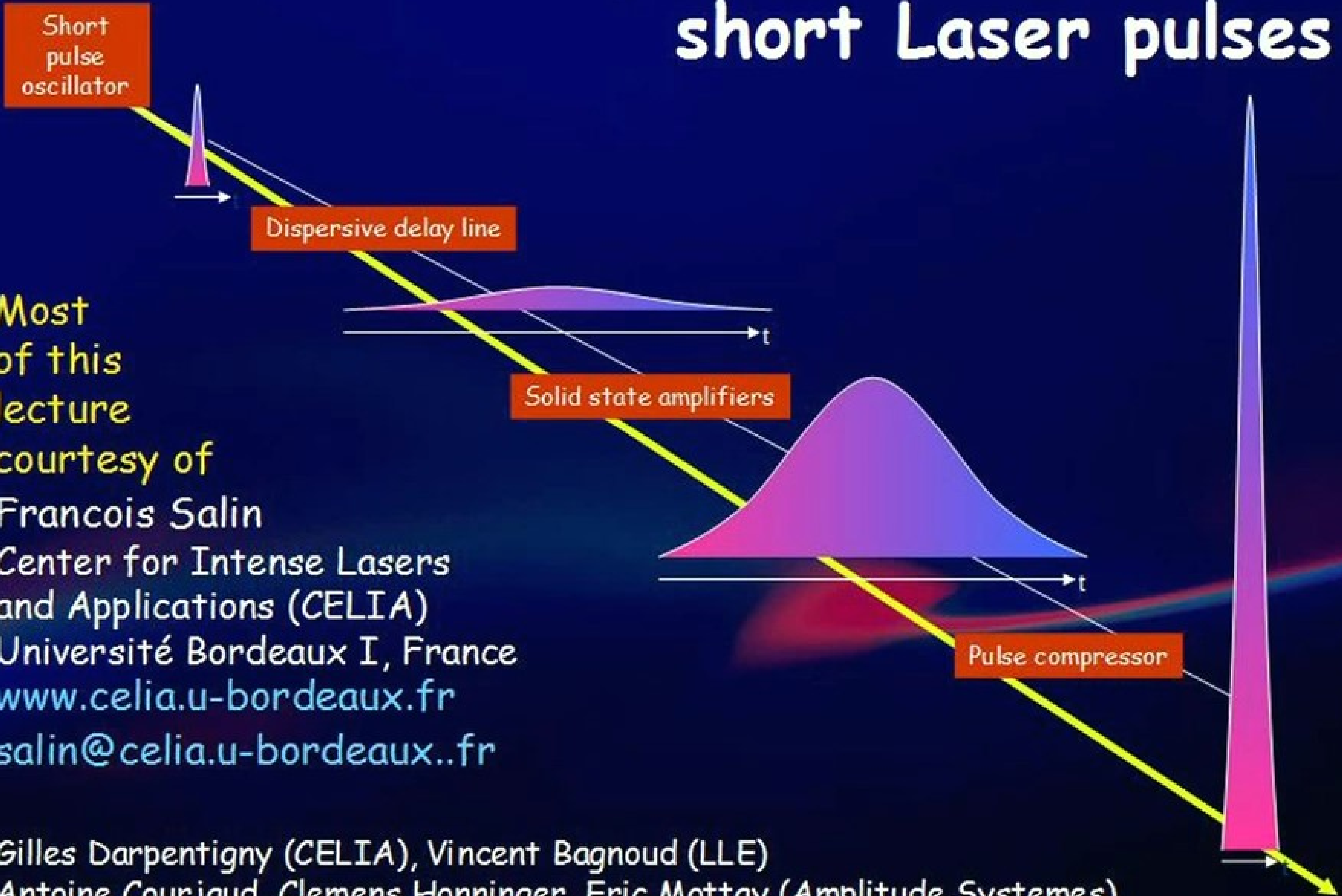
The Amplification of Ultra-short Laser pulses



Most of this lecture courtesy of

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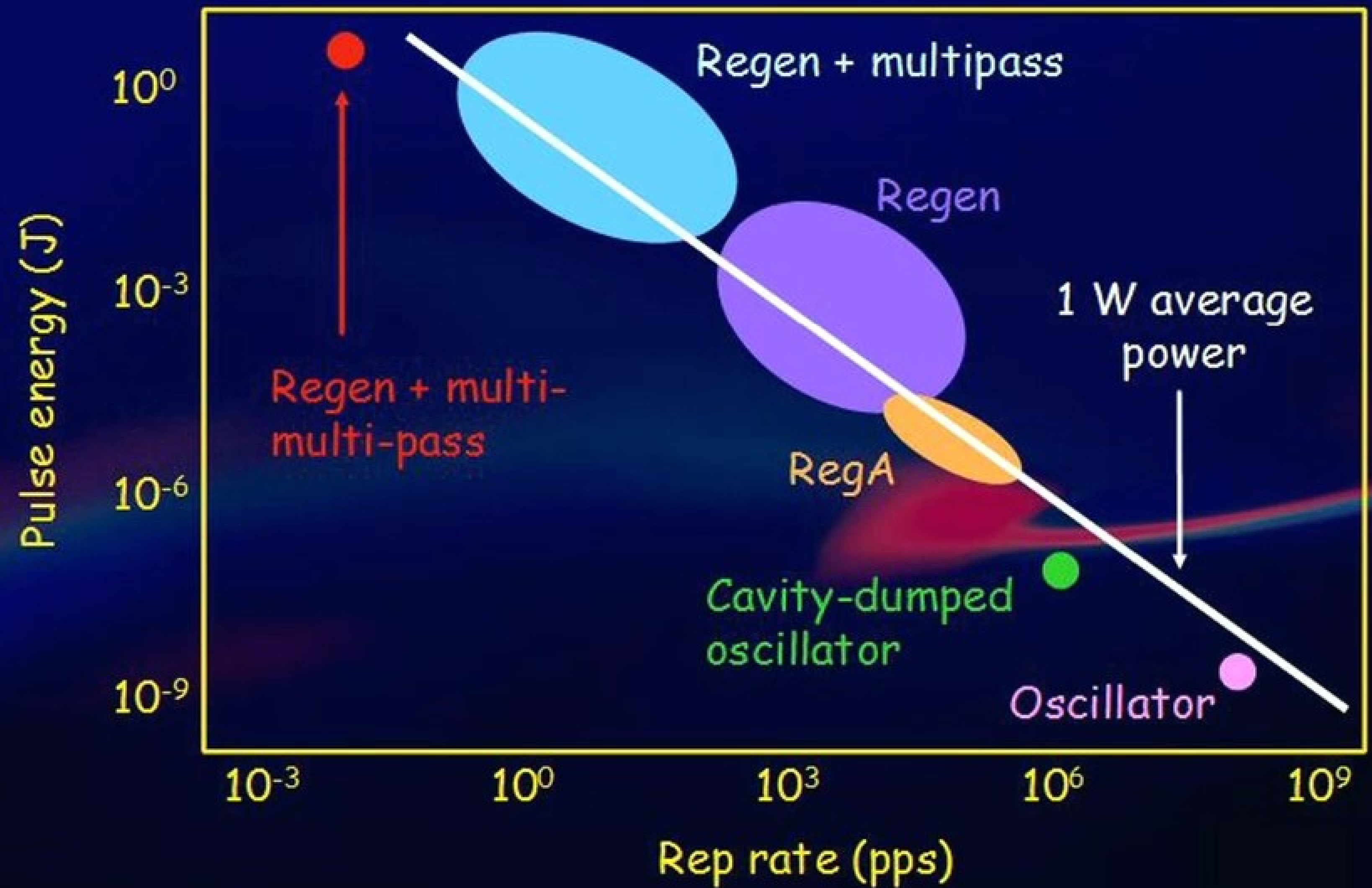
Luc Vigroux (Amplitude Technologies) and some additional stuff from Dan Mittleman, Rice

Pulse energy vs. Repetition rate



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

Issues in Ultrafast Amplification and Their Solutions

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

Damage: Chirped-Pulse Amplification (CPA)

Gain saturation: Frantz-Nodvick Equation

Gain narrowing: Birefringent filters

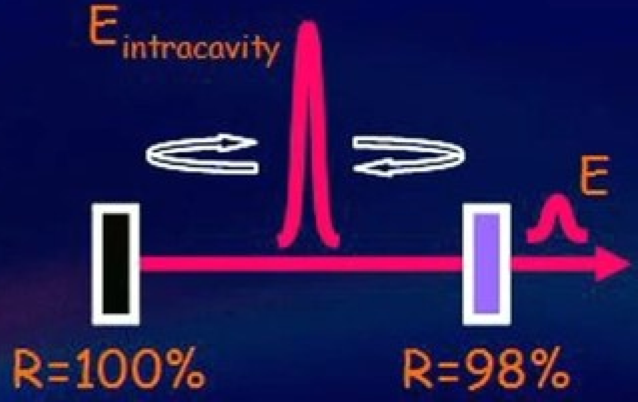
Thermal effects: cold and wavefront correction

Satellite pulses, Contrast, and Amplified Spontaneous Emission: Pockels' cells

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?



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

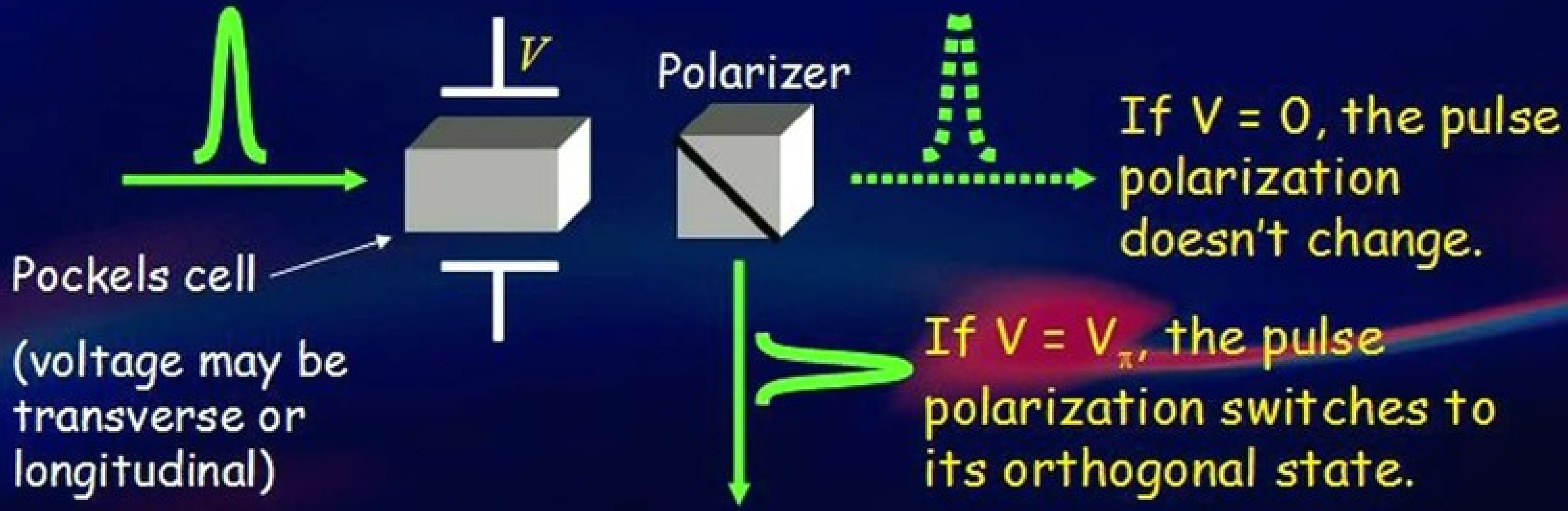
Transmission of output coupler: ~2%

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.

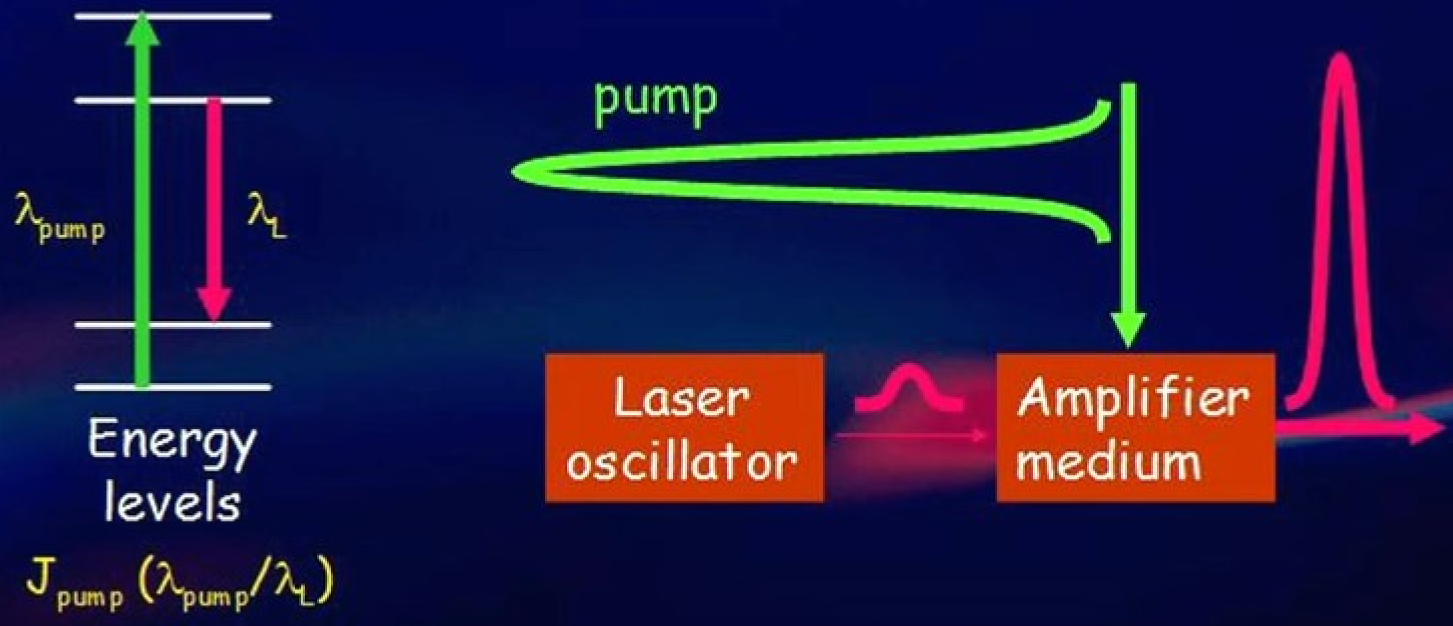
A voltage (a few kV) can turn a crystal into a half- or quarter-wave plate.



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).

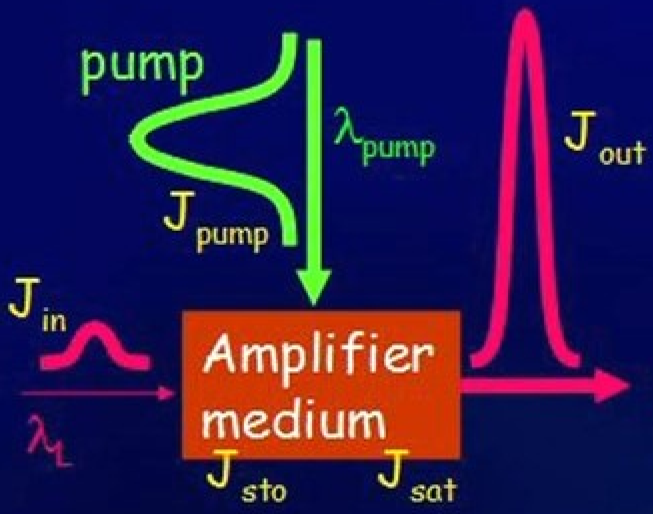
Amplification of Laser Pulses, in General

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



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)

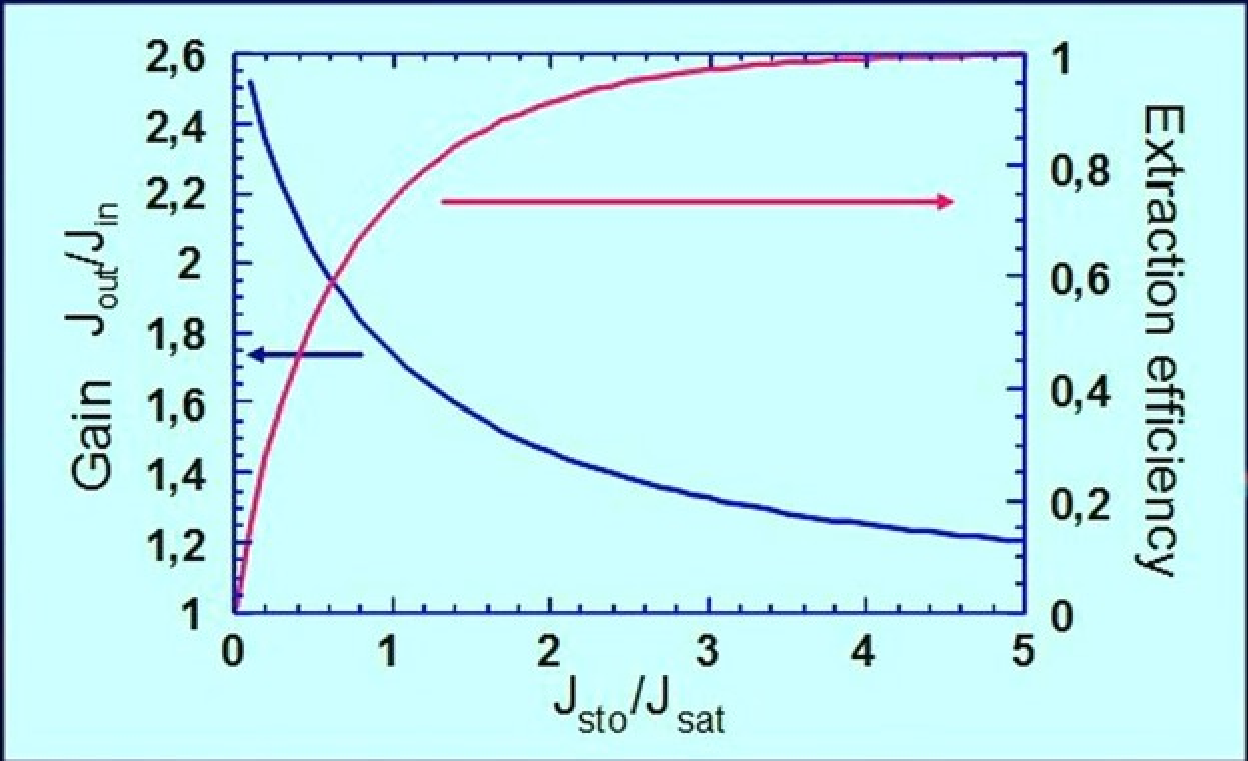
At low intensity, the gain is linear: $$\frac{dJ}{dz} = g_0 J \qquad \left(g_0 L = \frac{J_{sto}}{J_{sat}} > 0 \right)$$

At high intensity, the gain "saturates" and hence is constant: $$\frac{dJ}{dz} = g_0 J_{sat}$$

Intermediate case interpolates between the two: $$\frac{dJ}{dz} = g_0 J_{sat}\left(1 - e^{-J/J_{sat}}\right)$$

Frantz-Nodvick equation

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

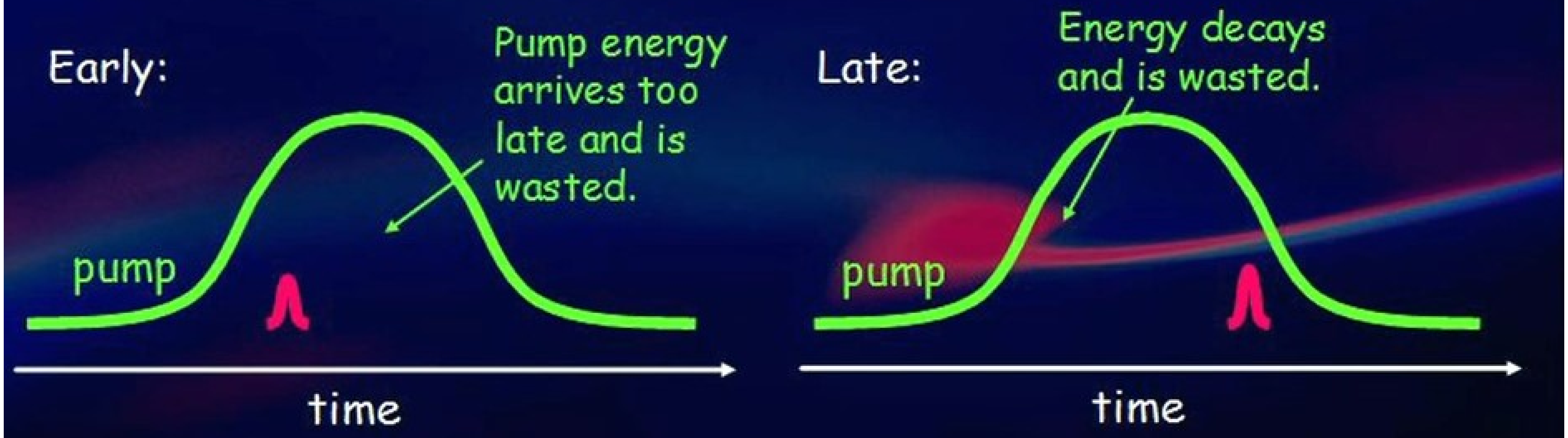


So you can have high gain or high extraction efficiency. But not both.

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?

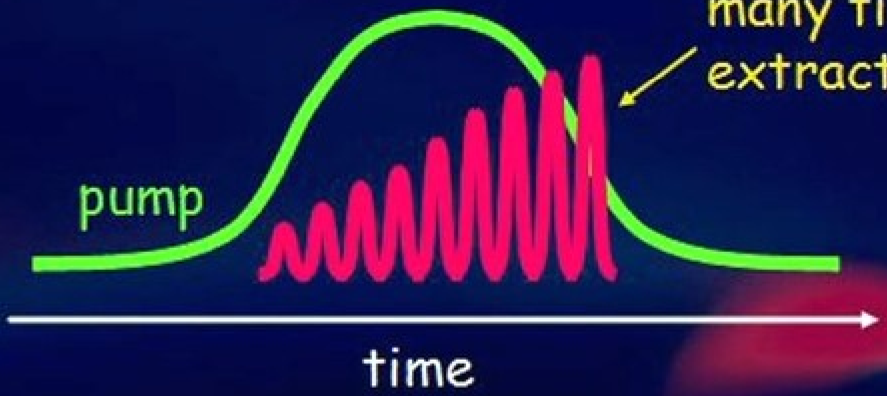


In both cases, pump pulse energy is wasted, and amplification is poor.

So we need many passes.

All ultrashort-pulse amplifiers are multi-pass.

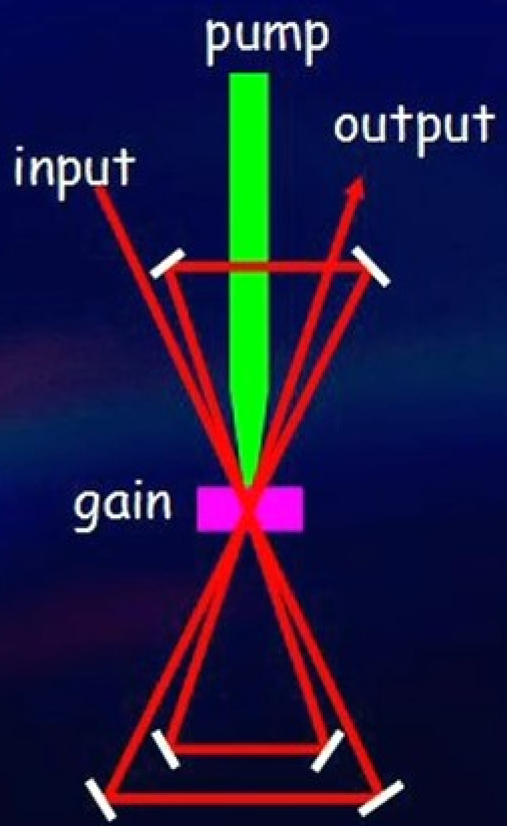
The ultrashort pulse returns many times to eventually extract most of the energy.



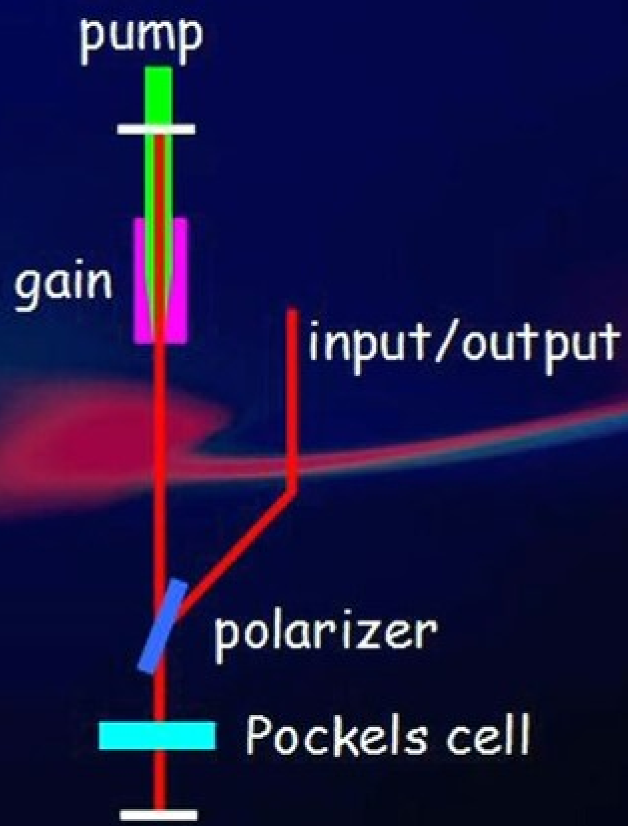
This approach achieves much greater efficiency.

Two main amplification methods

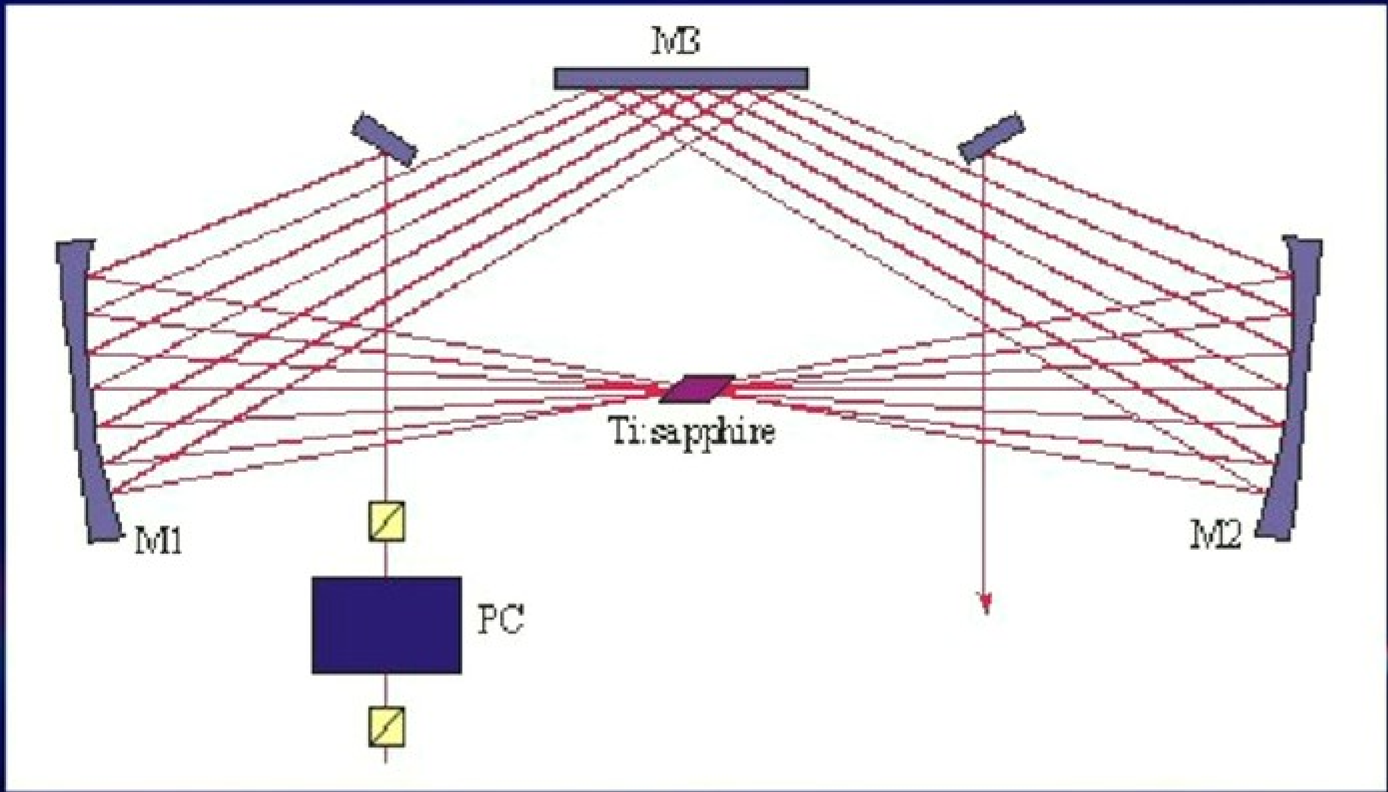
Multi-pass amplifier



Regenerative amplifier

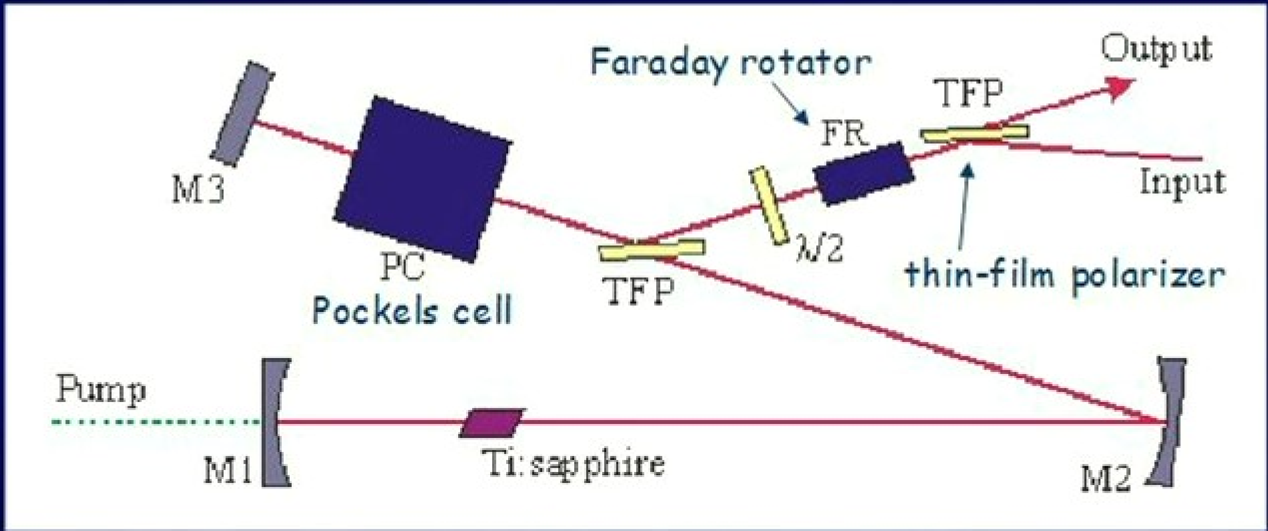


A multi-pass amplifier

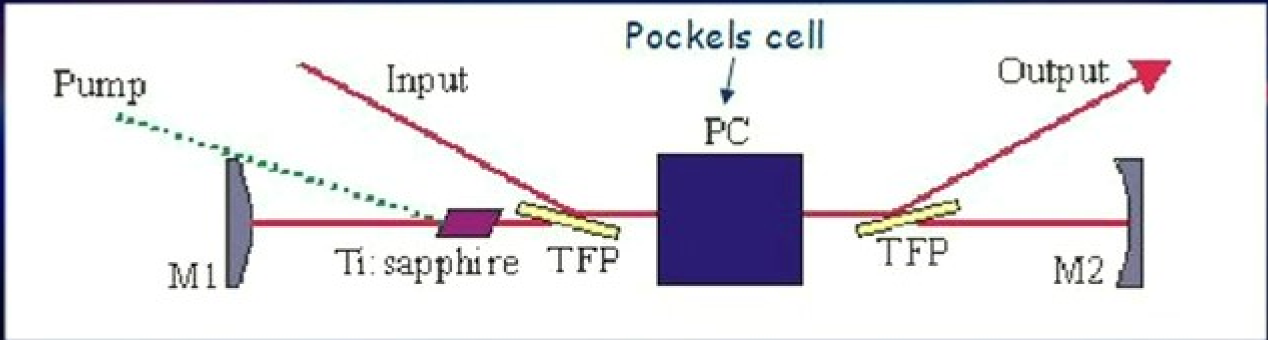


A Pockels cell (PC) and a pair of polarizers are used to inject a single pulse into the amplifier.

Regenerative amplifier geometries



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



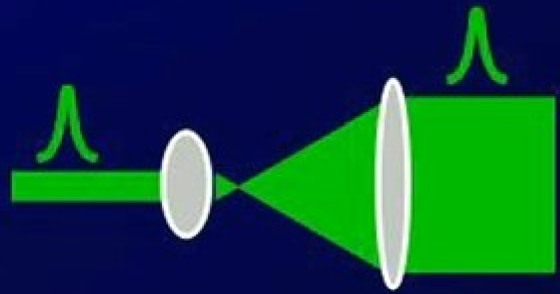
This is used for 10-20-Hz repetition rates. It has a larger spot size in the Ti:sapphire rod.

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:

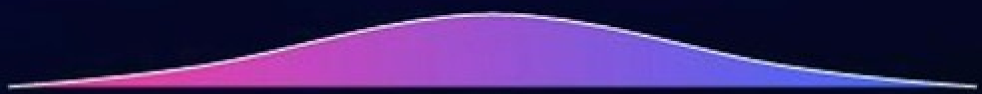


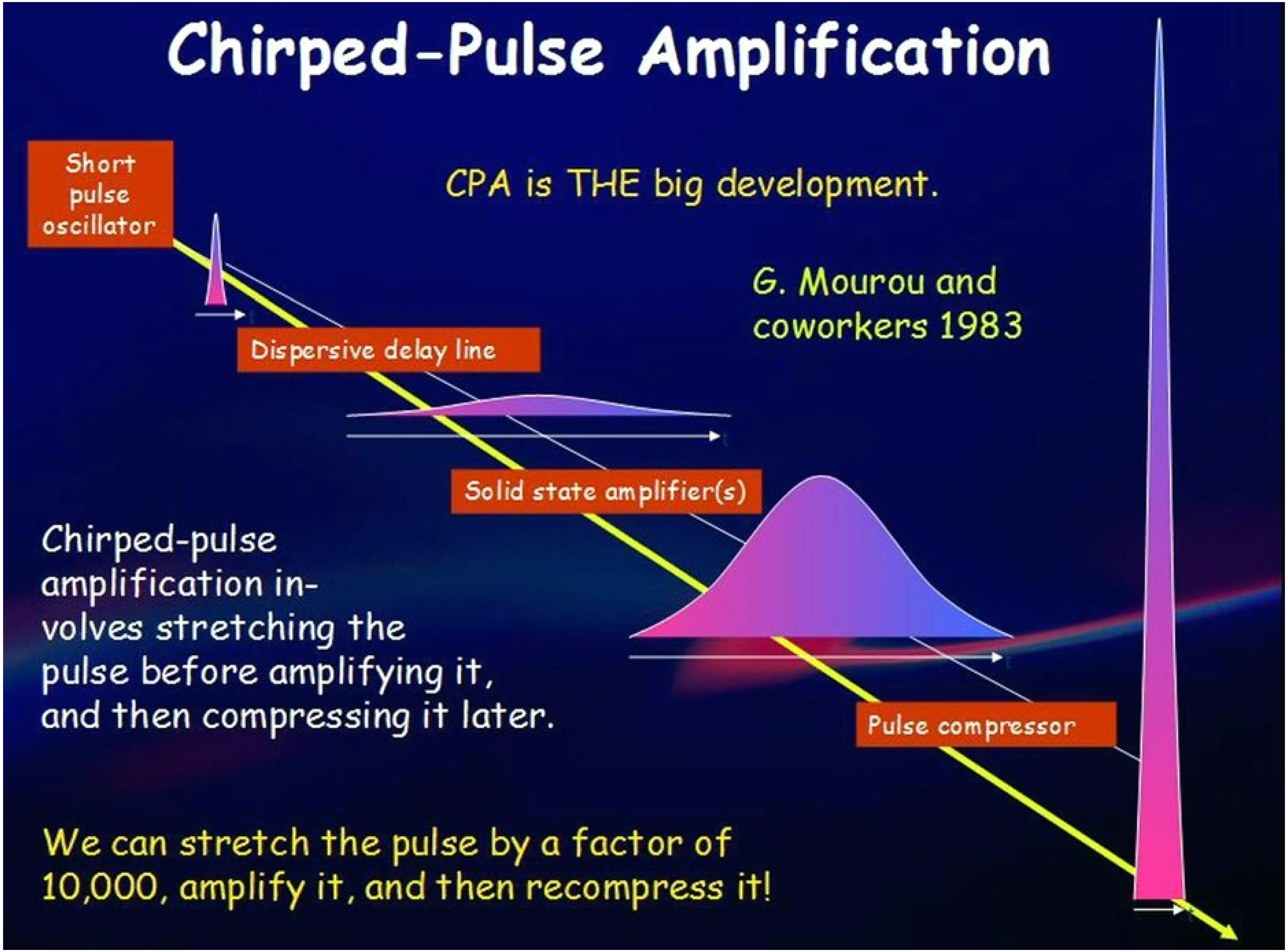
Expand the beam and use large amplifier media.

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

Solution:

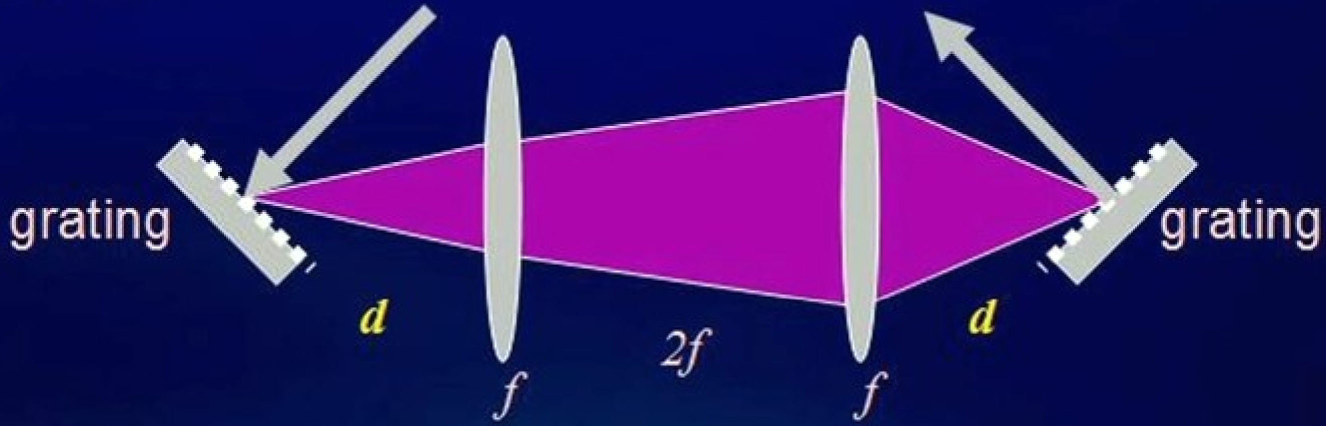
Expand the pulse **in time**, too.




Chirped-Pulse Amplification
Short pulse oscillator
CPA is THE big development.
G. Mourou and coworkers 1983
Dispersive delay line
Solid state amplifier(s)
Chirped-pulse amplification involves stretching the pulse before amplifying it, and then compressing it later.
Pulse compressor
We can stretch the pulse by a factor of 10,000, amplify it, and then recompress it!

Stretching and compressing ultrashort pulses

Pulse stretcher

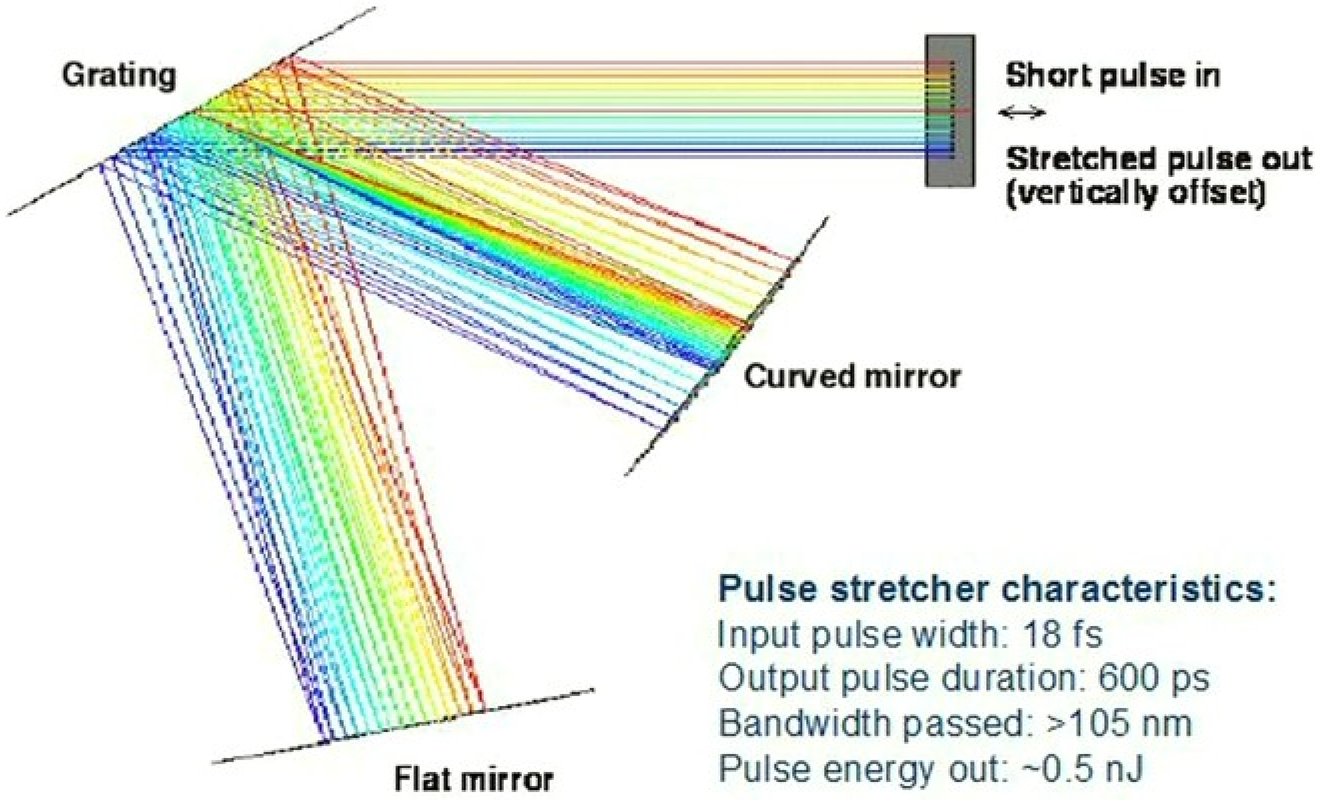


Okay, this looks just like a "zero-dispersion stretcher" used in pulse shaping. But when $d \neq f$, it's a dispersive stretcher and can stretch fs pulses by a factor of 10,000!

With the opposite sign of d-f, we can compress the pulse.

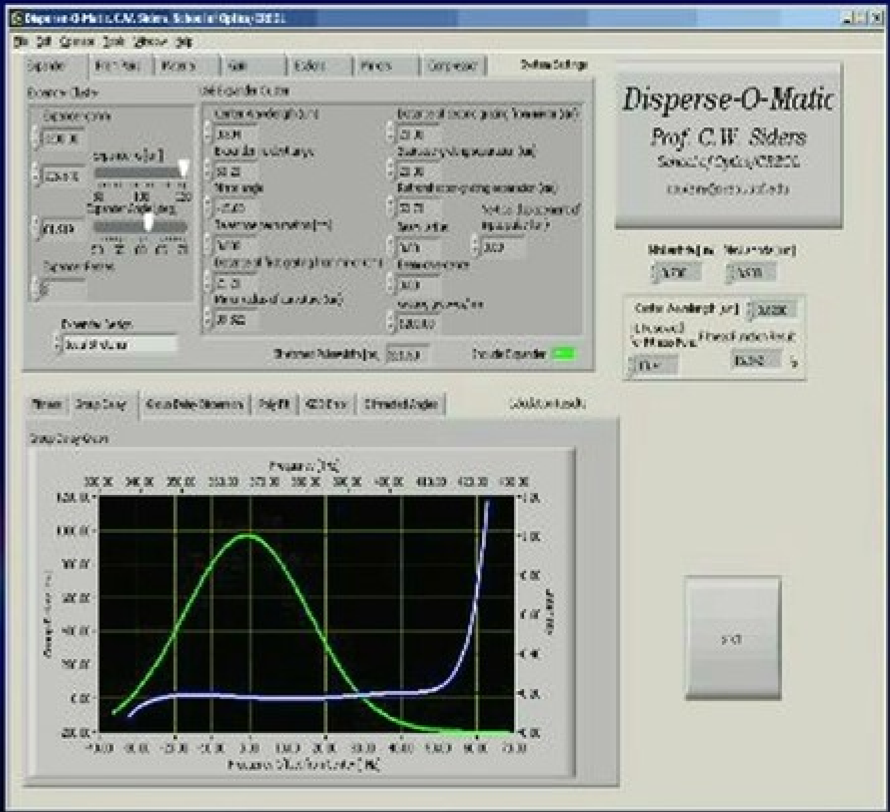
A pulse stretcher

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:



Pulse stretcher characteristics:
Input pulse width: 18 fs
Output pulse duration: 600 ps
Bandwidth passed: >105 nm
Pulse energy out: ~0.5 nJ

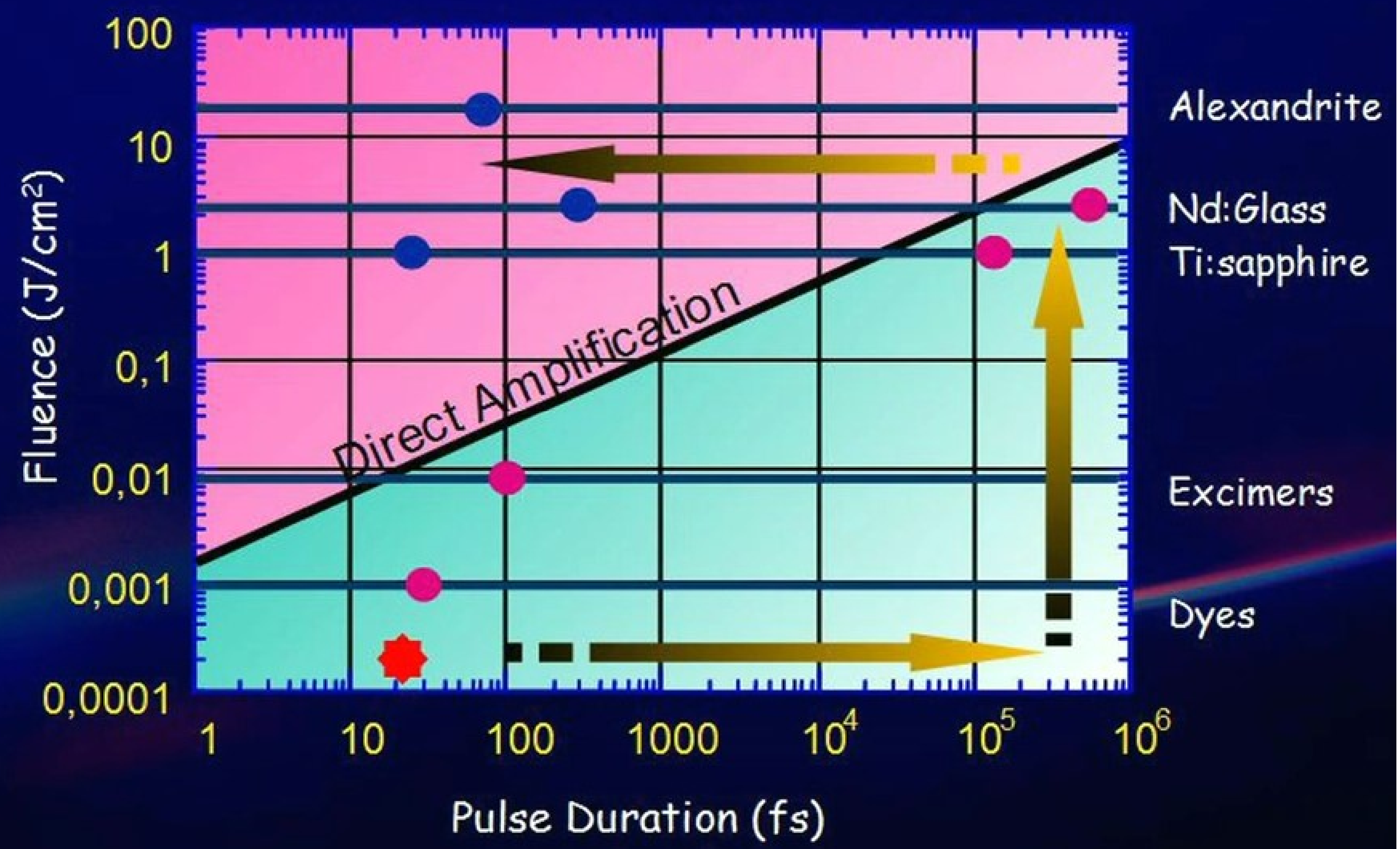
"Dispersomatic"—Free code to model dispersion in stretchers and compresssors



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/

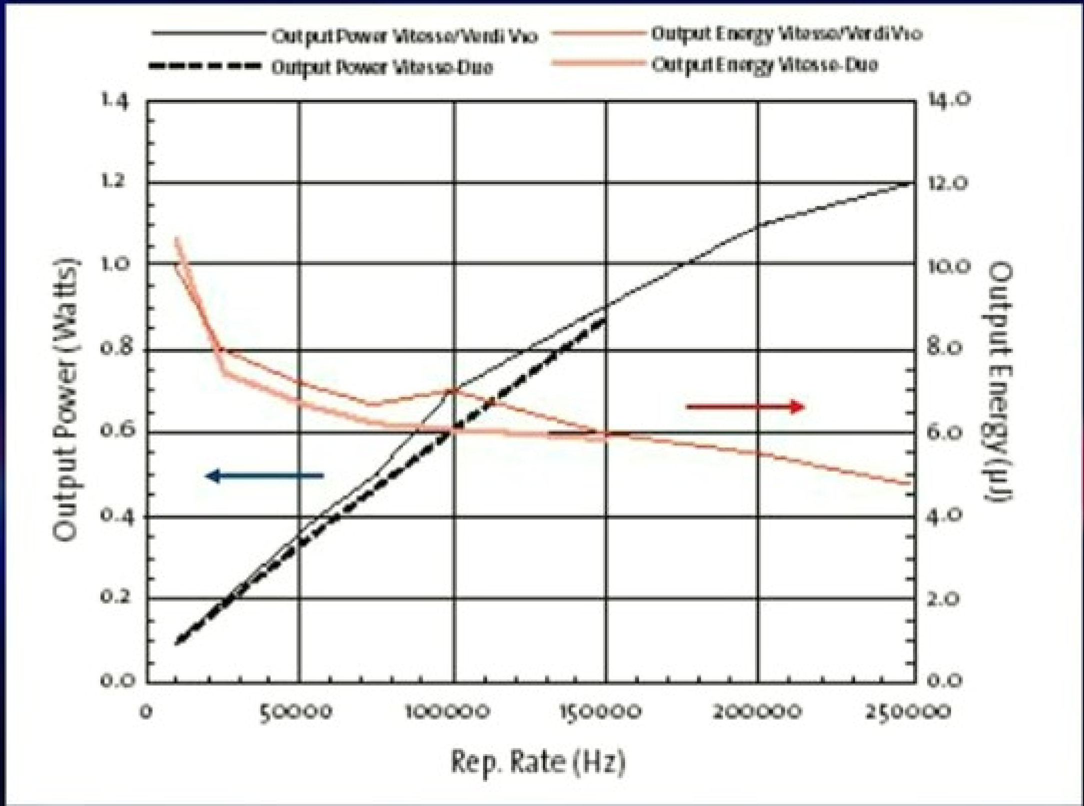
CPA vs. Direct Amplification



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 Argon laser provides up to 50 W. Use the rest to pump an amplifier. Today, we use an intracavity-doubled Nd:YLF pump laser (~10W).



Coherent RegA amplifier

Microjoules at 250 kHz repetition rates!

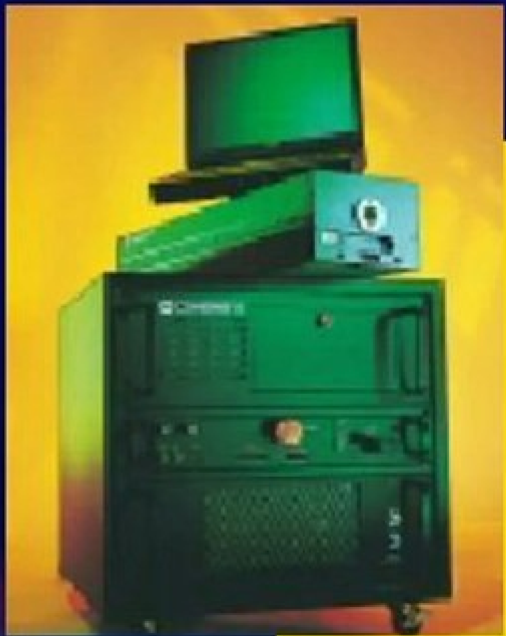
Regenerative chirped-pulse amplification with a kHz pulsed pump

Positive Light regen: the "Spitfire"

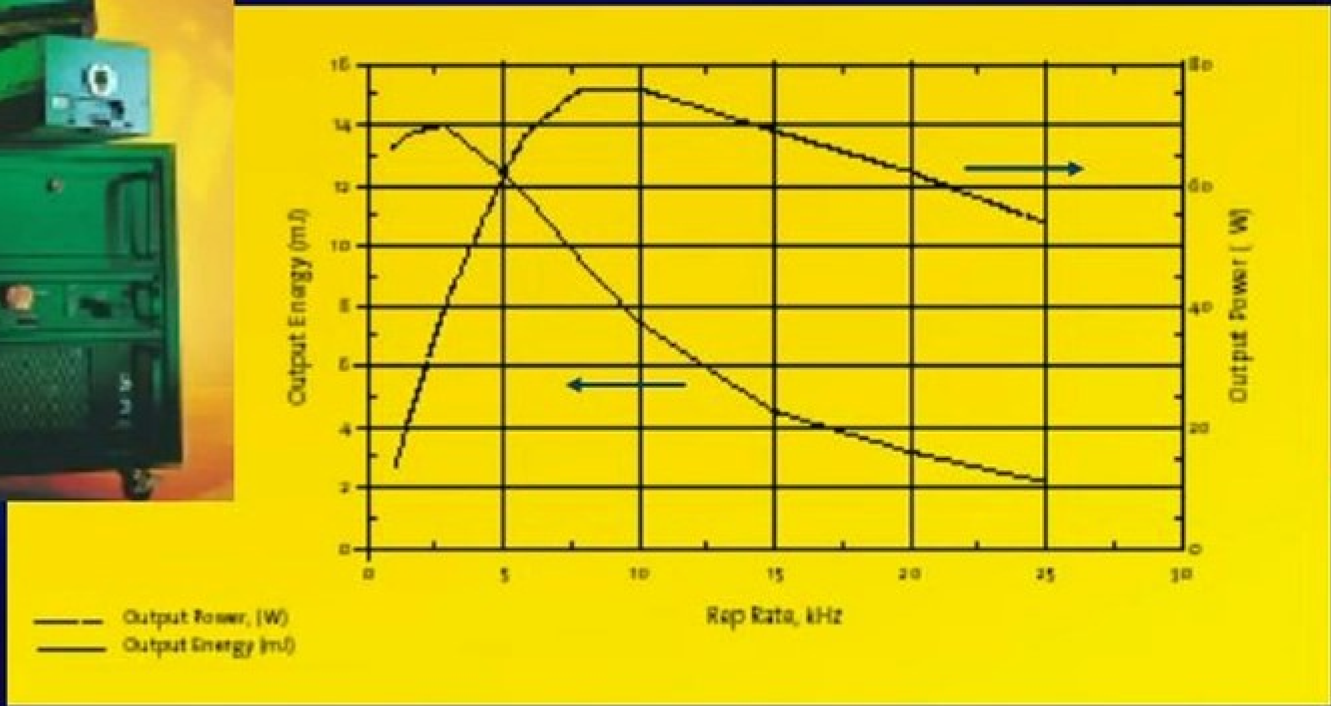
Wavelength: 800 nm
(Repetition rates of 1 to 50 kHz)
High Energy: <130 fs, >2 mJ at 1 kHz
Picosecond: ~80 ps, >0.7 mJ at 1 kHz
Short Pulse: <50 fs, >0.7 mJ at 1 kHz

Pump laser for ultrafast amplifiers

15 mJ (ns) at a 10 kHz rep rate (150W ave 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 also.

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

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 $t = 0$

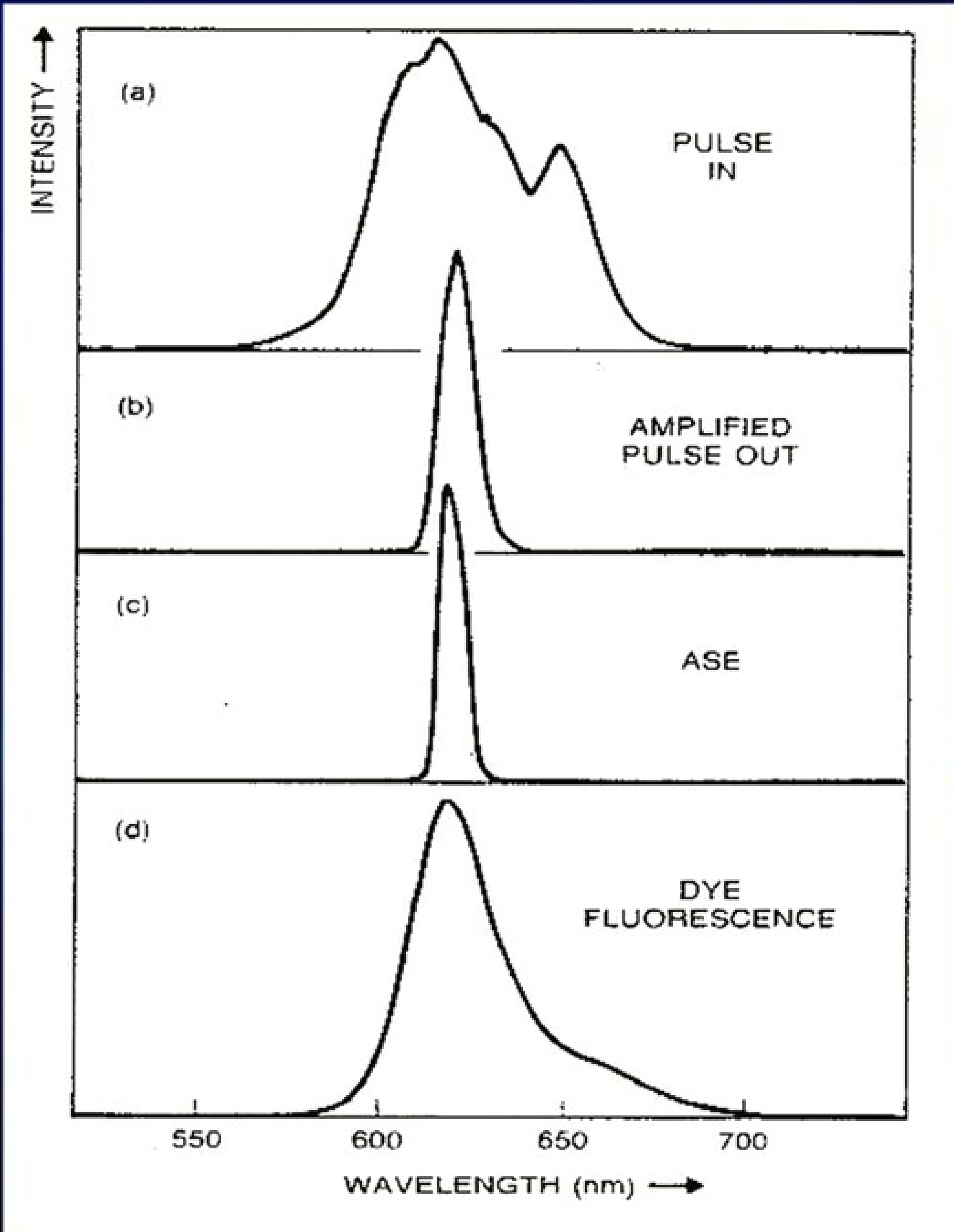
ASE shares the gain and the excited population with the pulse.

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

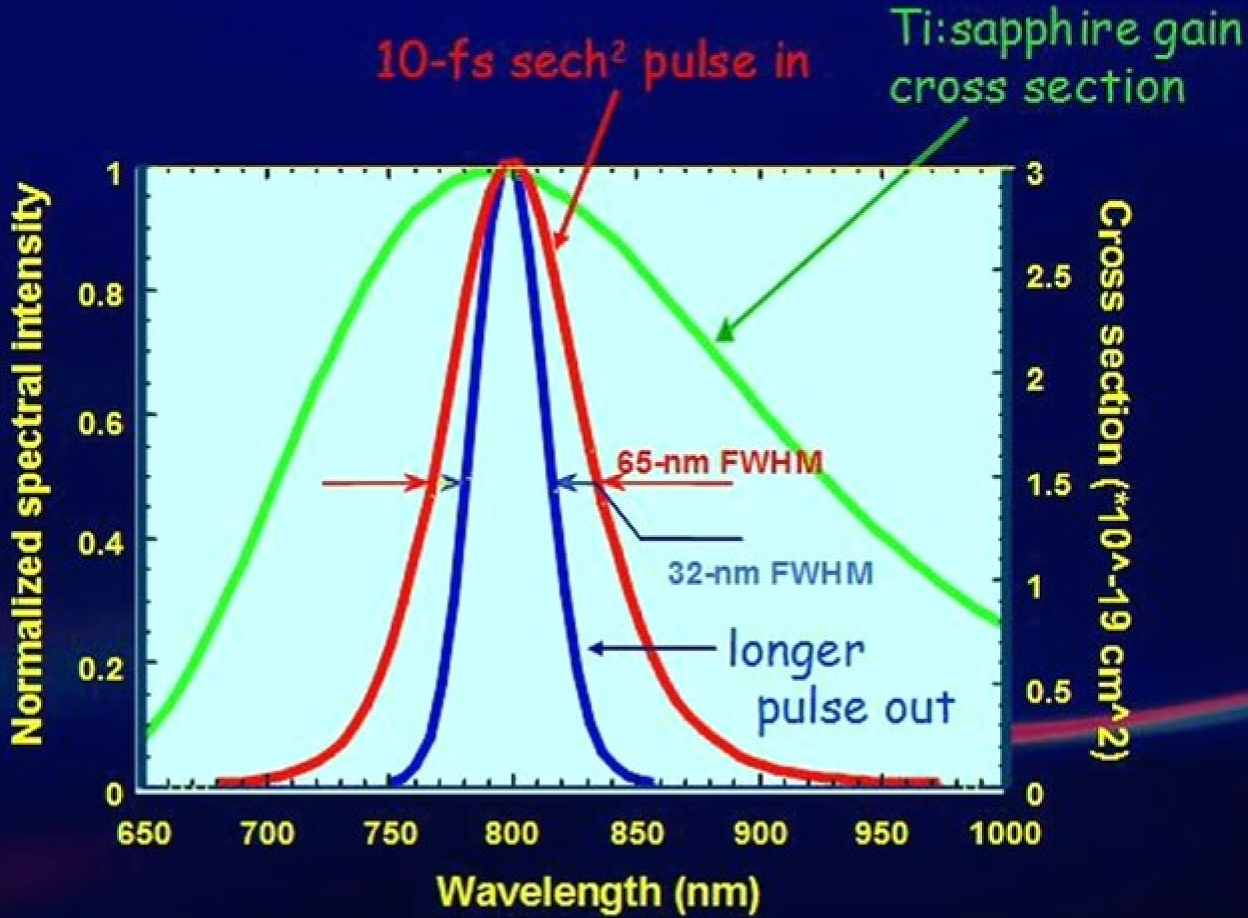
Gain Narrowing (and ASE)

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)



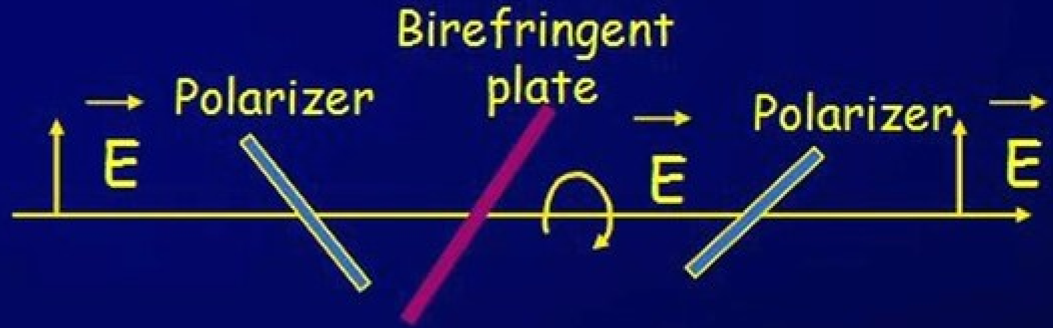
Gain narrowing example



Factor of 2 loss in bandwidth for 10^7 gain

Most Terawatt systems have $>10^{10}$ small signal gain

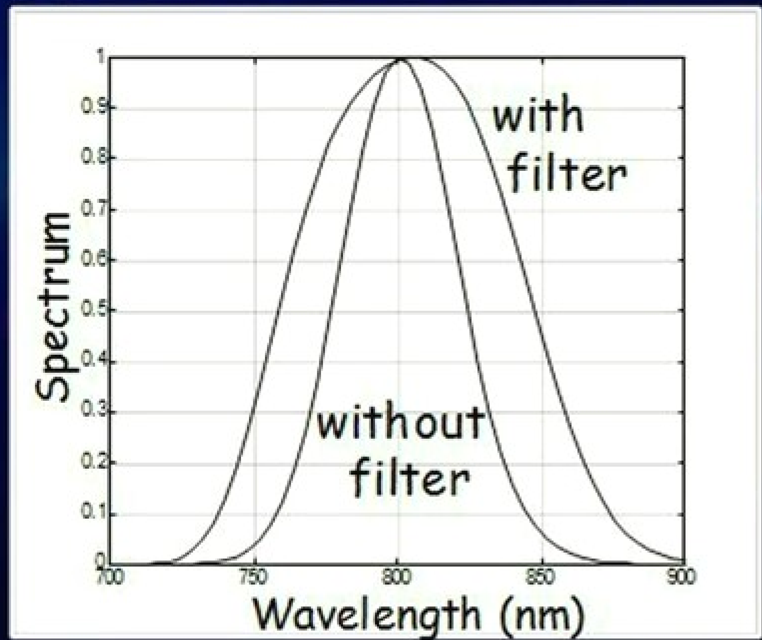
Beating gain narrowing



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

Gain and loss

Spectrum: before and after



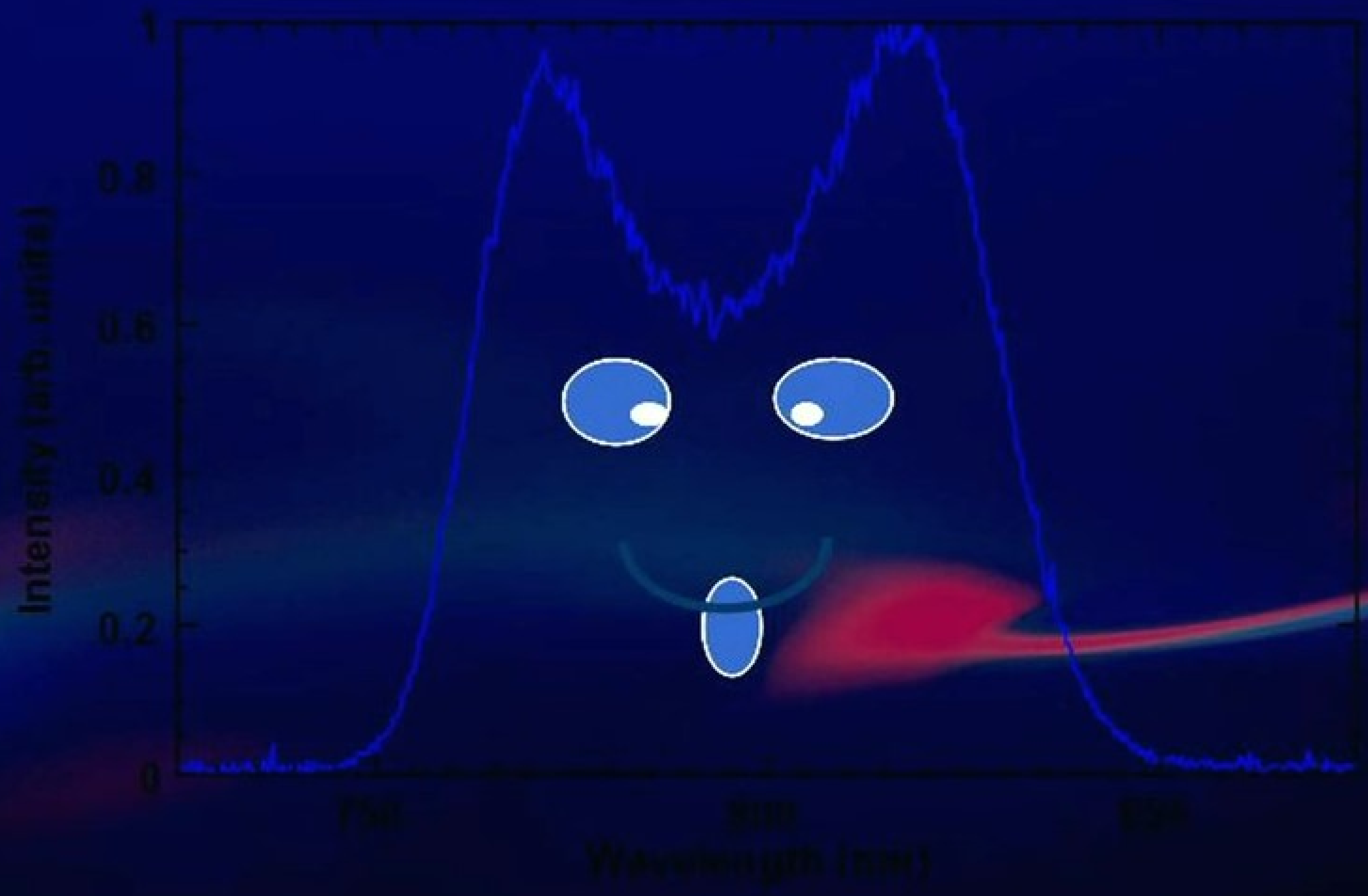
Gain-Narrowing Conclusion

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.

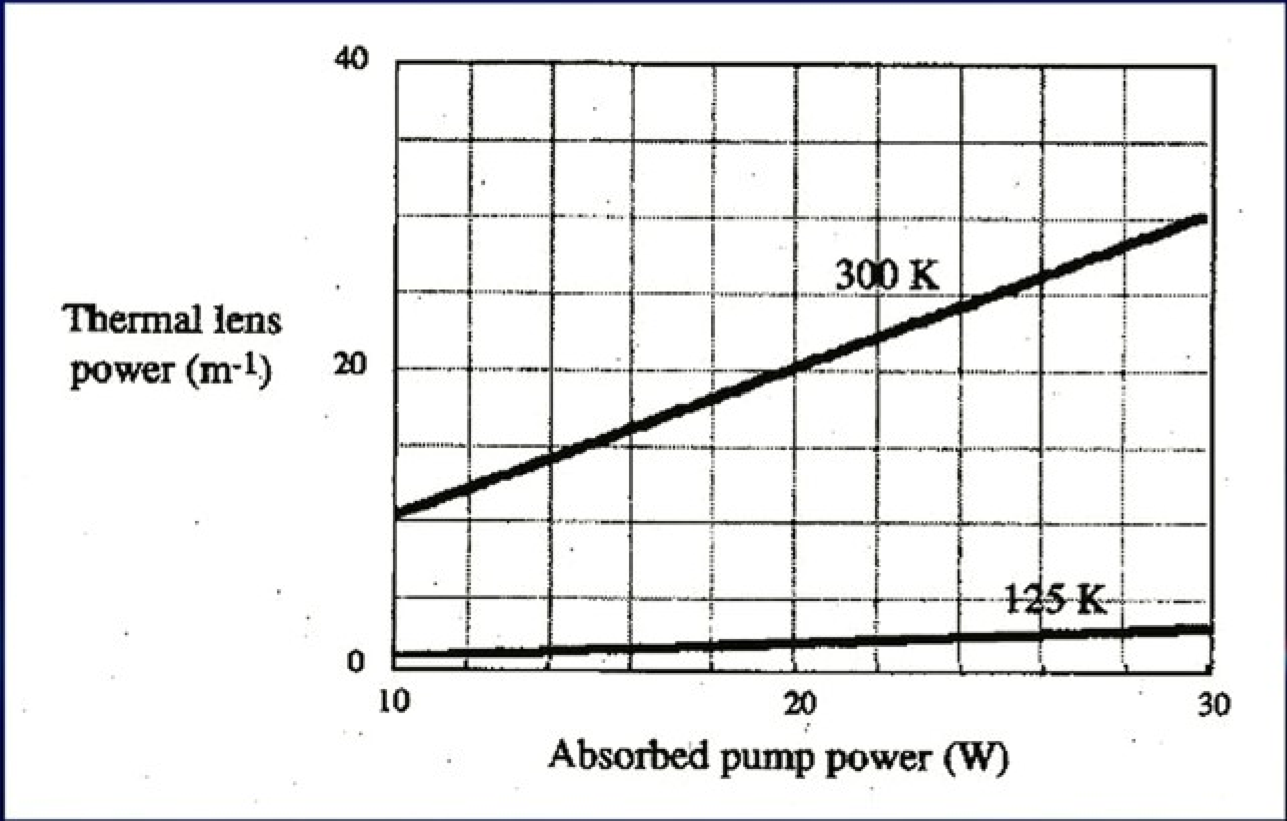
$$I_{peak} = \frac{E}{A\,\delta T}$$

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

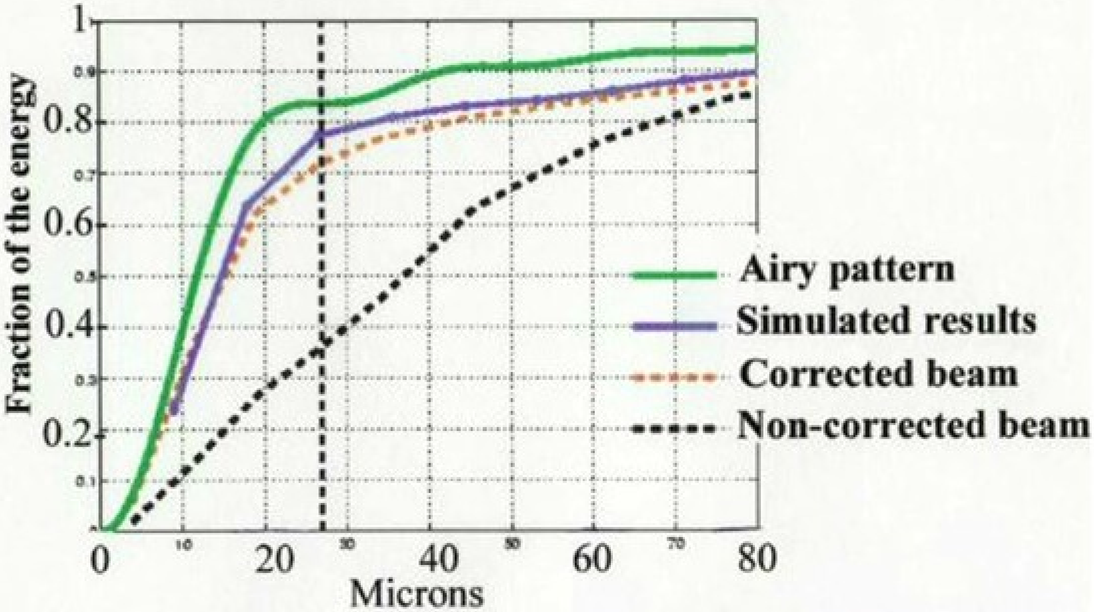
Cryogenic cooling results in almost no focal power

Murnane, Kapteyn, and coworkers

Static Wave-front Correction

Before correction
FWHM:39μm
1.4 times the diffraction limit

After correction
FWHM: 27μm
diffraction limited



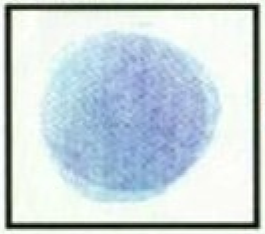
With the correction, the energy inside the diffraction limited spot size is multiplied by 2.1 (results taken at low energy). The simulation allows us to predict our energy distribution at high energy.

2.5 times improvement in peak intensity has been achieved

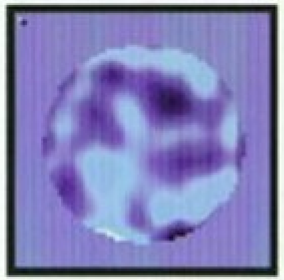
CUOS

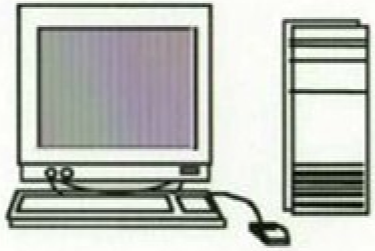
Dynamic Correction of Spatial Distortion

Wavefront sensor



interferogram





Wavefront reconstruction

Computation of the optimal shape of the mirror

Send voltages to the deformable mirror for the correction

Deformable mirror

Contrast ratio

Why does it take over 2 years between the first announcement of a new laser source and the first successful experiment using it?

Because the pulse has leading and following satellite pulses that 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!

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

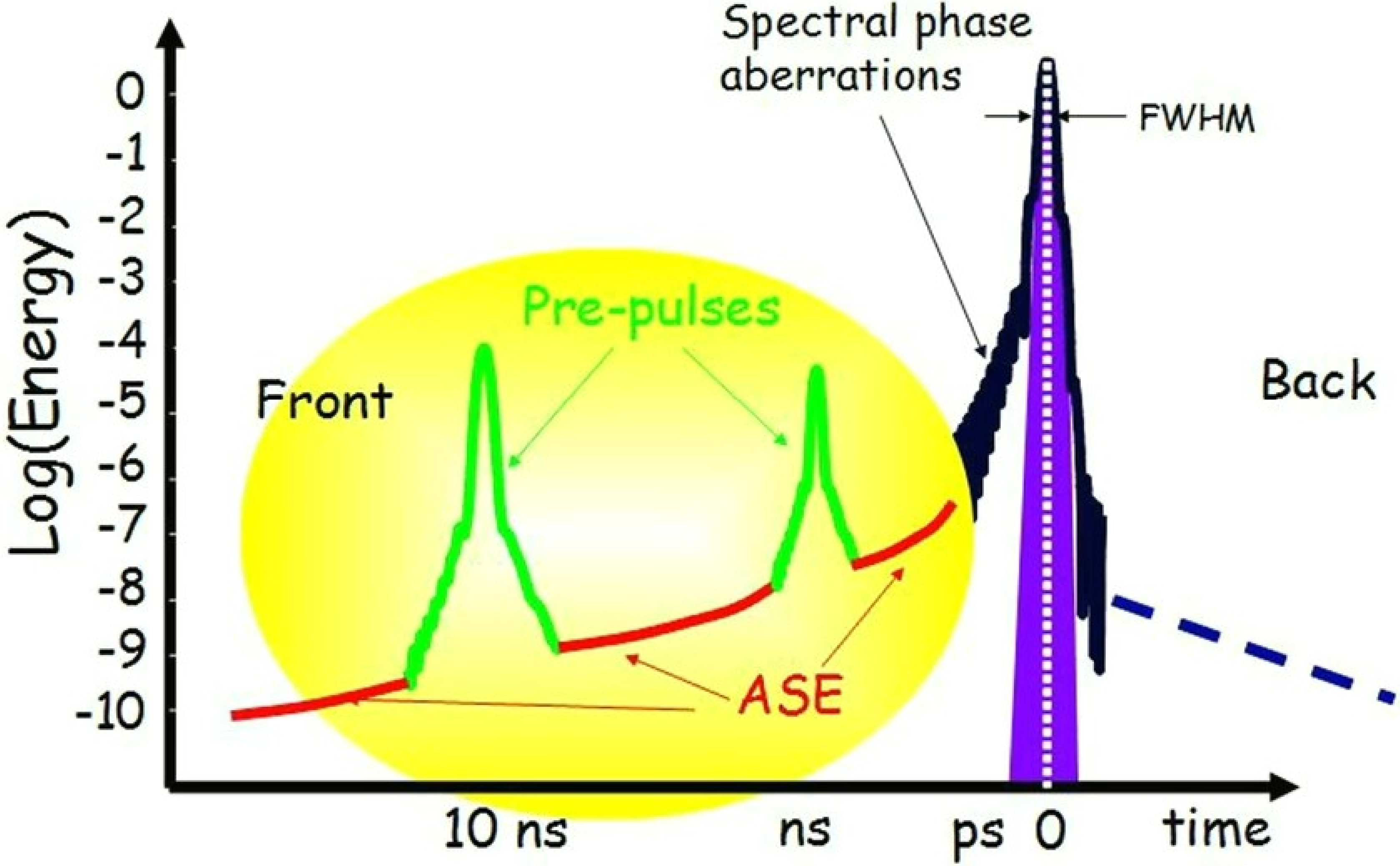
Nanosecond scale:

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

Picosecond scale:

- reflections in the amplifier
- spectral phase or amplitude distortions

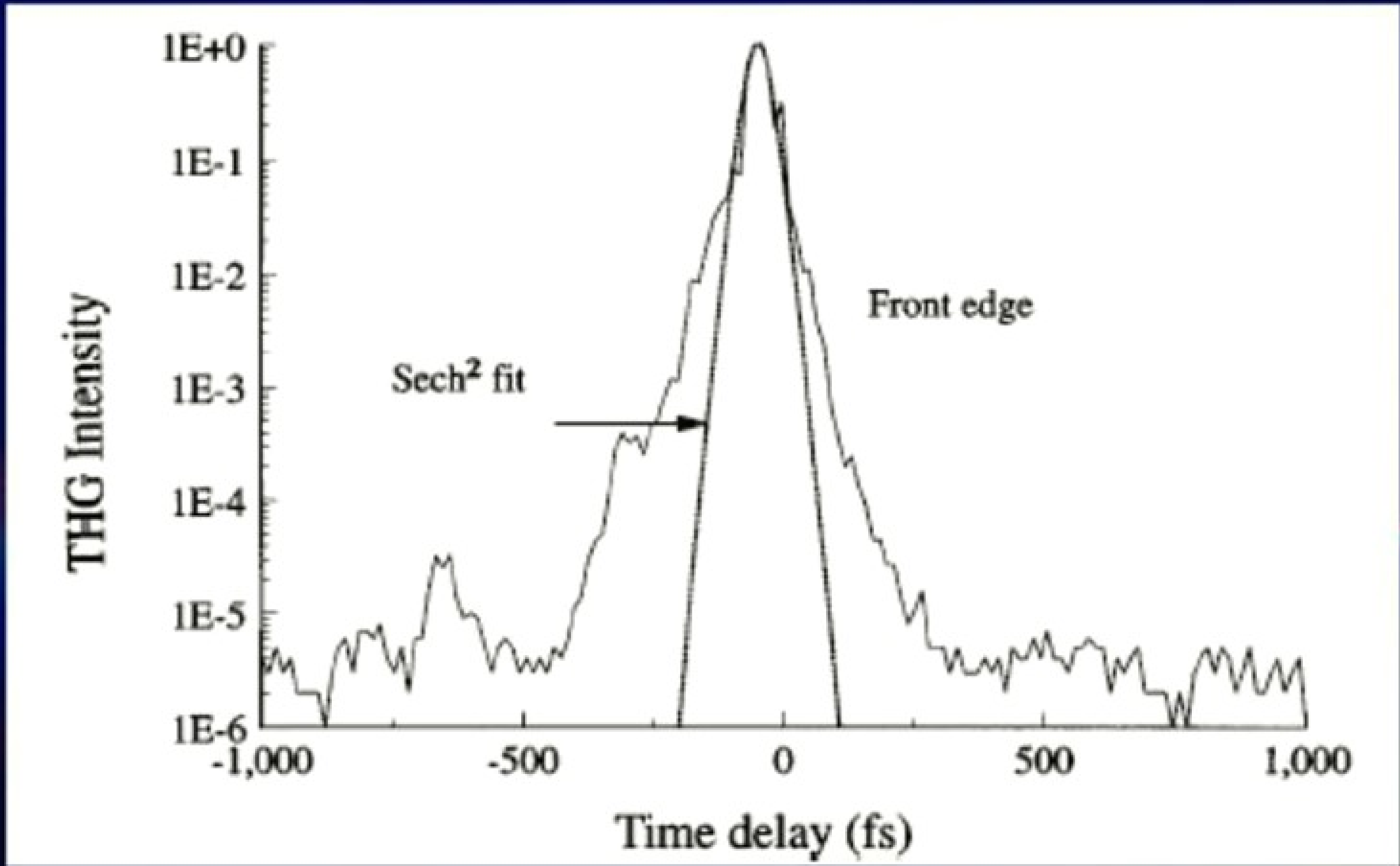
Amplified pulses often have poor contrast.



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

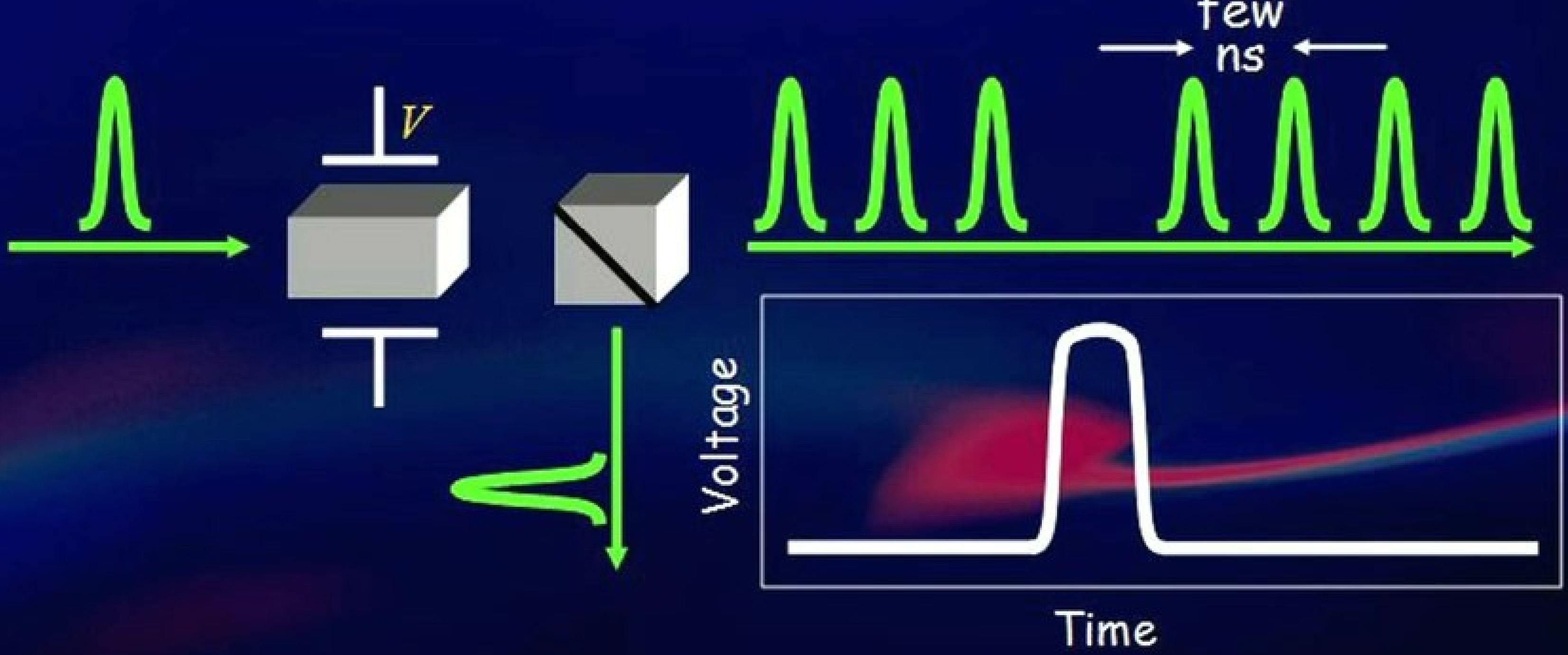
Amplified pulses have pre- and post-pulses.

Typical 3rd order autocorrelation

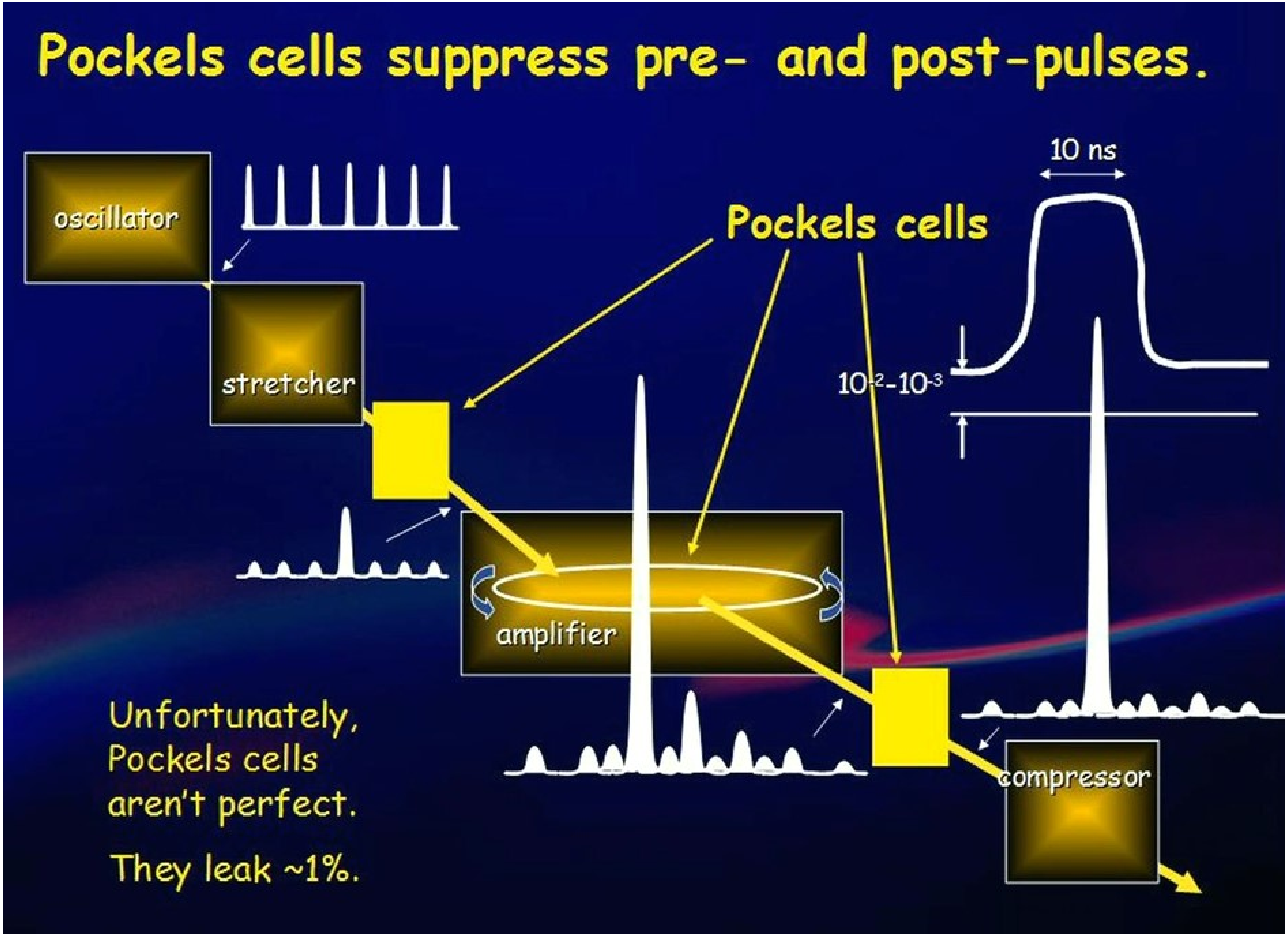


A Pockels cell "Pulse Picker"

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.
oscillator
stretcher
Pockels cells
10 ns
10^{-2}-10^{-3}
amplifier
compressor
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

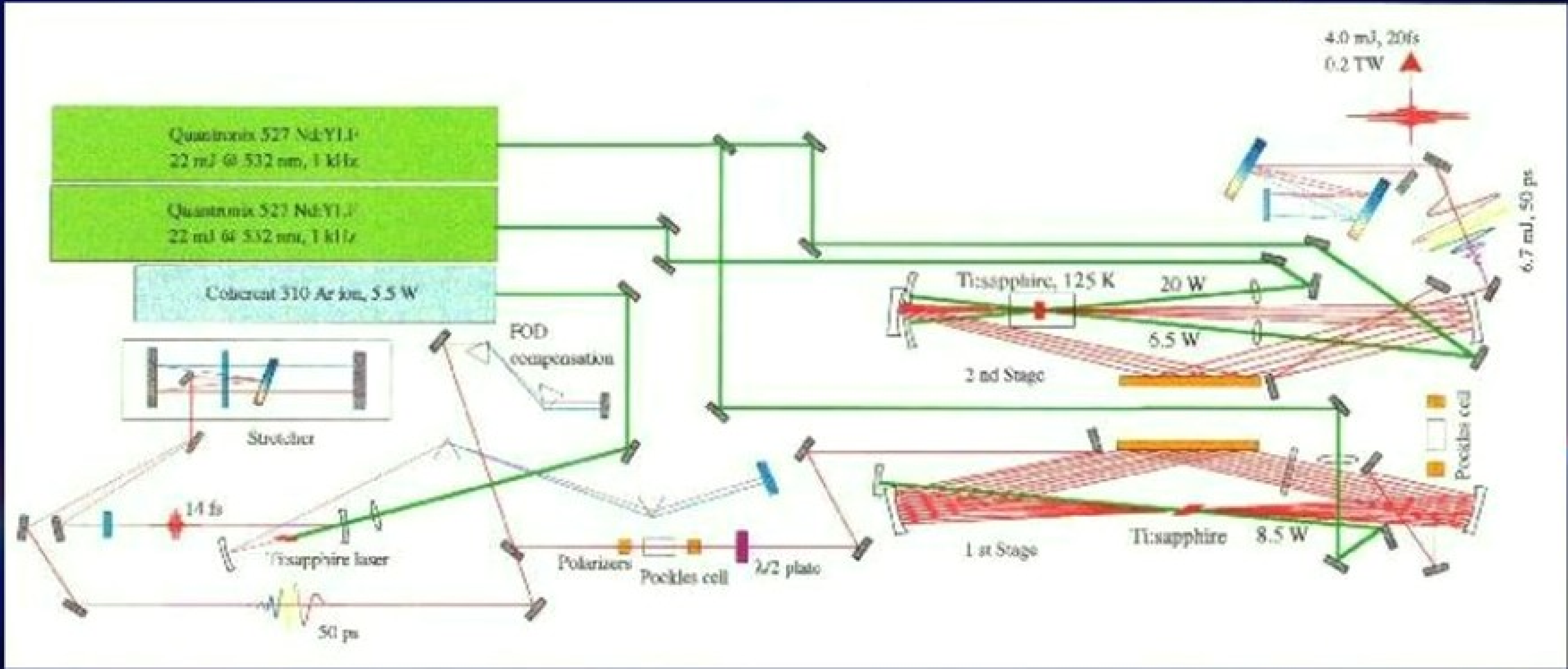
Temperature drift is also a problem in Pockels cells.

Also: Good pump synchronization gives a factor 3-10

Multiple-stage multi-pass amplifiers

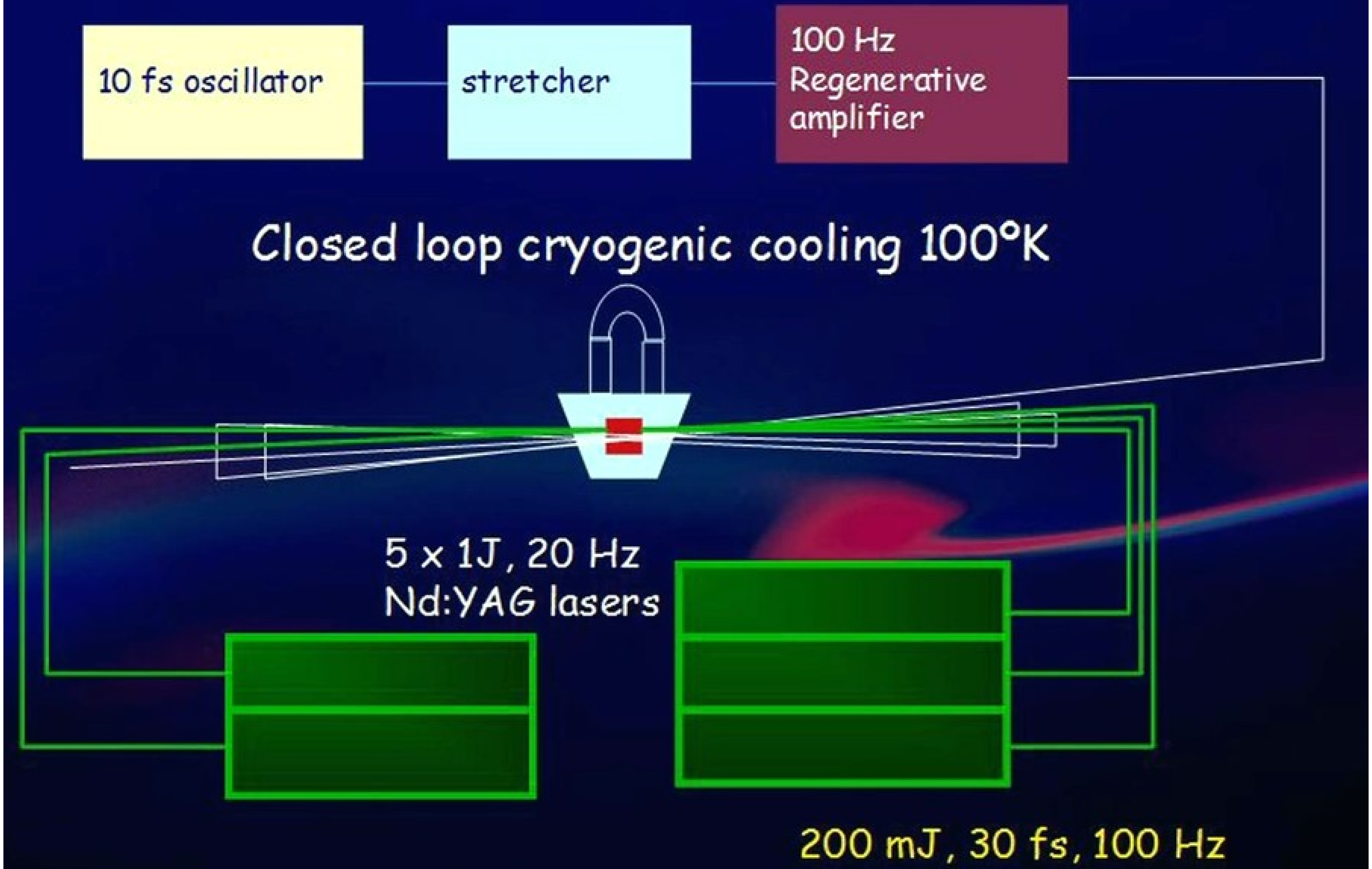
4 mJ, 20 fs pulse length

0.2 TW

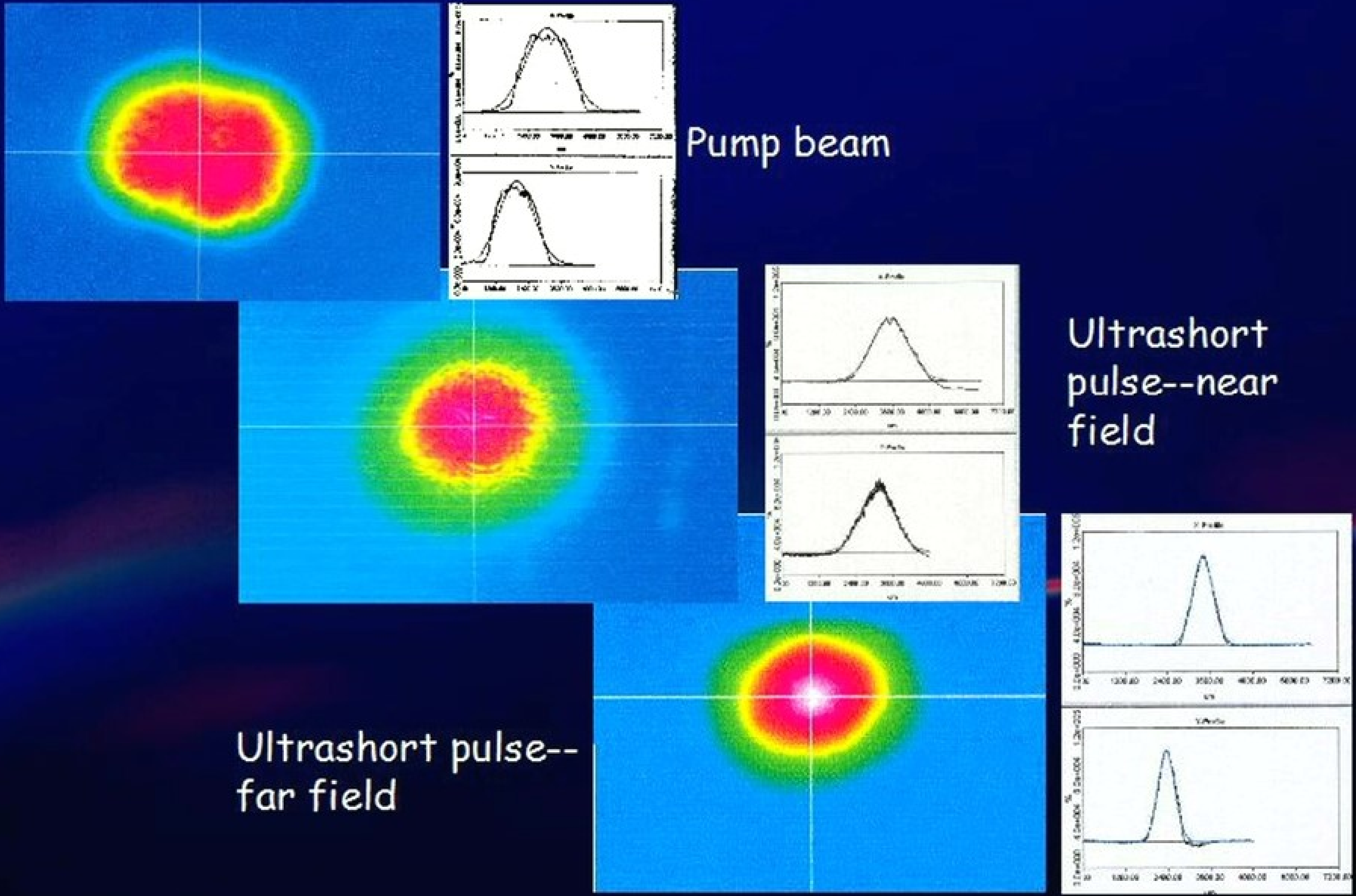


1 kHz Multi-pass system at the
University of Colorado (Murnane and Kapteyn)

High energy, high contrast 100-Hz system at CELIA

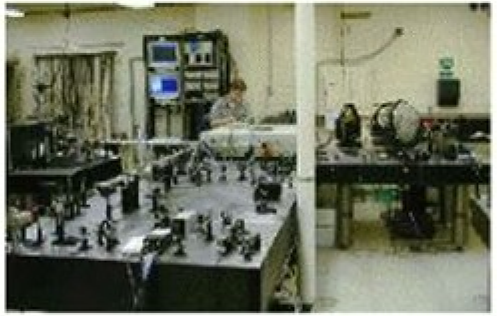


Amplified-pulse beam shapes

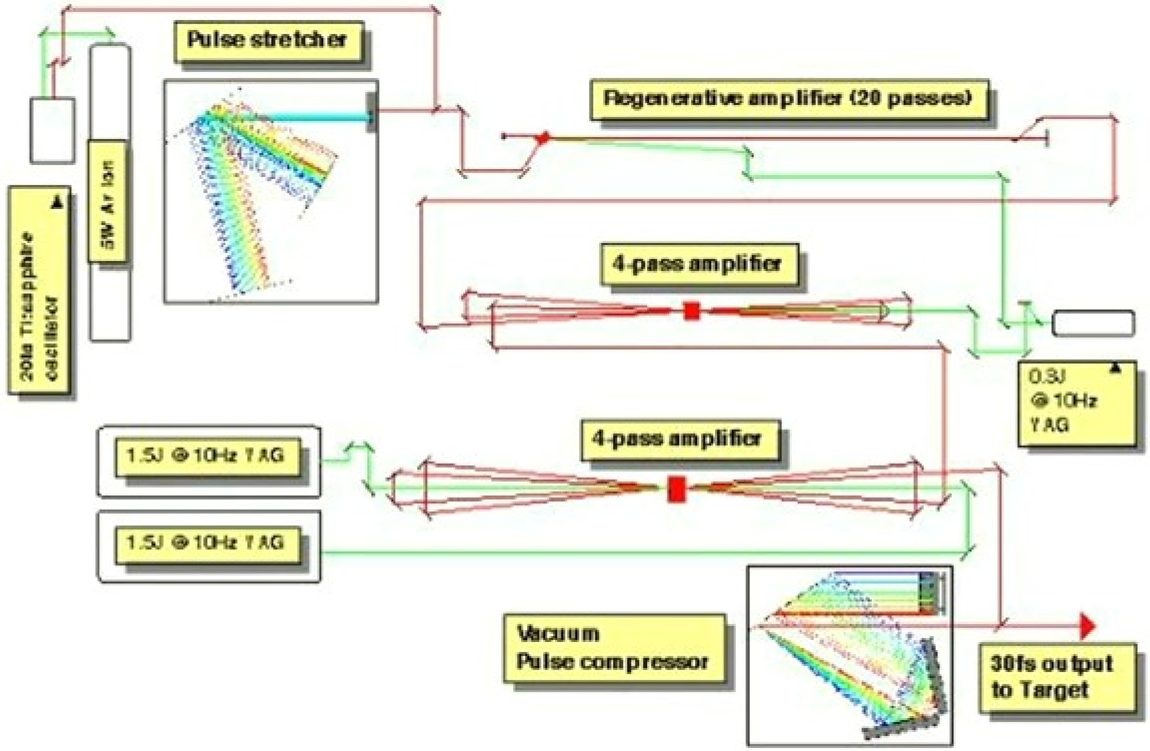


A 1-Joule Apparatus

The Texas High-Intensity Optical Research Laser - The THOR laser



It is designed to deliver 35 fs laser pulses with energy of 0.7 J, yielding a peak power of 20 terawatts.



Positive Light Multi-Joule Systems

Terawatt Laser System

Ti:sapphire
Energy > 1 Joule
Pulsewidth < 35 fs
Power > 10 TW
Repetition rates to 1 kHz

Nd:Glass
Energy > 20 Joules
Pulsewidth < 500 fs
Power > 40 TW
Repetition rates ~ every hour

You can buy these lasers!

Even Higher Intensities!

National Ignition Facility
(under construction)

192 shaped pulses
10.4 kJ per beam in UV (done)
21 kJ per beam in IR (done)
>1.8 MJ total energy (planned)
Pulses 0.2 to 25 ns in length