



**Szatmári Sándor**

SzTE Kísérleti Fizikai Tanszék

**Rövidimpulzusú Ultraibolya Lézerek**

Szeged, 2012. február 2.

# Nagy Intenzitású Lézer Laboratórium High Intensity Laser Laboratory (HILL)



Nagy intenzitású lézer-anyag kölcsönhatások vizsgálata

VUV és XUV keltése

**100 µJ, < 500 fs 83 nm-en**

Excimer lézerrel pumpált rövid impulzusú lézerrendszerek kutatása, fejlesztése

**80 mJ, 600 fs (100 fs) 248 nm-en**



## Munkatársak



**Dr. Földes István** *tudományos tanácsadó*



**Dr. Bohus János** *egyetemi adjunktus*



**Dajka Rita** *tudományos segédmunkatárs*



**Barna Angéla** *PhD hallgató*

**mechanikai és elektromos műhely**

Important figure of merits  
of high intensity laser systems is

how they can temporally and spatially  
concentrate their energy



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

$$\Delta t \geq \frac{1}{c} \frac{\lambda}{\Delta \lambda} \lambda$$

$$I \sim E \frac{\Delta \lambda}{\lambda} \frac{1}{\lambda^3}$$

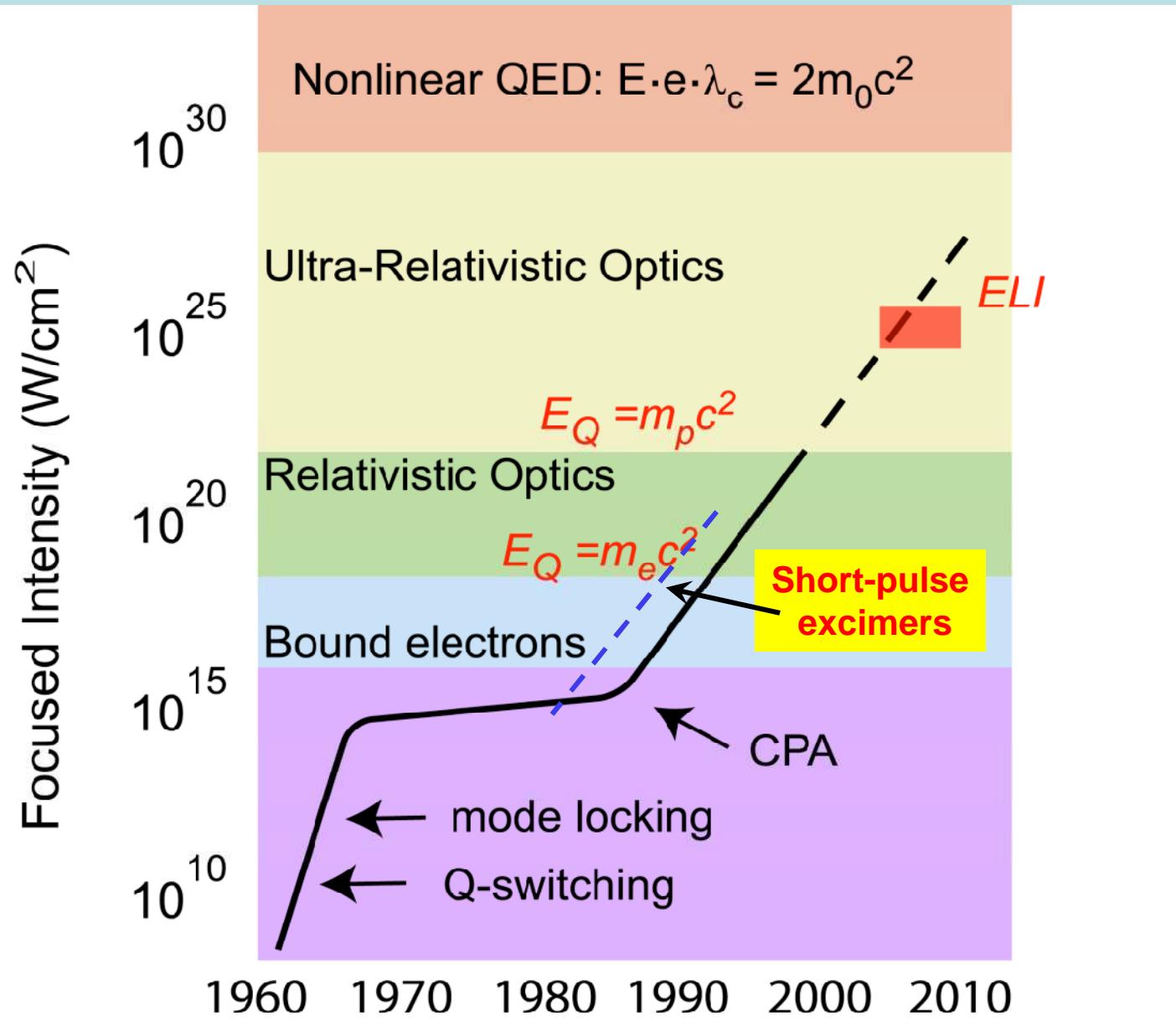
$$d \geq \frac{1}{n \cdot \sin \alpha} \lambda$$

solid-state (or OPA)

↓  
excimer

high harmonic generation

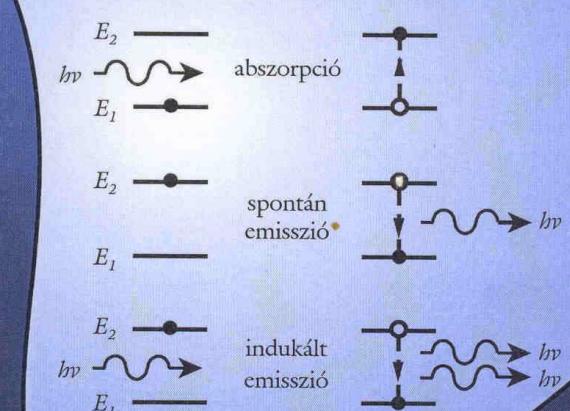
## Lézerek intenzitásának fejlődése



# BEVEZETÉS

Hevesi Imre  
Szatmári Sándor

## AZ ATOMFIZIKÁBA



DATPress  
Szeged 2002

Hétfizika

A. Einstein (1917)  
indukált emisszió

bekövetkezési valószínűség  $\sim$

$$B_{12} \propto N_1 w$$

$$A_{21} \propto N_2$$

$$B_{21} \propto N_2 w$$

$$A_{21} = \frac{16\pi^3}{3\epsilon_0 hc^3} \boxed{v^3} |M_{21}^0|^2$$

$$A_{21} = \frac{8\pi h}{c^3} \boxed{v^3} B_{21} \quad B_{21} = B_{12}$$

$$\frac{d}{d} = -(N_1 B_{12} - N_2 B_{21})w$$

$$\frac{h\nu d}{V d} = -(N_1 B_{12} - N_2 B_{21}) \frac{h\nu}{c} \frac{1}{V} w$$

$$\frac{d}{d} = -(n_0 \sigma_a - n_1 \sigma_e)w$$

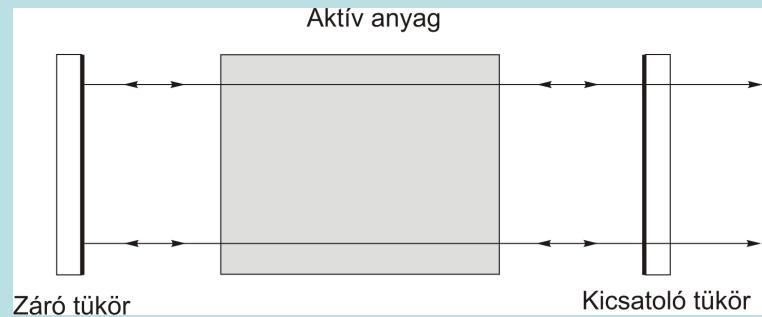
$$\frac{dI}{d} = -(n_0 \sigma_a - n_1 \sigma_e)I$$

$$n_0 = \frac{N_1}{V} \quad \sigma_a = \frac{h\nu}{c} B_{12}$$

$$n_1 = \frac{N_2}{V} \quad \sigma_e = \frac{h\nu}{c} B_{21}$$

$$d = cd$$

## Gyakorlati lézer elrendezések

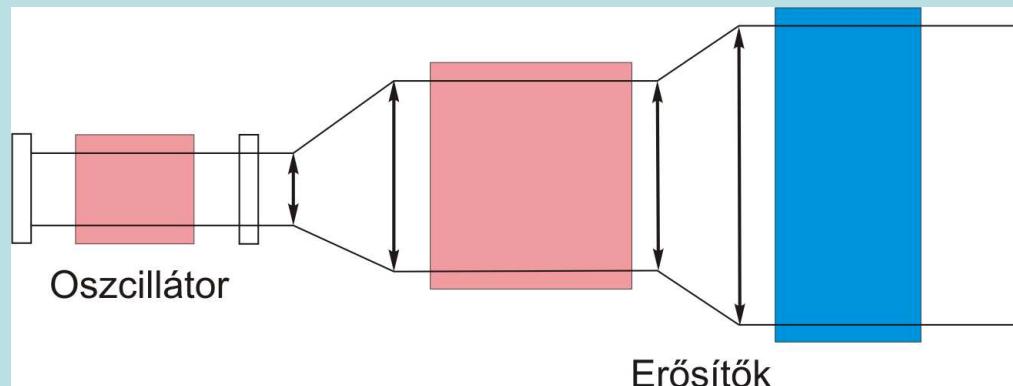


A konvencionális elrendezésekben a fény többszöri körbejárása szükséges a rendezett fény keletkezéséhez.

$$A_{21} = \frac{8\pi\hbar\nu^3}{c^3} B_{21}$$

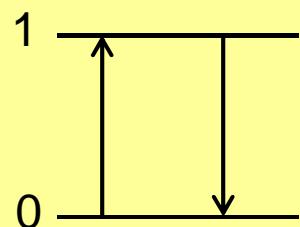
$$\tau \sim \frac{1}{\nu^3} \quad \left( A_{21} = \frac{1}{\tau} \right)$$

Rövid hullámhosszakon az energia jó tér és időbeli koncentrálására alkalmas lézerek más felépítésűek.



Gerjesztés:

2 szintes rendszer



optikai pumpálás

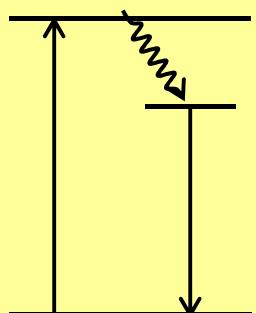
$$\frac{d}{dt} n_1 = I_p \sigma_a n_0 - I_p \sigma_e n_1 - \frac{n_1}{\tau}$$

stac. eset:  $\frac{d}{dt} n_1 = 0$

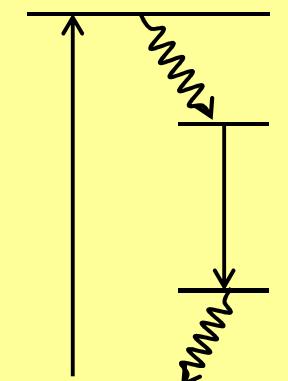
$$I_p \sigma_a n_0 = I_p \sigma_e n_1 + \frac{n_1}{\tau}$$

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

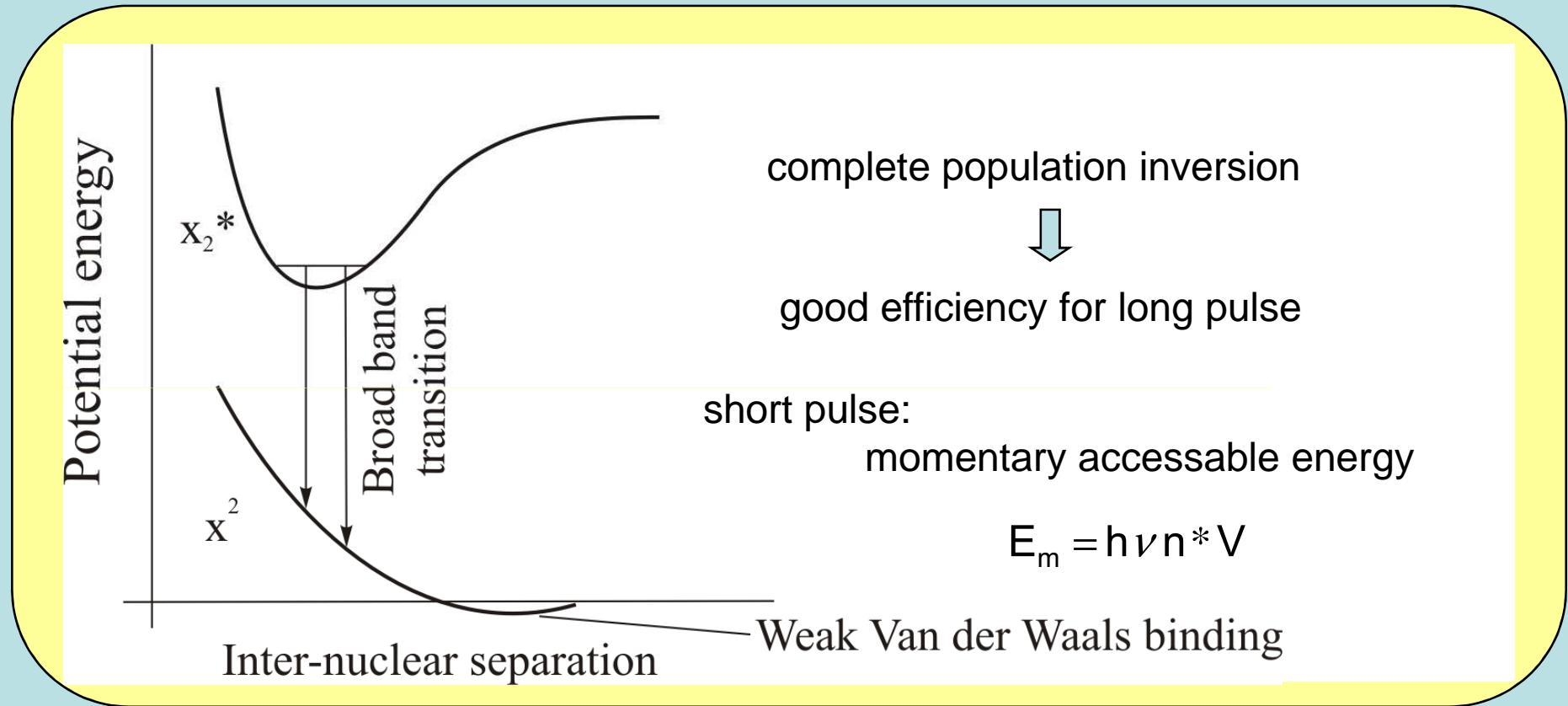
3 szintes rendszer



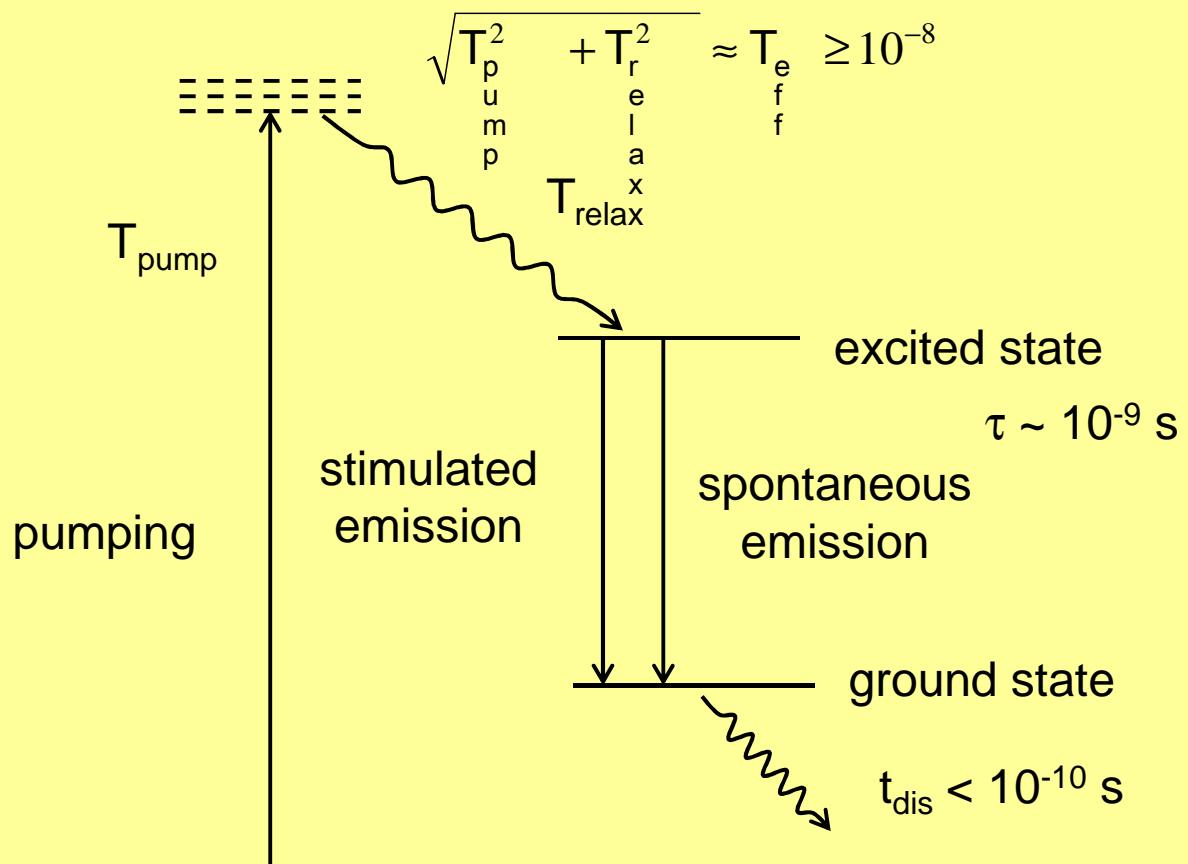
4 szintes rendszer



## Potential energy curves for a typical excimer molecule

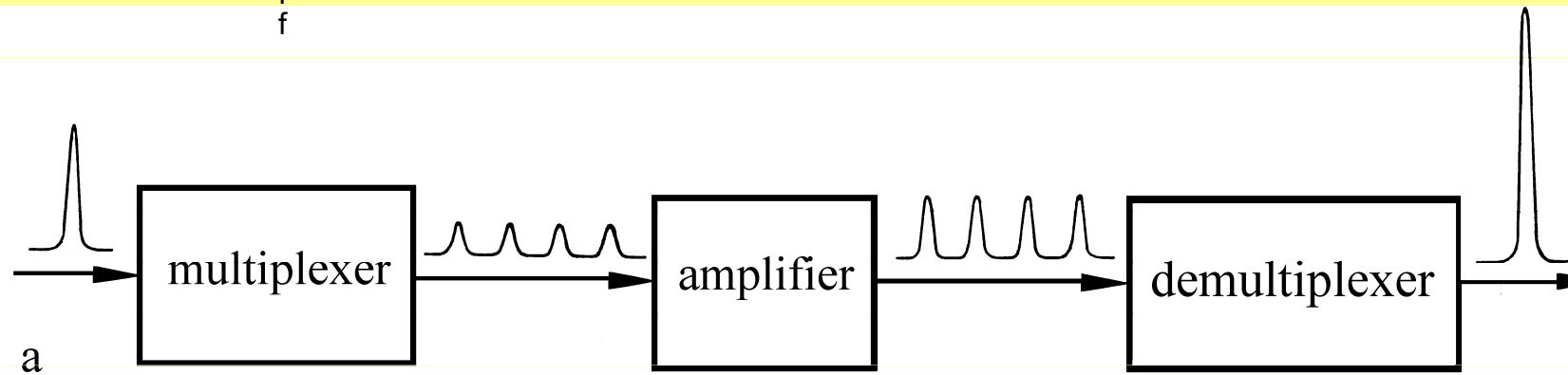


## Typical level diagram of an excimer molecule



# Optical multiplexing

$$\frac{\tau}{T_{eff}} = \frac{E_m}{E_t} = \frac{1}{n}$$



a

output

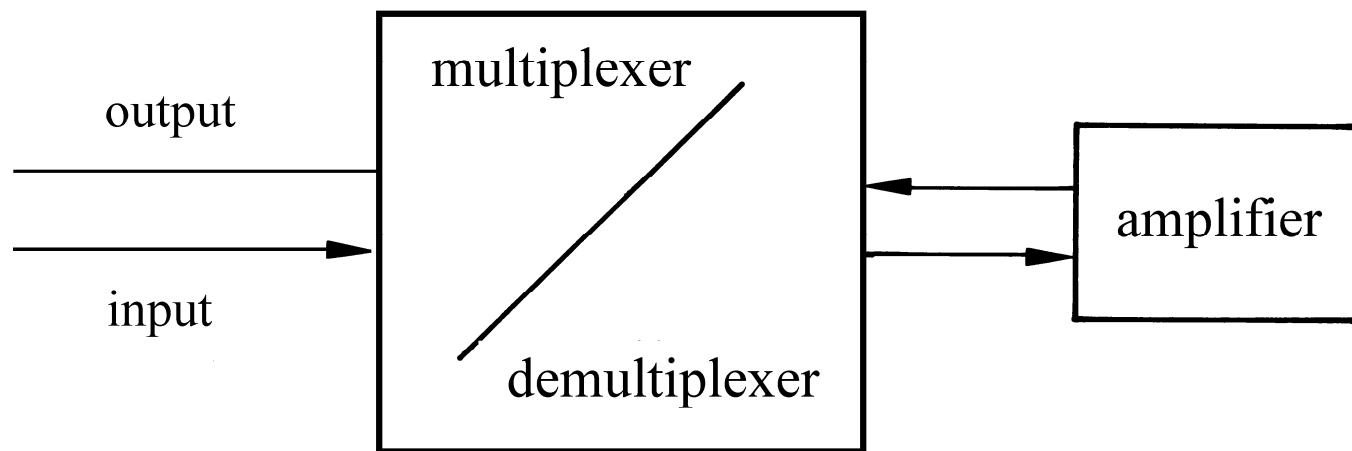
input

multiplexer

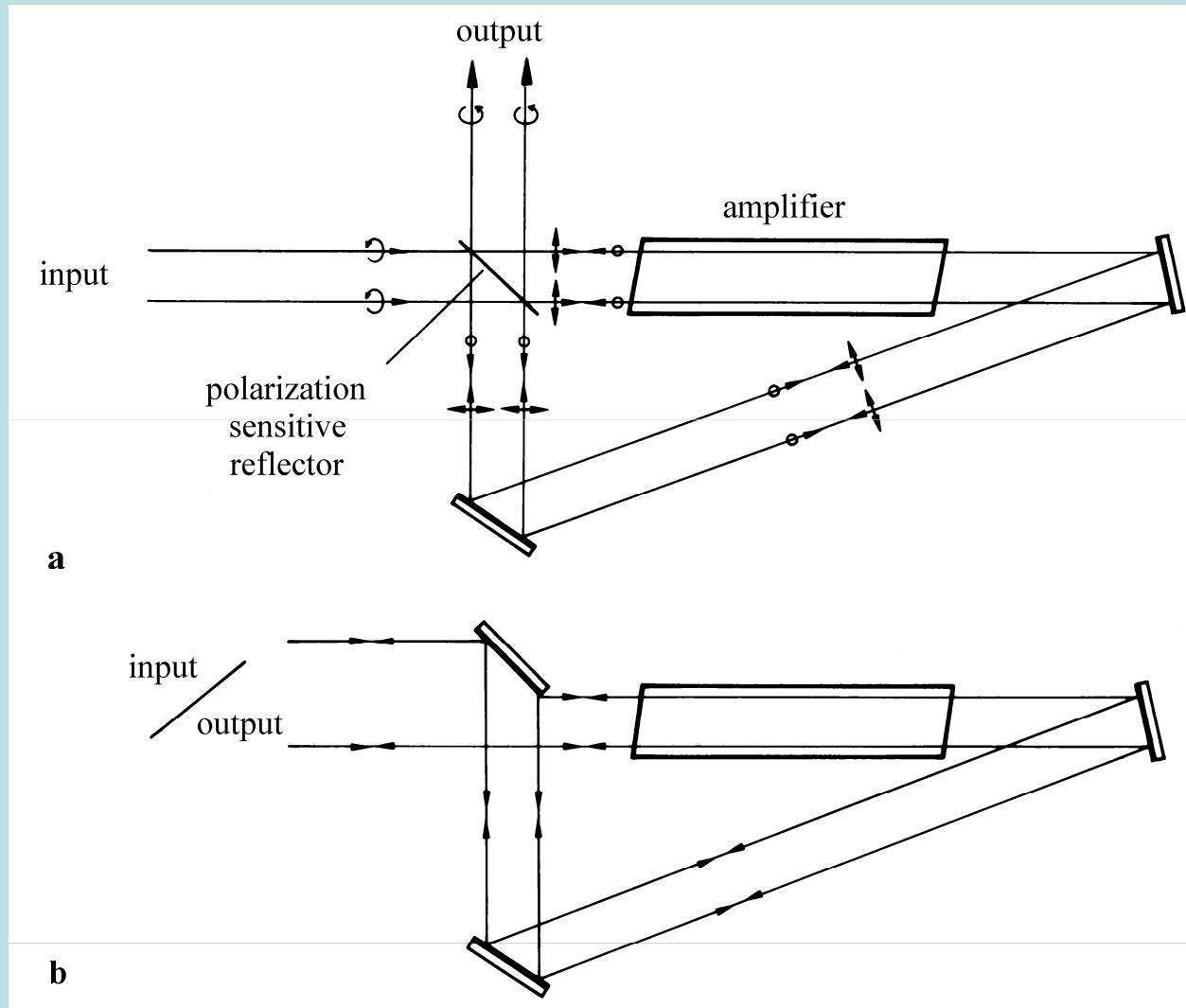
amplifier

demultiplexer

b

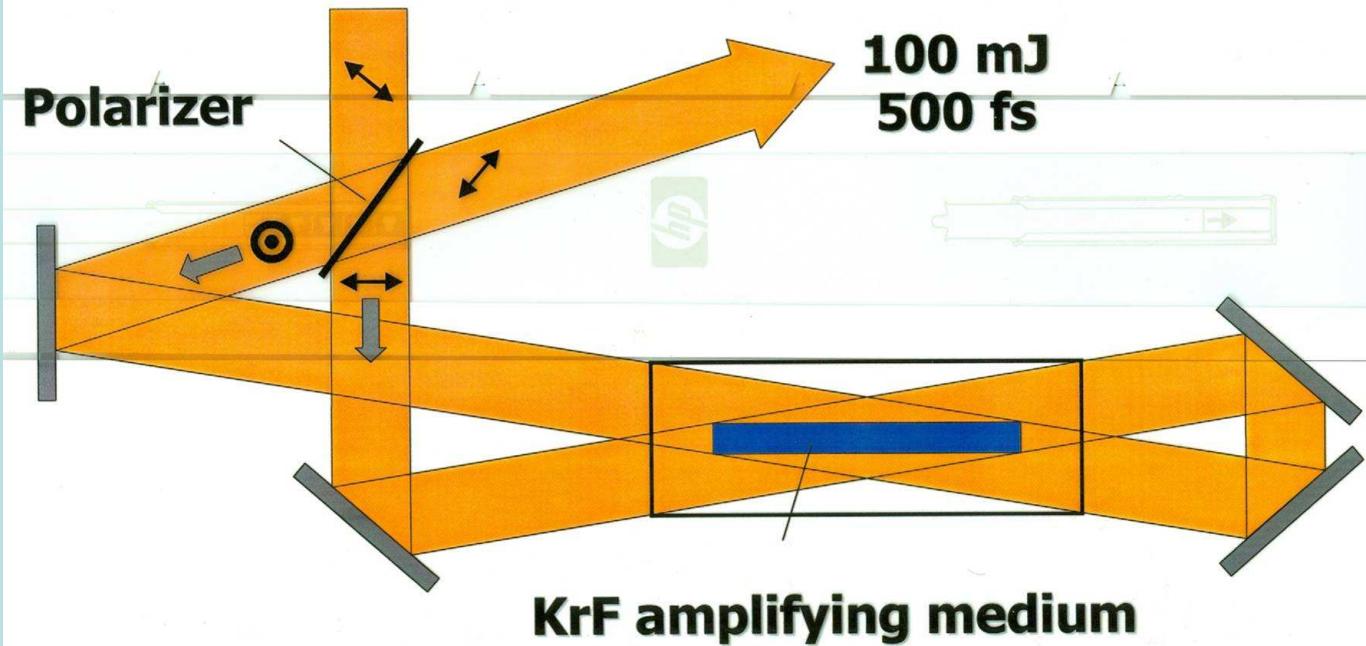


# Practical multiplexing schemes of interferometric accuracy (based on Sagnac interferometers)



(already operational)

## Interferometric Multiplexing



## Rövid impulzusok erősítése abszorpció esetén

$$\frac{\partial I}{\partial x} + \frac{1}{v} \frac{\partial I}{\partial t} = In_1\sigma_e - I\alpha$$

$$[g(x) = \sigma_e n_1(x)]$$

$$\frac{\partial n_1}{\partial t} = -In_1\sigma_e$$



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

$$\alpha = 0$$

**Frantz-Nodvik formula**

$$\alpha \neq 0$$

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

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

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

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

$\alpha = 0$

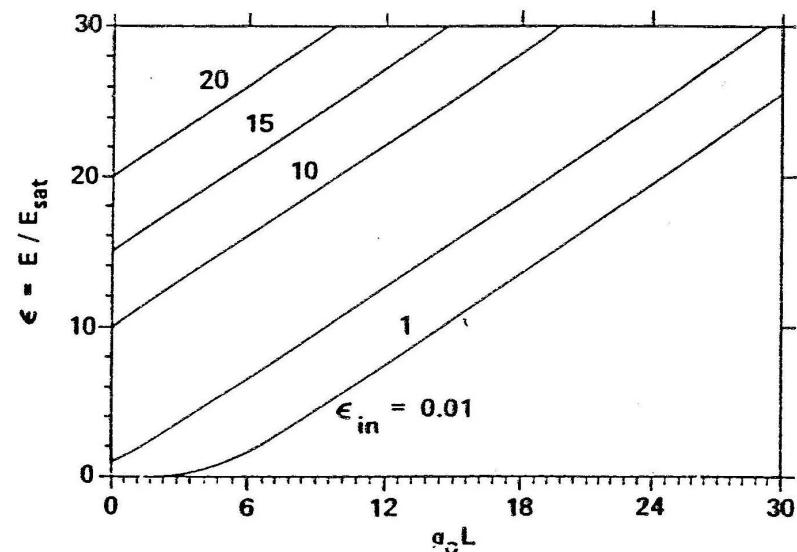


FIG. 1. Normalized laser energy in an amplifier vs total gain in a medium, with no absorption.

$g/\alpha = 15$

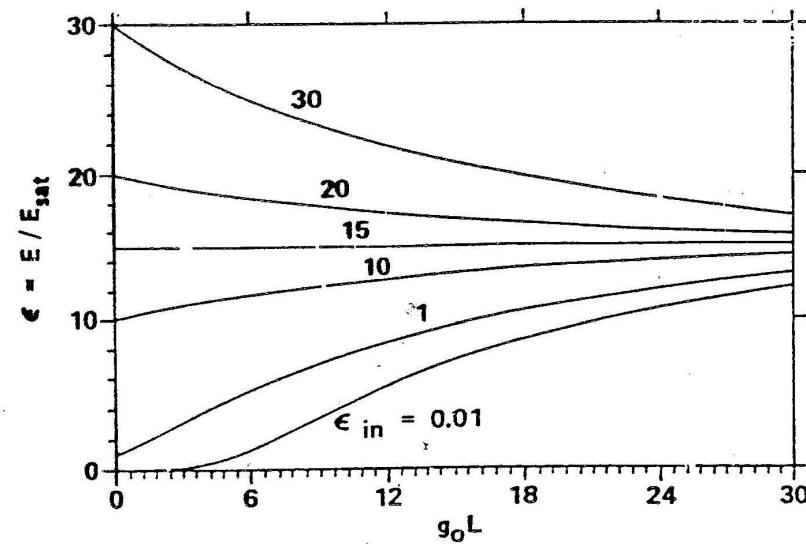
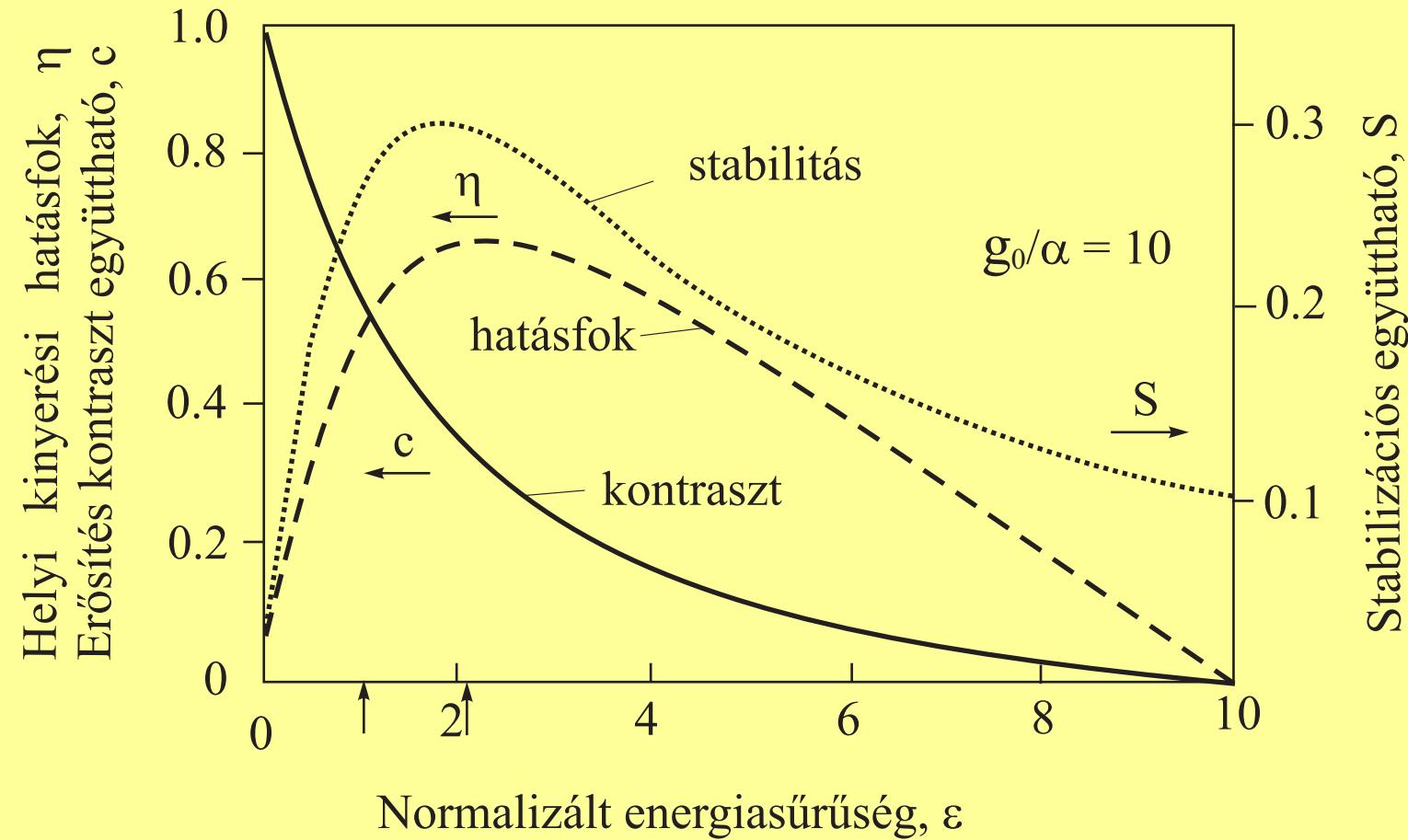


FIG. 2. Normalized laser energy in an amplifier vs total gain in a medium with absorption of  $\alpha = g_0/15$ . Convergence takes place at  $E/E_{\text{sat}} = 15$  for large  $g_0 L$ , as predicted by the analysis.

## Optikai erősítők főbb paraméterei az energiasűrűség függvényében



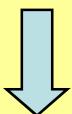
## A tér- és időbeli kontraszt fontossága

Az irány szerinti tulajdonságok (a nyaláb homogenitás) megszabják a fókuszálhatóságot.

Az időbeli (vagy intenzitás) kontrasztnak olyannak kell lenni, hogy a zaj ne lépjen kölcsönhatásba a targettel.

Ennek a határa  $10^7\text{-}10^{10}\text{ W/cm}^2$ .

A hasznos jel megcélzott intenzitása  $10^{25}\text{ W/cm}^2$



A megkívánt intenzitás kontraszt  **$10^{15}\text{-}10^{18}$  !**

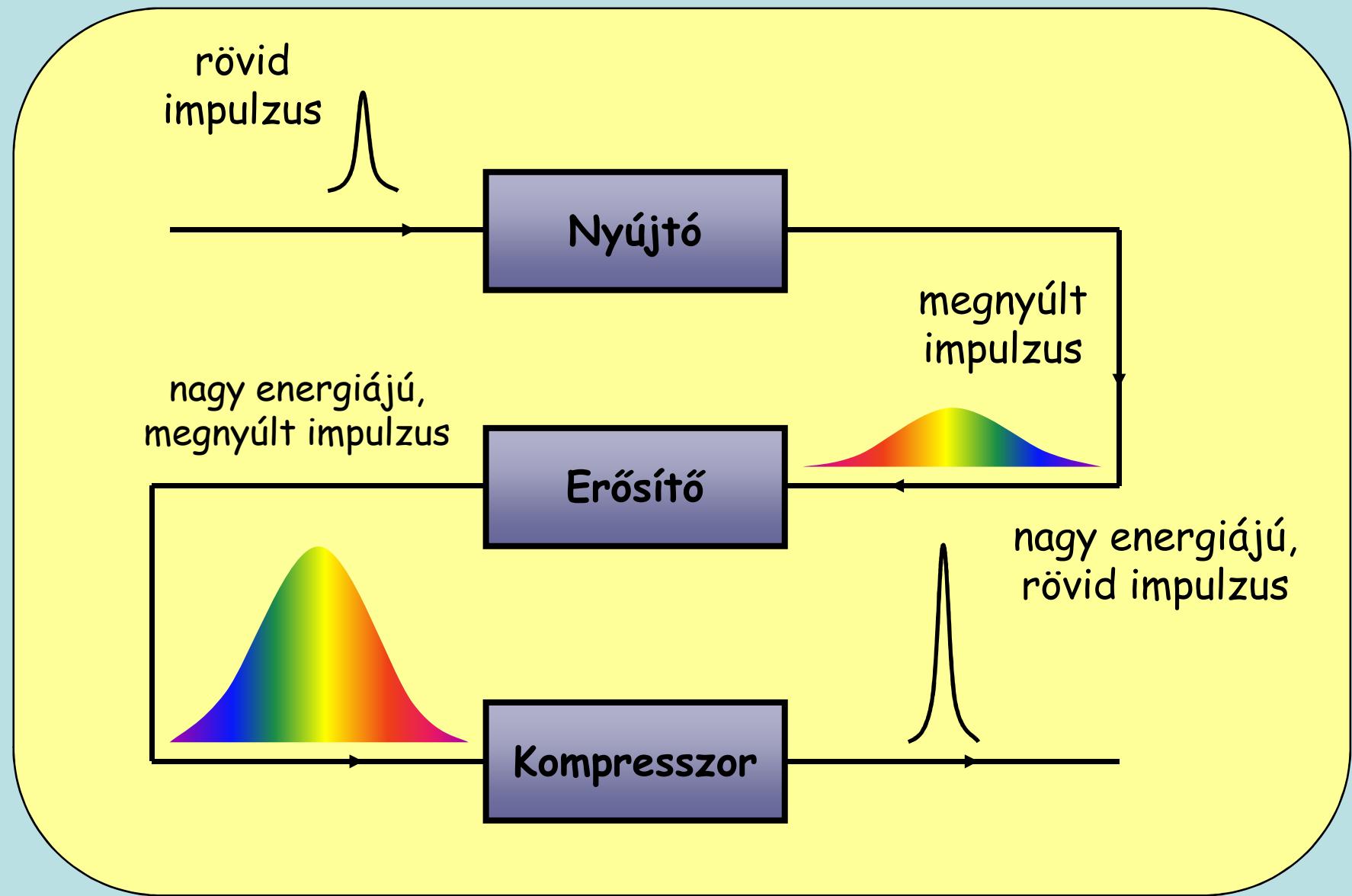
Optikai erősítők a jó hatásfoknak megfelelő tartományban a hasznos jelet kevésbé erősítik, mint a zajt.

Ezt elvileg kompenzálni lehet telítődő abszorberekkel, melyek telítés esetén nagyobb transzmissziót eredményeznek a hasznos jelre.

A zaj összetétele: ASE  
CPA-ból származó jel

# Fázismodulált impulzuserősítés

## Chirped Pulse Amplification (CPA)



## A „kétszínű” lézerrendszerek előnyei

a rövid impulzus

keltése

erősítése

} optimális helyen végezhető

Erősítés egy része hosszú hullámhosszon

nemlineáris zajszűrés (ASE)

spektrális szűrés

aktív térszűrés

hosszú hullámhosszú  
oszcillátor és erősítő

frekvencia-  
konverter

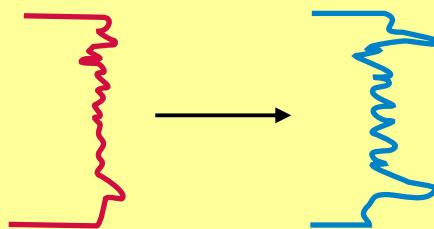
rövid hullámhosszú  
végerősítő



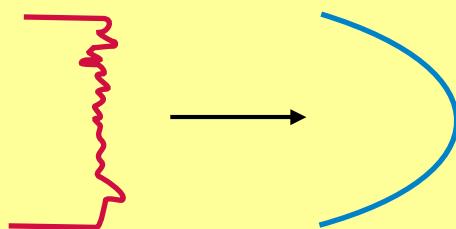
# A nyaláb térbeli tulajdonságainak változása nemlineáris frekvencia-konverzió esetén.



**klasszikus eset:**

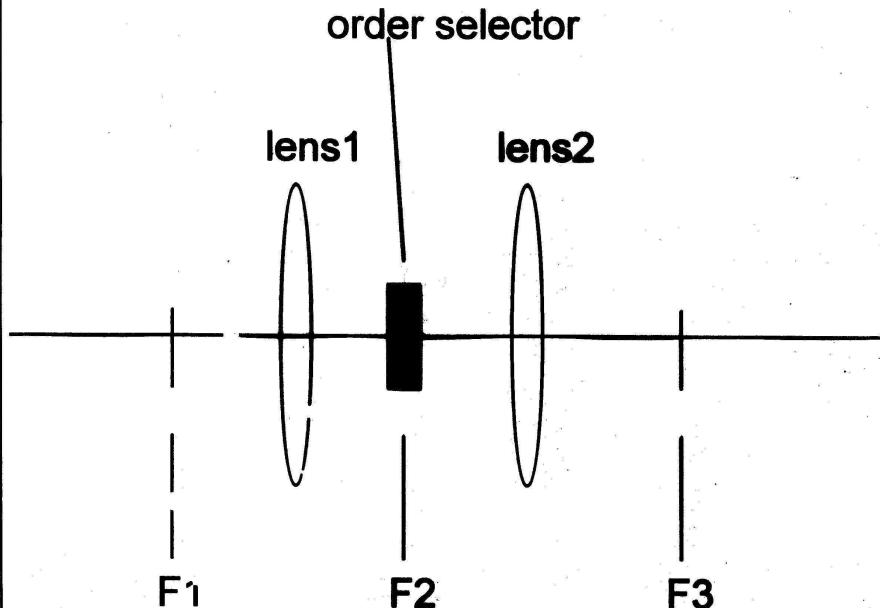


**„ideális” eset:**

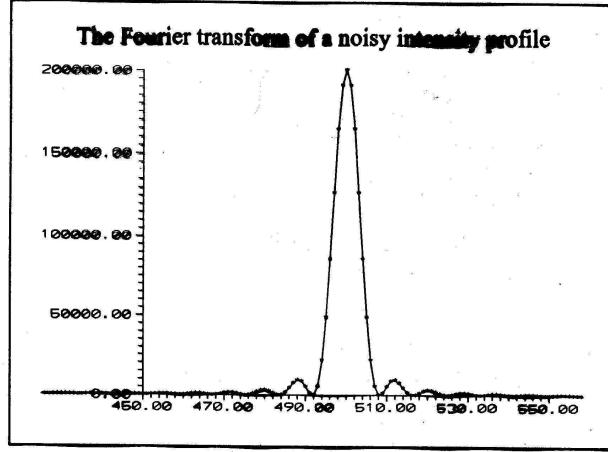
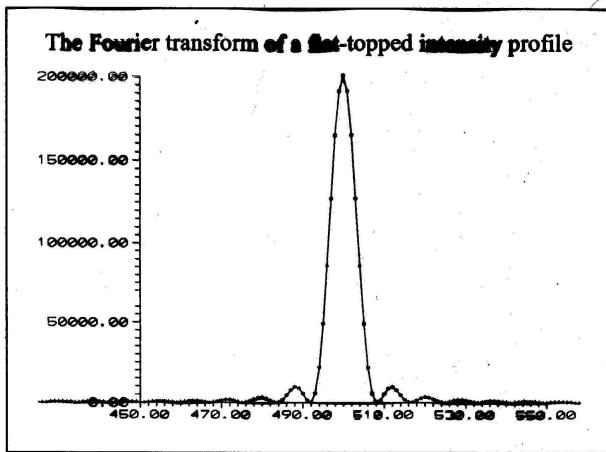
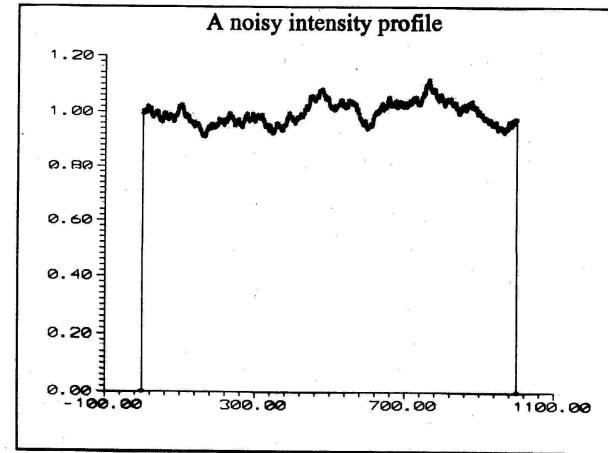
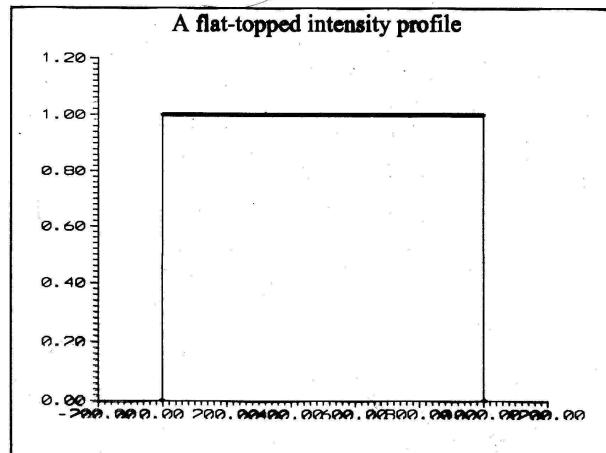


## a) Spatial filtering

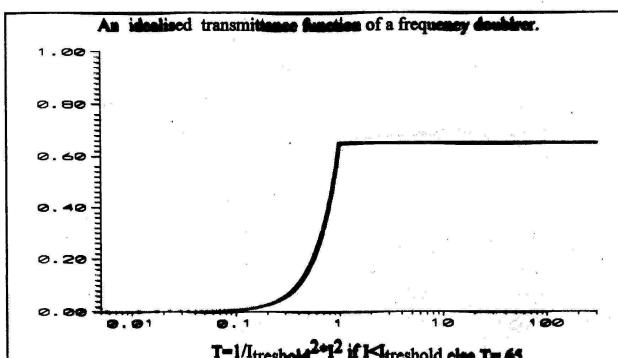
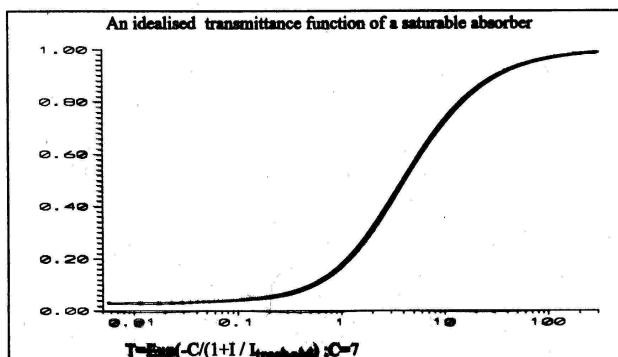
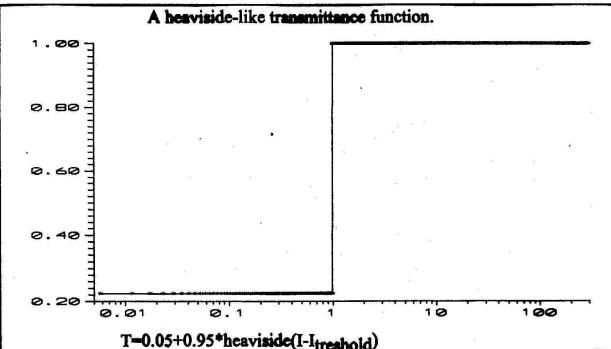
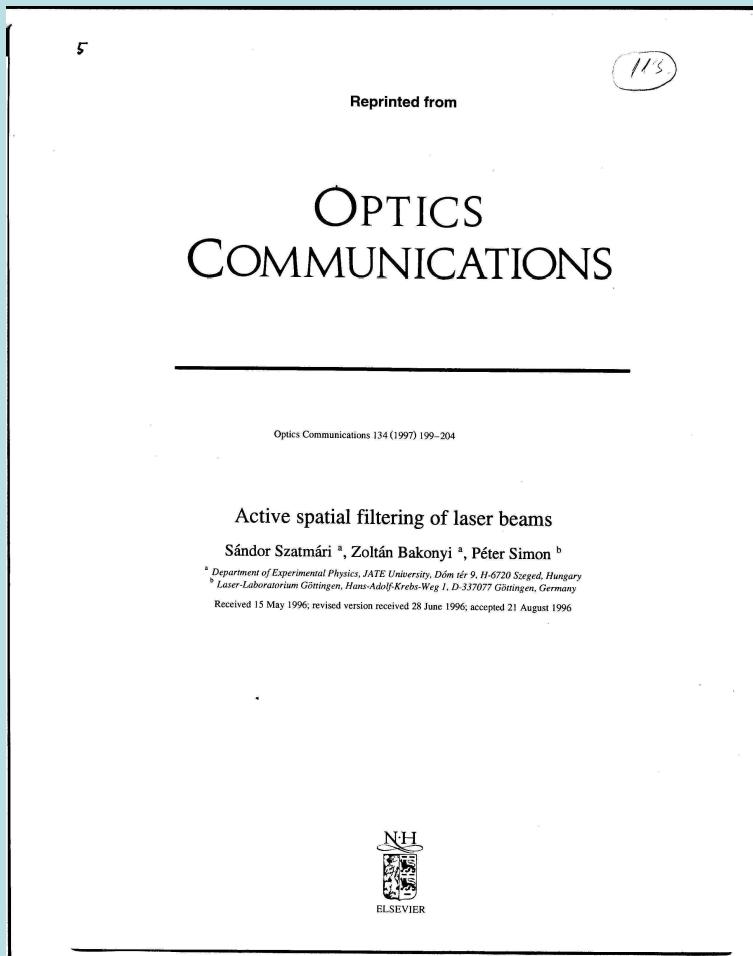
Confocal arrangement for fourier filtering of  
laser beams



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



# *Active spatial filtering: Nonlinear transmission instead of the aperture*



## SHG

# Saturable absorber as an order selector

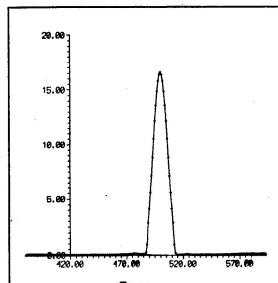
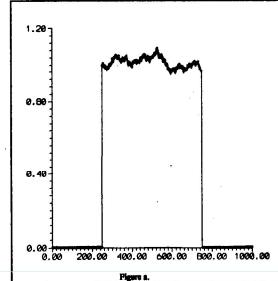


Figure a : A noisy intensity profile.

Figure b : It's Fourier transform

Figure c : The Fourier transform filtered with the transmittance of:

$T = 0.65 / (I_{threshold})^{2*1^2}$  if  $I < I_{threshold}$  else  $T = 0.65$  ;  $I_{threshold} = 4$

Figure d : The re-transformed , filtered picture.

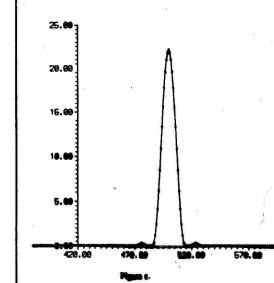
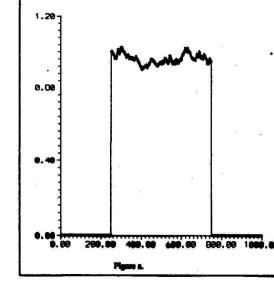
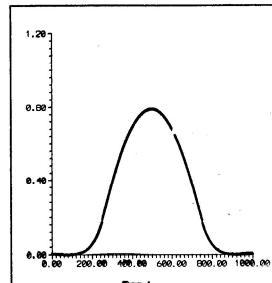
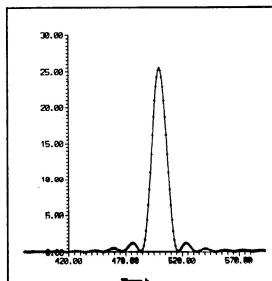


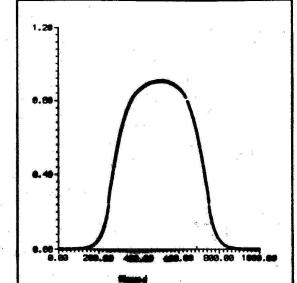
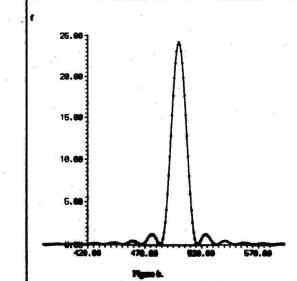
Figure a : A noisy intensity profile

Figure b : It's Fourier transform

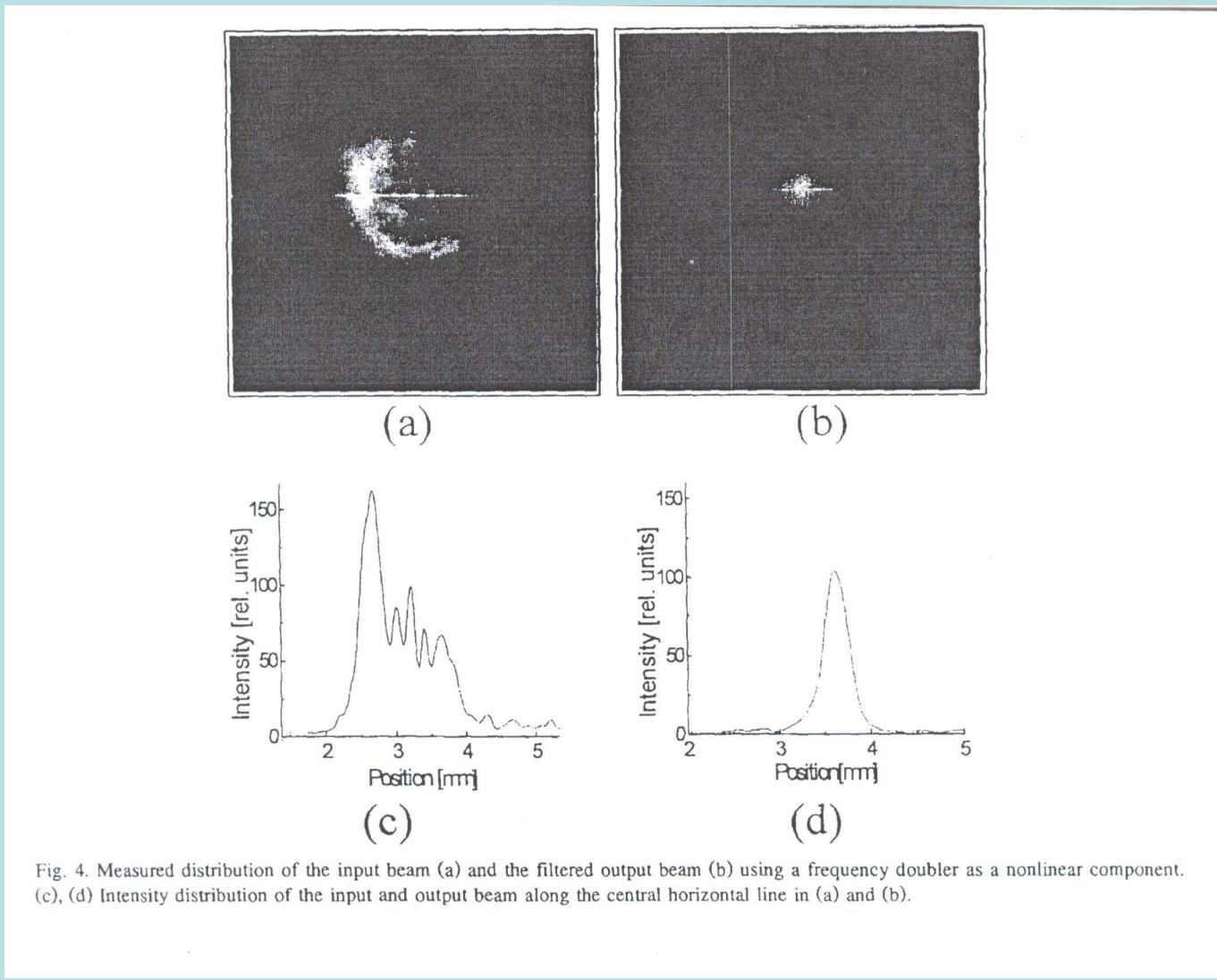
Figure c : The Fourier transform filtered with the transmittance of:

$T = \text{Exp}(-C/(1+I/I_0))$  ;  $C = 7$  ,  $I_0 = 0.3$

Figure d : The re-transformed , filtered picture.



# Kísérleti eredmények



**„Kétszínű” lézerek:**

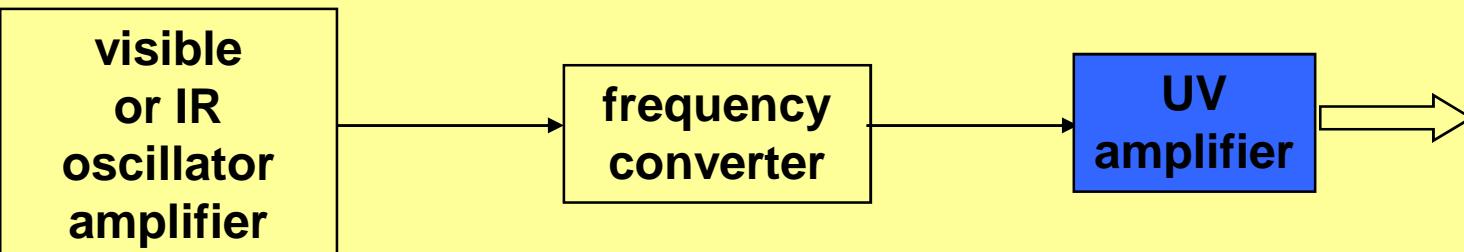
**a „színváltásnál” mind az idő, mind a térszűrés megvalósítható  
(ezzel a spektrális tulajdonságok és a nyalábhomogenitás is kontrollálható)**

**„Egyszínű” lézerek:**

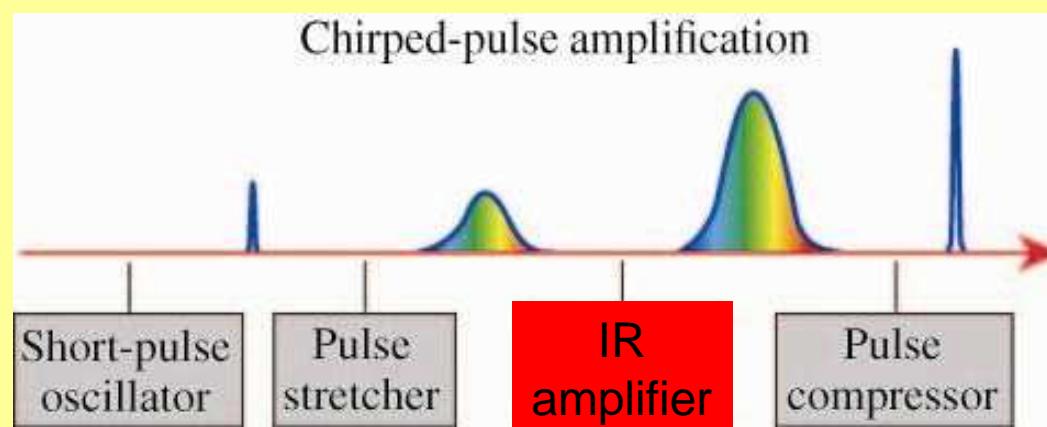
**?**

# Architecture

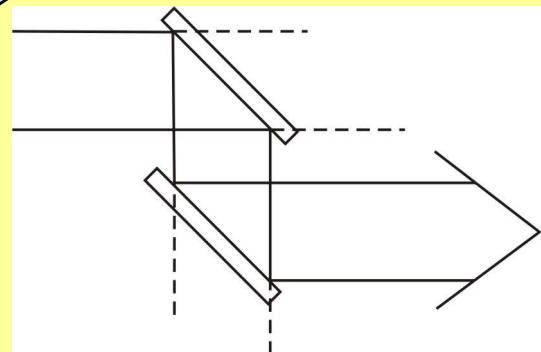
short-pulse excimer lasers are double wavelength systems



solid-state systems use CPA



## b) Temporal filtering

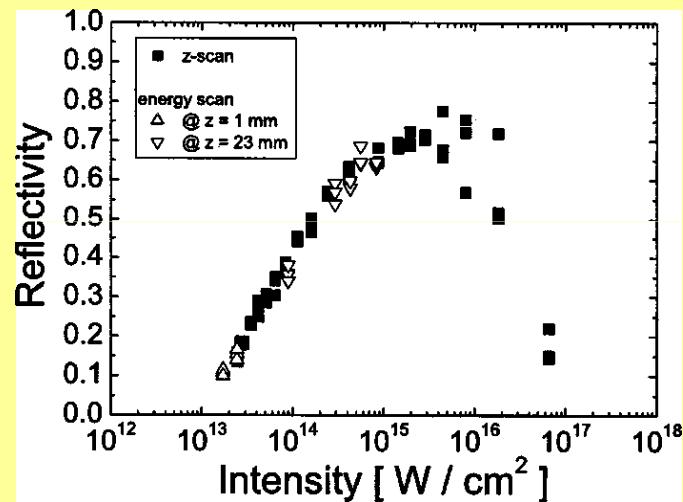


Plasma mirror technique  
intensity dependent reflection



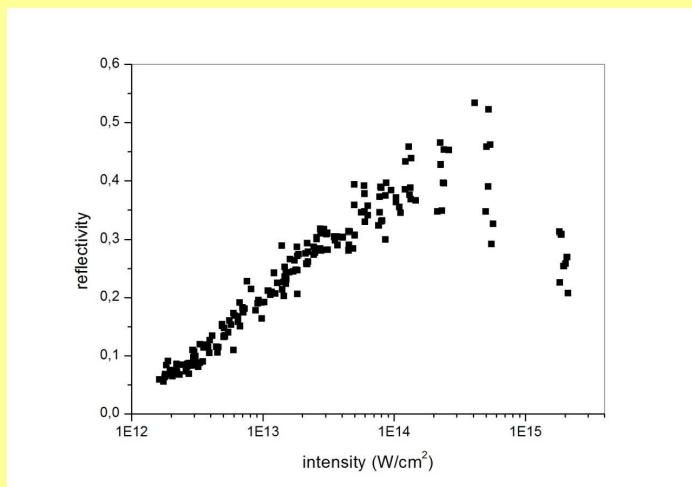
temporal modulation

Ti:Sa



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

KrF



I.B. Földes et al, Rad. Eff. & Def. **165**, 429 (2010)

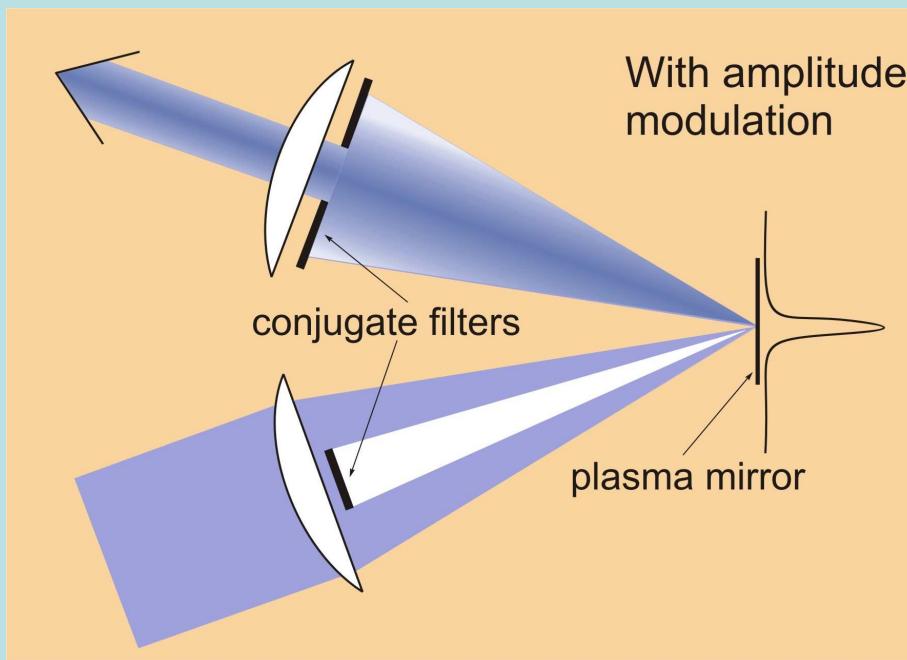
- Disadvantages:**
- loss in energy (power),
  - limited improvement in the contrast (governed by the ratio of the plasma reflectivity and of the reflectivity of the sample) (more one order of magnitude improvement for one mirror),
  - optical quality of the plasma front influences the phase front,
  - fresh target area is needed for each shot.

# 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.

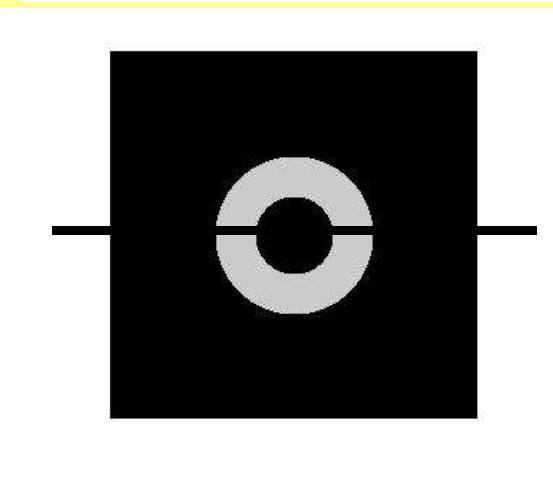
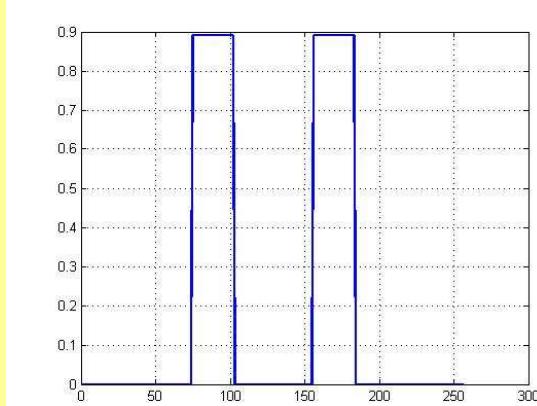
If the reflectivity (either the amplitude or the phase) is different for the more intense central lobe of the diffraction pattern, the central hole of the aperture becomes illuminated.



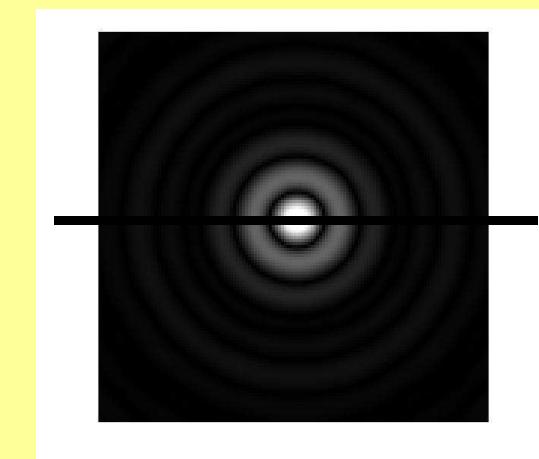
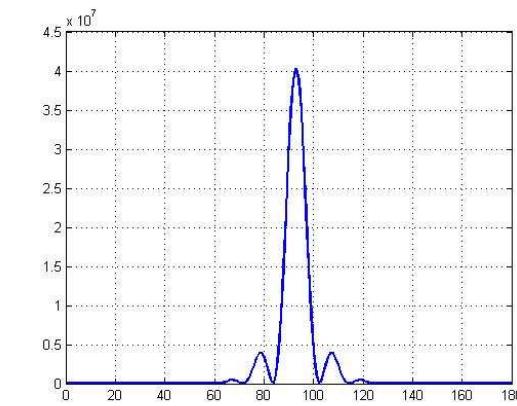
Extremely high contrast!

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

Input



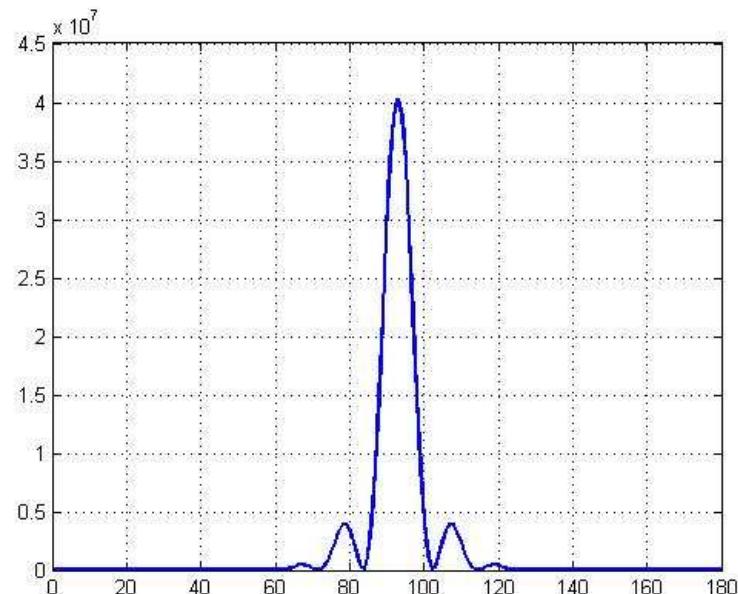
Fourier-plane:



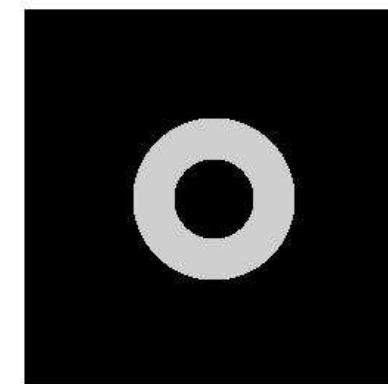
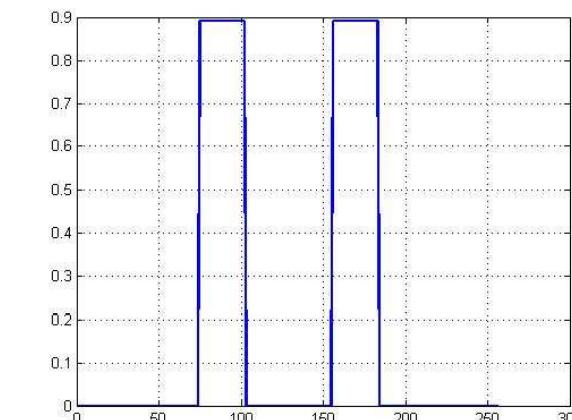
## Output distribution:

### a) With no modulation at the Fourier-plane

#### Fourier-plane



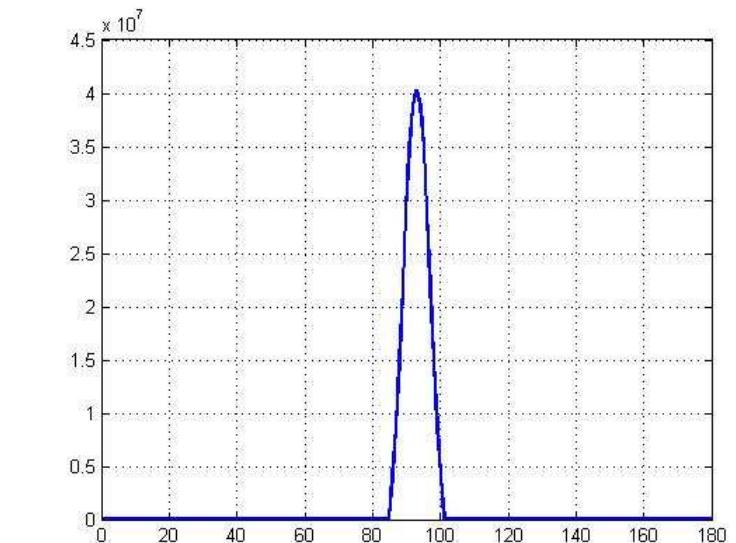
#### Output



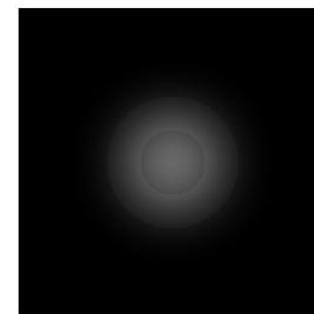
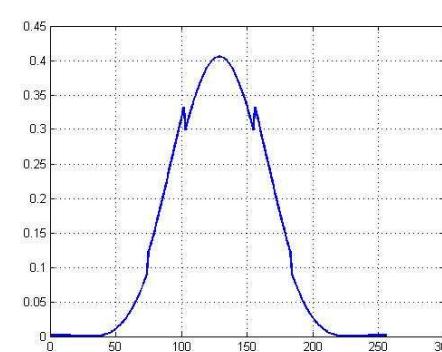
## b) With amplitude modulation at the Fourier-plane:

higher (than 0th) orders are suppressed by a factor of 25 (plasma mirror effect)

Fourier-plane



Output



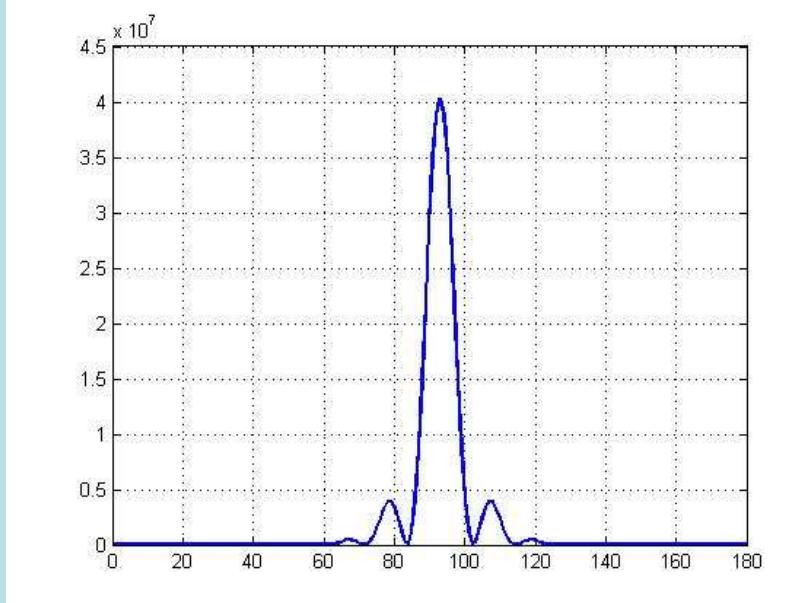
Disadvantages: limited throughput (diffraction losses, limited plasma reflectivity)  
fresh target area is needed for each shot.

**Much better results are obtained and simultaneous temporal and spatial filtering occurs, when phase modulation is introduced in the focal plane instead of amplitude modulation.**

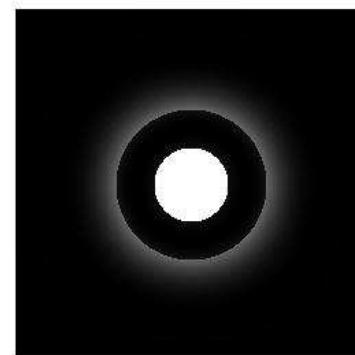
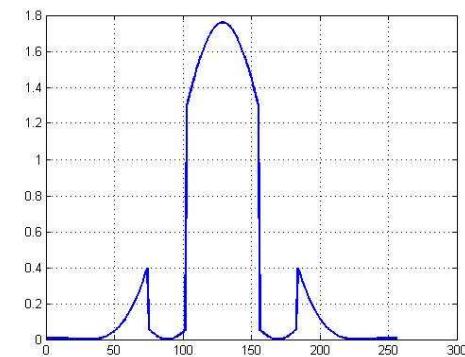
**c) With phase modulation at the Fourier-plane:**

the 0<sup>th</sup> order is shifted by  $\lambda/2$  (in the self generated plasma)

Fourier-plane



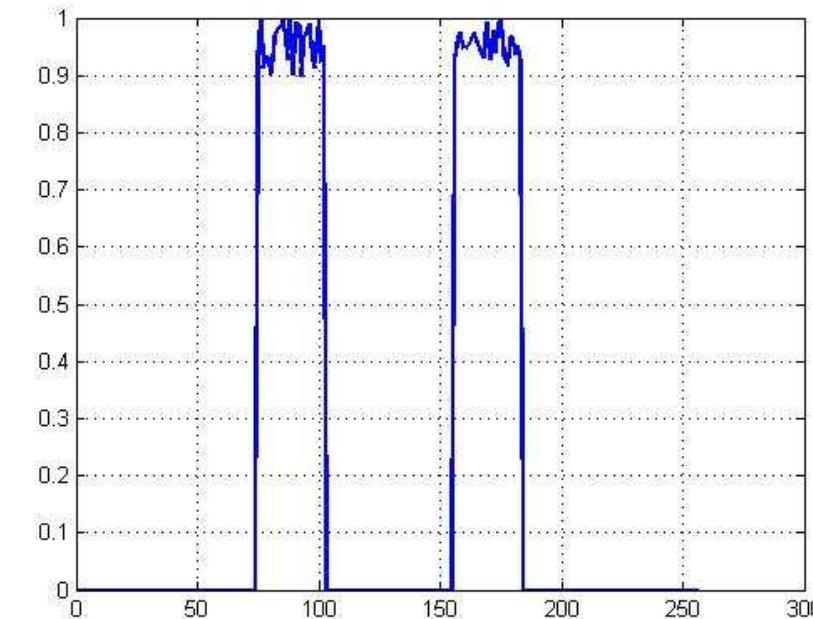
Output



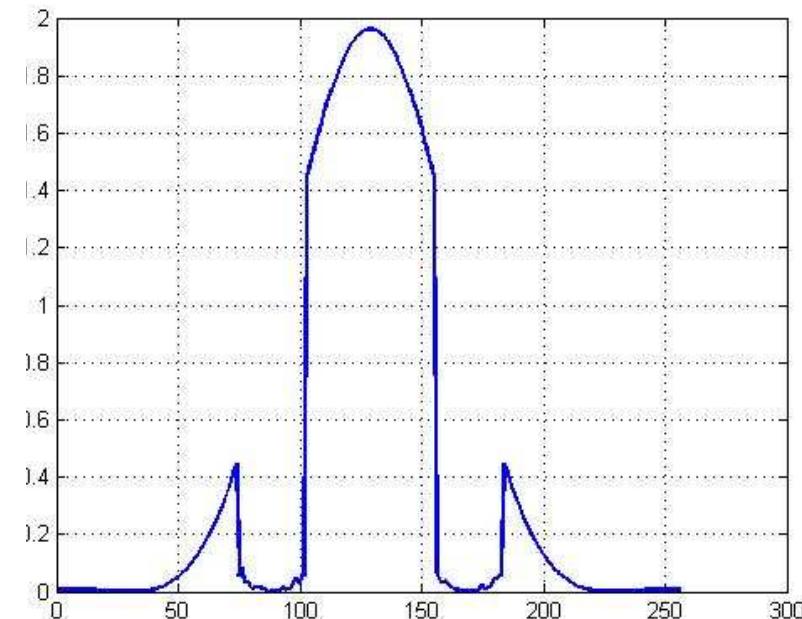
# Simultaneous spatial filtering occurs in the central (transmitted) part of the beam

Output distribution with noisy input  
with phase modulation at the Fourier-plane:  
the 0<sup>th</sup> order is shifted by  $\lambda/2$

Input



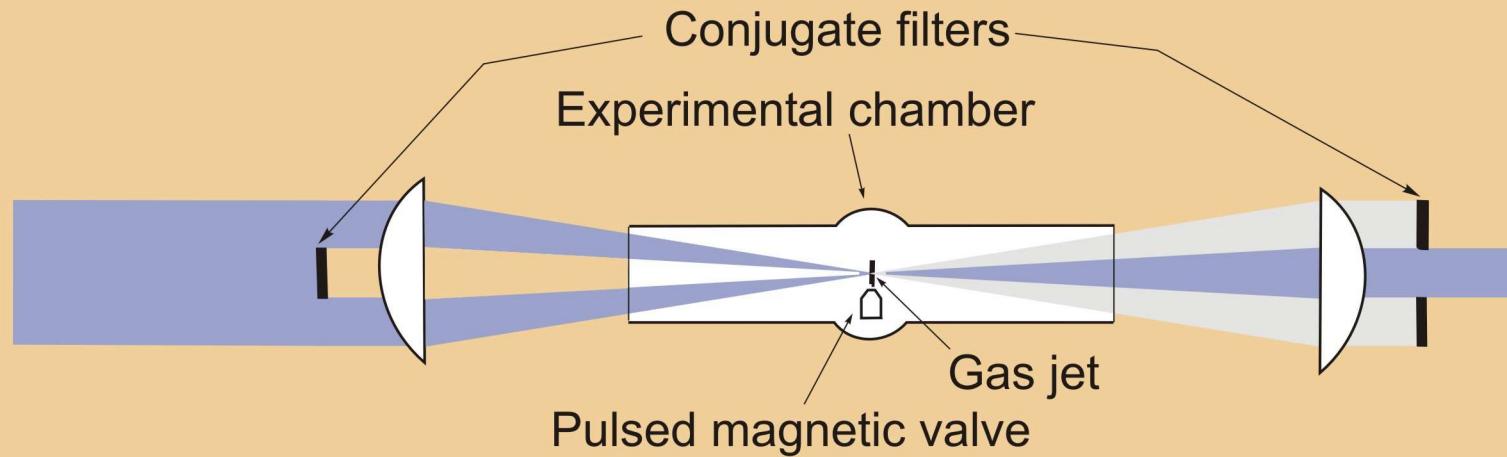
Output



**Self-focusing in a self-generated laser plasma in a gas jet  
is capable of shifting the phase of the central lobe of the  
diffraction-pattern by  $\lambda/2$ .**

*Experimental realization of the nonlinear plasma filter*

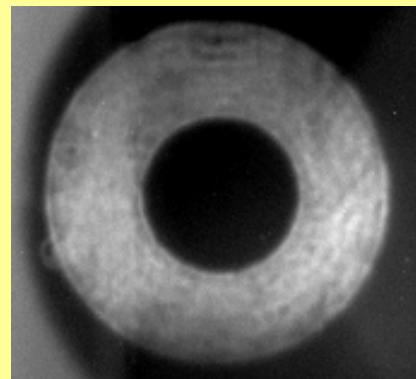
At high intensity



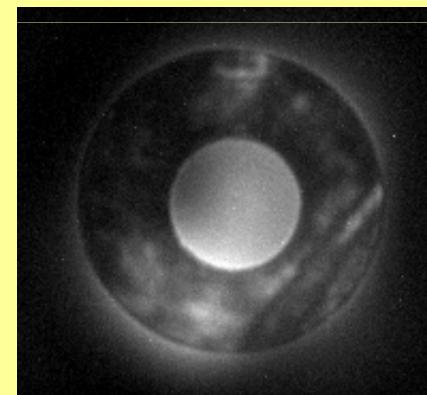
# Experimental results

- a Kepler telescope of  $f = 670\text{mm}$  focal length
- argon as a nonlinear medium
- pulsed gas jet of 1mm diameter, opened for  $\sim 1.5\text{ ms}$

Without gas in the focus

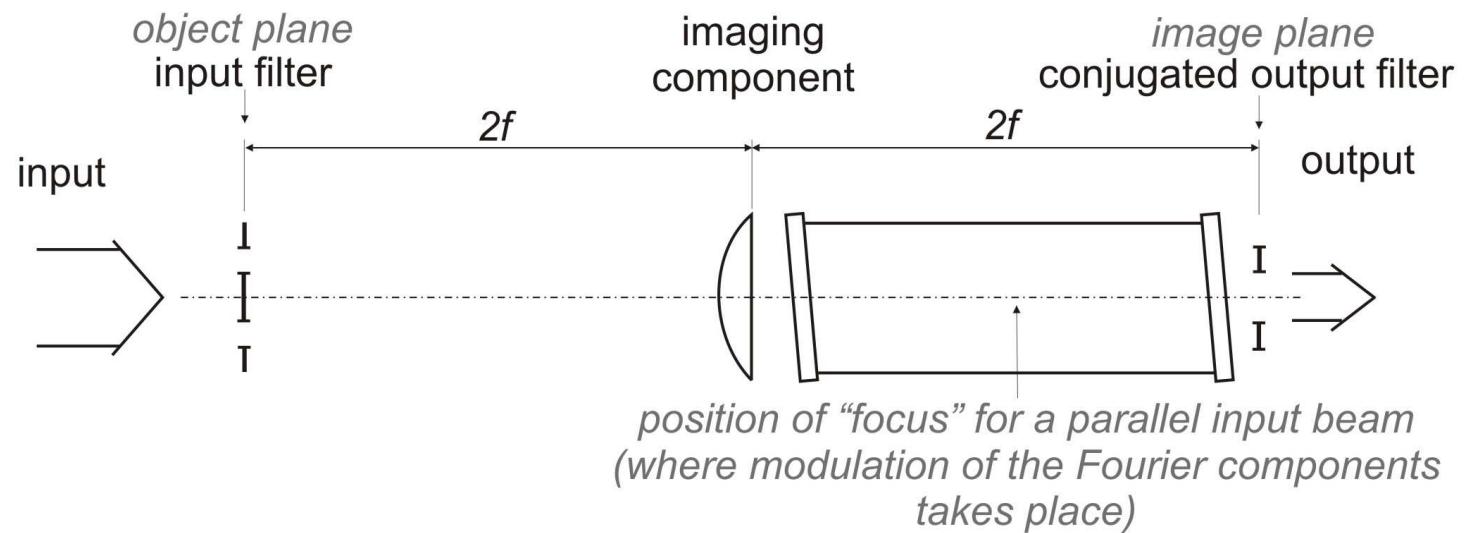


With gas in the focus  
(plasma generation)



Understanding/description of the „transversal” effects in the Fourier-plane, together with optimization of the experimental parameters for maximum throughput ( $> 40\%$ ) and contrast ( $> 10^3$ ) are in progress.

# Nonlinear filter as an image system



# Conclusion

Main features of the nonlinear plasma filter:

- high improvement of the temporal contrast ( $>10^3$ ) sharpening of the leading edge (temporal filtering),
- beam smoothing (spatial filtering),
- self-adjusting (no need for precise alignment),
- applicable in a broad wavelength range,
- very high overall transmission ( $>40\%$  obtained experimentally).

**Köszönöm a figyelmet!**

**(és az érdeklődést!)**