Recent progress on LULI high power laser facilities

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Abstract. LULI is actively involved in laser developments to continuously upgrade its facilities. We will report on the optimization of the dynamic wavefront control for the LULI2000 facility and on the first phase of the LULI PW project (200J, 1ps). We will also present the ELFIE project, the upgrade of the 100TW system, including an energy enhancement and the development of a short-pulse high-energy OPCPA beam line.

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1. Optimized Dynamic wavefront control for the LULI2000 facility

Laser intensity enhancement on target could not be efficiently achieved without dynamic wavefront control which is particularly important for large-scale, flash-lamp pumped laser facilities. In fact, the imperfection of large optics in the chain, the beam misalignment and especially the thermal effect induced by flash-lamp pumping system in amplifiers degrade the wavefront quality. As a result, the focal spot on target is dramatically deteriorated and laser shot repetition rate is severely limited. In this chapter, after a complete analysis of wavefront deformation of LULI2000 facility, we present our adaptive optics (AO) closed-loop system design and the dynamic wavefront control optimization using the closed-loop and a precise alignment system.

1.1. Wavefront deformation analysis

The LULI2000 facility is a Nd:phosphate system, composed of 2 kJ/ns chains. Each of the chains consists of 4 amplification stages (50 mm rod amplifiers and 94, 150, 208 mm disk amplifiers). More than 100 large optical components are used with conventional transmission or reflection quality. The beam alignment on the LULI2000 chain is performed by means of a precise semi-automatic system. Its accuracy at each intermediate Near Field is about 2 % of beam diameter at different stages. The pointing accuracy is different along the chain, according to pupil conjugations. It is about 3 µrad at the chain output. The total PtV wavefront distortion due to passive aberrations is around 0.5 λ and the total rms is about 10 times smaller.

Defocus and astigmatism are two most important thermal aberrations, induced by a kJ shot. During recovery time, the typical evolution of the wavefront distortion as a function of time shows three distinguished zones: the distortion increases rapidly during about 10 minutes and then decreases during 50 minutes owing to cooling effect. After one hour, the residual wavefront deformation is about 1 λ PtV and varies very slowly.
To study the spatial phase degradation under cumulated thermal effects, we have carried out a sequence of 5 full-energy shots with two different delays between shots. With a 2 hour delay, we measure a PtV wavefront aberration of 1.6 $\lambda$ after the 5th shot. It proves that the laser chain is not completely thermalized if we fire a shot every two hours. By reducing the delay time to 1 hour between shots, cumulated thermal effects are intensified. At the 5th shot, PtV wavefront defaults amount to more than 3 $\lambda$ and the deduced Strehl ratio is less than 0.2. Under cumulated thermal effect, astigmatism 0° and defocus are always two most important aberrations among phase errors.

1.2. AO closed-loop design and wavefront control optimization
We designed and implemented an AO system using a deformable mirror and a wavefront sensor. We set up at the second amplification stage output a 100mm dielectric-coated deformable mirror with 32 actuators. The applied voltage range is $\pm$ 300 V for a dynamic deformation correction of more than 6 $\lambda$. The wavefront sensor SID-4, developed by PHASICS, is located at the chain output, coupled with a far field measurement device in order to qualify wavefront correction by the improvement of the focal spot quality. With correction and measurement planes optically conjugated, a linear response is established between them.

The study in 1.1 enabled us to adopt an optimized procedure for operating our wavefront-control system. (1) We perform a rigorous beam alignment before the first shot. In addition, the AO loop is activated to reduce the total static wavefront error from 0.5 to 0.2 $\lambda$ PtV; (2) In order to minimize the thermo-induced tilt and coma, beam pointing and centering are checked and readjusted systematically with a semi-automatic alignment system before a next shot; (3) The AO system is used before each shot and corrects mainly the aberrations generated by thermal effect.

The residual rms phase distortion has been studied with respect to mode number in the convergence loop. With 24 modes (8 modes filtered), a minimum residual phase distortion is obtained. In addition, in this configuration, the voltage range is low, typically $\pm$ 50 V for a 2 $\lambda$ PtV aberration. Nevertheless the voltages applied to the outer ring actuators get very close to $\pm$300 V, when high order modes are activated. An adequate high order mode filtering allows to operate our AO system with a higher dynamics and especially a very stable convergence result.

1.3. Dynamic wavefront correction results
We carry out dynamic wavefront correction during a “kJ”-shot sequence of one shot every hour. First we measure both phase distortions and focal spots one hour after shots. Then we perform a precise alignment to correct the residual thermal tilt and coma. This alignment allows a very accurate beam centering and pointing on the deformable mirror so that its response-matrix is always available from shot to shot. Finally we start the convergence loop. Figure 1a illustrates the focal spots measured by a 10 Hz probe beam before and after the loop.

With our AO system and its optimized operation mode, significant wavefront improvement has been obtained, such as a focal spot size close to the diffraction limit, a reproducible beam focusability up to 0.7 in terms of Strehl ratio (Figure 1b) and the increasing of the shot repetition rate by a factor of 2.

Fig. 1. a) Focal-spot patterns measured using 10 Hz probe beam before and after the loop during
a 5-shot sequence with a repetition rate of one shot per hour. b) With dynamic wavefront control, encircled energy of the focal-spot pattern measured during a kJ-shot and its deduced Strehl ratio.

2. 200J@1ps: first phase achievement of the LULI PW project

For driving plasma physics experiments in new regime or in extreme conditions, laser performance should be continually improved. Based on the concept of short pulse and high energy, the LULI has built its PW system. This system, combining femtosecond front-ends, large-scale glass chains and a pulse compressor using large size gratings, will be capable of delivering on target laser pulses of 500 fs/500 J. New experimental configurations have been proposed coupling both ns/kJ and sub-ps/PW pulses. In this chapter, we first present the schematic of our PW project and then the results of its first phase.

2.1. Laser architecture

The schematic of the LULI PW beam line is illustrated in Figure 2. The front end laser starts with a diode-pumped Ti:Sa oscillator, operating at 1053 nm. An Offner triplet stretches the pulse from 80 fs to up to 5 ns. The stretched pulses are first amplified to up to 5 mJ in a diode-pumped Nd:phosphate large-mode regenerative amplifier. The further chirped pulse amplification is carried out in the south Nd:glass chain of the LULI2000. The pulse compression is performed in a home-designed compressor using 4 large multi-layer-dielectric gratings. A PW-level compressed pulse should be coupled with a ns/kJ pulse and a 100 J probe beam in the interaction chamber “MILKA”.

2.2. First phase achievement of the LULI PW upgrade

The PW laser facilities request high damage threshold, high efficiency and larger size gratings. The PW upgrade at LULI is to be achieved in 3 stages which will be coupled with grating-evolutions: four dielectric 485x330 mm² gratings are used in the first stage; the manipulation of tiled gratings has been demonstrated at LULI¹ and will be set up during the second stage; in the third stage the beam will be enlarged to 350 mm and the high damage threshold, larger size gratings will be used for the compression of a PW pulse. The objective of the first phase is to validate the femtosecond front-end, to optimize the chirped pulse amplification in a Nd: phosphate chain, to investigate the good functionality of the compressor and the main diagnostics, including: energy measurement, near field and far field spatial profiles, single-shot auto-correlator, spectrometer, and to improve beam quality as well. We have studied the compensation of the strong gain-narrowing and gain saturation, induced by Nd:phosphate in the regenerative amplifier and the main amplification chain by the use
of a birefringent filter in the preamplifier. At the amplification chain output a quasi-gaussian spectrum has been obtained with an energy level of about 400 J and a bandwidth of about 3 nm.

We have succeeded in producing a compressed pulse of 200 J/1 ps in the first step of the LULI PW upgrade. This beam line, coupled with kJ/ns chain, is now operational to the user community for different experiments.

3. ELFIE: upgrade of the LULI 100TW system
The LULI 100TW facility is a Ti:Sa and mixed Nd:glass system which has operated since 1997. Based on CPA technique, this system has proposed versatile configurations to a large number of plasma experiments with a main beam of 30 J/300 fs, coupled with another compressed pulse of 5 J/300 fs-5 ps, a chirped pulse of 50 J/500 ps and a probe beam of 100 mJ/300 fs-ps. High laser operation efficiency has been demonstrated all along these ten years. Laser quality and performance of this system have been continually improved. Thanks to the dynamic wavefront control, we can fire a full energy shot every 20 minutes while keeping excellent beam focusability on target. Recently, the enlargement of beam diameter before compressor allows to increase the compressed energy by a factor of 1.5.

In order to increase laser intensity on target, and to have also multi-beams with higher energy and still larger pulse duration scale, we initiated the project ELFIE which is devoted to the upgrade of the LULI 100TW facility. Figure 3 illustrates the principal stages of the ELFIE from front-end laser to interaction chamber. This project will begin at the middle of 2008 and is articulated in three phases which include:

1) the laser and the interaction chamber re-implementation in a renovated area, based on a new set-up; In this phase, radio-protection is taken into consideration in the new infrastructure.

2) the output energy enhancement; The 100TW facility is a monochain system with 4 amplification stages using Nd: silicate and phosphate amplifiers. It is capable of delivering at the chain output an energy of 100 J. During the second phase, this mono-beam will be separated into two. The second amplification chain will be implemented. Hence, the total output energy will be doubled.

3) the development of a short-pulse high-energy OPCPA beam line. Under a non co-linear OPCPA single-shot configuration, a broad-band, chirped pulse will be amplified to 5-10 J and compressed to 50 fs. The calculation using Miro code has been done for optimizing amplification gain while minimizing spectral narrowing in the case where the pumping beam is not a monochromatic one. We are working also on the generation of the broad-band spectrum in a non-linear fiber.

Fig. 3. Schematic of the ELFIE project.

In this project, the Ti:Sa regenerative preamplifier will be replaced by OPCPA and the temporal contrast should be significantly increased by the use of the technique of cross-polarized wave (XPW).³

References
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