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INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

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Winter College on Ultrafast Phenomena

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Methods for Single-Shot Measurements of Ultrashort Pulses

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METHODS FOR SINGLE-SHOT MEASUREMENTS OF ULTRASHORT PULSES

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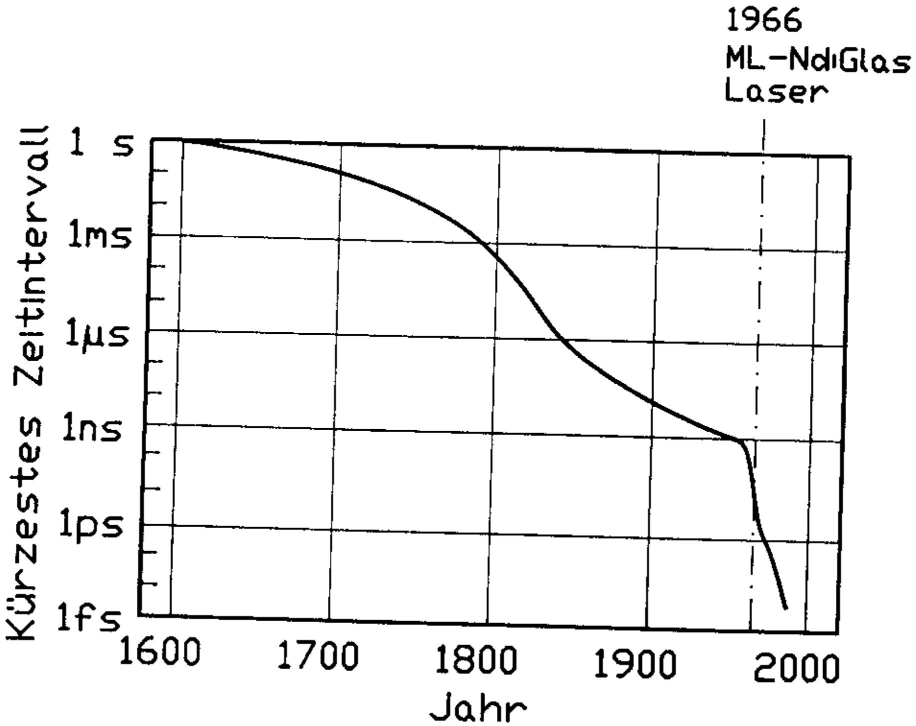
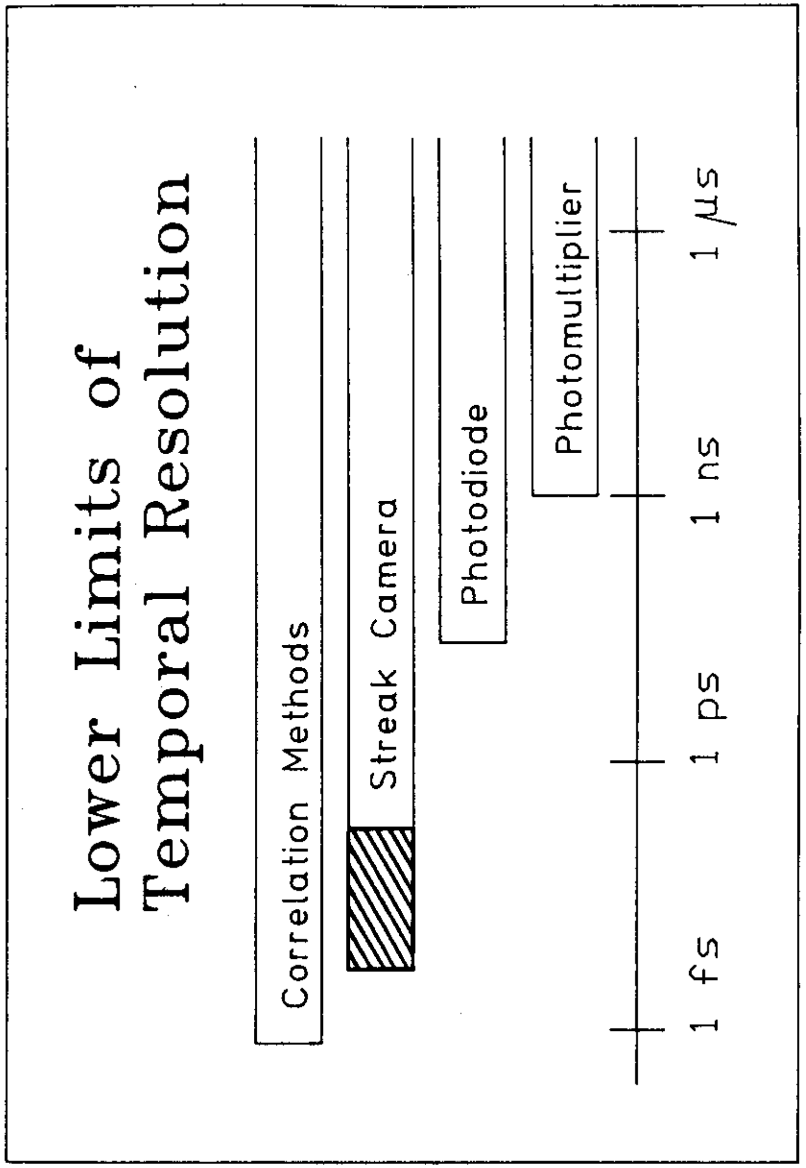
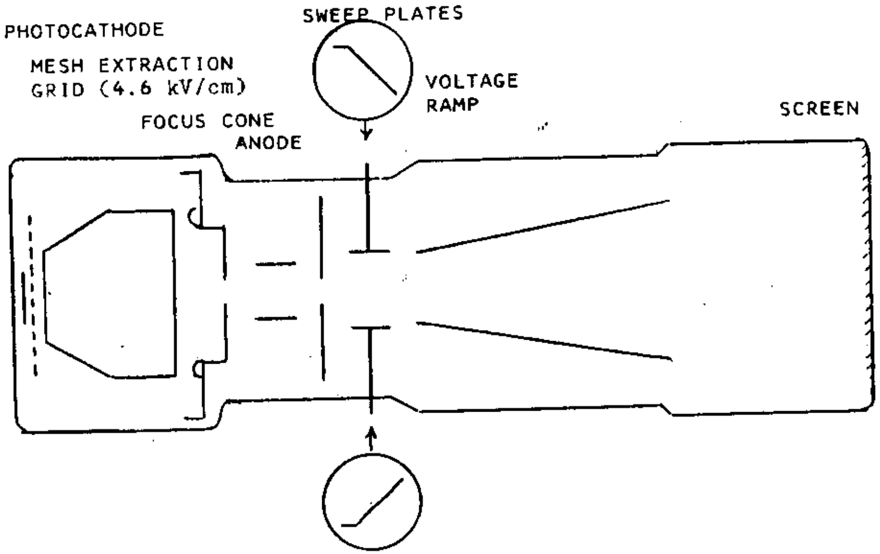
GÖTTINGEN

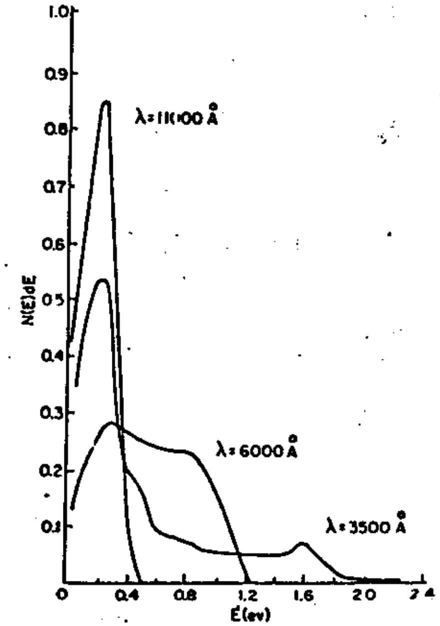
GERMANY


1966
ML-NdiGlas
Laser
Kürzestes Zeitintervall
1 s
1ms
1µs
1ns
1ps
1fs
1600
1700
1800
1900
2000
Jahr


Lower Limits of
Temporal Resolution
Correlation Methods
Streak Camera
Photodiode
Photomultiplier
1 fs
1 ps
1 ns
1 µs

P 855 STREAK TUBE (HADLAND IMACON 600)





ENERGY DISTRIBUTION OF PHOTOELECTRONS FROM AN Ag-O-Cs (S-1) PHOTOCATHODE AS A FUNCTION OF WAVELENGTH

(SOBOLEVA ET AL. 1965)

TEMPORAL RESOLUTION:

$$T^2_{RECORDED} = T^2_{INSTRUMENTAL} + T^2_{PULSE}$$

$T_{INSTRUMENTAL}$ LIMITED BY
1. SPATIAL RESOLUTION (T_{SR})
2. ELECTRON TRANSIT TIME SPREAD (T_{EL})
3. DYNAMIC RANGE

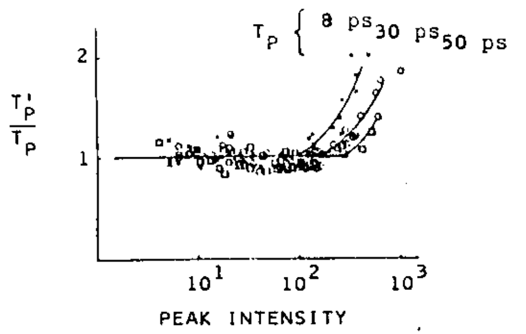
P 855 STREAK TUBE
S 20 PHOTOCATHODE AT 530 nm } $T_{INSTRUMENTAL} \approx 11$ ps

$$T_{EL} \approx 7.8 \times 10^{-11} \left[(\Delta\varepsilon)^{1/2}/E\right]$$

S-20 PHOTOCATHODE: $\Delta\varepsilon \approx 1$ eV
IMACON 600 EXTRACTION FIELD: $E = 4600$ V/cm $\hat{=}$ 15 esu

$T_{EL} \approx 5$ ps

DYNAMIC RANGE CHARACTERISTICS

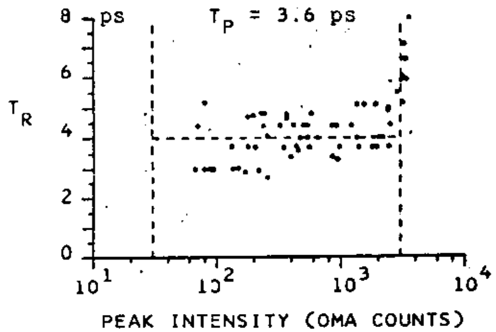


IMACON 675
(P855 STREAK TUBE)
S20 AT 530 nm

MULLARD CHANNEL PLATE INTENSIFIER

PHOTOGR. RECORD

(HULL & FREEMAN 1980)

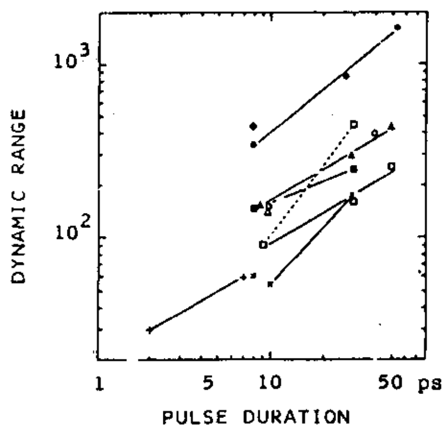


PHOTOCHRON II
S20 AT 530 nm

MULLARD CHANNEL PLATE INTENSIFIER

OMA RECORD

(BRADLEY ET AL. 1980)

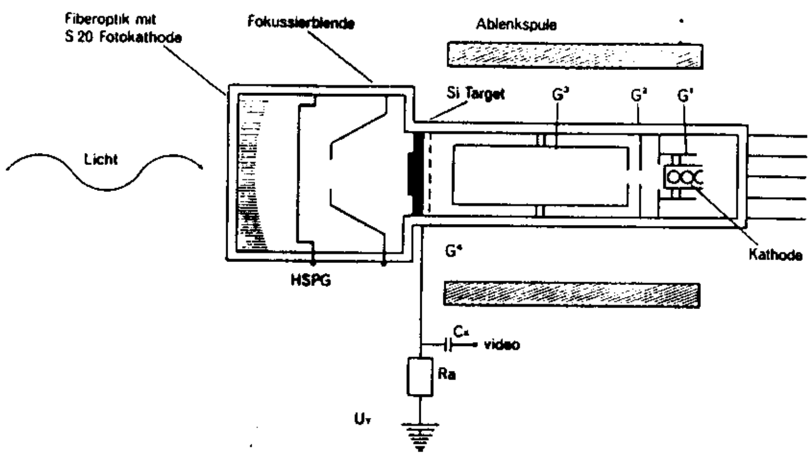


SUMMARY
OF DYNAMIC RANGE
RESULTS

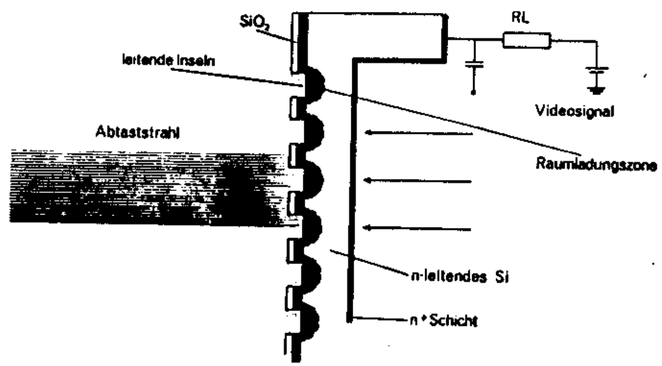
(VARIOUS TUBES)

(HULL & FREEMAN 1980)

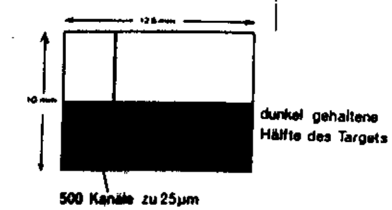
SIT VIDIKON

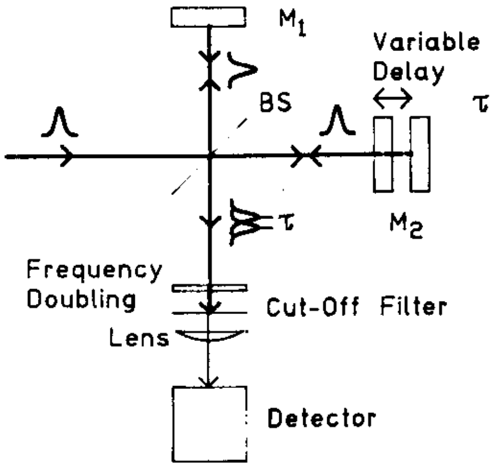


Si Multidiodentarget



Target des Standardvidikons



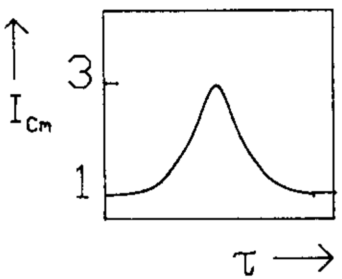


Observed Intensities

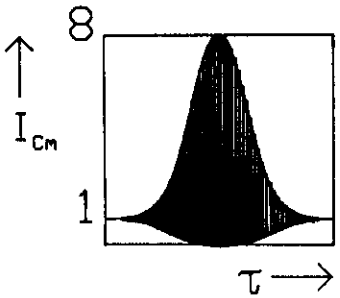
Autocorrelation with Background:

$$I_{Cm} = 1 + 2\,\frac{\int I(t)\,I(t-\tau)\,dt}{\int I^2 dt} + r(\tau)$$

(1a) Averaged



(1b) Interferometric



(2) Background Free Autocorrelation

$$I_{Co} = \frac{\int I(t)\,I(t-\tau)\,dt}{\int I^2 dt} + r(\tau)$$

Second-Order Autocorrelation Functions and Bandwidth Products for various Pulseshape Models

$I(t)$	$\Delta\nu \cdot \Delta t$	τ_p / T	$G_0^2(\tau)$	τ_G / T	τ_p / τ_G
Gaussian $\exp(-x^2)$	0.4413	$2\sqrt{\ln 2}$	$\exp(-y^2/2)$	$2\sqrt{2\ln 2}$	0.7071
$\mathrm{sech}^2(x)$	0.3148	1.627	$\frac{3}{\sinh^2(y)}\left[y\coth(y)-1\right]$	2.7196	0.6482
Lorentzian $1/(1+x^2)$	0.2206	2	$\frac{1}{\left[1+(y/2)^2\right]^2}$	4	0.5000

Sala et al. (1980)

$x \equiv \frac{t}{T}$ $\qquad y \equiv \frac{\tau}{T}$

Square Pulse: $\tau_p / T = 1$ $\qquad \tau_G / T = 1$

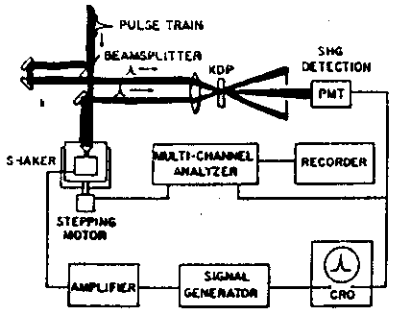


Fig. 1. Experimental arrangement.

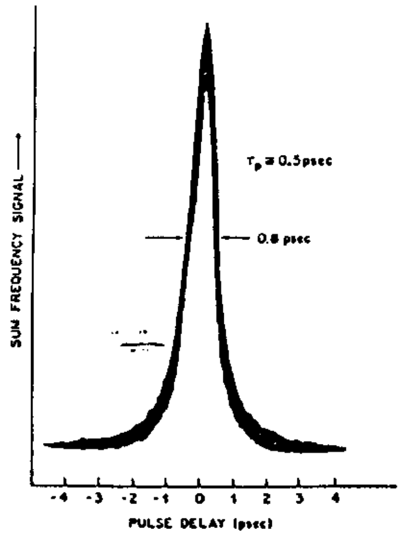
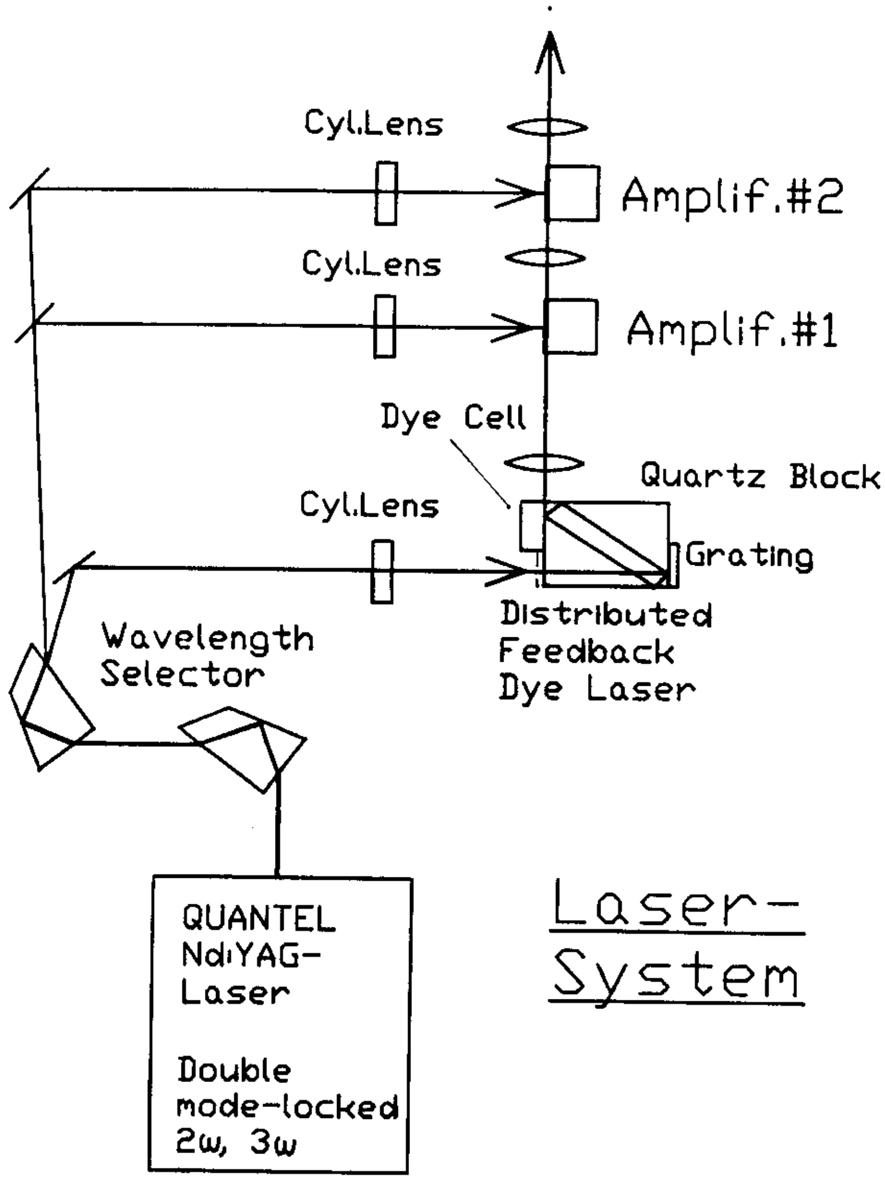


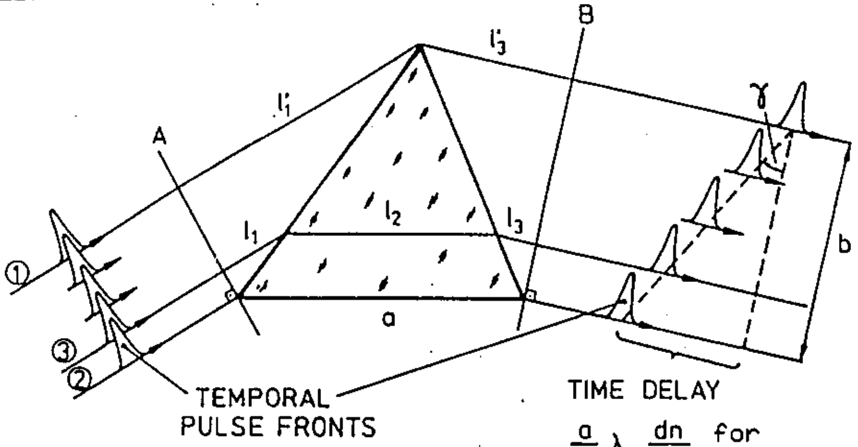
Fig. 2. Oscilloscope display of autocorrelation trace. The pulse width is slightly greater than half the width of the autocorrelation trace, i.e., ~0.5 psec for the displayed autocorrelation trace.



τ_p (FWHM)	≈ 2 ps
$\Delta\lambda$	≈ 3 Å
E_p	≈ 5 μJ

Pulse Front Delay by Prisms and Gratings

(1)



$\frac{a}{c}\lambda\frac{dn}{d\lambda}$ for min. dev.

Zs.Bor, B.Racz (1985)

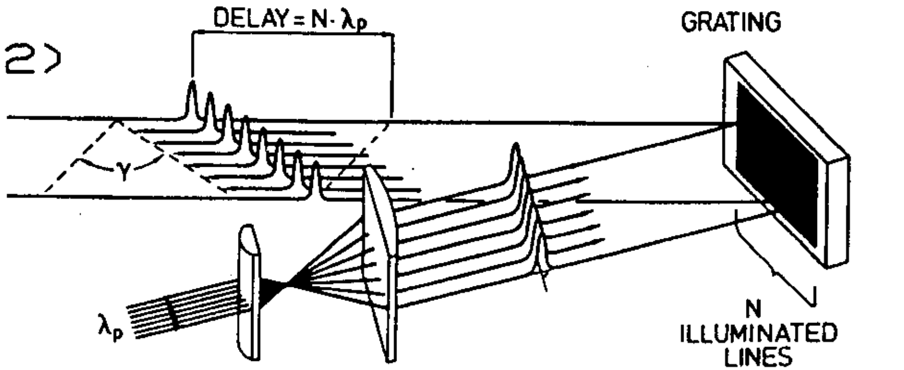
$dn/d\lambda$ = dispersion

c = light velocity (vac.)

$\tan\gamma = \frac{a}{b}\lambda\,(dn/d\lambda) = \lambda\,(d\varepsilon/d\lambda)$

$d\varepsilon/d\lambda$ = angular dispersion

(2)

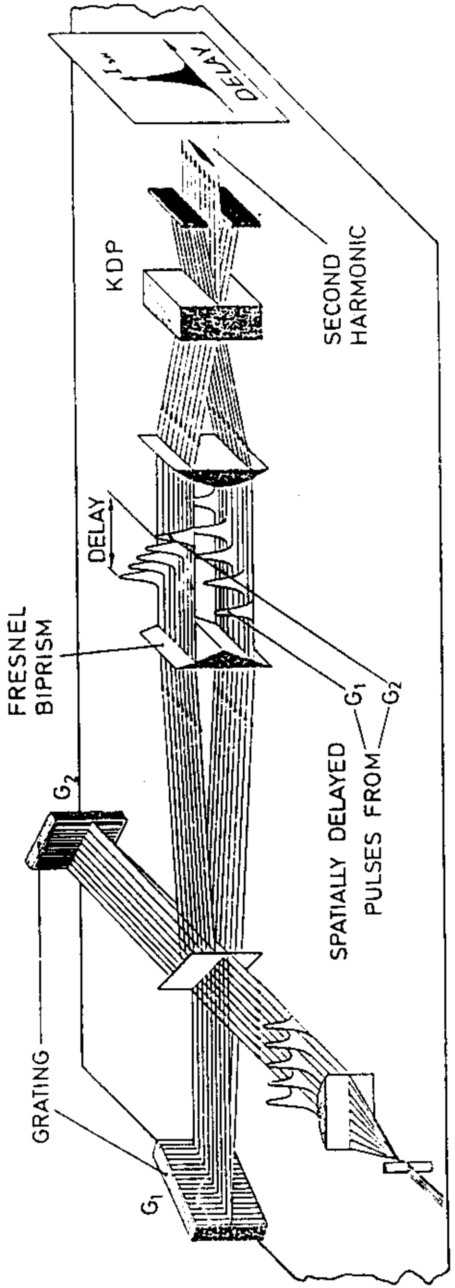


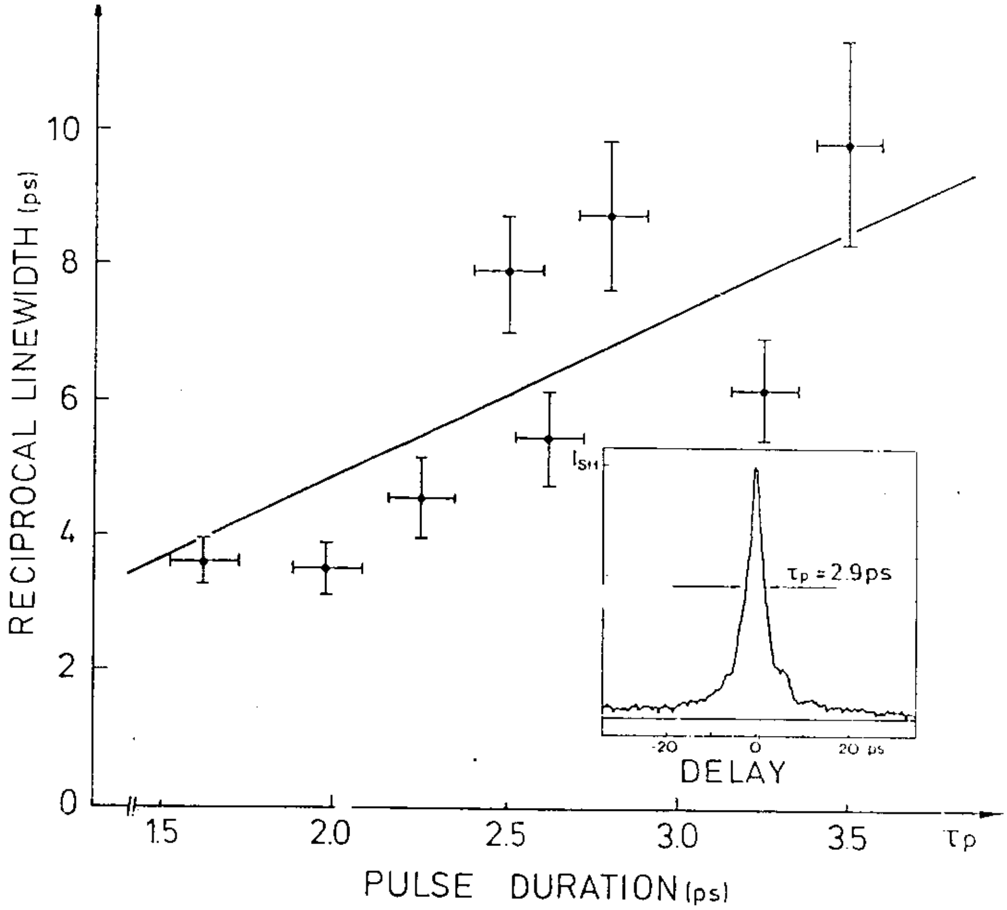
b = beam width

Zs.Bor, S.Szatmari, A.Müller (1983)

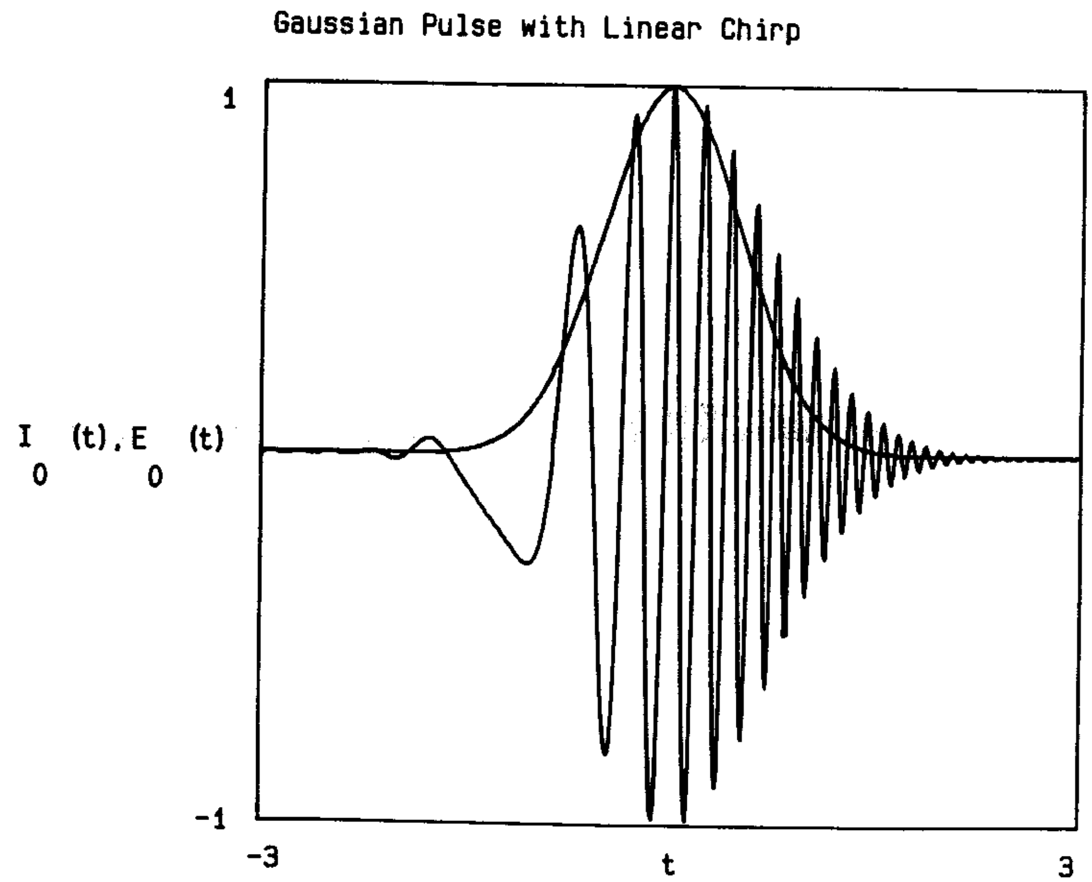
TIME DELAY

$\frac{b}{c}\tan\gamma = \frac{b}{c}\lambda\,(d\varepsilon/d\lambda)$





RECIPROCAL LINEWIDTH (ps)
10
8
6
4
2
0
1.5
2.0
2.5
3.0
3.5
τp
PULSE DURATION (ps)
I_{SH}
$\tau_p = 2.9$ps
-20
0
20 ps
DELAY



Gaussian Pulse with Linear Chirp
1
-1
I (t), E (t)
0 0
-3
t
3

Description of a Gaussian pulse with Chirp

E-Field:

Envelope — Carrier frequency — Linear Chirp

$$E(t) = e^{-at^2} \cdot e^{i(\omega_0 + bt)t}$$

$$= e^{-(a-ib)t^2} \cdot e^{i\omega_0 t}$$

$$= e^{-\Gamma t^2} \cdot e^{i\omega_0 t}$$

$$\boxed{\Gamma = a - ib}$$ komplex Gaussian Parameter

Instantaneous Intensity:

$$I(t) = |E(t)|^2 = e^{-2at^2} = e^{-\frac{4\ln 2}{\tau_p^2}t^2}$$

Pulsewidth (FWHM):

$$\boxed{\tau_p = \sqrt{\frac{2\ln 2}{a}}}$$

Instantaneous Frequency:

$$E(t) \sim e^{i(\omega_0 + bt)t} = e^{i\phi_{tot}(t)}$$

total instantaneous phase

-> Rate at which the total phase of the signal rotates forward

-> $2\pi \cdot$ number of cycles completed per unit time

$$\boxed{\omega_i(t) = \frac{d\phi_{tot}}{dt}}$$

Instantaneous frequency:

$$\omega_i(t) = \frac{d\phi_{tot}}{dt} = \frac{d}{dt}(\omega_0 t + bt^2)$$

$$\boxed{\omega_i(t) = \omega_0 + 2bt}$$

Chirped Signal:	$b \neq 0$
Upchirp:	$b > 0$
Downchirp:	$b < 0$
Unchirped Signal:	$b = 0$

Gaussian Pulse Spectrum

$$E(t) = e^{-\Gamma t^2} \xrightarrow{\text{Fourier Transform}} \tilde{E}(\omega) = e^{-\frac{(\omega-\omega_0)^2}{4\Gamma}}$$

$$\Gamma = a - ib$$

$$\frac{1}{\Gamma} = \frac{1}{a-ib} \cdot \frac{a+ib}{a+ib} = \frac{a-ib}{a^2+b^2}$$

$$\tilde{E}(\omega) = e^{-\frac{1}{4}\cdot\frac{a}{a^2+b^2}\cdot(\omega-\omega_0)^2 - i\cdot\frac{1}{4}\cdot\frac{b}{a^2+b^2}(\omega-\omega_0)^2}$$

Power Spectrum:

$$|\tilde{E}(\omega)|^2 = e^{-\frac{1}{2}\cdot\frac{a}{a^2+b^2}\cdot(\omega-\omega_0)^2} = e^{-\frac{4\ln 2}{\Delta\omega_p^2}(\omega-\omega_0)^2}$$

Spectral Width: (FWHM, $\frac{rad}{s}$)

$$\Delta\omega_p = \sqrt{8\cdot\ln 2\cdot\frac{a^2+b^2}{a}}$$

Pulse Bandwidth: (FWHM, Hz)

$$\boxed{\Delta f_p = \frac{\Delta\omega_p}{2\pi} = \frac{\sqrt{2\ln 2}}{\pi}\cdot\sqrt{a\left[1+\left(\frac{b}{a}\right)^2\right]}}$$

→ With respect to an unchirped pulse of duration τ_p a chirped pulse of the same duration has a bandwidth increased by

$$\boxed{\sqrt{1+\left(\frac{b}{a}\right)^2}}$$

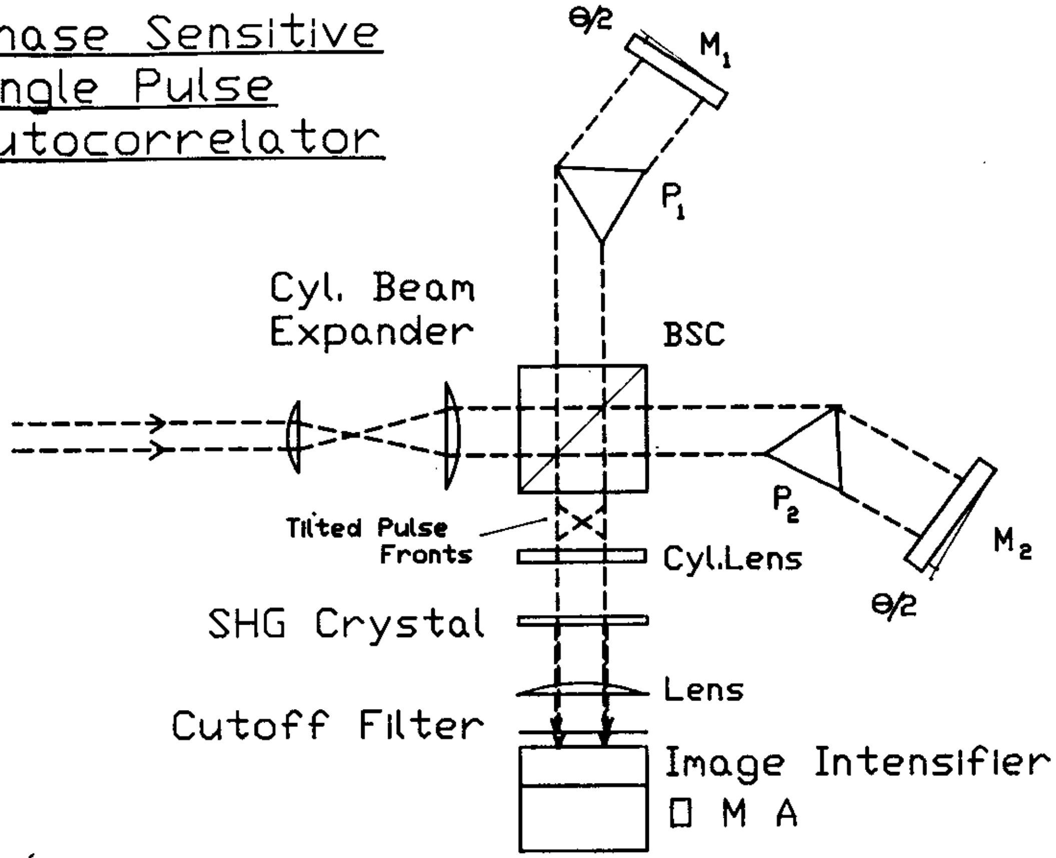
Time-Bandwidth-Product of a Gaussian Pulse with linear Chirp

$$\tau_p\cdot\Delta f_p = \sqrt{\frac{2\ln 2}{a}}\cdot\frac{\sqrt{2\ln 2}}{\pi}\cdot\sqrt{a\left[1+\left(\frac{b}{a}\right)^2\right]}$$

$$= \frac{2\ln 2}{\pi}\cdot\sqrt{1+\left(\frac{b}{a}\right)^2}$$

$$= 0.44\cdot\alpha$$

Phase Sensitive Single Pulse Autocorrelator



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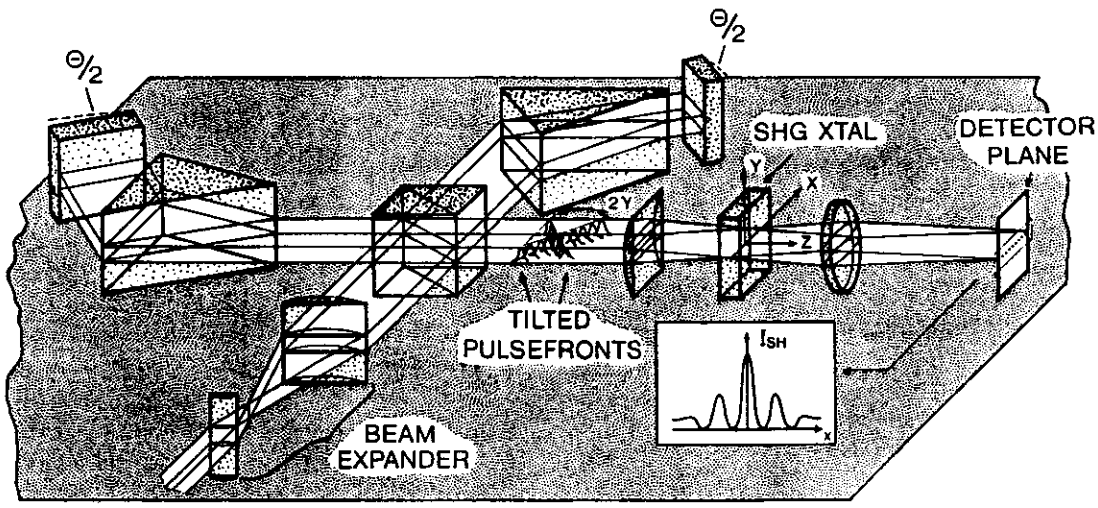
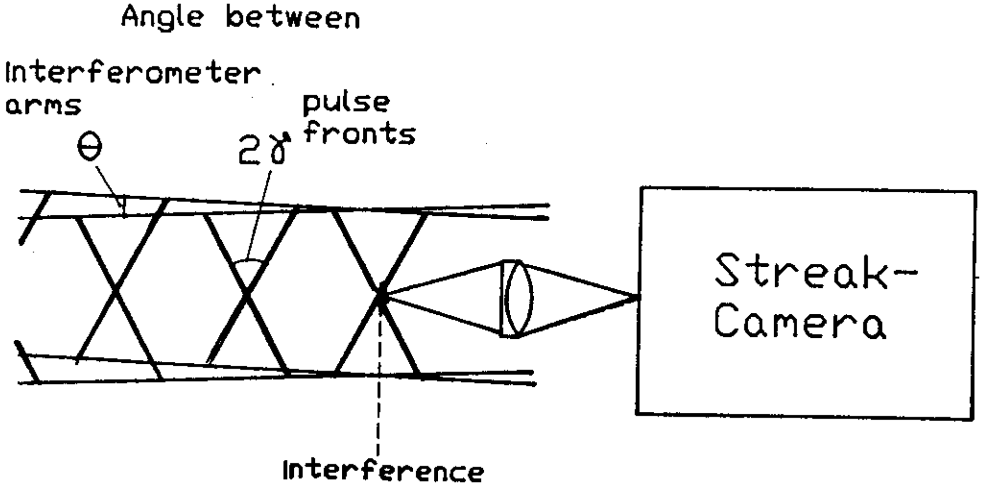
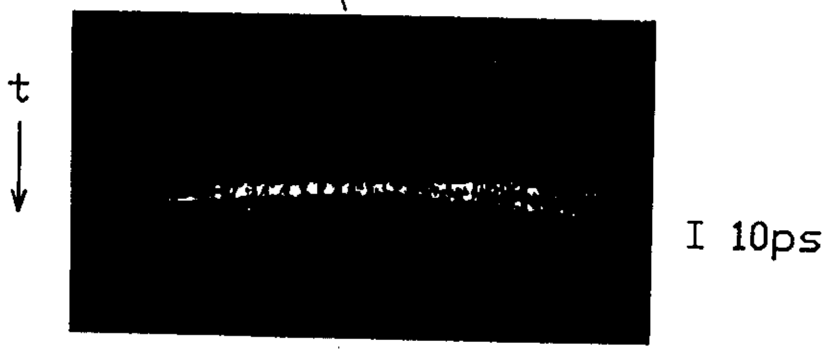
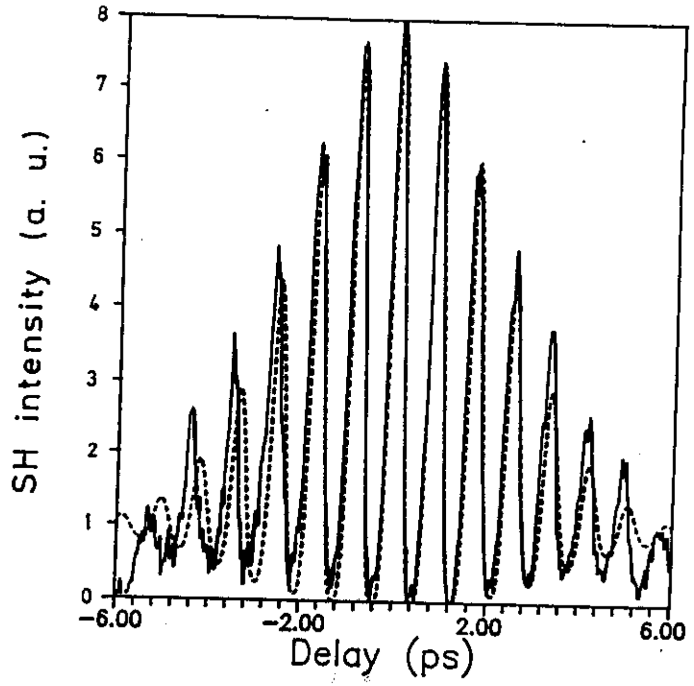




Streak recording





Unchirped Pulse
(fully coherent)

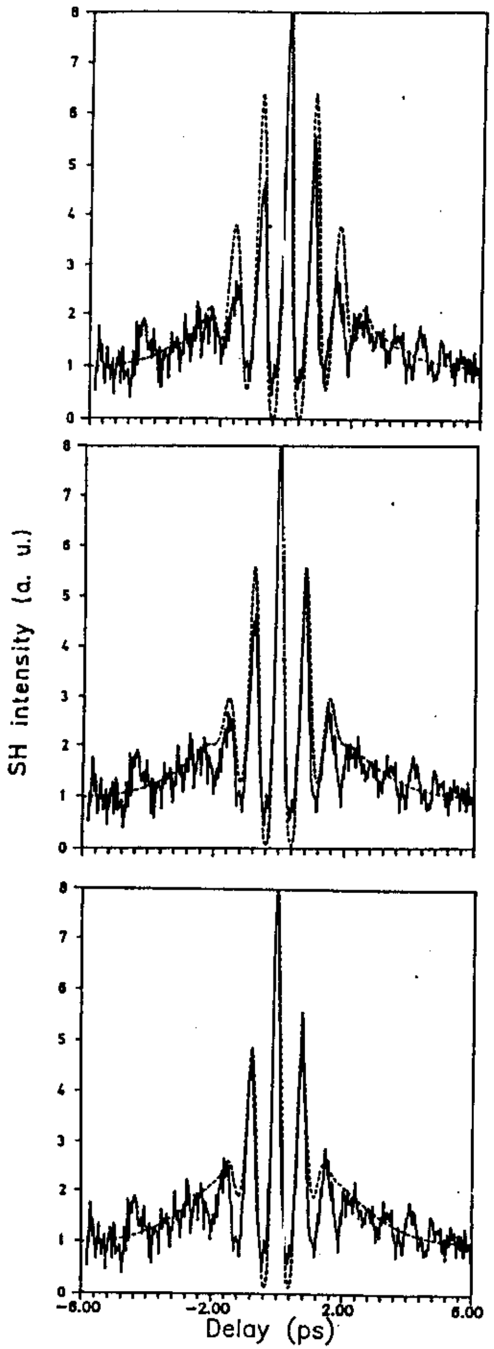
$\tau = 3.5$ ps $\quad \Delta t_a = 5.4$ ps

$a = 0$

Total Phase Shift = 0

—— recorded Phase Sensitive Single Shot Autocorrelation

------ Model Calculation



Chirped Pulse

$\tau = 3.5$ ps
$\Delta t_a = 5.4$ ps

$a = 1.03 \cdot 10^{24}\ s^{-2}$

Total Phase Shift $= 2 \cdot 2\pi$

$\alpha = 5.9$

$a = 1.53 \cdot 10^{24}\ s^{-2}$

Total Phase Shift $= 3 \cdot 2\pi$

$\alpha = 13.6$

$a = 2.05 \cdot 10^{24}\ s^{-2}$

Total Phase Shift $= 4 \cdot 2\pi$

$\alpha = 23.1$

—— recorded Phase Sensitive Single Shot Autocorrelation
------ Model Calculation

The Model

2nd Order Autocorrelation Function

$$I_{SH\omega} \sim \int_{-\infty}^{\infty} \left[E_1(t,x) + E_2(t,x)\right]^4 dt$$

$$E_{\frac{1}{2}}(t,x) = \exp\left\{-2\ln 2\left[\frac{t \pm \frac{2x\tan\gamma}{c}}{\tau}\right]^2\right\} \cdot \exp\left[i\left\{\omega + a\left(t \pm \frac{2x\tan\gamma}{c}\right)\right\}t - k_{\frac{1x}{2}}x\right] + \text{c.c.}$$

correction for tilt of pulse front ($\frac{2x\tan\gamma}{c}$)

instantaneous frequency

$$k_{\frac{1x}{2}}x = \frac{\omega + at \pm \frac{2ax\tan\gamma}{c}}{c} \sin\theta$$

θ: angle between interferometer arms

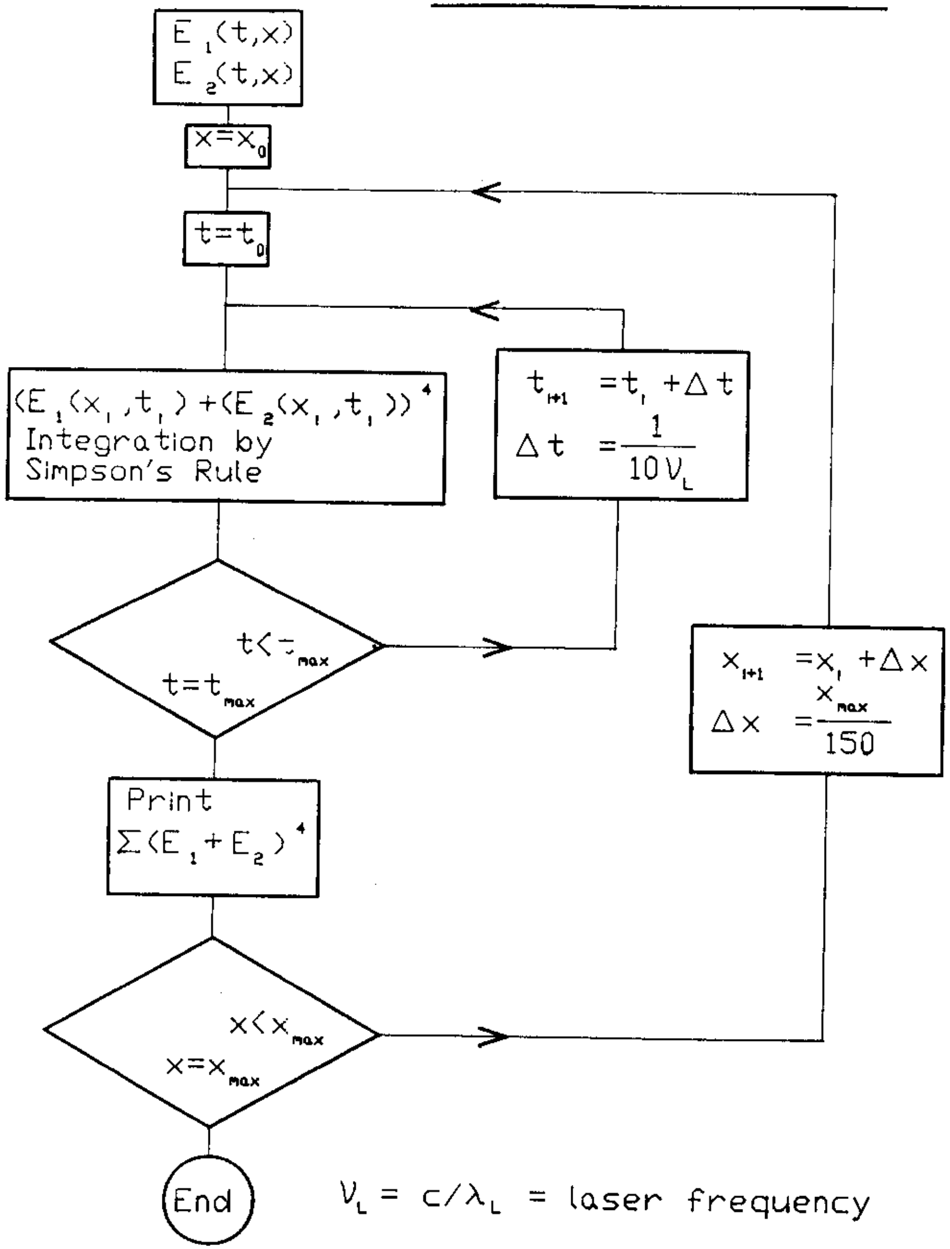
τ = width of pulse intensity (FWHM)

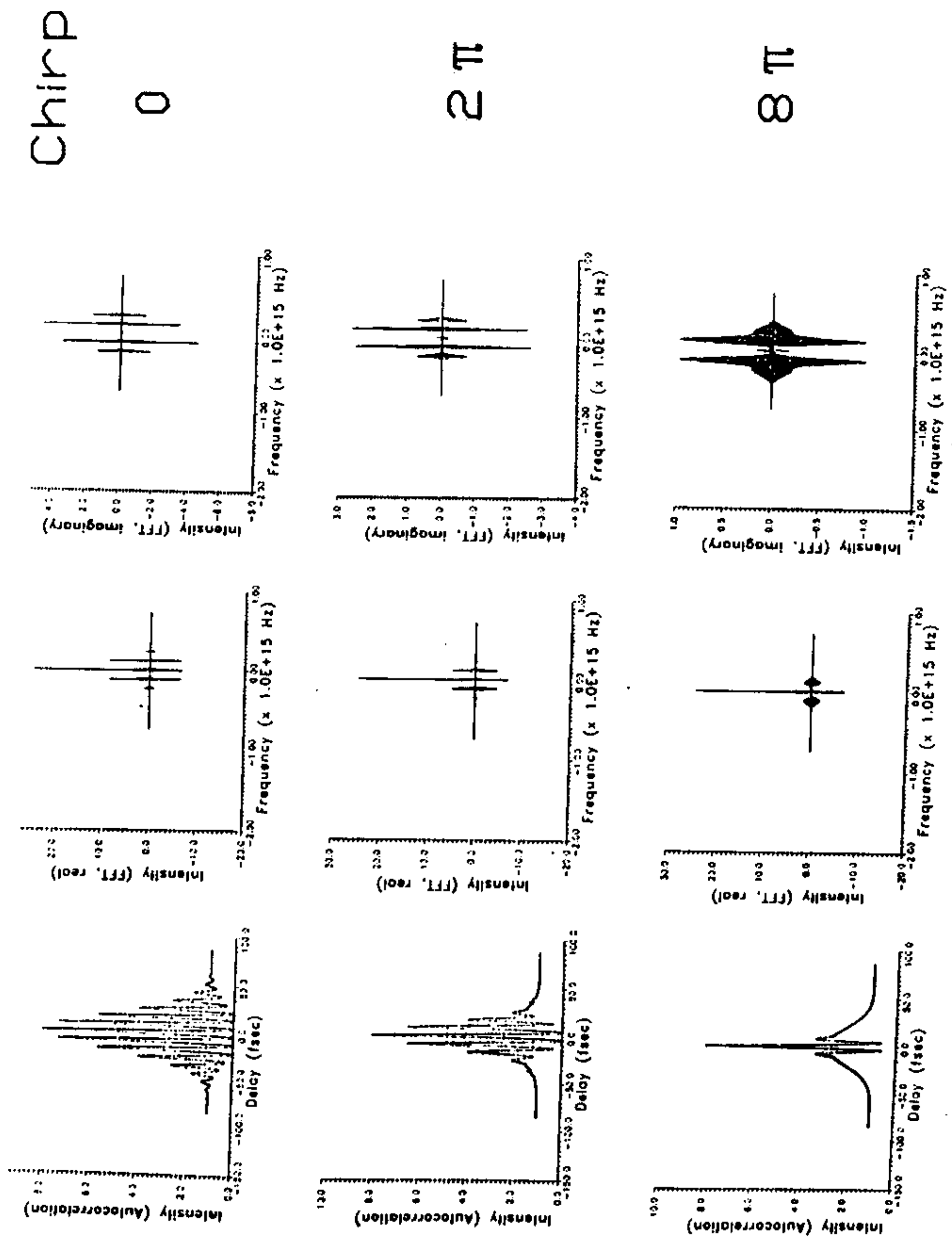
$$\tan\gamma = \lambda \frac{d\varepsilon}{d\lambda}$$

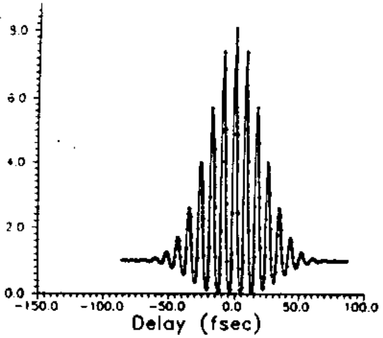
$\frac{d\varepsilon}{d\lambda}$: angular dispersion

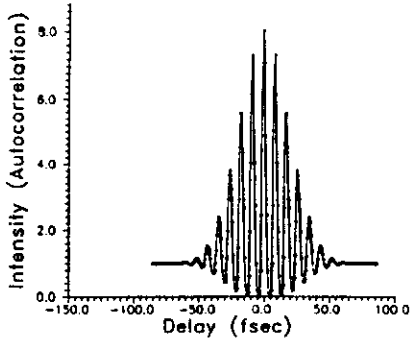
γ: half angle between pulse fronts

Model Calculation







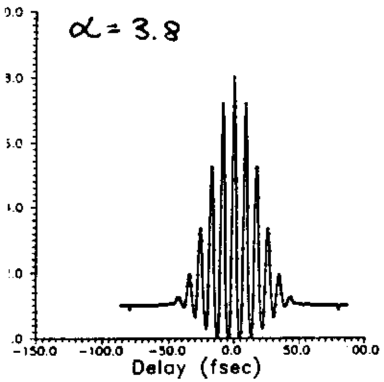


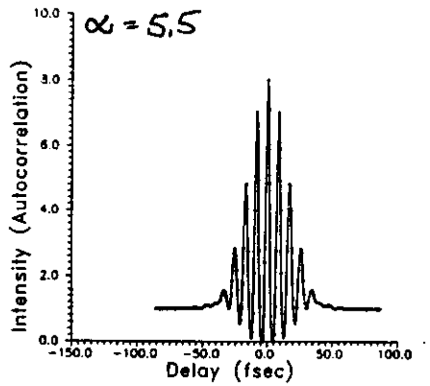
Time Window of the Phase Sensitive Single Shot Autocorrelator:

$$\Delta T = \frac{4a}{c} \lambda \frac{dn}{d\lambda}$$

prisms oriented for minimum deviation

a = width of prism base



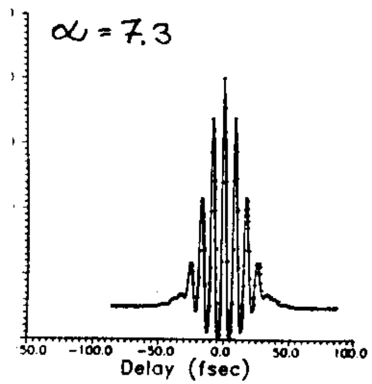


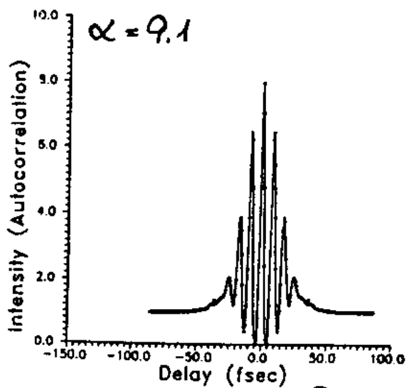
a = 50 mm, λ = 600 nm				
Prism Material	Silica	BK7	F3	SF10
ΔT/ps	12.6	15.5	38.7	50.5

ΔT can be decreased by

(a) rotating both prisms by a small angle

(b) rotating one prism by about 180 deg. to invert the direction of dispersion





8.11.89

PSA_FFT.SKD

Pulse broadening by Group Velocity Dispersion

$$\Delta\tau = \frac{\lambda\, a}{c}\,\frac{d^2 n}{d\lambda^2}\,\Delta\lambda$$

$$\frac{\Delta\tau}{\tau} = \frac{\Delta T}{\tau}\;\frac{\lambda \dfrac{d^2 n}{d\lambda^2}}{\dfrac{dn}{d\lambda}}\;\frac{1}{\tau\nu}$$

ΔT: Time Window of the Phase Sensitive Single Shot Autocorrelator

$\frac{\lambda\, d^2n/d\lambda^2}{dn/d\lambda}$: This ratio has a value of approx. 3 for all materials of interest

$\tau\nu$: Number of optical cycles

Table computed using:

$\Delta T / \tau = 4$

τ/ps	10	5	2	1	0.5	0.2	0.1
$\tau\nu$	5000	2500	1000	500	250	100	50
$\Delta\tau/\tau$	0.002	0.004	0.01	0.02	0.04	0.1	0.2

	Advantage	Disadvantage
Prism	High transmission, 1:1 intensity ratio of the branches easy to achieve	Limitation by group velocity dispersion (<50fs)
Grating	Highest time resolution possible	Low efficiency

Propagation of a Gaussian pulse through a dispersive medium

Plane wave:

$$E(z,t) = \frac{1}{2}\left[\tilde{E}_+ \cdot e^{i(\omega t - \beta z)} + c.c.\right]$$

wave travelling in +z direction

$$+ \frac{1}{2}\left[\hat{E}_- \cdot e^{i(\omega t + \beta z)} + c.c.\right]$$

wave travelling in −z direction

Propagation constant:

$$\beta = \omega\sqrt{\mu\varepsilon} = \frac{\omega}{c} = \frac{n\omega}{c_0}$$

$$= \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_0}$$

c_0 velocity, λ_0 wavelength } in vacuo

$\frac{c}{c_0} \equiv c$ velocity, $\frac{\lambda_0}{n} \equiv \lambda$ wavelength } in a dielectric medium

$$n \equiv \sqrt{\frac{\mu \cdot \varepsilon}{\mu_0 \varepsilon_0}} \approx \sqrt{\frac{\varepsilon}{\varepsilon_0}} \quad \text{if } \mu \approx \mu_0$$

Non-dispersive medium: $\beta = \frac{\omega}{c}$

For narrowband signal in a dispersive medium:

$$\beta(\omega) = \beta(\omega_0) + \left(\frac{d\beta}{d\omega}\right)_{\omega_0} \cdot (\omega - \omega_0) + \frac{1}{2} \cdot \left(\frac{d^2\beta}{d\omega^2}\right)_{\omega_0} \cdot (\omega - \omega_0)^2$$

center frequency — β' — β''

Gaussian pulse (as before) input to dispersive system:

$$E_0(t) = e^{-\Gamma_0 t^2} \cdot e^{i\omega_0 t} \qquad \tilde{E}_0(\omega) = e^{-\frac{(\omega-\omega_0)^2}{4\Gamma_0}}$$

Pulse

$$\Gamma_0 = a_0 - i b_0$$

Output pulse spectrum after propagating a distance z through the dispersive system:

$$\tilde{E}(z,\omega) = \tilde{E}_0(\omega) \cdot e^{-i\beta(\omega) z}$$

input spectrum × freq. dependent propagation through system

after substituting expansion of $\beta(\omega)$ about its value at ω_0:

$$\tilde{E}(z,\omega) = e^{-i\beta(\omega_0)z - i\beta' z \cdot (\omega-\omega_0) - \left(\frac{1}{4\Gamma_0} + i\frac{\beta'' z}{2}\right)(\omega-\omega_0)^2}$$

Inverse Fourier Transform:

$$E(z,t) = \frac{1}{2\pi} e^{i(\omega_0 t - \beta(\omega_0) z)} \int_{-\infty}^{\infty} e^{-\frac{(\omega-\omega_0)^2}{4\Gamma(z)} + i(\omega-\omega_0)(t-\beta' z)} \, d(\omega-\omega_0)$$

Output pulse

Modification of initial pulse parameter:

$$\boxed{\frac{1}{\Gamma(z)} = \frac{1}{\Gamma_0} + 2i\beta'' z}$$

$$E(z,t) = e^{-i\omega_0 t - \beta(\omega_0) z} \cdot e^{-\Gamma(z) \cdot (t - \beta' z)^2}$$

$$= e^{-i\omega_0\left(t - \frac{z}{v_\phi(\omega_0)}\right)} \cdot e^{-\Gamma(z) \cdot \left(t - \frac{z}{v_g(\omega_0)}\right)^2}$$

Midband phase delay:

$$t_\phi = \frac{z}{v_\phi(\omega_0)} = \frac{\beta(\omega_0)}{\omega_0} \cdot z$$

Phase velocity:

$$v_\phi(\omega_0) = \frac{z}{t_\phi} = \frac{\omega_0}{\beta(\omega_0)}$$

Velocity of sinusoidal cycle within pulse envelope

Midband group delay:

$$t_g = \frac{z}{v_g(\omega_0)} = \beta' z$$

Group velocity:

$$v_g(\omega_0) = \frac{1}{(d\beta/d\omega)_{\omega_0}}$$

Velocity of pulse envelope

→ **Meaning of the coefficients in the power series expansion of $\beta(\omega)$:**

$$\beta \equiv \frac{\omega_0}{v_\phi(\omega_0)} = \frac{\omega_0}{\text{Phase velocity}}$$

$$\beta' \equiv \frac{1}{v_g(\omega_0)} = \frac{1}{\text{group velocity}}$$

$$\beta'' \equiv \frac{d}{d\omega}\left(\frac{1}{v_g(\omega_0)}\right) \equiv \text{group velocity dispersion}$$

$$\boxed{\frac{1}{\Gamma(z)} = \frac{1}{\Gamma_0} + i \cdot 2 \cdot \beta'' \cdot z}$$

Modified pulse parameter

$$\beta'' \cdot z = \frac{1}{\mu}$$

$$\boxed{\frac{1}{\Gamma} = \frac{1}{\Gamma_0} + i \cdot \frac{2}{\mu}}$$

$$\Gamma_0 = a_0 - i b_0$$

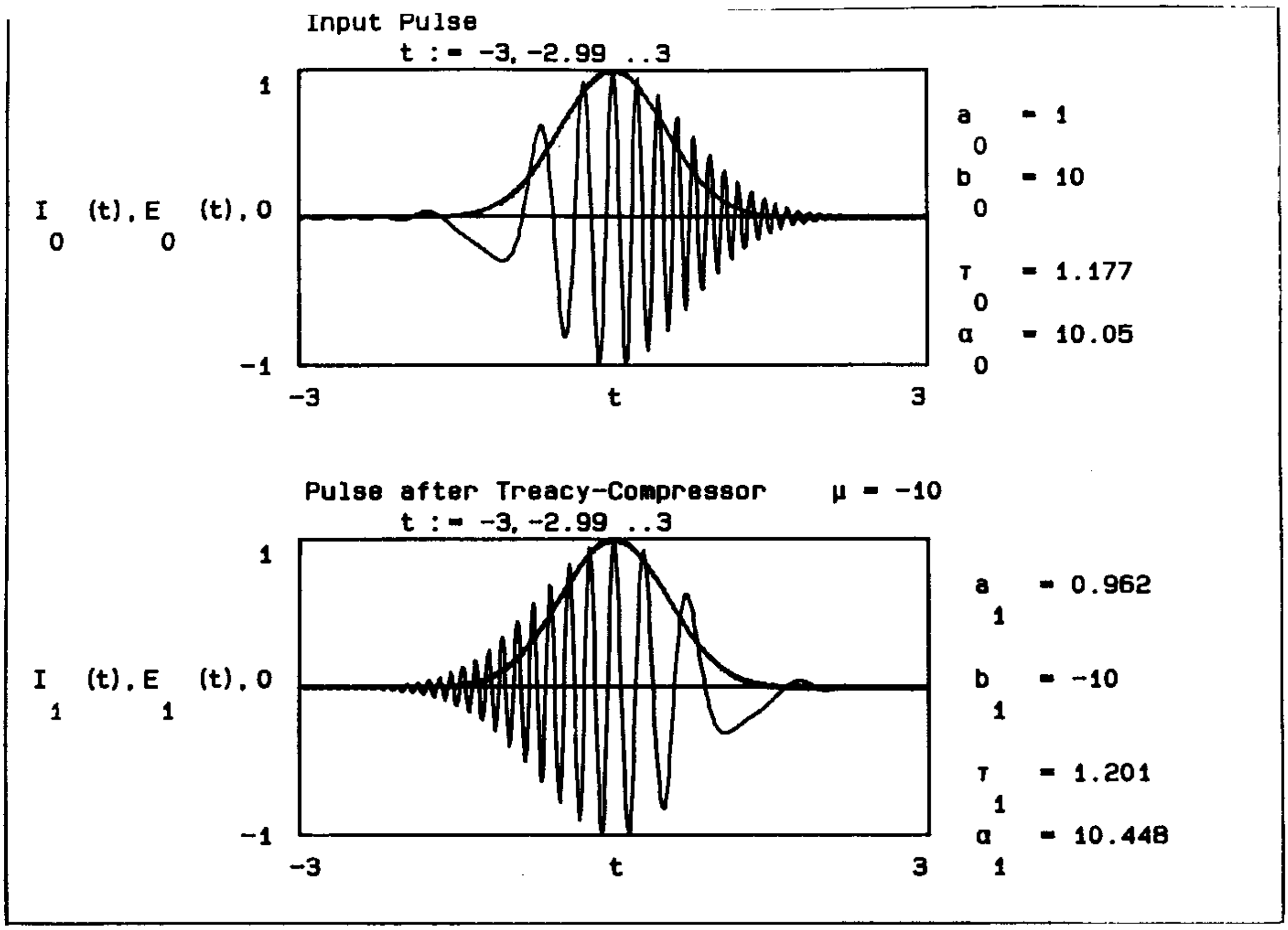
$$\Gamma = a_1 - i b_1$$

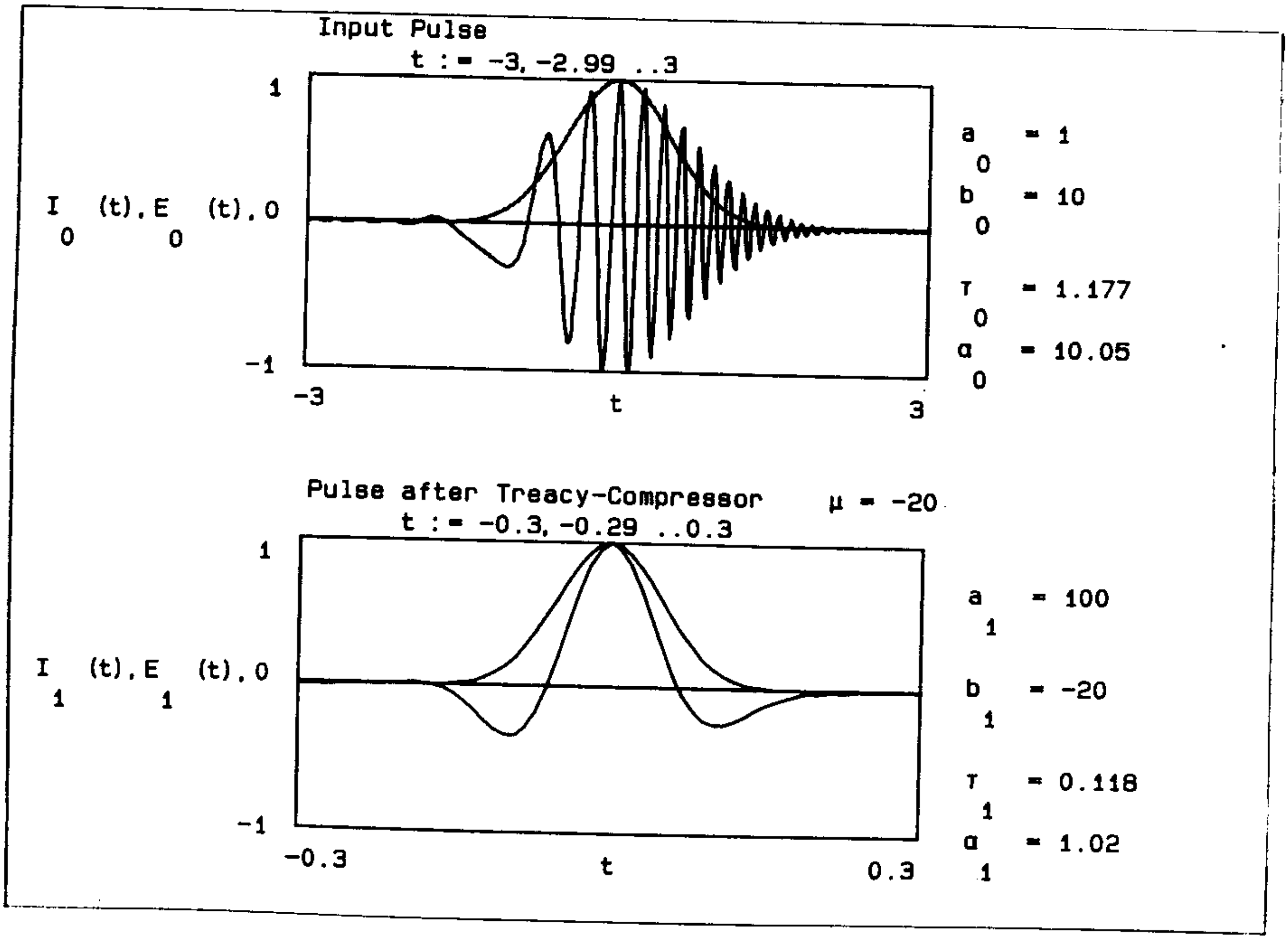
$$\boxed{a_1 = \frac{a_0}{\left[1 + \frac{2b_0}{\mu}\right]^2 + \left[\frac{2a_0}{\mu}\right]^2}}$$

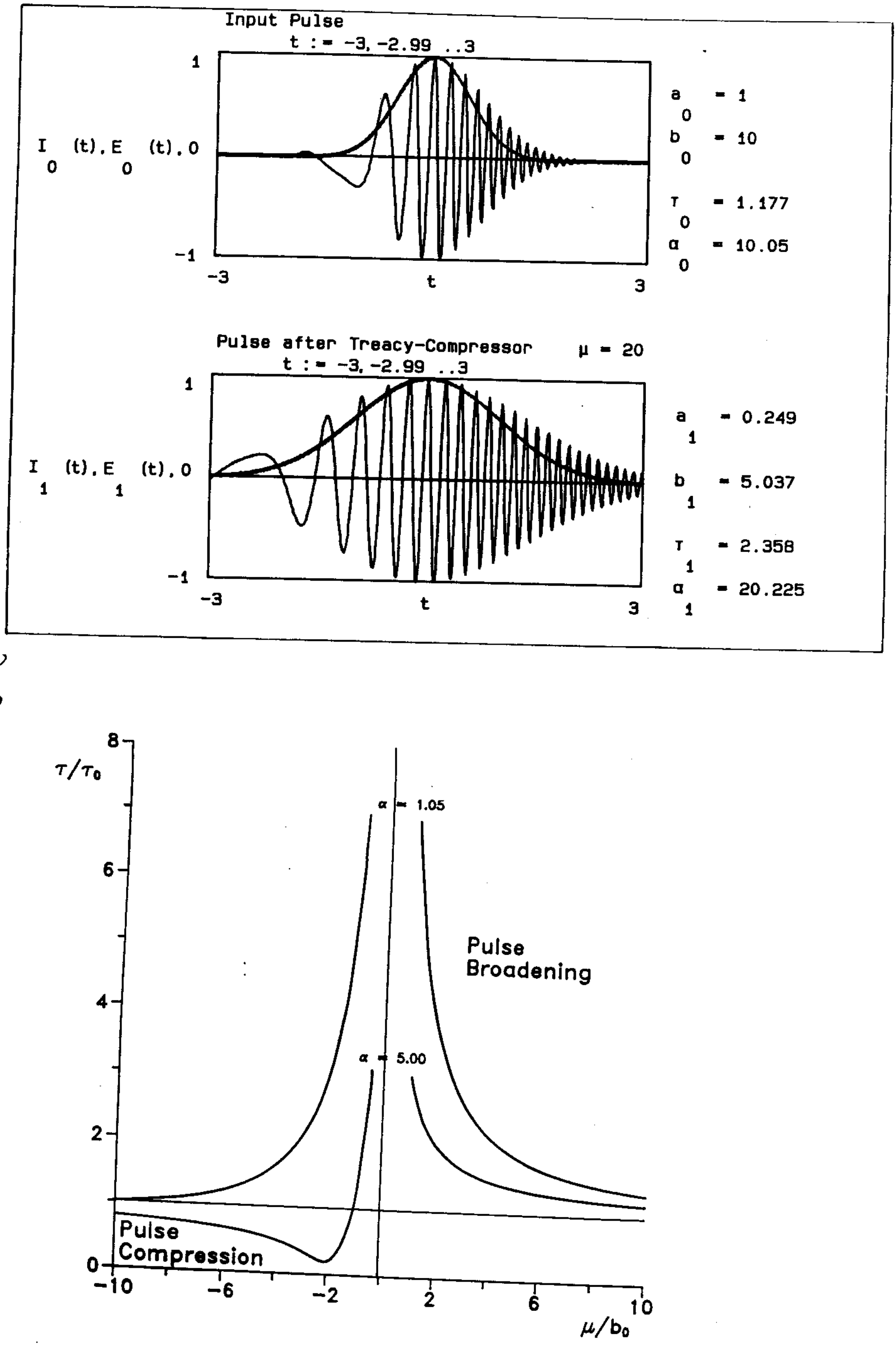
$$\boxed{b_1 = \frac{\frac{2a_0^2}{\mu} + b_0\left[1 + \frac{2b_0}{\mu}\right]}{\left[1 + \frac{2b_0}{\mu}\right]^2 + \left[\frac{2a_0}{\mu}\right]^2}}$$

New values after passage through dispersive medium:

$$\tau_1 = \sqrt{\frac{2\ln 2}{a_1}} \qquad \alpha_1 = \sqrt{1 + \left(\frac{b_1}{a_1}\right)^2}$$


Input Pulse
t := -3, -2.99 ..3
I_0(t), E_0(t), 0
a_0 = 1
b_0 = 10
τ_0 = 1.177
α_0 = 10.05
Pulse after Treacy-Compressor μ = -10
t := -3, -2.99 ..3
I_1(t), E_1(t), 0
a_1 = 0.962
b_1 = -10
τ_1 = 1.201
α_1 = 10.448
t

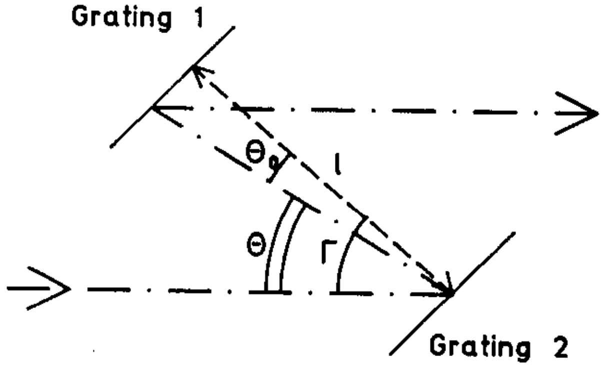

Input Pulse
t := -3, -2.99 ..3
I_0(t), E_0(t), 0
a_0 = 1
b_0 = 10
τ_0 = 1.177
α_0 = 10.05
Pulse after Treacy-Compressor μ = -20
t := -0.3, -0.29 ..0.3
I_1(t), E_1(t), 0
a_1 = 100
b_1 = -20
τ_1 = 0.118
α_1 = 1.02
t


Input Pulse
t := -3, -2.99 ..3
I0 (t), E0 (t), 0
1
-1
-3
t
3
a0 = 1
b0 = 10
τ0 = 1.177
α0 = 10.05
Pulse after Treacy-Compressor
μ = 20
t := -3, -2.99 ..3
I1 (t), E1 (t), 0
a1 = 0.249
b1 = 5.037
τ1 = 2.358
α1 = 20.225
τ/τ0
8
6
4
2
0
α = 1.05
α = 5.00
Pulse Broadening
Pulse Compression
-10
-6
-2
2
6
10
μ/b0

20

Fig. 1

Treacy Compressor



$$\mu = \frac{-d^2\omega^3}{4\pi^2 c_0 l}\left[1-\left[\frac{2\pi c_0}{d\omega}-\sin\Gamma\right]^2\right]^{\frac{3}{2}}$$

$\mu < 0$

E.B. Treacy: IEEE J.Q.E. QE-5, 454 (1969)

Sign Reversal of μ of a Treacy compressor

O.E. Martinez, J.P. Gordon & R.L. Fork: J. Opt. Soc. Am. A-10, 1003 (1984)

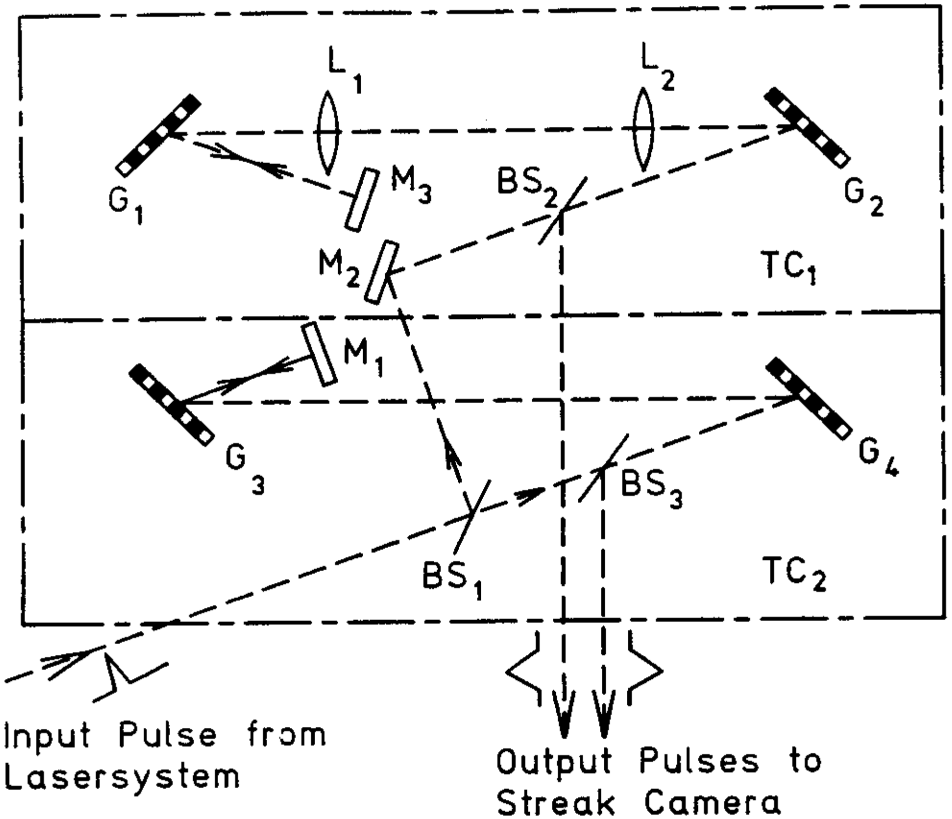
→ Magnification of the angular dispersion by a telescope between the gratings.

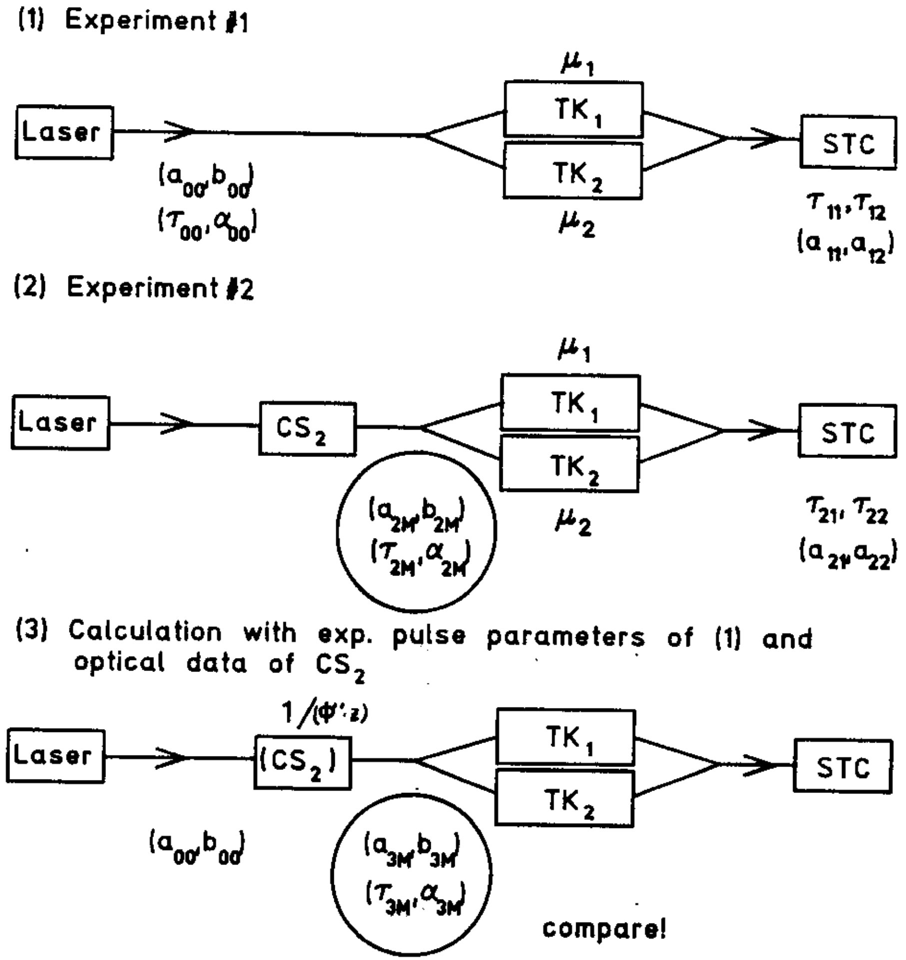
$$l_{eff} = [l - 2(f_1 + f_2)]\left(\frac{f_1}{f_2}\right)^2$$

special case:

$f = f_1 = f_2$

$l_{eff} = l - 4f$





$$\mu \equiv \mu_2 = |-\mu_1|$$

Evaluation of the Experiments:

#1 (air):

measured: $\tau_{11} \longrightarrow a_{11} = \frac{2\ln 2}{\tau_{11}^2}$

$\tau_{12} \longrightarrow a_{12} = \frac{2\ln 2}{\tau_{12}^2}$

wanted: $a_{00} \longrightarrow \tau_{00} = \sqrt{\frac{2\ln 2}{a_{00}}}$

$b_{00} \longrightarrow \alpha_{00} = \sqrt{1-\left(\frac{b_{00}}{a_{00}}\right)^2}$

#2 (CS_2): analogous procedure

$\tau_{21} \longrightarrow \tau_{2M}$

$\tau_{22} \longrightarrow \alpha_{2M}$

Analytical Solution:

$\mu \equiv \mu_2 = |-\mu_1|$

$$a_{00} = \frac{1+\sqrt{1-\left(\frac{D}{S}\right)^2-\left(\frac{8P}{S\cdot\mu}\right)^2}}{\frac{D^2}{4PS}+\frac{16P}{S\mu^2}}$$

$$b_{00} = -a_{00}\cdot\frac{D\mu}{8P}$$

$S = a_{11}+a_{12} \quad D = a_{11}-a_{12} \quad P = a_{11}\cdot a_{12}$

if $\mu_1 \neq \mu_2$ → numerical solution

Simulation for CS_2

R.L. Fork et al.: Opt. Lett. 12, 483 (1987)

$\beta''\cdot z$ for dispersive material

$$\beta''\cdot z = \frac{d^2\beta_m}{d\omega^2} = \frac{\lambda^3\cdot l_m}{2\pi c^2}\cdot\frac{d^2 n_m}{d\lambda^2}$$

Material: CS_2

Cuvette (double pass): 2 x 1.5 m

λ : 604 nm

$n_{CS_2}(\lambda)$: Internatl. Critical Tables

Sellmeier Equ. for CS_2:

$$n_{CS_2}(\lambda) = \sqrt{1+\frac{1.50\cdot\lambda^2}{\lambda^2-3.18\cdot 10^4}}$$

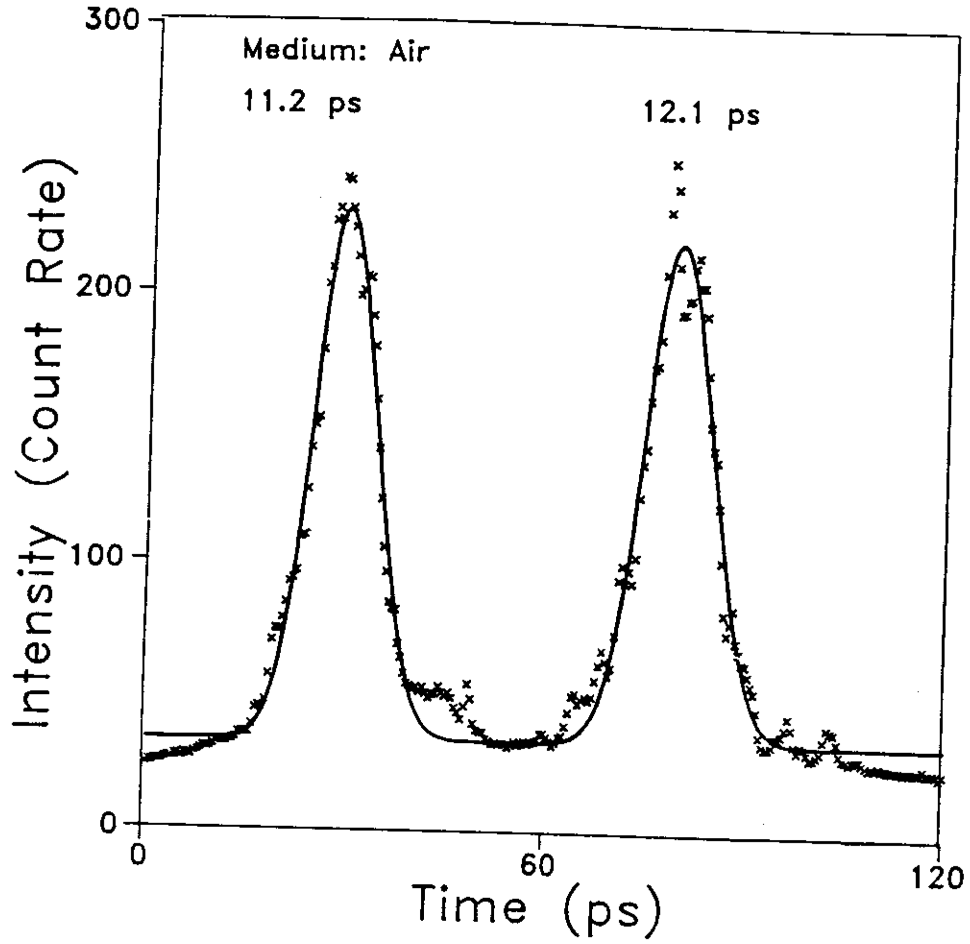
$$\left(\frac{dn_{CS_2}}{d\lambda}\right)_{604\,nm} = -1.60\cdot 10^{-4}\,nm^{-1}$$

$$\left(\frac{d^2n_{CS_2}}{d\lambda^2}\right)_{604\,nm} = 8.80\cdot 10^{-7}\,nm^{-2}$$

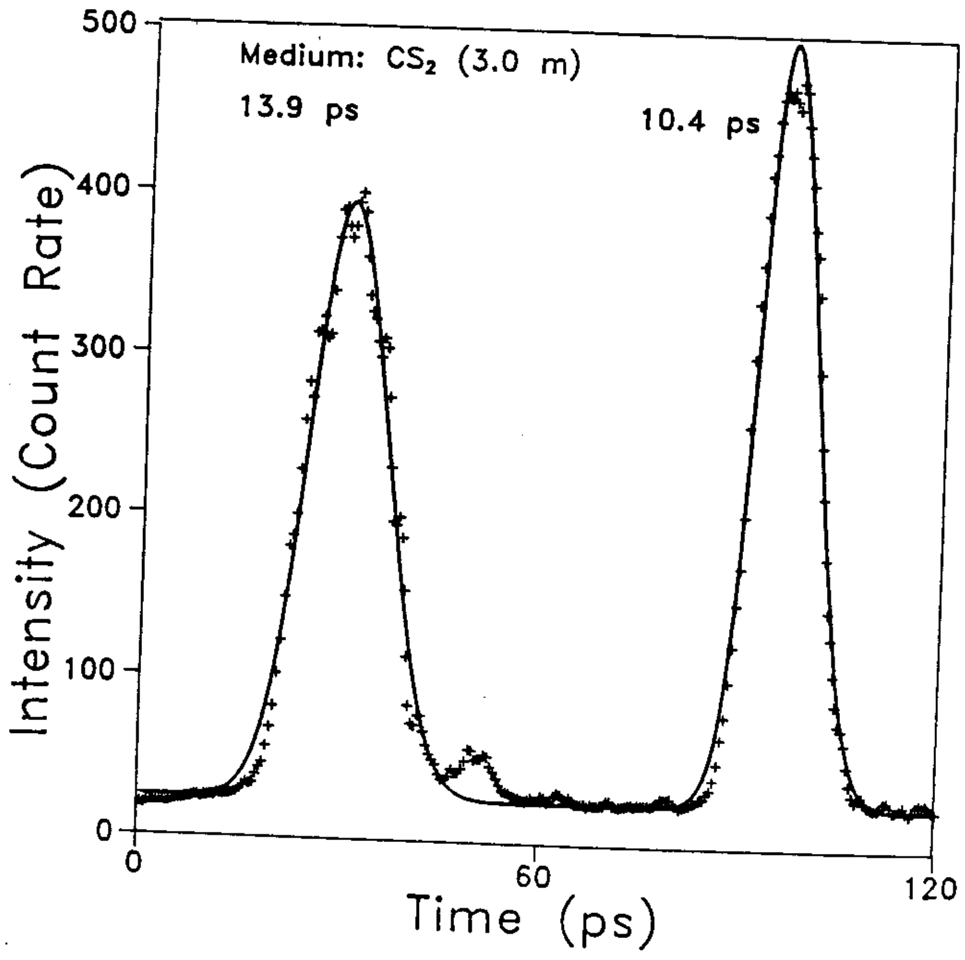
use $\mu = \frac{1}{\beta''\cdot z}$ and formula $a_1 = f(a_0, b_0, \mu)$

to obtain a_{3M} and b_{3M}

$$\mu_{CS_2} = 9.10\cdot 10^{-1}\,ps^{-2}$$



Medium: Air
11.2 ps
12.1 ps
Intensity (Count Rate)
Time (ps)
0
100
200
300
0
60
120



Medium: CS_2 (3.0 m)
13.9 ps
10.4 ps
Intensity (Count Rate)
Time (ps)
0
100
200
300
400
500
0
60
120

(1) Experiments

Exp. #	Medium	Exp.Results τ_{11} ps	τ_{12} ps	Calculated Values τ_{00} ps	α_{00}	
TC5	Air	11.1	12.7	2.13	1.08	b<0 !
TC10	Air	11.2	12.1	2.06	1.03	b<0 !
TC12	Air	14.2	14.2	1.64	1.00	b=0

Exp. #	Medium	Exp.Results τ_{11} ps	τ_{12} ps	Calculated Values τ_{2M} ps	α_{2M}	
TC17	CS_2	13.9	10.4	2.62	1.36	b>0
TC20	CS_2	14.6	12.0	2.19	1.25	b>0

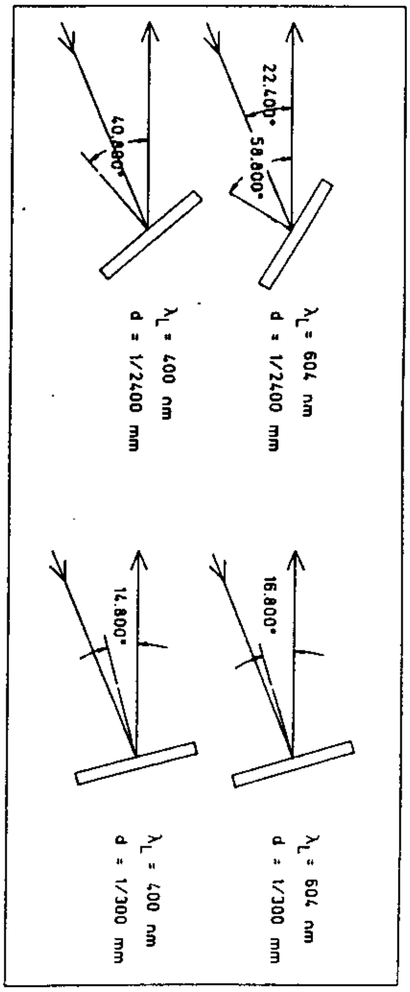
$\lambda = 604$ nm
$E_p' = \frac{5\,\mu J}{10^3}$
$d_G = \frac{1}{2400}$ mm
$\ell_{eff} = \pm 1000$ mm
$\Gamma = 1027$ mrad
$\mu = 0.12$

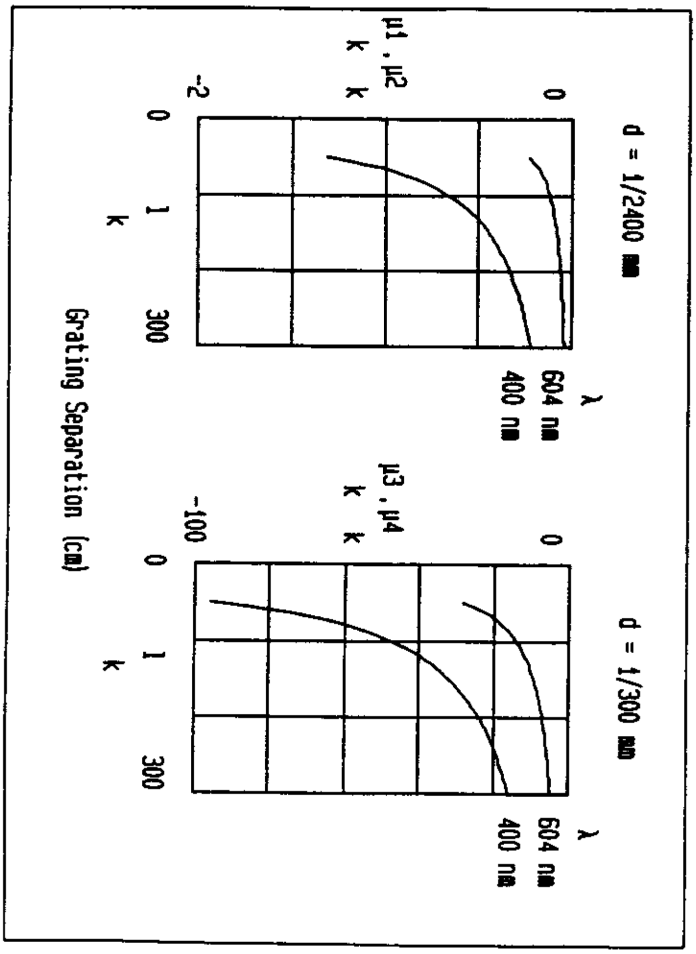
(2) Simulation

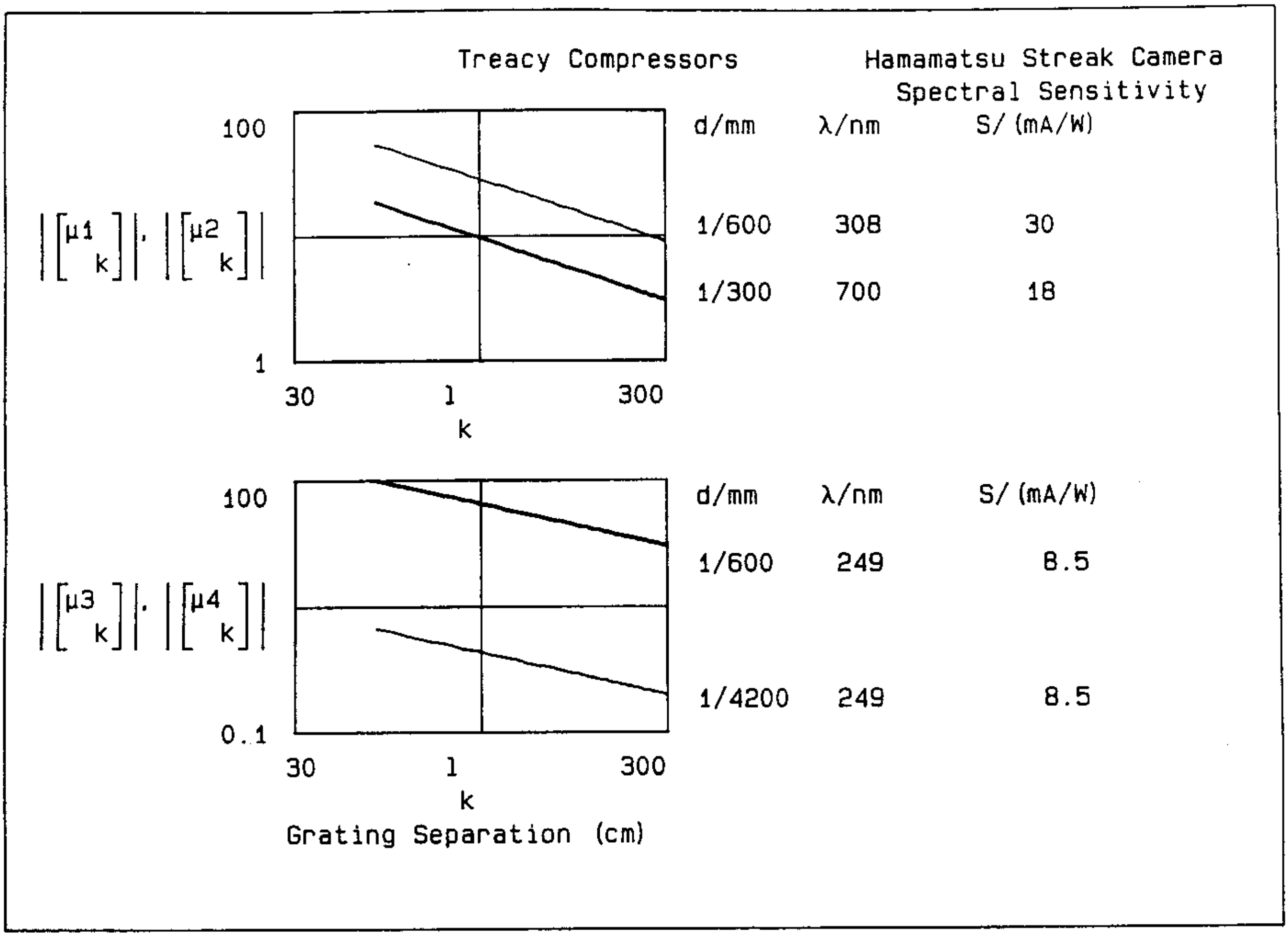
Data from	Medium (opt.Data)	τ_{00} ps	α_{00}	Calculated Values τ_{3M} ps	α_{3M}
TC5	CS_2	2.13	1.08	2.47	1.16
TC10	CS_2	2.06	1.03	2.23	1.11
TC12	CS_2	1.64	1.00	2.39	1.46

25

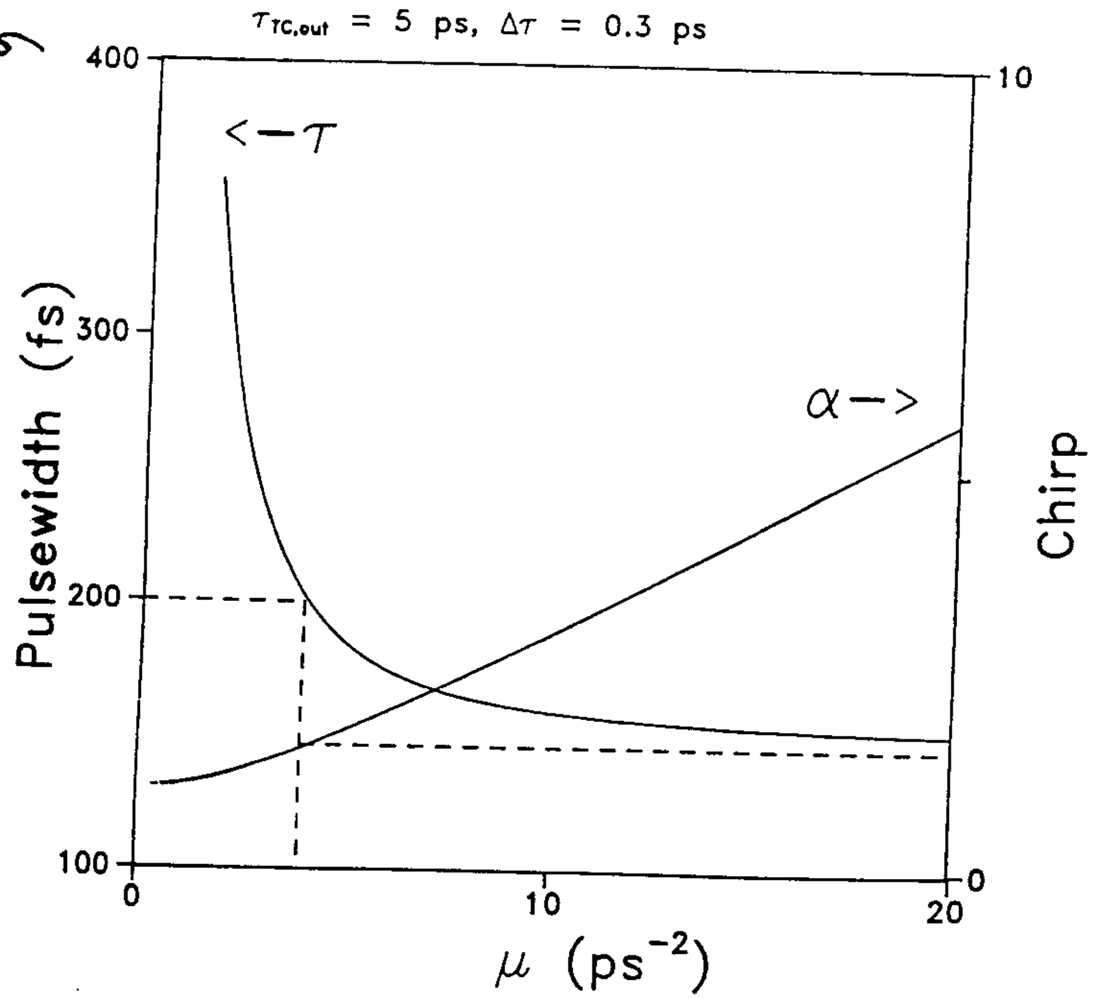
Treacy Compressor







Treacy Compressors
Hamamatsu Streak Camera Spectral Sensitivity
d/mm λ/nm S/(mA/W)
1/600 308 30
1/300 700 18
d/mm λ/nm S/(mA/W)
1/600 249 8.5
1/4200 249 8.5
100
1
0.1
30
1
300
k
Grating Separation (cm)



$\tau_{TC,out}$ = 5 ps, Δτ = 0.3 ps
<-τ
α->
Pulsewidth (fs)
Chirp
μ (ps^-2)
400
300
200
100
0
10
20

Fig. 6

Summary

(1) $\Gamma_0 = a_0 - ib_0$ of ultrashort pulse can be determined in a single shot.

(2) By proper choice of Treacy compressor pulse can be stretched.
$\tau_p < \tau_{STC}$ can be measured.

(3) Spectral range limited only by spectral range of STC photocathode and availability of Treacy compressor.

(4) Sensitivity $\lesssim$ 5 nJ

(5) $\alpha \approx 1$ can be measured

(6) Sign of b (up- or downchirp) can be determined

(7) Other pulseshapes than Gaussian can be analyzed using numerical methods.

(8) Resolution down to $\tau \lesssim$ 100 fs appears possible

Selected literature on Methods for single-shot measurements of ultrashort pulses:

(1) S.L. Shapiro, Ed.: Ultrashort Light Pulses, Topics in Appl. Physics, Vol. 18, 2nd Edition, Springer Verlag, Berlin (1984)

(2) K. Kinoshita et al.: Rev. Sci. Instr. [58], 932-938 (1987)

(3) K.L. Sala et al.: IEEE J. Quant. Electron. [QE-16], 990-996 (1980)

(4) G. Szabo, Zs. Bor, A. Müller: Appl. Phys. [B31], 1-4 (1983)

(5) G. Szabo, Zs. Bor, A. Müller: Opt. Lett. [13], 746-748 (1988)

(6) A.E. Siegman: Lasers, Univ. Science Books, Mill Valley, CA, USA (1986)
Chapt. 9: Linear Pulse Propagation

(7) E.B. Treacy: IEEE J. Quant. Electron. [QE-5], 454-458 (1969)

(8) G. Szabo, A. Müller, Zs. Bor: Optics Commun., in press (1991)