Laser Review

Basic Concepts and Current Status of the Petawatt Field Synthesizer
− A New Approach to Ultrahigh Field Generation

Zsuzsanna MAJOR,[1,2] Sergei A. TRUSHIN,[1] Izhar AHMAD,[1] Mathias SIEBOLD,[1] Christoph WANDT,[1]
Sandro KLINGEBIEL,[1] Tie-Jun WANG,[1] József András FÜLÖP,[3] Andreas HENIG,[1,2]
Sebastian KRUBER,[1] Raphael WEINGARTNER,[1,2] Antonia POPP,[1] Jens OSTERHOFF,[1]
Rainer HÖRLEIN,[1,2] Joachim HEIN,[4] Vladimir PERVAK,[1,2] Alexander APOLONSKI,[1,2,5]
Ferenc KRAUSZ,[1,2] and Stefan KARSCH[1,2]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany*
[3]*Department of Experimental Physics, University of Pécs, Ifjúság u. 6., H-7624 Pécs, Hungary*
[4]*Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany*
[5]*Institute of Automation and Electrometry, Russian Academy of Sciences, 630090 Novosibirsk, Russia*

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Optical parametric amplification (OPA) has opened a path towards a completely new regime of generating ultrashort, high-power laser pulses, that reaches well beyond the limits of conventional laser technology.1) In combination with the chirped-pulse amplification (CPA) principle2) (i.e. OPCPA) few-cycle pulses and pulse energies of several tens of Joules have already been achieved,3−6) however, not yet simultaneously. The Petawatt-Field-Synthesizer (PFS) project at the Max-Planck-Institut für Quantenoptik (Garching), aims at combining few-cycle pulse durations with petawatt scale peak powers by using short pulses (on the few-ps scale) for both seeding and pumping an OPCPA chain. Here we present the design considerations for PFS, including the main OPCPA chain and the special pump source that is required for short-pulse pumping, which itself is a CPA system. The seed pulses for these two chains are obtained from a common frontend in order to provide optical synchronization. We report on the current experimental status of the PFS development.

Key Words: High-power laser, Short-pulse OPCPA, Diode-pumped CPA pump source

1. Introduction and basic concepts

The quest for understanding and controlling microscopic processes at a fundamental level, i.e. the dynamics of the electron motion in atoms and molecules, has been driving the development of tools that allow for temporal and spatial resolutions on the order of the characteristic time and length scales of these processes. For a full 4D investigation an infrastructure would be necessary, which delivers Å-wavelength X-ray and electron pulses with sub-fs duration that can be used for both probing these processes and controlling them by inducing the appropriate excitation.

The Petawatt Field Synthesizer (PFS), currently under construction at the Max-Planck-Institut für Quantenoptik (Garching, Germany), represents a project for developing a facility which will allow for accessing this very fundamental regime. The PFS light-source is expected to deliver wave-form controlled, few-cycle laser pulses with petawatt-scale peak power. Such pulses will firstly enable the generation of intense isolated attosecond extreme ultraviolet (XUV) pulses by using the higher-harmonic radiation emerging during an interaction between the light pulse and a solid surface.7) Secondly, the PFS laser pulses can be used to drive a laser-wakefield accelerator in the "bubble" regime8) generating GeV-scale, monoenergetic electron pulses. Such laser-driven acceleration has already been demonstrated, however, using PW-scale few-cycle pulses is expected to improve the stability of the electron-pulse source as well as increase the accelerated charge and allow for the observation of phase-sensitive effects.9) The resulting electron beam can be used for probing matter with sub-atomic spatio-temporal resolution and, in addition, for seeding a table-top X-ray free-electron laser10) generating high peak brilliance and ultrashort (possibly sub-fs) X-ray pulses.

The PFS light source is designed to deliver fully wave-form controlled (i.e. carrier phase stabilized), few-cycle (5 fs) laser pulses with an energy of > 3 J and a repetition rate of 10 Hz. The focussed intensity is expected to reach or exceed 10^{22} W/cm^2.

In order to achieve these ambitious goals and combine such high energy levels with few-cycle pulse durations, the PFS design is based purely on optical parametric chirped pulse amplification (OPCPA) technology.1) Here the gain bandwidth limitations of conventional laser amplification are circumvented by the ultra-broadband gain bandwidth of OPA in a noncollinear geometry.[11] The combination with the chirped-pulse amplification scheme,[2] where a temporally stretched pulse is amplified and subsequently compressed, allows for very high pulse energies without the risk of optical damage in the system. On one hand OPCPA systems have already been demonstrated to deliver pulse energies as high as 35 J in 84-fs pulses[3] as well as 90 mJ in the few-cycle regime (sub-10 fs).[4,5] However, the generation of Joule-scale pulse energies in the few-cycle regime has yet to be demonstrated and constitutes the aim of the PFS development.

To allow for this, in the PFS design short pulses are used to pump the OPA stages, i.e. on the order of $\sim$ 1 ps, in contrast to $\sim$ 100 ps-ns pulse durations in previous systems (e.g. in Refs. 3–5). This approach improves the conditions for high-power few-cycle-pulse generation as compared to long-pulse-pumped OPCPA in several ways. Firstly, the significantly increased pump power permits the use of thinner OPA crystals while keeping the same level of gain, which implies an increase of amplification bandwidth as compared with OPA driven by longer pulses. Secondly, the short pump-pulse duration reduces the necessary stretching factor for the seed pulse, thereby increasing stretching and compression fidelity and allowing the use of simple, high-throughput stretcher-compressor systems, consisting of bulk glass and chirped multilayer mirrors. Finally, the short pump-pulse duration results in a short amplification time window and hence a dramatically enhanced pulse contrast outside this window. However, as a drawback inherent to the OPA principle the pump and seed pulses need to be synchronized on a timescale much shorter than the pulse durations in order to provide a stable temporal overlap which is essential for the amplification. This issue clearly becomes especially severe, if short pulses are used. We therefore use optical synchronization between the pump and seed pulses by deriving them from the same "master oscillator".

The OPCPA process is also expected to sensitively depend on the spatial profile of the pump pulse and on the exact temporal shape of both the pump and the seed beams. These issues have to be borne in mind throughout the design and development of the PFS system.

Compared to other CPA or OPCPA systems, the short-pulse-pumped OPCPA scheme of the PFS design requires a very special pump source, delivering 1 ps pulses with 15-20 J pulse energy in the green, i.e. $\sim$ 50 J in the fundamental (infrared) beam, at 10 Hz repetition rate. Such a system is not commercially available and therefore represents a challenge for development on its own right. The requirements for this pump source are expected to be met by the following design features. As a consequence of the high output peak power the system will be based on the CPA principle using conventional laser amplification. Owing to the short pulse duration of $\sim$ 1 ps a laser material with a large gain bandwidth is required. In addition, for the high repetition rate the medium needs to display low heat deposition and allow for efficient pumping using diodes.

The planned layout of the PFS system is schematically shown in Fig. 1. In this paper we first present the design considerations of the main OPCPA amplifier chain supported by theoretical calculations. This will be followed by a detailed description of the pump-laser design, the common frontend, and the methods for generating the synchronized seed pulses, taking into account the stringent requirements imposed by the short-pulse-pumped OPCPA scheme. Finally we report on the current experimental status of the PFS frontend and CPA pump-laser chain.

2. Design considerations for the pfs system

2.1 Short-pulse-pumped OPCPA

In most existing OPA systems the nonlinear medium used for amplification is BBO (β-BaB$_2$O$_4$) or LBO (LiB$_3$O$_5$) due to the extraordinarily large phase-matching bandwidth they can

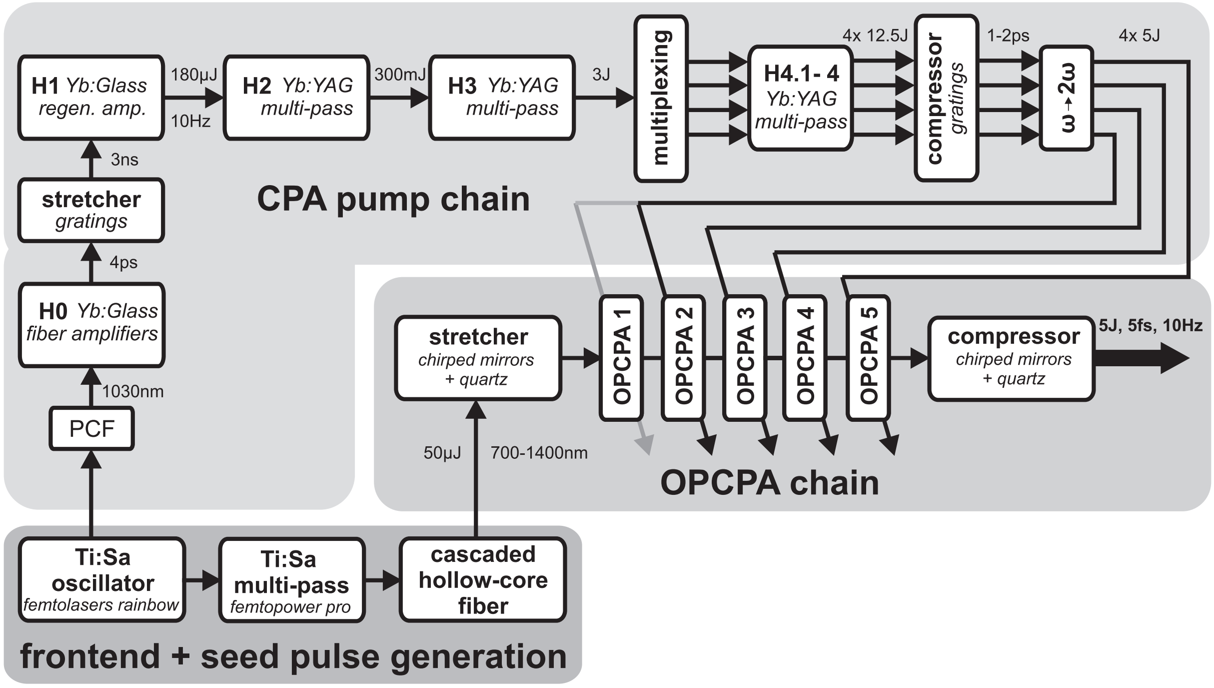

Fig. 1 Schematic layout of the PFS system. The seed pulses for both the main OPCPA chain and the pump-laser CPA chain are derived from the common master oscillator and are therefore optically synchronized.

support.[12,13] However, when scaling to higher power levels, the aperture of these amplifier crystals also needs to be scaled. Since current technology does not allow for BBO or LBO to be grown in the sizes required for the Joule-level pulses targeted by PFS, as an alternative approach the more narrowband DKDP (KD_2PO_4) crystal has been chosen. DKDP can be produced with sufficiently large apertures as well as small thicknesses, as needed for the short-pulse-pumped OPCPA approach. In contrast to the BBO and LBO crystals, DKDP displays the broadest amplification bandwidth in the range of 700-1,400 nm[6] as shown in Fig. 2 (a) for the unsaturated case. In order to model the full amplification chain more realistically we have employed a simple 1D model of the parametric amplification[14] which also accounts for saturation, i.e. pump depletion, during the process. Fig. 2 (b) shows the amplified spectra of 8 subsequent OPA stages, in which a model input pulse (of Gaussian shape in frequency space) is amplified from the μJ to the Joule level. The spectrum of the last amplifier stage corresponds to a sub-5 fs Fourier limited pulse duration. Starting from the 2nd stage the amplifiers operate in saturation and the overall conversion efficiency from pump energy into the amplified pulses is predicted to be ∼ 15-20 %. In summary this simple 1D model suggests a feasible amplification scheme in DKDP for reaching PW-scale pulses using ps-timescale amplification.

Owing to the small stretching factor and the negative chirp of the amplified pulse, in our design several tens of milimetres of bulk glass, in combination with chirped mirrors for fine dispersion control, are sufficient for compression. The beam diameter will be adjusted such that the resulting B-integral in the bulk material remains well below unity, even at Joule-scale pulse energies.

In order to validate the concept of the short-pulse OPCPA scheme also in experiment and thereby evaluate the reliability of our simplified modelling, we have conducted a test experiment using the ATLAS Ti:Sapphire CPA system (delivering up to 1 J in 42 fs, centred on 790 nm) at MPQ. In this proof-of-principle experiment both the pump and seed pulses were derived from ATLAS and the amplification took place in a thin (0.5 mm - 2 mm) BBO crystal. We were able to verify various aspects of the short-pulse OPCPA scheme, including the high gain when high pump intensities are used, the ultra-broadband amplification in noncollinear geometry, pulse-front matching between seed and pump pulses, compressibility of the pulses and their preserved focusability (for full detail see Ref. 15). The good agreement between calculations and our experimental findings supports the feasibility of our design for the scaling of the short-pulse OPCPA to Joule level in the few-cycle regime.

2.2 Diode-pumped Yb:YAG pump source

Recent advances of semiconductor high-power laser technology has allowed diode-pumped solid-state lasers to become the most promising candidates for high average power operation, therefore also enabling high repetition rates. Exploiting this development, several high-energy class diode-pumped solid-state lasers (HEC-DPSSL) are being constructed worldwide at present with expected energies of 100 J or more.[16–19] Amongst these projects is the development of the pump source of the PFS system, with the aim to generate 50 J pulses using diode pumping.

Owing to such high peak powers the amplification chain has to be based on the CPA principle. As schematically indicated in Fig. 1, the pump-laser chain of the PFS consists of a grating-based stretcher, several diode-pumped amplifier stages and a grating-based compressor. As one of the most developed laser materials for high-average-power diode-pumped operation Ytterbium-doped Yttrium Aluminum Garnet (Yb:YAG) has been chosen for the power amplifier stages of the laser chain. Its emission cross section is peaked at 1,030 nm and its 10 nm-linewidth at room temperature allows for mode-locking operation down to the sub-ps time-scale.[20]

Before the amplification in Yb:YAG can take place in the PFS pump-laser chain, the nJ-scale pulses centred at 1030 nm (with a bandwidth of 10 nm FWHM), which are generated in the common PFS frontend (cf. Section **2.3**), will be stretched to ∼ 3 ns pulse duration in a stretcher supporting a bandwidth of 4 nm, and then boosted to the 200 μJ level in a regenerative Yb:Glass amplifier. The power amplifiers (H2-H4) employ Yb:YAG as the gain material. In order to match the absorption spectrum of Yb:YAG, which is peaked at 940 nm, the pumping diodes with a spectral width of 6.5 nm over the pump pulse are temperature stabilized in terms of their emission wavelength. The gain medium is a homogeneously doped single crystal with an optimized aspect ratio between length and diameter taking care of thermal issues and suppressing parasitic lasing. Furthermore, for these Yb:YAG amplifier stages the multipass geometry was chosen in order to achieve gain saturation at a saturation fluence of 10 J/cm^2 while the peak fluence is limited by laser induced damage. When scaling the pulse energy to 4×12.5 J in the final amplifiers, we foresee the required pump power to be 4×96 kW. In

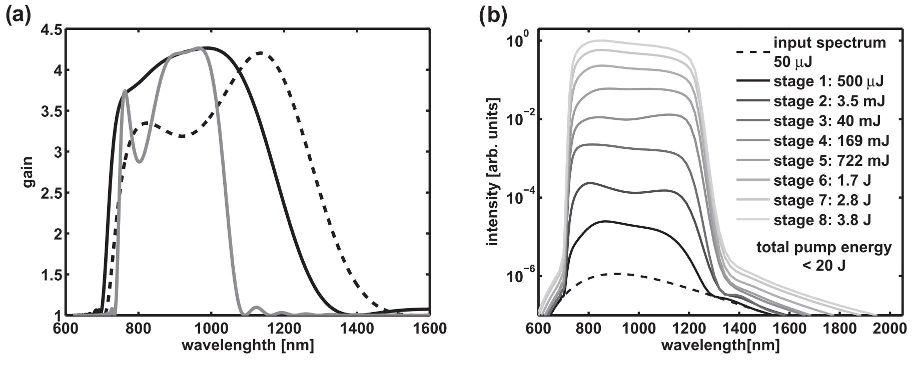

Fig. 2 (a) Comparison of the unsaturated gain for ns pulses in 10 mm DKDP (grey) and ps pulses in 2 mm DKDP (black solid line, with slightly tilted crystal: black dashed line). (b) 1D saturated gain calculation of broadband optical parametric amplification in 8 subsequent stages using DKDP. The total pump-to-signal conversion efficiency is ∼20 %. The transform limit of the amplified spectrum is < 5 fs.

Table 1 the major design parameters regarding the gain material and the pumping diodes of the multipass amplifiers are summarized. After amplification the compression of the pump pulses to a duration of about 1 ps will be carried out using reflective diffraction gratings.

2.3 Requirements for the common frontend

Since for the short-pulse-pumped OPCPA scheme optical synchronization is the easiest way to provide the required accuracy, we derive both the seed pulses, i.e. that of the pump-laser chain and that of the main OPCPA chain, from a common "master oscillator". For this purpose we use a commercially available ultra-broadband Ti:Sapphire oscillator (Rainbow, Femtolasers GmbH), delivering pulses of < 7 fs duration at a repetition rate of 70 MHz with a spectrum ranging from 620 nm-950 nm. Firstly, we will describe the way of generating appropriate seed pulses for the main OPCPA chain in the wavelength range of 700 nm-1,400 nm from the oscillator output at an energy level as high as possible. Secondly, the shifting of a fraction of the oscillator output energy into a narrowband spectral region around 1,030 nm, which is required for the seeding of the Yb:YAG pump-laser chain, will be discussed.

In order to reach higher pulse energies, the nJ-level pulses of the oscillator are amplified using a commercial Ti:Sapphire-based CPA setup (Femtopower Compact Pro, Femtolasers GmbH) consisting of a multipass amplifier and a subsequent hybrid compressor, i.e. a combination of a double-prism-pair and chirped mirrors. At optimum performance this system delivers 1.5 mJ energy pulses in a pulse duration of 23 fs at 1 kHz repetition rate. For a detailed description and evaluation of the hybrid compression scheme see Ref. 21. Using these pulses we pursue several possible ways to produce the desired broadband NIR seed pulse: (i) spectral broadening in two subsequent hollow-core fibers (HCF); (ii) spectral broadening in a single HCF followed by spectral broadening in a filament in a gas cell; (iii) spectral broadening of a part of the pulse in a single HCF followed by a noncollinear OPA stage in BBO pumped at the second harmonic of the remaining amplifier output. In case (iii) the idler beam of this OPA process ranges from 700-1,400 nm, however, it contains an inherent angular chirp due to the noncollinear geometry.14) Investigations into the possibility of compensating this angular chirp and the search for the most efficient energy conversion are ongoing. Currently, case (i) appears to be the most viable route for the seed generation and our results will be discussed in Section **3.1**.

Table 1 Parameters of the PFS Yb:YAG pump laser amplifiers.

	H2	H3	H4
pulse energy [J]	0.3	3	4×12
pump power [kW]	2.5	26	4×96
beam cross section [cm^2]	0.1	1	4
Yb-concentration [mol%]	3	1.4	1.4
crystal length [mm]	8	16	16

Since the emission cross section of Yb:YAG is peaked around 1,030 nm, our second aim is to generate a seed pulse for the pump-laser CPA chain in this spectral range. This is accomplished by coupling part of the master-oscillator output into a commercially available photonic-crystal fiber (PCF) where due to the efficient soliton based self-frequency shift (SSFS)22) a portion of the input light is shifted into the 1,030 nm wavelength range. Subsequently, these pJ-scale pulses are then boosted to nJ pulse energies in two Yb-doped fiber amplifiers (IAP Jena). With these pulses we can now seed the CPA chain of the diode-pumped Yb:YAG pump-laser chain, the status of which will be discussed in more detail in Section **3.2**.

3. Current status

3.1 Frontend and seed generation

The ultrabroad output spectrum of the cascaded HCF setup (case (i)) which we propose to use as the seed pulse for the main OPCPA chain of PFS is shown in Fig. 3 (a). Here the 1.5 mJ, 23 fs pulses were first focussed into a 1 m long HCF with an inner diameter of 300 μm using a 2 m focal length lens and 1.5 bar Neon. After the first HCF the pulses were collimated and compressed to ~5 fs pulse duration using chirped mirrors and subsequently focussed into the second HCF of 1 m length and 250 μm inner diameter at 3.3 bar of Ne. The total throughput in this setup is around 15 %, i.e. the ultrabroadband output shown in Fig. 3 (a) contains around 200 μJ out of which ~50 μJ are contained in the spectral range of 700-1,400 nm.

Fig. 3 (b) shows the spectrally shifted output of the PCF for generating the seed pulse of the CPA pump-laser chain. The PCF (type NL-PM-750, Crystal Fiber Ltd.) had a length of 25 cm and a core diameter of 1.6 μm. At its output we obtained approximately 3.4 pJ pulse energy at a central wavelength of 1,030 nm in a bandwidth of 10 nm (FWHM).

In order to evaluate the level of synchronization between these two pulses we have performed cross correlation measurements using the compressed Ti:Sapphire multipass ampli-

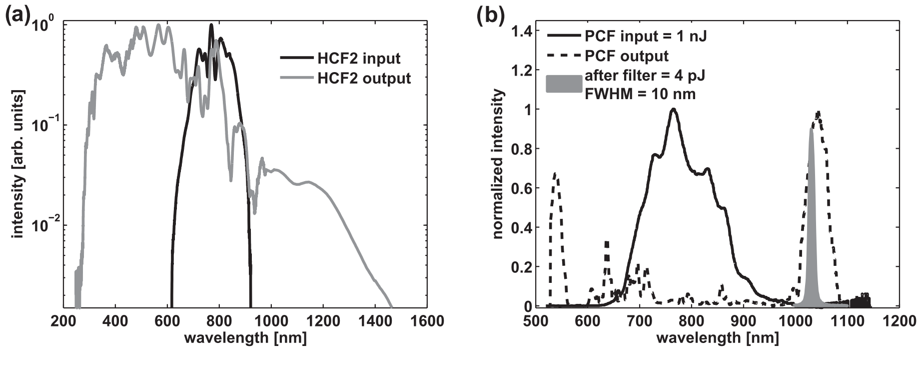

Fig. 3 (a) Input and output spectra of the second HCF in the cascaded-HCF setup. (b) Input spectrum of PCF from master oscillator (black solid line), output of PCF (black dashed line), output after filtering around 1,030 nm (grey shaded area).

fier output (cf. Section **2.3**) and the PCF output after amplification in the Yb-doped fiber amplifiers and the regenerative amplifier (cf. Section **2.2**) which allows to account for most of the path difference between the two pulses. A short-term drift below the 100 fs level was found, making the generation scheme of the two seed pulses suitable for short-pulse-pumped OPCPA. Full detail of the temporal drift measurement, the ultrabroadband pulse generation and the spectral shifting in the PCF is given in Ref. 21.

3.2 High-energy amplification of ns pulses in Yb:YAG

In order to verify the feasibility of the pump-laser design, in this early stage of the PFS development a stand alone Master-Oscillator-Power-Amplifier-System (MOPA) was developed in close collaboration with the Polaris-Group of the Friedrich-Schiller University (Jena, Germany). This experiment allowed the development and operation of the first stages of the diode-pumped amplifier chain even before the completion of the synchronized and stretched seed pulse of the CPA chain and provided proof for further scalability towards the later amplifier stages.

As the first stage of this MOPA an Yb:YAG-oscillator was used, working in Q-switch operation, where an Yb:YAG crystal rod (∅ 6 mm×3 mm, 3 %-doped) was pumped by a laser-diode stack (JOLD) allowing for maximum pump energy of 3.75 J (2.5 kW, 1.5 ms) at a centre wavelength of 940 nm and a repetition rate of 10 Hz. The oscillator generates pulses with a pulse duration of 6.4 ns (FWHM) and bandwidth of 1 nm at a center wavelength of 1,030.5 nm. The maximum output pulse energy was 3 mJ when pumped with 1 J, and the beam had a measured M^2 of 1.2. This initial stage was followed by a multipass amplifier, which used the same pump-diode configuration as the oscillator. The four-pass amplification was realized using a pump mirror directly behind the Yb:YAG crystal (∅ 6 mm×8 mm, 3 %-doped, AR-coated) and four turning mirrors at a distance of 800 mm from the crystal. For input pulse energies above 1 mJ an output energy of 220 mJ, the limit for damage-free operation, could be achieved at a repetition rate of 10 Hz without applying the maximum pump energy.[23] The measured amplifier output energy is shown as a function of pump energy for different input energies in Fig. 4 alongside the calculated behaviour. Another important outcome is the fact that even very low seed-pulse energies (~150 μJ) were amplified to the 150 mJ-level while the beam profile was nearly unchanged even for the highest amplification levels.

For the next amplification stage a novel pump scheme was introduced using two-side transverse pumping and cooling. For pumping of the Yb:YAG-slab (3.3×16×16 mm, 1.4 %-doped, brewster-cut) we used two custom-made laser-diode modules with adapted collimating optics each having a peak output power of 13 kW. Another four-pass amplifier was employed using a 4-f configuration for relay imaging between the passes. With this configuration we were able to achieve an output pulse energy of 2.9 J when seeded with the 200 mJ from the first amplifier. The repetition rate in this case was reduced to 1 Hz due to thermally-induced stress birefringence. The experimentally observed amplification dynamics are shown in Fig. 5. We achieved an optical-to-optical efficiency of 10 %. A full discussion of this experiment is given in Ref. 24.

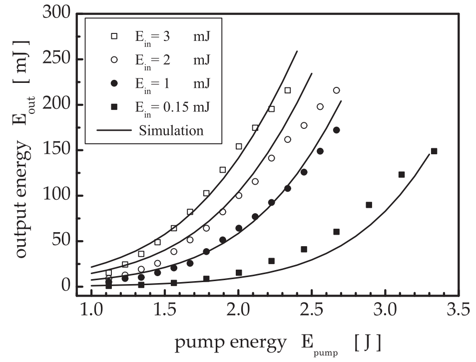

Fig. 4 Measured and simulated output pulse energy after the four-pass amplifier for different pump energies (reproduced from Fig. 2 in Ref. 23).

4. Conclusions and outlook

We have presented a concept for generating petawatt peak power laser pulses in the few-cycle regime based on the novel short-pulse-pumped OPCPA technique, the realization of which is pursued within the PFS project at MPQ. The requirements and constraints imposed by this concept have been incorporated into specific design considerations for the common frontend, for the diode-pumped CPA pump-laser chain and for the main OPCPA amplifier chain. We have also sketched out the current experimental status of both the frontend and the pump-laser chain.

In the immediate future the existing amplifier stages of the pump laser will be integrated into the CPA scheme, i. e. they will be seeded with stretched pulses and compressed after amplification. The main longer term task is the scaling of the amplifier stages to the 4×12 J level. In parallel to these developments, once the first ps-scale pump pulses are available, the experiments on the OPCPA in DKDP will commence, in order to verify the feasibility of the design for the entire system.

Acknowledgements

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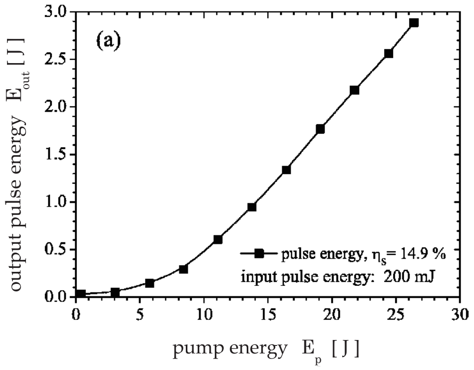

Fig. 5 Nanosecond pulse amplification in four-pass geometry with a pulse duration of 6.4 ns. The output pulse energy is shown vs. the pump pulse energy at an input pulse energy of 200 mJ (reproduced from Fig. 3 in Ref. 24).

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