Investigation of the thermally induced laser beam distortion associated with vacuum compressor gratings in high energy and high average power femtosecond laser systems

S. Fourmaux*, C. Serbanescu, L. Lecherbourg, S. Payeur, F. Martin, and J. C. Kieffer
INRS-EMT, Université du Québec, 1650 Lionel Boulet, Varennes J3X 1S2, Québec, Canada

Abstract

We report successful compensation of the thermally induced laser beam distortion associated with high energy 110 mJ and high average power femtosecond laser system of 11 Watts operated with vacuum compressor gratings. To enhance laser-based light source brightness requires development of laser systems with higher energy and higher average power. Managing the high thermal loading on vacuum optical components is a key issue in the implementation of this approach. To our knowledge this is the first time that such thermal induced distortions on the vacuum compressor gratings are characterized and compensated.

1. Introduction

High energy, femtosecond laser pulses can attain high intensities when focused on target to produce secondary light sources covering a wide energy range from THz radiation up to hard x-rays. These laser-based light sources, like large scale synchrotron facilities, open the way for new experimental investigation techniques with applications in various fields including material science, physics, chemistry and medical research. Laser-based light sources allow easy access, table-top experimental set-ups and low cost facilities.

Light source brightness is an important factor for many measurements techniques such as phase contrast imaging. 2D imaging has been demonstrated with laser-produced plasma Kα X-ray source [1]. The next development would be to achieve x-ray micro-Computed Tomography (μ-CT) to study the evolution of cancer models inserted into small living animals such as mice. This is presently out of reach using available laser-produced plasma x-ray sources since tomography imaging has to be performed in less than one hour to keep the mouse under anaesthesia. Laser produced plasma x-ray sources can also be used for x-ray absorption measurements. This has been demonstrated by several groups [2 and references therein] but, up to now, due to the limited brightness available the application range has been limited to simple samples and direct transmission measurements. Such new measurement procedures, illustrated by these types of application, require a large number of data samples. Hence, in order to limit the data acquisition time, they require relatively high repetition rate laser systems.

Thus, implementation of such measurement procedures with laboratory scale facilities requires high average brightness laser systems. One means to attain this objective is to enhance the average brightness of laser-based light sources by using laser systems with higher energies and repetition rate reaching an average power well in excess of 10 W. Since high intensity laser systems generally require a vacuum compressor to produce the short femtosecond pulse,

*Corresponding author: fourmaux@emt.inrs.ca.
managing the high thermal loading on vacuum optical components is a key issue in the implementation of this approach.

Ti:Sapphire laser technology has demonstrated 100 TW scale laser systems with laser pulse energy of several Joules with repetition rates up to 10 Hz corresponding to an average power over 10 Watts [3–5]. However, up to now, these laser systems have been mainly operated in single shot mode. The hydrocarbon pollution observed on critical optical components prevents these laser systems from being operated at their maximum repetition rate for long periods [6, 7]. As a result, there have been no reports of sustained operation of 100 TW scale laser system at high repetition rates except for filamentation applications where compression is achieved in air [8].

High average powers laser systems can be achieved by increasing the pulse energy and/or repetition rate. Higher repetition rate laser systems (up to 10 kHz) have been demonstrated with a maximum average power of 40 Watts, but the studies have been limited to the laser system characterization itself and no application implementation has been presented [9,10]. Several kHz repetition rate laser systems were reported for laser-produced Kα x-ray generation [11–14]. Among them, a maximum of 12 mJ per pulse and 12 W average power was demonstrated for time resolved x-ray protein crystallography [15], but vacuum compression was not required because of the limited energy per pulse before compression (18 mJ).

To develop the next generation of laser based source with high average brightness, it has recently been proposed to build a laser for biomedical imaging with 100 TW of instantaneous power, 100 Hz repetition rate and 400 W of average power [16]. It is crucial for the development of this new generation of laser-based light sources to investigate the technical issues involved in operating such high energy and high power laser systems. In this respect, it is of prime importance to ensure that its optical elements will not degrade the energy profile and the quality of the beam wavefront which can affect directly the quality of the laser spot. Here we report the first characterisation of the focussing stability of a high energy 110 mJ (before compression) high repetition rate 100 Hz laser system corresponding to an average power of 11 Watts with pulse compression under vacuum. We believe that this is an important benchmark toward high average power laser system. The construction of such a laser system was motivated by the need of a stable and high average brightness laser based x-ray source that is usable for x-ray imaging studies. In this paper, we report that the thermal load on the compressor gratings produces distortion of the laser beam wavefront drastically decreasing the x-ray yield. We propose a simple way to compensate for this distortion so as to achieve a constant average x-ray flux over long periods of time.

2. Experimental set-up

The measurements presented here have been performed at the Advanced Laser Light Source (ALLS) Canadian facility. The ALLS 100 Hz laser system is a commercial prototype (Thalès Laser) and has already been described elsewhere in a study on the development of time resolved x-ray absorption spectroscopy [2]. This laser is based on Ti:Sapphire amplification crystals and the chirp pulse amplification (CPA) technique. It produces laser pulses at 800 nm at a 100 Hz repetition rate, 35 fs pulse duration and a maximum 80 mJ after pulse compression. The incident average power on the compressor gratings reaches 11 Watts.

The thermal load in the last amplification stage is managed by a cryogenic unit that cools the Ti:Sapphire crystal down to −110°C to minimize changes in the beam divergence due to thermal lensing. After this last amplification stage, the output laser energy can conveniently be adjusted on a 1–100% scale with no deterioration of the beam quality by the use of a λ/2 waveplate followed by two Thin Film Polarizers.
Figure 1 shows the experimental set up located inside two vacuum vessels: the compressor chamber and the target chamber. The laser pulse contrast ratio at the fundamental frequency is $10^6$ both in the picosecond and the nanosecond time range measured respectively by a third order autocorrelator and a fast photodiode. For maximum resolution, X-ray imaging applications require a small source size, of the order of the laser focal spot. This can only be attained with a high contrast laser pulse [17] produced by frequency doubling after compression with a KDP crystal. The measured conversion efficiency of KDP is 20% which reduces the average power on target to 1.5 Watts. We estimate the laser pulse contrast at 400 nm to be around $10^{10}$.

The 400 nm beam is focused to a 8 $\mu$m (FWHM) diameter spot using an f/3 off axis parabola, achieving an intensity of $5\times10^{17}$ W/cm$^2$ on target. A permanent imaging system consisting of a lens (f=10 cm) and a CCD camera with a 10× microscope objective is used to monitor the beam focal spot at the target position with a magnification of 45 time. The target holder can conveniently be translated under vacuum to properly position the target during the experiment or to allow the beam to propagate through the imaging system. A protective fused silica thin plate is used in front of the off axis parabola focusing optic to avoid any coating from the ablation debris produced during the laser plasma interaction. This plate is changed after 5 h of continuous operation. The x-ray radiation is monitored using two identical scintillator-photomultiplier (PMT) detectors filtered by a beryllium (Be) window, symmetrically positioned outside of the vacuum chamber at a distance of 62 cm away from the plasma source.

Each vacuum vessel is operated at low pressure ($<10^{-6}$ Torr). Careful attention is taken to install only clean, grease free, opto-mechanical components. As a result, no significant hydrocarbon pollution is observed on the optical surfaces located in the compression chamber. As opposed to the compressor vacuum vessel, the target chamber is vented regularly and hydrocarbon pollution is gradually generated. Thus, the optics in the target chamber must be renewed once per year.

3. Results and discussion

The laser beam is injected into the vacuum compressor by a mechanical shutter located just before the entrance of the compressor chamber. The temporal evolution of the laser focal spot when working under vacuum at maximum laser energy is shown in Fig. 2. We observe a focal spot distortion after 10 sec at laser repetition rate of 100 Hz. The beam distortion evolves in the first 90 seconds, after which the focal spot shape of the distorted beam remains unchanged.

This effect is observed while the two vacuum vessels are under vacuum which impedes heat dissipation of energy absorbed by the optical components. When the windowed gate-valve (WGV, Fig. 1) is closed and the target chamber is kept at air, we observe an identical distortion of the focal spot which indicates that the beam distortion occurs in the compressor chamber.

A leak at the fundamental frequency from one of the mirrors in the compressor chamber is propagated through a 40 cm focal length biconvex lens. The resultant focal spot is observed by means of an imaging system similar to the one used to image the laser focal spot at the center of the target chamber (Fig. 1). A beam distortion similar to the one show in Fig. 2 is observed. This excludes the KDP doubling crystal as a possible source for the beam distortion.

The only remaining optics in the compressor vacuum chamber are the compressor gratings and the high reflectivity dielectric mirrors. Because no deposited overlayer is observed on the latter, we conclude that thermal loading on the gratings produces the focal spot distortion. These ones are gold holographic gratings (Spectrogon, 43° incidence angle, 1500 grooves/mm). The gold layer is located on top of a layer of resin, deposited on a glass substrate. The exact thickness of each layer and the resin composition is not specified by the manufacturer.
To determine the nature of this thermal distortion, we have characterized the wavefront of the beam from the compressor leak at the fundamental frequency. A reducing lens is used to transpose the laser beam to a Shack-Hartmann wave-front sensor. The fine alignment of this measurement system was previously tested using the beam produced by an optical fiber coupled at the exit of a 675 nm laser diode and collimated with a 75 cm large lens. This procedure produces a plane wavefront which is used as a reference. Figure 3 shows the wavefront phase map measured at the compressor leak output, without thermal effect for laser pulses with energy of less than 1 mJ (Fig. 3-a) and with thermal effect for the maximum energy of 110 mJ (Fig. 3-b).

The first observation is that the original phase map at low energy is close to a flat phase. The RMS value is 0.061 corresponding to a Strehl ratio of 0.86. At maximal energy, the RMS value is 0.082 for a Strehl ratio of 0.77. The main aberration measured in this case is defocusing. From 1% up to 100% energy (changed as explained in the 2nd paragraph of section 2), the Zernike polynomial coefficient corresponding to defocusing evolves gradually from $-0.094$ up to $+0.116$, while all the others Zernike polynomial coefficients increase as well but remain below $\lambda/10$.

Since the phase distortion is mainly defocusing, in principle it is possible to compensate for the thermal loading by moving the off-axis parabola inside the interaction chamber along the focal axis; made possible by a motorized 3-axis translation system. The laser beam is maintained under operation for more than 100 s to stabilize the beam distortion, after which the defocusing is corrected by adjusting the off axis parabola position. The corrected beam is displayed in Fig. 4-a. After compensation, monitoring the laser focal spot shape for more than 60 minutes showed no additional change.

We have measured the position of best focus as a function of the laser energy at the compressor entrance. We observed a gradual displacement of the position of best focus in the direction of the laser propagation vector for increasing laser energy. This focal spot displacement is equivalent to the addition of a divergent lens at the location of the compressor gratings. A defocusing of 60 $\mu$m is already observable at an average power of 1 Watt at the compressor entrance. The defocusing is 500 microns at maximum energy. We report on Fig. 4-b the best focus displacement as a function of the density of average power $P_{av} = (4 \times E \times RR) / (\pi \times d_{hor} \times d_{vert})$, where E is the incident energy on the grating, RR is the repetition rate, $d_{hor}$ and $d_{vert}$ are respectively the horizontal and the vertical diameter of the laser pulse near field ($d_{hor} \times d_{vert} = 17.2 \times 16.6 \text{ mm}^2$ FWHM, Fig. 4-c). Note that we took into consideration the angle of incidence of the laser beam on the grating for the calculation. The equivalent focal length of the thermally induced divergence at the position of the gratings is estimated to be 57 m. From this result, assuming a spherical distortion on only one grating surface, the maximum distortion of the phase front is estimated to be close to 1 $\mu$m. This distortion results in a change of the gratings spacing that is negligible to affect the laser pulse duration. This is confirmed by a second order autocorrelator measurement at 800 nm (after the leak) which show that the pulse duration remain identical.

To demonstrate that we compensate this thermal distortion, we monitored the x-ray emission produced by focusing the laser beam onto a Mo solid target. At best focus without correction for thermal distortions, we observe a massive decrease of the x-ray flux occurring in 30 s. After 1 minute the PMT signal has decreased by 80%. However, after translating the off-axis parabola to compensate for thermal distortions at maximum power, we observe the X-ray emission to be stable for more than 60 minutes.
4. Conclusion

We reported the first characterization of the focussing stability of a high energy 110 mJ high repetition rate 100 Hz laser system corresponding to an average power of 11 Watts with pulse compression under vacuum. In this paper, we demonstrated that the thermal load on the compressor gratings produces distortion of the laser beam wavefront, which in turn drastically decrease the x-ray yield. We proposed a simple way to compensate for this distortion as to achieve a constant average x-ray flux over long periods of time.

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References and links

1. Toth R, Kieffer JC, Fourmaux S, Ozaki T, Krol A. In-line phase-contrast imaging with a laser-based hard x-ray source. Rev Sci Instrum 2005;76:083701.
2. Fourmaux S, Lecherbourg L, Harmand M, Servol M, Kieffer JC. High repetition rate laser produced soft x-ray source for ultrafast x-ray absorption near edge structure measurements. Rev Sci Instrum 2007;78:113104. [PubMed: 18052462]
3. Pittman M, Ferré S, Rousseau JP, Notebaert L, Chambaret JP, Chériaux G. Design and characterization of a near-diffraction-limited femtosecond 100-TW 10-Hz high-intensity laser system. Appl Phys B 2002;74:529.
4. Akahane Y, Ma J, Fukuda Y, Aoyama M, Kiriyama H, Sheldavoka J, Kudryashov A, Yamakawa K. Characterization of wave-front corrected 100 TW, with peak intensities greater than 10^{20} W/cm^2. Rev Sci Instrum 2006;77:023102.
5. Fourmaux S, Payeur S, Alexandrov A, Serbanescu C, Martin F, Ozaki T, Kudryashov A, Kieffer JC. Laser beam wavefront correction for ultra high intensities with 100 TW laser system at the Advanced Laser Light Source. Opt Express 2008;16:11987. [PubMed: 18679471]
6. Martin, F.; Fourmaux, S.; Paynter, R.; Côté, C.; Sarkissian, A. Surface cleaning of Au mirrors using an RF plasma O source. Advanced Laser Light Source Annual Report 2005–2006. 2006. http://lmn.emt.inrs.ca/EN/ALLS.htm
7. Antonetti A, Blasco F, Chambaret JP, Chériaux G, Darpentigny G, Le Blanc C, Rousseau P, Ranc S, Rey G, Salin F. A laser system producing 5x10^{19} W/cm^2 at 10. Appl Phys B 1997;65:197.
8. Châteauneuf M, Payeur S, Dubois J, Kieffer JC. Wave guiding in air by a cylindrical filament array waveguide. Appl Phys Lett 2008;92:091104.
9. Matsushima I, Yashiro H, Tomie T. 10 kHz 40 W Ti:Sapphire regenerative ring. Opt Lett 2006;31:2066. [PubMed: 16770434]
10. Matras G, Huot N, Baubeau E, Audouard E. 10 kHz water-cooled Ti:Sapphire femtosecond laser. Opt Express 2007;15:7528. [PubMed: 19547077]
11. Jiang Y, Lee T, Li W, Ketwaroo G, Rose-Petruck C. High-average-power 2-kHz laser for generation of ultrafast x-ray pulses. Opt Lett 2002;27:963. [PubMed: 18026338]
12. Zhavoronkov N, Grisai Y, Korn G, Elsaesser T. Ultra-short efficient laser-driven hard X-ray source operated at a kHz repetition rate. Appl Phys B 2004;79:663.
13. Reich C, Laperle CM, Li X, Ahr B, Benesch F, Rose-Petruck C. Ultrafast x-ray pulses emitted from a liquid mercury laser target. Opt Lett 2007;32:427. [PubMed: 17356675]
14. Serbanescu CG, Chakera JA, Fedosejevs R. Efficient K_{α} x-ray source from submillijoule femtosecond laser pulses operated at kilohertz repetition rate. Rev Sci Instrum 2007;78:103502. [PubMed: 17979414]
15. Bonvalet A, Darmon A, Lambry JC, Martin J-L, Audebert P. 1 kHz tabletop ultrashort hard x-ray source for time resolved x-ray protein crystallography. Opt Lett 2006;31:2753. [PubMed: 16936881]

16. Kieffer, JC. The 200 TW laser at the Advanced Laser Light Source facility: Progress, first experiments and perspectives of high power femtosecond technology. CAP congress; Université Laval; 2008.

17. Toth R, Fourmaux S, Ozaki T, Servol M, Kieffer JC, Kincaid RE, Krol A. Evaluation of ultrafast laser-based hard x-ray sources for phase-contrast imaging. Phys Plasmas 2007;14:053506.
Fig. 1. Experimental set-up. The laser beam is represented by the red lines at 800 nm and by the turquoise lines at 400 nm. M, high reflectivity mirror; G, compressor gratings; CC, corner cube (beam elevator); DC, KDP doubling crystal. The compressor chamber can be isolated from the target chamber by a windowed gate valve (WGV) that allows the beam to propagate into the interaction chamber even if the latter is at air. OAP, off-axis parabola; TCC, target chamber center. The wavefront measurement system allows measuring the beam wavefront at 800 nm by using a leak at the back of a high reflectivity mirror: W, high transmission window; L1, f=+40 cm, aspheric lens; WFS, wave-front sensor. The imaging system allows to observe the focal spot at TCC with 45 times magnification: L2, biconvex f=+10 cm lens; MO, microscope objective; CCD, far-field monitor CCD.
Fig. 2.
Focal spot measured at the target center chamber position under vacuum for 400 nm, 110 mJ at the compressor entrance and 15 mJ incident at the target position. Each picture on this figure is taken for a different delay following insertion in the experimental setup and indicated below the picture number for a range from 5 up to 130 s.
Fig. 3.
Phase map of the laser beam. The phase map diameter corresponds to the entrance iris of the laser beam which is 21 mm for this measurement. a- Energy below 1 mJ at the compressor chamber entrance (no thermal loading). The RMS wavefront value is 0.061. b- Maximal energy of 110 mJ at the compressor entrance (thermal loading). The measurement is achieved after a delay higher than 100 sec. The RMS wavefront value is 0.081.
Fig. 4.
(a) Beam shape at the target center chamber after moving the off-axis parabola along the focal
axis to compensate for the beam defocusing. This picture is taken with 110 mJ energy at the
compressor entrance and for a delay higher than 100 s. Pictures from this figure and pictures
set from Fig. 1 have been taken during the same set of measurement. (b) Best focus
displacement as function of average power. The red line is a second order polynomial fit. (c)
Laser pulse near field and corresponding cross sections. Gaussian fit is shown in red line.