Laser damage phenomena relevant to the design and operation of an ICF laser driver

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Abstract. Laser damage performance of optical components is a defect related material characteristic. Recent advances were made to realize repeatable and accurate measurements of surface density of damage initiation due to pulses of nanosecond duration. This new measurement technique was used to guide the improvement of surface damage resistance. Fractures must be eliminated from surfaces, in order not to suffer a damage growth phenomenon, whose exponential character will endanger the optical component. A dedicated set-up was mounted on ALISÉ laser. With it, laser damage growth was measured accurately, as well as its dependence on parameters like pulse length and pulse shape. Using data from LIL, a prototype of Laser Megajoule (LMJ), and from a specific set-up, we can estimate the effect of multi wavelength illumination on damage growth. High intensity hot spots due to beam modulations can also cause surface damage. New measurements of self-focusing were obtained. The predictions derived from this laboratory work were cross checked with LIL data. They are also useful to predict damage events during the operation of a large laser facility.

1. Introduction
The replacement cost of optical components is an important part of Laser Megajoule (LMJ) forecasted operation budget. A new focus on laser damage to optical components emerged during the development of LMJ, in France, and the National Ignition Facility (NIF), in the US. This paper is an update concerning damage due to nanosecond pulses.

The final optics of LMJ are the most exposed to laser damage, due to conversion of the beam to higher energy photons of the tripled frequency (3ω), at a wavelength of 351 nm. Thus this paper will concentrate on the effect of this wavelength. Considerations of 1ω and 2ω will be briefly discussed.

The final optics are made of only two different materials. Frequency conversion is realized with Potassium DiHydrogen Phosphate crystals [noted KDP, or DKDP when deuterated]. Bulk damage problems of these were shown to be solved by a pre irradiation with UV pulses of the whole aperture, a process called laser conditioning [1]. The rest of the optics is made of fused silica (SiO₂), which poses no bulk damage problem. However, surface damage of fused silica is a major concern and a potential threat for optics operational lifetime. This problem is related to polishing processes and much more important for SiO₂ than for KDP; thus our discussion will focus on SiO₂, mainly on the rear surface (i.e. the surface crossed by the beam when coming out of the component).

The laser line was designed with the consideration of damage threshold, dependent of materials, wavelength and pulselength [2]. However, research to quantify and improve laser resistance of the
optics showed that the description in terms of a threshold for damage occurrence was not sufficient. This evolution is described in section 2. The operation of LIL, a prototype for LMJ, brought some new insight on the topic, presented in section 3. Taking into account laboratory measurements and LIL experience, predictions of the lifetime of optical components are discussed in section 4.

Since the development of Inertial Fusion Energy (IFE) is often considered as an ultimate goal, let us first mention that our discussion only treats the case of a few hundred shots. The implementation of IFE will need to demonstrate laser resistance to billions of shots: this will be another challenge.

2. Progress in measurements, physical understanding and technology

2.1. Initiation of damage sites at 3ω, 351 nm

Large aperture damage testing of fused silica [3] showed that catastrophic damage was created by fluences lower than damage threshold measured with small samples. Not only low fluences could induce damage growth (see § 2.2.), but initiation of damage sites on a pristine surface was also observed for fluences smaller than the threshold of small area standardized damage tests. Following this discovery, laser damage laboratory measurements of fused silica optics were realized by scanning large surface areas with the UV beams [4] to determine the surface density of damage sites.

2.1.1. Measurement of damage density. This metrology has been developed and improved in our laboratory and is now considered a repeatable measurement process [5]. In figure 1, damage densities of 3 samples are compared. One, sample A, was polished with techniques available at the end of the nineties, when LIL was equipped: it shows tens of laser induced craters /cm² in the 5 – 10 J/cm² fluence range. Our first work [6] to improve the industrial processes brought damage characteristics to the level of sample B. The existence of two different populations of damaging defects is revealed in this curve, one type of flaws dominating above 15 J/cm², the other under 15 J/cm². Further efforts were focused onto the elimination of low fluence damaging defects, identified with subsurface fractures remaining after polishing. Sample C benefited from these improvements: the scan of about 70 cm² created no damage site under 12 J/cm². An error bar at 2σ confidence level [5] gives an upper density of 0.2 /cm² in the 5 – 10 J/cm² range.

2.1.2. Damage initiation due to hot spots. Due to the threat of damage growth (cf. §2.2.), all causes of damage initiation must be known and eliminated. Small scale self-focusing is a possible cause of rear surface damage in thick optical components, like LMJ vacuum window, or NIF focusing lenses: this cause is enhanced by spatial modulation in the beam, caused by components defects or damage sites upstream, and amplified by non linear propagation. Recent measurements at 3ω [7] showed that the product of the peak intensity incident on a component by its thickness must be well under 20 GW/cm to guaranty a negligible contribution of this damage cause.

Figure 1. Measurements of density of damage sites on 100 mm diameter polished fused silica flats. Sample A is representative of the first equipment of LIL 3ω optics. Samples B and C were obtained after successive improvements of the polishing process. Error bars [5] are shown for the best sample only (C). This measurement can be used to predict components lifetime.
2.2. Damage growth
Exponential damage growth was demonstrated in output surface of fused silica at 3ω by Norton et al at Boulder Damage Symposium in 2000. Later, specific measurements showed that input (front) surfaces followed a linear growth law [8]. In output surfaces, instead of a linear rate of growth, they found that each shot would increase the average diameter by a given factor, inducing a catastrophic increase of the damaged region. They also found a threshold for this phenomenon, of about 5 J/cm², nearly independent of pulse duration from 1 to 10 ns. The increase factor is 1 at the threshold: by commodity, everyone is now using the logarithm of growth factors, which is zero at the threshold.

With ALISÉ laser, we studied damage growth in output surfaces, and studied also the effect of spectral width (figure 2). We find better to measure the surface area of craters, instead of their diameter. A given shot, of number n, increases damaged area from A_{n-1} to A_n. The following graphic shows the logarithm of growth parameters, i.e. k = ln(A_n/A_{n-1}).

![Figure 2. Rates of damage growth measured with ALISÉ laser in output surface of polished fused silica. Each point is k for one shot on one damage crater (cf. text). Results are found slightly dependent on spectral width, and almost independent on pulse length between 1 and 3 ns. No dependence of growth rates on polishing processes has been reported yet, contrary to damage density measurements. The 3 ns case is taken for lifetime calculations in §4.](image)

In laboratory experiments, it was shown that damage growth varies when the incidence is changed. The important figure was fluence of the beam propagating inside the component [9].

2.3. Effect of combinations of wavelengths
In 2005, Norton et al showed that residual unconverted light could enhance growth [10]. Since conversion efficiency is about 50 %, this contribution had to be considered. Their analysis of growth data [10] concluded that 1ω residual energy was as effective as 3ω light to produce growth, once sufficient 3ω energy was present. A subsequent experiment [11] was set up in a CEA laboratory to check these findings. In our case [11], pulse lengths (about 5 ns) were of the order of LMJ requirements, whereas data of ref. 10 were obtained with pulse lengths significantly longer than LMJ standard (15 ns). A 1ω beam was fired on the same site as a 3ω beam : the delay between the two pulses was varied, the IR hitting the sample either 6 ns before, 6 ns after or at the same time as the UV pulse. Only the IR energy coming with or after the UV was efficient in enhancing damage growth rates. This point is important to draw conclusions concerning the operational life of components (cf. §4). Further details on the results and implications of this experiment may be found elsewhere [11].

3. Observations on LIL
Beginning in 2002, the operation of LIL was first dedicated to demonstrate 3ω performance [12] for LMJ. It was also a practical test of laser damage behavior in the final optics section. Among fused silica 3ω components, the focusing grating (FG) and the vacuum window (VW) were particularly looked at. Damage densities observed on both types of components were very near those expected from the measurements of sample A of figure 1. On the VW, filamentation damage was also created by hot spots, due to its thickness of 4.3 cm. The exact incoming intensity on the VW could not be determined. In the other hand, using the filamentation threshold recalled in § 2.1.2., we got estimates of light intensity: these estimated figures are compatible with our knowledge of the beam. These hot
spots are undesirable because they create damage craters that were shown to grow under subsequent shots. Several technological actions were taken to limit the causes of these peak intensities: decrease VW thickness, improve the laser cavity deformable mirror, the beam shaping device...

Damage growth was also observed on the output surface of LIL components. In the VW, estimations of growth rates were consistent with the measurements of figure 2, made in similar beams conditions with ALISÉ installation. Contrary to the VW which sees only UV light, the FG is illuminated by residual 1ω and 2ω beams. The analysis of output surface damage craters showed that residual wavelength contributed to growth, as discussed in §2. However, in contrast to ref. 10, our calculations show that IR and visible energy was only half as efficient as 3ω light in its contribution to the growth rate. This point is still under numerical and experimental study.

4. Optics lifetime projections

Because of exponential damage growth above 5 J/cm², spatial intensity modulation is a major contributor to the degradation of the optics, due to small scale self-focusing [13]. Thus, it is necessary to decrease the occurrence of peak fluences, especially for the VW.

The case studied is that of a component seeing both 3ω light and a residual 1ω+2ω beam of equivalent energy. Following the observations made on LIL, half of this energy adds up to 3ω in inducing damage growth. As illustrated with sample C of figure 1, polishing processes now can yield fused silica components with less than 100 damaging defects for standard LMJ shots. On these damage sites, a CO2 laser mitigation process [14] can be used, decreasing the number of potential damage events under 1 per optic during laser operation. After some shots, we suppose that 1 damage site appears on one optic, with an initial area of about 10⁻⁵ cm². The growth of this site limits lifetime.

Considerations of component lifetime must be related to an optic replacement criterion. We take 1 cm² as maximum damaged area. The fluence distribution is thus defined with a similar resolution: the total aperture of 1200 cm² is divided in 1000 pixels, on which fluence takes values according to a normal law, with a 13 % standard deviation [15]. Hot spots keep the same position during the all series of shots. These hypotheses give a distribution of component behavior, illustrated in the table below.

| 3ω mean fluence on the component (J/cm²) | 4  | 5  | 7.5 | 10 |
|----------------------------------------|----|----|-----|----|
| Average number of shots before criterion is reached | 145 | 59 | 24  | 15 |
| minimum number of shots before criterion (on 1000 parts) | 40  | 25 | 13  | 9  |

After the potential appearance of 1 damage site, tens of shots are still possible at LMJ required fluence of 7.5 J/cm². If damage initiation events are avoided or mitigated, lifetime can be much longer.

References

[1] J. J. Adams et al, *Proc. of SPIE* 5647 (2005).
[2] For example : F. Rainer et al, *Proc. of SPIE* 1624 (1992).
[3] M. R. Kozlowski et al, *Proc. of SPIE* 3578 (1999) pp. 436-445.
[4] S. Schwartz et al, *Proc. of SPIE* 3578 (1999) pp.314-321.
[5] L. Lamaignère et al, submitted for publication in *Review of Scientific Instruments*.
[6] J. Néauport, L. Lamaignère, H. Bercegol, F. Pilon and J.-C. Birolleau, *Opt Exp.* 13, n°25 (2005)
[7] H. Bercegol, L. Lamaignère, V. Cavaro, M. Loiseau, *Proc. of SPIE* 5991 (2006) p.59911Z
[8] M. A. Norton et al, *Proc. of SPIE* 6403 (2007) p.64030L
[9] G. Razé et al, *Proc. of SPIE* 4932 (2003), pp. 127-135
[10] M. A. Norton et al, *Proc. of SPIE* 5991 (2006) p.599108
[11] L. Lamaignère et al, to be published at Boulder Damage Conference 2007, *Proc. of SPIE* 6720
[12] J-M. Di-Nicola et al, Proc. of the 4th IFSA conference, *J. Phys. IV France* 133 (2006) 595–600
[13] H. Bercegol et al, *Proc. of SPIE* 5273 (2004) pp. 312-324
[14] For example : P. Bouchut et al, *Proc. of SPIE* 5273 (2004) pp. 250-256
[15] with 10⁶ pixels, like in most CCD cameras, a σ of 13 % gives a peak to average ratio of about 2.