INTERNATIONAL STANDARD

ISO 11254-2

First edition
2001-09-15

Lasers and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces —

Part 2: **S-on-1 test**

Lasers et équipements associés aux lasers — Détermination du seuil d'endommagement provoqué par laser sur les surfaces optiques —

Partie 2: Essai S sur 1

Reference number
ISO 11254-2:2001(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.ch
Web www.iso.ch

Printed in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 11254 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 11254-2 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

ISO 11254 consists of the following parts, under the general title *Lasers and laser-related equipment — Dtermination of laser-induced damage threshold of optical surfaces*:

— *Part 1: 1-on-1 test*

— *Part 2: S-on-1 test*

Annexes A to D of this part of ISO 11254 are for information only.

Introduction

Repetitive laser radiation may deteriorate and damage optical surfaces at irradiation levels below those measured for single shot damage (ISO 11254-1 refers). Besides reversible mechanisms induced by thermal heating and distortion, irreversible damage mechanisms due to ageing, microdamage and generation or migration of defects are observed. This part of ISO 11254 is concerned with the determination of irreversible damage of optical surfaces under the influence of a repetitively pulsed laser beam. The degradation of the optical quality is a function of the laser operating parameters and the optical system in which the component is placed.

In this part of ISO 11254, two evaluation methods are described for the reduction of raw data of a damage test. The characteristic damage curve method is based on a large number of S-on-1 test sites on the optical surface of the specimen. The characteristic damage curve comprises a set of three graphs indicating energy density values with damage probability values of 10 %, 50 % and 90 % for a selected number of pulses. The characteristic damage curve represents the results of a complete and extended laser-induced damage test, and it is recommended for basic investigations in newly developed or critical laser optics.

The second method, the extrapolation method, is created from a considerably smaller number of test sites. This method generates a distribution diagram of damage and non-damage regions for the behaviour of the damage threshold as a function of the number of pulses per site. This diagram is of limited reliability and may be employed for the quality control of optical laser components, which are already qualified by a complete damage test, or for the preparation of extended damage testing.

The present state of research in laser-induced damage and ageing is not sufficient for an accurate quantitative determination of the service life for optical components under real operating conditions. Realistic laser damage tests adapted to industrial applications are dependent on a large number of pulses (10^9 to 10^{11} pulses) and require a disproportionate experimental expense. This part of ISO 11254 therefore also outlines a procedure for an extrapolation of the S-on-1 threshold from the characteristic damage curve to estimate the real lifetime of an optical component.

NOTE 1 This part of ISO 11254 is provisionally restricted to irreversible damage of optical surfaces. Laser-induced damage to the bulk of optical components shall be considered in a revision of this part of ISO 11254.

NOTE 2 The laser-induced damage threshold (LIDT) of an optical component which is subjected to repetitive radiation can be affected by a variety of different degradation mechanisms including contamination, thermal heating, migration or generation of internal defects and structural changes. These mechanisms are influenced by the laser operating parameters, the environment and the mounting conditions of the component under test. For these reasons, it is necessary to record all parameters and to realize that the damage behaviour may differ in systems with altered operating conditions.

Safety Warning: The extrapolation of damage data may lead to bad or erroneous calculated results and to an overestimation of the LIDT. This may in the cases of toxic materials (e.g. ZnSe, GaAs, CdTe, ThF_4, chalcogenides, Be, Cr, Ni) lead to severe health hazards. See annex D for further comments.

Lasers and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces —

Part 2:
S-on-1 test

1 Scope

This part of ISO 11254 specifies a test method for determining the laser-induced damage threshold of optical surfaces subjected to a succession of similar laser pulses.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 11254. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 11254 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 10110-7:1996, *Optics and optical instruments — Preparation of drawings for optical elements and systems — Part 7: Surface imperfection tolerances*.

ISO 11145:1994, *Optics and optical instruments — Lasers and laser-related equipment — Vocabulary and symbols*.

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this part of ISO 11254, the terms and definitions given in ISO 11145 and the following apply.

3.1.1
surface damage
any permanent laser radiation-induced change of the surface characteristics of the specimen which can be observed by an inspection technique described within this part of ISO 11254

3.1.2
S-on-1 test
test programme that uses a series of pulses with constant energy density on each unexposed site with a short and constant time interval between two successive pulses

NOTE The length of the time interval between the pulses of a series is given by the inverse value of the pulse repetition rate of the laser source.

3.1.3
typical pulse
pulse with temporal and spatial shapes that represent the average properties of the pulses forming the pulse series

3.1.4
minimum number of pulses
number of incident pulses causing detectable surface damage

3.1.5
threshold
highest quantity of laser radiation incident upon the optical surface for which the extrapolated probability of damage is zero

NOTE 1 The quantity of laser radiation may be expressed in energy density H_{th}, power density E_{th}, or linear power density F_{th}, depending on the pulse duration.

NOTE 2 The maximum power density E_{max} of the typical pulse is given by:

$$E_{max} = \frac{H_{max}}{\tau_{eff}} \quad (1)$$

3.1.6
target plane
plane tangential to the surface of the specimen at the point of intersection of the test laser beam axis with the surface of the specimen

3.1.7
effective area
ratio of pulse energy to maximum energy density in the target plane

NOTE 1 For spatial beam profiling perpendicular to the direction of beam propagation and angles of incidence differing from 0 rad, the cosine of the angle of incidence is included in the calculation of the effective area. In this case, the effective area may be approximated by the following formula:

$$A_{T,eff} = \frac{Q}{H_{max}\cos(\alpha)} \quad (2)$$

NOTE 2 For the special case of a circular flat-top beam profile with diameter d_{100}, the effective area is given by:

$$A_{T,eff} = \frac{Q}{H_{max}} = \frac{H_{max}\pi d_{100}^2}{H_{max}} = \pi d_{100}^2 \quad (3)$$

For a focused Gaussian beam with a beam diameter $d_{86,5}$, the effective area is given by:

$$A_{T,eff} = \frac{Q}{H_{max}} = \frac{H_{max}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-8\frac{x^2+y^2}{d_{86,5}^2}}\,dxdy}{H_{max}} = 2\pi\int_0^{\infty} e^{-\frac{8r^2}{d_{86,5}^2}}\,rdr = \frac{1}{8}\pi d_{86,5}^2 \quad (4)$$

With the definition of the second moment of the energy density distribution function $H(x,y,z)$ at the location z,

$$\sigma^2(z) = \frac{\int_0^{\infty}\int_0^{2\pi} r^2 H(r,\varphi)\, r\, dr\, d\varphi}{\int_0^{\infty}\int_0^{2\pi} H(r,\varphi)\, r\, dr\, d\varphi} \tag{5}$$

and the definition of the beam diameter d_σ as a function of the second moment

$$d_\sigma(z) = 2\sqrt{2}\sigma(z) \tag{6}$$

the effective area can be expressed in the following forms:

a) flat top beam: $$A_{\mathrm{T,eff}} = \tfrac{1}{4}\pi d_{100}^2 = \tfrac{1}{4}\pi d_\sigma^2 = 2\pi\sigma^2\,;\; d_{100} = d_\sigma \tag{7}$$

b) Gaussian beam: $$A_{\mathrm{T,eff}} = \tfrac{1}{8}\pi d_{86,5}^2 = \tfrac{1}{8}\pi d_\sigma^2 = \pi\sigma^2\,;\; d_{86,5} = d_\sigma \tag{8}$$

3.1.8
effective beam diameter
double the square root of the effective area divided by the factor π:

$$d_{\mathrm{T,eff}} = 2\sqrt{\frac{A_{\mathrm{T,eff}}}{\pi}} \tag{9}$$

3.1.9
effective pulse duration
ratio of pulse energy to maximum pulse power

3.1.10
characteristic damage curve
representation of the S-on-1 laser-induced damage threshold as a function of the number of pulses per site at a specified pulse repetition rate

3.2 Symbols and units

Table 1 — Symbols and units of measurement

Symbol	Unit	Term
λ	nm	wavelength
α	rad	angle of incidence
p		degree of polarization
N_{min}		minimum number of pulses causing damage
N_{p}		number of pulses per site
N_{TS}		total number of sites for the test
d_{T}	mm	beam diameter in the target plane
$d_{\mathrm{T,eff}}$	mm	effective beam diameter in the target plane
$A_{\mathrm{T,eff}}$	cm^2	effective area in the target plane
τ_{H}	ns, µs, s	pulse duration
τ_{eff}	ns, µs, s	effective pulse duration
f_{p}	Hz	pulse repetition rate
Q	J	pulse energy
P_{pk}	W	peak pulse power
E_{max}	W/cm^2	maximum power density
F_{max}	W/cm^2	maximum linear power density
H_{max}	J/cm^2	maximum energy density
E_{th}	W/cm^2	threshold power density
F_{th}	W/cm	threshold linear power density
H_{th}	J/cm^2	threshold energy density
P_{av}	W	average power

4 Sampling

Either a functional component or a witness specimen shall be tested. If a witness specimen is tested, the substrate material and surface finish shall be the same as for the component, and the witness specimen shall be coated in the same coating run as the component. The coating run number and date shall be identified for the test component.

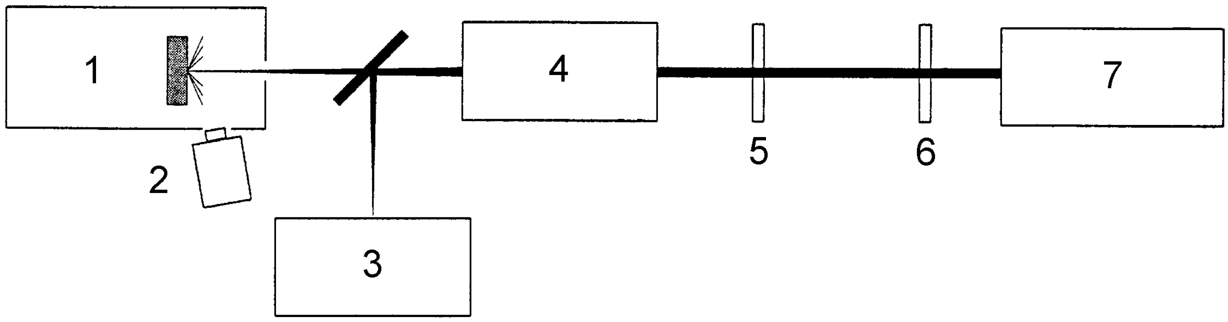
5 Test method

5.1 General

For determining the S-on-1 damage threshold, extensions of the set-up and the evaluation procedure for 1-on-1 damage thresholds measurements (ISO 11245-1 refers) are necessary. However, the S-on-1 measurement facility described in this part of ISO 11245 can be applied for 1-on-1 measurements if the on-line damage detection system is combined with a Nomarski-type differential interference contrast microscope. It is recommended that the on-line damage detection system should have the facility for cutting off subsequent pulses and for stopping the pulse counter.

5.2 Principle

The basic approach to laser damage testing is shown in Figure 1. The output of a well-characterized stable repetitive laser is set to the desired energy or power with a variable attenuator, and delivered to the specimen located at or near the focus of a focusing system.



Key

1 Sample compartment
2 On-line damage detector
3 Beam diagnostic
4 Focusing system
5 Waveplate
6 Variable attenuator
7 Laser system

Figure 1 — Basic approach to S-on-1 laser damage testing

The specimen is mounted in a manipulator which is used to position different test sites in the beam and to set the angle of incidence. The polarization state is set with an appropriate waveplate. The incident laser beam is sampled with a beamsplitter which directs a portion of the beam to a diagnostic unit. The beam diagnostic unit permits simultaneous determination of the total pulse energy and the spatial and temporal profiles.

The specimen is positioned at a defined location with reference to the laser beam at the specified angle of incidence. Each test site is irradiated with pulse trains of constant energy density and repetition rate. Each test is conducted without moving the sample, and subsequent tests are made moving the test point across the sample at a known distance between each test site. It is recommended that the distance between each test site be greater than three times the laser spot diameter d_T. During the series of tests, a sufficient number of test sites shall be tested at different energy densities. The determination of the damage threshold is based on the total data and not on the state of damage for any individual site.

This procedure is applicable to testing with all pulsed laser systems, irrespective of pulse length, repetition rate, and wavelength. Pulse durations widely used in industrial and scientific applications are summarized and grouped in Table 2.

Table 2 — Laser groups

Group	Pulse duration
1	1 ns to 3 ns
2	10 ns to 30 ns
3	1 µs to 3 µs
4	200 µs to 1 000 µs
5	to be specified

Repetition rate classes widely used in industrial and scientific applications are given in Table 3. Lasers of these classes are recommended for S-on-1 tests. Pulse repetition rates other than those specified in Table 3 are allowed for the purposes of this part of ISO 11254. The pulse repetition rate classes are permitted in conjunction with every possible laser group. The pulse duration and the pulse repetition rate of the test laser shall be documented in the test report.

Laser-induced damage threshold values are dependent on the operating parameters of the laser system employed for testing. For a comparison of threshold data under slightly different operating conditions, scaling laws, which are based on modelling of experimental data, may be used. Safety aspects shall be considered for the application of scaling laws to hazardous materials.

Table 3 — Repetition rate classes

Class	Pulse repetition rate f_p in Hz
A	1
B	10
C	30
D	100
E	300
F	1 000
G	to be specified

5.3 Apparatus

The test facility consists of individual sections with specific functions.

5.3.1 Laser

A laser delivering pulses with a reproducible near-Gaussian or near-flat-top spatial profile is required. The temporal profile of the pulses is monitored during the measurement. Pulse trains containing pulses with a maximum power density exceeding the variation of E_{max} in Table 4 shall be rejected for the evaluation procedure. The pulse repetition rate shall be constant within an error margin of ± 1 %. For the different laser groups, the maximum allowable variations of the pulse parameters are compiled in Table 4. As a minimum specification of a laser system not included in rows 1 to 4 in Table 2, the pulse-to-pulse variation of the maximum power density shall be less than ± 20 %. Stability criteria for the beam parameters shall be determined and documented in an error budget.

Table 4 — Maximum percentage variation of laser parameters and corresponding percentage variation of maximum pulse power density E_{max}

Laser group	Pulse energy Q	Pulse duration τ_H	Effective area $A_{T,eff}$	Power density E_{max}
1	± 5	± 10	± 10	± 15
2	± 5	± 5	± 6	± 10
3	± 5	± 5	± 6	± 10
4	± 5	± 5	± 6	± 10

5.3.2 Variable attenuator and beam delivery system

The laser output shall be attenuated to the required level with an external variable attenuator that is free of drifts in transmissivity and imaging properties.

The beam delivery system and the attenuator shall not affect the properties of the laser beam in a manner inconsistent with the tolerances given in 5.3.1. In particular, the polarization state of the laser beam shall not be altered by the beam delivery system.

5.3.3 Focusing system

The arrangement of the focusing system should be adapted to the special requirements of the laser system and to the intended beam profile in the target plane. The specific arrangement and the parameters of the focussing system shall be documented in the test report. The specifications of the active area and the energy density shall be referred to the location of the test surface.

For Gaussian beams, it is advisable to select an aperture of the focusing system which amounts to not less than three times the beam diameter at the entrance of the focusing system. A minimum effective *f*-number of 50 and a beam diameter in the target plane not less than 0,8 mm are recommended. The target plane shall be located at or near the focal waist formed by the focusing system. For Groups 3 to 5, the beam diameter may be reduced depending on the power density necessary, but should not be smaller than 0,2 mm. In such cases the effective *f*-number may be reduced below a value of 50.

For near-flat-top laser beams, it is advisable to position the test surface in the image plane of the focusing system with a focal length > 0,2 m that forms an image of a suitable aperture in the optical path.

Coherence effects in specimens with parallel surfaces can occur and affect the measurement. These effects shall be eliminated by appropriate techniques, such as wedging or tilting of the specimen. The application of a highly converging beam is also a practical method for removing coherence effects in the specimen.

5.3.4 Specimen holder

The test station shall be equipped with a manipulator which allows for a precise placement of the test sites on the specimen with an accuracy sufficient for the specimen size.

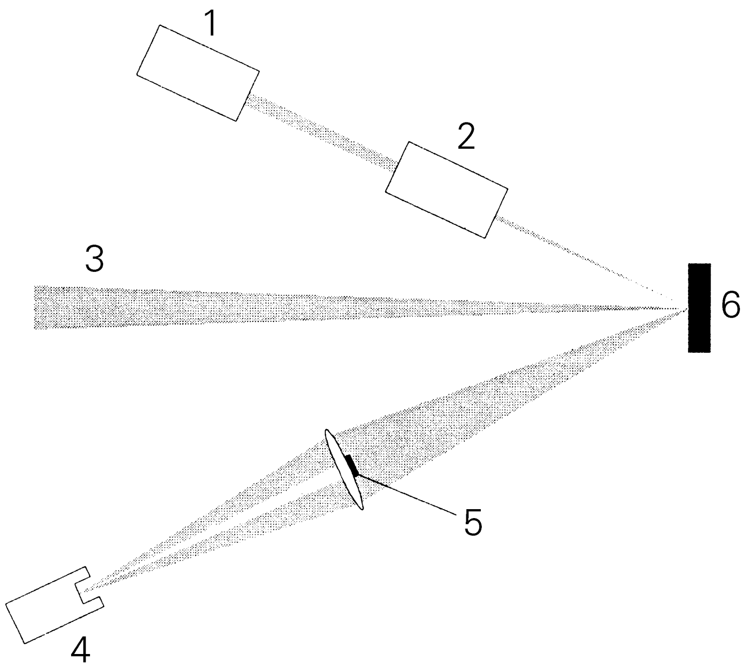
5.3.5 Damage detection

A microscope technique shall be used to inspect the surface before and after the test. The investigations shall be made with an incident light microscope having Nomarski-type differential interference contrast. A magnification in the range from × 100 to × 150 shall be used.

NOTE 1 For routine inspection and objective measurement of laser damage, an image analyser may be attached to the microscope.

An appropriate on-line damage detection system shall be installed to evaluate the state of the surface under test. After detection of damage, the minimum number of pulses N_{min} shall be recorded, and the measurement for the next site shall be started.

NOTE 2 For S-on-1 damage testing, the detection limit of the damage monitor is not critical due to the accumulative behaviour of the surface mechanisms. For on-line damage detection, any appropriate technique may be used. Techniques suited to this purpose are, for instance, on-line microscopic techniques, photoacoustic and photothermal detection, as well as scatter measurements using a separate laser or radiation from the damaging laser.



Key

1 Laser

2 Beam preparation system

3 Test beam

4 Detector

5 Negative aperture

6 Test sample

Figure 2 — Typical set-up for an on-line scatter measurement system

NOTE 3 For example, the measurement of radiation scattered by the optical surface may be applied for damage detection. A typical set-up for on-line scatter measurements is given in Figure 2. A laser with excellent pointing stability and minimum intensity fluctuations is used as radiation source. The laser light is refined by a beam preparation system that normally consists of telescope systems with apertures, spatial filters and optical components for modulating the laser power density. After beam preparation, the laser beam is focused onto the actual site of the specimen under damage test. The scattered radiation is collected by a lens and detected by a photodetector. The fraction of the laser beam reflected by the specimen surface is cut out by a negative aperture. To achieve high sensitivity and low interference with other light sources in the environment of the set-up, phase sensitive detection techniques and an interference filter for the laser wavelength are recommended.

5.3.6 Beam diagnostics

5.3.6.1 Total pulse energy and average power

The diagnostic package shall be equipped with a calibrated detector to measure the pulse energy delivered to the target plane for each individual pulse. This instrument shall be traceable to a national standard with an absolute uncertainty of ± 5 % or better. For laser systems with high repetition frequencies, the total pulse energy may be determined by measuring the average power, P_{av}, and the pulse repetition rate, f_p. In this case, the pulse energy, Q, is given by:

$$Q = \frac{P_{av}}{f_p} \quad (10)$$

5.3.6.2 Temporal profile

The diagnostic package shall include suitable instrumentation for analysing the temporal profile of the laser to determine the pulse duration. The temporal profile shall be integrated to determine the ratio of total pulse energy, Q, to peak pulse power, P_{pk}. This ratio is called the effective pulse duration τ_{eff}:

$$\tau_{eff} = \frac{Q}{P_{pk}} = \frac{\int_0^{1/f_p} P(t)dt}{P_{pk}} \quad (11)$$

For lasers of the Groups 1 to 4, upper limits for the temporal resolution of the pulse duration measurement are defined in Table 5. For lasers not included in Table 5, the upper limit of the temporal resolution shall not exceed 10 % of the effective pulse duration.

Table 5 — Upper limits for the temporal resolution of the pulse duration measurement

Group	Temporal resolution
1	100 ps
2	1 ns
3	100 ns
4	10 µs

5.3.6.3 Spatial profile

In all cases, the spatial profile shall be analysed in the target plane or an equivalent plane. The diagnostic package shall be equipped with instrumentation to measure the two dimensional spatial profile with a spatial resolution of ± 1,5 % of the beam diameter or better.

The maximum energy density of the beam shall be determined as follows:

The two dimensional profile shall be integrated to determine the ratio of total pulse energy, Q, to maximum energy density, H_{max}. This ratio is called the effective area $A_{T,eff}$.

$$A_{T,eff} = \frac{Q}{H_{max}} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(x,y)\,dx\,dy}{H_{max}} \quad (12)$$

The maximum energy density, $H_{max,}$, may be expressed in terms of total pulse energy or average power and pulse repetition rate:

$$H_{max} = \frac{Q}{A_{T,eff}} = \frac{P_{av}}{A_{T,eff}\ f_p} \quad (13)$$

5.3.6.4 Typical pulse

For the determination of the spatial profile of the typical pulse, a significant fraction of the number of pulses used for an individual site shall be recorded by the spatial profiling system. The spatial profile of the typical pulse is defined by the average distribution of the power density recorded during the measurement cycle for an individual site. The temporal profile and the energy of the typical pulse are given by the corresponding average data of all pulses employed for testing of an individual site on the test surface. The test report shall contain a depiction of the temporal and spatial profile of the typical pulse.

NOTE For the evaluation of the temporal profile, the power, $P_j(t_i)$, of the laser may be determined at equally spaced time coordinates, t_i, for every pulse. The position of the pulse in a sequence of N_p pulses per testing site is identified by the counting variable j. The sampling of each pulse shall be started at the first time coordinate t_0 with a power that differs from zero. On the basis of this measurement technique, the temporal profile $P_{tp}(t_i)$ of the typical pulse can be calculated by the average of the pulses forming a testing sequence of N_p pulses:

$$P_{\text{tp}}(t_i) = \frac{1}{N_{\text{p}}} \sum_{j=0}^{N_{\text{p}}} P_j(t_i) \qquad (14)$$

The energy of the typical pulse may be expressed by the sum of the energy contents assigned to time intervals $t = t_{i+1} - t_i$.

$$Q_{\text{tp}} = \sum_{i=0}^{N_{\text{s}}} P_{\text{tp}}(t_i)\, \Delta t \qquad (15)$$

where N_s is the number of time intervals necessary for describing the complete temporal shape of the typical pulse, the average power, $P_{av,id}$, expected for an ideal damage test is given by

$$P_{\text{av,id}} = Q_{tp}\, f_{\text{p}} \qquad (16)$$

By relating the average power calculated from the energy of the typical pulse to the measured average power, P_{av}, the accuracy and stability of the laser may be evaluated. The stability of the spatial profile can be assessed by recording the temporal behaviour of the local intensity at selected positions in the spatial beam profile.

5.3.6.5 Test parameters

The testing equipment shall be characterized by the following parameters:

a) wavelength, λ;

b) angle of incidence, α;

c) degree of polarisation, p;

d) pulse repetition rate, f_p;

e) beam diameter of the typical pulse in the target plane, d_T;

f) effective beam diameter of the typical pulse in the target plane, $d_{T,eff}$;

g) pulse duration of the typical pulse, τ_H;

h) effective pulse duration of the typical pulse, τ_{eff};

i) number of pulses per site, N_p;

j) total number of sites per test, N_{Ts}.

5.4 Preparation of test specimens

Wavelength, angle of incidence and polarization of the laser radiation as used in the test shall be in accordance with the specifications by the manufacturer for normal use. If ranges are given for the values of these parameters, an arbitrary combination of wavelength, angle of incidence and polarization within these ranges may be used.

Storage, cleaning and preparation of the specimens is done according to the specimen specifications by the manufacturer for normal use.

In the absence of manufacturer-specified instructions, use the following procedure.

a) Store the specimen at less than 50 % relative humidity for 24 h prior to testing. Handle the specimen by the non-optical surfaces only.

b) Before testing, carry out a microscopic evaluation of surface quality and cleanliness in accordance with ISO 10110-7 using a Nomarski/darkfield microscope at 150 × magnification or higher.

c) If contaminants are observed on the specimen, the surface shall be cleaned. The cleaning procedure shall be documented. If the contaminants are not removable, document them by photographic and/or electronic means before testing.

d) Inspect the test site for dust particles during irradiation. The test environment shall be clean filtered air of less than 50 % relative humidity and shall be documented.

e) The test sites shall be in a defined and reproducible arrangement. Refer the test grid to fixed reference points on the specimen. It is acceptable to make marks at known locations on the specimen as reference points only after testing is completed and before the specimen is removed from the specimen positioner.

NOTE It is usually possible to use one or more large damage spots as reference points, rather than potentially contaminating the surface of the specimen. This is preferable if there is any likelihood of having to make further tests on the specimen.

5.5 Procedure

An unexposed test site is positioned into the beam and irradiated by a series of N_p pulses with a selected energy, Q_{tp},of the typical pulse. If damage is observed by the on-line damage detection system before the series of N_p pulses is completed, stop the irradiation of the site and record the minimum number of pulses N_{min}. Repeat this procedure for different energy densities of the typical pulse. The number of pulses, N_p, shall be constant for the entire test procedure and shall be selected such that the specific laser-induced damage behaviour of the specimen is registered by the S-on-1 test.

6 Evaluation

6.1 Principle

After the inspection by the microscope technique (see 5.3.5), the result of the described S-on-1 test programme is a file of data points of the type

(Q_{tp}, N_{min}) $N_{min} \leqslant N_p$ in case of damage

(Q_{tp}, N_p) in case of no detectable damage

The evaluation of the data obtained (see Figure 3) may be performed by using the characteristic damage curve (see 6.2) or the extrapolation method (see 6.3). The method of the characteristic damage curve allows for a precise determination of the laser-induced damage threshold on the basis of an experimental procedure that is practicable only for numbers N_p of shots below 10^7 per site. Besides this accurate technique, which should be used for fundamental investigations and for testing prototype components, the extrapolation method is a practical technique to estimate the S-on-1 threshold for a large number of pulses.

6.2 Characteristic damage curve

Apply the procedure for the S-on-1 damage threshold (see 5.5) and record the resulting file of data points. For an evaluation with sufficient significance, a minimum number, N_{ms}, of sites shall be tested for each energy value, Q_{tp}, of the typical pulse. This minimum number of sites, N_{ms}, can be approximated by the relation

$$N_{ms} = 5 \cdot \mathrm{int}\left[(1 + \log(N_p))\right] \tag{17}$$

The range of typical pulse energies, Q_{tp}, employed must be sufficiently broad to include points of zero damage probability as well as points of 100 % damage probability.

Damage probability values for a defined number, N, of pulses and specified energy value, Q, are calculated on the basis of the following data reduction technique:

The energy scale is divided into a series of intervals ($Q - \Delta Q$, $Q + \Delta Q$) covering the energy range accessible by the experimental set-up. For the calculation of damage probability for a certain energy value, Q, and for a selected number, N, of pulses, data points with $Q_{tp}(Q - \Delta Q,\ Q + \Delta Q)$ are selected from the file of data points. Data points with $N_{min} \leqslant N$ correspond to sites damaged, meanwhile data points with $N_{min} > N$ or $N_p \geqslant N$ correspond to sites not damaged during the test. The damage probability for the energy, Q, is calculated by the ratio of the number of data points corresponding to damaged sites with respect to the total number of data points considered for the evaluation.

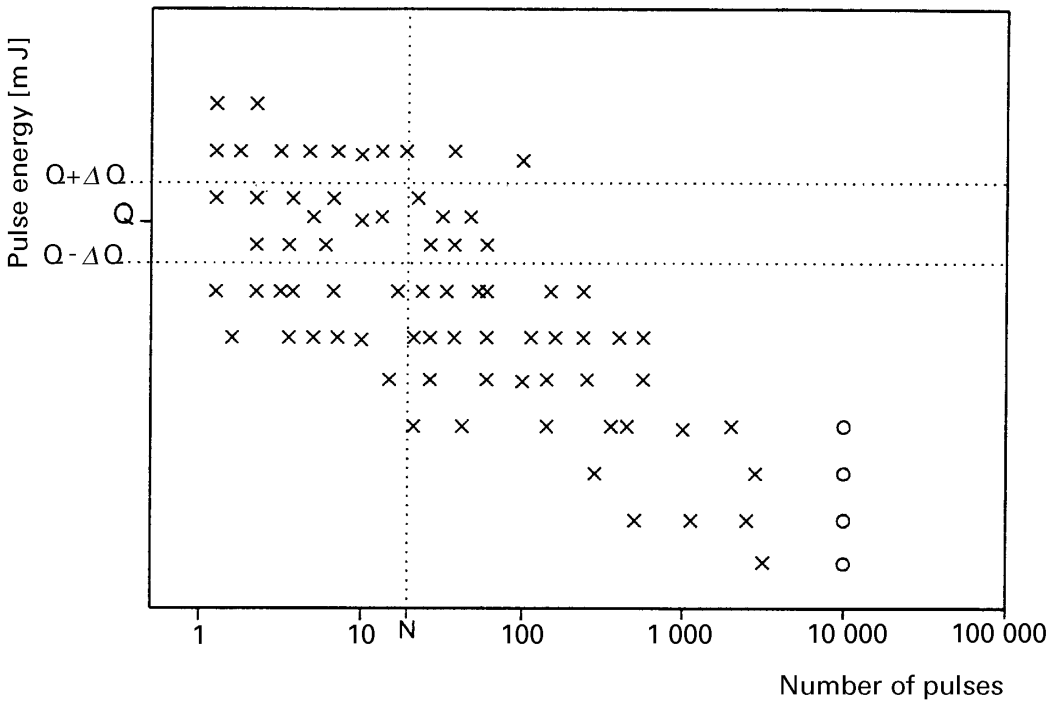
NOTE 1 The value of ΔQ is chosen such that a significant fraction of data points is available for a distinct interval ($Q - \Delta Q$, $Q + \Delta Q$). The value Q is kept constant during the evaluation procedure, and it determines the statistical error of the threshold values. An example of an efficient measurement procedure and an adapted selection of the parameters is given in annex B.

This procedure is repeated for other energy values, Q, to generate a data set of damage probability values for the selected number, N, of pulses. The resulting data set represents discrete points of a damage probability curve which is plotted versus the energy of the typical pulse. From this curve, energy values Q_{10}, Q_{50}, and Q_{90} are deduced for the corresponding damage probability values of 10 %, 50 %, and 90 % by extrapolation.

A linear extrapolation involving the two data points next to the targeted damage probability is sufficient. If an experimental basis with a large number of data points is available, more sophisticated extrapolation methods are permitted. The extrapolation procedure shall be documented in the test report.

For the determination of the laser-induced damage threshold, the damage probability curve shall be linearly extrapolated to a damage probability of zero, and the resulting threshold energy value shall be converted to the units of threshold energy density, H_{th}, threshold power density E_{th}, or linear threshold power density, F_{th} (see 5.3.6.3 and 3.1.5).

If an experimental basis with a large number of data points is available, more sophisticated extrapolation methods are permitted for the determination of the damage threshold. The extrapolation procedure shall be documented in the test report.



Key

o Undamaged

x Damaged

NOTE Data points corresponding to damaged spots are represented by "×". Undamaged spots are represented by "o". The evaluation procedure for the damage probability method is illustrated by the interval ($Q - \Delta Q$, $Q + \Delta Q$) marked in the diagram. More than one point may occur for a specific data pair (Q_{tp}, N_p) or (Q_{tp}, N_{min}) during the experiment. The number of points for a specific data pair may be indicated in the plot.

Figure 3 — Depiction of data resulting from the evaluation of the damage tests

For the creation of the characteristic damage curve, the energy values Q_{10}, Q_{50}, and Q_{90} are converted to the units of the damage threshold (see 5.3.6.3) and plotted versus the number of pulses. The number of pulses shall be selected in a way that at least 5 data points are located in the significant region of the characteristic damage curve. Log-log-coordinates are recommended for the representation to render possible a linear extrapolation of the characteristic damage curve for large numbers of pulses (see Figure 4).

NOTE 2 Log-log-coordinates may not be appropriate for an extrapolation of the characteristic damage curve for extremely large numbers of pulses. In many cases, the characteristic damage curve converges to a finite energy density and the shape of this convergence may contain information on the laser-induced ageing mechanisms (see annex C).

6.3 Extrapolation method

A distribution diagram of damage and non-damage regions can be created on the basis of a file with a reduced number of data points. For this method, S-on-1 test procedures are performed covering a range of numbers of pulses per test site that is appropriate for an extrapolation of the S-on-1 damage threshold for a defined large number of pulses. A slightly modified test procedure (see 5.5) is performed for a selected set of data points. For the extrapolation method, the number of pulses, N_p, is varied during the test procedure, and it shall be selected such that a significant number of sites is irradiated for a selected number of pulses, N_p. The irradiation of an individual test site is stopped after the defined number of pulses has been reached or damage has been detected. For specimens which show self-quenching damage mechanisms, the extrapolation method can be also applied in damage test facilities without an on-line damage detection system. In this case, each site is subjected to the selected number of pulses independently of the state of damage.

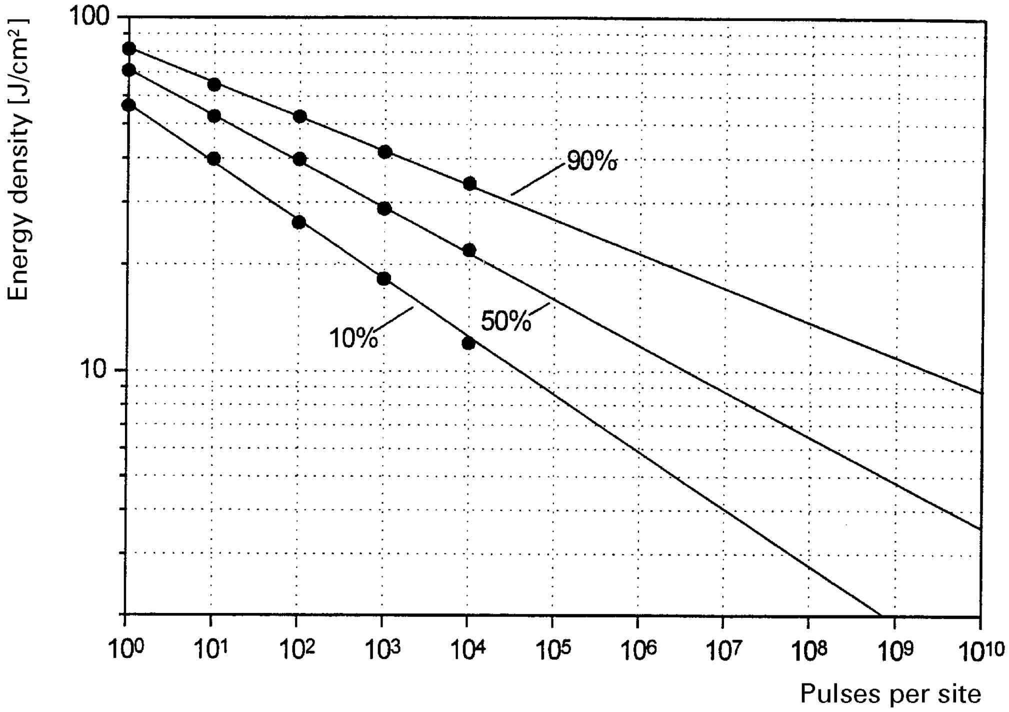
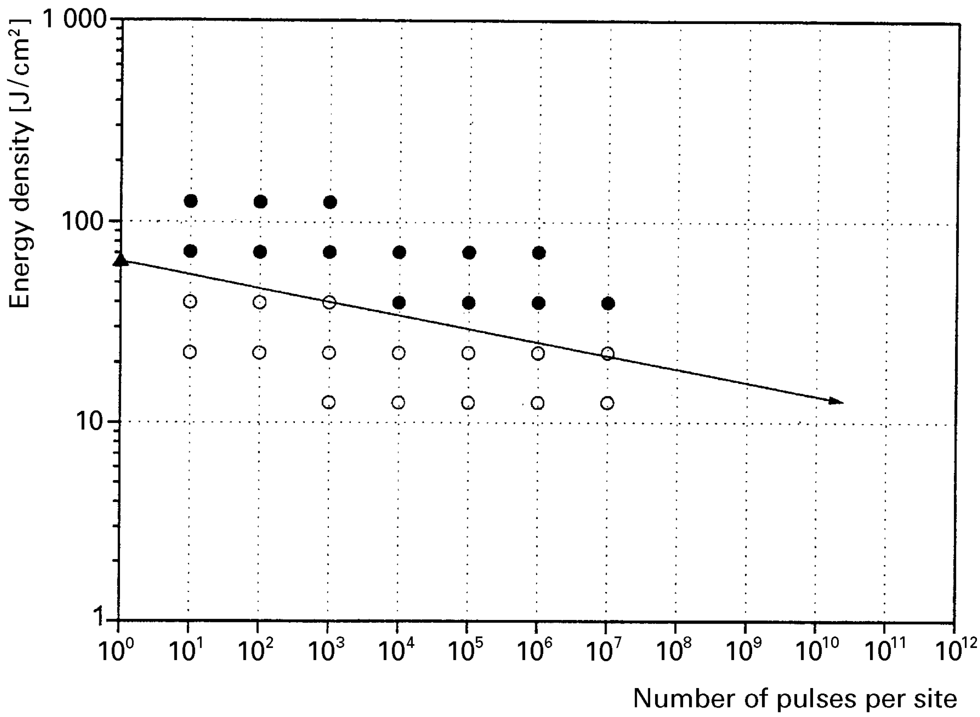


Figure 4 — Characteristic damage curve

For each data point, the energy value, Q_{tp}, is converted to the unit of energy density or power density and plotted in a diagram presenting this value versus number of pulses. By separating the data points with respect to the state of damage, regions of damage and non-damage are marked in the diagram. This resulting distribution diagram (see Figure 5) renders possible an approximate estimation of the threshold energy density for large numbers of pulses.

NOTE Compared to the method of the characteristic damage curve, the extrapolation method is based on a considerably smaller number of S-on-1 test procedures, and it may be performed on one specimen. The limited reliability of the extrapolation method may be sufficient for the quality control of a production process already certified by a complete damage probability test or for the preparation of extended damage tests. The distribution diagram resulting from the extrapolation method can be interpreted as a rough estimation of the characteristic damage curve (see Figure 4), and it can be also deduced from the data file of the characteristic damage curve.



Key

▲ 1on1LIDT

● Damage

○ No damage

Figure 5 — Distribution diagram of damage and non-damage regions

7 Accuracy

The calibration error budget shall be prepared to determine the overall measurement accuracy. Variations in the pulse repetition rate, total energy or beam power, spatial profile and temporal profile shall be included in the error budget.

An example for Group 2 lasers is given in Table 6. Similar formats are appropriate for other laser groups.

Table 6 — Error budget for a Group 2 laser-damage testing facility

Random variations:	
Pulse repetition rate	± 1 %
Pulse-to-pulse energy stability	± 3 %
Pulse-to-pulse spatial profile stability	± 5 %
Pulse-to-pulse temporal profile stability	± 5 %
Systematic variations:	
Calorimeter calibration	± 3 %
Calorimeter-energy monitor correlation	± 2 %
Overall energy density measurement reproducibility	± 5,8 %
Overall energy density measurement uncertainty	± 6,8 %

8 Test report

To guarantee a reliable in-process documentation, each specimen tested is assigned a unique run number, which accompanies it through the test process from initial receipt to submission of the final report. All pertinent information pertaining to test station configurations, source calibration, cleaning, microscopic inspections, exposure parameters, raw data and reduced test results shall be traceable to this run number. These data shall be retained by the test laboratory as a primary permanent reference.

For the purpose of documentation and presentation of measured data, the test report shall include the following information:

a) Information on the testing institute

  1) name and address of the testing institute;

  2) date of testing;

  3) name of the operator;

  4) references to the International Standards used as basis for the test.

b) Information on the specimen

  1) type of the specimen (part or witness);

  2) manufacturer of the specimen;

  3) specifications of the manufacturer for storage, cleaning, and preconditioning;

  4) specifications of the manufacturer for normal use (wavelength, pulse duration, polarization, angle of incidence, purpose);

  5) part identification number, date of production.

c) Information on the test (test specifications)

  1) test equipment including focusing system and effective *f*-number;

  2) laser parameters according to 5.3.6.5 a) to 5.3.6.5 h);

  3) diagrams of the spatial and temporal profile of the typical laser pulse;

  4) error budget (see Table 6);

  5) arrangement of the testing sites on the specimen;

  6) damage detection method;

  7) methods for storage, cleaning and preconditioning;

  8) test environment.

d) Information on the result, characteristic damage curve

  1) at least one Nomarski micrograph of a typical damaged testing site; a pulse energy in the range between 20 % and 80 % damage probability shall be chosen for each number of pulses per site;

  2) diagram according to Figure 4 with data points joined by lines for S-on-1 damage probability data or diagram according to Figure 5;

3) result of the test according to Figure 4 or Figure 5.

e) In the case of changes in damage mechanisms with the number of pulses, a brief statement shall be given on the observed damage behaviour.

An example of a test report is given in annex A.

Annex A
(informative)

Example of test report

Laser-induced damage threshold, S-on-1 test
(ISO 11254-2)

Testing Institute

Testing Institute:	Xaa Xaaaaa Xaaa Xaaaaa xaa XX Xaaaa XXX X-XXXX Xaaaaa XX
Date/Tester:	X. Xaaaaaaaa / 1994-02-28

Specimen

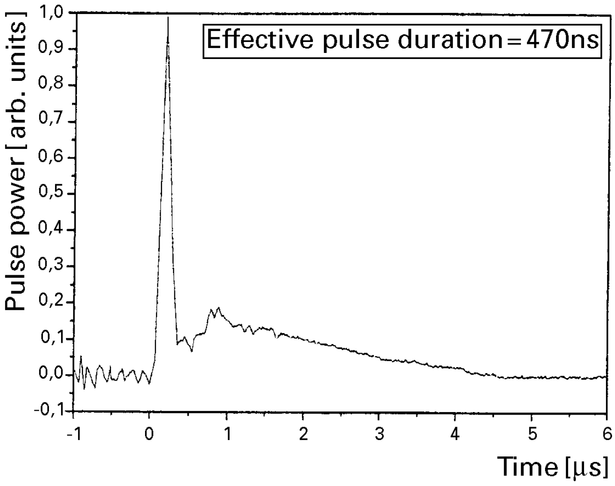
Type of Specimen:	NaCl-windows, uncoated
Manufacturer:	Xaa Xaaaaa XaaA Xaaaaa xaa XX Xaaaa XXXX-XXXX Xaaaaa XX
Storage, Cleaning:	Sealed plastic container, dessication with silica gel
Specification:	Laser windows from crystal No. 128, purified raw material Czrochalski method CO_2-laser window, ∅ = 38 mm, d = 6 mm
Part identification, Date of production:	Production Run No. 128, oven K0

Test specification

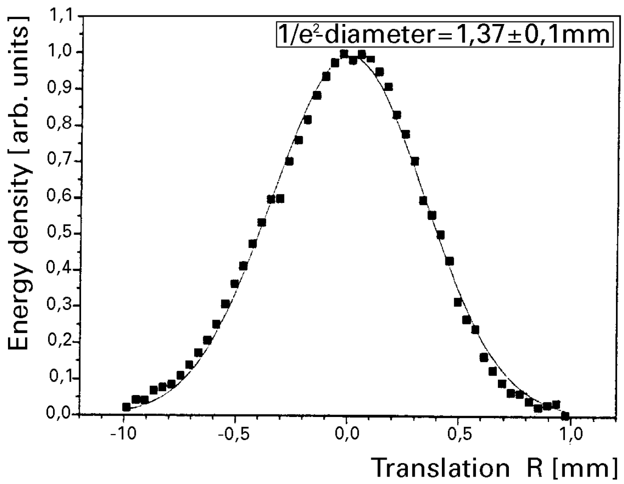
TEA-CO_2-laser, two-stage system with linear stable resonator and mode aperture, twin rotating thin film attenuator, photon drag detector for recording the temporal profile, pyroelectric array for on-line recording of the spatial beam profile, off-line beam profiling with scanning slit, focusing with ZnSe-lens (f = 500 mm), on-line damage detection by video-microscopy and optical scatter measurement, computer-controlled system.

Laser parameters

Wavelength	10,6 µm
Angle of incidence	0 rad
Polarization state	random
Pulse repetition frequency	max. 20 Hz
Beam profile in target plane	TEM_{00}
Effective beam diameter	1,36 mm
Pulse duration	100 ns pulse, 4,5 µs tail
Effective pulse duration	470 ns for damage test



Temporal Profile



Spatial Profile

Error budget

a) random variations:

pulse repetition rate	± 1 %
pulse-to-pulse energy stability	± 5 %
pulse-to-pulse spatial profile stability	± 5 %
pulse-to-pulse temporal profile stability	± 7 %

b) systematic variations:

energy monitor calibration	± 5 %
online energy monitor — energy monitor correlation	± 8 %
overall energy density measurement reproducibility	± 15 %
overall energy density measurement uncertainty	± 23 %

Test procedure

Number of sites per specimen:	typ. 40, 10 specimens
Arrangement of test sites:	equally spaced
Minimum distance between sites:	4 mm
Damage detection:	video microscope, scatter measurement
Storage of the specimen:	sealed PMMA-cabinet, dessication with silica gel
Test environment:	industrial environment
Cleaning:	dust off with dry nitrogen

Test Result

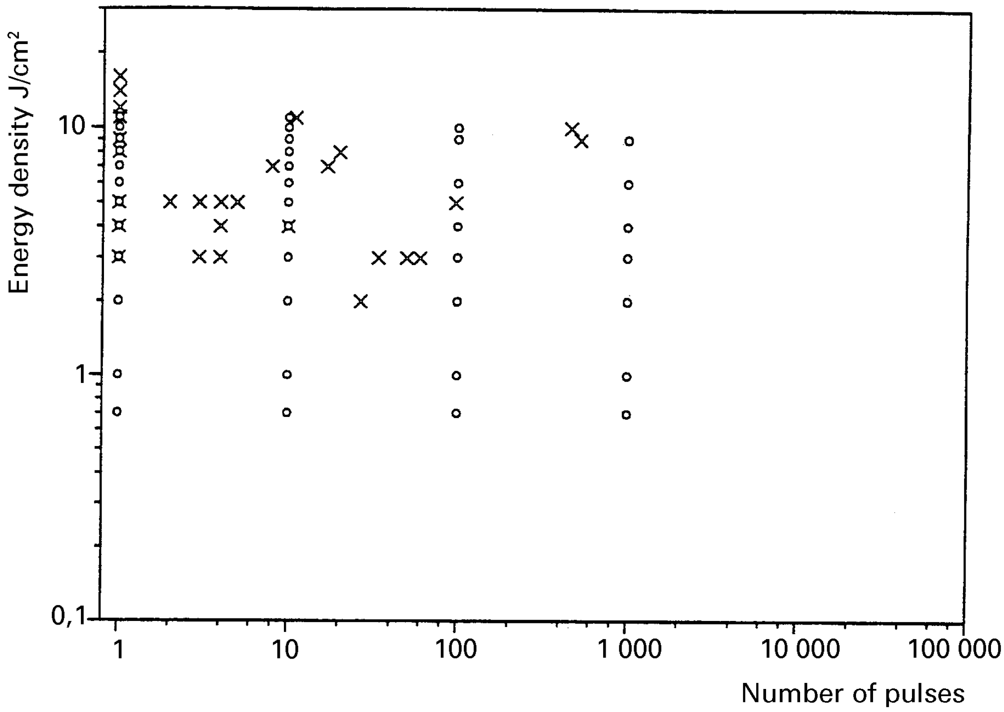


Figure A.1 — Distribution diagram of damage and non-damage regions

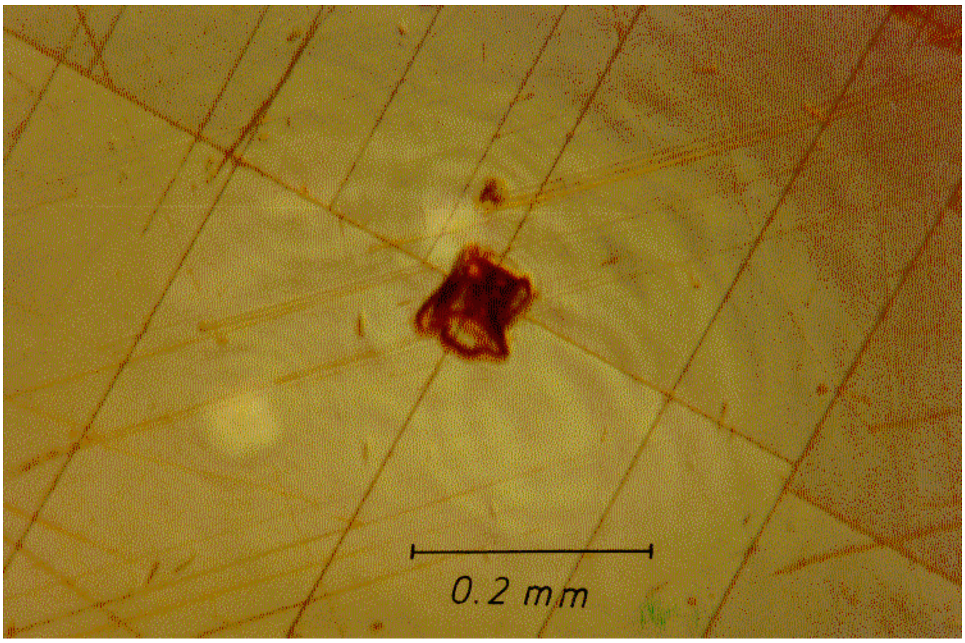


Figure A.2 — Nomarski micrograph for an energy density of 14,6 J/cm^2, number of pulses: 7

Comment: Damage induced by inclusions at the surface or in the bulk of the component.

Annex B
(informative)

Example of a measurement procedure

B.1 General

This annex describes an example for a measurement procedure, which has been developed for a special laser-induced damage threshold measurement facility with a high repetition Nd:YAG-laser. The basic structure of the procedure is oriented towards an efficient determination of the laser-induced damage threshold on the basis of a minimum number of test sites.

In the first initialization step, the fundamental parameters of the test are calculated or defined. The initialization also includes a preliminary test routine for an estimation of the actual damage threshold. In the second step, the sites on the sample surface are interrogated and the data are collected. On the basis of the data recorded during the preceding test cycles, a recommended energy level is calculated for the subsequent site on the sample surface. For this purpose, an individual model for the damage probability as a function of the energy density is to be included in the calculation. In the present example, this model is based on the logistic regression for binary data. However, any statistical or physical model can be employed for the simulation of the damage behaviour. The final step of this measurement procedure example consists of the evaluation of the collected data and the computation of the damage probability curve.

B.2 Initialization of the measurement procedure

B.2.1 Test parameters

In the initialization procedure, the fundamental test parameters are specified on the basis of the intended application, information available from former tests of similar samples and the specific limitations of the damage measurement facility.

The following definitions apply for the test procedure example:

Table B.1 — Definitions for the test procedure

Symbol	Meaning
N_L	minimum pulse number for data evaluation: $0 < N_L < N_P$
A_{optic}	area of the sample available for the damage test
d_{sep}	separation of test sites in terms of spot size $d_{T,eff}$
δQ	minimum interval width of energy classes
$P_N(Q)$	damage probability after N pulses (specific model)
δ_N	uncertainty of the fit $P_N(Q)$

B.2.2 Total number of test sites for the test, N_{TS}

From the area, A_{optic}, on the sample available for the damage test, the beam diameter, $d_{T,eff}$, and the separation of test sites in terms of laser spot size, d_{sep}, the total number, N_{TS}, of test sites can be determined. Assuming that the dimensions of the area available for the test are large compared to the separation between the test sites, the following approximations may be applied.

If a rectangular array of test sites is assumed, the total number of sites is determined by:

$$N_{TS} = \frac{A_{optic}}{(d_{sep} d_{T,eff})^2} \tag{B.1}$$

In the case of an arrangement of the test sites according to a hexagonal close-packed (HCP) structure, a factor of $2/\sqrt{3}$ has to be introduced in equation (B.1):

$$N_{TS} = \frac{2}{\sqrt{3}} \frac{A_{optic}}{(d_{sep} d_{T,eff})^2} \tag{B.2}$$

In this HCP-arrangement, all next-neighbour test sites are $d_{sep} \cdot d_{T,eff}$ apart. As minimum conditions for the method of characteristic damage curve, the value of N_{TS} should exceed 100 sites, and d_{sep} should range between 3 and 5 for a beam with a Gaussian spatial distribution.

B.2.3 Minimum number of pulses, N_L

The minimum number of pulses per site is selected according to the intended application of the samples and the pulse counting and switching uncertainty of the on-line damage detection system. In most S-on-1 damage threshold measurements, $N_L = 1$ will be preferred, because this selection includes the important case of 1-on-1 damage. However, a higher value might be chosen for N_L in the case of damage threshold measurements involving very high repetition rates in the kHz-regime. Also, for laser components in special applications with restricted operation conditions, a higher value of N_L might be advantageous. The maximum number of pulses per site, N_P, is dependent on the accuracy required for the extrapolation of the characteristic damage curve for high pulse numbers, and it is restricted by the measurement time reasonable for the damage test.

B.2.4 Energy resolution, δQ

The energy resolution, δQ, is to be selected according to the energy-reproducibility of the test laser in conjunction with the attenuation system.

B.2.5 Fitting function, $P_N(Q)$, and uncertainty, δ_N

For the calculation of the recommended energy value for the subsequent test site, an individual model for the damage probability, $P_N(Q)$, has to be included. The probability, $P_N(Q)$, is a function of energy density and contains, besides the number of pulses, N, a set of characteristic parameters. The uncertainty, δ_N, is a quantity which describes the deviation of a parametric fit of the probability function, $P_N(Q)$, from the measured data for a given value of N.

In this example, the inverse logistic function commonly used for the analysis of binary data (see reference [4] in the Bibliography), is applied:

$$P_N(Q) = \frac{\exp(a_N + b_N \cdot Q)}{1 + \exp(a_N + b_N \cdot Q)} \tag{B.3}$$

where a_N and b_N are characteristic parameters to be fitted according to the measured data for a given value of N. As uncertainty, δ_N, the standard deviation of the fit is used.

B.3 Initial test

An initial test is necessary to obtain a data base for the calculation of the energy values of the subsequent test procedure. For this purpose, at least 10 sites are to be subjected to pulse trains of N_P pulses with energy values, which are selected in respect of an estimation of the energy interval meaningful for the test. Therefore, it is important to find energy values for sites tested without damage after N_P shots, as well as energy values for sites tested with damage after at least N_L shots.

B.4 Test procedure

During the test procedure, the results of the current damage test are used for fitting the damage behaviour of the sample to a theoretical model. The theoretical model describes the damage probability of the sample surface as a function, $P_N(Q)$, of the pulse number, N, and the energy, Q. It might be based on the description of damage mechanisms or statistical algorithms specific for the actual sample type. The fit parameters of this model are recalculated after each interrogation of the sample. By evaluation of the damage behaviour predicted by this recalculated modelling, the energy value, Q_{NS}, for the following test site is determined. The major criterion for the determination of this energy value is the improvement of the uncertainties δ_{N_L}, δ_{N_P} for the damage probabilities $P_{N_L}(Q)$, $P_{N_P}(Q)$. These steps are repeated until the test surface is exhausted or the required uncertainty of the characteristic damage curve is reached. The algorithm for the test procedure is illustrated for an example involving a statistical model (logistic regression) in the following:

The initial fit parameters are computed by using the data of the initial test routine.

Step 1: Initialization (see equation B.2).

Step 2: For pulse numbers N_L and N_P, compute the damage probability fit curves $P_{N_L}(Q)$, $P_{N_P}(Q)$ and their uncertainties δ_{N_L}, δ_{N_P} by a fit to the currently available data set.

In the example given above (see equation B.3), the parameter sets (a_{N_P}, b_{N_P}) and (a_{N_L}, b_{N_L}) have to be calculated independently for both pulse numbers. An iteration procedure for this special case is given in clause B.2.

Step 3: An auxiliary variable n is calculated: The variable n may adopt the value N_L or N_P, depending on which corresponding uncertainty δ_{N_L} or δ_{N_P} is higher:

$$n = \begin{cases} N_L, & \text{if } \delta_{N_L} > \delta_{N_P} \\ N_P, & \text{else} \end{cases} \tag{B.4}$$

The energy range between Q_L and Q_H, indicating the increase of damage probability from $P_n(Q_L) = 5\ \%$ up to $P_n(Q_H) = 95\ \%$ is divided into a series of intervals:

$$\left[Q_L + i \cdot \mathrm{d}Q, Q_L + (i+1) \cdot \mathrm{d}Q\right] \tag{B.5}$$

where i is a counting variable for the ajar interval {(Q_L,dQ,i)}. The interval width dQ is given by the maximum of the resolution δQ and the energy range divided by the square root of N_{TS}.

$$\mathrm{d}Q = \max(\delta Q, \frac{Q_H - Q_L}{\sqrt{N_{TS}}}) \tag{B.6}$$

Example: In the case of the logistic function, the energy range is given by the following approximations:

$$Q_L = \max(-\frac{a_n + 2{,}94}{b_n}, 0) \quad \text{and} \quad Q_H = \max(-\frac{a_n - 2{,}94}{b_n}, 0) \tag{B.7}$$

NOTE The damage probability values of 5 % and 95 % are suitable for the selected logistic function. If other models are applied, these limits may have to be adjusted.

Step 4: Randomly select one interval [Q_L,dQ,r] of those with a minimum number of data points collected in the preceding interrogations. The energy value, Q_{NS}, for the next site is given by the position of this interval:

$$Q_{NS} = Q_L + (r + 0{,}5) \cdot dQ \quad \text{(B.8)}$$

Step 5: Subject the next site to the calculated energy, $Q_{NS.}$ If test sites are left go to Step 1, if not stop the measurement cycle and start the evaluation of the collected data.

B.5 Evaluation of the test

In the final step of the algorithm, an evaluation procedure of the data stored during the test routine is performed in accordance with 6.2.

Annex C
(informative)

Extrapolation method for S-on-1 tests

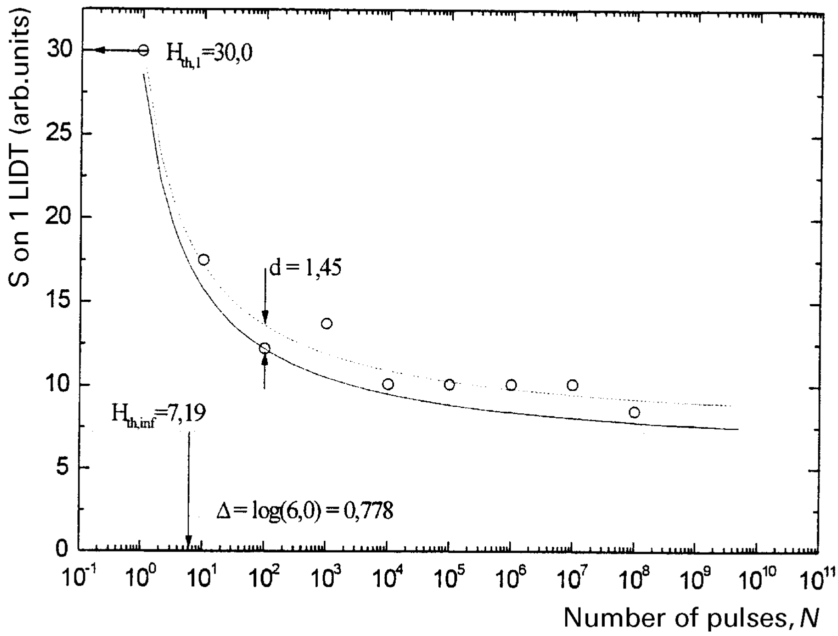
In this annex, a formula is described allowing for an extrapolation of the S-on-1 damage threshold H_{th} for large numbers, N, of pulses. The extrapolation model is based on three fit parameters $H_{th,1}, H_{th,\infty}$ and Δ, which can be interpreted as characteristic parameters of the damage behaviour:

$$H_{th}(N) = H_{th,\infty} + \frac{H_{th,1} - H_{th,\infty}}{1 + \frac{1}{\Delta}\log_{10}(N)} + d \tag{C.1}$$

In this equation, the parameter $H_{th,1}$ describes the 1-on-1 damage threshold, meanwhile $H_{th,\infty}$ can be considered as the endurance limit of the optical surface. The parameter Δ is given by the intersection of the tangent at the point (1, $H_{th,1}$) and the constant level $H_{th,\infty}$ (see also Figure C.1), and it describes the decrease of the characteristic damage curve with the number of pulses. These three parameters, $H_{th,1}, H_{th,\infty}$ and Δ, are calculated by a least square fit routine keeping the constant d equal to zero. The resulting characteristic damage curve is a realistic estimation for the lifetime of the tested specimen (see Figure C.1, fit). The constant d is introduced in equation (C.1) for a displacement of the characteristic curve towards smaller damage thresholds in order to mark the safe operations limit of the specimen (see Figure C.1, shifted fit). As a recommendation, the displacement is chosen such that the displaced curve is intercepting the measured data point with the lowest damage threshold.

EXAMPLE

Consider the data collected for a typical coating given in Figure C.1. For this experiment, a least square fit gives $H_{th,1} = 30{,}0$, $H_{th,\infty} = 7{,}19$ and $\Delta = 0{,}778$. This realistic characteristic damage curve is displaced by $d = 1{,}45$ in order to mark the safe operations limit. The displacement $d = 1{,}45$ corresponds to an intercept of the displaced characteristic damage curve with the lowest damage threshold measured for 100 pulses.



Key

○ Data

···· Fit

— Shifted fit

Figure C.1 — Measured S-on-1 damage threshold as a function of pulse number, N, with fit according to equation C.1 (laser mirror, 248 nm)

Annex D
(informative)

Units and scaling of laser-induced damage thresholds

D.1 General

It is the purpose of this annex to inform the user of potential dangers in scaling results of a damage threshold measurement when applied to different conditions.

Excluding environmental conditions, damage is a function of material properties and the laser parameters, in particular wavelength, spot size and irradiation duration. Scaling broadly falls into three groups, depending on the component properties.

For pulsed laser irradiation in insulators, the laser-induced damage threshold correlates with dielectric breakdown. The laser-induced damage thresholds in this case are usually reported in units of watts per square centimetre (W/cm^2). Where dielectric breakdown is the dominant mechanism, there are four regimes where the scaling laws with respect to pulse duration are different. In this case, a statement of laser-induced damage threshold specifically states wavelength, spot size and pulse duration.

For absorbing and semi-transmitting materials and coatings, where the laser pulses are short with respect to the thermal diffusion time, the laser-induced damage threshold is driven by the energy density level, units of joules per square centimetre (J/cm^2). For those materials subjected to longer pulses, there is significant flow of heat out of the vicinity of the laser spot; the key parameter is peak power, which is expressed in watts (W).

For very long pulses or cw-operation, for all materials, the LIDT is thermally dominated, and scales with linear power density, whose units are watts per centimetre (W/cm).

D.2 Example of incorrect scaling

This clause describes the pitfalls of an incorrect scaling and the potential dangers therein. This specific case deals with a mirror made of beryllium (Be-mirror). With a spot diameter of 0,33 mm, the maximum safe operating power is determined to be 56 W (power for cw-operation or average power for repetitive operation with long pulses). If this result is scaled using the power density as a variable to a beam size of 5 mm diameter, the safe operating power is calculated to be 12,8 kW. When the LIDT is scaled in terms of the linear power density, the safe operating power is calculated to be 0,85 kW. The estimate of safe operating power obtained by scaling in power density is 15 times greater than the estimate derived from scaling in linear power density. If the Be-mirror were to be exposed to a laser with a spot diameter of 5 mm and 12,8 kW it would probably melt, causing an extreme safety problem.

Bibliography

[1] ISO 11146:1999, *Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor*.

[2] ISO 11254-1:2000, *Lasers and laser-related equipment — Determination of laser-induced damage threshold of optical surfaces — Part 1: 1-on-1 test*.

[3] ISO 11554:1998, *Optics and optical instruments — Lasers and laser-related equipment — Test methods for laser beam power, energy and temporal characteristics*.

[4] McCullagh, P and Nelder, J.A. Generalized Linear Models, 2. edition, Chapman and Hall, London 1989. ISBN 0-412-31760-5. Chapter 4, Binary data.

Damage in laser glass

[5] ASTM STM STP 469 (1969)

Damage in laser materials

[6] NBS SP 341 (1970)

[7] NBS SP 356 (1971)

Laser-induced damage in optical materials (1972 - 1995)

[8] NBS SP 372 (1972)

[9] NBS SP 387 (1973)

[10] NBS SP 414 (1974)

[11] NBS SP 435 (1975)

[12] NBS SP 462 (1976)

[13] NBS SP 509 (1977)

[14] NBS SP 541 (1978)

[15] Index of Papers 1969 - 1978 (1979)

[16] NBS SP 568 (1979)

[17] NBS SP 620 (1981)

[18] NBS SP 638 (1983)

[19] NBS SP 669 (1984)

[20] NBS SP 688 (1985)

[21] NBS SP 727 (1986)

[22] NBS SP 746 (1987)

[23] NBS SP 752 (1987)

[24] NBS SP 756 (1988)

[25] NBS SP 775 (1989)

[26] NBS SP 801, ASTM STP 1117, and SPIE Vol. 1438 (1989)

[27] ASTM STP 1141, and SPIE Vol. 1441 (1991)

[28] SPIE Vol. 1624 (1992)

[29] SPIE Vol. 1848 (1993)

[30] SPIE Vol. 2114 (1994)

[31] Index: 1969 - 1993, SPIE Vol. 2162 (1994)

[32] SPIE Vol. 2428 (1995)

[33] SPIE Vol. 2714 (1995)

[34] SPIE Vol. 2966 (1997)

[35] SPIE Vol. 3244 (1998)

[36] SPIE Vol. 3578 (1999)

ICS 31.260

Price based on 28 pages