Ultra-intense laser technologies comparison: Chirped Pulse amplification (CPA) vs Optical Parametric Chirped Pulse Amplification (OPCPA)

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High-power multi-petawatt (PW) lasers are key tools for exploring frontier fundamental researches.
The peak power of femtosecond lasers has been raised from terawatt (TW) level to 10-PW level during the past decades, giving rise to 10^{23} W/cm^2 peak laser intensity by tight focalization.
The purpose of this presentation is to discuss some techniques and technologies that allow the amplification of femtosecond laser pulses at such power levels.

Outline

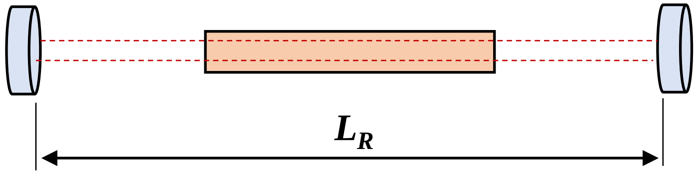
- **Introduction about ultra-short pulse laser amplification**
- **Chirped Pulse Amplification (CPA) technique – advantages and drawbacks**
- **Optical Parametric Chirped Pulse Amplification (OPCPA) technique – advantages and drawbacks**
- **Hybrid femtosecond laser systems**
- **Prospects of 100-PW class femtosecond laser systems**
- **Conclusions**

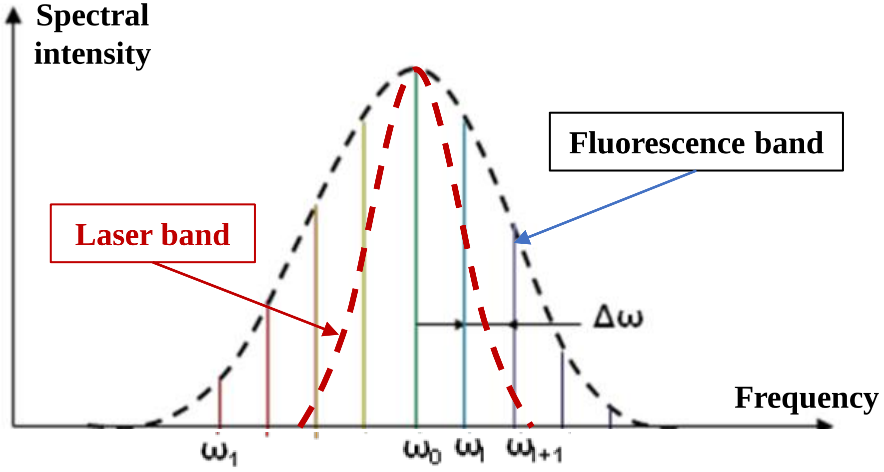
Main steps toward high-power ultra-short pulse laser systems:

- Femtosecond pulse oscillators based on self-mode-locking (Kerr Lens Mode-locking – KLM) in large spectral band laser media.

- Chirped Pulse Amplification (CPA) technique for femtosecond pulses amplification

Principle of mode-locking for ultra-short pulse generation





$$2L_R = n\times\lambda_n,\ 2L_R = (N+1)\times\lambda_{n+1}$$

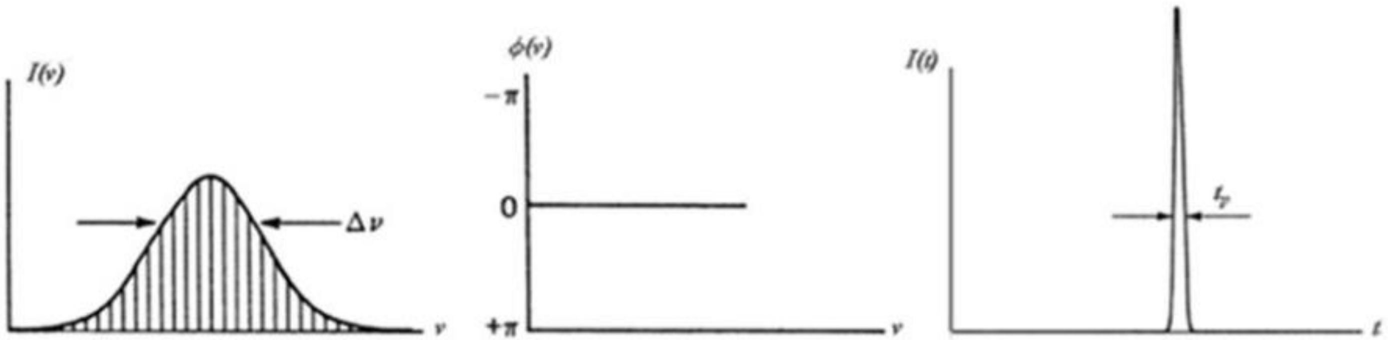
$$\Delta\lambda = \lambda_n - \lambda_{n+1} \cong \frac{\lambda_0^2}{2L_R},\quad \Delta\nu = \frac{c}{2L_R},\quad \Delta\omega = 2\pi\,\Delta\nu = \frac{\pi\,c}{L_R}$$

$$\omega_l = \omega_1 + (l-1)\,\Delta\omega,\ \ l = 1,2,\ldots,N$$

$$E_n(t) = E_n \exp\{i[(\omega_0 + n\,\Delta\omega)t + \varphi_n]\} = E_n\exp(i\,\Phi_n)$$

$$\varphi_1 \neq \varphi_2 \neq \ldots \neq \varphi_l \neq \ldots\varphi_N\,.$$

$$\boxed{\frac{I_{ML}^{peak}}{I_{CW}} = \frac{(NE)^2}{NE^2} = N}$$



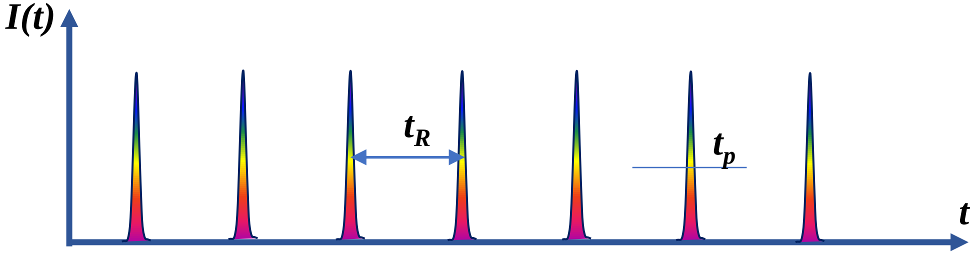
N, number of phase-locked longitudinal modes

Fixed relationship between independent phases:
$\varphi_1 = \varphi_2 = \ldots = \varphi_N = \varphi$

$$E(t) = \sum_{n=1}^{N} E_n(t)$$

$$\Phi_{n+1} - \Phi_n = \omega_0 t + (n+1)\Delta\omega t + \varphi_{n+1} - \omega_0 t - n\,\Delta\omega t - \varphi_n = \Delta\omega t$$

$$I \propto E^2$$



$$\boxed{\Delta\omega t = \frac{2\pi}{N}}$$

$$\downarrow$$

$$\boxed{t_p \propto \frac{1}{\Delta\nu\,N} = \frac{1}{B_\nu}}$$

$$\boxed{\Delta\omega t_R = 2\pi,\qquad t_R = \frac{2\pi}{\Delta\omega} = \frac{2\,L_R}{c}}$$

In case of a big number of coupled in phase oscillating longitudinal modes, there is a high contrast between mode-locking and cw intensity.
A self-mode-locking becomes possible based on Kerr lens effect:

Kerr Lens Mode-locking - KLM

KLM femtosecond oscillators

$$\varphi(\omega)=\varphi(\omega_0)+\frac{1}{1!}\frac{\partial\varphi}{\partial\omega}\bigg|_{\omega_0}\Delta\omega+\frac{1}{2!}\frac{\partial^2\varphi}{\partial\omega^2}\bigg|_{\omega_0}(\Delta\omega)^2+\frac{1}{3!}\frac{\partial^3\varphi}{\partial\omega^3}\bigg|_{\omega_0}(\Delta\omega)^3+\ldots$$

$$\varphi(\omega)=\omega t+\varphi_0$$

$$\varphi(\omega_0)=\omega_0 t+\varphi_0 \qquad \Delta\omega=\omega-\omega_0$$

$$\frac{\partial\varphi}{\partial\omega}=t_{pr}$$

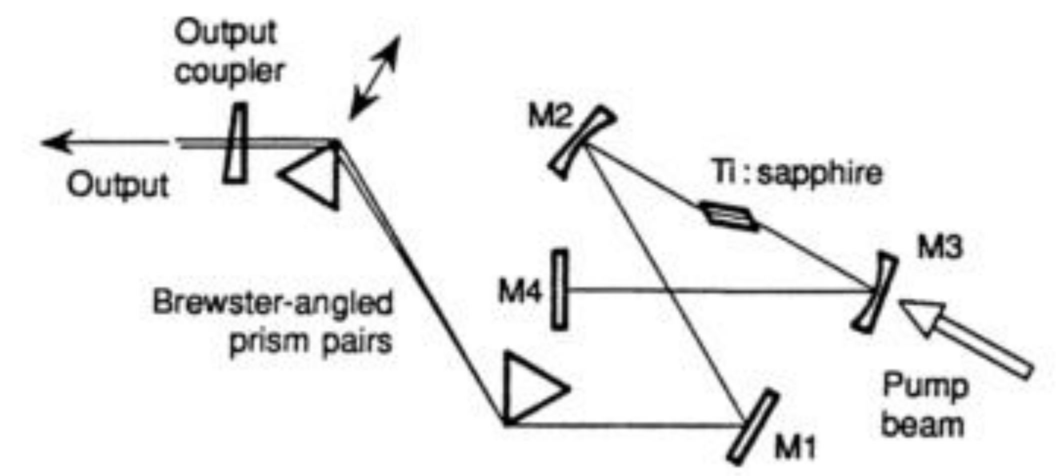
$t_{pr}\rightarrow$ propagation time of the ω frequency component

$$\frac{\partial^2\varphi}{\partial\omega^2}\bigg|_{\omega_0}=\frac{\partial^3\varphi}{\partial\omega^3}\bigg|_{\omega_0}=\ldots=0$$ $\rightarrow$ Pulse propagation without dispersion

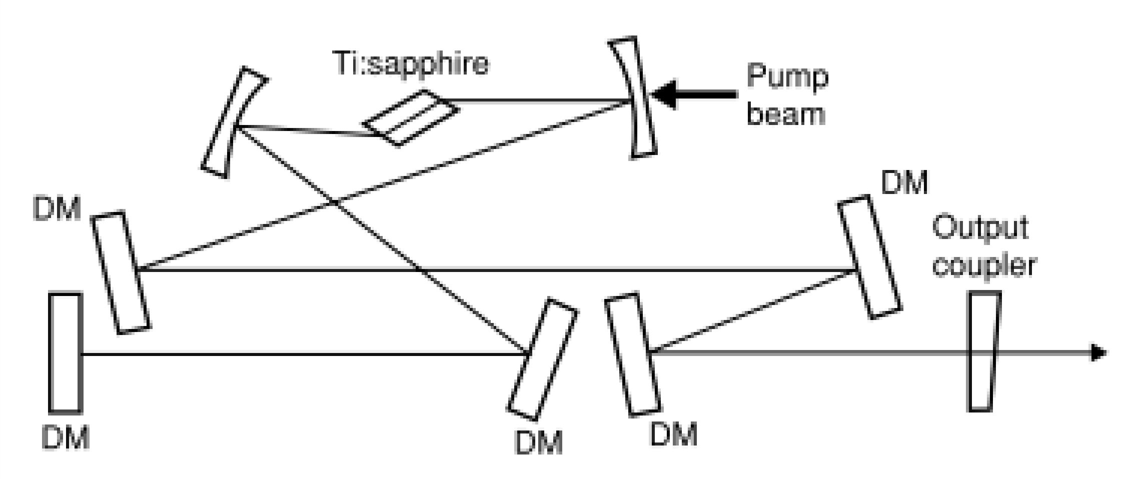
$$\frac{\partial^2\varphi}{\partial\omega^2}=\frac{\partial t_{pr}}{\partial\omega}\neq 0 \rightarrow \textit{linear frequency chirp}$$

$$\frac{\partial^3\varphi}{\partial\omega^3}=\frac{\partial^2 t_{pr}}{\partial\omega^2}\neq 0 \rightarrow \textit{quadratic frequency chirp}$$

Positive dispersion in Ti:sapphire: $\frac{\partial t_{pr}}{\partial\omega}>0$, $\frac{\partial t_{pr}}{\partial\lambda}<0$



Optical schematic of a KLM Ti:sapphire oscillator using a pair of prisms to compensate for group velocity dispersion in the Ti:sapphire crystal.
Pulse duration: a couple of 10-fs – 100 fs



Optical schematic of a KLM Ti:sapphire oscillator using dispersive mirrors (DM) for intracavity group velocity dispersion.
Sub 10-fs pulses can be obtained.

W. Koechner, *"Solid-state laser engineering"*, Springer Verlag, Berlin, 2006

Problems of femtosecond pulses amplification

$$n = n_0 + n_2 I \qquad B = \frac{2\pi}{\lambda}\int_0^L n_2 I \, dx$$

For nanosecond pulses, F = 1.5 J/cm^2 , I = (1-2) × 10^8 W/cm^2

For femtosecond pulses, near saturation fluence, to get high energy extraction efficiency, the intensity can reach very high values
I = 10^{12}-10^{14} W/cm^2, n_2 (Ti:sapphire) = 5×10^{-16} cm^2/W

For propagation length L in the range of ***mm*** or more, the B integral value is >>1, significant wavefront distortion and self-focusing can be produced

- Volume damage due to the beam wavefront distortion and self-focusing
- Surface damage due to the lower fluence of LIDT in case of ultra short (ps-fs) pulses compared to ns pulses

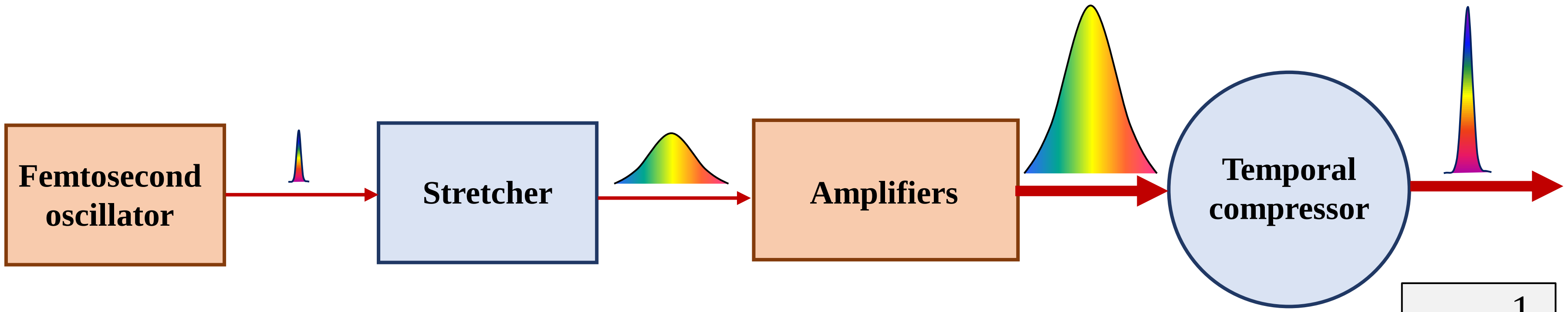
Possible solutions:

A. Very large aperture optical components to accommodate large diameter beams

B. Increasing the amplified pulse duration

- **Pulse stretching to increase the laser pulse duration.** Surface damage threshold increases and the value of B integral decreases.
- **Stretched pulse amplification**
- **Temporal re-compression of the amplified pulse**

Principle of Chirped Pulse Amplification (CPA)



$$\tau_p \propto \frac{1}{B_\nu}$$

$\boldsymbol{\tau_p}$, recompressed amplified pulse duration
$\boldsymbol{B_\nu}$, amplified pulse frequency bandwidth

D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**(3), 219–221 (1985).

Chirped Pulse Amplification System - Standard Architecture

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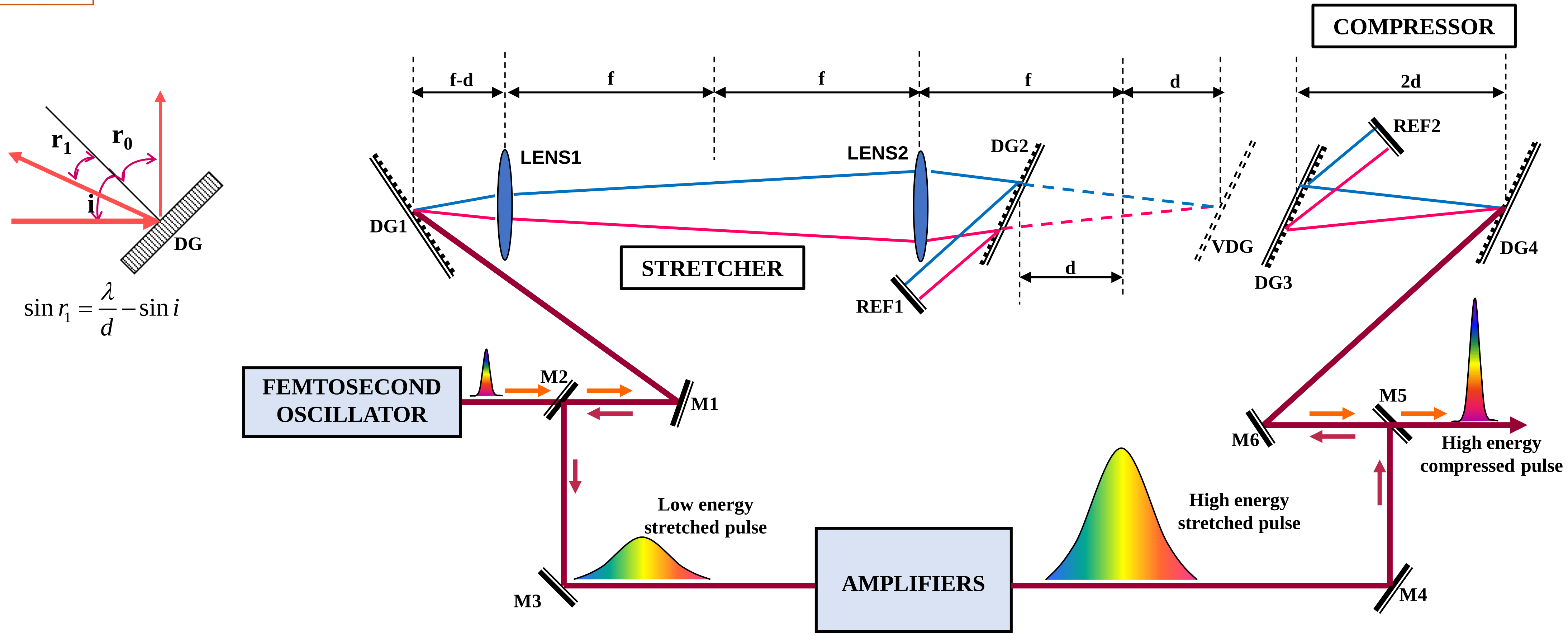

$$\sin r_1 = \frac{\lambda}{d} - \sin i$$

- Stretcher-compressor matched configuration is the key element of CPA
- Stretcher with diffraction gratings in a M×1 magnification telescope configuration
- Treacy configuration of the temporal compressor
- Positive group velocity dispersion in the stretcher must be fully compensated for by the negative group velocity dispersion in the temporal compressor
- Second order and third order phase distortions can be compensated for by the translation/rotation of the diffraction gratings of the temporal compressor or stretcher
- For shorter pulses, advanced methods for phase dispersion compensation are required

D. Strickland and G. Mourou, “Compression of amplified chirped optical pulses,” Opt. Commun. **56**(3), 219–221 (1985).
E. B. Treacy, „Optical pulse compression with diffraction gratings”, IEEE J. Quantum Electron. **5**, 454-458 (1969).
O. E. Martinez, „Design of high-power ultrashort pulse amplifiers by expansion and recompression”, IEEE J. Quantum Electron. **23**, 1385-1387 (1987).

Essential techniques and technologies related to high power femtosecond laser systems

- Technology of KLM ultra-broad band femtosecond laser oscillators (< 10 fs pulse-width) with chirped mirrors for phase distortion compensation.
- Large bandwidth diffraction gratings with high laser induced damage threshold (LIDT) for temporal stretchers-compressors.
- Different stretcher configurations.
- Large size diffraction gratings for temporal compressors.
- Techniques for laser pulse amplification:
  - Chirped Pulse Amplification (CPA) in large bandwidth laser media
  - Optical Parametric Chirped Pulse Amplification (OPCPA)
  - Hybrid CPA-OPCPA
- Advanced techniques for the control and improvement of the spectral, temporal and spatial parameters of the amplified pulses: keeping a broad spectral band, phase dispersion compensation, improvement of the contrast intensity of compressed femtosecond pulses, wavefront correction, aberration correction.
- Ultra-short pulses metrology
- Pump lasers technology

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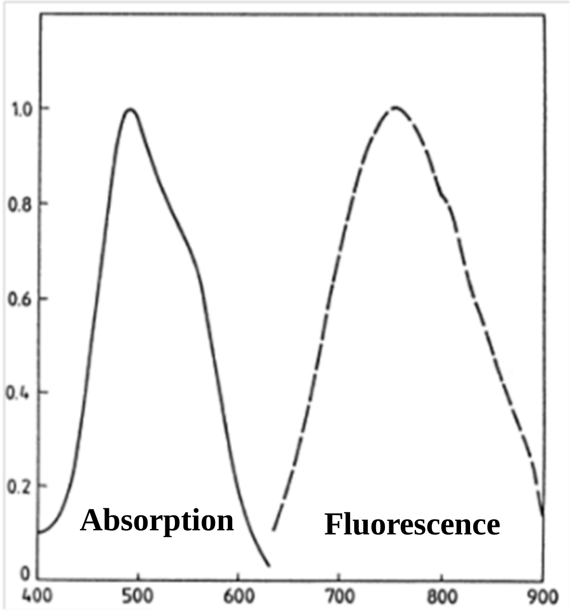
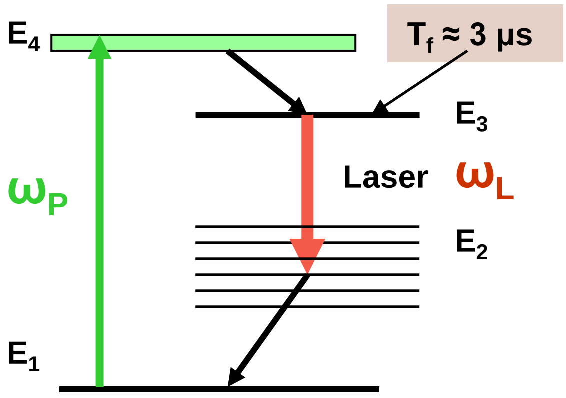
Ti:sapphire "Classical" CPA



Absorption spectrum and fluorescence emission



Ti:sapphire is a 4-level solid-sate amplifying mdium

The highest gain is obtained for ***c***-axis parallel polarized radiation

Regenerative amplifiers, many passes (~ 30) of chirped pulses through the Ti:sapphire crystal: nJ → mJ

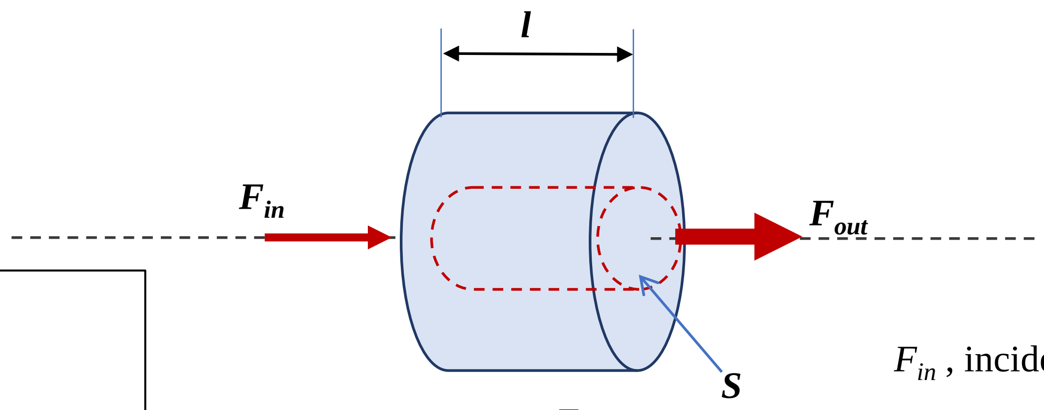
Medium energy multi-pass (4-6) chirped pulse amplifiers: mJ → 100 mJ

High energy multi-pass (2-4) chirped pulse amplifiers: 100 mJ → 10-300J

In a multi-PW femtosecond laser system the overall amplification factor is more than 11 orders of magnitude, from nJ to a couple of hundred Joules.

R. Dabu, "Femtosecond Laser Pulses Amplification in Crystals", Crystals **9** (7), 347 (2019)

Short laser pulse amplification



$$G = \frac{F_{out}}{F_{in}}$$

Gain calculation for :

Rectangular input pulse
$t_p \ll \tau_F$
Uniform inverted population density n throughout the laser material
Negligible absorption and scattering losses in the laser medium

Energy gain, G:

$$G = \frac{F_{sat}}{F_{in}} \ln\left\{1 + \left[\exp\left(\frac{F_{in}}{F_{sat}}\right) - 1\right] G_0\right\} =$$

$$= \frac{F_{sat}}{F_{in}} \ln\left\{1 + \left[\exp\left(\frac{F_{in}}{F_{sat}}\right) - 1\right] \exp\left(\frac{F_{lav}}{F_{sat}}\right)\right\}$$

F_{in} , incident fluence (energy per surface unit)

$$F_{sat} = \frac{h\nu_L}{\sigma_a},$$ saturation fluence

F_{sat} (Ti:sapphire) $\approx$ 0.9 J/cm^2

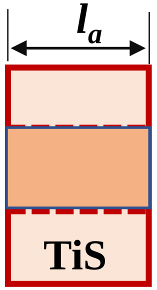
ν_L , laser frequency;
σ_a , stimulated amplification cross-section
$G_0 = exp(\sigma_a nl)$, low-signal exponential gain
n, population inversion per unit of volume
l, propagation length in the amplifying medium
t_p, laser pulse duration
τ_F, fluorescence life-time
F_{lav} , laser energy available for amplification in an active medium volume with an aperture equal to a surface unit.

$$F_{lav} = \frac{nV_{ol}\, h\nu}{S} = n\, l\, h\nu$$

L.M. Frantz and J.S. Nodvik, J. Appl. Phys. **34**, 2346 (1963)
W. Koechner, *„Solid-State Laser Engineering”,* Chapter 4.1– „Pulse Amplification”, Springer Verlag Berlin Heidelberg, 2006

Single-pass, small signal gain ($F_{L(IN)} << F_{SAT}$) in Ti:sapphire

$$F_p = \frac{E_p}{S}$$

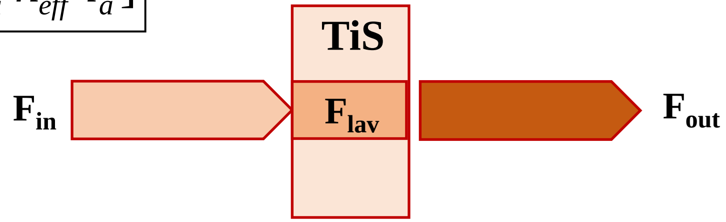


$$n = \frac{E_{abs}}{S\, l_a\, h\nu_P} = \frac{\eta_{abs}\, E_P}{S\, l_a\, h\nu_P} = \frac{\eta_{abs}\, F_P}{l_a\, h\nu_P}$$

$$n_{eff} = \eta_{qe} \times n$$

$$\eta_{abs} = \frac{F_{abs}}{F_p}, \ \eta_{qe} \cong 0.8$$

$$\boxed{G_0 = \exp[\sigma_a\, n_{eff}\, l_a]}$$



Small signal amplification for <u>one face end-pumped</u> TiS crystal:
F_{sat} = 0.9 J/cm^2,
η_{abs} = 0.9,
$\eta_{qd} = \lambda_p / \lambda_L \approx$ *0.665 (*λ_p = 532 nm*)*
η_{qe} = *0.8*

$$G_0 = \exp\left[\frac{\sigma_a \eta_{qe} \eta_{abs} F_p}{l_a\, h\nu_p}\, l_a\right] = \exp\left[\frac{\sigma_a \eta_{qe} F_{abs}}{l_a\, h\nu_p} \frac{h\nu_L}{h\nu_L}\right] = \exp\left[\frac{\eta_{qe}\, F_{abs}}{F_{sat}} \frac{\nu_L}{\nu_p}\right] = \exp\left[\frac{F_{lav}}{F_{sat}}\right]$$

$$F_{lav} = \eta_{qe} \times \eta_{qd} \times \eta_{abs} \times F_p$$

$$G_{small\,signal} \cong \exp\left[0.53 \times F_p\left(J/cm^2\right)\right]$$

$n_{eff} \approx \eta_{qe} \times n$, η_{qe} - *quantum efficiency*
$\eta_{qd} = \nu_L / \nu_P \approx$ *0.665 (*λ_p = 532 nm*) , quantum defect*
η_{abs} *, absorption efficiency*

F_p = 1 J/cm^2 → G = 1.7
F_p = 1.5 J/cm^2 → G = 2.2

~1/3 of the absorbed pump laser energy is the heat dissipated in the Ti:sapphire crystal

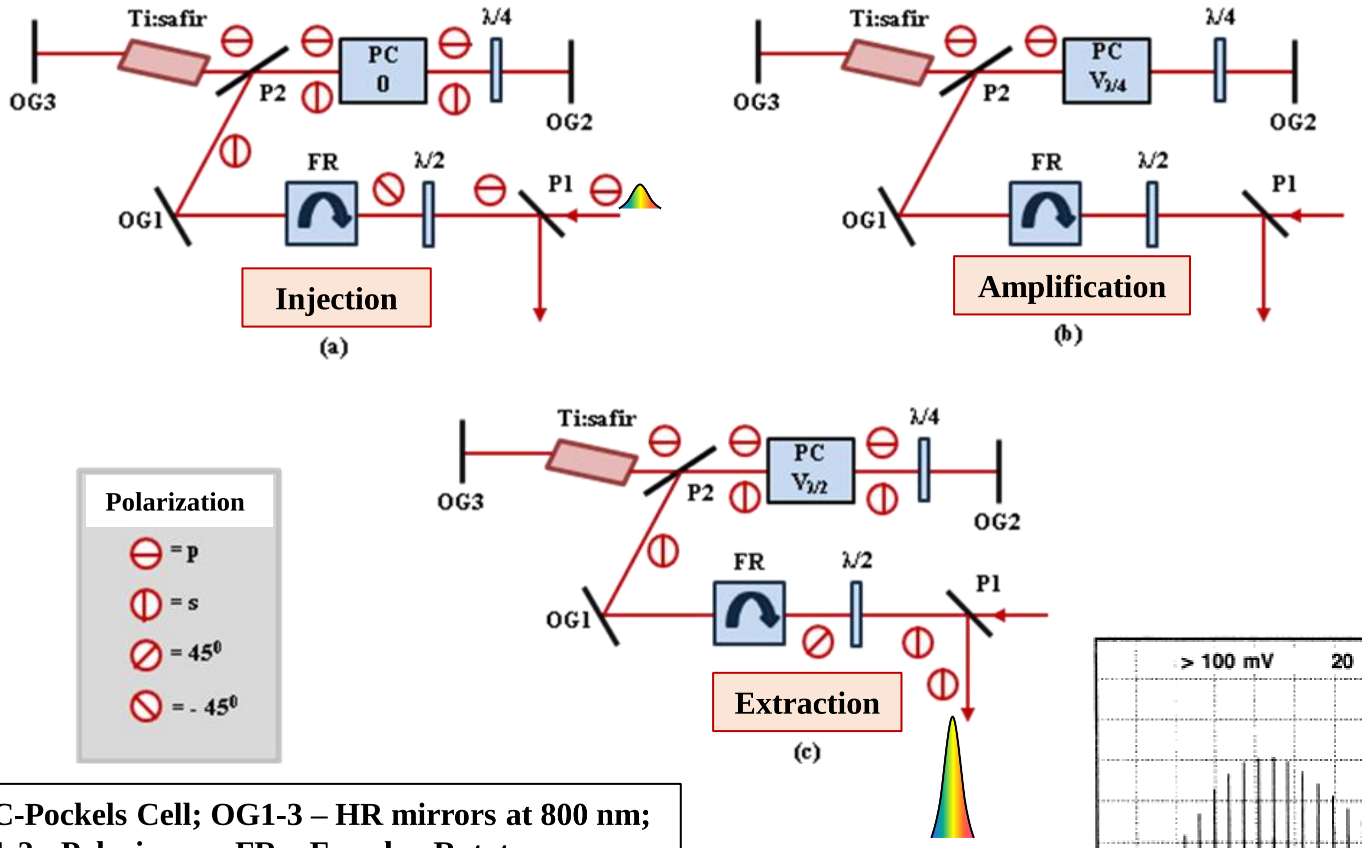
Single-pass gain in a Ti:sapphire crystal is limited in the range of 2-5

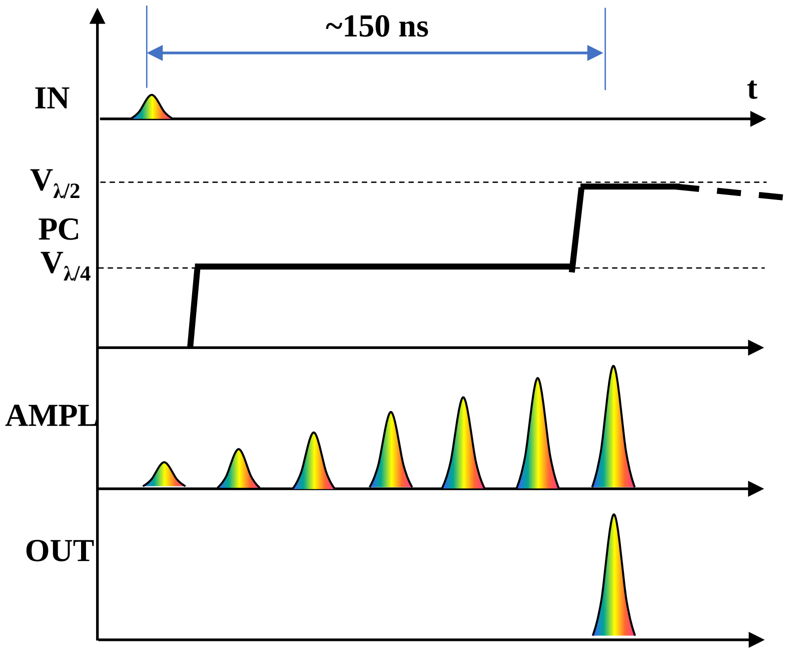
Small signal amplification for an end pumped TiS crystal <u>on both faces</u>:
G ≈ 3-5

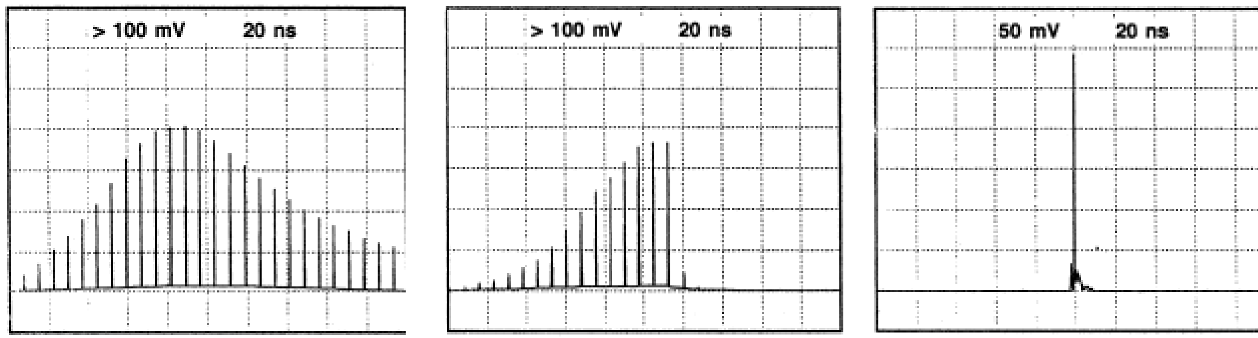
Schematic Configuration of a Regenerative Amplifier

Principle of a regenerative amplifier:
(a) Low energy pulse injection.
(b) Multi-pass amplification process.
(c) Amplified laser pulse extraction.

5-6 orders of magnitude amplification of stretched pulses from nJ to mJ
26-30 paths through the Ti:sapphire crystal

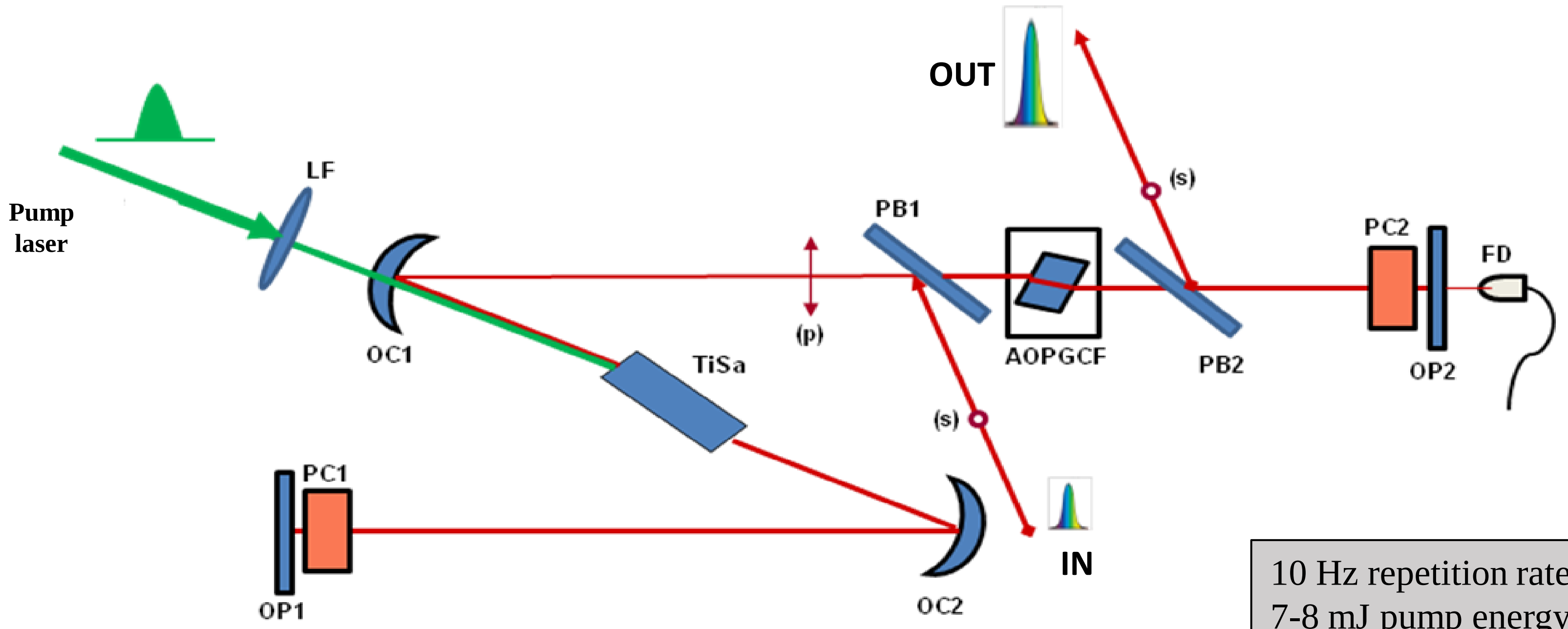




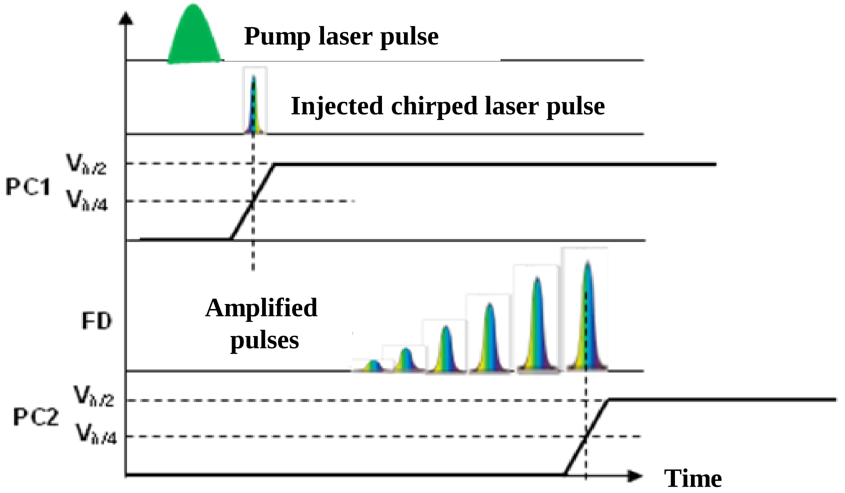


PC-Pockels Cell; OG1-3 – HR mirrors at 800 nm;
P1-2 - Polarizers ; FR – Faraday Rotator.

Two-Pockels Cell configuration of a regenerative amplifier (TEWALAS, Amplitude Technologies)

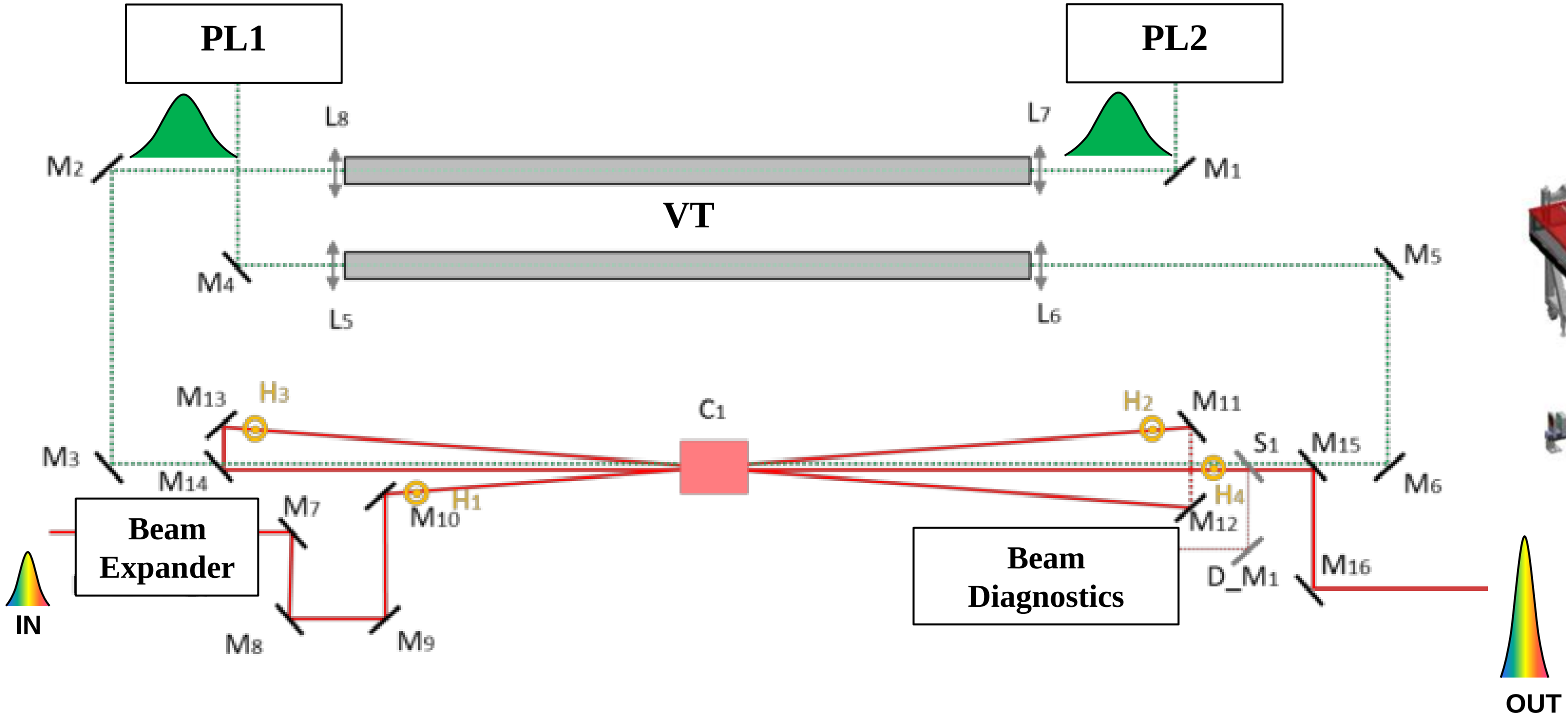


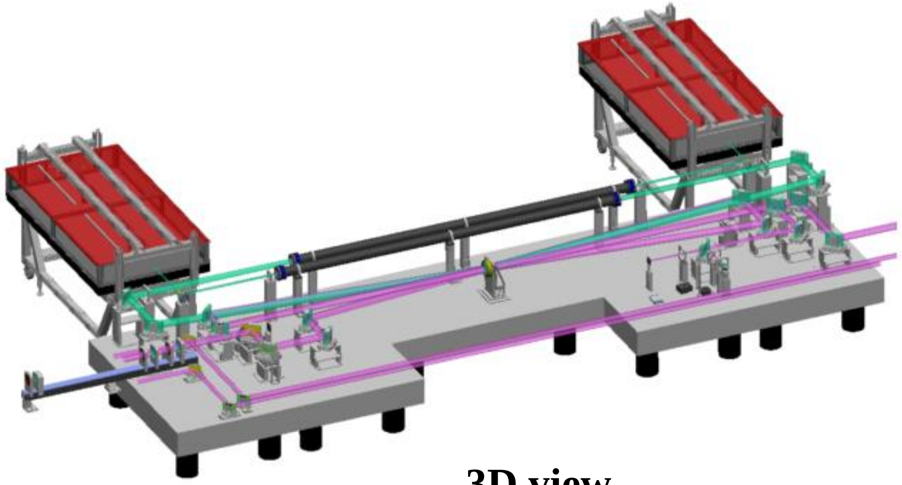
10 Hz repetition rate
7-8 mJ pump energy at 532 nm
~ 100 nJ input pulse energy
~150 ns rise-time of pulses
~ 0.5 mJ output energy



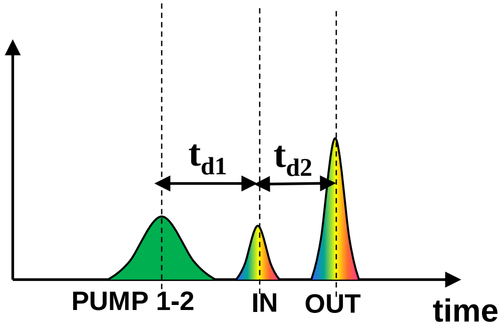
PC1, PC2 – Pockels Cells; PB1,PB2 – Brewster angle thin film polarizers; AOPGCF –acousto-optic programmable gain filter; OP1, OP2 -HR @ 800 nm flat mirrors; OC1, OC2 – Spherical mirrors, HR @ 800 nm, HT @ 532 nm; FD – photodiode.

High Energy 3-pass Amplifier





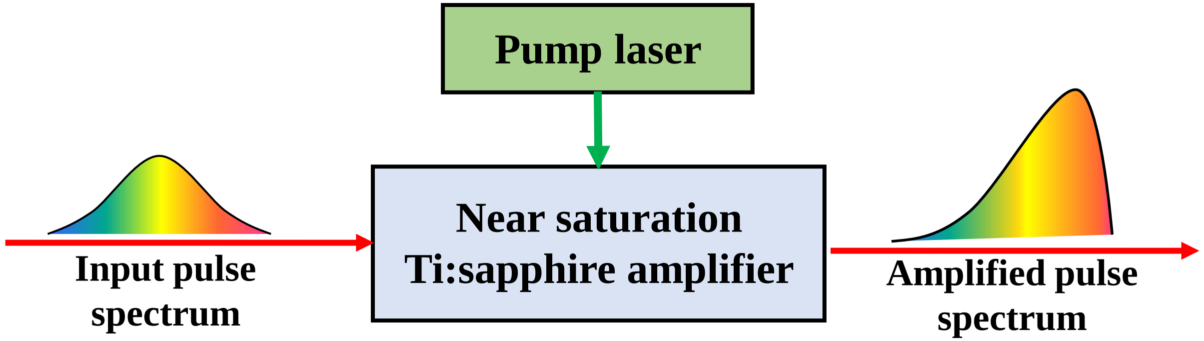
3D view



Optical layout

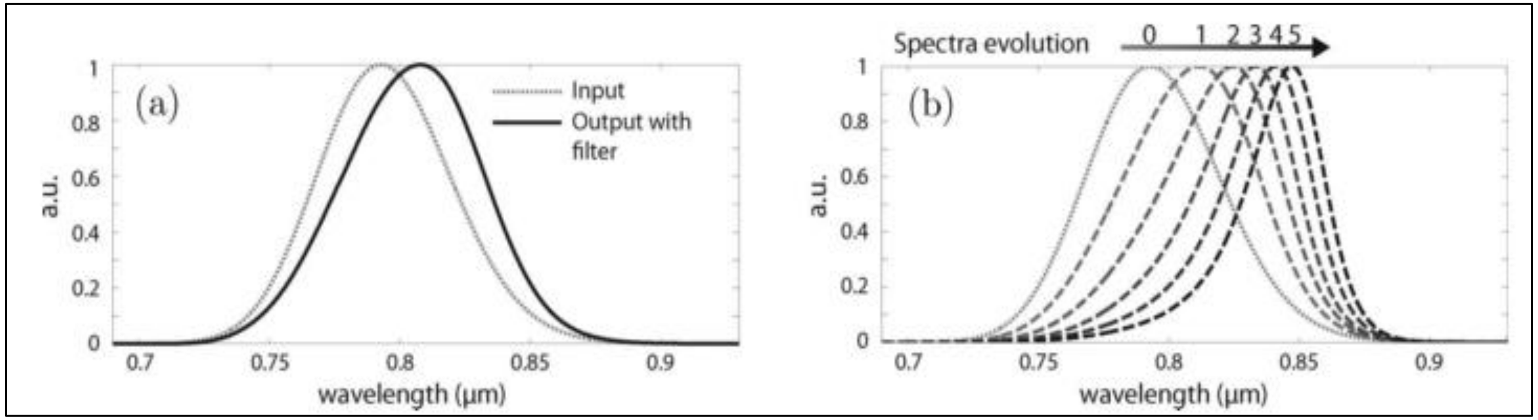
C_1, Ti:sapphire crystal; M_1-M_6, HR steering mirrors at 527 nm; M_7-M_{16}, HR large bandwidth at 800 nm steering mirrors; PL1,2 – frequency doubled ns Nd:glass (527 nm) pump lasers; VT, vacuum tubes for relay imaging.

Problems of Ti:sapphire laser amplification – Spectral Band Narrowing and Red Shifting

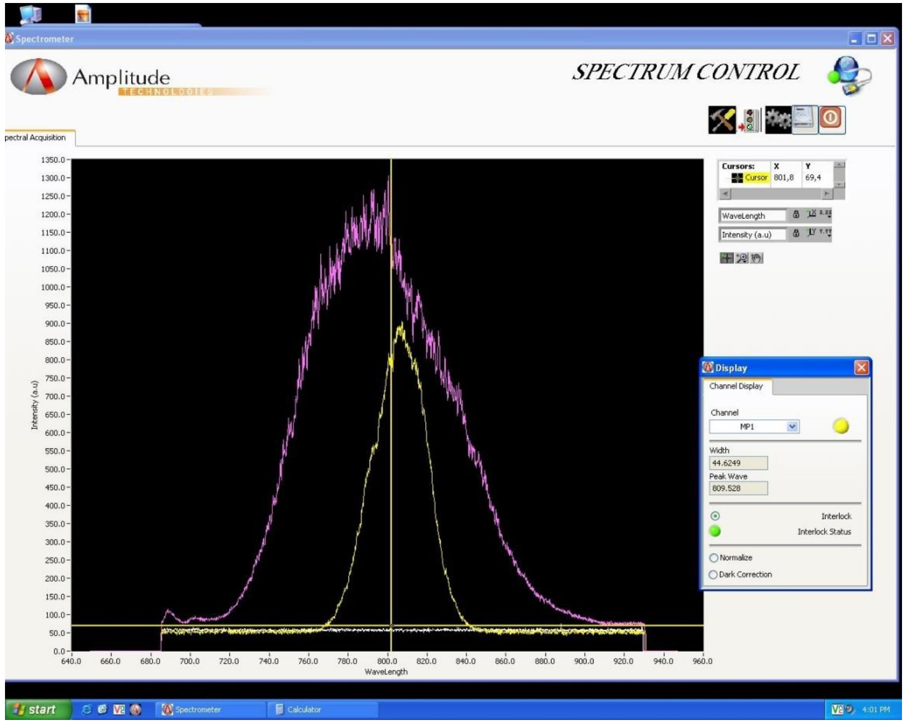


Significant Red-shifting effect in near saturation regime amplifiers ($E_{ampl} \approx E_{in} + E_{ac}$).

Gain narrowing - due to the higher gain near 800 nm wavelength, spectral band narrowing can be observed, particularly for many passes amplifiers



Amplification simulation for 10-PW APOLLON laser
(a) With spectral shaping before each multi-pass amplifier except the last one.
(b) Without spectral shaping



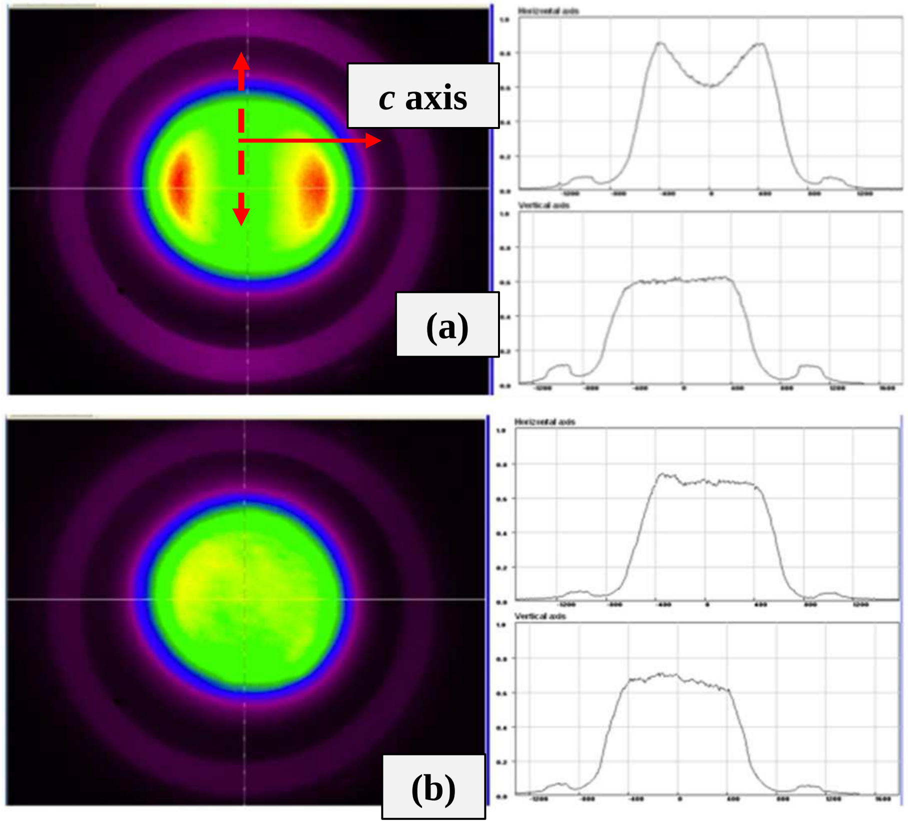
Spectrum narrowing and Red-shifting after Regen Amplifier and first Multi-pass Amplifier (25 mJ pulse energy) in a 10 TW laser system

F. Giambruno et al., Appl. Optics **50** (17), 2617-2621 (2011)

Transversal lasing – a limiting factor of laser amplification in large size Ti:sapphire crystals

Non-transversal lasing condition: $\boxed{G_T R < 1}$

R **= side reflectivity of the TiS crystal**



Fluorescence spatial profile
(a) Transversal lasing on the direction of normal propagation on the crystal ***c*** axis of Ti:sapphire crystal. (b) Without transversal lasing.

S. Laux et al., Opt. Lett. **37** (11), 1913 (2012)

Highest transversal gain is at the input pump radiation face of the Ti:sapphire crystal (z = 0):

$$F_p(z) = F_p(z=0)\exp[-\alpha z]$$

$$E_{abs}(z=0) = -\left.\frac{\partial F_p(z)}{\partial z}\right|_{z=0} = \alpha F_p(z=0)$$

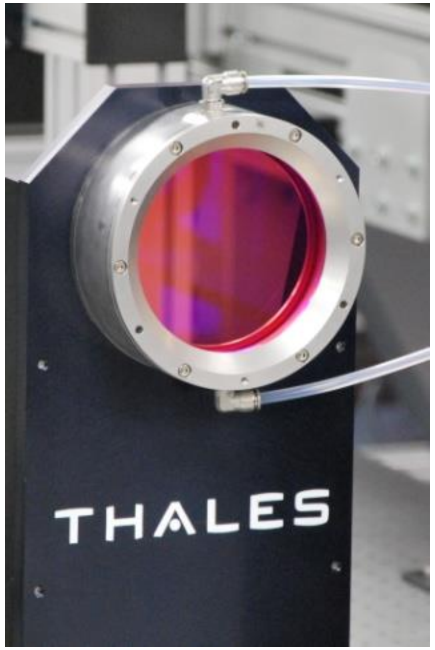
$$\boxed{\begin{aligned} G_T(z=0) &= \exp\left[n_{eff}(z=0)\sigma D\right] = \exp\left[\frac{E_{abs}(z=0)}{h\nu_P}\eta_{qe}\sigma D\right] = \\ &= \exp\left[\frac{\nu_L}{\nu_P}\frac{E_{abs}(z=0)}{F_{sat}}\eta_{qe} D\right] = \exp\left[\frac{\nu_L}{\nu_P}\frac{F_P(z=0)}{F_{sat}}\eta_{qe}\alpha D\right]\end{aligned}}$$

G_T – transversal gain
D **– TiS crystal diameter**
σ – emission cross-section
n(z = 0) – population inversion per volume unit
$n_{eff} \approx \eta_{qe} \times n \approx 0.8 \times n$
$E_{abs}(z=0)$ – pump laser energy density absorbed per volume unit at input face
α **– absorption coefficient**
$\boldsymbol{F_p(z=0)}$ **- input pump fluence**
ν_L – amplified laser pulse frequency
ν_P – pump laser frequency

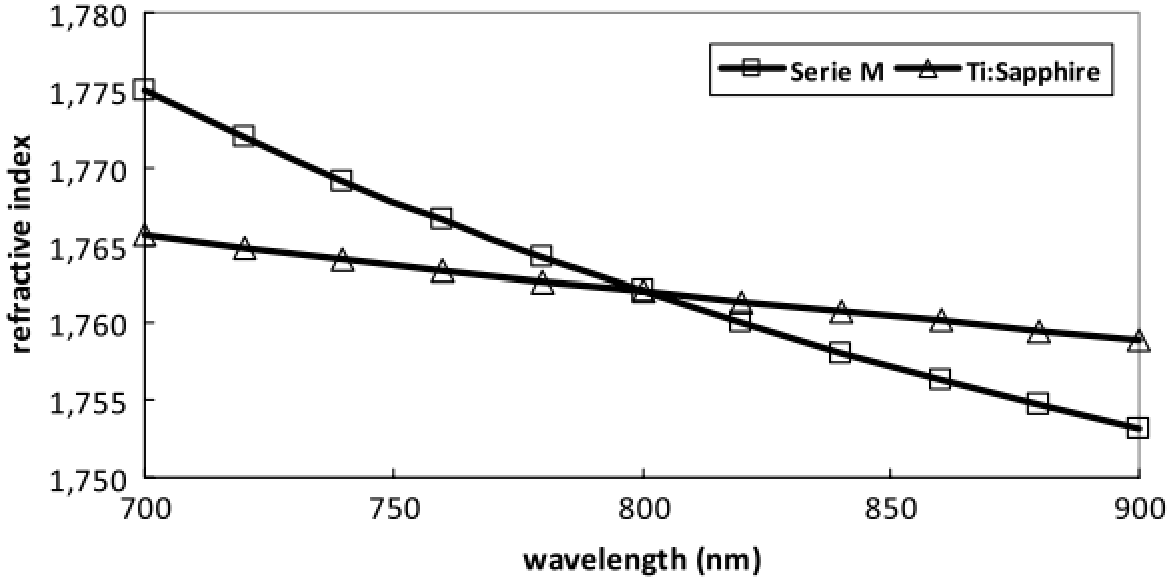
Transversal gain decreases if:
- Pump fluence decreases
- Absorption coefficient decreases (Ti doping of the crystal decreases)
- Pumped crystal area decreases

Methods to avoid transversal lasing

1. Matching the refractive index of TiS crystal and cooling liquid to reduce the transversal side reflectivity
2. Low doping of TiS crystal
3. Delayed pumping during amplification process



Liquid cooled Ti:sapphire crystal in a Thales mount



Refractive index curve of Ti:sapphire versus refractive index of the liquid (Cargille Serie M)
It is practically impossible a perfect index matching over the whole laser pulse spectral band.

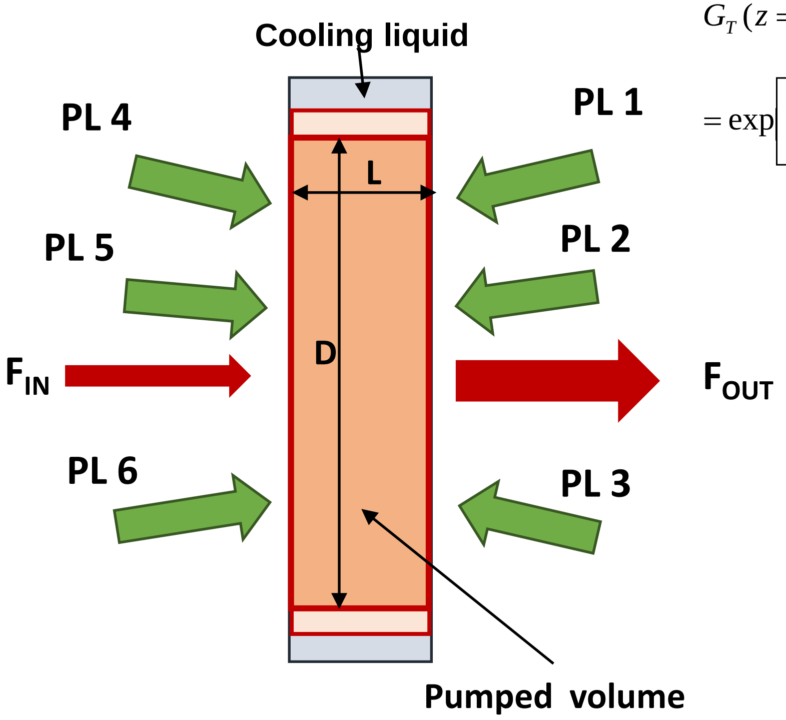
S. Laux et al., Opt. Lett. **37** (11), 1913 (2012)

Avoiding transversal lasing in the last amplifier of a 10 PW laser system by “extraction during pumping”

Reflectivity with index matched cooling liquid = 0.04%
$G_T < 2500$

For simultaneously pumping with all six 100 J lasers:
$G_T > 15000$

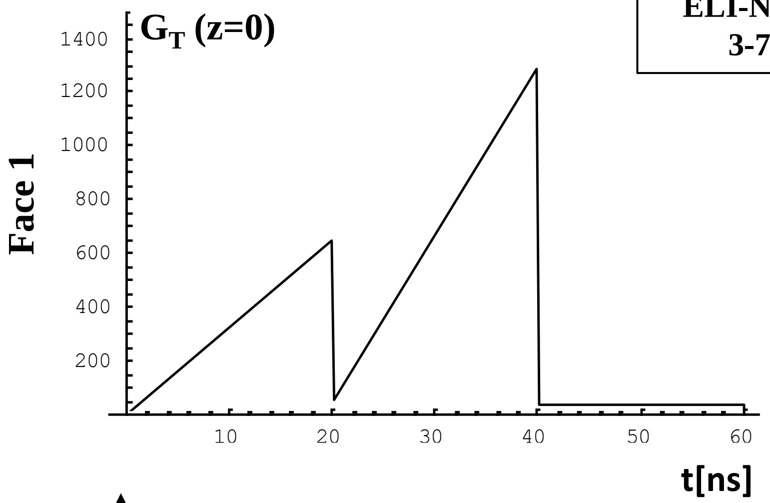
	Input	First Pass	Second Pass	Third Pass
Fluence [J/cm²]	0.45	0.978	1.719	1.915
Energy [J]	90	195	343	383

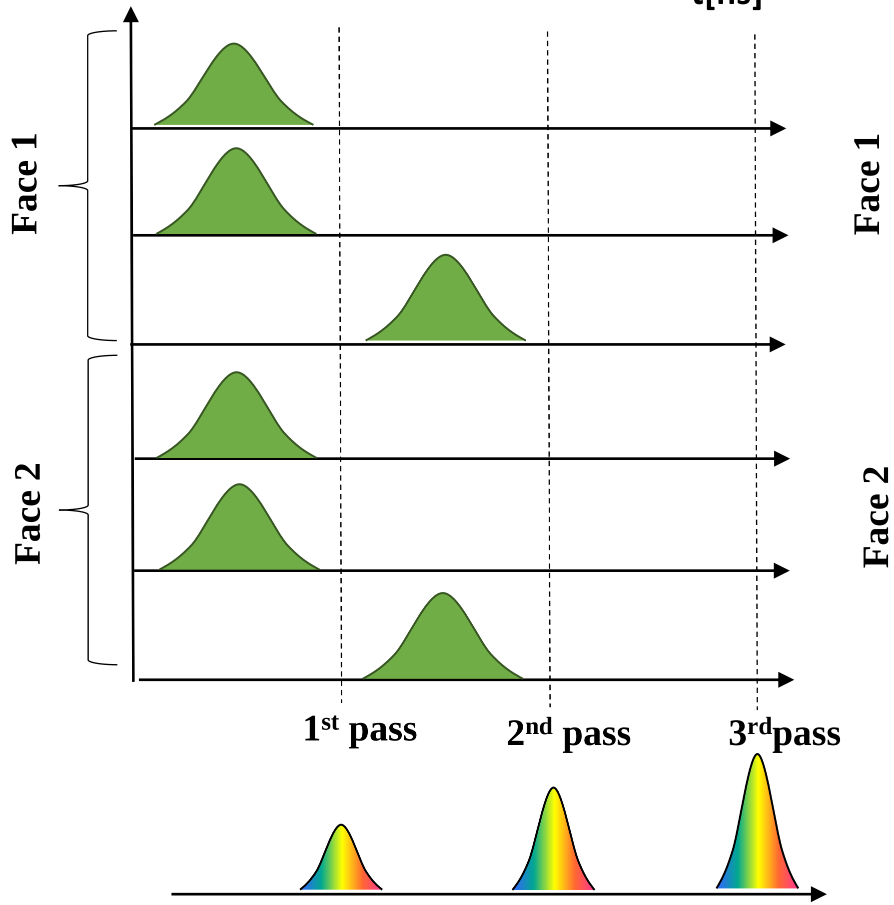


$$G_T(z=0)=\exp[n(z=0)\,\sigma\,D]=\exp\left[\frac{E_{ac}(z=0)}{h\nu_L}\sigma\,D\right]=$$

$$=\exp\left[\frac{E_{ac}(z=0)}{F_{sat}}D\right]=\exp\left[\frac{\nu_L}{\nu_P}\frac{F_P(z=0)}{F_{sat}}\alpha\,D\right]$$

α = 0.66
Ti doping [wt] = 0.035%
D = 160 mm
E_{IN} = 90 J
F_{IN} = input fluence = 0.45 J/cm^2
L = 4.65 cm
Absorption = 95%
PL, pump laser, 100 J @ 532 nm



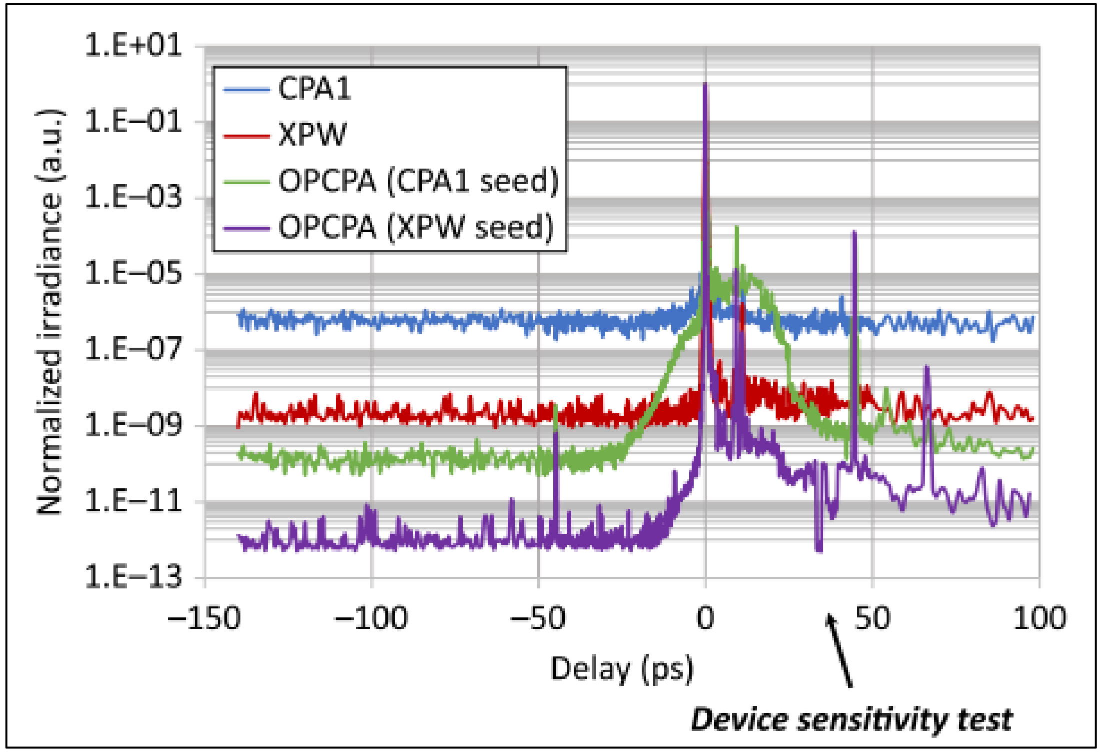


ELI Nuclear Physics

Amplified spontaneous emission (ASE) – limiting factor of intensity contrast in femtosecond laser systems based on CPA in Ti:sapphire

ELI-NP Autumn School
3-7 October 2022

Experiments with tightly focused laser beams require very good spatio-temporal characteristics of the high-power femtosecond pulses, particularly **high intensity contrast** and **low wavefront distortion.**



ELI-NP HPLS FE intensity contrast assessment using a test compressor

CPA1 – only CPA in the Regenerative Amplifier
XPW – CPA followed by XPW in BaF_2 crystals
OPCPA (CPA1 seed) – ps OPCPA in BBO crystals seeded by CPA1 laser pulses
OPCPA (XPW seed) – ps OPCPA seeded by CPA1 & XPW laser pulses

Without improvement methods, the intensity contrast in Ti:sapphire CPA laser systems is about 10^{-6}

Techniques for intensity contrast improvement

- **Femtosecond pulses filtering by saturable absorbers**
- **Crosses-polarized wave generation (XPW) in crystals**
- **Optically synchronized picosecond OPCPA**

High Power Laser Science and Engineering, (2020), Vol. 8, e43, 15 pages.
doi:10.1017/hpl.2020.41

HIGH POWER LASER SCIENCE AND ENGINEERING

RESEARCH ARTICLE

High-energy hybrid femtosecond laser system demonstrating 2 × 10 PW capability

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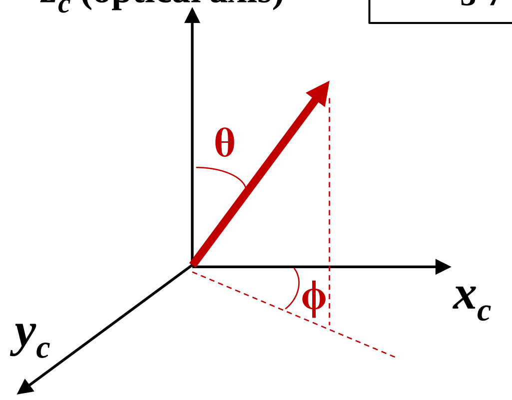
Advantages and Drawbacks of Ti:sapphire CPA femtosecond laser systems

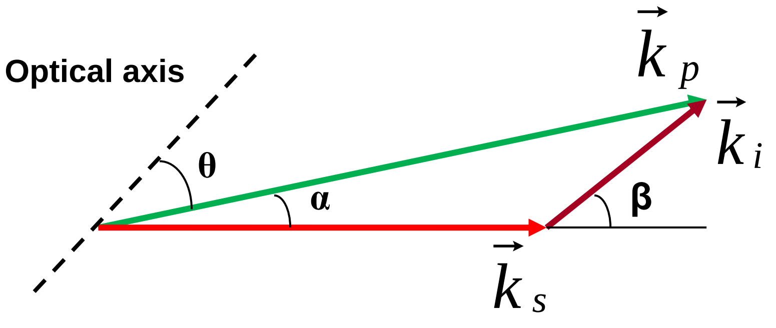
Advantages	Drawbacks
Noncritical pump pulse duration **Non-critical signal-pump pulse synchronization** (Ti:sapphire fluorescent lifetime time ~3.2 μs) **A couple of high energy green pump lasers, with 6-20 ns pulse duration, can be used for high energy amplifiers**	**Spectral band narrowing & Red shifting:** Longer recompressed amplified pulse **Amplification of spontaneous emission:** Relatively low intensity contrast **Thermal loading:** Part of the pump energy (~ 33% in case of Ti:sapphire) is dissipated in the amplifying medium ⟶ **Wavefront distortion** **Transversal lasing and ASE** in large size Ti:sapphire crystals Damage of optical components due to the **back reflected laser radiation amplification**

Drawbacks can be partially removed using advanced enhancement techniques

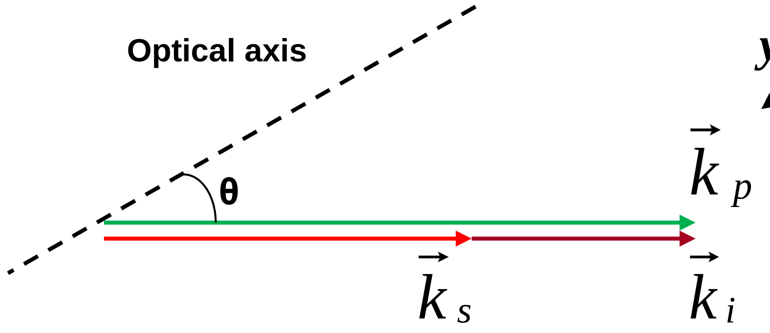
Principle of Optical Parametric Amplification (OPA)

p → pump beam
s → signal beam
i → idler beam
$\omega_p > \omega_s , \omega_i$

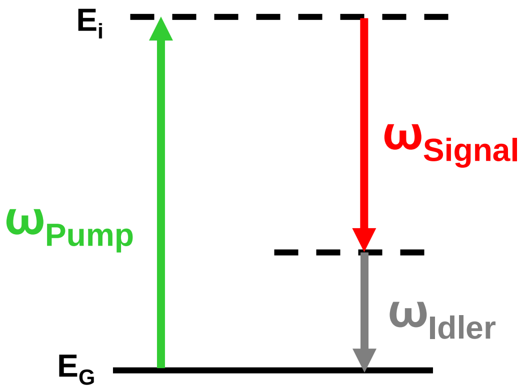




Non-collinear OPA, NOPA



Collinear OPA



Parametric amplification

$$\omega_p = \omega_s + \omega_i$$

Quanta Energy conservation
and
Wave-vectors Phase-Matching condition must be fulfilled for optical parametric amplification

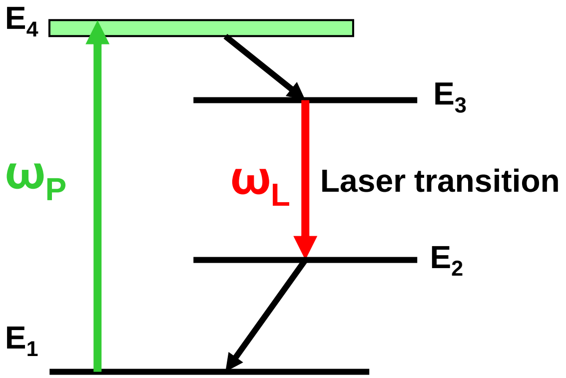
$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}$$

$$\frac{n_p}{\lambda_p} = \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i}$$

$$\Delta\vec{k} = \vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

$$|\vec{k}| = \frac{2\pi}{\lambda} n$$

n → index of refraction

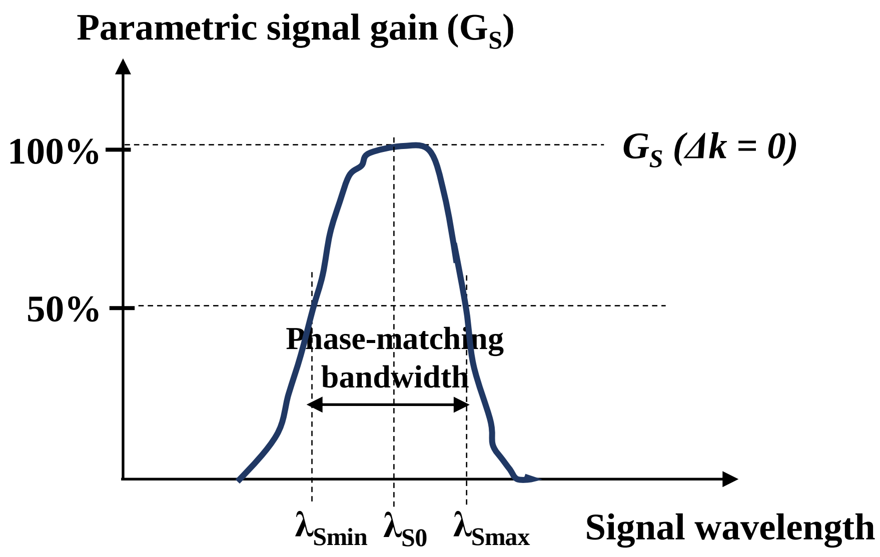


Laser amplification

Parametric gain bandwidth

Coupled equations that describe the parametric amplification process (neglected waves absorption in crystal):

$$\frac{dA_s}{dz} = -j\frac{\omega_s d_{eff}}{n_s c} A_p A_i^* \exp(-j\Delta k z)$$
$$\frac{dA_i}{dz} = -j\frac{\omega_i d_{eff}}{n_i c} A_p A_s^* \exp(-j\Delta k z)$$
$$\frac{dA_p}{dz} = -j\frac{\omega_p d_{eff}}{n_p c} A_s A_i \exp(j\Delta k z)$$



Under following approximations (small-signal) :

$A_s(0) << A_p(0)$ small initial signal amplitude

$A_i(0) = 0$ no initial idler beam

$A_p(L) \cong A_p(0)$ neglected pump depletion

L, length of nonlinear crystal

Parametric gain: $G_s(L) = \frac{I_s(L) - I_s(0)}{I_s(0)} = \Gamma^2 \frac{\sinh^2(gL)}{g^2} = \frac{\Gamma^2}{g^2}\left(\frac{e^{gL} - e^{-gL}}{2}\right)^2$

where $g^2 = \Gamma^2 - \left(\frac{\Delta k}{2}\right)^2$ $\quad \Gamma^2 = \frac{2\omega_s \omega_i d_{eff}^2 I_p}{n_s n_i n_p \varepsilon_0 c^3} = \frac{8\pi^2 d_{eff}^2 I_p}{n_s n_i n_p \lambda_s \lambda_i \varepsilon_0 c}$

$\Delta k = k_p - k_s - k_i$ wave-vectors mismatch

I_p – pump intensity, d_{eff} – nonlinear coefficient,
ε_0 – vacuum permittivity, c - speed of light

Phase-matching bandwidth: $G_s(\Delta k) = \frac{1}{2} G_s(\Delta k = 0)$

Approximation of high parametric gain:
$\Delta k = 0,\ \Gamma L >> 1$
$G_S(L) \approx \frac{\exp(2\Gamma L)}{4}$

OPA for large bandwidth signals

Exact phase-matching condition is fulfilled for monochromatic pump, signal, and idler wavelengths

Wave-vector mismatch, *Δk*, calculated by a Taylor expansion:

$$\vec{k}_p(\omega_p)-\vec{k}_s(\omega_s)-\vec{k}_i(\omega_i)=\Delta\vec{k}$$

$$\omega_p-\omega_{s0}-\omega_{i0}=0$$

$$k_p(\omega_p)-k_s(\omega_{s0})-k_i(\omega_{pi0})=\Delta k^{(0)}=0$$

Phase-matching

$$\omega_s=\omega_{s0}+\Delta\omega,\quad \omega_i=\omega_{i0}-\Delta\omega\ \Rightarrow d\omega_s=-d\omega_i$$

$$\Delta k=\Delta k^{(0)}+\left(\frac{\partial\Delta k}{\partial\omega_s}\right)_{\omega_{s0}}d\omega_s+\frac{1}{2!}\left(\frac{\partial^2\Delta k}{\partial\omega_s^2}\right)_{\omega_{s0}}(d\omega_s)^2+\frac{1}{3!}\left(\frac{\partial^3\Delta k}{\partial\omega_s^3}\right)_{\omega_{s0}}(d\omega_s)^3+\frac{1}{4!}\left(\frac{\partial^4\Delta k}{\partial\omega_s^4}\right)_{\omega_{s0}}(d\omega_s)^4+\ldots\approx$$

$$\Delta k^{(0)}-\left(\frac{\partial k_s}{\partial\omega_s}-\frac{\partial k_i}{\partial\omega_i}\right)\Delta\omega-\frac{1}{2!}\left(\frac{\partial^2 k_s}{\partial\omega_s^2}+\frac{\partial^2 k_i}{\partial\omega_i^2}\right)(\Delta\omega)^2-\frac{1}{3!}\left(\frac{\partial^3 k_s}{\partial\omega_s^3}-\frac{\partial^3 k_i}{\partial\omega_i^3}\right)(\Delta\omega)^3-\frac{1}{4!}\left(\frac{\partial^4 k_s}{\partial\omega_s^4}+\frac{\partial^4 k_i}{\partial\omega_i^4}\right)(\Delta\omega)^4\ldots=$$

$$\Delta k^{(0)}+\Delta k^{(1)}+\Delta k^{(2)}+\Delta k^{(3)}+\Delta k^{(4)}+\ldots$$

Low order factors prevail over high order ones

$\Delta k^{(0)}=0$ Phase matching

$\Delta k^{(1)}=0$ Broad gain bandwidth

$\Delta k^{(2)}=0$ Ultra-broad gain bandwidth

$$\Delta k^{(0)}=0,\Delta k^{(1)}\neq 0$$

Narrow gain bandwidth, suitable for mono-chromatic or quasi-monochromatic signal amplification

$$\Delta\omega^{(1)}=4(\ln 2)^{1/2}\left(\frac{\Gamma}{L}\right)^{1/2}\frac{1}{\left|\frac{\partial k_s}{\partial\omega_s}-\frac{\partial k_i}{\partial\omega_i}\right|}=4(\ln 2)^{1/2}\left(\frac{\Gamma}{L}\right)^{1/2}\frac{1}{\left|\frac{1}{v_{gs}}-\frac{1}{v_{gi}}\right|}$$

Narrow gain bandwidth (quasi-monochromatic) non-collinear optical parametric amplification (NOPA)

Six parameters are involved in a non-collinear parametric amplification:

- Wavelengths (frequencies) of interacting waves: λ_p, λ_s, λ_i (ω_p, ω_s, ω_i)

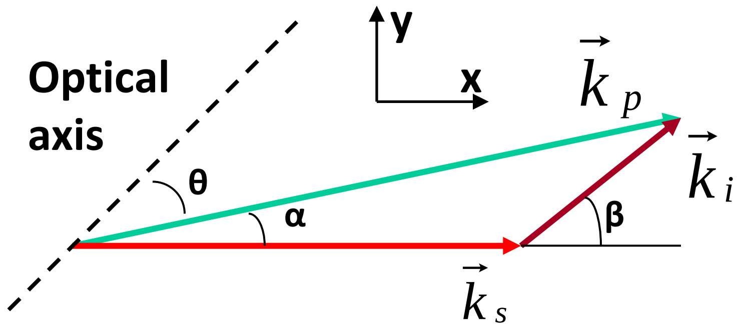
- Interaction angles inside crystal: θ, α, β

N1 – number of equations which describe the OPA for quasi-monochromatic wave interactions

N2 – number of equations related to requirements concerning gain bandwidth of OPA

FP – free parameters which can be chosen for an experimental set-up

FP = 6 – N1 – N2



$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}$$

$$\frac{n_p(\lambda_p,\theta)}{\lambda_p}\sin\alpha - \frac{n_i(\lambda_i)}{\lambda_i}\sin\beta = 0$$

$$\frac{n_p(\lambda_p,\theta)}{\lambda_p}\cos\alpha - \frac{n_s(\lambda_s)}{\lambda_s} - \frac{n_i(\lambda_i)}{\lambda_i}\cos\beta = 0$$

N1 = 3, N2 = 0, FP = 3

Free (chosen) parameters: λ_p, λ_s, α

Calculated parameters: θ, β, λ_i

Broad and ultra-broad bandwidth NOPA

Broad bandwidth

$\Delta k^{(0)} = 0, \Delta k^{(1)} = 0$

$$\left.\begin{aligned} &\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \\ &\frac{n_p(\lambda_p,\theta)}{\lambda_p}\sin\alpha - \frac{n_i(\lambda_i)}{\lambda_i}\sin\beta = 0 \\ &\frac{n_p(\lambda_p,\theta)}{\lambda_p}\cos\alpha - \frac{n_s(\lambda_s)}{\lambda_s} - \frac{n_i(\lambda_i)}{\lambda_i}\cos\beta = 0 \end{aligned}\right\} \Delta k^{(0)} = 0$$

$$\left. v_{gs} = v_{gi}\cos\beta \right\} \Delta k^{(1)} = 0$$

N1 = 3, N2 = 1, FP = 2

Free (chosen) parameters: λ_p, λ_s

Calculated parameters: α, θ, β, λ_i

Ultra-broad bandwidth

$\Delta k^{(0)} = 0, \Delta k^{(1)} = 0, \Delta k^{(2)} = 0$

$$\left.\begin{aligned} &\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \\ &\frac{n_p(\lambda_p,\theta)}{\lambda_p}\sin\alpha - \frac{n_i(\lambda_i)}{\lambda_i}\sin\beta = 0 \\ &\frac{n_p(\lambda_p,\theta)}{\lambda_p}\cos\alpha - \frac{n_s(\lambda_s)}{\lambda_s} - \frac{n_i(\lambda_i)}{\lambda_i}\cos\beta = 0 \end{aligned}\right\} \Delta k^{(0)} = 0$$

$$\left. v_{gs} = v_{gi}\cos\beta \right\} \Delta k^{(1)} = 0$$

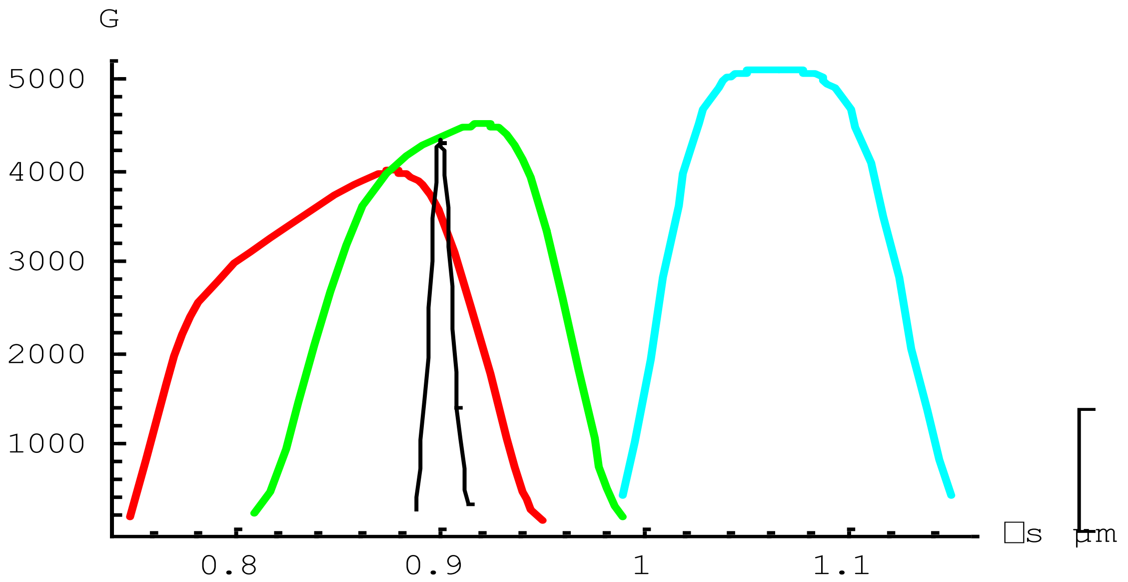
$$\left. \frac{\partial^2 k_s}{\partial \omega_s^2}\cos\beta + \frac{\partial^2 k_i}{\partial \omega_i^2} - \frac{\sin^2\beta}{v_{gs}^2 k_i} = 0 \right\} \Delta k^{(2)} = 0$$

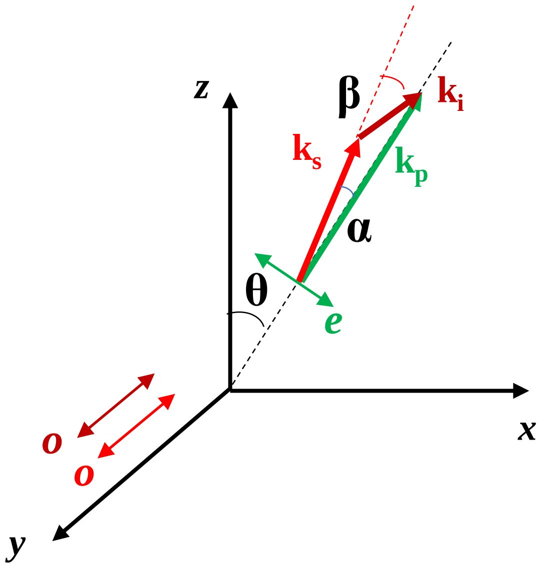
N1 = 3, N2 = 2, FP = 1

Chosen parameter: λ_p

Calculated parameters: λ_s, θ, α, β, λ_i

Gain bandwidths in BaB_2O_4 (BBO) crystals





Small signal gain spectra for type - I OPA in a 10-mm length BBO crystal, I_P = 1 GW/cm^2.

λp= 0.532 µm. Black color – collinear interaction, λs = 0.9 µm; Blue color – collinear degenerated (CD) OPA, λs = λi = 1.064 µm; Green color – NOPA, λs = 0.9 µm; Red color – UBB-NOPA, λs = 0.825 µm.

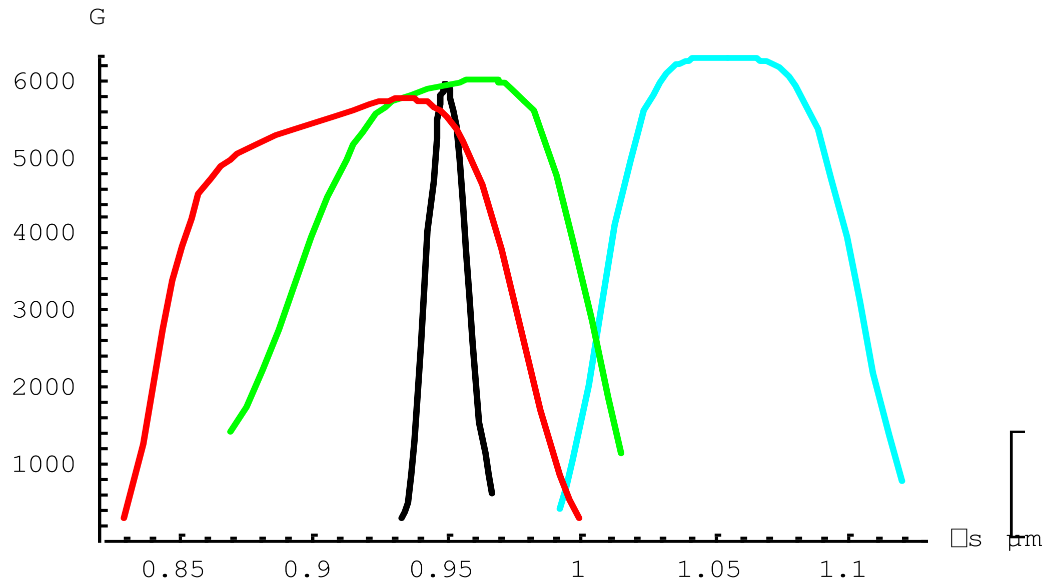
Parametric process	λ_p [µm]	λ_s [µm]	λ_i [µm]	d_{eff} [pm/V]	θ [deg]	ϕ [deg]	α [deg]	β [deg]	FWHM-GB [nm]
Collinear OPA	0.532	0.900	1.301	2.07	22.6	0	0	0	13
CD-OPA	0.532	1.064	1.064	2.06	22.8	0	0	0	115
NOPA	0.532	0.900	1.301	2.07	23.7	0	2.26	5.55	120
UBB-NOPA	0.532	0.825	1.497	2.07	23.8	0	2.41	6.82	150

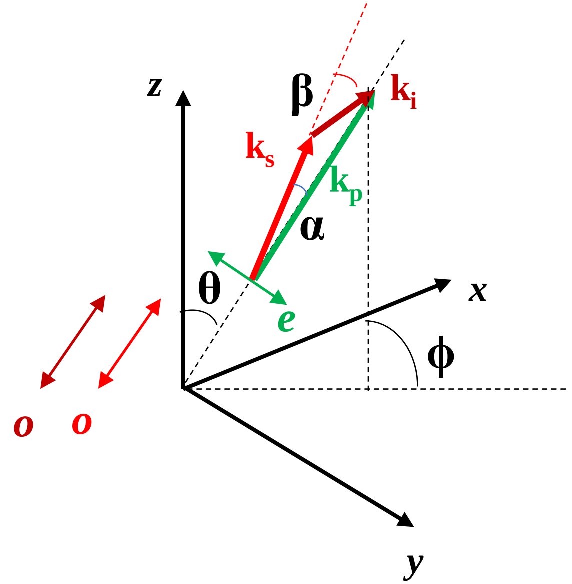
Ultra-broad gain bandwidths can support the amplification of 10 fs range laser pulses

R. Dabu, Opt. Express **18**, 11689-11699 (2010)

Gain bandwidths in KD_2PO_4 (DKDP) crystals

$KH_2PO_4 \rightarrow$ KDP
$K(H_2)_{1-d}(D_2)_dPO_4 \rightarrow$ P-DKDP
$KD_2PO_4 \rightarrow$ DKDP





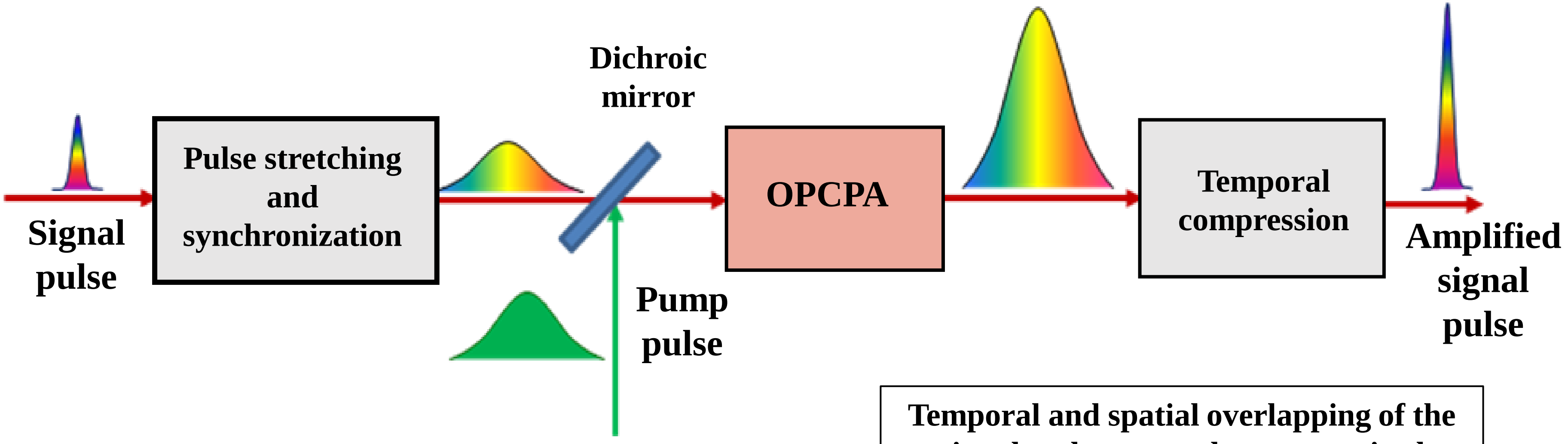
Small signal gain spectra for type – I OPA in a 80-mm length DKDP crystal, I_P = 1 GW/cm^2.

λp= 0.527 µm. Black color – collinear interaction, λs = 0.95 µm; Blue color – collinear degenerated (CD) OPA, λs = λi = 1.054 µm; Green color – NOPA, λs = 0.95 µm; Red color – UBB-NOPA, λs = 0.900 µm.

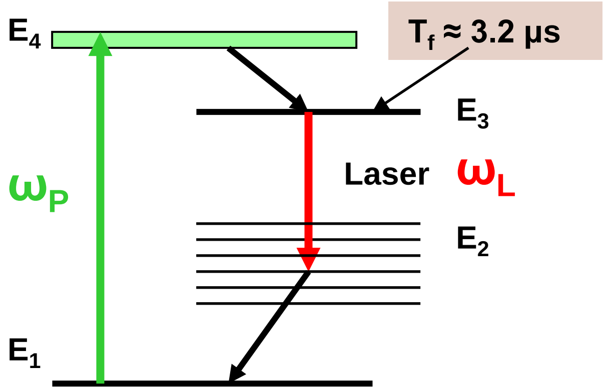
Parametric process	λ_p [µm]	λ_s [µm]	λ_i [µm]	d_{eff} [pm/V]	θ [deg]	ϕ [deg]	α [deg]	β [deg]	FWHM-GB [nm]
Collinear OPA	0.527	0.950	1.184	0.22	36.7	45	0	0	15
CD-OPA	0.527	1.054	1.054	0.22	36.6	45	0	0	100
NOPA	0.527	0.950	1.184	0.22	37.0	45	0.85	1.92	110
UBB-NOPA	0.527	0.900	1.271	0.22	37.0	45	0.92	2.22	135

R. Dabu, Opt. Express **18**, 11689-11699 (2010)

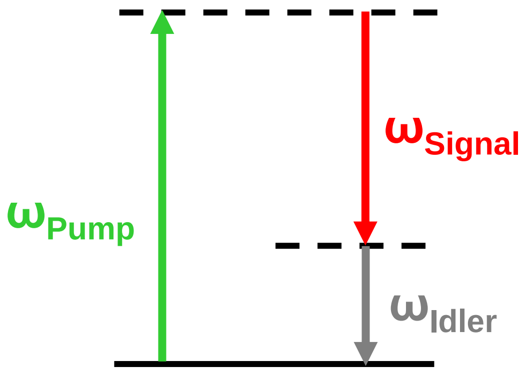
Principle of Optical Parametric Chirped Pulse Amplification (OPCPA)



Temporal and spatial overlapping of the signal and pump pulse are required



Ti:sapphire CPA versus OPCPA



Amplification process based on accumulated inversion population versus an instantaneous nonlinear process which takes place only when signal and pump waves are simultaneously present

A. Dubietis et al, "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal". Optics Commun. **88**, 437 (1992).

Nonlinear crystals for OPCPA

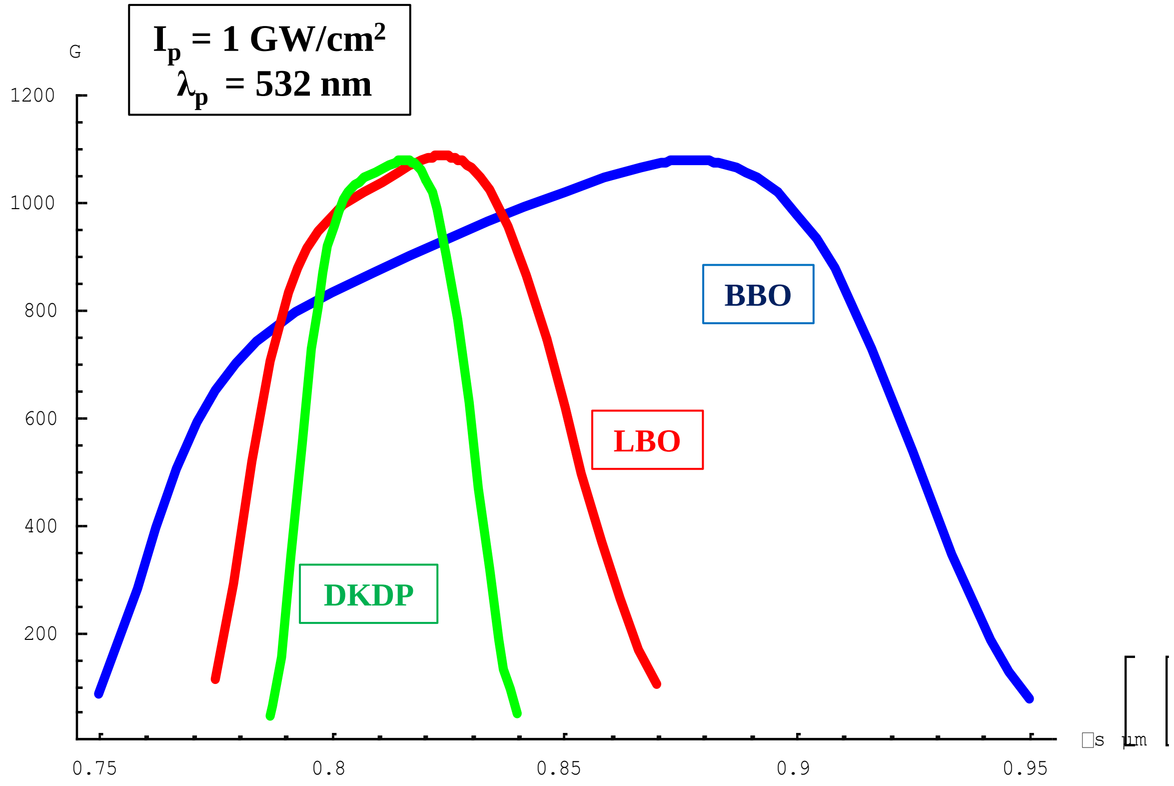
Comparison of bulk damage threshold (@1064 nm, 1.3 ns):

Crystal	Energy Fluence (J/cm^2)	Power Density (GW/cm^2)
KTP	6.0	4.6
KDP	10.9	8.4
BBO	12.9	9.9
LBO	24.6	18.9

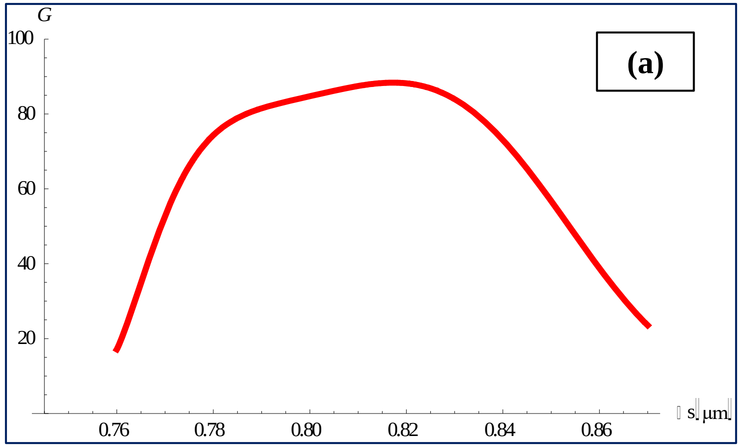
Nonlinear crystal	Available clear aperture diameter	Gain bandwidth
BBO	Few cm	Can amplify 10-fs laser pulses with 800 nm central wavelength up to ~100 mJ pulse energy
DKDP, KDP	Up to 50 cm	Can amplify kJ 10-fs pulses in 900 nm spectral band; requires shifting of the Ti:sapphire laser pulses spectrum (central wavelength)*
LBO	More than 10 cm	Can amplify laser pulses with 10-fs range pulse duration in the 900 nm spectral band. Can amplify >100 J/ 20 fs laser pulses at 800 nm central wavelength**

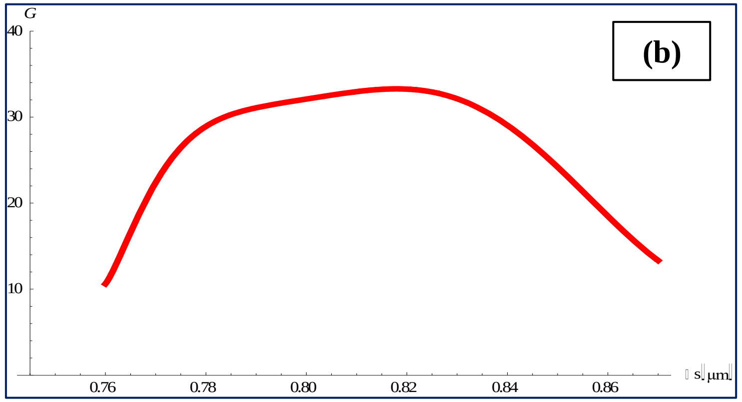
*V.V. Lozhkarev et al, „Compact 0.56 Petawatt laser system based on optical parametric chirped pulse amplification in KD*P crystals", Laser Phys. Lett. **4** (6), 421–427 (2007).
*Y. Tang et al, "Optical parametric chirped-pulse amplification source suitable for seeding high-energy systems", Opt. Lett. **33** (20), 2386 (2008)
L.Yu et al., "Optimization for high-energy and high-efficiency broadband optical parametric chirped-pulse amplification in LBO near 800 nm", Opt. Lett. **40 (14), 3412 (2015).

NOPA Gain Bandwidth of some nonlinear crystals in the 800 nm range



Crystal	Length [mm]	Central wavelength [nm]	Gain bandwidth - FWHM [nm]
BBO (blue)	8.7	825	156
LBO (red)	21	810	71
DKDP (green)	70	810	37





	Pump intensity [GW/cm^2]	Crystal Length [mm]	Gain Bandwidth-FWHM [nm]
(a)	1.5	12	~ 90
(b)	1.5	10	~ 97

LiB_3O_5 (LBO) NOPA small signal gain bandwidth (FWHM) around 810 nm wavelength

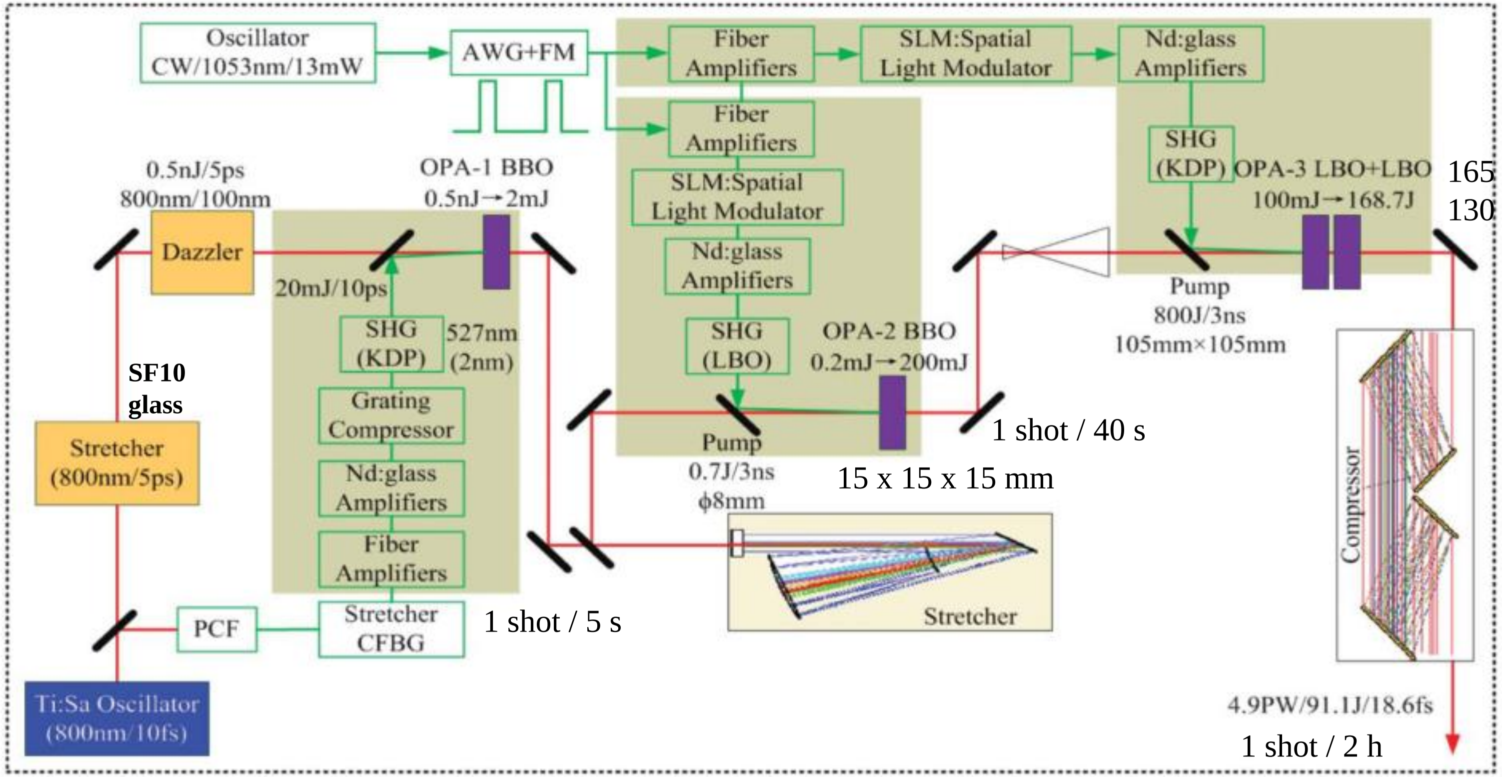
ELI-NP Autumn School
3-7 October 2022

Multi-petawatt laser facility fully based on optical parametric chirped-pulse amplification

Xiaoming Zeng,[1,2,3] Kainan Zhou,[1,2,3] Yanlei Zuo,[1,2,3,*] Qihua Zhu,[1,2,3] Jingqin Su,[1,2,3] Xiao Wang,[1,2,3] Xiaodong Wang,[1,2] Xiaojun Huang,[1,2] Xuejun Jiang,[1] Dongbin Jiang,[1,2] Yi Guo,[1] Na Xie,[1,2] Song Zhou,[1,2] Zhaohui Wu,[1,2] Jie Mu,[1,2] Hao Peng,[1,2] and Feng Jing[1,2]

2014 Vol. 42, No. 10 / May 15 2017 / *Optics Letters*

Laser Fusion Research Center, China Academy of Engineering Physics

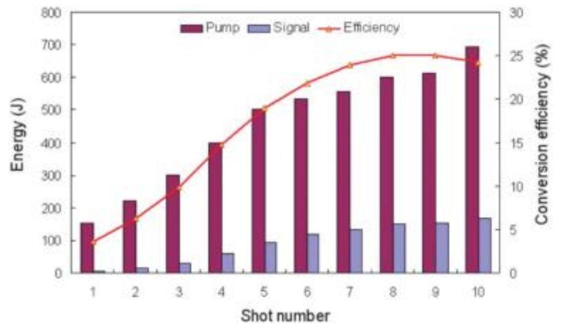


165 x 120 x 10 mm
130 x 130 x 10 mm

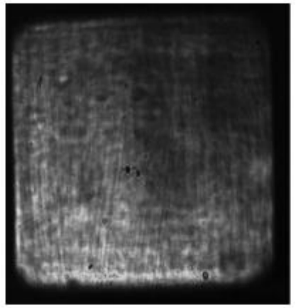
Schematic of the CAEP-PW laser facility.

4.9 PW / 91.1 J / 18.6 fs

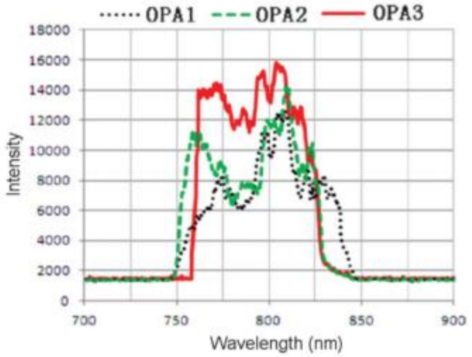
PCF, photonic crystal fiber
CFBG, fiber Bragg grating
AWG, arbitrary wave-form generator



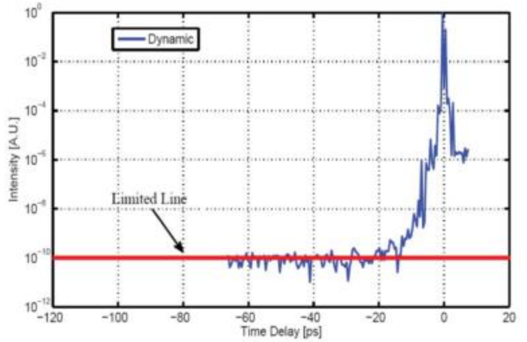
Amplified energies and conversion efficiency of OPA-3.



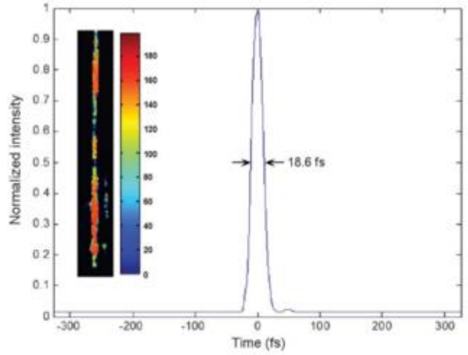
Near-field profile after OPA-3.



Typical output spectrum of three amplifiers.



Temporal profile after the compressor measured by a single-shot third-order autocorrelator.



Compressed duration of 18.6 fs (single-shot autocorrelation trace, by applying a Gaussian deconvolution factor).

Advantages and Drawbacks of all-OPCPA femtosecond laser systems

Advantages	Drawbacks
No Spectral band narrowing & Red shifting: Large spectral bandwidth could be preserved during amplification process **Signal pulse is amplified only when signal and pump pulses are temporally and spatially overlapped:** **Intensity contrast is improved outside the overlapping time range of seed and pump pulses** (using optically synchronized ps seed and pump pulses) **No thermal loading ⟶ Low wavefront distortion** **No back-reflected radiation amplification**	**Critical signal-pump pulse synchronization and spatial overlapping** Optical synchronization is necessary in case of picosecond-femtosecond signal and pump lasers Critical signal-pump wave vectors angle **Many technical difficulties are related to the pump lasers:** High energy single beam pump laser Useful pump energy is in the range of 1-3 nsec pulse duration **Low repetition rate of pump laser pulses** **Critical spatial and temporal pump laser beam profiles** Very stable flat top and smooth spatial and temporal profile of the pump pulses are required Amplified spectrum strongly depends on pump pulse fluctuations

Hybrid chirped pulse amplification

combines CPA in Ti:sapphire crystals with OPCPA in nonlinear crystals

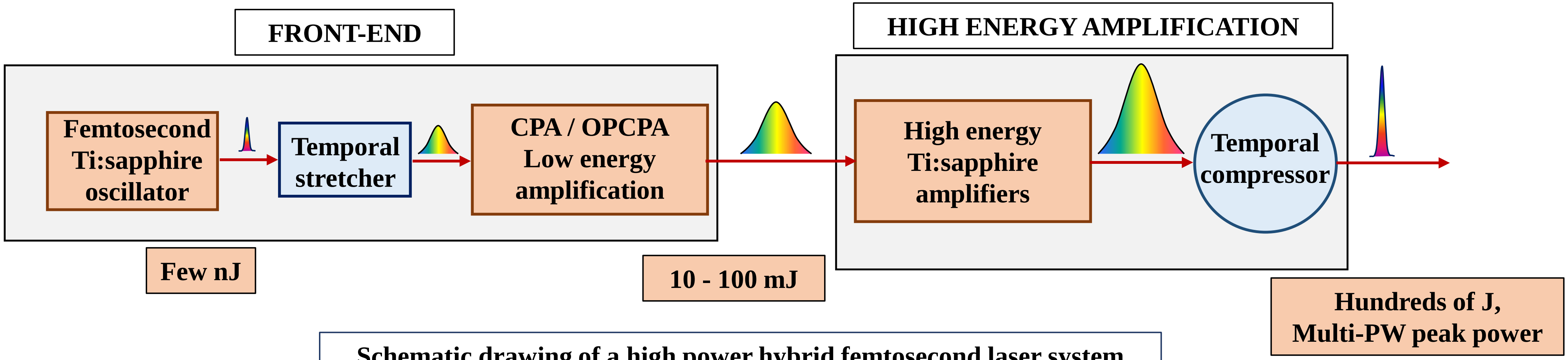
Key feature of hybrid femtosecond lasers is the matching of Ti:sapphire laser spectrum with the gain bandwidth of OPCPA nonlinear crystals.

OPCPA in BBO (β-BaB_2O_4) crystals: the central wavelength of the ultra-broad gain bandwidth corresponds to the central wavelength of the amplified spectrum of Ti:sapphire, about **800 nm**. The amplification in **BBO** crystals can be easily combined with high energy Ti:sapphire amplification.

OPCPA in KDP, DKDP and LBO (LiB_3O_5) crystals: the central wavelength of the ultra-broad gain bandwidths is in the range of **900 nm.** It is more difficult to combine the amplification in these crystals with Ti:sapphire amplification.

Features of hybrid CPA:

- **High intensity contrast**
- **Broad-bandwidth amplified pulses → very short duration recompressed laser pulses**
- **Low thermal effects and beam distortions**
- **A couple of high energy pump lasers with relatively high repetition rate can be used for pumping the large aperture Ti:sapphire crystals from high energy amplification stages**



Schematic drawing of a high power hybrid femtosecond laser system

Hybrid multi-PW femtosecond laser system

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Optics Letters

4.2 PW, 20 fs Ti:sapphire laser at 0.1 Hz

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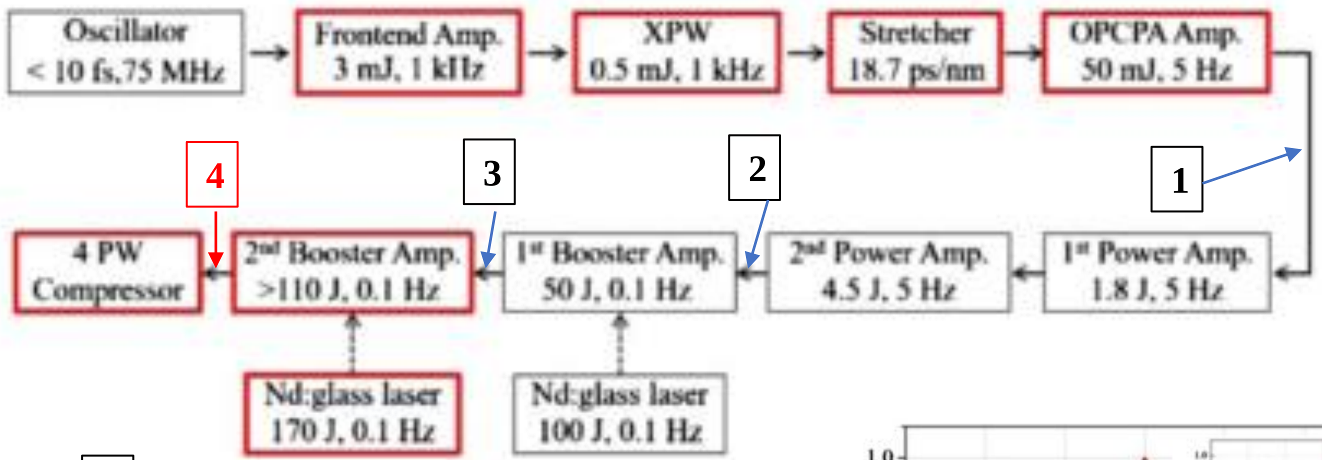
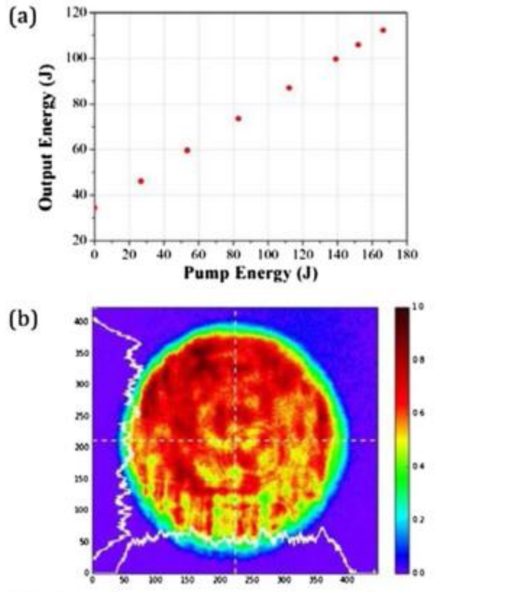
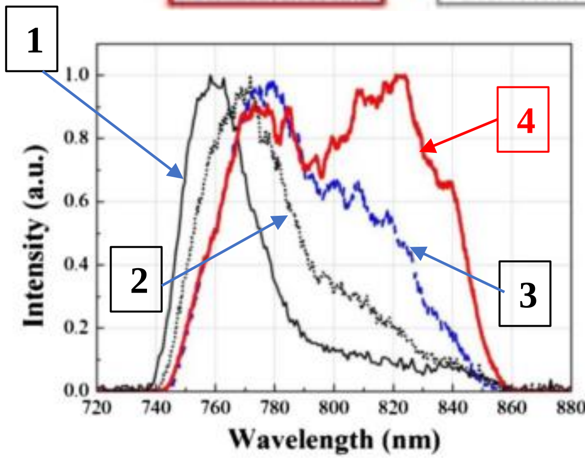
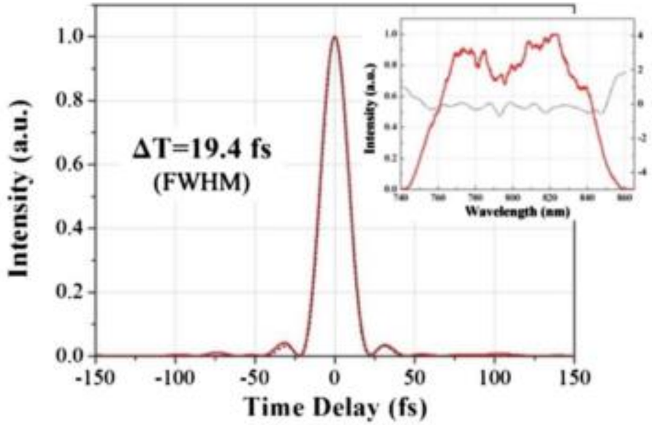




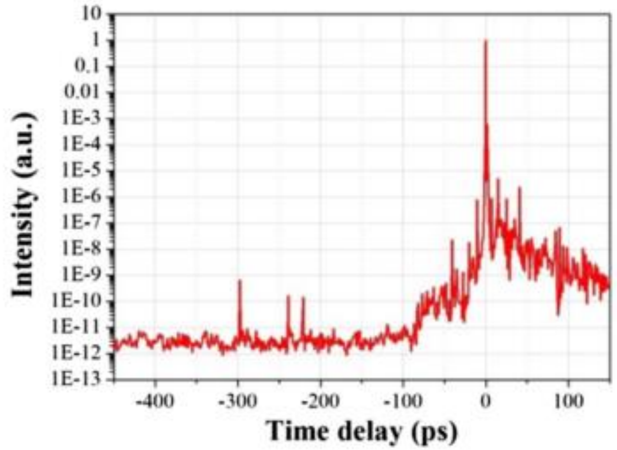
(a) Measured output energy as a function of pump energy in the final booster amplifier. (b) Spatial beam profile after the final booster amplifier.



Laser spectra after the OPCPA amplifier (thin solid line), the second power amplifier (dotted line), the first booster amplifier (dashed line), and the second booster amplifier (thick solid line).



Reconstructed temporal profile of the 4.2 PW laser pulse (solid line) and calculated temporal profile of the Fourier-transform-limited pulse (dotted line). The inset shows the final spectrum (solid line) and the final spectral phase (dotted line).



Temporal contrast of the compressed laser pulse without the pumping of two booster amplifiers.

Prospects towards 100 PW laser systems

100 PW Laser Projects

1. USA, University of Rochester, Department of Energy, Optical Parametric Amplifier Line (OPAL), 75 PW – "single beam"
2. China, Shanghai, Super-intense Ultrafast Laser Facility , Station of Extreme Light (SEL), >100 PW (3 × 40 PW).
3. Russia, Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Exawatt Center for Extreme Light Studies (XCELS), 180 PW (12 × 15 PW)

E. Cartlidge, "The light fantastic", Science, **359**, 382-383 (2018).

All project conceptual designs were based on OPCPA in large size DKDP, P-DKDP crystals.

Why OPCPA for 100-PW class laser systems?

- **DKDP crystals have clear aperture significantly larger compared to Ti:sapphire crystals (> 400 mm vs ~200 mm)**
- **Ultrabroad spectral band of amplified pulses (~200 nm), ~2 times broader than in Ti:sapphire laser systems**

Technical challenges and critical technologies

(1) Generation of ultra-broadband pulse seed in the 900 nm spectral range
(2) Ultra-broadband front-end amplification, ~200 nm, at the low energy level (mJ)
(3) Large aperture (> 400 mm), high optical quality, partially-deuterated DKDP crystals cut for type I phase-matching, ~200 nm gain bandwidth.
(4) Development of high energy (~10 kJ), few-nanosecond green lasers, with increased repetition rate, super-Gaussian spatial and temporal profile, for high energy OPCPA pumping.
(5) Pulse compression technology for single-beam laser systems:
- Hybrid dielectric-on-metal gratings that may be available in the future with high diffraction efficiency and higher damage threshold.
- Multi-step pulse compressor.

(6) Techniques for tiled-aperture coherent beam combining in multi-beam laser systems.
(7) Development of ultra-short pulse diagnostics, particularly vacuum pulse measurements using a sample of the laser beam.

OPAL 100 PW class laser project
University of Rochester, USA

ELI-NP Autumn School
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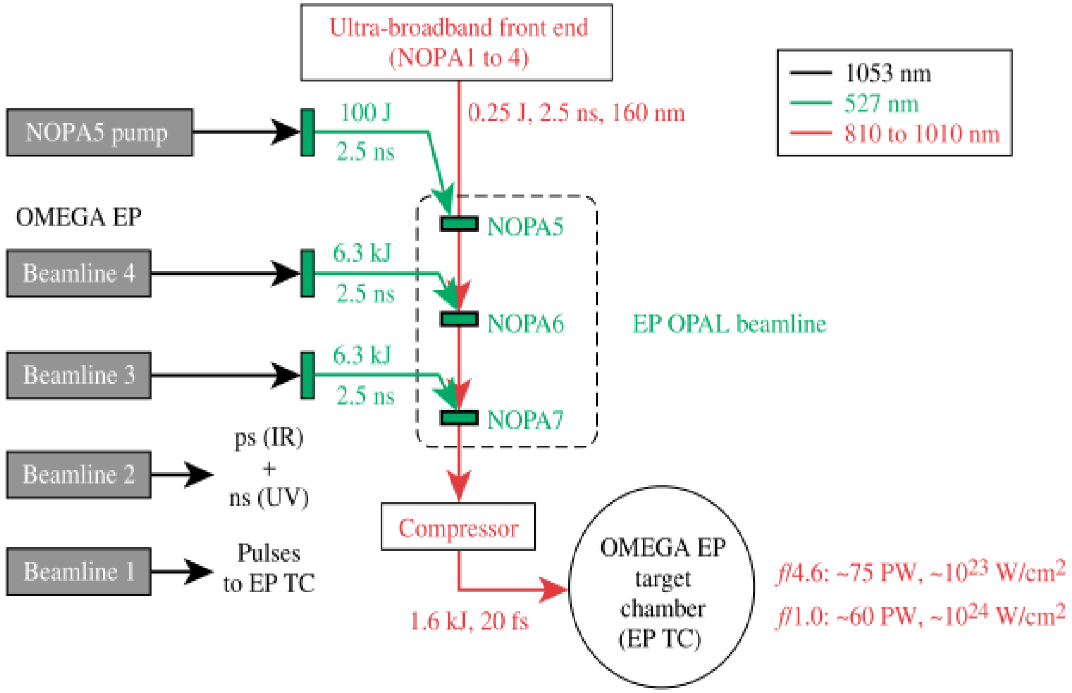
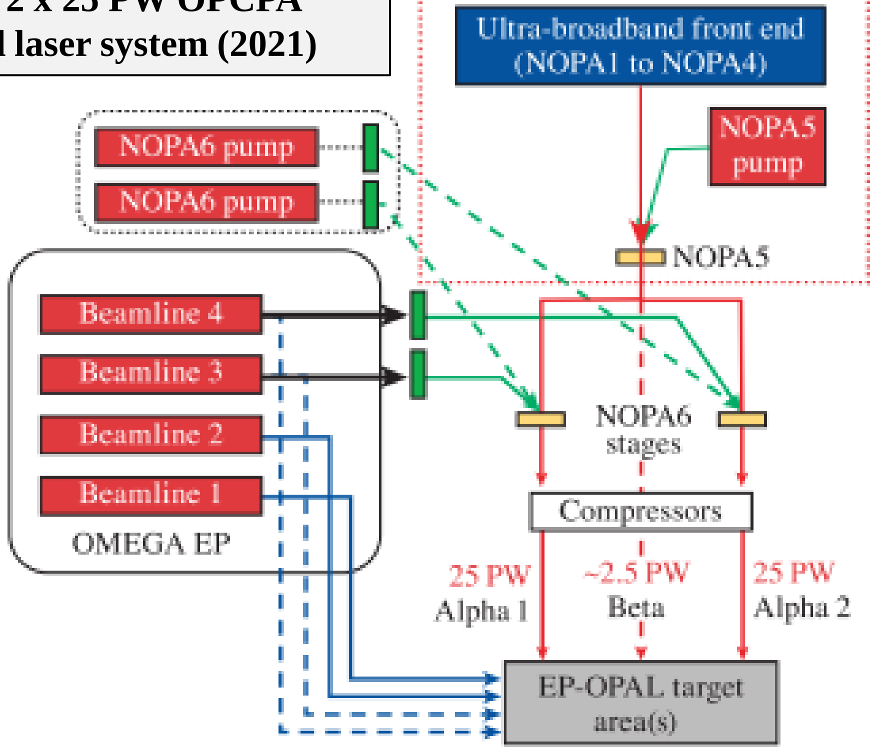
Concept of a single beam 75 PW OPCPA femtosecond laser system (2019)



Top level of the EP OPAL (optical parametric amplifier line) system, showing the major subsystems and the neighboring OMEGA EP beamlines that would be available for joint shots. NOPA, noncollinear optical parametric amplifier; EPTC, OMEGA EP target chamber.

Concept of 2 x 25 PW OPCPA femtosecond laser system (2021)

MTW-OPAL is the prototype + compressor and target area



EP-OPAL schematic showing two options for pumping the final amplifiers, NOPA6, for the two 25-PW beamlines that are seeded by a common front end.

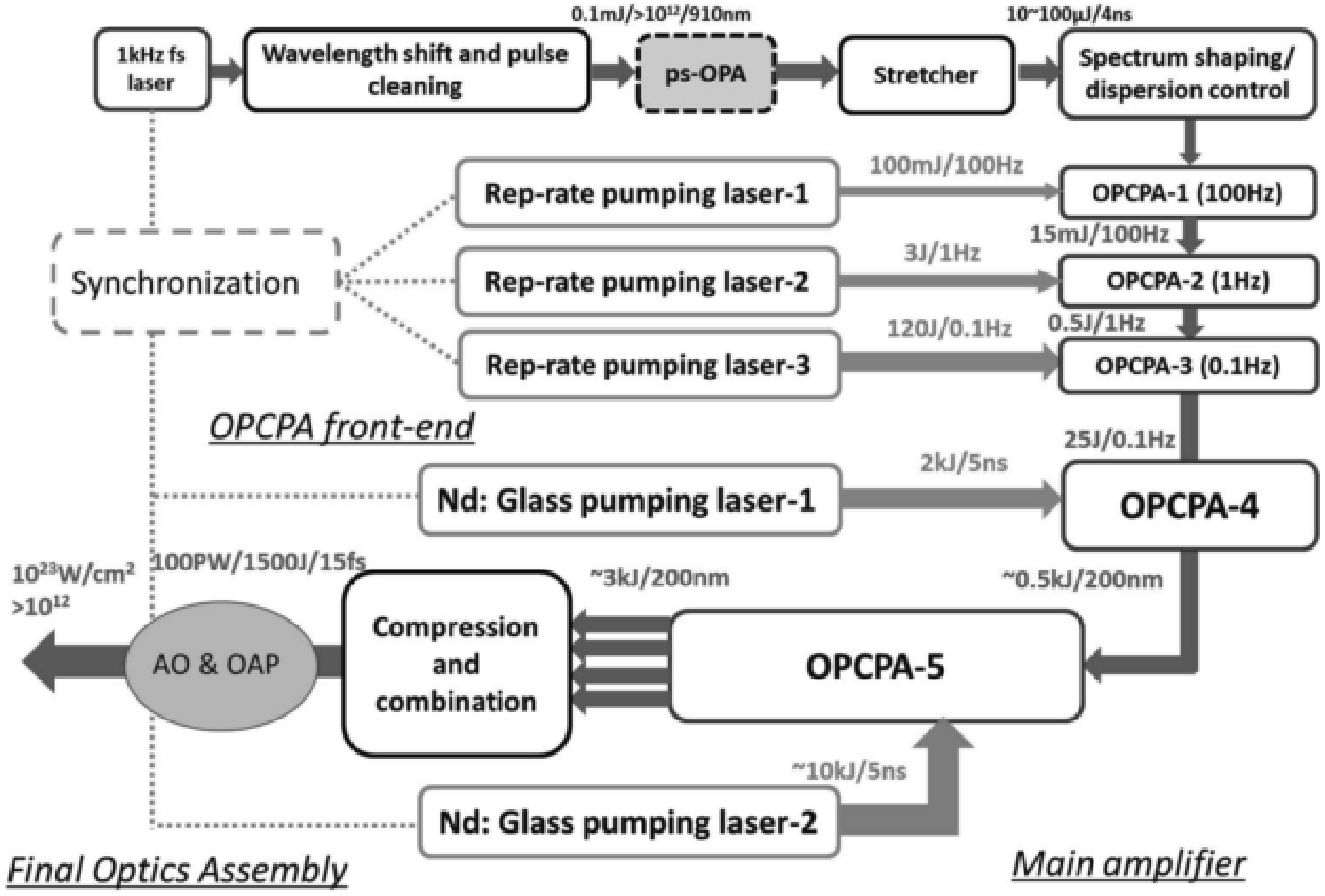
Broad-band seed pulses are produced from a self-focusing filament and white light continuum generation in an undoped YAG crystals pumped by a Yb–doped fiber CPA laser (about 200 nm bandwidth around 920 nm wavelength)

Optical synchronization of picosecond seed and pump pulses up to the 5 mJ broad-band pulse energy

J. Bromage et al., "Technology development for ultraintense all-OPCPA systems", High power Laser Science and Engineering (2019), Vol. **7**, e4.

J. Bromage et al., "MTW-OPAL: a technology development platform for ultra-intense optical parametric chirped-pulse amplification systems ", High power Laser Science and Engineering (2021), Vol. **9**, e63.

Conceptual design of 100-PW laser system at Station of Extreme Light (SEL), Shanghai Institute of Optics and Fine Mechanics, China



The layout of the SEL-100 PW laser.

The size of current gratings cannot support 100 PW (1.5 kJ/15 fs) laser compression directly.

The expanded beam will be divided in 4 smaller beams of ~400 mm x 400 mm

These four beams will be separately compressed and coherently recombined in a whole one by multi-beam tiled aperture combination.

Current status: Front-End development for the 100 PW-Class laser facility

Using three stages of OPCPA based on LBO crystals, 5.26 J/0.1 Hz amplified output with bandwidth over 200 nm near the central wavelength of 925 nm was obtained.
After 67% compression efficiency, 13.4 fs pulses with peak power of > 260 TW were reported.

Y. Peng et al., "Overview and Status of Station of Extreme Light toward 100 PW", Reza Kenkyu, Vol. **49** (2), pp. 93-96, 2021.

X. Wang et al., "13.4 fs, 0.1 Hz OPCPA Front End for the 100 PW-Class Laser Facility", Ultrafast Science, Volume 2022, Article ID 9894358

It is practically possible multi-beam tiled aperture coherent combination?

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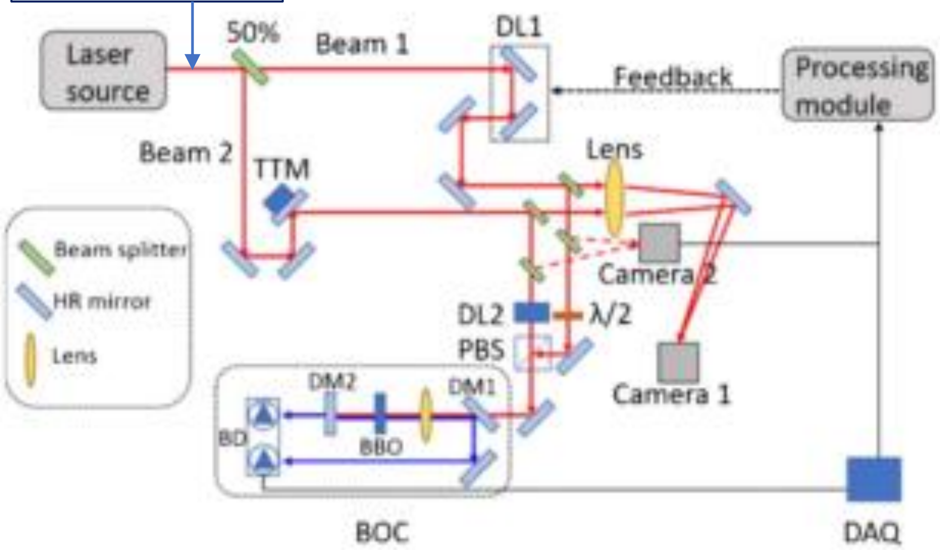
1 mJ / 50 fs / 1 kHz



Experiment setup. BD, balanced photodetector; BOC, balanced optical cross-correlator; DL1/DL2, delay line; DM1, dichroic mirror, AR at 800 nm, HR at 400 nm; DM2, dichroic mirror, AR at 400 nm, HR at 800 nm; PBS, polarization beam splitter; TTM, tip-tilt mirror; BBO, beta barium borate crystal; DAQ, data acquisition card.

The time domain synchronization was controlled by a piezoelectric transducer (PZT) in DL1. RMS error was controlled to λ/51.
BBO crystal cut for type II SFG. Two sum-frequency signals are generated
Temporal and spatial overlapping of fs pulses was controlled by BOC.
The phase difference between two beams was controlled using near-field interference beam pattern.


3960 Vol. 42, No. 19 / October 1 2017 / Optics Letters Letter

Optics Letters

High-precision active synchronization control of high-power, tiled-aperture coherent beam combining

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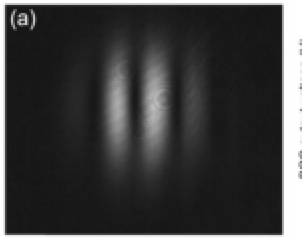
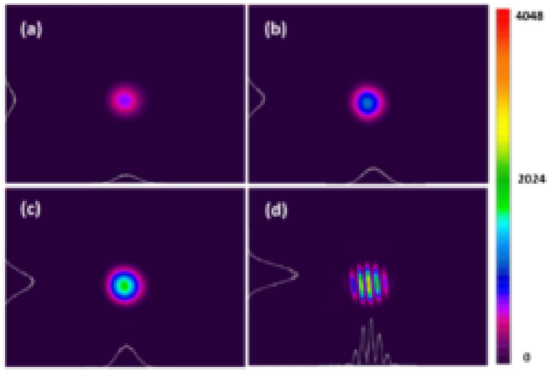


Interference pattern recorded by Camera 2.



Beam profiles in the focal plane: (a) beam one, (b) beam two, (c) two beams incoherently combined, and (d) two beams coherently combined.

Camera 1

Combining efficiency was $\boldsymbol{\eta}$ = 93%

$$\eta = \frac{I_\Sigma}{I_1 + I_2 + 2\sqrt{I_1 I_2}}$$

where I_Σ is the peak intensity of the far-field spot of the combined pulses, and I_1, I_2 are those of the single beams.

S.N. Bagayev et al, "Coherent combining of femtosecond pulses parametrically amplified in BBO crystals ", Opt. Lett. **39** (6), p. 1517 (2014).

Hybrid dielectric on metal gratings for a single-beam 100-PW class laser compressor?

170 OPTICS LETTERS / Vol. 39, No. 1 / January 1, 2014

High-efficiency, broad-bandwidth metal/multilayer-dielectric gratings

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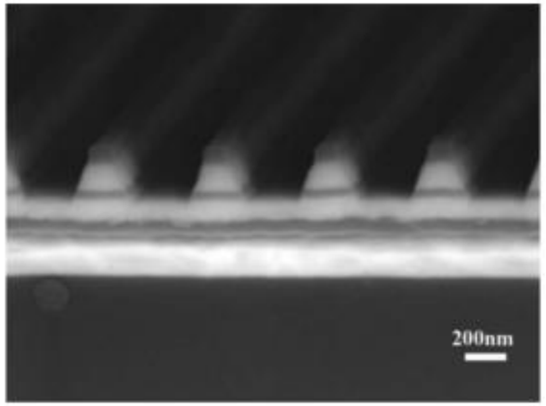
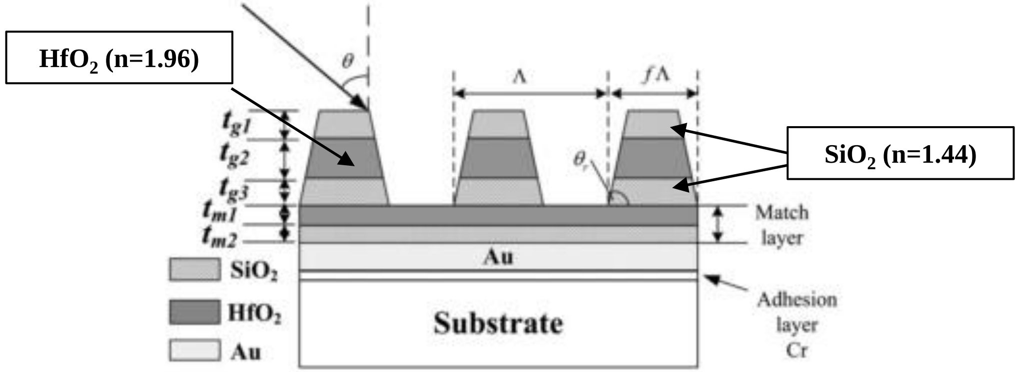
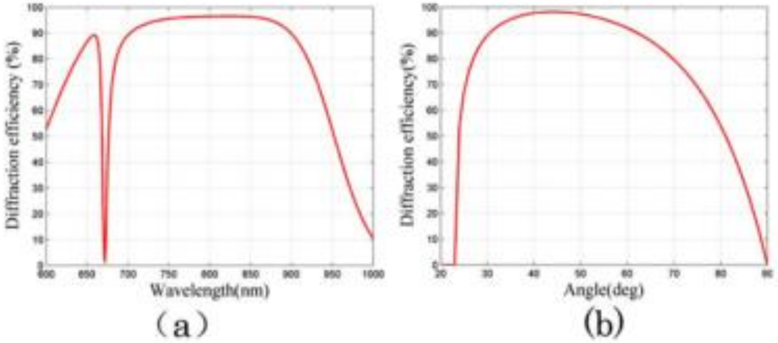
We report on an 800 nm center-wavelength metal/multilayer-dielectric grating (MMDG) with broadband, high diffraction efficiency. The trapezoidal grating ridge consists of an HfO_2 layer sandwiched between two SiO_2 films. Combining the advantages of SiO_2 and HfO_2, the grating ridge reduces the difficulties of grating ridge attainment. For such a configuration, high-performance MMDG can be successfully fabricated using the existing technology. Experimentally we demonstrated a 163 nm bandwidth MMDG with −1st-order diffraction efficiency greater than 90%. The fabricated MMDG achieved high performance as the design with large fabrication tolerances.



Cross-sectional views of MMDG.



Structure of MMDG.



−1st-order diffraction efficiencies versus (a) incident wavelength and (b) angle for the designed MMDG with $f = 0.43$, $t_{g1} = 100$ nm, $t_{g2} = 150$ nm, $t_{g3} = 57$ nm, $t_{m1} = 119$ nm, $t_{m2} = 81$ nm, $\Lambda = 574.7$ nm, and $\theta_r = 75°$.

LIDT at 800 nm / 45 fs, 0.32-0.47 J / cm^2 ?

Multi-step pulse compressor (MPC), a solution for a single beam 100 PW-class femtosecond laser system?

ELI-NP Autumn School
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Research Article | Vol. 29, No. 11 / 24 May 2021 / *Optics Express* 17140

Optics EXPRESS

Multistep pulse compressor for 10s to 100s PW lasers

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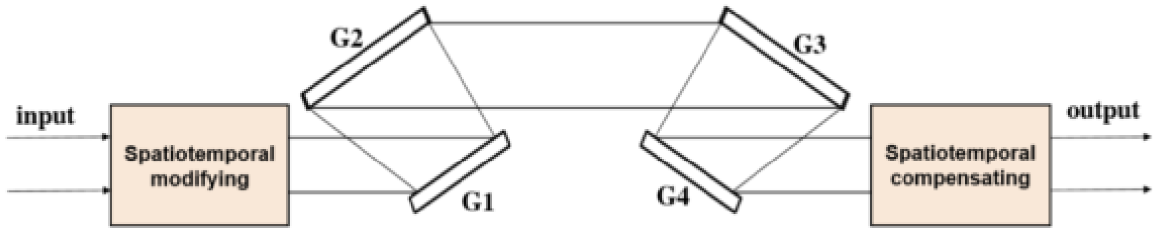
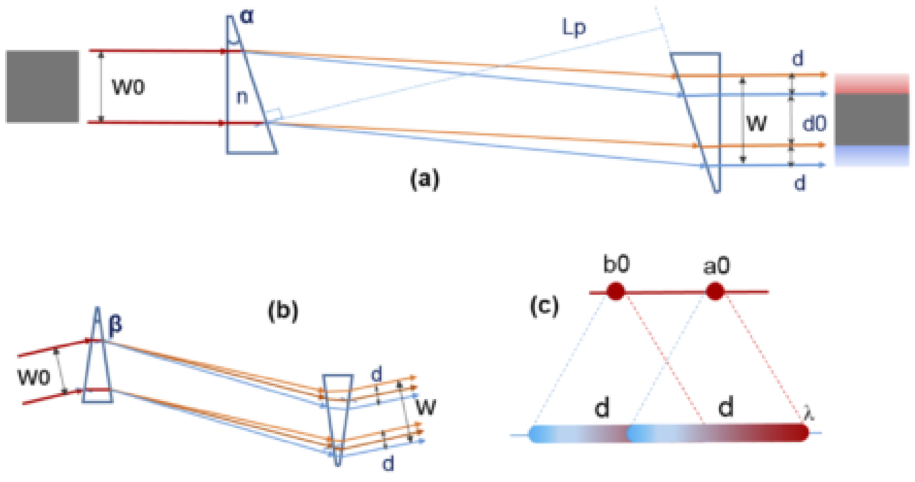
Abstract: High-energy tens (10s) to hundreds (100s) petawatt (PW) lasers are key tools for exploring frontier fundamental researches such as strong-field quantum electrodynamics (QED), and the generation of positron-electron pair from vacuum. Recently, pulse compressor became the main obstacle on achieving higher peak power due to the limitation of damage threshold and size of diffraction gratings. Here, we propose a feasible multistep pulse compressor (MPC) to increase the maximum bearable input and output pulse energies through modifying their spatiotemporal properties. Typically, the new MPC including a prism pair for pre-compression, a four-grating compressor (FGC) for main compression, and a spatiotemporal focusing based self-compressor for post-compression. The prism pair can induce spatial dispersion to smooth and enlarge the laser beam, which increase the maximum input and output pulse energies. As a result, as high as 100 PW laser with single beam or more than 150 PW through combining two beams can be obtained by using MPC and current available optics. This new optical design will simplify the compressor, improve the stability, and save expensive gratings/optics simultaneously. Theoretically, the output pulse energy can be increased by about 4 times using the MPC method in comparison to a typical FGC. Together with the multi-beam tiled-aperture combining method, the proposed tiled-grating based tiled-aperture method, larger gratings, or negative chirp pulse based self-compression method, several 100s PW laser beam is expected to be obtained by using this MPC method in the future, which will further extend the ultra-intense laser physics research fields.

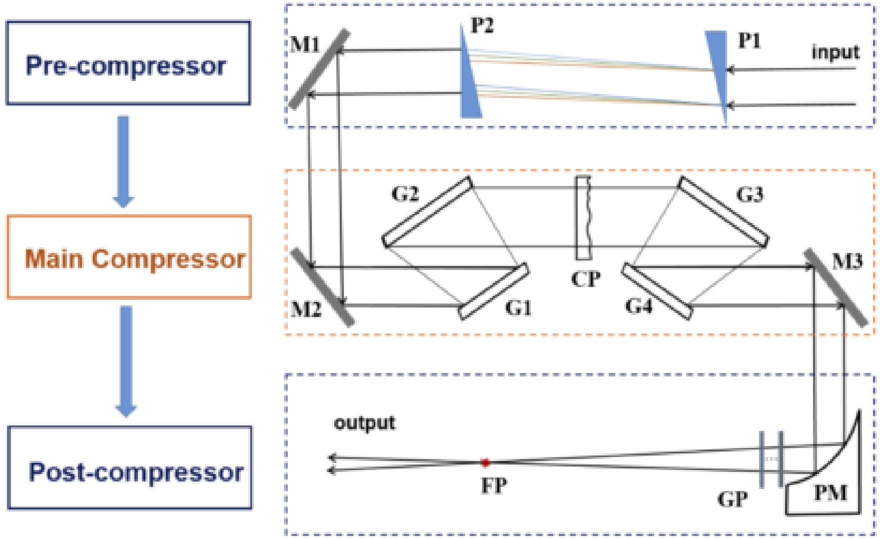


Principle of MPC. Spatiotemporal modifying and spatiotemporal compensating modules are added before and after the main FGC. G1-G4 are diffraction gratings for a typical FGC.

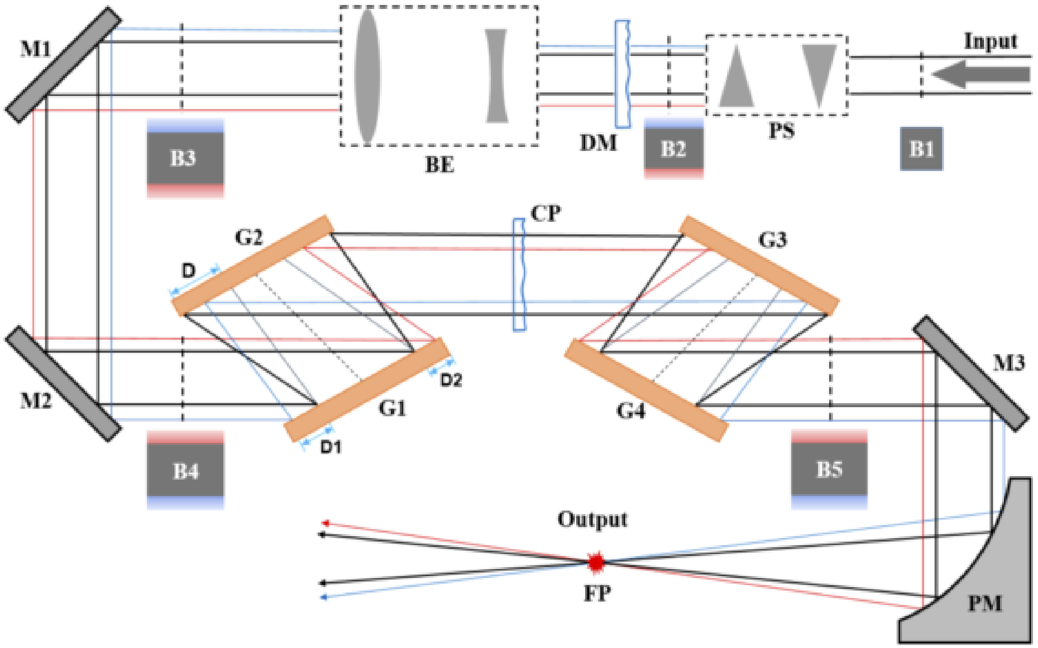


(a). The optical setup of (a) right angle prism pair and (b) isosceles prism pair for pre-compression. *W0*: input laser beam width, *W*: output laser beam width, d: spatial dispersion width, *Lp*: the perpendicular distance between the two prisms, α and β are the apex angles of the right angle prism and isosceles prism, respectively. (c) Principle of beam smoothing using angular/spatial dispersion.a0 and b0: two hot spots with high intensity and full spectral bandwidth, *d*: extended length of a0 or b0 after the prism pair.

Proposed three-stages compressor configuration



The basic scheme of MPC including pre-compressor, main compressor, and post-compressor. P1, P2: Prism, M1-M3: reflective mirrors, G1-G4: diffraction gratings, CP: compensating plate, GP: thin glass plates, PM: parabolic mirror, FP: focal point.



The optical diagrammatic sketch of the proposed single MPC for 100 PW laser. B1-5, beam profiles at five different positions indicated by the dashed lines. PS, prism pair system inducing spatial dispersion. DM, deformable mirrors for precisely spatial-spectral phase compensating besides CP. BE, beam expander. M1-3, reflective mirrors. G1-4, diffraction gratings. D, the maximum extended length of a full bandwidth laser on G2. D1-2, the extended length of blue and red regions with spatial dispersion on G1, respectively. CP, compensating plate. PM, parabolic mirror. FP, focal point.

- **Practically due to the hot-spots a two-times smaller acceptable fluence on gratings is considered for compressor design.**
- **The dangerous peak fluence on the G_1 diffraction grating would be reduced by a factor of ~2.**
- **From experimental data the highest damage threshold of fluence (mJ/cm^2) for ns, ps and fs laser pulses is about 2.67:1.66:1 for gold-coated diffraction gratings at 800 nm central wavelength.**
- **If the last G_4 grating operates at picosecond level, the output pulse energy could be improved by ~1.6 times**

Theoretically, the output pulse energy with single-beam can be increased by about 4 times using the MPC method in comparison to that of a typical four-grating compressor

It had been proved experimentally and theoretically that the negative chirped laser pulse can be reshaped and self-compressed in a piece of glass plate.
J. Liu et al., "Spectrum reshaping and pulse self-compression in normally dispersive media with negatively chirped femtosecond pulses ", Opt. Express **14**(2), 979-987 (2006).
The negatively chirped input pulse based self-compression will avoid the using of large chirped mirrors for dispersive compensation.

CONCLUSIONS

Advantages of CPA: non-critical pump pulse duration and signal-pump pulse synchronization, high energy nanosecond green pump lasers with relatively high-repetition rate are available.

Drawbacks of CPA: spectral band narrowing and red shifting, relatively low intensity contrast due to spontaneous emission amplification, wave-front distortions due to the thermal loading, parasitic lasing in large aperture Ti:sapphire crystals, amplification of the back-reflected radiation from targets.

Advantages of OPCPA: large spectral bandwidth is preserved, intensity contrast is improved outside the pump pulse duration, no thermal loading of the amplifying medium.

Drawbacks of OPCPA: signal-pump pulse temporal and spatial overlapping is required, stable spatial and temporal pump laser pulse beam profile is required, low repetition rate of single beam few-ns kJ pulse energy pump lasers.

Hybrid multi-PW laser systems based on low energy OPCPA and high energy CPA in Ti:sapphire crystals represent a solution for the improvement of amplified femtosecond pulse characteristics.

High energy OPCPA in large aperture P-DKDP crystals was proposed for the development of 100-PW class femtosecond laser systems.

Thank you for your attention