Chin. Phys. B Vol. 21, No. 7 (2012) 077901

The effect of laser beam size on laser-induced damage performance

Han Wei(韩 伟)†, Wang Fang(王 芳), Zhou Li-Dan(周丽丹),
Feng Bin(冯 斌), Jia Huai-Ting(贾怀庭), Li Ke-Yu(李恪宇),
Xiang Yong(向 勇), and Zheng Wan-Guo(郑万国)

Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900, *China*

(Received 12 August 2011; revised manuscript received 2 February 2012)

The influence of laser beam size on laser-induced damage performance, especially damage probability and the laser-induced damage threshold (LIDT), is investigated. It is found that damage probability is dependent on beam size when various damage precursors with different potential behaviors are involved. This causes the damage probability and the LIDT to be different between cases under a large-aperture beam and a small-aperture beam. Moreover, the fluence fluctuation of the large-aperture laser beam brings out hot spots, which move randomly across the beam from shot to shot. Thus this leads the most probable maximum fluence after many shots at any location on the optical component to be several times the average beam fluence. These two effects result in the difference in the damage performance of the optical component between the cases under a large-aperture and small-aperture laser.

Keywords: laser-induced damage, beam aperture, beam modulation

PACS: 79.20.Ds, 42.60.Jf, 42.70.Ce **DOI:** 10.1088/1674-1056/21/7/077901

1. Introduction

In large high-power laser facilities, such as the National Ignition Facility[1] in the United States, the Laser Megajoule[2] in France, and the prototype of SG-III laser facility[3] in China, laser-induced damage of the optical component is a major concern. Much research[4−9] has been performed to understand damage initiation and damage growth. It is believed that material imperfection and contamination are the main causes of laser-induced damage, and the strategies developed to avoid the damage rely on reducing the initiator density.[10] However, most of the research has been carried out at a small aperture and low energy platform. From our operational experience of the prototype of the SG-III laser facility, we find that there is a significant difference in the laser-induced damage performance between the cases under a small-aperture laser and under a large-aperture laser. For example, the optical components in large-aperture laser facilities are usually damaged at a fluence much lower than the laser-induced damage thresholds (LIDTs) obtained in the case of a small-sized laser beam. In order to figure out the difference, in this paper we investigate the effect of laser beam size on the laser-induced damage performance of optical components.

2. Laser beam aperture influence

Laser-induced damage performance is usually represented by the damaged probability and the onset LIDT (laser fluence for 0% damage probability). The studies of laser damage to optical components are carried out at different fluences on a sample with given laser beam sizes. The most commonly used test is the 1-on-1 test, defined by the ISO 11254-1 standard, which recommends the use of a beam size at least 400 μm for laser damage tests.

The laser damage probability obtained by the 1-on-1 mode can be modeled. The model used in this paper is the one developed by Krol *et al.*[11] According to the model, the beam size dependences of the damage probability and the LIDT can be predicted. First, we consider a material with a single damage precursor class, denoted as Φ. And we assume that the damage precursor ensemble function is a Gaussian distribution with three variable parameters, i.e., damage threshold mean value, threshold standard deviation, and damage precursor density. The damage precursor ensemble function represents the density of damage

†Corresponding author. E-mail: tonyhan2000@163.com

precursor initiating damage at a threshold fluence, as shown in Fig. 1(a).

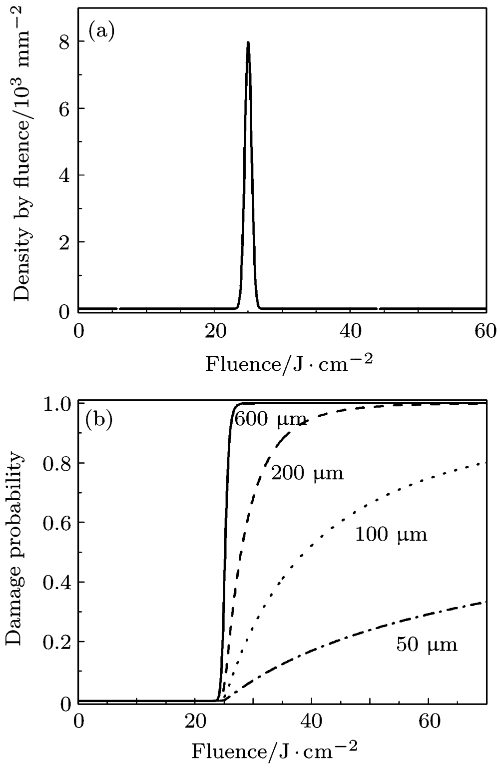

Fig. 1. (a) The damage precursor class ensemble with the damage threshold mean value being 25 J/cm^2, threshold standard deviation 1 J/cm^2, and damage precursor density 100 mm^{-2}. (b) Laser damage probabilities versus fluence for different beam size diameters.

For a given Gaussian distribution, the laser damage probability curve can be calculated with the model mentioned above. The plots of damage probability versus fluence for some different beam size diameters are shown in Fig. 1(b). In this case, we should find the same LIDT independent of the beam size. The beam size should theoretically have no influence on the measured LIDT. However, an increase in the laser beam size changes the damage probability curve slope. And as the beam size increases, the absolute LIDT (laser fluence for 100% damage probability) decreases. When the beam size is larger than 300 μm, the absolute LIDT almost equals the onset LIDT.

In a second case, we consider that different damage precursor classes can be embedded in a material. In Fig. 2(b), we plot the damage probability in the case of two classes of damage precursors, Φ_1 and Φ_2, with the density of Φ_1 being larger than that of Φ_2, and the threshold of the Φ_1 damage precursors being higher than that of the Φ_2 damage precursors.

From the simulations, we find that in the case of a beam size in the range of few tens of micrometers, the onset LIDT will be 25 J/cm^2, which is the intrinsic threshold of the damage precursors Φ_1. In this case, the probability of finding a damage precursor Φ_2 under the laser beam is negligible. The same material tested with a larger beam size (> 400 μm) should exhibit another LIDT around 12 J/cm^2, which is close to the intrinsic threshold of the Φ_2 damage precursor. For intermediate beam sizes, a break in the slope of the damage probability curve is expected. This occurs when the probabilities of finding damage precursors Φ_1 and Φ_2 under the beam are almost equal. Therefore, if different classes of damage precursors can initiate the laser damage, the LIDT is beam size dependent, and no scaling law can be used to predict the damage threshold of an optical component from the tests made with a small beam size.

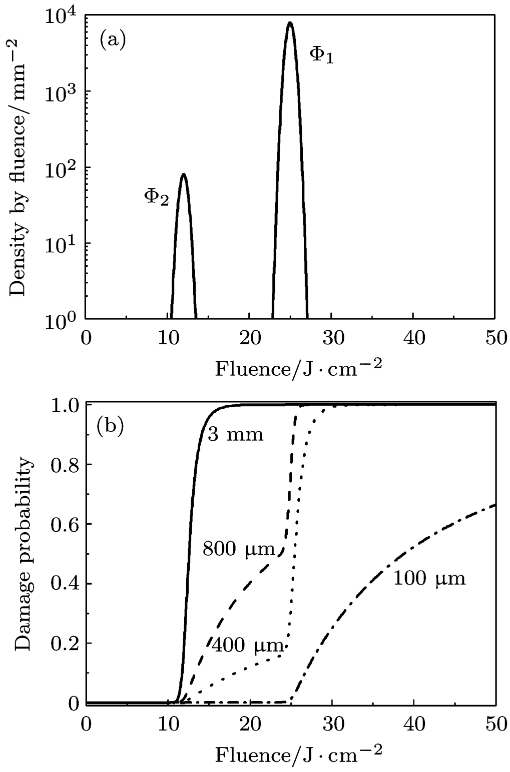

Fig. 2. (a) Two damage precursor class ensembles with the Φ_1 damage threshold mean value 25 J/cm^2, threshold standard deviation 1 J/cm^2, damage precursor density 100 mm^{-2}, Φ_2 damage threshold mean value 12 J/cm^2, threshold standard deviation 1 J/cm^2, and damage precursor density 1 mm^{-2}. (b) Laser damage probabilities versus fluence for different beam size diameters.

It is shown in Fig. 2 that the beam size effect on damage performance leads to the differences in the damage probability curve and LIDT between the cases under a small laser beam and under a large laser beam in the case of different classes of damage precursors. In high-power laser facilities, the damage precursors with the lowest damage threshold are the most concerned. According to Fig. 2, a large beam size is necessary to find the damage precursors with the lowest damage threshold and to measure the real LIDT of the large-area optical component. A beam size larger than 400 μm, which is recommended in the ISO 11254-1 standard, is not sufficient. How large the laser beam should be in order to measure the onset LIDT depends on the density of the damage precursor with the lowest LIDT. Without pre-knowledge of the damage precursors, a laser beam with a size equal to the optical component area is required. Or raster scanning[12] can be implemented for a laser-induced damage study of the large-area components.

3. Laser beam modulation influence

In addition, most of the small-aperture damage performance tests have not taken into account the damage due to the statistical fluctuation typical of large-aperture lasers. A large-aperture beam has a distribution of fluences (i.e., fluence beam contrast) in the cross section of the beam. The operational beam is assumed to have a nominal flattop with the intensity fluctuation described by a Rician distribution. The single shot Rician probability distribution is given by

$$p\left(F, \bar{F}, c\right) = \frac{1}{2\sigma^2}\exp\left[-\left(\frac{F+\bar{F}-2\sigma^2}{2\sigma^2}\right)\right] \times \mathrm{I}_0\left(\frac{\sqrt{F(\bar{F}-2\sigma^2)}}{\sigma^2}\right),$$

where $\bar{F}$ is the mean fluence, σ is the standard deviation of the noisy field amplitude, and I_0 is a Bessel function of the second kind. The fluence beam contrast c is σ divided by $\bar{F}$. The Rician distribution is completely parameterized by two quantities, the mean fluence and the contrast ratio of the beam.

The hot spots in the large laser beam are assumed to move spatially from shot to shot, meaning that at any given location, a different fluence for each shot at a constant average beam fluence can be seen. For a randomly migrating fluence, the distribution of maximal fluence at each location after n shots is given by

$$p_n\left(F\right) = np\left(F\right)\left[\int_0^F p\left(F\right)\mathrm{d}F\right]^{n-1}.$$

The maximal fluence distributions for the Rician distribution after 1, 10, 100, and 1000 shots are plotted in Fig. 3 respectively. Note that after many shots for this assumption, most locations on the large aperture component have been exposed to the fluence at the high tail of the single shot distribution. For example, the most probable maximum fluence at any location after 1000 shots is 1.23 times the average beam fluence. Thus due to the fluence fluctuation of the large aperture laser, the optical components actually bear a higher fluence than the average beam fluence. The cumulative damage probability after n shots at any location is the damage probability under the most probable maximum fluence instead of the average beam fluence.

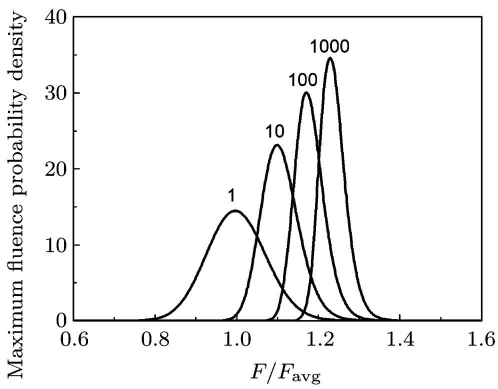

Fig. 3. Probability distributions of maximal fluence after 1, 10, 100, and 1000 shots with average beam fluence 6 J/cm^2 and beam fluence contrast 0.05.

The most probable maximum fluence is affected by laser shots and the fluence beam contrast. The most probable maximum fluence after 1000 shots is plotted as a function of beam contrast in Fig. 4. As can be seen, the most probable maximum fluence decreases linearly with the decrease in the beam contrast.

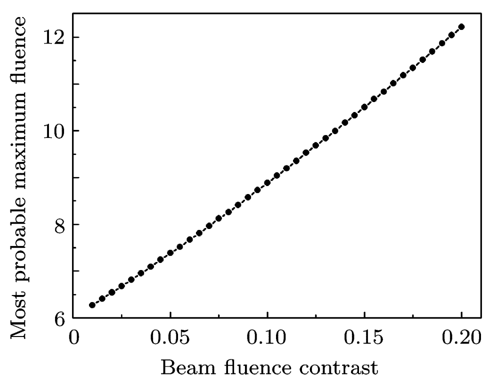

Fig. 4. Most probable maximum fluence as a function of beam fluence contrast (the average beam fluence is 6 J/cm^2).

4. Conclusion

In this paper, we investigate the influence of laser beam size on laser-induced damage performance, especially damage probability and LIDT. We find that the effects of beam size on damage performance have two aspects. First, the damage probability is beam size dependent when various damage precursors with different potential behaviors are involved, and a large beam size can measure the lowest LIDT among various damage precursors. Second, the fluence fluctuation of a large aperture laser beam and the hot spots moving randomly from shot to shot lead the most probable maximum fluence at any location on the large-aperture component to be several times the average beam fluence. The effects of laser beam size on damage performance can be used to explain the phenomenon that optical components in large-aperture laser facilities are usually damaged under a beam fluence which is much lower than their LIDTs.

References

[1] Lowdermilk W H 1996 *Proc. SPIE* **3047** 16

[2] Andre M L 1996 *Proc. SPIE* **3047** 38

[3] Peng H S, Zhang W Y and Wei X F 1998 *Proc. SPIE* **3492** 25

[4] Papernov S and Schmid A W 2008 *Proc. SPIE* **7132** 7132J1

[5] Bercegol H, Bouchut P, Lamaignere L, Garrec B and Le Raze G 2004 *Proc. SPIE* **5273** 312

[6] Han W, Huang W, Wang F, Li K, Feng B, Li F, Jing F and Zheng W 2010 *Chin. Phys.* B **19** 106105

[7] Xiang X, Chen M, Chen M, Zu X, Zhu S and Wang L 2010 *Chin. Phys.* B **19** 018107

[8] Liu F, Zhang L and Li G 2005 *Chin. Phys.* **14** 2145

[9] Han P G, Ma Z Y, Xia Z Y, Chen D Y, Xu J, Qian B, Chen S, Li W, Huang X F, Chen K J and Feng D 2007 *Chin. Phys.* **16** 1410

[10] Menapace J A, Penetrante B, Golini D, Slomba A F, Miller P E, Parham T G, Nichols M and Peterson J 2001 *Proc. SPIE* **4679** 56

[11] Krol H, Gallasi L, Grezes-Besset C, Natoli J Y and Commandre M 2005 *Opt. Commun.* **256** 184

[12] Demange P, Carr C W, Radousky H B and Demos S G 2004 *Rev. Sci. Instrum.* **75** 3298