a fény-anyag kölcsönhatás leírása

(kis intenzitások)

$P = \chi E$ lineáris optika

(superpozíció - elve)

$\Downarrow$

törés, reflexió, abszorpció

növekvő intenzitások $I \sim 10^6 \, W/cm^2$

$$P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \dots$$

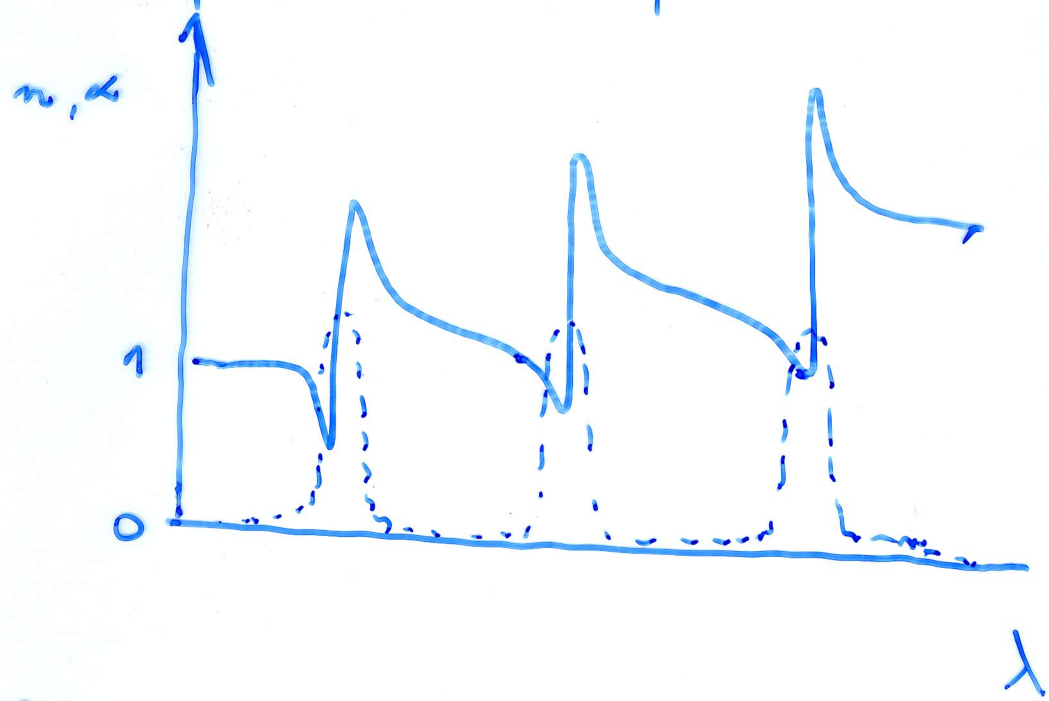
nemlineáris optika

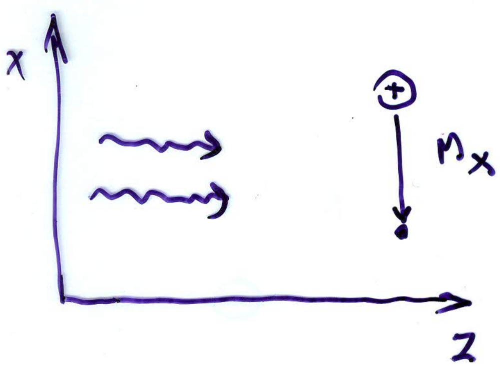
fény elektromos tere kisebb, mint az atom Coulomb-tere (perturbációs elmélet)

$\Downarrow$

felharmonikus keltés, frekvencia keverés

Diszperzió abszorpció





$$M_x = e x \qquad E_x = B e^{i(\omega t - kz)}$$

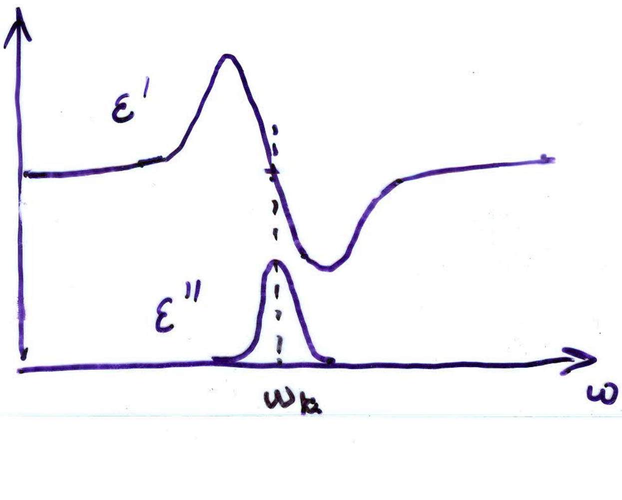
$$x = x_0 e^{i\omega t}$$

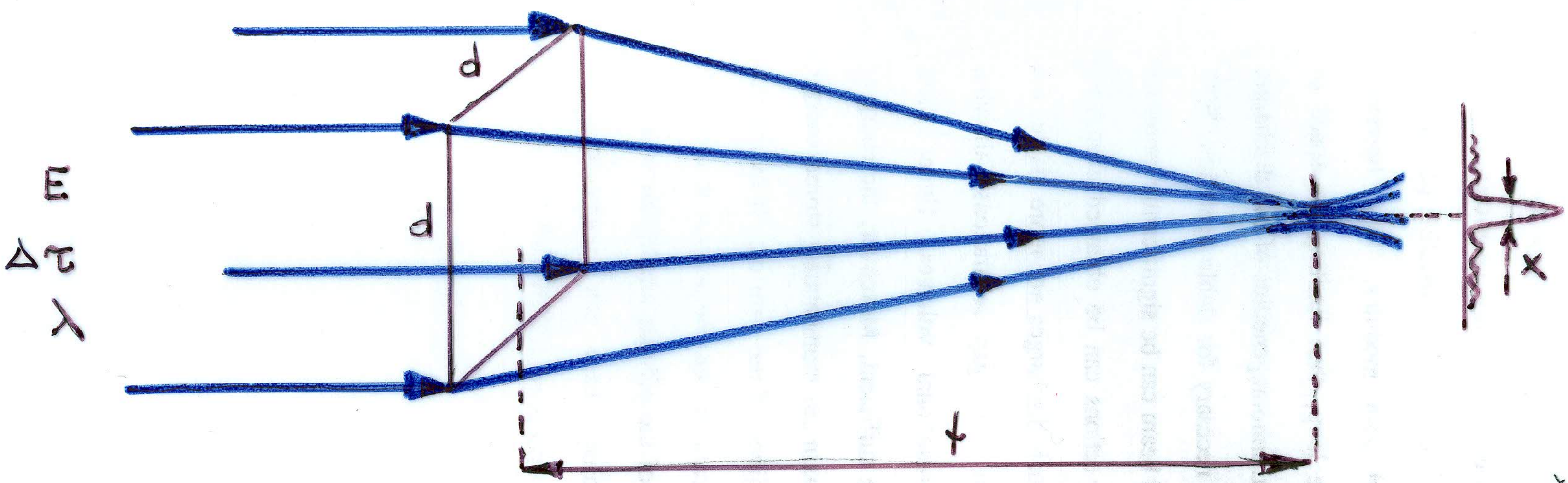
$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = a e^{i(\omega t - kz)} \quad \Rightarrow \quad x = \frac{e/m}{\omega_0^2 - \omega^2 + 2i\beta\omega} E_x$$

$$\omega_0^2 = \frac{D}{m} \qquad 2\beta = \frac{\alpha'}{m} \qquad a = \frac{eB}{m}$$

$$P_x = \sum_k e x_k = E_x \sum_k \frac{N_k e^2/m}{\omega_k^2 - \omega^2 + 2i\beta_k\omega} = \chi E_x$$

$$(\varepsilon' - i\varepsilon'' =)\, n^2 = \varepsilon = 1 + 4\pi\chi$$





$$\frac{x}{f} = \frac{\lambda}{d} C_2$$

$$P = \frac{E}{\Delta\tau} = \frac{Ec}{C_1 \lambda} \frac{\Delta\lambda}{\lambda}$$

$C_2 = 1$ for diffr. limited beams

$C_2 > 1$ otherwise

$$I_{focus} = \frac{P}{x^2} =$$

$$x = \frac{\lambda C_2 f}{d} = \lambda C_2 F$$

$$= \frac{P}{\lambda^2 C_2^2 F^2} = \frac{B}{F^2} = \frac{E}{\lambda^3 C_1 C_2^2} \frac{1}{F^2} \frac{\Delta\lambda}{\lambda}$$

$$C_1 = \Delta\nu \Delta\tau$$

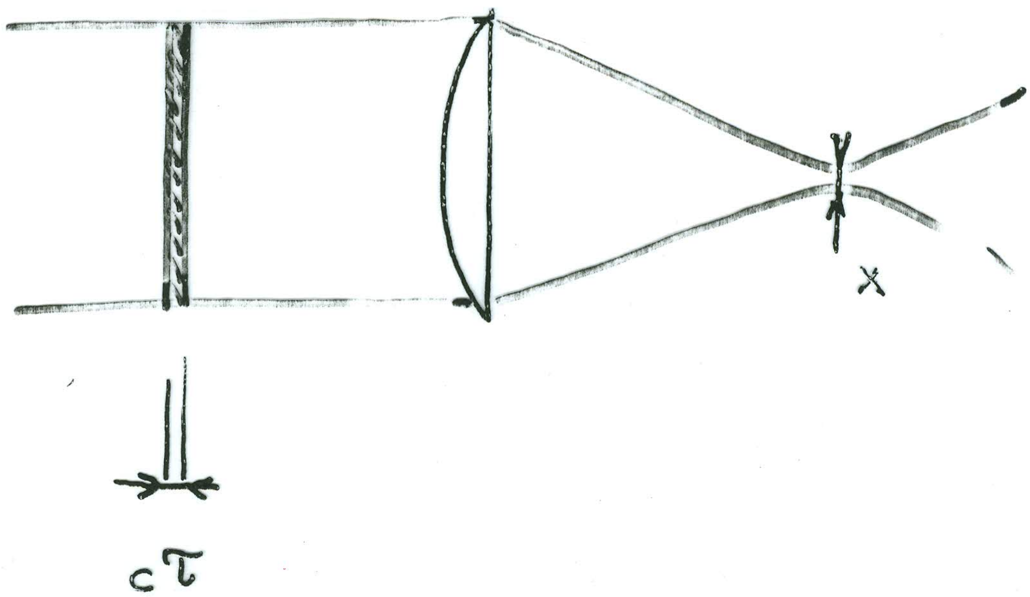
$C_1 = 1$ for transform limited pulses

$C_1 > 1$ otherwise

(Brightness) $B = \frac{P}{\lambda^2 C^2} = \frac{\rho d^2}{\lambda^2 C^2} = \frac{\rho f^2}{x^2} = \frac{\rho}{\Theta}$

$$\frac{1}{\Delta\tau} = \frac{\Delta\nu}{C_1} = \frac{c}{C_1 \lambda} \frac{\Delta\lambda}{\lambda}$$

ρ (power density) Θ (solid angle)



τ figure of merit of temporal

x spatial

concentration

both τ and x are dependent on λ and on the coherence properties of the radiation

Potential advantages of short-wavelength lasers

potential possibility for shorter pulse length

for a fixed $\frac{\Delta\lambda}{\lambda} \left(= \frac{\Delta\nu}{\nu}\right)$

Temporal concentration $\sim \nu$

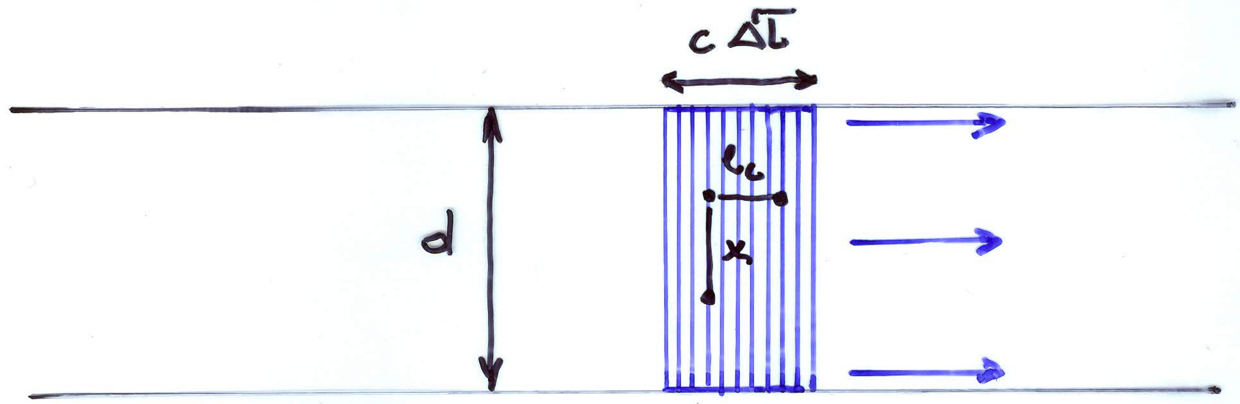
better focusability

spatial concentration $\sim \nu^2$

$$\boxed{I \sim E\nu^3}$$

This scaling is only true, if the pulse has the maximum quality allowed by uncertainty principle and diffraction.

Fényimpulzus rendezettsége
(koherencia)



térbeli (időbeli) koherencia →

az impulzus egy (különböző) idejű, de különböző (azonos) térbeli pontból származó részeinek interferenciaképessége

általában: az impulzusnak a terjedésre merőleges irányba (a terjedés irányába) eső pontjainak interferenciaképessége

Abszolút mennyiségek: x, l_c [cm]

$\left(l_c = \frac{c}{\Delta\nu}\right)$

Relatív mennyiségek: $\frac{x}{d}$, $\frac{l_c}{c\Delta t}$ [1]

$$\Delta t\, \Delta\nu \geq 1$$

$$c\Delta t \geq \frac{c}{\Delta\nu} \left(= l_c\right)$$

maximális rendezettség, ha:

$\frac{x}{d} = 1$ diffrakció - limitáltság

$\frac{l_c}{c\Delta t} = 1$ transzformáció - limitáltság

A sugárzás kvantummechanikai alapjai

$$P = \frac{16\pi^4}{3c^3} M^2 \nu^4$$

P sugárzási teljesitmény

M dipolmomentum

ν a rezgés frekvenciája

Atomok stacionárius és átmeneti dipolmomentuma

Klasszikus felfogás

$$M = -er$$

Kvantummechanika

E_j energiájú stacionárius állapot

$$\Psi_j = \psi_j e^{-2\pi i \frac{E_j}{h} t}$$

$\psi_j^{x}\psi_j\, dV$ tartózkodási valószinüség

$-er\,\psi_j^{*}\psi_j\, dV$ dipolmomentum (maggal együtt)

$$M_{stac} = -e\int \psi_j^{*}\, r\, \psi_j\, dV = -e\int \psi_j^{x}\, r\, \psi\, dV$$

időben állandó!

átmeneti dipolmomentum

$$M_{jk} = e\int \psi_j^{+}\, r\, \psi_k\, dV_z$$

$$= -e\int \psi_j^{*}\, r\, \psi_k\, dV e^{2\pi i \frac{E_j - E_k}{h} t}$$

$$= M_{jk}^{o}\, e^{2\pi i \nu_{jk} t}$$

időben ν_{jk} frekvenciával rezeg

$$M_o \rightarrow M_{jk} + M_{jk}^{*} = |M_{jk}|(e^{i 2\pi \nu_{jk} t} + e^{-i 2\pi \nu_{jk} t}) =$$

$$= 2\,|M_{jk}^{o}| \cos 2\pi \nu_{jk} t$$

atomhalmaz és sugárzási tér termikus egyensúlya

$$P_s = N_j A_{jk} h\nu_{jk}$$

$$P_i = N_j B_{jk}\, w(\nu_{jk})\, h\nu_{jk}$$

$$P_a = N_k B_{kj}\, w(\nu_{jk})\, h\nu_{jk}$$

$$P_s + P_i = P_a$$

$$N_j\left[A_{jk} + B_{jk}\, w(\nu_{jk})\right] = N_k B_{kj}\, w(\nu_{jk})$$

$$\frac{N_j}{N_k} = \frac{g_j}{g_k} e^{-(E_j - E_k)/kT}$$

$$\Downarrow$$

$$w(\nu_{jk}) = \frac{A_{jk}/B_{jk}}{\frac{B_{kj} g_k}{B_{jk} g_j} e^{\frac{h\nu_{jk}}{kT}} - 1}$$

$$\Downarrow$$

$$B_{kj} g_k = B_{jk} g_j$$

$$\frac{A_{jk}}{B_{jk}} = \frac{8\pi h \nu^3}{c^3}$$

$$M_{jk} = -e\int \psi_j \, r \, \psi_k \, dV = -e\int \psi_i \, r \, \psi_k \, dV \, e^{2\pi i \frac{E_j - E_k}{h}t}$$

Az Einstein - féle átmeneti valószínűségek

$j \rightarrow k$ spontán átmenetek száma

arányos: $N_j A_{jk}$

(A: átmeneti valószínűség)

$$P = N_j A_{jk} h\nu_{jk} \qquad P = N_j \frac{64\pi^4}{3c^3}\nu_{jk}^4 |M_{jk}^0|^2$$

$$\boxed{A_{jk} = \frac{64\pi^4}{3hc^3}\nu_{jk}^3 |M_{jk}^0|^2}$$

indukált emisszió, abszorpció

arányos

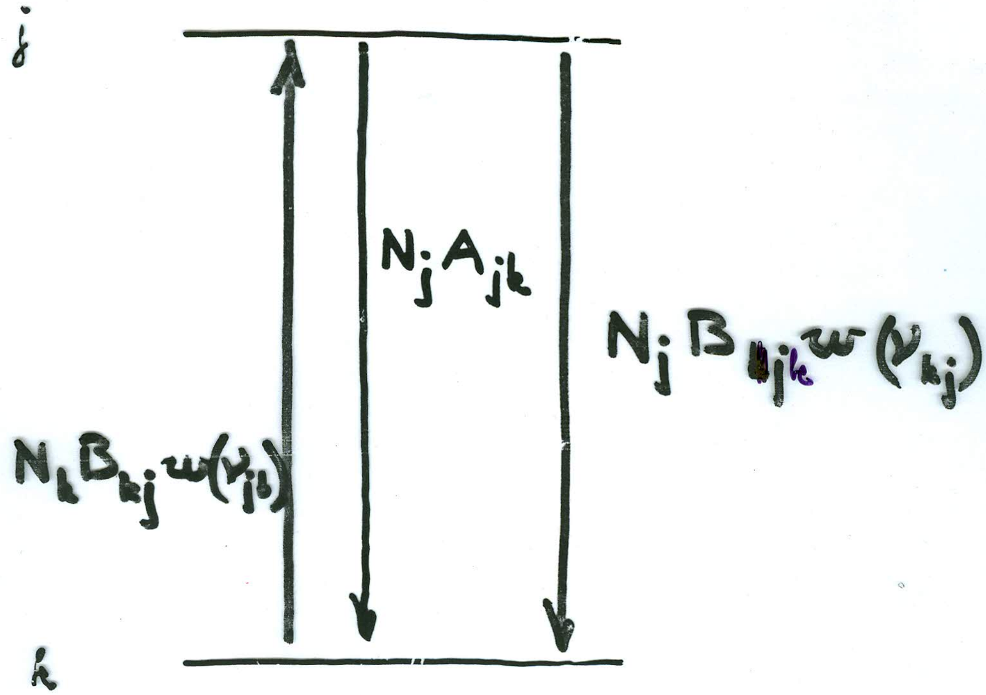
$$N_j B_{jk} w(\nu_{jk}) \qquad N_k B_{kj} w(\nu_{jk})$$

B_{jk} indukált emissziós átmeneti valószínűség

B_{kj} abszorpciós — " — — " —

$$g_j B_{jk} = g_k B_{kj}$$

$$B_{jk} = \frac{c^3}{8\pi h \nu_{jk}^3} A_{jk} \Rightarrow \boxed{B_{jk} = \frac{8\pi^3}{3h^2} |M_{jk}^0|^2}$$



B_{kj} abszorpciós valószinüség

A spontán átmeneti valószinüség

$$A_{jk} = \frac{64\pi^4}{3hc^3} \nu_{jk}^3 \, |M_{jk}|^2$$

B_{jk} indukált emissziós átmeneti valószinüség

ha $g_j = g_k \Rightarrow B_{jk} = B_{kj}$

$$B_{jk} = \frac{c^3}{8\pi h \boxed{\nu_{jk}^3}} A_{jk}$$

$$\frac{dN}{dt} = -\left(N_k B_{kj} - N_j B_{jk}\right)w$$

$$\frac{h\nu}{Vc}\frac{dN}{dt} = -\left(N_k B_{kj} - N_j B_{jk}\right)\frac{h\nu}{c}\frac{1}{V}w$$

$$n_o = \frac{N_k}{V} \qquad \sigma_a = \frac{h\nu}{c}B_{kj}$$

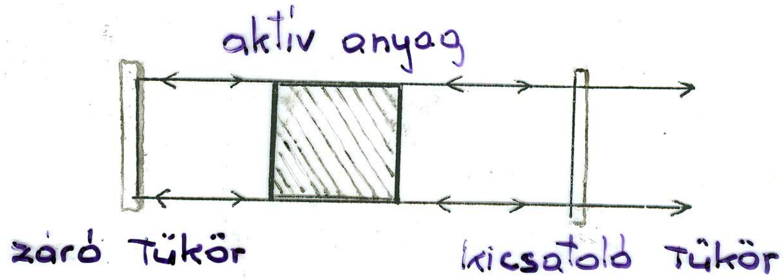
$$n_1 = \frac{N_j}{V} \qquad \sigma_e = \frac{h\nu}{c}B_{jk}$$

$$dx = cdt$$

$$\frac{dw}{dx} = -\left(n_0\sigma_a - n_1\sigma_e\right)w$$

$$\frac{dI}{dx} = -\left(n_0\sigma_a - n_1\sigma_e\right)I$$

Hagyományos lézerek



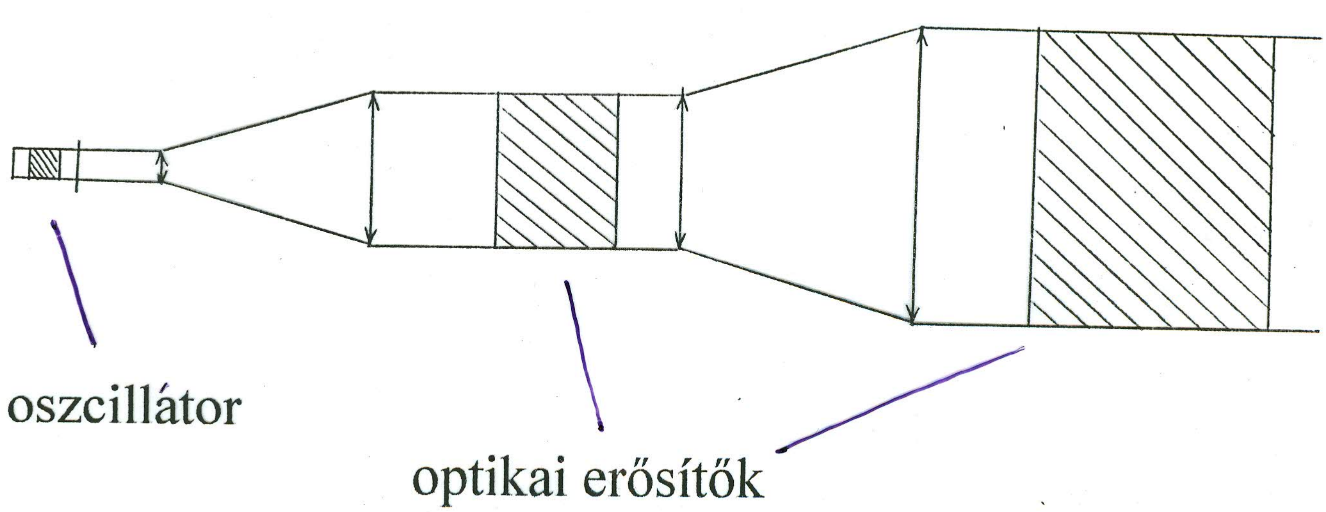
a nagy tér és időbeli koherenciájú nyaláb kialakulásához sok körbejárás szükséges

$$A_{jk} = \frac{8\Pi h\nu^3}{c^3} B_{jk}$$

$$\Downarrow$$

$$(A = \frac{1}{\tau}) \qquad \tau \sim \frac{1}{\nu^3}$$

rövid hullámhosszakon
az energia jó tér és időbeli koncentrálására alkalmas lézerek <u>más felépítésűek</u>



Rövid hullámhosszú lézerek specifikus problémái

fizikai

$$B_{jk} \sim \frac{1}{\nu^3_{jk}} A_{jk}$$

σ_{em} "nagy" $\Rightarrow$ ε_{sat} "kicsi"

g "nagy"

$\tau_{exc.\ state}$ "rövid" $\Rightarrow$ energia tároló képesség rossz

"pumpálás" nehezebb

technikai

diszperzió

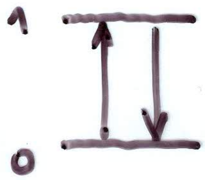
abszorpció

nemlineáris tulajdonságok

Gerjesztés : optikai pumpálás

2. szintes rendszer

$$\frac{dn_1}{dt} = I_p \sigma_a n_0 - I_p \sigma_e n_1 - \frac{n_1}{\tau}$$

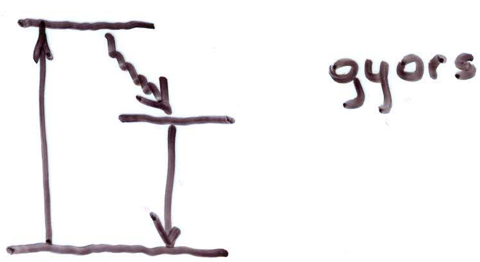


stac. eset : $\frac{dn_1}{dt} = 0$

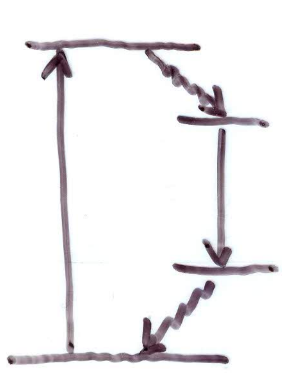
$$I_p \sigma_a n_0 = I_p \sigma_e n_1 + \frac{n_1}{\tau}$$

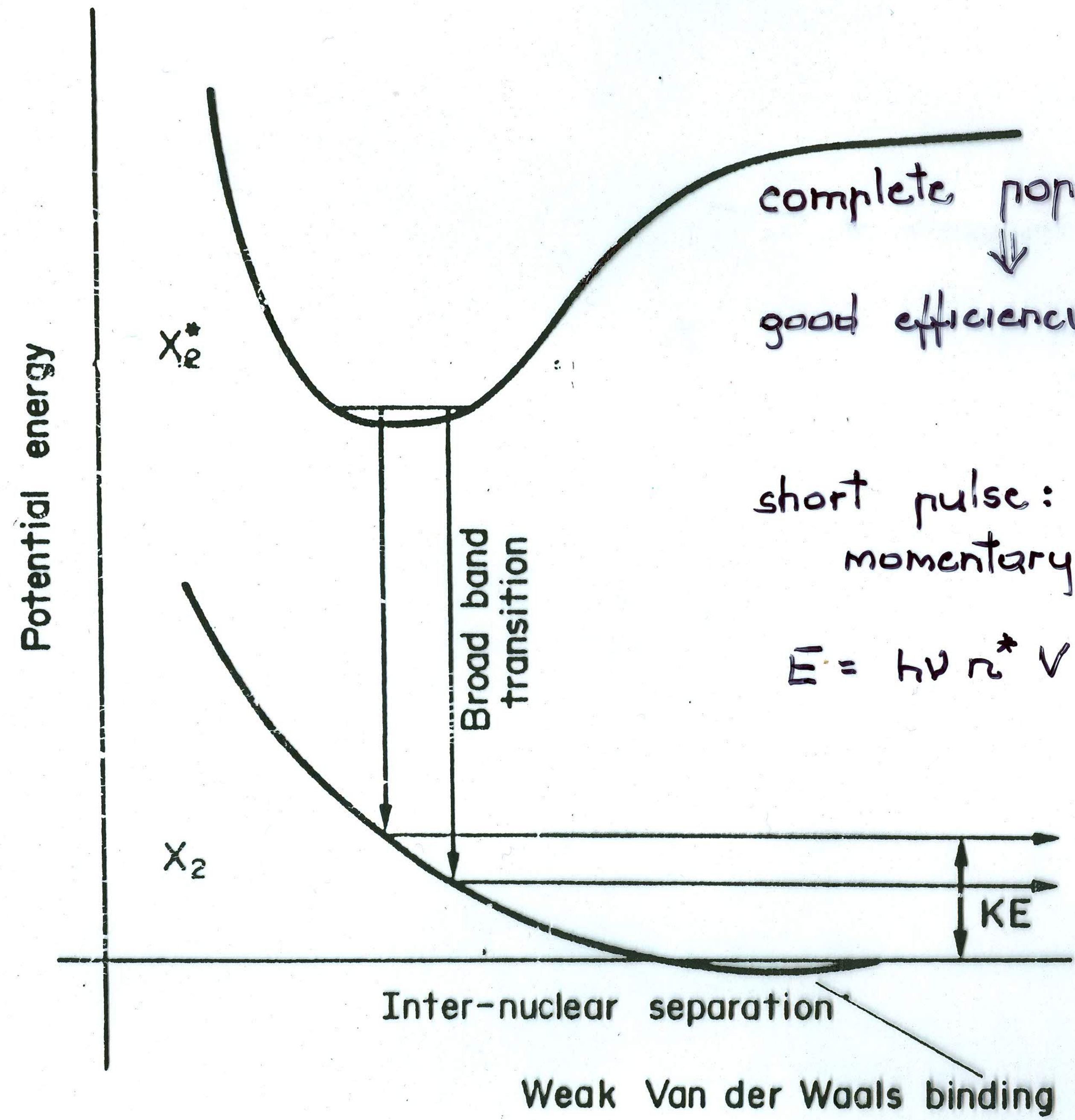
$$\frac{n_1}{n_0} = \frac{1}{1 + \frac{1}{I_p \sigma_a \tau}} < 1 \quad \text{(abszorpcio)}$$

3. szintes rendszer



4. szintes rendszer





complete population inversion

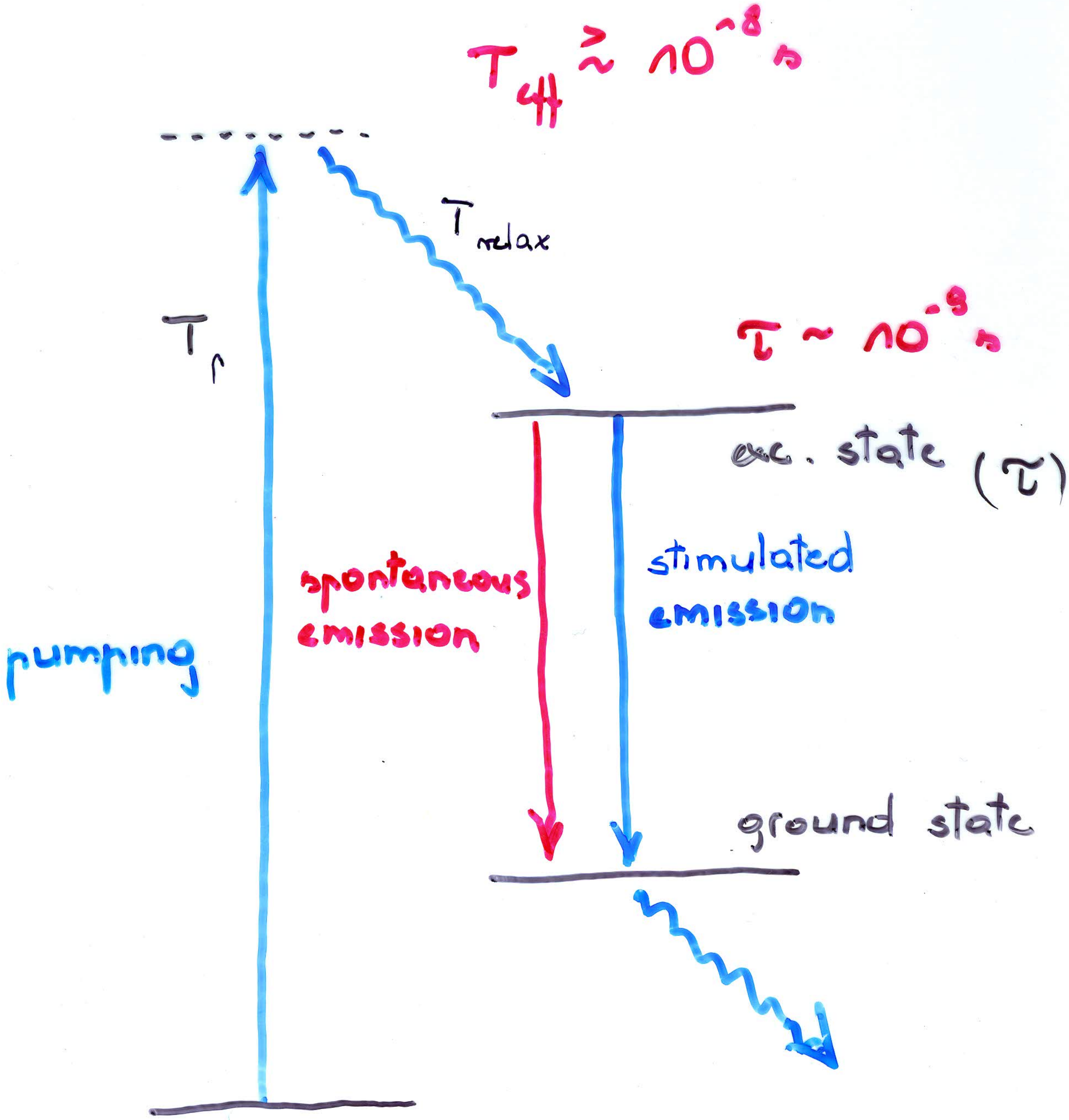
⇓

good efficiency for long pulses

short pulse:
momentary extractable energy

$E = h\nu n^* V$

FIG. 1. Potential energy curves for a typical excimer molecule.



$T_{eff} \gtrsim 10^{-8}$ s
T_{relax}
$\tau \sim 10^{-8}$ s
T_r
exc. state (τ)
spontaneous emission
stimulated emission
pumping
ground state

A "telítés" fogalma

Telítődő abszorpció

$$n_0 + n_1 = n$$

n_1 ———

n_0 ———

$$\frac{dn_1}{dt} = I\sigma_a n_0 - \frac{n_1}{\tau}$$

$$\frac{dn_1}{dt} = I\sigma_a (n - n_1) - \frac{n_1}{\tau}$$

stac. eset: $\frac{dn_1}{dt} = 0$ $\qquad n_1 = n \frac{1}{1 + \frac{1}{\tau \sigma_a I}}$

telítési intenzitás: $I_T = \frac{1}{\tau \sigma_a}$

$$n_1 = n \frac{1}{1 + \frac{I_T}{I}} \qquad n_0 = n\left(1 - \frac{1}{1 + \frac{I_T}{I}}\right)$$

$$dI = -I\sigma_a n_0 \, dx = -I\sigma_a n \left(1 - \frac{1}{1 + \frac{I_T}{I}}\right) dx$$

$$\frac{dI}{dx\, I} \neq \text{const}$$

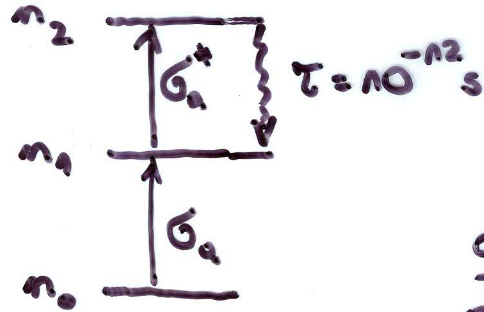
ha $I \ll I_T$ $\quad \frac{dI}{I\,dx} = -\sigma_0 n$ (klasszikus eset)

ha $I \approx I_T$ $\quad \frac{dI}{I\,dx} = -\frac{\sigma_0 n}{2}$ $\quad (\times \, ^1\!/_2)$

ha $I \to \infty$ $\quad \frac{dI}{I\,dx} \to 0$ $\quad (T \to 1)$

Többszintes eset

(nem telítődő gerjesztett-szint-abszorpció)



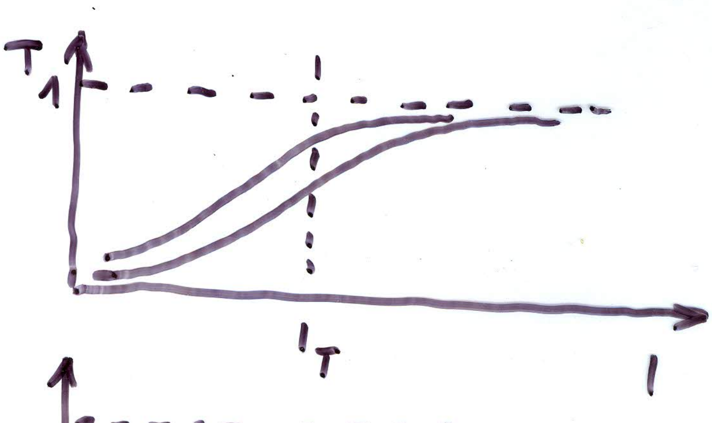
$$n_0 = n - n_1$$

$$\frac{dI}{dx} = -I\left(\sigma_a n_0 + \sigma_a^* n_1\right) =$$

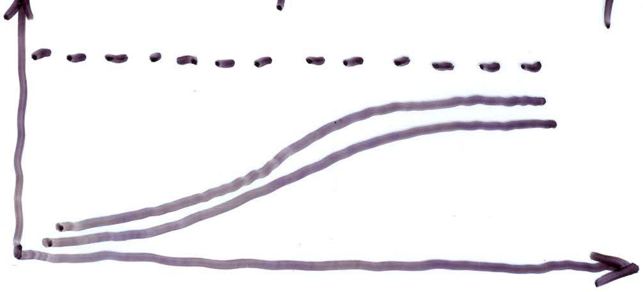
$$= -I\left(\sigma_a n - \sigma_a n_1 + \sigma_a^* n_1\right) =$$

$$= -In\underbrace{\left(\sigma_a - \sigma_a \frac{1}{1+\frac{I_T}{I}} + \sigma_a^* \frac{1}{1+\frac{I_T}{I}}\right)}_{\sigma_{eff} = \sigma_{eff}(I)}$$

ha $\sigma_a^* = 0$

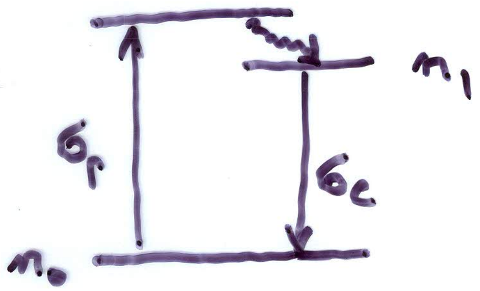


ha $\sigma_a > \sigma_a^*$



ha $\sigma_a < \sigma_a^*$

Az erősítés Telítődése



$$n_1 + n_0 = n$$

$$\frac{dn_1}{dt} = n_0 I_p \sigma_p - \frac{n_1}{\tau} - I\sigma_e n_1$$

stac. eset: $\frac{dn_1}{dt} = 0$

$$\Downarrow$$

$$n_1 = n \frac{I_p \sigma_p}{I_p \sigma_p + \frac{1}{\tau} + I\sigma_e}$$

$$\alpha = n_1 \sigma_e$$

$$\left(\frac{dI}{dx} = \alpha I \right)$$

$$n_1 \sigma_e = n \sigma_e \frac{1}{1 + \frac{1}{\tau \sigma_p I_p} + \frac{I\sigma_e}{\sigma_p I_p}}$$

ha $\frac{1}{\sigma_p I_p \tau} \ll 1$ $\qquad$ $I_T = \cancel{\frac{1}{\sigma_e \tau}} + I_p \frac{\sigma_p}{\sigma_e}$

$$\Downarrow$$

$$\alpha = \alpha_0 \frac{1}{1 + \frac{I}{I_T}}$$

ha $I \ll I_T$ $\qquad$ $dI = I\alpha_0 dx$

$$I = I_0 e^{\alpha_0 x}$$

$$\sigma_a = \frac{h\nu_{jk}}{c} B_{kj}$$

$$\sigma_e = \frac{h\nu_{jk}}{c} B_{jk}$$

$$dI = \underbrace{-(n_0\sigma_a - n_1\sigma_e)}_{\alpha} \, I \, dx$$

$\alpha > 0$ abszorpcio

$\alpha < 0$ erősítés $\Rightarrow \frac{n_1}{n_0} > \frac{\sigma_a}{\sigma_e}$

Lézerben az oszcillacio feltetele

$$I \geq I_0 R_1 R_2 e^{-2\alpha l}$$

küszöbfeltetel

$$I_0 = I_0 R_1 R_2 e^{-2\alpha l}$$

$$-\alpha = \frac{1}{2l} \ln \frac{1}{R_1 R_2}$$

Lézerek nemstacionarius elmélete

$$\frac{dn_1}{dt} = W - \frac{n_1}{\tau} - \frac{c}{n}\sigma_e n_1 I$$

$$\frac{dI}{dt} = \frac{c}{n} I \sigma_e n_1 - \frac{I}{\tau_c} + \frac{\Omega n_1}{\tau}$$

$\tau_c = ?$

τ_c fotonok átlagos élettartama

$$I = I_0 e^{-\frac{t}{\tau_c}}$$

"normál" eset

$$I_0 e^{-\frac{2\ell}{c\tau_c}} = I_0 R_1 R_2$$

$$\Downarrow$$

$$\tau_c = \frac{2\ell}{c \ln R_1 R_2}$$

elosztott visszacsatolású lézerek

$$\tau_c(t) = \frac{n L^3}{8 c \pi^2}\left[n_1(t)(\sigma_e - \sigma_a) V\right]^2$$

V = láthatoság

Rövid impulzusok erősítése

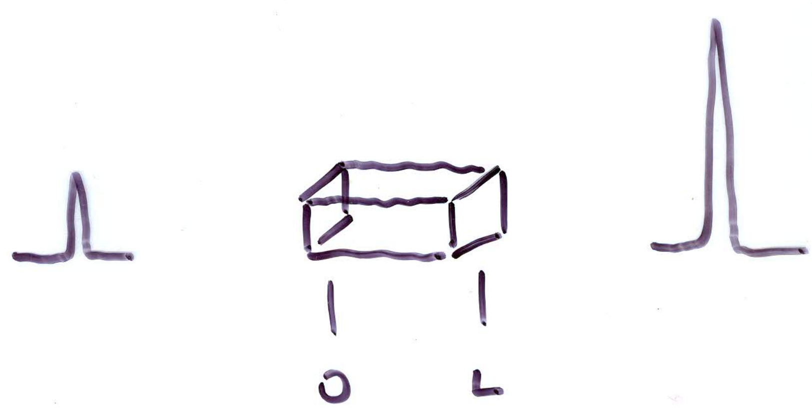
$t_{imp} \ll \tau$ spontán emisszió

$n_0 I_p \sigma_p \ll I \sigma_e n_1$ pumpálás

elhanyagolható

$$\frac{\partial I(x,t)}{\partial x} + \frac{1}{v}\frac{\partial I(x,t)}{\partial t} = n_1(x,t)\, I(x,t)\, \sigma_e$$

$$\frac{\partial n_1(x,t)}{\partial t} = - n_1(x,t)\, I(x,t)\, \sigma_e$$



$$I(t) = I_0(t) \frac{e^{z} e^{E_0(t)}}{1 + \left(e^{E_0(t)} - 1\right) e^{z}}$$

$I_0(t) = I(x=0, t)$ $I(t) = I(x=L, t)$

$z = \sigma_e \int_0^L n_1(x)\, dx$ $(t<0)$

$E_0(t) = \sigma_e \int_{-\infty}^{t} I_0(t')\, dt'$

Telítési energiasűrűség definíciója

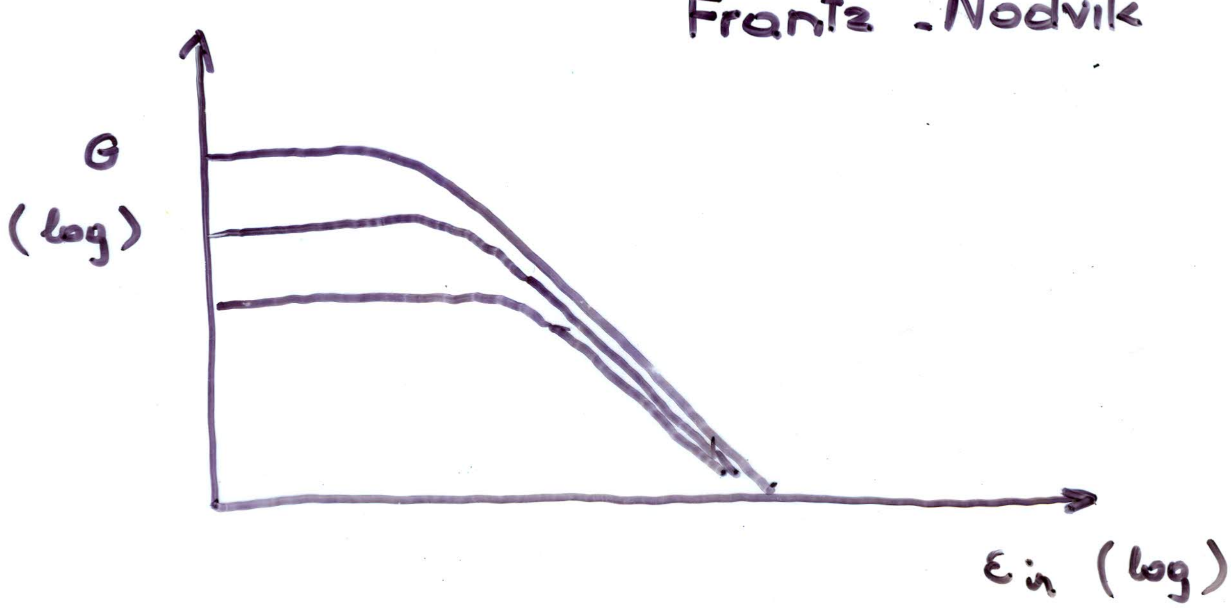
$$\mathcal{E}_{sat} = \frac{h\nu}{\sigma_{em}} \qquad \left[\frac{J}{cm^2}\right]$$

$$\mathcal{E}_{out} = \mathcal{E}_{sat} \ln \left\{ 1 + \exp z \left[\exp \frac{\mathcal{E}_{in}}{\mathcal{E}_{sat}} - 1 \right] \right\}$$

normált energiasűrűség $\quad \mathcal{E}^* = \frac{\mathcal{E}}{\mathcal{E}_{sat}}$

$$\mathcal{E}^*_{out} = \ln \left\{ 1 + \exp z \left[\exp \mathcal{E}^*_{in} - 1 \right] \right\}$$

Frantz - Nodvik



Rövid impulzusok erősítése abszorpció esetén

$$\frac{\partial I}{\partial x} + \frac{1}{v}\frac{\partial I}{\partial t} = I n_1 \sigma_e - I \alpha$$

$$\frac{\partial n_1}{\partial t} = - I n_1 \sigma_e$$

$$\left(g(x) = \sigma_e n_1(x) \right)$$

$$\Downarrow$$

$$\frac{d\varepsilon^*}{dx} + \alpha \varepsilon^* + g_0 e^{-\varepsilon^*} = g_0$$

$\alpha = 0 \quad \Rightarrow$ Frantz - Nodvik formula

(1. ábra)

$\alpha \neq 0$

$$\lim_{x \to \infty} \varepsilon^* = \frac{g_0}{\alpha}$$

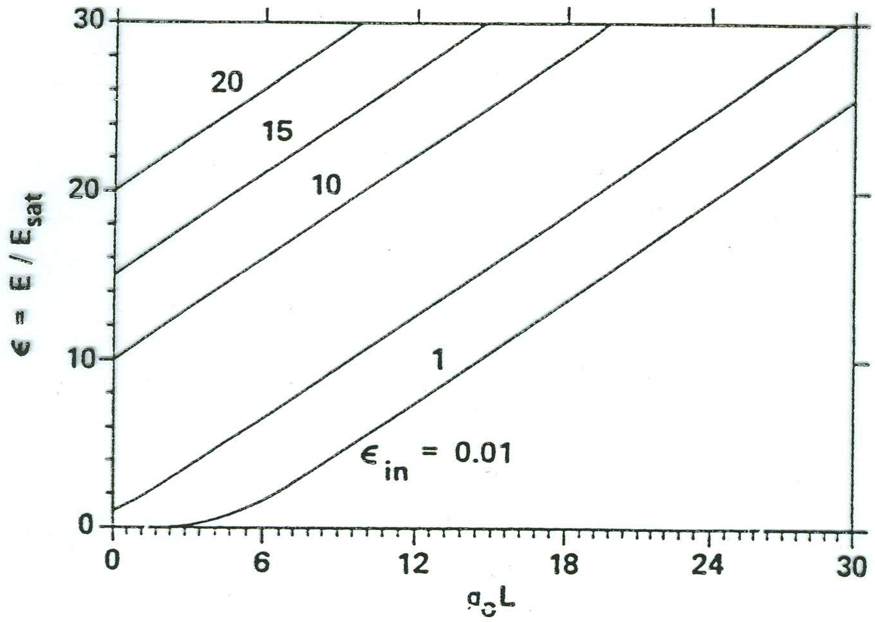
(2. ábra)

"helyi" hatásfok : $\eta(\varepsilon^*) = \frac{1}{g_0}\frac{d\varepsilon}{dx}$

$$\eta_{max} = 1 - \alpha/g_0 \left[1 + \ln(g_0/\alpha) \right]$$

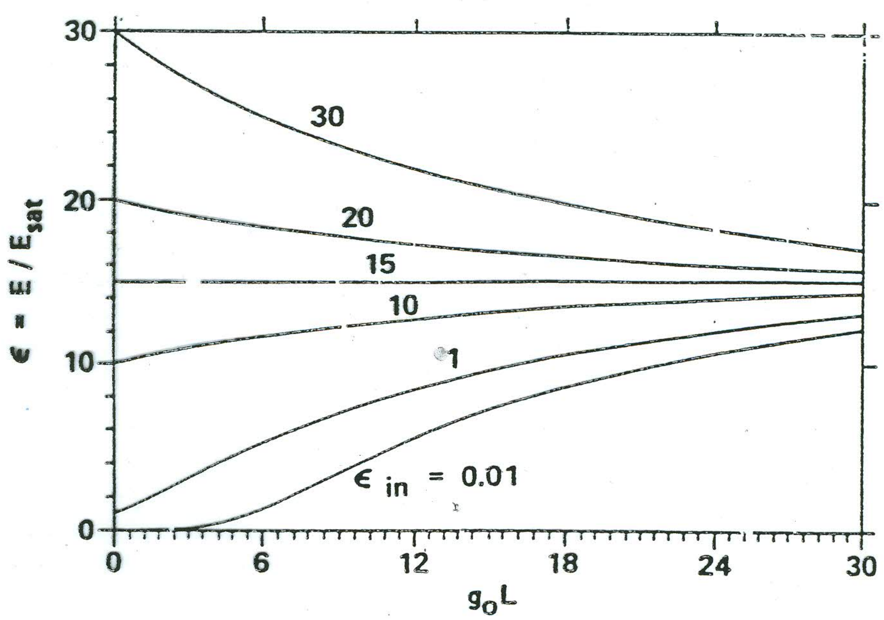
$$\varepsilon^* = \ln(g_0/\alpha)$$

Spatial development of the energy (density) in amplifiers



$\alpha = 0$

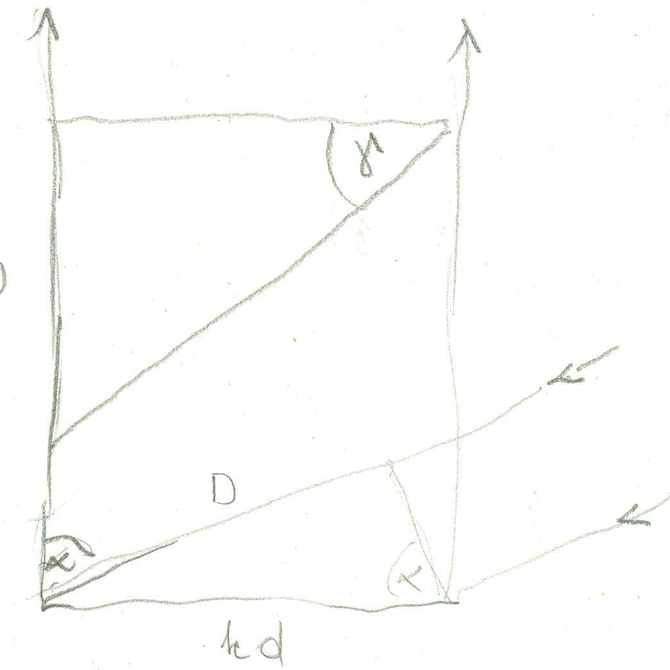
FIG. 1. Normalized laser energy in an amplifier vs total gain in a medium, with no absorption.



$\frac{g_0}{\alpha} = 15$

FIG. 2. Normalized laser energy in an amplifier vs total gain in a medium with absorption of $\alpha = g_0/15$. Convergence takes place at $E/E_{sat} = 15$ for large g_0L, as predicted by the analysis.

Tilt of the Pulse-front after a grating



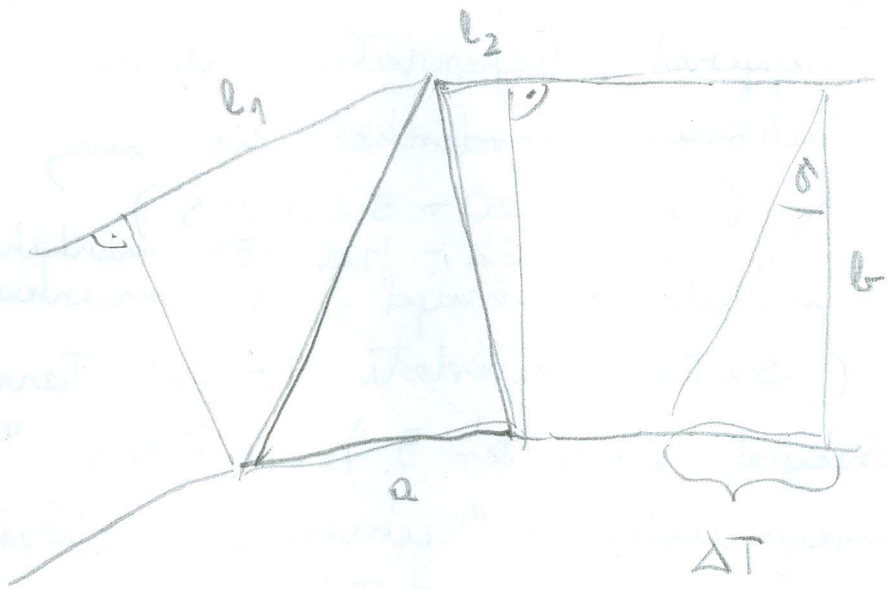
$$D = kd \sin\alpha \qquad \frac{d\varepsilon}{d\lambda} = \frac{1}{d\cancel{\cos\beta}} = \frac{1}{d}$$

$$d(\sin\alpha + \cancel{\sin\beta}) = \lambda \qquad \beta \text{ legyen } 0$$

$$d\sin\alpha = \lambda$$

$$\operatorname{tg}\gamma = \frac{D}{kd} = \frac{kd\sin\alpha}{kd} = \sin\alpha = \frac{\lambda}{d} = \lambda\frac{d\varepsilon}{d\lambda}$$

Tilt of the pulse-front after a prism



$$\frac{l_1}{c} + \frac{l_2}{c} = \frac{an}{c}$$

$$v_g = \frac{c}{n - \lambda \frac{dn}{d\lambda}}$$

$$n_g = n - \lambda \frac{dn}{d\lambda}$$

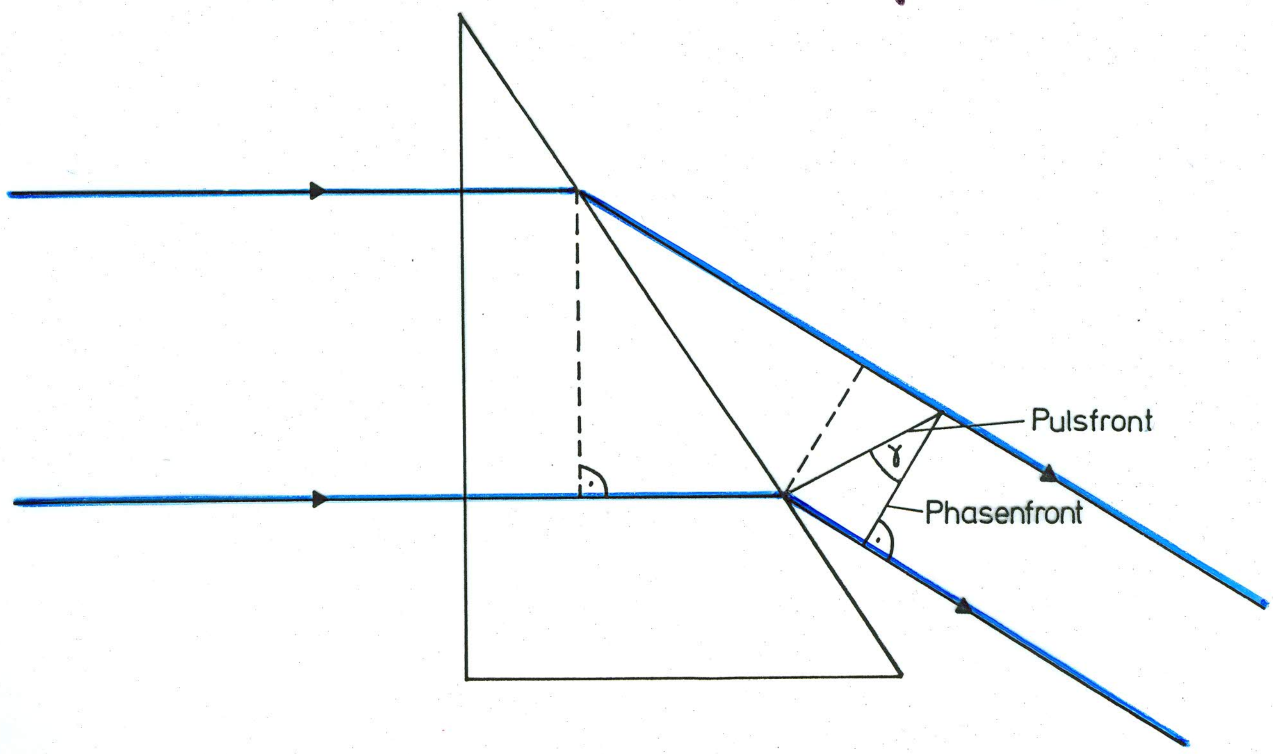
$$\Delta T = \frac{a}{c} \; \lambda \frac{dn}{d\lambda}$$

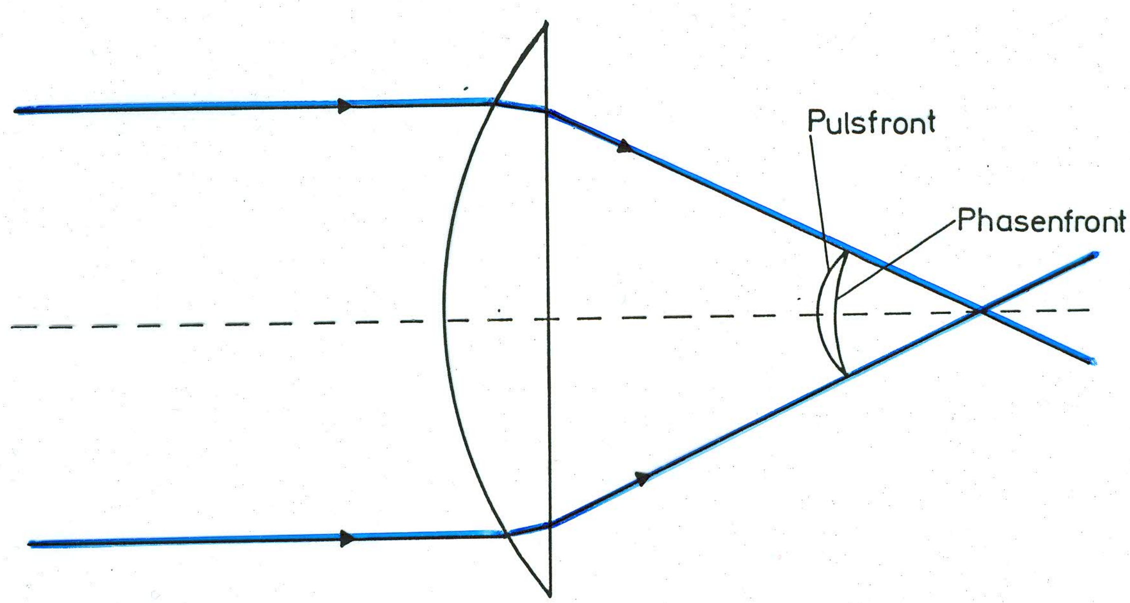
$$\operatorname{tg} \gamma = \frac{a}{b} \frac{dn}{d\lambda}$$

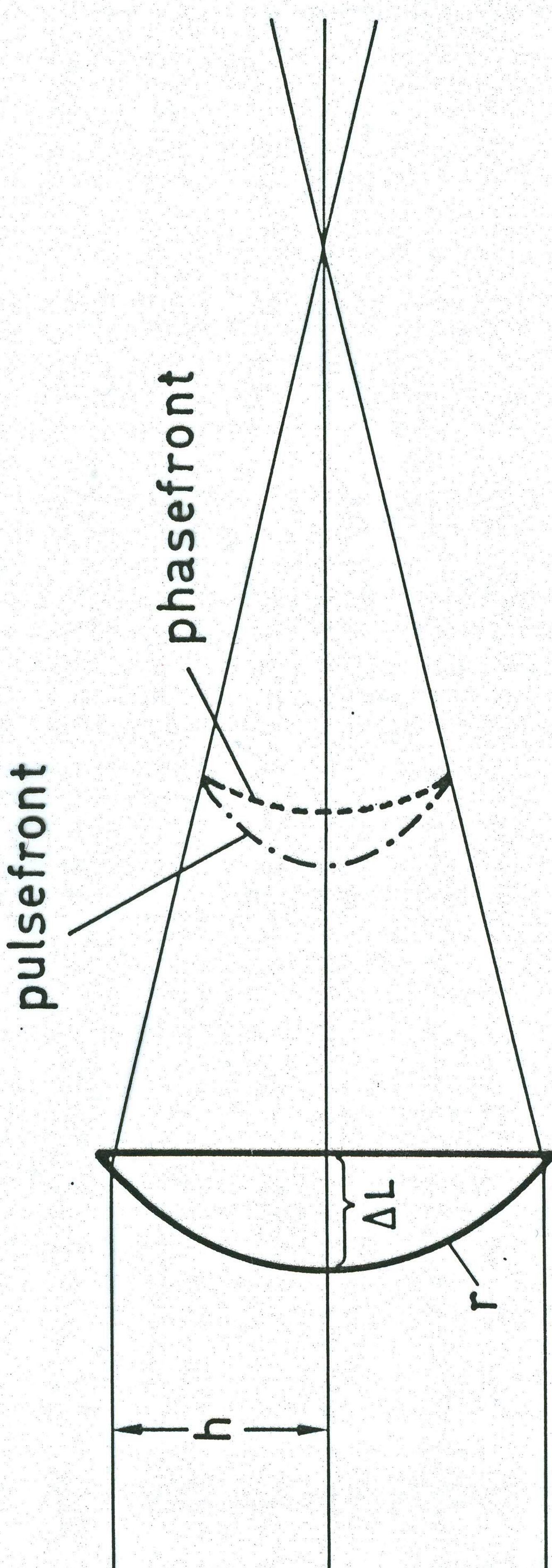
$$\frac{d\varepsilon}{d\lambda} = \frac{a}{b} \frac{dn}{d\lambda}$$

$$\operatorname{tg} \gamma = \lambda \frac{d\varepsilon}{d\lambda}$$

Spatially dependent distortion of the pulse front and pulse duration







S. Szatmári, G. Kühnle: Pulse
Front and Pulse Duration ...
Fig. 1

Pulse front delay

the time difference (ΔT) between the phase and pulse fronts

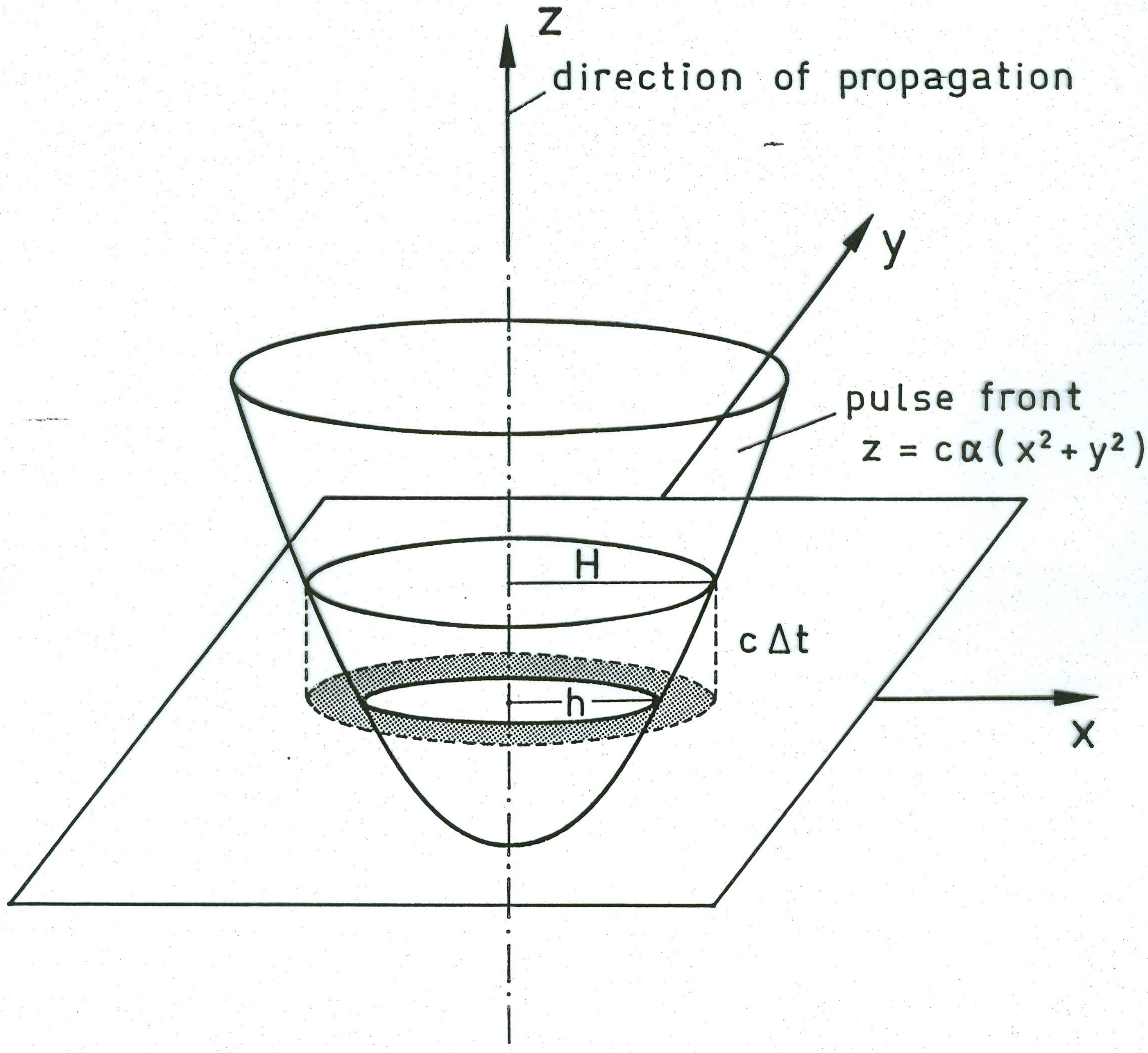
$$\Delta T = \frac{\lambda}{c} \Delta L \frac{dn}{d\lambda}$$

for a single thin lens:

$$\Delta T = \frac{\lambda}{c} \frac{h^2}{2} \frac{1}{r} \frac{dn}{d\lambda}$$

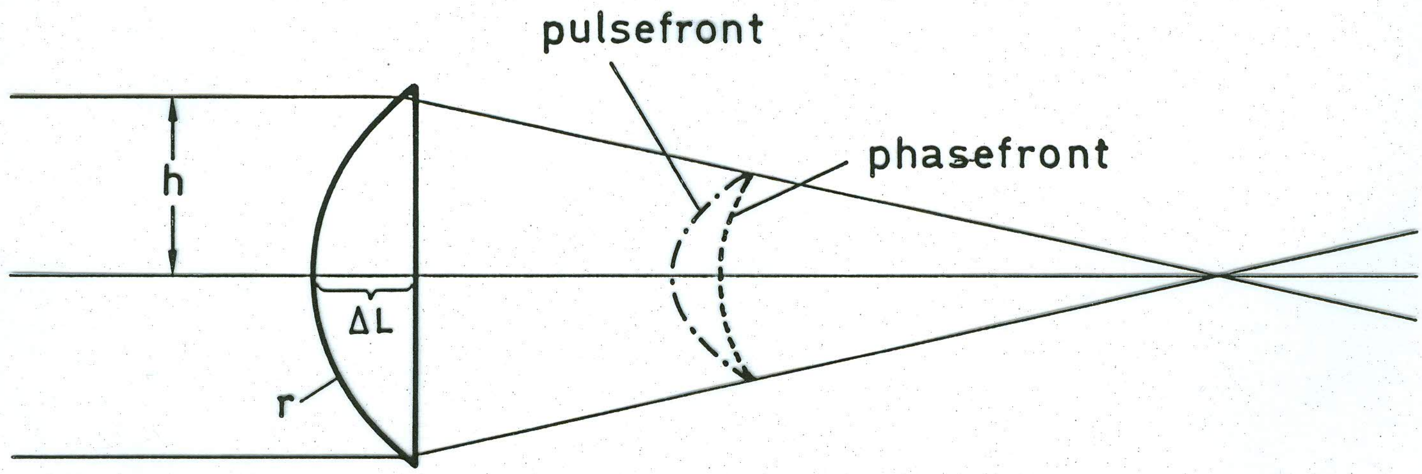
for a lens system:

$$\Delta T = \frac{\lambda}{c} \frac{h^2}{2} \sum_i \frac{1}{r_i} \frac{dn_i}{d\lambda}$$



z
direction of propagation
y
pulse front
z = cα(x² + y²)
H
c Δt
h
x

$$\Delta T = -\frac{\lambda}{c}\ \Delta L\ \frac{dn}{d\lambda}\ , \tag{1}$$



$h/r \ll 1$

$$\Delta L = r\left[1 - \sqrt{1 - \left(\frac{h}{r}\right)^2}\ \right] \approx \frac{h^2}{2r}\ . \tag{2}$$

Kepler telescope

$$\Delta L = \frac{h_{in}^2}{2r_{in}} + \frac{h_{out}^2}{2r_{out}} = \frac{h_{in}^2}{2r_{in}}(1 + M)$$

Galilean telescope

$$\Delta L = \frac{h_{in}^2}{2r_{in}}(1 - M) \qquad (r_{in} < 0 \text{ for } M > 1)$$

By combining eqs. (1) and (2)

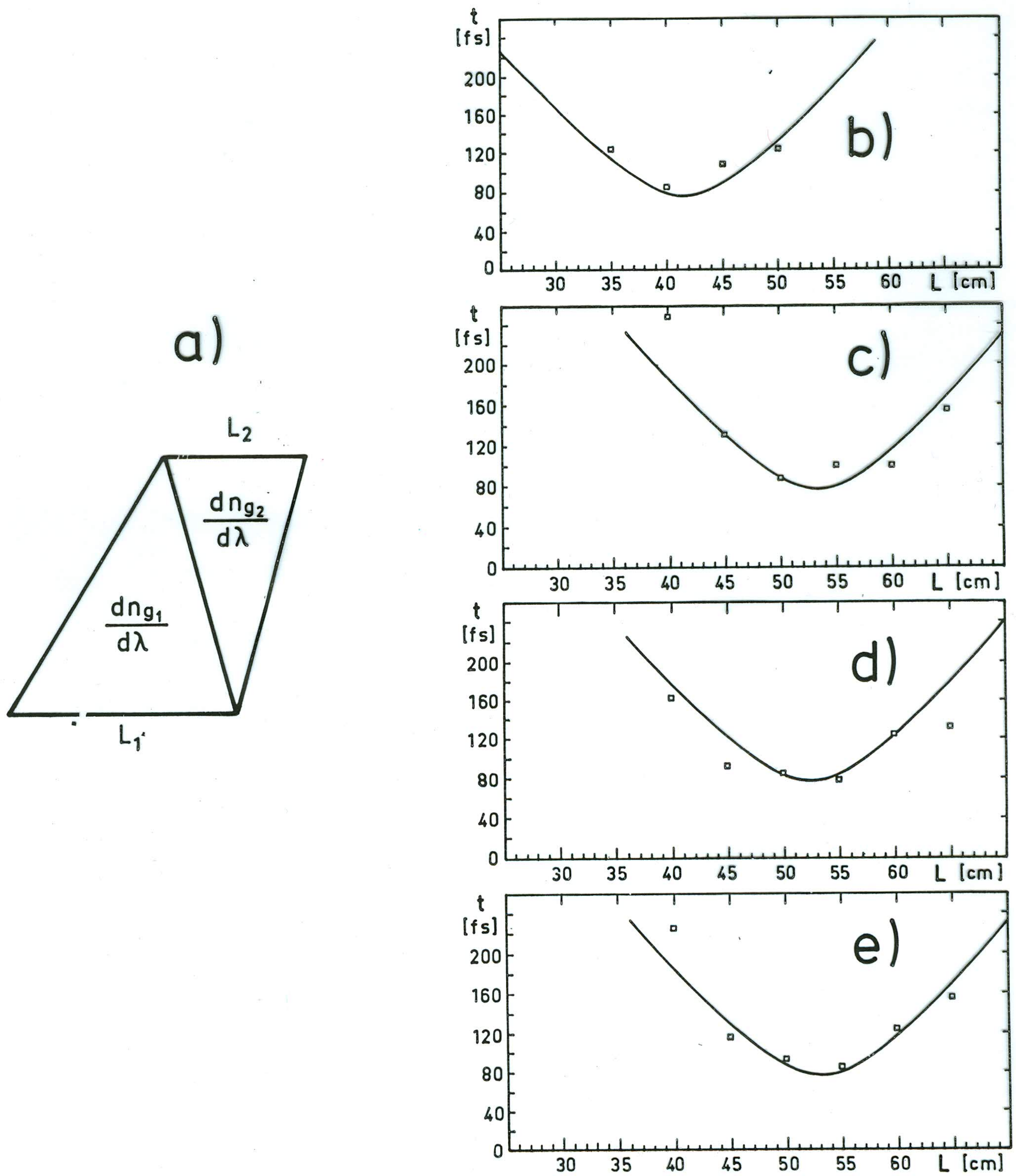
$$\Delta T = -\frac{\lambda}{c}\ \frac{h^2}{2}\ \frac{1}{r}\ \frac{dn}{d\lambda}\ .$$

For a lens system

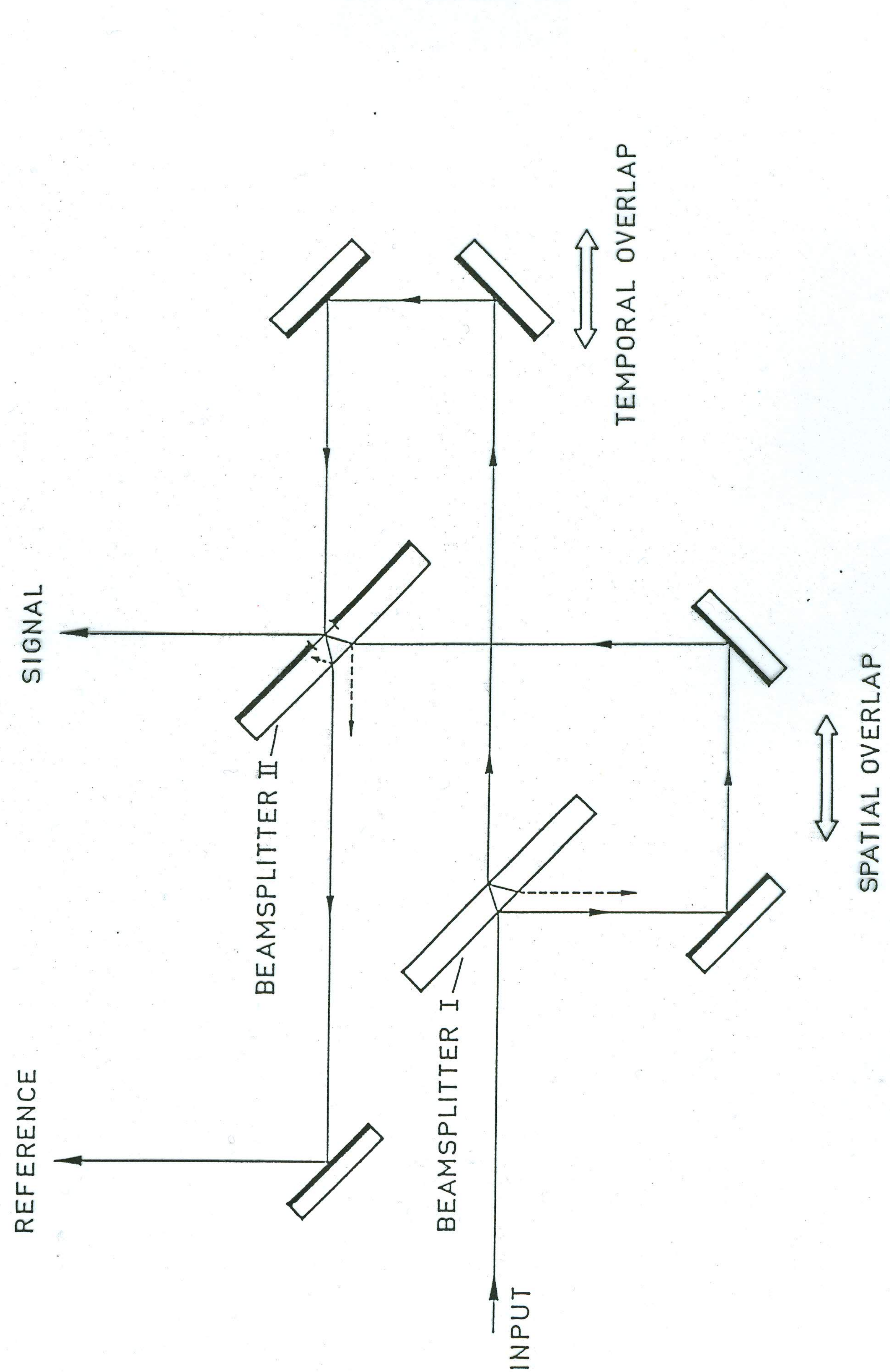
$$\Delta T = -\frac{\lambda}{c}\ \frac{h^2}{2}\ \sum_i \frac{1}{r_i}\ \frac{dn_i}{d\lambda}\ .$$

For a perfect lens system ΔT has to be zero, consequently

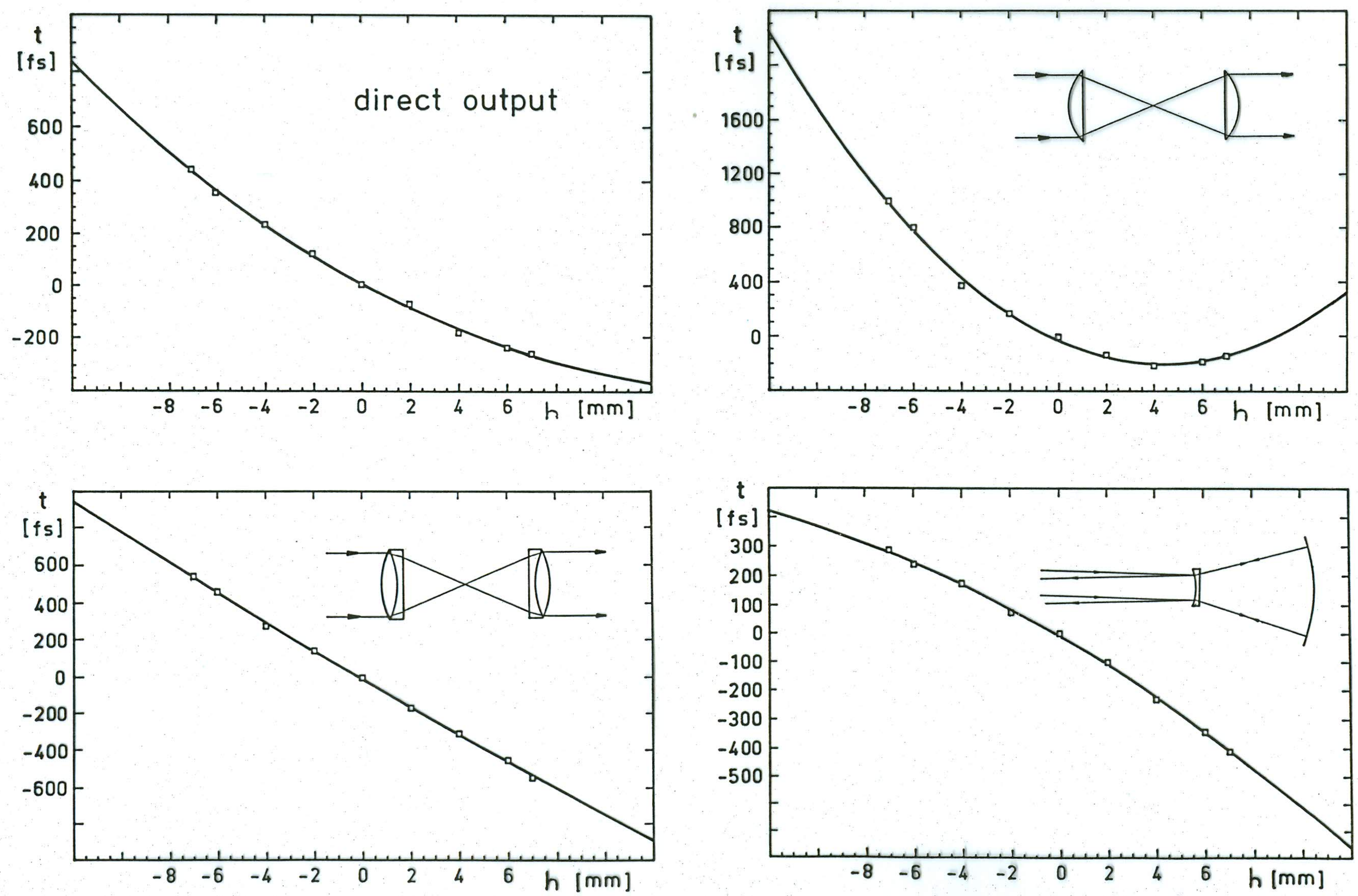
$$\sum_i \frac{1}{r_i}\ \frac{dn_i}{d\lambda} = 0\ .$$



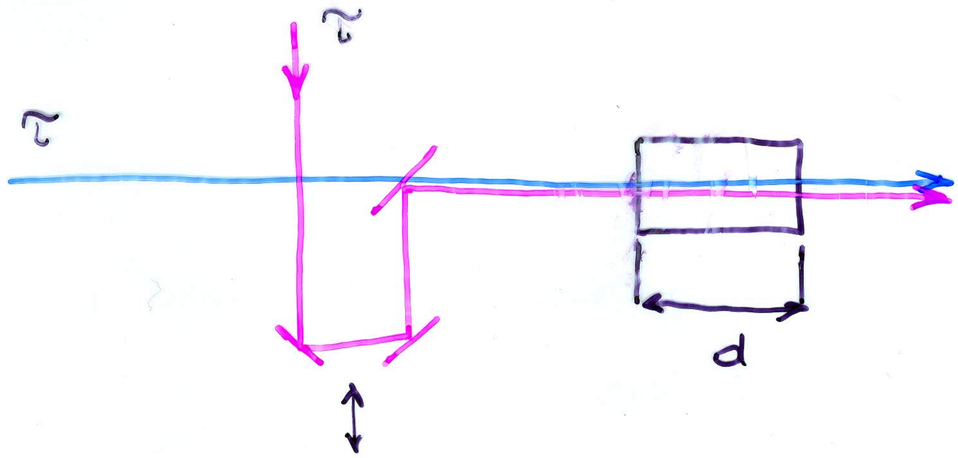
S. Szatmári, G. Kühnle: Pulse Front and Pulse Duration ...
Fig. 7



Szatmári/Kühnle/Jasny/Schäfer: KrF
Laser System with Corrected Pulse
Front ...
Fig. 5


t [fs]
600
400
200
0
-200
-8 -6 -4 -2 0 2 4 6 h [mm]
direct output
t [fs]
1600
1200
800
400
0
-8 -6 -4 -2 0 2 4 6 h [mm]
t [fs]
600
400
200
0
-200
-400
-600
-8 -6 -4 -2 0 2 4 6 h [mm]
t [fs]
300
200
100
0
-100
-200
-300
-400
-500
-8 -6 -4 -2 0 2 4 6 h [mm]

⑥ GVD-compensated propagation



pump-probe arrangements:

d is a trade-off between

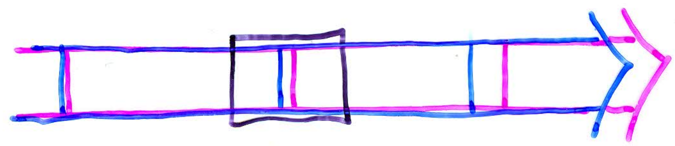
sensitivity

⇕

temporal resolution (T)

$T \sim \tau$

τ is increased by GVD

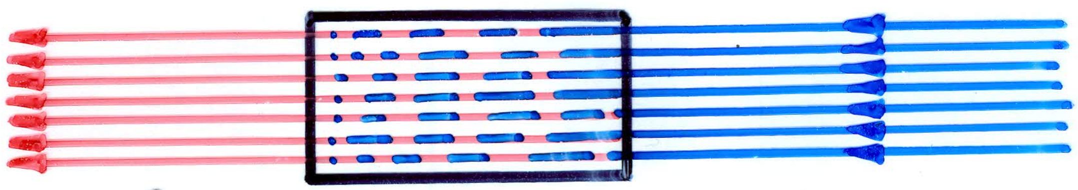


GVD compensation ?

1. exact synchronism of the pump pulse to the generated pulse,
2. pulse compression of the pump pulse to get minimum pulse duration at the target,
3. avoidance of spatially dependent distortion of the pulse front and pulse duration.

Conventional pump-probe arrangement

Longitudinal pumping of TWE ASE



mismatch between the pump and the generated (or transmitted) pulse

$$\Delta\tau = \frac{L}{c}(\eta_L - \eta_P)$$

if $\Delta\tau < \tau$

for $\lambda_P = 248$ nm $\quad \lambda_L = 340$ nm

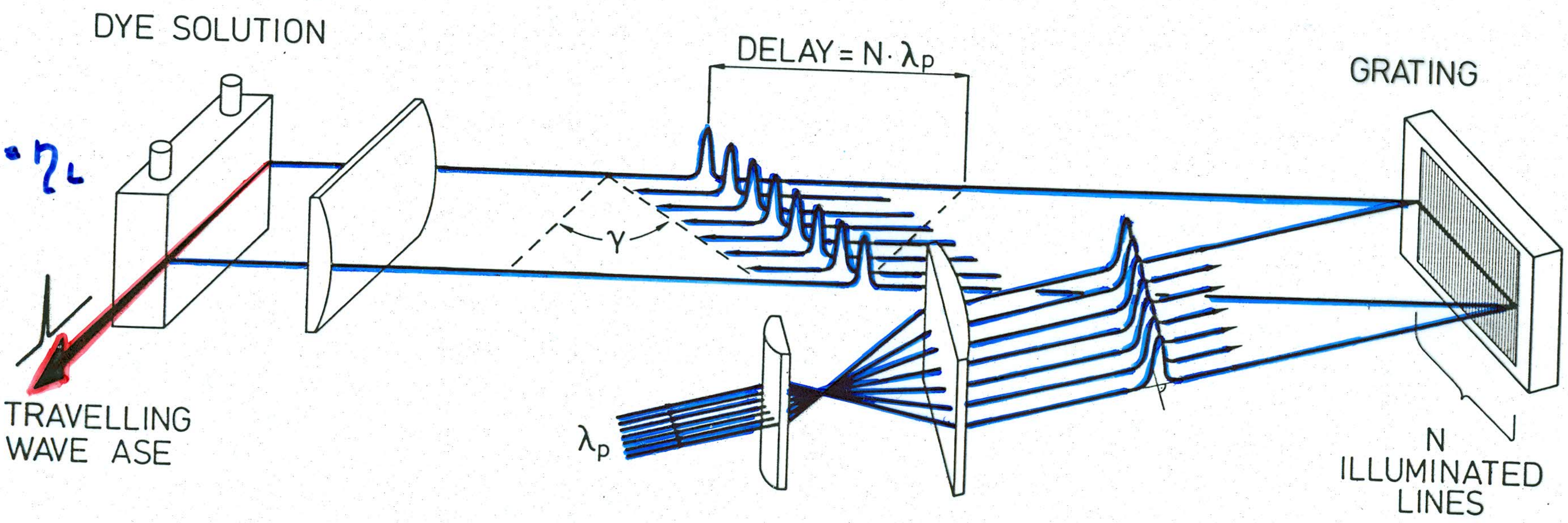
$\tau = 100$ fs $\quad L < 0.3$ mm !

$\tau = 10$ fs $\quad L < 0.03$ mm !!

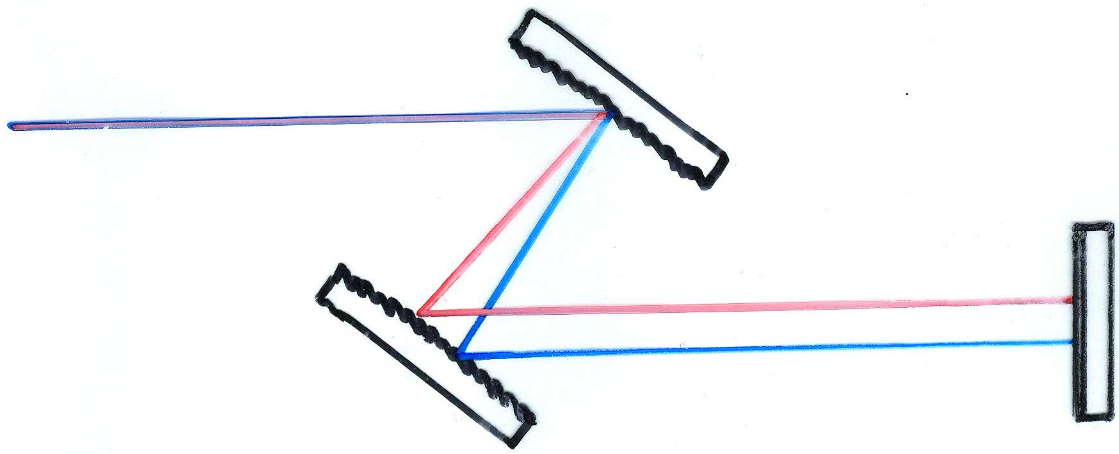
TWE

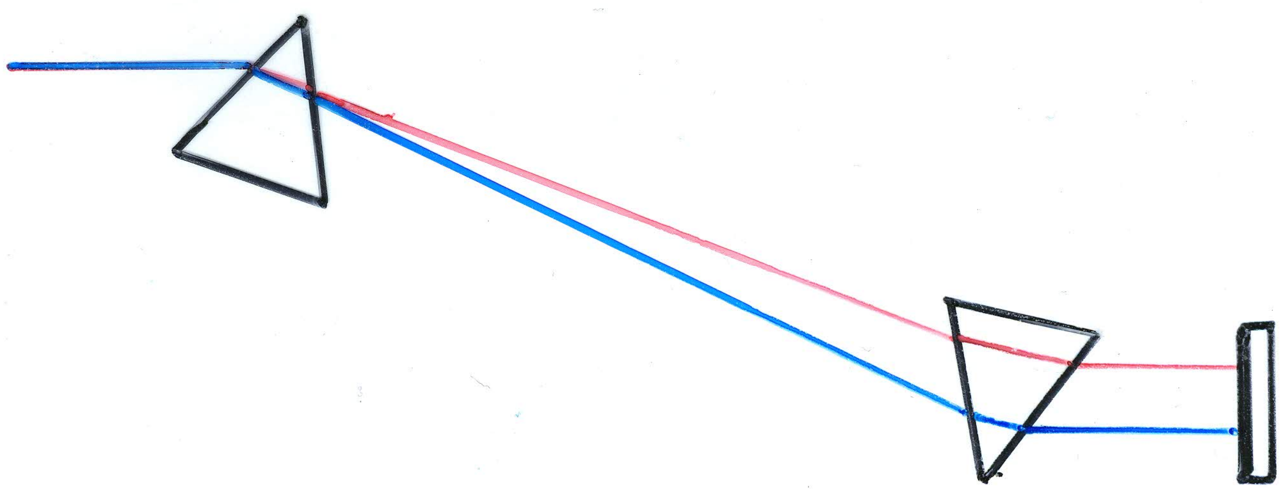
Transversal pumping

$\tan\gamma = \eta_L$



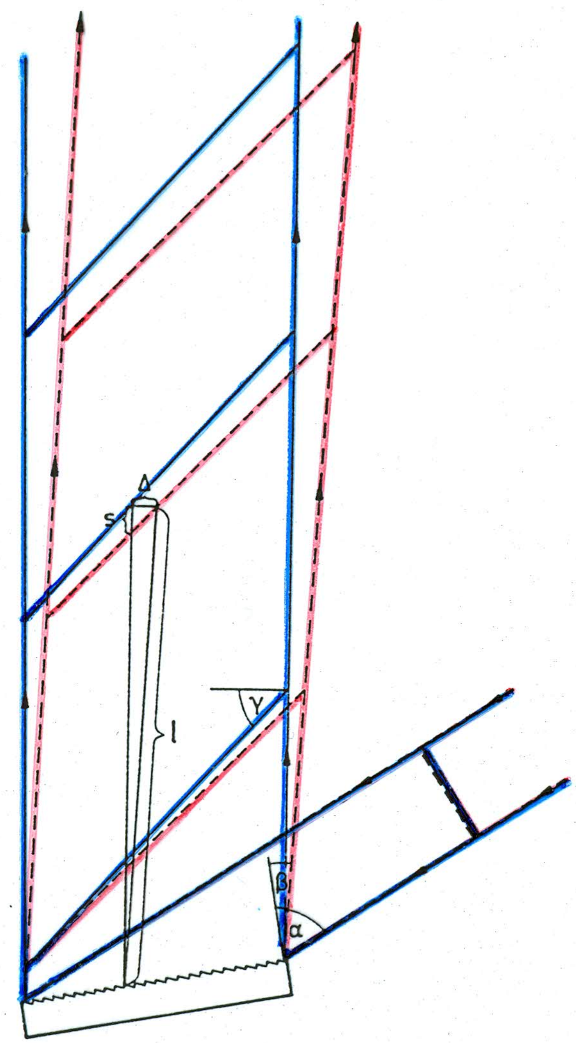
Pulse compression





temporal dispersion constant:

$$\frac{dT}{d\lambda} = \frac{\ell\lambda}{c}\left(\frac{d\varepsilon}{d\lambda}\right)^2$$



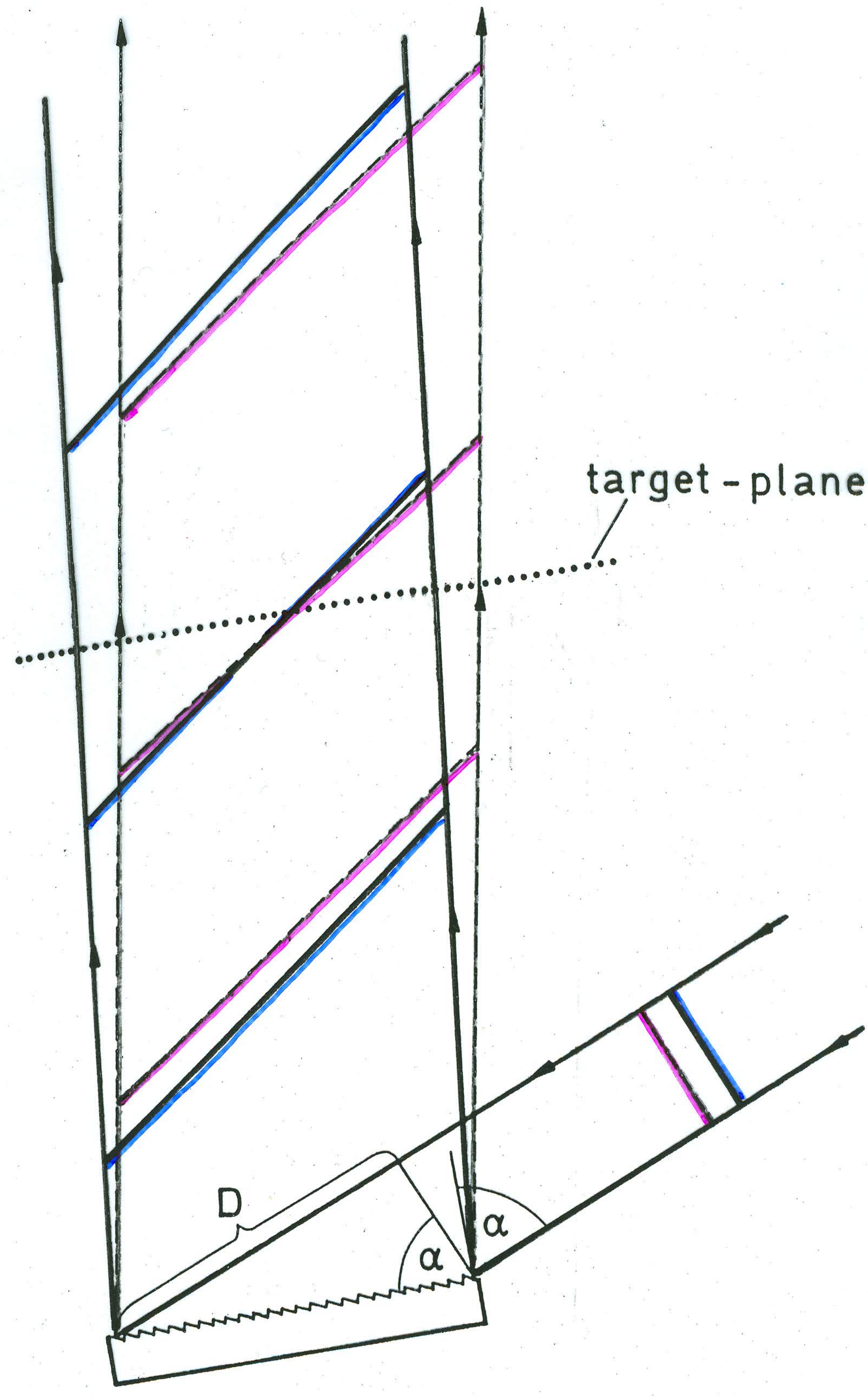
$$\frac{d\epsilon}{d\lambda} = \frac{1}{d\cos\beta}$$

$$\Delta = l\,\frac{d\epsilon}{d\lambda}\,\Delta\lambda,$$

$$\tan\gamma = \lambda\,\frac{d\epsilon}{d\lambda} \qquad s = \Delta\tan\gamma,$$

$$s = l\lambda\left(\frac{d\epsilon}{d\lambda}\right)^2\Delta\lambda.$$

$$\frac{dT}{d\lambda} = \frac{s}{c\Delta\lambda} = \frac{l\lambda}{c}\left(\frac{d\epsilon}{d\lambda}\right)^2$$



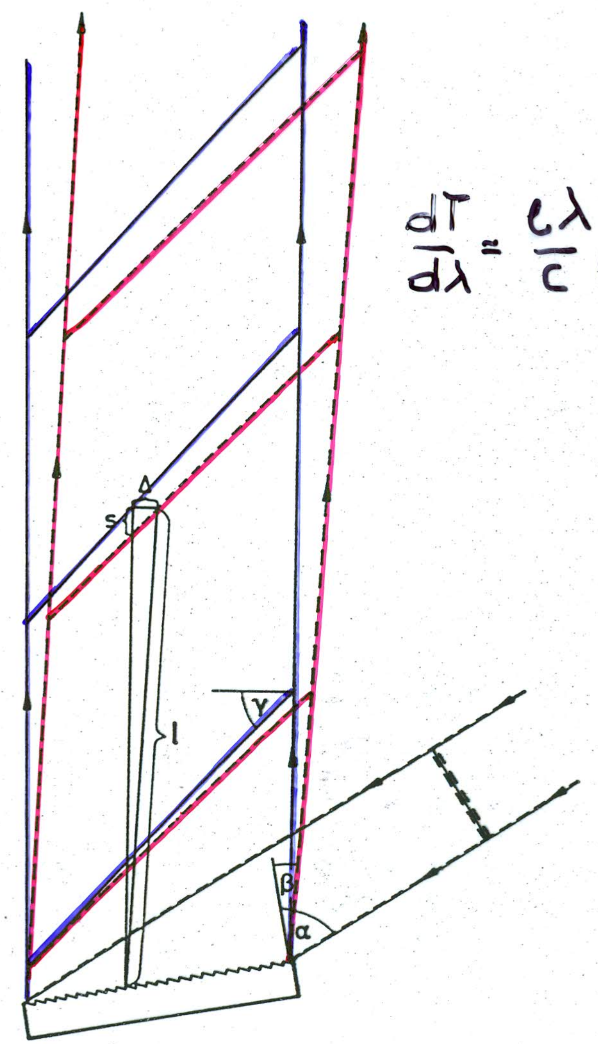
Szatmári/Simon/Gerhardt: Generation of 135 fs pulses ...

Fig. 1

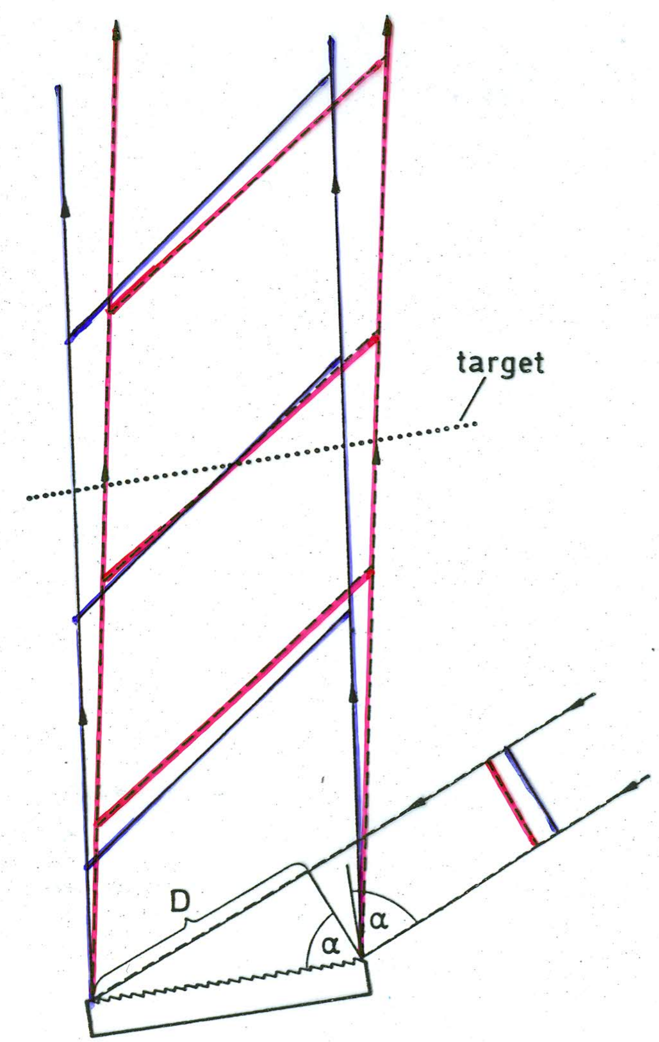
Spatially-evolving negative "chirp" (negative "GVD")

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

$$\frac{dT}{d\lambda} = \frac{l\lambda}{c}\left(\frac{d\varepsilon}{d\lambda}\right)^2$$



a)



b)

* $$\frac{d\varepsilon}{d\lambda} = \frac{1}{d\cos\beta}$$

$$\Delta = \ell \frac{d\varepsilon}{d\lambda} \Delta\lambda$$

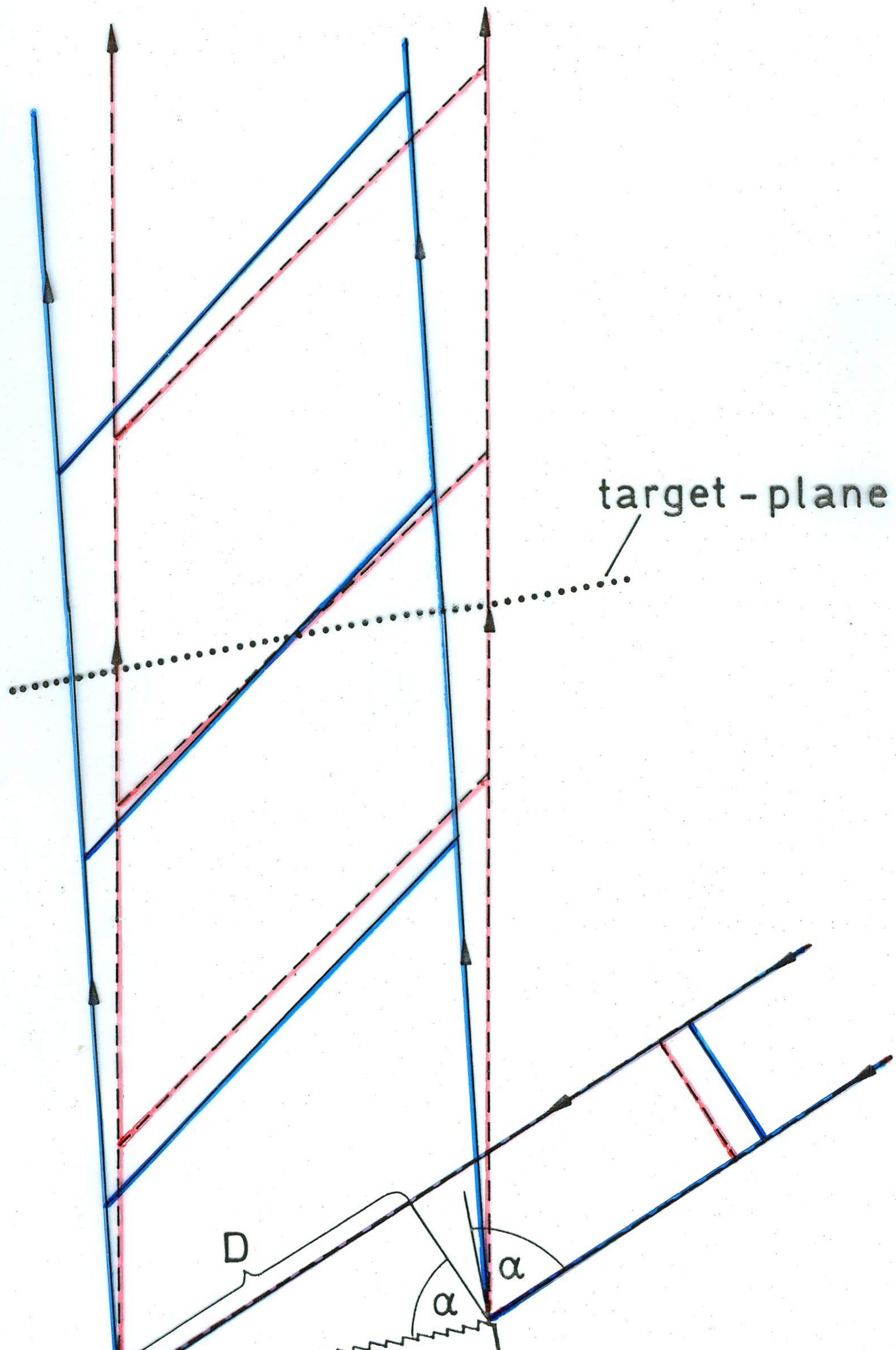
* $$\tan\gamma = \lambda \frac{d\varepsilon}{d\lambda} \qquad s = \Delta \tan\gamma$$

$$\Downarrow$$

$$s = \ell\lambda \left(\frac{d\varepsilon}{d\lambda}\right)^2 \Delta\lambda$$

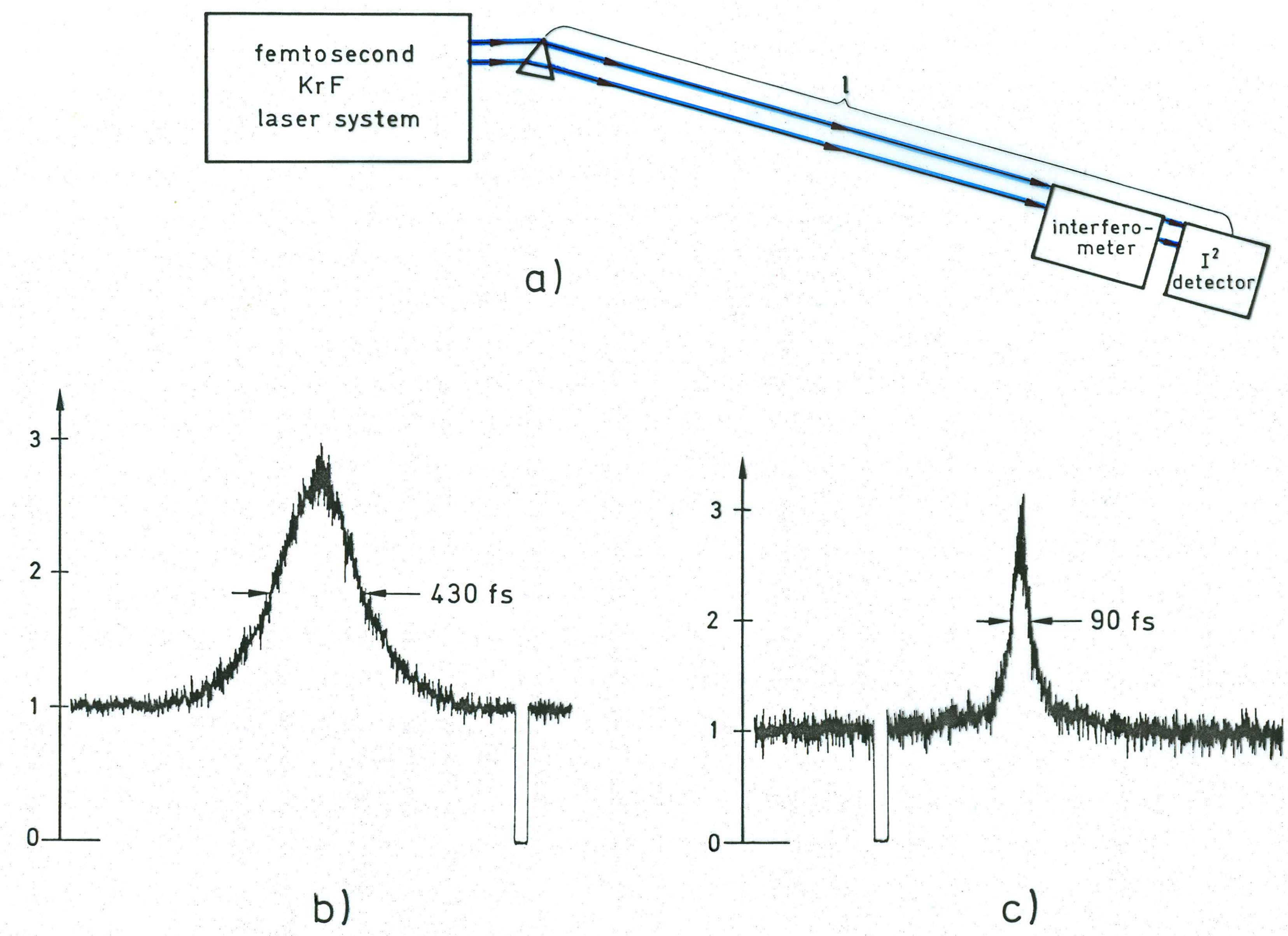
$$\Downarrow$$

** $$\frac{dT}{d\lambda} = \frac{s}{c\Delta\lambda} = \frac{\ell\lambda}{c}\left(\frac{d\varepsilon}{d\lambda}\right)^2$$

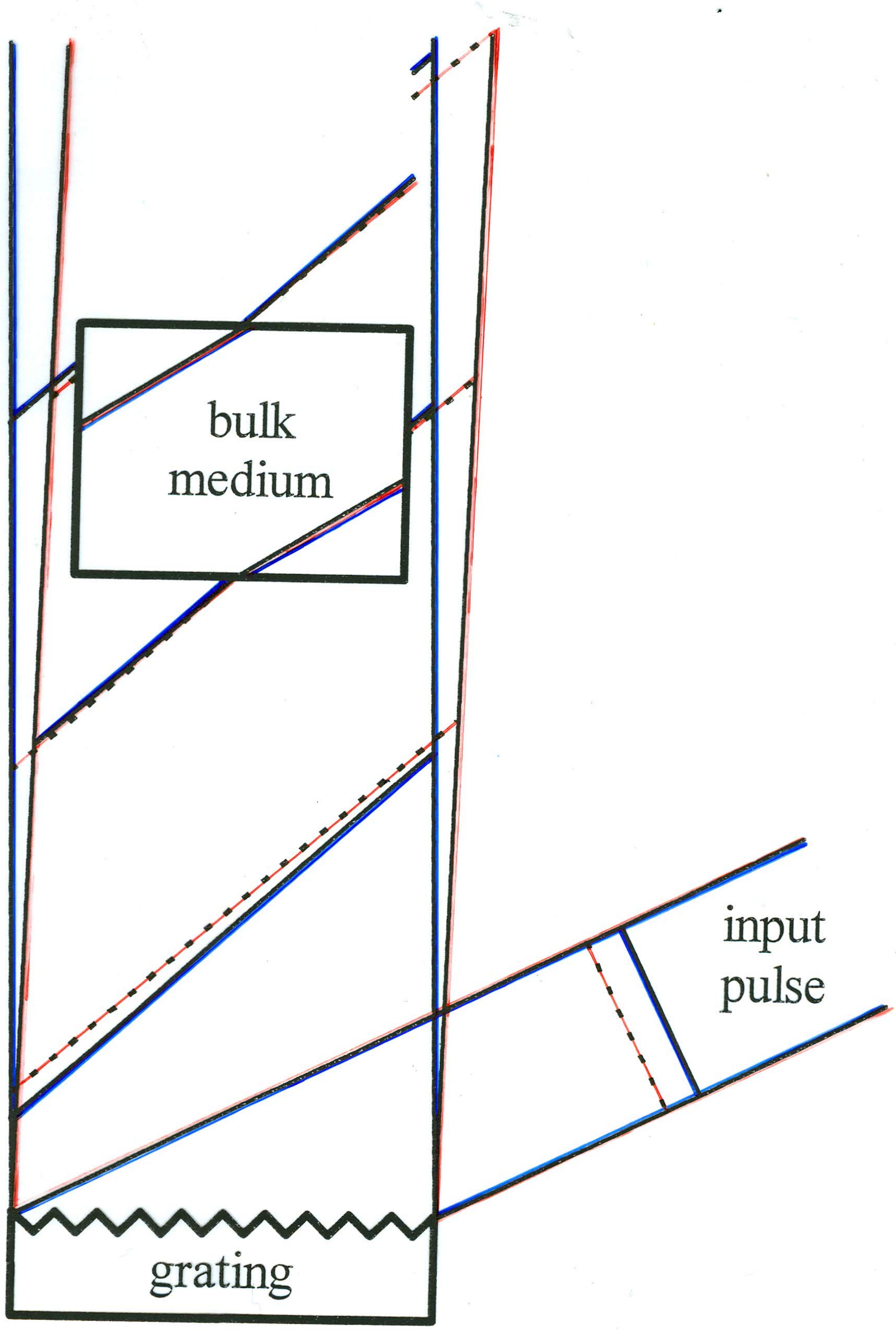


Szatmári/Simon/Gerhardt: Generation of 135 fs pulses ...

Fig. 1

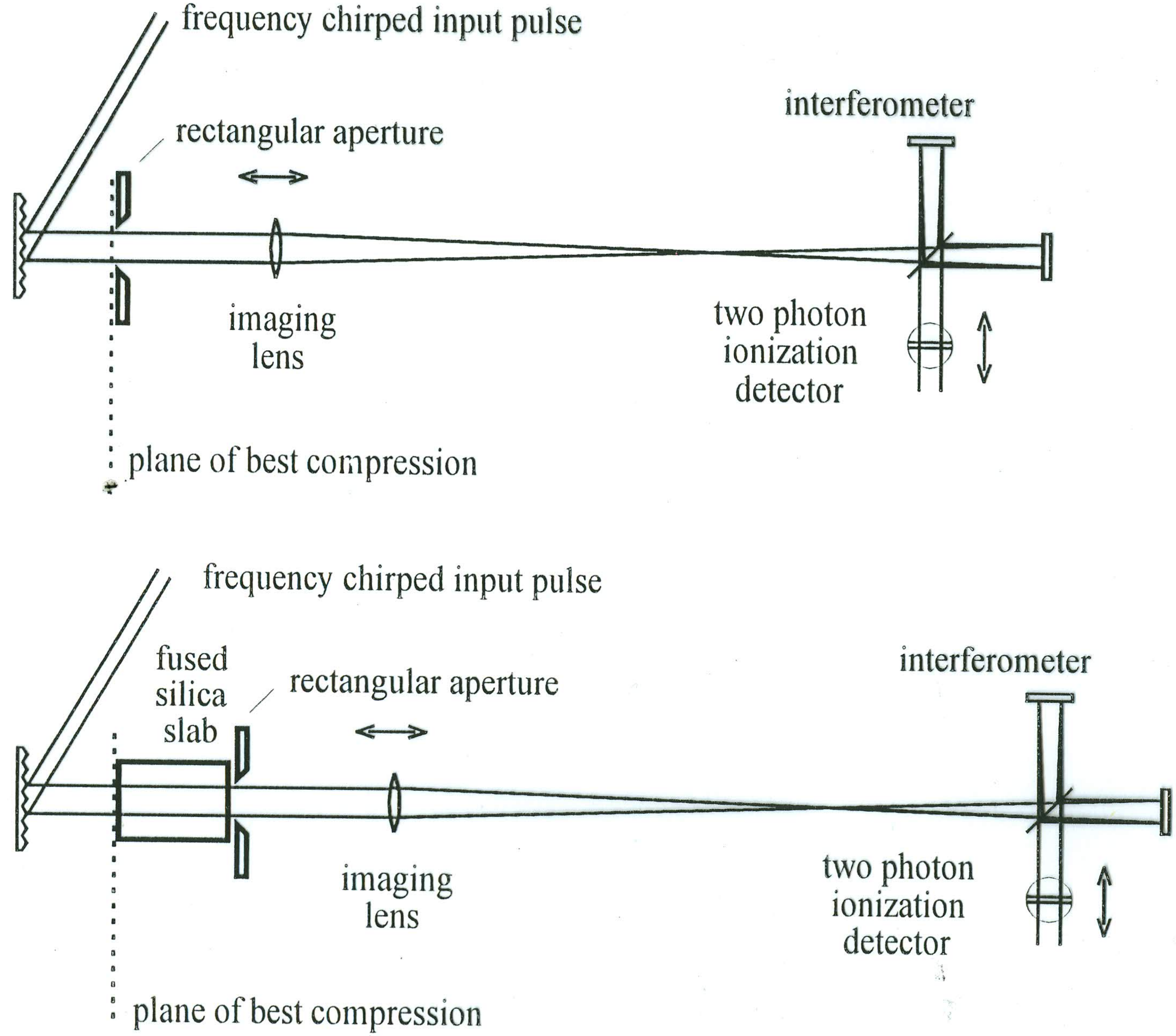

femtosecond
KrF
laser system
l
interfero-
meter
I²
detector
a)
3
2
1
0
430 fs
b)
3
2
1
0
90 fs
c)

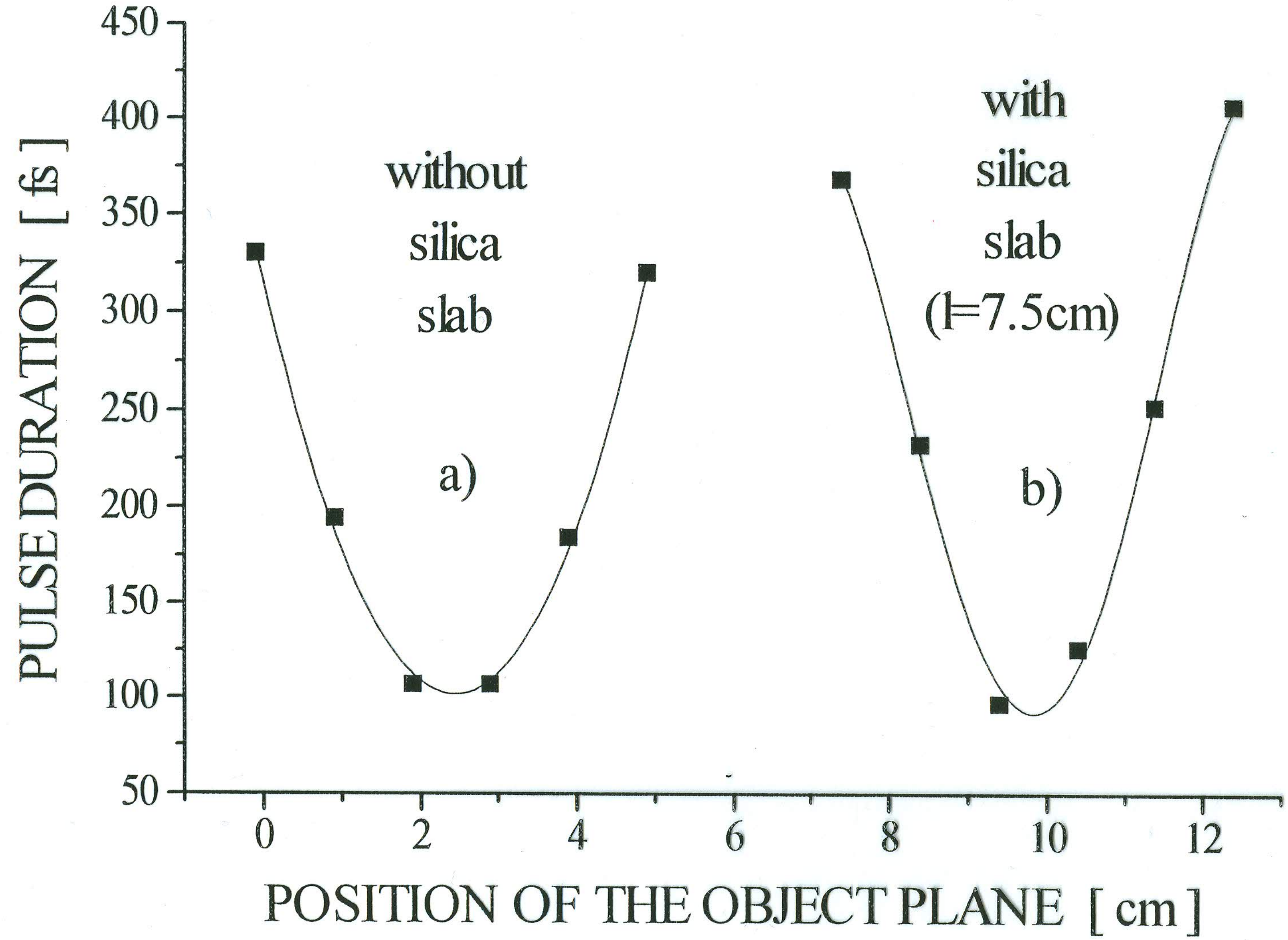
GVD compensated propagation in a bulk medium



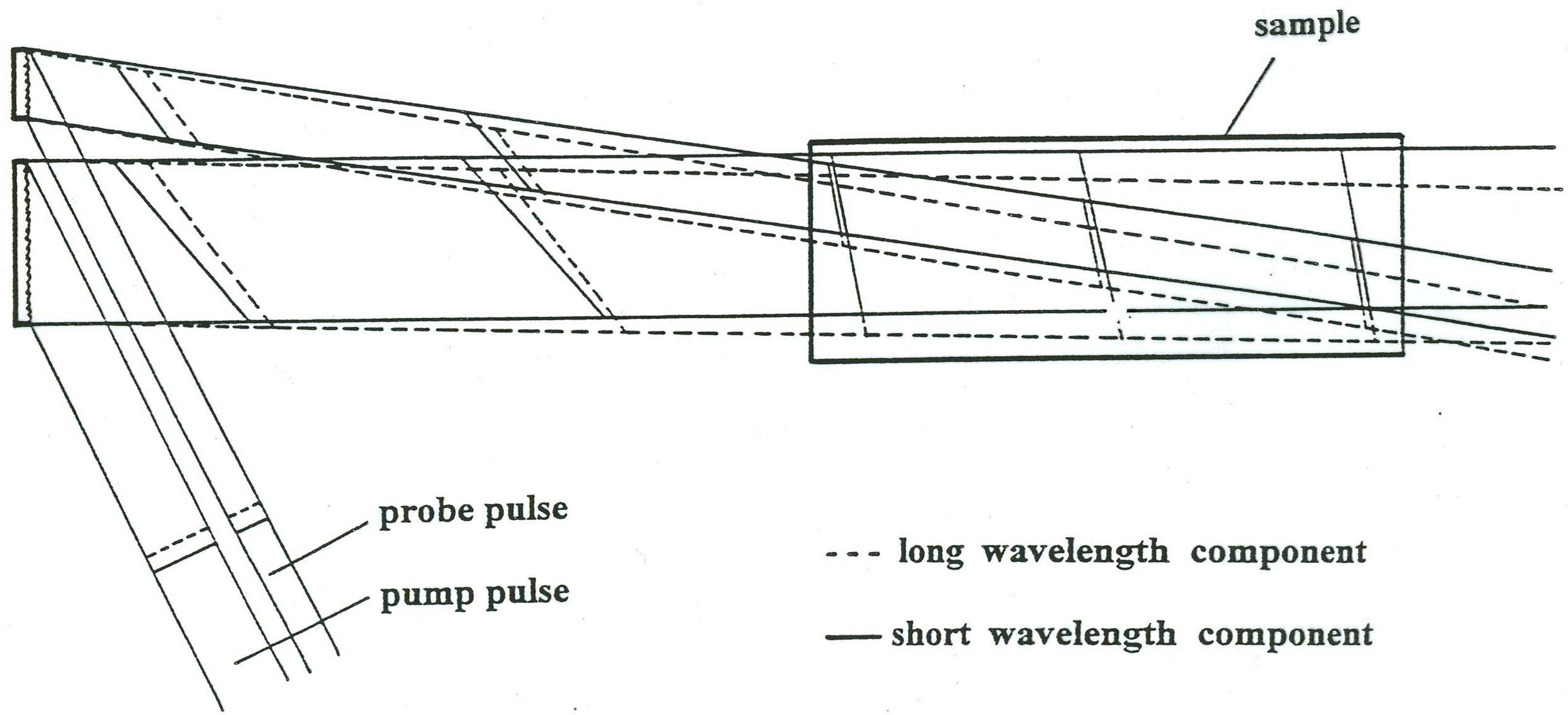
a)

b)


frequency chirped input pulse
rectangular aperture
interferometer
imaging
lens
two photon
ionization
detector
plane of best compression
frequency chirped input pulse
fused
silica
slab
rectangular aperture
interferometer
imaging
lens
two photon
ionization
detector
plane of best compression



PULSE DURATION [fs]
450
400
350
300
250
200
150
100
50
0
2
4
6
8
10
12
POSITION OF THE OBJECT PLANE [cm]
without
silica
slab
a)
with
silica
slab
(l=7.5cm)
b)


sample
probe pulse
pump pulse
--- long wavelength component
— short wavelength component

Limitations for GVD compensated arrangements

$$\frac{dT}{d\lambda} = \frac{L\lambda}{c}\left(\frac{d\varepsilon}{d\lambda}\right)^2$$

actual delay between the marginal rays
(for parallel Target and grating)

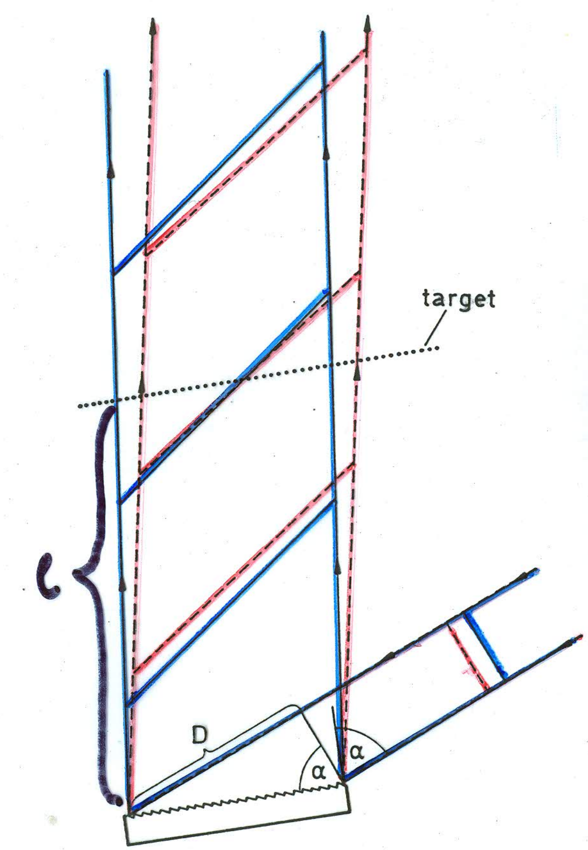
$$D = L \sin\alpha$$

the needed delay

$$D = \eta_L L$$

$$\Downarrow$$

$$\sin\alpha = \eta_L$$



b)

Limitations for GVD compensated arrangements

the needed delay between the marginal rays

$D = \eta_L L$

the actual delay (for parallel grating and target)

$D = L \sin \alpha$

$\Downarrow$

$\sin \alpha = \eta_L$

for non-parallel configuration

$\lambda = 248\,nm$

$\Delta\lambda = 1\,nm$

$\tau = 500\ (100)\ fs$

$L = 5\,cm$

$\eta = 1$ $\Downarrow$ $\Delta\tau = 17\,fs$

$n = 1.5$ $\Downarrow$ $\Delta\tau = 150\,fs$

for a prism arrangement

$\eta = 1$ $\Downarrow$ $\Delta\tau = 160\,fs$

$\eta = 1.5$ $\Downarrow$ $\Delta\tau = 1.6\,ps$

$D = \eta_r L \sin\alpha \Rightarrow \eta_r \sin\alpha = \eta_L$

$\sin\varphi = -\lambda \frac{d\eta_r}{d\lambda} \frac{\sin\alpha \cos\delta}{\tan^2\gamma'}$

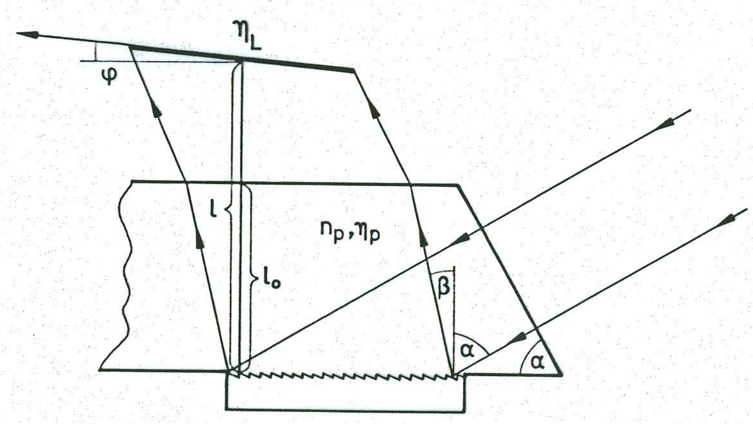
$\tan\gamma = \frac{D}{L'} = \frac{L \sin\alpha}{L'}$

for KrF pumping

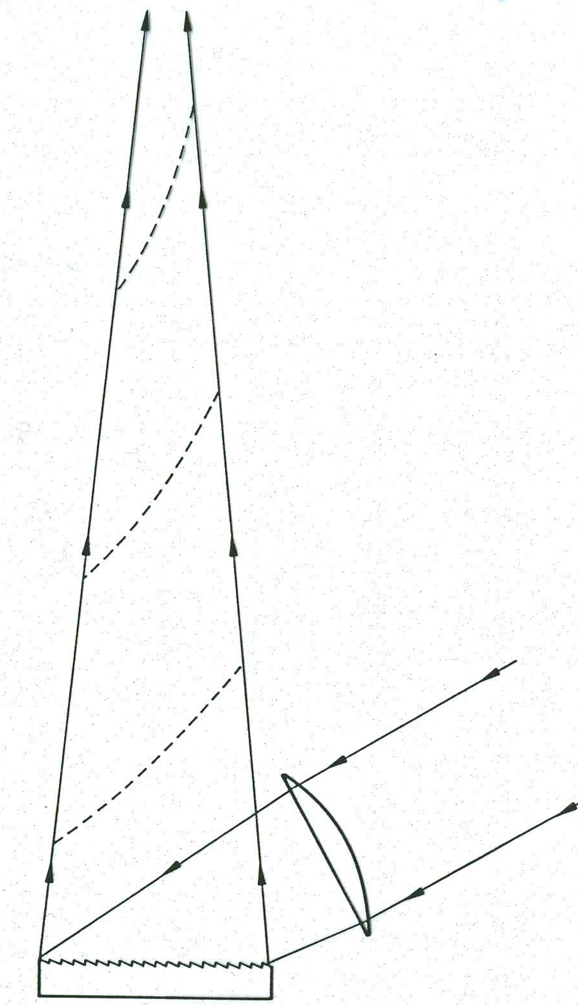
$\eta_L = 1.5$

$\Downarrow$

$\Delta\tau = 0.5 fs$!



a)



b)

$$\underset{\overset{\uparrow}{B}}{\tan\gamma'} = M \underset{\overset{\uparrow}{A}}{\tan\gamma}$$ assuming $\beta = 0$

$$\tan\gamma' = \eta_L$$

$$\Downarrow$$

$$\tan\gamma = \frac{\eta_L}{M}$$

from *

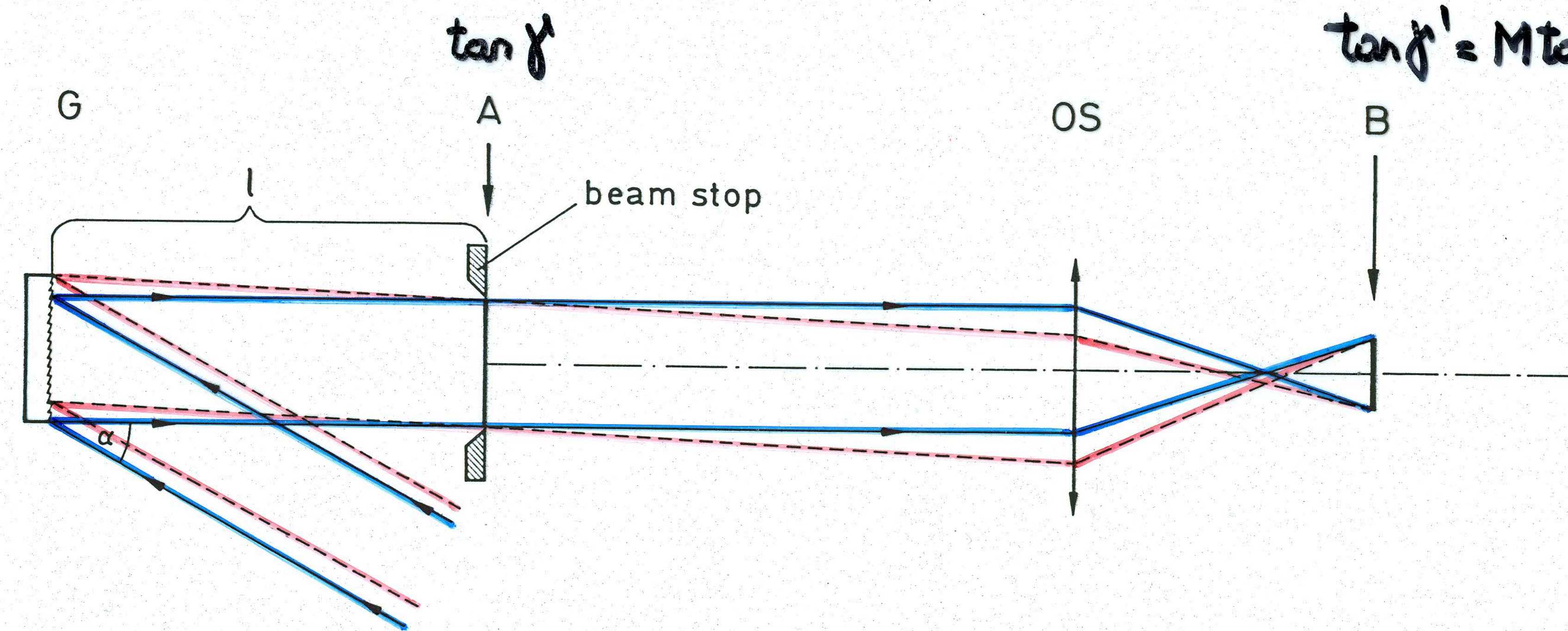
$$\tan\gamma = \frac{\lambda}{d}$$

from these equations

$$\frac{M}{d} = \frac{\eta_L}{\lambda}$$ and $$d \sin\alpha = \lambda$$

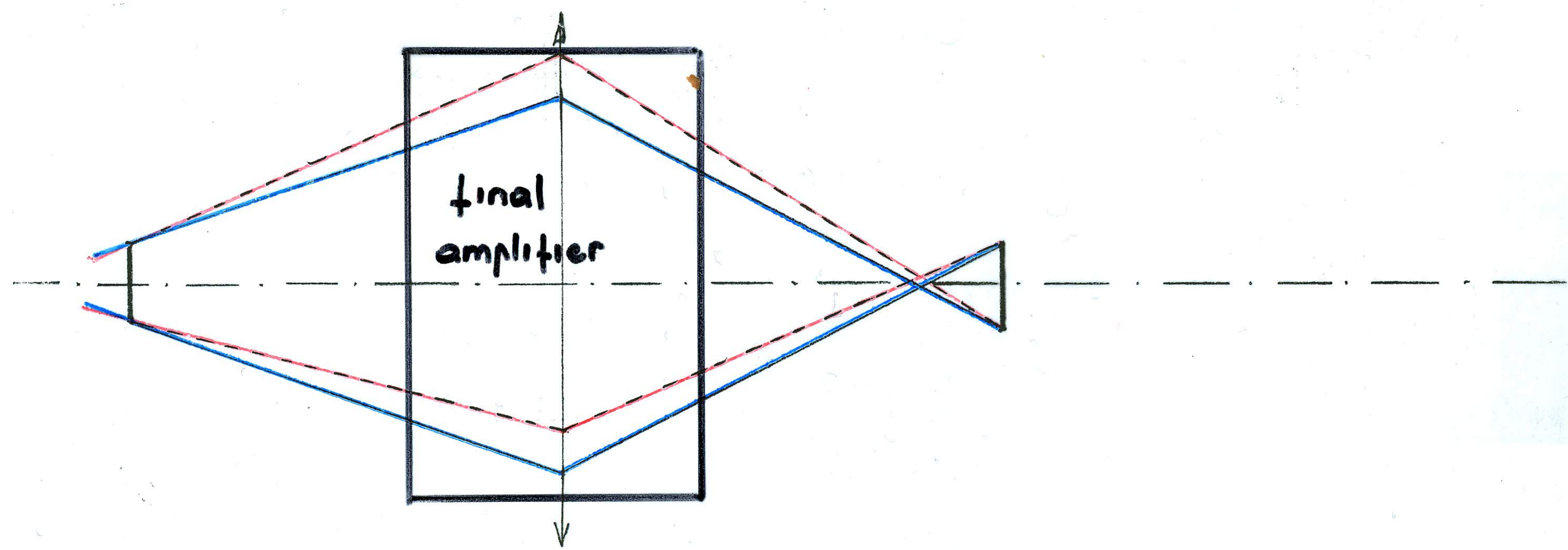
from **

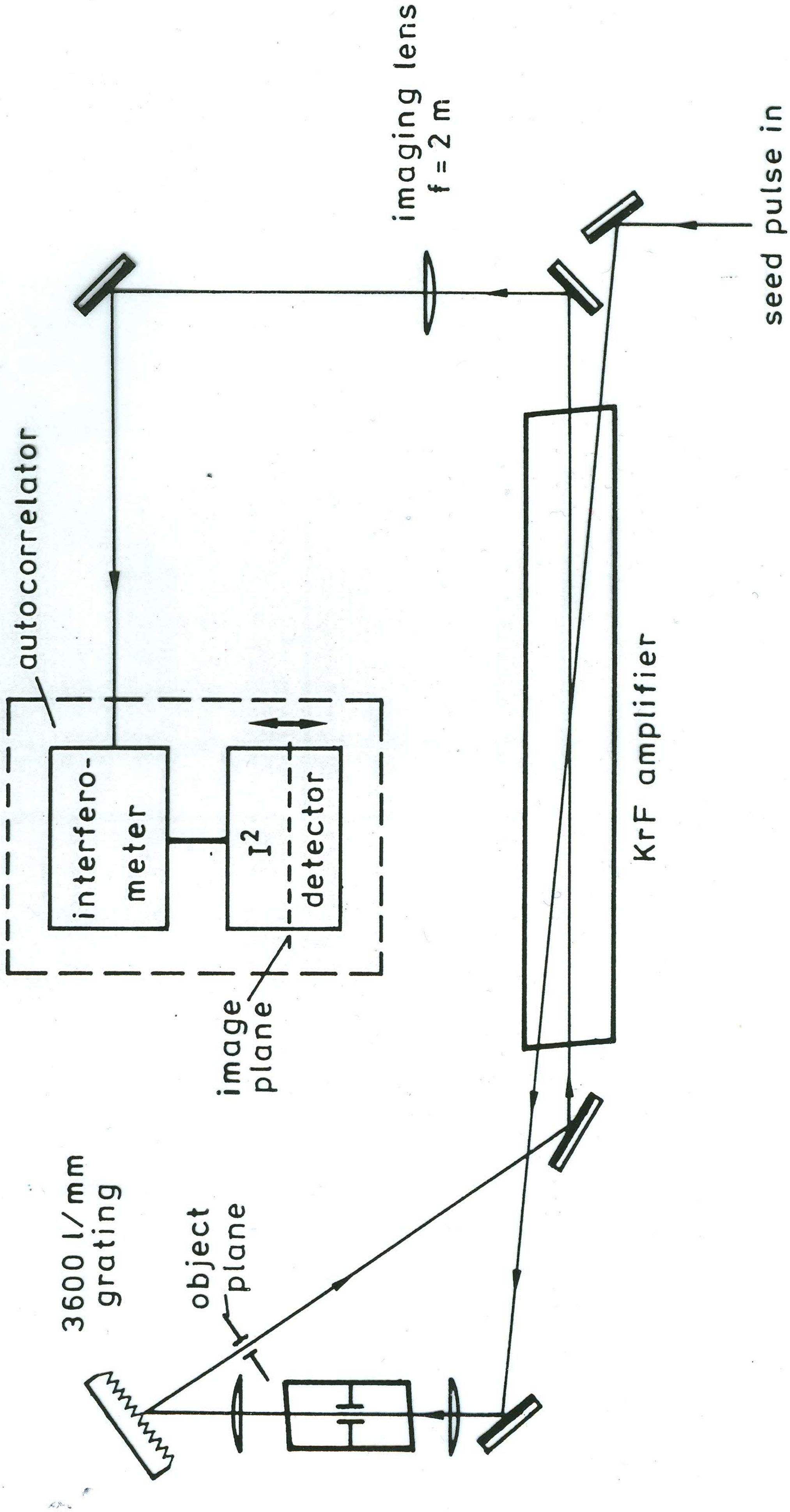
$$\ell = \frac{c d^2}{\lambda} \frac{dT}{d\lambda}$$


$\tan\gamma$
$\tan\gamma' = M\tan\gamma$
G
A
OS
B
l
beam stop
α

Spatially-evolving chirped-pulse amplification

os'





Szatmári/Simon/Gerhardt: Generation of 135 fs pulses ...

Fig. 3

Active (nonlinear) temporal and spatial filtering of short pulses

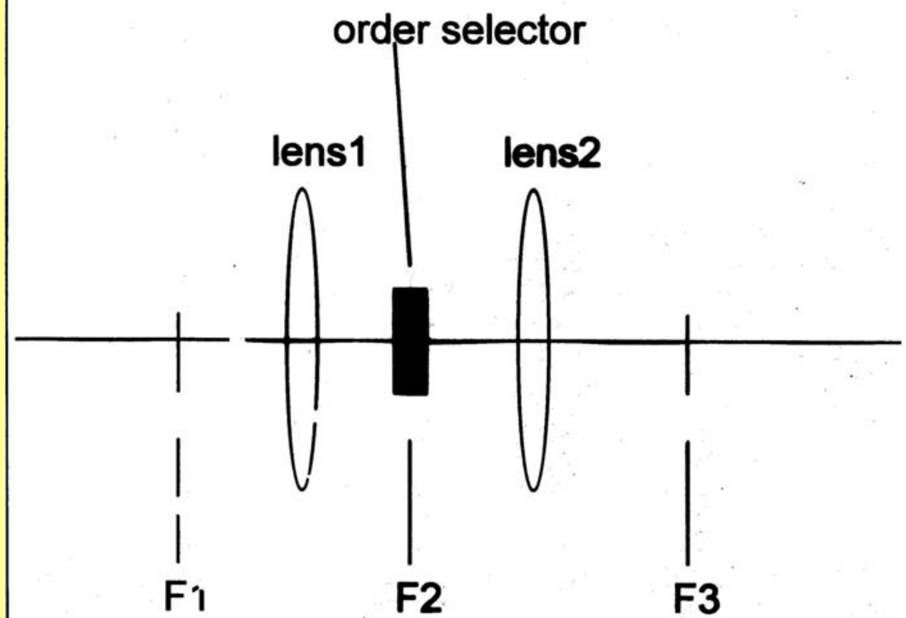
Important figure of merits

of high intensity laser systems:

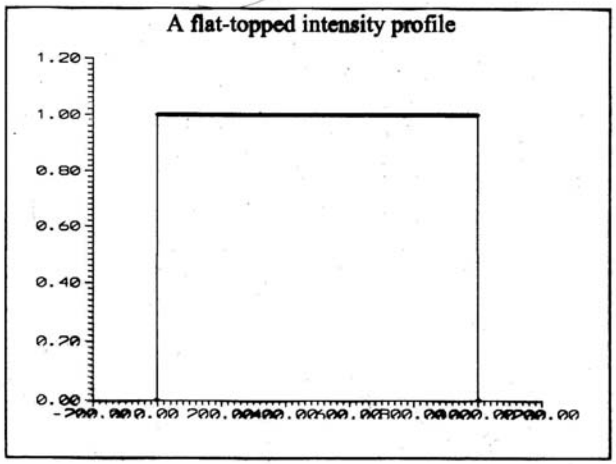
a) spatial and
b) temporal quality of the pulses.

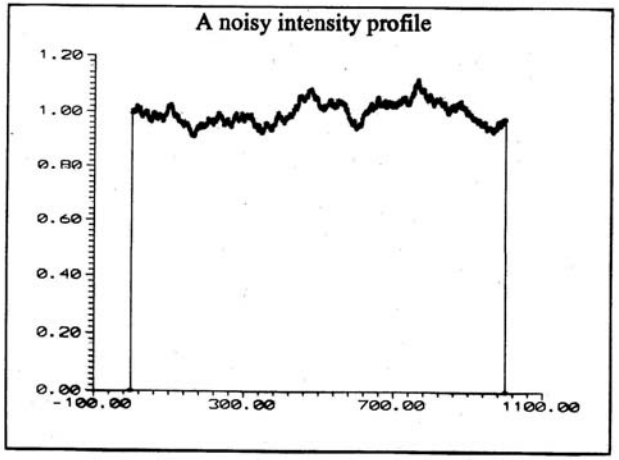
a) Spatial filtering

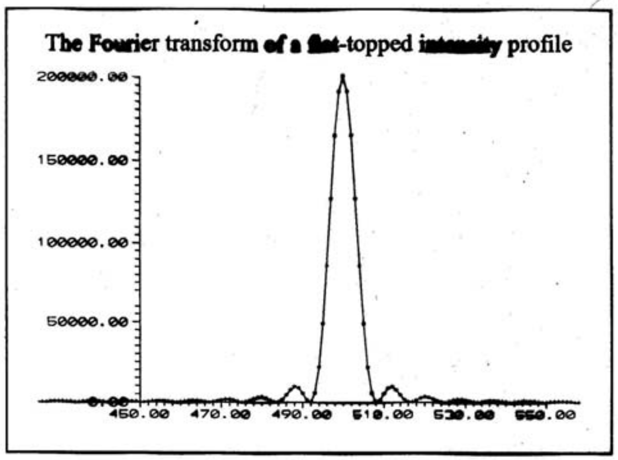
Confocal arrangement for fourier filtering of laser beams

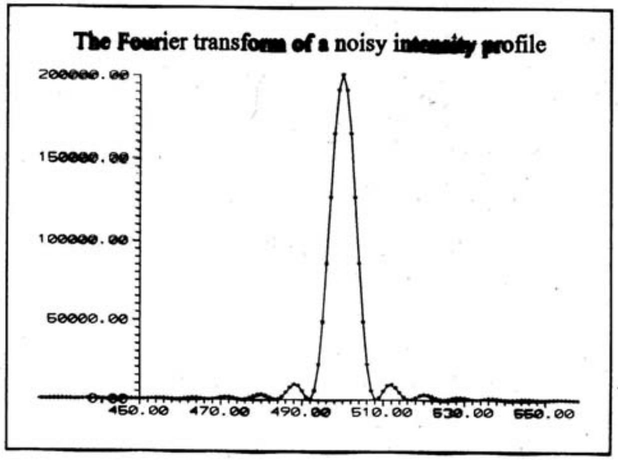


Fourier transform of a flat-topped and a noisy intensity distribution









Output distribution by removing the different, higher orders

Retransformations after selecting the main order(s) of a noisy flat-top curves fourier transform.

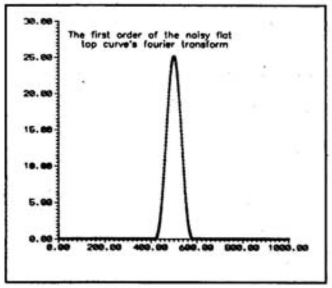


Figure 4.a

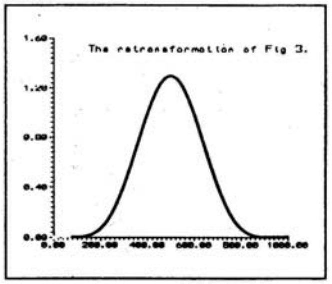


Figure 4.b

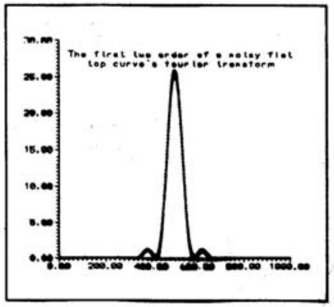


Figure 4.c

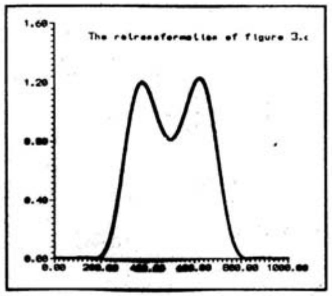


Figure 4.d

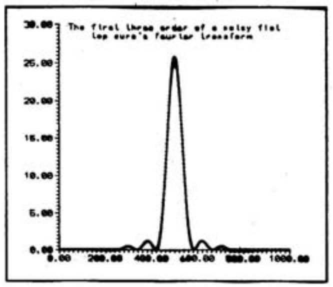


Figure 4.e

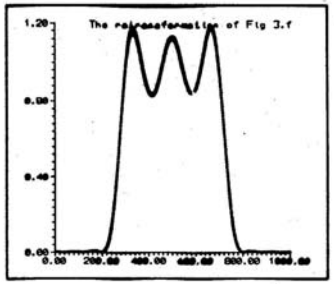


Figure 4.f

Active spatial filtering: Nonlinear transmission instead of the aperture

Reprinted from

OPTICS COMMUNICATIONS

Optics Communications 134 (1997) 199–204

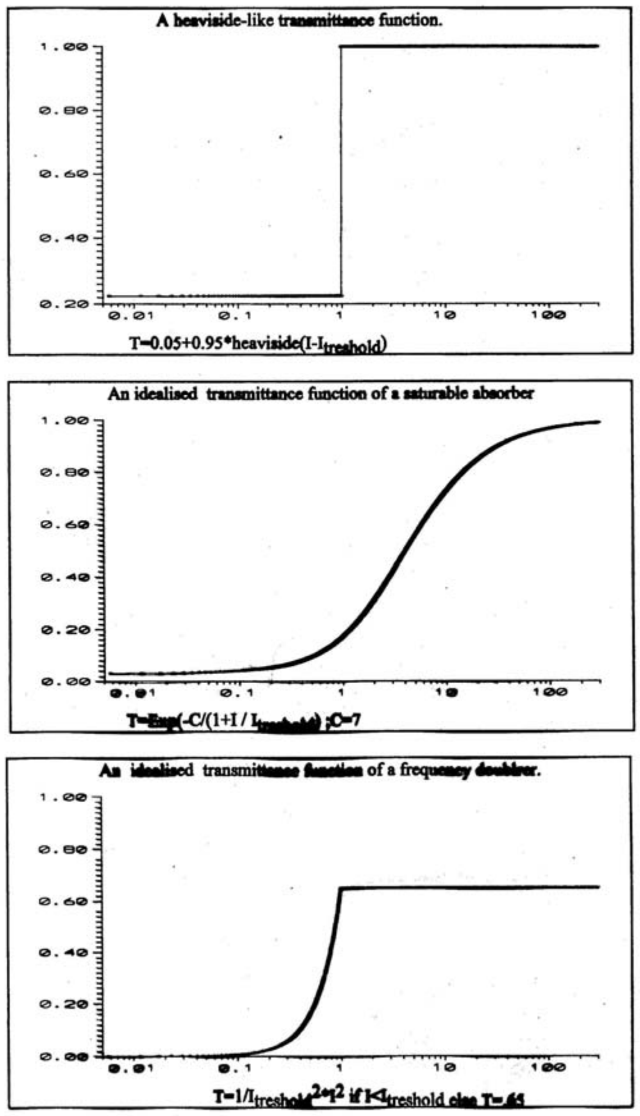
Active spatial filtering of laser beams

Sándor Szatmári [a], Zoltán Bakonyi [a], Péter Simon [b]

[a] Department of Experimental Physics, JATE University, Dóm tér 9, H-6720 Szeged, Hungary
[b] Laser-Laboratorium Göttingen, Hans-Adolf-Krebs-Weg 1, D-337077 Göttingen, Germany

Received 15 May 1996; revised version received 28 June 1996; accepted 21 August 1996

N·H
ELSEVIER



SHG Saturable absorber as an order selector

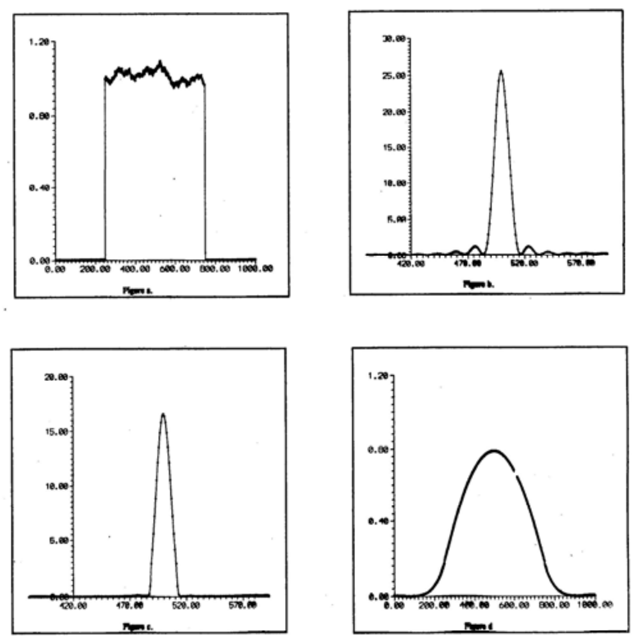


Figure a : A noisy intensity profile.
Figure b : It's Fourier transform
Figure c : The Fourier transform filtered with the transmittance of:
$T= 0.65/(I_{treshold})^{2} * I^{2}$ if $I<I_{treshold}$ else $T=0.65$; $I_{treshold}=4$
Figure d : The re-transformed , filtered picture.

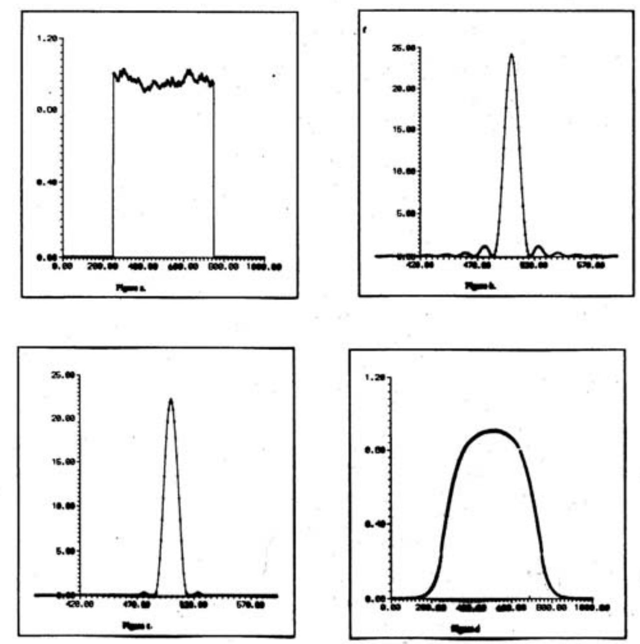


Figure a : A noisy intensity profile
Figure b : It's Fourier transform
Figure c : The Fourier transform filtered with the transmittance of:
$T= \mathrm{Exp}(-C/(1+I/Is))$; $C=7$, $I_s=0.3$
Figure d : The re-transformed , filtered picture.

b) Temporal filtering: The use of plasma mirrors

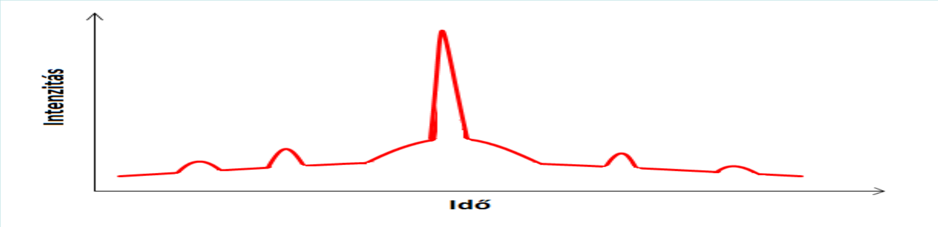
KrF lasers have a good focusability and high available contrast.

Plasma mirrors are the most efficient cleaning tools in the generation of femtosecond laser pulses of ultrahigh contrast .

Idea: Only the leading edge of the ultrashort pulse is above plasma threshold, i.e. prepulses and pedestals are transmitted by a transparent target, the short pulse is reflected and „cleaned”.

Plasma mirrors provided several orders of magnitude improvement of the contrast for Ti-sapphire allowing surface harmonics generation up to several keV (Dromey et al.).

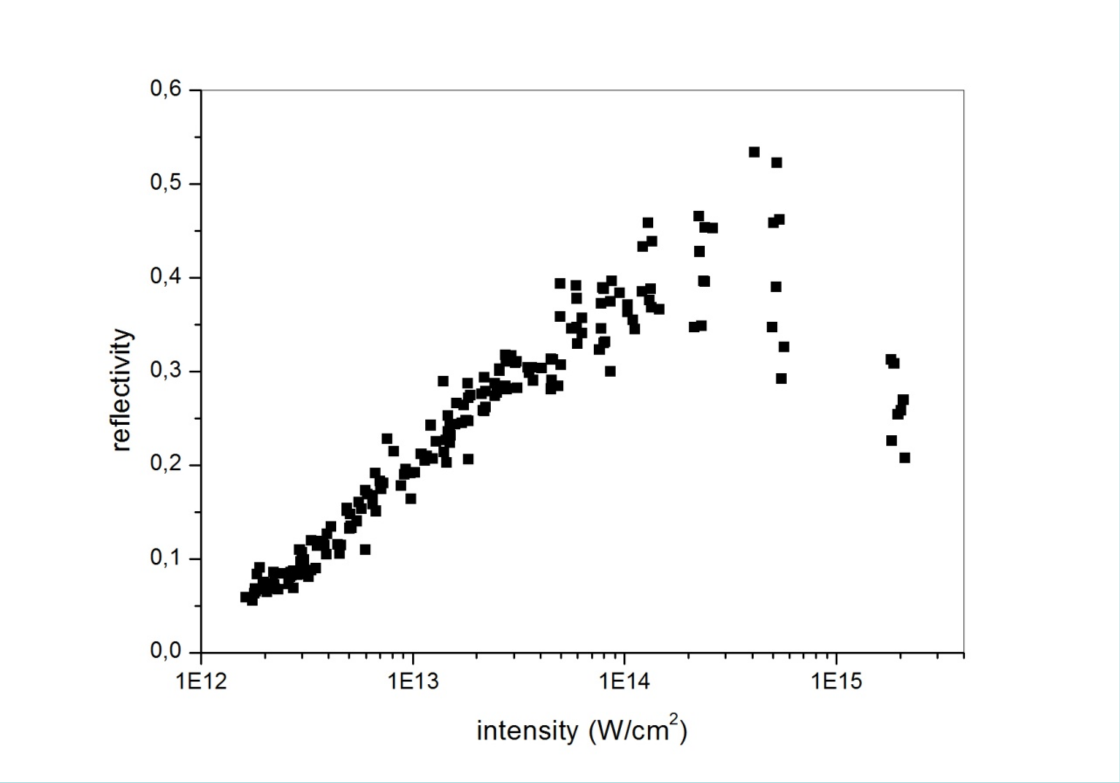
The ultrashort KrF laser of the HILL laboratory is based on direct amplification.
Only ASE prepulse is present – partially suppressed by off-axis amplification.
But: Surface photoionization by the 5eV KrF photons must be avoided,
Prepulse intensity < 10^7 W/cm^2 needed.



Plasma Mirror *for Short-Pulse KrF Lasers*

First succesful demonstration of the plasma mirror effect for KrF laser.

After a logarithmic increase saturation of the reflectivity (>40%) is reached at ~10^{14}W/cm^2 intensity, for 12.4°angle of incidence. For shorter pulses a reflectivity in excess of ~50% can probably be obtained.



Comparison with Ti-sapphire Plasma Mirror

Origin of the „noise” at the output:

Ti:Sapphire — CPA scheme, ASE

KrF — ASE (10^9-10^{10} contrast)

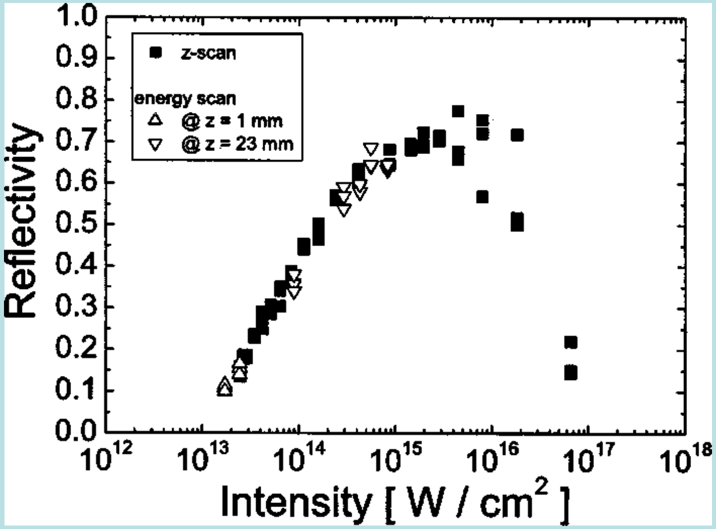
The plasma mirror effect is considered as an effective way of improving the contrast.

Disadvantages: loss in energy (power)

limited improvement in the contrast (governed by the ratio of the plasma reflectivity and of the reflectivity of the sample)

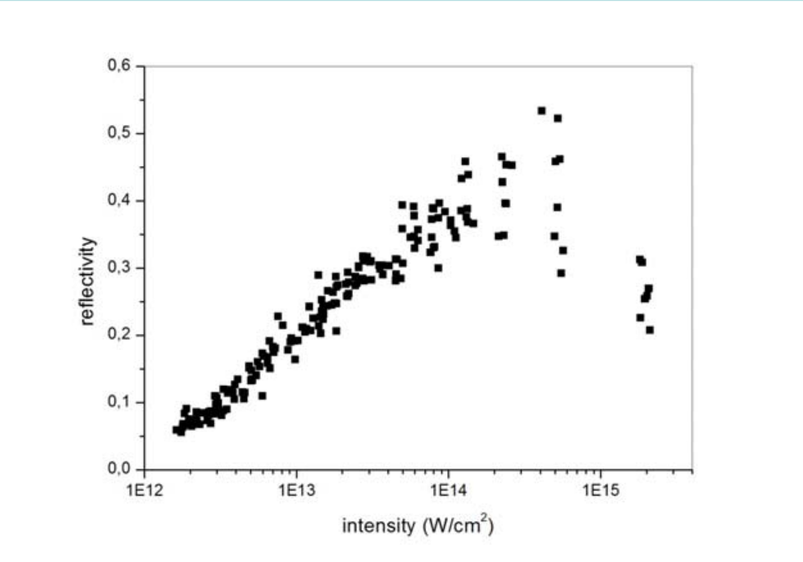
(typically one order of magnitude improvement for one mirror)

Ti:Sa



Ziener et al, J. Appl. Phys. **93**, 768 (2003)

KrF

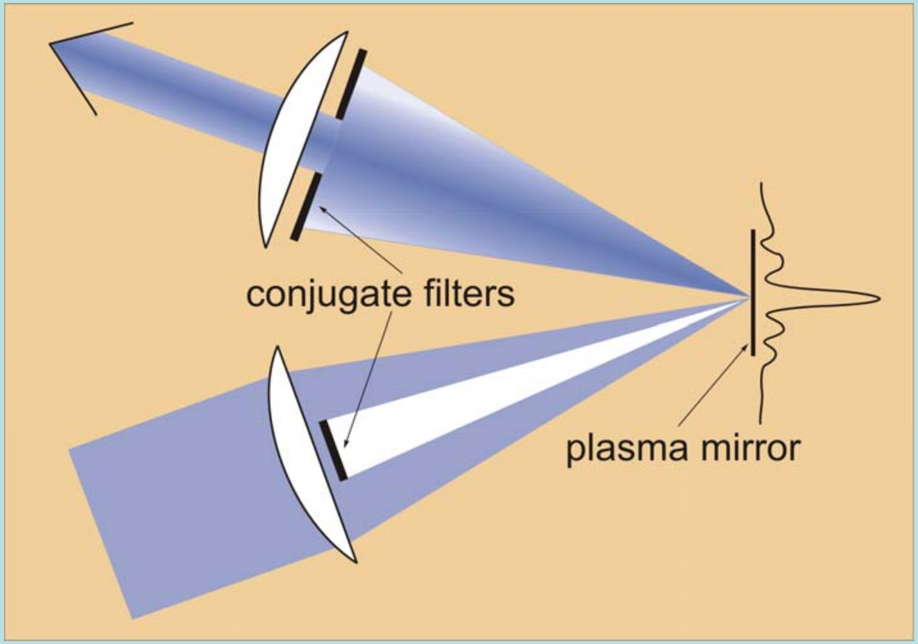


New Idea: Combination of the Plasma Mirror with a „conjugate" Spatial Filter

In this new arrangement the plasma mirror is positioned in the Fourier-plane of a focussing mirror put into the input beam.

The use of an annular input beam and an output aperture - allowing transmission only in the „central hole" of the annular beam - gives no transmission as long as the reflectivity is the same for the different diffraction orders.

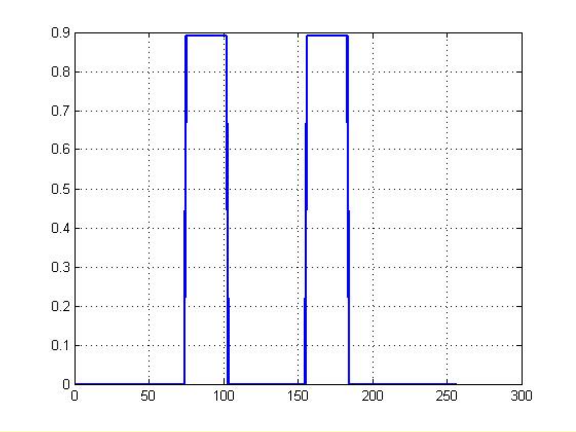
If the reflectivity (either the amplitude or the phase) is different for the more intense central lobe of the diffraction pattern, the central hole of the aperture becomes illuminated.

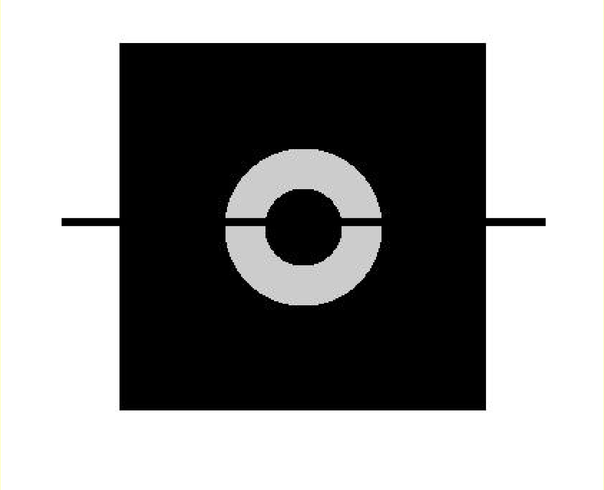


Extremely high contrast!

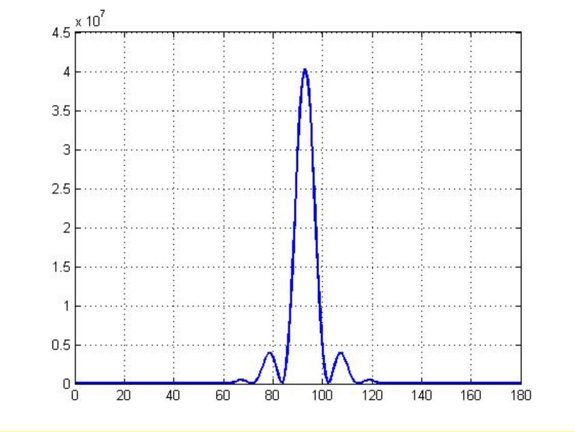
Intensity distribution at the Fourier-plane for an annular input beam

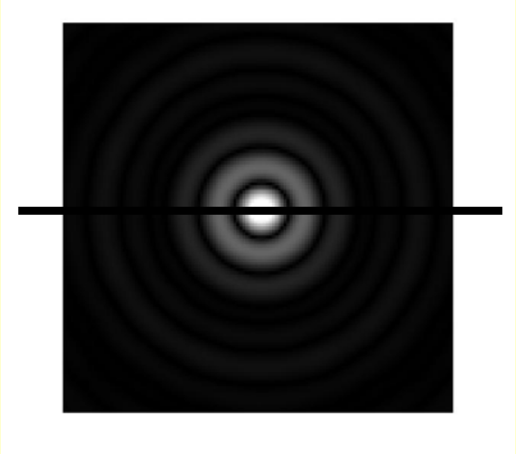
Input





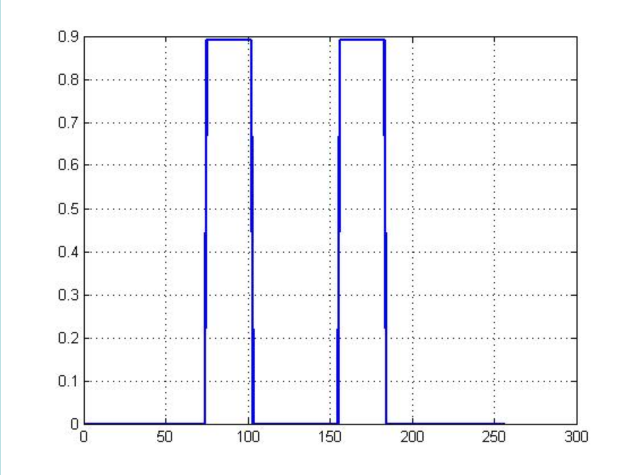
Fourier-plane:

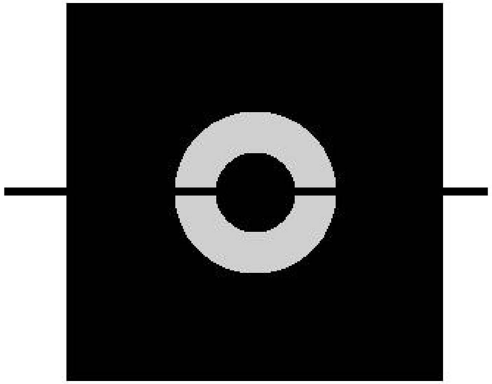




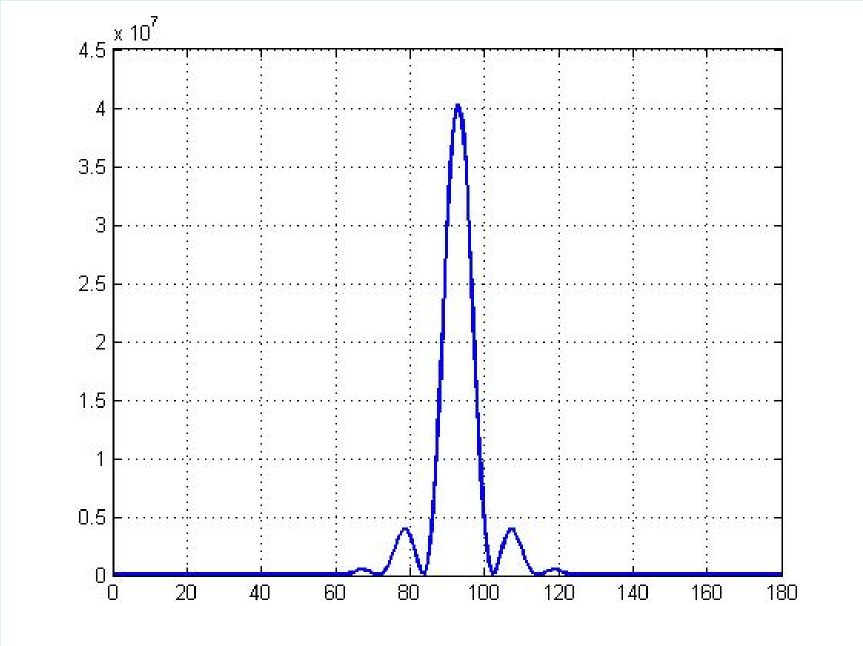
Output distribution:
a) With no modulation at the Fourier-plane

Output





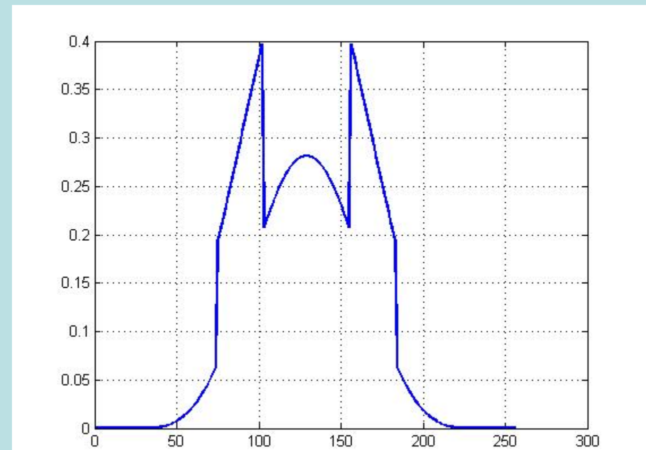
Fourier-plane

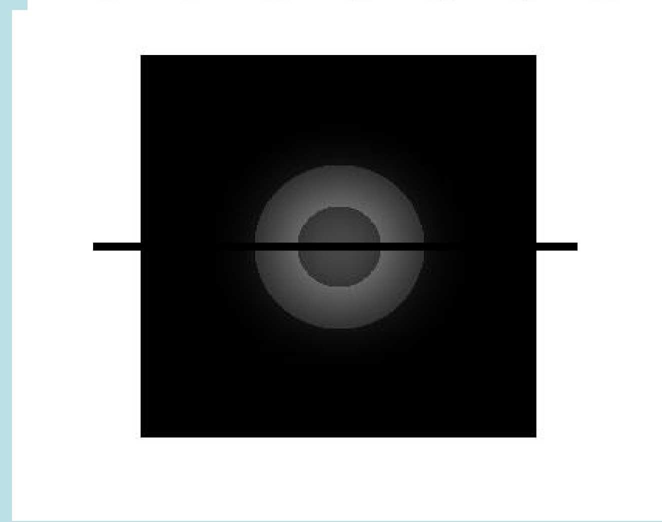


Output distribution

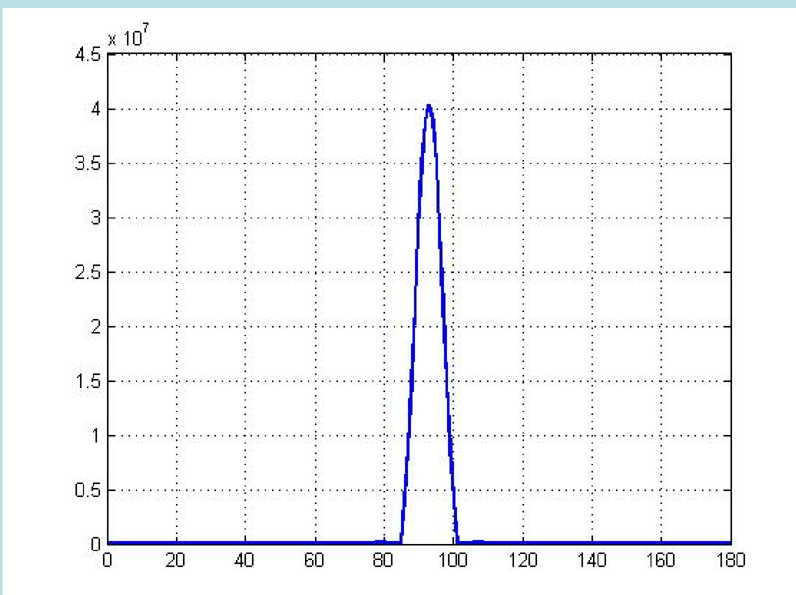
With amplitude modulation at the Fourier-plane: the 0th order is enhanced (plasma mirror effect) by a factor of 5

Output





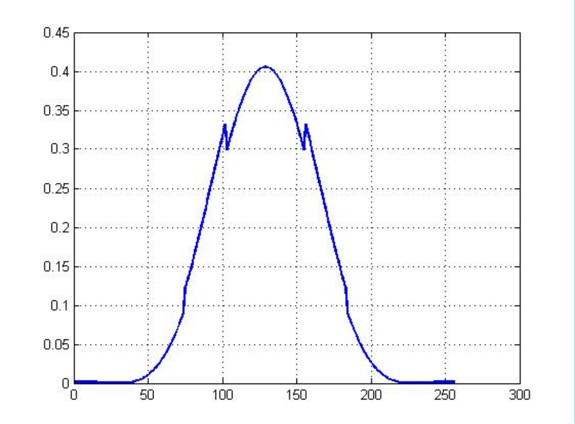
Fourier-plane

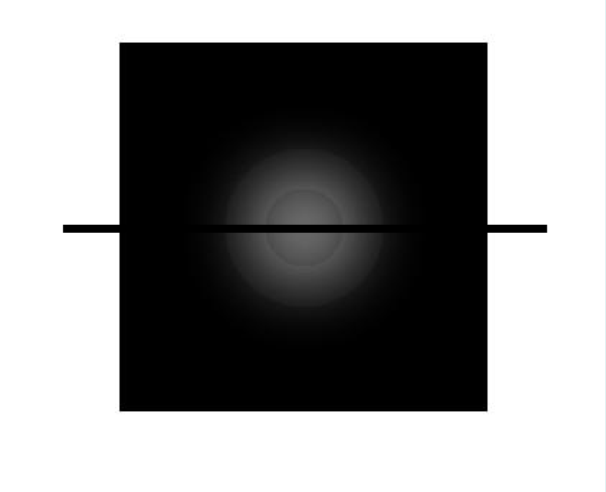


Output distribution

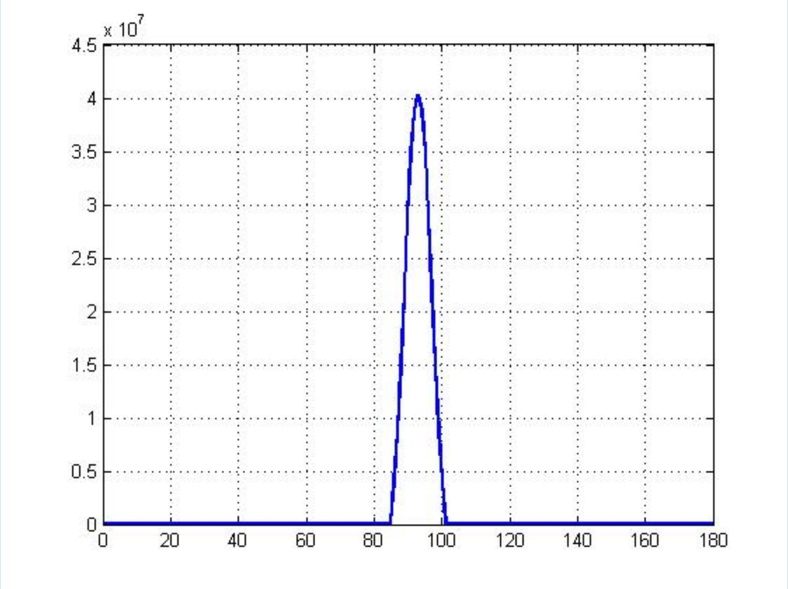
b) With amplitude modulation at the Fourier-plane: the 0th order is enhanced (plasma mirror effect) by a factor of 25

Output





Fourier-plane

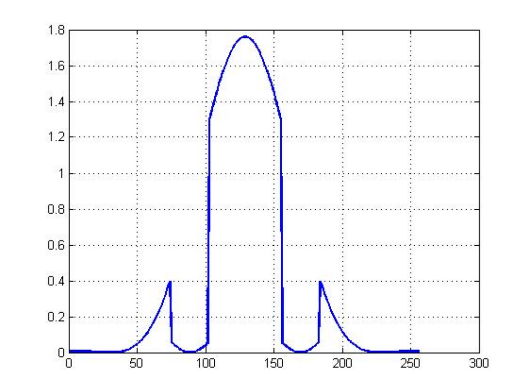


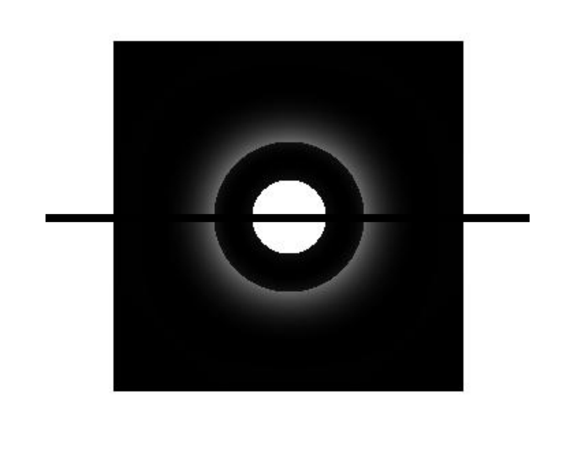
New approach: phase modulation!

Output distribution

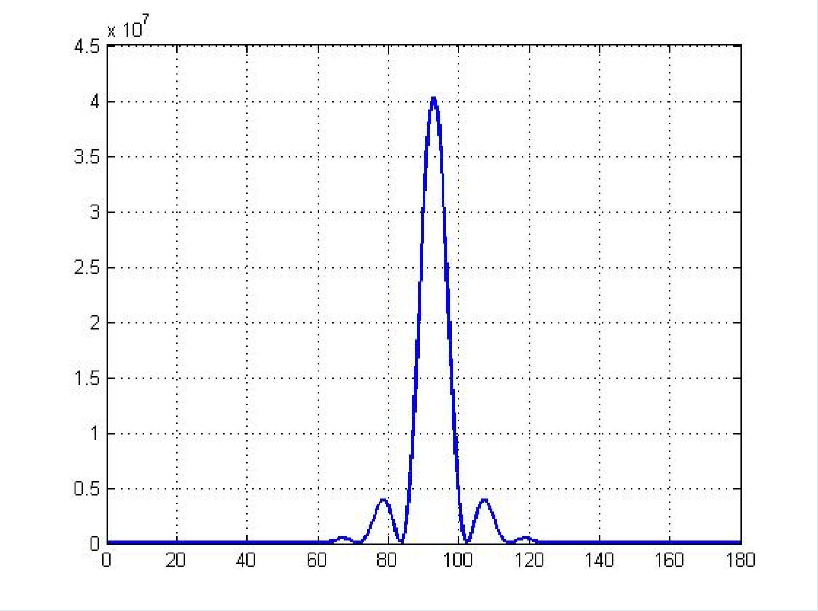
c) With phase modulation at the Fourier-plane: the 0th. order is shifted by $\lambda/2$ (in the self generated plasma)

Output



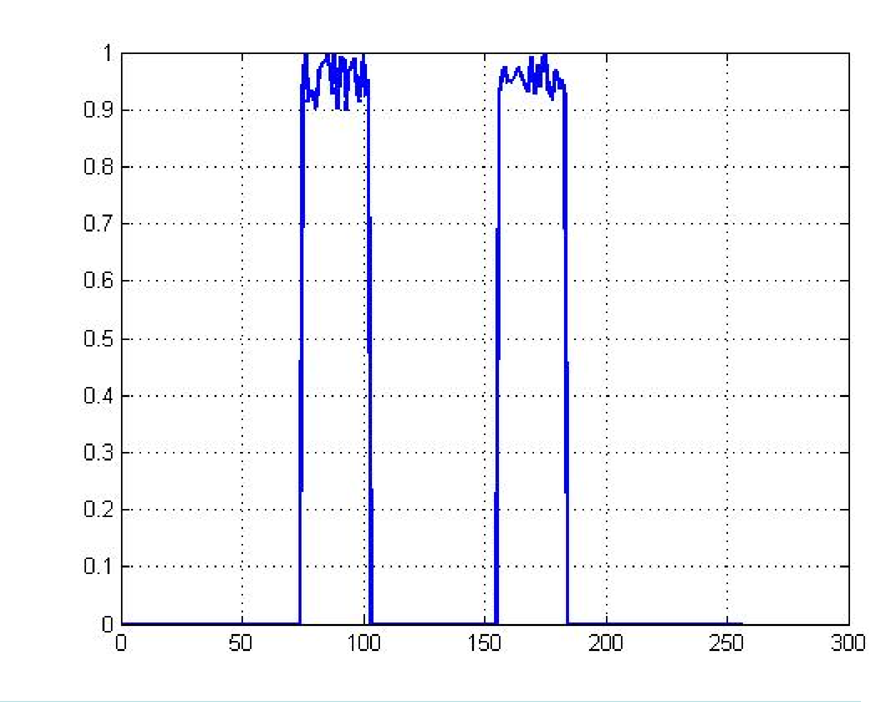


Fourier-plane

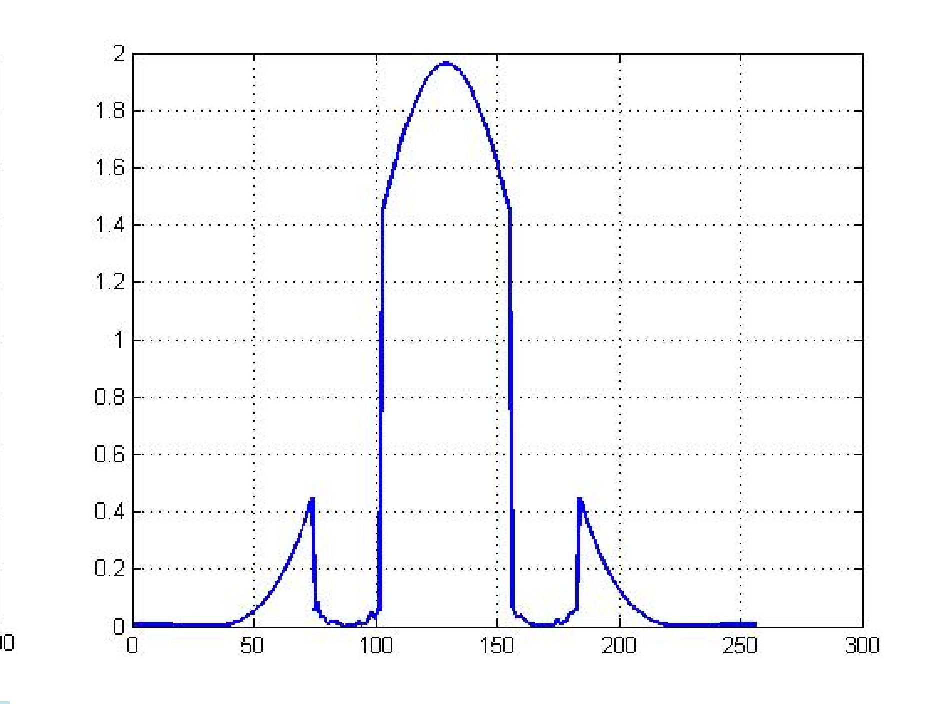


Output distribution with noisy input
d) With phase modulation at the Fourier-plane: the 0th. order is shifted by $\lambda/2$ (in the self generated plasma)

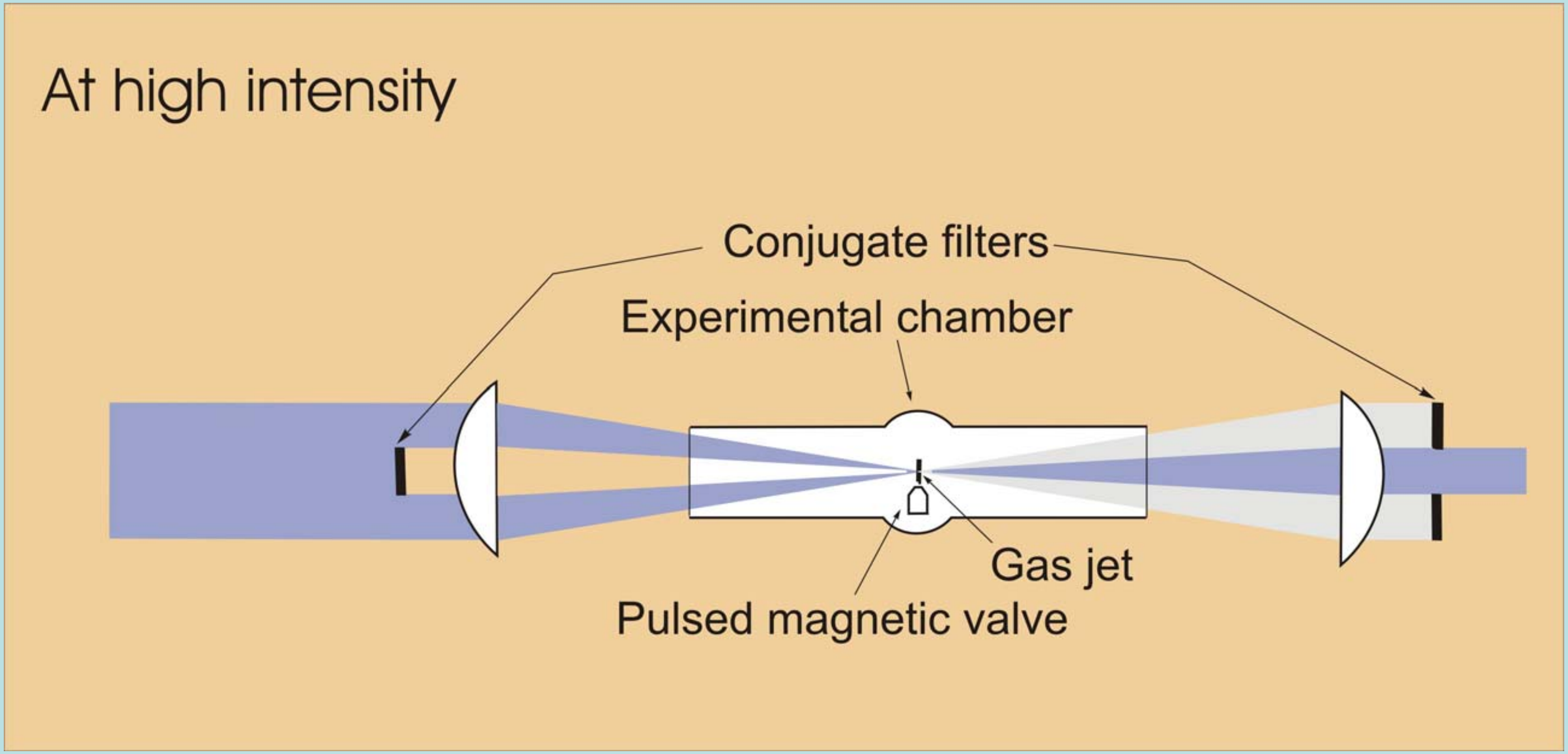
Input



Output



Experimental realization of the nonlinear plasma filter



Conclusion

Main features of the nonlinear plasma filter:

- high temporal contrast referred to the noise, sharpening of the leading edge,
- beam smoothing (spatial filtering),
- self-adjusting (no need for precise alignement),
- very high overall transmission.