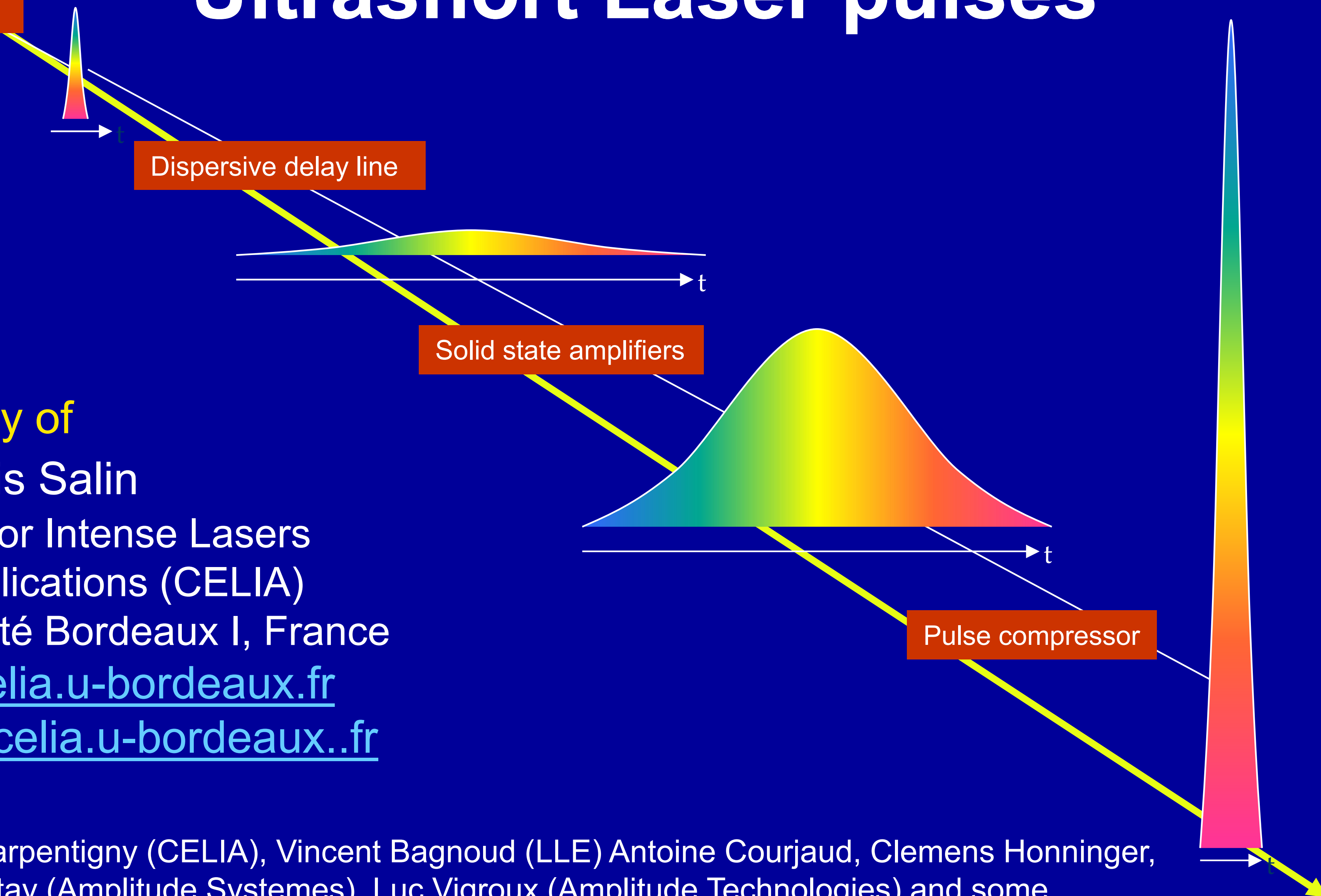
The Amplification of Ultrashort Laser pulses



Most of this lecture courtesy of

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Gilles Darpentigny (CELIA), Vincent Bagnoud (LLE) Antoine Courjaud, Clemens Honninger, Eric Mottay (Amplitude Systemes), Luc Vigroux (Amplitude Technologies) and some additional stuff from Rick Trebino, Ga. Tech, and Daniel Mittleman, Rice

Even the unamplified pulse can reach a pretty impressive intensity

1 nanojoule in 100 femtoseconds: $\dfrac{10^{-9}\text{ J}}{10^{-13}\text{ sec}} = 10^4\text{ W}$

Focus this to a 10 μm spot size (easy to do): $\dfrac{10^4\text{ W}}{10^{-10}\text{ m}^2} = 10^{14}\text{ W/m}^2$

For comparison:

threshold for second harmonic generation in BBO: $<10^{13}$ W/m^2

threshold for ionization of air: $>10^{15}$ W/m^2

Conclusions:

- You can access the lowest-order NLO effects without an amplifier.
- But many effects are out of reach unless you amplify.

What are the goals in ultrashort pulse amplification?

Maximum intensity on target

$$I_{peak} = \frac{\overset{\text{Pulse energy}}{E}}{\underset{\text{Beam area}}{A}\;\underset{\text{Pulse length}}{\delta t}}$$

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

Needed to start the experiment

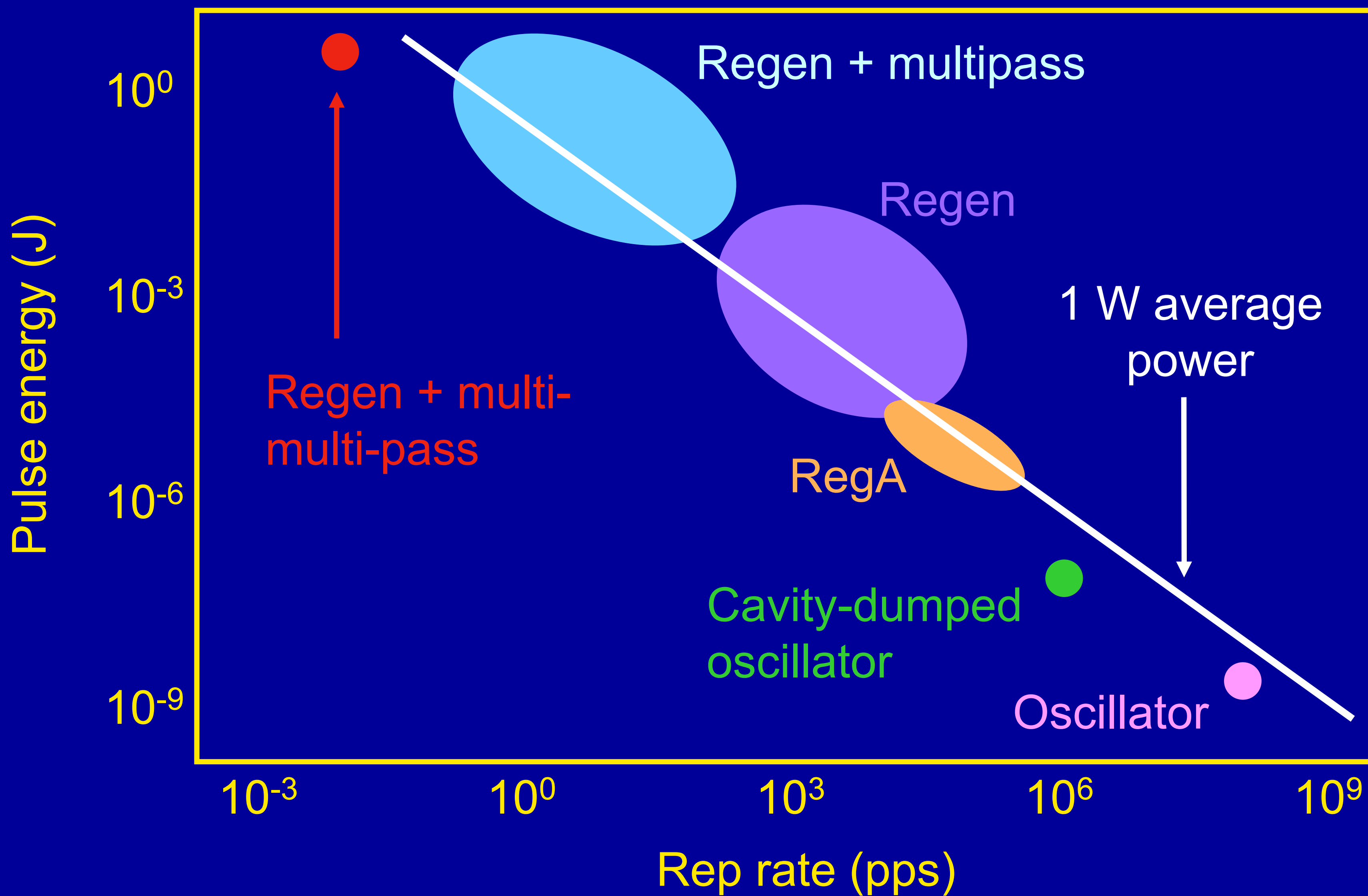
Maximum average power at the detector

$$P_{ave} = \underset{\text{Pulse energy}}{E}\;\underset{\text{Rep rate}}{r}$$

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

Needed to get useful results

Pulse energy vs. Repetition rate



Issues in Ultrafast Amplification and Their Solutions

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

Damage: Chirped-Pulse Amplification (CPA)

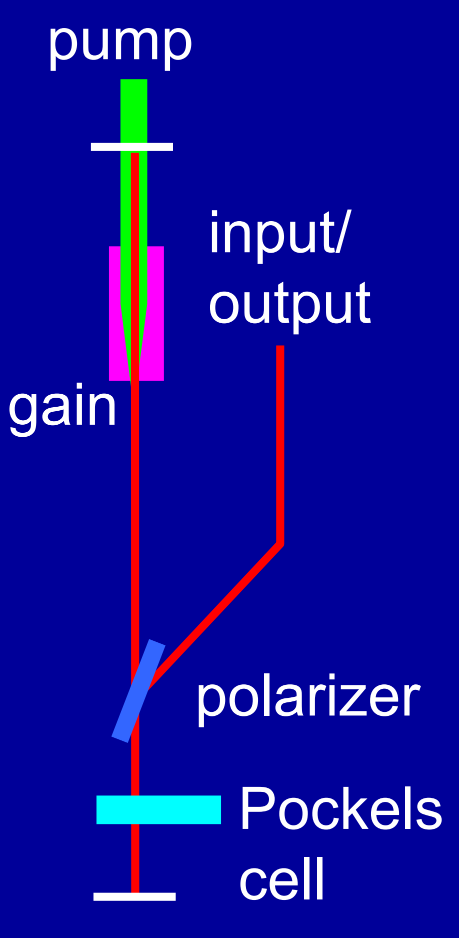
Gain saturation: Frantz-Nodvick Equation

Gain narrowing: gain-flattening filters

Thermal effects: cryogenics, and wavefront correction

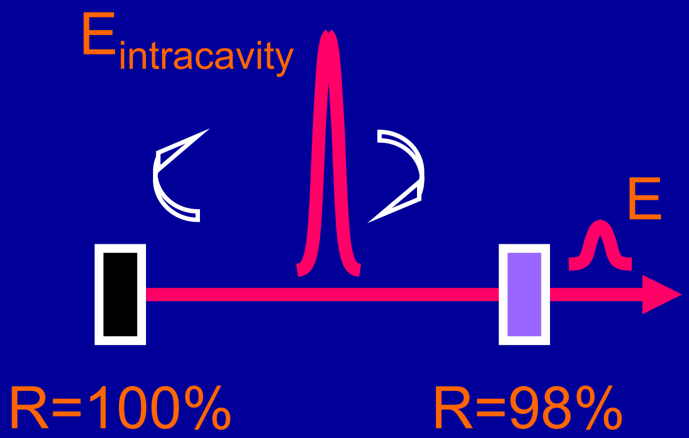
Satellite pulses, Contrast, and Amplified Spontaneous Emission: Pockels' cells

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?



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

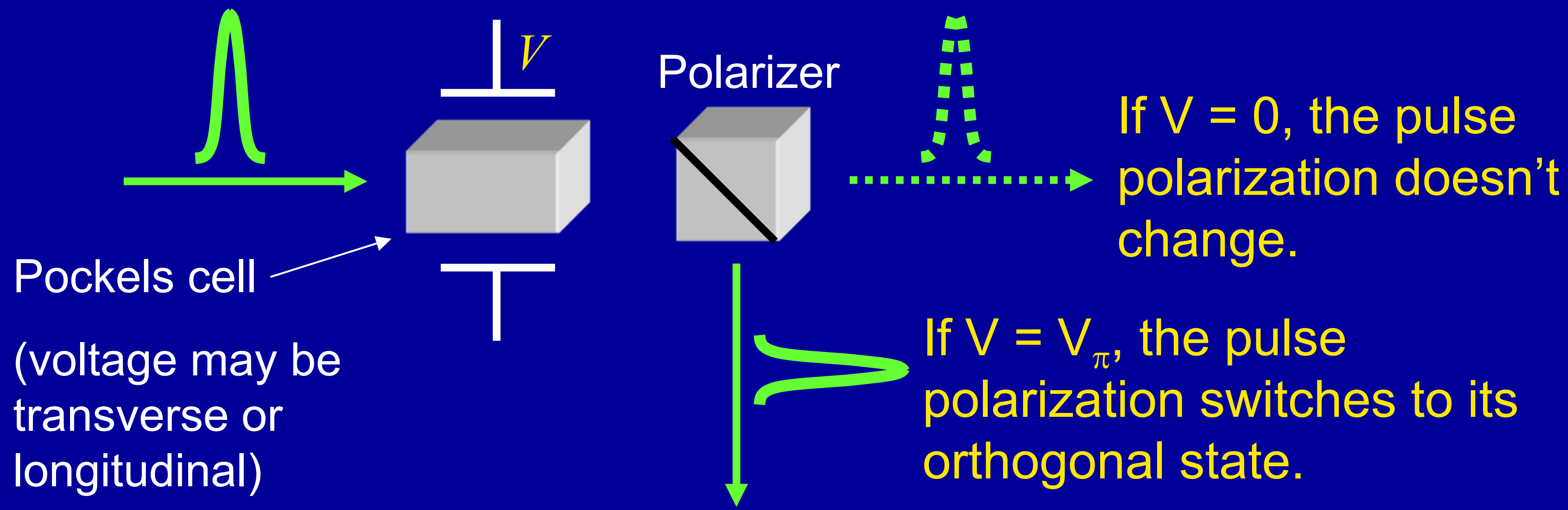
Transmission of output coupler: ~2%

What if we instead used two high reflectors, let the pulse energy build up, and then switch out the pulse. This 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.

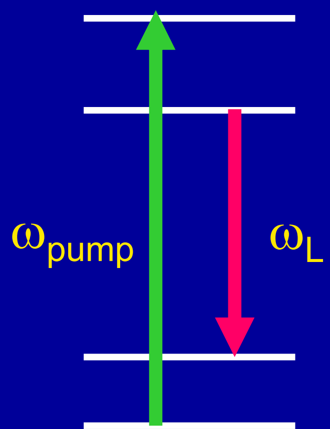
A voltage (a few kV) can turn a crystal into a half- or quarter-wave plate.



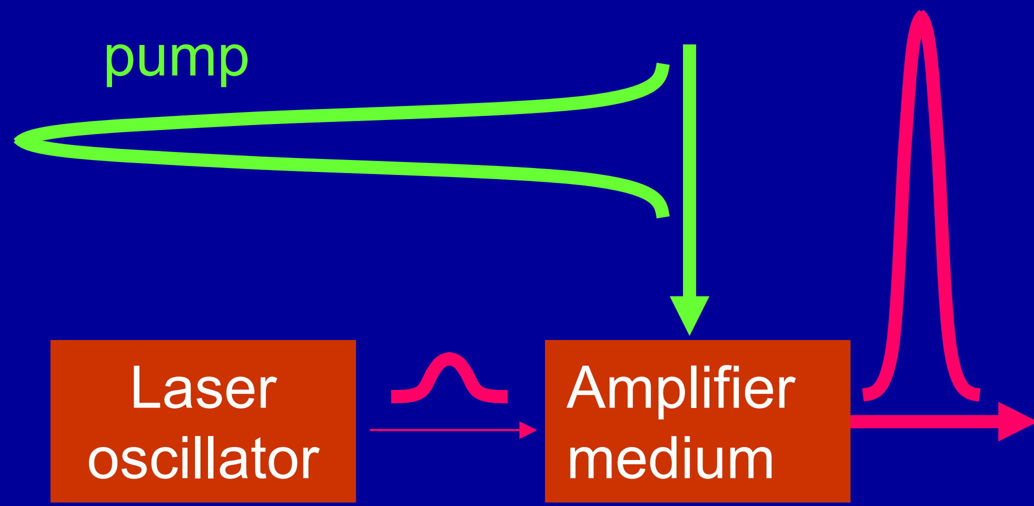
Abruptly switching a Pockels cell allows us to extract a pulse from a cavity. This allows us to achieve ~100 times the pulse energy at 1/100 the repetition rate (i.e., 100 nJ at 1 MHz).

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.



Energy levels

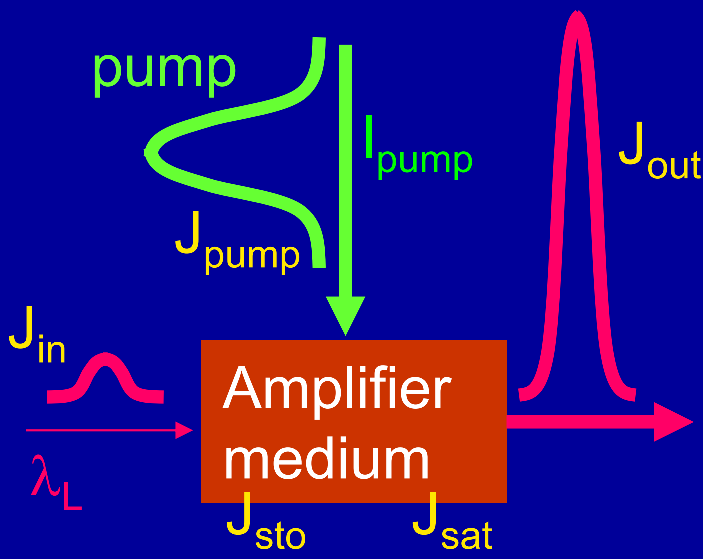


Stored energy = $J_{pump}(\omega_L/\omega_{pump})$

the quantity $(1 - \omega_L/\omega_{pump})$ is known as the 'quantum defect'

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:

$$\frac{dJ}{dz} = g_0 J \qquad \left(g_0 L = \frac{J_{sto}}{J_{sat}} << 1 \right)$$

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

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

A simple formula that interpolates between these two limits:

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

Single-pass Amplification Math

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

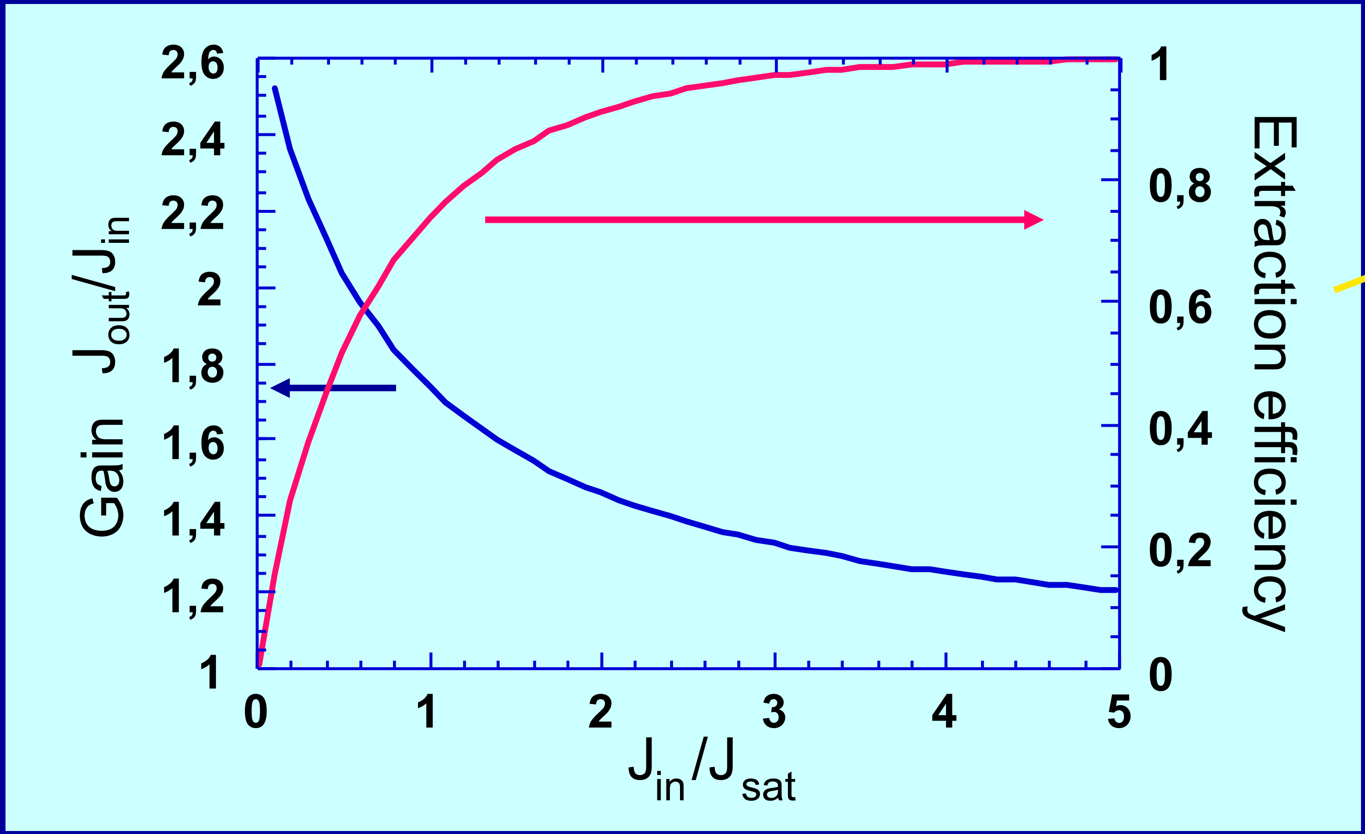
$$J_{out} = J_{sat} \log\left\{ G_0 \left[\exp\left(\frac{J_{in}}{J_{sat}} \right) - 1 \right] + 1 \right\}$$

where the small signal gain per pass is given by:

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

Frantz-Nodvick equation

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



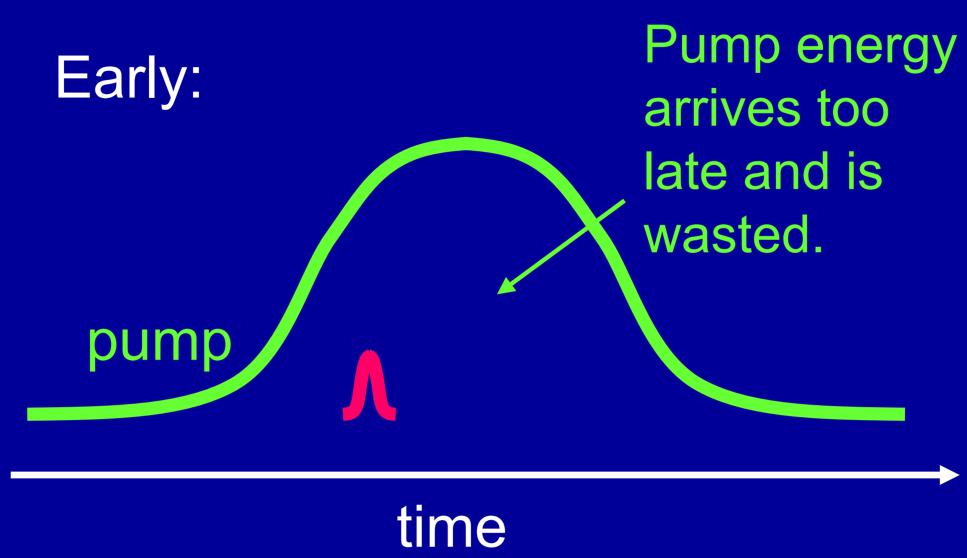
$$\frac{J_{out} - J_{in}}{J_{sto}}$$

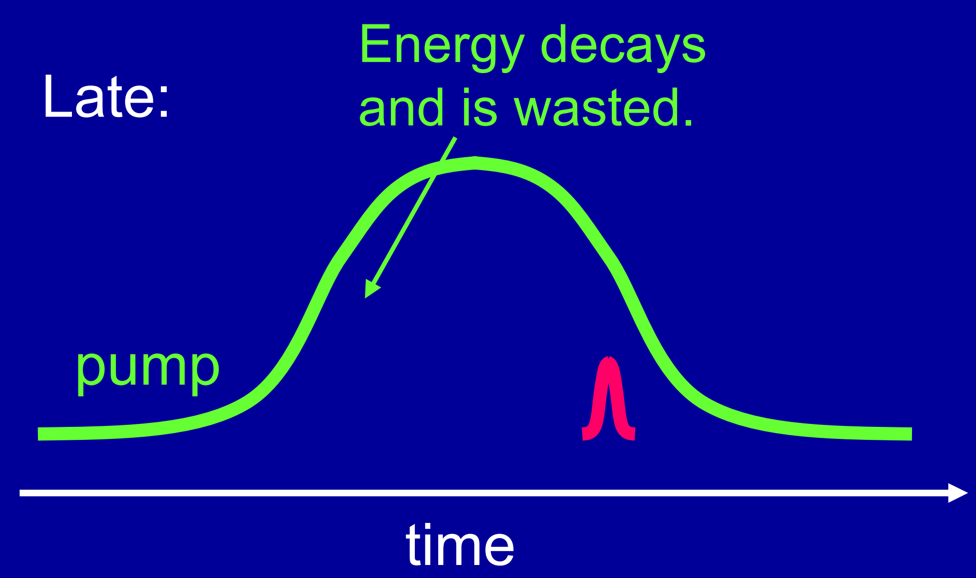
So you can have high gain or high extraction efficiency.
But not both.

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?

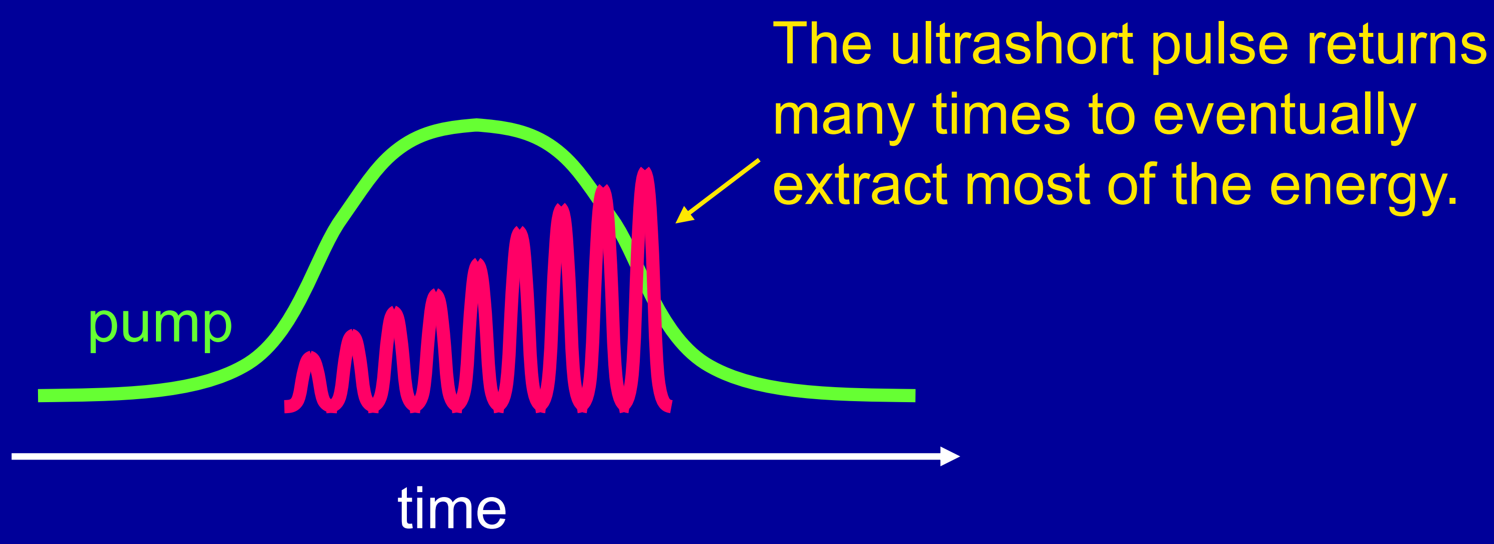




In both cases, pump pulse energy is wasted, and amplification is poor.

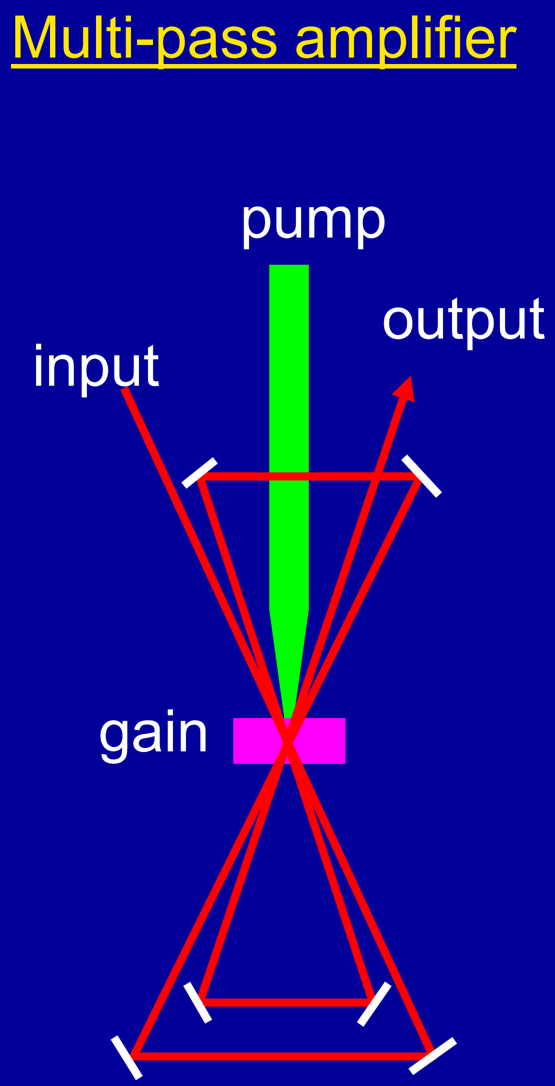
So we need many passes.

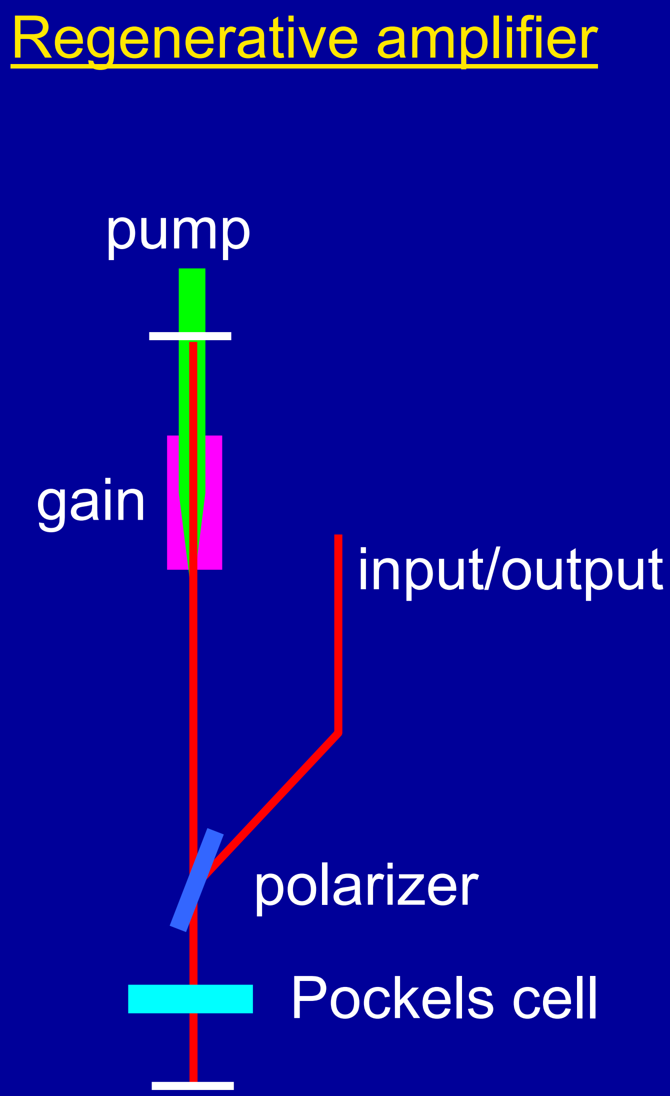
All ultrashort-pulse amplifiers are multi-pass.



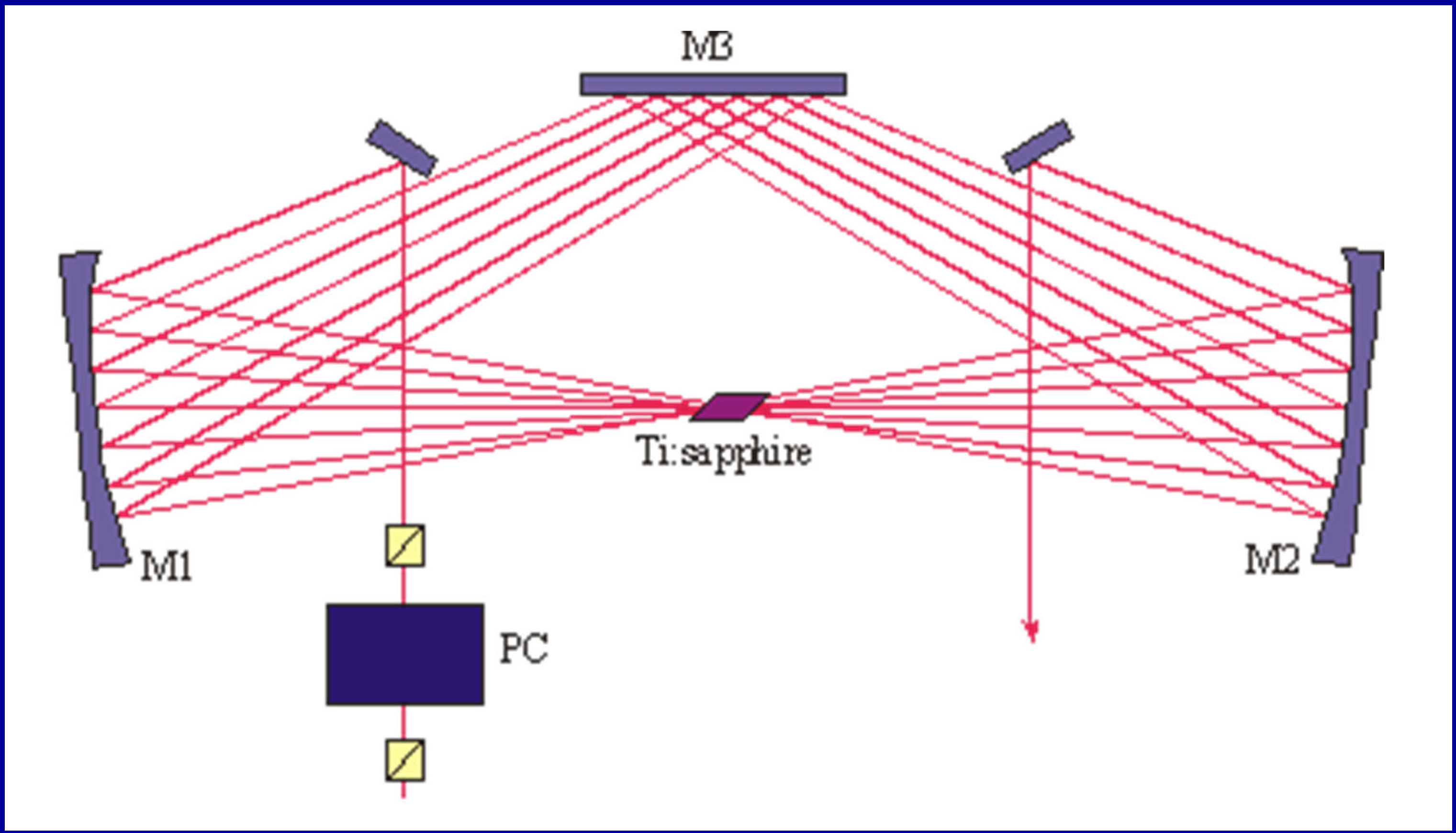
This approach achieves much greater efficiency.

Two main amplification methods



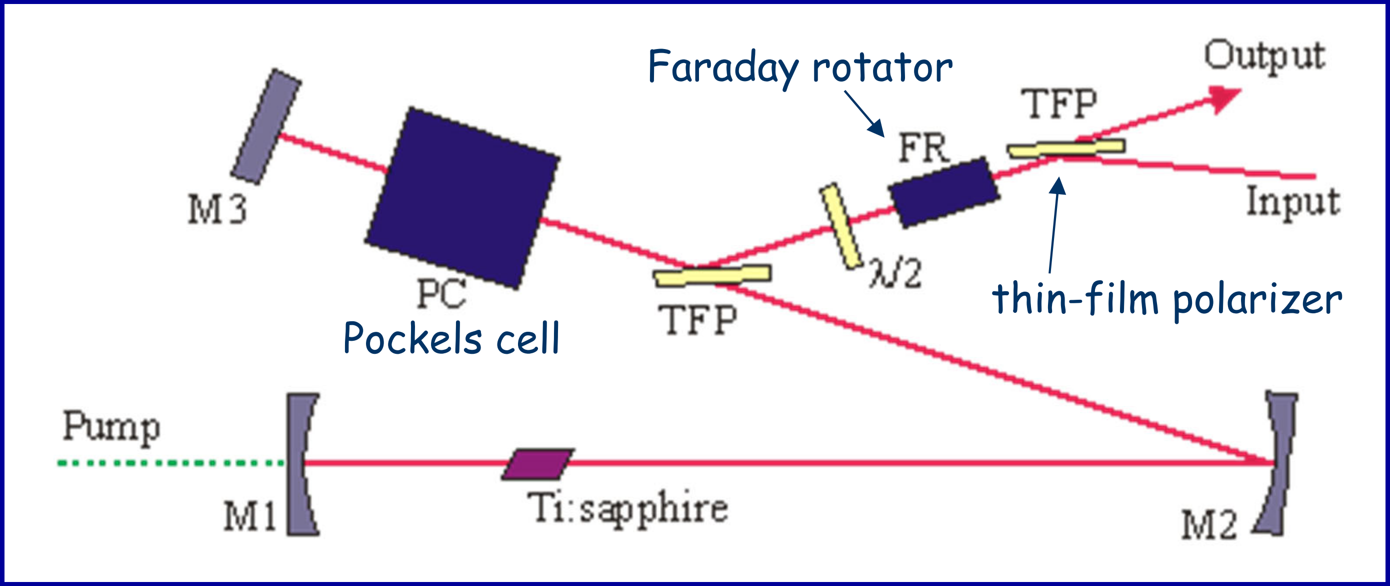


A multi-pass amplifier

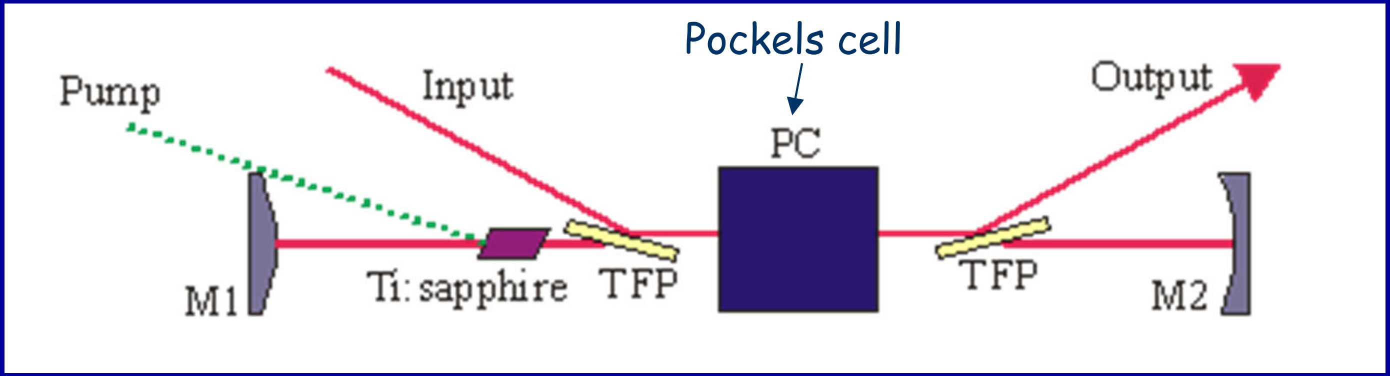


A Pockels cell (PC) and a pair of polarizers can be used to inject a single pulse into the amplifier.

Common 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.

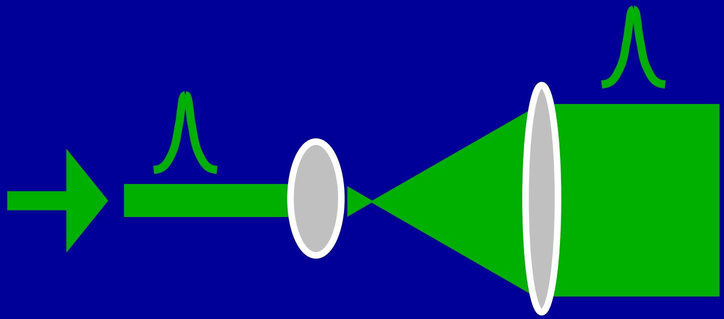
The Ti:Sapphire rod is ~20-mm long and doped for 90% absorption.

Okay, so what next?

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

Solution:

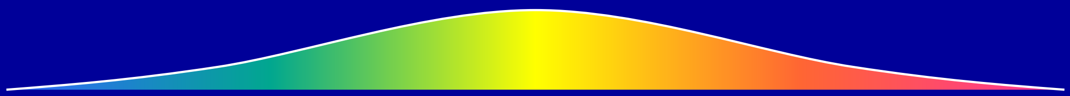
Expand the beam and use large amplifier media.



Okay, we can do that. But that's still not enough.

Solution:

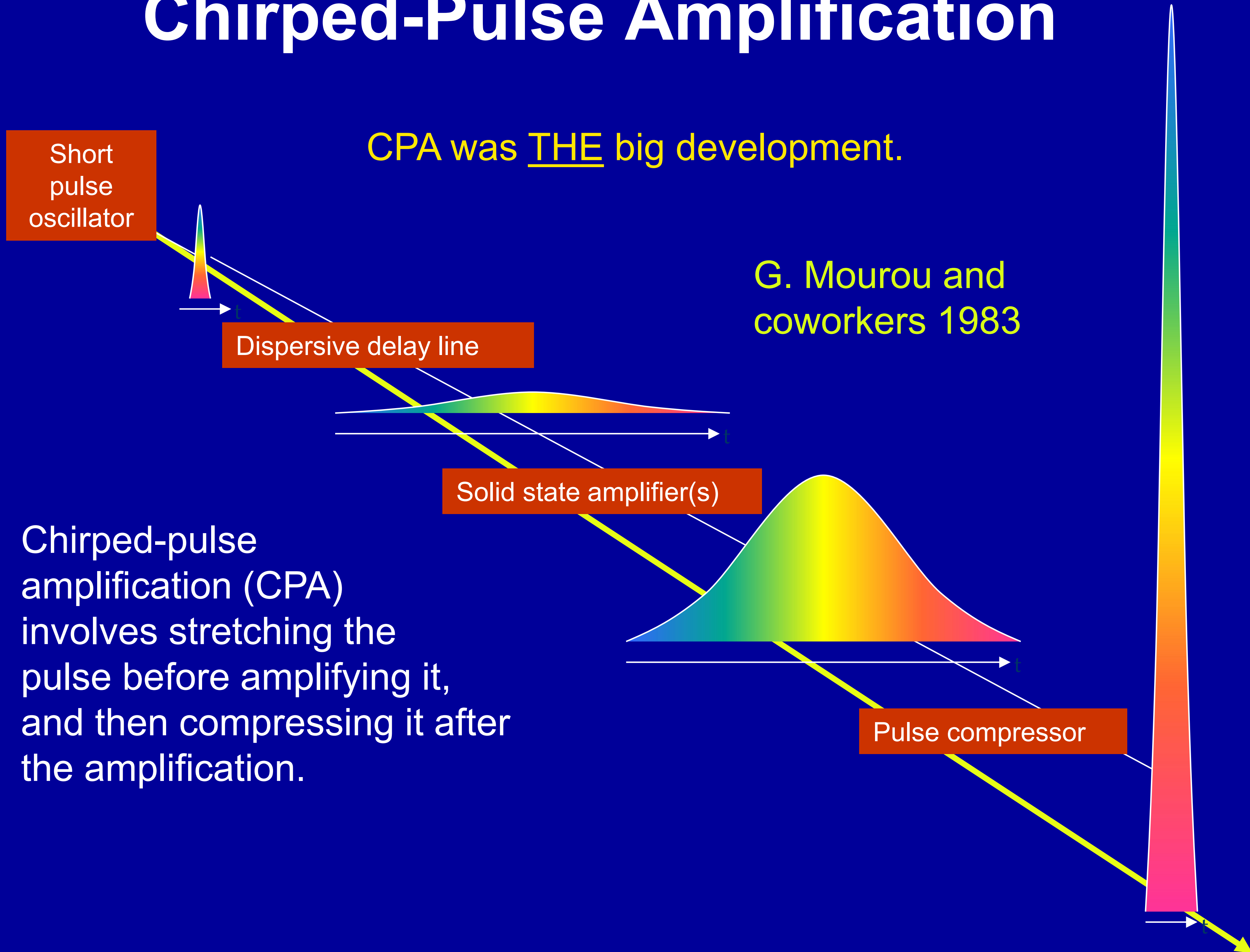
Expand the pulse **in time**, too.



Chirped-Pulse Amplification

CPA was THE big development.

G. Mourou and coworkers 1983



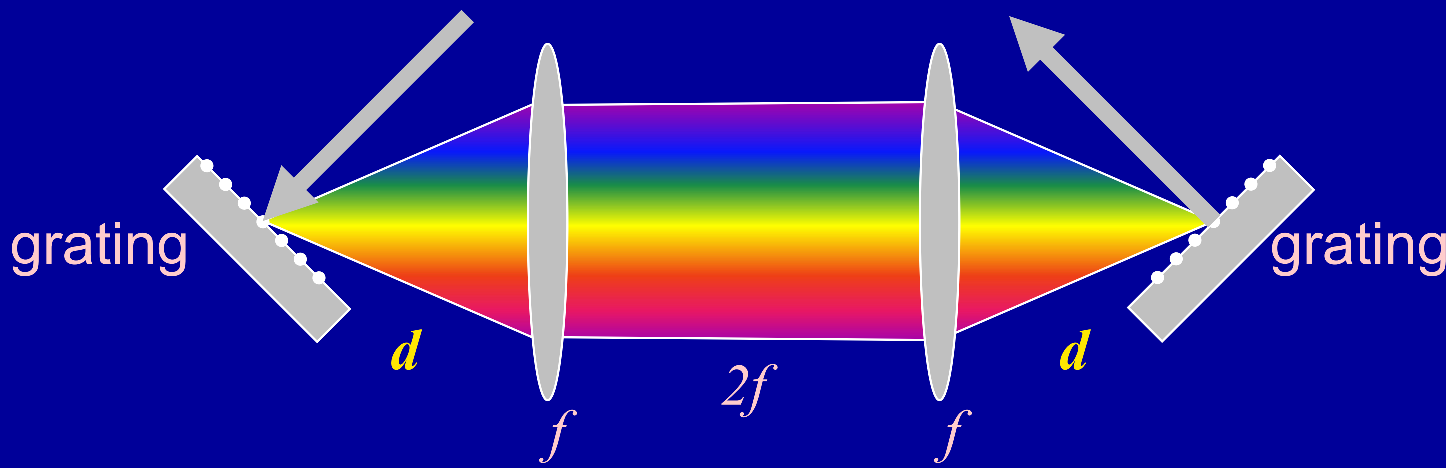
Chirped-pulse amplification (CPA) involves stretching the pulse before amplifying it, and then compressing it after the amplification.

Chirped-Pulse Amplification: Nobel Prize in Physics (2018)

Gerard Mourou and Donna Strickland

Stretching and compressing ultrashort pulses

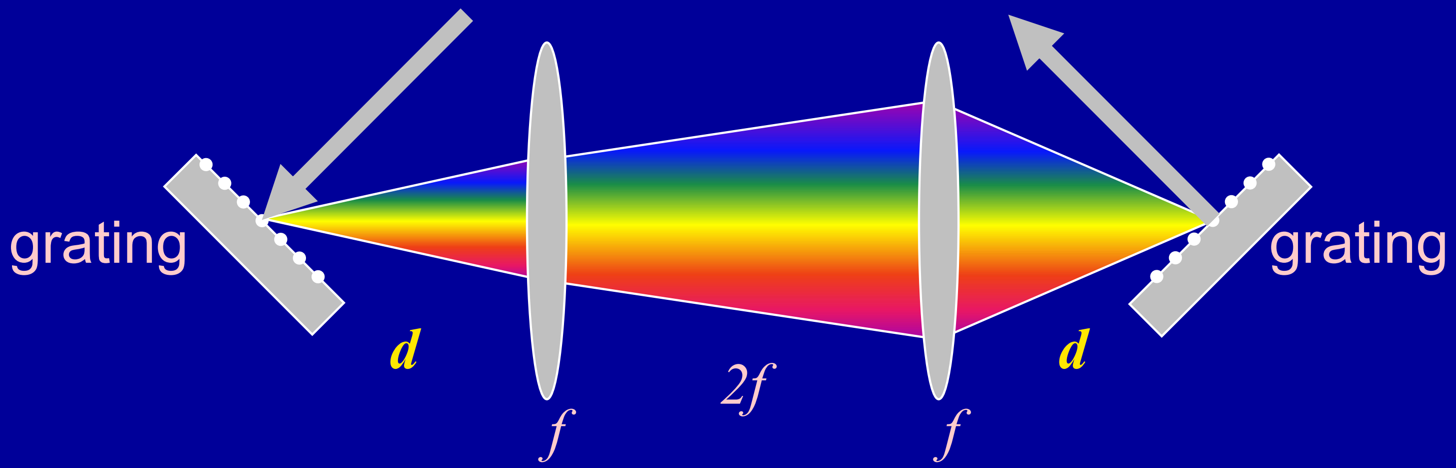
Pulse stretcher



In this configuration, where $d = f$, this is a “zero-dispersion stretcher” – the pulse that comes out is identical to the pulse that goes in (except weaker, because of losses due to the fact that the gratings do not diffract 100% of the input energy into the 1st-order diffracted beam)

Stretching and compressing ultrashort pulses

Pulse stretcher

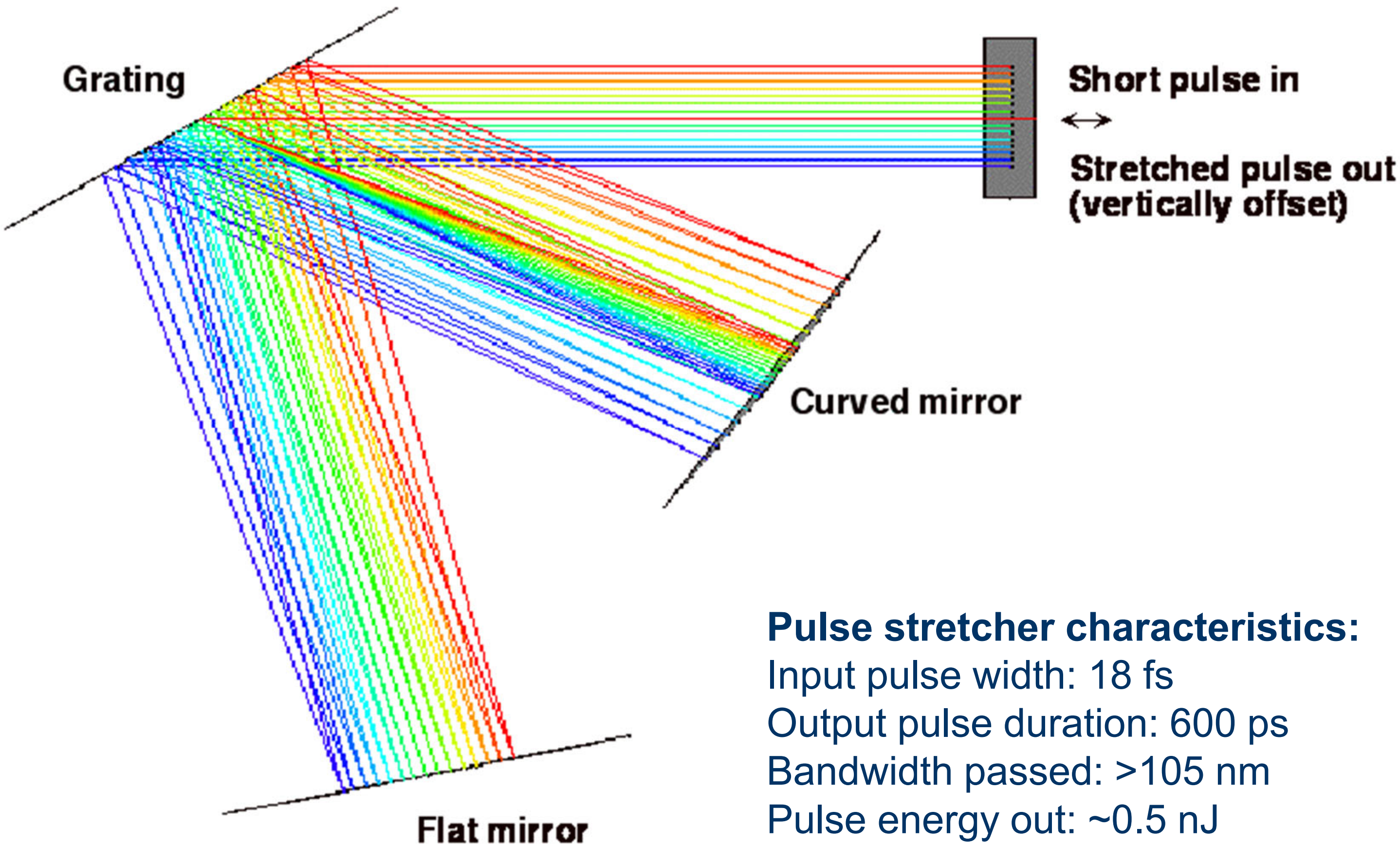


But when $d \neq f$, it's a dispersive stretcher and can stretch fs pulses by a large factor. A stretch factor of 10,000 is not unusual.

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

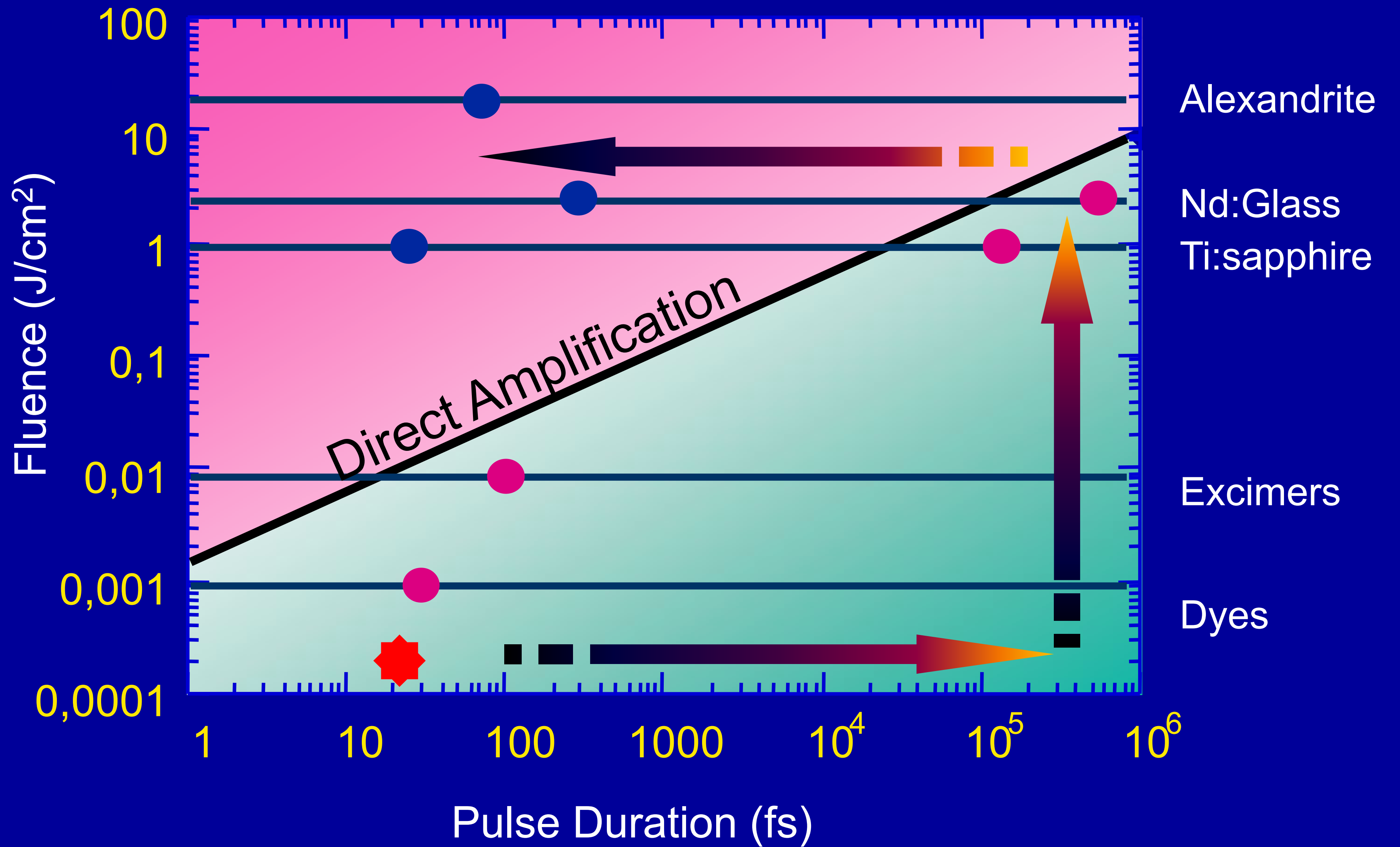
A pulse stretcher

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

CPA vs. Direct Amplification



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

Regenerative Chirped-Pulse Amplification at ~1 kHz rep rates with a cw pump

A Ti:sapphire oscillator requires only ~5 W of cw green laser power.
An intracavity-doubled Nd:YLF pump laser can provide up to 50 W.
One can therefore use the excess to pump an amplifier.

Coherent
Legend Amplifier

Typical performance specs:
pulse duration: 25 fs
pulse energy: 10 mJ
repetition rate: 1 kHz
ave. power: 10W
wavelength: 800 nm (Ti:sapphire)

Regenerative chirped-pulse amplification at a higher rep rate

Coherent RegA

Typical performance specs:
pulse duration: 50 fs
pulse energy: 6 μJ
repetition rate: 250 kHz
wavelength: 800 nm (Ti:sapphire)

$\left.\begin{array}{l}\text{pulse energy: 6 μJ}\\\text{repetition rate: 250 kHz}\end{array}\right\}$ ave. power: 1.5W

Higher peak power at lower rep rate

This is a two-stage amplifier: a regen pre-amp followed by a multi-pass power amp. The pump laser for the amplifiers is typically pulsed, not cw, so it is not the same laser used to pump the oscillator.

Coherent
Hidra

Typical performance specs:
pulse duration: 40 fs
pulse energy: 100 mJ
repetition rate: 10 Hz
ave. power: 1W
wavelength: 800 nm (Ti:sapphire)

Some typical power specs

	Rep rate		
	10 Hz	1 kHz	250 kHz
Extracted energy	100 mJ	10 mJ	6 μJ
Average Power	1 W	10 W	1.5 W
Peak Power	2.5 terawatts	0.4 terawatts	120 megawatts
Beam diameter	35 mm	1 mm	250 μm

These average powers are high. And the required pump power is also.

These are **dangerous** lasers.

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 amplifier's 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 $t = 0$

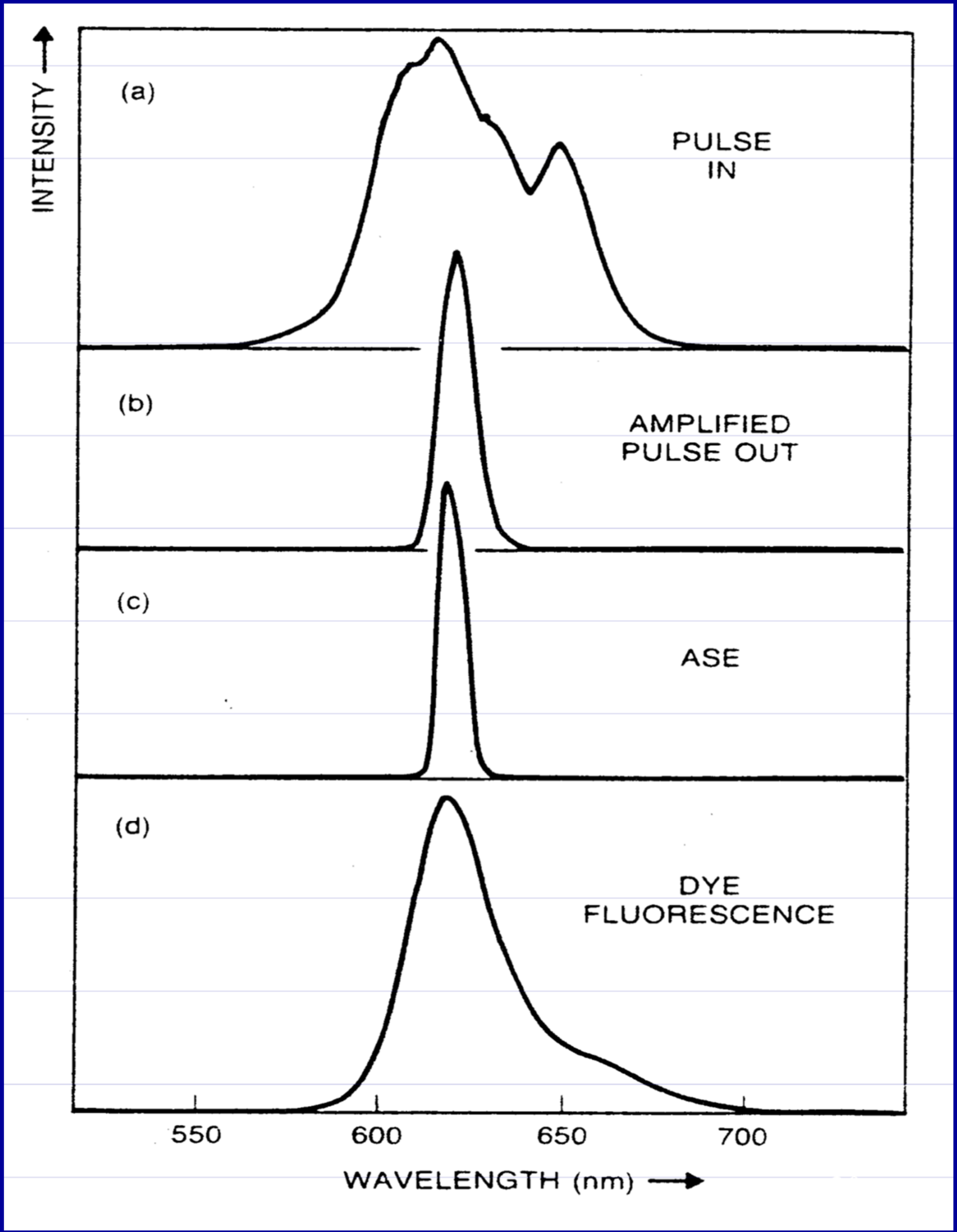
ASE shares the gain and the excited population with the pulse.

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

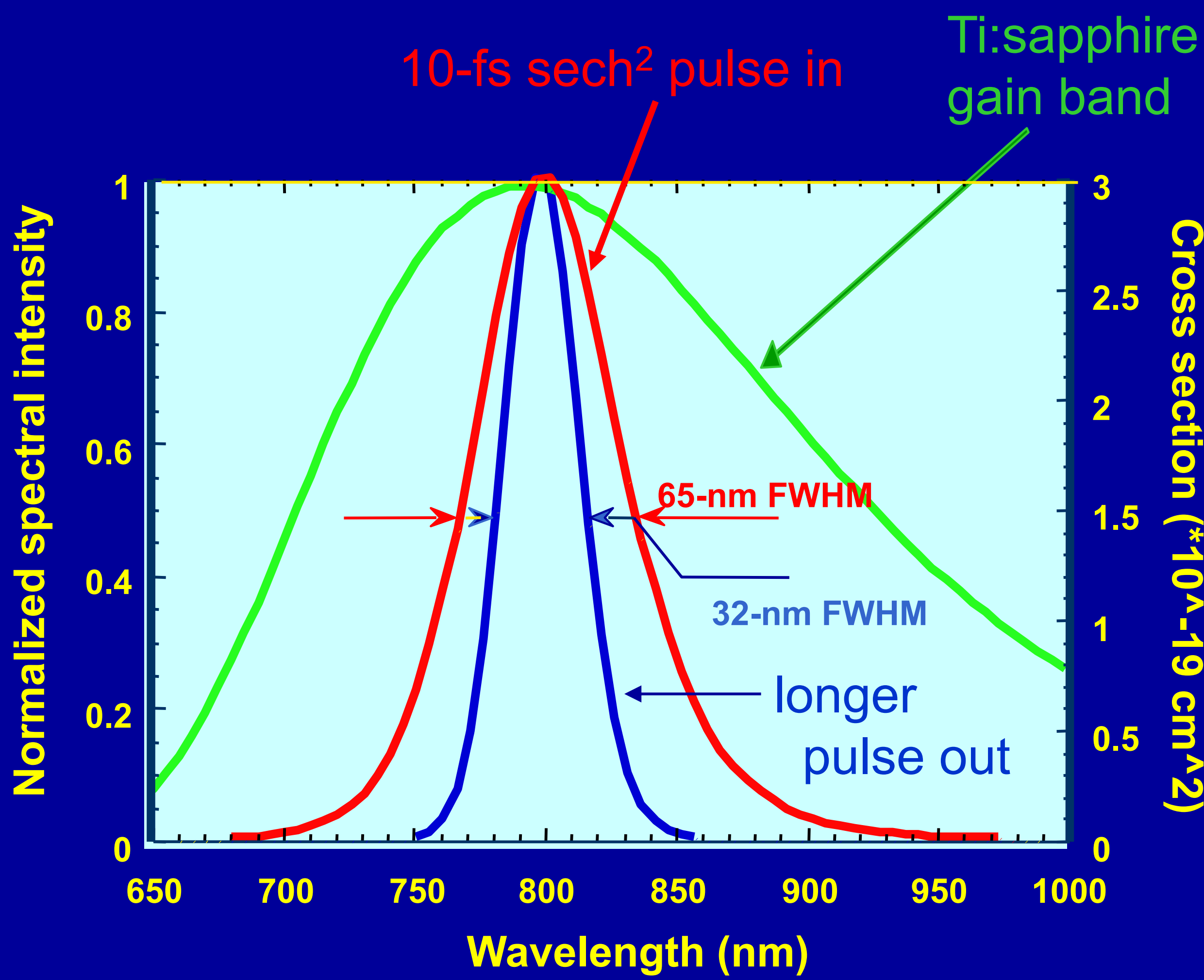
Gain Narrowing (and ASE)

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)



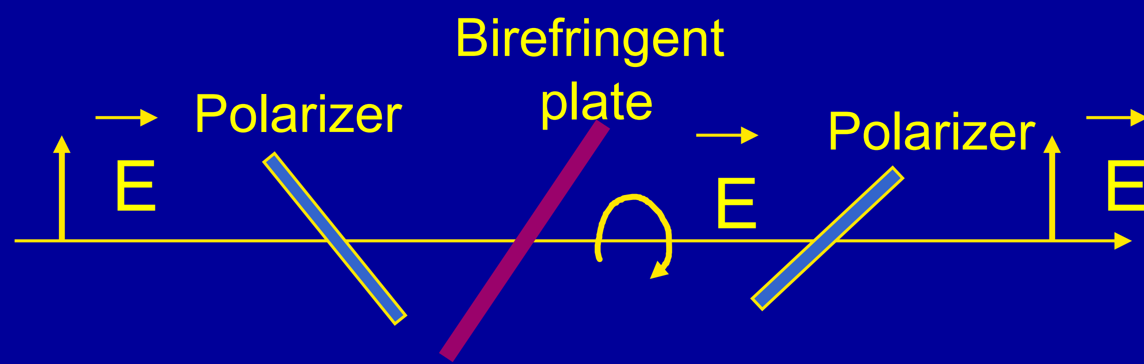
Gain narrowing example



Factor of 2 loss in bandwidth for 10^7 gain

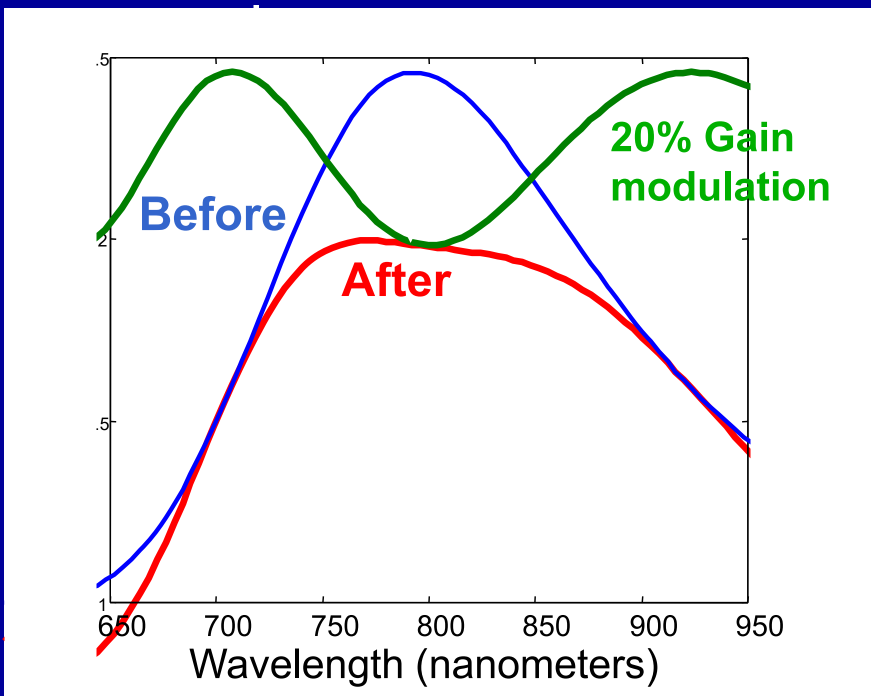
Most Terawatt systems have $>10^{10}$ small signal gain

Beating gain narrowing

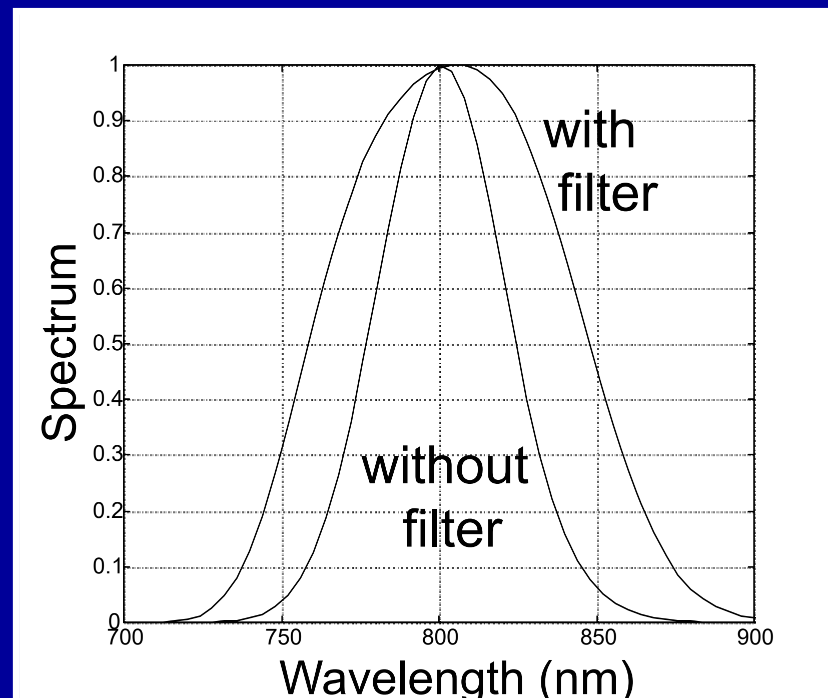


Introduce some loss at the gain peak to offset the high gain there.

Gain and



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

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.

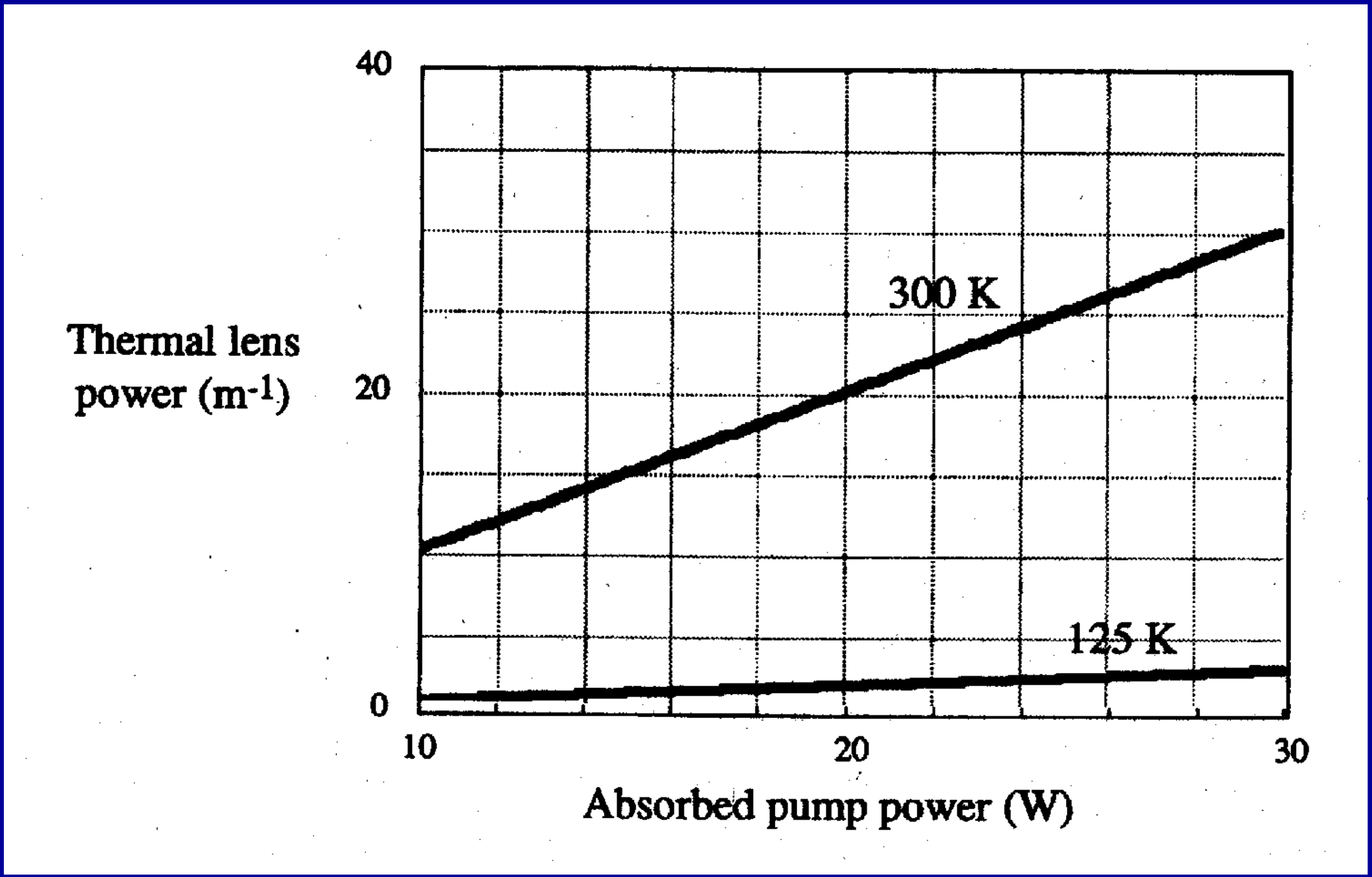
$$I_{peak} = \frac{E}{A\,\delta T}$$

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.

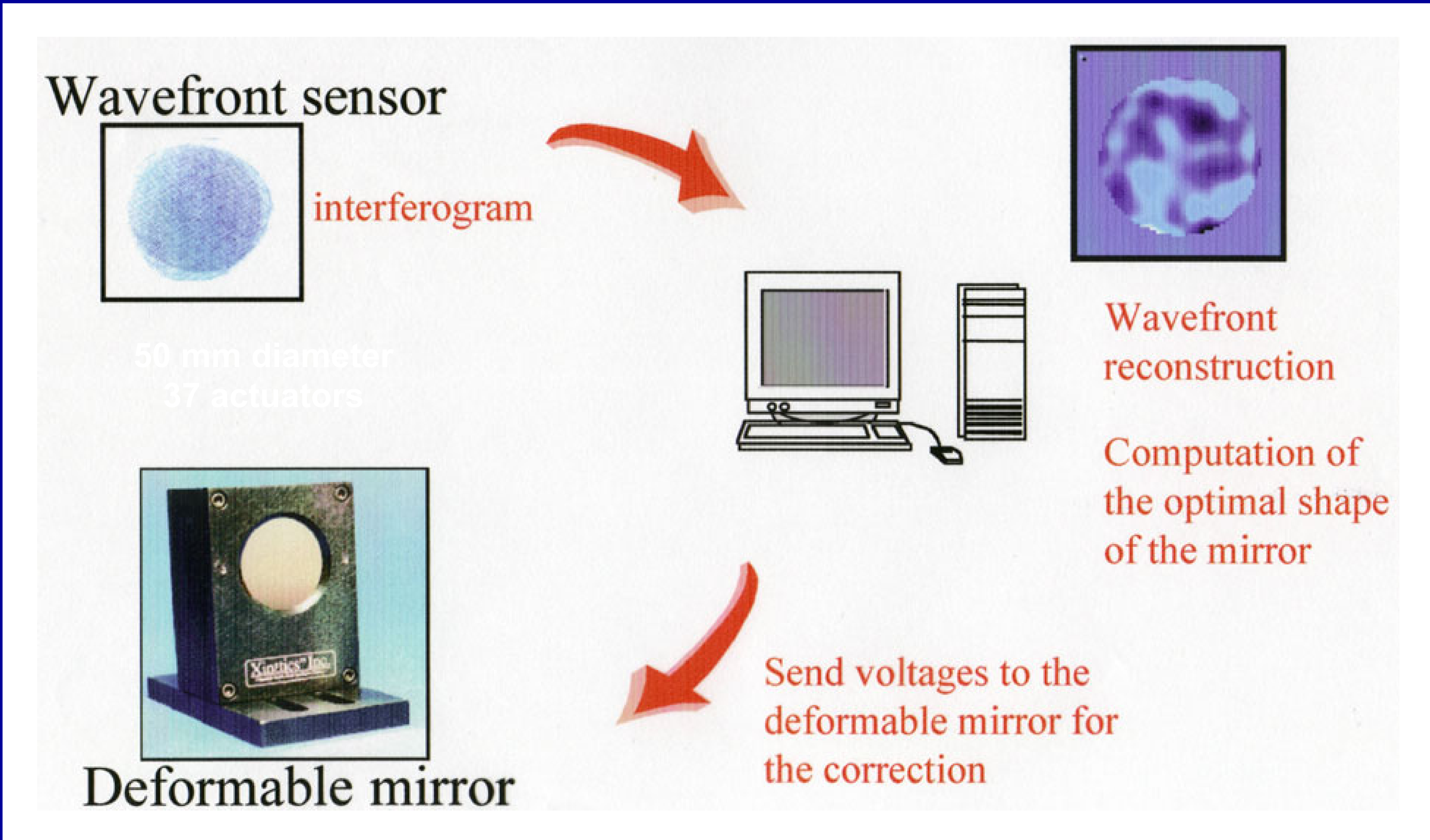


Calculations for kHz systems

Cryogenic cooling results in almost no focal power

Murnane, Kapteyn, and coworkers

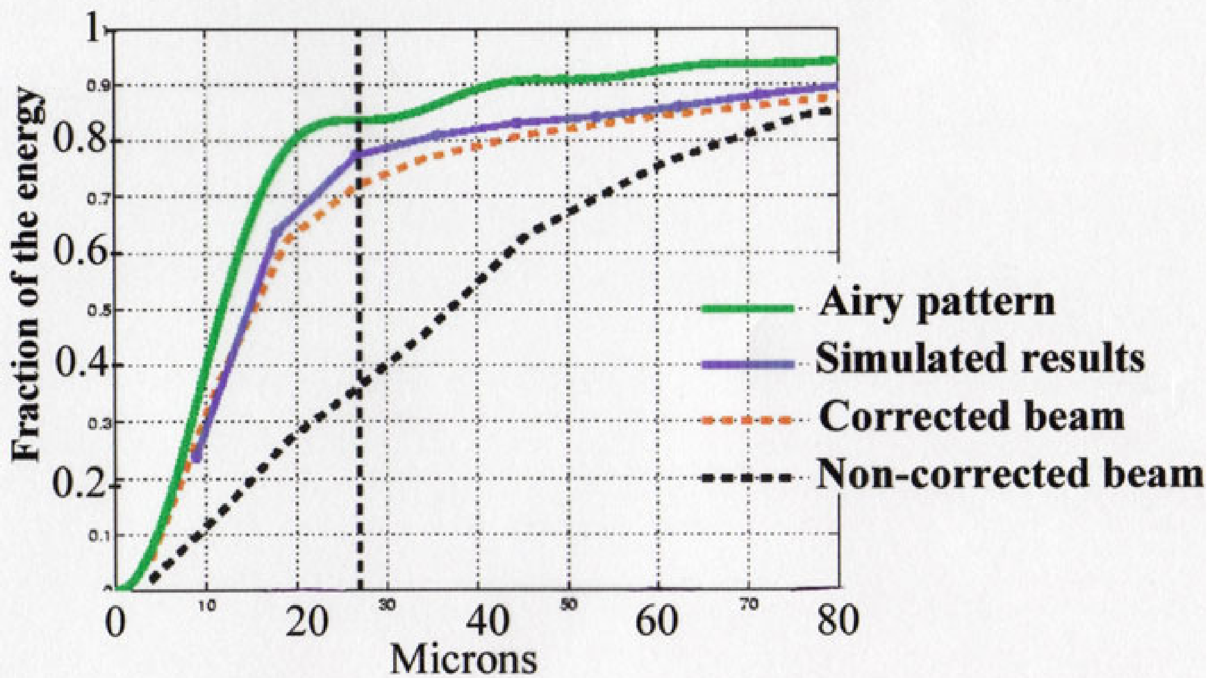
Dynamic Correction of Spatial Distortion



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

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

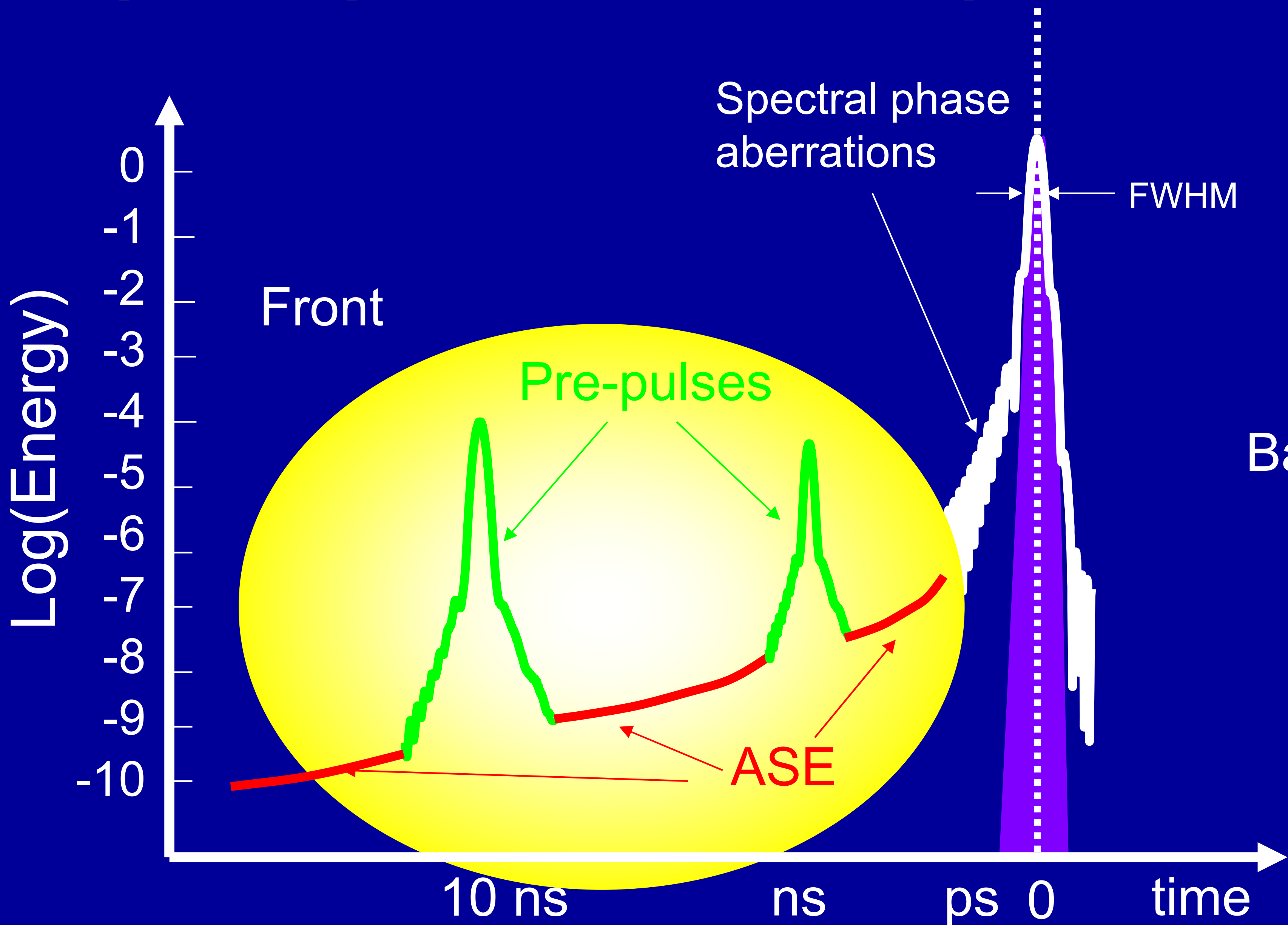
ASE from amplifier

Picosecond scale:

reflections in the amplifier

spectral phase or amplitude distortions

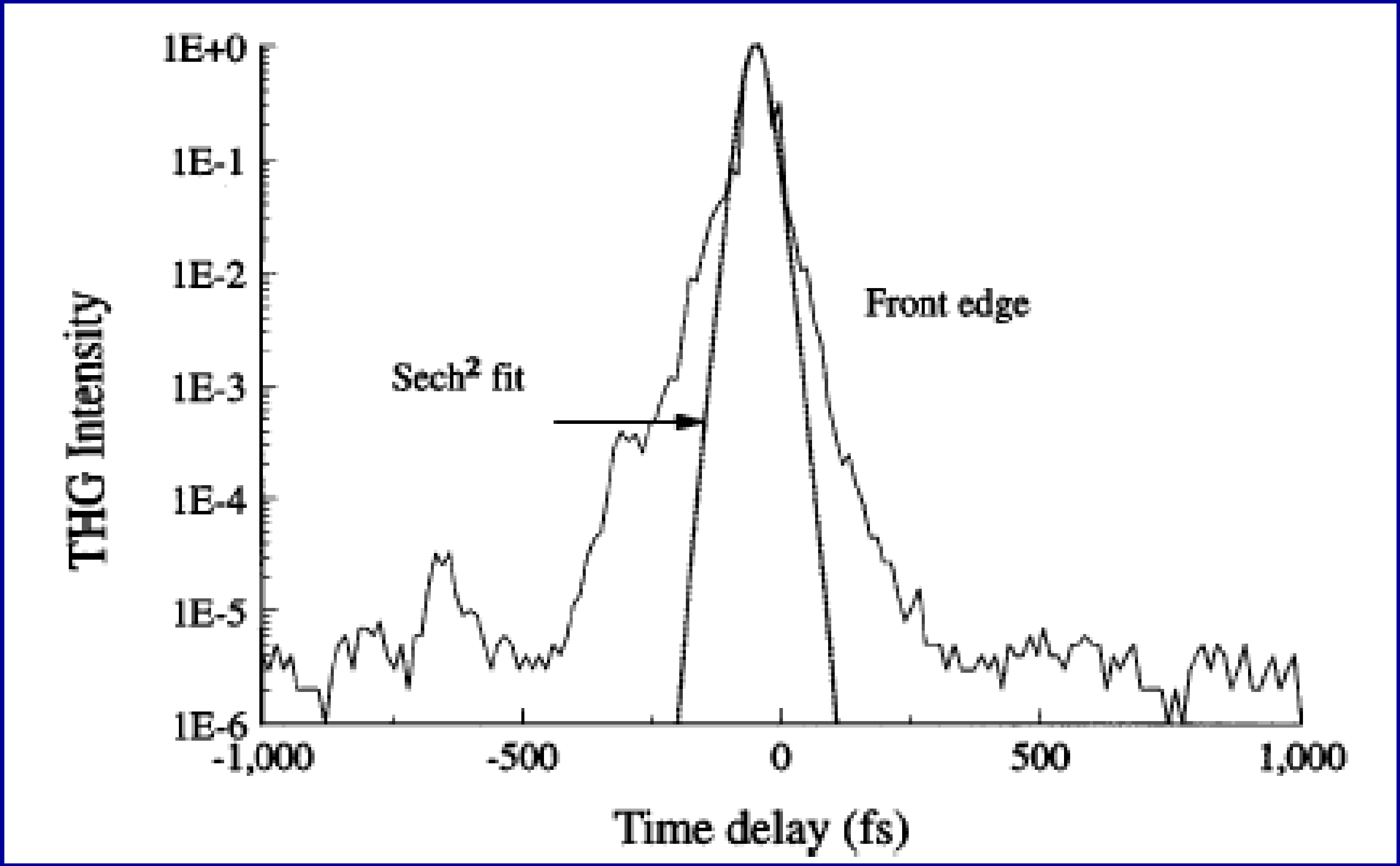
Amplified pulses often have poor contrast.



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

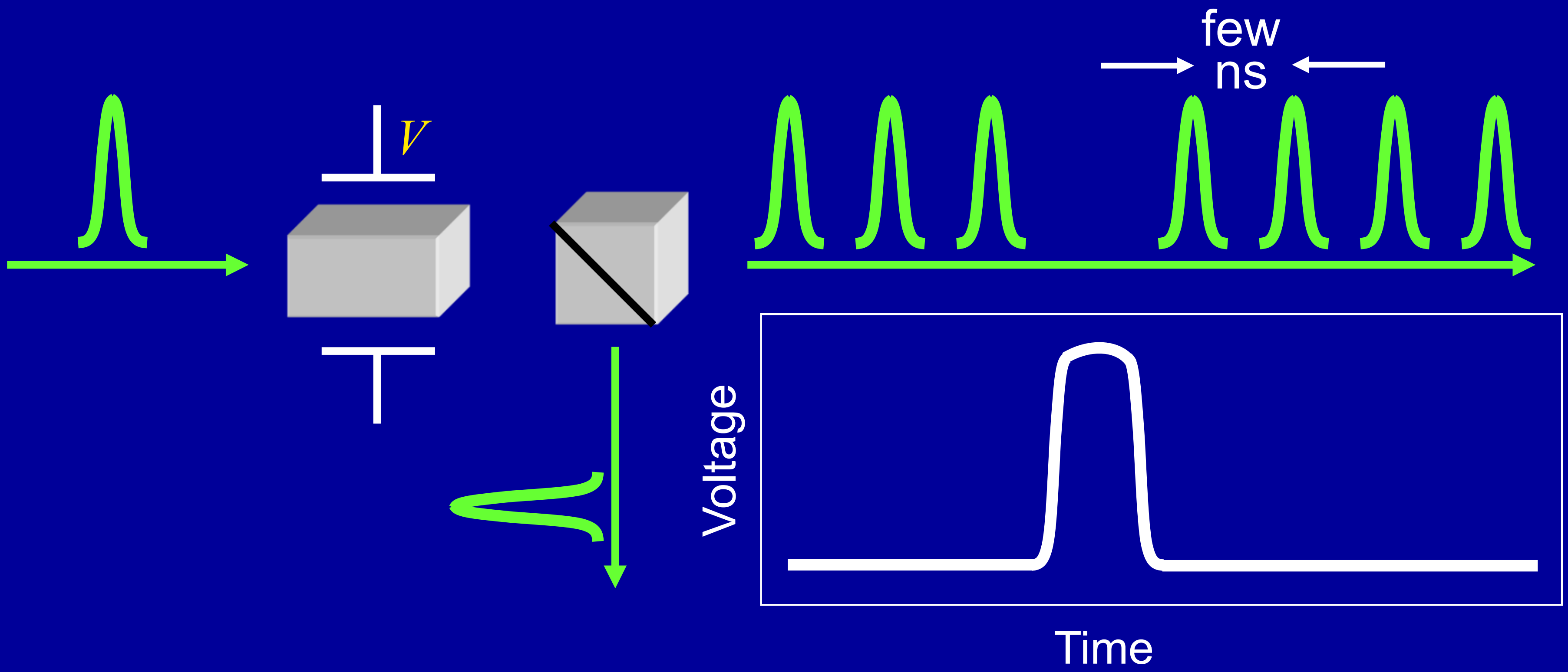
Amplified pulses can have pre- and post-pulses.

Typical 3rd order autocorrelation



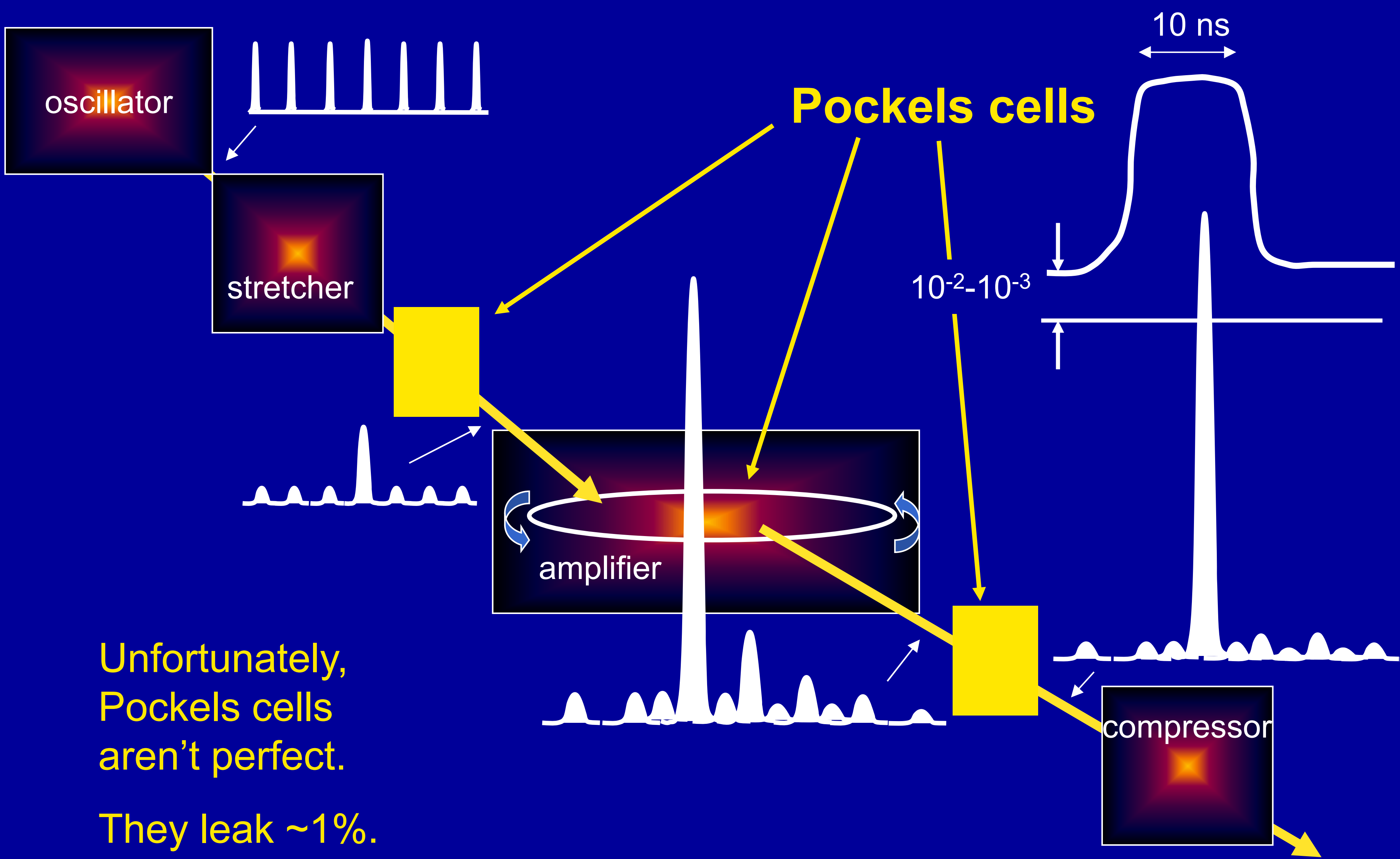
A Pockels cell "Pulse Picker"

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:

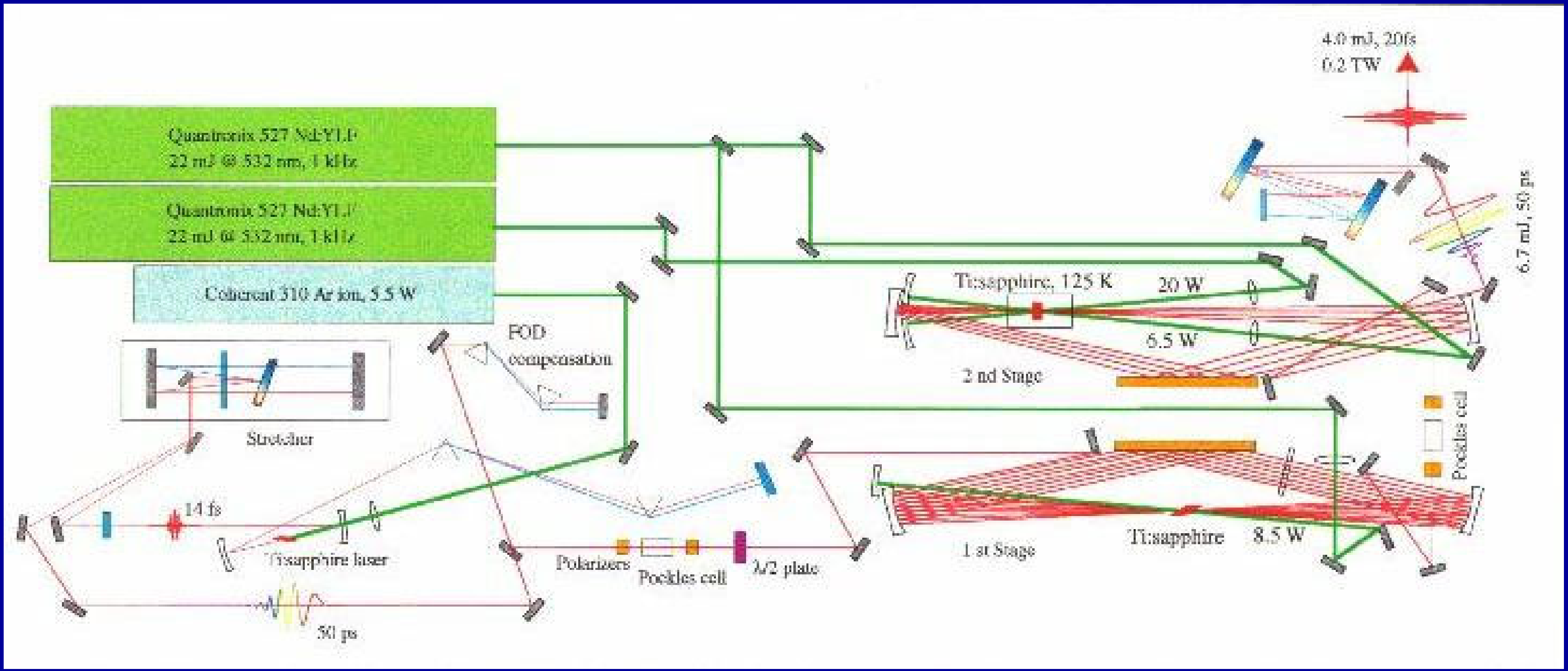
- on axis (do not tilt a Pockels cells)
- broadband high-contrast polarizers (not dielectric)
- fast rise time (<<2 ns 10-90%)
- collimated beams

Temperature drift is also a problem in Pockels cells.

Multiple-stage multi-pass amplifiers

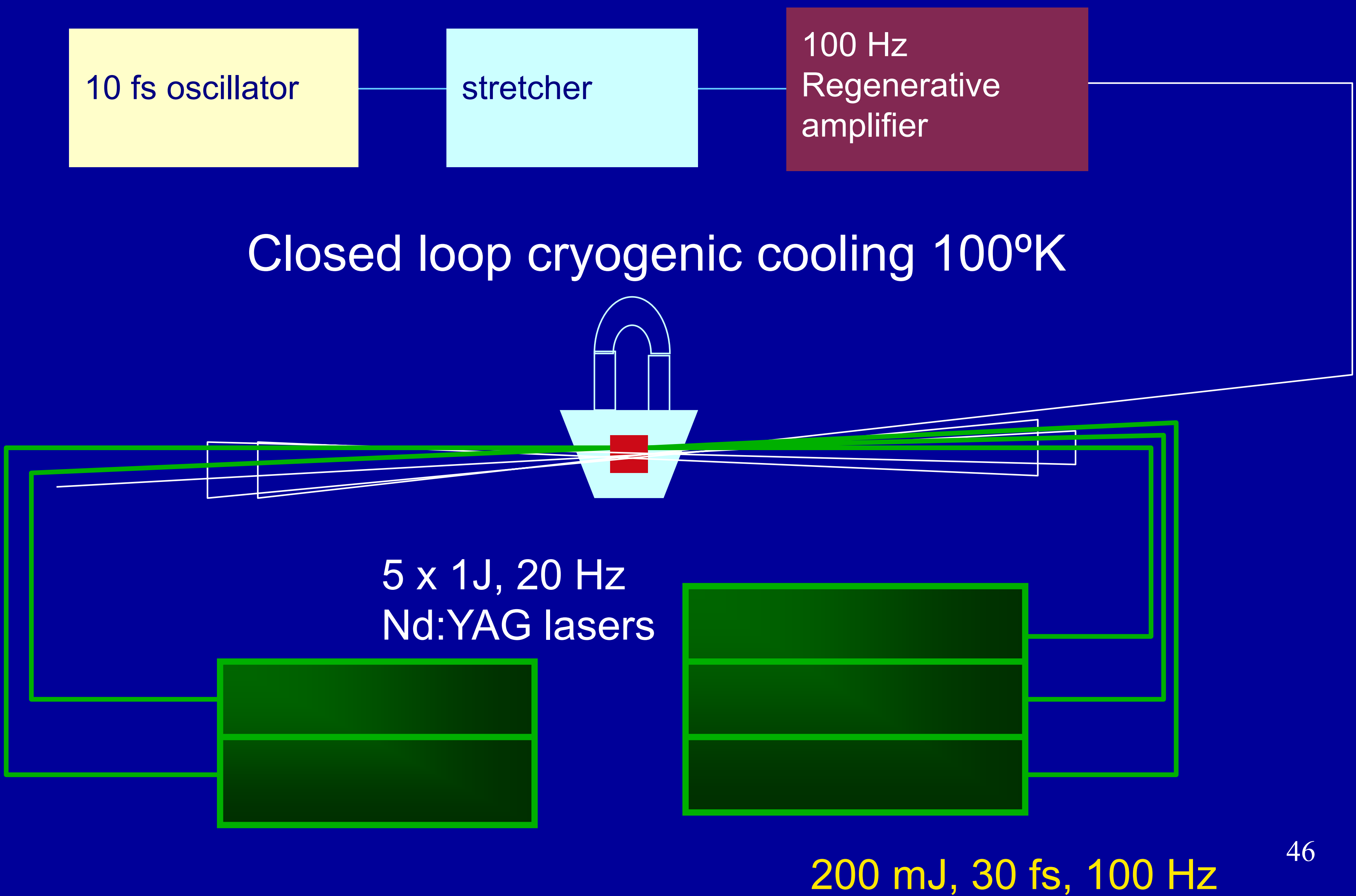
4 mJ, 20 fs pulse length

0.2 TW



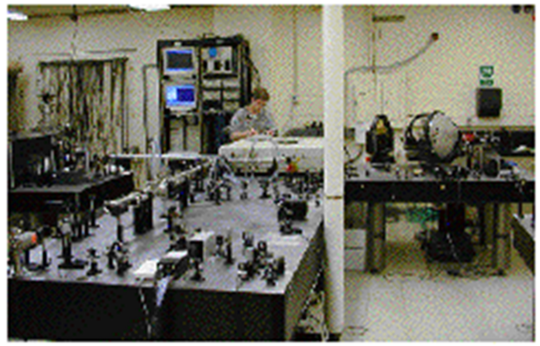
1 kHz Multi-pass system at the
University of Colorado (Murnane and Kapteyn)

High energy, high contrast 100-Hz system at CELIA (Bordeaux)

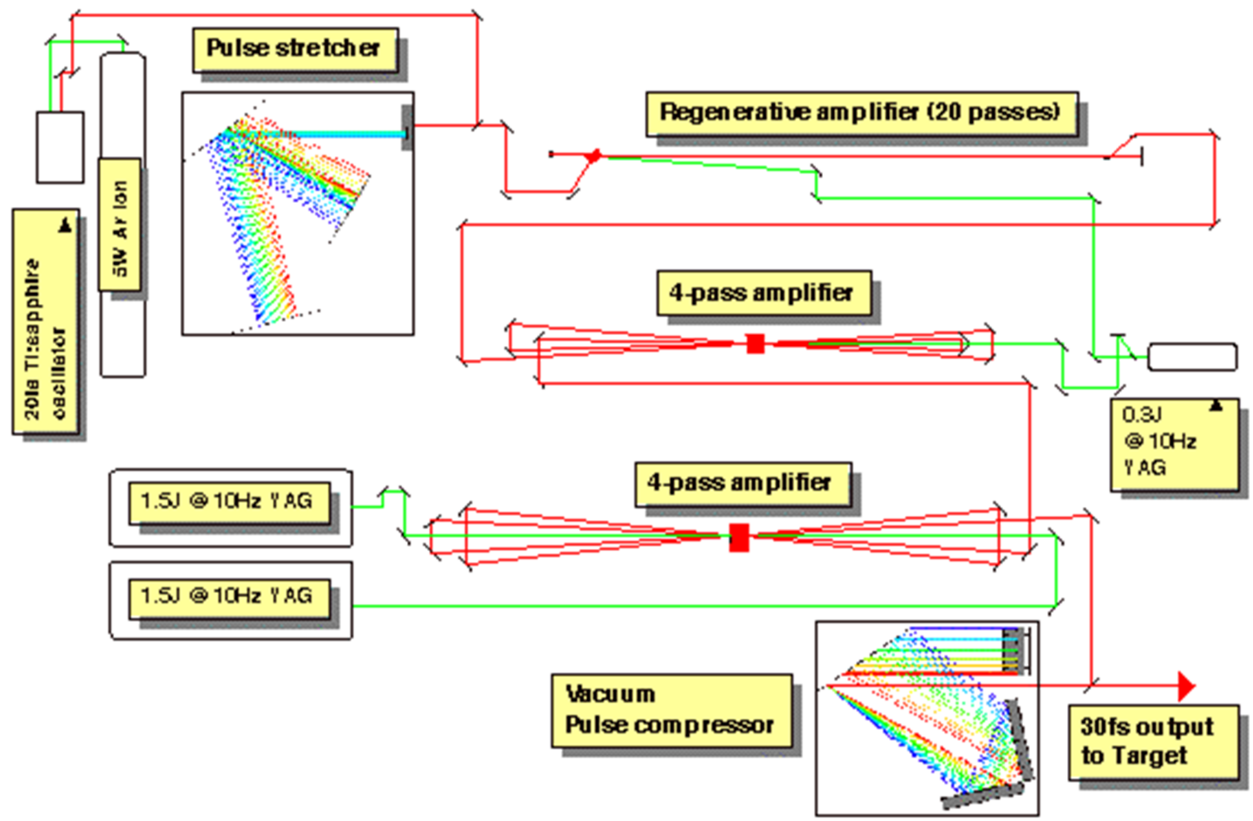


A 1-Joule Apparatus (scary)

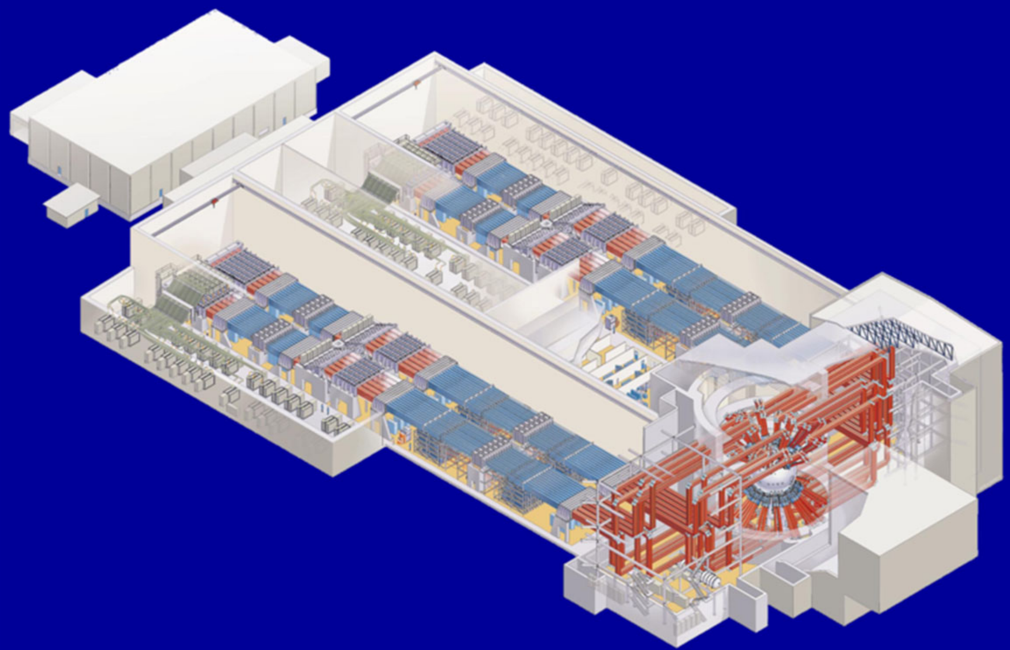
The Texas High-Intensity Optical Research Laser - The THOR laser



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



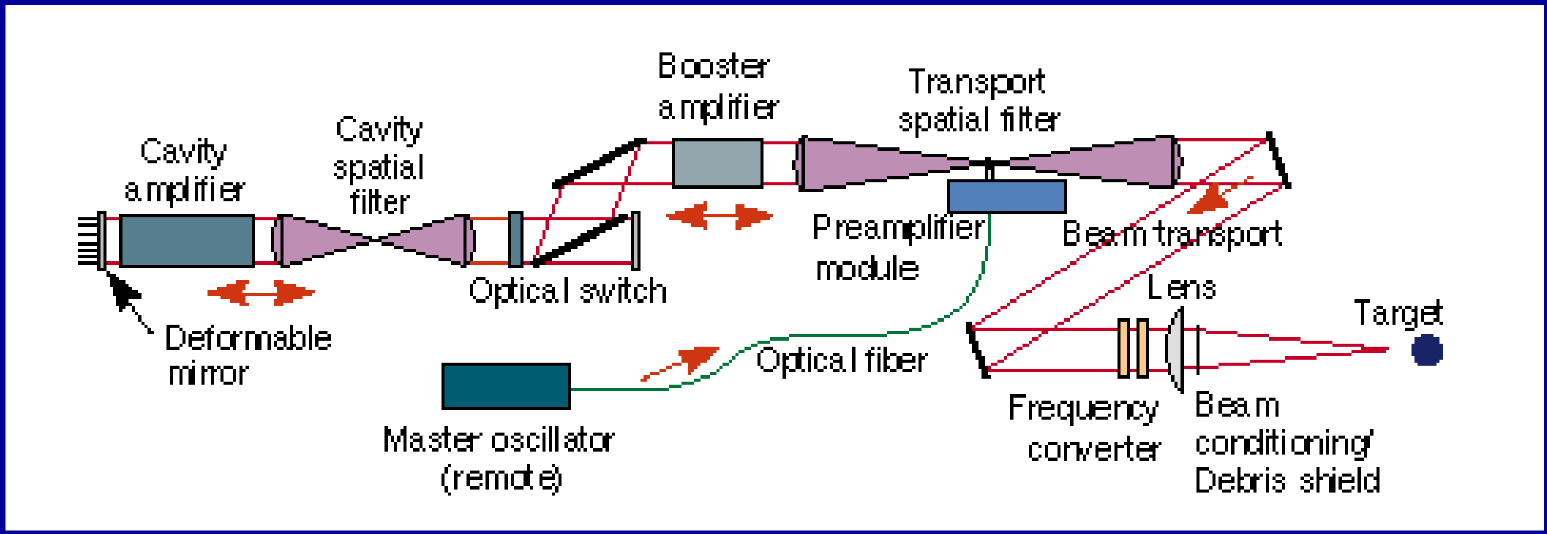
Even Higher Intensities!



National Ignition Facility
(dedication ceremony: May 2009)

192 shaped pulses
>1.8 MJ total energy on target
(achieved in July 2012)
Pulses 0.2 to 25 ns in duration

Rep rate: ~50 pulses/month



What to do with such high intensities