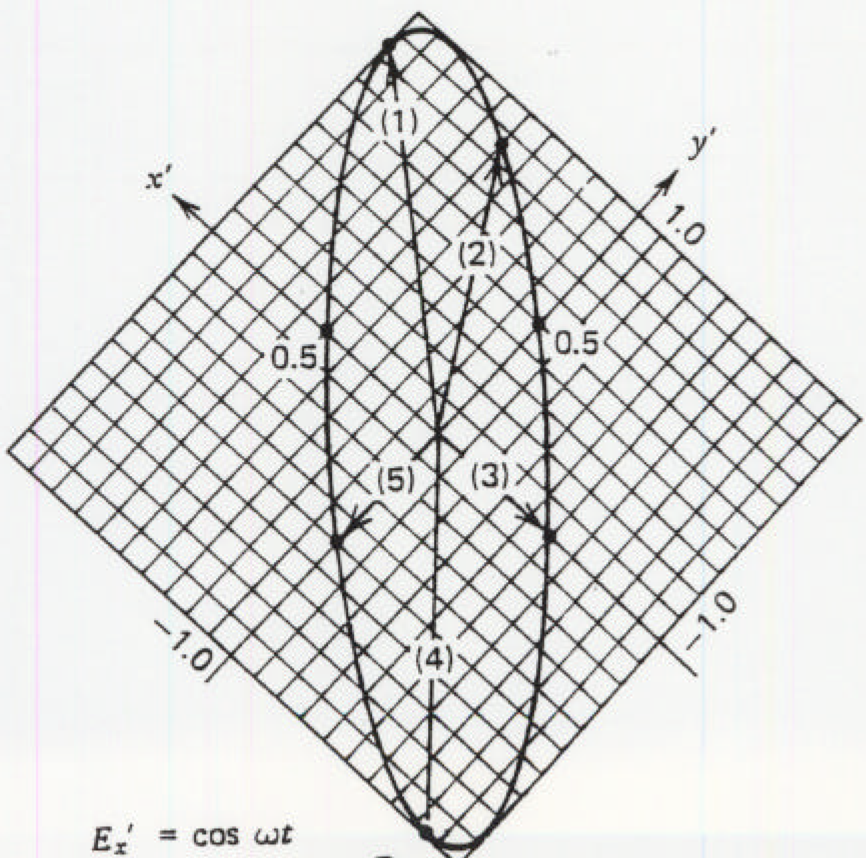
Laser light which had been extinguished by means of a crossed polarizer (analyzer) is then transmitted to an appropriate detector.

Appropriate materials have beneficial properties such a large EO coefficient, a small dielectric constant and of course transparency at the wavelength of the laser light.

The EO effect depends on the material. Amorphous materials produce an effect the is quadratic in electric field, E while the EO effect in uniaxial crystals is linear in E. The quadratic effect is called the Kerr effect after its discoverer, J. Kerr 1875 and the linear effect is known as the Pockels effect published in 1894 by F. Pockels.

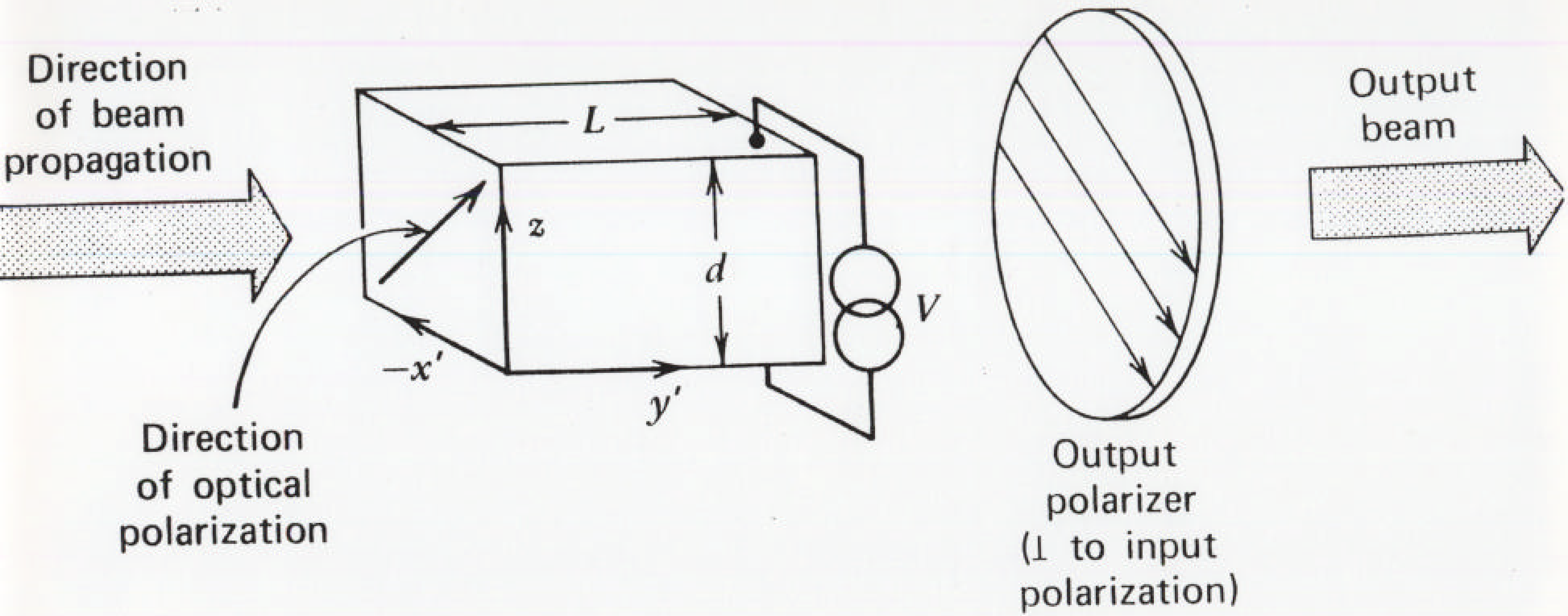


(d)



$E_x' = \cos \omega t$

$E_y' = \cos (\omega t - \frac{\pi}{2})$


Direction
of beam
propagation
L
z
d
V
−x′
y′
Direction
of optical
polarization
Output
polarizer
(⊥ to input
polarization)
Output
beam

Kerr Coefficients

Material	meter/volt^2
Nitrobenzene	2.4×10^{-10}
Water	4.4×10^{-14}
Benzene	0.7×10^{-14}
Optical fibers/quartz rods	$10^{-16} - 10^{-15}$

E field and Phase Shift

	d(m)	N	E(V/m))	ϕ(radians)
Lab	10^{-3}	[redacted]	1.0×10^{6}	6.0×10^{-4}
Au	10^{-6}	1	1.1×10^{5}	7.7×10^{-11}
ATF	10^{-6}	10^{10}	1.4×10^{3}	1.2×10^{-4}
ATF	10^{-3}	10^{10}	1.4×10^{-3}	1.4×10^{-10}

Pockels Coefficients

Material	Pockels Constant(m/V)	Refractive Index
$LiNbO_3$	3.08×10^{-11}	2.286
$LiTaO_3$	3.03×10^{-11}	2.180
KD_2PO_4	2.36×10^{-11}	≈ 1.5

Principle of Operation

After measuring the EO constants of optical fibers and quartz rods we used $LiNbO_3$ crystals for our measurements.

EO signal detection requires a laser, polarizer, an EO material subjected to an electric field and a crossed polarizer (analyzer).

The signal amplitude can be enhanced by introducing a quarter wave plate between the EO crystal and the analyzer.

A quarter wave plate is a transparent birefringent material of thickness d, such that a phase difference $\pi/2$ is produced for a given wavelength.

$$\pi/2 = \phi_e - \phi_o = 2\pi/\lambda(n_e - n_o)d \tag{1}$$

where $(n_e - n_o)$ is the difference between the refractive indexes for the two orthogonal polarizations.

This enables one to remove the phase difference between the two components of polarization, thereby converting the elliptical polarization back to a linear one at an angle θ given by

$$\tan\theta = E_{fast}/E_{slow}. \tag{2}$$

For small signals it is useful to introduce a small angular misalignment of the analyzer α, in order to enhance the signal to background ratio. The intensity exiting the analyzer is given by

$$I = I_0[\sigma^2 + (\alpha + \epsilon(t))^2] \approx I_0[\sigma^2 + \alpha^2 + 2\alpha\epsilon(t)] \tag{3}$$

where $\epsilon(t)$ is the induced ellipticity and $\sigma^2 \equiv$ extinction, i.e. the ratio I/I_0 when $\alpha = \epsilon = 0$.
Using α to linearize and amplify the signal ϵ also allows one to change the sign of the EO signal by changing the misalignment-angle α to the other side of the best extinction.

The signal to noise ratio is then

$$SNR = \epsilon\sqrt{\frac{PTq_p}{2h\nu}} \tag{11}$$

where P $\equiv$ power (watts),
T $\equiv$ detection system time resolution or inverse of its bandwidth,
$q_p \equiv$ quantum efficiency of detector (fast photodiode)and $h\nu \equiv$ laser photon energy

The Electric Field

The electric field of a relativistic charged particle in its rest frame is given by Gauss' Law. In a transparent medium the field is reduced by the dielectric constant, κ.

$$E = \gamma N_e \frac{q}{4\pi\kappa\epsilon_0 r_0^2} \tag{4}$$

where $\gamma = 1/\sqrt{1-\beta^2}$ and N_e is the number of electrons in a beam bunch.

In the laboratory, the electric field is present for

$$\Delta t = r_0/\gamma c \tag{5}$$

and the electric field distribution is contained in a disk whose axis is along the direction of motion.

During this time the laser light travels

$$\Delta l = (c/n)\Delta t = r_0/n\gamma \tag{6}$$

Integrating the electric field over the dimensions of the laser light in the crystal yields

$$\int E dl = \frac{N_e \gamma q}{2\pi\kappa\epsilon_0 r_0} \tag{7}$$

The sensitivity of commercially produced $LiNiO_3$ crystals is normally given in terms of the electric field times the length of to produce a phase difference of π. For the crystal used in early tests this was $V_\pi = 5.7V$ across 15 μm with a length of 1.5cm.

$$(\int E\, dl)_\pi = \int 5.7V/(15 \times 10^{-6}\,\mathrm{m})\, dl = 5700\ V \tag{8}$$

At a distance of closest approach between the charged particles and the laser beam of 5mm , with $\kappa = 32$ and n=2.2

$$\int E dl = 4.1 \times 10^{-9} N_e V \tag{9}$$

Combining this with the EO crystal calibration we obtain

$$\epsilon = \frac{\int E dl}{(\int E dl)_\pi} \times \pi/\sqrt{2} = 7.2 \times 10^{-13} N_e \tag{10}$$

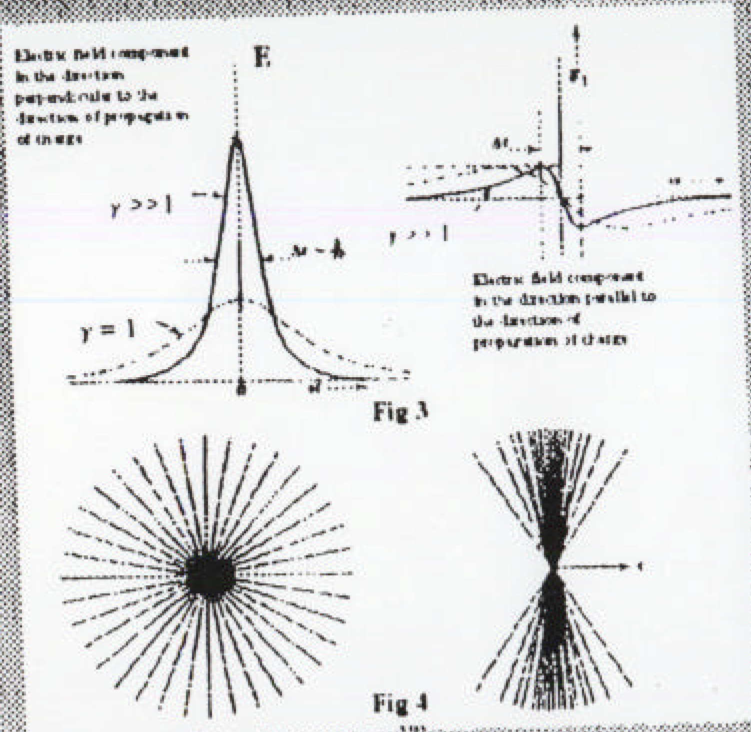


Fig 3

Fig 4

Electric field due to relativistic point charge

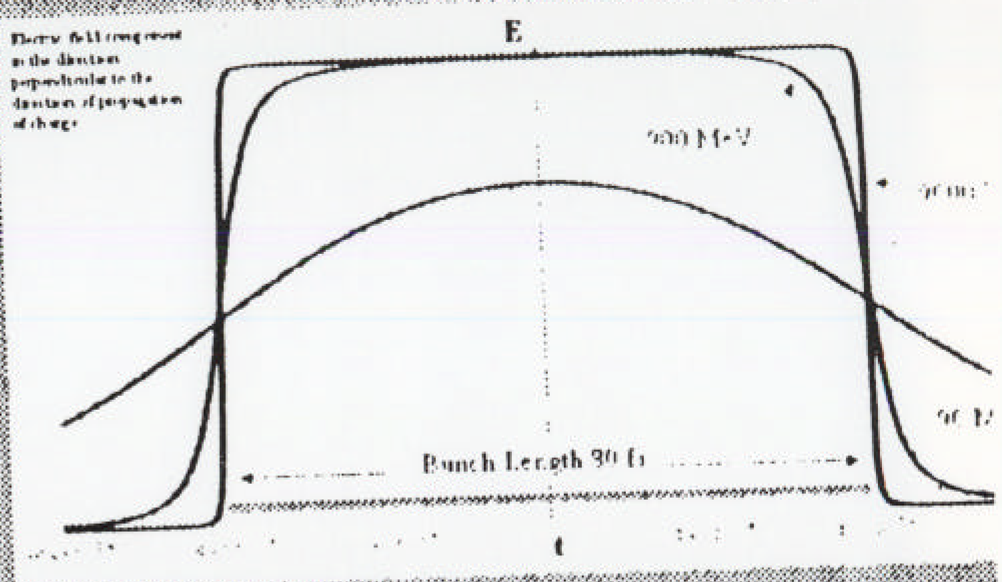


Fig 5. Temporal behavior of the Electric field due to a relativistic line charge (bunch length 80 fs). For large Energies the the duration of he temporal field approaches the bunch length

Nuts & Bolts

Since our sensitivity is inadequate for the detection of singly charged particles or even relativistic Au ions, we performed out studies at Brookhaven's Accelerator Test Facility which provides a 45 MeV beam of up to 600 pC in 10 ps bunches at 1.5 Hz.

Initial tests were performed with a 20 mW CW laser operating at λ =1320 nm. A fast photodiode and pre-amplifier were followed by a 10 GHz amplifier and digitized and stored in the memory of a 7 GHz oscilloscope which limited our time resolution to $\approx$ 150 ps.

Later tests required a pulsed laser in order to measure time resolutions of several ps with a streak camera. A triggerable NdYAG laser at $\lambda = 532$ nm with $\approx 10\mu$J per pulse was used.

The streak camera was a Hamamatsu C6860 and came with an operator.

It converts photons at a photocathode, accelerates the electrons by means of a high voltage mesh, narrows their dimensions in the deflection direction with an adjustable slit with a range of several microns prior to deflection by pulsed high voltage and multiplication by a multichannel plate. They then impinged on a phosphor screen which is digitized. This model has a synchroscan feature which allows triggering with minimum jitter on a periodic source signal such as the laser pulse in the electron source gun of the accelerator.

The pulsed laser enabled us to obtain spectra time spectra with resolutions of 20-30 ps in the single shot mode.

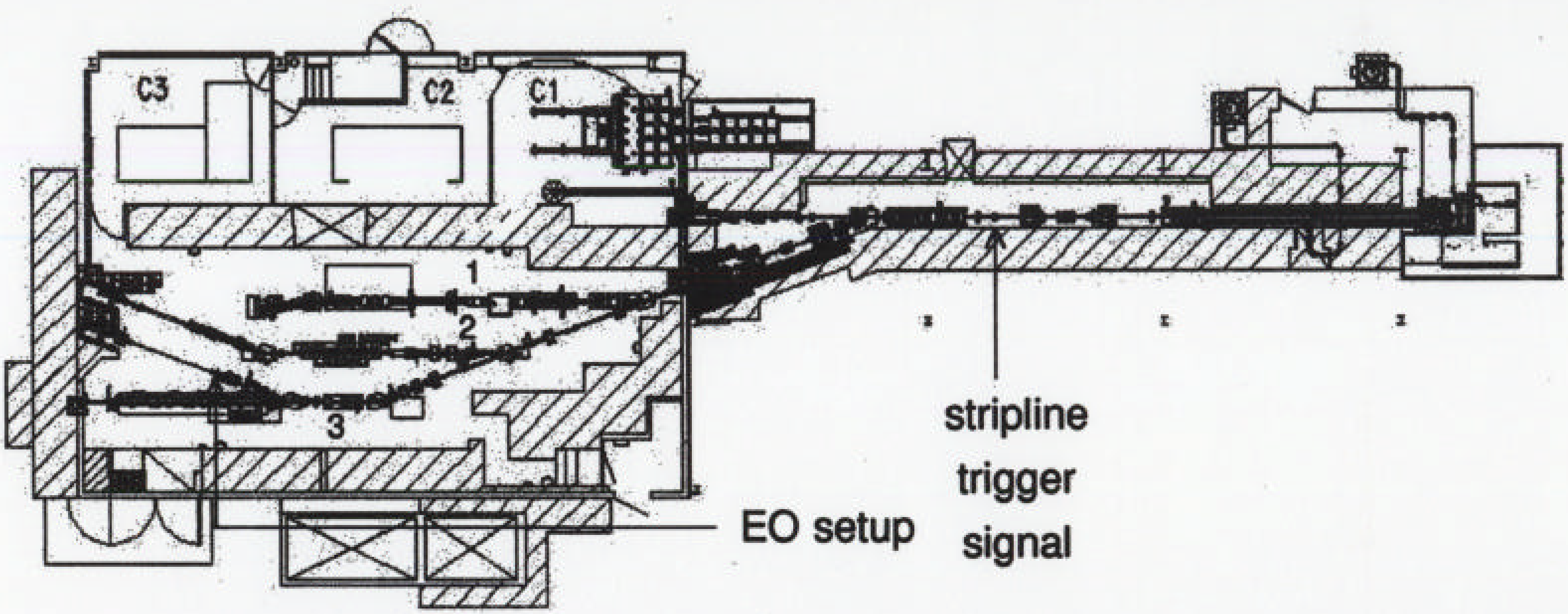
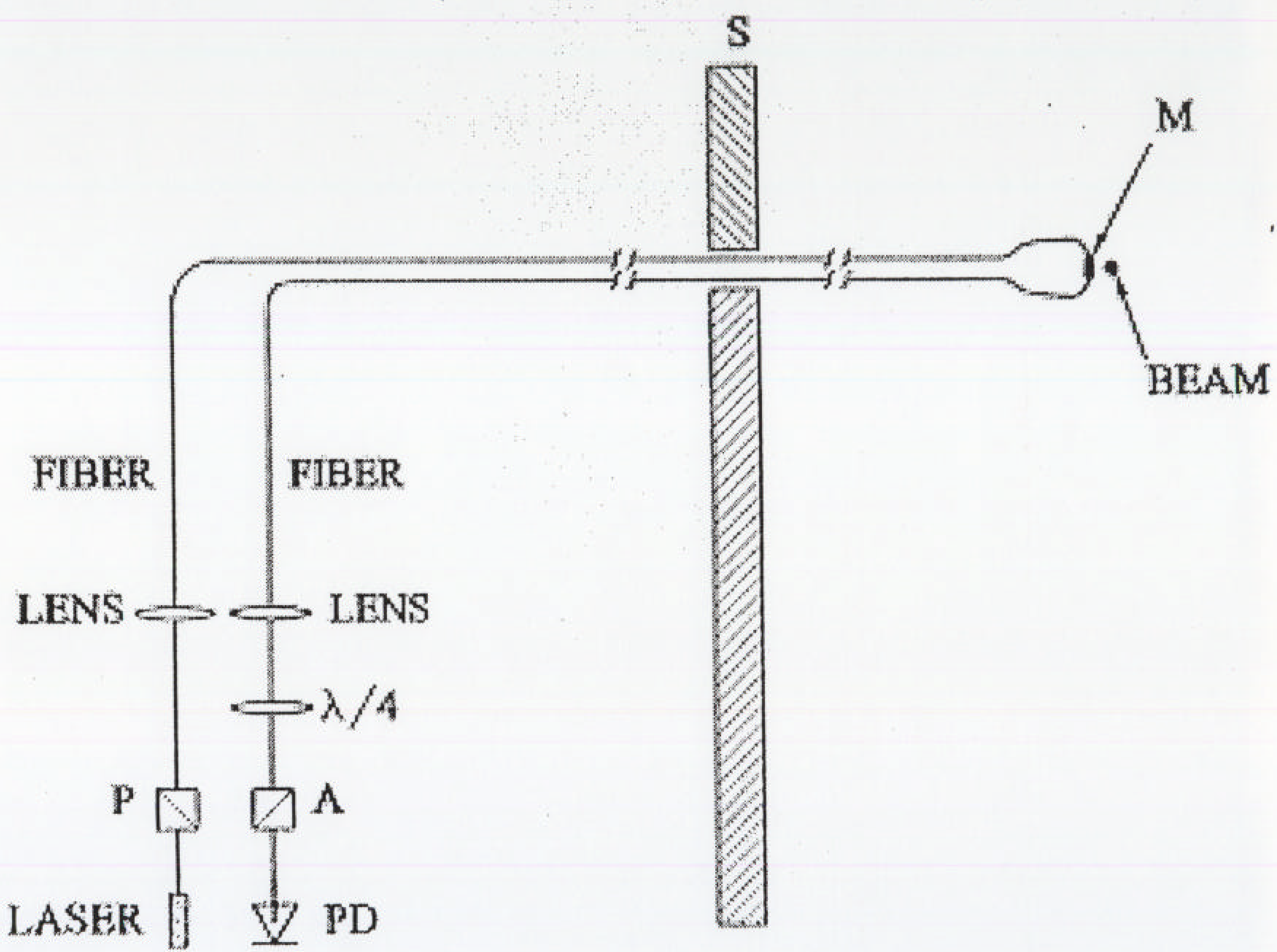


Fig. 3


S
M
BEAM
FIBER
FIBER
LENS
LENS
λ/4
P
A
LASER
PD

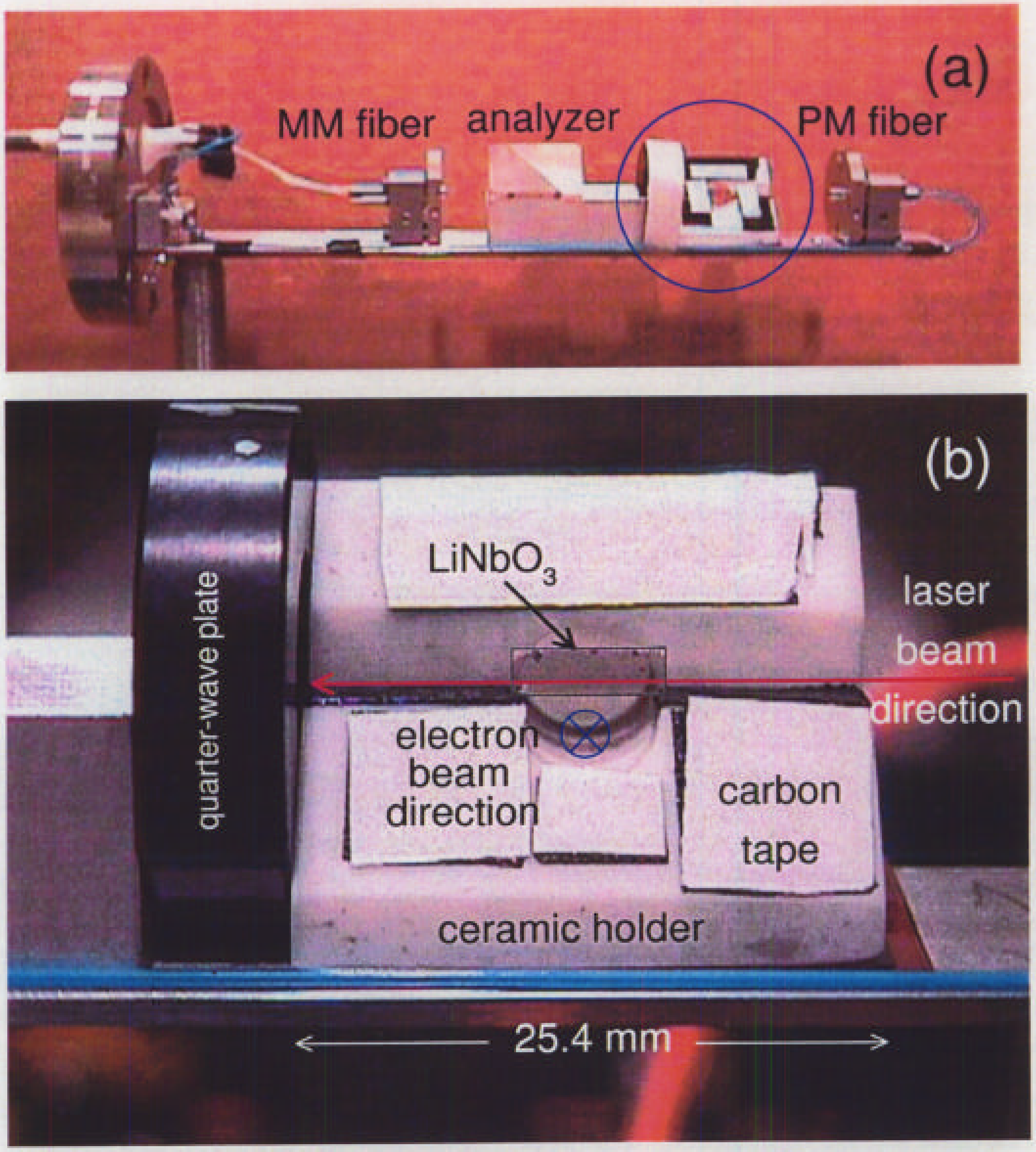
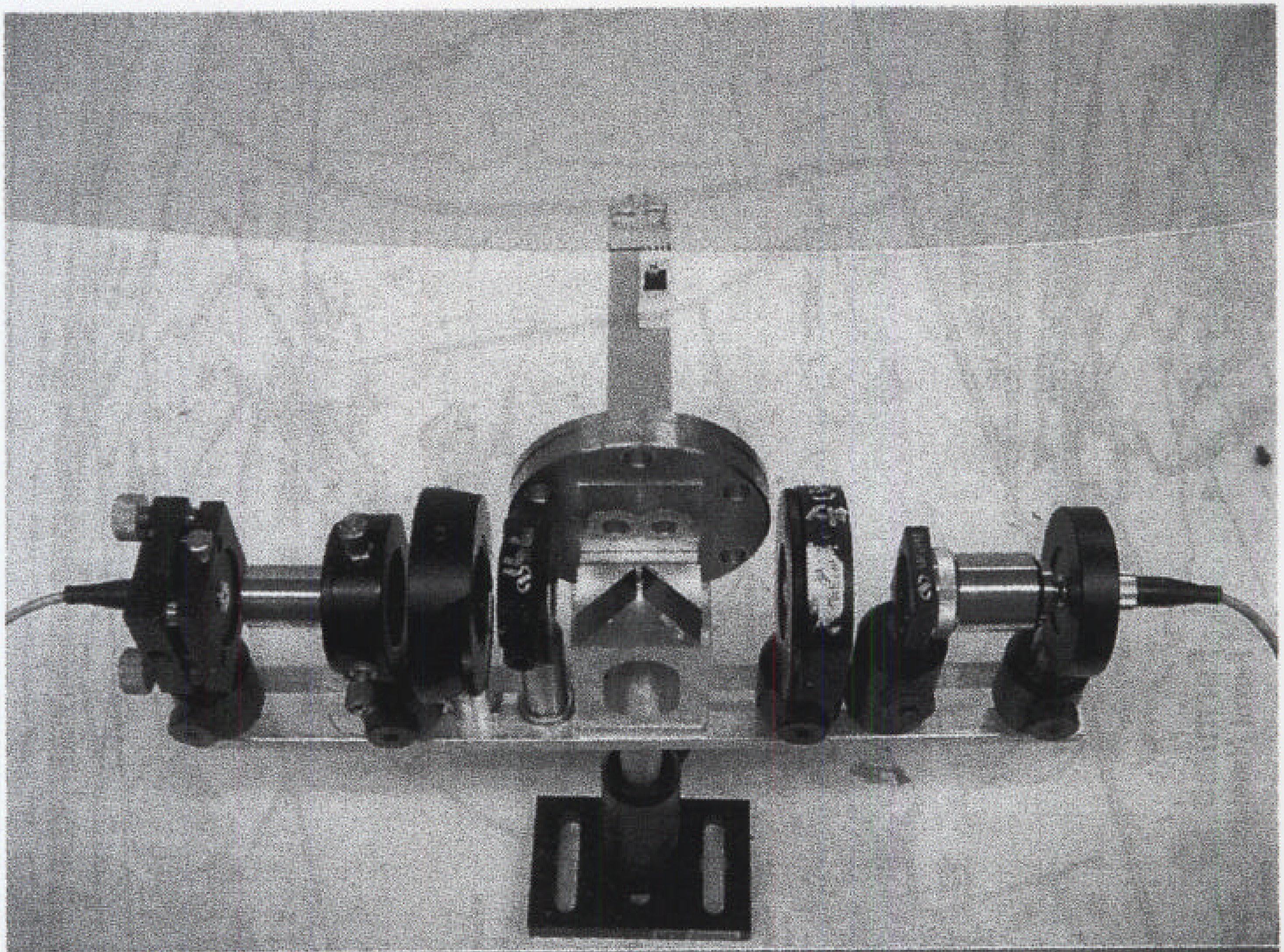
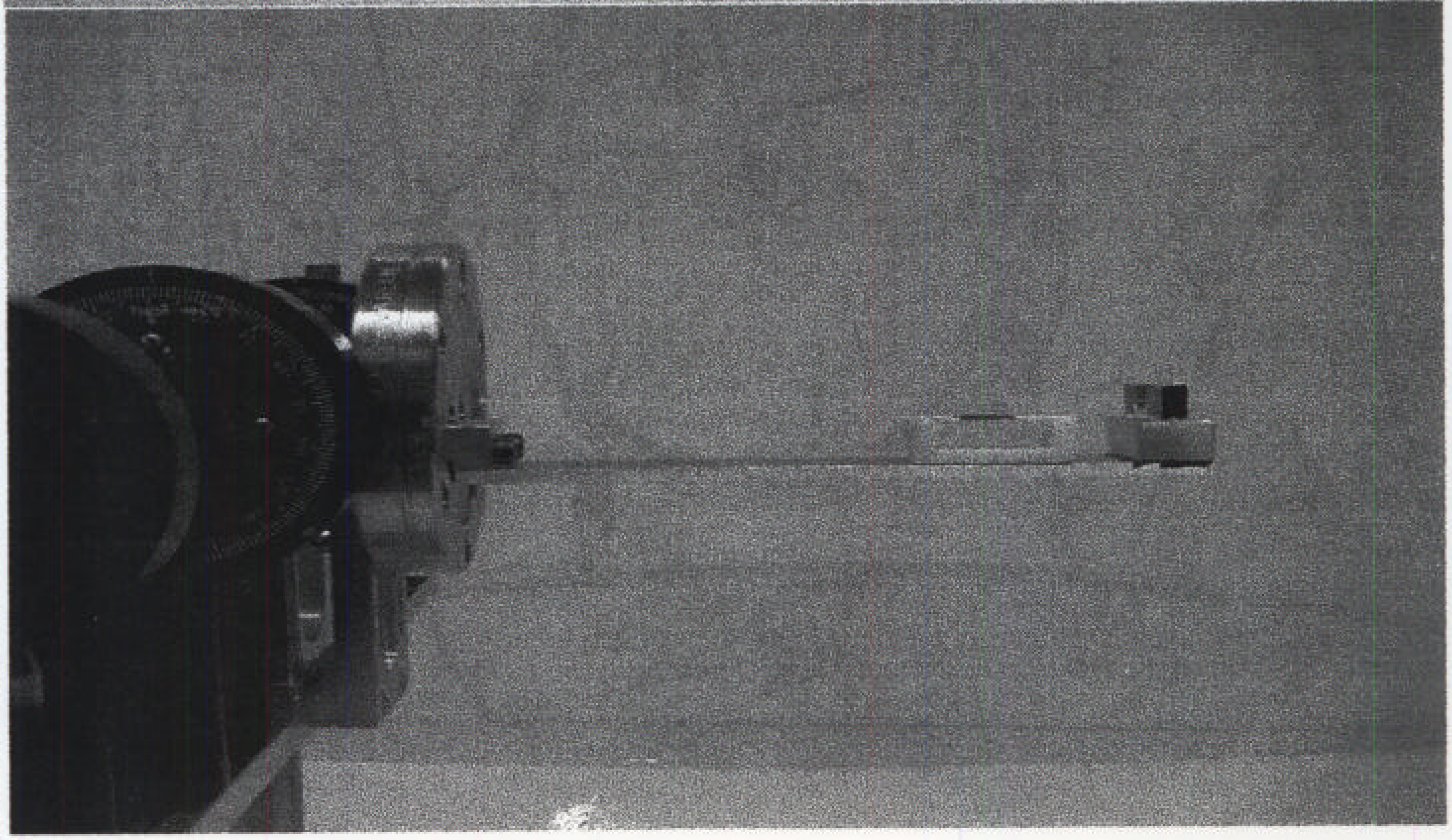
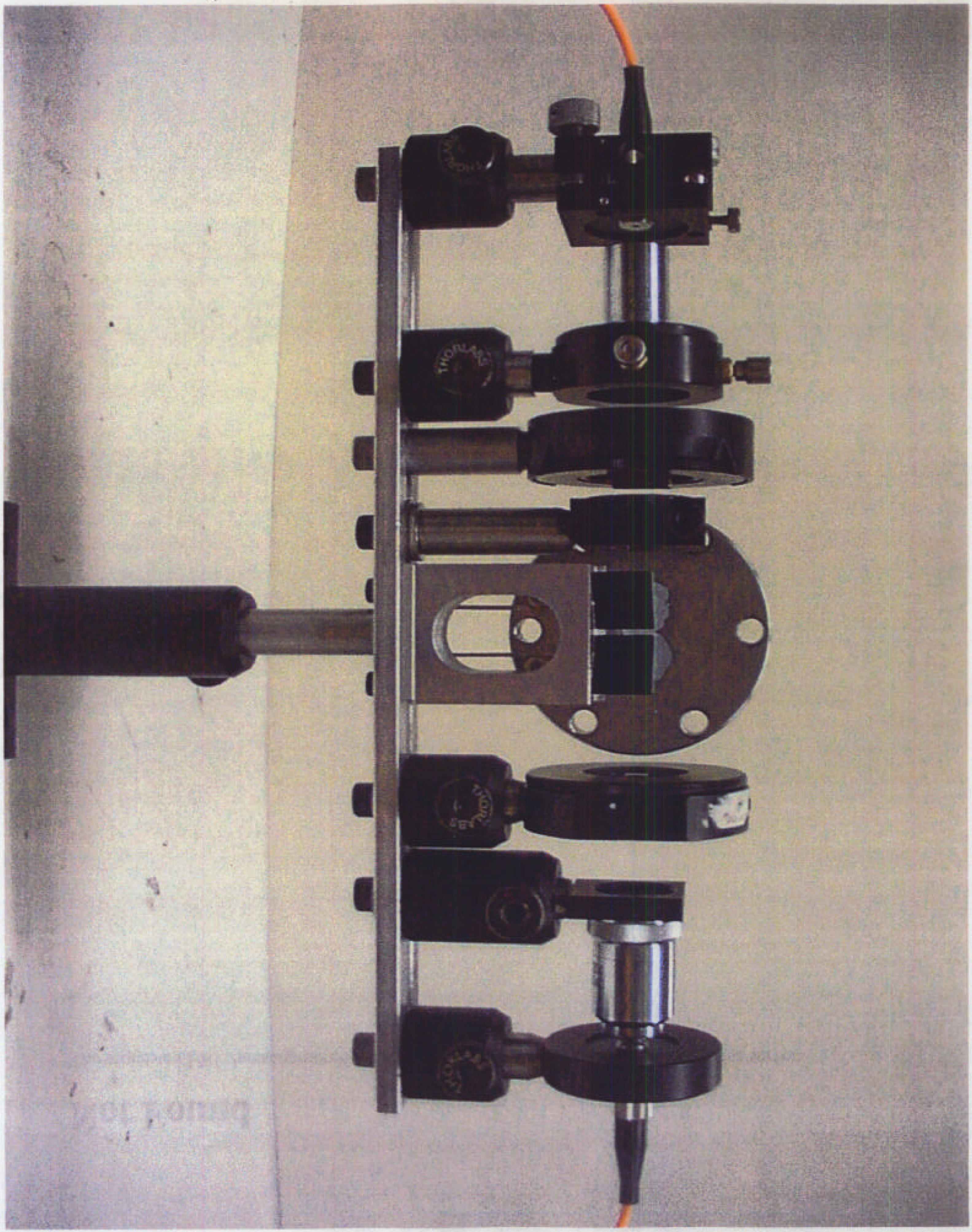
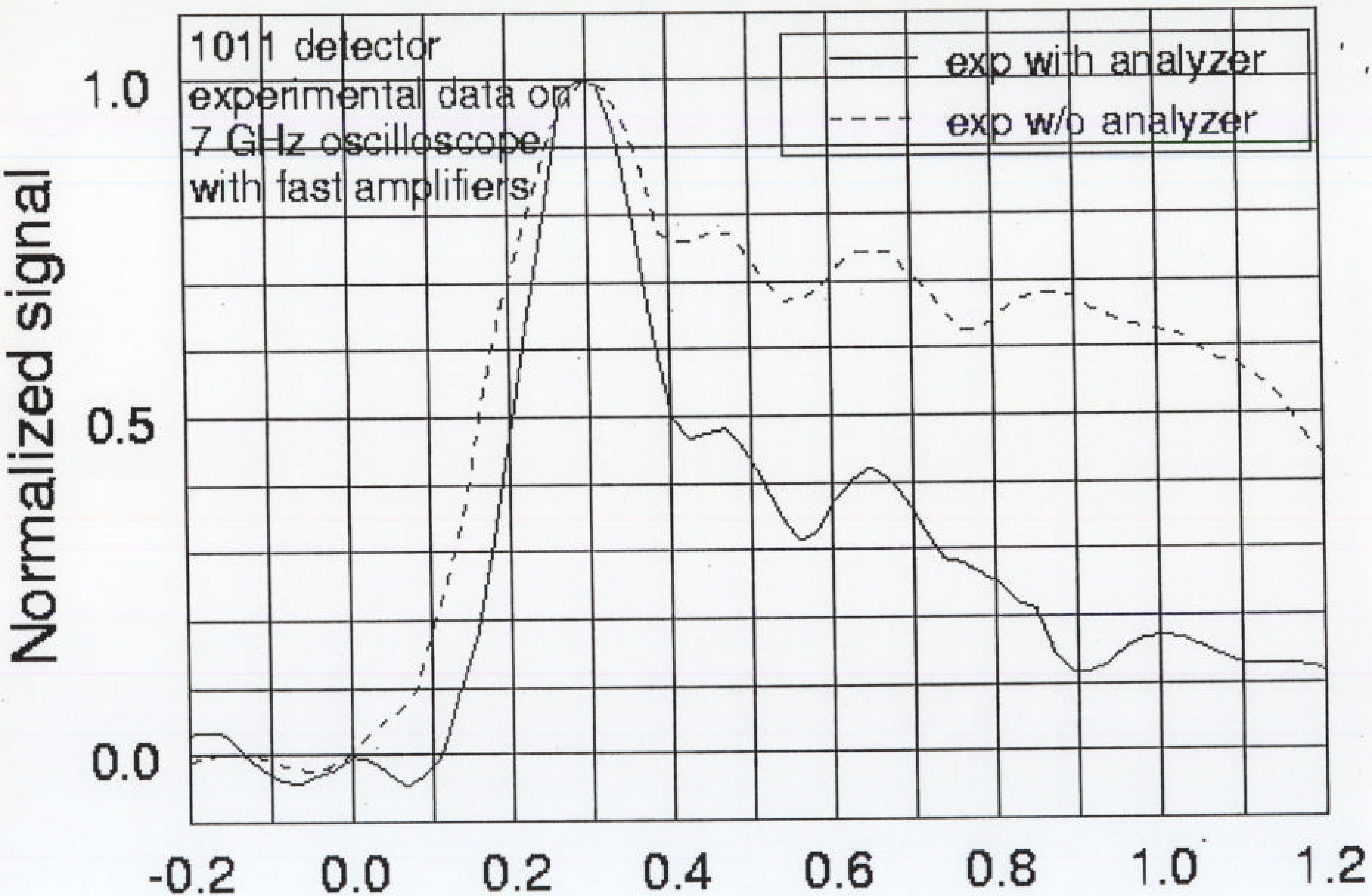

(a)
MM fiber
analyzer
PM fiber
(b)
LiNbO3
laser
beam
direction
quarter-wave plate
electron
beam
direction
carbon
tape
ceramic holder
25.4 mm

Fig. 1






THORLABS


Normalized signal
1.0
0.5
0.0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1011 detector
experimental data on
7 GHz oscilloscope
with fast amplifiers
exp with analyzer
exp w/o analyzer

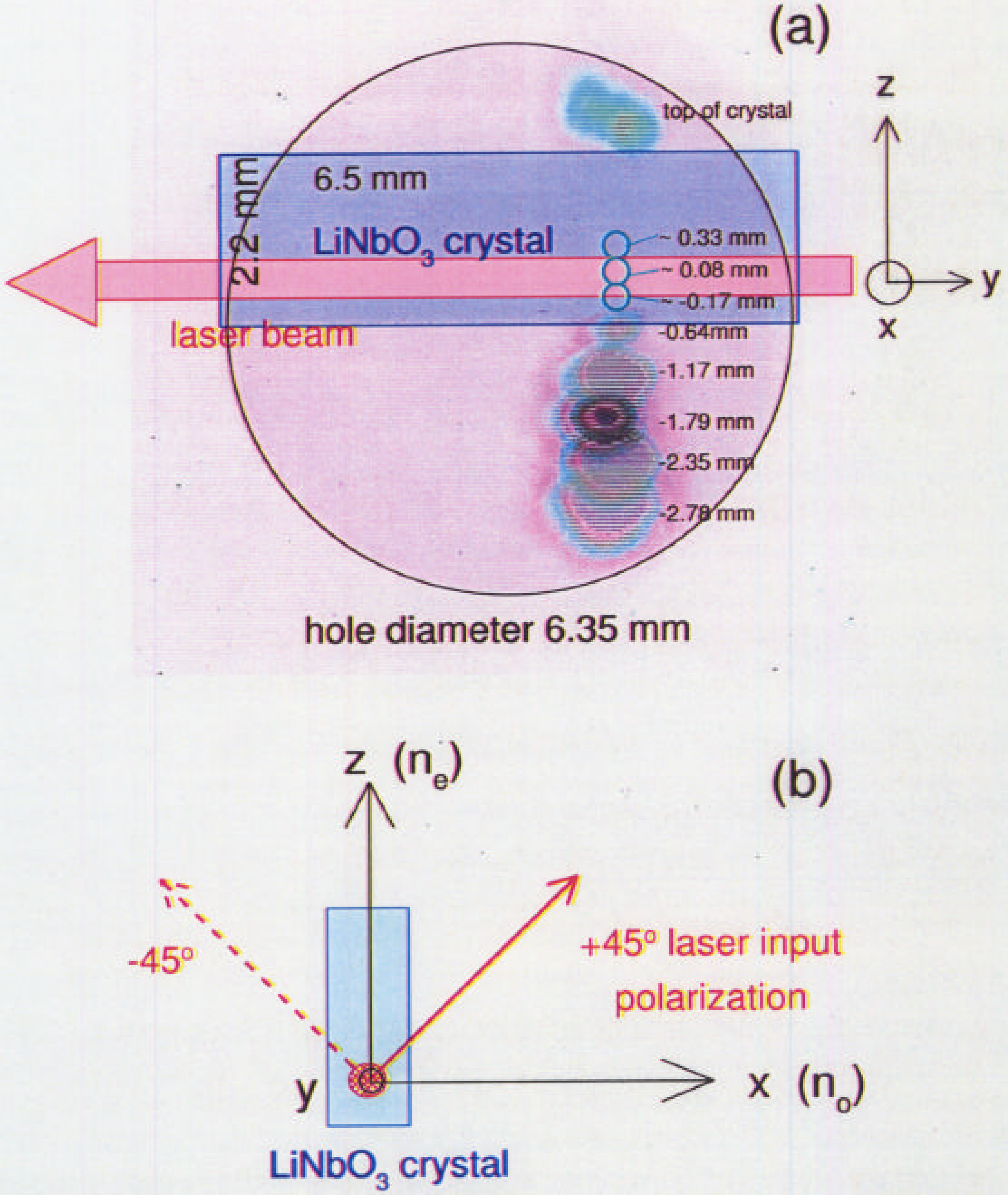

(a)
top of crystal
6.5 mm
2.2 mm
LiNbO3 crystal
~ 0.33 mm
~ 0.08 mm
~ -0.17 mm
-0.64mm
-1.17 mm
-1.79 mm
-2.35 mm
-2.78 mm
laser beam
hole diameter 6.35 mm
z
y
x
(b)
z (ne)
-45°
+45° laser input
polarization
y
x (no)
LiNbO3 crystal

Fig. 2

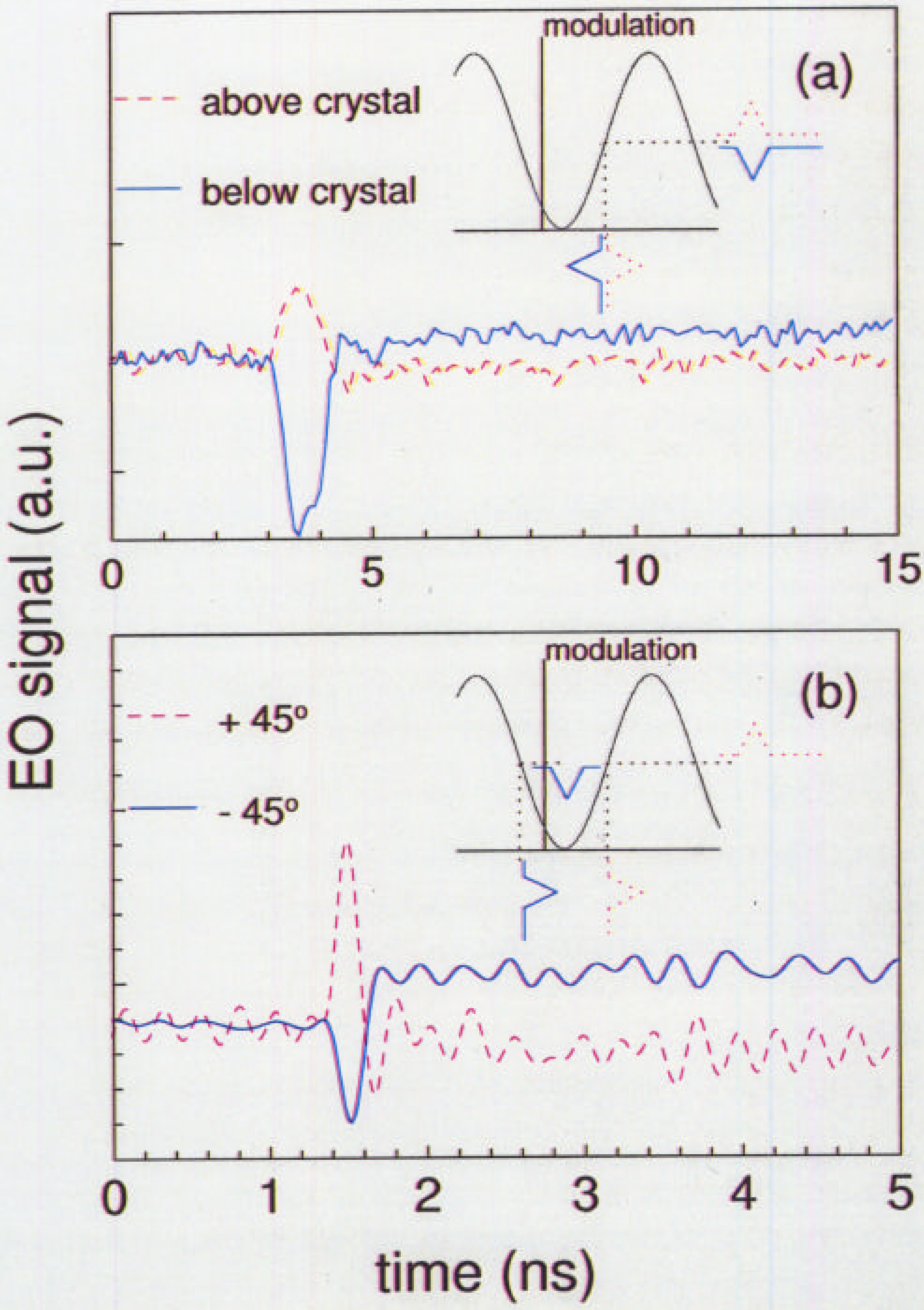
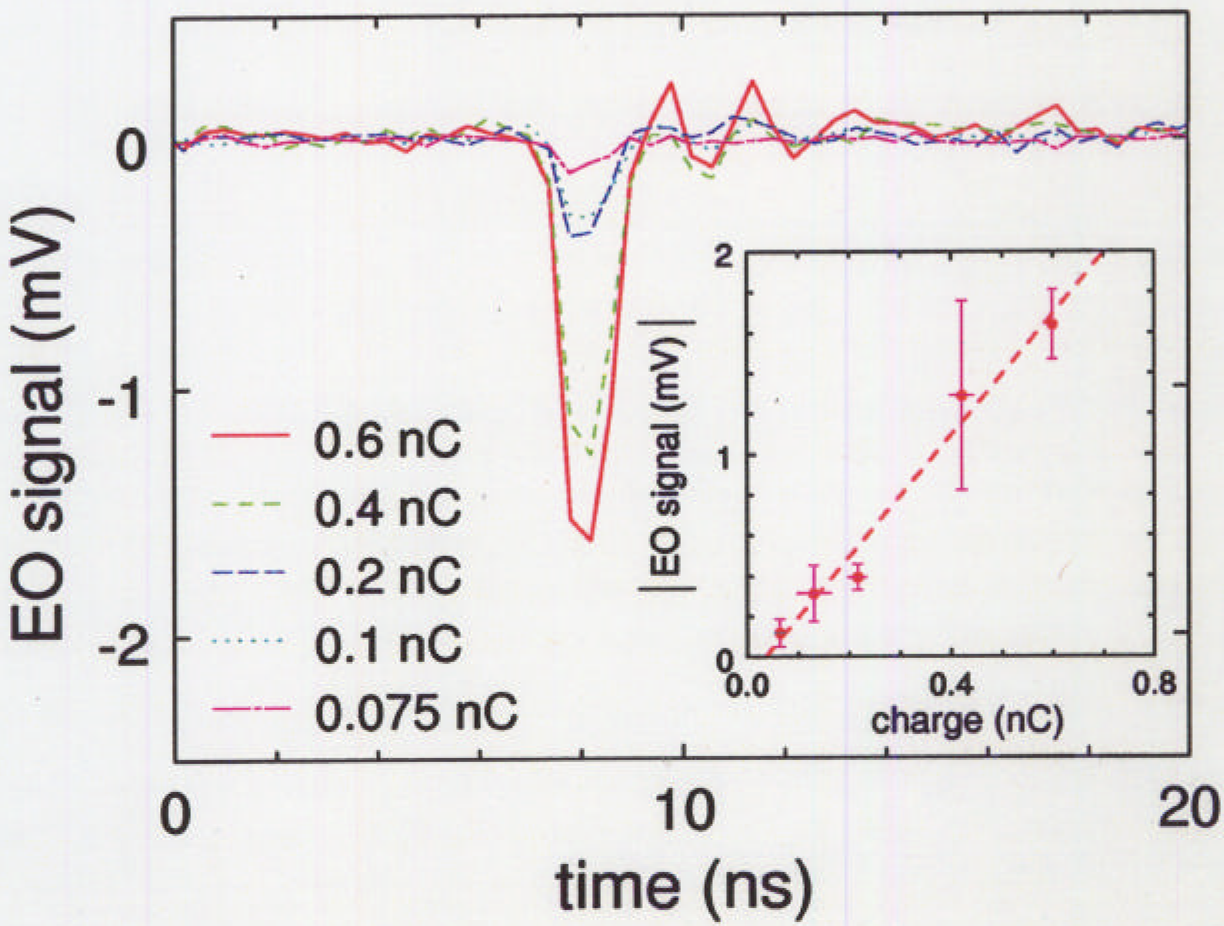

modulation
(a)
above crystal
below crystal
0
5
10
15
EO signal (a.u.)
modulation
(b)
+ 45°
- 45°
0
1
2
3
4
5
time (ns)

Fig. 4



0
-1
-2
EO signal (mV)
0
10
20
time (ns)
0.6 nC
0.4 nC
0.2 nC
0.1 nC
0.075 nC
|EO signal (mV)|
2
1
0
0.0
0.4
0.8
charge (nC)

Fig. 5

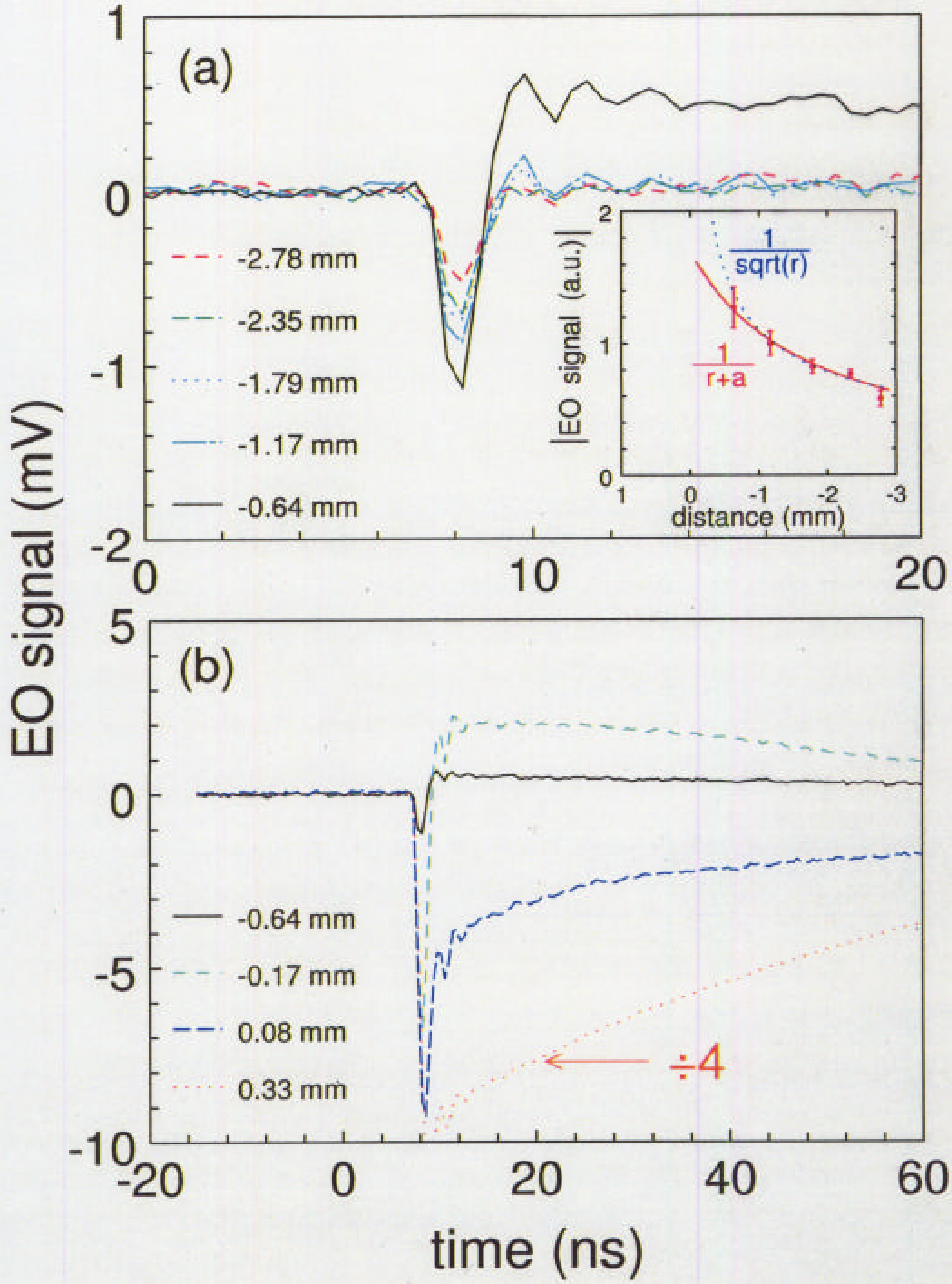

(a)
-2.78 mm
-2.35 mm
-1.79 mm
-1.17 mm
-0.64 mm
|EO signal| (a.u.)
distance (mm)
1/sqrt(r)
1/(r+a)
(b)
-0.64 mm
-0.17 mm
0.08 mm
0.33 mm
÷4
EO signal (mV)
time (ns)

Fig. 6

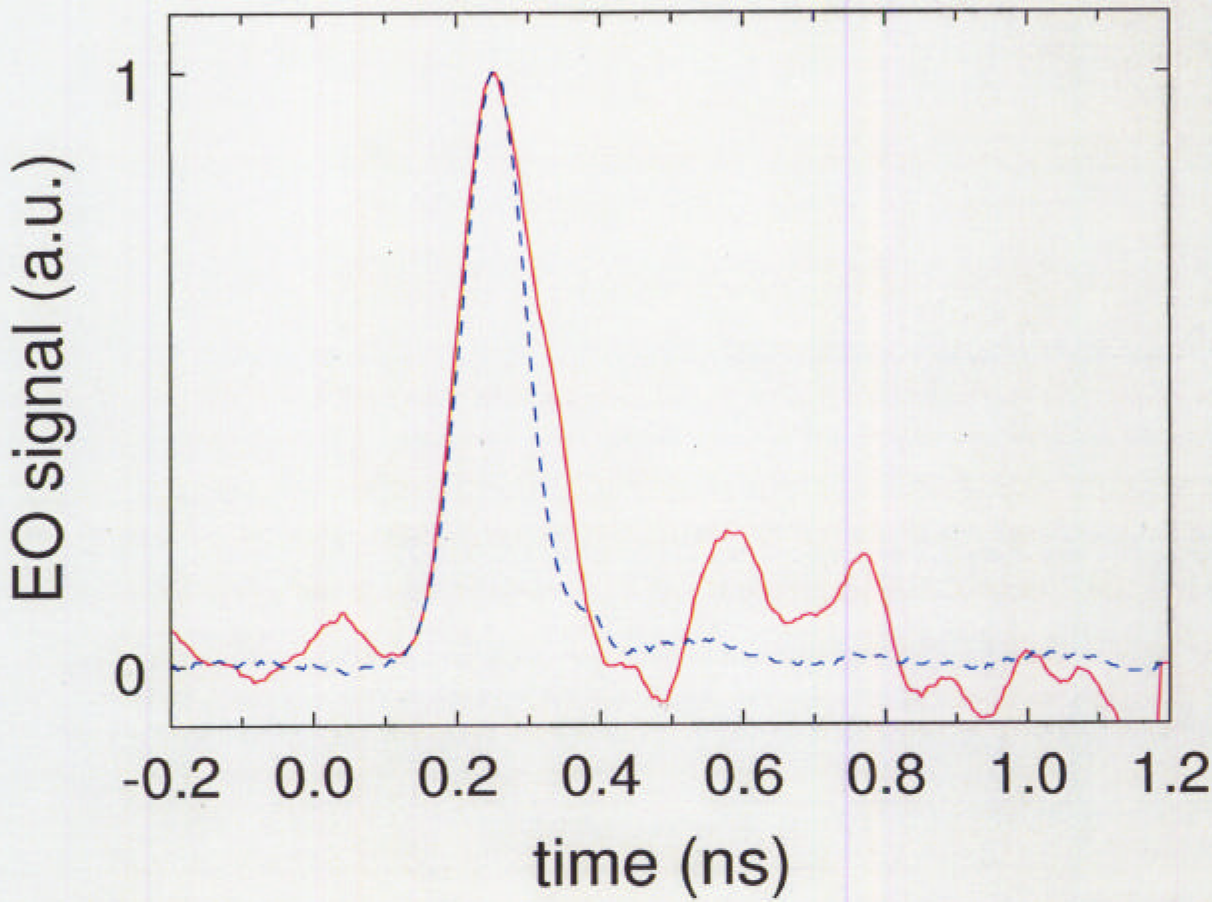
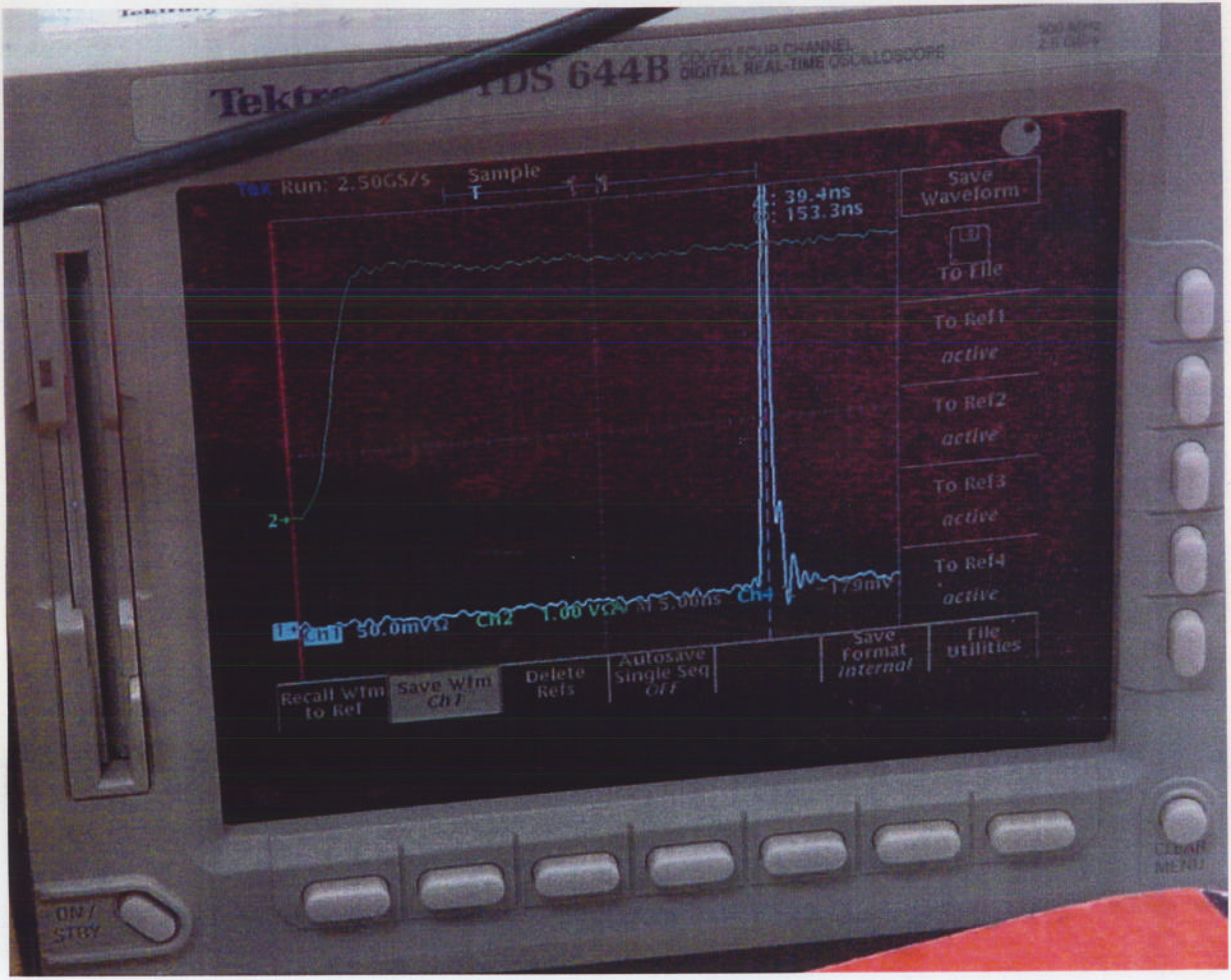


Fig. 7


TDS 644B
DIGITAL REAL-TIME OSCILLOSCOPE
Run: 2.50GS/s
Sample
: 39.4ns
: 153.3ns
Save Waveform
To File
To Ref1
active
To Ref2
active
To Ref3
active
To Ref4
active
Ch1 50.0mVΩ
Ch2 1.00 VΩ
Ch4
Recall Wfm to Ref
Save Wfm Ch1
Delete Refs
Autosave Single Seq Off
Save Format Internal
File utilities
ON/STBY
CLEAR MENU

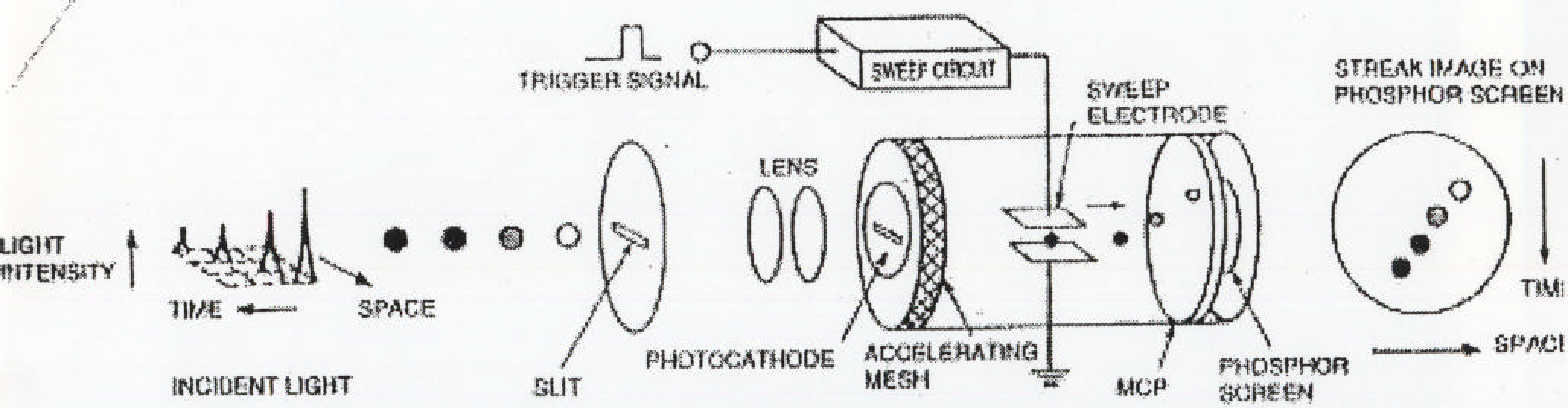
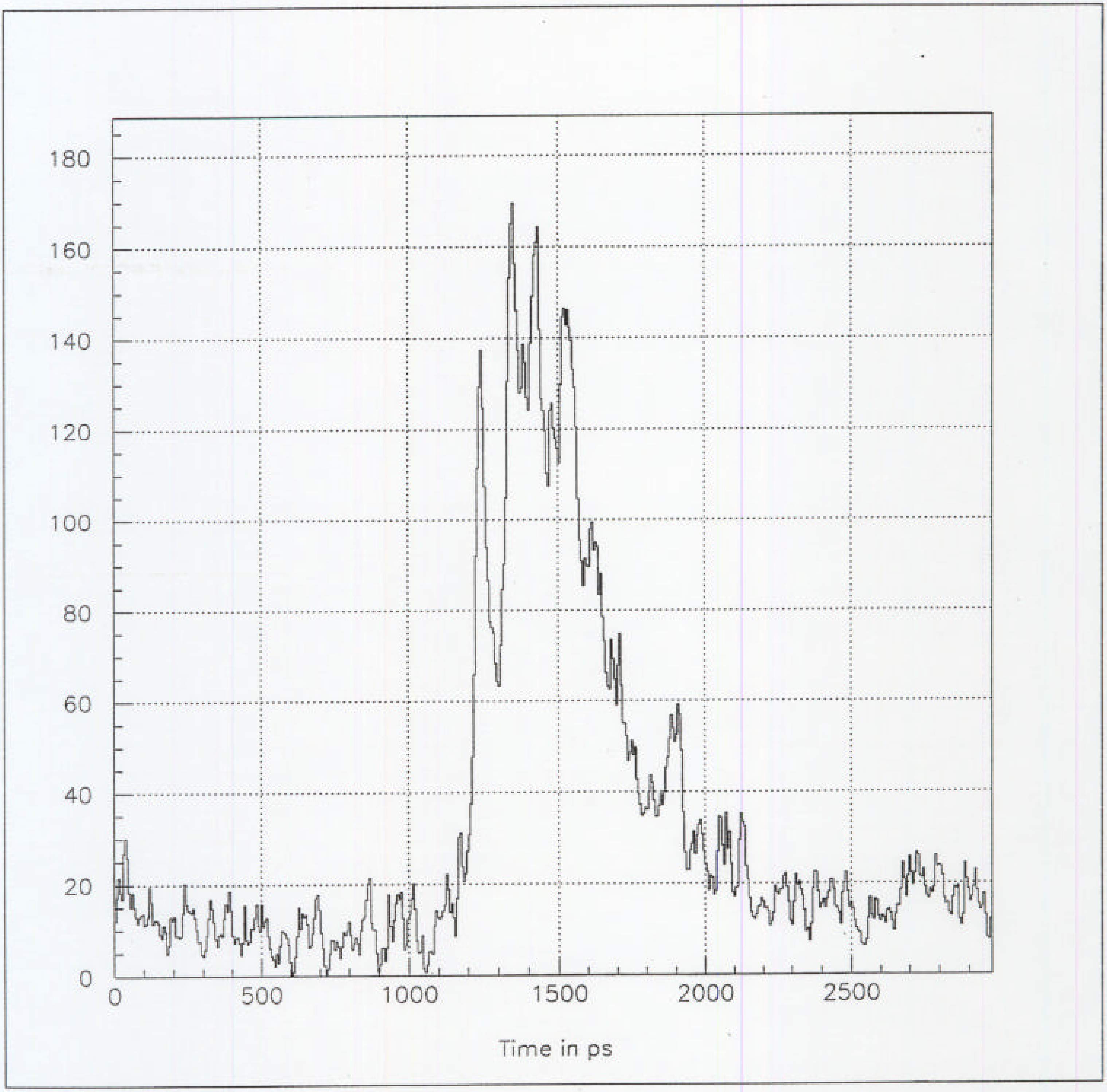
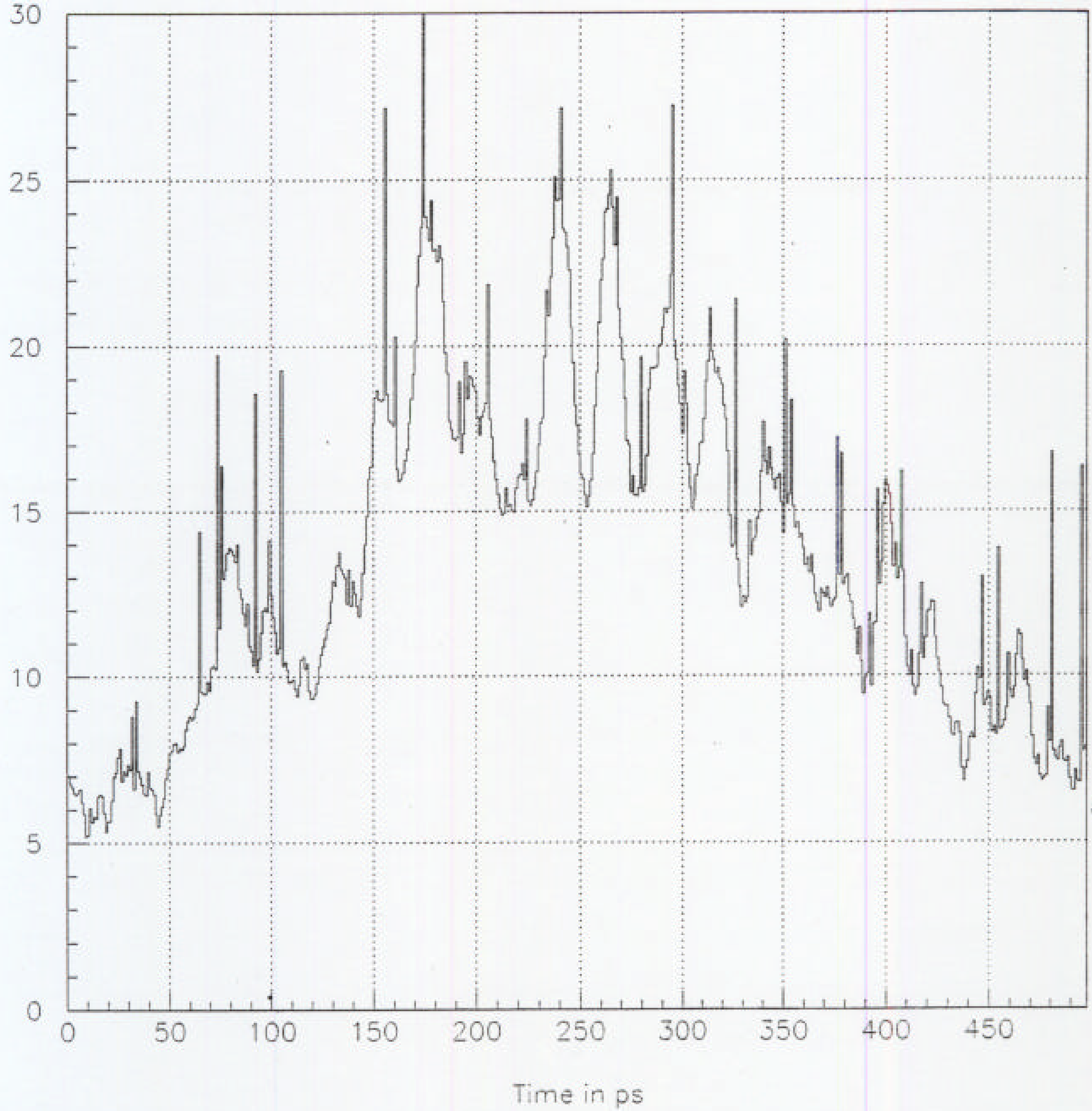


Fig.1 Operating Principle of the Streak Tube



0
20
40
60
80
100
120
140
160
180
0
500
1000
1500
2000
2500
Time in ps



30
25
20
15
10
5
0
0
50
100
150
200
250
300
350
400
450
Time in ps

The Future

A goal of building a vertex detector consisting of parallel single particle EO detectors arrayed in planes with spacings of tens of microns and sub-ps time resolution with a high power pulsed laser synchronized to the bunch crossing time in colliding beam machines appears distant at this time. With a 10^9 W pulsed laser (10 mJ in 10 ps) ellipticities of 10^{-10} and SNRs of 10^{-2} would result. Au ions (Z=79) at RHIC would be sub-marginal and the elementary particles produced would be maximally singly charged.

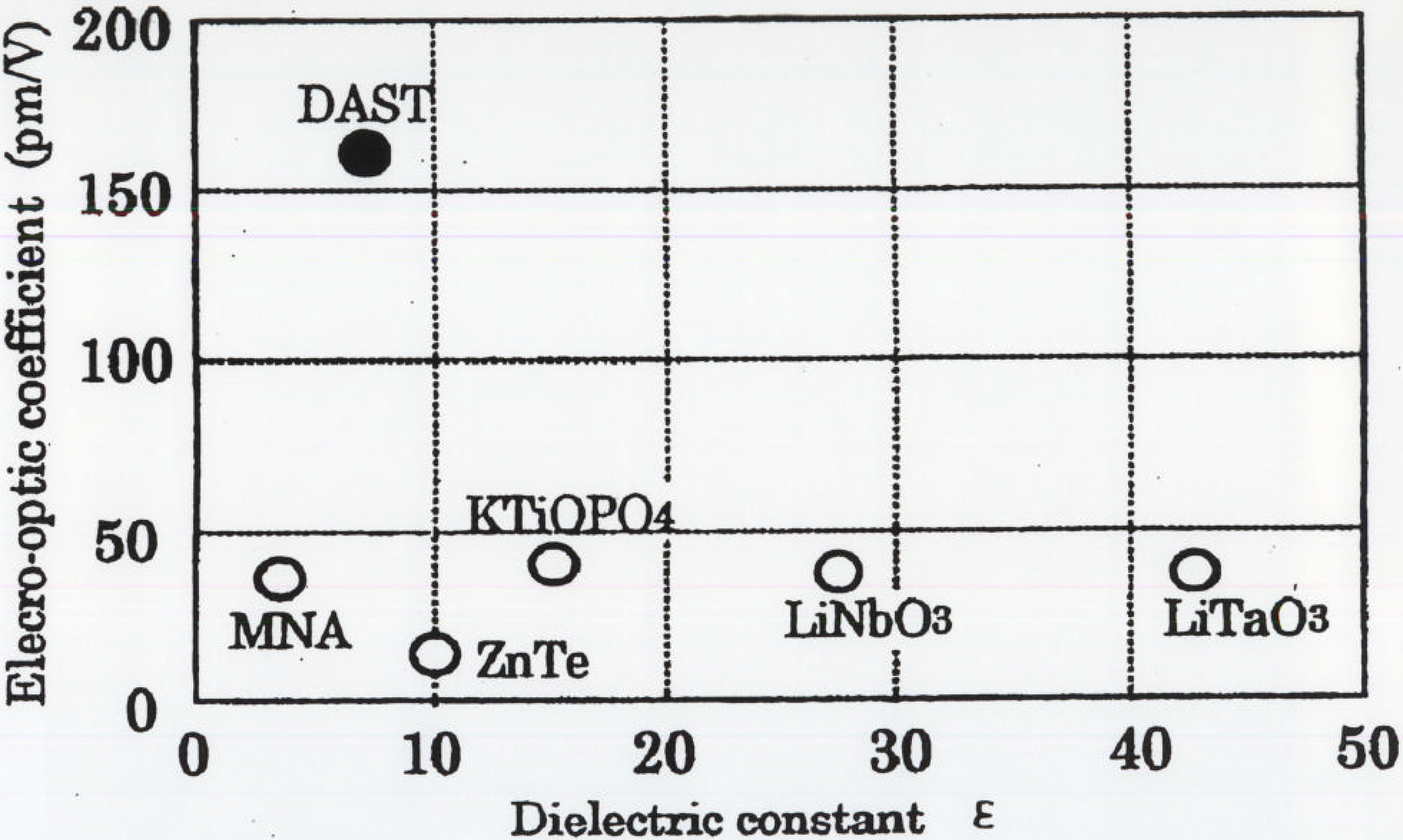
EO Crystals are expensive and lose sensitivity when stuck by large numbers of beam particles. There may be long term radiation effects.

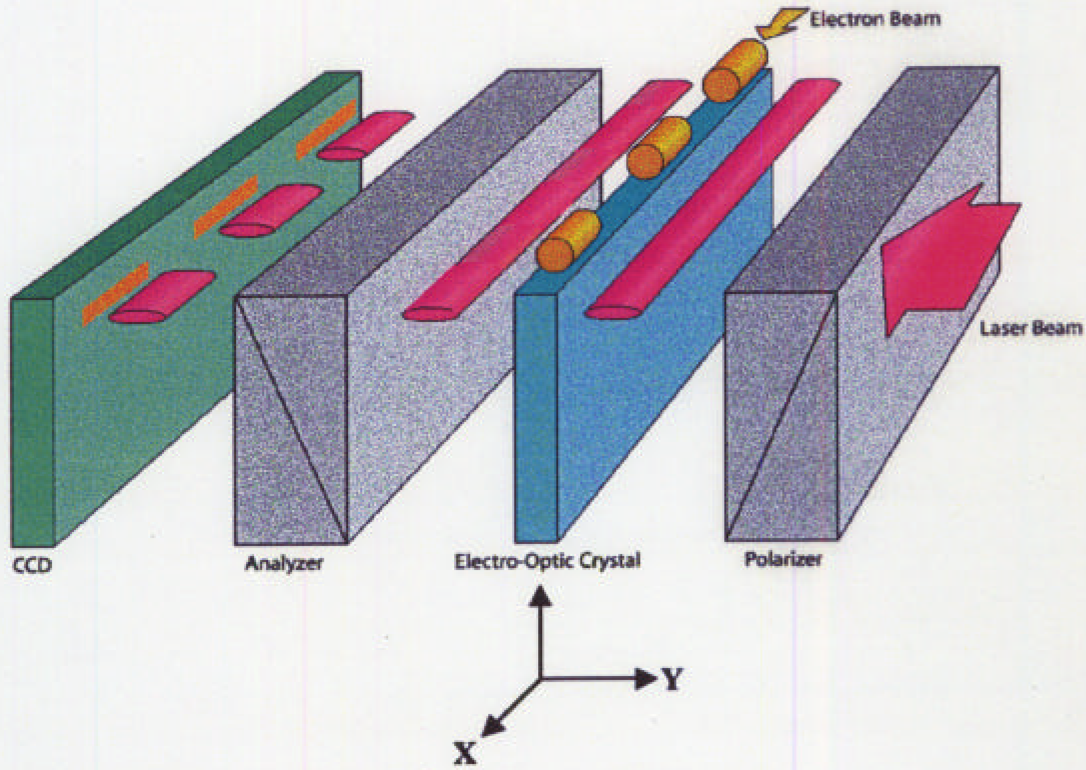
EO crystals are of great interest to the communications industry where they are used for fast switching optical modulation of optical signals. A new EO crystal dimethyl amino 4-N-metyhylstilbazolium tosylate (DAST) which has EO sensitivity as more than 10 times greater than $LiNbO_3$ was a laboratory development several years ago but is now commercially available.

Physicists working on FEL and electron linear collider have expressed interest in EO devices as a beam diagnostic device and have proposed having us as collaborators and they will have a future in in these areas of research.

In the past year a FNAL/Rochester collaboration published a PRL on the observation of wake field effects using this technique and a Dundee/Nieuwegein/Dresden Group at the FELIX FEL facility in the Netherlands also published one on direct beam observation and wake field measurements. The FEL researchers are dependent on extremely short high peak current to operate in the UV and soft x-ray. Production of self-amplified spontaneous emission (SASE) in which the relativistic electron bunch amplifies its own spontaneous emission in a single pass through an undulator.

Recently Triveni Srinivasan-Rao, of our group. suggested a new configuration that was presented at the 21^{st} ICFA Beam Dynamics Workshop on Laser-Beam Interactions. It converts time to a spatial distribution on a CCD array which receives a "flash photo" of the beam taken with a 100 fs laser pulse which is now an off the shelf purchase..


Elecro-optic coefficient (pm/V)
200
150
100
50
0
DAST
KTiOPO4
MNA
ZnTe
LiNbO3
LiTaO3
0
10
20
30
40
50
Dielectric constant ε



Electron Beam
Laser Beam
CCD
Analyzer
Electro-Optic Crystal
Polarizer
Y
X

M. Amin, R. Burns, D.M. Lazarus, D. Nikas, [illegible],
Y.K. Semertzidis, T. Srinivasan-Rao, and T. Tsang.
Brookhaven National Laboratory

L. Kowalski
Montclair State University

Summary

EO Characterization of Bunched Electron Beams

It is fast and non-destructive.

It is already being used for FEL work and interest has been expressed by linear collider builders at CERN, DESY and SLAC.

The "EO flash camera" promises to be a major step forward in beam bunch characterization.

Detection of single charged particles

Present limitations include:

- low EO constants and high dielectric constants
- radiation induced degradation.
- small and expensive crystals.

Poled fibers might be a solution but much more work must be done.

It's well suited for collider physics with tightly bunched beams.

References

J. Kerr, Philos. Mag.**50**, 337, 446 (1875)

F. Pockels, Abhandl. Ges. Gottingen Math-Phizik. Kl. **39**, 1 (1894)

Q. Wu and X.-C. Zhang Appl. Phys. Lett. **71**, 1285 (1997)

Y.K Semertzidis *et al.,* Proceedings of the 1999 Particle Accelerator Conference, 490, (1999)

Y.K. Semertzidis *et al.,* Nucl. Inst. & Meth. **A452**, 396 (2000)

X. Yan *et al.,* Phys. Rev. Lett. **85**, 3404 (2000)

T. Tsang *et al.,* J. Appl. Opt., **89**, 4921 (2001)

M.J. Fitch *et al.,* Phys. Rev. Lett. **87**, 034801-1 (2001)