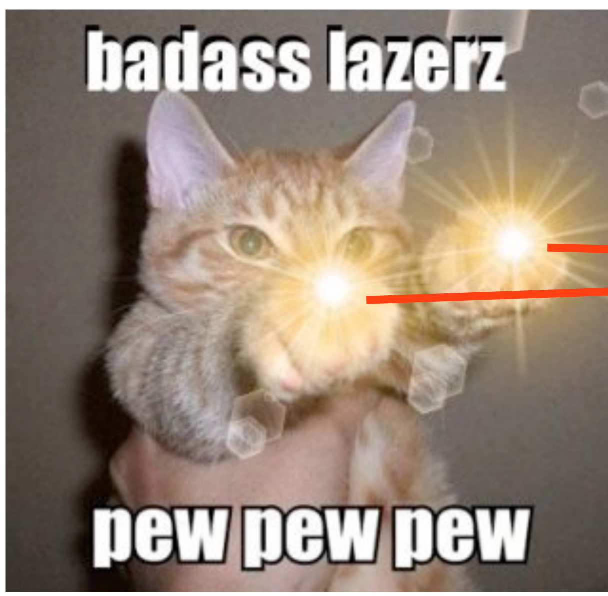
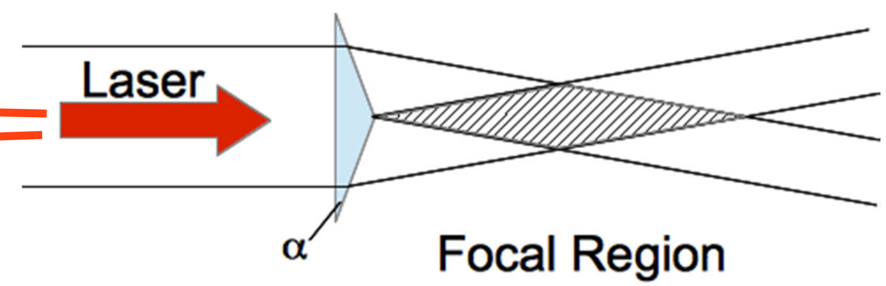
Chirped Pulse Amplification for the FACET Ionization Laser





Spencer Gessner

Laser Applications to Accelerators
USPAS January 2013

FACET

SLAC
NATIONAL ACCELERATOR LABORATORY

Plasma Wakefield Acceleration at FACET

Goal:

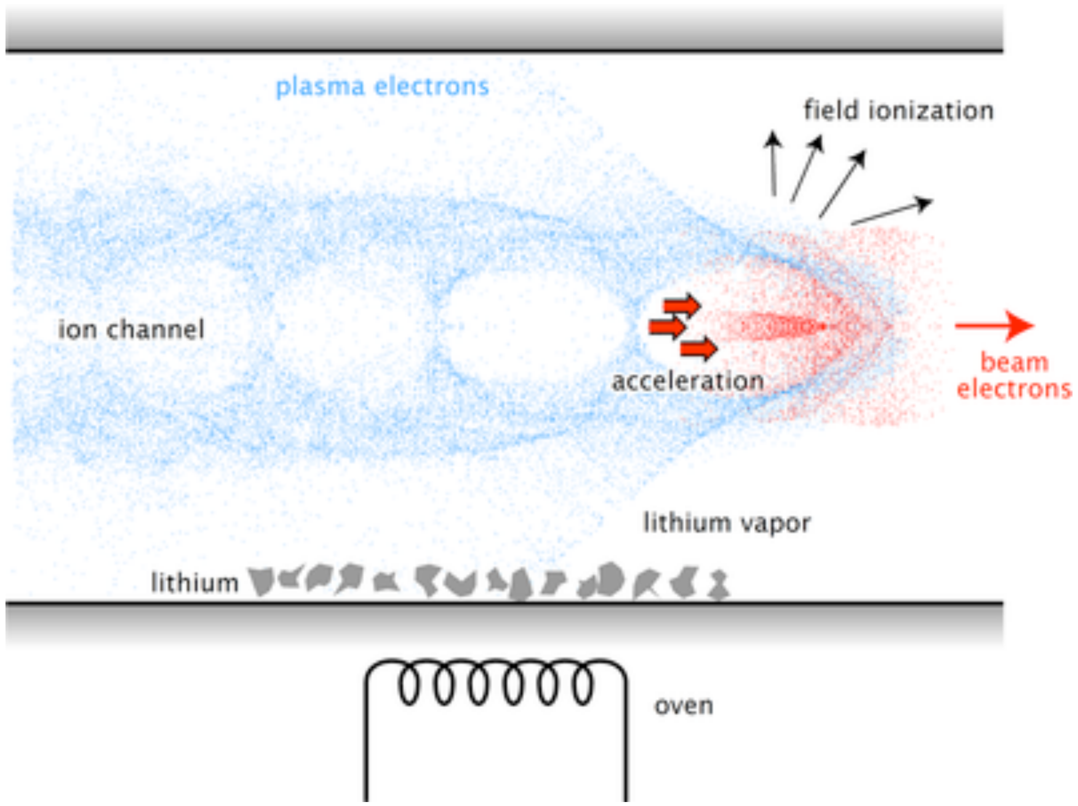
Double energy of 20 GeV FACET electron beam in one meter of Lithium plasma (Gradient = 20GV/m).

Requires:

One meter of Lithium plasma.

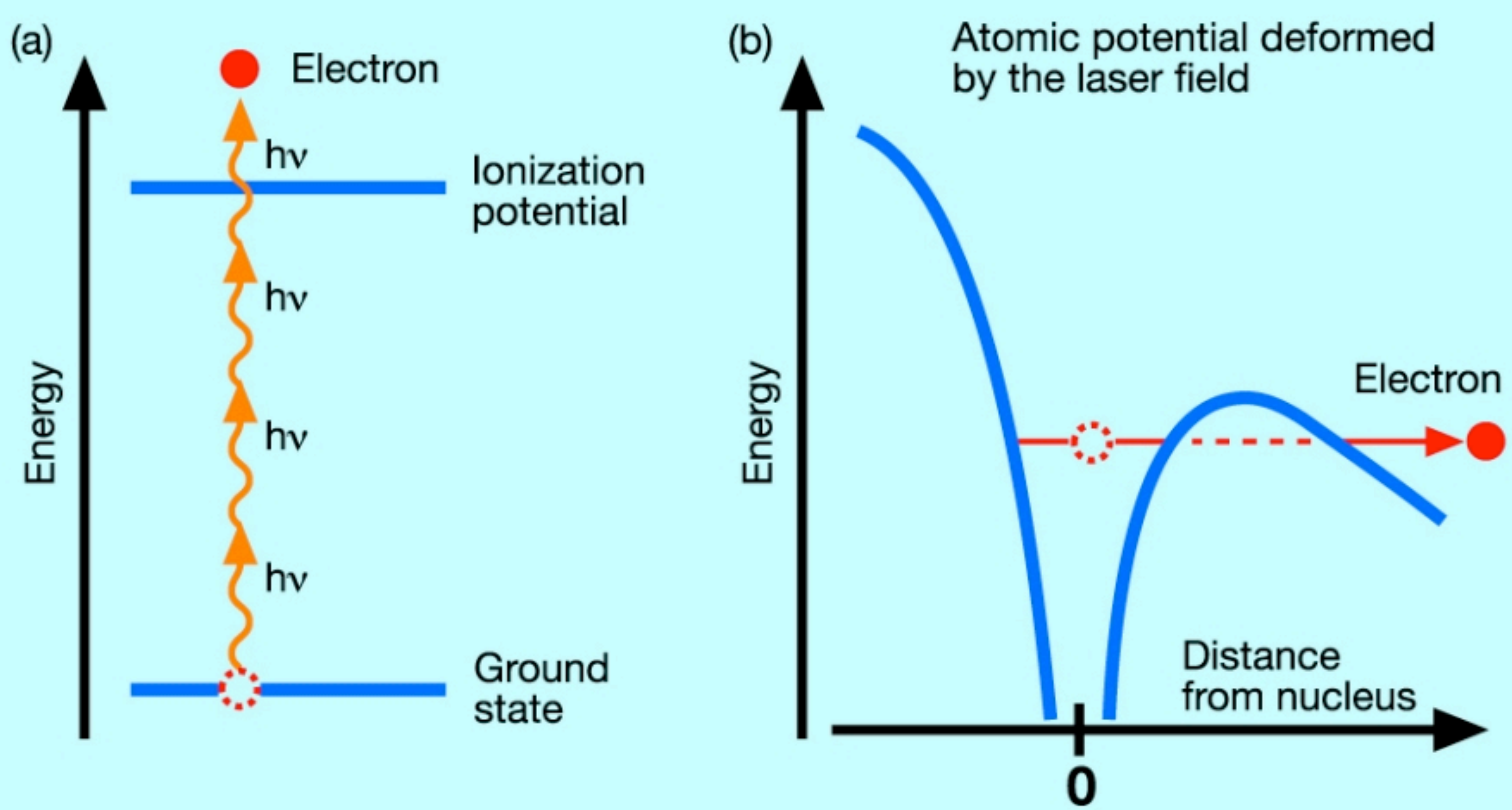
Beam Field Ionization

In the existing scheme at FACET, the intense field of the beam ionizes the Lithium vapor to create a plasma and also drives a wake in the plasma.



Beam energy is “wasted” in order to crate the plasma.

Laser Ionization



Multi-Photon Ionization

ADK Tunnel Ionization

Solution is to pre-ionize the plasma with an intense laser pulse.

Laser Requirements

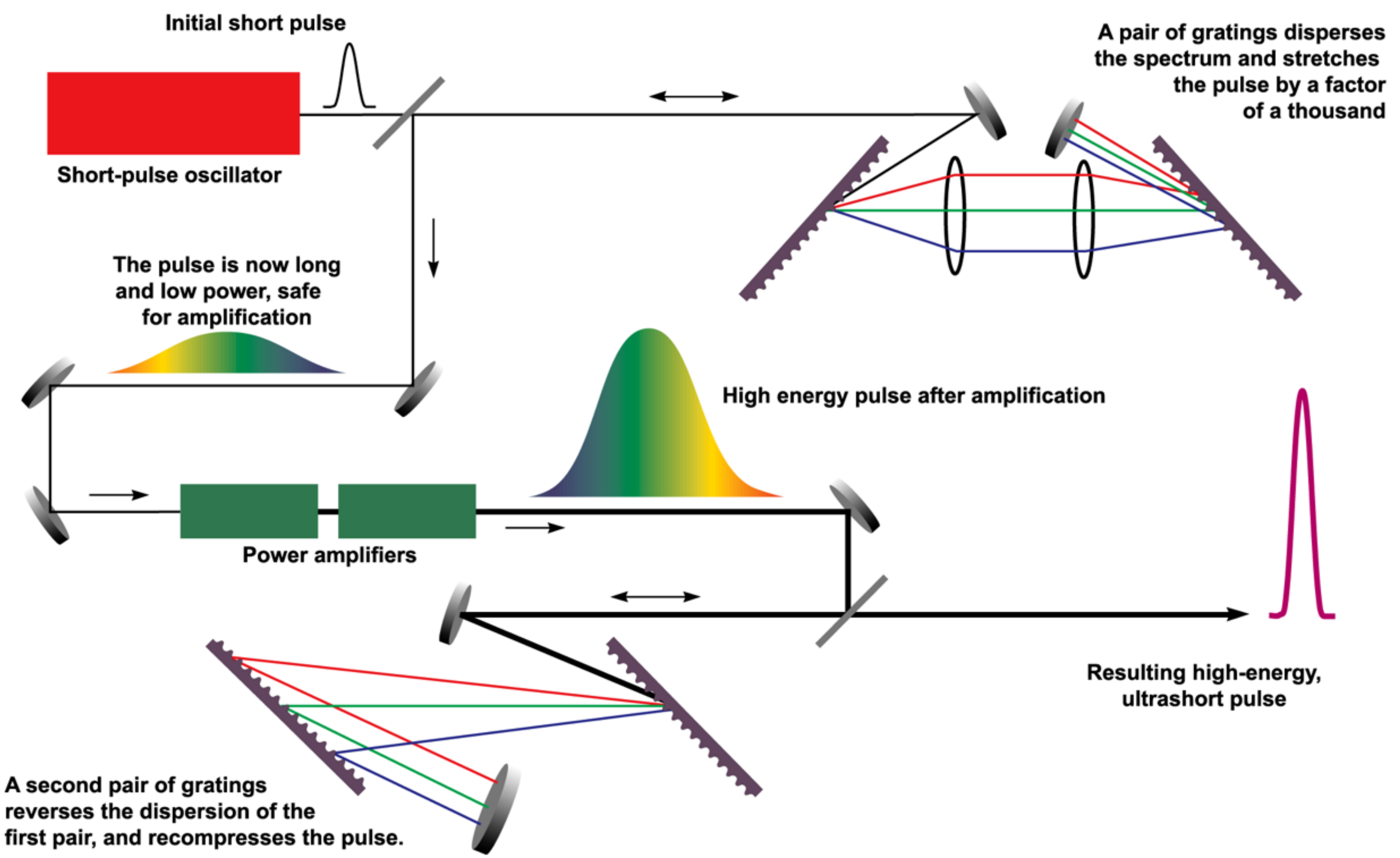
Ionization physics motivates laser requirements.

Element	IP (eV)	Ionization Threshold (ADK Tunnel)	Energy Requirement (mJ)	Ionization Threshold (MPI)
Rb	4.17	2.6×10^{12} Wcm^{-2}	26	4.2×10^{11} Wcm^{-2}
Li[1]	5.39	7×10^{12} Wcm^{-2}	34	4×10^{11} Wcm^{-2}
H_2	13.6	1×10^{14} Wcm^{-2}	85	--
Ar	15.8	3×10^{14} Wcm^{-2}	98	--

- Ionization thresholds are calculated for a 50 fs, 800 nm beam
- Energy requirement is calculated for a cylinder of 1 mm diameter, 1 m long, at a density of 5×10^{16} cm^{-3}

High intensities are achieved with chirped pulse amplification.

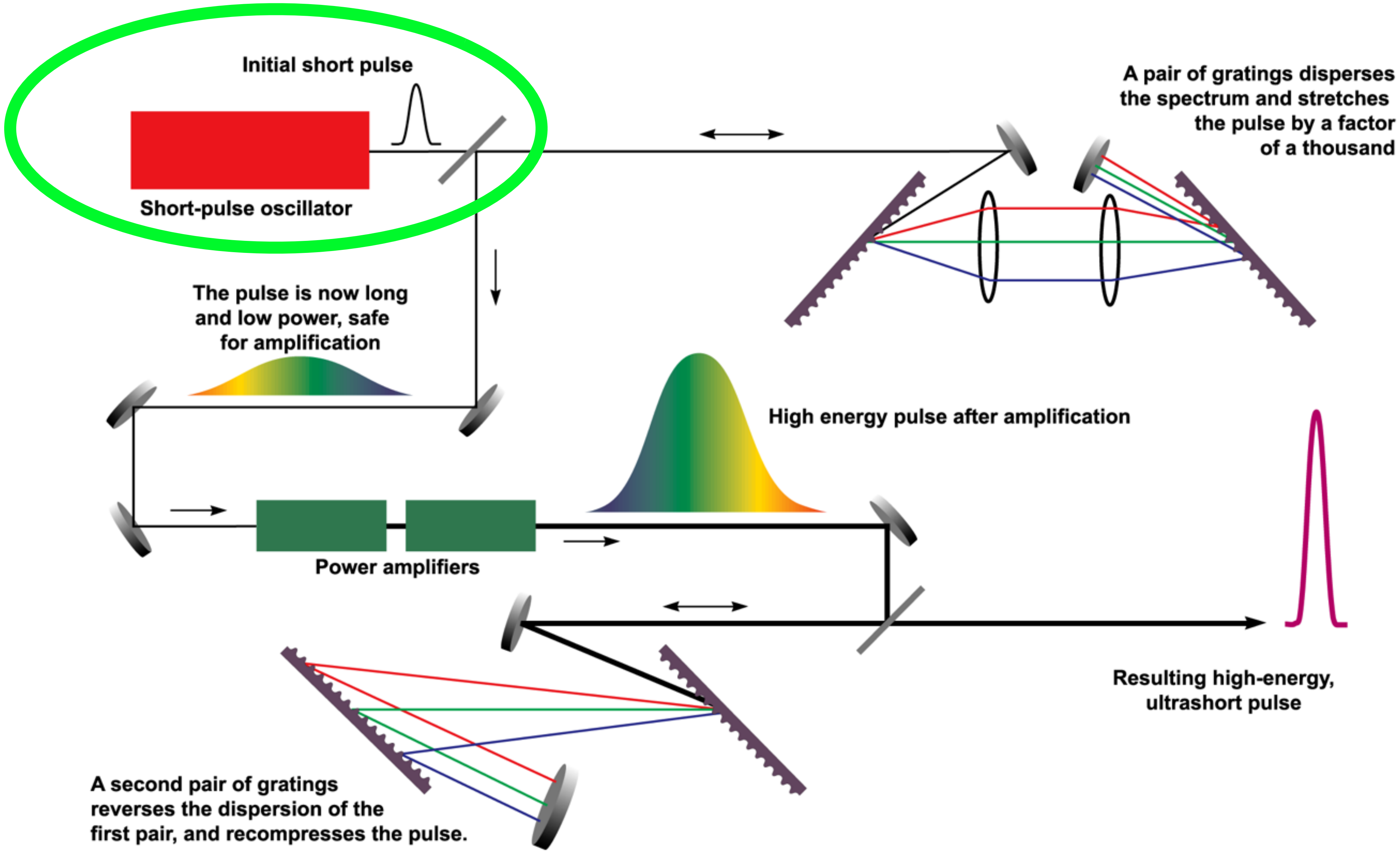
Chirped Pulse Amplification



Problem Statement:

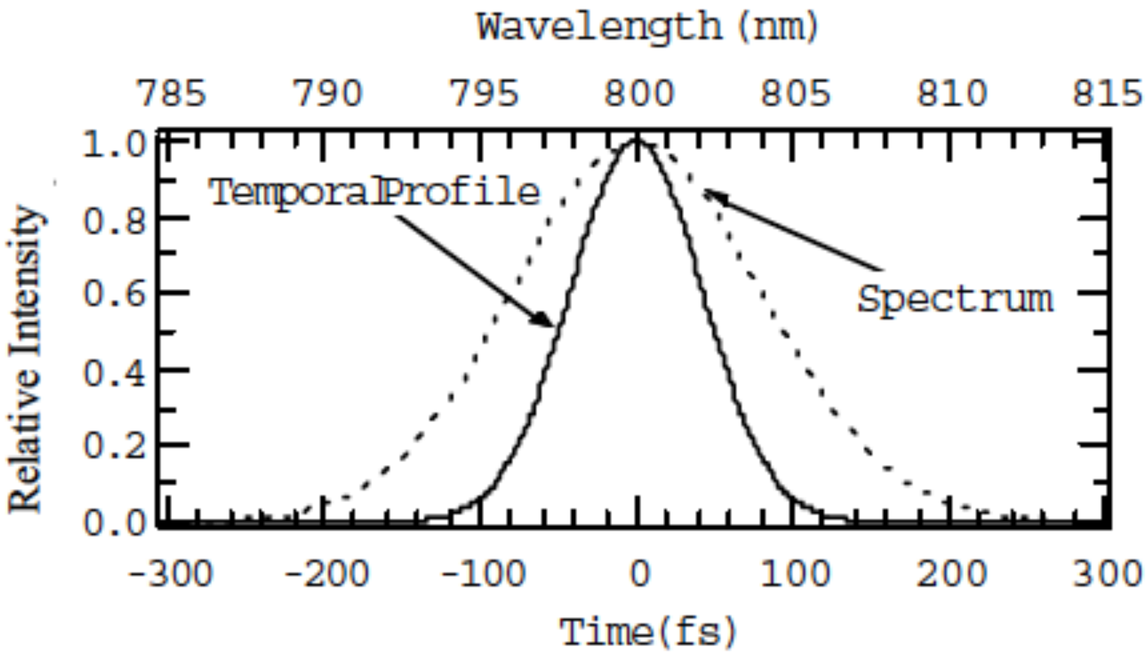
Do a study of a regenerative amplifier Ti:Saph CPA system. Assume that the initial pulsewidth is 50 fsec, and that it makes 18 round-trips in the cavity. Choose a grating and optics that makes a reasonably-sized stretcher and compressor. Make reasonable estimates for the material dispersion encountered (Ti:Sapph crystal, Pockels Cell Crystal, Faraday Isolator…) and be sure to compensate (to second order) in the compressor.

Pulse Generation



Pulse Generation

A short pulse, mode-locked oscillator provides a transform limited Gaussian (assumed) pulse.

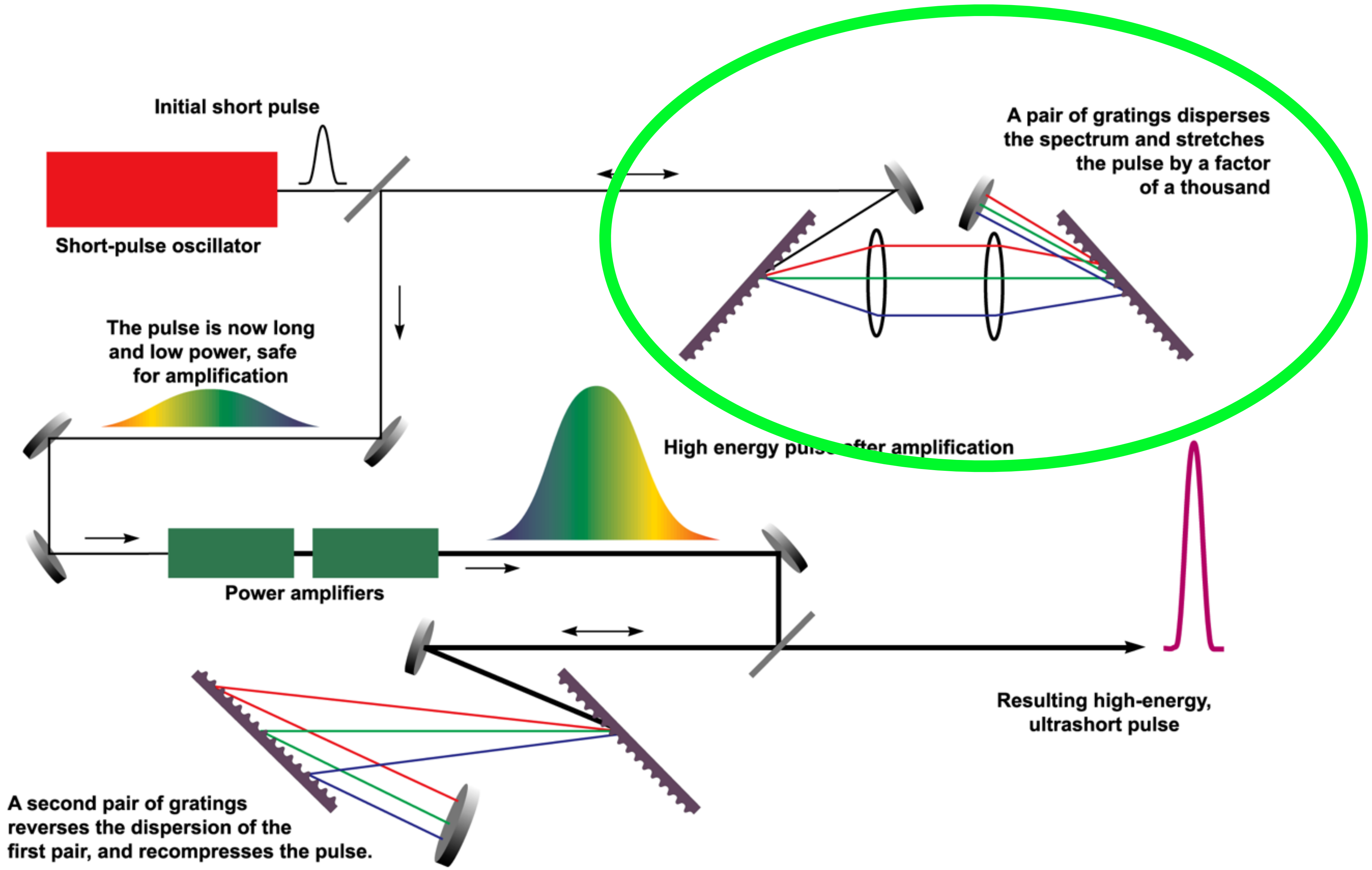


$\Delta f = 2\ln 2/\pi\Delta t$, $\Delta t = 50$ fs

$\Delta f = 8.8$ THz $= 8.8 \times 10^{-3}$ fs^{-1}

$\Delta\lambda = 18$ nm

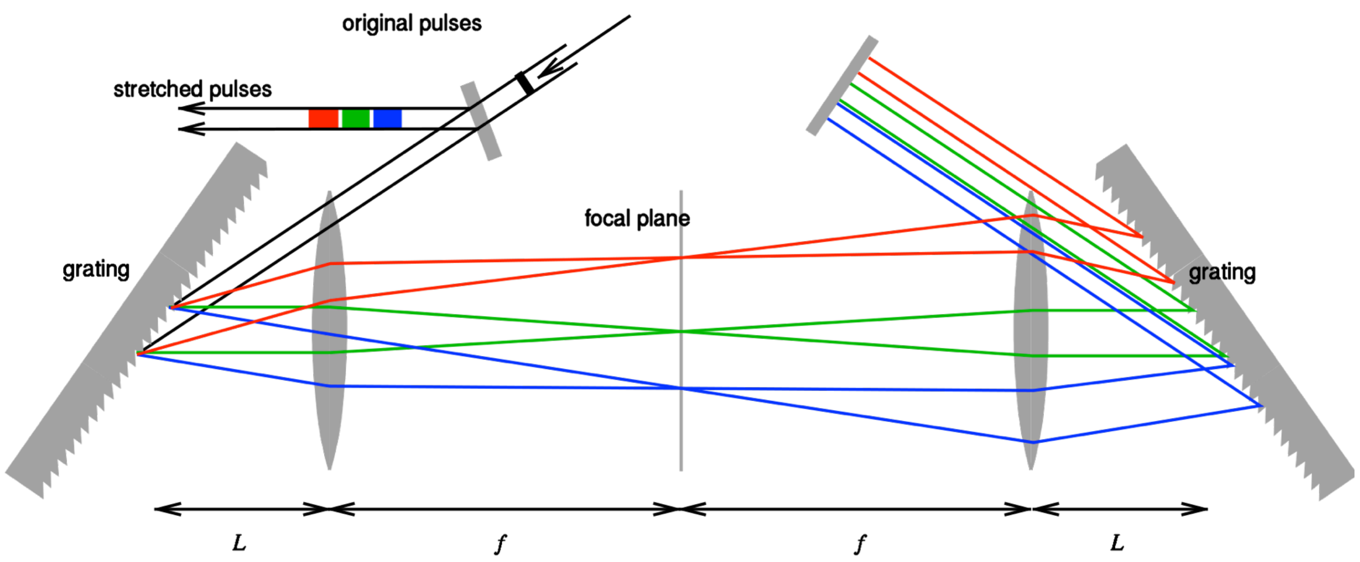
Stretching


Initial short pulse
Short-pulse oscillator
A pair of gratings disperses
the spectrum and stretches
the pulse by a factor
of a thousand
The pulse is now long
and low power, safe
for amplification
High energy pulse after amplification
Power amplifiers
Resulting high-energy,
ultrashort pulse
A second pair of gratings
reverses the dispersion of the
first pair, and recompresses the pulse.

Stretching

Can't amplify short pulses because that would damage components. Need to stretch.

$$\frac{d^2\phi_c(\omega)}{d\omega^2} = \frac{\lambda^3 L_g}{\pi c^2 d^2}\left[1-\left(\frac{\lambda}{d}-\sin\gamma\right)^2\right]^{-3/2}$$



λ = Central Pulse Wavelength = 800 nm
d = Grating line spacing = 575 nm
γ = Incident pulse angle on grating = 44°
L_g = Grating length = ?

Stretching

Plugging the values into this equation we get:

$\phi''/L = 85 \times 10^3\ fs^2/cm$

How long should the grating be?

50 fs → 50 ps

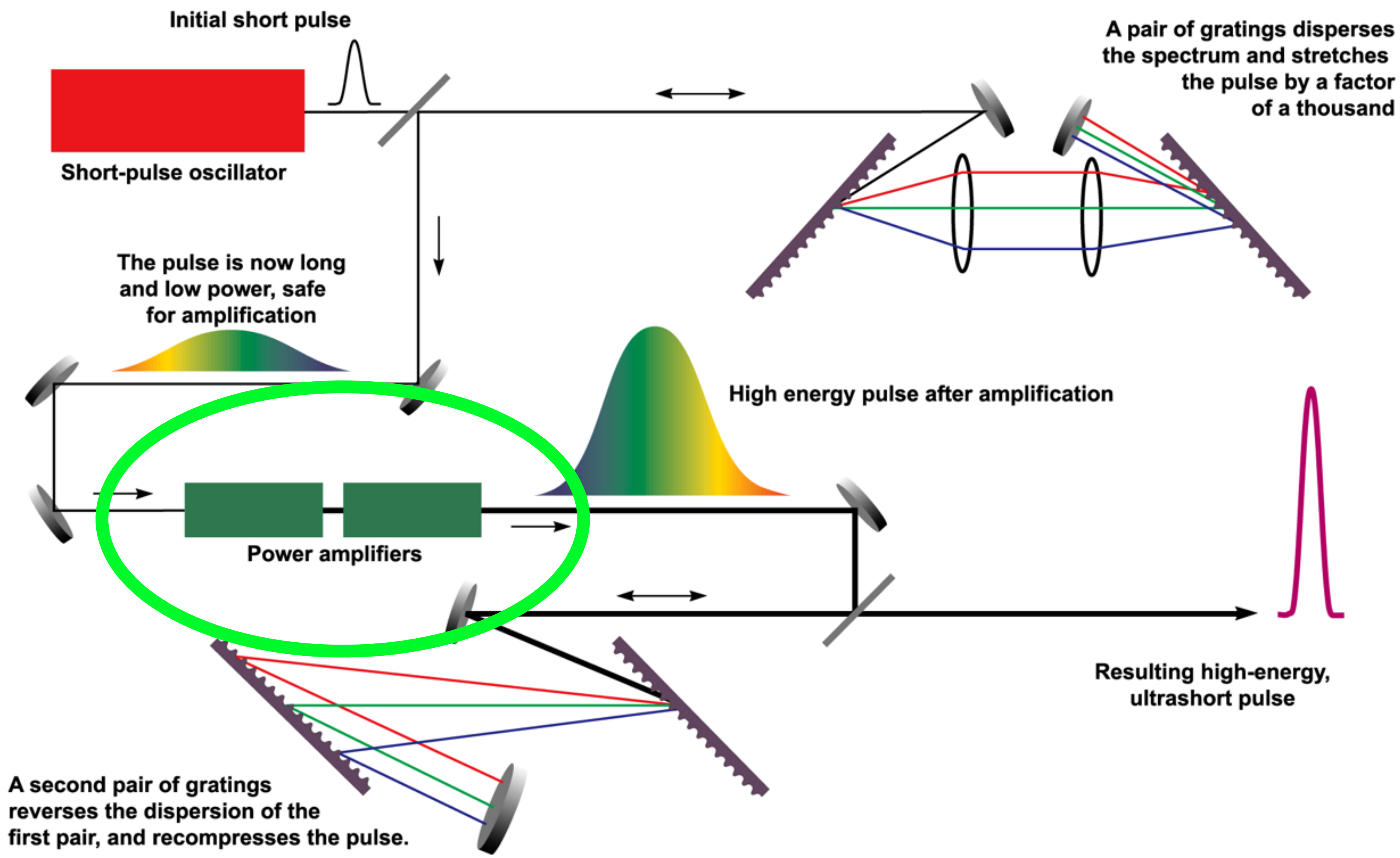
The final pulse length is the frequency spread times the second order dispersion:

$\Delta f\ \phi'' = 50\ ps$

Plugging in 8.8×10^{-3} for Δf we find:

$\phi'' = 5.686 \times 10^6\ fs^2 \rightarrow L = 67.25\ cm$

Amplification



Amplification

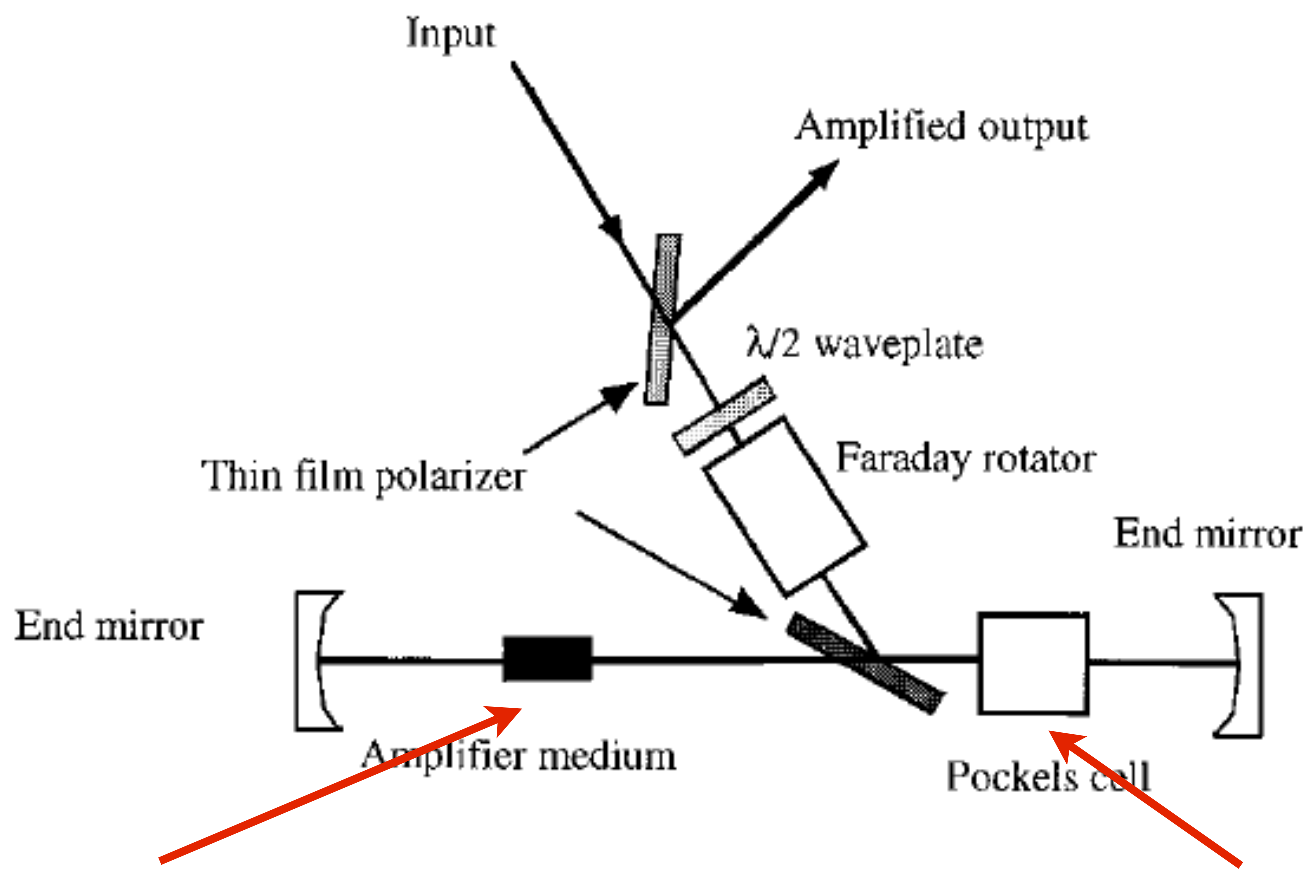
Dispersion/cm for common materials in an amplifier.

TABLE II. Sample values of dispersion for material (1 cm), grating pairs, and prism pairs at 800 nm wavelength.

Optical element	GVD $d^2\varphi/d\omega^2$ (fs^2)	TOD $d^3\varphi/d\omega^3$ (fs^3)	FOD $d^4\varphi/d\omega^4$ (fs^4)
Fused silica	361.626	274.979	−114.35
BK7	445.484	323.554	−98.718
SF18	1543.45	984.277	210.133
KD*P	290.22	443.342	−376.178
Calcite	780.96	541.697	−118.24
Sapphire	581.179	421.756	−155.594
Sapphire at the Brewster angle	455.383	331.579	−114.912
Air	0.0217	0.0092	2.3×10^{-11}
Compressor: 600 ℓ/mm, $L=1$ cm, 13.89°	−3567.68	5101.21	−10226
Prism pair: SF18	−45.567	−181.516	−331.184

Amplification

The pulse makes 18 round trips in the amplifier.

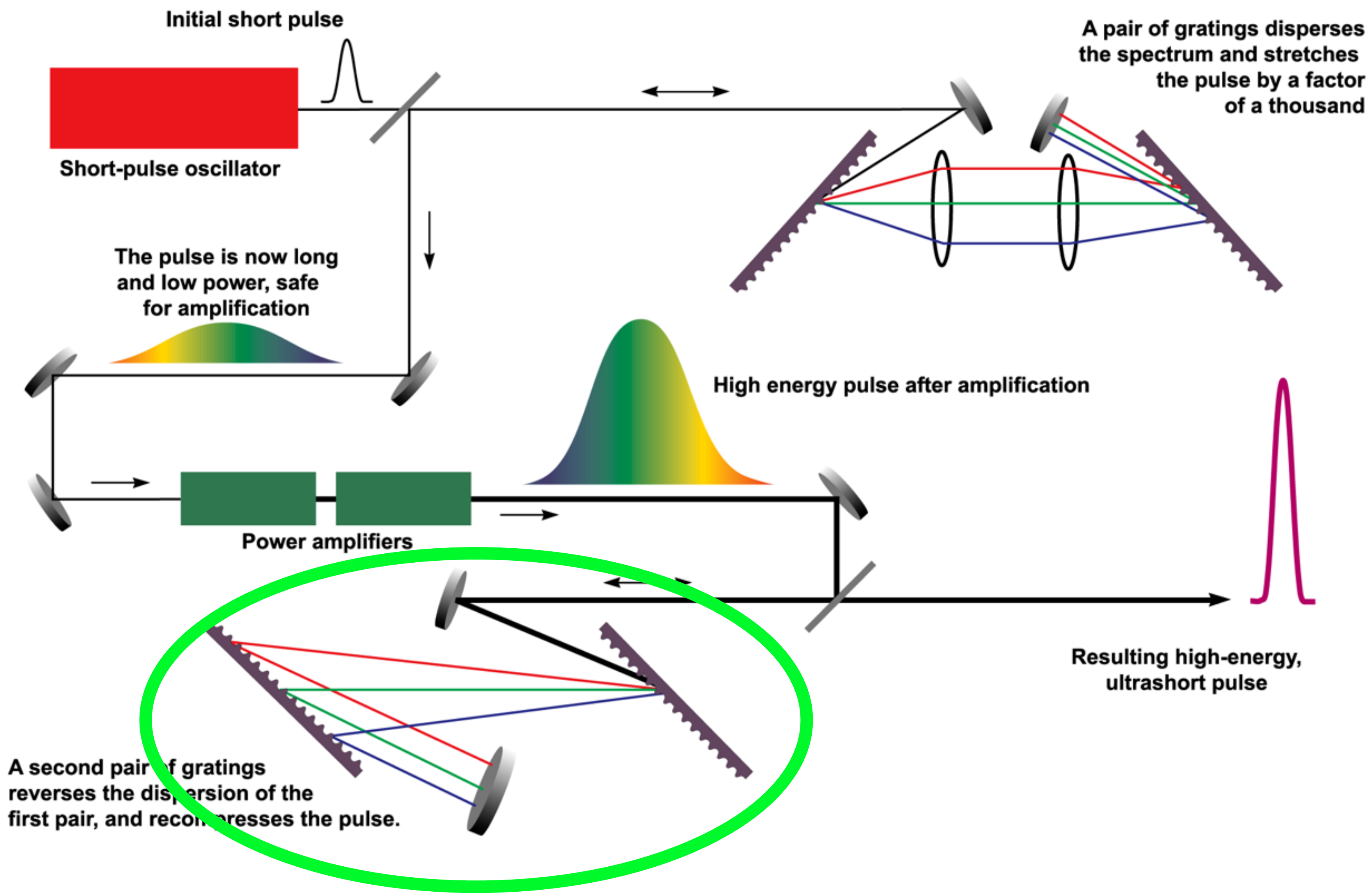


2 cm Ti:Saph
$\phi'' = 1160\ \text{fs}^2$

4 cm KD*P
$\phi'' = 1160\ \text{fs}^2$

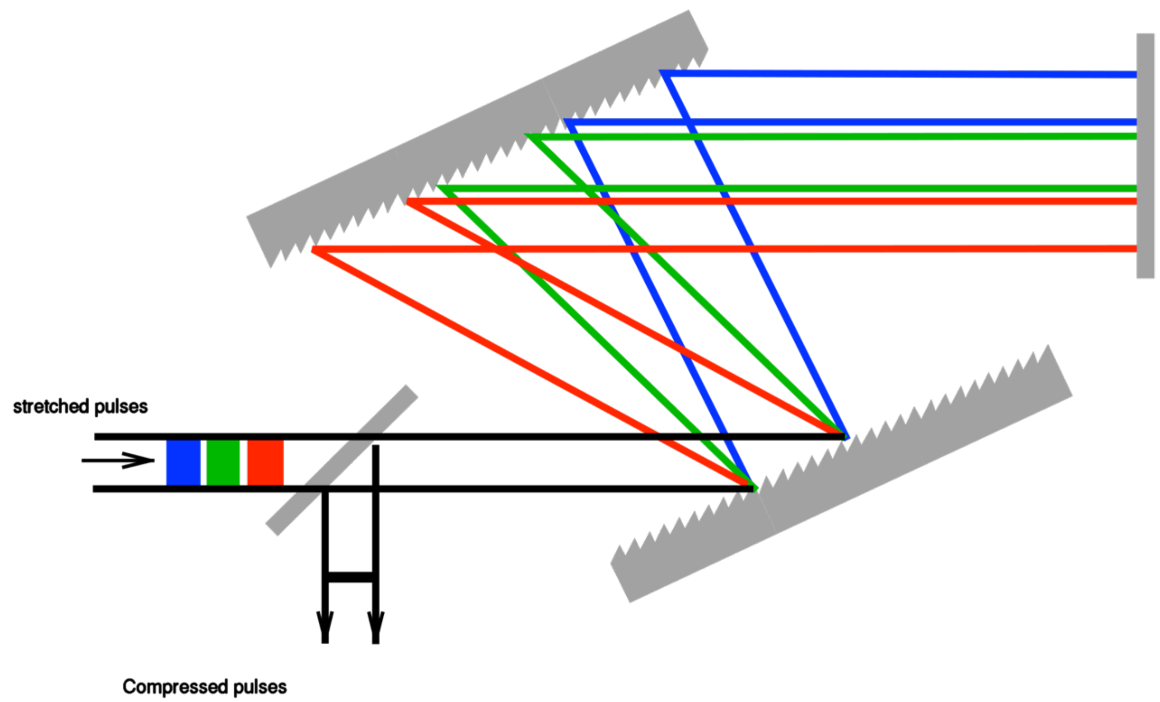
Total $\phi'' = 36 * (1160\ \text{fs}^2 + 1160\ \text{fs}^2) = 83520\ \text{fs}^2$

Compression



Compression

After amplification the pulse has 500 mJ energy! Need to compress down to 50 fs to get our 10 TW ionization pulse.



The formula for dispersion in the compressor is the same as for the stretcher but the sign is switched.

Compression

The residual dispersion is:

$$\phi''_{stretch} + \phi''_{amp} = 5.769 \text{ x } 10^6 \text{ fs}^2$$

At this point, the pulse width due to dispersion is:

$$\Delta f \; \phi'' = 50.77 \text{ ps}$$

This is nearly the same as the pulse length after the stretcher. Assuming the same grating material, we can determine the relative length of the compressor:

$$-\phi''_{comp}/\phi''_{stretch} = 1.017$$

So the length of the compressor is:

$$1.017 * L_{comp} = 68.24 \text{ cm}$$

Finito

This is an excellent paper

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 69, NUMBER 3 MARCH 1998

REVIEW ARTICLE

High power ultrafast lasers

Sterling Backus, Charles G. Durfee III, Margaret M. Murnane,[a)] and Henry C. Kapteyn
Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

(Received 25 March 1997; accepted for publication 2 December 1997)

In this article, we review progress in the development of high peak-power ultrafast lasers, and discuss in detail the design issues which determine the performance of these systems. Presently, lasers capable of generating terawatt peak powers with unprecedented short pulse duration can now be built on a single optical table in a small-scale laboratory, while large-scale lasers can generate peak power of over a petawatt. This progress is made possible by the use of the chirped-pulse amplification technique, combined with the use of broad-bandwidth laser materials such as Ti:sapphire, and the development of techniques for generating and propagating very short (10–30 fs) duration light pulses. We also briefly summarize some of the new scientific advances made possible by this technology, such as the generation of coherent femtosecond **x**-ray pulses, and the generation of MeV-energy electron beams and high-energy ions. [S0034-6748(98)00303-7]

rsi.aip.org/resource/1/rsinak/v69/i3/p1207_s1