View from the experimentalist:

Realization of relativistic light intensities with ultrafast TW-lasers for particle acceleration

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Outline

- Motivation
- Introduction: laser intensity @ interpretation of experimental data
- Energy measurement of ultra-short TW - laser pulses
- Measurement of temporal pulse width
- Fokusing to relativistic intensities (wavefront errors and control)
- Direct measurements @ theoretical calculation of laser intensity
- Pulse synchronization of TW – beamlines
- Ultra-high contrast of femtosecond laser pulses
- Summary

LA3NET Workshop, ILT Aachen, November 6, 2013

Motivation: Driving aims and key problems in laser ion and laser electron acceleration

Ion energies:

- ***several MeV*** to tens of MeV
  - material research (structure analysis, device tests)
  - energy dissipation in cold and dense warm matter
  - dynamical imaging of strong fields
  - biological application (stopping length between microns and centimeter)
- ***several 100 MeV*** for protons
  - cf. above & medical application (stopping length between 0.1 – 1 meter)

Electron energies:

- ***GeV*** to several GeV
  - new type of electron accelerator
  - ultrafast XUV / X-ray radiation sources (up to FEL)

Tasks: (important for application)

parameter steering with light – offers new class of devices

parameter control determines the competiveness of a new technology

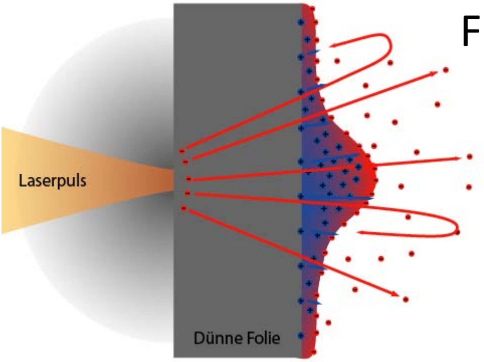
Tasks: (scientific)

- study of ***acceleration mechanisms***:
  - ion /electron energy scaling inclusive staging
  - laser to ion / electron energy transfer efficiency
  - stability (robustness) of the process
  - range of parameter steering (bandwidth of energies)

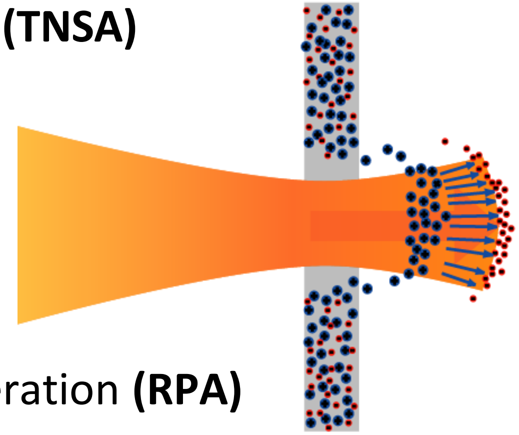
Introduction: Ion and Electron acceleration with lasers

Laser – high intensity: strong EM-fields – polarization of matter – strong acceleration fields (kind of rectification)

Ion acceleration



From **T**arget **N**ormal **S**heath **A**cceleration **(TNSA)**

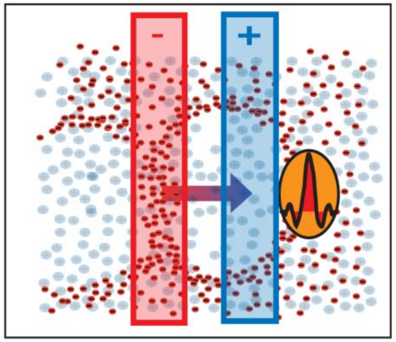


To **R**adiation **P**ressure **A**cceleration **(RPA)**

– the most efficient acceleration

Electron acceleration

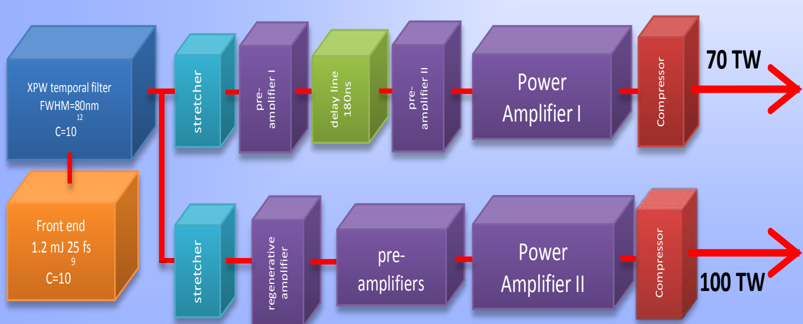
From **electron acceleration via self-injection**



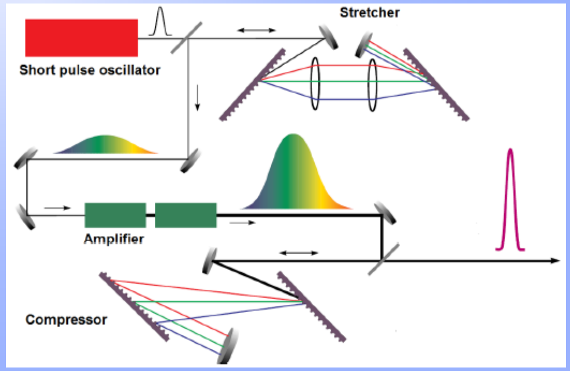
To **electron acceleration using electron injection**

Introduction: ultrafast TW-laser systems for particle acceleration

100 TW @ 25 fs | synchronized | 70 TW @ 35 fs



Dual Beam
DCPA - system



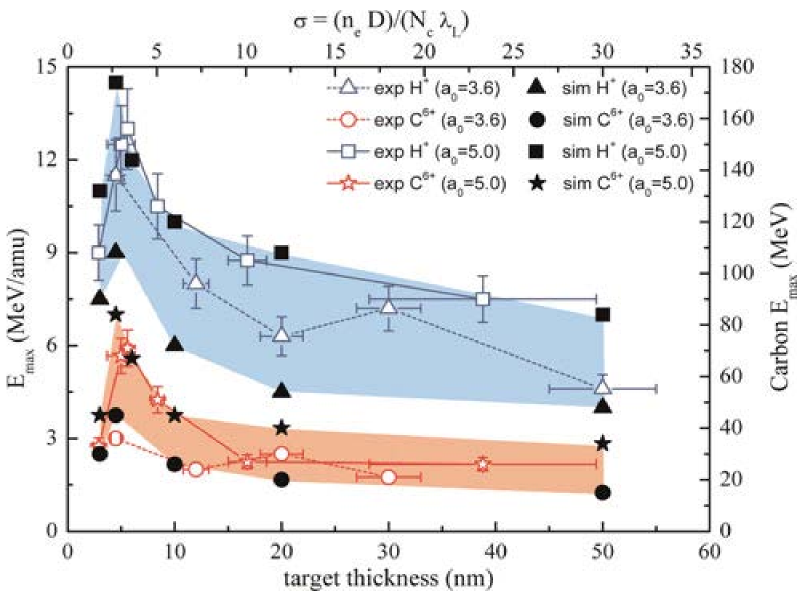
in operation and upcoming: PW – lasers within national and ELI – initiatives

Introduction: Importance of laser parameter – for evaluation of experiments

in plasma phenomena => collective effects matter
=> therefore several parameter
energy, duration, intensity (released forces) of impact
are important
quite different to laser – atom interaction
e.g.: ionization via inverse Bremsstrahlung absorption in a plasma
versus field ionization of an atom

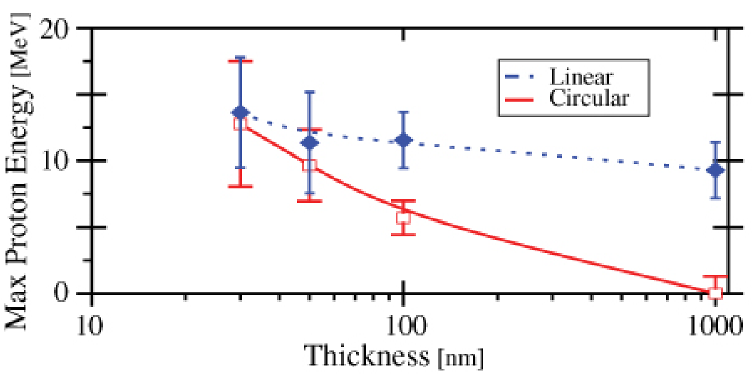
parameters are difficult to discriminate for plasma effects => cause problems in interpretation

Example for laser-ion acceleration:



DLC, I_L=**5x10^{19} W/cm^2** @ 45fs, 800nm, **0.7 J**
MBI-HFL

Steinke, Laser Part. Beams, 28, 2010
Henig, PRL 103, 2009



Si_3N_4, I_L=**2x10^{21} W/cm^2** @ 40fs, 800nm, **1.5 J**

HERCULES
Dollar, PRL 208, 2012

What do we have to realize and to measure ?

o simple formula, apparently well defined measures,
but no real satisfactory and complete measurement solution for TW-pulses

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o no device to do it in a practicable and defined way

o why: nonlinear response, collective response, threshold of effects not sharp

o even more awful: there is no standard method
to do some kind of precise quantification for comparison of TW-lasers

o different methods for approximation:

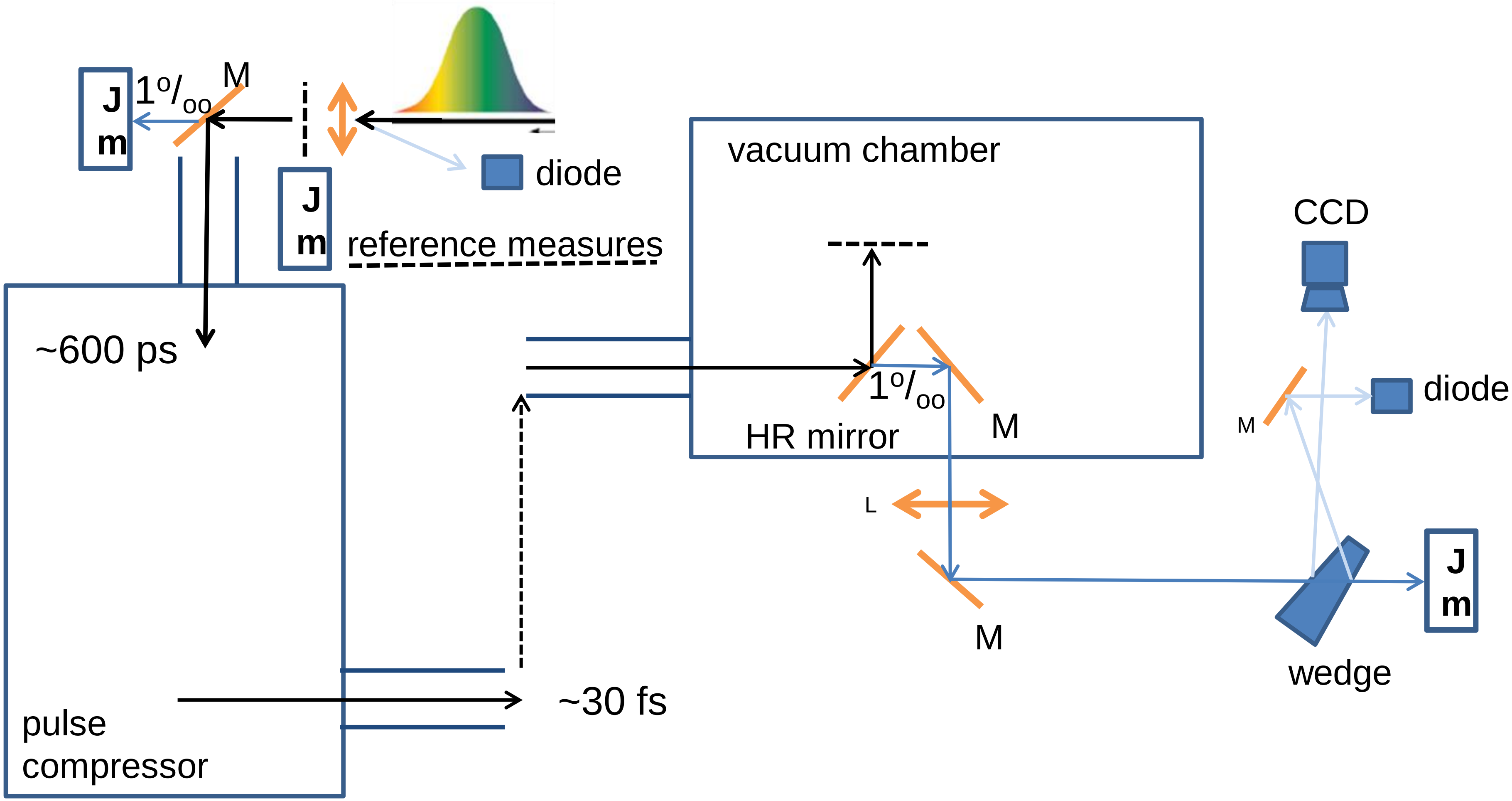
- single measurements of attenuated beams or beam parts and extrapolation

- effects on single particle (atom or electron) & using theoretical relations

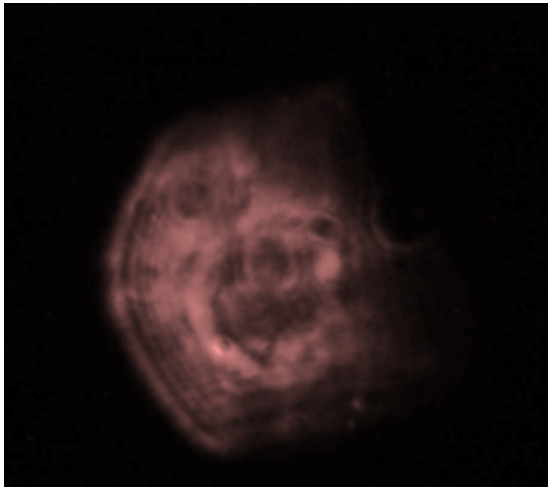
Determination of laser pulse energy in case of TW-laser pulses

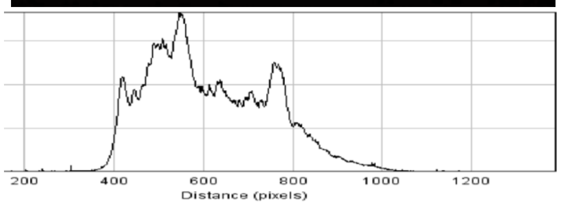
Direct measurement with "Joulemeter" not possible: => $I_{area\ detector}$ ~ $5*10^{11} – 10^{12}$ W/cm2 *(safe region ~ GW/cm², at about 10^{10} W/cm² (Ø level) we observed nonlinear problems)*

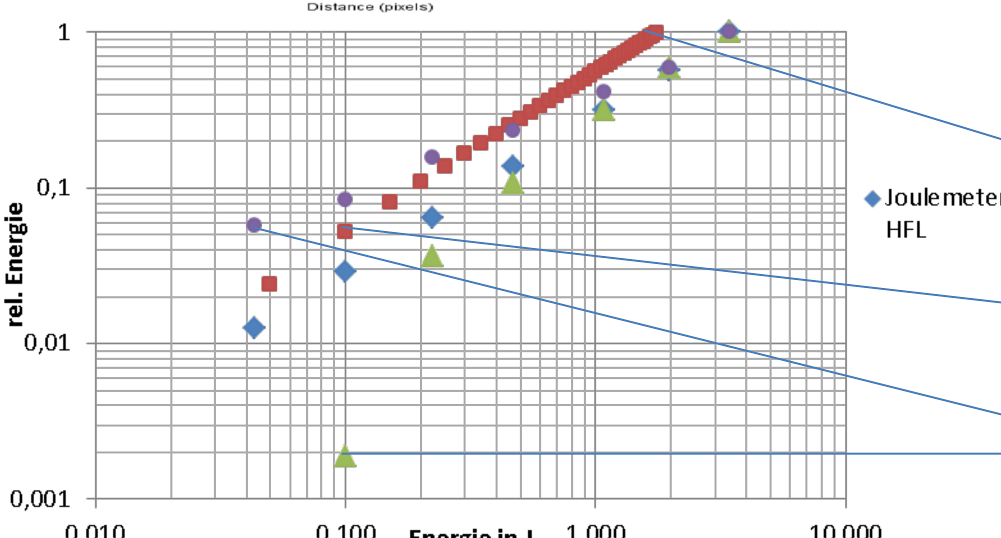
=> Determination of relative transmission of measurement lines (including attenuation)



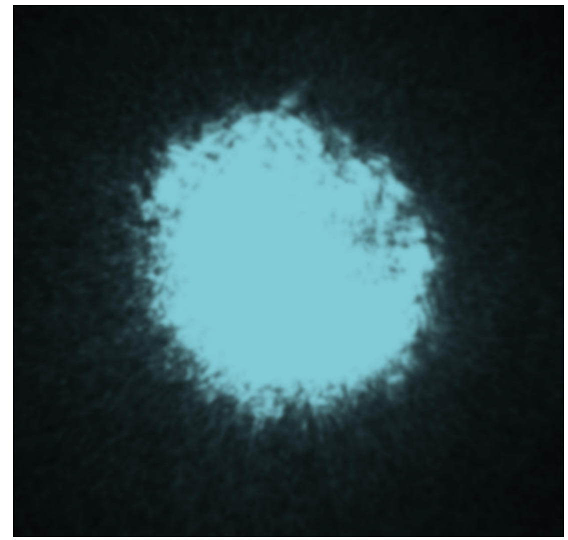
Determination of laser pulse energy in case of TW-laser pulses







advantage:
accidents become immediately visible



count integration CCD
gives relative signal

cross-calibration gives energy

error due to background
in case of too weak signal

Measurement of temporal pulse width

technique	single pulse	multiple pulses, scanning
Autocorrelation 2nd order	yes	yes
Autocorrelation 3rd order	low dynamic range	yes
Spider	yes	
FROG	yes	

problems:

- dynamic range of temporal pulse profile
- no measurement with real focusing optics (practical issue)
- measurement across beam profile (practical issue)

- e.g. beam diameter demagnification with a telescope may generate pointing problem

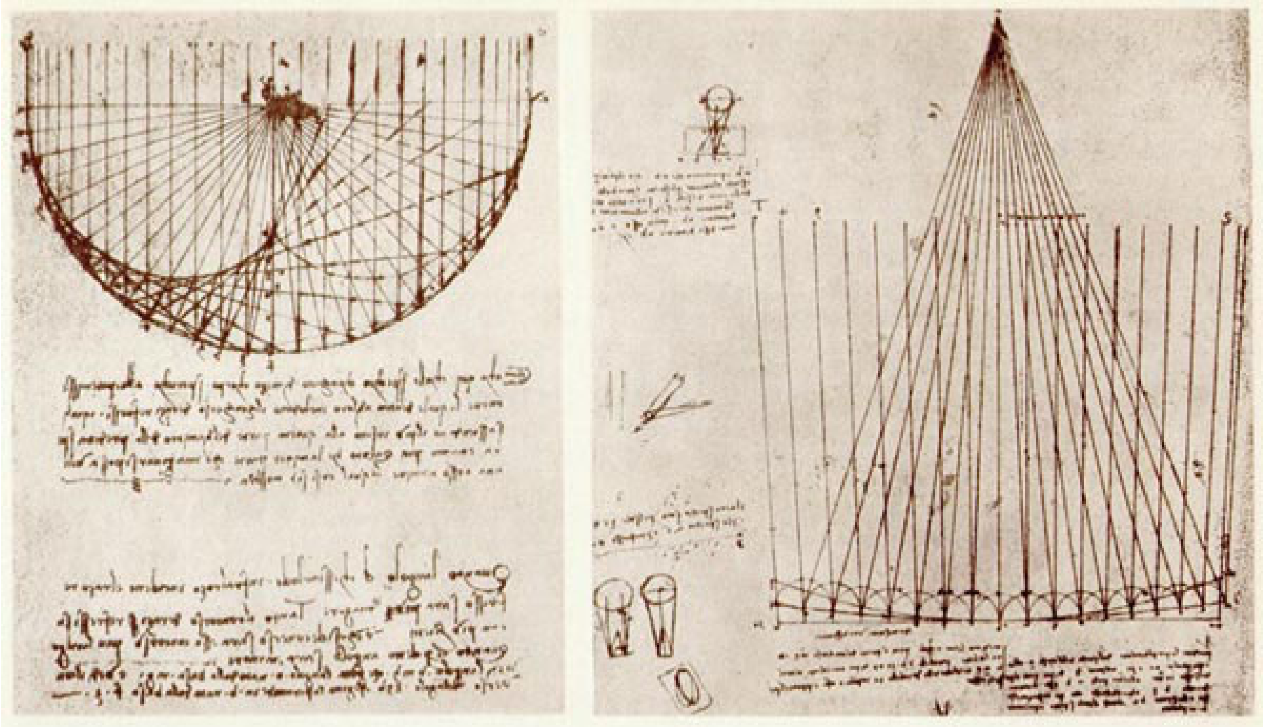
other methods: measurement and control of angular chirp, phase front tilt
c.f. e.g. A. Borzsonyi et al. Applied Sciences 3, 515 (2013)

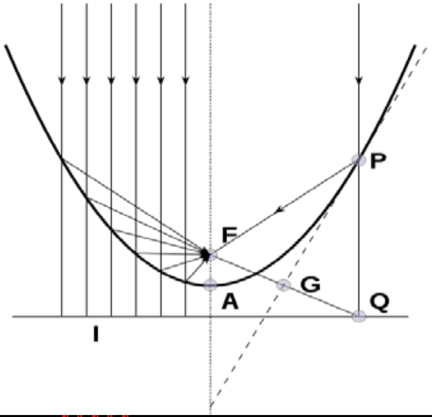
Focusing to relativistic intensities – parabolic mirrors

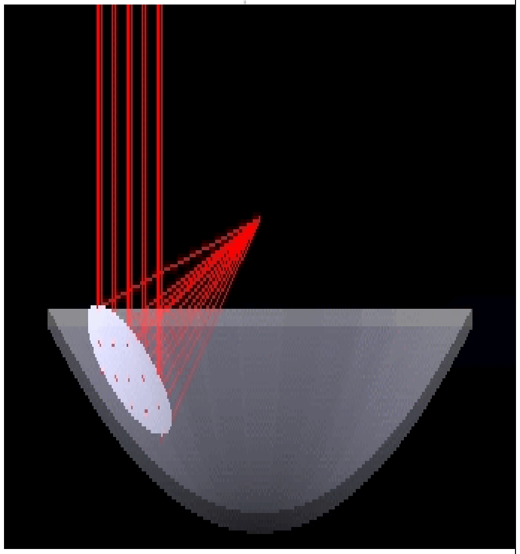
Greek mathematician Diocles described them in his book *On Burning Mirrors*

Comparison of reflection from spherical and parabolic surfaces - unique property

Drawing by Leonardo da Vinci, ca. 1510-1515





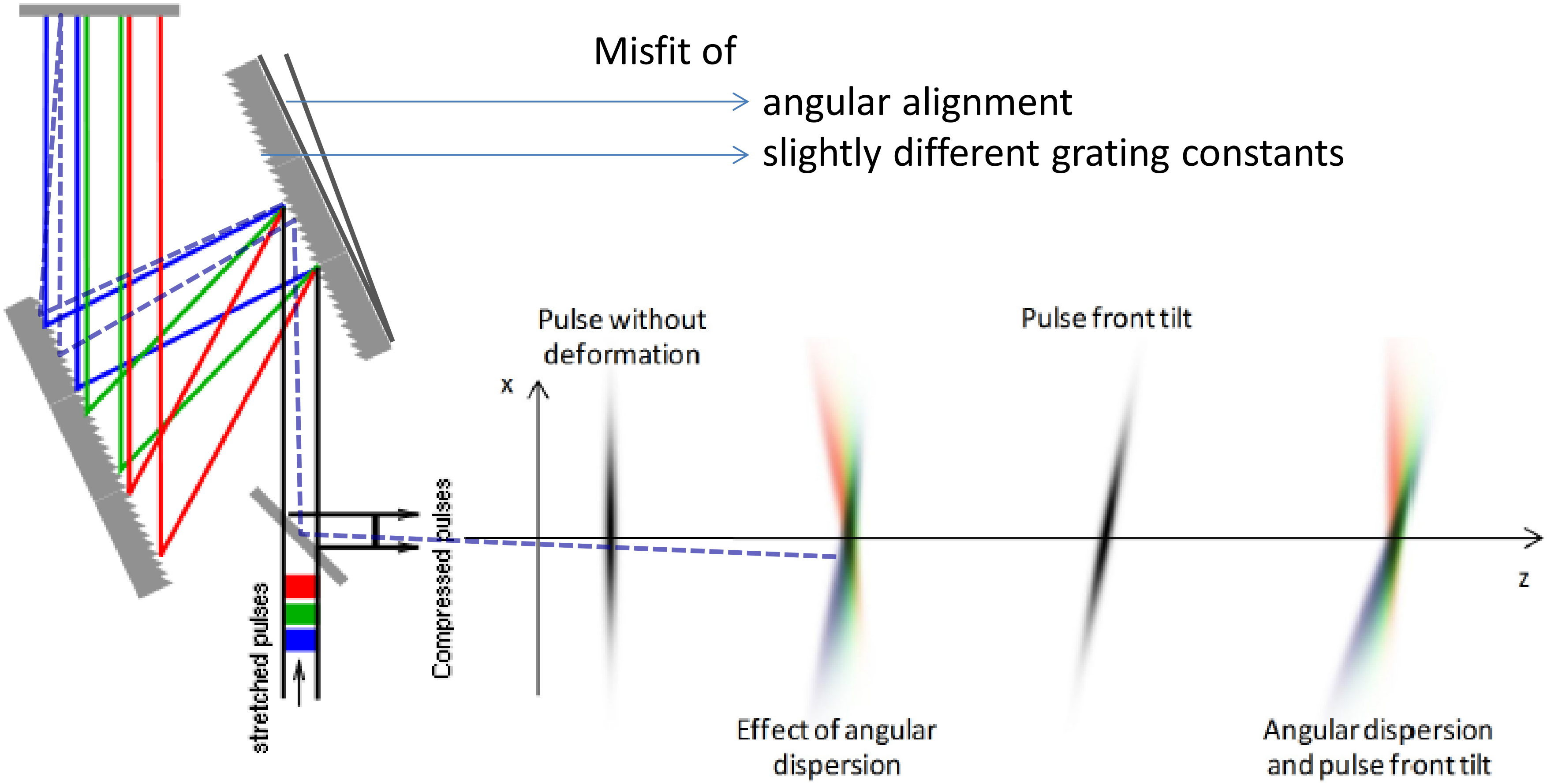


large off-axis angles – large preforms => **€$**

http://en.wikipedia.org/wiki/Parabolic_reflector#cite_note-AutoVC-3-3

Final pulse compression in CPA-systems
can introduce easily spatial and temporal pulse degradation:

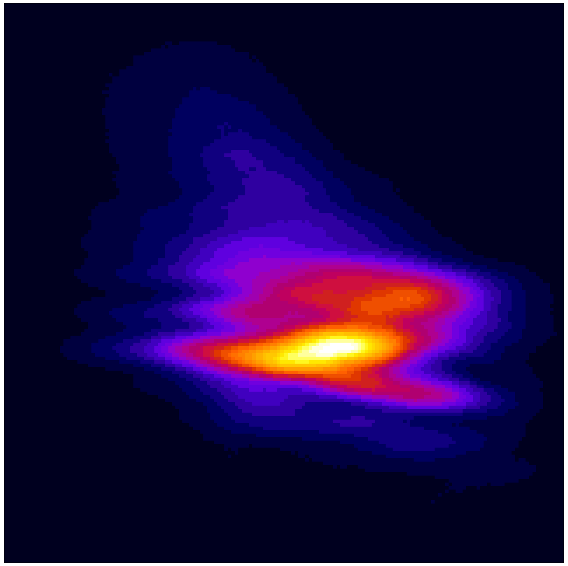
Misfit of
- angular alignment
- slightly different grating constants



A. Borzsonyi et al. Applied Sciences 3, 515 (2013)

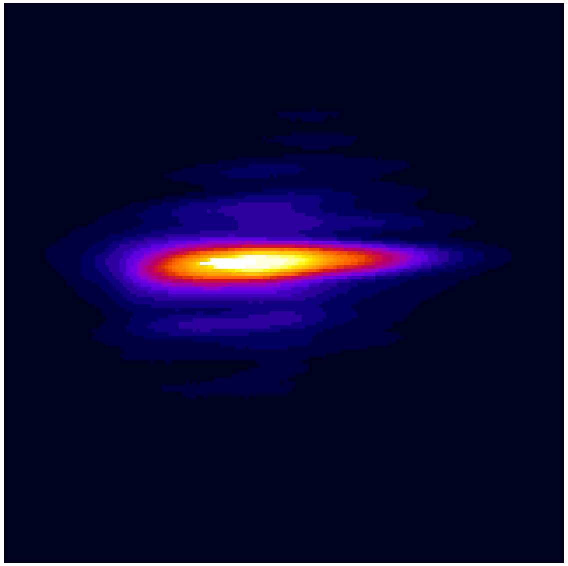
http://en.wikipedia.org/wiki/Chirped_pulse_amplification

Focus problems due to imperfect LLNL-gratings:
a discrepancy of 0.5 lines/mm
degrades the focus at perfect parallel grating alignement



Reflection with flat bulk mirror

dispersion ↔ direction



Reflection with AOM-system on

Chromatic far field distortion
can not be compensated with an AOM-system

Solution: grating detuning for chromatic compensation

Fokussing to relativistic intensities
(wavefront errors and control)

Relativistic intensity is given if $a_0 > 1$

$$a_0^2 = I\,[\mathrm{W/cm^2}]\,\lambda^2\,[\mu\mathrm{m}^2] \times 0.73 \times 10^{-18}\ ,$$

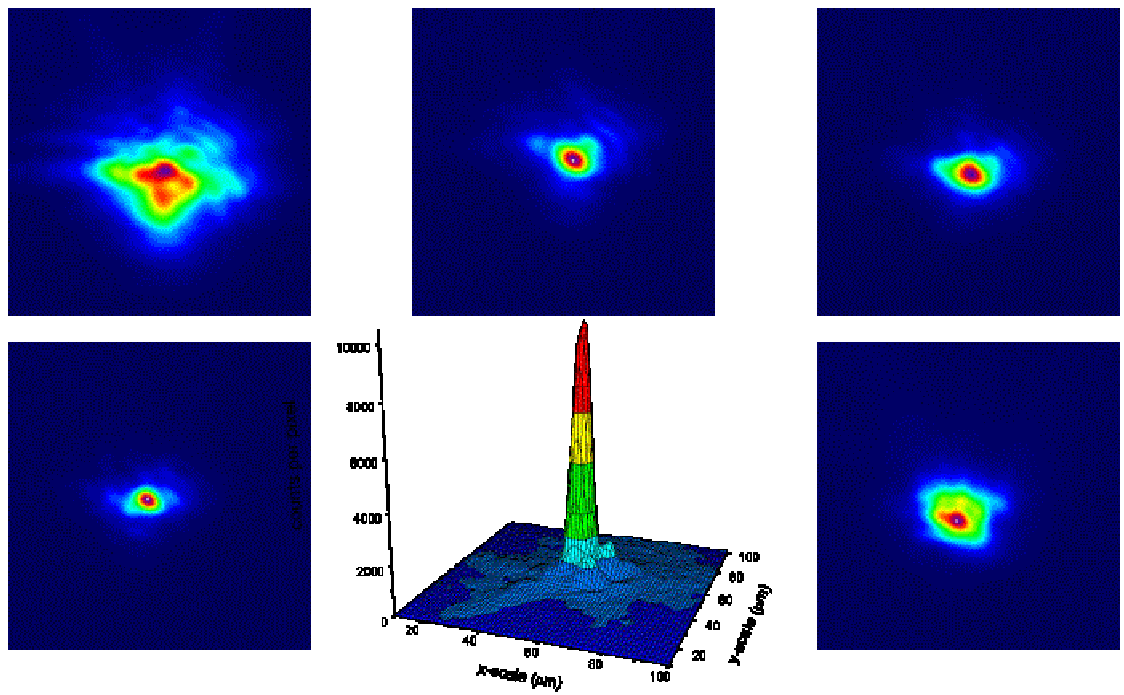
the relativistically normalized laser vector potential

-- relativistic effects of electron kinematics became apparent --

Example of different optimization steps including spectral divergence (grating alignment) and wave front (adaptive mirror) correction

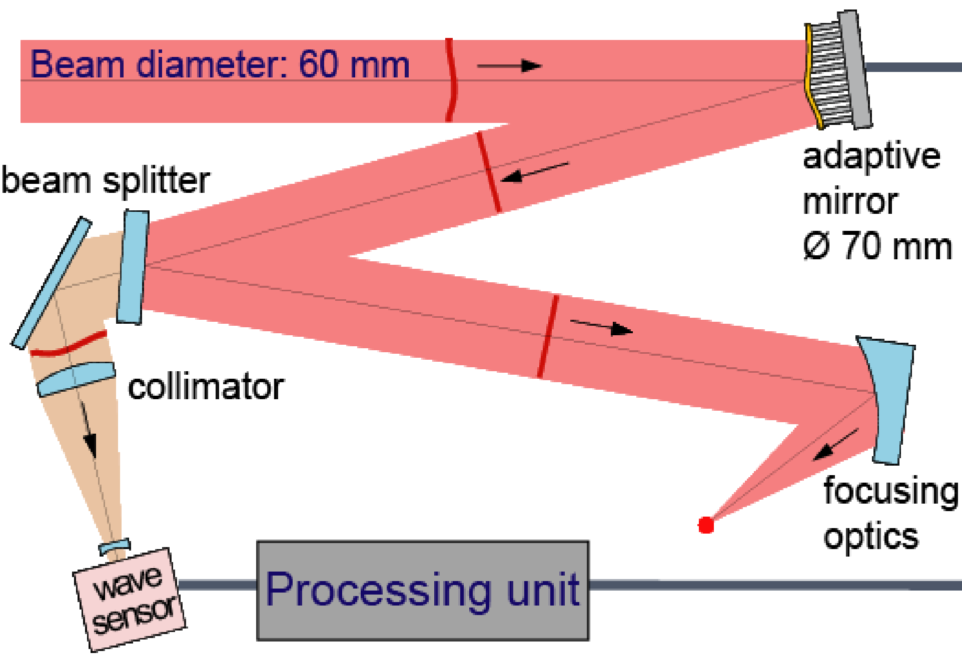
focus issue :
- need well defined intensity distribution – focus quality

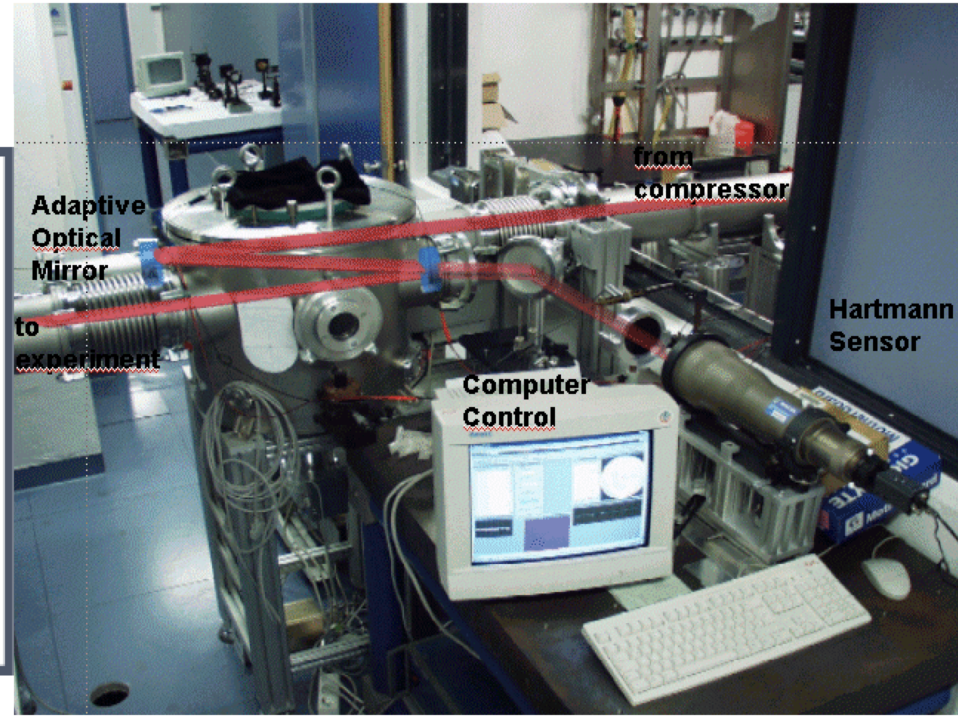
- CPA systems with a grating compressor require simultaneous optimization of focus and temporal compression (compensation of slight grating mismatches)



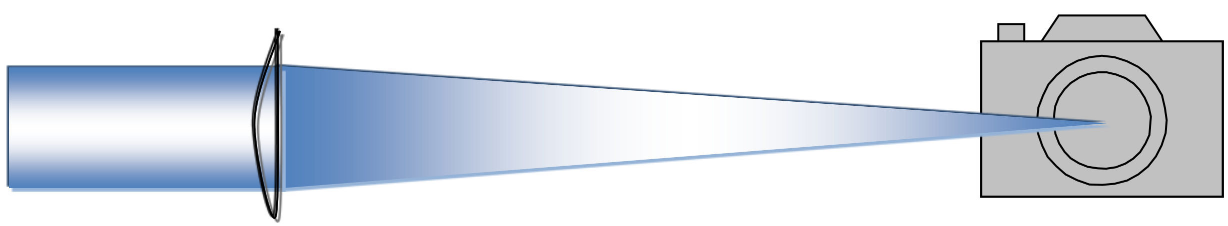
Wave front control and focusing

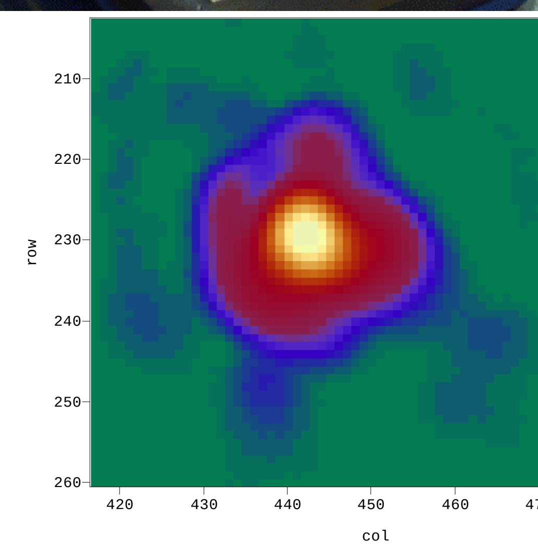
adaptive (or deformable) mirror





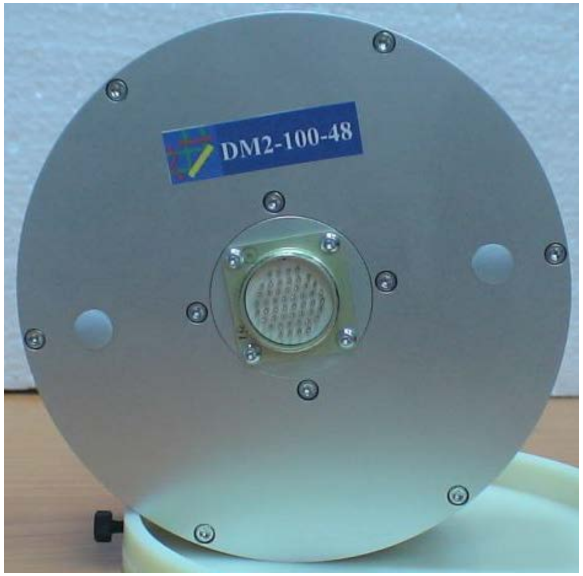
simple and robust measurement:



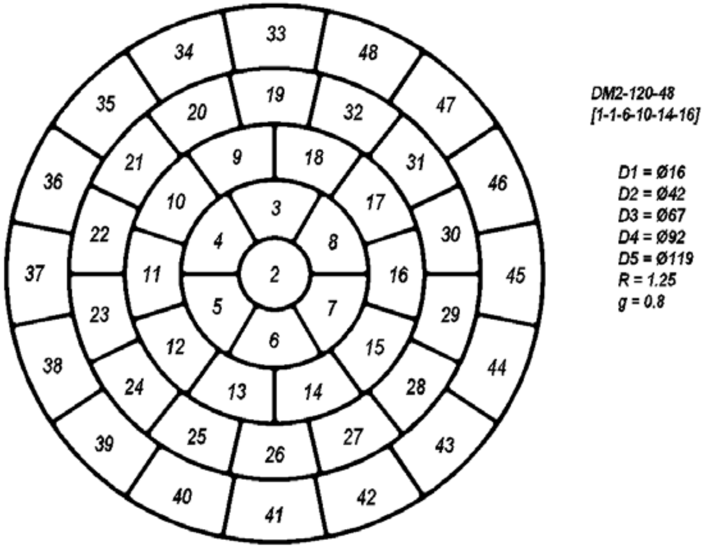


example: f/70 focusing – exposure of high dynamic range CCD

Wave front control – deformable mirror



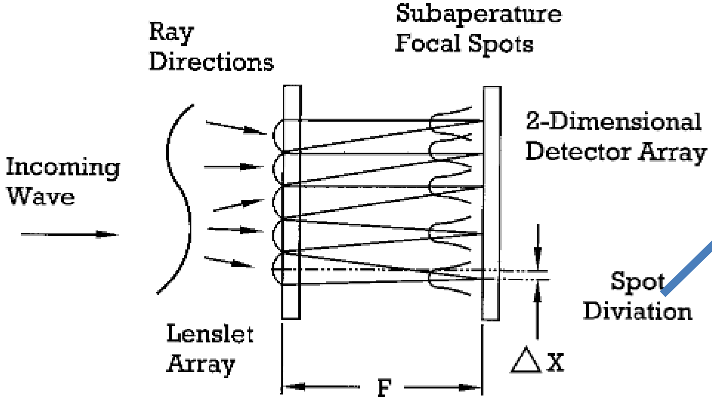
120 mm diam deformable mirror
for 100 TW beamline



Active Optics NightN Ltd.
Adaptive Optics Group

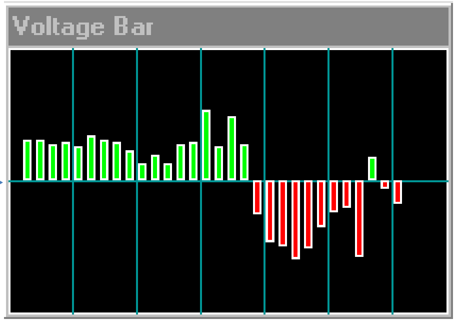
Wave front control – deformable mirror

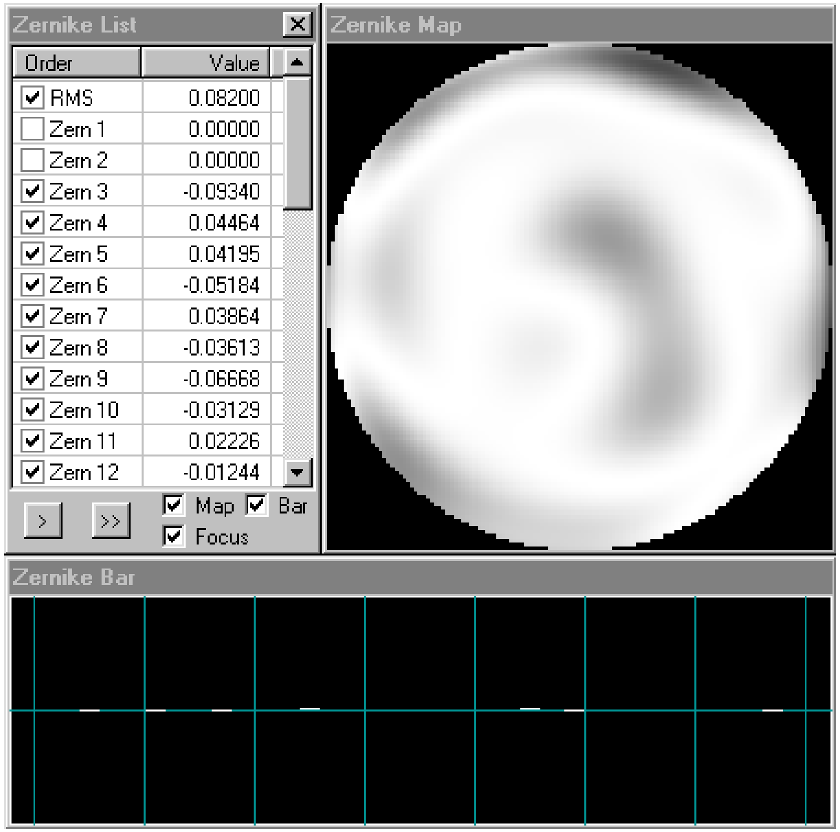
Shack- Hartmann sensor



B.C. Platt e.g. Journal of Refractive Surgery 17, S573 (2001)

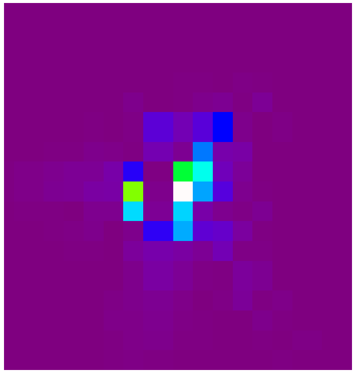
Feed-back
to voltage control
of AOM





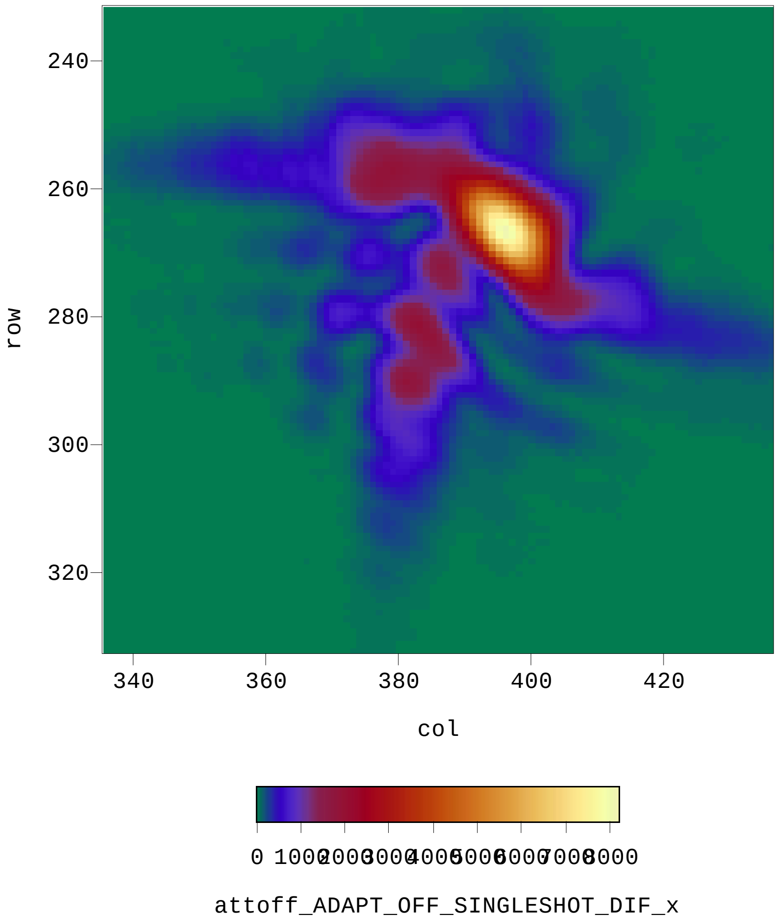
corrected wave front with λ/10 RMS

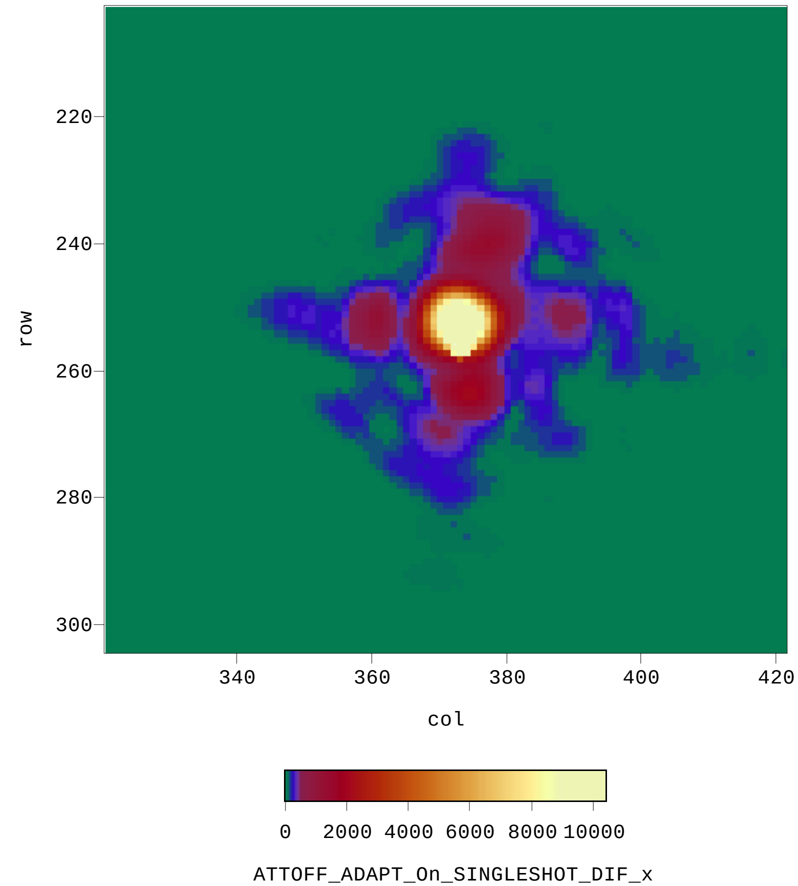
improved focal distribution



Far field improvement of the MBI high field Ti:Sapph laser

with appropriate grating alignement
and an adaptive optical mirror system



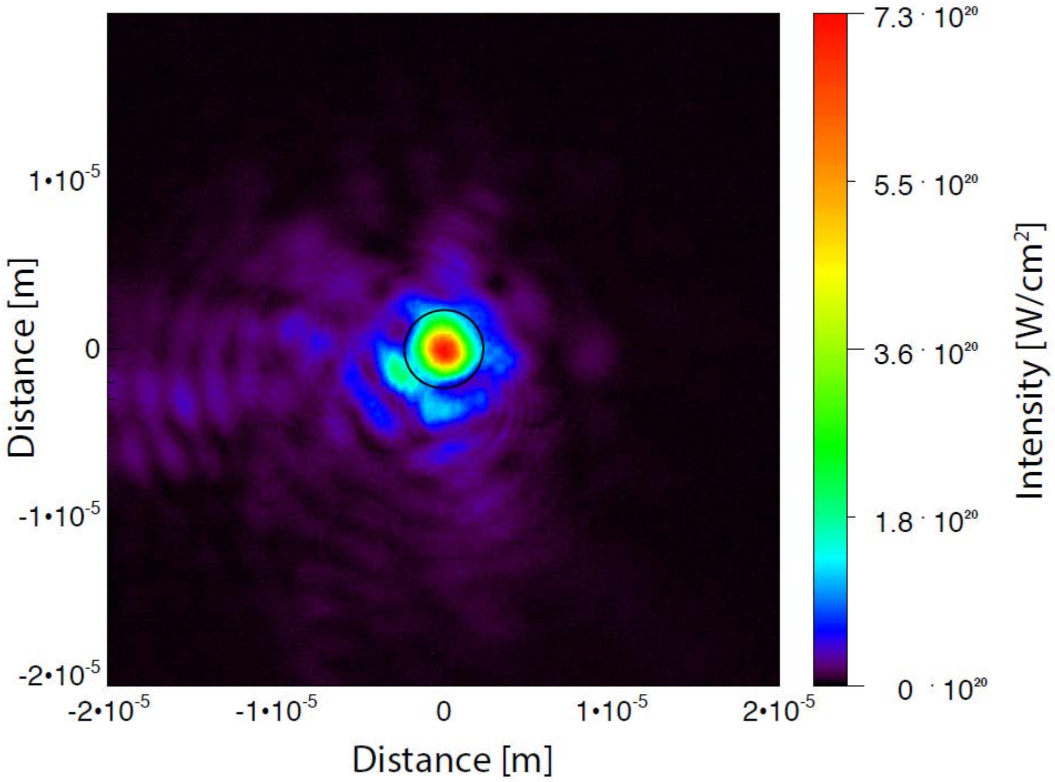


energy content determination with a f=4000 mm lens, focussed directly on a CCD:

27% diffraction limited (AOM-off) 50% diffraction limited (AOM-on)

Peak intensity performance of HFL - MBI

with 100 TW Amplitude Laser System & AOM
as it results from energy, pulse duration and focus measurements

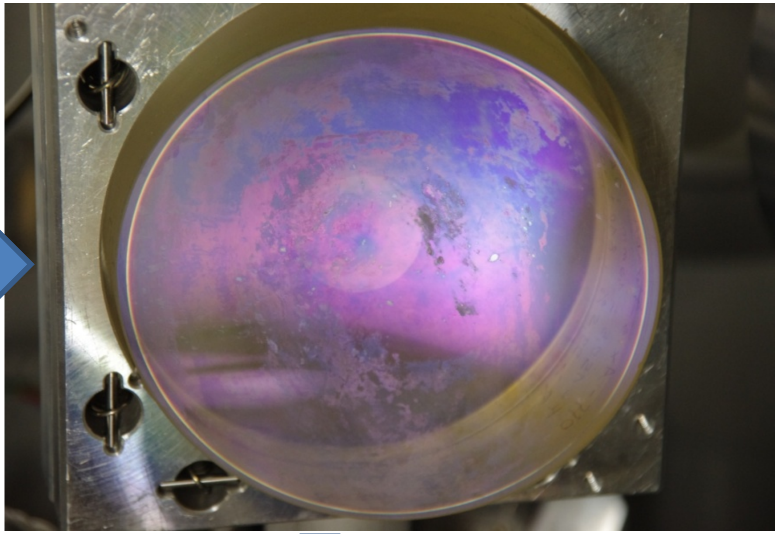


OAP focal distance – 150 mm
beam diameter – 90 mm
energy on OAP: 1.9 J
pulse duration: 30 fs
encircled $2w_o$ - diameter 4.6 μm

diameter FWHM: 2.75 μm
energy content within FWHM: 40 %

FWHM intensity: ~ 5 * 10^{20} W/cm^2
Peak intensity: ~ 7 * 10^{20} W/cm^2

Focusing: coating degradation & intensity drop

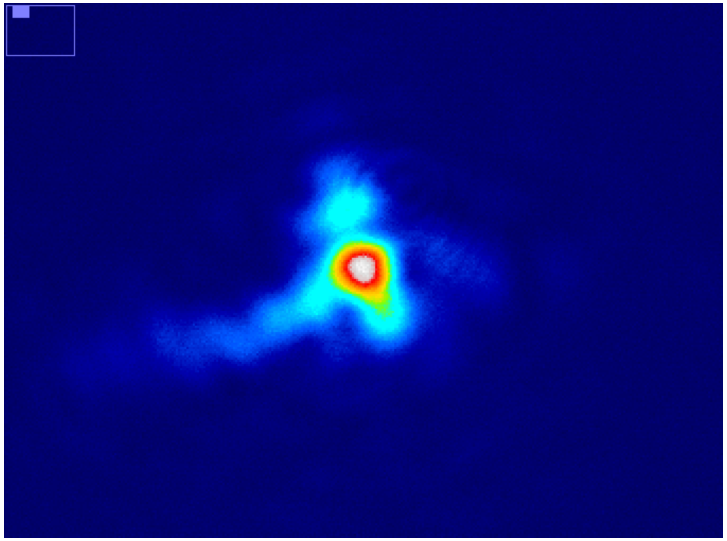


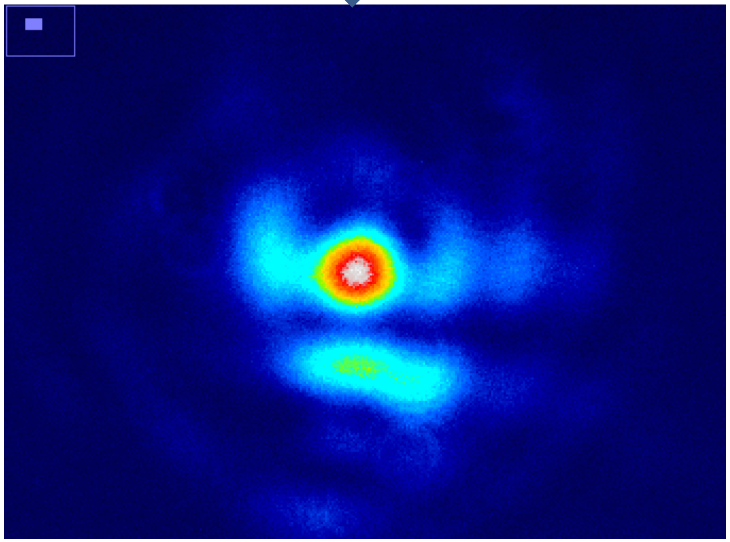
example of coating degradation
after use with different target systems
~ few 10^4 shots in ~ 4 years (single shot experiments)
~ 10^6 shots in ~ 10 days (10 Hz rep. rate experiment)

energy content within FWHM

achieved best value so far: 40%

14%



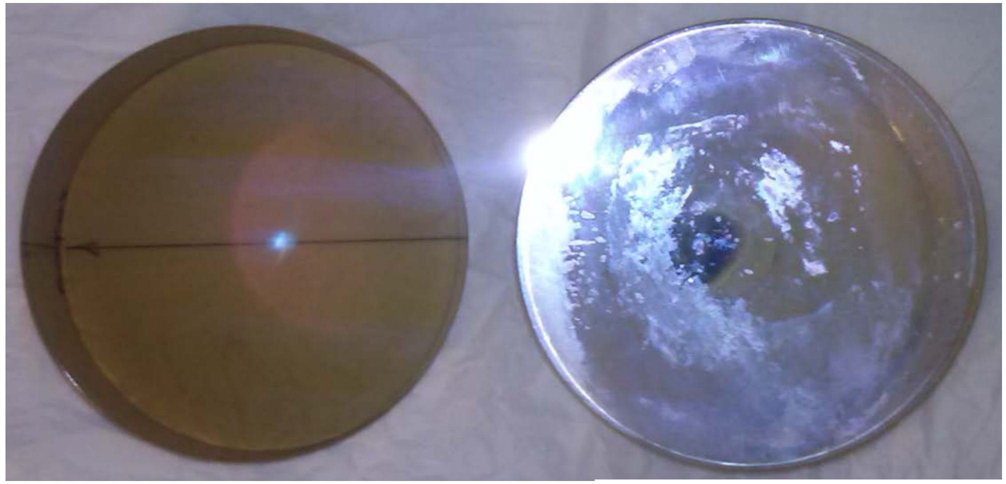


Focusing: coating degradation & intensity drop (comparison 2: same beam, same day, same AOM compensation)

f=150mm OAP 4´´

20% E_L in
FWHM ellipse
3.3 x 2.9 μm^2
diff.lim.~ 2.5 μm
for HFL-MBI
1.4X x 10^{20} W/cm^2

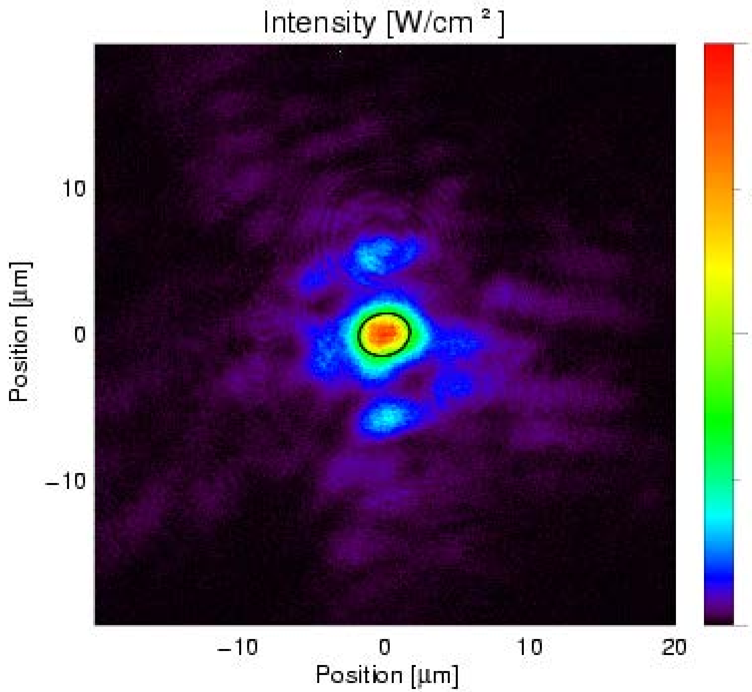
X = 1 – 2 possible

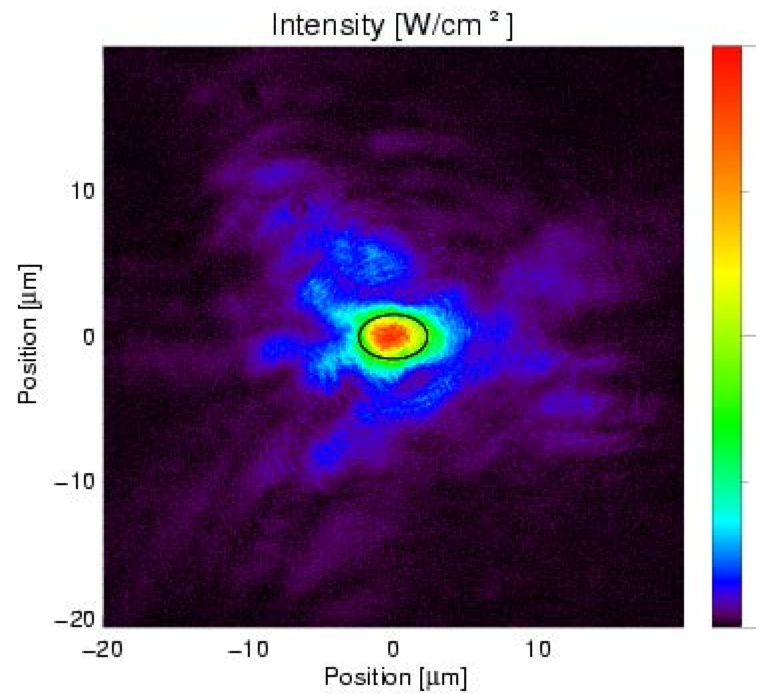


f=150 mm OAP 4´´

20% E_L in
FWHM ellipse
4.3 x 3.1 μm^2
diff.lim.~ 2.5 μm
for HFL-MBI
X x 10^{20} W/cm^2

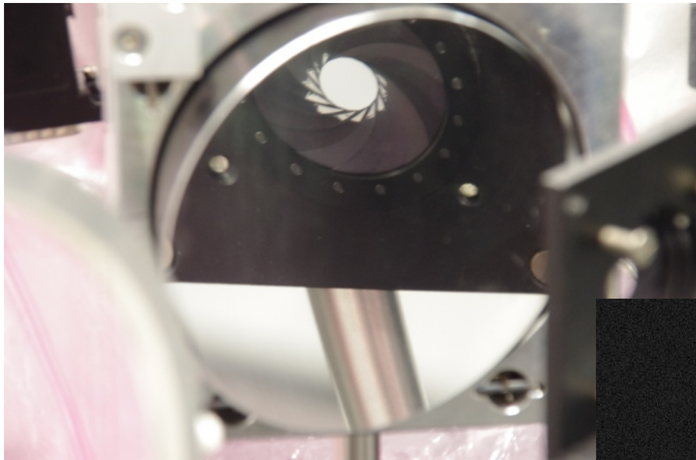
X = 1 – 2 possible



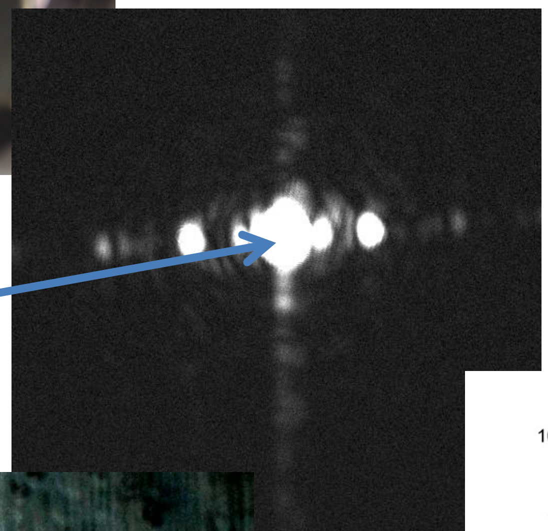


accuracy not satisfactory – problems: background, fluctuation, attenuation

Focusing: diamond turned parabolic mirrors



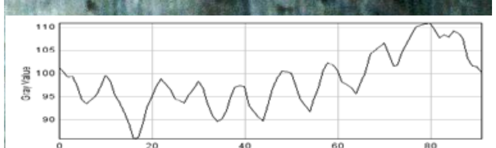
experiment determines
if one can stay with
several ***side-maxima***
reaching ***up to 1%*** of peak intensity

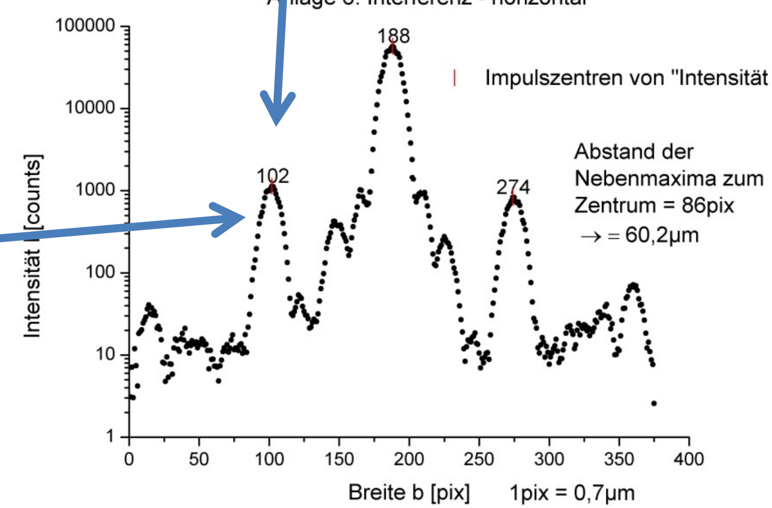


measured focal
spot sizes and FWHM
energy concentration
(up to 40 %) is not much
different to
high quality OAP)

(The price differs about
a factor of 100 ☺)

diamond
turned
surface

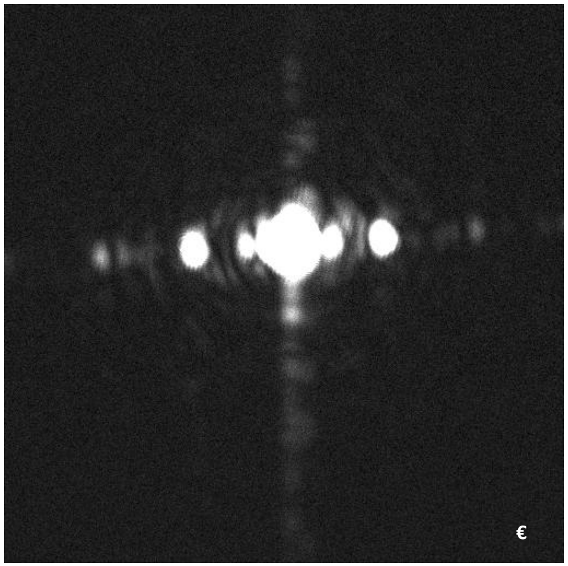


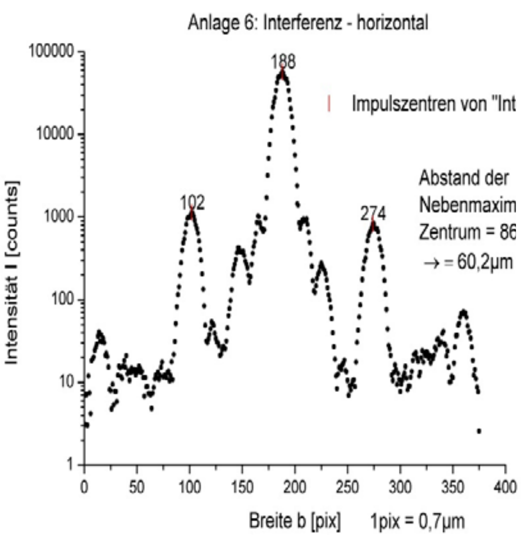


groove spacing
about 6 micron

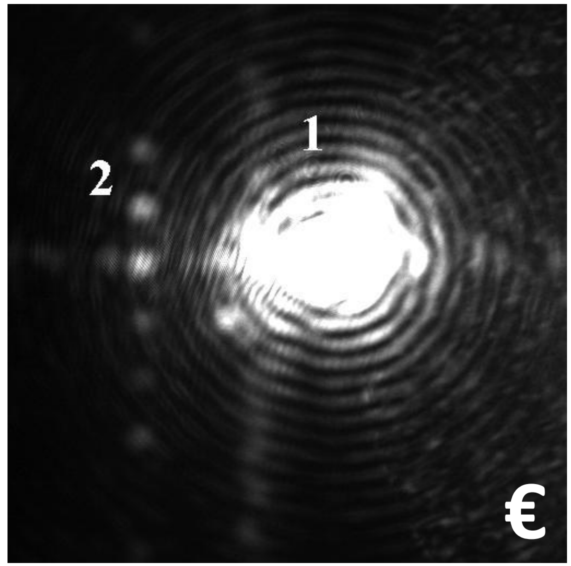
Focusing: comparison of used parabolic mirrors

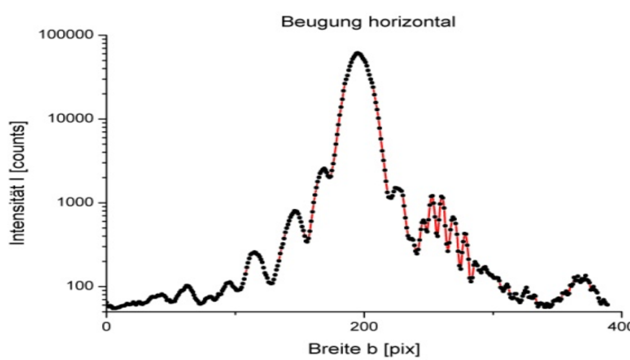
Janos Technology
metal, turned



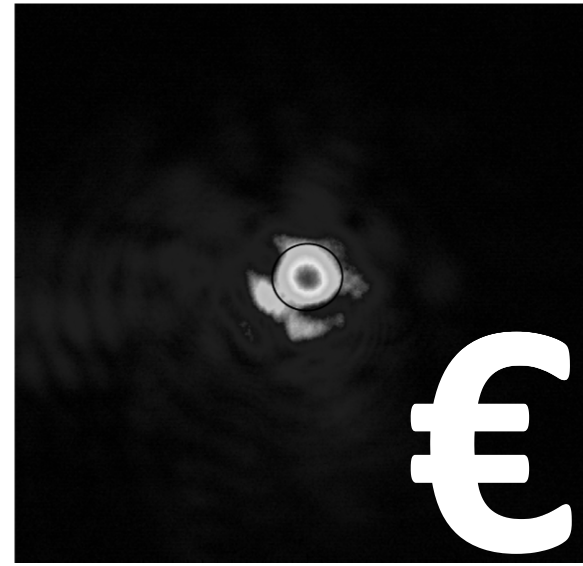


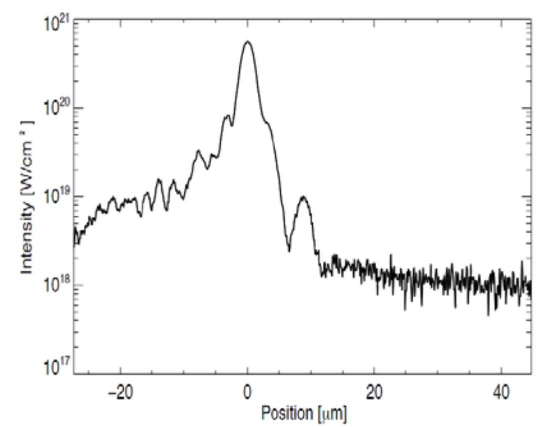
Kugler GmbH
metal, turned





Berliner Glas
glass, polished



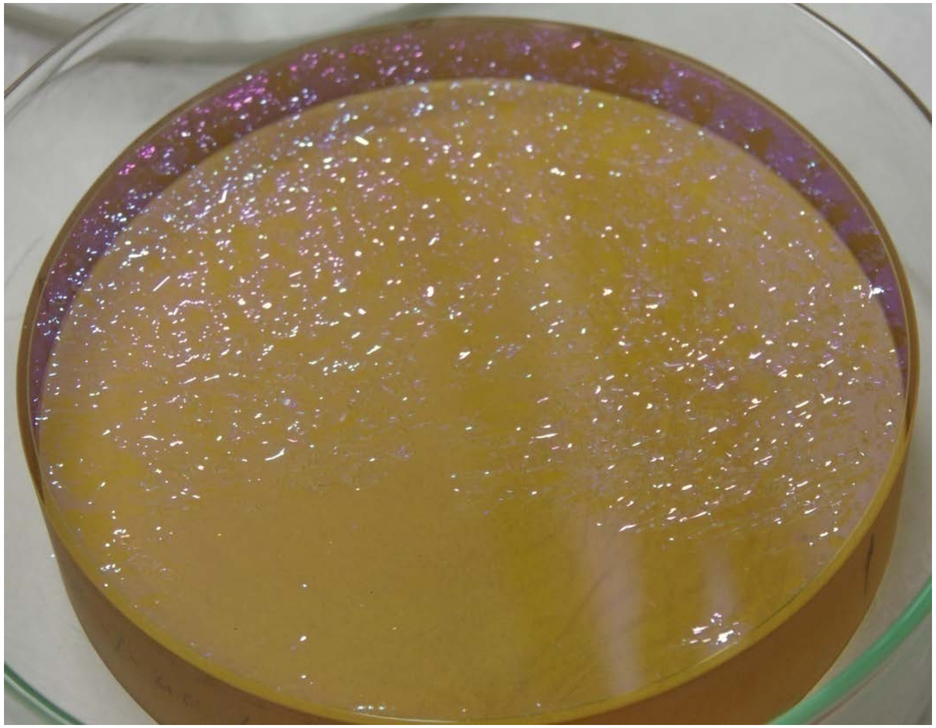


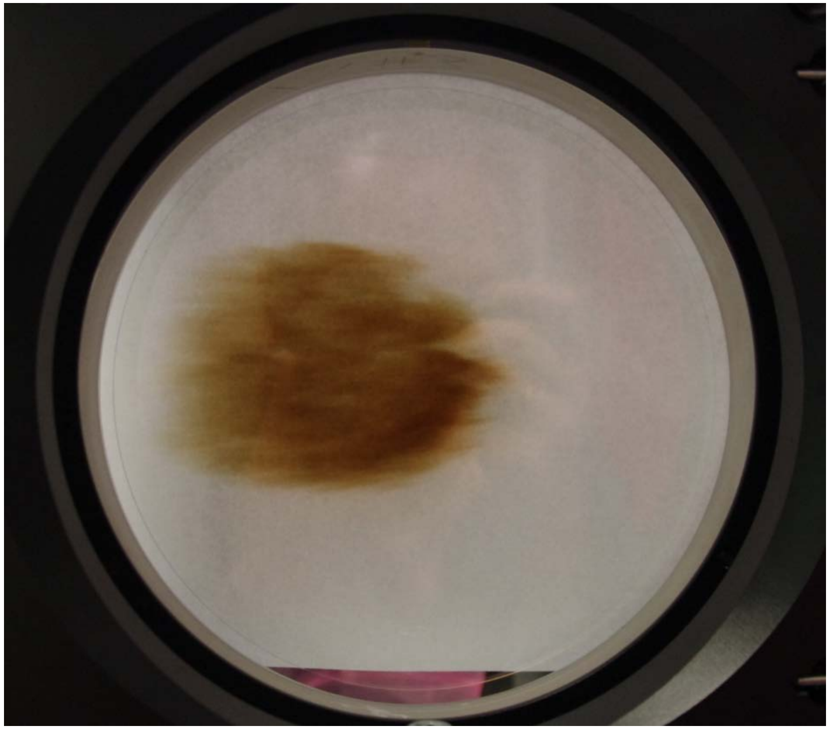
other manufacturer:
Zeiss, optical surfaces (lambda/10), SORL

Beamline mirrors: coating problems

coating destruction
after first vacuum insertion

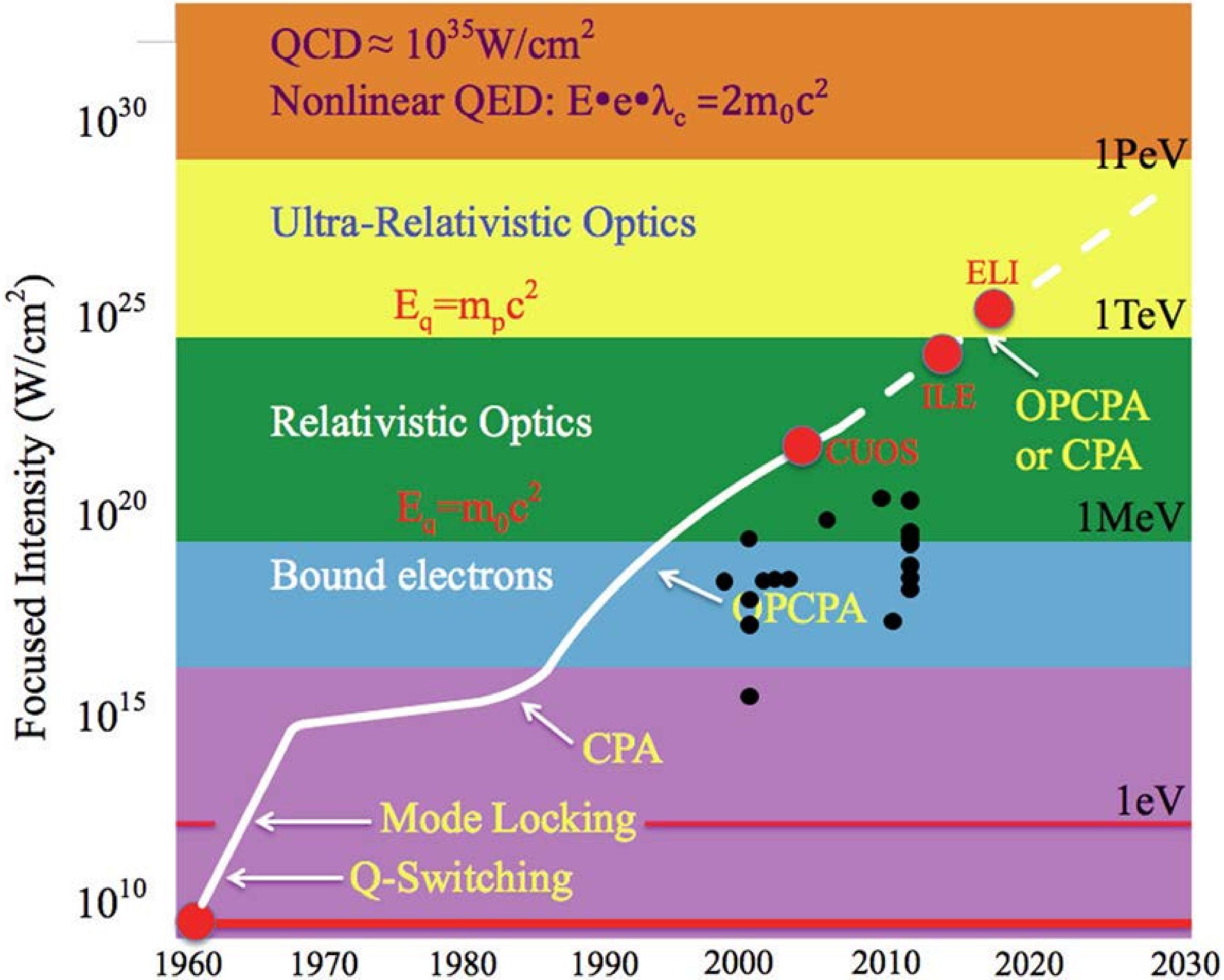
color centers in glass substrate
due to few percent laser transmission
of coating





- carbon contamination (of gratings / mirrors) – plasma- or UV- cleaning

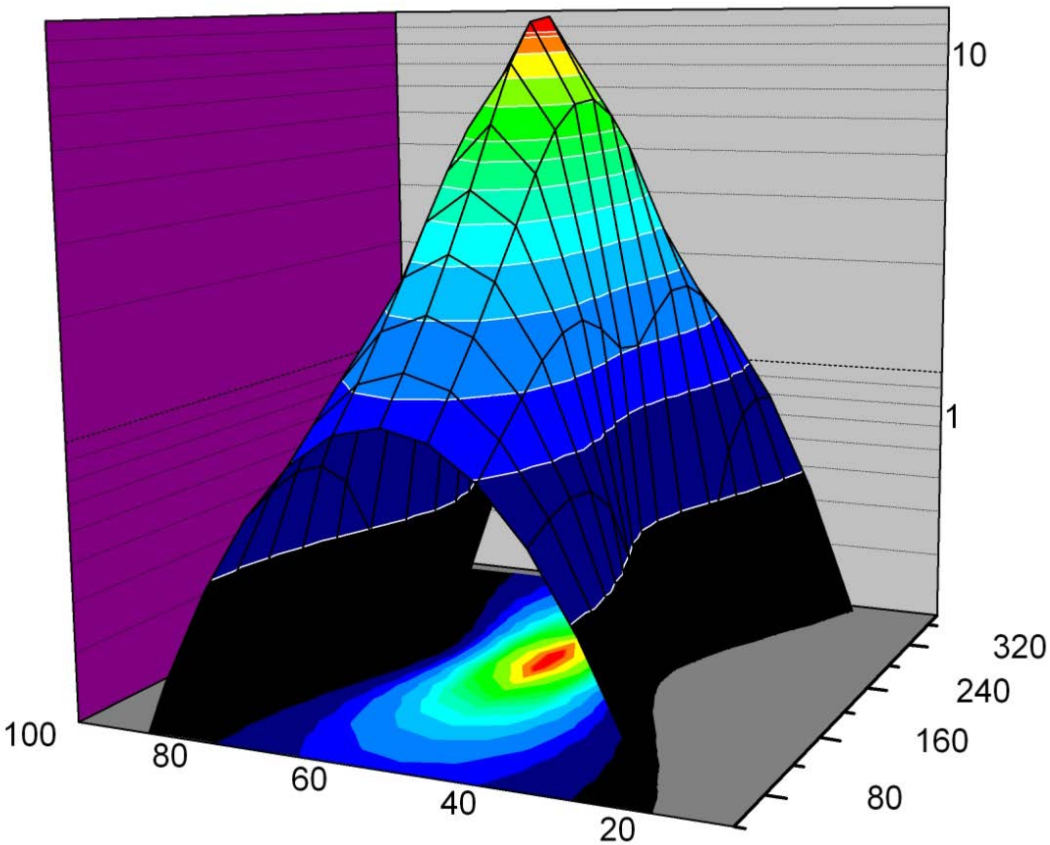
Intensity expectations and reported values in experiments



better intensity determination (in the relativistic regime) would give a much better quality in data analysis

Focusing: high intensity, high field strength – direct measurement ?

example plot: focused gaussian beam
with w_0 = 5 beam waist parameter



consequences of field gradients:

-> most important
– ponderomotive potential

effects:
- ionization of atoms
- acceleration (scattering) of electrons / ions (atoms)
- radiation of e.g. scattered electrons

consequences of intensity distribution:

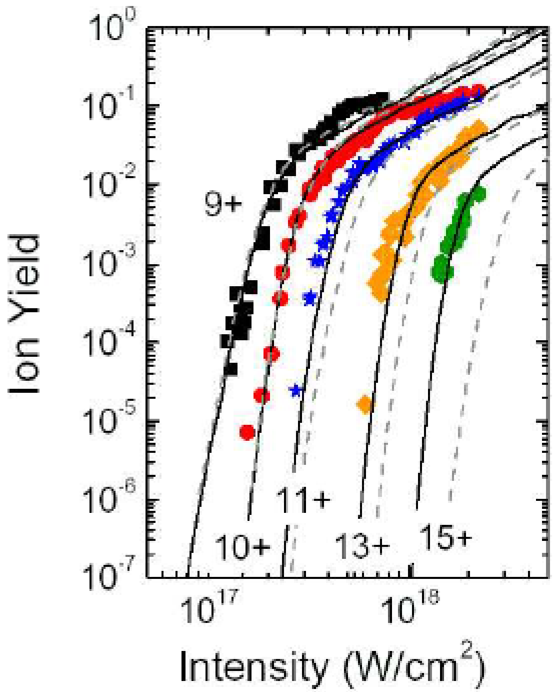
-> extended regions of lower intensity produce
– obstructive background signals in experiments

Direct measurements @ theoretical calculation of laser intensity

laser interaction with single atoms

measurement of ionization stages

Kr-ionization



measurement of electron spectra

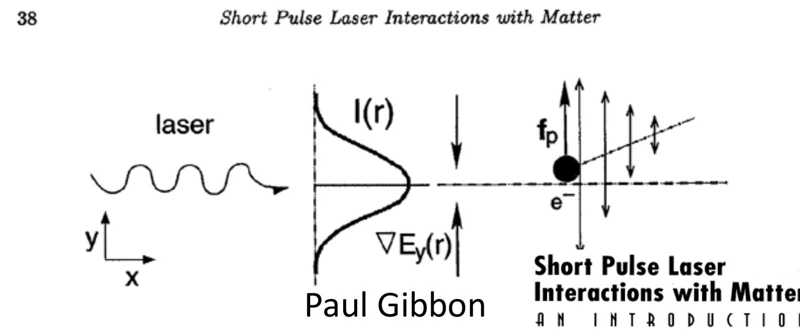
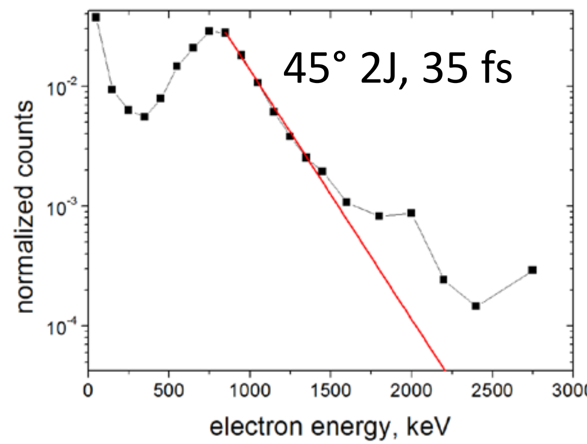


Fig. 3.4 Schematic view of the radial ponderomotive force due to a focused beam.



electron energy and emission angle depend on ponderomotive potential

theoretical calculation of field ionization (ADK & relativistic corrections) gives relation between ionization rate and laser intensity

MBI- Thesis E.Gubbini 2005

theoretical calculation of ponderomotively accelerated electrons gives relation between electron spectra and laser intensity

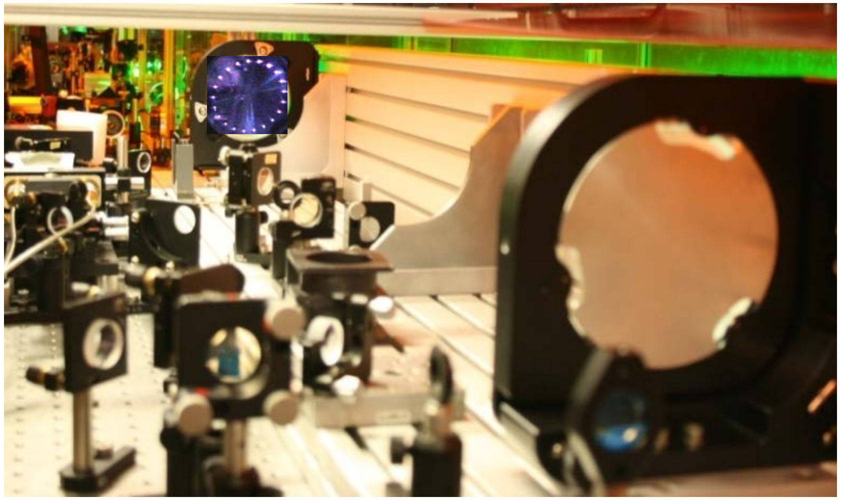
MBI-LL experiment 2012: ~ 2 x 10^{20} W/cm^2

Problems: count rate and volume effects

Pulse synchronization of TW - beamlines

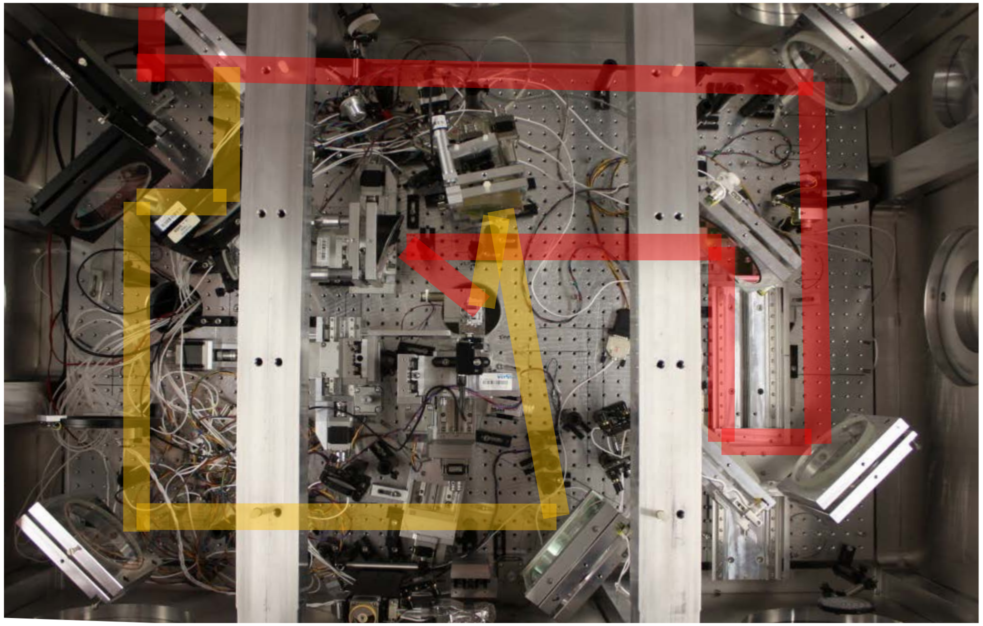
- Dual laser operation
  in different experiments

- Synchronized laser operation
  with newly developed (180 ns) delay unit



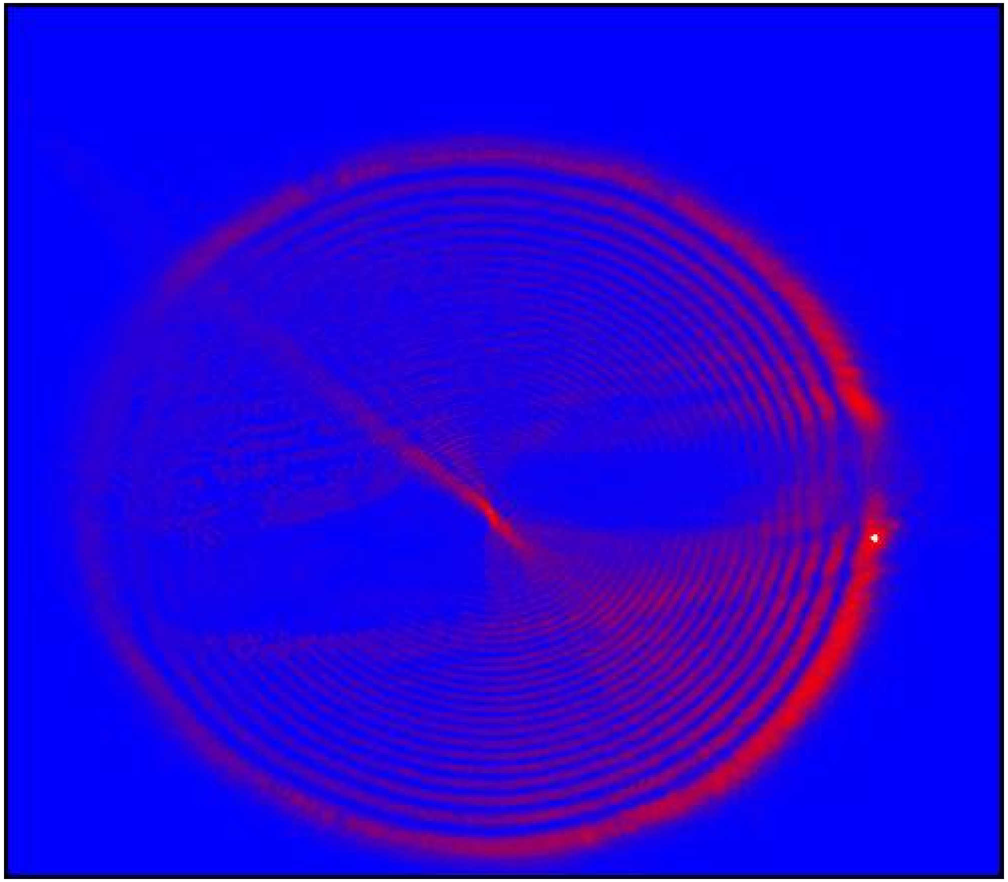
beamline and

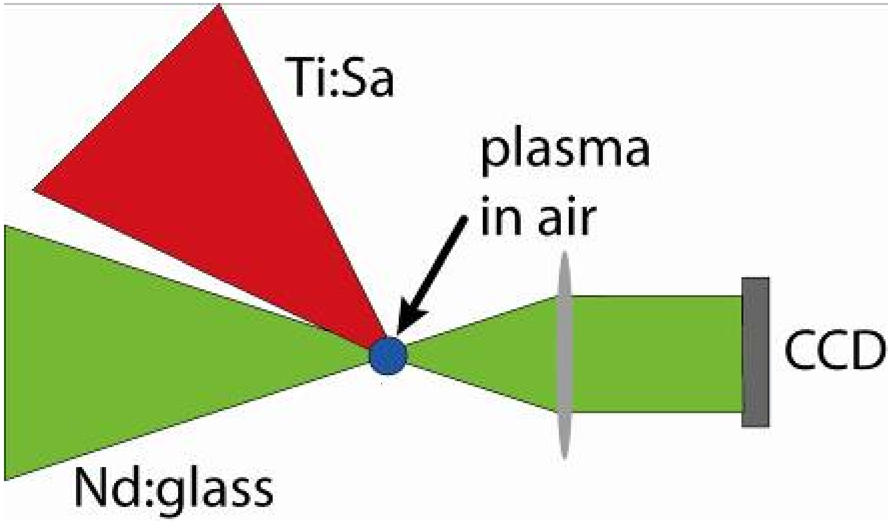
experiment setup for proton imaging

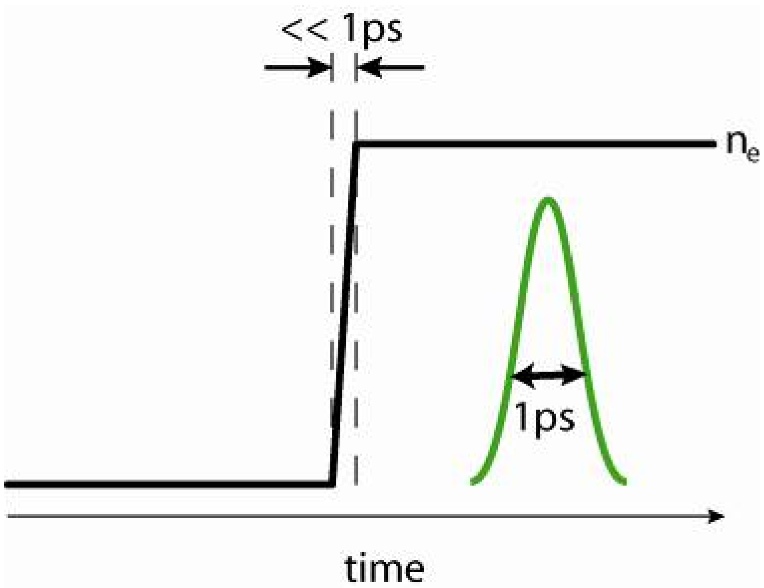


A simple method for beam (2 colors) synchronization

with plasma shadow





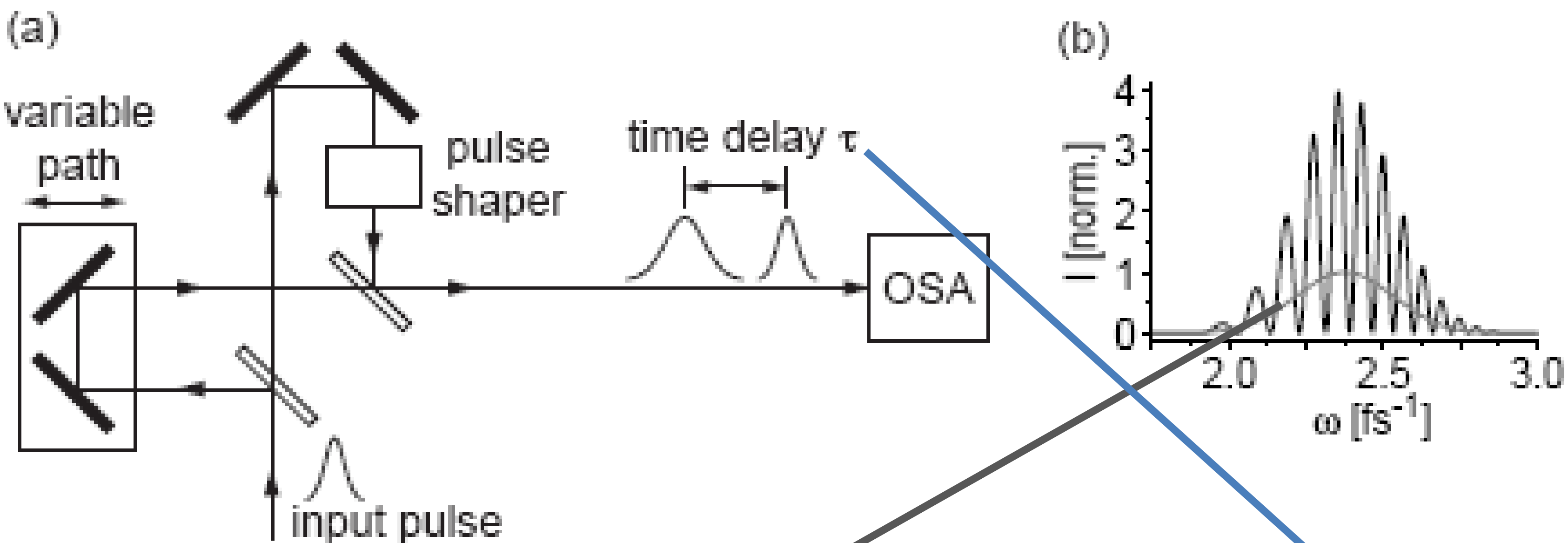


Ti:Sa t = 35 fs

Nd:glass t = 1 ps

„time resolution“ ≤ 1 ps

spectral interference



we applied:
2nd order single shot autocorrelator

$$I_{SI}(\omega) = 2\varepsilon_0 cn \left| E_0^+(\omega) + E^+(\omega)e^{-i\omega\tau} \right|^2$$

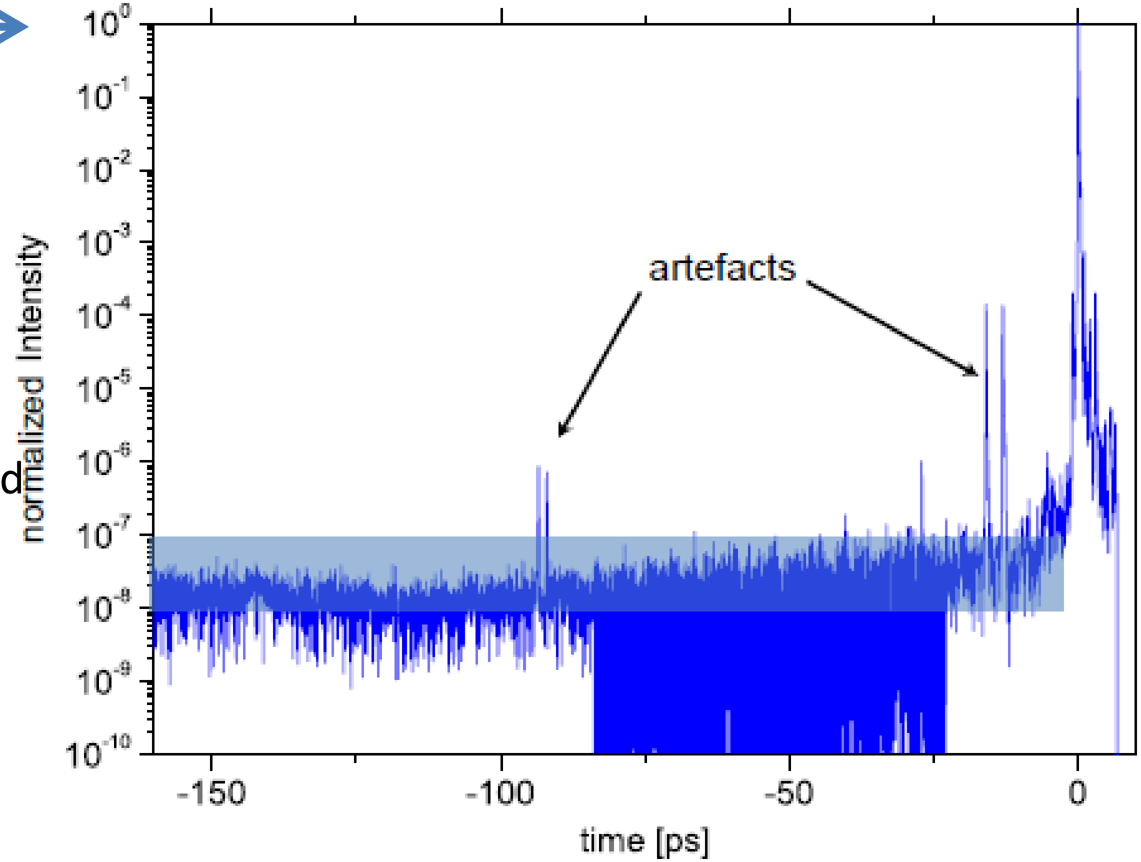
$$E_0^+(\omega) = A_0(\omega)e^{-i\Phi_0(\omega)} \quad E^+(\omega) = A(\omega)e^{-i\Phi(\omega)}$$

Gerhard Kampert, PhD-Thesis , Würzburg 2004
http://deposit.ddb.de/cgi-bin/dokserv?idn=97440814x&dok_var=d1&dok_ext=pdf&filename=97440814x.pdf

Ultra-high contrast of femtosecond laser pulses

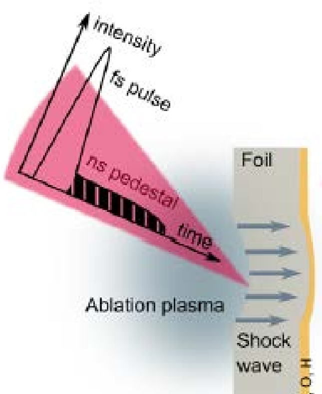
the temporal contrast of the laser pulse is a critical issue

~ 10^{19} W/cm^2



contrast issue:

~ 10^{11} … 10^{12} W/cm^2
plasma creation threshold
for ~ ns pulses
ns pedestal launches
shock and heat waves



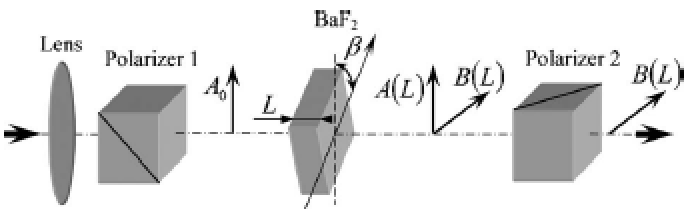
Improvement necessary,
otherwise interaction with low density plasma at pulse peak

K Zeil et al. New Journal of Physics **12** (2010) 045015

Pulse cleaning with non-linear methods: XPW - frontend

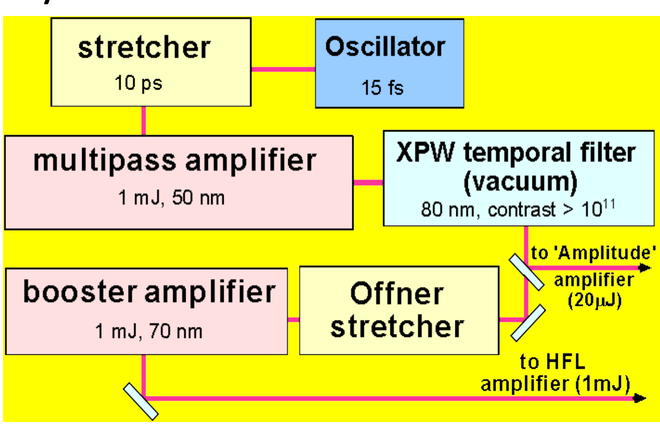
Principle

cross-polarized wave generation

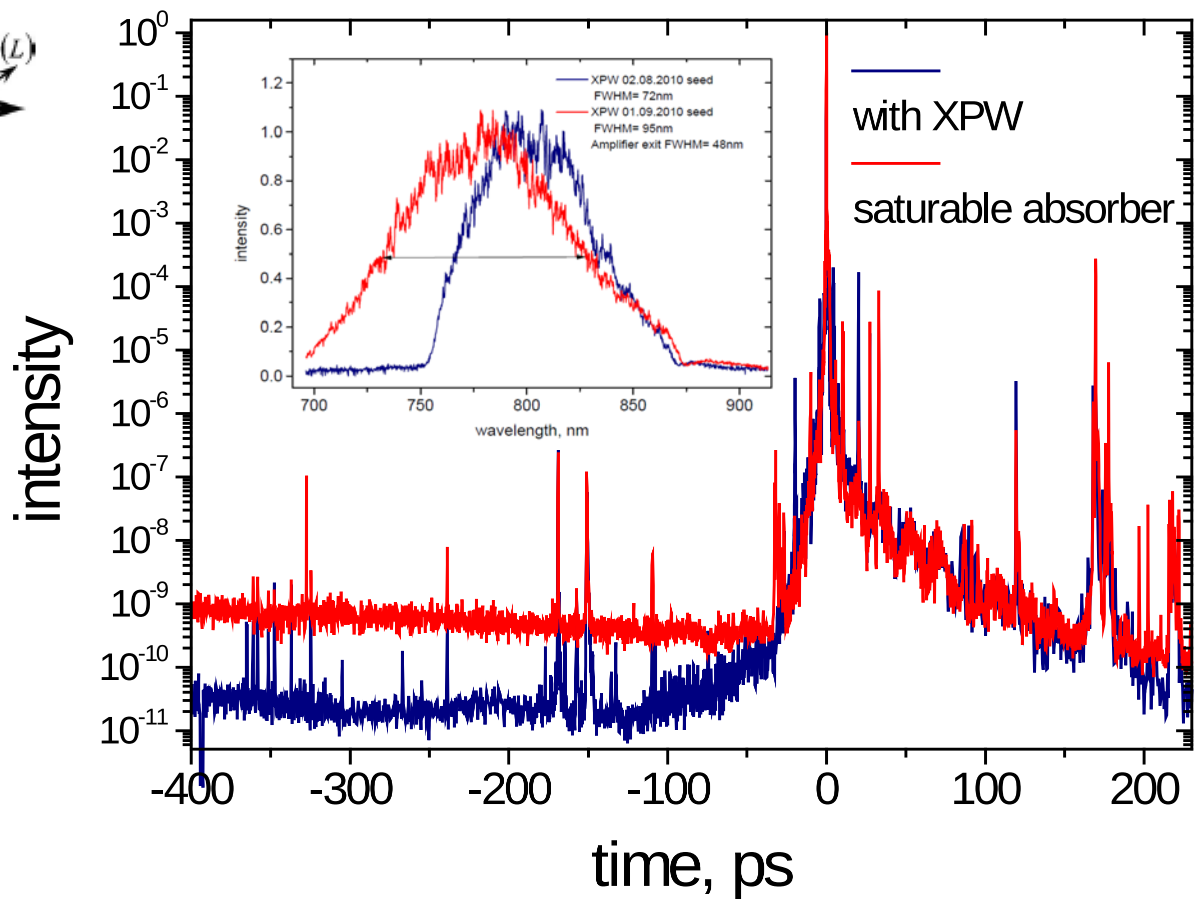


degenerated four wave mixing process in non-linear media

layout



results



Ultra-high temporal contrast - the plasma mirror technique

Initial Parameter

(2010) 2013

- pulse energy:

(1.2 J)

2 J

- pulse duration

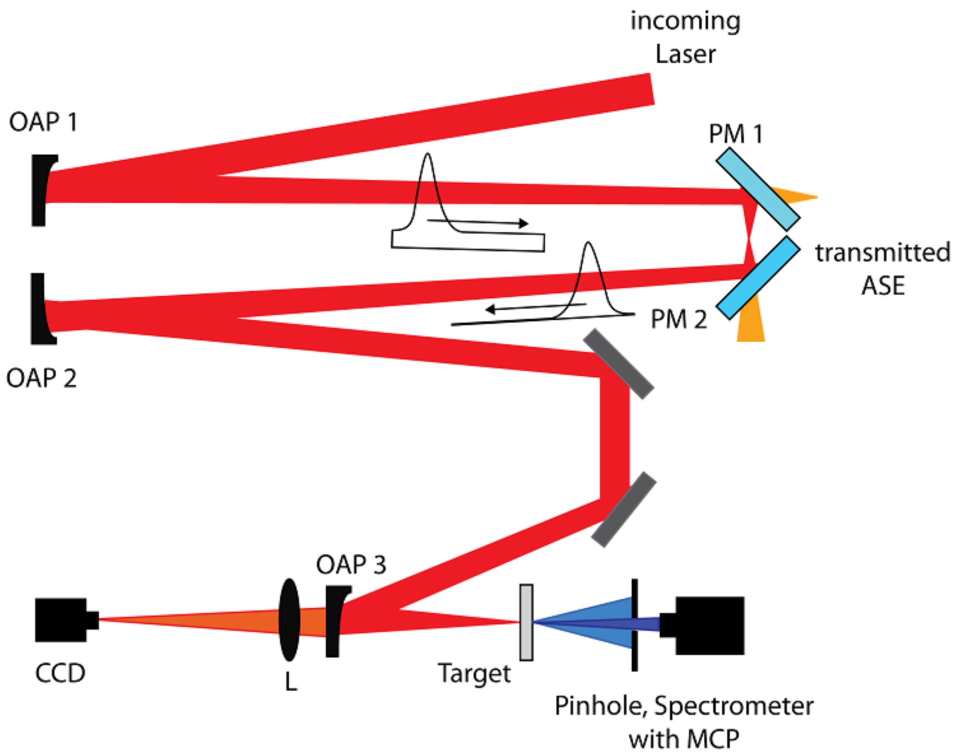
(45 fs)

35 fs

- ns - ASE contrast:

(5 x 10^{-8})

1 x 10^{-10}



Double – Plasma Mirror (DPM)

- energy throughput

~60 %

with XPW-frontend

~ 70 % - 80 %

- no decrease of

focusability

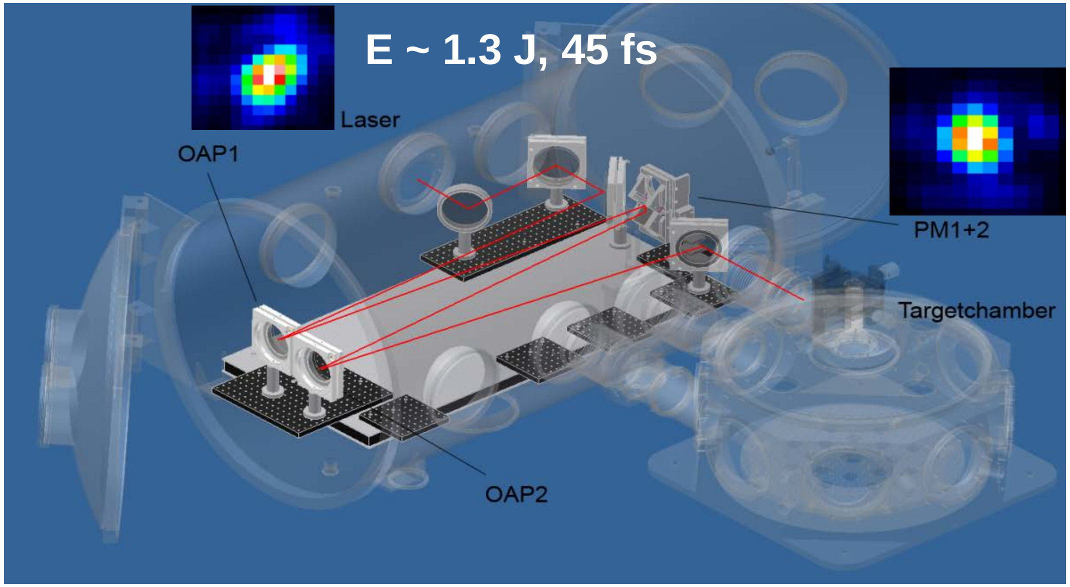
Target chamber

focused with f /2.5 Off-Axis Parabola (OAP)

→achievable intensities with MBI – HFL system ~ 5 x 10^{19} W/cm² – 2 x 10^{20} W/cm² → a_0 ~ 5 -10

Data from literature and qualitative comparison suggest $I_{pedestal} < 10^{-11} I_{peak}$
with XPW- frontend : $I_{pedestal} < 10^{-13} I_{peak}$

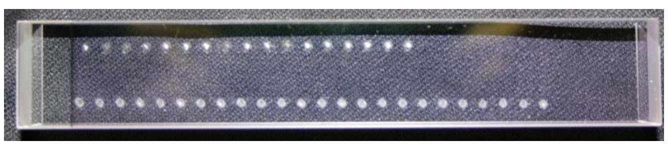
Plasma Mirror: technical realization



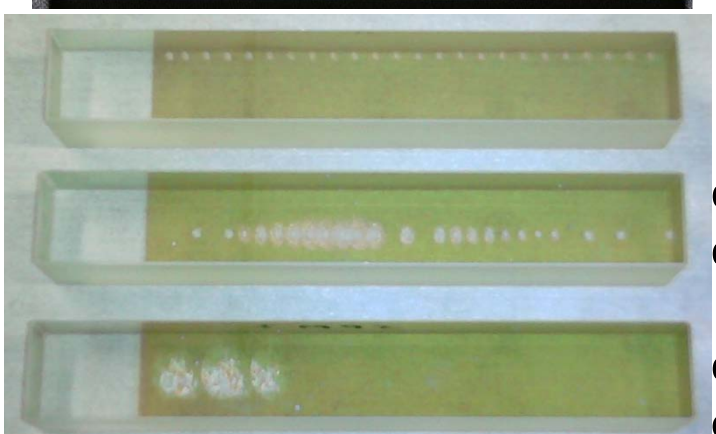
Interaction with nm-thick foils:
contrast > 10^{10}
E ~ 0.7 J, 45 fs,
I_{Lpeak} ~ 5 x 10^{19} W/cm^2

Henig et al. PRL 2009
Steinke et al. LPB 2010

plasma mirror - coated substrates



best with XPW-frontend



perfect shot series

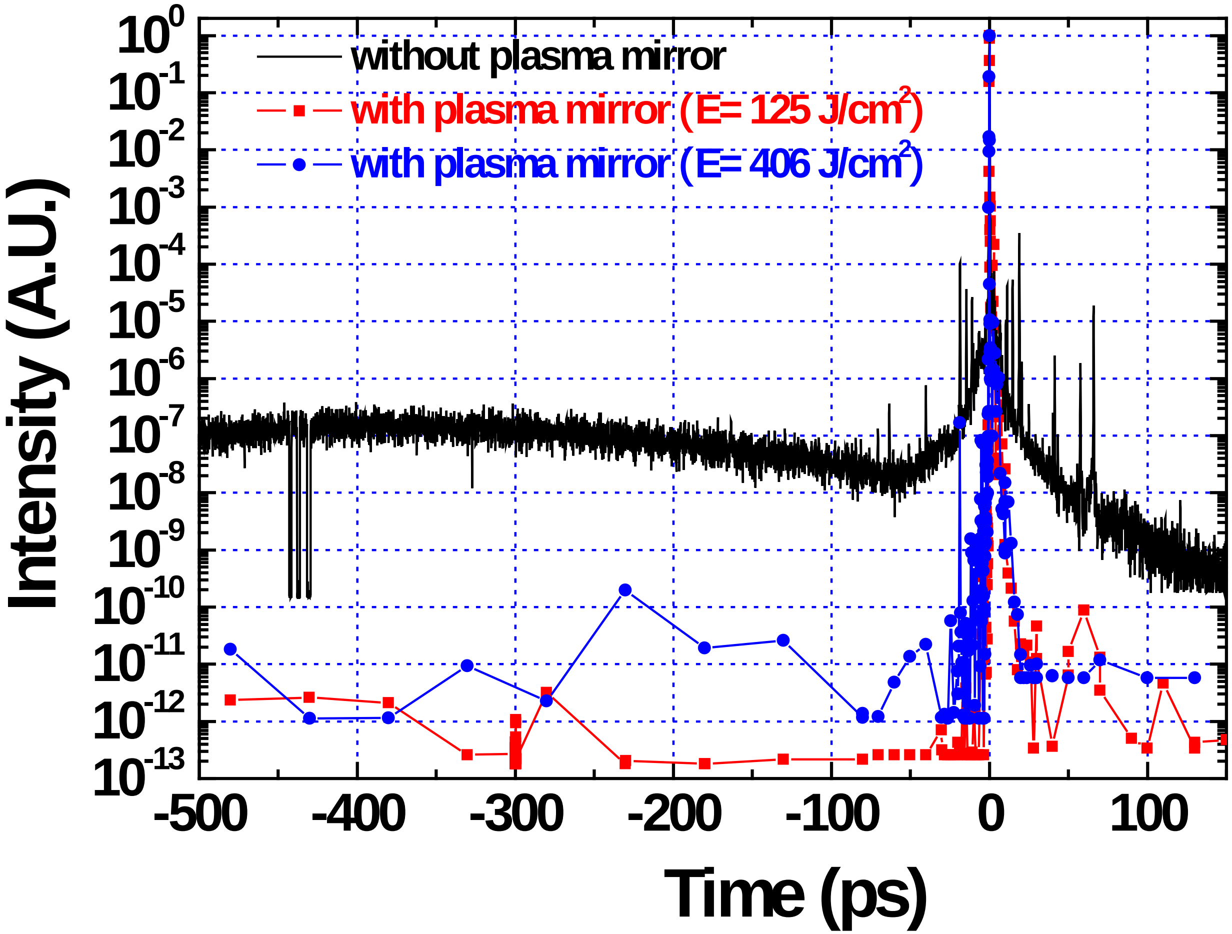
degradation due to debris

damage of test coating

view inside:
plasma mirror
in vacuum chamber

Temporal contrast produced with a plasma mirror

Double plasma mirror at GIST – APRI (Korea)
3rd order correlation measurement
I.J. Kim et al. APB104(2011)81



R=0.42
R=0.48

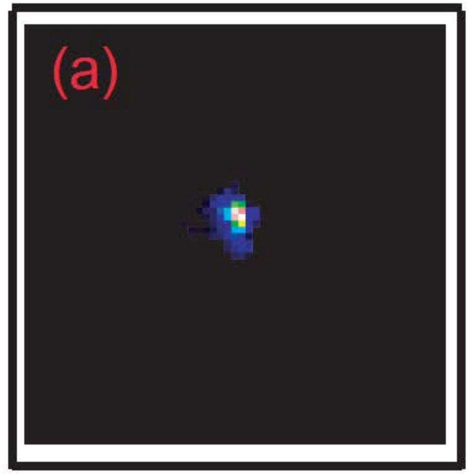
publication also shows: distortion in focal distribution

cf. other systematic work – Ch. Rödel Diploma 2009 FSU-Jena

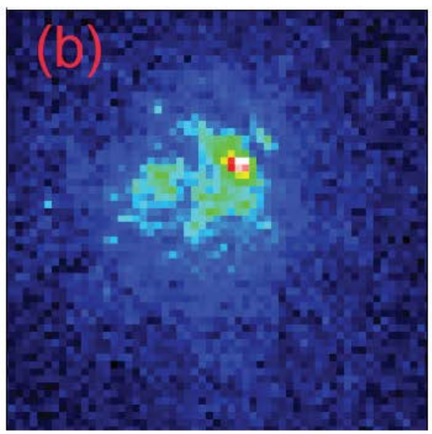
Signatures of temporal contrast in experiments with nm-foils

Images of back-reflected light from target

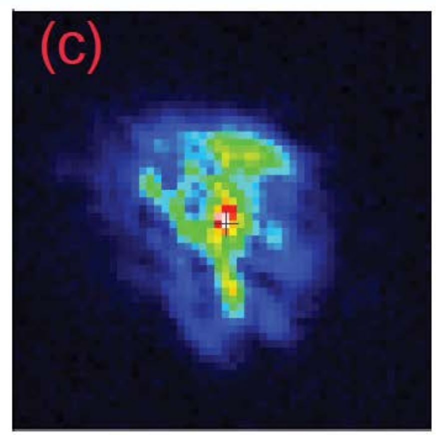
Focus of a low-energy shot without plasma generation



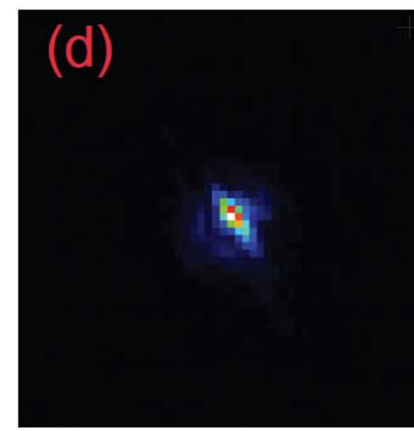
high power shots



no DPM
$CR \sim 5 * 10^{-8}$



DPM with glass
$CR \sim 10^{-10}$

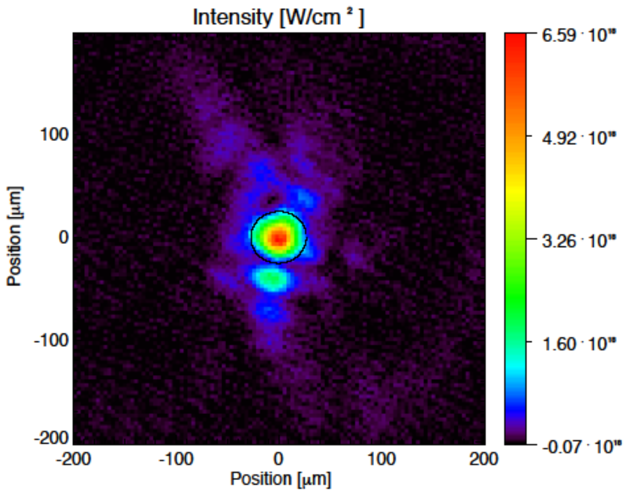


DPM with AR-coating
$CR \sim 10^{-12}$.

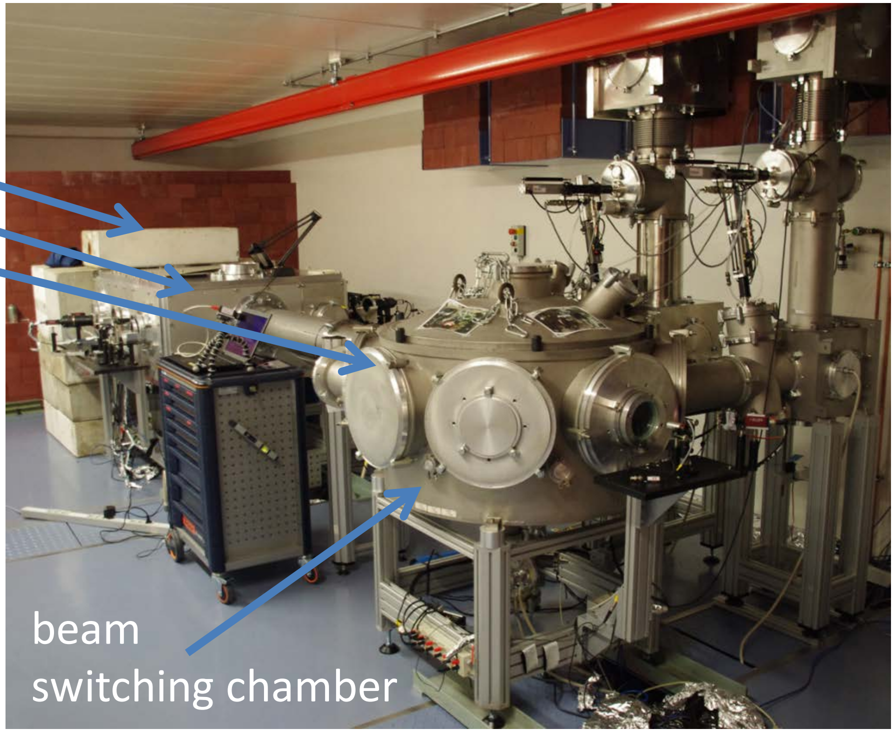

A glimpse of
an experiment
for laser-ion acceleration

Electron acceleration: experiment with radiation enclosure

enclosed magnet spectrometer
experimental chamber
long distance focusing



anticipated intensity with 70 TW on target & OAP f=2500



remote control
of laser and experiment

Credits

F. Abicht, J. Bränzel, Ch. Koschitzki,

A.A. Andreev

M.P. Kalashnikov, U. Eichmann

L. Ehrentraut, G. Kommol, D. Rohloff, P. Friedrich, D. Sommer (engineering and technical staff)

G. Priebe (now XFEL-GmbH), S. Steinke (presently LBNL), P.V. Nickles (MBI / GIST Korea),
T. Sokollik (presently Shanghai Jiao Tong University), T. Paasch-Colberg (MPQ)

S. Ter-Avetisyan (ELI-beamlines)

W. Sandner (Director MBI / Director General ELI-DC)

Transregio 18 collaboration:

MPQ / LMU München,

HHU Düsseldorf, FSU Jena

Summary

- experiments with ultrafast TW-lasers for laser-particle acceleration need careful parameter measurement, control/correction and dedicated optics for establishing relativistic intensities

- a reliable parameter determination (energy, intensity, contrast) being relevant for the interaction zone is of utmost importance for comparison of results from different experiments and analysis of complex laser-plasma interaction

- due to present technical and principal (anticipated unrealistic effort) problems, and the lack of a genuine method and/or calibration, the introduction of some standard "how to measure …" agreements is desirable (my personal perception)

Thank You