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ORIGINAL ARTICLE

A concept for multiterawatt fibre lasers based on coherent pulse stacking in passive cavities

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Since the advent of femtosecond lasers, performance improvements have constantly impacted on existing applications and enabled novel applications. However, one performance feature bearing the potential of a quantum leap for high-field applications is still not available: the simultaneous emission of extremely high peak and average powers. Emerging applications such as laser particle acceleration require exactly this performance regime and, therefore, challenge laser technology at large. On the one hand, canonical bulk systems can provide pulse peak powers in the multi-terawatt to petawatt range, while on the other hand, advanced solid-state-laser concepts such as the thin disk, slab or fibre are well known for their high efficiency and their ability to emit high average powers in the kilowatt range with excellent beam quality. In this contribution, a compact laser system capable of simultaneously providing high peak and average powers with high wall-plug efficiency is proposed and analysed. The concept is based on the temporal coherent combination (pulse stacking) of a pulse train emitted from a high-repetition-rate femtosecond laser system in a passive enhancement cavity. Thus, the pulse energy is increased at the cost of the repetition rate while almost preserving the average power. The concept relies on a fast switching element for dumping the enhanced pulse out of the cavity. The switch constitutes the key challenge of our proposal. Addressing this challenge could, for the first time, allow the highly efficient dumping of joule-class pulses at megawatt average power levels and lead to unprecedented laser parameters.

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INTRODUCTION

The scope of any laser application crucially depends on the quality of the driving light source, i.e., the laser itself. Hence, it is not surprising that improved laser output parameters have repeatedly extended the range of applications or even opened up novel opportunities.[1,2] Today, ultrafast laser systems are considered as unique tools for many industrial and scientific applications, the latter one being an incubator for seminal discoveries and new technologies. One of these emerging applications is laser-wakefield particle acceleration. Here, an extremely intense femtosecond laser pulse that propagates in a plasma can be employed to accelerate particles, such as electrons, in its wakefield.[3,4] There is a growing interest in laser-wakefield particle acceleration schemes due to the fact that classical radiofrequency-driven machines are about to reach their intrinsic limitations given by their acceleration gradient and, thus, size and cost.[5]

However, even near-future accelerator applications will require parameters that are beyond the ones that can be achieved with state-of-the-art ultrafast lasers, particularly in terms of average power. To achieve TeV-level energies for electrons and positrons *via* laser plasma acceleration with fluxes comparable to those of radiofrequency accelerators, a laser architecture that efficiently allows for the combination of petawatt peak powers with megawatt average powers is required. For example, Leeman *et al.*[6] estimated that at a laser wavelength of around 1 μm, a pulse energy of 32 J at a repetition rate as high as 15 kHz is required. This corresponds to an average power of 480 kW, combined with pulse durations as short as possible (preferably sub-100 fs) and an almost diffraction limited beam quality. Once these parameters are reached, about 100 of those stages are needed to enable a compact TeV-scale accelerator facility. This parameter range is far beyond the capability of any existing laser technology today. Hence, developing such a laser system is an extremely challenging task. Such a development might well take several decades of aggressive research and development, and, most importantly, novel concepts and approaches.

Current state-of-the-art femtosecond solid-state lasers, such as titanium–sapphire-based amplification systems, can generate high peak intensities. In terms of peak power, one benchmark laser system currently is BELLA[7] producing 30-fs pulses with 40 J of pulse energy, i.e. >1 PW peak power, at a repetition rate of 1 Hz resulting in an average

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power of 40 W. Still, BELLA is far from being compact or efficient with a wall-plug efficiency in the range of 10^{-4}. Taking into account the envisaged performance and number of stages mentioned above, such a poor efficiency and high costs would be a roadblock for laser-based particle accelerators. Moreover, a scaling of the average power and, hence, of the repetition rate, is inhibited by thermo-optical problems such as thermal lensing and stress-induced birefringence in the amplifying medium. Thus, a PW-class laser with a repetition rate of 1 Hz (corresponding to a few 10s of Watts of average power) constitutes the frontier of laser technology today. This performance has opened the door to a vast range of scientific opportunities, including proof-of-principle experiments on the most advanced accelerator concepts, among them plasma-channel waveguide-assisted wake-field accelerators that enable enormous accelerating gradients and mono-energetic particles.[7] However, only a higher average power and a high-repetition-rate driving laser source, respectively, can bring these laboratory-tested concepts to a facility which benefits a broad range of users and their industrial and medical applications. This requirement leads to a major challenge lying in the fact that scaling the peak and the average power of a laser are two completely different tasks, which usually impose contradictory requirements on the geometry of the active medium.

Over the past decades, solid-state-laser concepts with advanced active medium geometries have been developed, including the thin disk,[8] the slab[9] or the fibre.[10] All of them feature an improved thermal management, which has enabled scaling the average power while preserving an excellent spatial beam quality. In particular, fibre-based amplifiers are well known for their outstanding beam quality, high efficiency and high average powers even in the femtosecond-pulse regime.[11] However, fibres face serious challenges when to be pushed to high peak powers. The tight transverse confinement of the optical pulses over considerable lengths typically enforces nonlinear pulse distortions and damage. Thus, to generate high pulse energies and, consequently, peak powers, fibres with large mode-field areas are employed.[12] Moreover, the technique of chirped-pulse amplification (CPA) is essential to stretch the laser pulses in time and, hence, reduce their peak power during amplification.[13] State-of-the-art grating-based stretchers lengthen femtosecond pulses up to several nanoseconds and have allowed fibre-based systems to produce pulse peak powers of up to 3.8 GW.[14] In principle, the stretched pulse duration could be further increased but in practice this parameter is limited to about 10 ns by the dimensions of the laser system and the available grating sizes.

Parallelisation offers an intuitive approach of overcoming the fundamental limitations of a single amplifier channel. Here, the basic idea is the coherent combination of multiple emitters to reach peak and average powers not achievable with single-aperture systems.[15] This technique has been first applied to continuous-wave lasers[16] and more recently extended to ultrafast systems.[17–19] This is a particularly interesting approach for fibre amplifiers, since their high gain and compact single-pass set-ups allow for straight-forward parallelisation. Parallel amplification can be regarded as an artificial increase of the mode-field diameter, which, therefore, enables the scaling of both the pulse peak power and the average power by a factor roughly equal to the number of amplification channels. So far, in low-power operation up to 64 passive channels have been combined,[20] whereas in high-power operation the state of the art is a set-up combining the output of four femtosecond amplifiers.[21] With this system 530 W of average power and a pulse energy of 1.3 mJ have been realized with combining efficiencies exceeding 93%. Furthermore, it has also been theoretically shown[22,23] that the efficiency can be kept high even up to more than thousand channels. These promising experimental results have encouraged research into particle acceleration based on the coherent combination of a large number (possibly millions) of fibre amplifiers.[24] In this concept, each fibre amplifier would have to generate pulses with energies in the mJ range at a kHz repetition rate. As a consequence, they would have to be operated at average power levels as low as a few watts. This means that the fibres would be underperforming in terms of average power leaving their essential advantage unexploited. Additionally, due to the immense number of required optical elements, the complexity and the cost of such an approach would be far beyond any tolerable value.

A possible solution for this problem is the temporal combination of several pulses, a technique that has been successfully shown in so-called divided-pulse-amplification (DPA) systems.[25–27] Here, each pulse is split in time into a train of pulses *via* birefringent crystals or *via* a combination of beam splitters and free-space delay lines. Subsequently, the individual lower-intensity pulses are amplified and, finally, coherently temporally combined. This method can be considered as an effective increase of the stretched pulse duration and thereby, correspondingly, of the compressible pulse energy beyond the limits imposed by conventional stretchers. Moreover, DPA can also be implemented in combination with the spatially separated amplification discussed above. Thus, in the ideal case, with DPA, the output pulse energy emitted by a single fibre amplifier can be increased according to the number of pulse replicas. Therewith, DPA is a promising way to scale the pulse energy by about one order of magnitude. However, increasing the number of pulse replicas to 100 or even 1000 with traditional DPA approaches in the CPA regime and, thus, achieving TW-peak powers with fibre amplifiers will become extremely challenging due to the required number and length of the delay lines, their individual stabilisation and the necessary mitigation of saturation effects in the amplifier.[26] Hence, an interesting alternative to DPA is to start with a higher repetition rate and to use only one delay line for stacking hundreds or even thousands of pulses. Such a delay line can be realized in the form of a passive enhancement cavity. In this paper, we analyse the concept of stacking stretched pulses of a high-repetition-rate, high-average-power femtosecond CPA system in a passive cavity. After a certain number of pulses, i.e., one stacking period, a fast switching element is used to couple out the intense circulating pulse, which is then compressed back to its fs-duration. Although the use of cavity-dumped enhanced pulses has already been demonstrated in the past for low-power systems,[28,29] the combination of today's femtosecond laser systems together with state-of-the-art enhancement cavities[30] can result in a new class of laser output parameters vastly outperforming anything demonstrated before. In general, this 'stack-and-dump' (SnD) technique can be applied to any existing amplifier technology. However, it is particularly well suited for amplifier geometries that can deliver very high average powers such as rare earth-doped fibres.

MATERIALS AND METHODS

Ultrashort-pulse enhancement cavities have already shown their huge potential for stacking laser pulses over the last decade. Such cavities are simple mirror arrangements without any transmissive elements and, therefore, ideally suited for handling highest laser powers. Recently, with an enhancement factor of 2000, 10 ps pulses were enhanced to 670 kW of intracavity average power.[31] So far, these systems are mainly used for the generation of short-wavelength radiation *via* intracavity high-harmonic generation[31–34] or inverse Compton scattering.[35]

The SnD concept employs an enhancement cavity for coherent pulse stacking. The main difference, however, is that the pulses are coupled out of the cavity after a certain number of round-trips before the steady state is reached. Potential intensity-related limitations are mitigated due to the long pulse durations of the stretched CPA pulses, which, in principle, should allow for much higher pulse energies in a loaded cavity than fs- or ps-pulses did in the past.[30] A schematic drawing of the basic concept is depicted in Figure 1a. For their temporal stacking, the pulses are coupled into a cavity with a length corresponding to the repetition rate f_{rep} of the incident pulse train, which is typically on the order of 10 MHz. Initially, there is no field inside of the cavity and, therefore, only a small fraction of the first pulse (given by the transmittivity T of the input-coupling mirror) is coupled in. When the cavity roundtrip time is matched to the repetition rate of the incident pulses, coherent build-up inside the cavity is ensured. In this way, the pulse energy stored in the cavity increases with every round trip. Steady-state is reached when the energy coupled to the cavity balances exactly the roundtrip losses L. Typically, a power enhancement of a few orders of magnitude can be achieved.[30,36] However, before this state is reached, in the SnD concept the intracavity pulse is coupled out *via* a switch faster than $1/f_{\mathrm{rep}}$ and at a switching rate f_{switch} before the next stacking period begins, i.e., the cavity is operated in a non-steady-state regime.

The main challenge of the proposed approach lies in the dumping of the enhanced pulse. On the one hand, the cavity should be as long as possible in order to provide a sufficiently long time window for the switch. On the other hand, for practical reasons (number of required mirrors, stability, foot-print of the system) the cavity should be as short as possible. A practical tradeoff is a cavity length of 30 m corresponding to a repetition rate of 10 MHz and a required switching time of 100 ns between two successive pulses. Such a length can, if folded, still be operated on one optical table and these values are assumed in the following calculations. In order to achieve an output repetition rate of e.g., $f_{\mathrm{switch}}=15$ kHz, $N=666$ pulses have to be stacked within one stacking period according to $f_{\mathrm{switch}}=f_{\mathrm{rep}}/N$.

For a sufficiently high overall wall-plug efficiency of the proposed system, a high stacking efficiency g_{cav} is crucial. This parameter is defined as the circulating energy of the enhanced pulse divided by the sum of the energy of the input pulses over one complete stacking period. The output pulse energy E_{out} of a non-steady-state enhancement cavity is given by

$$E_{\mathrm{out}} \sim E_{\mathrm{in}} N g_{\mathrm{cav}} g_{\mathrm{switch}} \tag{1}$$

where N denotes the number of input pulses with energy E_{in} over one stacking period and g_{switch} is the output-coupling efficiency of the switch. The stacking efficiency of the cavity g_{cav} is determined by the round-trip losses L (this comprises all losses inside the cavity except for the transmission losses at the input-coupler) and the loading losses, i.e., the amount of energy reflected at the input port during the build-up. The stacking efficiency g_{cav} can be further improved by shaping the amplitude of the incident pulse trains, as discussed later. Figure 2 depicts the calculated stacking efficiency g_{cav} as a function of the input-coupler transmittance T for different cavity round-trip losses L. The graphs have been derived assuming perfect phase stabilization, i.e., possible decreases in efficiency due to residual phase fluctuations are neglected. There is a clear optimum for the input coupler transmittance T. For values of T smaller than this optimum value, the loading losses are dominant, while for values of T higher than the optimum, the round-trip losses dominate. Analogously to the steady-state case, the optimum transmittance also increases for higher losses.

It can be seen from Figure 2 that the round-trip losses have to be well below 0.1% in order to stack 666 pulses within the cavity without causing a critical reduction of the wall-plug efficiency due to cavity losses. This strict demand on L could be relaxed by employing a non-uniform input pulse train of increasing amplitude within a stacking period. Two possible pulse-train shapes are depicted in Figure 3a. A stacking period of constant pulse energy (orange curve) and exemplary a slow exponential growth (blue dashed curve) are considered in the following. The efficiency improvement that can be achieved by using a pulse train with growing amplitude (Figure 3b) results from two effects. First, a part of the total input energy is shifted towards the end of the stacking period where the effective input-coupling efficiency of each pulse (defined by the intracavity field and T) is higher. Since this energy shift decreases the impact of the loading losses, a higher T value can be chosen compared to the case of constant amplitude, which additionally increases the efficiency. Generally, the efficiency gets better for a stronger growth of the pulse train. However, typically a tradeoff between the stacking efficiency and the restrictions from the input-signal amplifiers has to be found.

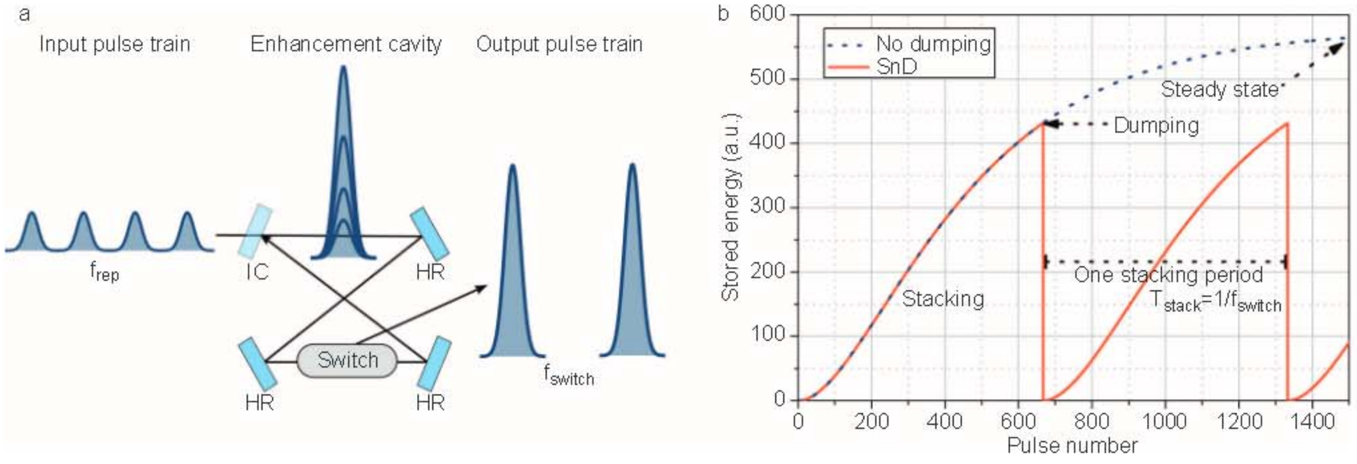

Figure 1 (**a**) Basic principle of a stack-and-dump enhancement cavity consisting of one input coupling mirror (IC) and three high reflective mirrors (HRs). The pulses are continuously coupled to the cavity with a repetition rate f_{rep} leading to a high-energy intracavity pulse. After a certain number of incident pulses, the intracavity pulse is coupled out *via* a fast switch operating at a rate f_{switch}. (**b**) In this schematic, the stored energy within the cavity in dependence on the incoming pulse number is depicted for the steady-state operation as well as for the SnD case. One stacking period is defined as $T_{\mathrm{stack}}=1/f_{\mathrm{switch}}$. SnD, stack-and-dump.