ULTRAFAST OPTICS

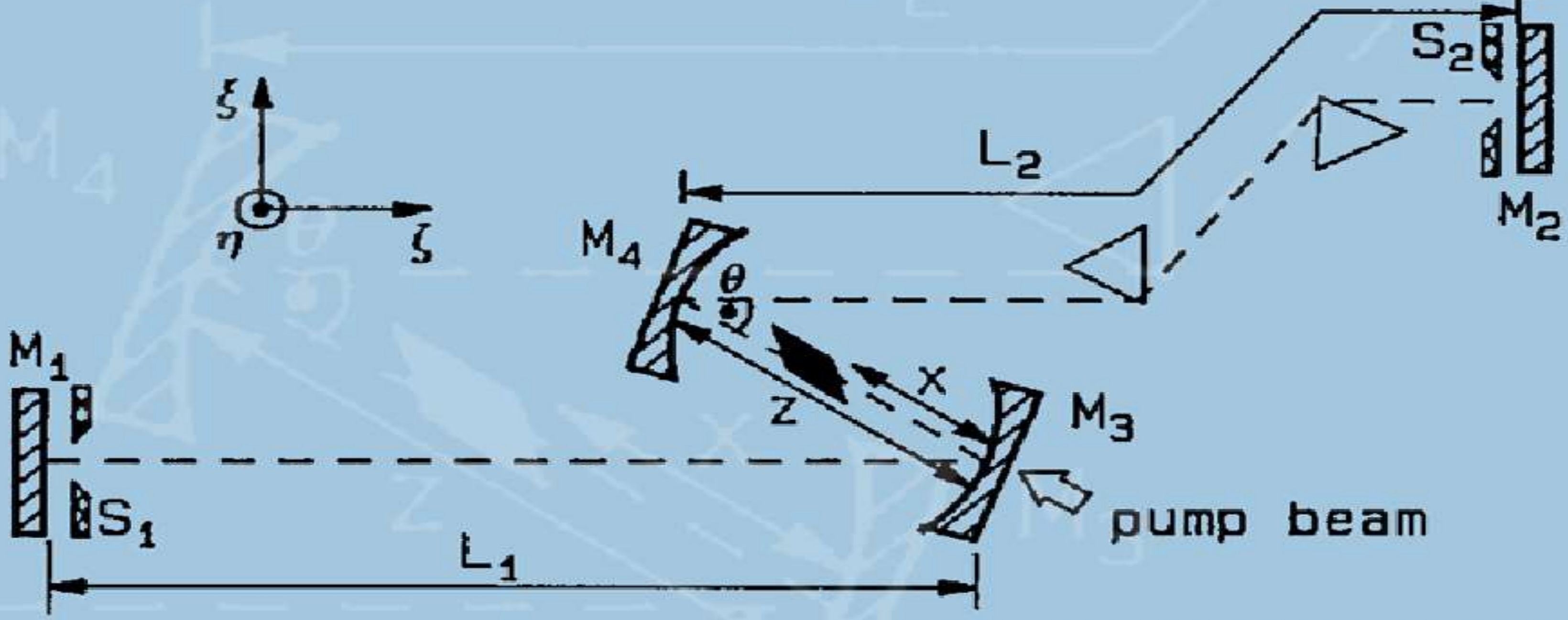
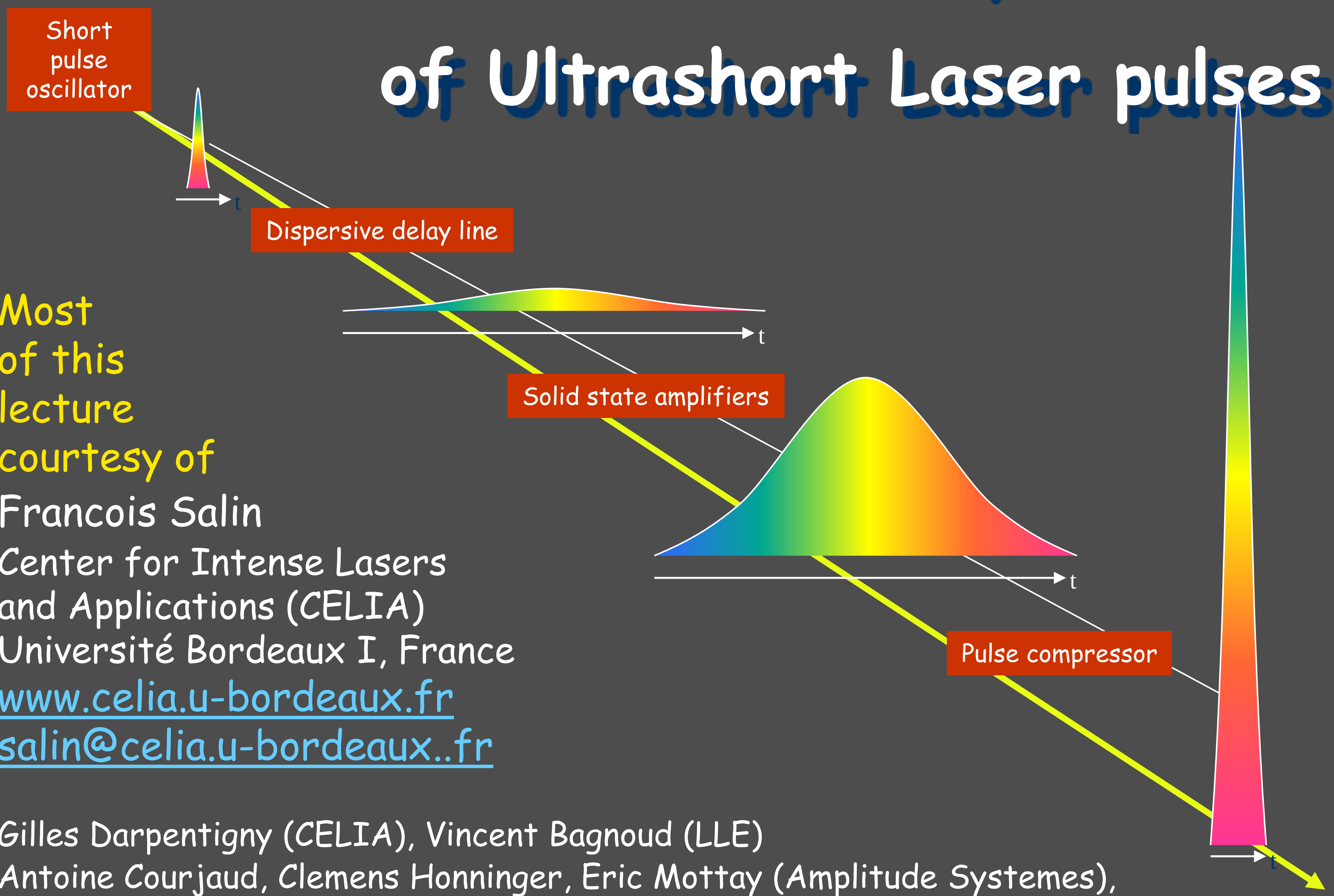


image from G. Cerullo et al., Opt. Lett. 19, 807 (1994), © OSA

by PIOTR WASYLCZYK

Lecture 4. Amplification of Ultrashort Laser pulses



Short pulse oscillator

Dispersive delay line

Solid state amplifiers

Pulse compressor

Most
of this
lecture
courtesy of

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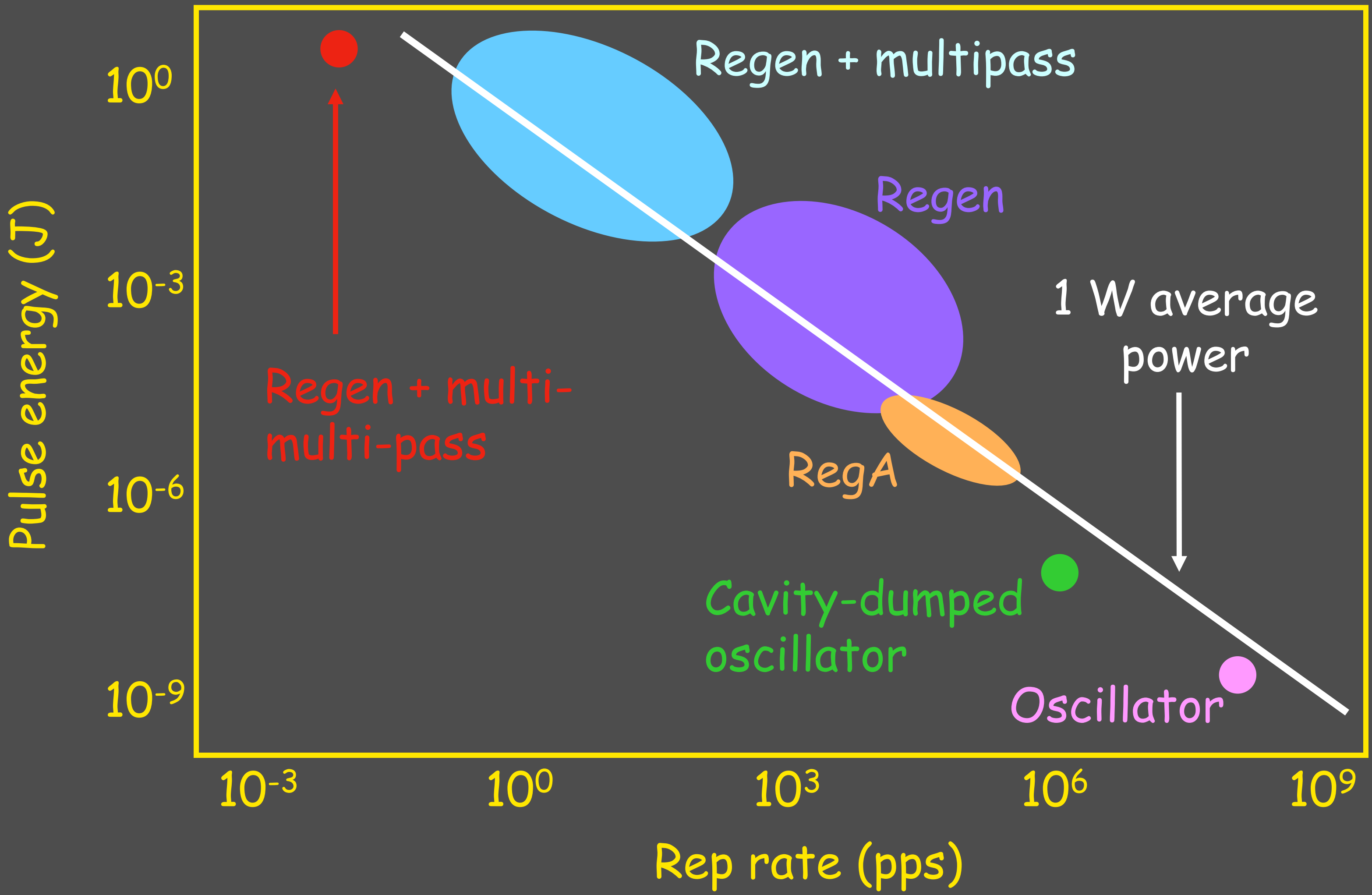
Luc Vigroux (Amplitude Technologies) and some additional stuff from Dan Mittleman, Rice

Pulse energy vs. Repetition rate



Typical pulse parameters

	Fs oscillator	Fs amplifier
Repetition rate	100 MHz	1 kHz
Average power	1 W	10 W
Pulse duration	10 fs	100 fs
Pulse energy	10 nJ	10 mJ
Peak power	1 MW	100 GW

What are the goals in ultrashort pulse amplification?

Maximum intensity on target

Pulse energy

$$I_{peak} = \frac{E}{A\,\delta t}$$

Beam area

Pulse length

Increase the energy (E),
Decrease the duration (δt),
Decrease the area of the focus (A).

Needed to start the experiment

Maximum average power at the detector

$$P_{ave} = E\,r$$

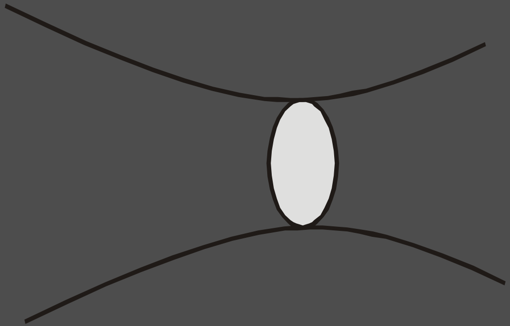
Pulse energy

Rep rate

Signal is proportional to the number of photons on the detector per integration time.

Needed to get useful results

A tightly focused (ultra)short laser pulse



100 fs
1 mJ

<u>10 μm spot</u>
10^{20} W/m^2

electric field 1.4 x 10^{11} V/m
comparable with
hydrogen atom E_{at}= 6 x 10^{11} V/m

Issues in Ultrafast Amplification and Their Solutions

Pulse length discrepancies: Multi-pass amplifiers and regenerative amplifiers ("Regens").

Damage: Chirped-Pulse Amplification (CPA)

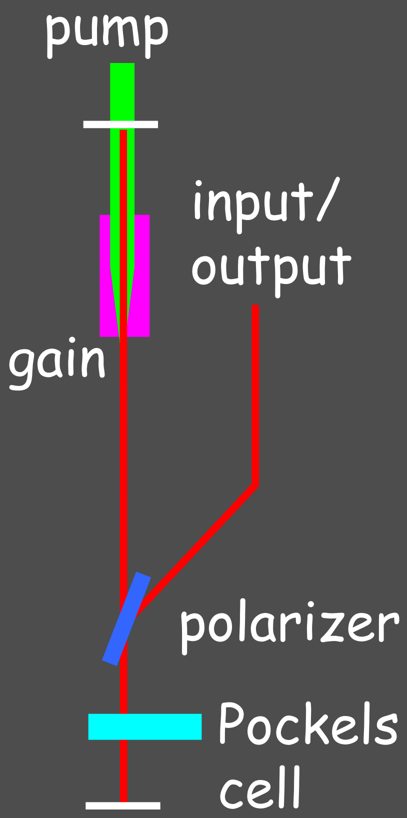
Gain saturation

Gain narrowing

Thermal effects

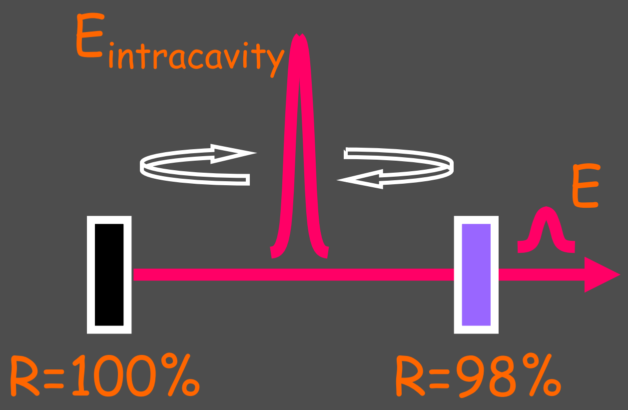
Satellite pulses, Contrast, and Amplified Spontaneous Emission

Systems cost lots of money: Earn more money…



Cavity Dumping

Before we consider amplification, recall that the intracavity pulse energy is ~50 times the output pulse energy. So we have more pulse energy. How can we get at it?



$$E = T_{output}\ E_{intracavity}$$

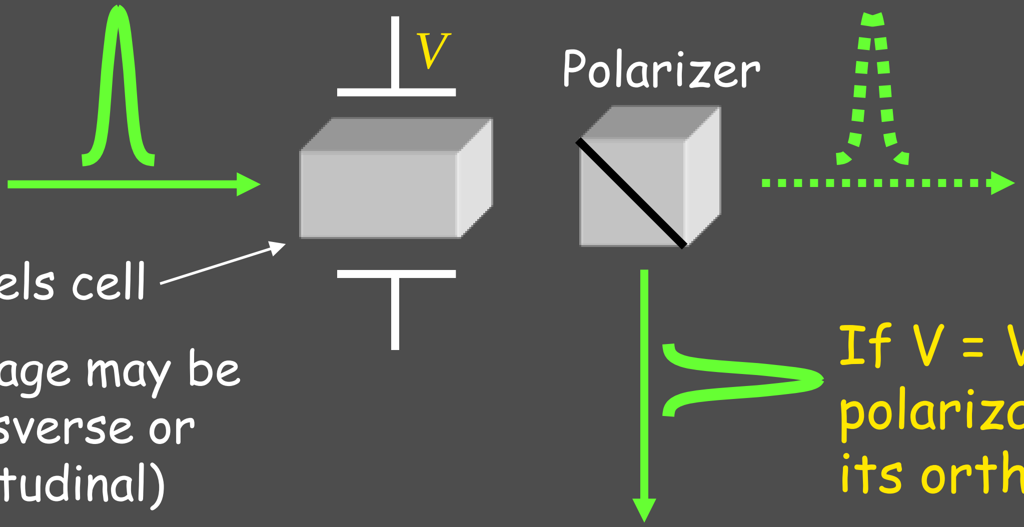
Transmission of output coupler: ~2%

What if we instead used two high reflectors, let the pulse energy build up, and then switch out the pulse. This is the opposite of Q-switching: it involves switching from minimum to maximum loss, and it's called "Cavity Dumping."

Cavity dumping: the Pockels cell

A Pockels cell is a device that can switch a pulse (in and) out of a resonator. It's used in Q-switches and cavity dumpers.

A voltage (a few kV) can turn a crystal into a half- or quarter-wave plate.



Pockels cell

(voltage may be transverse or longitudinal)

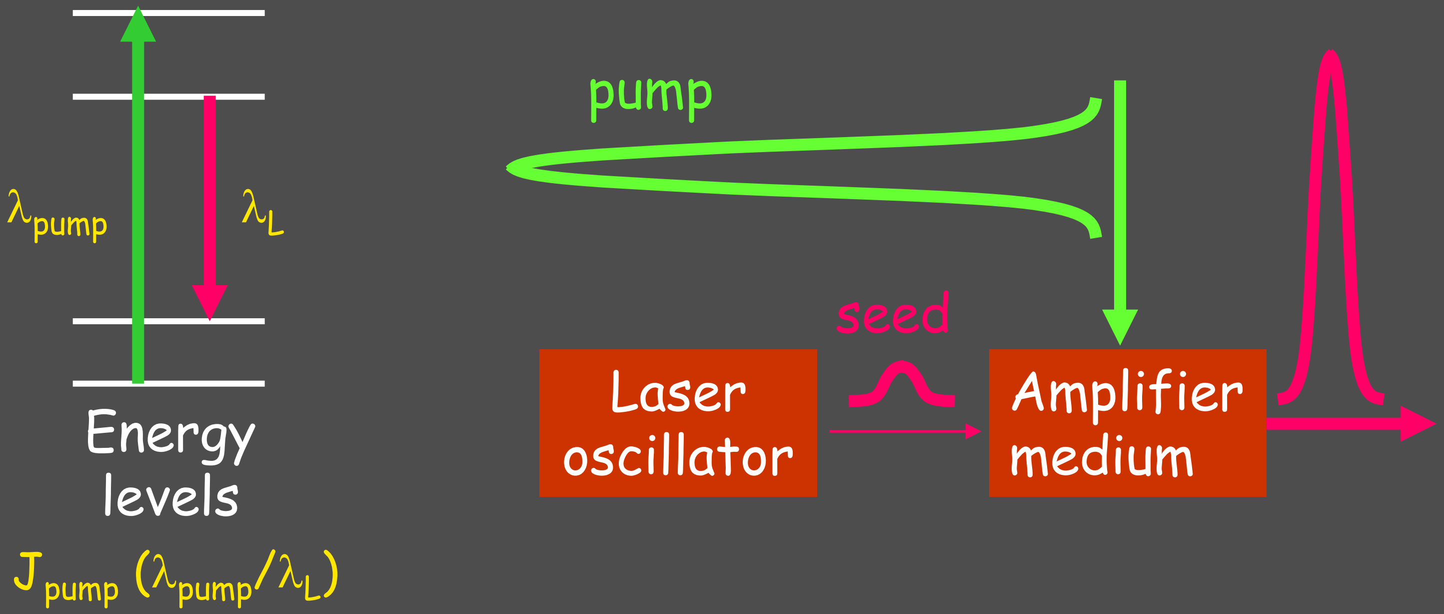
If $V = 0$, the pulse polarization doesn't change.

If $V = V_\pi$, the pulse polarization switches to its orthogonal state.

Abruptly switching a Pockels cell allows us to extract a pulse from a cavity. This allows us to achieve ~100 times the pulse energy at 1/100 the repetition rate (i.e., 100 nJ at 1 MHz).

Amplification of Laser Pulses, in General

Very simply, a powerful laser pulse at one color pumps an amplifier medium, creating an inversion, which amplifies another pulse.



λ_{pump}

λ_L

Energy levels

$J_{pump}\ (\lambda_{pump}/\lambda_L)$

pump

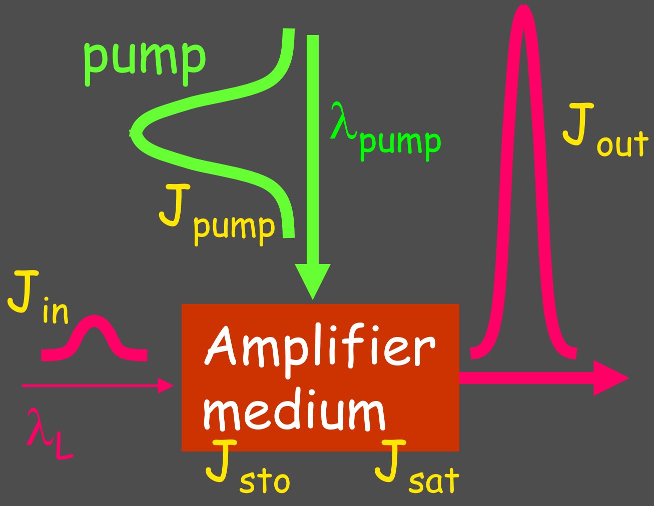
seed

Laser oscillator

Amplifier medium

Nanosecond-pulse laser amplifiers pumped by other ns lasers are commonplace.

Single-pass Amplification Math



Assume a saturable gain medium and J is the fluence (energy/area).

Assume all the pump energy is stored in the amplifier, but saturation effects will occur.

J_{sto}= stored pump fluence = J_{pump} $(\lambda_{pump}/\lambda_L)$
J_{sat}= saturation fluence (material dependent)

At low intensity, the gain is linear:

$$\frac{dJ}{dz} = g_0 J \qquad \left(g_0 L = \frac{J_{sto}}{J_{sat}} > 0 \right)$$

At high intensity, the gain "saturates" and hence is constant:

$$\frac{dJ}{dz} = g_0 J_{sat}$$

Intermediate case interpolates between the two:

$$\frac{dJ}{dz} = g_0 J_{sat} \left(1 - e^{-J/J_{sat}} \right)$$

Single-pass Amplification Math

This differential equation can be integrated to yield the Frantz-Nodvick equation for the output of a saturated amplifier:

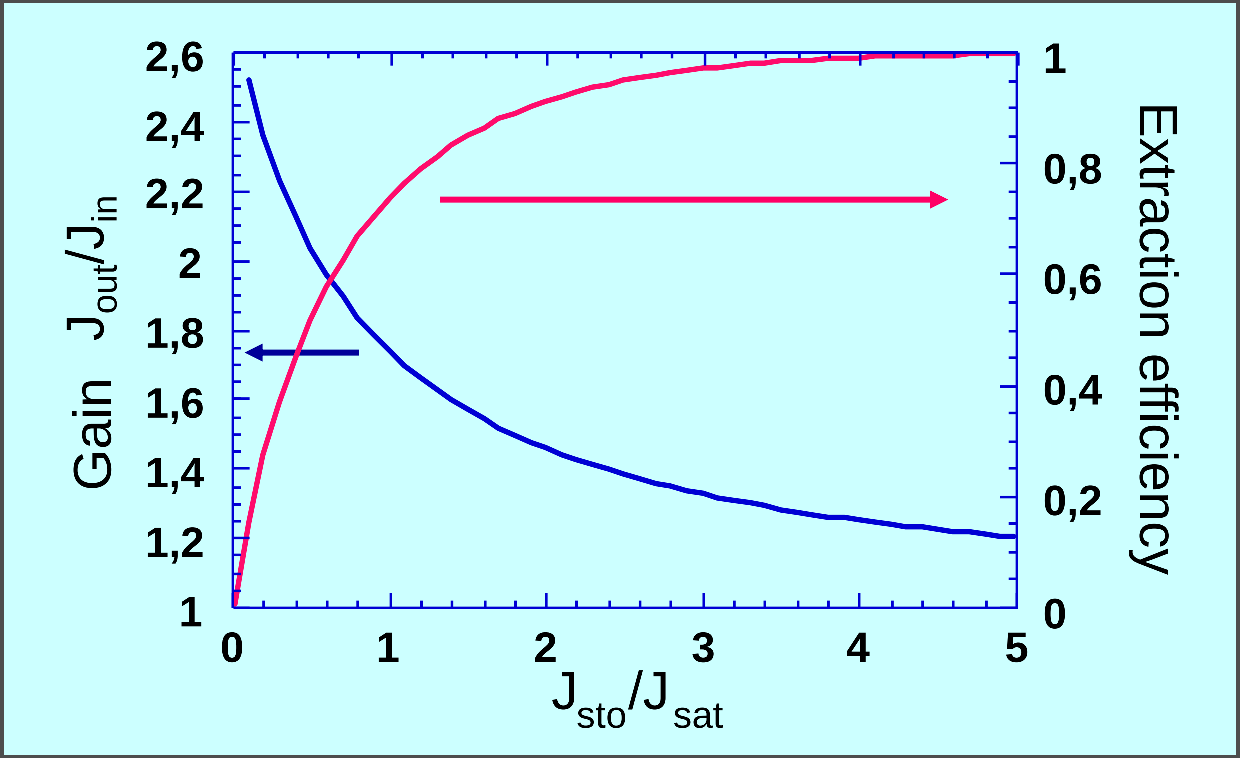
$$J_{out} = J_{sat} \log\left\{ G_0 \left[\exp\left(\frac{J_{in}}{J_{sat}} \right) - 1 \right] + 1 \right\}$$

where the small signal gain per pass is given by:

$$G_0 = \exp(g_0 L) = \exp(\frac{J_{sto}}{J_{sat}})$$

Frantz-Nodvick equation

$$J_{out} = J_{sat} \log\left\{ G_0 \left[\exp\left(\frac{J_{sto}}{J_{sat}} \right) - 1 \right] + 1 \right\} \qquad G_0 = \exp(g_0 L) = \exp\left(\frac{J_{sto}}{J_{sat}} \right)$$

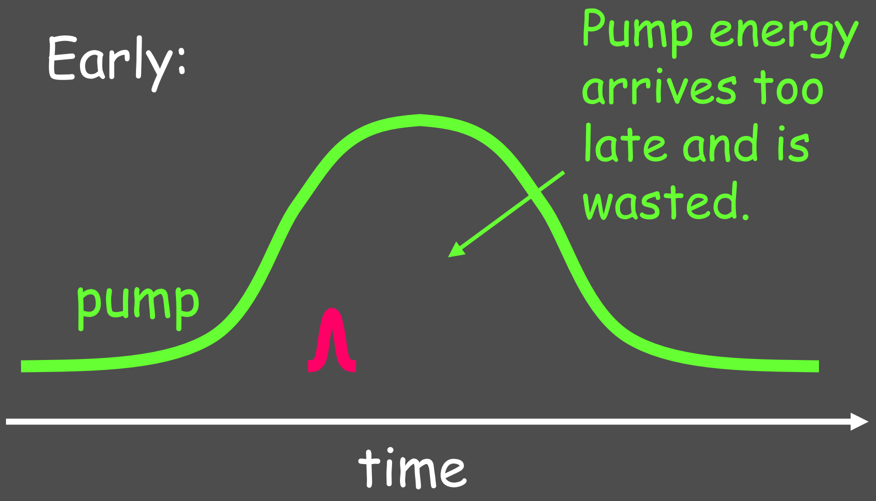


So you can have high gain or high extraction efficiency. But not both.

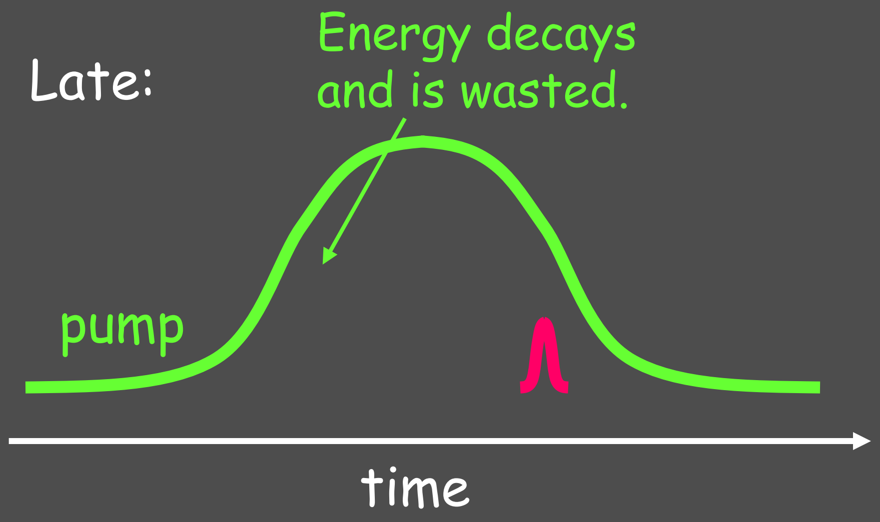
Another problem with amplifying ultrashort laser pulses…

Another issue is that the ultrashort pulse is so much shorter than the (ns or μs) pump pulse that supplies the energy for amplification.

So should the ultrashort pulse arrive early or late?


Early:

Pump energy arrives too late and is wasted.

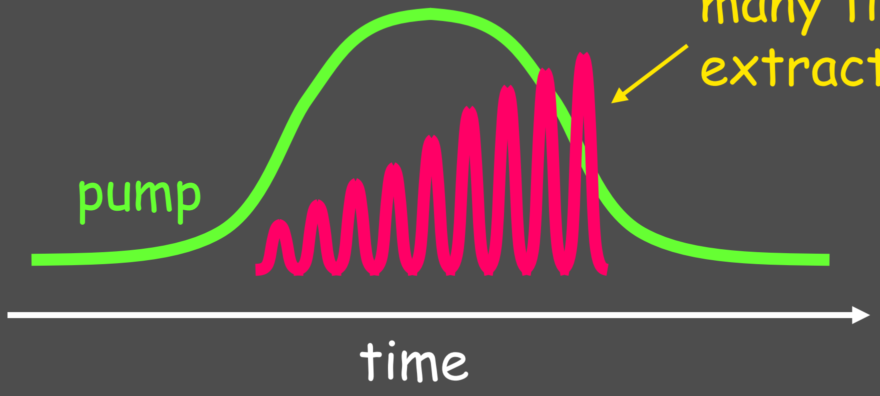

Late:

Energy decays and is wasted.

In both cases, pump pulse energy is wasted, and amplification is poor.

So we need many passes.

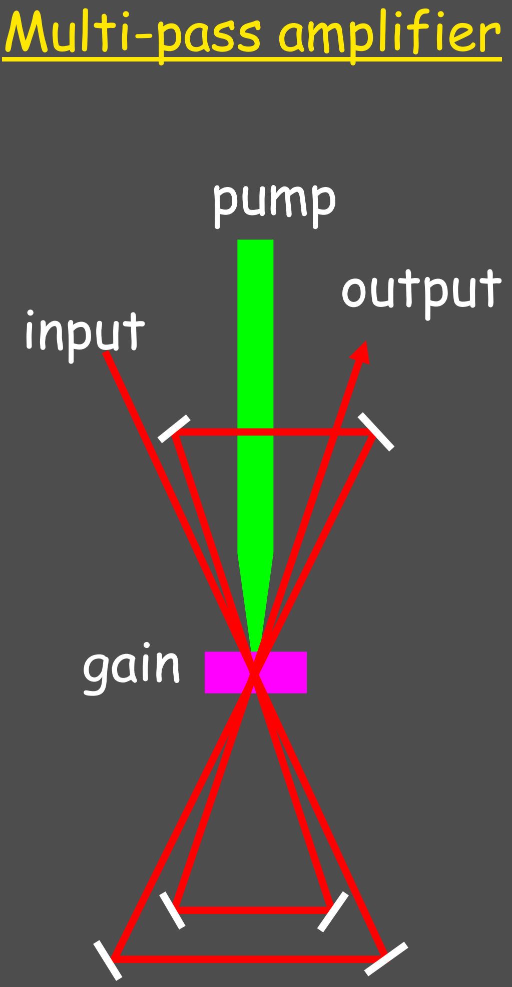
All ultrashort-pulse amplifiers are multi-pass.

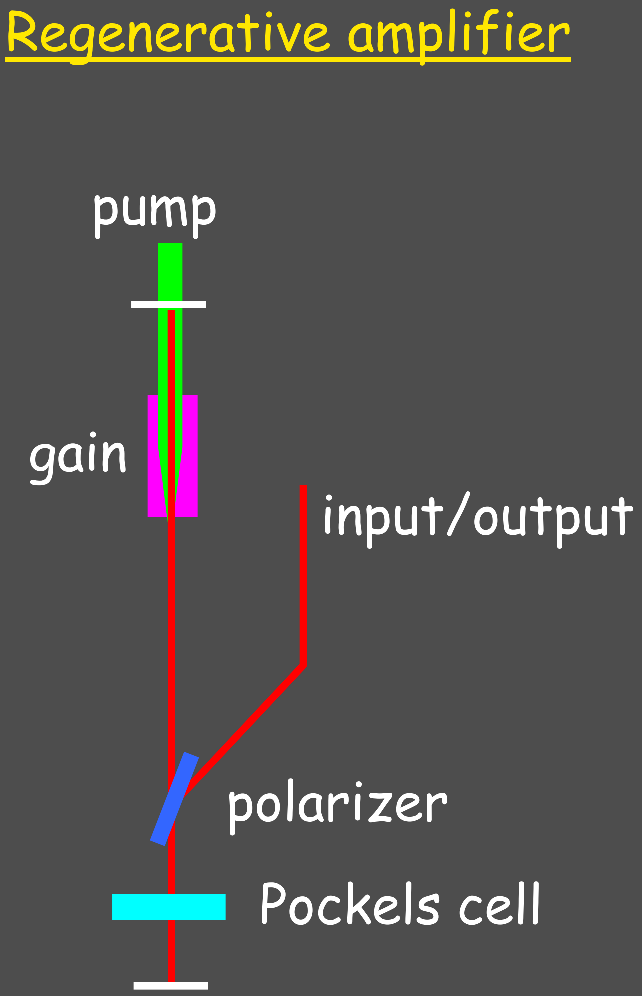


The ultrashort pulse returns many times to eventually extract most of the energy.

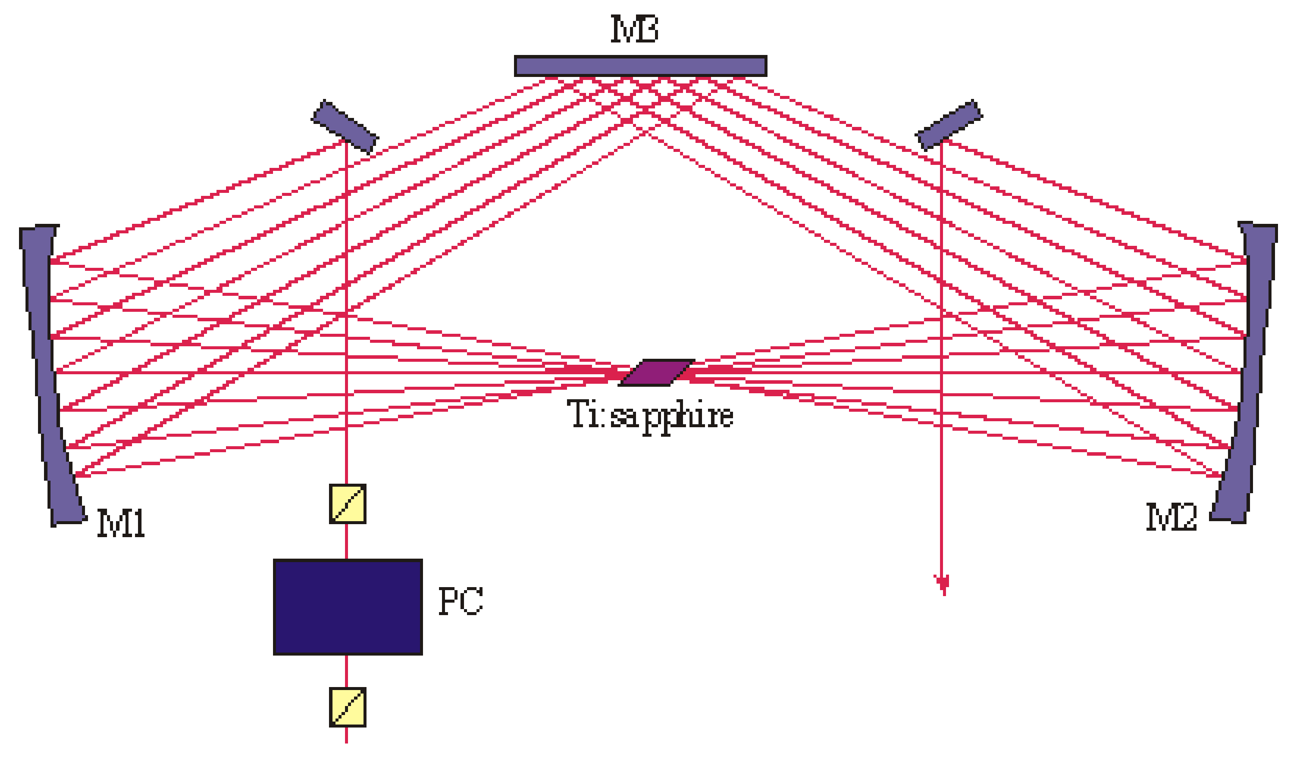
This approach achieves much greater efficiency.

Two main amplification methods



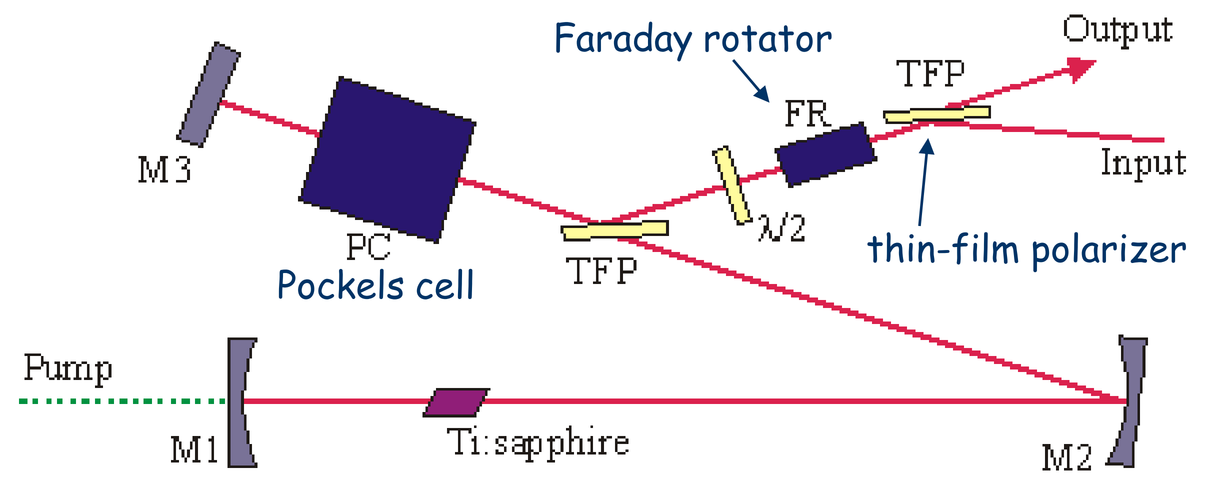


A multi-pass amplifier

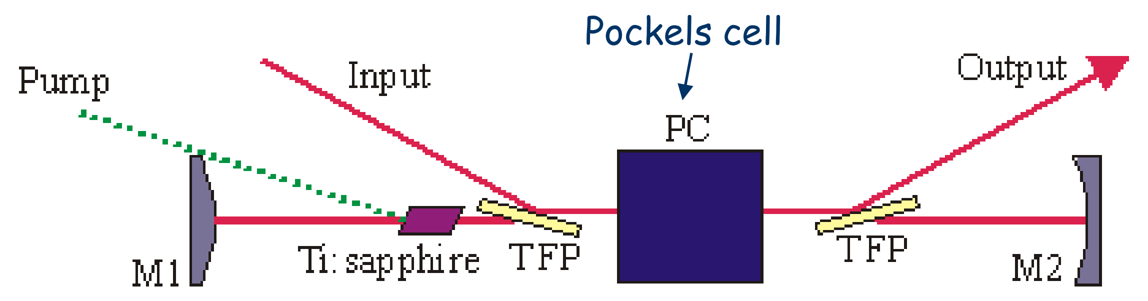


A Pockels cell (PC) and a pair of polarizers are used to inject a single pulse into the amplifier.

Regenerative amplifier geometries



This design is often used for kHz-repetition-rate amplifiers.



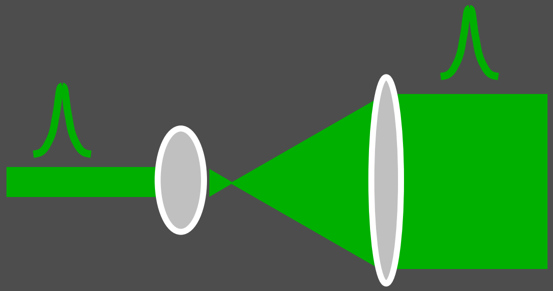
This is used for 10-20-Hz repetition rates. It has a larger spot size in the Ti:sapphire rod.

The Ti:Sapphire rod is ~20-mm long and doped for 90% absorption.

Okay, so what next?

Pulse intensities inside an amplifier can become so high that **damage** (or at least small-scale self-focusing) occurs.

Solution:



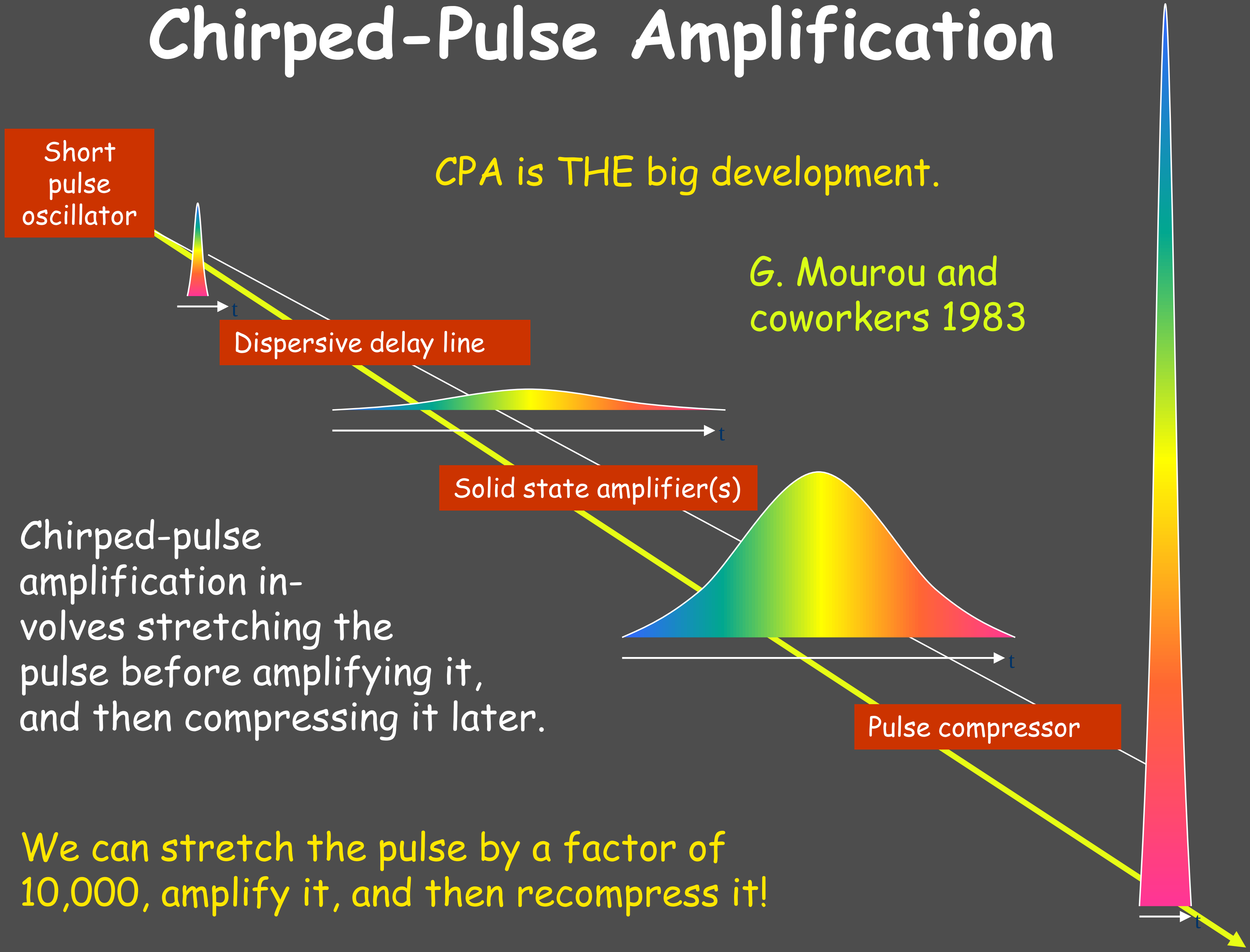
Expand the beam and
use large amplifier media.

Okay, we did that. But that's still not enough.

Solution:

Expand the pulse **in time**, too.

Chirped-Pulse Amplification



Short pulse oscillator

Dispersive delay line

Solid state amplifier(s)

Pulse compressor

CPA is THE big development.

G. Mourou and coworkers 1983

Chirped-pulse amplification involves stretching the pulse before amplifying it, and then compressing it later.

We can stretch the pulse by a factor of 10,000, amplify it, and then recompress it!

Nobel Prize in physics 2018

"for groundbreaking inventions in the field of laser physics"

"for the optical tweezers and their application to biological systems"

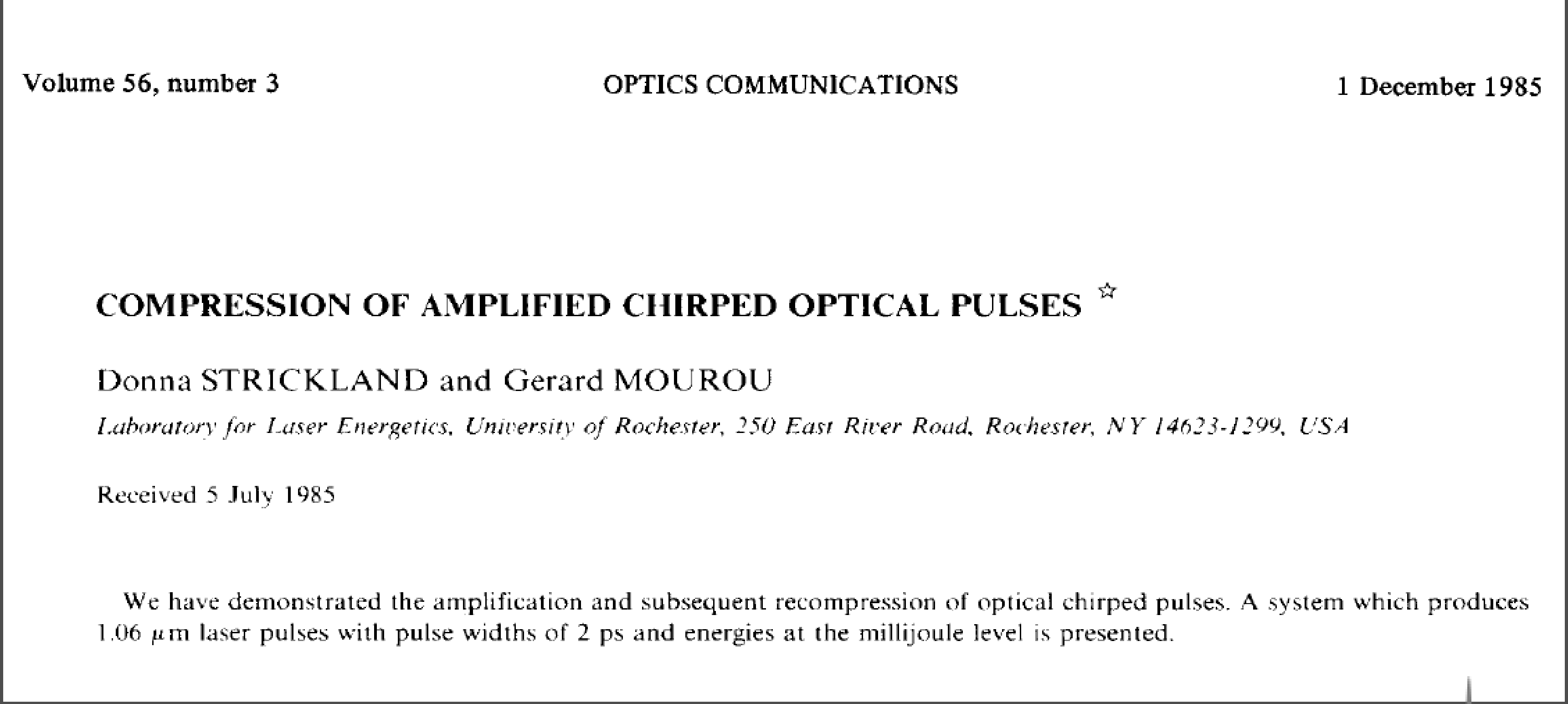
"for their method of generating high-intensity, ultra-short optical pulses"

Arthur Ashkin
½ of the prize

Gerard Mourou

Donna Strickland
½ of the prize

Chirped Pulse Amlification (CPA) – the first paper



Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

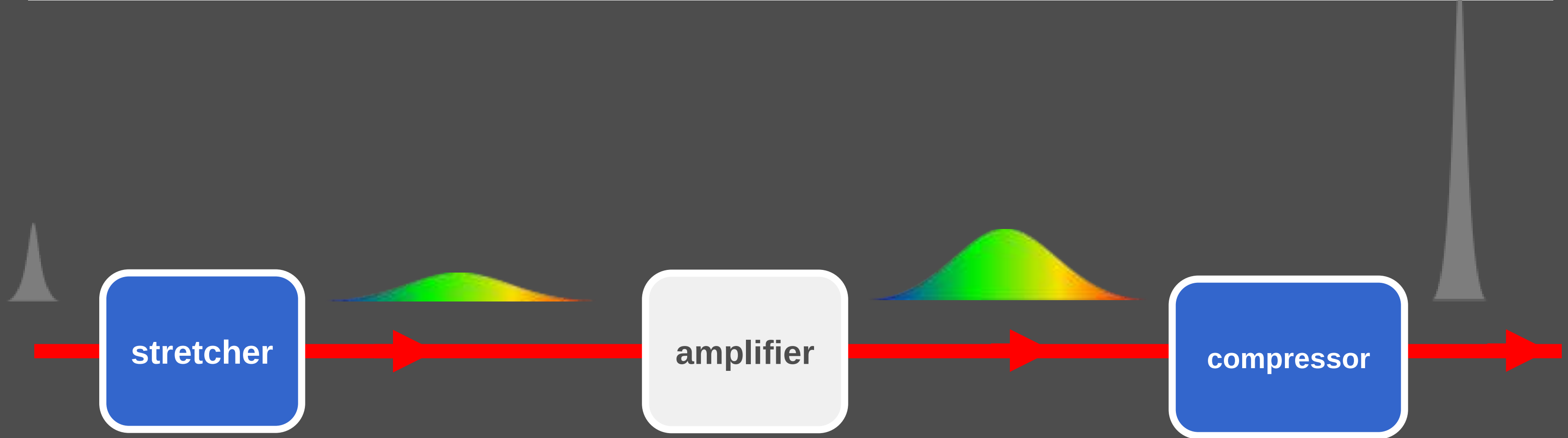
COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

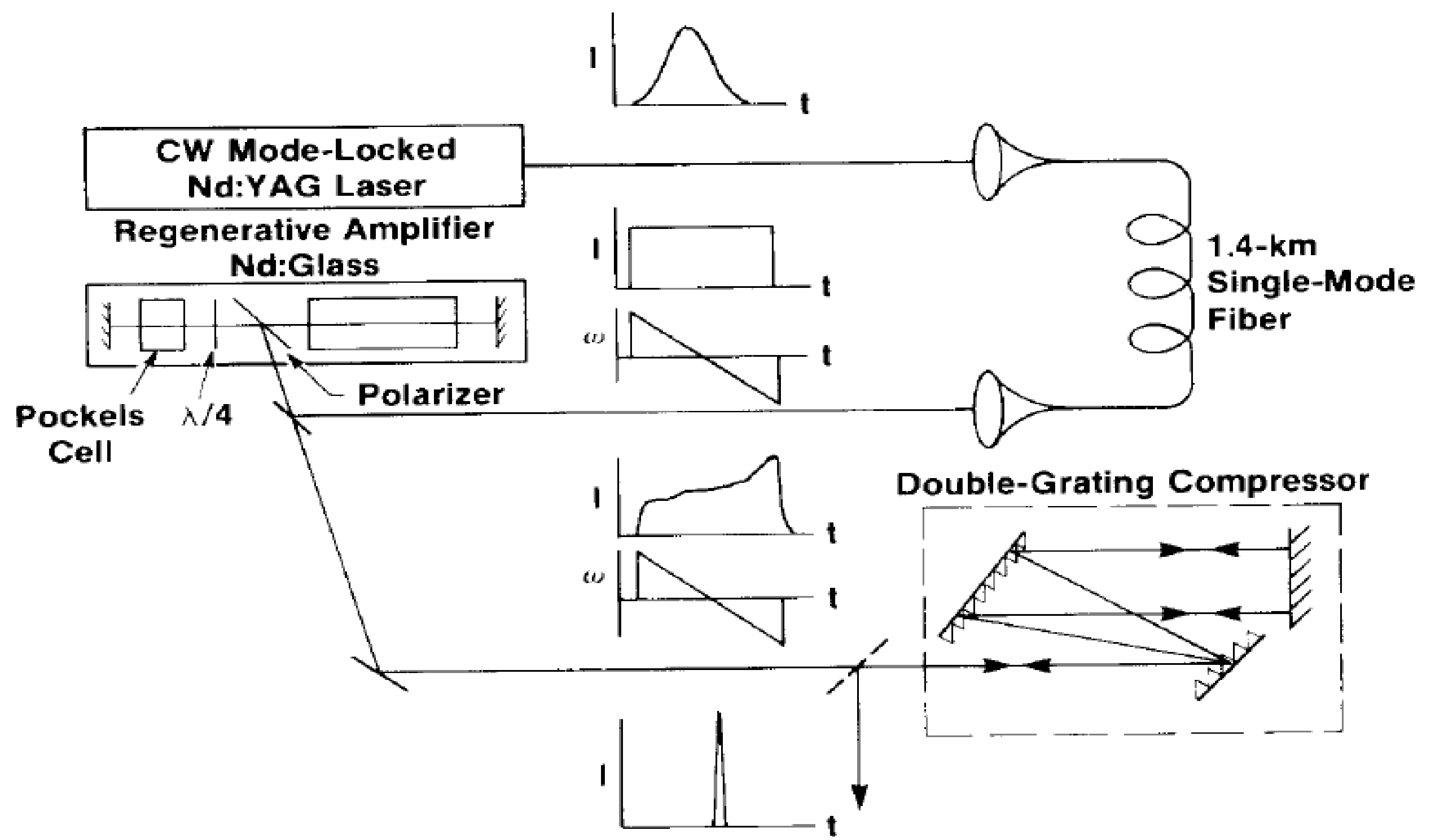
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

Received 5 July 1985

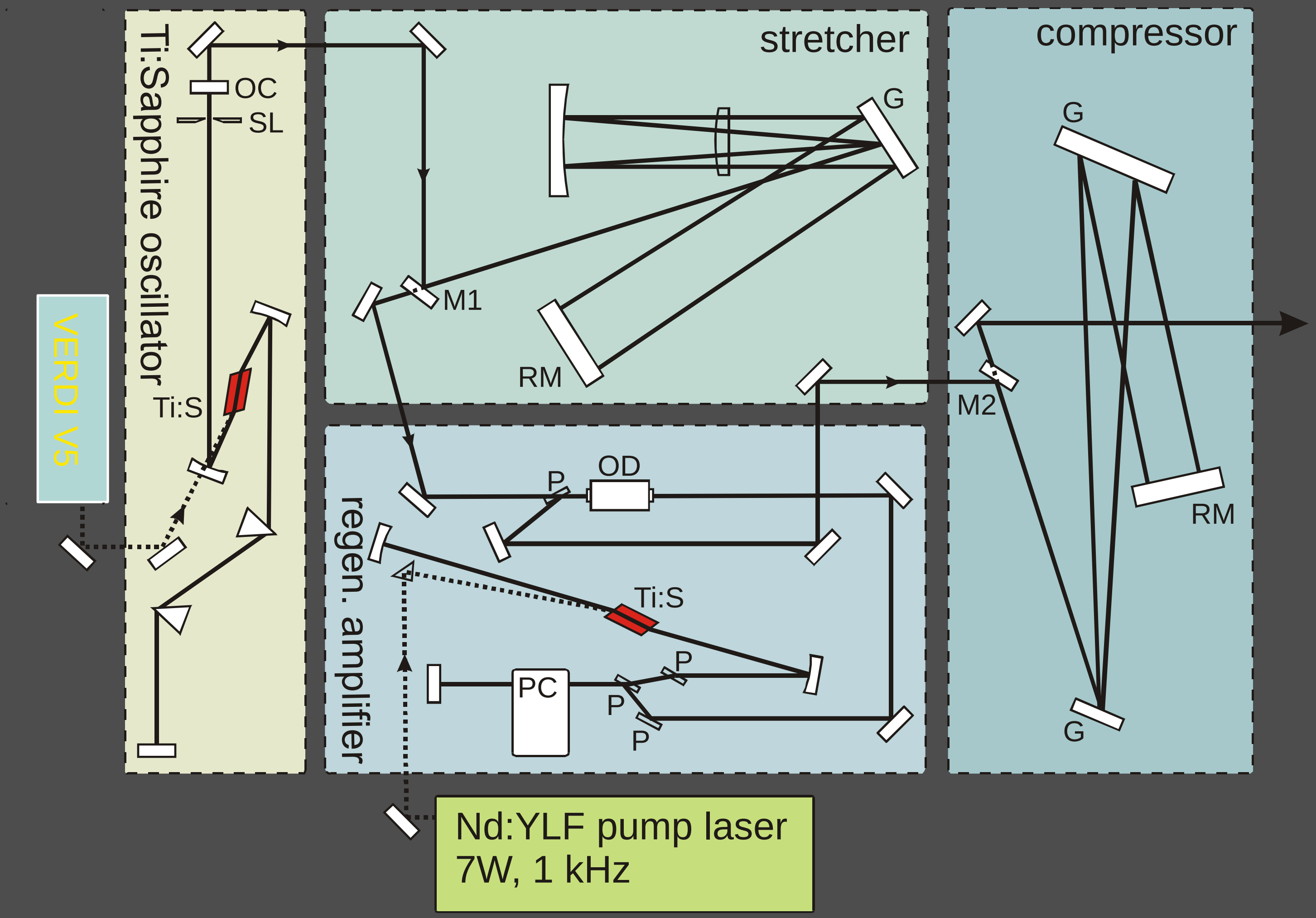
We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.



CPA – first implementation

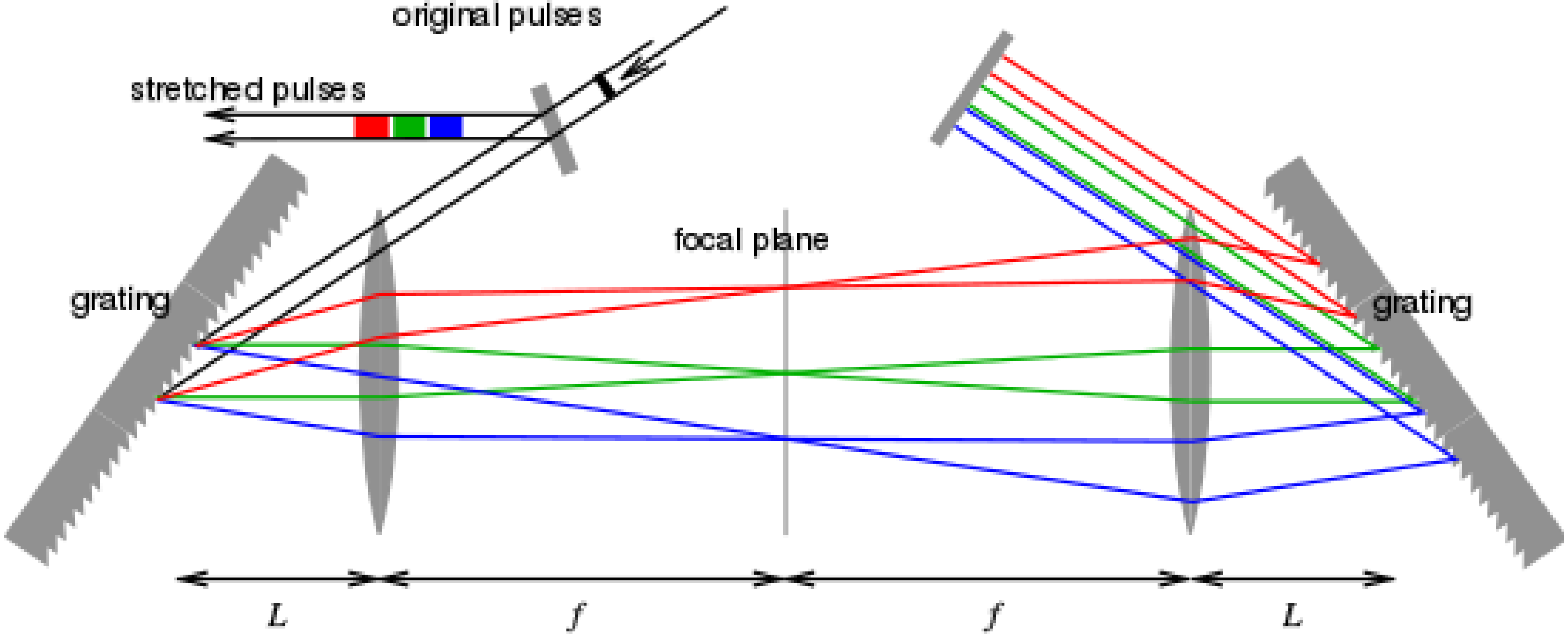


CPA – around year 2000



A pulse stretcher

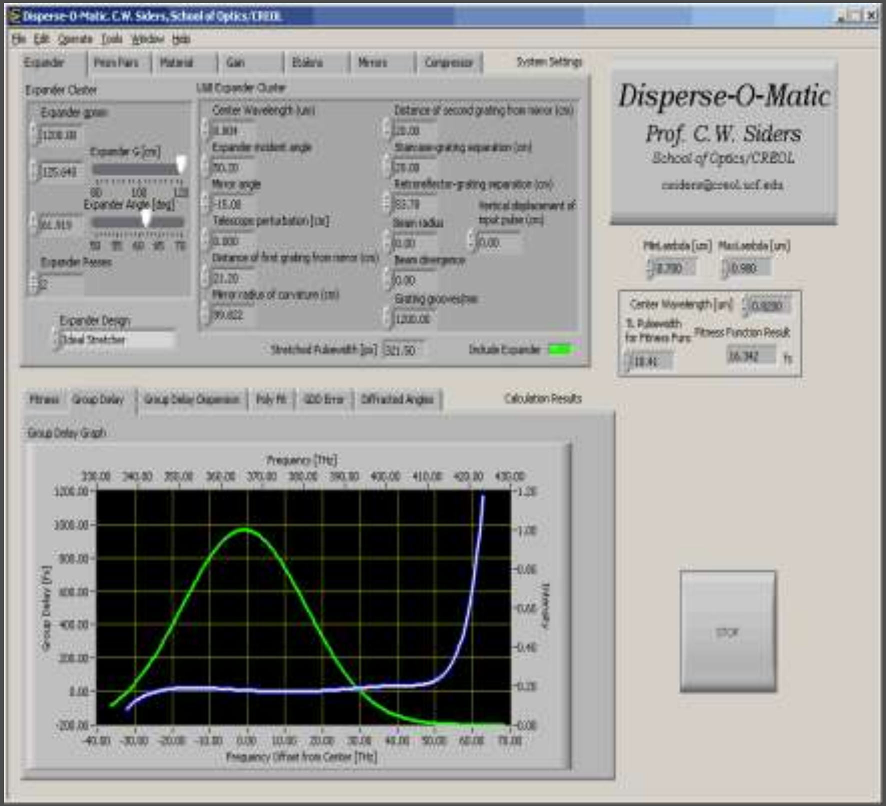
This device stretches an 18-fs pulse to 600 ps—a factor of 30,000!
A ray trace of the various wavelengths in the stretcher:



A rule of thumb: the streched pulse may be as **long** as the grating is **wide** (times the number of passes).

Image source: Wikipedia

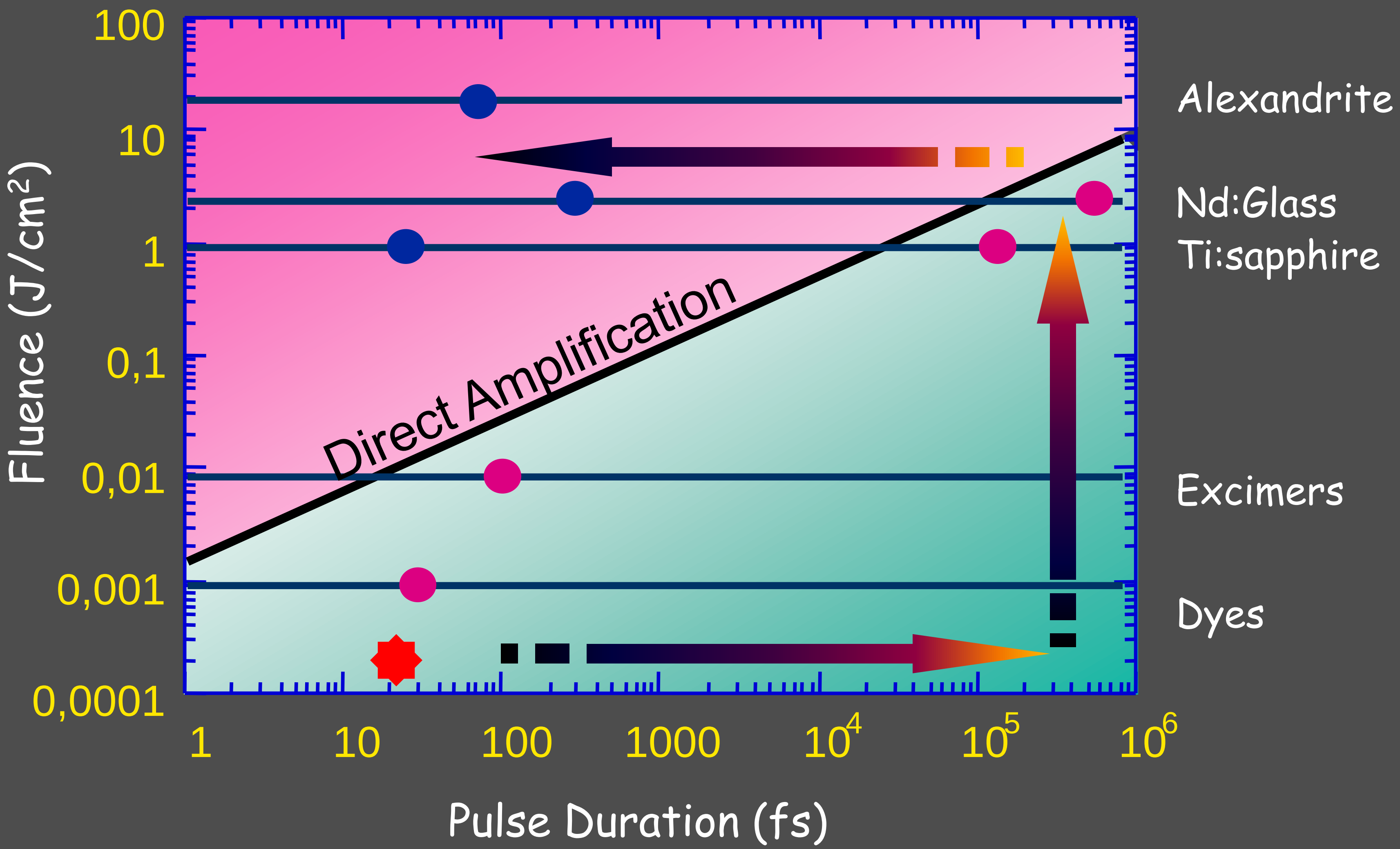
"Dispersomatic"—Free code to model dispersion in stretchers and compresssors



DOM calculates the dispersive properties (i.e. the wavelength-dependent propagation delay) through optical materials, stretcher/compressors, and prism pairs, etc. Applications include optimizing a chirped-pulse amplified laser system.

http://dom.creol.ucf.edu/

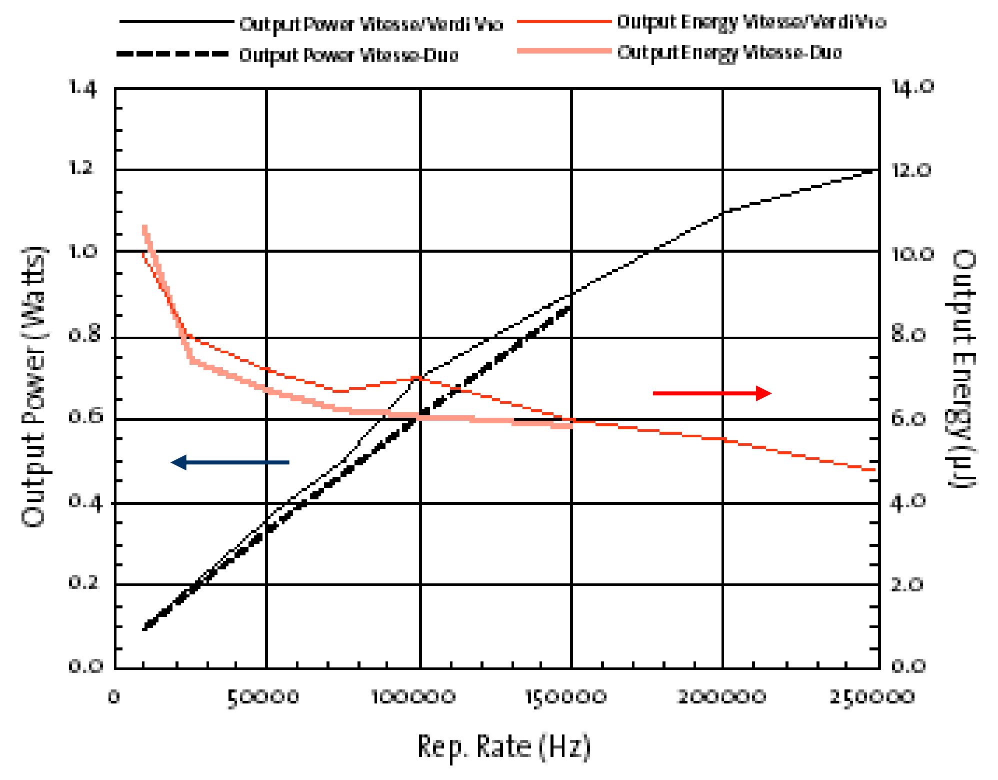
CPA vs. Direct Amplification



CPA achieves the fluence of long pulses but at a shorter pulse length!

Regenerative Chirped-Pulse Amplification at ~100 kHz rep rates with a cw pump

A fs oscillator requires only ~5 W of green laser power. An intracavity-doubled Nd:YLF or Nd:YAG pump laser provides up to 50 W. Use the rest to pump an amplifier.



Coherent
RegA amplifier

Microjoules at 250 kHz repetition rates!

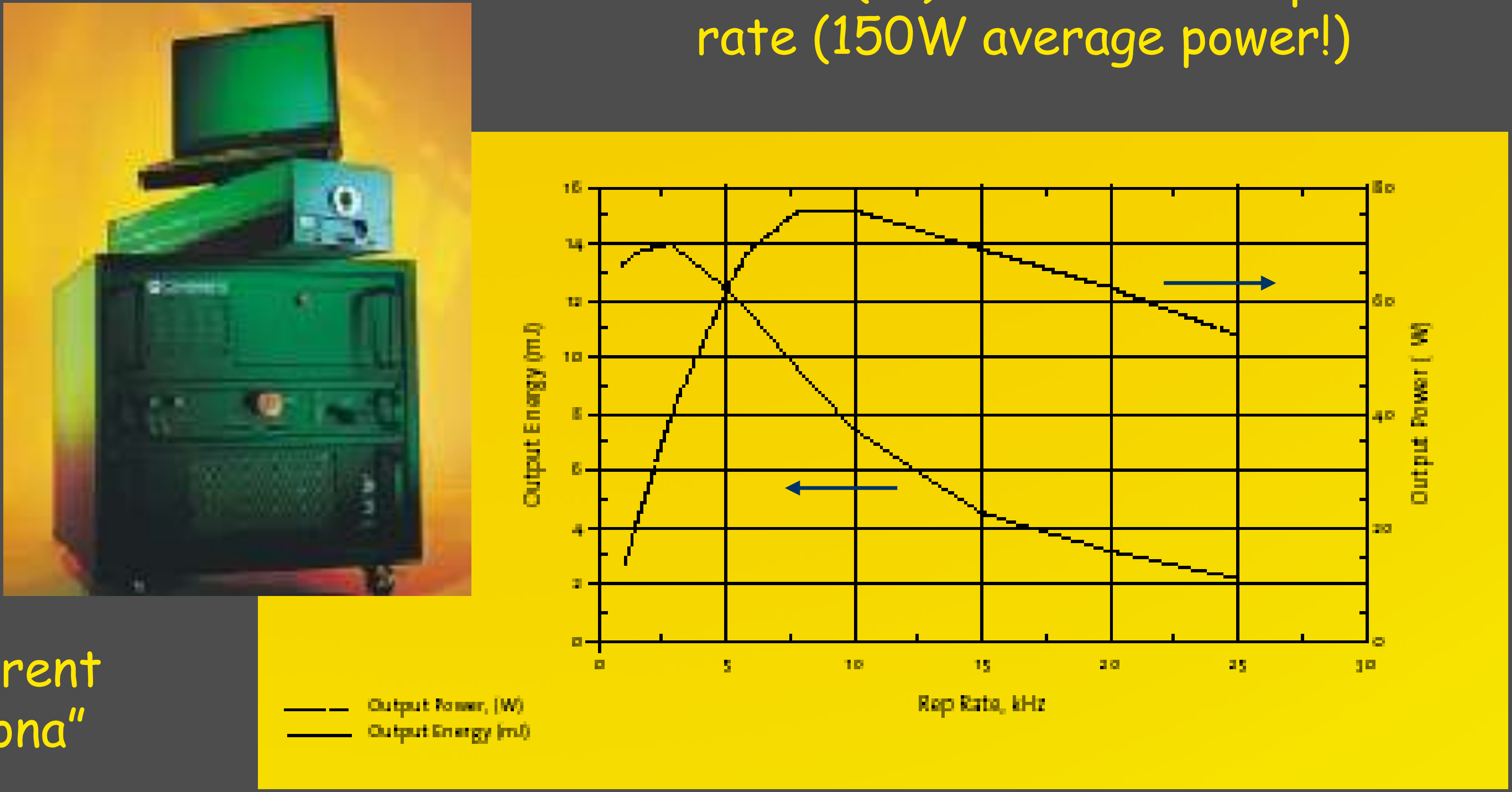
Regenerative chirped-pulse amplification with a kHz pulsed pump

Positive Light regen: the "Spitfire"

Wavelength: 800 nm
(Repetition rates of 1 to 50 kHz)
High Energy: <130 fs, >2 mJ at 1 kHz
Picosecond: ~80 ps, >0.7 mJ at 1 kHz
Short Pulse: <50 fs, >0.7 mJ at 1 kHz

Pump laser for ultrafast amplifiers

15 mJ (ns) at a 10 kHz rep rate (150W average power!)



Coherent
“Corona”

high power, Q-switched green laser in a compact and reliable diode-pumped package

Average power for high-power Ti:Sapphire regens

Rep rate

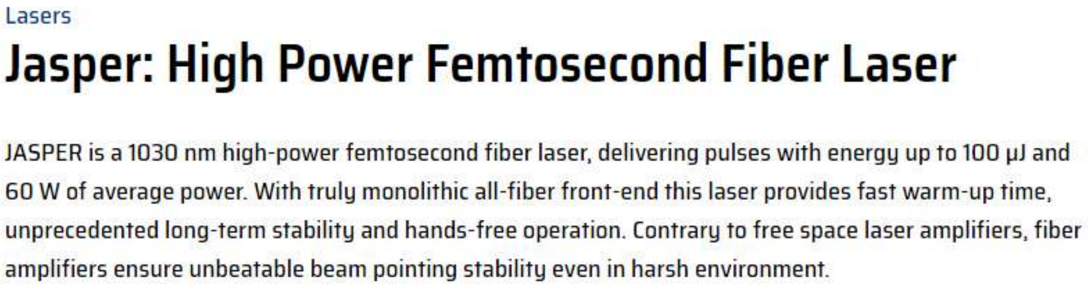
	1 kHz	10 kHz	100 kHz
Extracted energy	20 mJ	1.8 mJ	0.2 mJ
Average Power	20 W	18 W	20 W
Beam diameter	3 mm	1 mm	250 μm

Pump power 100 W

These average powers are high. And this pump power is too.

If you want sub-100fs pulses, however, the energies will be less.

All-fiber femtosecond amplifier


Lasers

Jasper: High Power Femtosecond Fiber Laser

JASPER is a 1030 nm high-power femtosecond fiber laser, delivering pulses with energy up to 100 µJ and 60 W of average power. With truly monolithic all-fiber front-end this laser provides fast warm-up time, unprecedented long-term stability and hands-free operation. Contrary to free space laser amplifiers, fiber amplifiers ensure unbeatable beam pointing stability even in harsh environment.

Maximum pulse energy	> 50 µJ	> 100 µJ	> 100 µJ	> 100 µJ
Internal repetition rate	200 kHz – 20 MHz		300 kHz – 20 MHz	600 kHz – 20 MHz
Pulse picker	0 Hz – 1 MHz			
Pulse duration	< 250 fs (FWHM)			
Pulse duration tuning	< 250 fs – 8 ps			
Central wavelength	1030 ± 5 nm			
Optional wavelengths	515 nm, 343 nm, 258 nm			
Built-in pulse picker	Pulse on demand, any division of the base repetition rate			
Beam quality M^2	< 1.3 (typical <1.2)			
Polarization	Linear, vertical			

CPA is the basis of thousands of systems.

It's available commercially in numerous forms.

It works!

But there are some issues, especially if you try to push for really high energies:

Amplified spontaneous emission (ASE)

Gain saturation: gain vs. extraction efficiency

Gain narrowing

Thermal aberrations

Contrast ratio

Damage threshold *vs* extraction efficiency

Amplified Spontaneous Emission (ASE)

Fluorescence from the gain medium is amplified before (and after) the ultrashort pulse arrives.

This yields a 10-30 ns background with low peak power but large energy.

Depends on the noise present in the amplifier at t = 0

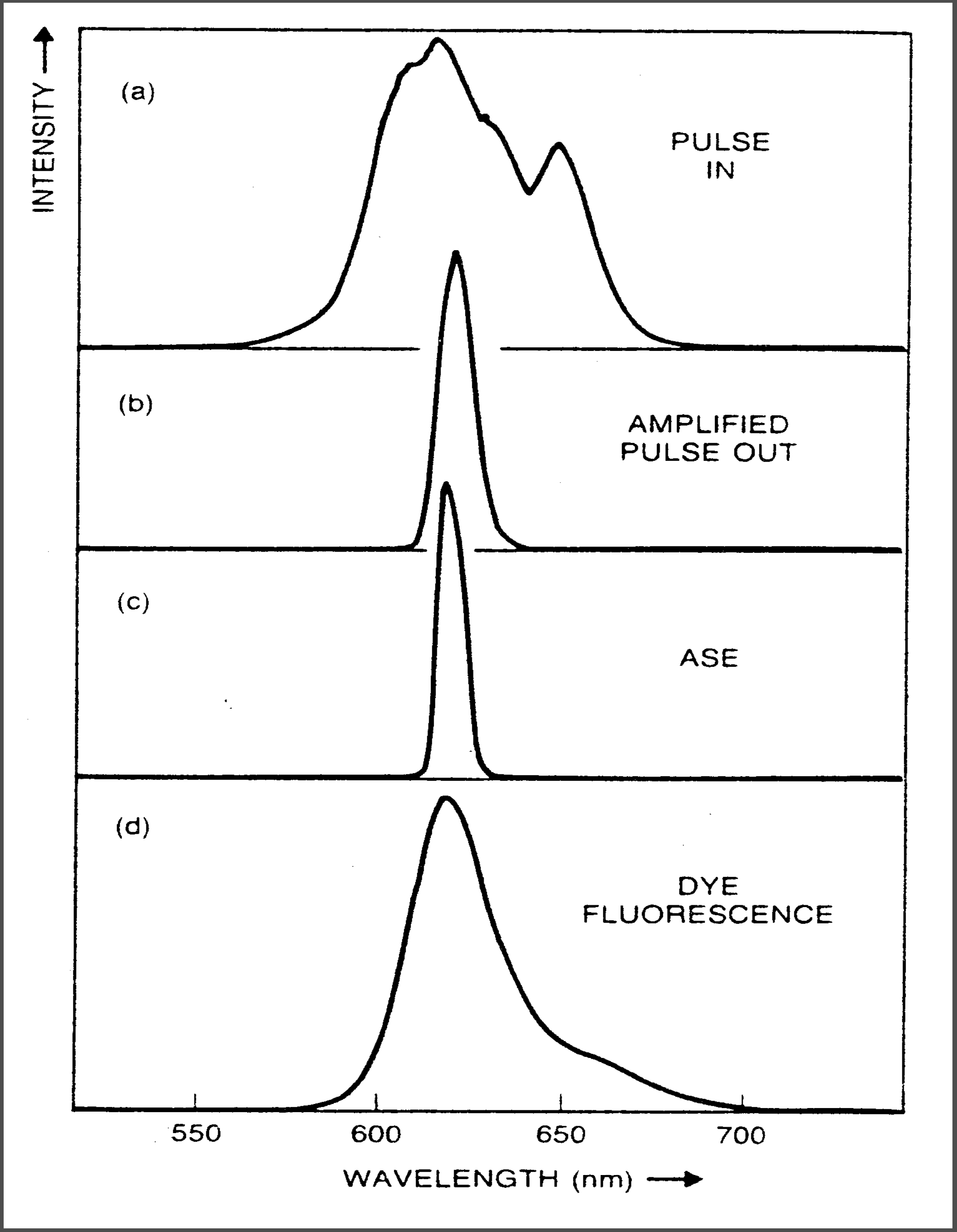
ASE shares the gain and the excited population with the pulse.

Amplification reduces the contrast by a factor of up to 10.

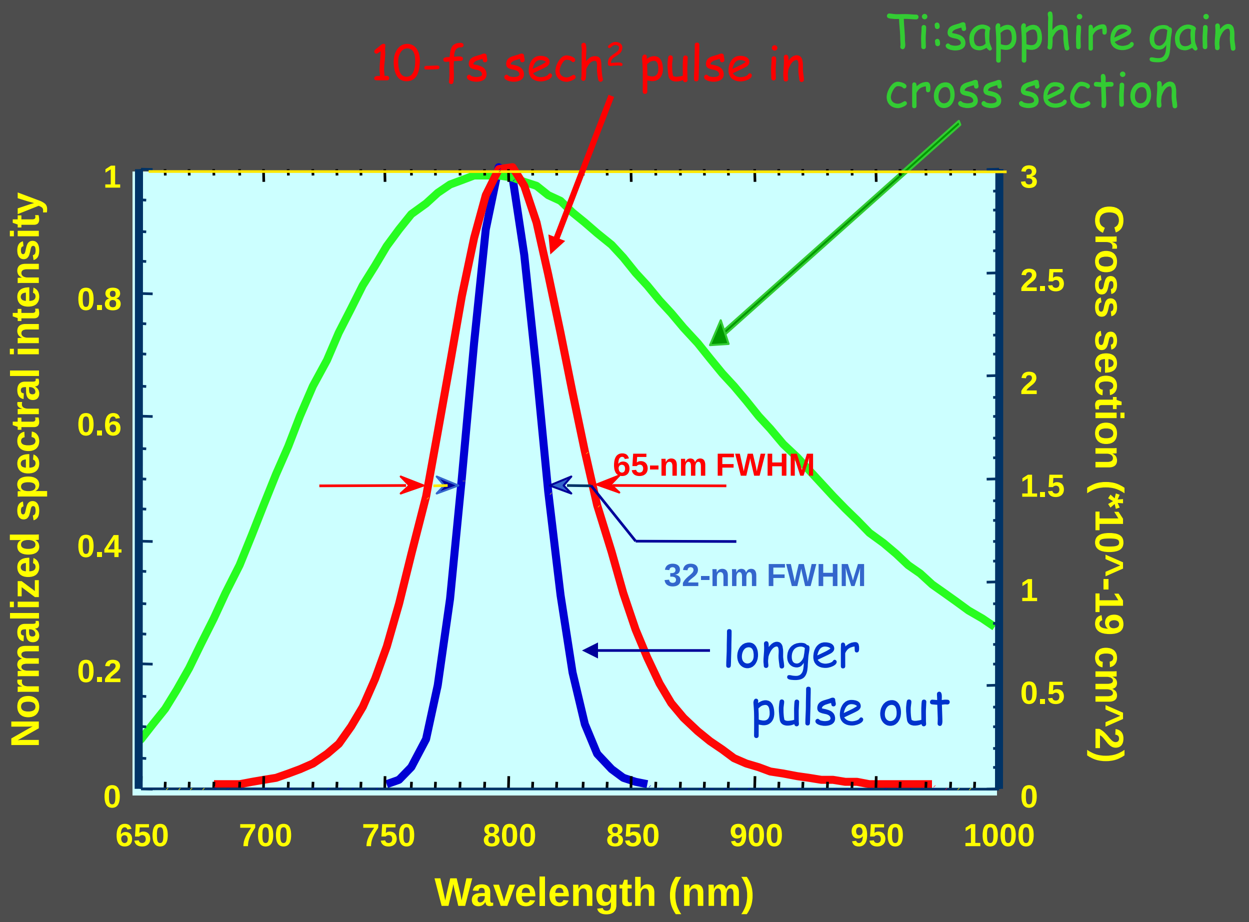
Gain Narrowing (and ASE)

On each pass through an amplifier, the pulse spectrum gets multiplied by the gain spectrum, which narrows the output spectrum—and lengthens the pulse!

As a result, the pulse lengthens, and it can be difficult to distinguish the ultrashort pulse from the longer Amplified Spontaneous Emission (ASE)

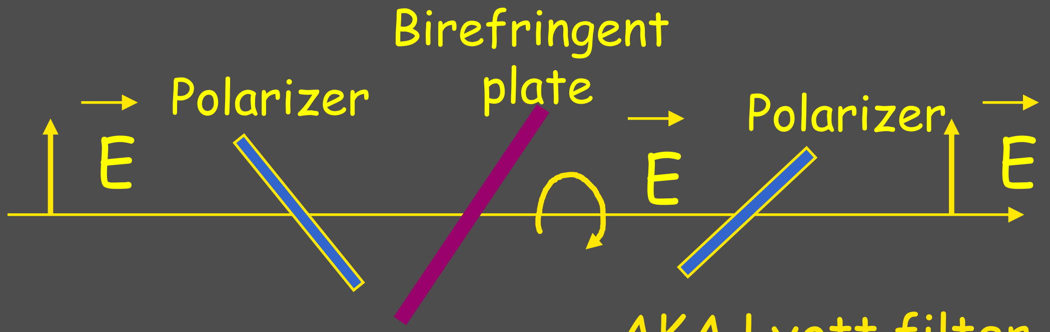


Gain narrowing example



Factor of 2 loss in bandwidth for 10^7 gain
Most Terawatt systems have $>10^{10}$ small signal gain

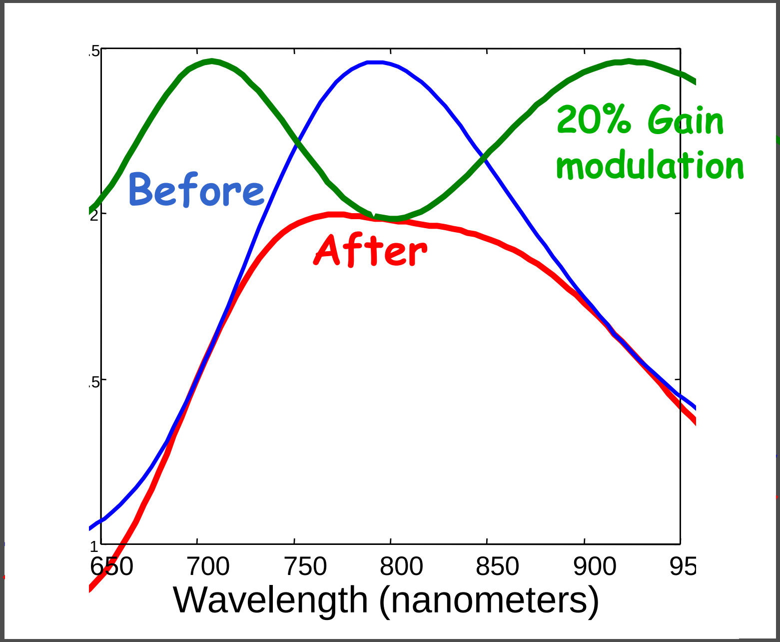
Beating gain narrowing



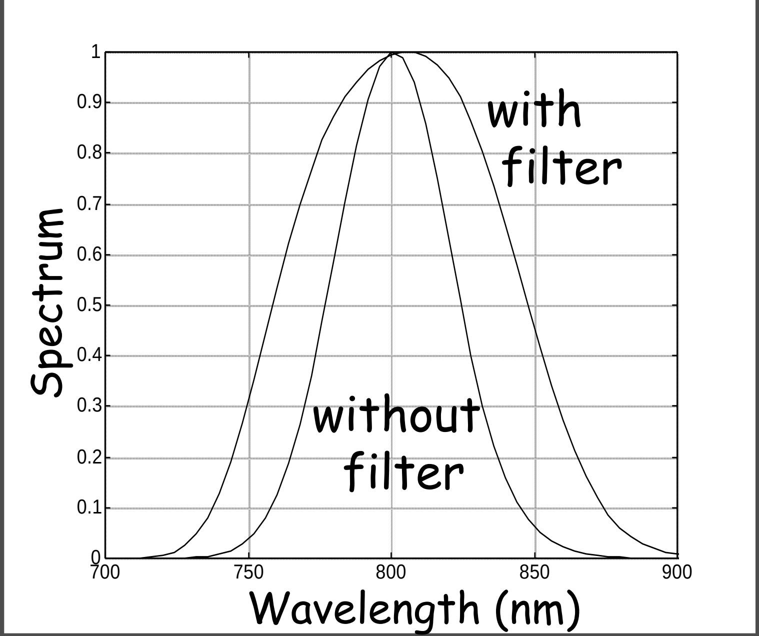
AKA Lyott filter

Introduce some loss at the gain peak to offset the high gain there.

Gain and loss



Spectrum: before and after



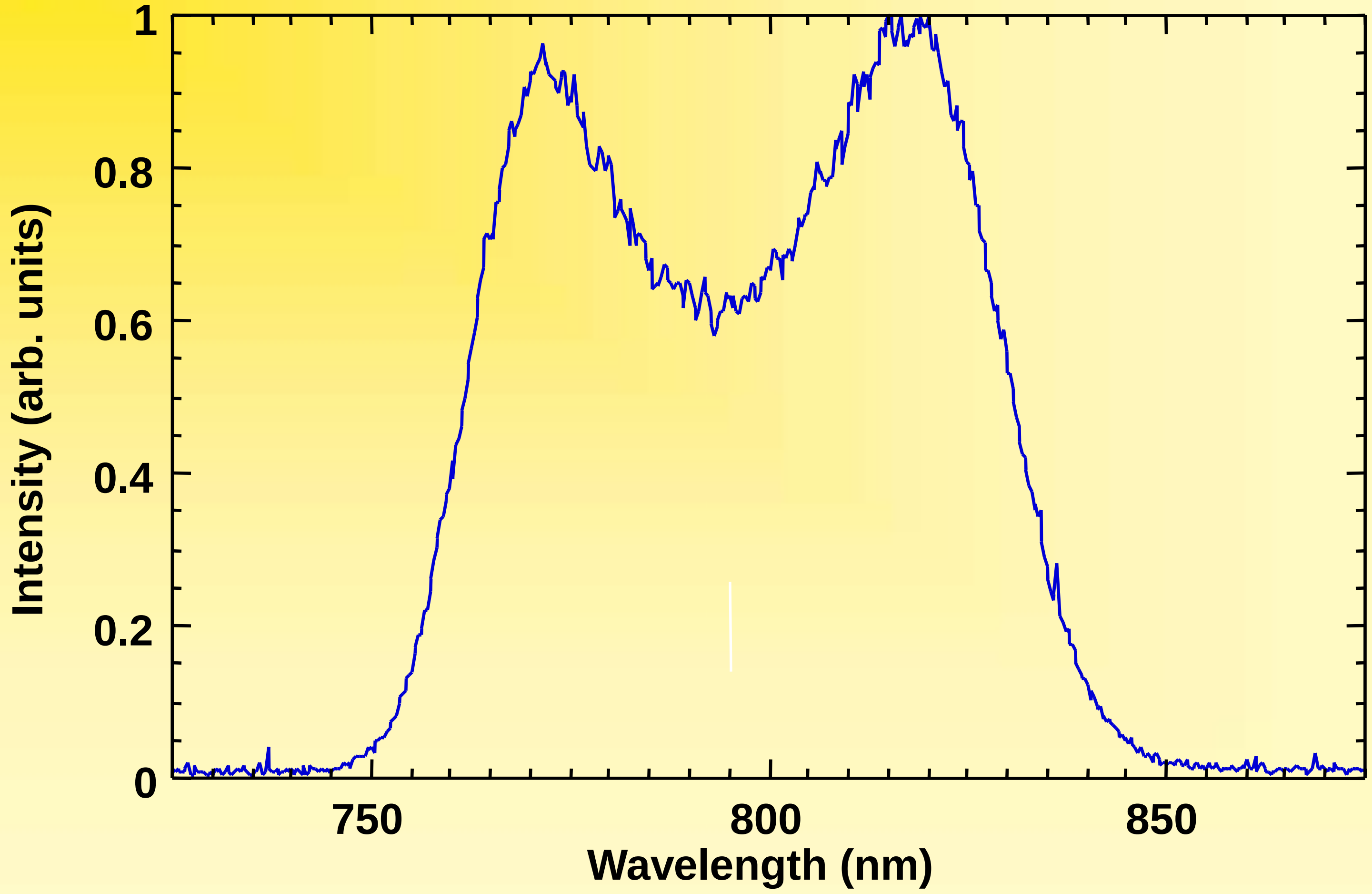
Gain-Narrowing Conclusion

Gain narrowing can be beaten.

We can use up to half of the gain bandwidth for a 4 level system.

Sub-20 fs in Ti:sapphire
Sub-200 fs in Nd:glass
Sub-100 fs in Yb:XX

Very broad spectra can be created this way.



A 100-nm bandwidth at 800 nm can support a 10-fs pulse.

Thermal Effects in Amplifiers

Heat deposition causes lensing and small-scale self-focusing. These thermal aberrations increase the beam size and reduce the available intensity.

$$I_{peak} = \frac{E}{A\,\delta T}$$

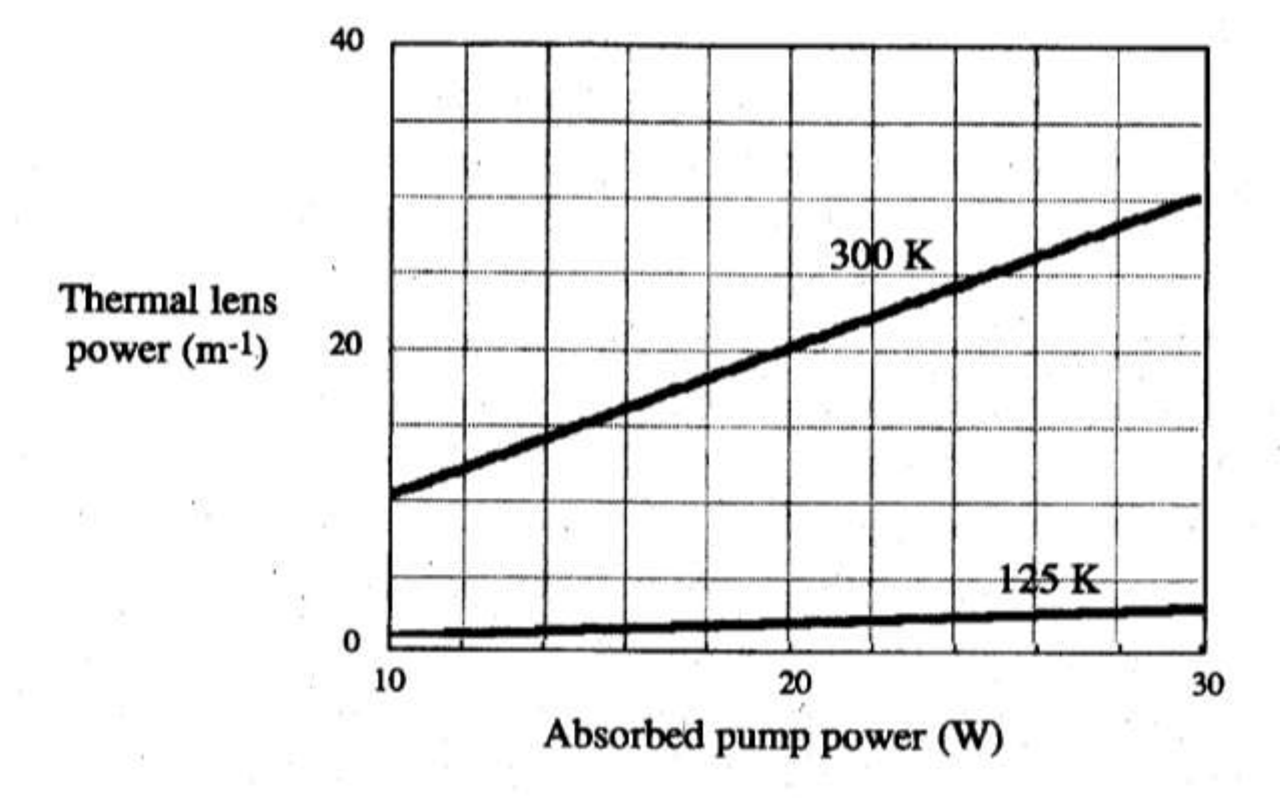
Beam area

We want a small focused spot size, but thermal aberrations increase the beam size, not to mention screwing it up, too.

Now the average power matters. The repetition rate is crucial, and we'd like it to be high, but high average power means more thermal aberrations...

Low temperature minimizes lensing.

In sapphire, conductivity increases and dn/dT decreases as T decreases.

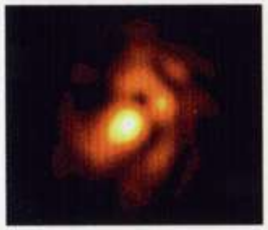


Calculations for kHz systems

Cryogenic cooling results in almost no focal power

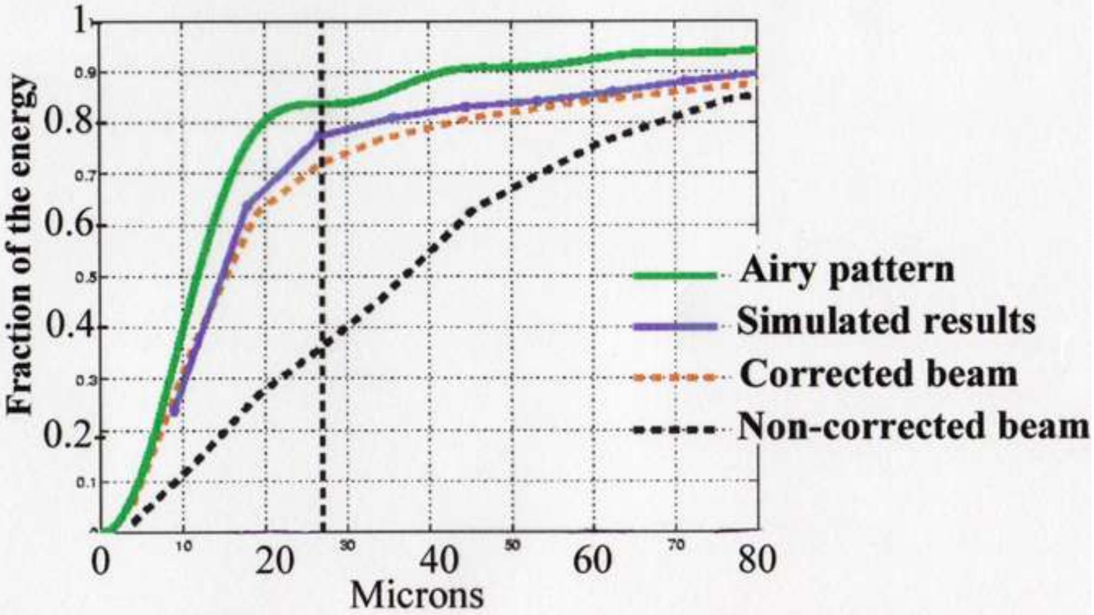
Murnane, Kapteyn, and coworkers

Static Wave-front Correction



Before correction
FWHM:39μm
1.4 times the diffraction limit

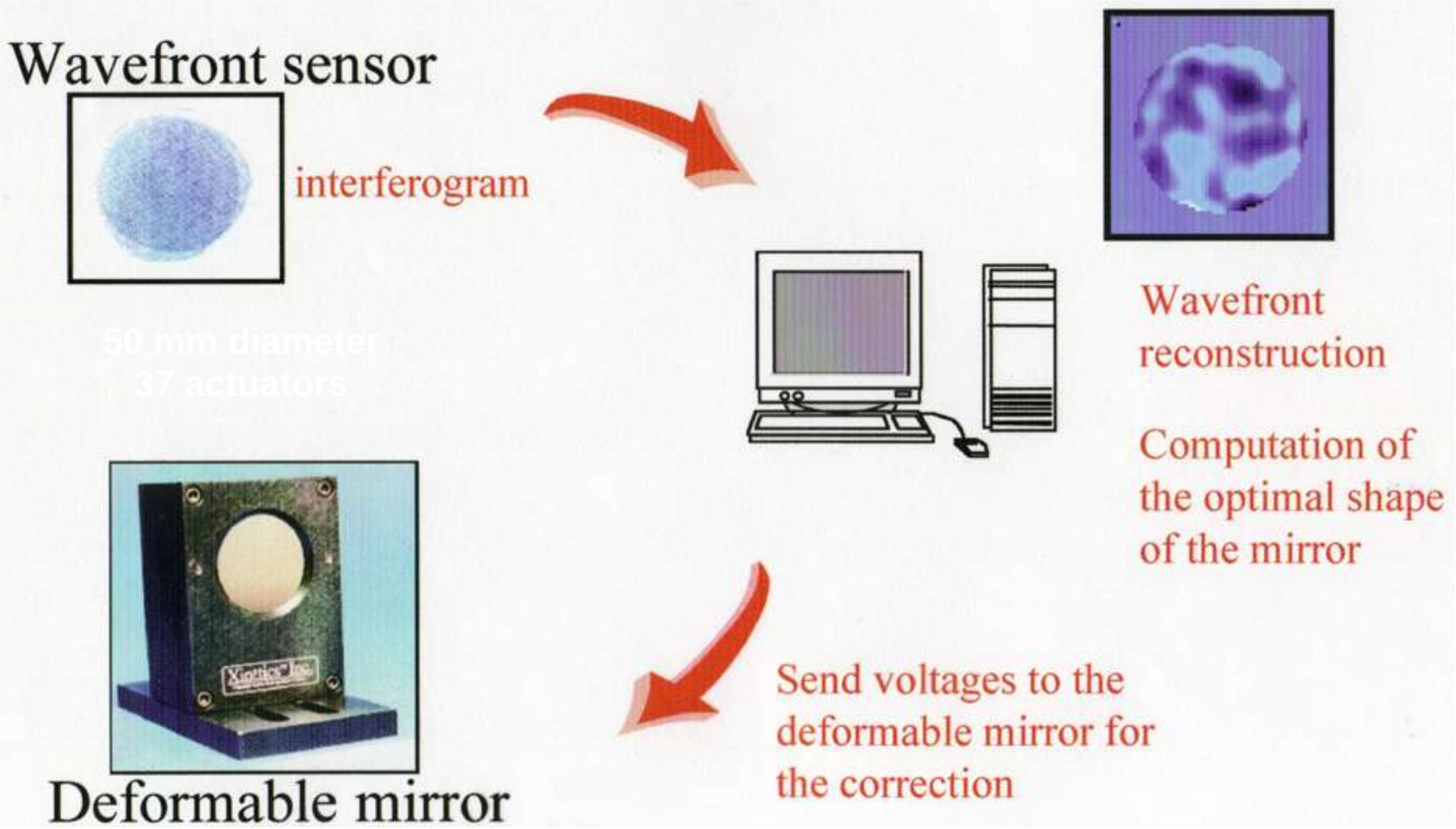
After correction
FWHM: 27μm
diffraction limited



With the correction, the energy inside the diffraction limited spot size is multiplied by 2.1 (results taken at low energy). The simulation allows us to predict our energy distribution at high energy.

2.5 times improvement in peak intensity has been achieved

Dynamic Correction of Spatial Distortion



Wavefront sensor

interferogram

50 mm diameter
37 actuators

Wavefront reconstruction

Computation of the optimal shape of the mirror

Send voltages to the deformable mirror for the correction

Deformable mirror

Contrast ratio

The pulse has leading and following satellite pulses wreak havoc in any experiment.

If a pulse of 10^{18} W/cm^2 peak power has a “little” satellite pulse one millionth as strong, that’s still 1 TW/cm^2! This can do some serious damage!

This is one of the main problem with the fussion reaction ignition by laser pulses – the pre-pulses create plasma that acts like a mirror.

Ionization occurs at 10^{11} W/cm^2

so at 10^{21} W/cm^2 we need a 10^{10} contrast ratio!

Major sources of poor contrast

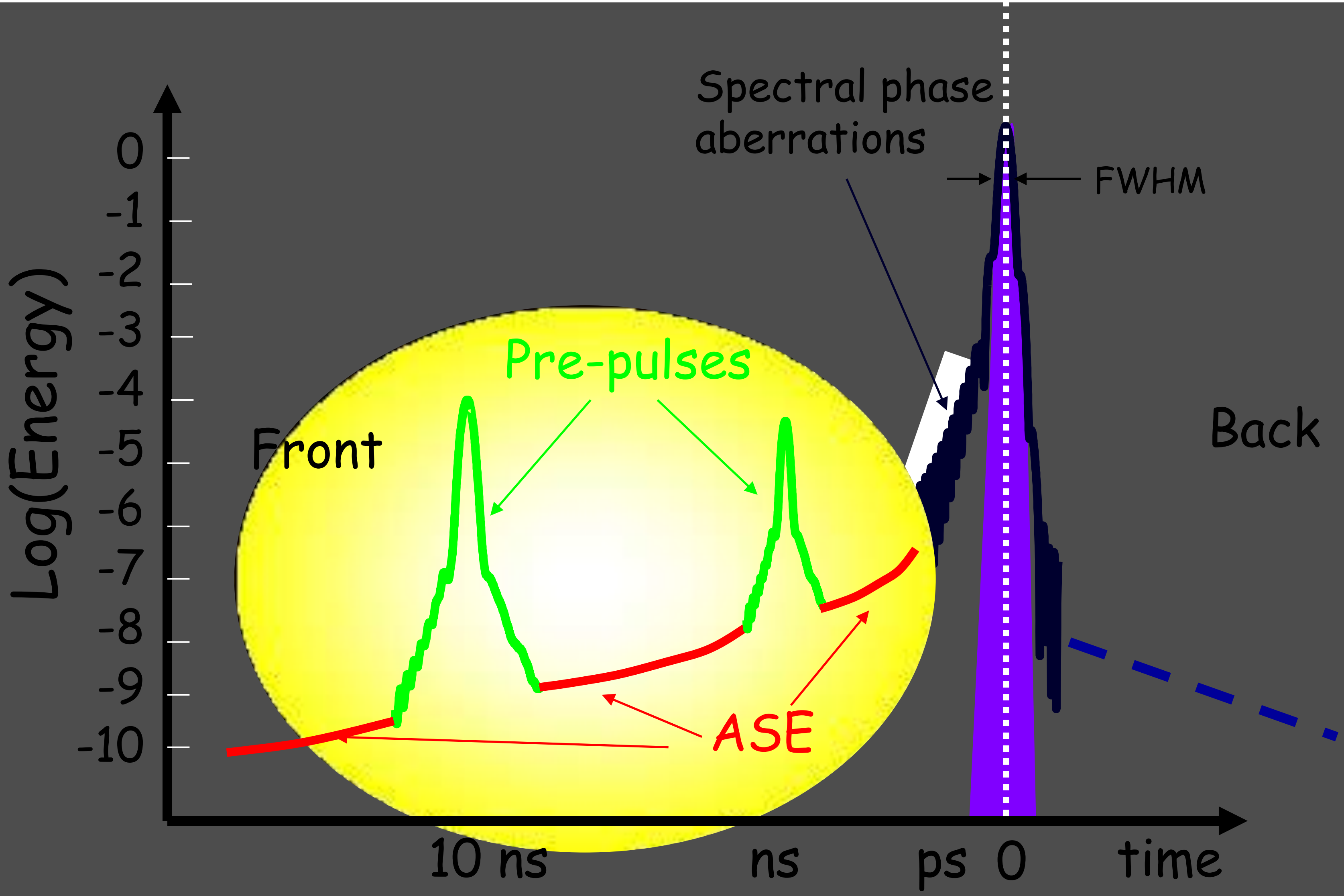
Nanosecond scale:

- pre-pulses from oscillator
- pre-pulses from amplifier
- ASE from amplifier

Picosecond scale:

- reflections in the amplifier
- spectral phase or amplitude distortions

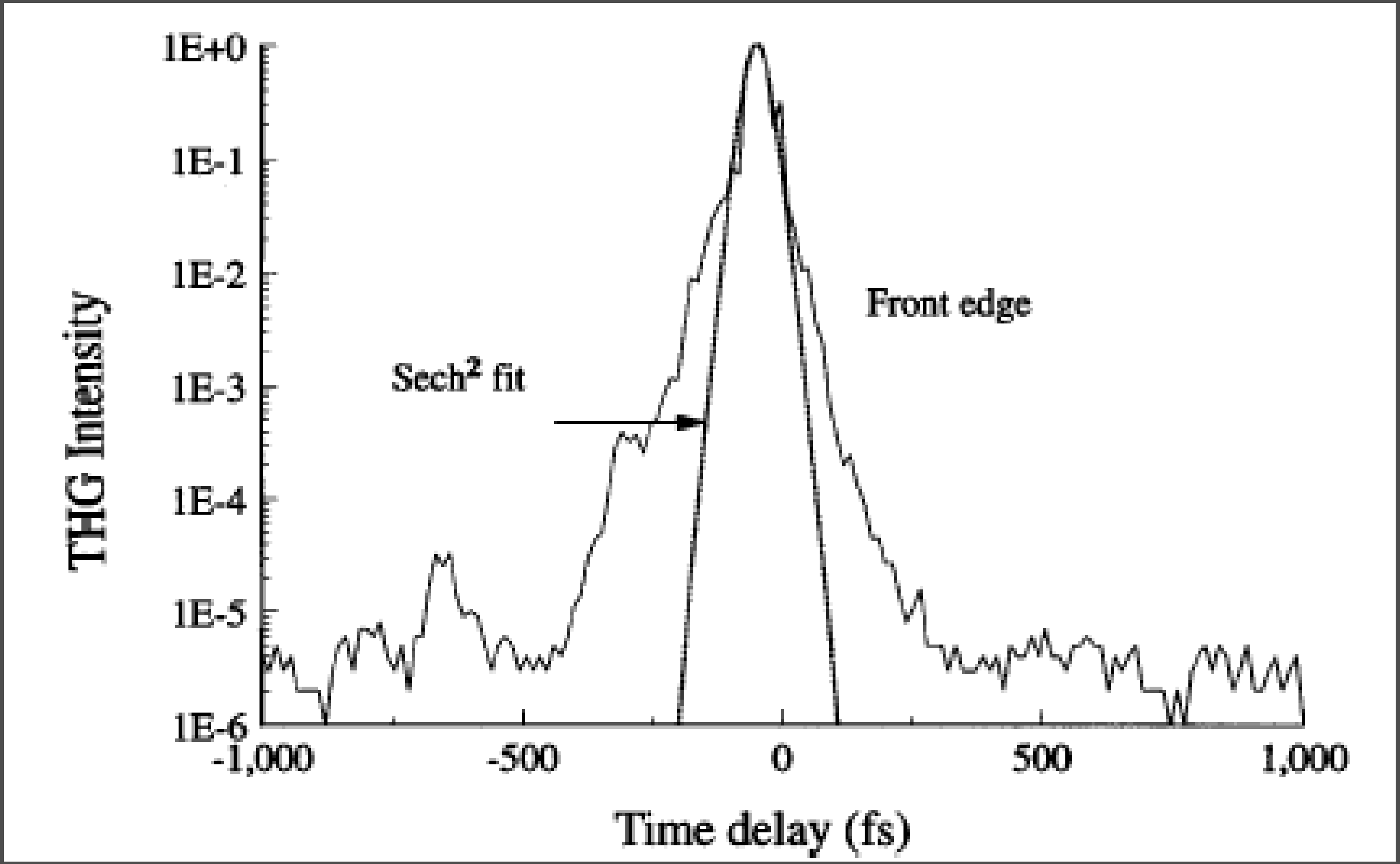
Amplified pulses often have poor contrast.



Pre-pulses do the most damage, messing up a medium beforehand.

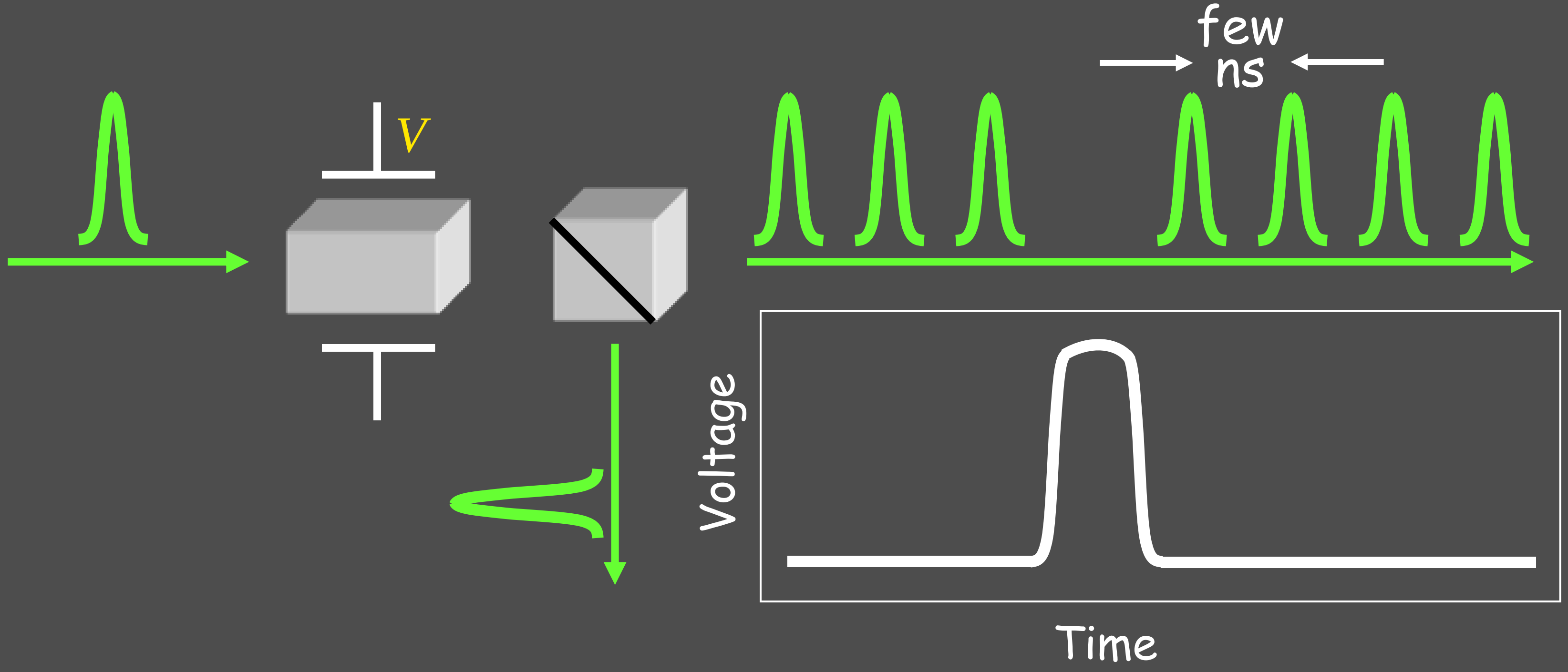
Amplified pulses have pre- and post-pulses.

Typical 3rd order autocorrelation



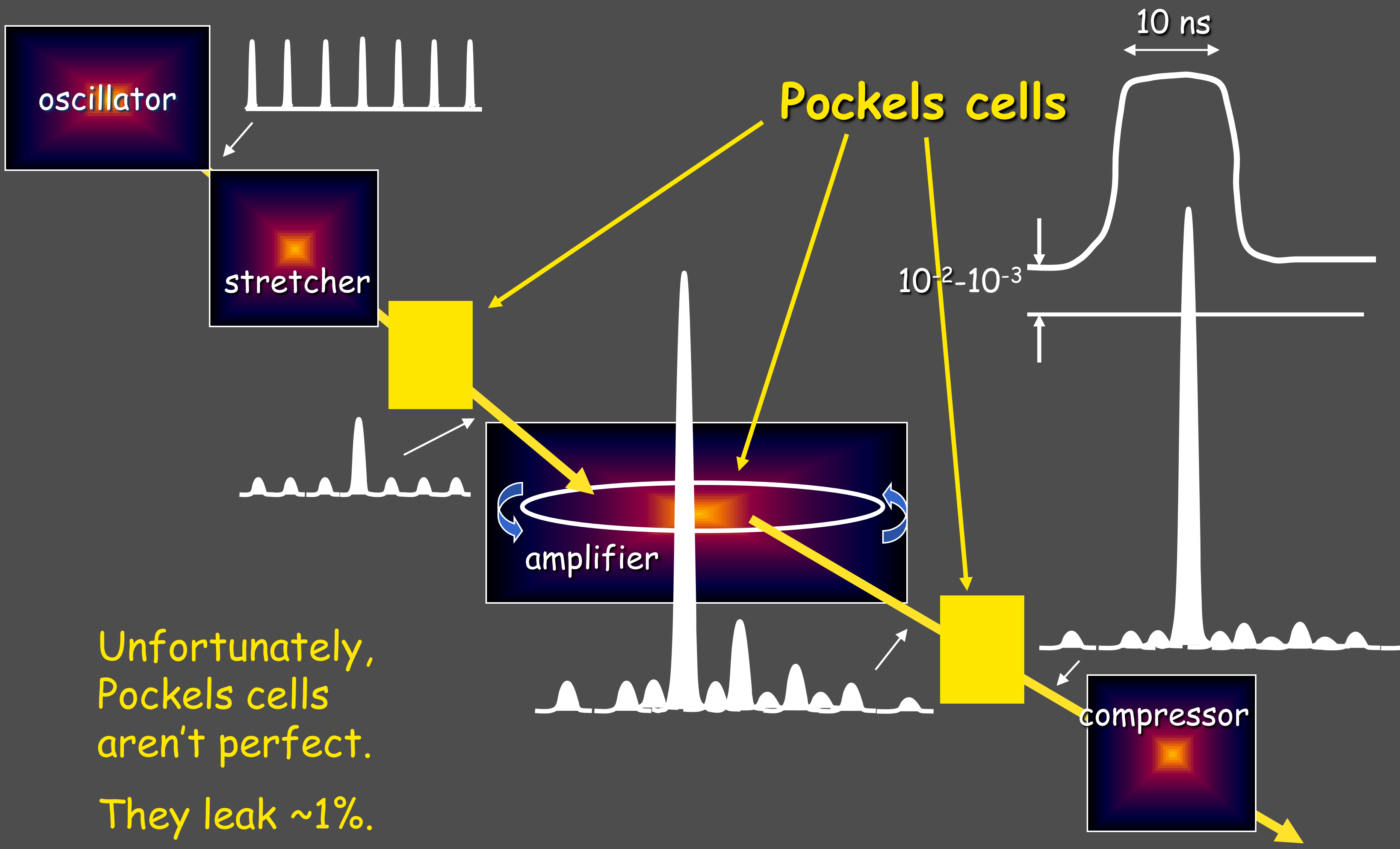
A Pockels cell "Pulse Picker"

A Pockels cell can pick a pulse from a train and suppress satellites. To do so, we must switch the voltage from 0 to kV and back to 0, typically in a few ns.



Switching high voltage twice in a few ns is quite difficult, requiring avalanche transistors, microwave triodes, or other high-speed electronics.

Pockels cells suppress pre- and post-pulses.



Unfortunately, Pockels cells aren't perfect.

They leak ~1%.

Contrast improvement recipes

A Pockels cell improves the contrast by a few 100 to 1000.

We need at least 3 Pockels cells working in the best conditions:

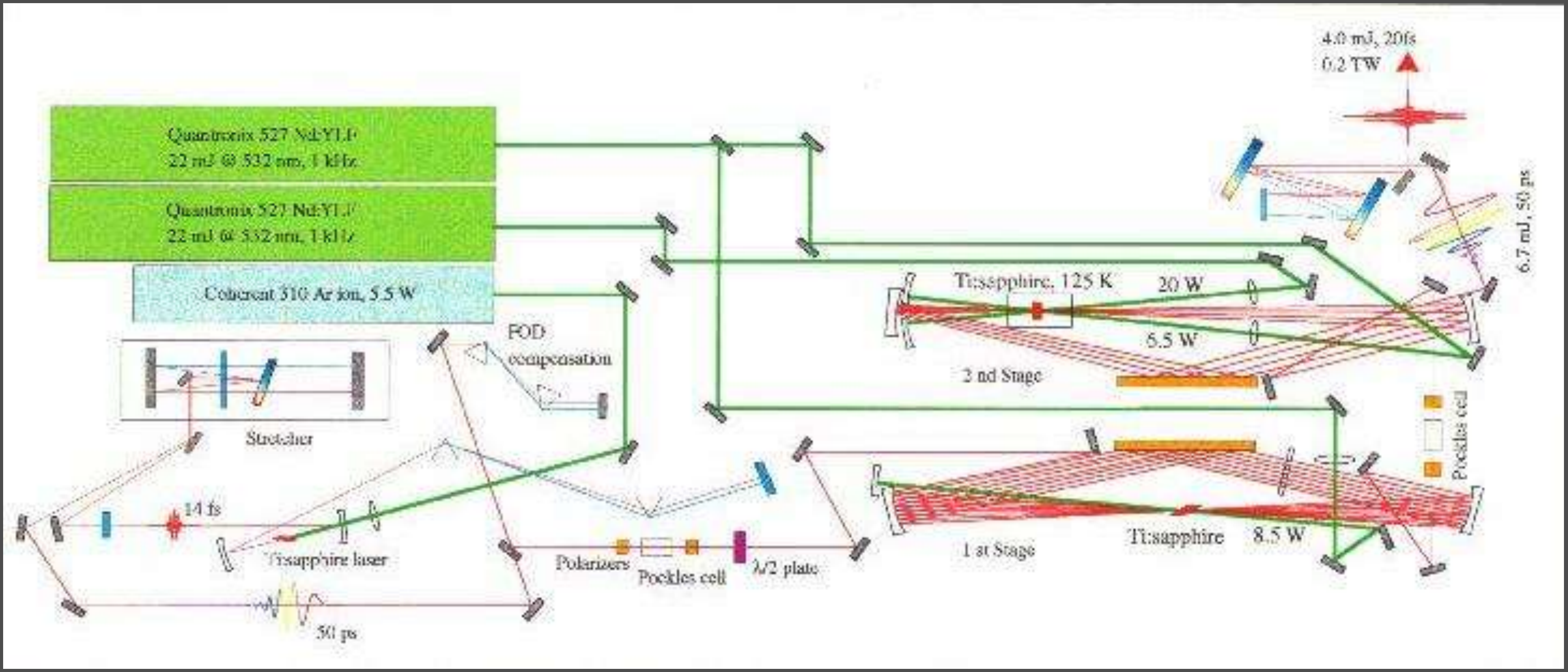
- on axis (do not tilt a Pockels cells)
- broadband high-contrast polarizers (not dielectric)
- fast rise time (<<2 ns 10-90%)
- collimated beams

Temperature drift is also a problem in Pockels cells.

Multiple-stage multi-pass amplifiers

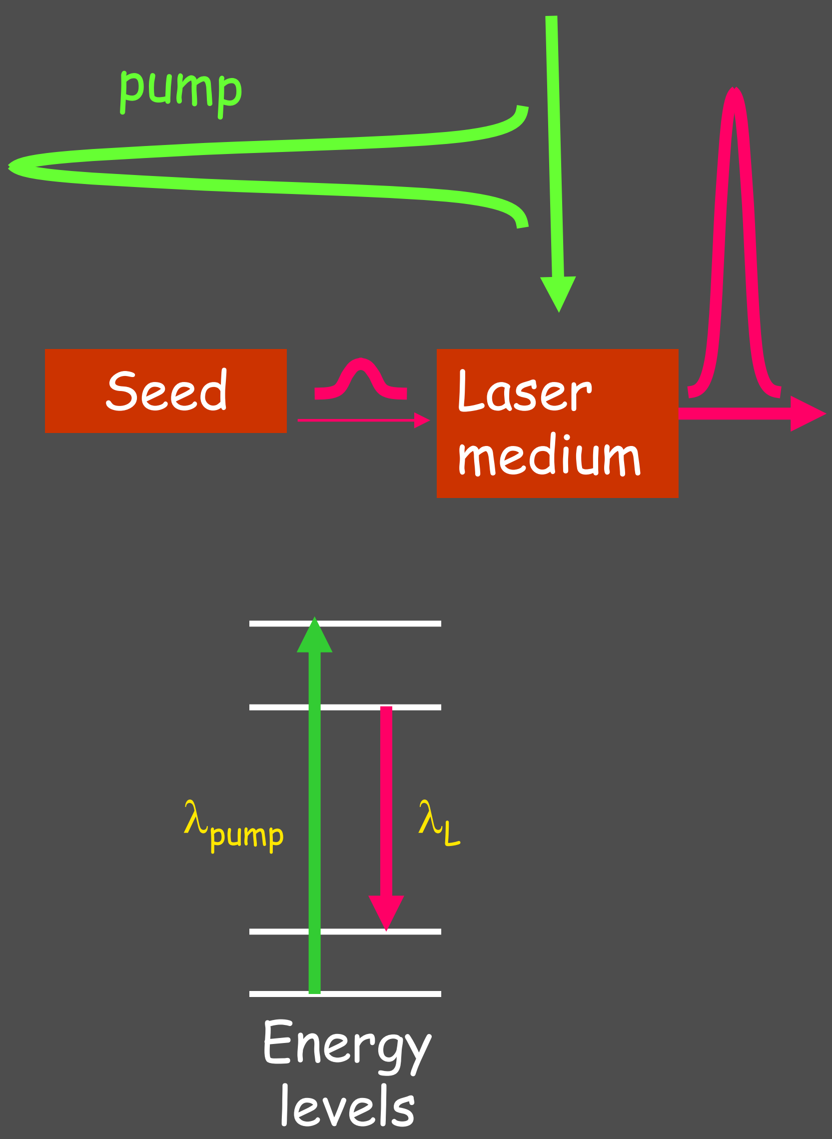
4 mJ, 20 fs pulse length

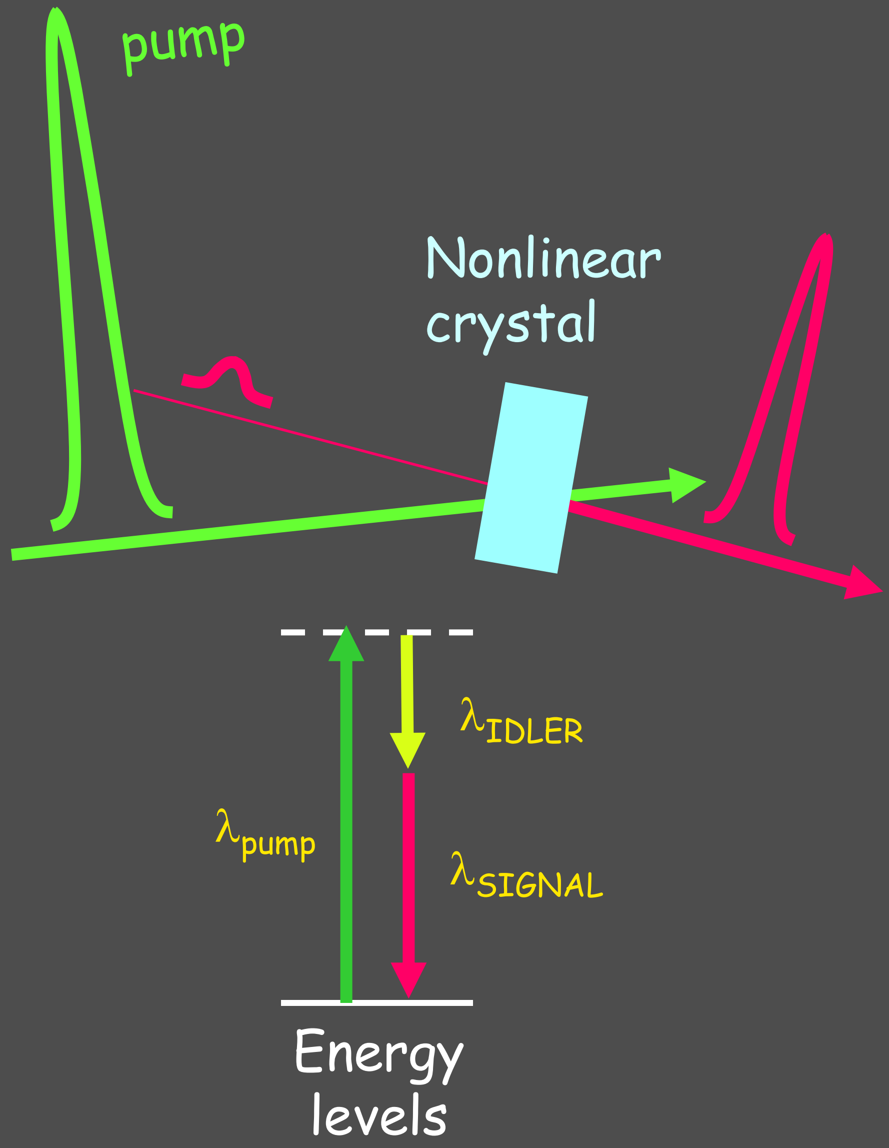
0.2 TW



1 kHz Multi-pass system at the
University of Colorado (Murnane and Kapteyn)

Laser vs. Parametric Amplification



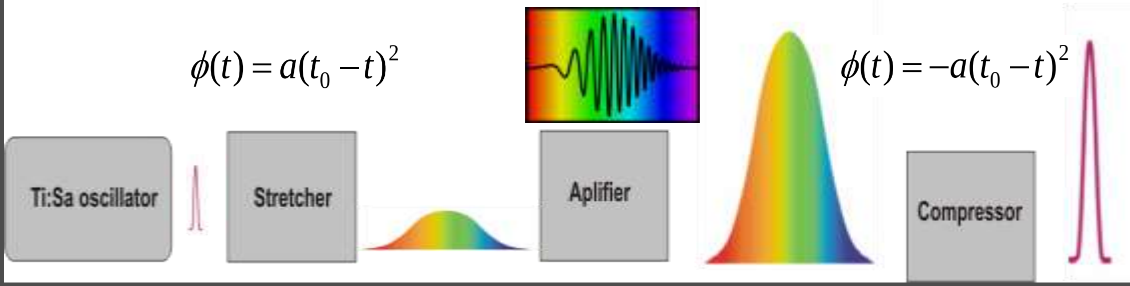


OPCPA amplifiers - advantages

OPCPA*

Optical **P**arametric **C**hirped **P**ulse **A**mplification

CPA** – chirped pulse amplification



Advantages of OPCPA comparing to standard laser amplifier

- Broadband amplification range (>250nm for BBO with 532nm pump laser)
- High single pass amplification, easily $>10^2$
- Low level of amplified parametric fluorescence
- No thermal effects, since no energy storage in nonlinear crystal
- High energies possibile

But:

- Energy conversion efficiency highly sensitive to temporal overlap between seed and pump pulse

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[*] A. Dubietis, G. Jonusauskas and A. Piskarskas, "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal," Opt. Commun. **88**, 437-440 (1992)

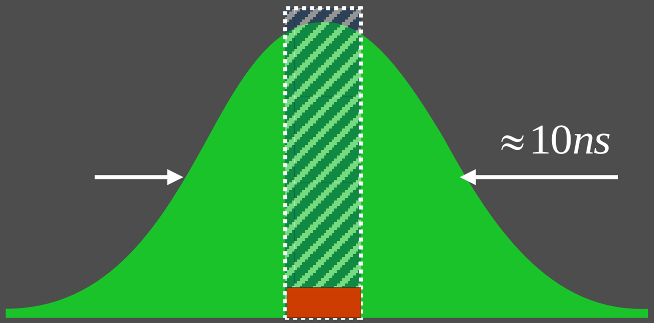
[**] D. Strickland, G. Mourou, Compression of amplified chirped optical pulses, Opt. Commun. **56**, 219 (1985)

Methods for highly efficient energy transfer in OPCPA

Typical commercial available Nd:YAG laser $\tau_{pump} \approx 5\text{–}10$ ns

With broadband pulse stretchers $\tau_{seed} \approx 0.5\text{-}2$ ns

Low overall energy transfer efficiency!



Possible solutions:

- ps pump lasers with ps seed pulses
- Narrow band stretchers with τ_{seed} >2 ns
- Large stretching factor stretchers, or double pass stretchers >2ns
- Hybrid setups

But:

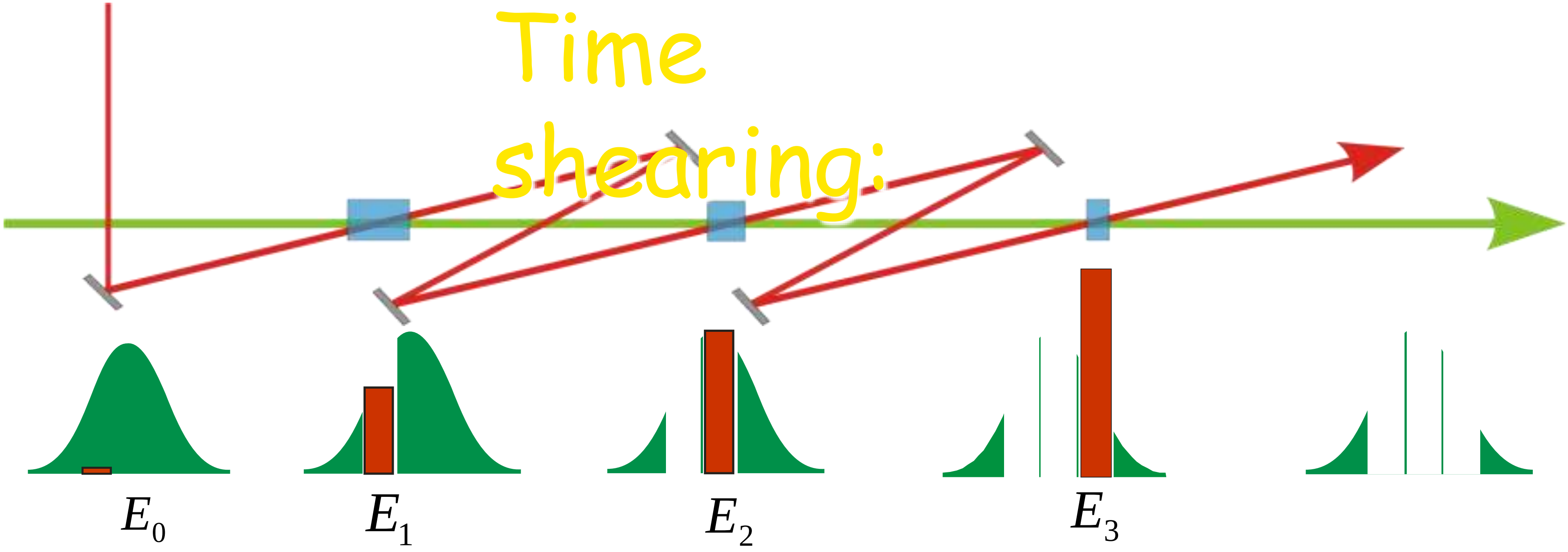
- Sophisticated time synchronization requirement,
custom design pump lasers
- <10nm bandwidth, thus amplified pulses >100fs
- Complicated stretcher, large gratings in compressor
- Gain narrowing, beam deterioration without cryo cooling

Power amplifier – time shearing concept
Energy extraction efficiency improvement

$$\tau_{in} = 20\,fs$$
$$\tau_{out} = 1ns$$

Stretching factor of 50k

Pump pulse 8ns FWHM



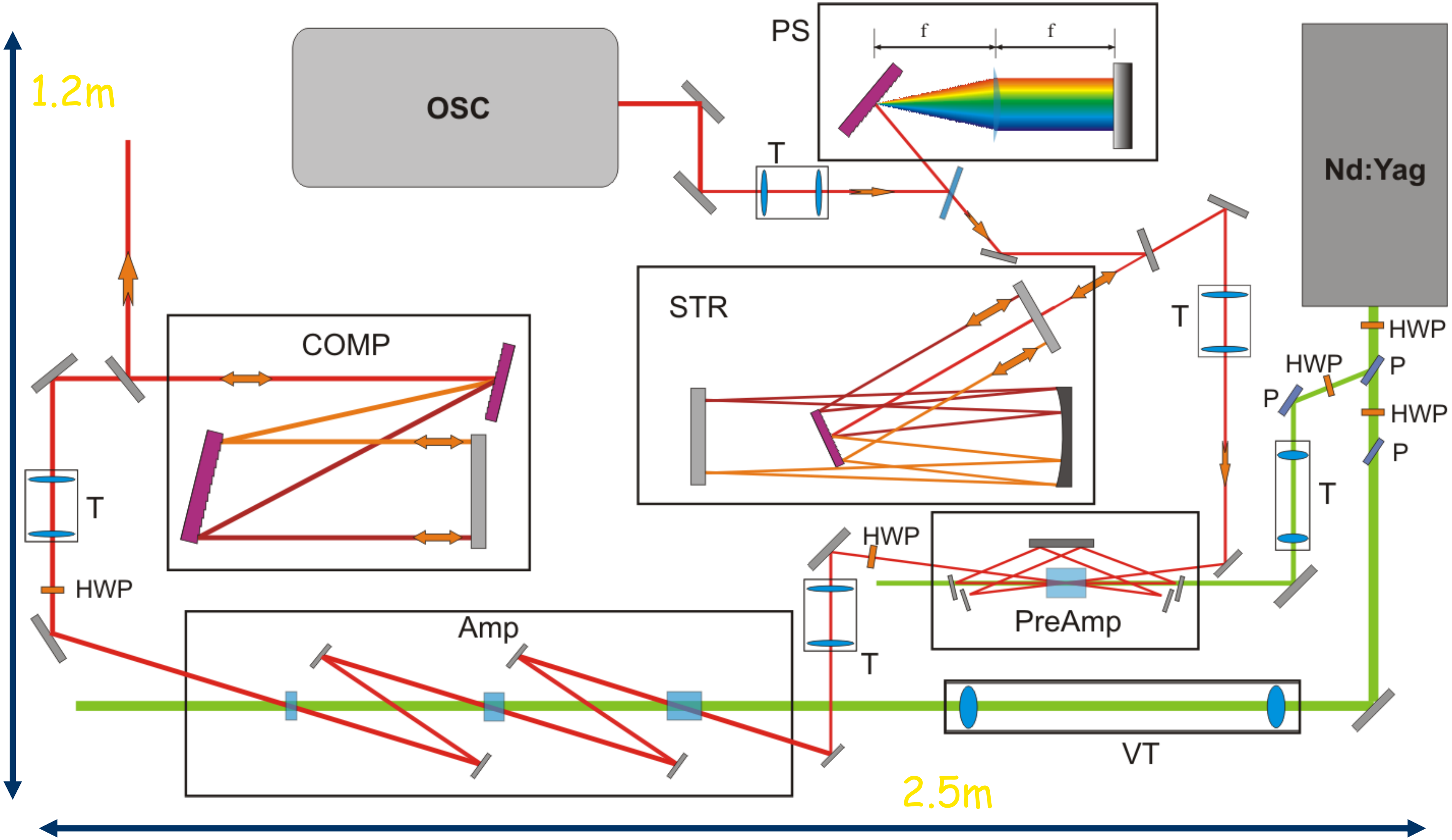
Time shearing:

Time shearing technique advantages:

- Seed pulse interacts each time with undepleted part of the pump pulse
- Each crystal work in a fully saturated regime – energy self stabilization
- Easily adopted in a OPCPA systems with ns pump laser

T. Harimoto and K.Yamakawa, "Numerical analysis of optical parametric chirped pulse amplification with time delay," Opt. Express **11**, 939-943 (2003)

OPCPA experimental setup



Two-stage, TTT-class system at the
Institute of Phys. Chemistry, Warsaw, Poland (Wnuk, Radzewicz)

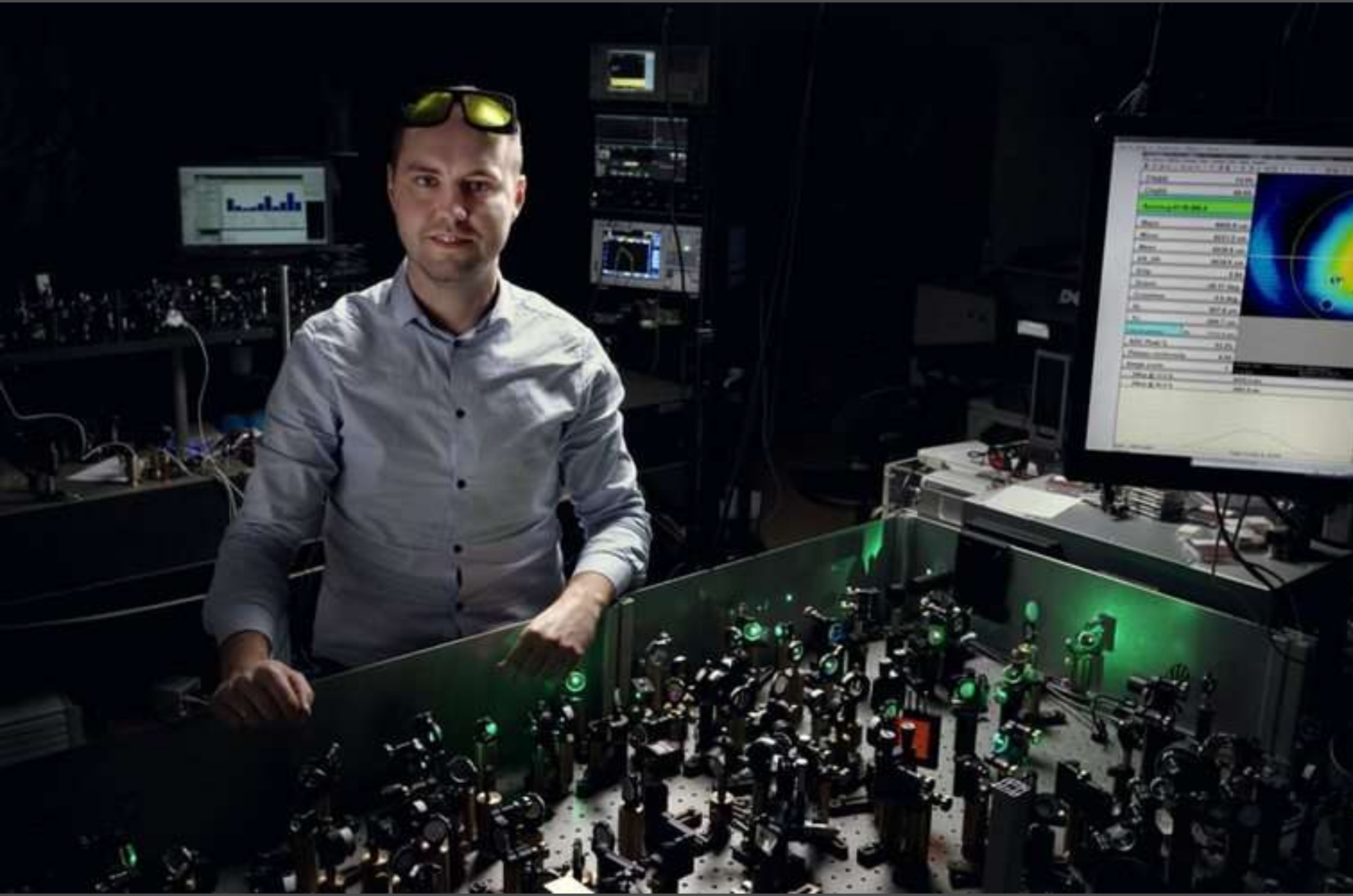
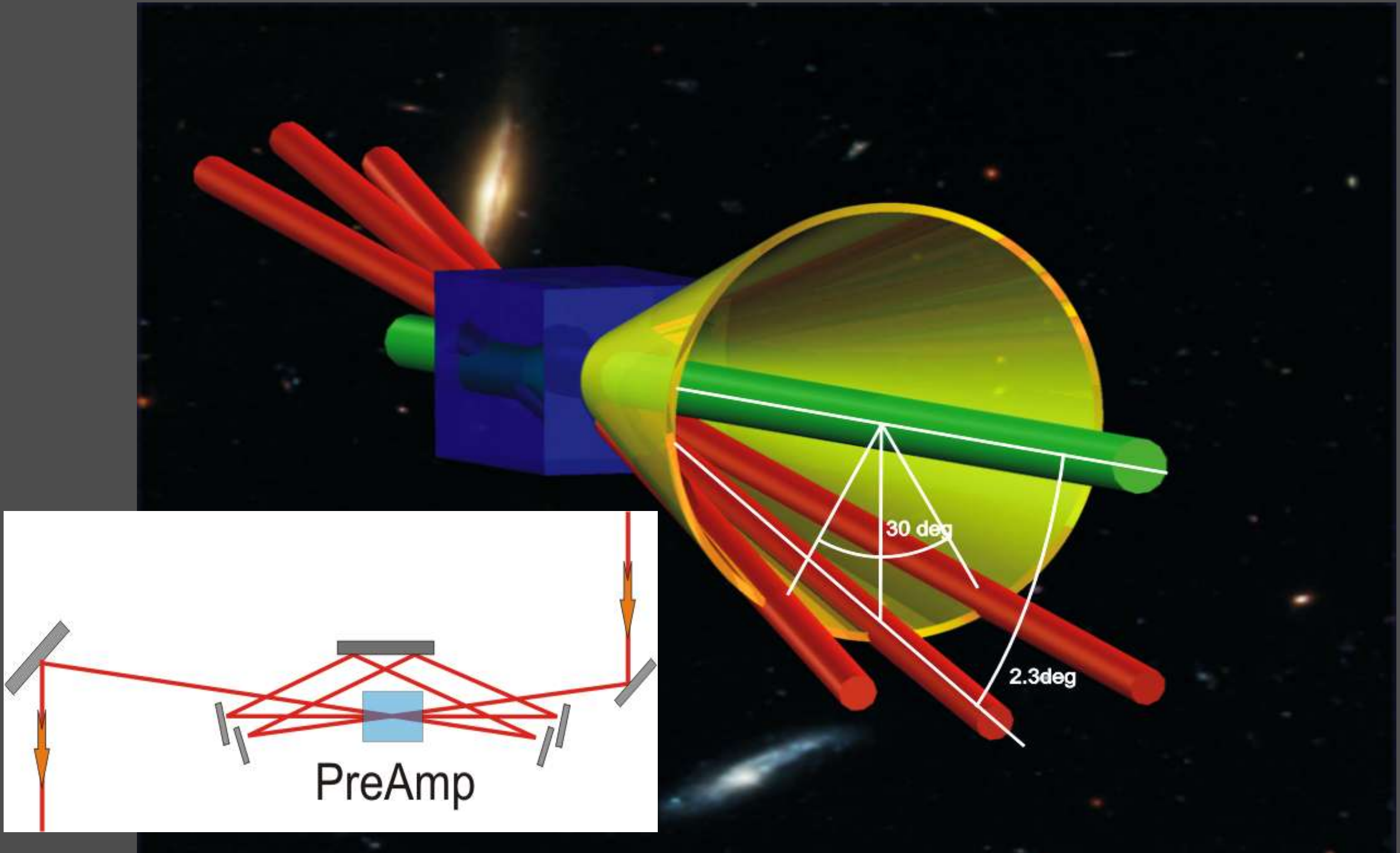


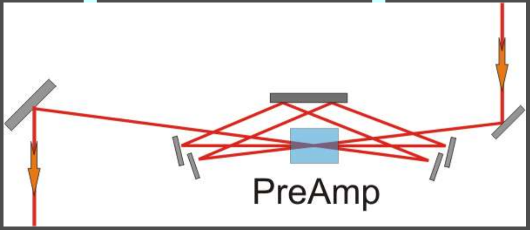
Foto: Bernard Pielach

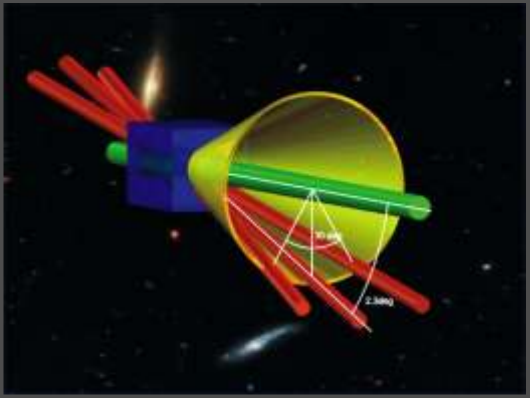
Multipass preamplifier
Single crystal - 3 pass configuration



Yuriy Stepanenko and Czesław Radzewicz, "High-gain multipass noncollinear opticalp parametric chirped pulse amplifier," Appl. Phys. Lett. **86**, 211120 (2005)

High gain multipass preamplifier

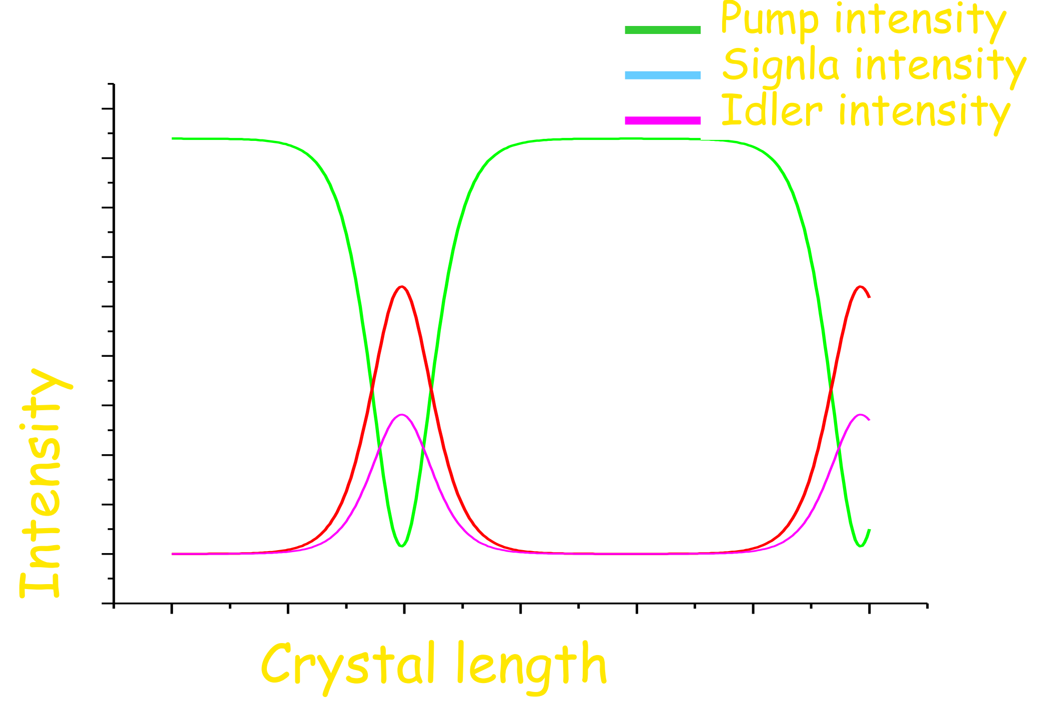




Preamplifier:

- 3 passes through BBO crystal
- High gain for single pass
- Low efficiency for this stage

Pump depletion and energy backconversion



Selection of proper parameters (crystal length, pump and seed beam intensities) is essential for OPCPA

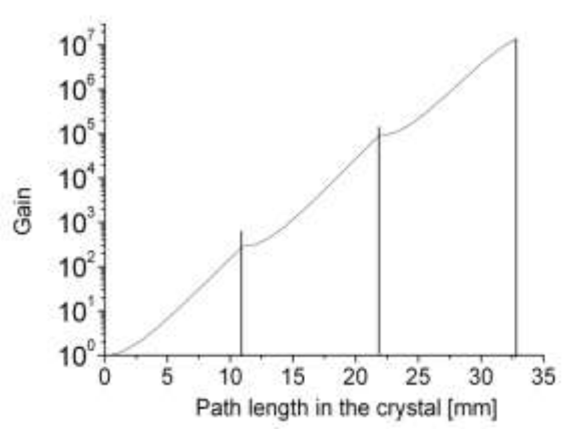
Numerical 2.5D simulation – preamplifier parameters determination

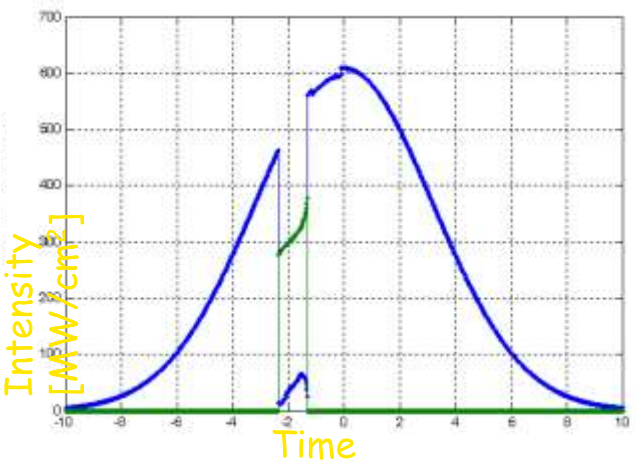
The simulation takes into account:

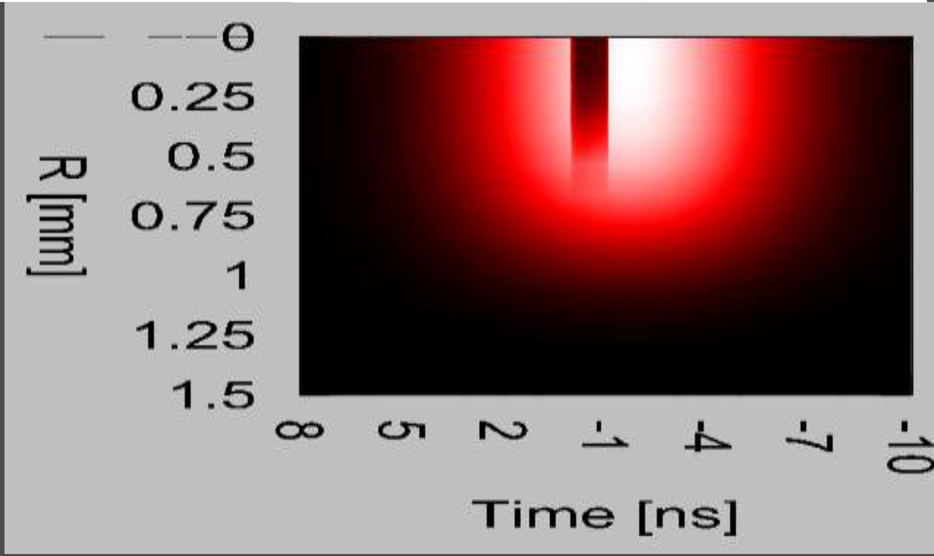
- Spatial beams distribution
- Pump and seed pulse temporal profiles
- Seed pulse stretching (chirp)
- Pump energy depletion
- Cylindrical symmetry assumed ->2.5D

Preamplifier parameters:

- BBO crystal: L=11mm, 3 passes
- Pump energy: 95 mJ
- Signal energy :
  - E_{in} = 180 pJ
  - E_{out} = 1.5 mJ
- Single pass gain of 260

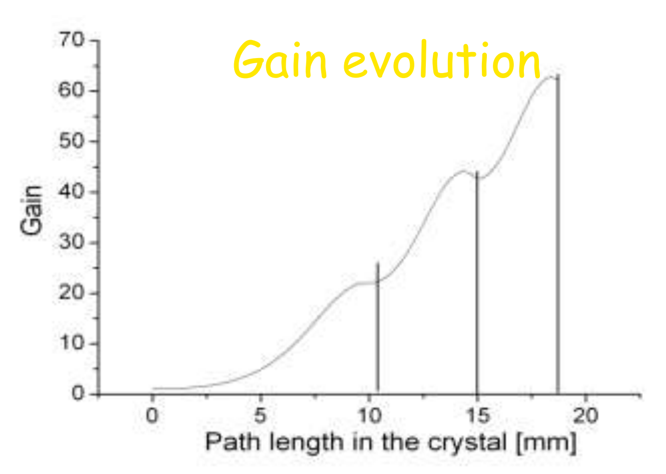




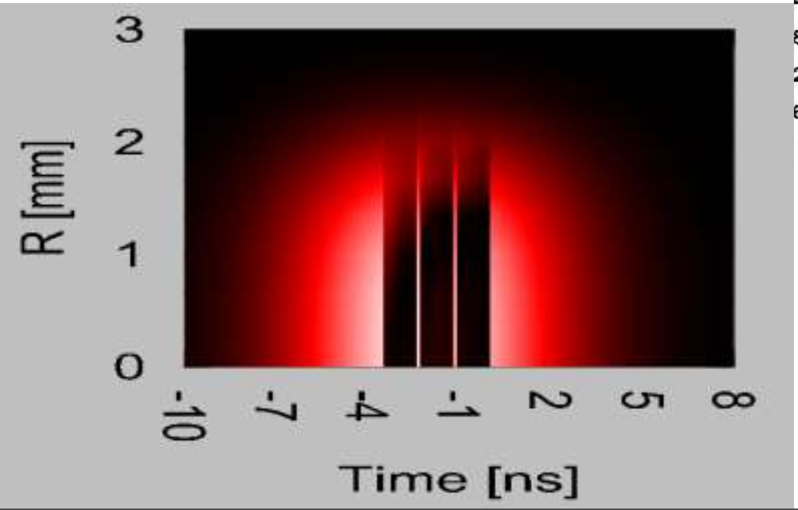


Spatial profile - evolution

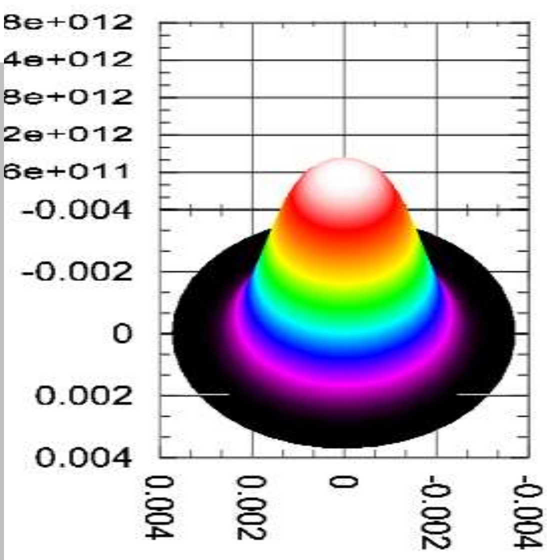
Power stage in time shearing configuration – simulations



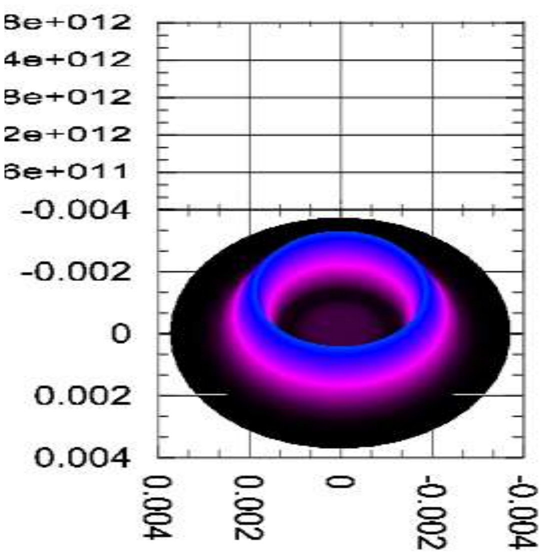
Power amplifier parameters
- Three BBO crystals: L_1=10mm, L_2=5mm, L_3=3.8mm
- Pump energy = 430 mJ
- Pump intensity = 460MW/cm^2
- Seed energy = 1.5mJ



Spatial profile evolution



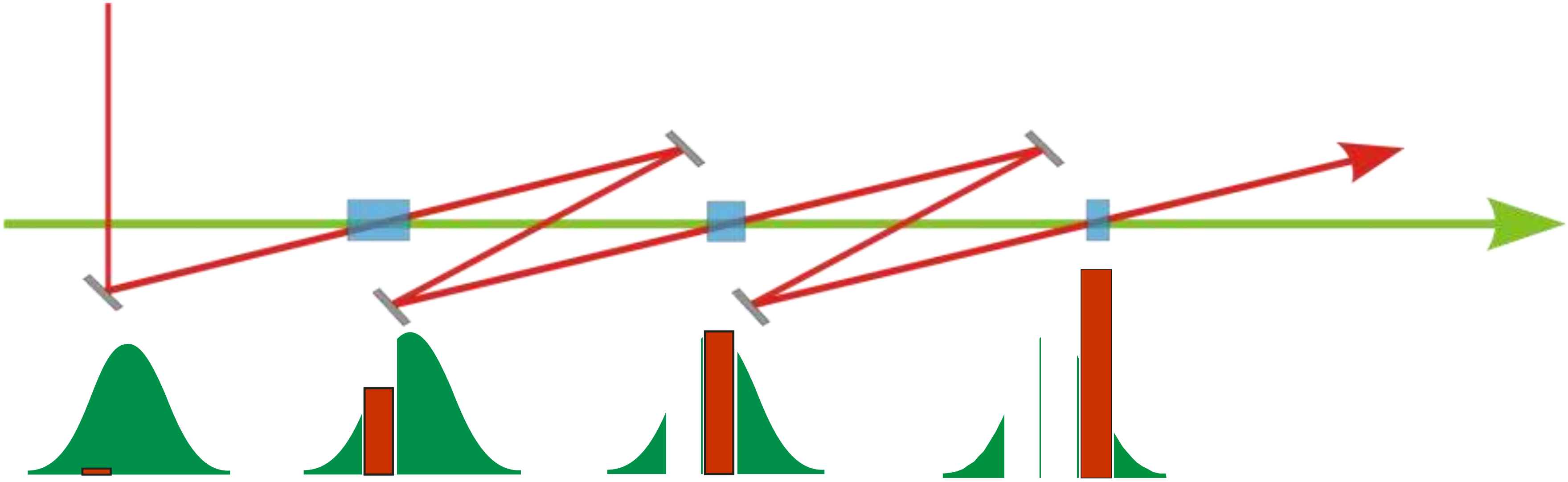
No seed beam



With seed beam

Power amplification results:

Time shearing concept



$E_0 = 1.5mJ$ $E_1 = 24mJ$ $E_2 = 46mJ$ $E_3 = 66mJ$

$$\frac{E_3}{E_1} \approx 3$$

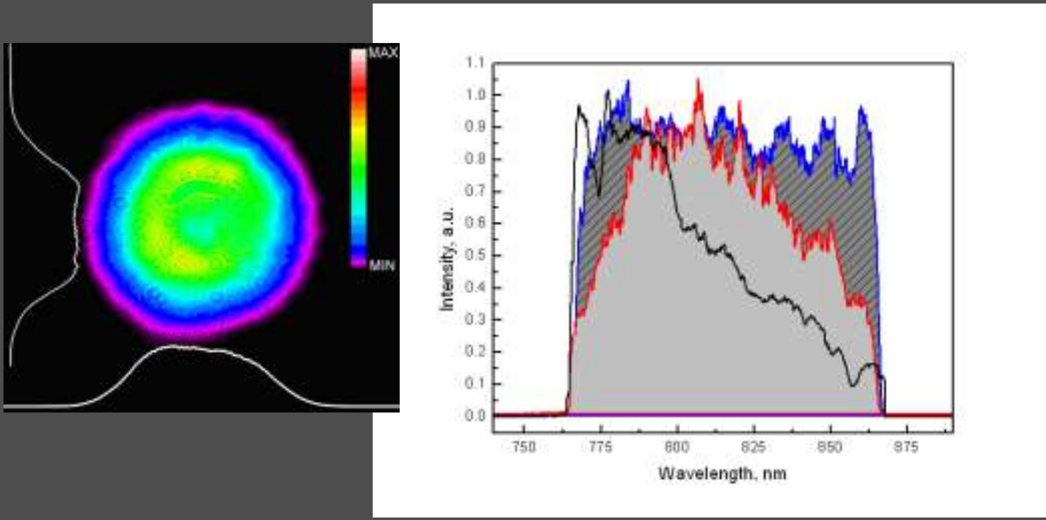
Three times higher conversion efficiency comparing to single crystal configuration

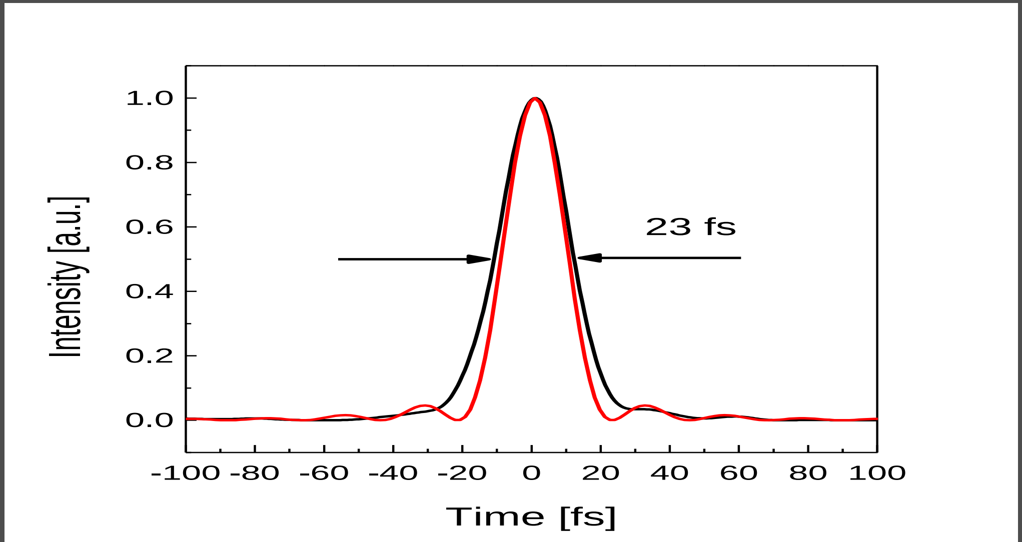
OPCPA experimental parameters

Pulse duration FWHM: 23 fs
Compressed pulse energy: 49 mJ
Overall gain: 36M
Stability: 2% RMS
Repetition rate: 10Hz
Pulse contrast: 10^{-8}
Overall efficiency: 10%

Peak power: 2 TW

The largest Polish power plant (Bełchatów): 5 GW





What to do with such high intensities