Chapter 3

High-Power, High-Intensity Contrast Hybrid Femtosecond Laser Systems

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Additional information is available at the end of the chapter

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Abstract

Hybrid femtosecond lasers combine the chirped pulse amplification (CPA) in laser media with optical parametric chirped pulse amplification (OPCPA) in nonlinear crystals. Gain bandwidths as broad as 150 nm can be obtained by noncollinear optical parametric chirped pulse amplification in nonlinear crystals. Therefore, stretched laser pulses compressible to sub-10-fs pulse duration can be amplified in crystals like beta-barium borate (BBO) and potassium dideuterium phosphate (DKDP). The ultra-broad phase-matching bandwidth near 800 nm wavelength of beta-barium borate crystals pumped by green nanosecond lasers and the gain bandwidth of Ti:sapphire laser crystals are practically overlapped. Optical parametric chirped pulse amplification in beta-barium borate crystals at low-energy level in the laser system Front-End (FE), combined with high-energy chirped pulse amplification in Ti:sapphire crystals, represents an advanced solution for petawatt-class femtosecond laser systems. A couple of worldwide developed hybrid amplification high-power femtosecond laser systems are presented. The configuration and output beam characteristics of the hybrid amplification petawatt laser of the Extreme Light Infrastructure: Nuclear Physics (ELI-NP) facility are described.

Keywords: chirped pulse amplification, noncollinear optical parametric amplification, ultra-broad gain bandwidth

1. Introduction

High-power femtosecond laser systems were developed using chirped pulse amplification (CPA) technique [1]. PW-class Ti:sapphire laser systems have been demonstrated worldwide in the last years [2–6].

To attain a high peak pulse power, we need high pulse energy in a short pulse duration. In a laser amplifier system, the maximum acceptable laser fluence is restricted by the damage risks. The amplified laser pulse energy is limited by the size of currently existing optical components,

like Ti:sapphire crystals and diffraction gratings from optical compressors. To attain multi-PW peak pulse power in CPA systems based on available optical components, it is necessary to deliver the output laser energy in 10-fs range duration laser pulses. The recompressed amplified pulse duration is inversely proportional to the spectral bandwidth, which contains the phase-locked spectral components, which means flat-phase spectral bandwidth. The spectral band narrowing and the increase of the recompressed amplified pulse duration are the result of gain narrowing and redshifting in Ti:sapphire crystals [7]. A broad spectral bandwidth of amplified laser pulses throughout CPA laser systems can be preserved by special techniques, like optical cross-polarized wave (XPW) generation [8] and spectral filters for spectrum management [7]. Flat spectral phase over a large bandwidth can be obtained by the correction of high-order phase distortions using acousto-optic programmable dispersion filters (AOPDFs) [9].

For many research applications, very high laser intensity in the focused beam is required. The capability to tightly focus the laser beam in a very small spot is one of the most important features of the high-power CPA laser systems. Tight focusing significantly depends on the quality of the amplified pulse beam wavefront. Thermal loading of Ti:sapphire crystals is one of the main reasons of wavefront distortions in CPA systems. The focused beam intensity related to the ideal case of an undisturbed flat wavefront, having the same intensity profile as the real beam, is given by the Strehl ratio (SR) [10]. By focusing 300-TW femtosecond laser beams in few-μm diameter spots, 2×10^{22} W/cm^2 peak intensity has been obtained [11]. More than 10^{23} W/cm^2 peak power is expected by tightly focusing 10-PW femtosecond laser pulses.

If a laser intensity of about 10^{11} W/cm^2 is attained on the target before the main laser pulse, the generated pre-plasma could disturb the experiment. High-intensity contrast becomes a crucial laser beam parameter for accessing high-field physics in various experimental targets. Some techniques for improving the intensity contrast of laser emission, such as saturable absorbers [12, 13] and XPW [14–16], were used inside high-power femtosecond CPA laser systems. Plasma mirrors, based on self-induced plasma shuttering, were proposed for improving intensity contrast after the temporal compression of amplified chirped laser pulses [17, 18]. Reaching an intensity contrast in the range of 10^{12} represents a challenging task for a multi-PW all Ti:sapphire CPA laser.

Optical parametric chirped pulse amplification (OPCPA) in nonlinear crystals provides large amplification spectral bandwidth and improves the intensity contrast of the amplified pulses outside the temporal window of the parametric amplification process [4, 19]. In case of OPCPA with high-energy laser pulses, an important technical problem consists in the generation of a single pump beam with simultaneously difficult-to-accomplish specifications: hundreds of Joules laser pulse energy, about one nanosecond pulse duration, spatial and temporal smooth and nearly flat intensity profile, very good stability from pulse to pulse, high repetition rate.

Hybrid femtosecond lasers combine OPCPA in nonlinear crystals at low-medium energy with CPA in large size Ti:sapphire crystals at high energy. A key feature of high-power 10-fs laser systems consists in the adaptation of the parametric amplification phase matching bandwidth of nonlinear crystals to the spectral gain bandwidth of laser amplifying Ti:sapphire crystals. The ultra-broad phase-matching spectral bandwidth near 800 nm wavelength of beta-barium

borate (BBO) crystals pumped by green lasers and the gain bandwidth of Ti:sapphire crystals are practically overlapped. In this case, a large spectral gain bandwidth can be preserved over the whole hybrid amplification chain. High-power, high-intensity contrast recompressed femtosecond pulses can be obtained. OPCPA in BBO crystals up to mJ energy level in the Front-End, followed by CPA in large-aperture Ti:sapphire crystals up to 10/100 Joules, represents a suitable solution for PW-class femtosecond laser systems.

A couple of worldwide developed hybrid amplification high-power femtosecond laser systems are described. The hybrid amplification configuration has been considered as an appropriate solution for the 2 × 10 PW femtosecond laser system of the Extreme Light Infrastructure: Nuclear Physics (ELI-NP) facility.

2. Chirped pulse amplification in broad spectral bandwidth laser media

The principle of CPA in broad gain bandwidth laser media (e.g., Ti:sapphire crystals) is presented in **Figure 1**. Femtosecond laser pulses generated by a large spectral bandwidth oscillator are temporally stretched with dispersive optical elements, in most cases diffraction gratings, up to few-hundred picoseconds or about one nanosecond pulse duration.

The Ti:sapphire laser is a four-level system as depicted by a simplified energy level diagram in **Figure 1**. Ti:sapphire crystals are optically pumped by nanosecond green lasers. By absorption of pump laser photons, the Ti atoms are raised from the ground energy level E1 to the spectral band E4. The excited atoms are rapidly transferred by nonradiative transitions from the absorption band E4 to the upper laser energy level E3. The spontaneous fluorescence lifetime of Ti atoms on the upper laser level is about 3 μs. The Ti atoms are accumulated on the upper laser level giving rise to a population inversion between E2 and E3 laser levels. Under these conditions, an input laser pulse with photon energy quanta corresponding to the energy difference between the E3 upper level and the E2 lower level is amplified by stimulated laser transitions between E3 and E2 levels. The generated laser radiation is coherently added to the input radiation.

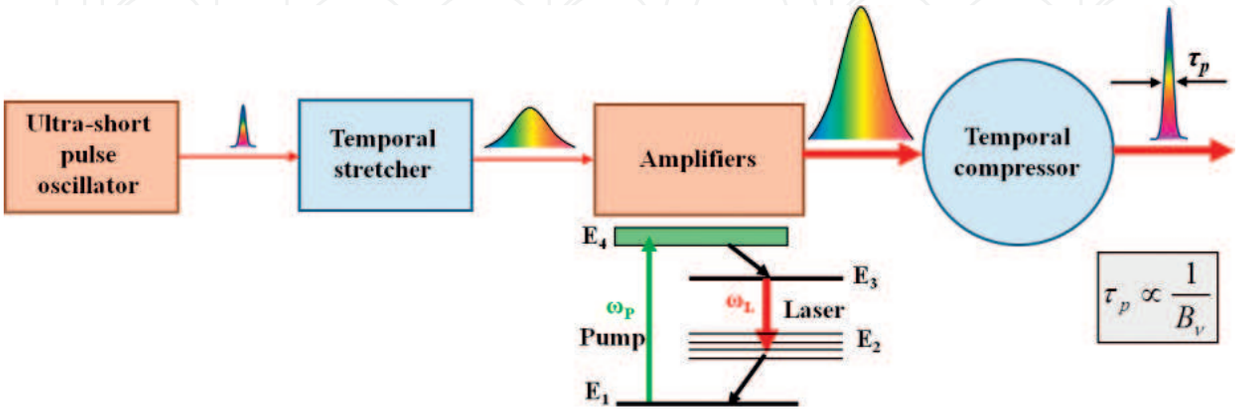

Figure 1. Chirped pulse amplification (CPA) in Ti:sapphire laser crystals. B_ν, amplified pulse frequency bandwidth; τ_p, temporally compressed pulse duration.

To get the population inversion between laser energy levels for laser amplification, we essentially need an efficient absorption of pump photons in Ti:sapphire crystals. The energy accumulated in the upper laser level can be the result of pumping with single or multiple pump laser beams. Angles between pump beams and seed pulse beam are noncritically defined and are practically imposed by the amplifier geometry.

Because the Ti atoms lifetime is in the range of few-μs, an acceptable delay between pump laser pulses and input stretched laser pulses is in the nanoseconds range. This temporal synchronization can be easily obtained with electronic devices.

Pulse duration of the recompressed pulse is inversely proportional to the optical frequency bandwidth which contains all phase-locked spectral components [20]. The highest amplification gain is obtained near the central wavelengths (790–800 nm) of the Ti:sapphire fluorescence spectrum, engendering the "gain narrowing" effect of the amplified laser pulse spectral band (**Figure 2a**). In the regenerative amplifiers and multi-pass amplifiers, with many passes through the laser amplifying media and high amplification factor, the effect of gain narrowing significantly contributes to the decrease of the spectral bandwidth of the amplified pulses (**Figure 2b**).

High-energy extraction efficiency can be obtained if laser amplifiers are working near the saturation regime, where the input laser pulse fluence is higher than the saturation fluence of the amplifying laser medium [20]. In this case, almost all accumulated energy on the upper level of the laser medium could be extracted and added to the input pulse energy [20]. The "red" spectral components travel in the leading edge of the temporally stretched pulse, whereas the "blue" spectral components are delayed in the trailing edge. In the amplifiers working near the saturation regime, due to the significant depletion of the upper laser-level population, the amplification factor of the "red" spectral components coming first in the amplifying medium is higher than that of the "blue" spectral components arriving on the trailing edge of the stretched pulse. The result is a redshift of the amplified laser pulse spectrum, associated with a spectrum narrowing (**Figure 2b** and **c**).

Stretched amplified pulses are recompressed in a temporal stretcher with diffraction gratings, where "red" spectral components are delayed compared to the "blue" components. Both "gain narrowing" and "redshifting" effects contribute to the increase of the amplified pulse duration after temporal recompression.

The amplified spontaneous emission (ASE), which takes place in the laser media as long as the population inversion between the upper and lower laser levels exists, deteriorates the picosecond intensity contrast of femtosecond laser systems. By all Ti:sapphire amplification, it is very difficult to attain more than 10^{11} intensity contrast of femtosecond pulses, as it is required in case of PW-class femtosecond laser systems.

Dissipated heat in the active medium is given by the energy difference between the absorbed pump energy and the laser emitted energy. The thermal loading of the Ti:sapphire crystals produces beam wavefront distortions and phase dispersions of the spectral components of the large bandwidth laser pulses. It results in a poor beam focusing and an increase of the recompressed pulse duration.

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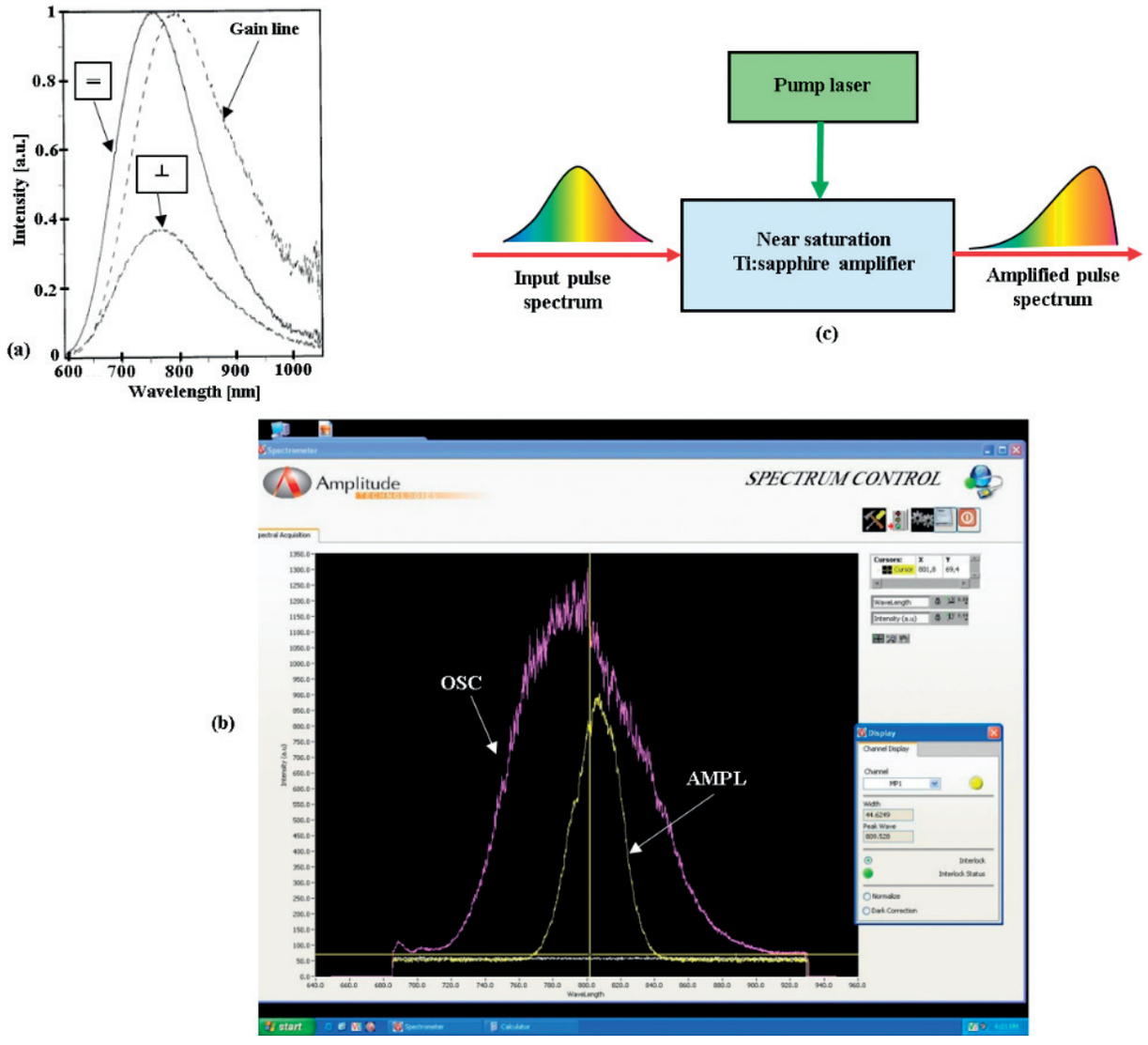

Figure 2. Gain narrowing and redshifting in Ti:sapphire amplifiers. (a) Polarized fluorescence spectra and calculated gain line for an optical *c*-axis normal cut Ti:sapphire rod; =, *c*-axis parallel polarization; ⊥, *c*-axis normal polarization. (b) Spectrum narrowing and redshifting after amplification in an all Ti:sapphire TW-class laser manufactured by Amplitude Technologies for the National Institute for Laser, Plasma, and Radiation Physics, Bucharest-Magurele; OSC: femtosecond oscillator spectrum; AMPL: spectrum after amplification. (c) Redshifting effect in nearly saturation operated Ti:sapphire amplifiers.

3. Broadband optical parametric amplification

Optical parametric amplification (OPA) is practically an instantaneous process without laser energy accumulation in the amplifying medium.

By absorption of pump photons with ω_p frequency, the crystal molecules leave from their ground energy level E_1 to an excited intermediate higher energy level E_2 (**Figure 3a**). While an excited molecule returns to its initial ground state, a photon with ω_s signal frequency and

one "idler" photon with $\omega_i = \omega_p - \omega_s$ are simultaneously created. This optical nonlinear process is very rapid compared to the signal and pump pulse duration.

A fraction of the pump beam energy is transferred to the signal beam. At the output of the nonlinear crystal, we get an amplified signal beam, a new generated idler beam, and a residual pump beam (**Figure 3b**).

Amplification takes place only if the seed pulse and the pump pulse are spatially and temporally overlapped in the nonlinear crystal, in a collinear (**Figure 3c**) or a noncollinear geometry (**Figure 3d**). In case of nanosecond pulses OPA, temporal overlapping can be obtained by electronic synchronization of the pump pulsed laser with the signal pulses. In case of femtosecond/picosecond pulses, temporal overlapping can be obtained only by optical synchronization of the interacting laser pulses.

The parametric amplification is produced under conditions of photon energy conservation and wave-vector phase matching, only for a certain orientation of the crystal and for well-defined angles between the wave vectors of the interacting laser beams (**Figure 3c**, **d**)

$$\begin{aligned} \omega_p &= \omega_s + \omega_i \\ \vec{k}_p &= \vec{k}_s + \vec{k}_i \end{aligned} \tag{1}$$

where $\vec{k}_j$, $j = p,s,i,$ are the wave vectors of the pump, signal, and idler beams.

The host crystal of the parametric process is transparent to the interacting waves, and the amplification takes place without thermal loading of the nonlinear crystal.

Exact phase matching condition can be fulfilled only by monochromatic waves. Three beam parameters and three geometrical parameters are involved in a noncollinear OPA (NOPA)

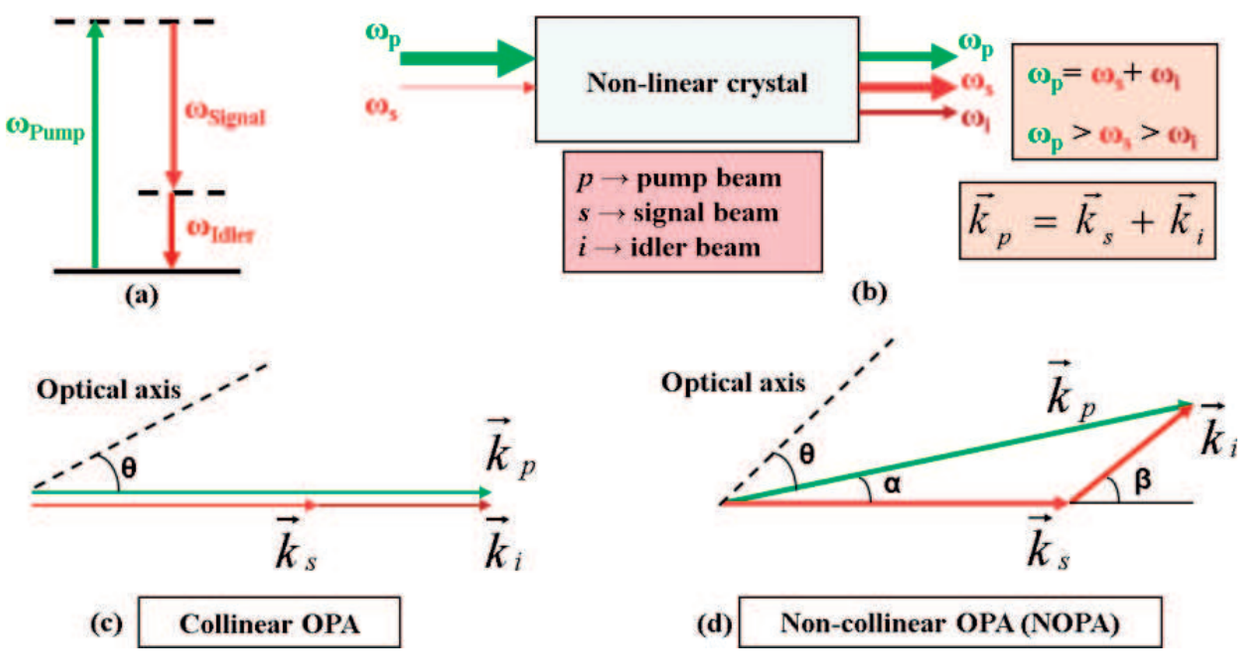

Figure 3. Optical parametric amplification in nonlinear crystals. (a) OPA energy level diagram. (b) Principle of OPA in a nonlinear crystal. (c) Collinear OPA geometry. (d) Noncollinear OPA (NOPA) geometry.

process: signal, pump and idler wavelengths, the angle between pump wave-vector and the crystal optical axis (θ), the angle between signal and pump wave-vectors (α), and the angle between signal and idler wave-vectors (β). For a monochromatic noncollinear parametric interaction, three parameters are free-chosen, usually signal wavelength, λ_s, pump wavelength, λ_p, and $\boldsymbol{\alpha}$ angle between signal and pump beams. The idler wavelength (λ_i), θ, and β angles of a NOPA process in a certain nonlinear crystal can be calculated using the phase-matching Eqs. [21]

$$\begin{aligned} &\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \\ &\frac{n_p(\lambda_p, \theta)}{\lambda_p} \sin\alpha - \frac{n_i(\lambda_i)}{\lambda_i} \sin\beta = 0 \\ &\frac{n_p(\lambda_p, \theta)}{\lambda_p} \cos\alpha - \frac{n_s(\lambda_s)}{\lambda_s} - \frac{n_i(\lambda_i)}{\lambda_i} \cos\beta = 0 \end{aligned} \tag{2}$$

Under approximations of small initial signal beam intensity, without input idler beam, and neglected pump beam depletion, the parametric gain is given by [21]

$$G_s(L) = \frac{I_s(L) - I_s(0)}{I_s(0)} = \Gamma^2 \frac{\sinh^2(gL)}{g^2} \tag{3}$$

where L is the length of the nonlinear crystal, $I_s(0)$ is the input signal beam intensity, $I_s(L)$ is the output signal intensity, $g^2 = \Gamma^2 - \left(\frac{\Delta k}{2}\right)^2$, $\Gamma^2 = \frac{2\omega_s \omega_i d_{eff}^2 I_p}{n_s n_i n_p \varepsilon_0 c^3}$, I_p is the pump beam intensity, d_{eff} is the effective nonlinear coefficient, $n_{p,s,i}$ are refractive indexes, ε_0 is the permittivity of free space, c is the speed of light, and $\Delta k = k_p - k_s - k_i$ is the wave-vector mismatch. The full width at half maximum (FWHM) phase-matching bandwidth is usually defined as the spectral range where the parametric gain $G_s(\Delta k)$ is at least 50% from the peak gain obtained in the case of exact phase-matching, $G_s(\Delta k = 0)$ [21]

$$G_s(\Delta k) = \frac{1}{2} G_s(\Delta k = 0) \tag{4}$$

Broad gain bandwidth can be obtained if, near the exact phase-matching condition, the wave-vector mismatch slowly varies depending on the signal wavelength. The Δk phase mismatch can be represented by Taylor series around the phase-matching signal frequency ω_{s0} [22]

$$\begin{aligned} &\Delta k = \Delta k^{(0)} + \left(\frac{\partial \Delta k}{\partial \omega_s}\right)_{\omega_{s0}} d\omega_s + \frac{1}{2!}\left(\frac{\partial^2 \Delta k}{\partial \omega_s^2}\right)_{\omega_{s0}} (d\omega_s)^2 + \frac{1}{3!}\left(\frac{\partial^3 \Delta k}{\partial \omega_s^3}\right)_{\omega_{s0}} (d\omega_s)^3 + \\ &+ \frac{1}{4!}\left(\frac{\partial^4 \Delta k}{\partial \omega_s^4}\right)_{\omega_{s0}} (d\omega_s)^4 + \ldots \approx \Delta k^{(0)} - \left(\frac{\partial k_s}{\partial \omega_s} - \frac{\partial k_i}{\partial \omega_i}\right)\Delta\omega - \frac{1}{2!}\left(\frac{\partial^2 k_s}{\partial \omega_s^2} + \frac{\partial^2 k_i}{\partial \omega_i^2}\right)(\Delta\omega)^2 - \\ &- \frac{1}{3!}\left(\frac{\partial^3 k_s}{\partial \omega_s^3} - \frac{\partial^3 k_i}{\partial \omega_i^3}\right)(\Delta\omega)^3 - \frac{1}{4!}\left(\frac{\partial^4 k_s}{\partial \omega_s^4} + \frac{\partial^4 k_i}{\partial \omega_i^4}\right)(\Delta\omega)^4 \ldots = \Delta k^{(0)} + \Delta k^{(1)} + \Delta k^{(2)} + \Delta k^{(3)} + \Delta k^{(4)} + \ldots \end{aligned} \tag{5}$$

where $\Delta k = 0$ represents the condition for quasi-monochromatic phase matching; $\Delta k^{(0)} = \Delta k^{(1)} = 0$ is the condition for optical parametric broad gain bandwidth.

An ultra-broad bandwidth (UBB) of phase-matching can be obtained for $\Delta k^{(0)} = \Delta k^{(1)} = \Delta k^{(2)} = 0$. In this case, two more equations must be added to the three-equation system (2) [22]

$$\begin{aligned} v_{gs} &= v_{gi} \cos\beta \\ \frac{\partial^2 k_s}{\partial \omega_s^2} \cos\beta &+ \frac{\partial^2 k_i}{\partial \omega_i^2} - \frac{\sin^2\beta}{v_{gs}^2 k_i} = 0 \end{aligned} \tag{6}$$

where v_{gs} and v_{gi} are group velocities of signal wave and idler wave, respectively.

Particularly in the case of high-energy laser pulse amplification, only a couple of existing high-energy lasers are suitable for OPA pumping. For this reason, usually the pump laser wavelength λ_p represents the free-chosen parameter of the OPA process. For a certain nonlinear crystal, the other five parameters, including signal central wavelength, are deduced from the five-equation system comprising Eqs. (2) and (6).

UBBs of more than 100 nm, able to support amplification of sub-10-fs laser pulses, can be obtained in nonlinear crystals [22], like potassium dideuterium phosphate (DKDP) and BBO. Ultra-broad gain bandwidths for BBO and DKDP crystals, pumped by green nanosecond lasers, in NOPA configuration are shown in **Figure 4**. Gain bandwidths were calculated assuming plane interacting waves, uniform pump intensity distribution, no input idler beam, and negligible pump beam intensity depletion. For both NOPA processes, I considered a flat pump intensity I_P of 1 GW/cm^2, which can be accepted without damage risk of currently used nonlinear crystals in case of about one-nanosecond pump pulse duration (e.g., the data sheets of the manufacturing company Altechna) [23]. Different lengths were considered for DKDP and BBO crystals, corresponding to similar gain values in the parametric amplification process.

The UBB phase-matching of DKDP crystals is centered around λ_{S0} = 900 nm central wavelength, whereas the UBB of BBO crystals is centered in the range of 800 nm wavelength, practically overlapped to the gain bandwidth of Ti:sapphire laser media.

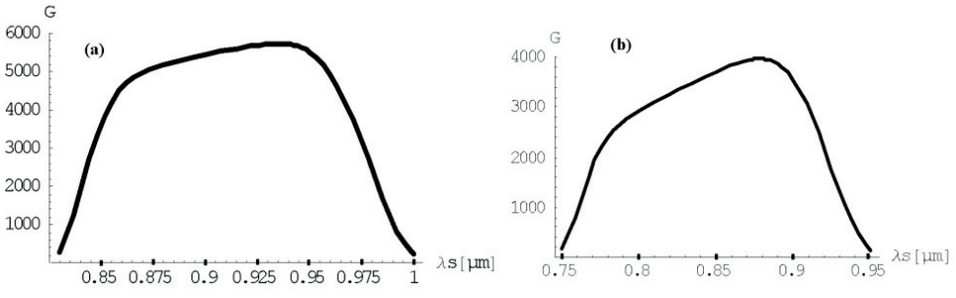

Figure 4. NOPA gain spectra. I_P = 1 GW/cm^2. (a) 80-mm-long DKDP crystal; $\lambda_{P(DKDP)}$ = 0.527 μm, θ_{DKDP} = 37.0°, α_{DKDP} = 0.92°, λ_{S0} = 900 nm; $UBB_{DKDP} \approx$ 135 nm. (b) 10-mm-long BBO crystal, $\lambda_{P(BBO)}$ = 0.532 μm, θ_{BBO} = 23.8°, α_{BBO} = 2.4°, λ_{S0} = 0.825 μm; $UBB_{BBO} \approx$ 150 nm.

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4. Optical parametric chirped pulse amplification

OPCPA was proposed as an alternative solution for the amplification of large bandwidth stretched laser pulses [24] (**Figure 5**). Drawbacks of the Ti:sapphire CPA, particularly those related to the amplified spectral band narrowing, intensity contrast decrease, and thermal loading, can be overcome in OPCPA laser systems. Signal pulses generated by a broad bandwidth femtosecond oscillator are temporally stretched and synchronized to the pump pulses. Signal and pump pulses have similar durations, usually in the range of picoseconds or nanoseconds. The pump laser wavelength is chosen among the available high-energy green nanosecond lasers, such as frequency-doubled Nd:YAG (532 nm), Nd:glass (527 nm), Yb:YAG (515 nm) lasers. After OPCPA in one or more amplifier stages with nonlinear crystals, enhanced signal pulses can be temporally recompressed to get higher power femtosecond laser pulses.

Unlike CPA, OPCPA is free from gain narrowing and redshifting effects. Because the host crystal is transparent to the interacting beams, thermal loading is practically absent in the parametric amplification process.

On the other hand, in the case of OPCPA, the spectrum of the amplified laser pulse is sensitive to the angle between signal and pump laser beams. The parametric amplification of each signal spectral component depends on the local instantaneous pump radiation intensity. In order to keep a stable amplified signal spectrum from pulse to pulse, high temporal and spatial stability of the pump beams, as well as very stable experimental setup, are required.

Unlike CPA amplifiers, due to angular constraints between pump and signal wave vectors, imposed by the unique phase-matching geometry, in OPCPA experimental setups usually a single pump laser beam can be used (**Figure 6**). To amplify broadband chirped laser pulses, laser systems based on noncollinear OPCPA (NOPCPA) configuration, imposed by the conditions of UBB parametric amplification in nonlinear crystals, were developed [3, 25–29].

For high-energy final amplifiers of multi-PW laser systems, as much as 10^2–10^3 J pump energy, within ~1 ns pulse duration, is required. It is a real challenge to build a single-beam laser able to deliver the pump pulses for these high-energy OPCPA stages.

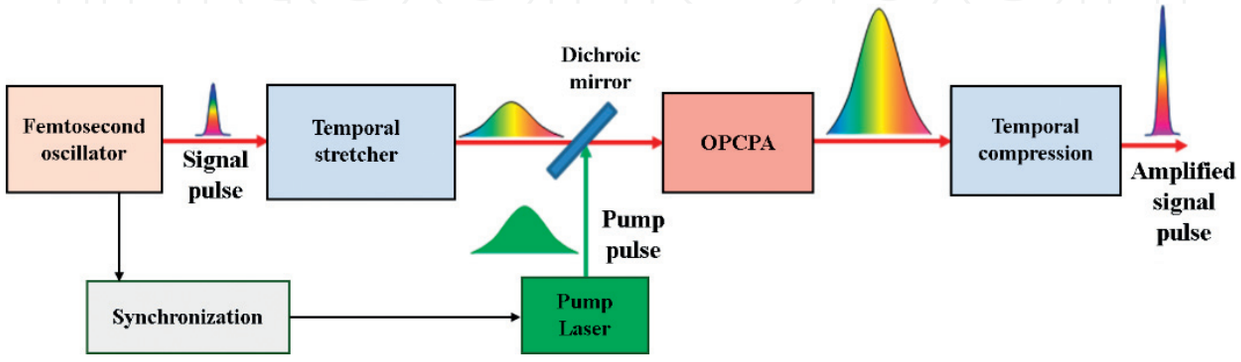

Figure 5. Principle of optical parametric chirped pulse amplification.

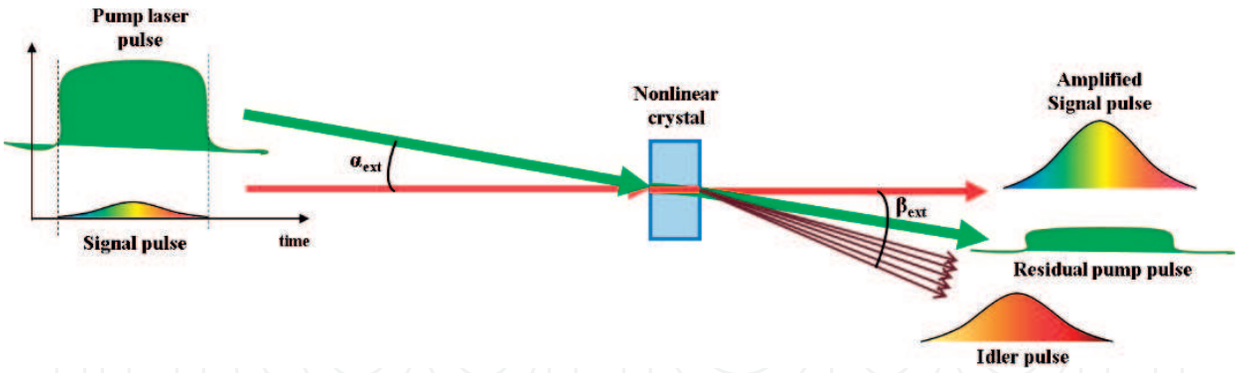

Figure 6. Schematic description of broadband noncollinear OPCPA in nonlinear crystals.

5. High-power laser systems based on hybrid amplification

A schematic configuration of a high-power hybrid femtosecond laser system is shown in **Figure 7**. In the low-energy amplification section, usually called the Front-End (FE) of the laser system, femtosecond pulses generated by a laser oscillator are temporally stretched up to 10 ps – 100 ps. Stretched laser pulses are mainly amplified by OPCPA from the nJ energy level up to 10 mJ – 100 mJ energy range, corresponding to seven to eight orders of magnitude amplification. By high-energy CPA in broad gain bandwidth laser media, chirped laser pulses, stretched in the range of one nanosecond pulse duration, are amplified by three to four orders of magnitude up to 10 J – 100 J and then temporally compressed back to the femtosecond range.

OPCPA is considered an appropriate technique in the low energy amplification FE, where large enough nonlinear crystals and good-quality beam ps-ns pump lasers are available. Output FE laser pulses with large spectral bandwidths, recompressible with high intensity contrast, are further amplified in high-energy Ti:sapphire amplifier stages.

In high-power laser systems (HPLS) based exclusively on parametric amplification, the technical bottlenecks move toward very high-energy pump lasers. Pump energy in the kJ range, few nanosecond pulse duration, flat intensity profile, and stable temporal and spatial beam profiles are required for pumping final OPCPA stages.

In femtosecond laser systems, the maximum amplified pulse energy is restricted by the size of available amplifying media. The clear aperture of largest available Ti:sapphire crystals for CPA

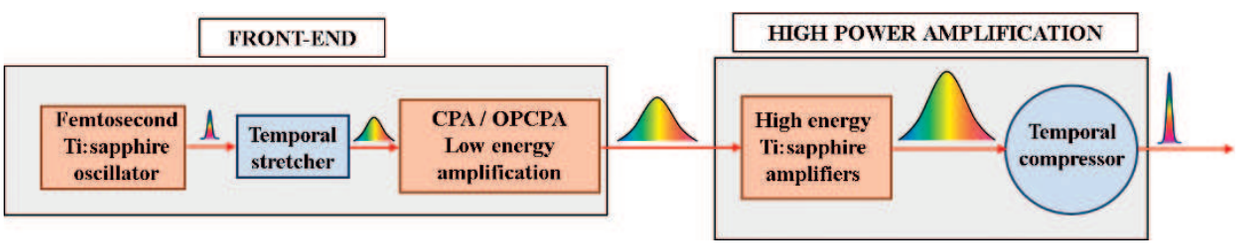

Figure 7. Basic configuration of a hybrid chirped pulse amplification laser system.

is smaller than the aperture of some available OPCPA nonlinear crystals, like DKDP, for example. Nevertheless, there is an advantage of Ti:sapphire CPA: for optical pumping of large-aperture Ti:sapphire crystals, several green pump lasers can be used, with output pulse energy of 50–100 J, less restrictive requirements concerning pulse duration, and much higher repetition rate compared to a single-beam kJ pump laser necessary for pumping a high energy OPCPA stage.

Because most of the amplification in hybrid lasers is realized by OPCPA, gain narrowing and ASE effects are attenuated compared to all Ti:sapphire amplifiers. It becomes easier to get high-intensity contrast, high-energy laser pulses, recompressible down to femtosecond pulse duration.

In a hybrid femtosecond pulse amplification system, based on both OPCPA and CPA, a key feature is the matching of the ultra-broad gain bandwidth of the nonlinear crystal to the amplification spectral band of Ti:sapphire laser crystals. In this case, stretched pulses amplified in the laser FE can be directly sent to the Ti:sapphire high-energy amplifiers.

The ultra-broad gain band of DKDP crystals is centered near 900 nm. OPCPA based on DKDP crystals can be used in hybrid femtosecond laser amplifiers. In this case, seed laser pulses must have a broad bandwidth adapted to the ultra-broad phase-matching spectral band of DKDP crystals. In DKDP-OPCPA laser systems equipped with Ti:sapphire broadband femtosecond oscillators, complicated experimental setups were realized to generate broadband laser pulses with the central wavelength shifted near 900 nm [25, 26]. BBO crystals, pumped by frequency-doubled Nd lasers, have a "lucky" ultra-broad phase-matching bandwidth in the range of 800 nm, practically overlapped to the gain bandwidth of Ti:sapphire laser crystals. Due to more than 100 nm phase-matching bandwidth, BBO crystals pumped by green lasers can support the amplification of stretched laser pulses recompressible at sub-10 fs pulse duration [22]. The available few centimeters clear aperture BBO crystals are large enough for OPCPA up to 100 mJ signal pulse energy. For this reason, BBO crystals are frequently used in the FEs of the PW-class hybrid amplification femtosecond laser systems.

Considering the currently available technical solutions, hybrid amplification represents a good choice for the development of petawatt-class femtosecond laser systems.

5.1. PW-class hybrid femtosecond laser systems

A couple of PW-class hybrid femtosecond laser systems are currently worldwide operated, while other 10-PW laser facilities are under development.

A high spatiotemporal quality PW-class laser system has been developed at Advanced Photon Research Center, Japan Atomic Energy Agency [3]. This laser system is based on a double CPA configuration (**Figure 8**). In the first CPA section, femtosecond laser pulses generated by a Ti:sapphire oscillator are stretched, pre-amplified in Ti:sapphire amplifiers, and temporally recompressed to get mJ-energy output pulses with sub-30 fs duration. To improve the intensity contrast, part of the ASE pedestal of these pulses is removed by a saturable absorber.

In the second CPA section, the intensity-filtered pulses, stretched up to ~1 ns pulse duration, are amplified by OPCPA. The conventional regenerative amplifier used in all Ti:sapphire

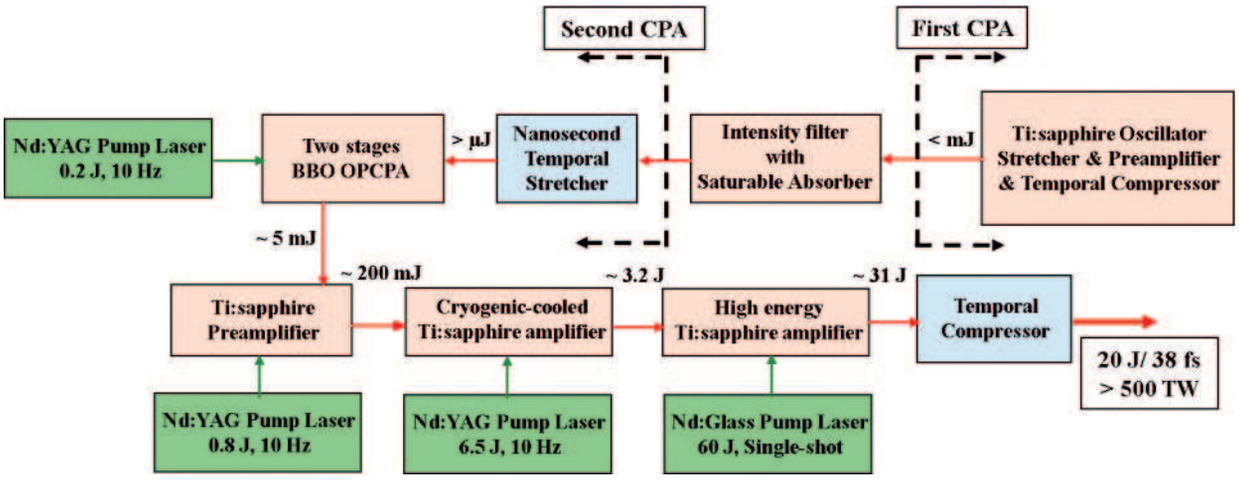

Figure 8. Schematic drawing of a hybrid PW-class laser amplifier based on low-energy OPCPA in BBO crystals and Ti: sapphire high-energy amplification [3].

lasers is replaced by a two-stage OPCPA with BBO crystals, pumped by a frequency-doubled Nd:YAG nanosecond laser. Pump and seed pulses are electronically synchronized with a timing jitter of ±0.5 ns. To avoid the parametric fluorescence, the OPCPA stages are operated with relatively high-energy seed pulses in a low gain mode. Seed pulses of ~2.5 μJ are amplified up to ~5 mJ, keeping each BBO stage to less than 100× amplification factor. Hereby, the intensity contrast of amplified pulses in the nanosecond time range is significantly improved, practically with the parametric amplification factor.

Laser pulses are amplified up to 3 J energy level in two Ti:sapphire stages pumped by 10 Hz repetition rate green (532 nm wavelength) Nd:YAG lasers. Final Ti:sapphire amplifier is pumped by a single-shot green (527 nm) nanosecond Nd:glass laser with ~60 J pulse energy. Pump laser beams with smooth homogenized spatial intensity profile are delivered to a large-aperture 80 mm diameter Ti:sapphire laser crystal. A near-homogenous flat-top intensity profile of the amplified pulse beam was obtained. After temporal compression, 20 J/38 fs pulses with more than 0.5 PW peak power and more than 10^{10} intensity contrast in sub-nanosecond temporal range were generated.

1.1 PW laser based on hybrid optical parametric chirped pulse amplification and mixed Nd: glass amplifiers (**Figure 9**) has been demonstrated at Texas Center of High Intensity Laser Science, Austin, USA [27].

Nano-Joule-energy seed pulses with 16 nm FWHM spectrum centered at 1058 nm are generated by a tunable Ti:sapphire laser oscillator. Hundred-femtosecond oscillator pulses are stretched to more than 1 ns pulse duration. Stretched pulses are amplified by approximate nine orders of magnitude in three OPCPA stages to attain ~1 J pulse energy: two stages with pairs of BBO crystals and the last one with a pair of yttrium calcium oxoborate (YCOB) crystals. OPCPA crystals are pumped by frequency-doubled Nd:YAG lasers at 532 nm. The parametric amplification takes place in a near-degeneracy type of interaction, where pump wavelength is about two times shorter than the signal wavelength, which assures a broad enough gain bandwidth to amplify ~30 nm broadband signal pulses. Nanosecond seed and

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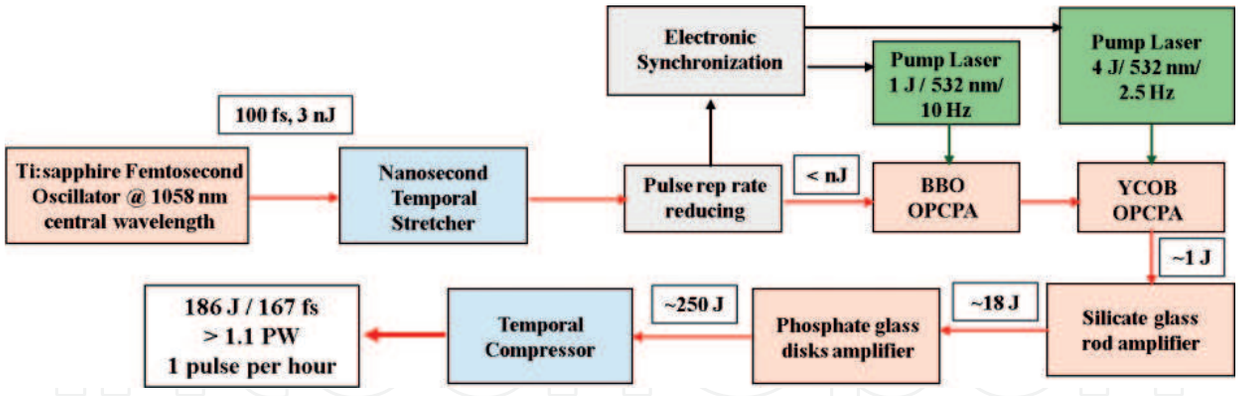

Figure 9. Schematic drawing of a PW laser system based on OPCPA in BBO and YCOB crystals and high-energy amplification in mixed glasses at 1 μm spectral range [27].

pump pulses are electronically synchronized. Up to 250 J energy, stretched laser pulses are amplified in two flash-lamp pumped Nd:glass amplifiers, with shifted peak gain wavelengths of the Nd-doped glasses. The gain spectral bandwidth of mixed Nd:glass amplifiers is about 15 nm near 1 μm central wavelength. First amplifier stage consists in a 64-mm-diameter silicate rod amplifier. In the second amplifier stage, the laser pulse passes four times through two pairs of 315 mm aperture phosphate disk amplifiers. Finally 186 J, 168 fs compressed pulses, with estimated nanosecond range contrast better than 10^{12} were obtained.

A high-contrast 1.16 PW laser system was developed at Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, by combining low-energy femtosecond optical parametric amplification with high-energy Ti:sapphire amplification [4]. Sub-10 fs pulses, with 4 nJ pulse energy, generated by a Ti:sapphire oscillator are split into two beams. About 70% energy pulse was used as the seed for a Ti:sapphire CPA to obtain 5 mJ, 50 fs pulses, which are frequency-doubled by BBO crystals to generate second harmonic pulses for pumping the two-stage broad bandwidth NOPA. The other 30% of the femtosecond oscillator pulse energy is used as the broadband seed, at 800 nm central wavelength, for the first NOPA. The optical synchronization of the signal and the pumping femtosecond pulses was accurately controlled by a Herriot telescope delay line. This way, large bandwidth femtosecond pulses are amplified to ~26 μJ energy without any temporal stretching in the two-stage NOPA with BBO crystals. The parametric amplification process which involves the signal and pump pulses occurs on few 10 fs timescale. The background noise beyond this time range cannot be amplified, and the amplified signal pulse contrast is improved by a factor equal to the parametric gain. In the second CPA stage, the clean signal pulses were stretched to about 600 ps. The medium energy Ti:sapphire amplifiers are pumped by 532 nm wavelength nanosecond Nd:YAG lasers running at 1 Hz repetition rate. The last high-energy amplifier consists in an 80-mm-diameter, 40-mm-thickness Ti:sapphire disk, pumped by a nanosecond Nd:glass laser, 120 J at 527 nm wavelength, 1 pulse/20 minutes repetition rate. After temporal compression, more than 32 J pulse energy at ~28 fs pulse duration, corresponding to a peak power up to 1.16 PW, with enhanced intensity contrast ratio of 10^{10}, has been obtained.

In the frame of the French project *Apollon*, an optically synchronized OPCPA with picosecond pulses was proposed for the Front-End configuration of a 10 PW laser system [28]. A similar

solution was considered for the 2 × 10 PW laser system of the ELI-NP laser facility from Bucharest-Magurele [29].

5.2. High-power laser system of the ELI-NP research facility

High-power laser system (HPLS) of the ELI-NP laser facility, developed by Thales Optronique, consists in a two-arm 10 PW peak power femtosecond laser amplifier. ELI-NP HPLS combines the advantages of a high amplification factor FE, based on OPCPA at low energy level, with the high energy amplification in large-size Ti:sapphire crystals pumped by high-energy frequency-doubled Nd:YAG and Nd:glass lasers [29]. For each arm, two additional output beams of 100 TW pulse peak power at 10 Hz repetition rate and 1 PW at 1 Hz are available. The schematic drawing of the ELI-NP 2 × 10 PW laser system is shown in **Figure 10**.

FE is based on OPCPA with optically synchronized seed and pump pulses of 20 to 25 ps duration (**Figure 11**). Seed and pump pulses for OPCPA are created by amplifying two output pulses generated by an ultra-broad bandwidth Ti:sapphire femtosecond oscillator (Venteon Company).

Pump pulse is obtained by amplifying a pJ-energy pulse, generated at the edge of the fs oscillator spectral bandwidth, with the central wavelength of 1064 nm and ~10 nm spectral bandwidth. In the first diode-pumped Ytterbium-doped fiber amplifier, pulse energy is increased to the nJ range. After spectral filtering in a Fiber Bragg Grating, the spectral bandwidth of the pulse is reduced to less than 0.1 nm bandwidth and its energy decreases in the range of 10 pJ. After amplification in the second Ytterbium-doped fiber amplifier, near-

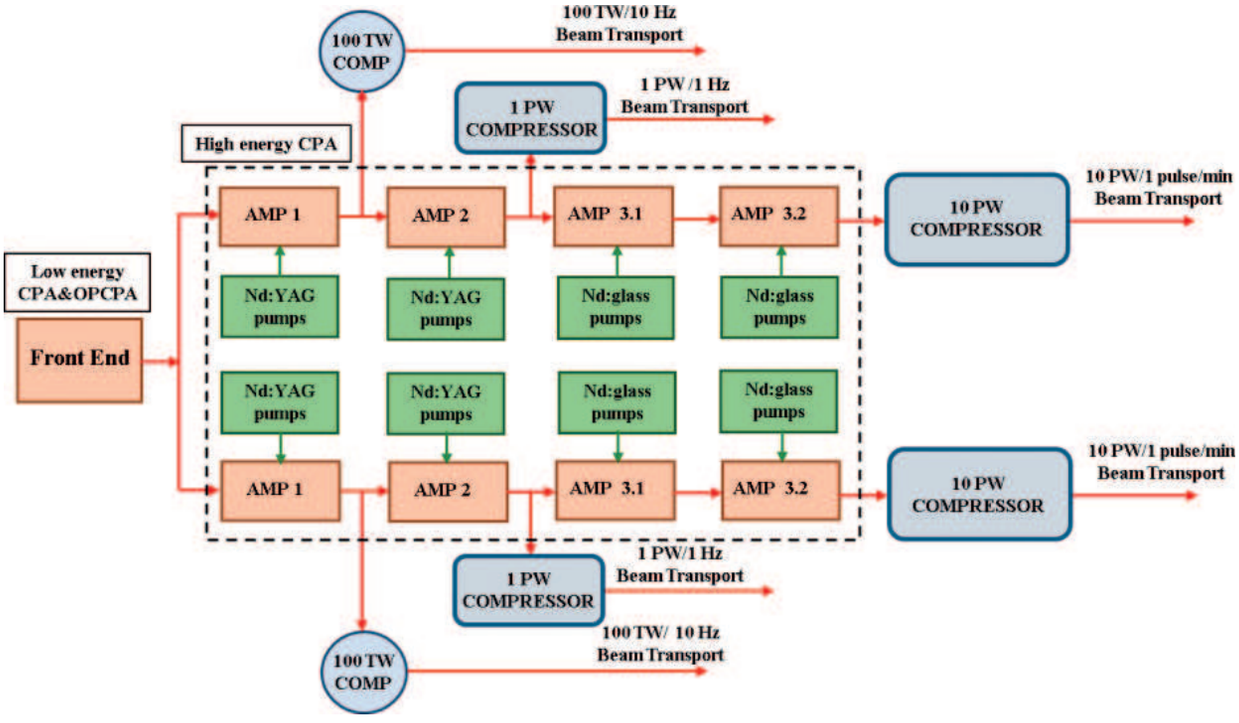

Figure 10. Schematic drawing of the 2 × 10 PW ELI-NP femtosecond laser system.

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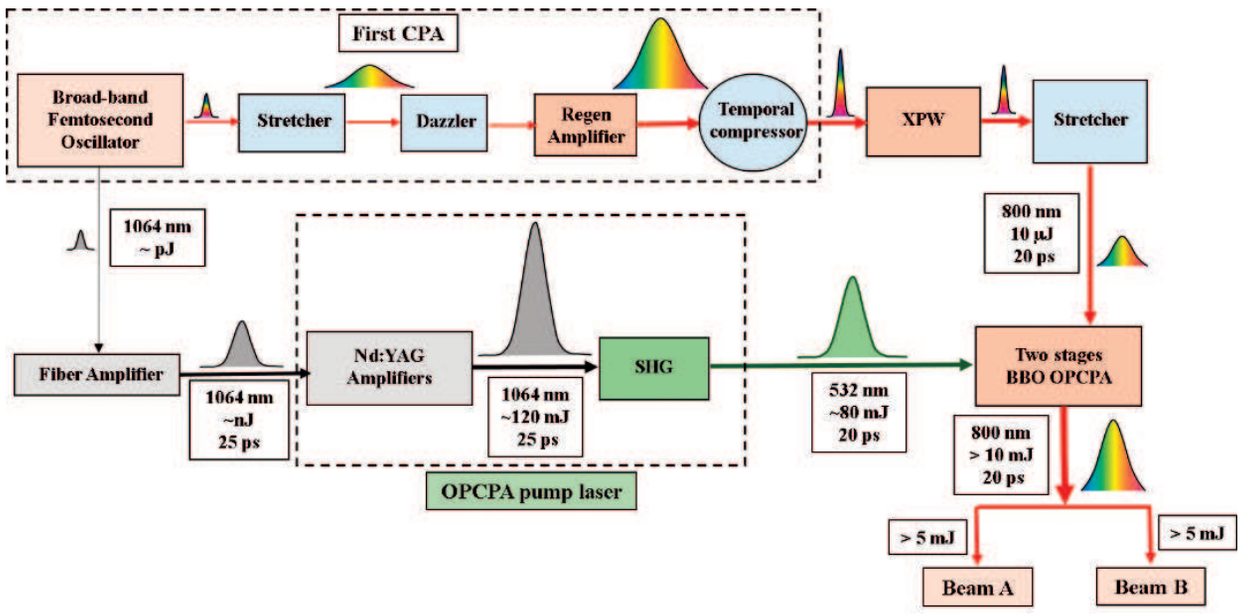

Figure 11. ELI-NP HPLS front-end based on optically synchronized OPCPA with BBO crystals.

Fourier-transform-limited pulses of ~1 nJ energy and ~25 ps pulse duration are amplified in bulk Nd:YAG amplifiers and frequency-doubled in a Lithium Triborate (LBO) crystal to get more than 80 mJ pump pulse energy at 532 nm wavelength and 10 Hz repetition rate.

The broadband seed pulses of nJ pulse energy at ~800 nm central wavelength are temporally stretched to 100 ps in a diffraction grating stretcher. An acousto-optic programmable dispersion filter (AOPDF), Dazzler type, is used to compensate for high-order phase distortions [9]. Stretched pulses are amplified to the mJ level in a Ti:sapphire regenerative amplifier and recompressed in the range of few 10 fs pulse duration. Femtosecond pulses amplified in the first CPA are intensity filtered and spectrally broadened by XPW generation in two barium fluoride (BaF_2) crystals. The femtosecond pulses with improved intensity contrast are stretched to ~20 ps pulse duration in a bulk glass stretcher. Broad bandwidth picosecond pulses are amplified in a two-stage NOPCPA with BBO crystals. To preserve a high intensity contrast during the parametric amplification process, the parametric fluorescence is hampered by keeping a relatively low parametric gain, less than 100× amplification factor for each NOPCPA stage. Outside the temporal window of the parametric process, the intensity contrast is improved by a numerical factor equal to the parametric gain.

By combining XPW and NOPCPA, the intensity contrast of recompressed pulses after FE amplification was improved by at least six orders of magnitude. More than 10^{12} ASE intensity contrast has been estimated in the few 10 ps range before the main femtosecond pulse. Spectral bandwidth narrowing and redshifting effects, specific to all Ti:sapphire amplification, were drastically reduced in the FE. Picosecond pulses with more than 70 nm FWHM spectral bandwidth were obtained at the FE output [30, 31]. Amplified pulses of ~10 mJ energy, split into two equal-energy beams, represent the seed pulses for A and B HPLS Ti:sapphire amplification arms.

After stretching to ~1 ns duration, laser pulses will be amplified up to the level of few 100 J in the all Ti:sapphire second CPA system (**Figure 10**). Ti:sapphire amplifiers AMP 1 are pumped by frequency-doubled Nd:YAG lasers at 10 Hz repetition rate. More than 4 J energy of the amplified chirped pulses can be obtained. By temporal compression of these pulses, 100 TW beams are generated in each arm of the HPLS. The next amplifier, AMP 2, is pumped by Nd:YAG lasers at 1 Hz repetition rate to get ~36 J pulse energy required for the generation of 1-PW temporally compressed laser pulses. In the last amplification stages, AMP 3.1 and AMP 3.2, Ti:sapphire crystals are pumped by 100-J energy frequency-doubled Nd:glass lasers (Atlas 100, Thales Optronique Company) at 1 pulse/min repetition rate [32].

To attain the 10-PW peak power with as low as possible pulse energy, a large spectral bandwidth of laser pulses must be preserved throughout all amplification process. To compensate for redshifting and gain narrowing effects in the high-energy Ti:sapphire amplifiers, the output spectrum will be managed using reflective filters for spectrum shaping at the input of AMP 1, AMP 2, and AMP 3 amplifiers, similar to the solution proposed for the 10-PW *Apollon* laser in a previously published work [7]. Final spectral bandwidth as broad as 60 nm with the central wavelength of ~815 nm is expected, compared to ~35 nm bandwidth at ~845 nm central wavelength, calculated without spectrum control. The improved spectral bandwidth theoretically allows the generation of recompressed pulses as short as 15 fs. To secure the 10-PW peak power of the HPLS in case of 22- to 23 fs duration of the temporally recompressed pulses, more than 300 J energy of amplified chirped pulses could be obtained by full energy pumping of the last amplifier stage, AMP 3.2. Considering a safe laser fluence of 1–1.5 J/cm^2, Ti:sapphire crystals with clear aperture diameter in the range of 160–200 mm are necessary for the last amplifier stages.

Main specifications of the ELI-NP HPLS are summarized in the **Table 1**.

To reach as high as 10^{23} W/cm^2 focused beam intensity, the 10-PW laser beam must be tightly focused in a few micrometers spot. Wavefront distortions, produced mainly by the thermal loading of Ti:sapphire amplifiers, give rise to focal intensity profile aberrations. They gather way by the enlargement of the focal spot size and the reducing of the energy content in the main spot. The associated Strehl ratio, which characterizes the peak intensity related to the ideal flat wavefront case, can decrease to values below 0.2 [10, 33]. Wavefront control and correction using adaptive optics are essential requirements for the laser beam focusing in an optimal and reproducible way. After high-energy amplifiers, deformable mirrors will be

Laser beam parameter	Estimated value
Laser pulse peak power	≥ 10 PW
Estimated pulse duration	15–25 fs
Estimated pulse energy	150–250 J
Repetition rate	1 pulse/min
Intensity contrast	≥ 10^{12}

Table 1. Main specifications of ELI-NP HPLS.

installed in each HPLS amplification arm. Output beam wavefronts with more than 0.8 Strehl ratio and near-diffraction-limited focal spots are expected.

6. Conclusions

Hybrid high-power femtosecond laser systems combine the advantages of ultra-broad bandwidth OPCPA in nonlinear crystals with the CPA technique in large size Ti:sapphire crystals. Ultra-broad gain bandwidths in the range of 150 nm can be obtained by noncollinear optical parametric chirped pulse amplification in nonlinear crystals, like BBO and DKDP, pumped by green lasers. A key feature of the hybrid amplification lasers consists in the adaptation of the phase-matching bandwidth of OPCPA nonlinear crystals to the gain bandwidth of the laser-amplifying media, such as Ti:sapphire crystals and Nd:doped glasses. The ultra-broad phase-matching bandwidth of BBO crystals and the gain bandwidth of Ti:sapphire laser crystals are spectrally overlapped. Many magnitude orders of amplification in hybrid femtosecond laser systems are obtained by OPCPA. Gain narrowing effect and ASE intensity pedestal are significantly attenuated compared to all Ti:sapphire amplifiers. It becomes easier to get high intensity contrast, large spectral bandwidth, and high-energy femtosecond laser pulses. High-power laser pulses in the range of 10-fs pulse width can be generated by hybrid femtosecond laser amplifiers based on OPCPA in BBO crystals and CPA in Ti:sapphire crystals.

A 2 × 10 PW hybrid amplification femtosecond laser system is currently under construction at ELI-NP research facility. The Front-End is based on optically synchronized picosecond pulses OPCPA in BBO crystals. Picosecond stretched pulses of ~10 mJ energy, with spectral bandwidth broader than 70 nm, were obtained at the output of ELI-NP laser Front-End. After high-energy chirped pulse amplification in large aperture Ti:sapphire crystals and temporal recompression, 10-PW pulses of about 20 fs duration, with more than 10^{12} picosecond ASE intensity contrast, are expected at the output of ELI-NP high-power laser system.

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References

[1] Strickland D, Mourou G. Compression of amplified chirped optical pulses. Optics Communication. 1985;**56**:219-221

[2] Sung JH, Lee SK, TJ Y, Jeong TM, Lee J. 0.1 Hz 1.0 PW Ti: sapphire laser. Optics Letters. 2010;**35**:3021-3023

[3] Kiriyama H, Michiaki M, Nakai Y, Shimomura T, Sasao H, Tanaka M, Ochi Y, Tanoue M, Okada H, Kondo S, Kanazawa S, Sagisaka A, Daito I, Wakai D, Sasao F, Suzuki M, Kotakai H, Kondo K, Sugiyama A, Bulanov S, Bolton PR, Daido H, Kawanishi S, Collier JL, Hernandez-Gomez C, Hooker CJ, Ertel K, Kimura T, Tajima T. High-spatiotemporal-quality petawatt-class laser system. Applied Optics. 2010;**49**:2105-2115

[4] Wang Z, Liu C, Shen Z, Zhang Q, Teng H, Wei Z. High-contrast 1.16 PW Ti: sapphire laser system combined with a doubled chirped-pulse amplification scheme and a femtosecond optical-parametric amplifier. Optics Letters. 2011;**36**:3194-3196

[5] TJ Y, Lee SK, Sung JH, Yoon JW, Jeong TM, Lee J. Generation of high-contrast, 30 fs, 1.5 PW laser pulses from chirped-pulse amplification Ti: sapphire laser. Optics Express. 2012;**20**:10807-10815

[6] Chu Y, Liang X, Yu L, Xu Y, Xu L, Ma L, Lu X, Liu Y, Leng Y, Li R, Xu Z. High-contrast 2.0 Petawatt Ti: sapphire laser system. Optics Express. 2013;**21**:29231-29239

[7] Giambruno F, Radier C, Rey G, Chériaux G. Design of a 10-PW (150J/15 fs) peak power laser system with Ti: sapphire medium through spectral control. Applied Optics. 2011;**50**:2617-2621

[8] Jullien A, Canova L, Albert O, Boschetto D, Antonucci L, Cha YH, Rousseau JP, Chaudet P, Cheriaux G, Etchepare J, Kourtev S, Minkovski N, Saltiel SM. Spectral broadening and pulse duration reduction during cross-polarized wave generation: influence of the quadratic spectral phase. Applied Physics B: Lasers and Optics. 2007;**87**:595-601

[9] Verluise F, Laude V, Huignard JP, Tournois P, Migus A. Arbitrary dispersion control of ultrashort optical pulses with acoustic waves. Journal of the Optical Society of America B: Optical Physics. 2000;**17**:138-145

[10] Akahane Y, Ma J, Fukuda Y, Aoyoma M, Kiriyama H, Sheldakova JV, Kudryashov AV, Yamakawa K. Characterization of wave-front corrected 100 TW, 10 Hz laser pulses with peak intensities greater than 10^{20} W/cm^2. Review of Scientific Instruments. 2006;**77**: 023102

[11] Yanovsky V, Chvykov V, Kalinchenko G, Rousseau P, Planchon T, Matsuoka T, Maksimchuk A, Nees J, Cheriaux G, Mourou G, Krushelnick K. Ultra-high intensity 300-TW laser at 0.1 Hz repetition rate. Optics Express. 2008;**16**:2109-2114

[12] Hong KH, Hou B, Nees JA, Power E, Mourou GA. Generation and measurement of >10^8 intensity contrast ratio in a relativistic kHz chirped-pulse amplified laser. Applied Physics B: Lasers and Optics. 2005;**81**:447-457

[13] Fourmaux S, Payeur S, Buffechoux S, Lassonde P, St-Pierre C, Martin F, Kieffer JC. Pedestal cleaning for high laser pulse contrast ratio with a 100 TW class laser system. Optics Express. 2011;**19**:8486-8497

[14] Minkovski N, Petrov GI, Saltiel SM, Albert O, Etchepare J. Nonlinear polarization rotation and orthogonal polarization generation experienced in a single-beam configuration. Journal of the Optical Society of America B: Optical Physics. 2004;**21**:1659-1664

[15] Jullien A, Albert O, Burgy F, Hamoniaux G, Rousseau JP, Chambaret JP, Augé-Rochereau F, Chériaux G, Etchepare J, Minkovski N, Saltiel SM. 10^-10 temporal contrast for femtosecond ultraintense lasers by cross-polarized wave generation. Optics Letters. 2005;**30**: 920-922

[16] Jullien A, Rousseau JP, Mercier B, Antonucci L, Albert O, Chériaux G, Kourtev S, Minkovski N, Saltiel SM. Highly efficient nonlinear filter for femtosecond pulse contrast enhancement and pulse shortening. Optics Letters. 2008;**33**:2353-2355

[17] Dromey B, Kar S, Zepf M, Foster P. The plasma mirror—A subpicosecond optical switch for ultrahigh power lasers. Revue of Scientifical Instruments. 2004;**75**:645-649

[18] Kapteyn HC, Murname MM, Szoke A, Falcone RW. Prepulse energy suppression for high-energy ultrashort pulses using self-induced plasma shuttering. Optics Letters. 1991;**16**:490-492

[19] Musgrave I, Shaikh W, Galimberti M, Boyle A, Hernandez-Gomez C, Lancaster K, Heathcote R. Picosecond optical parametric chirped pulse amplifier as a preamplifier togenerate high-energy seed pulses for contrast enhancement. Applied Optics. 2010;**49**:6558-6562

[20] Koechner W. Solid-State Laser Engineering. New York: Springer Science+Business Media; 2006 ISBN-10: 0-387-29094-X

[21] Cerullo G, De Silvestri S. Ultrafast optical parametric amplifiers. Review of Scientific Instruments. 2003;**74**. DOI: 10.1063/1.1523642

[22] Dabu R. Very broad gain bandwidth parametric amplification in nonlinear crystals at critical wavelength degeneracy. Optics Express. 2010;**18**:11689-11699

[23] www.altechna.com

[24] Dubietis A, Jonušauskas G, Piskarskas A. Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal. Optics Commun. 1992;**88**:437-440

[25] Tang Y, Ross IN, Hernandez-Gomez C, New GHC, Musgrave I, Chekhlov OV, Matousek P, Collier JL. Optical parametric chirped-pulse amplification source suitable for seeding high-energy systems. Optics Letters. 2008;**33**:2386-2388

[26] Lozhkarev VV, Freidman GI, Ginzburg VN, Katin EV, Khazanov EA, Kirsanov AV, Luchinin GA, Mal'shakov AN, Martyanov MA, Palashov OV, Poteomkin AK, Sergeev AM, Shaykin AA, Yakovlev IV. Compact 0.56 Petawatt laser system based on optical

parametric chirped pulse amplification in KD*P crystals. Laser Physics Letters. 2007;**4**: 421-427

[27] Gaul EW, Martinez M, Blakeney J, Jochmann A, Ringuette M, Hammond D, Borger T, Escamilla R, Douglas S, Henderson W, Dyer G, Erlandson A, Cross R, Caird J, Ebbers C, Ditmire T. Demonstration of a 1.1 petawatt laser based on a hybrid optical parametric chirped pulse amplification/mixed Nd: glass amplifier. Applied Optics. 2010;**49**:1676-1681

[28] Chambaret JP. The Extreme Light Infrastructure Project ELI and its prototype APOLLON/ ILE. LEI Conference, 21 October 2009, Brasov, Romania.

[29] http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf

[30] Chalus O, Pellegrina A, Casagrande O, Derycke C, Boudjemaa L, Simon-Boisson C, Laux S, Lureau F, Sanchez D, Biegert J, Ahrens J, Binhammer T, Prochnow O, Rausch S. High Contrast Broadband Seeder for Multi-PW Laser System. CF-P 19, CLEO-Europe EQEC, 21–25 June 2015, Munchen

[31] Lureau F, Laux S, Casagrande O, Chalus O, Duvochelle PA, Herriot S, Matras G, Radier C, Boudjemaa L, Simon-Boisson C, Dabu R, Dancus I, Ursescu D. Design and initial results of 10 PW laser for ELI-NP. CF-P 20, CLEO-Europe EQEC, 21–25 June 2015, Munchen

[32] Casagrande O, Derycke C, Soujae A, Ramos P, Boudjemaa L, Simon-Boisson C, Laux S, Lureau F. High energy pump laser for Multi-Petawatt laser. CA-3.2, CLEO-Europe EQEC, 21–25 June 2015, Munchen

[33] Fourmaux S, Payeur S, Alexandrov A, Serbanescu C, Martin F, Ozaki T, Kudryashov A, Kieffer JC. Laser beam wavefront correction for ultra-high intensities with the 200 TW laser system at the Advanced Laser Light Source. Optics Express. 2008;**16**:11987-11993