

Advanced numerical simulation of high energy thin plate post-compression in 3+1D

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Abstract: Energy scaling of the thin-plate post-compression technique was investigated with pulse energies up to 10 J by utilizing a novel 3+1D numerical simulation environment, with special focus on the few-to-single-cycle temporal regime and spatio-temporal couplings. © 2022 The Author(s)

1. Introduction

High intensity laser systems are able to generate ultrashort pulses with limited spectral bandwidth, hence the pulse duration is usually falling into the range of 15 to 30 fs [1]. In many applications few-to-single cycle pulses are desired [2,3], for which post-compression arrangements are heavily under investigation for both high energy and high average power laser systems [4]. The most promising method for pulse energies higher than tens of mJ, especially in the few-to-single-cycle temporal regime seems to be the multiple thin plate method [5], which operates with low-cost nonlinear media, and high optical efficiency. Nonlinear media in this scheme are dielectric thin plates with a typical thickness in the range of few hundred micrometers. The key of this concept is that the pulse leaves the solid medium before non-desirable effects occur, such as beam break up or filamentation. This method has been successfully utilized to achieve close to single-cycle pulses in the sub-mJ to mJ domain [6]. For these experiments the input pulse was provided by Yb- and Ti:Sa-based laser system, while the input pulse duration was between 200 fs and 25 fs, correspondingly. Extending this technique beyond the tens of mJ energy regime is posing significant challenges for every element of the setup, e.g. spherical mirrors, chirped mirrors, and generally the size of the required vacuum apparatus.

To fully understand the key physical processes in high energy thin plate post-compression setups, advanced numerical simulations are required. Development of 3+1D and 1+1D simulations have been done for multipass cells, which were able to accurately predict the beam profile and spectral broadening of Yb-based lasers [7,8]. Long propagation of large aperture beams with a non-Gaussian mode are challenging to simulate together with the nonlinear interaction in the solid media, for which further developments were necessary to avoid the need for horribly large computational power and time.

2. Simulation environment

Our model is based on the Unidirectional Pulse Propagation Equation (UPPE), which generally does not have analytical solution, except for linear pulse propagation. This motivated the use of the split-step Fourier method [9], which splits each step of the numerical solution of the differential equation to linear and the nonlinear part. The prior describes the dispersion and diffraction through the analytical solution in the Fourier-domain, while the latter contains the self-phase modulation, self-steepening and the self-focusing and given in the spatio-temporal domain. The main challenges for this approach is large changes in the beam size in linear propagation. Our solution to this problem is the advanced Fourier-transformation [9], which factorizes out the second derivate of the phase in one or more direction, which we chosen to be the two transverse one.

3. Results

The spectral broadening and the spatio-spectral couplings of the output pulses highly depend on the initial spectral shape and spatial intensity distribution. Consequently, in order to get realistic results, we used the output properties of the amplifier stages of the HF-PW laser of ELI-ALPS [10], which is under installation at the moment, as input for the simulations. The pulses after the individual amplifier stages were set to have energies of 70 mJ, 350 mJ, 2.1 J, and 10.5 J, where these values are taking the compressor efficiency of 70% into account. Spectral intensity distributions of the input pulses for each amplifier case are visualized in Fig 1. We assumed that the spectral phase is well compensated for each amplifier case. In our simulated optical arrangement a 500 μm thick fused silica plate was utilized, while the output beam profile of the amplifiers was imaged onto the thin plate with the appropriate beam size

to obtain the necessary peak intensity for efficient nonlinear phase accumulation. Peak intensity was investigated in the range of 2.5 to 7.5 TW/cm², above which ionization inside the plate becomes non-negligible.

For each beamline, the spectral broadening for three different peak intensities and the Fourier transformation limited (FTL) pulse duration distribution across the transverse plane at the output of the thin plate is shown in the most intense case is shown in Fig. 1. Although the spectral bandwidth of the different cases is similar due to their initial bandwidth, their spectral shape differs significantly, which is attributed to the well-controlled amplification in the laser system. For the highest energy case, the 1/e² beam size ranges from 70 mm to 120 mm while the intensity is between 7.5 TW/cm² and 2.5 TW/cm². Increasing the pulse energy translates to rapid growth in the size of the required optics for post-compression.

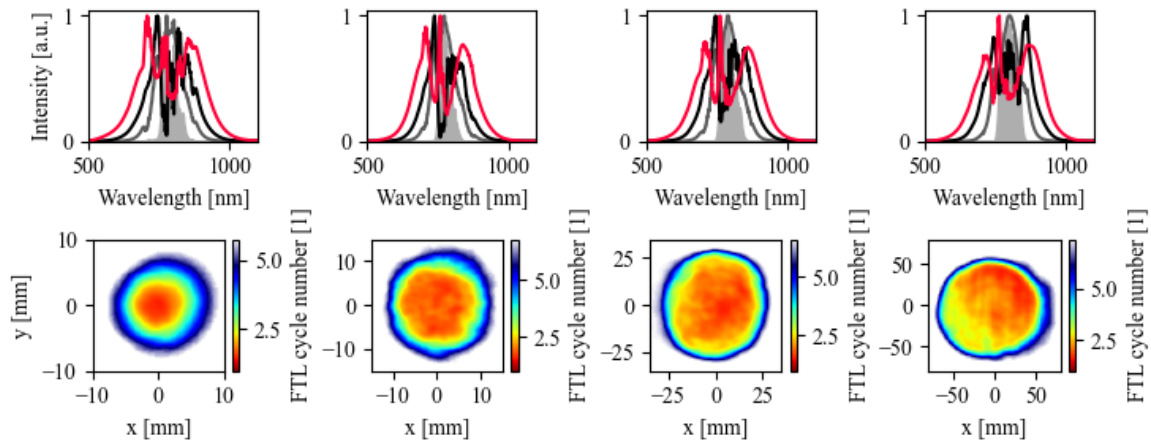


Fig. 1. The spectral broadening (first row), where the initial spectrum is the filled in light grey, the dark grey, black and red correspond to 2.5, 5 and 7.5 TW/cm² peak intensity, and the FTL pulse duration distribution in the transverse plane for the highest peak intensity (second row). The different columns corresponding to the different amplifier stages. From the left to the right, the pulse energy increases from 70 mJ through 350 mJ, and 2.1 J to 10.5 J.

4. Discussion

High energy pulses from saturated amplification stages with more and more homogeneous near field output profiles provide a good opportunity to get spatially homogeneous broadened spectra from thin plate arrangements, when combined with an imaging optical setup. By starting from sub-20 fs long laser pulses the spectrally broadened output can reach sub-2-cycle duration (<5 fs) after dispersion compensation. The limiting components in these arrangements can be the thin plates with clear apertures as high as 25-30 cm, and the chirped mirrors with even larger sizes, which are currently available typically with 10 cm diameter with the required 500-1050 nm bandwidth. Currently, the available chirped mirrors provide enough clear aperture to compress pulses with an energy of 1 J.

5. References

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