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Sándor Szatmári

R. Dajka, A. Barna, B. Gilicze, I.B. Földes

Contrast improvement by nonlinear temporal and spatial filtering of high-power laser beams

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NEW SZÉCHENYI PLAN

"The project was partially funded by „TÁMOP-4.1.1.C-12/1/KONV-2012-0005 – „Preparation of the concerned sectors for educational and R&D activities related to the Hungarian ELI project.” is supported by the European Union and co-financed by the European Social Fund."

Important figure of merits
of high intensity laser systems is

how they can temporally and spatially concentrate their energy

$\Downarrow$

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

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

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

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

excimer

solid-state (or OPA)

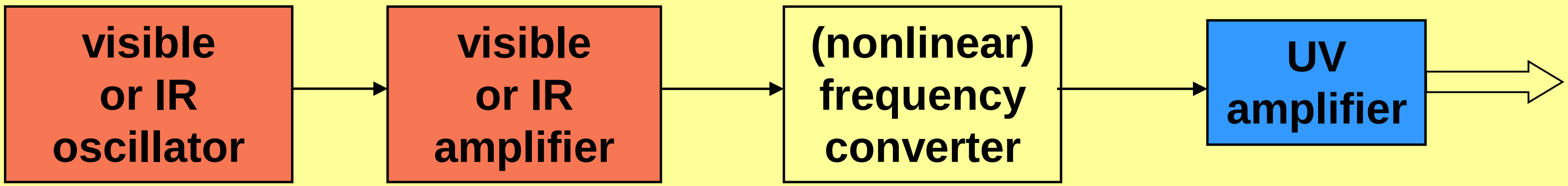
Requirements for the temporal contrast

Focused intensity of present laser systems approches 10^{22} W/cm^2 (ambitions plans are targeting 10^{25} W/cm^2).

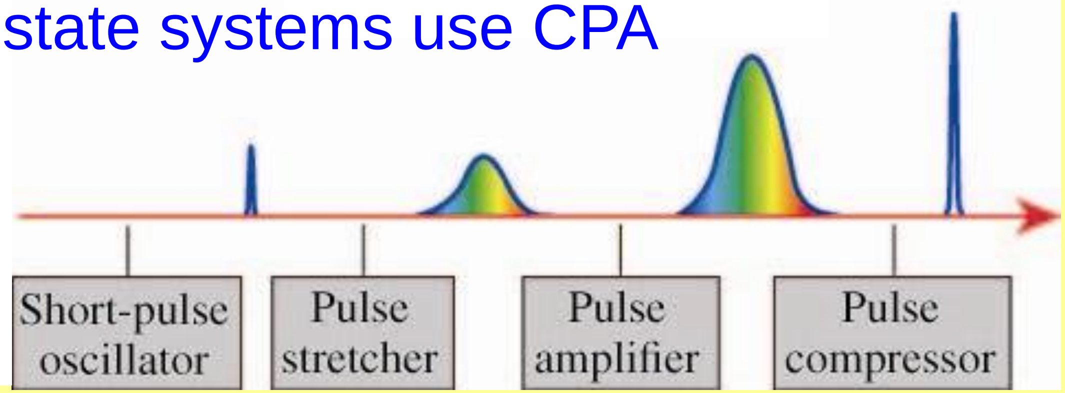
Intensity limit of prepulses of $10^7 – 10^8$ W/cm^2 (where plasma generation and/or photoionization) occurs, sets the necessary **contrast** beyond **$10^{14} – 10^{18}$** .

Architecture

short-pulse excimer lasers are double wavelength systems



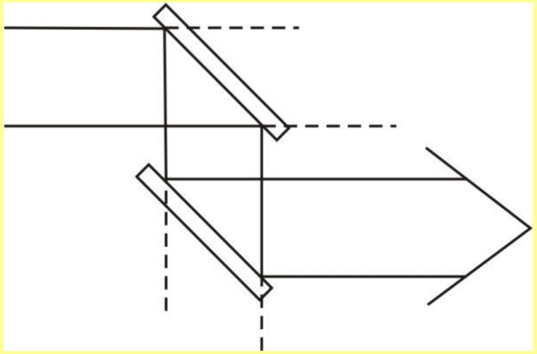
solid-state systems use CPA



Origin of prepulses: excimer: ASE (contrast of $>10^{10}$ easily accessible for TW pulses)

solid-state: imperfect pulse compression

a) Temporal filtering

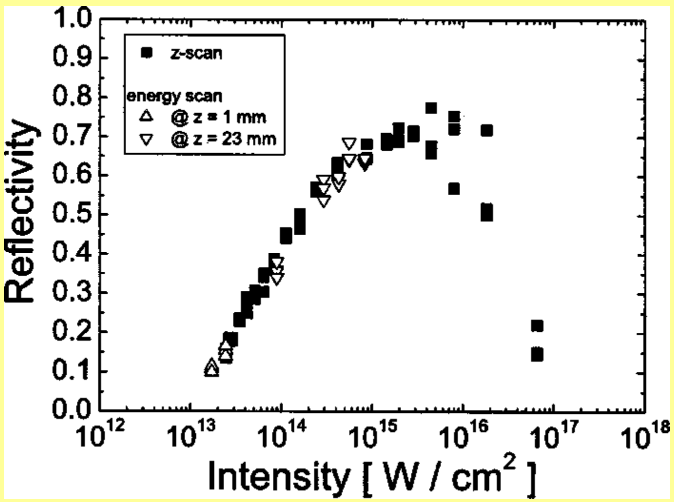


Plasma mirror technique

intensity dependent reflection

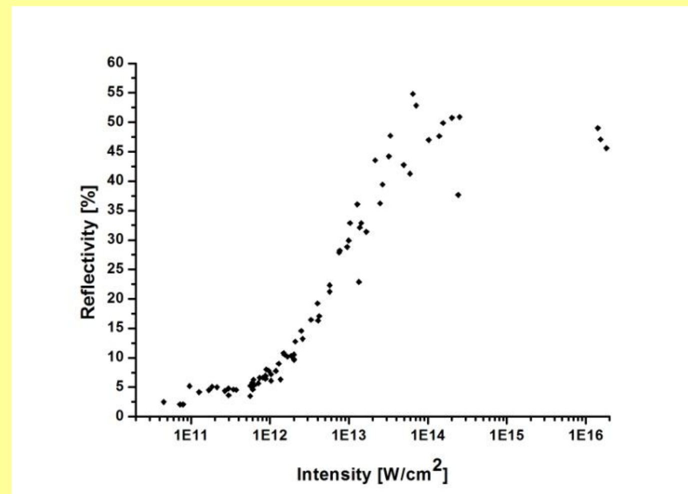
temporal modulation

Ti:Sa



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

KrF



Latest results (November, 2013)

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) (up to 2 orders of magnitude improvement for one mirror),
- optical quality of the plasma front influences the phase front,
- fresh target area is needed for each shot.

b) Spatial filtering

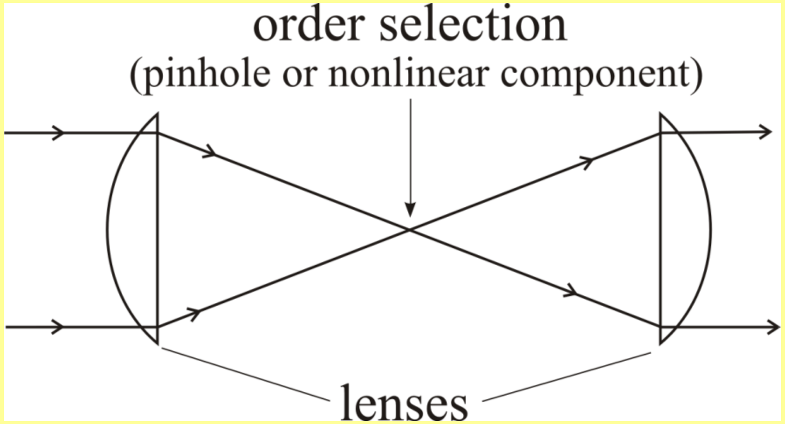
„Transverse" inhomogeneities– caused by pumping , self-focusing etc – are generally eliminated by the use of fibers.

Disadvantages: - limited energy (power) ,
- deterioration of the temporal contrast

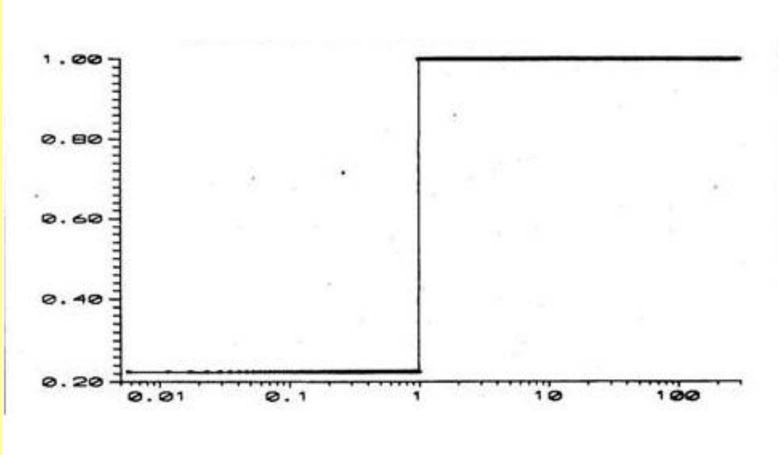
b) Spatial filtering

Confocal arrangement

for Fourier filtering of beams

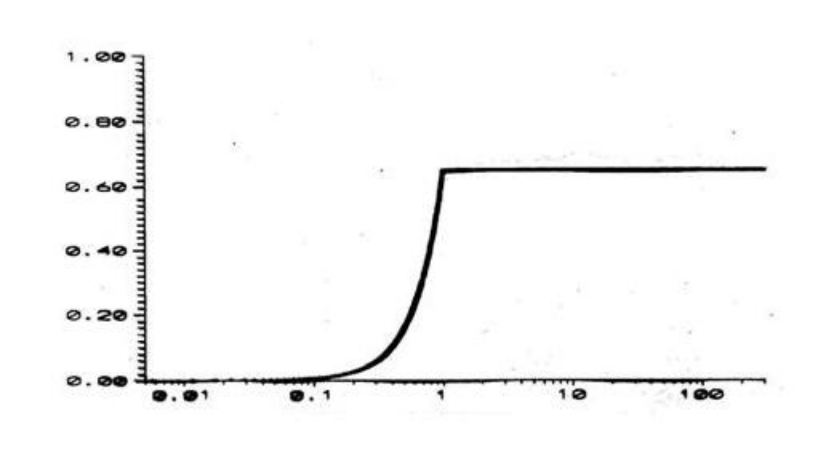


„classical" way



step function of a pinhole

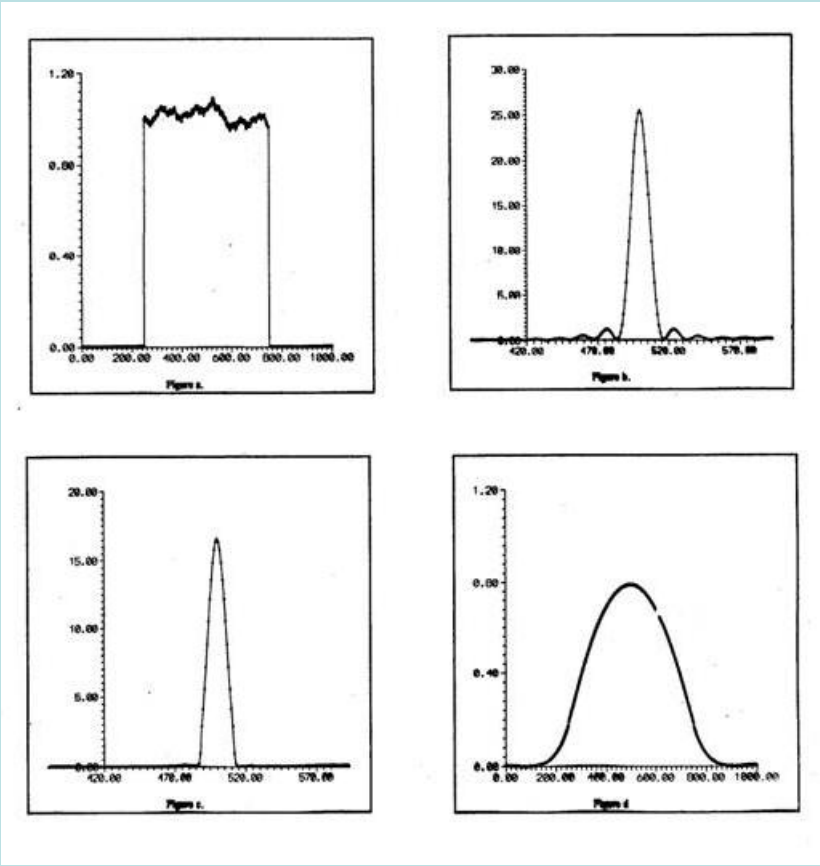
Active spatial filtering:
nonlinear transmission
instead of the aperture



nonlinear response of SHG

S. Szatmári et al. Opt. Comm. **134**, 199-204 (1997)

SHG as an order selector



For a double-wavelength system:
the inherent temporal cleaning of SHG is completed by efficient spatial filtering.

Both the temporal and spatial contrast are „reset” in the middle of the system.

Double wavelength excimer laser systems have excellent temporal and spatial beam quality.

Only the ASE of the UV amplifier contributes to the background output.

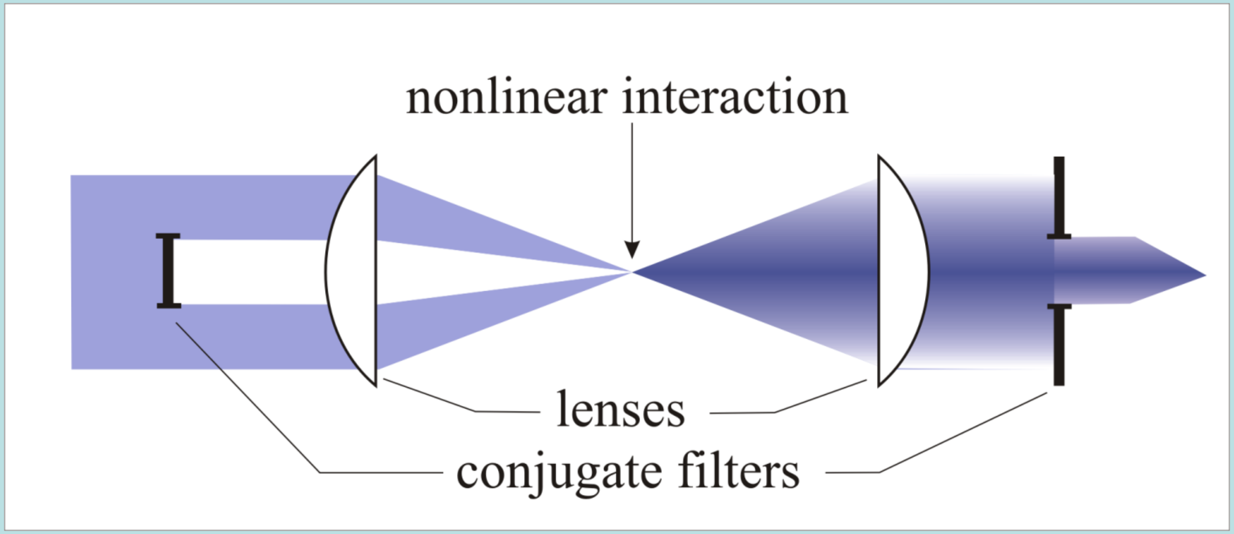
This however scales with the „optical length” of the amplifier.

A novel pulse cleaning method is needed,

which is generally applicable (for single-wavelength systems),

and does not suffer from the shortcomings of the former techniques.

nonlinear spatial filtering of an annular beam

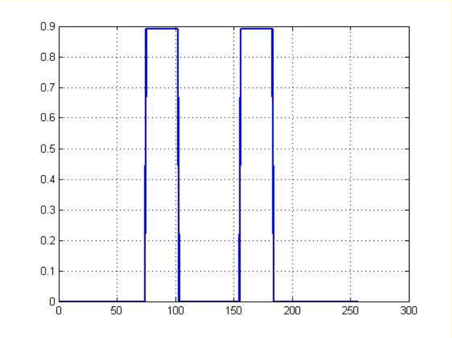


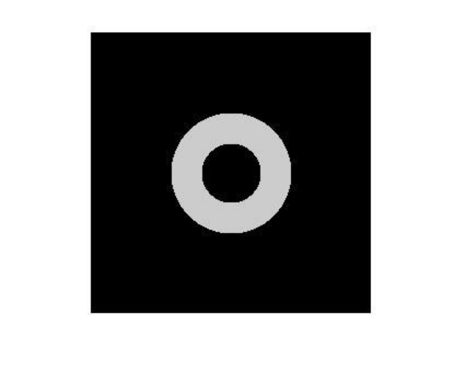
Combination of a confocal telescope and a conjugated beam-block filter pair:

- no transmission as long as no modulation occurs in the focal plane
- finite transmission if amplitude or phase modulation occurs in the focal plane (causing a diffracted beam of different directional properties).

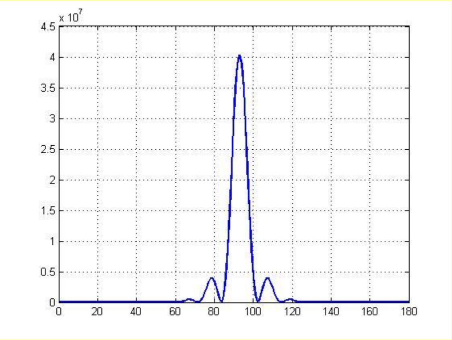
Connection to active spatial filtering:
The Fourier-transform of an annular beam is very similar to that of a „regular” flat-topped beam.

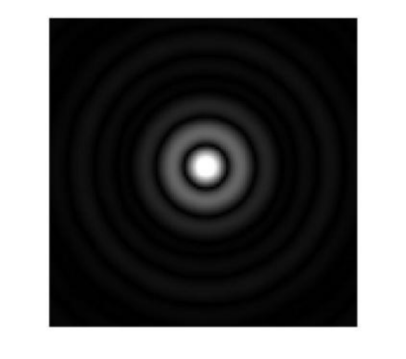
Input





Fourier-plane:



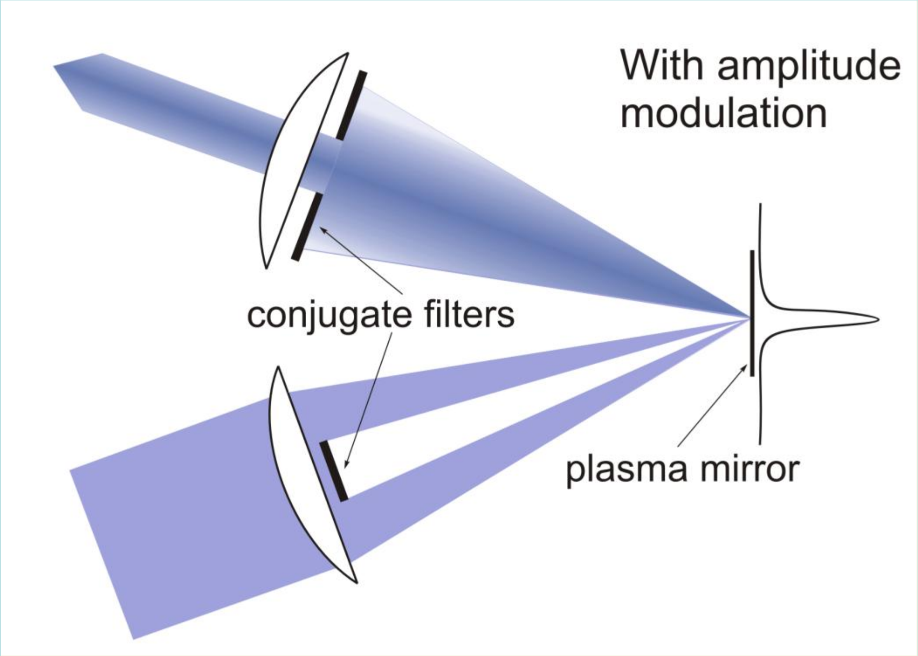


Combination of the Plasma Mirror with a „conjugate" Spatial Filter

In this new arrangement the plasma mirror is positioned in the Fourier-plane of a focusing 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.

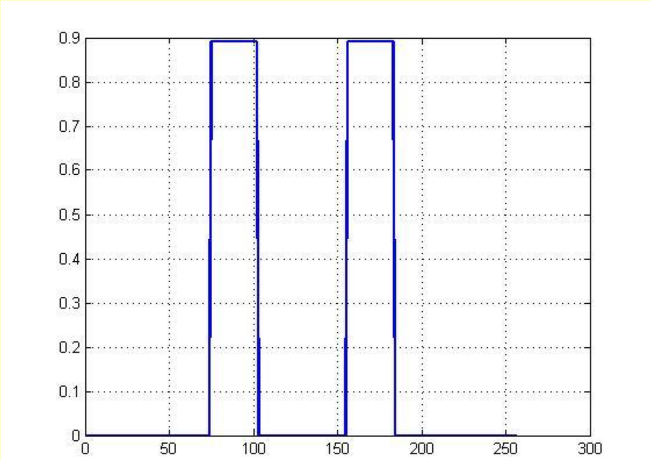
If the reflectivity (either the amplitude or the phase) is different for the more intense central lobe of the diffraction pattern, the distribution of the reflected beam changes; the central hole of the aperture becomes illuminated.

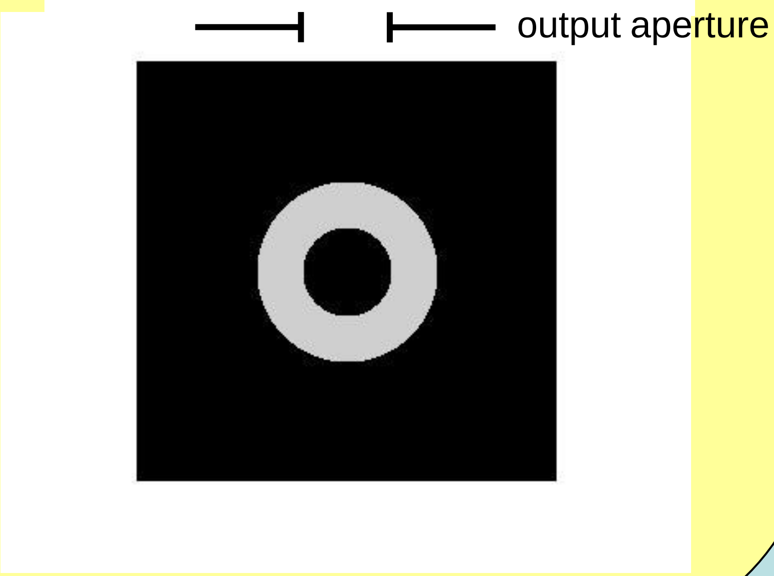


Very high improvement of the contrast is expected!

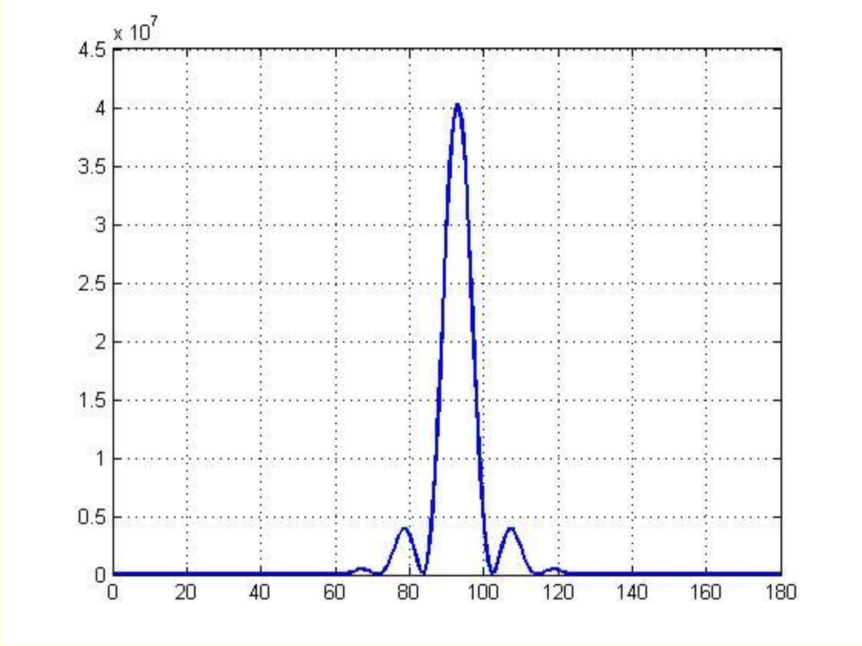
With no modulation at the Fourier-plane

Output



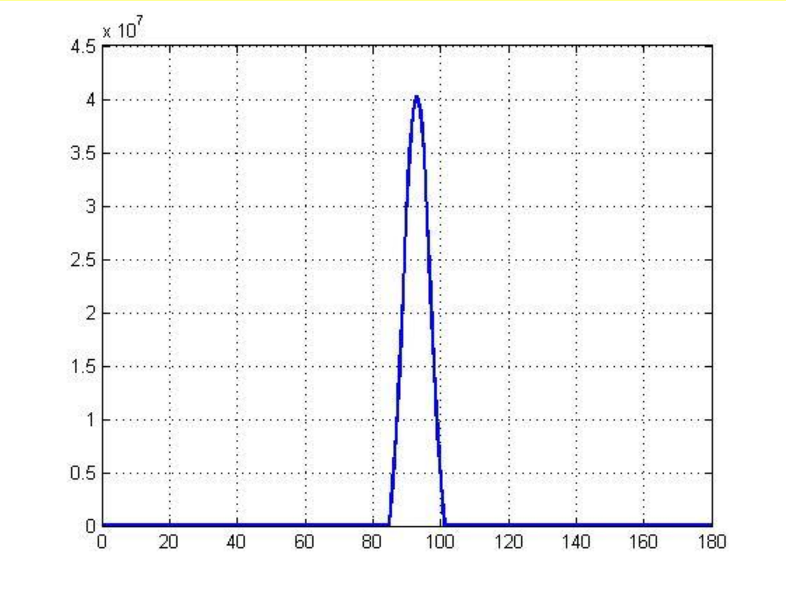


Fourier-plane

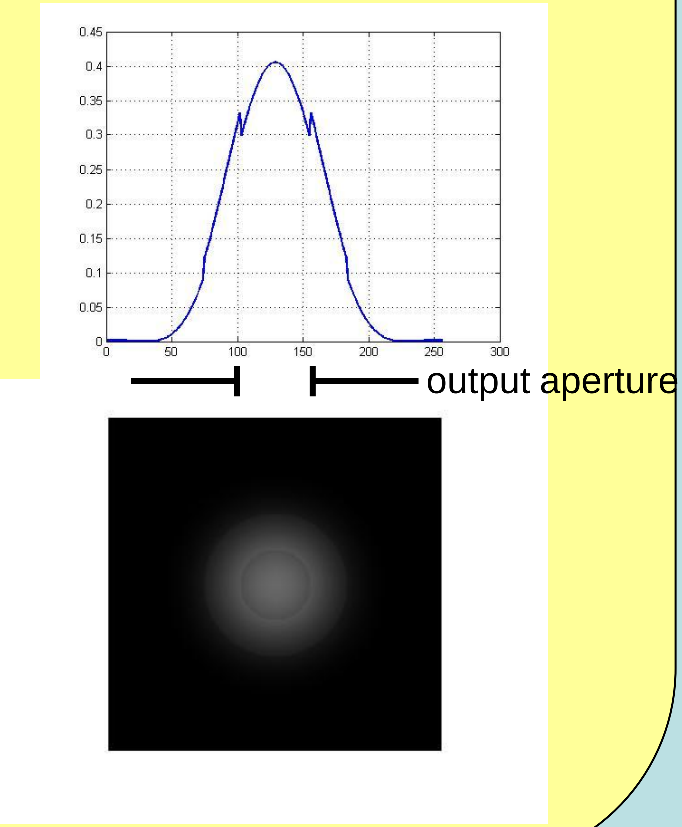


With amplitude modulation at the Fourier-plane:
higher (than 0th) orders are suppressed by a factor of 25
(plasma mirror effect)

Fourier-plane



Output



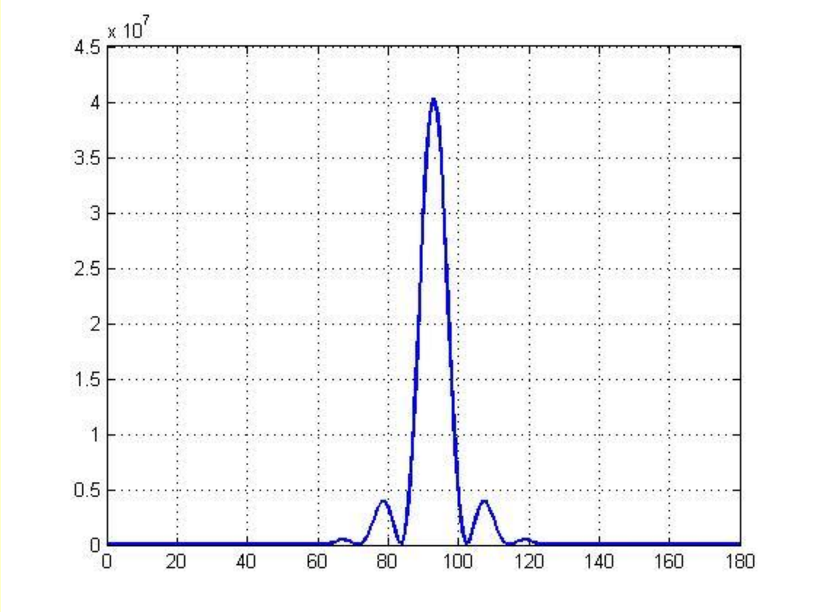
Disadvantages: limited throughput (diffraction losses, limited plasma reflectivity)
fresh target area is needed for each shot.

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.

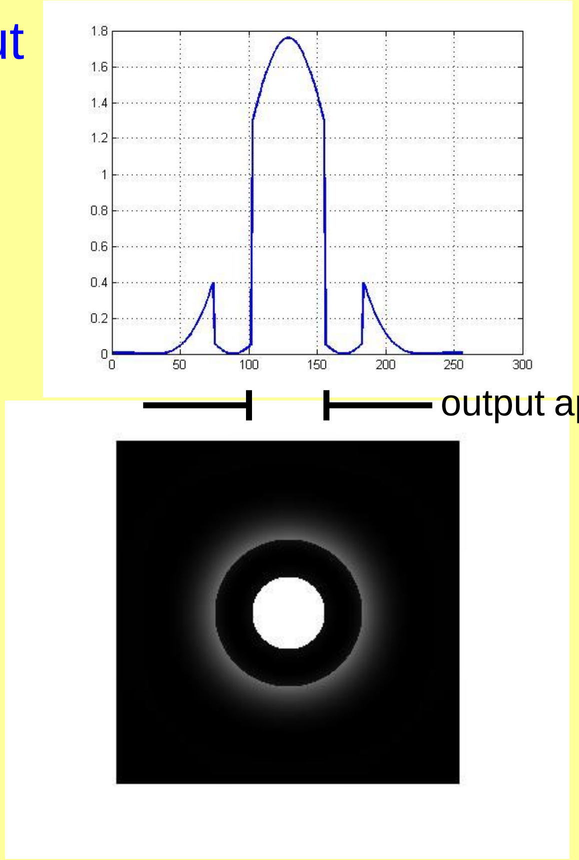
With phase modulation at the Fourier-plane:

the 0^{th} order is shifted by $\lambda/2$ (in the self generated plasma)

Fourier-plane



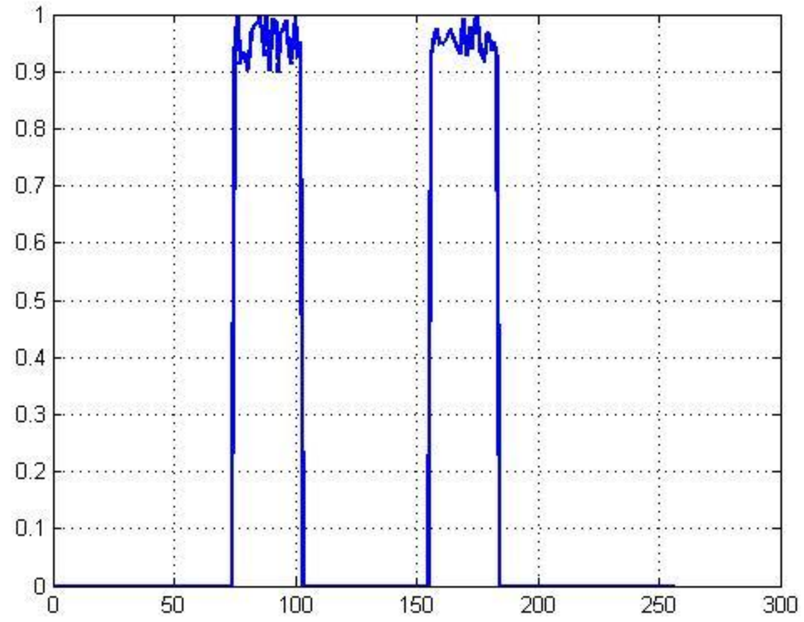
Output



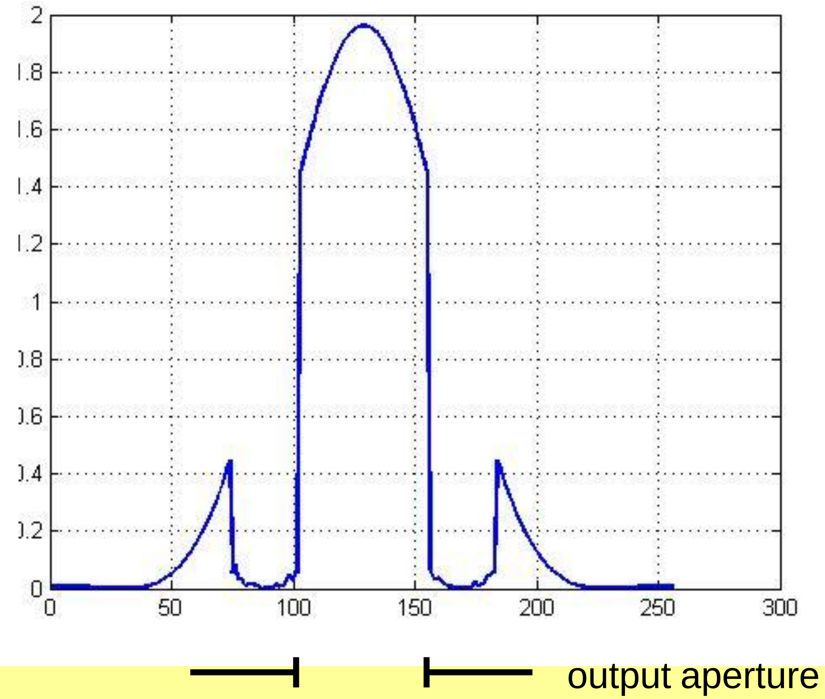
Simultaneous spatial filtering occurs
in the central (transmitted) part of the beam

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

Input



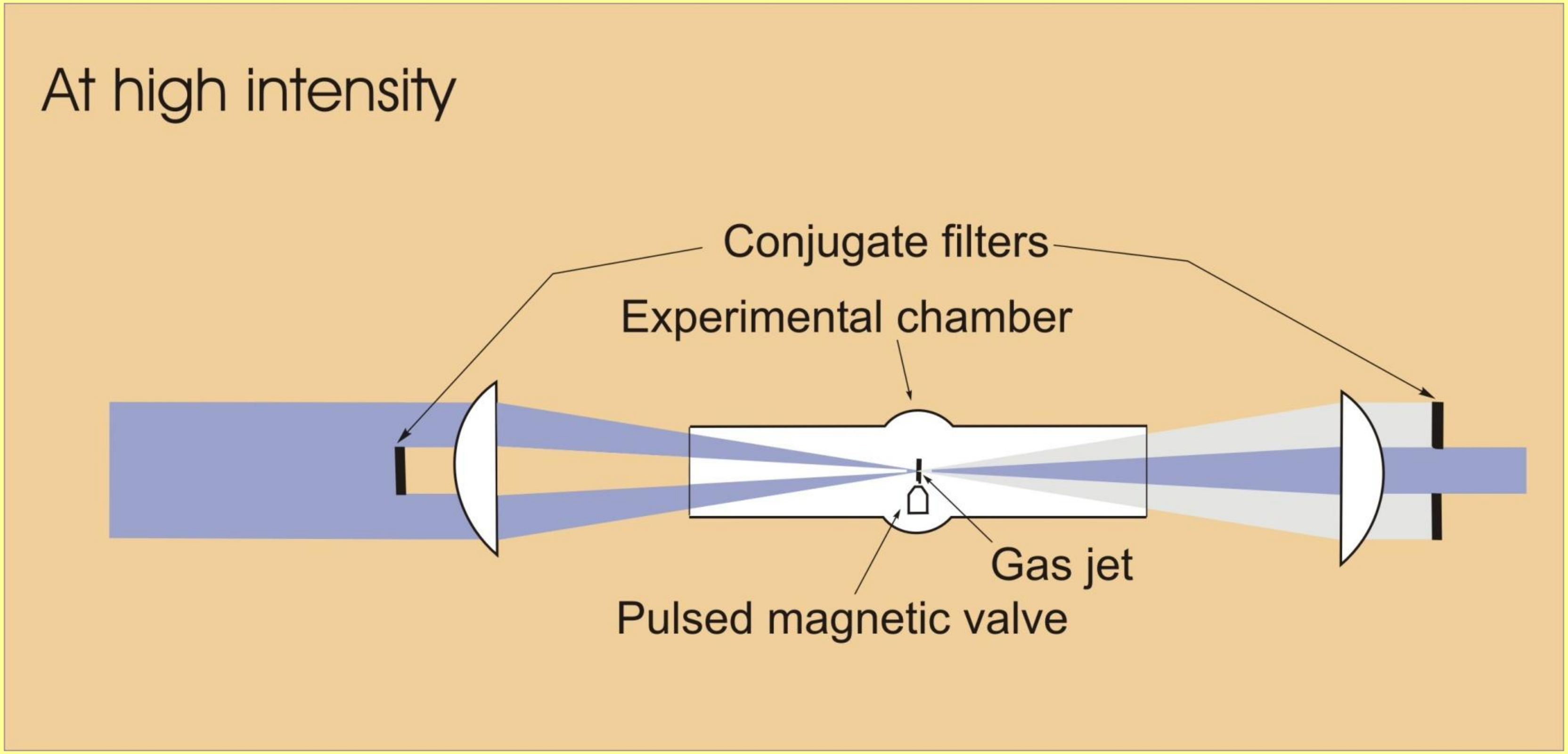
Output



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 $\lambda/2$.

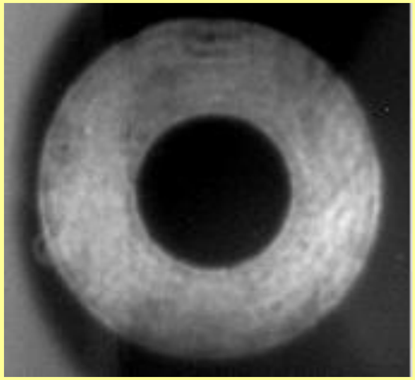
Experimental realization of the nonlinear plasma filter



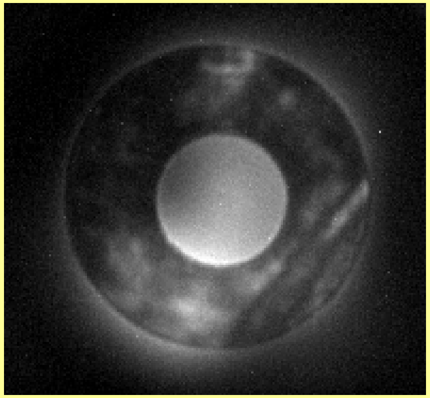
Experimental results

- a Kepler telescope of f = 670mm focal length
- argon as a nonlinear medium
- pulsed gas jet of 1mm diameter, opened for ~1.5 ms

without gas in the focus



with gas in the focus (plasma generation)



S. Szatmari et al. EPJ Web of Conferences **59**, 07006 (2013)

Different effects, experimental details contributing to the achievable value of contrast improvement are investigated and identified.

1. Maximum throughput of > 40% is obtained with optimization of the experimental parameters

2. The phase shift introduced by the plasma generation is found to have a „switching" feature by a combined effect of subsequent (or simultaneous) self-focusing in the gas and defocusing in the plasma. (Understanding/theoretical description of the „transversal" effects in the Fourier-plane is needed.)

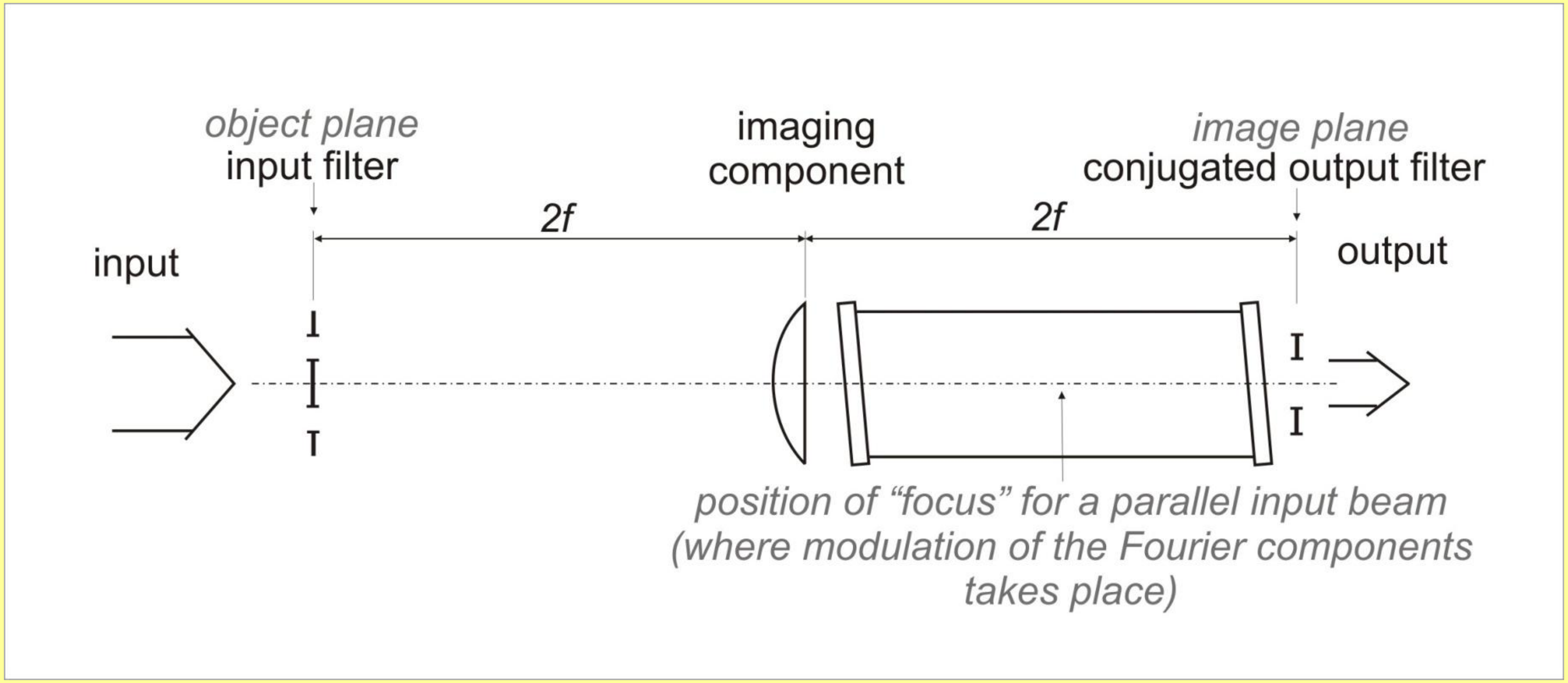
⇩

The nonlinear switching has minor contribution to the unwanted transmission of the background.

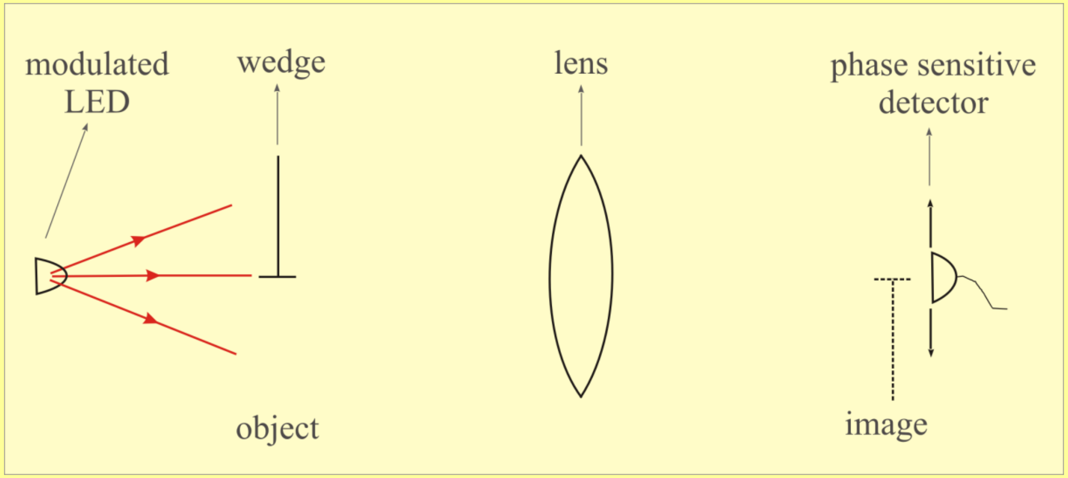
⇩

The low signal transmission (the achievable contrast improvement) is mainly determined by the quality (by the spatial contrast) of conventional imaging.

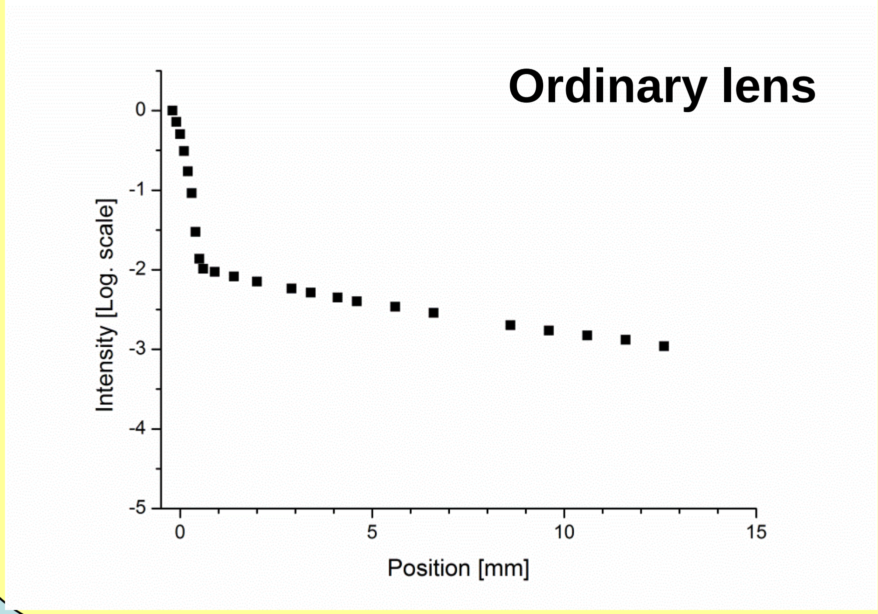
Nonlinear filter as an image system

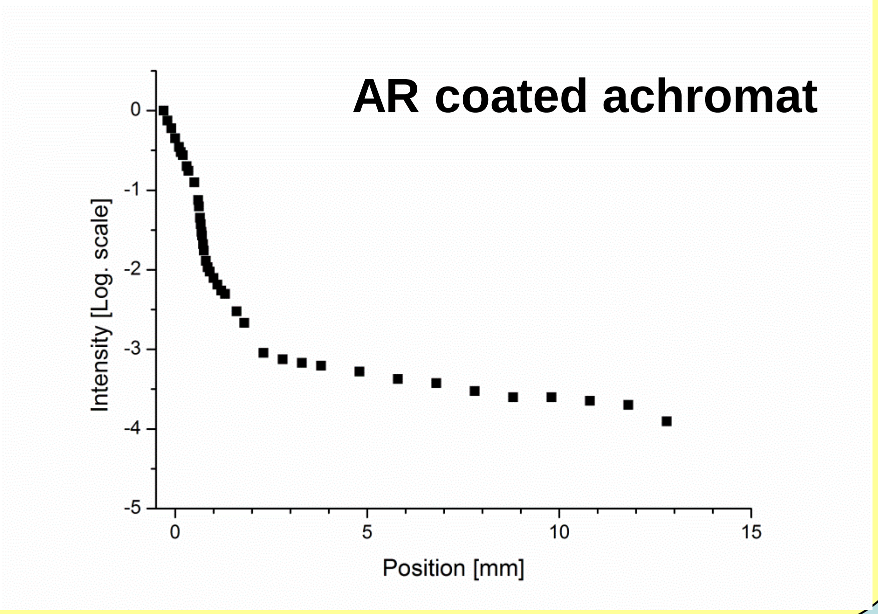


Measurement of the spatial contrast of imaging (of a wedge)



Intensity distribution of the image of a wedge





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 alignement),
- very high overall transmission (>40% obtained experimentally),
- applicable in a broad wavelength range (directly applicable in excimer systems, however, pulse compression and eventual streching is needed in CPA schemes).

Thank you for your attention!