Eur. Phys. J. Special Topics **224**, 2573–2577 (2015)
© EDP Sciences, Springer-Verlag 2015
DOI: 10.1140/epjst/e2015-02567-7

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

Stack and dump: Peak-power scaling by coherent pulse addition in passive cavities

S. Breitkopf[1,a], T. Eidam[1,2], A. Klenke[1,2], H. Carstens[3,4], S. Holzberger[3,4], E. Fill[3,4], T. Schreiber[5], F. Krausz[3,4], A. Tünnermann[1,2,5], I. Pupeza[3,4], and J. Limpert[1,2,5]

[1] Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
[2] Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[3] Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[4] Ludwig Maximilians University München, Department of Physics, Am Coulombwall 1, 85748 Garching, Germany
[5] Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany

Received 18 December 2014 / Received in final form 31 August 2015
Published online 26 October 2015

Abstract. During the last decades femtosecond lasers have proven their vast benefit in both scientific and technological tasks. Nevertheless, one laser feature bearing the tremendous potential for high-field applications, delivering extremely high peak and average powers simultaneously, is still not accessible. This is the performance regime several upcoming applications such as laser particle acceleration require, and therefore, challenge laser technology to the fullest. On the one hand, some state-of-the-art canonical bulk amplifier systems provide pulse peak powers in the range of multi-terawatt to petawatt. On the other hand, concepts for advanced solid-state-lasers, specifically thin disk, slab or fiber systems have shown their capability of emitting high average powers in the kilowatt range with a high wall-plug-efficiency while maintaining an excellent spatial and temporal quality of the output beam.

In this article, a brief introduction to a concept for a compact laser system capable of simultaneously providing high peak and average powers all along with a high wall-plug efficiency will be given. The concept relies on the stacking of a pulse train emitted from a high-repetitive femtosecond laser system in a passive enhancement cavity, also referred to as temporal coherent combining. In this manner, the repetition rate is decreased in favor of a pulse energy enhancement by the same factor while the average power is almost preserved. The key challenge of this concept is a fast, purely reflective switching element that allows for the dumping of the enhanced pulse out of the cavity. Addressing this challenge could, for the first time, allow for the highly

---

[a] e-mail: `sven.breitkopf@uni-jena.de`

efficient extraction of joule-class pulses at megawatt average power levels and thus lead to a whole new area of applications for ultra-fast laser systems.

1 Motivation

Nowadays, classical particle colliders are about to reach their intrinsic limitations given by the acceleration gradient and hence size and costs. Therefore, new accelerating-concepts are currently under development in projects such as ICAN [1] or ICFA-ICUIL [2]. The most promising approach appears to be laser-wake-field acceleration. In order to compete with rf-technology, the required pulse energy is estimated in [2] to be as high as 32 J with pulse peak powers of ∼100 TW at a repetition rate of ∼15 kHz and an excellent beam quality. The therewith resulting average power of ∼480 kW is, especially for femtosecond lasers, far beyond the capability of any existing amplifier technology. Today, on the one hand, canonical bulk systems can achieve very high pulse peak powers due to their large beam radii [3], but they cannot handle high average powers due to thermal issues. Therefore, peak powers on the PW-level can only be produced at a low Hz-level repetition rate. On the other hand, novel solid-state amplifiers are well known for their high efficiency and high average powers even in the femtosecond-pulse regime [4], but these lasers are typically limited in pulse energy due to nonlinear effects and damage. However, there is a way to take advantage of the high repetition rates of fiber-based systems to achieve the desired combination of pulse energy and repetition rate. The basic idea is to stack the pulses of a state-of-the-art ultrashort pulse fiber amplifier in the temporal domain using an enhancement cavity. Although a similar technique has been demonstrated for low-power oscillators [5,6], today's femtosecond coherent-combined fiber systems [7] can, for the first time, deliver a sufficient average power to reach the above mentioned parameters with a feasible amount of fibers. Furthermore, the capability of enhancement cavities to handle high average powers has seen a significant improvement within the last years [8], so that these developments allow for a novel laser amplification concept which can be superior in many ways.

2 Working principle

In an enhancement cavity, pulses from a mode-locked laser source can be coherently stacked allowing for a power enhancement of several orders of magnitude. With ps pulses 700 kW of intra-cavity average power have been obtained [8]. The all-reflective nature of enhancement cavities results in high damage thresholds and low thermal loads. Furthermore, power scaling can be achieved by adapting the cavity designs for an increased beam size on the surface of the cavity mirrors [9].

Fiber amplifiers work best in a high power regime with moderate pulse energies, therefore, it is preferable to use highly repetitive systems. Stretched femtosecond pulses (several ns long) are stacked in an enhancement cavity before being dumped out at the switching rate f_{switch} (see Fig. 1). The repetition rate f_{rep} of the laser pulses is hence reduced by a factor corresponding to the number of stacked pulses N, while the pulse energy is increased by a factor ηN, where η denotes the stacking efficiency, which is can be as high as 75% as shown in [10].

To couple the pulses out of the cavity, a switching element is necessary. It has to be fast enough to dump the enhanced pulse within the time between two successive pulses. For example, the 665th pulse has to pass by undisturbed, but the 666th pulse has to be coupled out by the switch. Therefore, a repetition rate of 10 MHz,

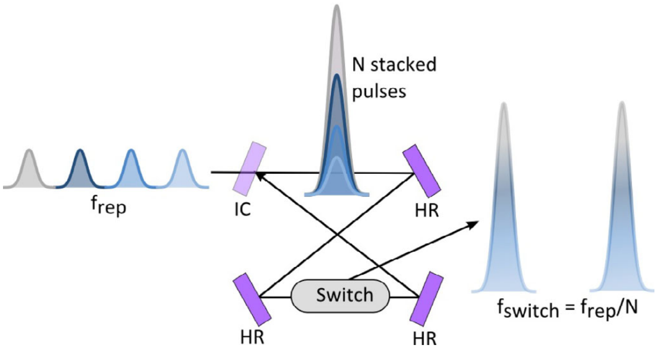

Fig. 1. Working principle of a stack and dump enhancement cavity.

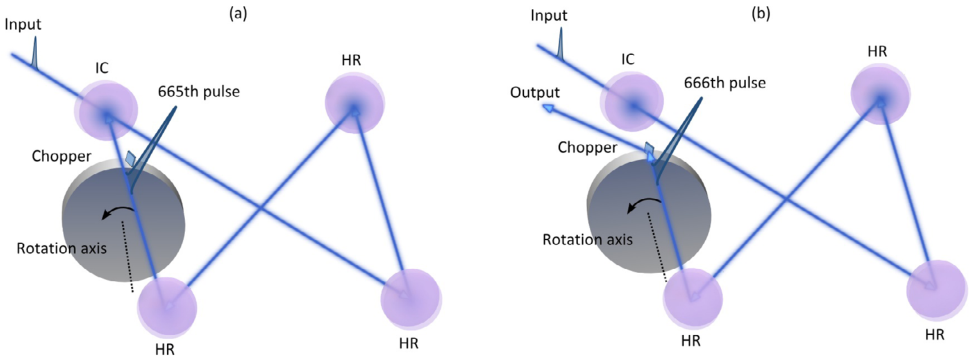

Fig. 2. Schematic concept of a chopper wheel employed as a cavity dumper. IC: Input-coupling mirror, HR: Highly reflective cavity mirror. The pulses are stacked (a) before the chopper wheel interacts with the beam and dumps it out of the cavity (b).

corresponding to a cavity length of 30 m and a switching time of 100 ns, is a suitable choice. This way the cavity is long enough to enable switching and short enough to keep the repetition rate of the incoming pulses in a regime that is preferred by fiber amplifiers. To stack 666 pulses with the mentioned efficiency η in a cavity, the roundtrip-losses have to be well below 0.1% [10]. This can only be achieved by preventing any additional losses due to the switching element, making a purely reflective dumper a necessity. There are several switching technologies that are currently being investigated.

One promising approach is a chopper wheel, similar to those used for pulse selection in particle beams [11]. The wheel has mirror segments attached and is rotating next to the beam within the vacuum chamber of the cavity as depicted in Fig. 2. For 665 round-trips, while the enhanced pulse builds up in the cavity, the wheel does not interact with the cavity at all. During the 666th round-trip the pulse is coupled out by the mirror attached to the wheel. The speed requirements necessary for this application are already fulfilled by available chopper wheels.

3 Proposed setup

The setup proposed within the ICAN project will be seeded with a front-end-laser system delivering stretched fs pulses, which are split into several fiber-amplifier channels

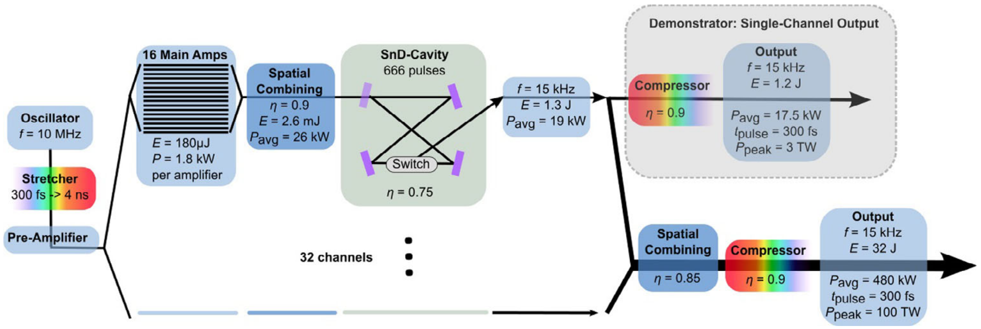

Fig. 3. Schematic setup of a laser system based on multidimensional coherent pulse combining of fiber-amplified ultra-short pulses.

(see Fig. 3). After amplification, 16 of these channels are combined and coupled into an enhancement cavity. When 666 pulses are stacked the switch dumps the enhanced pulse out, thus the repetition rate of the generated pulses is 15 kHz. The pulse energy achieved at this stage of the setup is already as high as 1.3 J (compressed ∼1.2 J) and could be well used for many demanding applications in fundamental science and in medicine.

To increase the output energy towards the values mentioned in [1,2], further parallelization can be implemented. With this scheme a total number of 512 main amplifier channels can allow for 32 J at 15 kHz with a pulse-duration shorter than 300 fs.

Furthermore, due to the cavity design the spatial mode quality of the beam is expected to be excellent. This occurs independently of the laser source, since the parts that do not overlap with the cavity mode (TEM-00) are not coherently combined and, therefore, not enhanced.

A much more detailed discussion of this concept can be found in [10].

4 Conclusions

The combination of spatial coherent combining of ultra-short pulses and additional cavity enhancement to stack the pulses in the temporal domain can improve the output parameters of high-power-laser systems in a way that allows for the efficient generation of a new class of laser parameters, i.e. the combination of highest peak power (approaching PW) and highest average power (approaching MW), to be used e.g. in laser-wake-field acceleration. Compared to the dimensions of an equally powerful inductor-based particle accelerator, such a system would be significantly smaller, cheaper and potentially more efficient in terms of energy consumption. The first experiments operating the 10 MHz cavity in a vacuum chamber using a fs oscillator as a seed source are currently carried out. A state-of-the art front-end fiber-CPA-system will be used as a seed for the cavity later on. The stretched pulses will be enhanced to confirm the high power capability of this concept. Different switching technologies, e.g. a chopper-wheel, will be investigated to evaluate the most promising ones for the implementation in the final system.

This work has been partly supported by the German Federal Ministry of Education and Research (BMBF) under contract 13N12082 “NEXUS”, by the Thuringian Ministry of Education, Science and Culture (TMBWK) under contract 12037-515 “BURST”, by the European Research Council under the ERC grant agreement no. [617173] “ACOPS” and by the Deutsche Forschungsgemeinschaft Cluster of Excellence "Munich-Centre for Advanced Photonics" (munich-photonics.de). A. K. acknowledges financial support by the Helmholtz-Institute Jena. T. E. acknowledges financial support by the Carl-Zeiss-Stiftung. I. P. and S. H. acknowledge financial support by the BMBF under PhoNa - Photonische Nanomaterialien, contract number 03IS2101B. We acknowledge the support and fruitful discussions within the International Coherent Amplifier Network (ICAN) Consortium. We also acknowledge the support and fruitful discussions about the chopper wheel with Eberhard Rosenthal and Michael Butzek from the Forschungszentrum Jülich.

References

1. G. Mourou, B. Brocklesby, T. Tajima, J. Limpert, Nature Photonics **7**, 258 (2013)
2. W. Leemans, E. Esarey, Phys. Today **62**, 44 (2009)
3. W.P. Leemans, R. Duarte, E. Esarey, S. Fournier, C.G.R. Geddes, D. Lockhart, C.B. Schroeder, C. Toth, J.L. Vay, S. Zimmermann, AIP Conf. Proc. **1299**, 3 (2010)
4. T. Eidam, S. Hanf, E. Seise, T.V. Andersen, T. Gabler, C. Wirth, et al., Opt. Lett. **35**, 94 (2010)
5. R.J. Jones, J. Ye, Opt. Lett. **27**, 1848 (2002)
6. Y. Vidne, M. Rosenbluh, T.W. Hansch, Opt. Lett. **28**, 2396 (2003)
7. A. Klenke, S. Breitkopf, M. Kienel, Opt. Lett. **38**, 2283 (2013)
8. H. Carstens, N. Lilienfein, S. Holzberger, C. Jocher, T. Eidam, J. Limpert, et al., Opt. Lett. **39**, 2595 (2014)
9. H. Carstens, S. Holzberger, J. Kaster, J. Weitenberg, V. Pervak, A. Apolonski, et al., Opt. Expr. **21**, 11606 (2013)
10. S. Breitkopf, T. Eidam, A. Klenke, L. von Grafenstein, H. Carstens, S. Holzberger, E. Fill, T. Schreiber, F. Krausz, A. Tünnermann, I. Pupeza, J. Limpert, Light Sci. Appl., e211 (2014), doi: 10.1038/lsa.2014.92
11. M. Cammarata, L. Eybert, F. Ewald, W. Reichenbach, M. Wulff, P. Anfinrud, et al., Rev. Scientific Instr. **80**, 015101 (2009)