ELI-NP Summer school

Bucharest, September 21-25, 2015

HIGH INTENSITY LASERS

Description, issues and state-of-the-art

Gilles Chériaux

LULI, École Polytechnique, France

Gilles.cheriaux@polytechnique.edu

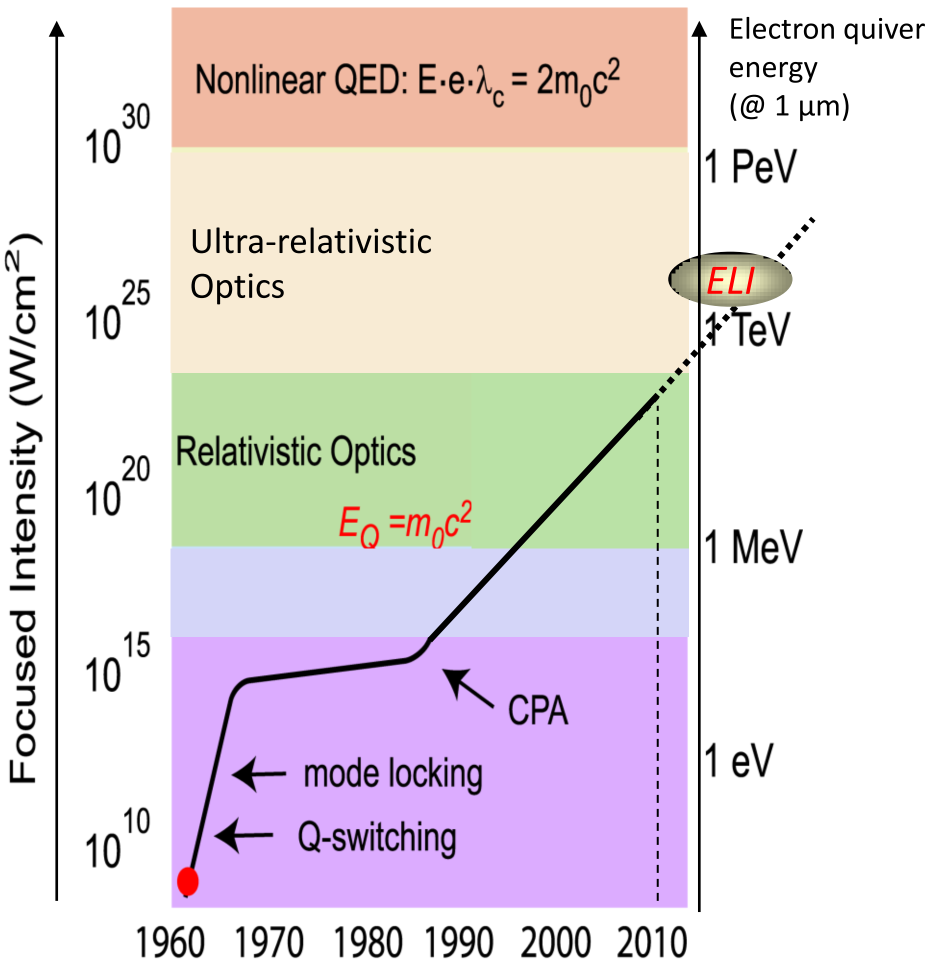
General description of high intensity laser system

Measurement tools

Issues relative to energy, temporal and spatial domains

World-wide State-of-the-art

The interest for ultra-intense lasers



Very motivating fields of physics
To be explored such as
Particles acceleration (e^-, hadrons), HHG,
Table-top X-rays, Gamma rays

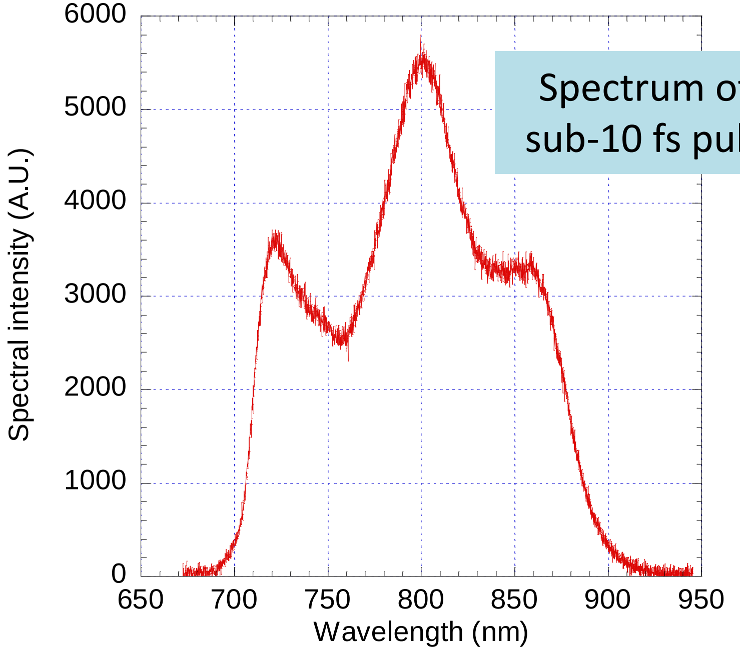
First application of fs pulses
Has been in ophthalmology for
Cornea surgery

A femtosecond pulse

As the pulse is short, the laser beam is no more monochromatic

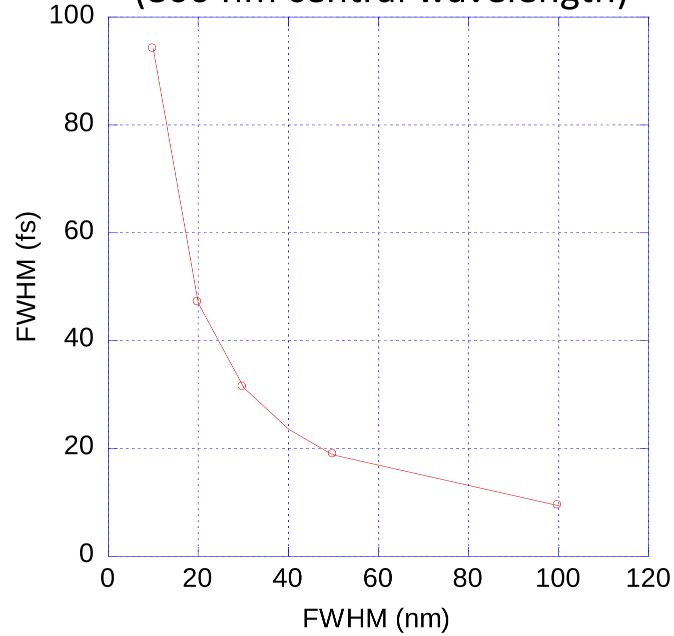
$$\Delta T_{1/2}\,\Delta\upsilon_{1/2} = k$$

k = 1 for rectangular
k = 0.441 for a Gaussian



FFT calculation required

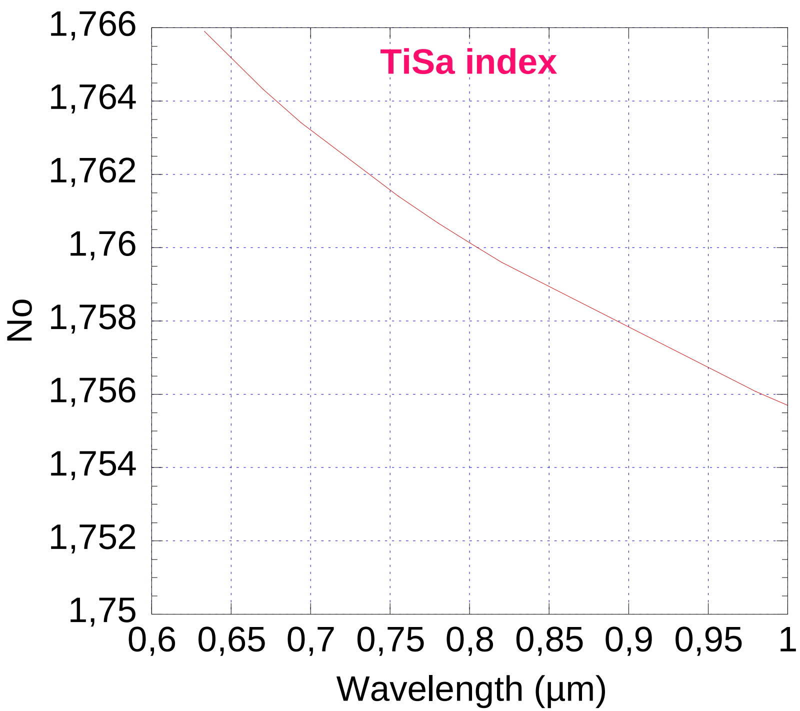
Spectral to Time domain relation
(800 nm central wavelength)



$$\Delta T_{1/2} = \frac{0.441 * \lambda^2}{c * \Delta\lambda_{1/2}}$$

The dispersion

Refractive index is changing with the wavelength



$$\phi(\omega) = \phi_0 + \phi^{(1)}\Omega + \frac{1}{2}\phi^{(2)}\Omega^2 + \frac{1}{6}\phi^{(3)}\Omega^3 + \ldots..$$

$$\Omega = \omega - \omega_0$$

For a pulse with Gaussian shape

$$\Delta T = \Delta T_0 \sqrt{1 + \frac{16(\ln 2)^2 \phi^{(2)2}}{\Delta T_0^{\ 4}}}$$

For 1cm TiSa crystal, the pulse duration lengthening is

30 fs => 62 fs
20 fs => 81.8 fs
10 fs => 159.6 fs

General description of high intensity laser system

Measurement tools

Issues relative to energy, temporal and spatial domains

World-wide State-of-the-art

The CPA concept

How to amplify the femtosecond pulses?

Femtosecond pulses (10^{-15} s)

$\Rightarrow$ Small amount of energy leads to high intensity

$\Rightarrow$ Non linear effect or optical breakdown and damage

$\Rightarrow$ 100 µJ in 20 fs on 200 µm spot size gives an intensity of $1.5.10^{13}$ W/cm²

$\Rightarrow$ Non linear effects occurs, that will destroy the beam quality in time and space

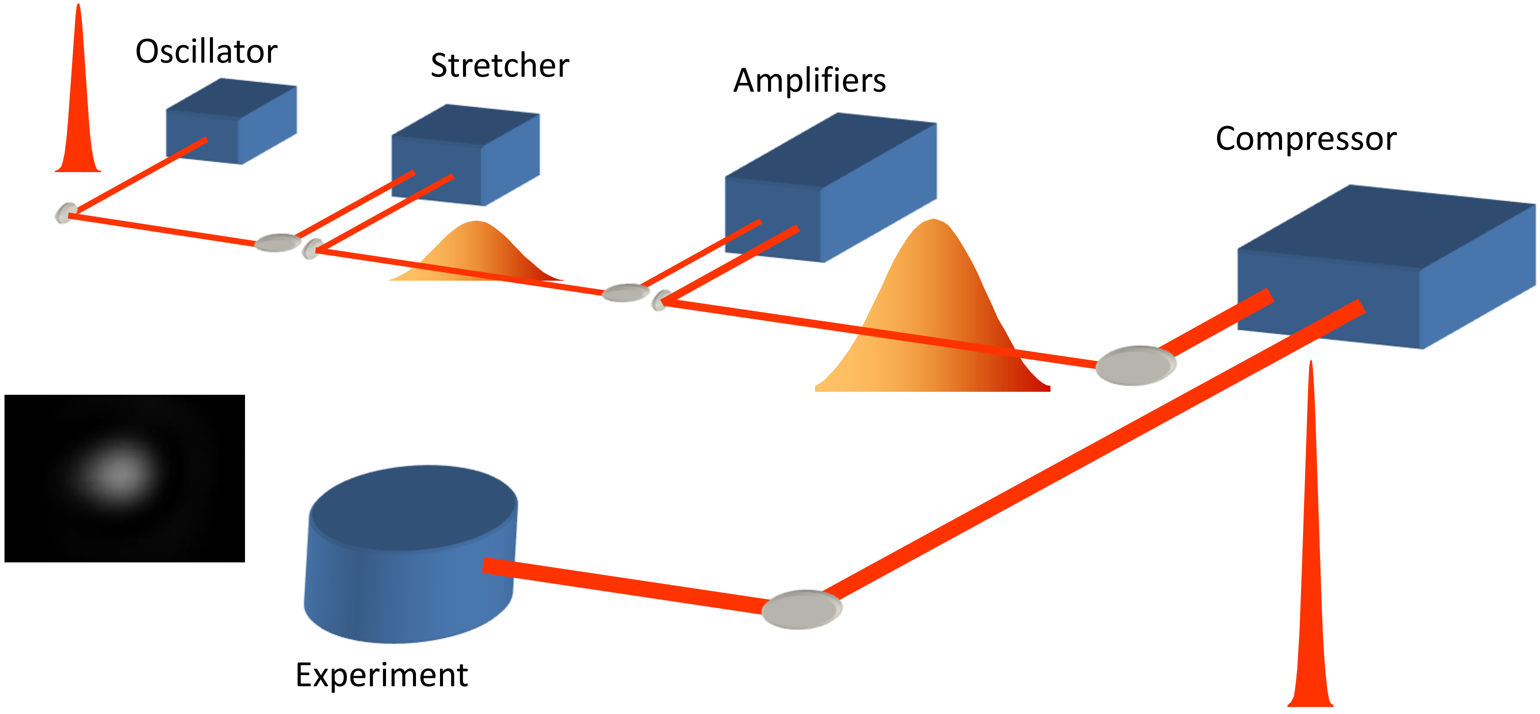
=> Optical breakdown on the optical surface of components that causes damage

The solution is to <u>lengthen</u> the pulse duration <u>while keeping a large spectrum</u>

The CPA concept

The basics scheme has been introduced in 1985 by Gérard Mourou and Dona Strickland

Donna STRICKLAND et Gérard MOUROU
Compression of amplified chirped optical pulses
Opt. Com., Vol 56, number 3, 1 December 1985



Simple scheme but with drawbacks for High energy and short pulse lasers

The generation of femtosecond pulses

The standard generation of fs pulses (TiSa, Yb doped):

The goal is to exploit the largest spectral bandwidth (Femtolasers, Venteon, Spectra-Physics, Coherent, KMLabs, Amplitude Systems, JDSU previously Time Bandwidth…)

Average power: up to 1W

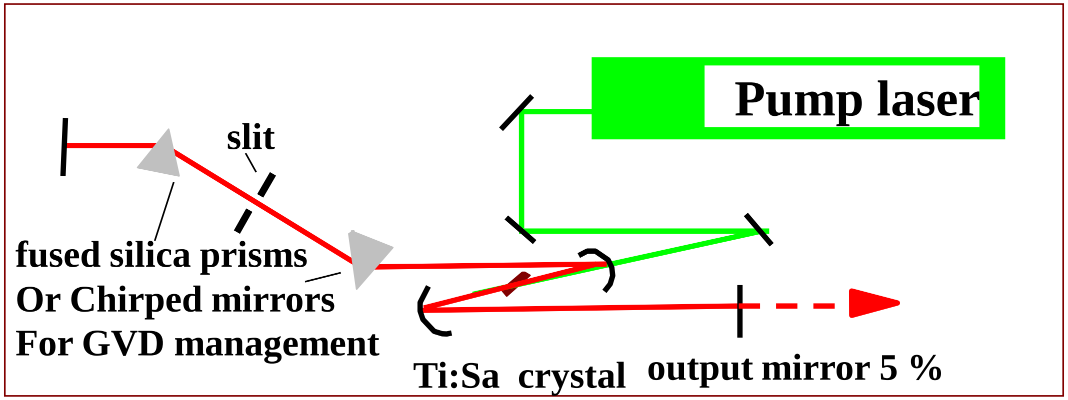
Pulse duration: as short as 5 fs

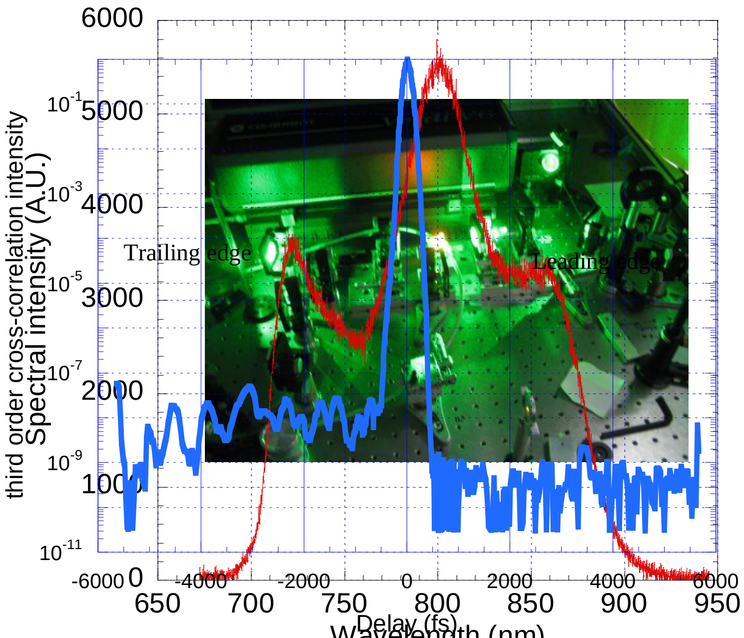
Water cooling

In a laser cavity, Kerr lens mode-locked:

Balance between intra-cavity intensity for non-linear effects and GVD

High temporal contrast => "ideal" for seeding amplifiers



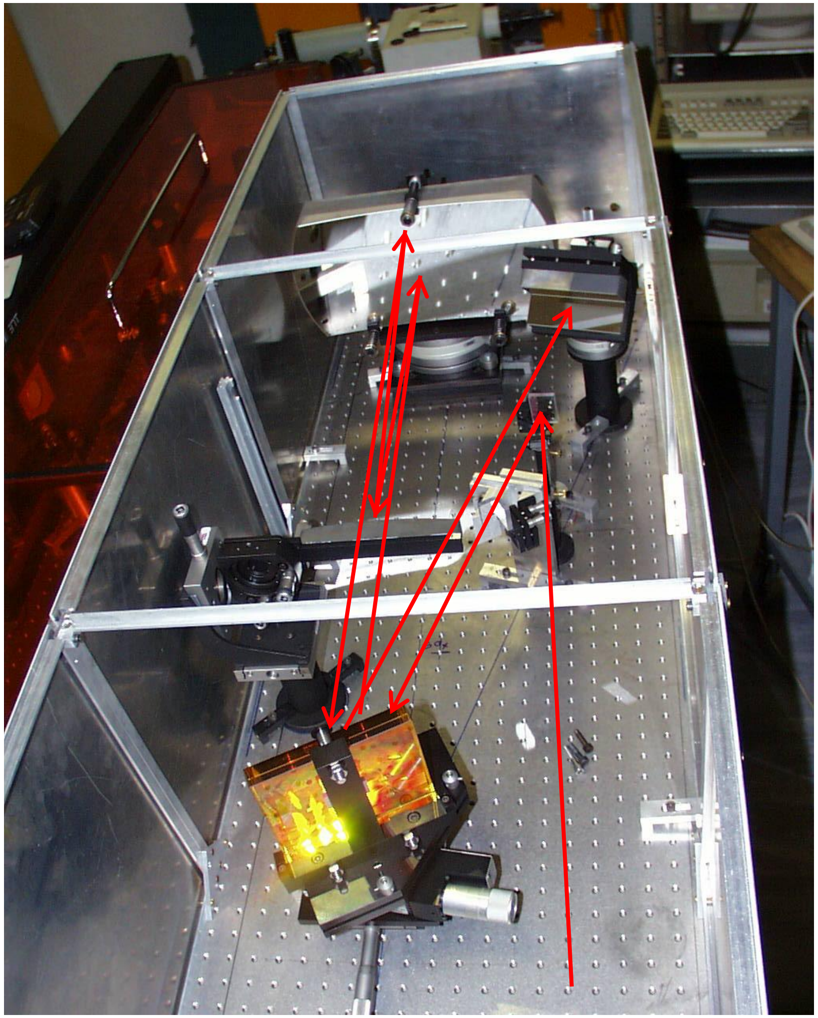


Stretching the seed pulse

The ways to stretch the laser pulses

- Fibers
- Grating and optical system
- Grisms
- Volume Bragg Gratings

$$\Delta T = \frac{\phi^{(2)} 4 \ln 2}{\Delta T_0} \quad / \quad \phi^{(2)}{}_{stret}(\omega_0) = \frac{L_{stret}\, \lambda^3}{\pi c^2 d^2 \cos^2 \theta}$$



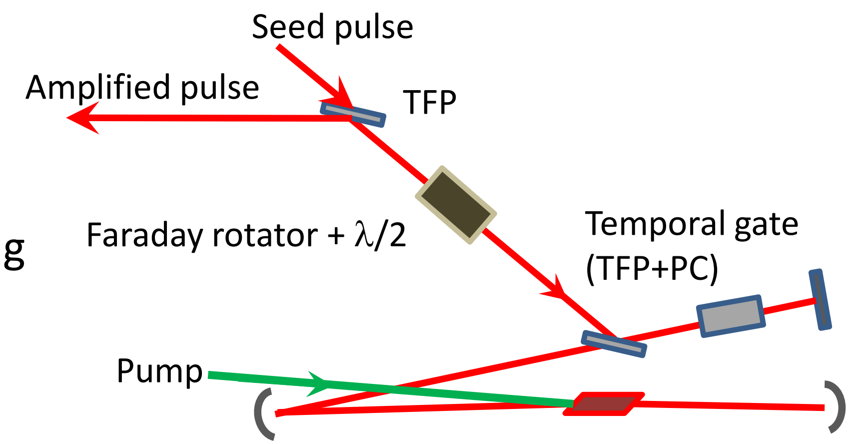
For high-intensity lasers, grating based stretcher is the solution

- Öffner type (spherical or cylindrical mirrors) is generally used

➢ large stretching ratio
➢ large spectral bandwidth
➢ very low aberrations

The amplification of femtosecond pulses

In a cavity:



⇒Regenerative amplifier

Increase the energy to mJ level of the pulse coming from the oscillator

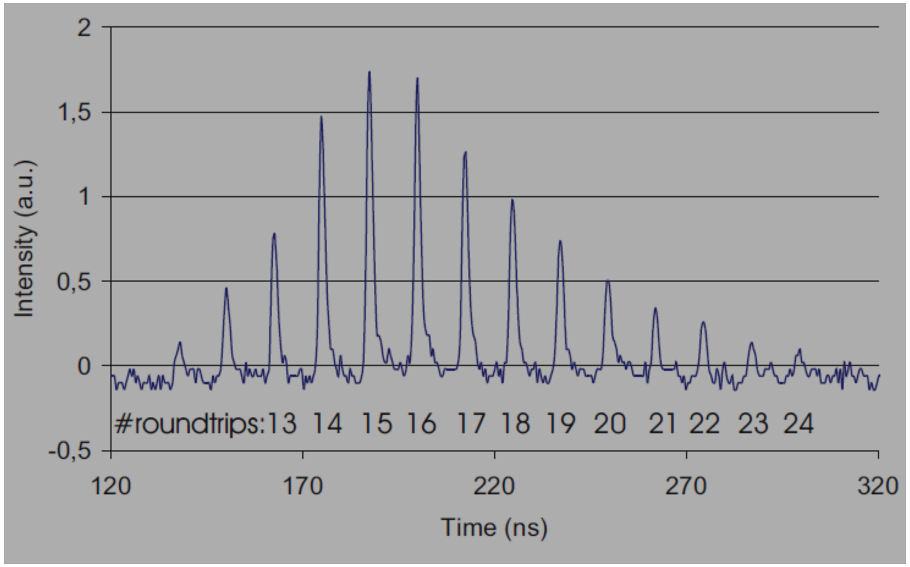
⇒ This requires high optical gain

High average power: up to 5 Watts

Relatively high fluency: ~2 J/cm² (far from TiSa damage threshold)

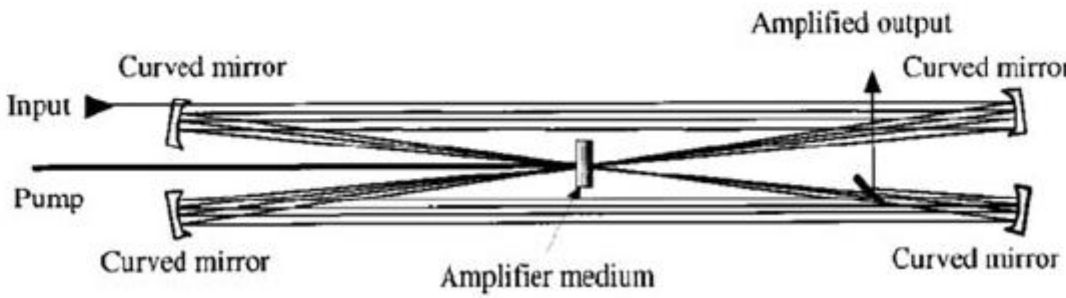
Brewster cut

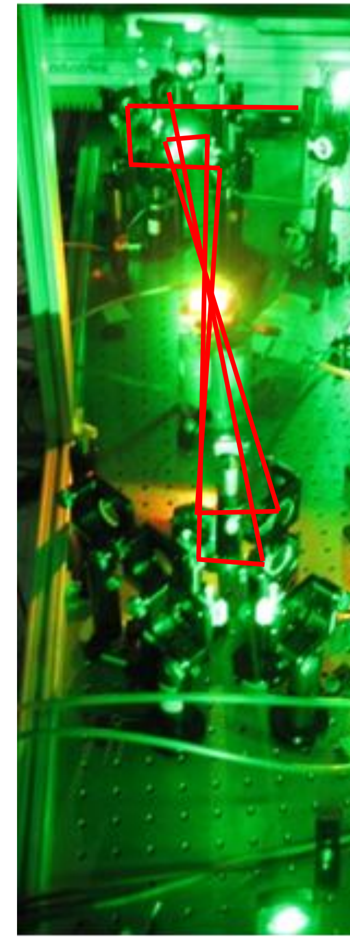
Water cooling or cryo cooling



The amplification of femtosecond pulses

In a multipass amplifier:

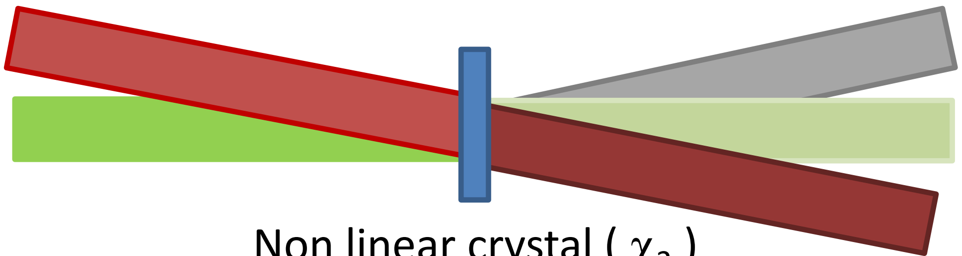




- The population inversion is obtained by one or more "pump lasers" irradiating the TiSa on both sides
- Many passes in the gain medium to extract the deposited energy
- The energy density are:
    - Up to 1.5 to 2 J/cm² for green light
    - Classically up to 2 J/cm² for the red.
- The size of the beam in the crystal can be from 500 µm to 150 mm
- The crystal can be surrounded by:
    - Air when it's a low rep rate laser and the energy modest (few tens of mJ)
    - Water when the rep rate is at maximum 10 Hz with energy up to few joules
    - Graphite or Indium if it is cryo cooled when the average pump power is > 50 W
    - Index matched liquid when the energy is > 10 joules
- The crystals are AR coated for both spectral bandwidth

The amplification of femtosecond pulses

In a Non collinear Optical Parametric Amplifier:



Benefits	Drawbacks
Single pass design	
NO transverse ASE	Parametric fluorescence
Large spectral bandwidth	Sensitive to angle
Scalable to kJ thanks to crystal size	Dedicated pump lasers Sensitive to intensity on both pump and signal

Can be used either in picosecond or nanosecond regime

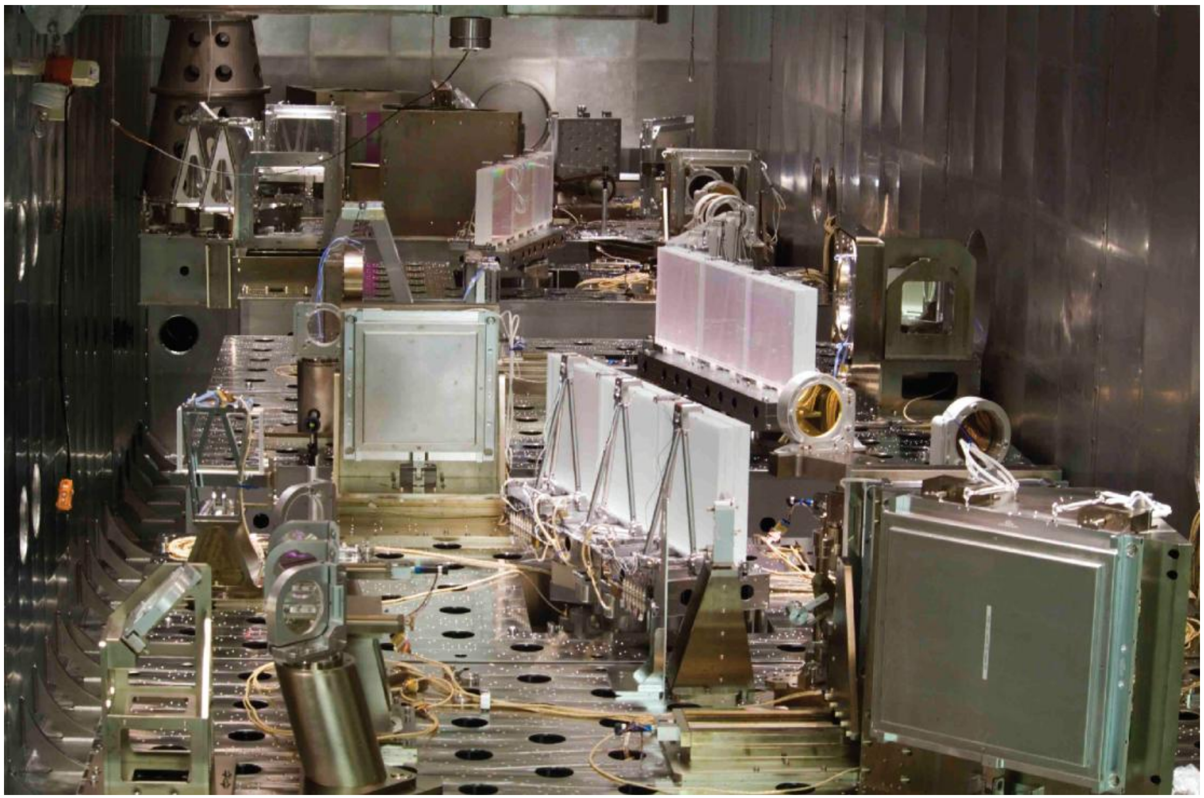
Seed for high energy system (800 or 900 nm)

Energetic Amplification for ultra-short pulses

The compression stage

Due to the very high intensity after compression, propagation in air can not be envisaged
=> under vacuum (10^{-6} mbar)

$$\Delta T = \frac{\phi^{(2)} 4 \ln 2}{\Delta T_0} \qquad \Phi^{(2)} > 0$$



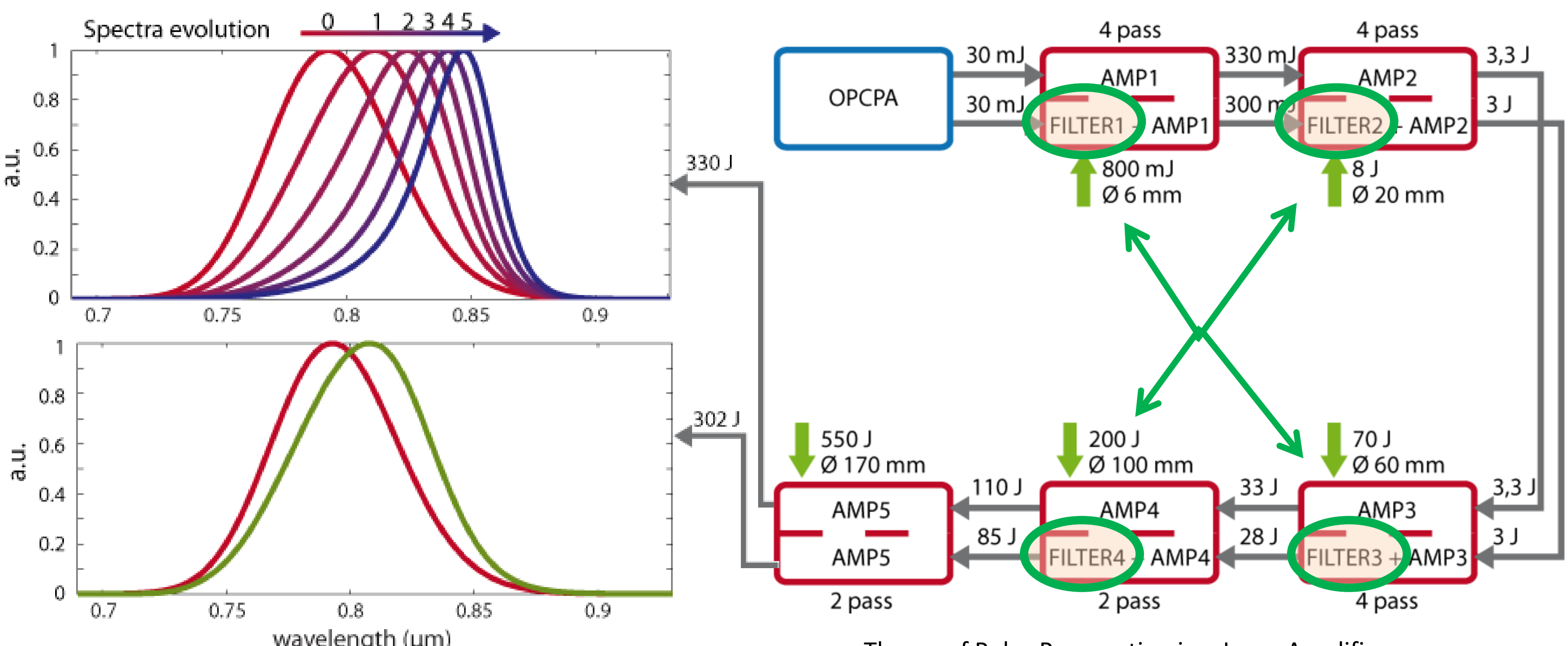
Omega EP compressor chamber

The amplification simulation

The model is based on the **Frantz and Nodvyk** equation for the standard amplification
The wavelength dependence is obtained thanks to the relation between time and frequency as the pulse is temporally chirped
Are taken into account:

- gain cross-section wavelength dependence
- properties of the coatings of the laser components
- losses

Output are: the energy, spectrum and Fourier Transform pulse duration



Theory of Pulse Propagation in a Laser Amplifier, J. Appl. Phys. 34, 2346 (1963);

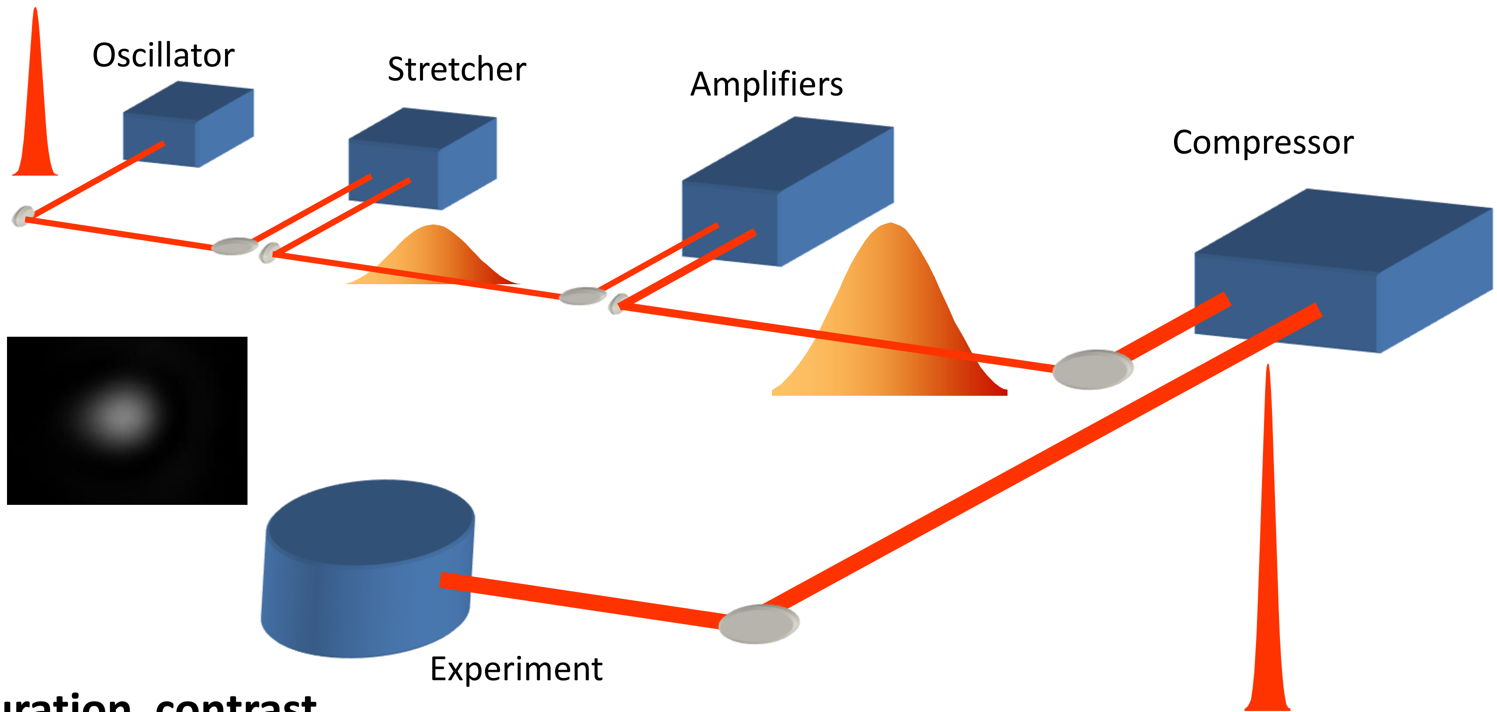
General description of high intensity laser system

Measurement tools

Issues relative to energy, temporal and spatial domains

World-wide State-of-the-art

Characterization of femtosecond intense pulses



Energy
Temporal: duration, contrast
Spatial: focusability

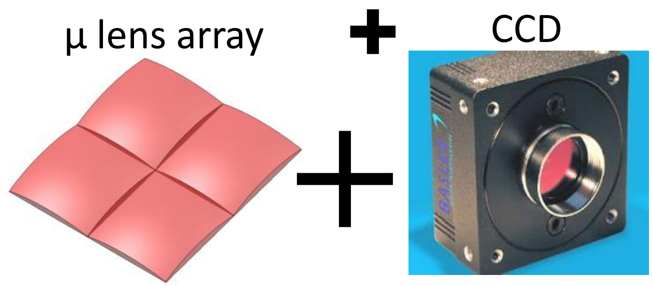
Ideally, measurement of the pulse on-shot in a plane equivalent to the experiment.
Among difficulties, the main is: HOW TO SAMPLE THE PULSE ?

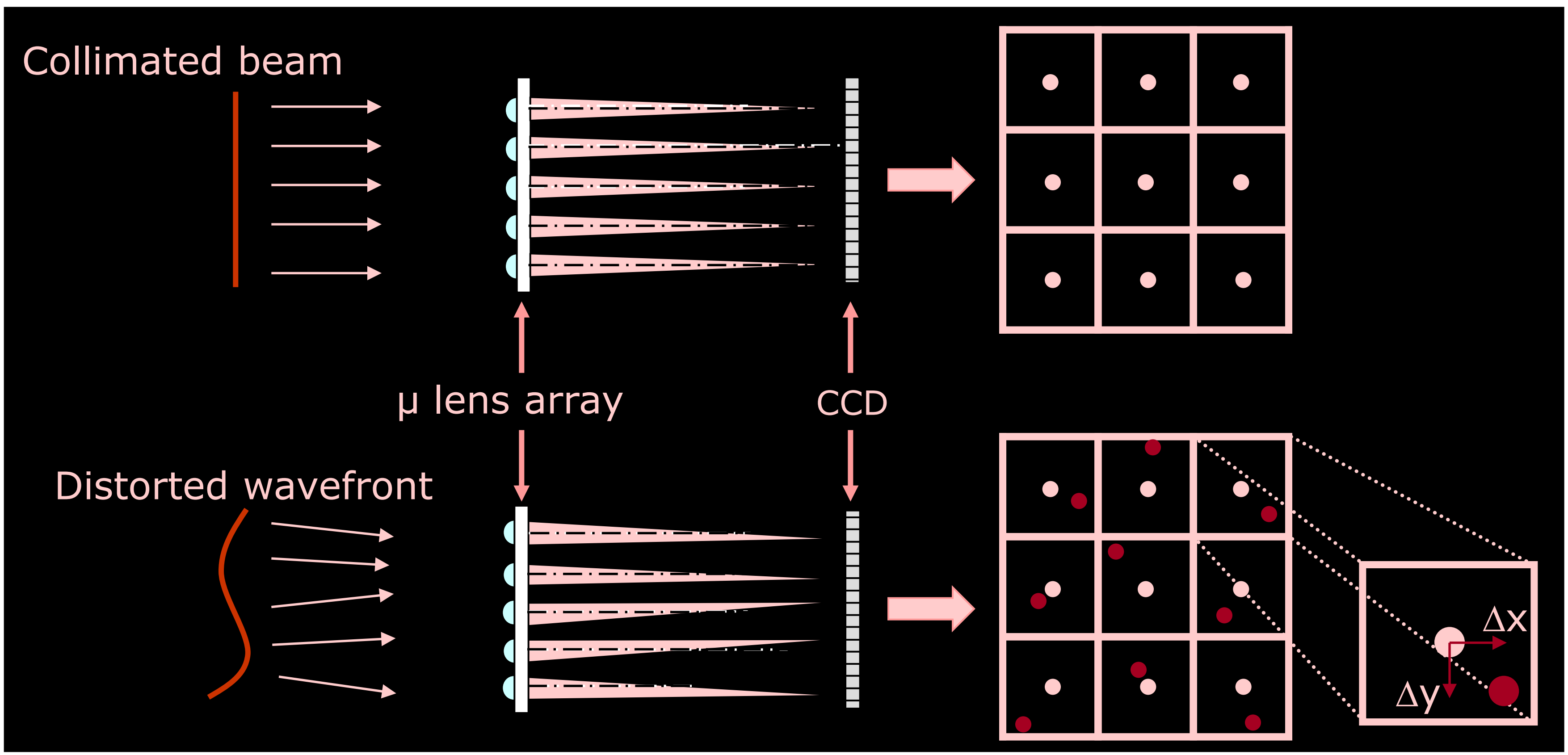
- ✓ **leaky mirror: non linear effects**
- ✓ **part of the beam: no info on 2D**

Usually the pulse is characterized with an attenuated energy

Spatial characteristics measurement

Shack-Hartmann (Imagine Optic, Night N, Adaptive Optic Associates …)

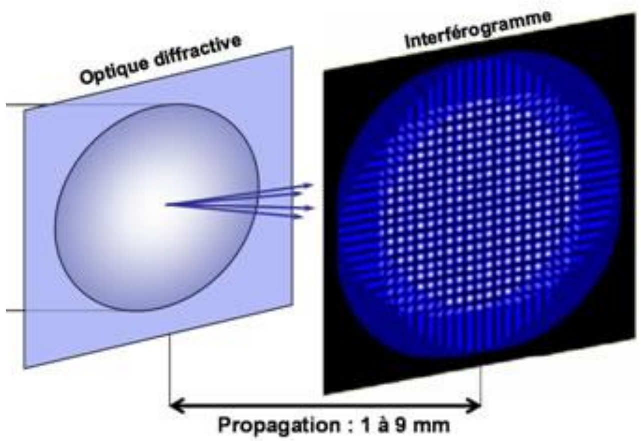


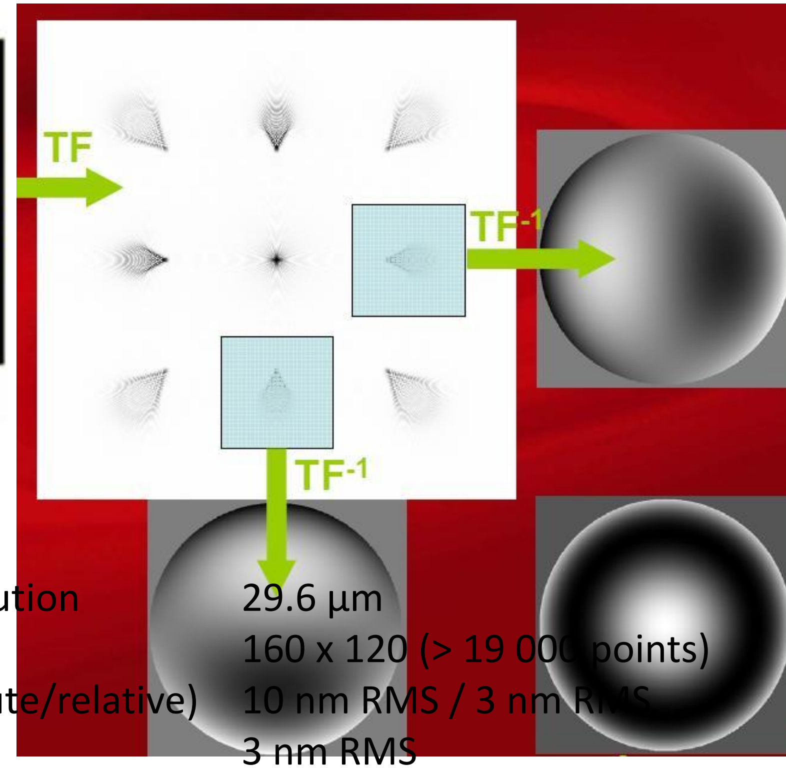


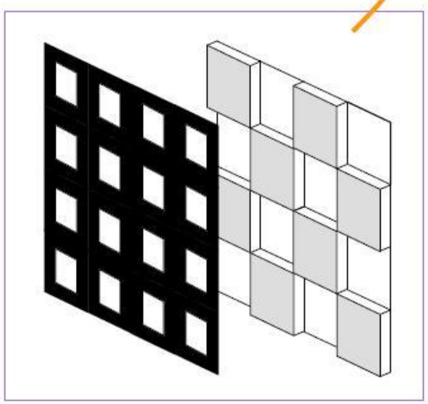
Spatial characteristics measurement

Lateral shearing interferometer (Phasics/ SID 4)

Based on interferometry







Grid + grating

After the grating, 4 waves are diffracted
They interfere on the CCD chip

Transverse resolution	29.6 µm
Sampling	160 x 120 (> 19 000 points)
Precision (absolute/relative)	10 nm RMS / 3 nm RMS
Repeatability	3 nm RMS
Dynamic	> 100 µm

FFT, spectral filtering and FFT^{-1}
$\Rightarrow$ Gradient of the wavefront
$\Rightarrow$ Integration
$\Rightarrow$ Wavefront

The edges of the pupil are not measured.
Good transverse resolution

Phasics : B. Wattelier

Spatial characteristics measurement

Based on propagation properties

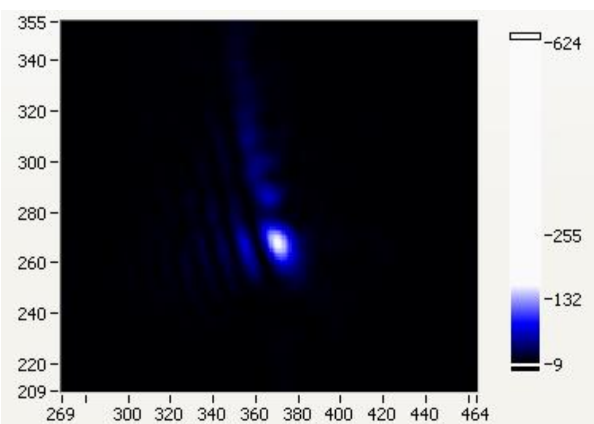
✓ Phase diversity

- ➢ Measurement of the beam in the focal plane in one or more planes before or after
- ➢ There is a unique wavefront for obtaining these patterns

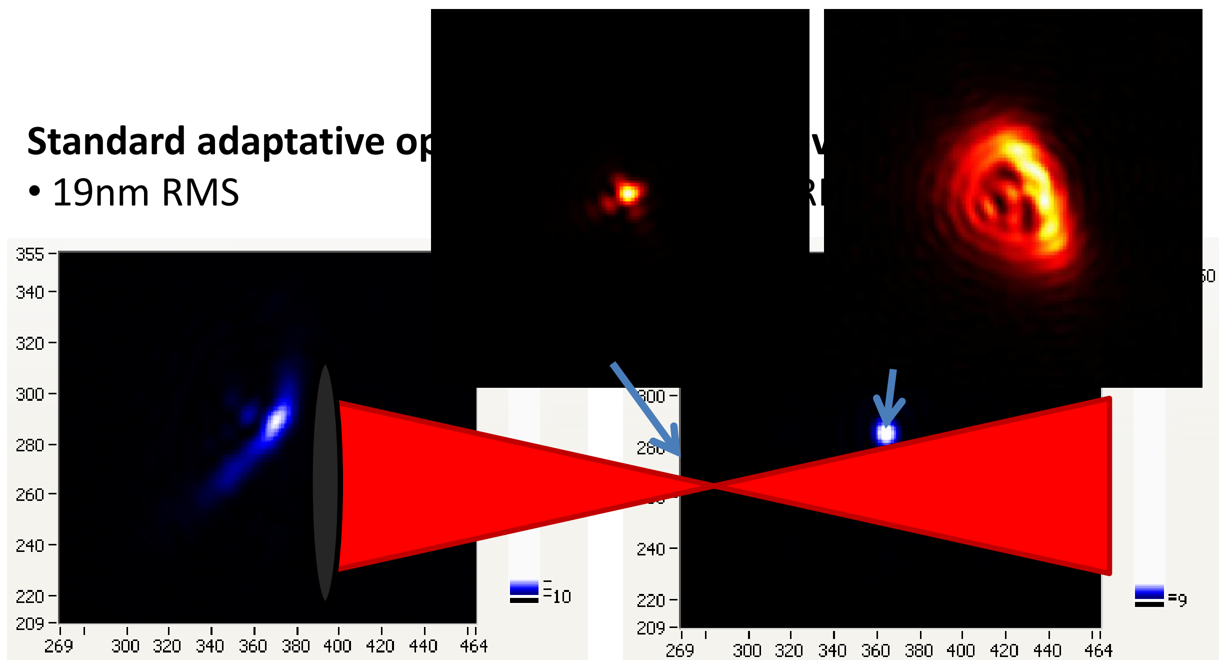
Advantages are:

- ➢ Optimizing the beam at focus
- ➢ Take into account the aberrations of the transport beam-line

Before adaptative optic:
• 250nm RMS



Standard adaptative op
• 19nm RMS



L. Meynadier, V. Michau, M.-T. Velluet, J.-M. Conan, L. M. Mugnier, and G. Rousset. *Appl. Opt.*, 38(23):4967–4979, August 1999

www.imagine-optic.com

Temporal characteristics measurement (duration)

Autocorrelation device

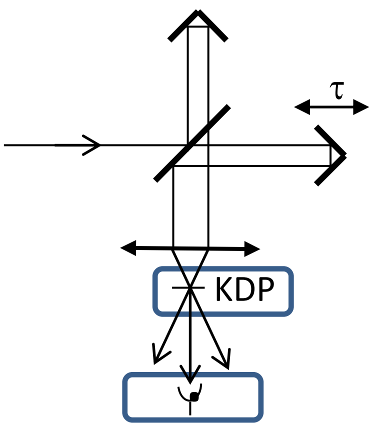
- Michelson interferometer
- 2ω generation
- Detector

Temporal characteristics measurement (duration)

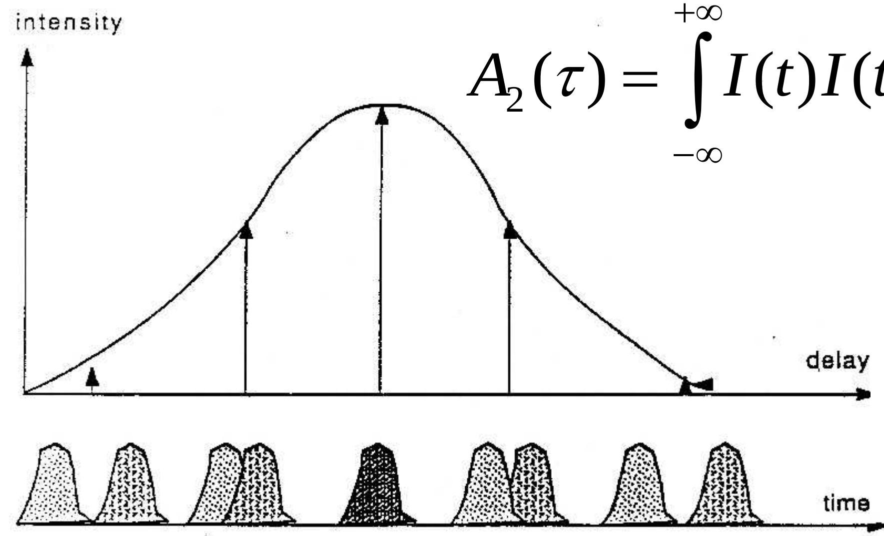
Autocorrelation device
- Michelson interferometer
- 2ω generation
- Detector

Deconvolution factor:
Gaussian: 1.41 $(\mathrm{sech})^2$: 1.55

Background-free correlator

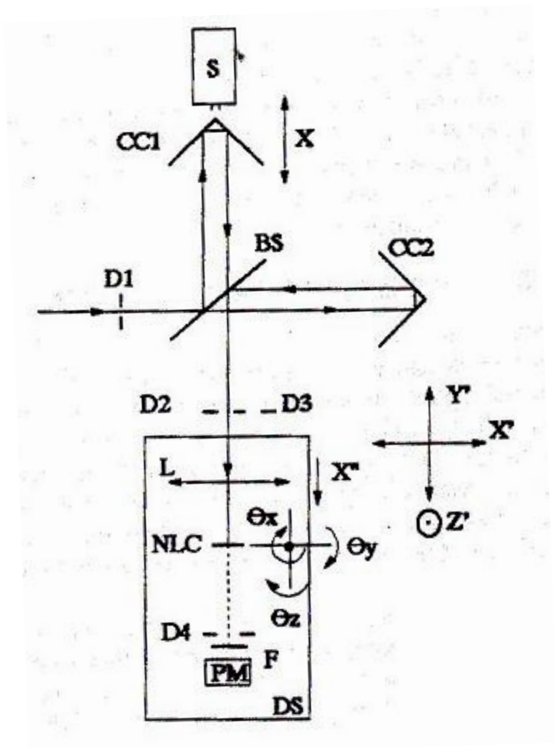


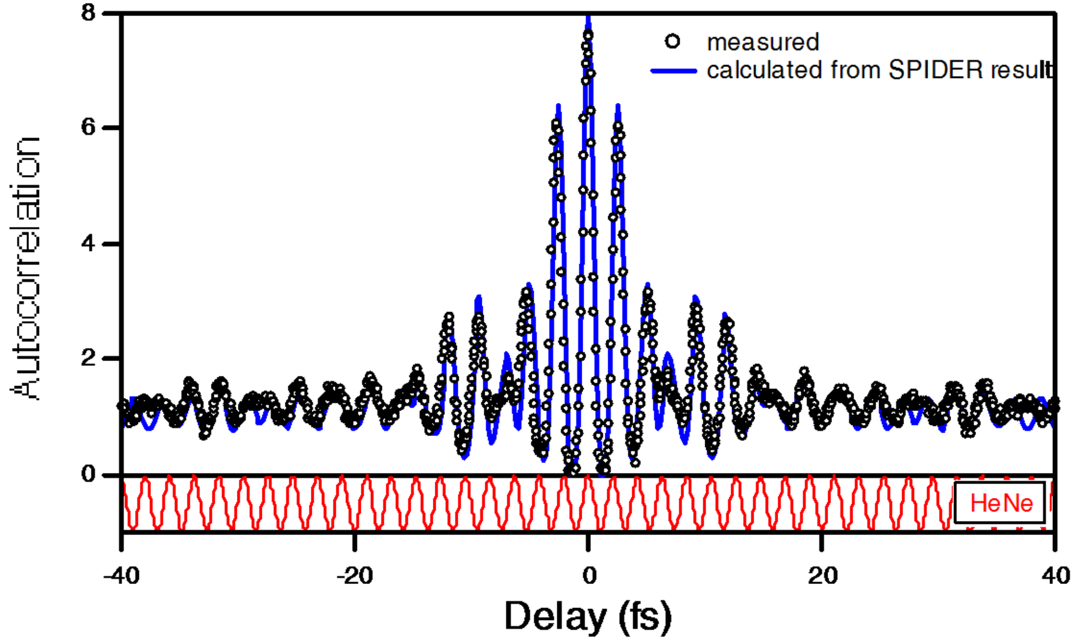
$$A_2(\tau) = \int_{-\infty}^{+\infty} I(t)\, I(t-\tau)\, dt$$



Temporal characteristics measurement (duration)

Interferometric correlator





At $\Delta = 0$, $E_{total} = E_1+E_2 = 2E$ si $E_1=E_2 = \sqrt{I}$. $\rightarrow I_{fondamental} \propto 4\,E^2 \rightarrow$ **$I_{2\omega} \propto 16\, I^2$**

At $\Delta = \infty$, $I_{fondamental} = 2\sqrt{I} \rightarrow$ **$I_{2\omega} \propto 2\, I^2$**

So $S_0/S_\infty = 8$

Both correlator does not give access to the pulse temporal profile

Temporal characteristics measurement (duration)

Pulse characterization ⇔ phase (temporal or spectral) measurement

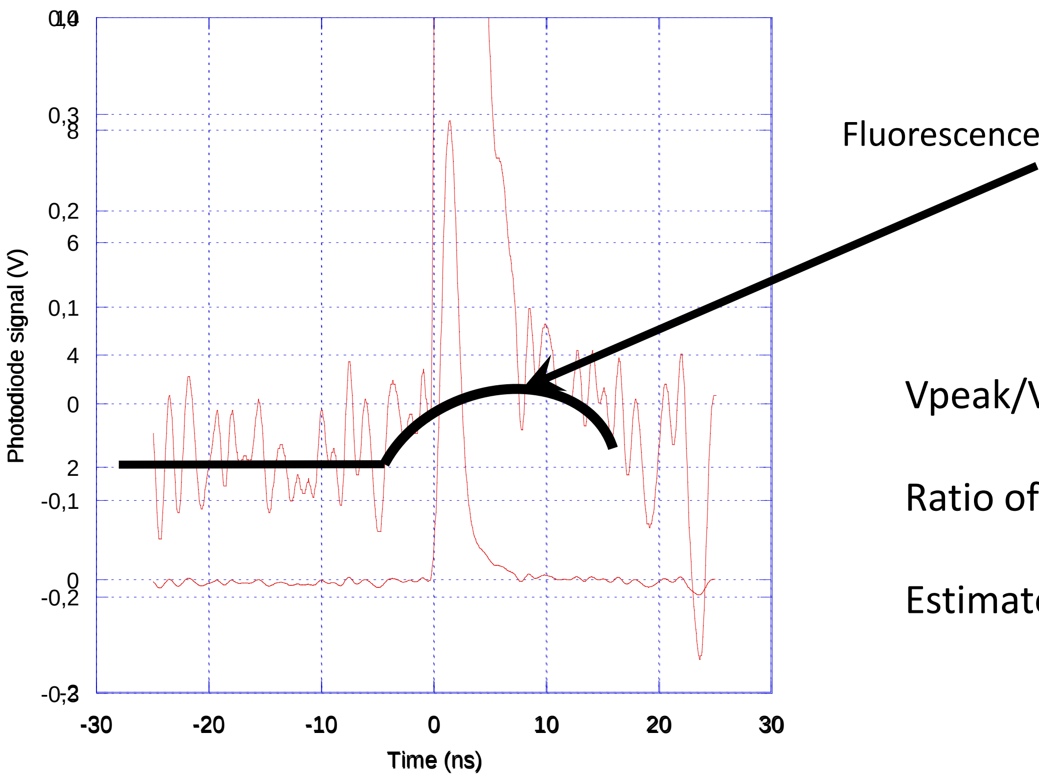
It requires a non linear effect if no reference pulse is used

FROG/GRENOUILLE	SPIDER	WIZZLER	D-Scan
Spectrometric approach	Interferometric approach		Spectrometric approach
Single shot			
2D	2D	1D	1D
Iterative algorithm	FFT calculations	Iterative alogorithm	2^{nd} ω theory
Info on the trace No info on the edges Difficult at focus	No info on the trace No info on the edges Not at focus	No info on the trace Good info on the edges Possible at focus	No info on the trace Info on the edges Possible at focus Demonstration under vacumm

Temporal characteristics measurement (contrast)

The temporal contrast is a key parameter for achieving controlled experimental conditions.

A simple way to measure on a long time scale the nanosecond contrast, is the use of a fast oscilloscope together with a fast photodiode or photoconductor switch and calibrated neutral filters



Fluorescence background

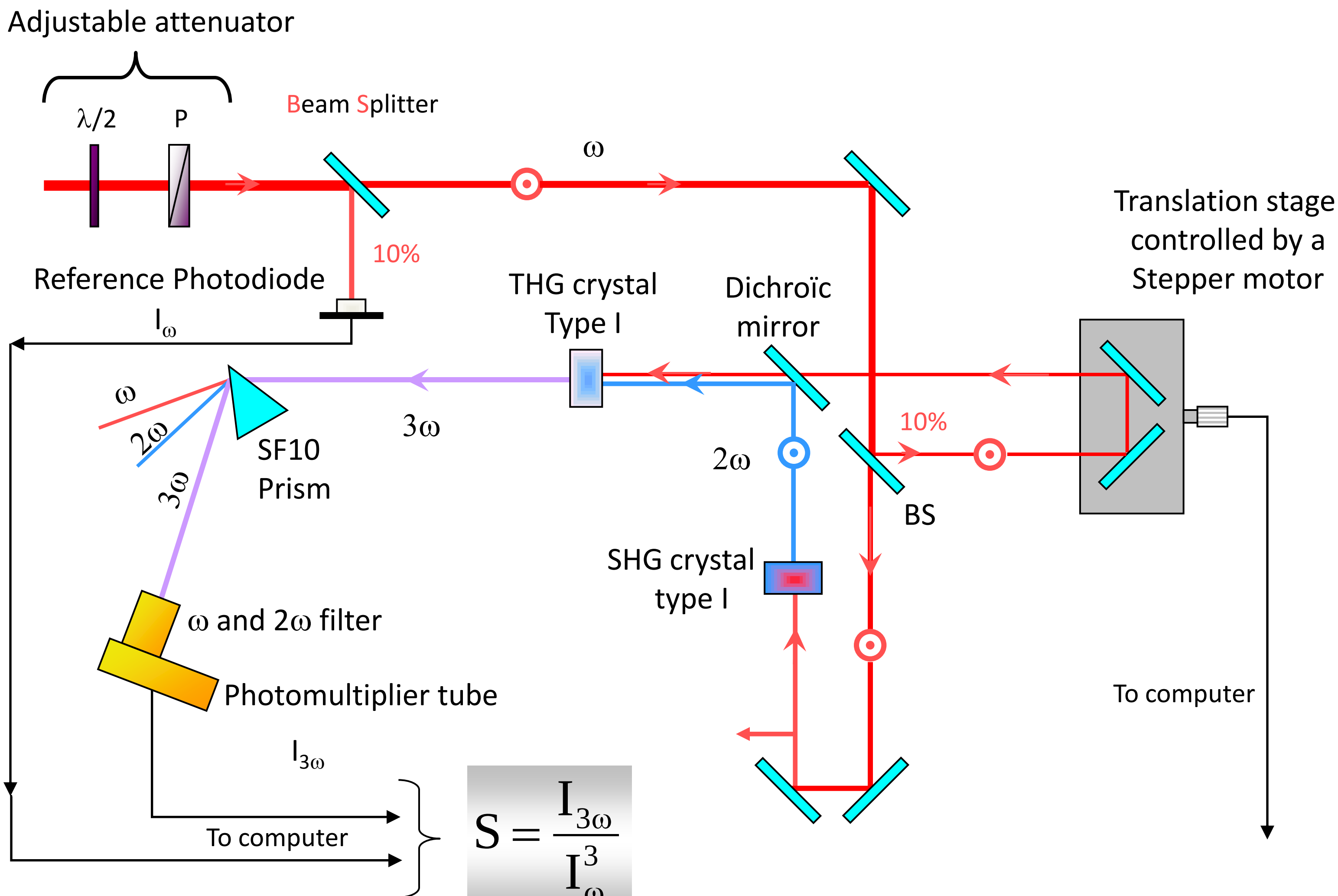
Vpeak/Vfluo = 160

Ratio of the final pulse durations = 2 ns vs 20 fs

Estimated ns contrast : ~6.10^{-8}

Temporal characteristics measurement (contratst)

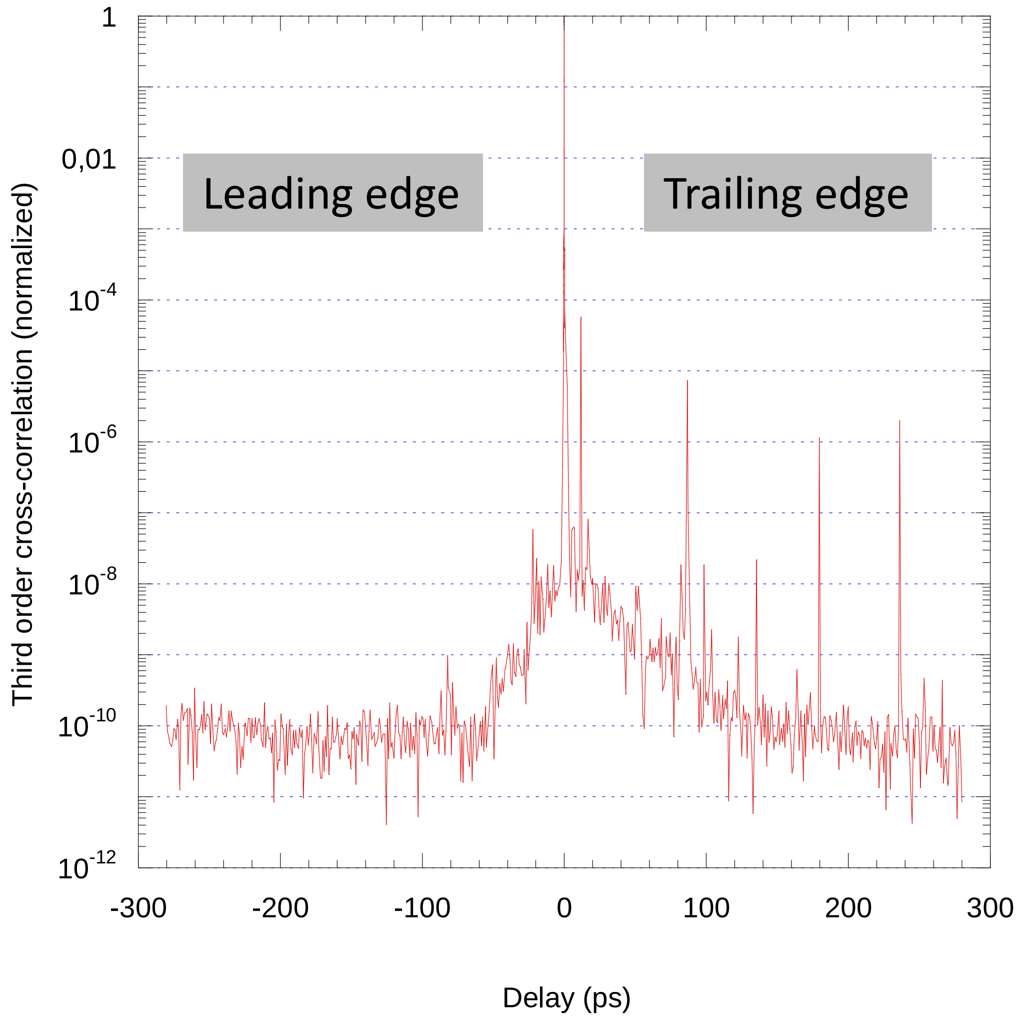
Contrast measurement by third order cross correlation



$$S = \frac{I_{3\omega}}{I_{\omega}^{3}}$$

Temporal characteristics measurement (contrast)

High dynamics correlation typical trace on a 10 Hz system at 2 joules per pulse



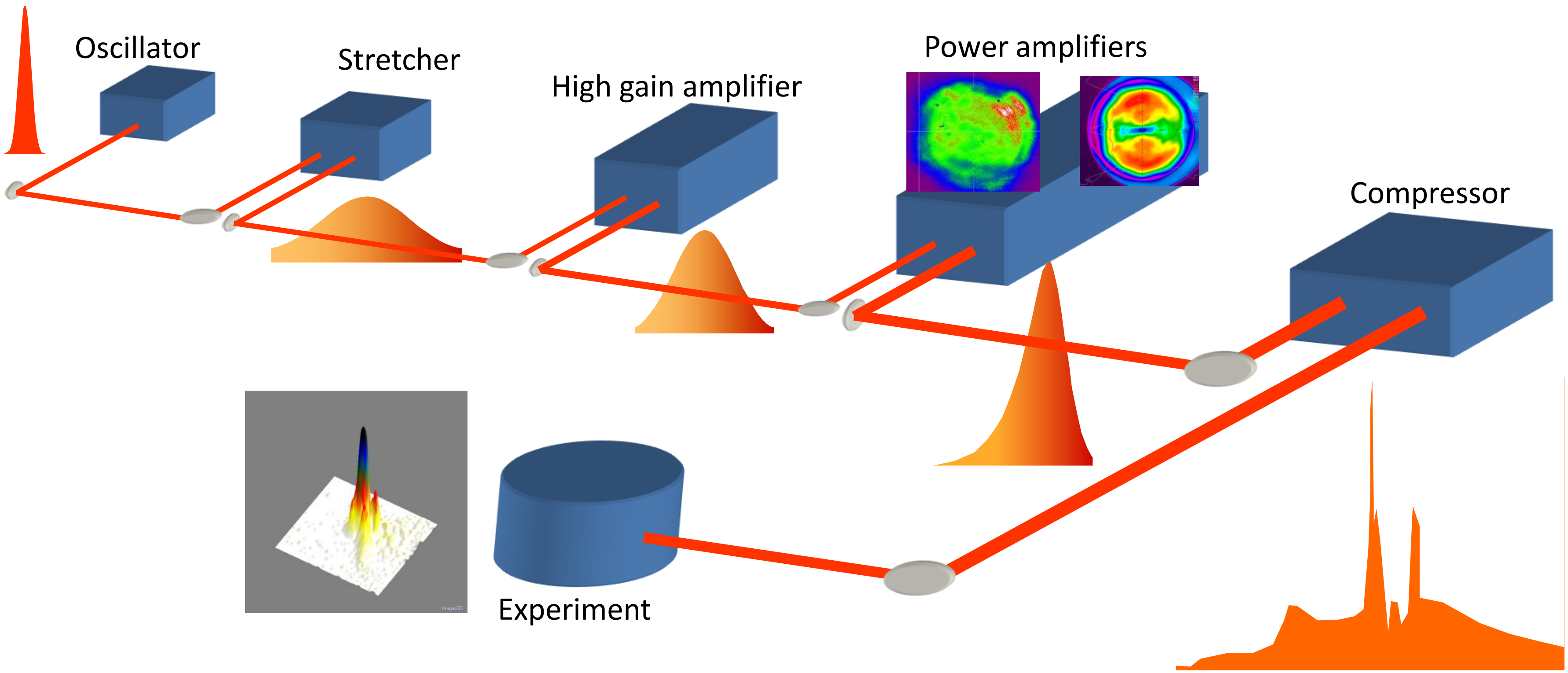
General description of high intensity laser system

Measurement tools

Issues relative to energy, temporal and spatial domains

World-wide State-of-the-art

The different issues on high energy and short pulses duration lasers



Limited spectral bandwidth and aberrations temporal profile degradation

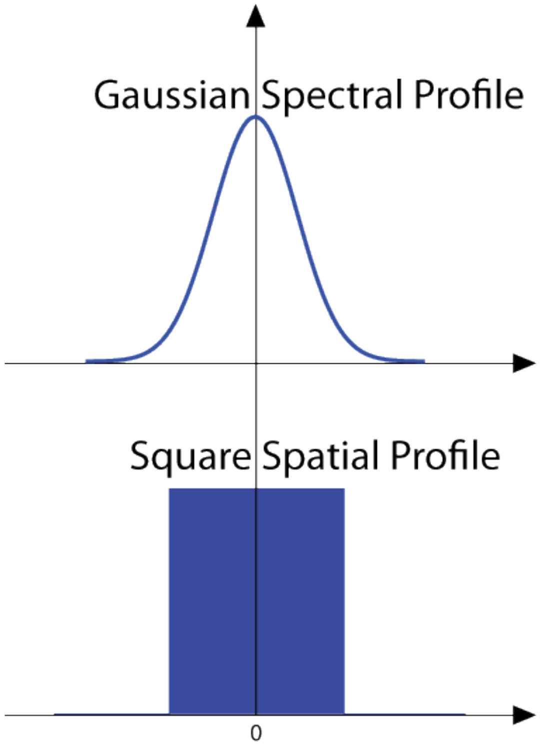
Spectral gain noarrowing, ASE => ↑ duration and ↓ temporal contrast

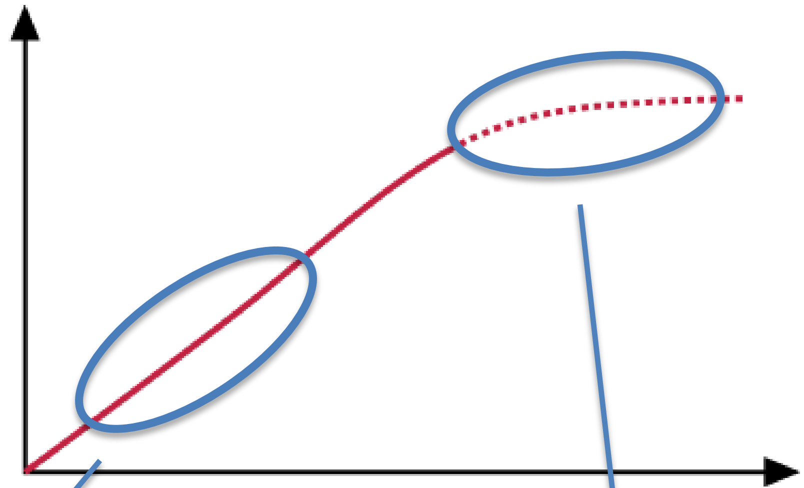
Spectral shifting, pump laser spatial profile, transverse lasing => ↑ duration, degraded beam and ↓ energy

Temporal phase defaults => temporal pulse profile degraded

Wavefront distortions=> lower intensity

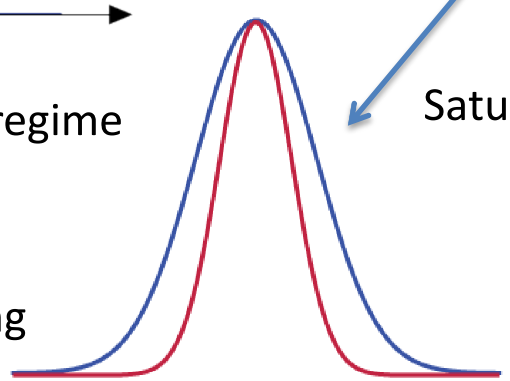
Spectral distortions with amplification





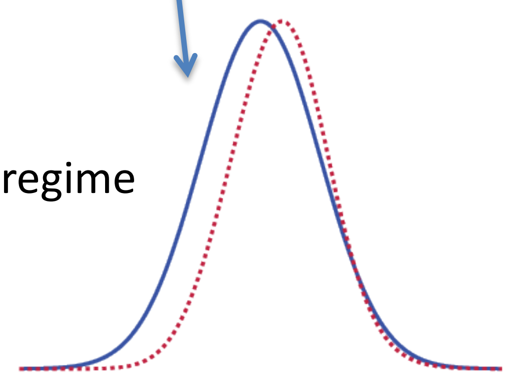
Linear amplification regime

Spectral narrowing



Saturation amplification regime

Red shifting



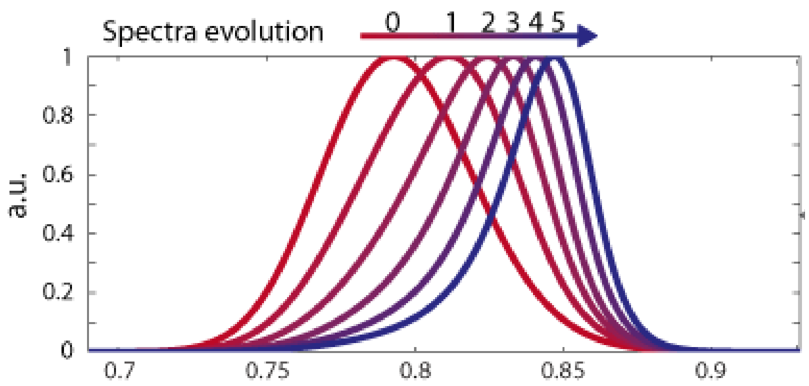
These changes induce pulse duration broadening and temporal profile distortions.

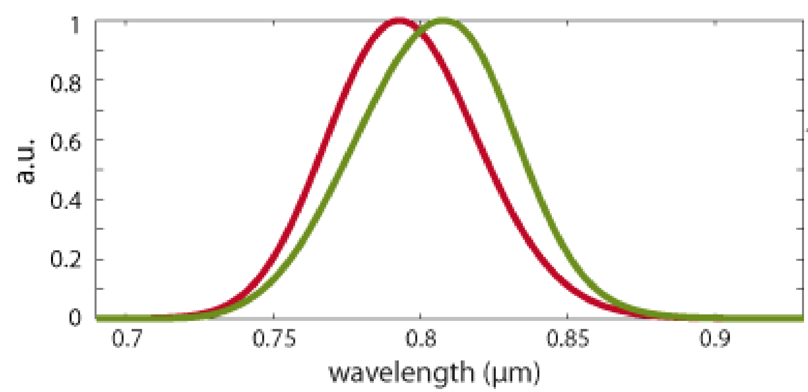
Spectral distortions with amplification: The solutions

Spectral filtering is used to pre or compensate the amplification effects

- Mirror with variable reflectivity:
  - Gaussian shape for gain narrowing only
  - Dedicated shape for pre-compensating gain narrowing and shifting
- AOPDF (Mazzler) in regenerative cavity

The other solution is to replace the TiSa amplifier by OPCPA stage



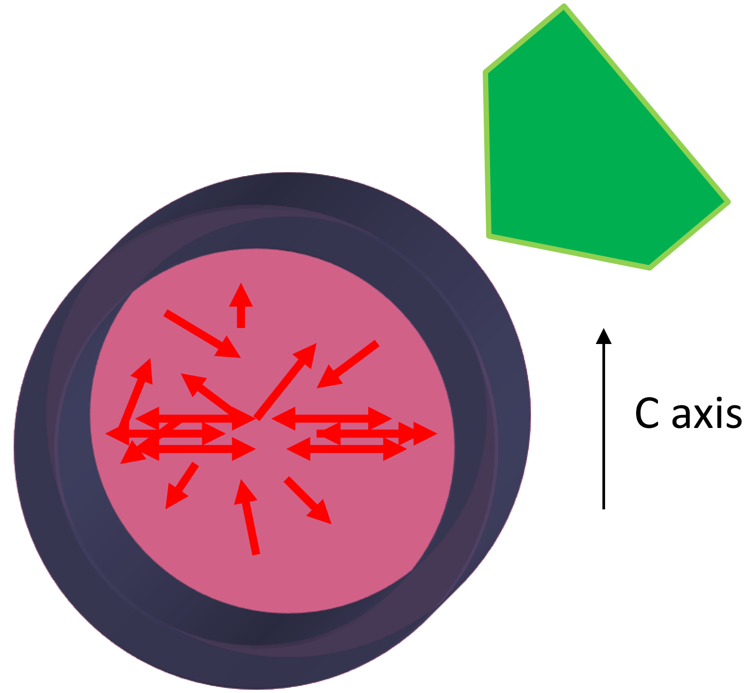


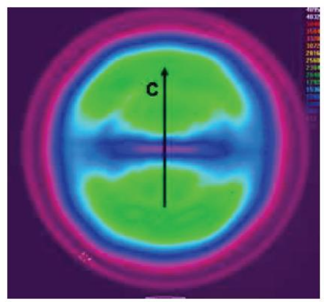
The parasitic effects in large crystals (> several cm diameter)

There are two effects:

- **<u>Transverse lasing</u>**

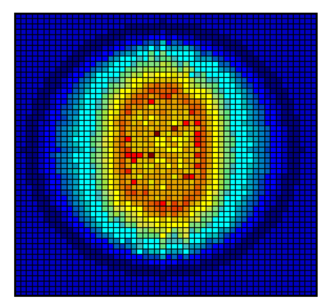
This is due to oscillation in the crystal
due to reflections on the edges of the crystal





- **<u>ASE depletion</u>**

This is unavoidable.
To reduce it, a low doping level is required

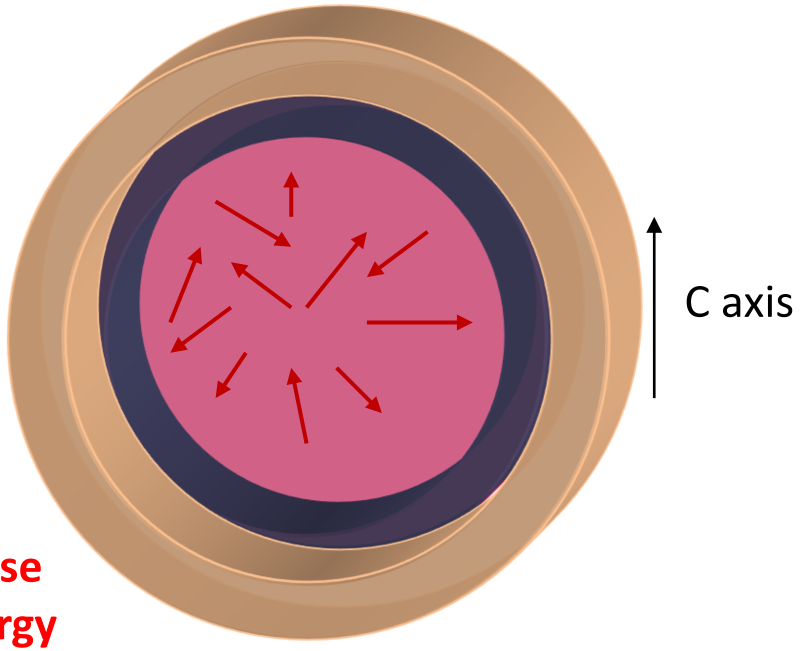


The parasitic effects in large crystals: Solution

- Low doping level
- Polished periphery
- Absorbing material around the crystal
    - Index matched liquid
    - Solid material
    - Ti^{4+}

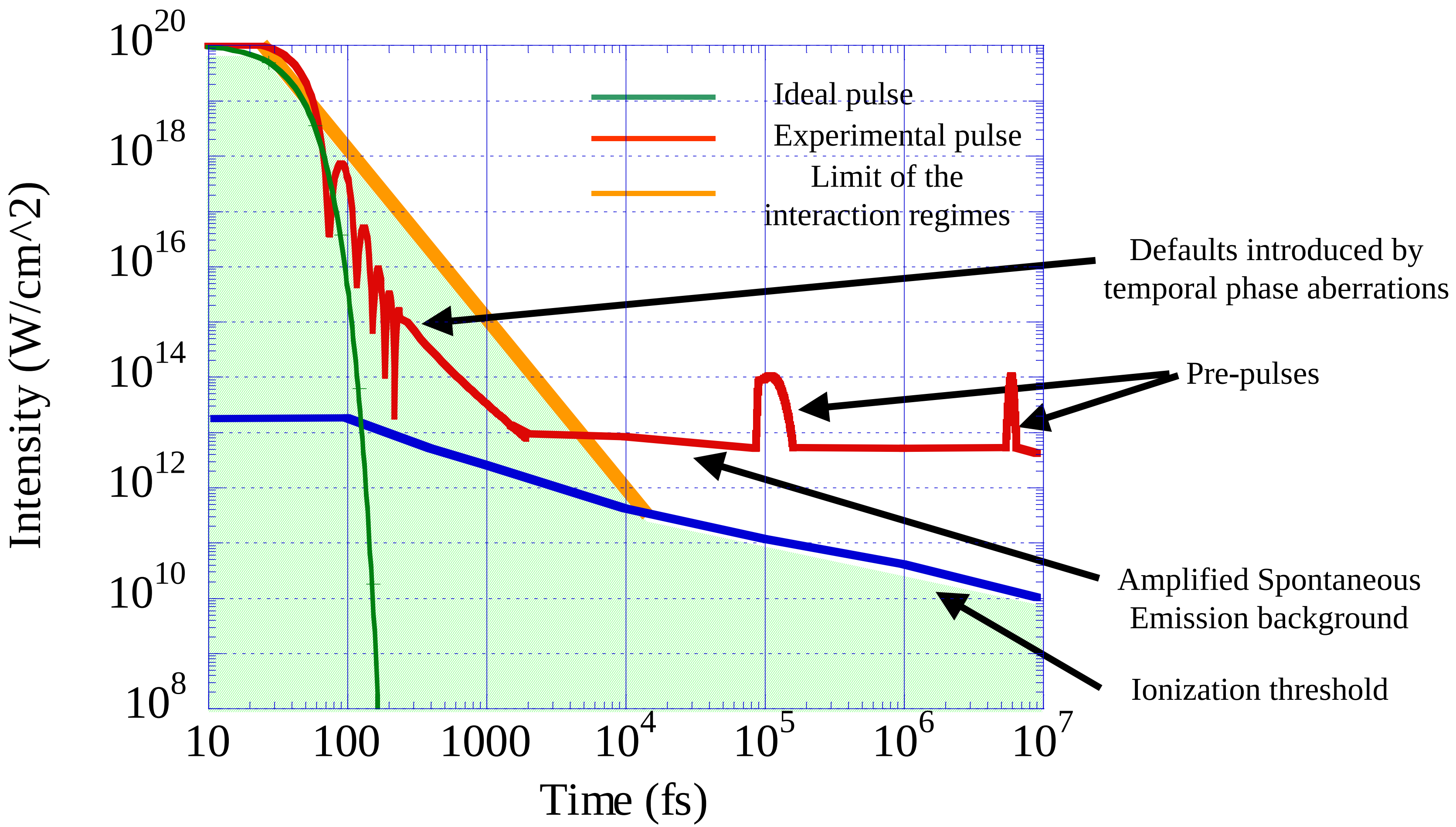
Index-matched liquid(diiodométhane – CH_2I_2) mixed with a dye absorbing 800 nm light.
This liquid will be circulating around the crystal periphery for ensuring good homogeneity of the mixture

Some characteristics of CH_2I_2	
Refractive index at 589,3 nm	1,7425[
Melting temperature	6°C
Boiling temperature	181°C



With a proper mixture, no transverse effect with 330 Joules pumping energy demonstrated

Temporal characteristics degradation



Coherent contrast: spectral clipping, spectral phase errors
Incoherent contrast: ASE pedestal

Temporal contrast degradation

Defect of the spectral phase

- Presence of large amount of material leads to residual GDD

The solutions are:

- Use some static correction: prism line, Chirped mirrors
- Use controllable tools: SLM in a 0 delay line, AOPDF (Dazzler)

ASE background

- In TiSa amplifier with high gain, generation of nanosecond background of ASE.

The level for mJ pulse can be 10^{-9} relatively to the peak power.

This pedestal is far not low enough for high intensity experiment.

The solutions are:

- Replace TiSa amplifier by picosecond OPCPA
- Implement ASE filtering in a double CPA configuration (Saturable absorber, XPW)
- Plasma mirrors before experiment

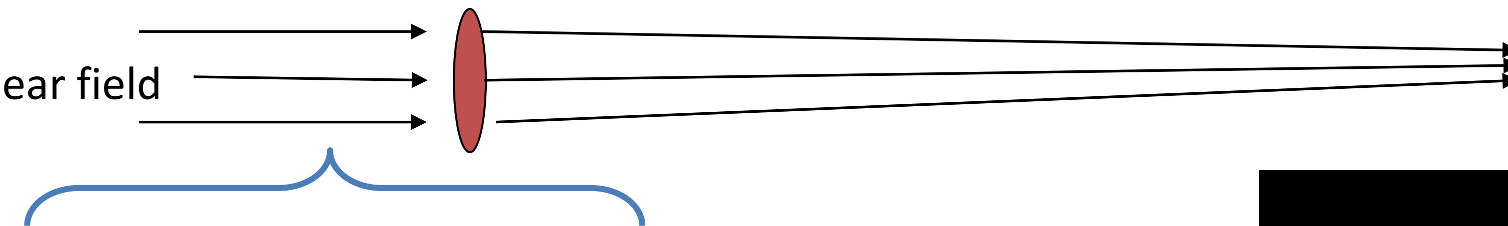
Spatial degradations

I (W/cm²) = E (Joule)/Δt * S → cm²

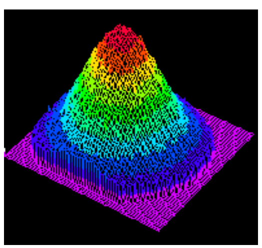
$$\boxed{S \propto \frac{\lambda f}{D}}$$

Depends on wavefront
At focus

Near field

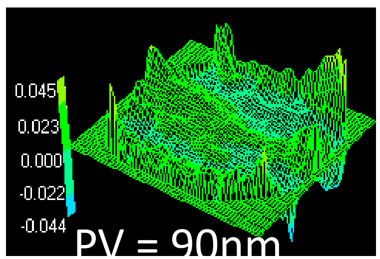


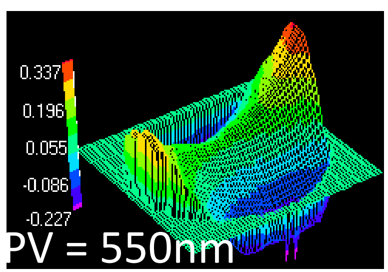
Far field



Beam profile

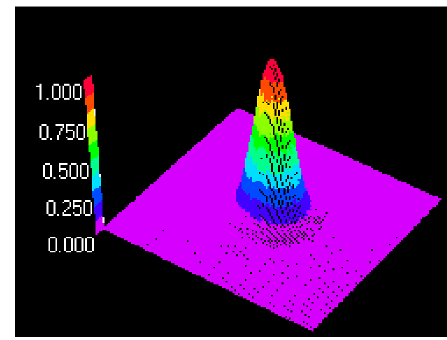
+

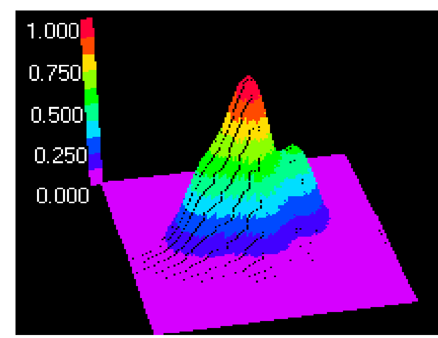




Wavefront

Focusing





- The focal spot size has increased.
  - ➢ the intensity is lower

Spatial degradations: causes

For PW class Lasers :

~200 components

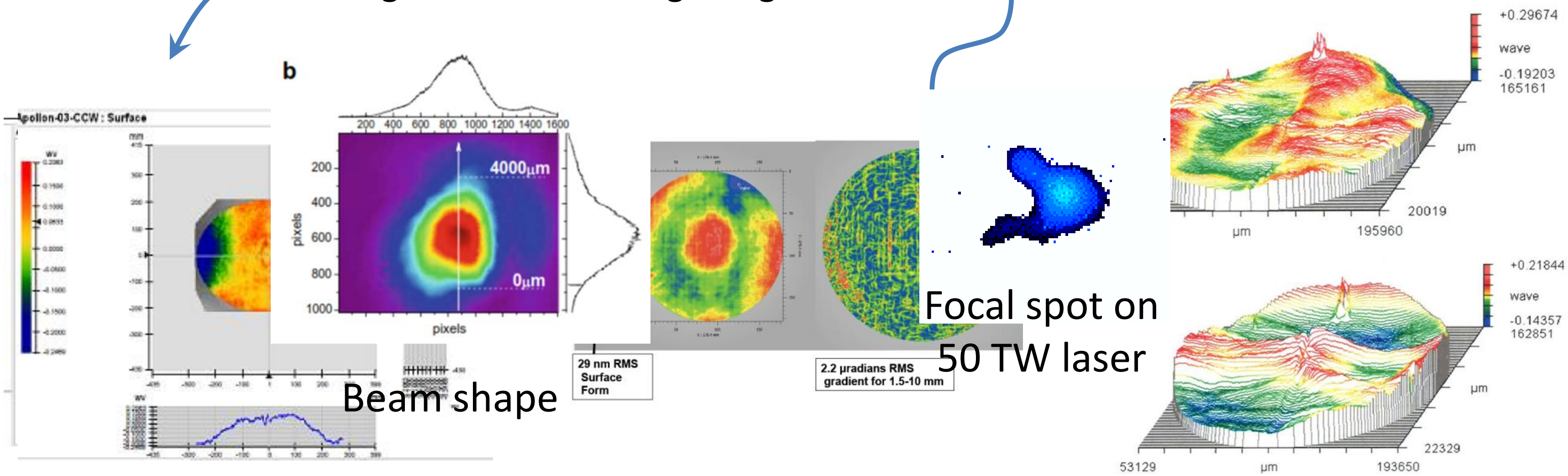
beam propagation : 300 - 400 meters

- ➢ beam profile deformation
- ➢ wavefront distortions

➢ Origins :

- ➢ Laser process; amplification (pump laser beam profile), thermal effects => A(x,y) and ϕ(x,y)
- ➢ Aberrations due to optical design : spherical, astigmatism, curvature => ϕ(x,y)
- ➢ Large components defaults : low and high spatial frequencies => A(x,y) and ϕ(x,y)
  - ➢ Laser media; Large size crystals
  - ➢ Large size mirrors (up to 650 mm)
  - ➢ Large size diffraction gratings

175 mm



Spatial degradations: quantification

Strehl ratio quantifies the degradation

$$SR = \frac{ExperimentalIntensity}{referenceIntensity}$$

Experimental beam and wavefront.

Reference beam and plane wavefront

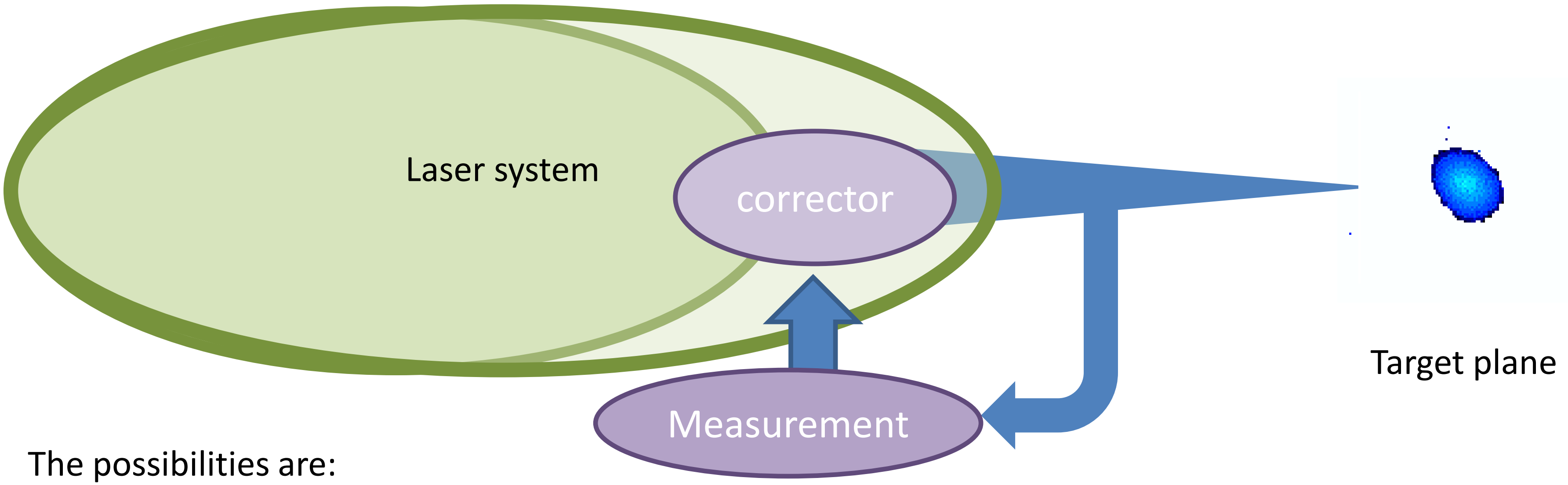
1. For astronomy, the energy is uniform in the pupil

2. For laser it can be relevant to choose another one.

➢ gaussian or experimental

Spatial degradations: solutions

Corrections of the wavefront distortions



The possibilities are:

- Spatial filter

+ inside the global laser set-up
+ remove high spatial frequencies
- damage threshold then destruction

- Optic valves

+ high spatial frequencies
- low damage threshold

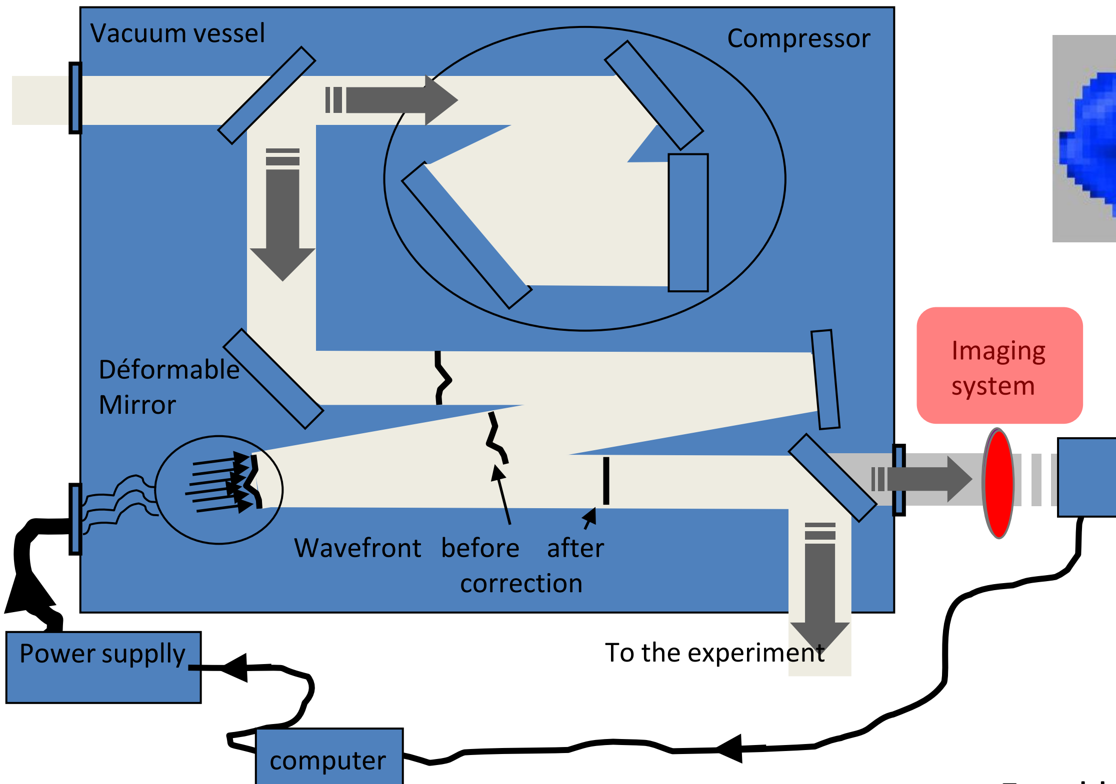
- Deformable mirrors

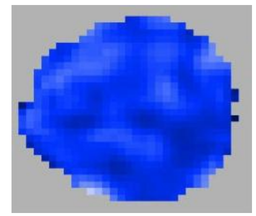
+ high damage threshold
+ large size
- low spatial frequencies

A combination of both seems to be the relevant solution

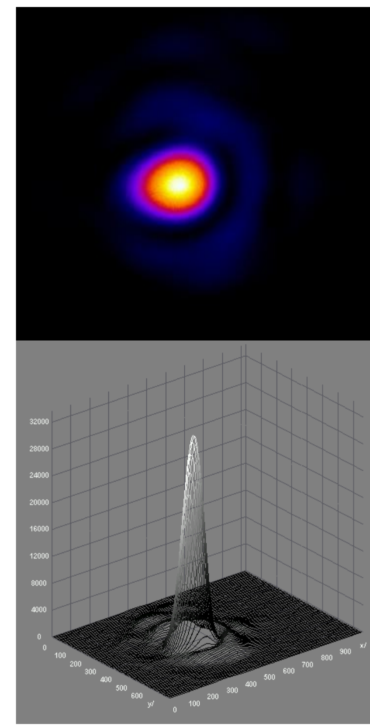
Different results obtained on ~100 TW laser beams

For **100 TW at LOA (2.5 J in 25 fs)** : after compression
The DM is a monomorph type (CILAS)





23 nm rms, 211 nm PV
Measurement 32x32 points



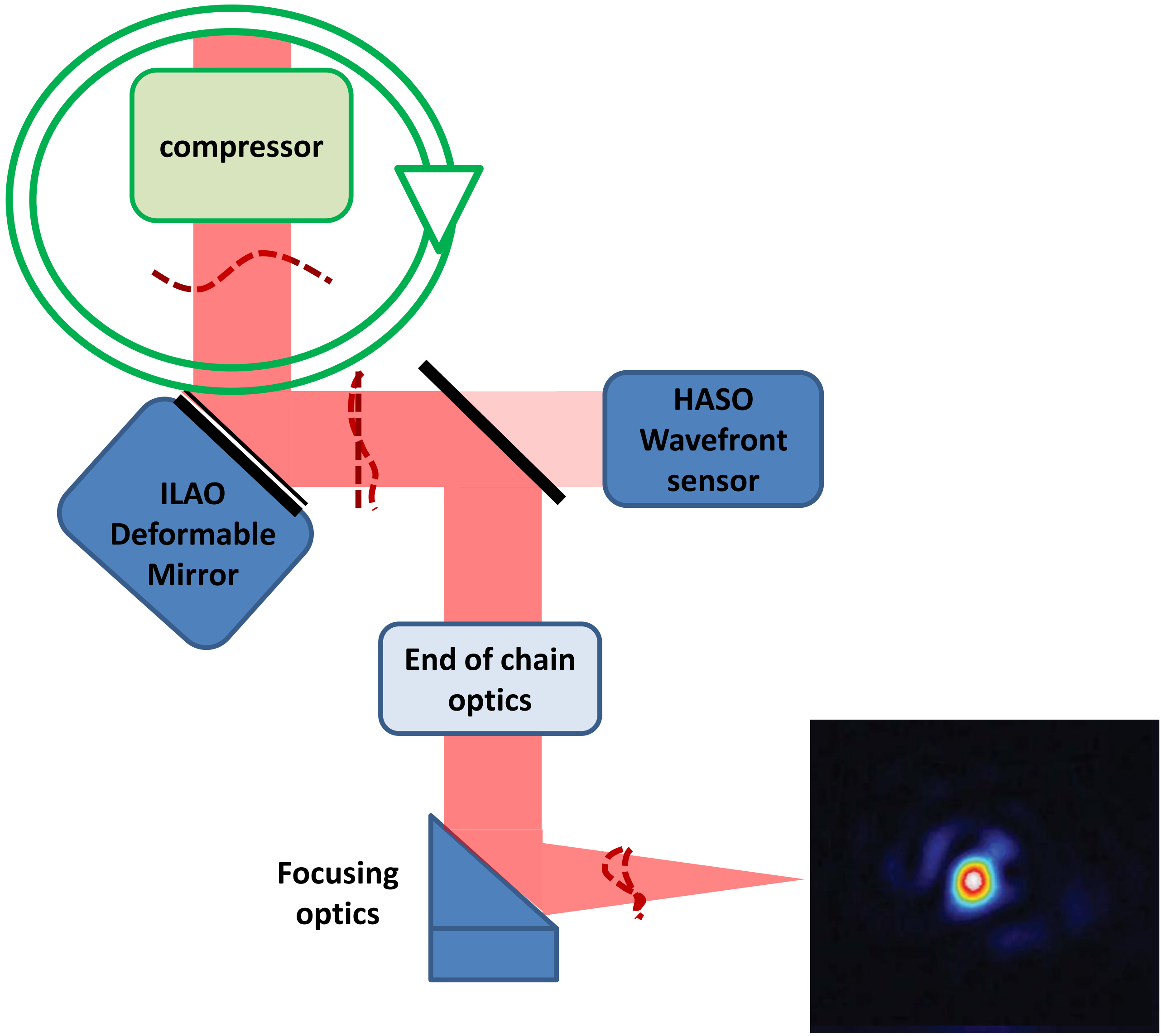
Focal length = 1000 mm
µscope objective : x 20
12 bits CCD

Single shot correction

Strehl ratio> 0,9

Different results obtained on ~100 TW laser beams

On UHI-100 at CEA Saclay (2.5 J in 25 fs) : after compression
The DM is baser on the use of mechanical actuators

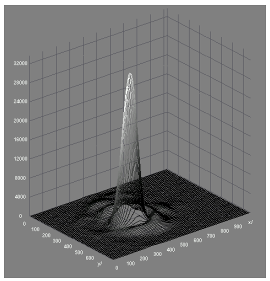


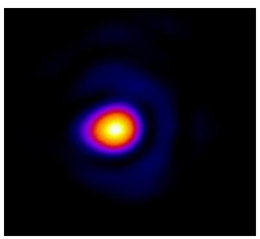
The limitations the actual corrections for high intensity laser beams

Beam shape modulations are limiting the far-field quality.

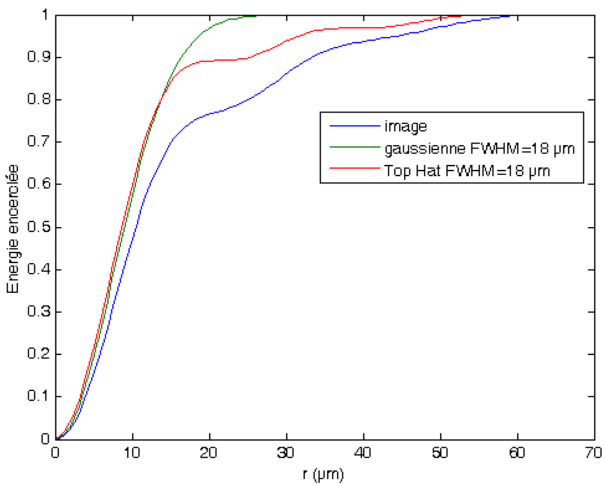
Measurement on 100 TW laser

Focal spot

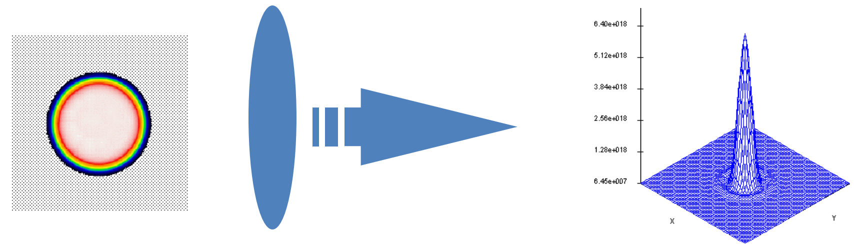


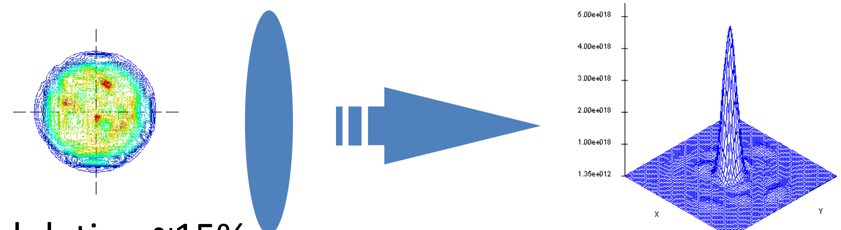


Encircled energy



72% of the energy is in the main peak.
To be compared to 88% for a « top hat »



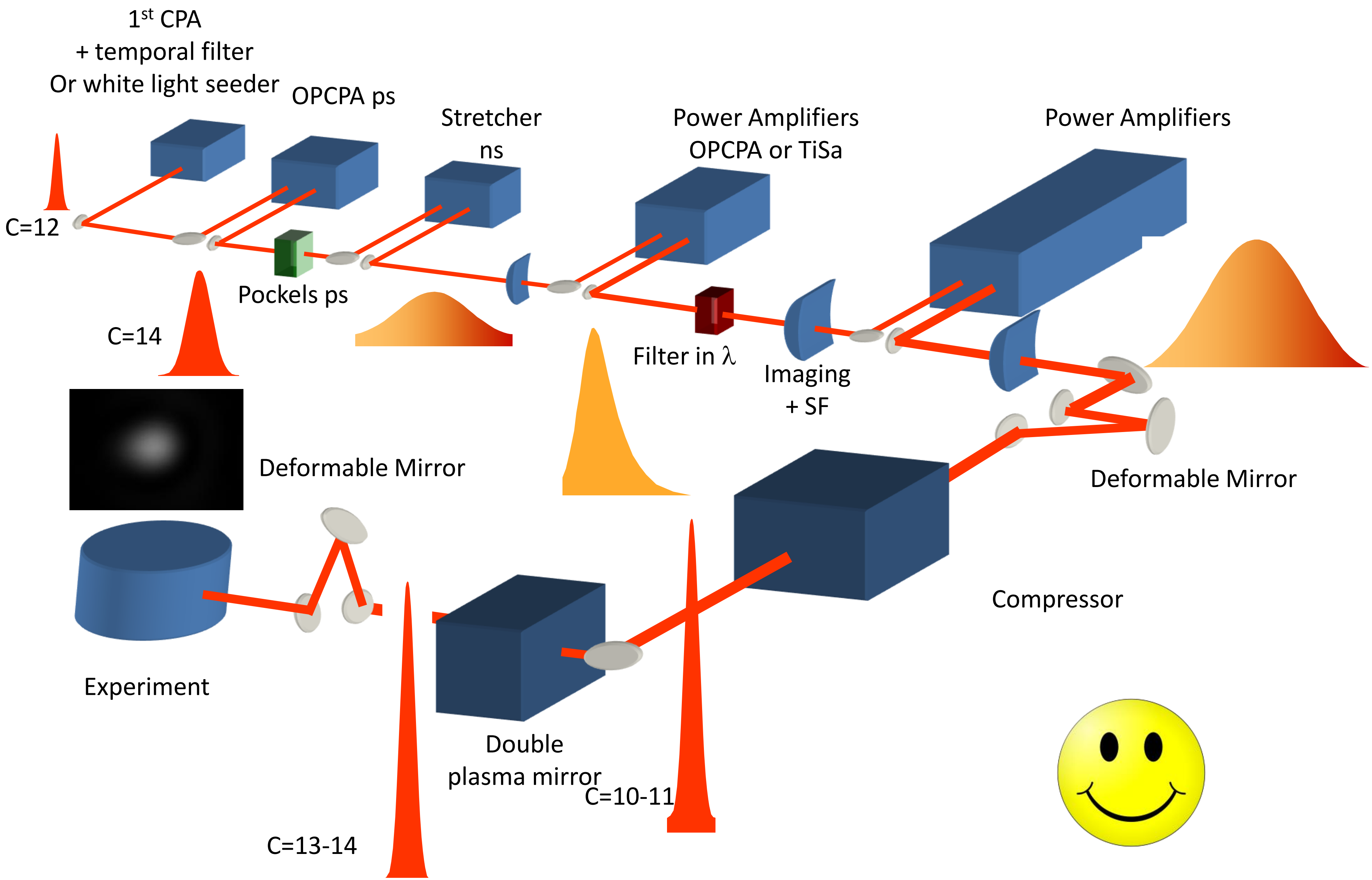


Modulation ~15%

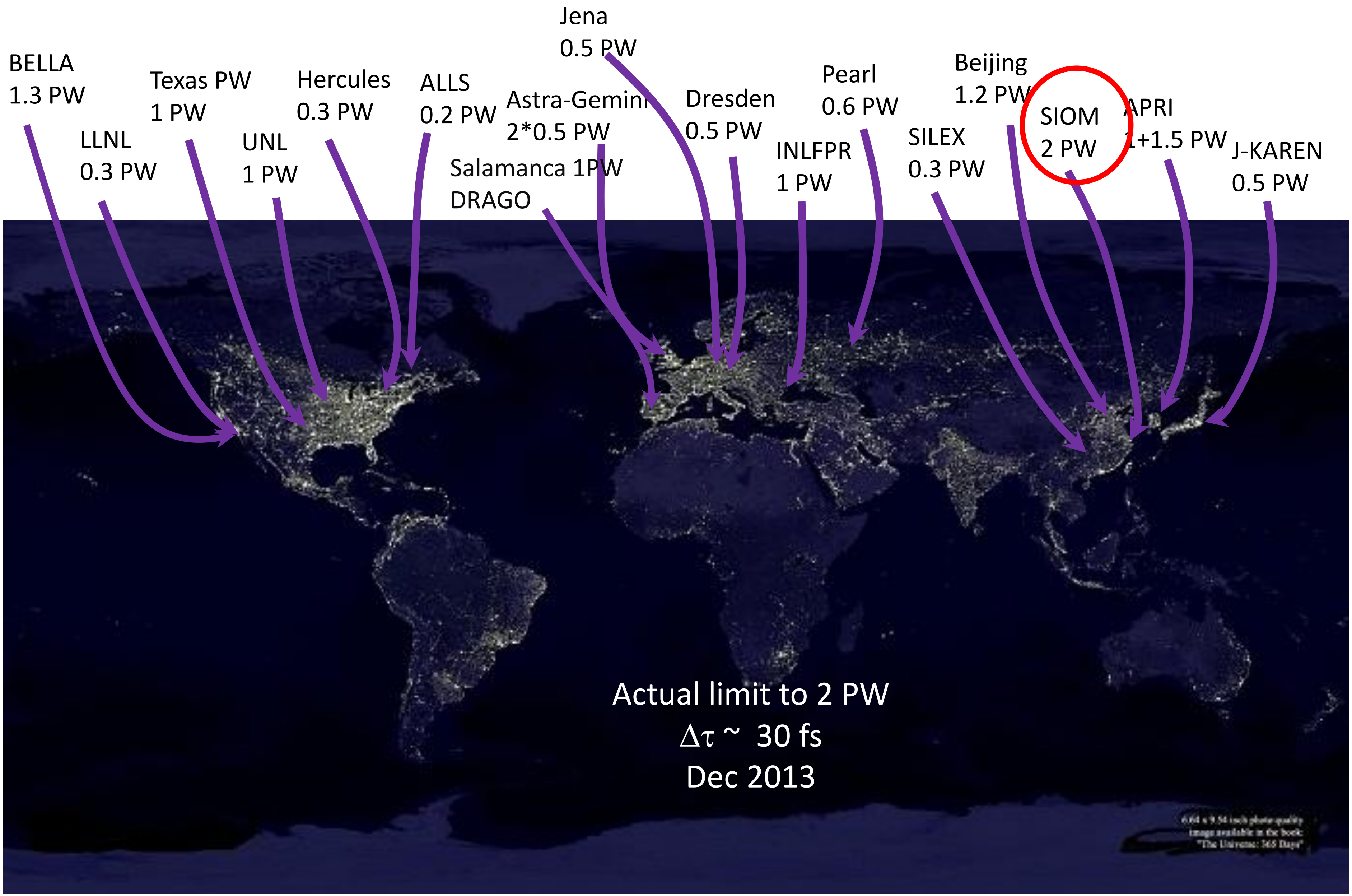
The **limitation is** no more the spatial phase but **the energy distribution**

➢ **to be controlled by the use of multi-conjugated AO**

The new architecture for achieving multi PW pulses

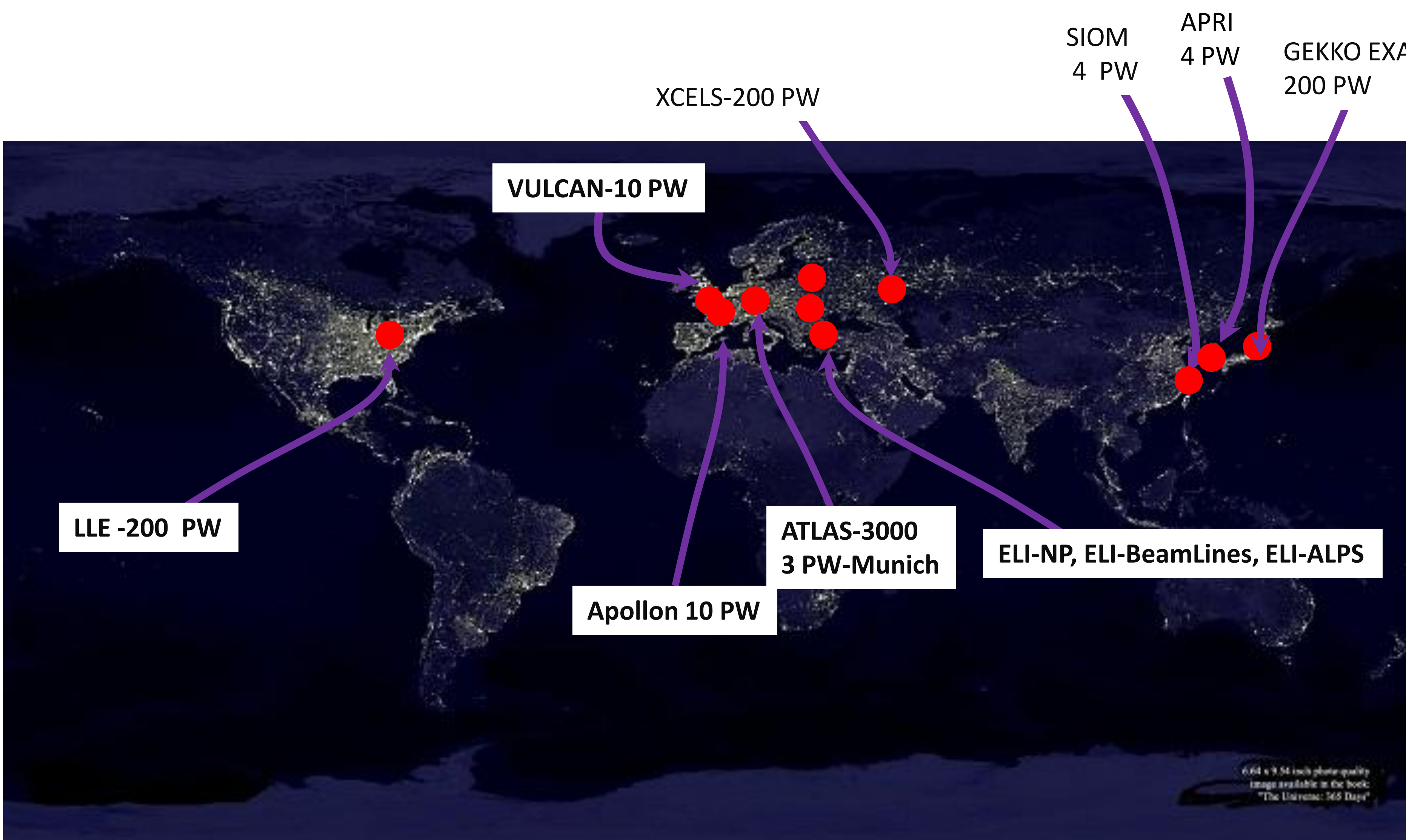


Intense laser systems with potential intensity higher than 10^{20} - 10^{21} W/cm²



MORE PW

$\Delta\tau$ ~ 15 - 30 – 150 fs ?



CONCLUSION

10 PW is the actual target for many projects

- **Different techniques are used: TiSa, Nd:Gass or KDP**
- **Most issues have been solved for reaching the peak intensity with good characteristics**
- **Demonstration on operation will have to be demonstrated**
- **The main challenge remains on the measurement of the final pulse characteristics ON SHOT**