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Invited paper

Importance of spatial quality of intense femtosecond pulses

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Abstract. The spatial quality of intense femtosecond pulses from chirped pulse amplification (CPA) systems is of great importance in order to reach very high peak intensity on the target. We review various aspects of this quality, present results obtained all along a CPA chain and discuss improvement implemented or still to be implemented.

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For many years now the chirped pulse amplification (CPA) technique [1] has produced powerful laser chains [2]. Today, pulses with 100-TW peak power have been reached [3]. During this period, great efforts were concentrated on increasing the pulse energy, decreasing the duration, or temporally cleaning the pulse. Those parameters, at least the pulse energy and duration, are very well controlled and now to fully characterize a laser chain, one needs to take a closer look at the spatial profile, and more precisely at the focusability of intense fs pulses, in order to get the highest peak power achievable. In CPA laser systems, geometrical aberrations and surface quality from optical elements, clipping on mirrors, thermal effects and doping inhomogeneities in TiSa crystals affect the beam focusability. In other words, every effect than can degrade the spatial characteristics, i.e. energy distribution and wave front, will lead to a different propagation pattern and so to a poor focusability. A large part of the energy will be spread out into the wings of the focal spot. This will lead to an increase in focal spot dimensions and so to a decrease in intensity.

The choice of a criterion to correctly quantify the spatial quality will be discussed and results obtained all along a powerful 10-Hz CPA chain will be presented. Solutions were found and improvements were implemented to limit aberrations and keep the best focusability from the oscillator to the experimental chamber. The goal of the control of spatial quality is to correctly focus the laser beam in the experimental chamber. In that case, all the energy exiting from the laser system will be fully used for physics experiments.

1 General considerations

1.1 Importance of spatial quality

Energy and duration are two parameters well controlled in powerful CPA chains. But one has to keep in mind that physicists are sensitive to the amount of energy encircled into the focal spot which is directly linked to the real intensity. A good spatial quality will lead to a very high intensity at focus. In other words, it is better to have a good focusability than very high energy in the beam but a very low intensity due to aberrations. A brief look at the theoretical definition of the intensity shows the importance of spatial quality:

$$I = \frac{E}{\pi r^2 \times \Delta\tau}\,, \tag{1}$$

where E is the energy of the beam, r the radius of the focal spot at $1/\mathrm{e}^2$ of the maximum intensity and $\Delta\tau$ the pulse duration. The focused intensity has a quadratic dependence with the radius of the beam compared to a linear dependence with the energy and the pulse duration. Then, it is more efficient and cheaper to reduce the size of the focal spot than increase the energy by adding an other amplifier stage to the laser chain or decreasing the pulse duration.

Talking about spatial quality means that one has to take into account both intensity profile and phase front. If the beam is aberrant, modulations will appear in intensity and phase. It will not be focused correctly and energy will be spread out from the central part. An easy way to increase the peak power is to shorten the focal length of the optic. The size of the focal spot will be reduced but it will not resolve the problem of encircled energy and the ratio between the usable and the unusable energy will remain the same. On the contrary, a good spatial quality is equivalent to trying to get the smallest size and to keeping the whole energy encircled into the central part of the spot. At this point we can separate the problem of the amplitude from the one of the phase. The deviations from an ideal energy distribution can be avoided by the use of spatial

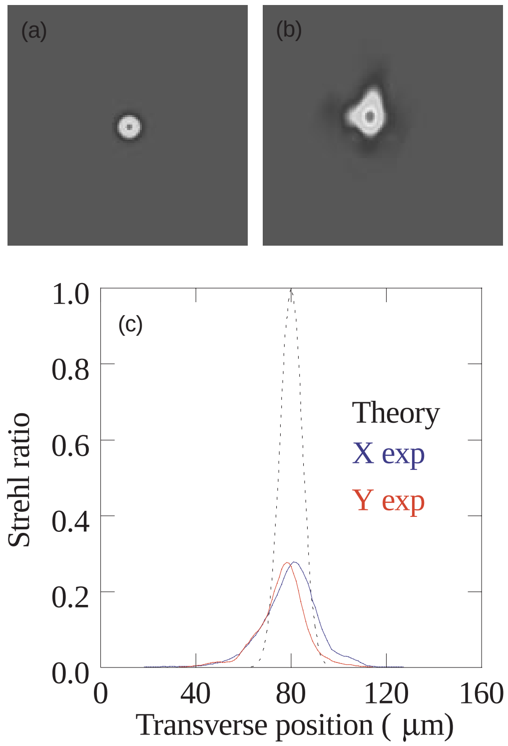

Fig. 1. a Theoretical focal spot. The spot size gives the diffraction limit size. **b** Experimental focal spot. The size is 1.5 times the diffraction limit. **c** Peak intensity at focus normalized versus the peak intensity of the perfect beam

filtering. The focusability will be increased at the expense of the energy. This point will be discussed later. As for the deviations to the flat wavefront, they can be corrected with an active optic, i.e. deformable mirror or liquid-crystal device, leading to an increase of the focused intensity [4].

1.2 Choice of a criterion

To fully characterize and quantify the quality of the beam a criterion must be chosen. The ratio to the diffraction limit size seems to be only a qualitative one. This criterion is based on the calculation of the focal spot dimension according to the size of the beam in the plane of the optic and assuming that this beam is aberration free. Then, it compares the size of the real focal spot with the one previously calculated. It does not take into account the amount of energy encircled into the focal spot [4] and then the real intensity is unknown. Figure 1 shows experimental data that describe this problem. The experimental spot size is, in this case, 1.5 times the diffraction-limited spot size. The diffraction limit is here the Fourier transform calculation of the same energy distribution with a flat phase. This mark seems to be good in terms of dimension. Furthermore, the shape is not so far from the theoretical limit. But this are only qualitative information and the peak power at focus is only 30% of what it should be if the beam was perfectly focused.

Another criterion has to be chosen: the Strehl ratio (or Strehl intensity) [5]. This ratio is well known in optics and the definition of the reference beam was modified to fit more precisely with the common Gaussian beam used in CPA laser systems.

$$\text{Strehl ratio} = \frac{\text{Peak intensity at focus of a real beam}}{\text{Peak intensity at focus of a reference beam}}\,. \tag{2}$$

The classical definition considers a flat field all over the pupil. The point spread function (PSF) of the reference beam corresponds to the real Fourier transform of the pupil function. In the case of CPA, the reference beam has Gaussian intensity profile truncated by the pupil and a flat phase front. This choice for the reference allows quantifying the decrease in focused intensity due to the energy distribution and the wavefront distortions at the same time. Figure 2 shows a simulation for a 85% Strehl ratio. Due to modulations both in intensity and phase, energy is lost at the peak and transferred in the wings. If the diffraction limit was chosen as the quality criterion, a number very close to 1 would be found and one would conclude that the laser is nearly perfect, but no information would be accessible concerning the amount of energy encircled into the focal spot. On the other hand, the Strehl ratio will tell right away what would be this amount of energy in the central part of the spot.

1.3 Wavefront sensor

To collect information about the phase front and the intensity profile, a one-dimensional Shack–Hartmann analyzer

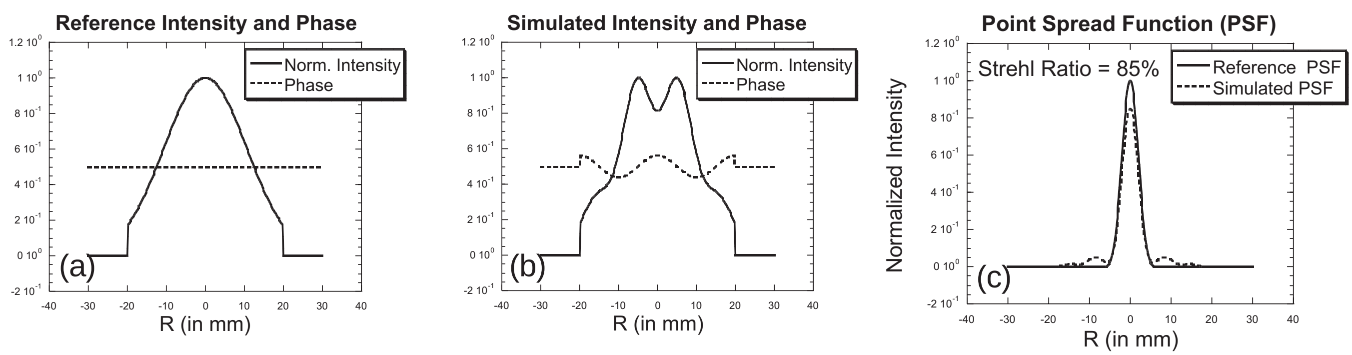

Fig. 2a–c. Definition of the Strehl ratio. **a** Reference intensity (*solid line*) and phase (*dashed*). The intensity is a 40-mm diameter at $1/e^2$ Gaussian distribution and the phase is flat. **b** Simulated intensity (*solid line*) and phase (*dashed*). **c** Calculated point spread function for the reference (*solid line*) and the simulated (*dashed*) beam. The Strehl ratio is 85%

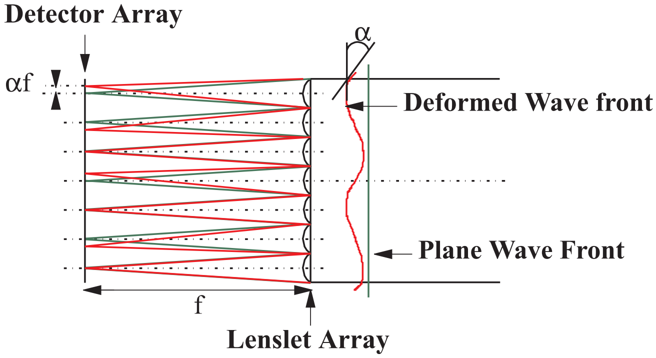

Fig. 3. Shack–Hartmann sensor. The incident beam is focused on a detector array and we have direct access to the local angle of incidence of the wavefront

(H-Line[TM]) was used. The diameter of the pupil is 30 mm and moreover the apparatus can work with either diverging or converging beam. The technique is very simple [6]. The wavefront is focused on a CCD chip (detector array) by a microlens array (Fig. 3). Each microlens is illuminating a definite part of the chip and the device is able to measure the local angle of incidence of the wavefront from the deviation seen on the CCD that is proportional to that angle. For a two-dimensional reconstruction of the wavefront, one has to record four lines by rotating the analyzer in its plane. Then with an algorithm using Zernicke polynomials, one can have the "spatial frequency" characteristics of the phase front and the intensity profile. Afterwards, it is possible to simulate the spot diagram, the PSF in different planes around the focus and calculate the Strehl ratio. For single-shot measurement, a two-dimensions Shack–

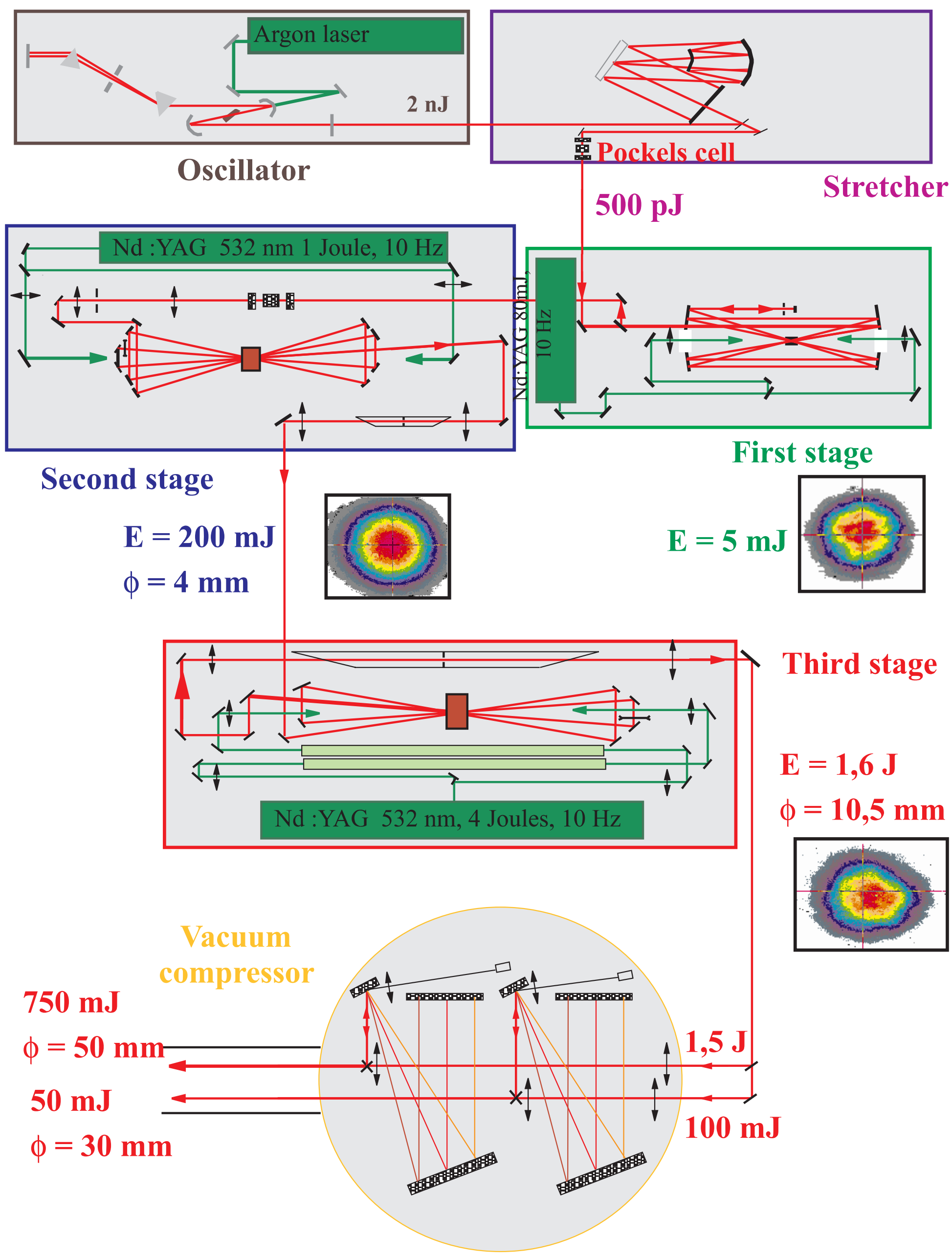

Fig. 4. Multiterawatt-10 Hz CPA chain

Hartmann (HASO^{TM}) was used. This device is well suited and very accurate for optimization in real time. Due to their compact size, it was possible to put them in every part of a multiterawatt-10 Hz CPA chain [7]. This chain consists of a fs oscillator, a stretcher, three power amplifiers, and a compressor in vacuum (Fig. 4).

2 Results

2.1 Stretcher and first stage

Figure 5a,b show some results obtained at the output of the stretcher. The beam energy is 500 pJ and the size of the beam is 2 mm in diameter. The phase distortions are smaller than $\lambda/20$ and the Strehl ratio is better than 90%. This is another confirmation that an Öffner triplet used as a stretcher [8] is aberration free. The amplifiers add some distortions due to thermal effects and doping inhomogeneities in TiSa crystals. In order to clean and reshape the beam profile, spatial filters were implemented after each stage [7]. A pinhole is introduced at the focal plane of a lens. Indeed, in the Fourier plane, that is the focal plane if the incident beam is collimated, spatial frequencies are separated spatially. The goal of the filter is, then, to cut off high frequencies that are responsible for aberrations. So, it is certain that all the energy that will exit from the filter will be encircled in the central part of the spot at focus. The filter has eliminated the undesirable energy. Furthermore, the following amplifier will be injected with a nearly perfect beam which should contribute to a better extraction efficiency. Figure 5c,d show the results after the first stage and a spatial filter. The beam energy is 5 mJ and the size of the beam is 2 mm in diameter. The phase distortions are smaller than $\lambda/25$ and the Strehl ratio is 93%. At this level, a spatial filter is very simple to implement. In fact, only energies as low as a few mJ in the ps regime have to be considered. So, no particular care must be taken and the only thing to be aware of is the dimension of the pinhole.

2.2 Second stage

Things become a little bit more difficult at the output of the second stage. Indeed, pulses with energies around 250 mJ must be spatially filtered. The fluence in the focal region is in the range of thousands of J/cm^2. The technique remains the same but the pinhole must be put into vacuum in order to avoid air ionization. Furthermore, a solution must be found to be less sensitive to laser pointing stability. As no material has the capacity to absorb such peak fluence without being damaged at normal incidence, conical pinholes were designed. It has been demonstrated that the damage threshold is increasing near grazing incidence [9]. For instance, it will be higher than 1000 J/cm^2 for angle of incidence below 10° for fused silica (Fig. 6). With this configuration, the beam will always be near grazing incidence even if the pointing of the laser is unstable. Such a pinhole was implemented after the second stage. The results are shown in Fig. 7. First of all,

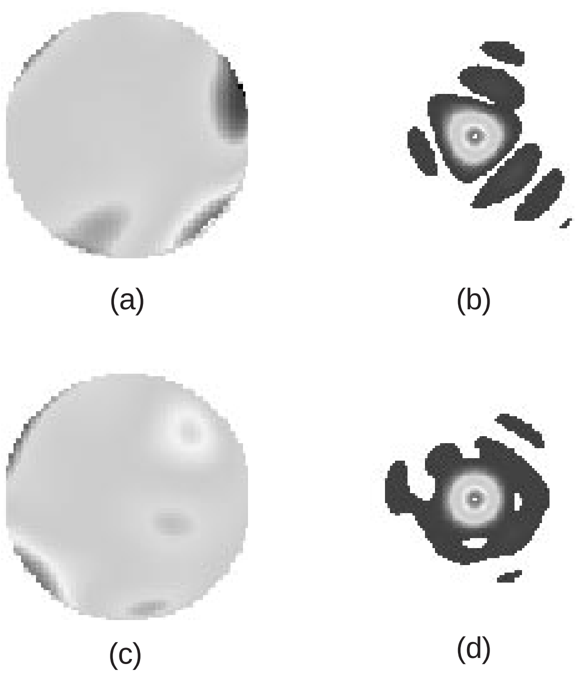

Fig. 5. a Phase front after the stretcher. The phase distortion is $\lambda/20$ RMS. **b** PSF after the stretcher. The Strehl ratio is 92%. **c** Phase front after the first stage and a spatial filter. The phase distortion is $\lambda/25$ RMS. **d** PSF after the first stage and a spatial filter. The Strehl ratio is 93%

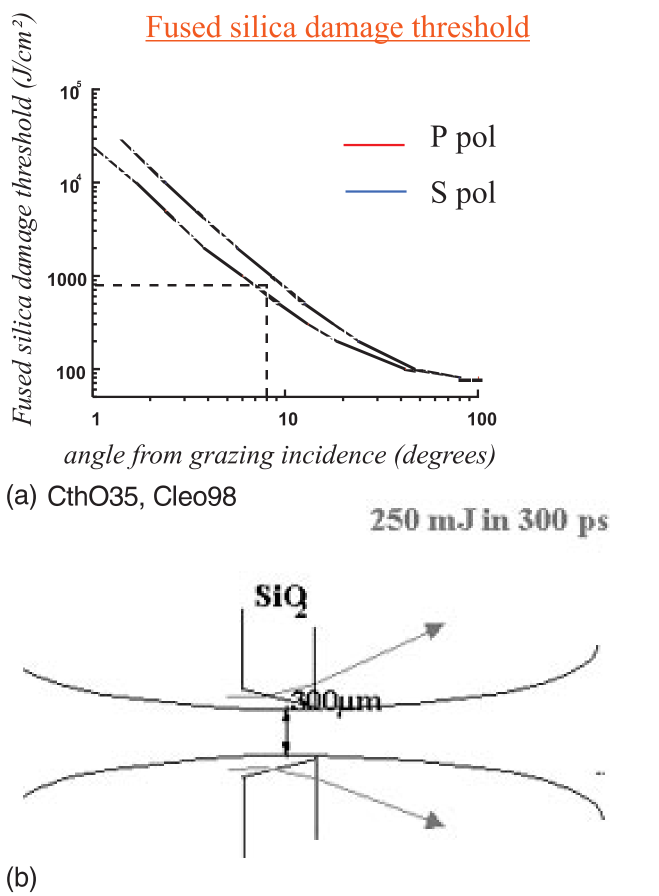

Fig. 6. a Damage threshold for fused silica near grazing incidence. **b** Conical design for pinholes

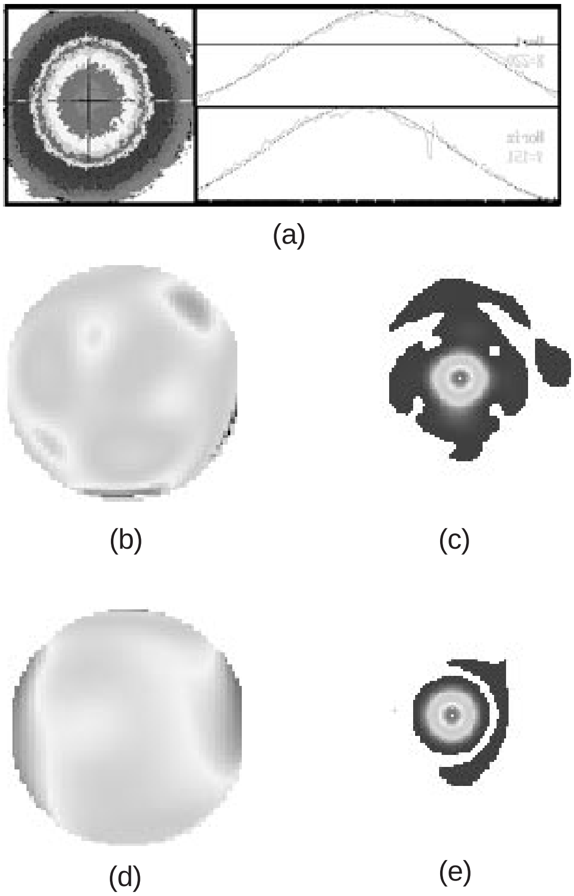

Fig. 7. a Near field pattern at the output of the second stage after filtering. The correlation with a Gaussian profile is 95%. **b** Phase front after the second stage before filtering. The phase distortion is $\lambda/10$ RMS. **c** PSF after the second stage before filtering. The Strehl ratio is 68%. **d** Phase front after the second stage and the spatial filter. The phase distortion is $\lambda/30$ RMS. **e** PSF after the second stage and the spatial filter. The Strehl ratio is 95%

in term of near-field pattern, it is very close to a Gaussian intensity distribution as the correlation factor is 95%. This factor is calculated using the best Gaussian fit to the intensity profile. Second, the focusability before and after the filter shows that the Strehl ratio is improved from 68% to 95%. The remaining phase distortions are smaller than $\lambda/30$. The life time of such a pinhole is up to now still undefined, but it has been used for one year without replacement. Obviously, the efficiency mainly depends on the input beam quality. For example, in our case, it is about 80% as the energy goes from 250 mJ to 200 mJ. The amount of energy encircled in the focal spot is the same as that of an unfiltered beam, but the propagation of the filtered beam is obviously different leading to a better coupling in the final stage of amplification.

2.3 Third stage

The filter used in the second stage is "home-made" and there is, for the moment, no way to implement it on the third stage. The problem is to drill such a pinhole in fused silica. It should be very well polished inside to avoid local incidence greater than 10° and so create local breakdown and damage. Studies

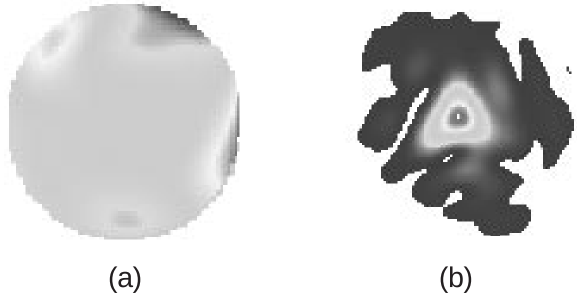

Fig. 8. a Phase front after the third stage. The phase distortion is $\lambda/8$ RMS. **b** PSF after the third stage. The Strehl ratio is 68%

are on their way but it seems to be a technical challenge considering the dimensions of the pinhole (few hundreds of μm for the exit diameter). The Strehl ratio is, then, only 68% and the phase distortions are $\lambda/8$ (Fig. 8). But it is obvious that one can reach Strehl ratios higher than 90% with an efficient filter at that level.

High thermal effects appearing in the power amplifiers must also be taken into account. The thermal focal length is proportional to 1/(Pump Power at 532 nm − Power extracted).

$$f_{\mathrm{th}} = \frac{\pi r^2 k}{P \frac{\mathrm{d}n}{\mathrm{d}T}}, \tag{3}$$

where r is the pump radius, k the thermal conductivity, P the part of the pump power responsible for the thermal load, n the refractive index, and T the temperature. It must be noted that this formula is only valid for steady-state. When the infrared beam to be amplified is injected in this stage, dramatic astigmatism patterns appears in the far-field during a few seconds before equilibrium (Fig. 9). This is due to the fact that the thermal charge goes from 40 W to 20 W as almost 50% of the energy of the pump lasers is converted in stimulated emission when the amplifier is injected. This leads to transient-state phase aberrations. It has been recently demonstrated that the cooling of the TiSa crystal below −150 °C can be a solution to avoid thermal lenses and high order distortions [10, 11].

2.4 Compressor gratings

Thermal problems also appear on compressor gratings. Some experiments were done using the second stage output beam. This beam presents a roughly perfect spatial quality with a Strehl ratio of 95%. The output energy is 200 mJ and the pulse was compressed in a two-gratings compressor. After the compression, the pulse duration is 35 fs and the diameter is 40 mm at $1/\mathrm{e}^2$. Even at that level of energy, an elongation of the focal spot was observed in the diffraction direction. This corresponds to a local change of the groove spacing and then of the diffraction angle that leads to spatial and temporal distortions for the compressed pulse. For the spatial distortions, the time constant is about 15 min and the elongation ratio is close to 1.5 (Fig. 10). Those thermal effects are probably due to the thermal properties of the polymeric material involved in the process of making replicas. This polymeric layer exhibits a very low thermal conductivity. High-efficiency gratings [12] were recently bought from the Lawrence Livermore National

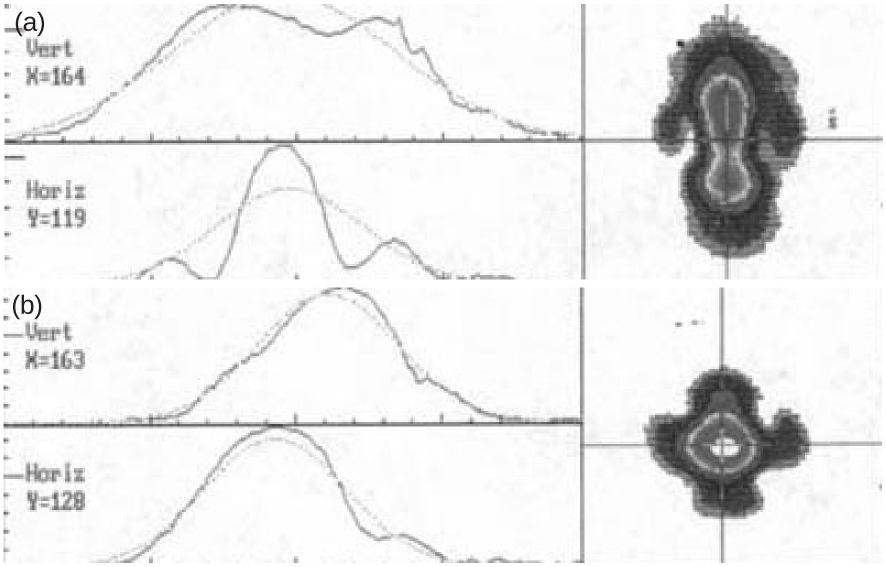

Fig. 9. **a** Far field pattern at the output of the third stage during transient state. **b** Far field pattern at the output of the third stage for steady state

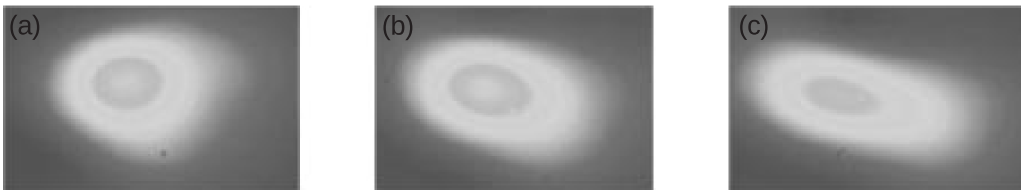

Fig. 10a–c. Elongation of the focal spot due to thermal effects on gratings. **a** Reference time and dimension. **b** After 5 min. The elongation ratio is 1.1 in the horizontal direction (diffraction direction). **c** After 15 min. The elongation ratio is 1.5

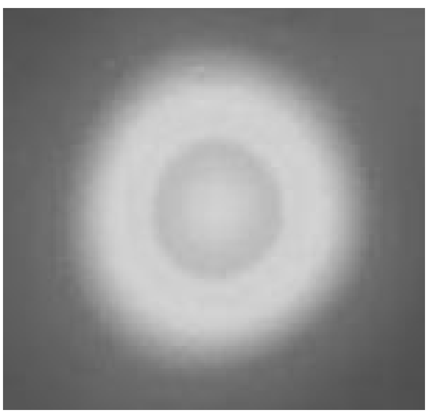

Fig. 11. Focal spot in the experimental chamber. A 50 mm beam is focused by a 1 m parabola. The size is 1.3 times the diffraction limit but the Strehl ratio is only 40%

Laboratory (LLNL) and it appears that there is no degradation of the far-field pattern along the time.

2.5 Experimental chamber

Once the thermal problems on gratings are eliminated, the focal spot of our CPA chain after focusing in the experiment chamber is shown in Fig. 11. These are experimental data that were taken at full power using a stigmatic image relay and a linear CCD camera. The beam is focused with a 1-m parabola. The spot looks fairly round and the size is 1.3 times the diffraction limit. But the Strehl ratio is only 40%. The difference between this Strehl ratio and the one obtained at the output of the third stage comes from the aberrations in optics and the clipping in the compressor and on mirrors.

3 Conclusion

The next step that has to be considered to get a better spatial quality at the output of large CPA laser systems will be to implement adaptive optics before focusing. Results obtained at the CUOS show that one can improve the beam quality from a 35% Strehl ratio to 88% using deformable mirrors [4]. With the addition of spatial filtering and cooling system in power amplifiers, this can lead to a Strehl ratio better than 90%. In other words, all the energy that will be exiting from the compression chamber will contribute to the main focal spot. This justifies the need to take a great care of the spatial quality and to provide a more usable tool to the physicists.

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