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NUMERICAL ANALYSIS OF SPATIO-TEMPORAL DISTORTIONS IN A CHIRPED PULSE AMPLIFICATION LASER-SOLID TARGET INTERACTION SYSTEM

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In the present work, we numerically investigate the spatio-temporal distortions effect in a chirped pulse amplification (CPA) laser – solid target interaction configuration in user-induced misalignments conditions. This study is based on a ray-tracing model from Optica module of MATHEMATICA software and it relates the spatial and temporal behavior of the aberrated beam at the interaction with a cone target in case of grating incident angle variation in the optical compressor. The numerical results show that uncompensated spatio-temporal distortions generate temporal resolution alteration, intensity reduction or beam pointing fluctuations at the output of the CPA system. This approach is relevant for ultra-intense laser - matter interaction experiments in petawatt regime offering an effective solution to improve the quality of the output laser beam profile.

Keywords: chirped pulse amplification, spatio-temporal distortions, CPA laser – solid target interaction, beam pointing

1. Introduction

One of the most important goals in the field of high power laser matter interaction is to reach intensities of the order of 10^{23} W/cm^2 and above which may bring various benefits for many applications from particle acceleration to head-on collision of the laser and relativistic electron beam, gamma radiation generation or even isotope production for medical use [1-3]. Lots of studies have been developed in order to investigate the optimum conditions to generate such high intensities. Recent works show that the interaction of a petawatt (PW) laser pulse with a flat-top micro-cone target results in a collimated beam of very energetic protons [4-5]. The study of interaction between laser fascicle and solid materials are important in practical applications like 3D printing [6-7]. In the field of high power lasers, in the last decade, Chirped Pulse Amplification method proved to be an essential tool for generating ultra-fast and ultra-intense laser pulses being successfully incorporated in a multitude of laser systems devices with a wide range of applications in science (plasma physics, atomic and condensed-matter

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studies, nuclear and high-energy density physics, general relativity and cosmology, laser fusion, astrophysics, studies of ultrafast phenomena, high-order harmonic emission, zettawatts generation), technology (isotope separation, microelectronics controllers, high-precision machining, terahertz imaging devices) and medicine (high resolution imaging in microscopy and ophthalmology, fabrication of micro-fluidic devices, ultra-precision surgery) [8-15].

In parallel with the CPA method implementation, complementary studies had been performed in the field of spatio-temporal distortions in order to provide a better control on the stretching and recompression of ultra-short pulses. These two processes are responsible with the introduction and the removal at ultra-fast scale of massive spatio-temporal aberrations which generate the group velocity dispersion and produce the stretching of the pulse to be amplified [16]. The most common spatio-temporal distortions introduced by CPA technique are the spatial chirp and the angular dispersion which are geometrical properties introduced by dispersive elements such prisms and gratings. The spatial chirp remains even after the second prism or grating while the angular dispersion, explained by pulse front tilt, is usually reduced to zero. The spatial chirp is removed by another inverted pair of prisms or gratings in accordance with the geometrical limitations imposed by the alignment conditions [17]. Taking into consideration the recent elaborated studies in terms of CPA optical distortions [18-24] and ultra-intense laser - mater interaction [25-26], in the present work, we investigate the spatio-temporal distortions effects on a high power laser - solid target interaction configuration in order to determine a versatile solution to optimize the necessary output CPA beam parameters to reach the high fields required for the planned experiments at laser facilities in petawatt regime. For this, we developed a complex spatio-temporal distortions study on the Gaussian beam after the propagation through the CPA system by using Optica software, a ray-tracing package of MATHEMATICA software, in order to optimize the laser beam used for interactions with cone targets. Cone targets may generate the enhancement of the maximum energy of laser-accelerated protons by using a smaller angle cone depending on the laser f-number [27]. Taking into account the actual inconveniences induced by the beam pointing fluctuations [28] which occur during the high-power CPA laser experiments, the study has been completed by investigating the intensity profile in the vicinity of the laser - target interaction point under the current geometrical limits of the petawatt laser systems.

2. CPA laser-cone target interaction system

In the frame of ultra-intense laser systems based on CPA technique, current studies show that the common improper alignments and the broadband characteristics cause a wide range of inconveniences such as temporal resolution alteration or intensity reduction [29]. To deepen the insight of the output CPA laser beam intensity evolution, in this work we elaborated a complex study related to spatio-temporal distortions effect in a preconfigured CPA laser - solid target interaction system. The CPA laser chain has been designed using ray-tracing model from OPTICA module of MATHEMATICA software to extract the wavelength - dependent phase for each ray. Initially, both optical stretcher (Offner-type) and single-pass compressor were projected to present no optical distortions of the output Gaussian beam. For this, optimum geometrical parameters have been calculated with high accuracy to design a CPA chain with zero dispersion. In order to point out the importance of the diffraction grating alignment in CPA laser systems, first, we made a study for several distinct incident angle (α) on the first diffraction grating of the optical compressor, monitoring the effect of the spatial chirp on the output pulse duration, analyzing both spatial and temporal aspects.

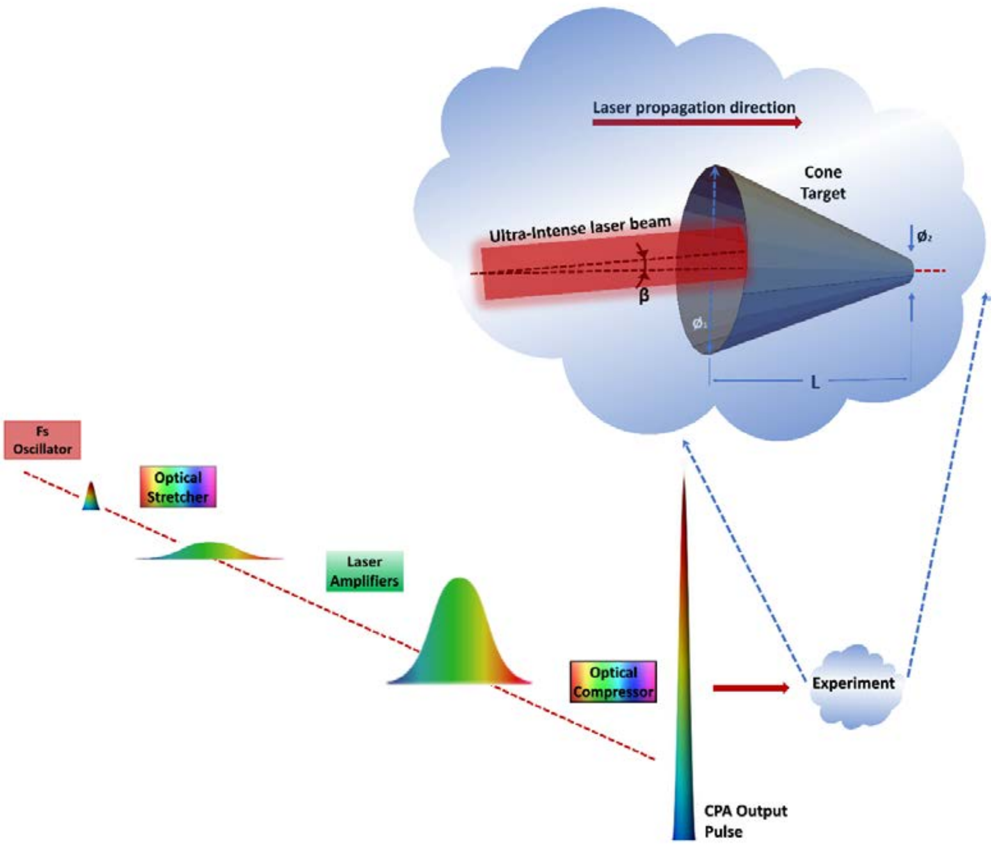

Fig. 1. Schematic representation of a chirped pulse amplification laser beam interaction with a cone target

According to the actual needs in high power laser field, the present study has been extended in the vicinity of the CPA laser – cone target interaction point, investigating the laser beam intensity evolution taking into account the beam pointing fluctuations which currently occur at the output of the petawatt laser systems. The intensity of the output CPA beams is of utmost importance for investigating the new perspectives offered by CPA laser – solid matter interaction approaches; it is an essential experimental parameter that needs to be characterized. In our study, the intensity patterns in the interaction point are also generated using MATHEMATICA software according to the optical path from the CPA laser chain. The numerical model has calculated the intensity value for each beam pointing shift induced by different incident angle values of the output laser beam, respecting the geometrical parameters of the actual petawatt laser systems.

This approach implies a collimated Gaussian beam which has the diameter of 80 μm, central wavelength λ of 800 nm and pulse duration τ of 50 fs. The cone target, positioned on the output of the CPA laser system (Fig. 1), has the base diameter ϕ_1 of 150 μm, the height L of 200 μm and the tip diameter ϕ_2 of 25 μm. The laser beam interacts the cone target under an angle β, which varies in the range of 0.1 - 1°, with 0.1° step. The beam pointing stability analysis has the aim to point out the influence of the spot displacement on the laser intensity profile measured in the laser – cone target interaction point.

3. Results and discussions

3.1. Spatio-temporal distortions study of the output CPA beam in case of the first grating incident angle variation in the single-pass compressor

The spatio-temporal distortions study is based on the wavelength-dependent phase for each beam which is extracted using ray-tracing model previously described. First, we collect the information related to the spatial chirp and pulse duration of the CPA Gaussian beam at the output of the numerically modelled stretcher-compressor system. The Offner-type stretcher has been designed to present no optical distortions at the input of the optical single-pass compressor. The aim of the study is to point out the role played by the beam incident angle on the diffraction gratings and how does it influence the pulse duration at the output of actual CPA configuration. Considering the optimum incident angle value of 21° on both diffraction gratings of the compressor, we investigated the spatial chirp effect by varying the incident angle value α on the first diffraction grating around the ideal value in the range of 14-32 ° (Fig. 2).

Fig. 2. Optica ray-tracing design of the single-pass compressor

For each value of α, a different setup geometry has been computed by using the numerical ray-tracing numerical model which automatically calculates the position of each optical component according to the ray-path and the normal incidence of the laser beam. Also, in each case the central wavelength remains centered on each optical component. The α variation introduces different optical paths at different wavelengths in the lasing range, producing group velocity dispersion which is responsible with the delay between the bluer part of the spectrum and the redder one. The spatial chirp is produced by the spatial variation of the average wavelength of the laser pulse across the beam, being explained in terms of central frequency (ωL). In our case, the spectral modulation introduced by the α variation results in a difference between the blue part and the red part of the pulse of 0.025 laser central frequency units and a gradual displacement between the spectral components of the rays around the ideal case of α equal to 21° related to the end position of each ray (a/λ) (Fig. 3). Δ

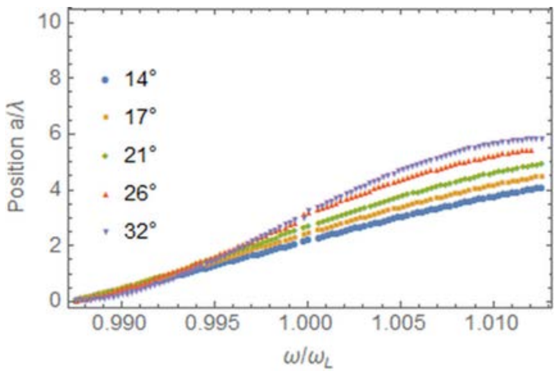

Fig. 3. The spatial chirp after the optical compressor in case of first grating incident angle variation in the range of 14-32°

The slightly misalignments in the optical compressor caused by the incident angle variation on the first diffraction grating introduce differences between the optical paths length of the spectral components (Δx) after the CPA system. Here, Δx parameter has been calculated as a difference between the average optical path length of the rays corresponding to the ideal case of α equal to 21° and the average optical path length of the rays corresponding to the other incident angle values. The obtained results denote a significant influence of α parameter variation on the length of the rays optical path (Fig. 4). The highest value of Δx is equal to 0.04 mm and it corresponds to the α value equal to 14°. Also, it was observed that Δx parameter doesn't exhibit a symmetrical increase for grating incident angle variation around the ideal case. These aspects underline the importance of the alignment accuracy in the optical CPA chains.

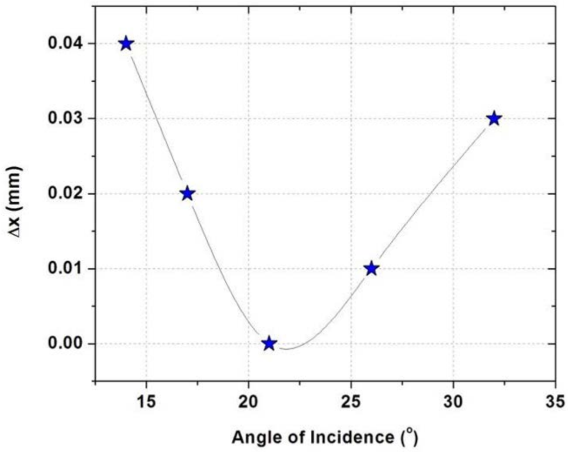

Fig. 4. Calculated values of optical path length of the spectral components in the presence of the first grating incident angle variation in the single-pass compressor

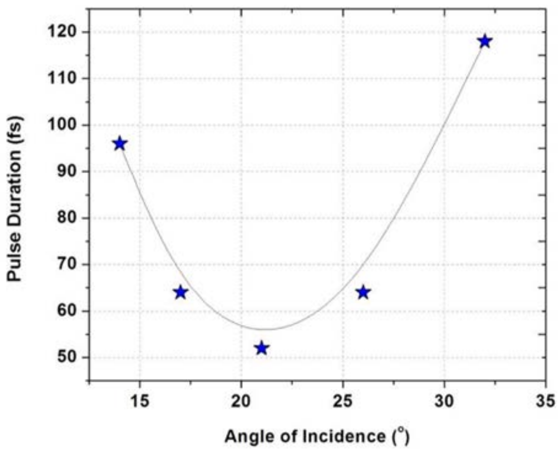

Fig. 5. Pulse duration after the optical single-pass compressor in case of first grating incident angle variation in the range of 14-32°

Moreover, the variation of α parameter influences the CPA pulse duration. In order to investigate the temporal aspects of the laser beam at the output of the optical compressor, the previously obtained ray-tracing numerical results are Fourier analyzed in Mathematica to generate the temporal intensity profile of the pulse. The algorithm uses 2^{13} samples points with 4 fs temporal resolution. According to the numerical results illustrated in figure 5, the pulse duration is significantly sensitive to the grating incident angle variation, obtaining a considerable increase of the pulse duration for each grating incident angle deviation around the ideal value of 21°. It can be observed that the pulse duration registered for α equal to 32 is higher with a factor larger than two comparing to the ideal value of α. This effect can be used to improve the accuracy of diffraction gratings alignments in CPA systems with this geometry by simply monitoring the spatio-temporal aspects of the laser beam at the output of the optical single-pass compressor. Also, it can be used for a particular type of experiments which require to fine tune the pulse duration of the laser beam at the output of the CPA chain.

3.2. Analysis of the CPA beam incident angle variation on the cone-target

Further, we performed a complementary study of the CPA laser intensity and pulse duration evolution in a laser – cone target interaction configuration in the presence of beam incident angle variation (β) in the range of 0.1 – 1° with 0.1° step. These values correspond to a lateral displacement of the beam spot related to the cone target center in the range of 5-50 µm. The ray-tracing numerical model has calculated the intensity value and the pulse duration for each beam pointing shift induced by different incident angle values of the CPA output laser beam. The effect of the beam spot displacement in the laser – cone target interaction point is depicted in figure 6. As it can be seen, the CPA laser intensity is almost linearly decreasing with increasing the spot displacement in the range previously specified. For 50 µm spot displacement, the beam intensity decreased with a factor larger than two and the pulse duration registers a slight increasement of 5 fs. These results may be useful to identify, control and mitigate the current inconveniences which occur during the CPA laser experiments in terms of beam pointing fluctuations which are usually generated by specific CPA internal processes. This study can be extended for tightly focused CPA laser beams - solid target interaction configurations. When a fs laser pulse is tightly focused in lambda cubed regime, the properties of the focused spot diverge out from diffraction limits. The changes in the behavior of a tightly focused beam in petawatt regime in terms of peak intensity deviation will be reported in a future work taking into account the effects of spatio-temporal aberrations in a similar geometrical configuration.

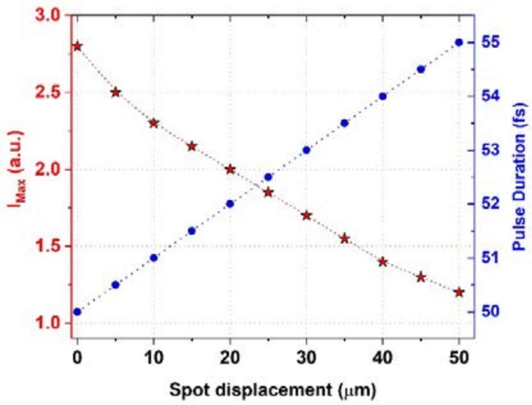

Fig. 6. The evolution of the CPA laser intensity and pulse duration after the single-pass compressor in case of beam incident angle variation in the range of 0.1 – 1° with 0.1° step

It was shown that the pulse duration and the laser intensity parameters are extremely sensitive on user-induced or spontaneously misalignments in the optical CPA chains. This approach can be widely used as an alternative method to optimize the output CPA laser beam parameters for laser – matter interaction experiments in ultra-intense regimes.

4. Conclusions

In conclusion, a ray-tracing numerical model has been elaborated to investigate the spatio-temporal distortions effect on the output beam of a CPA laser system at the interaction with a solid target in the presence of user-induced misalignments in the optical compressor. The numerical results show that uncompensated spatio-temporal distortions generate temporal resolution alteration and intensity reduction at the output of the CPA system, pointing out the importance of establishing the optimum values of the grating incident angle with minimum spatio-temporal distortions. This effect can be used to fine tune the output CPA beam pulse duration or to control or mitigate the current beam pointing fluctuations caused by specific internal processes during the CPA laser experiments.

The present approach relates that CPA laser – solid target interaction systems alignments present certain limitations and it can be used as an alternative method to improve the quality of the CPA beam profile for various laser – matter interaction experiments in petawatt regime.

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