BS EN ISO 21254-2:2011

BSI Standards Publication

# Lasers and laser-related equipment — Test methods for laser-induced damage threshold

## Part 2: Threshold determination (ISO 21254-2:2011)

## National foreword

This British Standard is the UK implementation of EN ISO 21254-2:2011. Together with BS EN ISO 21254-1:2011, it supersedes BS EN ISO 11254-1:2000 and BS EN ISO 11254-2:2001 which are withdrawn.

The UK participation in its preparation was entrusted to Technical Committee CPW/172/9, Electro-optical systems.

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**Compliance with a British Standard cannot confer immunity from legal obligations.**

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English Version

## Lasers and laser-related equipment - Test methods for laser-induced damage threshold - Part 2: Threshold determination (ISO 21254-2:2011)

Lasers et équipements associés aux lasers - Méthodes d'essai du seuil d'endommagement provoqué par laser - Partie 2: Détermination du seuil (ISO 21254-2:2011)

Laser und Laseranlagen - Prüfverfahren für die laserinduzierte Zerstörschwelle - Teil 2: Bestimmung der Zerstörschwelle (ISO 21254-2:2011)

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# Foreword

This document (EN ISO 21254-2:2011) has been prepared by Technical Committee ISO/TC 172 "Optics and photonics" in collaboration with Technical Committee CEN/TC 123 “Lasers and photonics” the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by January 2012, and conflicting national standards shall be withdrawn at the latest by January 2012.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document supersedes EN ISO 11254-1:2000, EN ISO 11254-2:2001.

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**Endorsement notice**

The text of ISO 21254-2:2011 has been approved by CEN as a EN ISO 21254-2:2011 without any modification.

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# 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 2.

The main task of technical committees is to prepare International Standards. 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 document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21254-2 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

This first edition of ISO 21254-2:2011, together with ISO 21254-1:2011, cancels and replaces ISO 11254-1:2000 and ISO 11254-2:2001, which have been technically revised.

ISO 21254 consists of the following parts, under the general title *Lasers and laser-related equipment — Test methods for laser-induced damage threshold*:

— *Part 1: Definitions and general principles*

— *Part 2 : Threshold determination*

— *Part 3: Assurance of laser power (energy) handling capabilities*

— *Part 4: Inspection, detection and measurement* [Technical Report]

# Introduction

This part of ISO 21254 specifies test methods for determining single-shot and multiple-shot laser-induced damage thresholds (LIDTs) of optical components, both coated and uncoated. The aim is to provide methods which will enable measurement results to be obtained which are consistent and can be rapidly and accurately compared between different test laboratories.

In the single-shot test, which is referred to as the 1-on-1 test in this International Standard, each unexposed site on the sample surface is subjected to only one pulse of laser radiation. Repeated laser radiation pulses can damage optical components, or otherwise cause them to deteriorate, at irradiation levels below those measured for single-shot damage. Besides reversible effects induced by thermal heating and distortion, irreversible damage due to ageing, microdamage and the generation or migration of defects is observed. The degradation of the optical quality is a function of the laser operating parameters and the optical system in which the component is located. The multiple-shot test, referred to as the S-on-1 test, is based on a protocol that uses a series of pulses with constant energy density at each unexposed test site.

In addition to an evaluation technique based on the survival curve for 1-on-1 tests, this part of ISO 21254 also describes two methods for the reduction of raw data obtained from S-on-1 damage tests: one using the characteristic damage curve and the other an extrapolation technique. The characteristic damage curve method calls for S-on-1 testing at a large number of sites on the optical surface of the specimen and generation of a set of three graphs indicating energy density values corresponding to probabilities of damage 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 of S-on-1 testing, the extrapolation method, uses a considerably smaller number of test sites. This method generates a distribution diagram of the damaged and undamaged regions for the behaviour of the damage threshold as a function of the number of pulses per site. This diagram is of limited reliability but may be employed for the quality control of optical laser components which have already been qualified by a complete damage test or as part of the preparation for extended damage testing.

Realistic laser damage tests suitable for industrial applications require a large number of pulses ($10^9$ to $10^{11}$ pulses) and hence involve a disproportionate experimental cost. This part of ISO 21254 therefore also outlines a procedure for obtaining the S-on-1 threshold by extrapolation of the characteristic damage curve in order to estimate the real lifetime of an optical component.

NOTE It should be realized that the laser-induced damage threshold of an optical component which is subjected to repeated pulses of 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 component mounting conditions. For these reasons, it is necessary to record all the parameters and to bear in mind that the damage behaviour might differ in tests carried out in different operating conditions.

The test procedures described in this part of ISO 21254 are applicable to all combinations of laser wavelengths and pulse lengths. However, comparison of laser damage threshold data can be misleading unless the measurements have been carried out at the same wavelength, using the same pulse length and beam diameter. Definitions and the general principles of laser-induced damage threshold measurements are given in ISO 21254-1.

# Lasers and laser-related equipment — Test methods for laser-induced damage threshold —

# Part 2: Threshold determination

**WARNING — The extrapolation of damage data can lead to an overestimation of the laser-induced damage threshold. In the case of toxic materials (e.g. ZnSe, GaAs, CdTe, $ThF_4$, chalcogenides, Be, Cr, Ni), this can lead to serious health hazards. See ISO 21254-1:2011, Annex A, for further comments.**

## 1 Scope

This part of ISO 21254 describes 1-on-1 and S-on-1 tests for the determination of the laser-induced damage threshold of optical laser components. It is applicable to all types of laser and all operating conditions.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 21254-1:2011, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 1: Definitions and general principles*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and ISO 21254-1 apply.

## 4 Test methods

### 4.1 General

The general principles of laser-induced damage threshold measurements, and the apparatus and sampling techniques used, are described in ISO 21254-1.

### 4.2 1-on-1 test method

#### 4.2.1 General

In the 1-on-1 test, each unexposed site on the surface of the sample is exposed to a single laser pulse with defined beam parameters. From the experimental data, a plot depicting the probability of damage as a function of the energy density or power density is constructed.

### 4.2.2 Test parameters

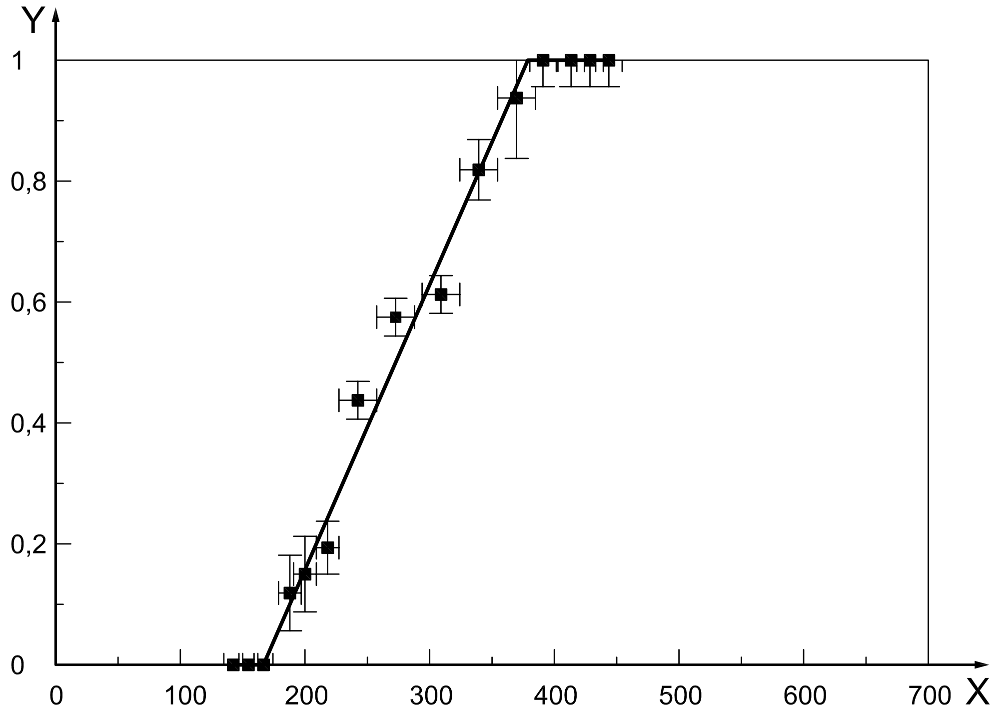
The test equipment shall be characterized by the parameters described in ISO 21254-1:2011, 6.2.6.5.

### 4.2.3 Procedure

Test sites are positioned in the beam and irradiated by single shots of laser radiation with different energy densities or power densities. Expose a minimum of ten sites to one preselected pulse energy (or beam power) and record, for each site, the actual pulse energy (or beam power) measured by the beam diagnostic unit as well as the state of damage after irradiation (damage or no damage). Repeat this sequence for other pulse energies or beam powers. The range of pulse energies or beam powers employed shall be sufficiently broad to include low values which result in no damage at any site and sufficiently high values which induce damage at each site tested.

### 4.2.4 Evaluation of measurements

Damage threshold data are obtained by the damage-probability method. To construct a plot of the probability of damage versus the quantity in terms of which the laser-induced damage threshold is to be expressed, the probability of damage is determined for each energy-density or power-density increment by calculating the ratio of the number of damaged sites to the total number of sites tested. Linear extrapolation of the damage-probability data to zero damage probability yields the threshold value. An example is shown in Figure 1.




**Key**

X energy, in millijoules

Y damage probability

NOTE The test conditions were as follows: $d_{86,5}$ = 1,44 mm, $\lambda$ = 10,6 µm, $\tau_H$ = 100 ns, tail 3,5 µs (TEA $CO_2$ laser), specimens: KBr windows, 50 items, diameter 40 mm.

**Figure 1 — Graph for the determination of the damage threshold from experimental data**

In the case of a laser system with a high pulse-to-pulse energy variation, it is permissible to expose the specimen to arbitrary pulse energies and to sort the data with respect to appropriate energy intervals after the test.

NOTE 1 Examples of an efficient measurement procedure giving maximum accuracy for a given number of sites are presented in Annex A and Annex C for the 1-on-1 and the S-on-1 test, respectively.

NOTE 2 The diameter of the test beam at the specimen position can influence the measurement result. Therefore, the beam diameter has to be kept constant throughout the entire measurement procedure.

## 4.3 S-on-1 test method

### 4.3.1 General

To determine the S-on-1 damage threshold, extensions of the set-up and procedure for 1-on-1 test damage threshold measurement are necessary. However, a measurement facility for S-on-1 tests can be used for 1-on-1 measurements if the online damage-detection system is combined with a Nomarski-type differential interference contrast microscope. It is recommended that the online damage-detection system have a facility for cutting off subsequent pulses and for stopping the pulse counter.

### 4.3.2 Test parameters

The test equipment shall be characterized by the parameters described in ISO 21254-1:2011, 6.2.6.5, and the following additional parameters:

a) number of pulses per site $S$;

b) total number of sites per test $N_{\mathrm{ts}}$.

NOTE For the S-on-1 test, the parameters given in ISO 21254-1:2011, 6.2.6.5 d) to g), refer to the properties of the typical pulse defined in ISO 21254-1:2011, 6.2.6.4.

### 4.3.3 Procedure

An unexposed test site is positioned in the beam and irradiated by a series of $S$ pulses, the pulse typical of the series having an energy $Q_{\mathrm{tp}}$. If damage is observed by the online damage detection system before the series of $S$ pulses is completed, stop the irradiation of the site and record the minimum number of pulses $N_{\mathrm{min}}$. Repeat this procedure for different energies of the typical pulse. The number of pulses $S$ shall be constant for the entire test procedure, and it shall be selected such that the S-on-1 test records the specific laser-induced damage behaviour of the specimen.

### 4.3.4 Evaluation of measurements

#### 4.3.4.1 General

After inspecting the specimen, the result of the S-on-1 test described above is a file of data points of the type

$(Q_{\mathrm{tp}}, N_{\mathrm{min}})$, where $N_{\mathrm{min}} \leqslant S$ in the case of damage,

$(Q_{\mathrm{tp}}, S)$ when no damage is detected

The evaluation of the data obtained (see Figure 2) may be performed using the characteristic damage curve (see 4.3.4.2) or the extrapolation method (see 4.3.4.3). The method using the characteristic damage curve allows accurate determination of the laser-induced damage threshold. This accurate technique should be used for fundamental investigations and for the testing of prototype components. The extrapolation method, on the other hand, is a practical technique for estimating the S-on-1 threshold for a large number of pulses.

### 4.3.4.2 Characteristic damage curve

The procedure for determining the S-on-1 damage threshold (see 4.3.3) is carried out and the resulting file of data points is recorded. For the evaluation to have 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 following relationship:

$$N_{ms} = 5 \times \text{integral value of } (1 + \log_{10} S) \tag{1}$$

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

Damage-probability values for a defined number $N$ of pulses and a specified energy $Q$ 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 with the experimental set-up. For the calculation of the damage probability for a certain energy $Q$ 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 which are damaged, whereas data points with $N_{min} > N$ or $S \geqslant N$ correspond to sites not damaged in the energy interval considered. The damage probability for the energy $Q$ is calculated as the ratio of the number of data points corresponding to damaged sites to the total number of data points considered in the evaluation.

NOTE 1 The value of $\Delta Q$ has to be chosen such that a significant fraction of data points is available for a distinct interval $[Q - \Delta Q, Q + \Delta Q)$. The value of $\Delta Q$ is kept constant during the evaluation procedure, and it determines the statistical error of the threshold values. An example of an efficient measurement procedure with suitably selected parameters is given in Annex C.

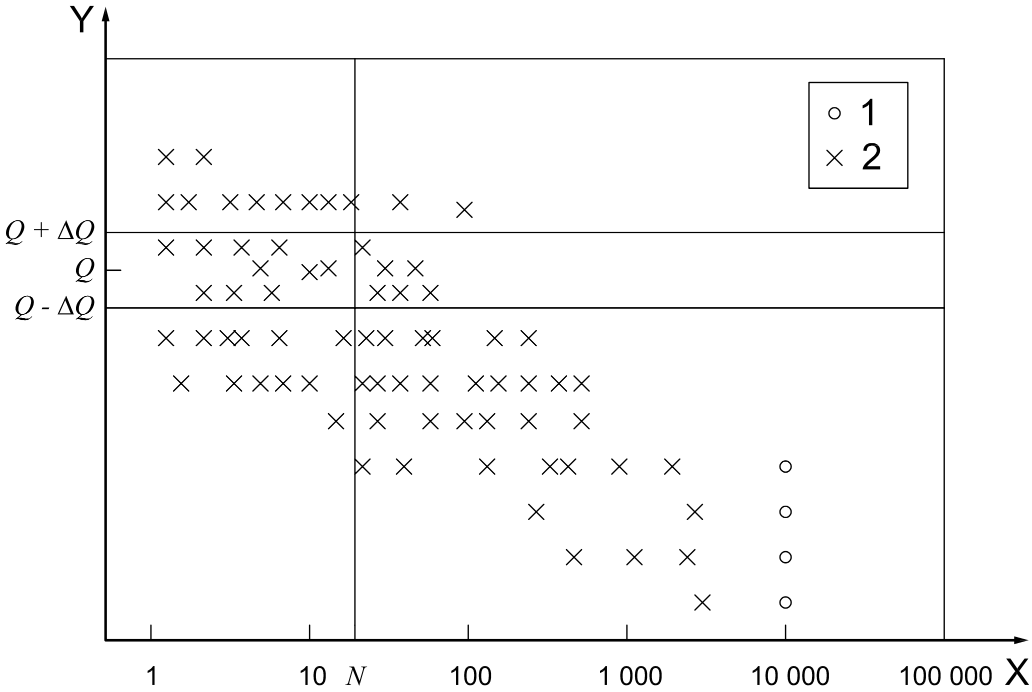
This procedure is repeated for other values of the energy $Q$ to generate a data set of damage-probability values for the selected number $N$ of pulses. The resulting data set represents discrete points on a damage-probability curve which is plotted versus the energy of the typical pulse. From this curve,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

Linear extrapolation of the damage-probability curve to zero damage probability yields the threshold energy (see 4.2.4) which shall be converted into units of threshold energy density $H_{th}$ or threshold power density $E_{th}$.

Linear extrapolation using the two data points next to the targeted damage probability is sufficient. If a large number of data points are available, more sophisticated extrapolation methods are permitted. The extrapolation procedure used shall be stated in the test report.

In Figure 2, data points corresponding to damaged spots are represented by × and those corresponding to undamaged spots are represented by o. The evaluation procedure used for the damage-probability method is illustrated by the interval $[Q - \Delta Q, Q + \Delta Q)$ marked on the graph. More than one point can occur for a specific data pair ($Q_{tp}$, $S$) or ($Q_{tp}$, $N_{min}$) during the test. The number of points for a specific data pair may be indicated on the graph.

Figure 2 is an illustrative representation of a typical data set obtained in an S-on-1 laser-induced damage threshold (LIDT) test. Therefore, the pulse energy scale is given in arbitrary units, and no numbers are given to indicate the presence of identical data points.




**Key**

X number of pulses

Y pulse energy, in millijoules

1 undamaged

2 damaged

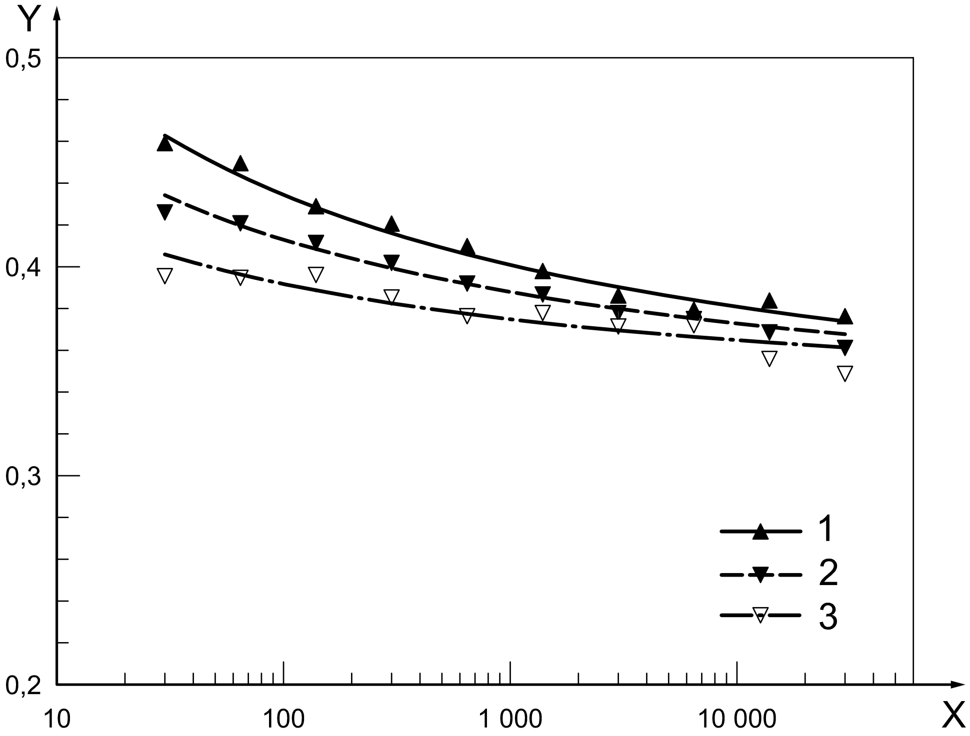
**Figure 2 — Data points resulting from damage testing**

To generate the characteristic damage curve, the algorithm described above is repeated for selected numbers $N$ of pulses to determine the corresponding energy values $Q_{10}$, $Q_{50}$, and $Q_{90}$. These values are converted into the units in which the damage threshold is expressed and plotted versus the number of pulses. The numbers of pulses shall be selected in a way that at least five data points are located in the significant region of the characteristic damage curve. Log-log coordinates are recommended for this plot to make it possible to carry out a linear extrapolation of the characteristic damage curve for large numbers of pulses (see Figure 3).

NOTE 2 Log-log coordinates might 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 might give information on the laser-induced ageing mechanisms involved (see Annex E).

### 4.3.4.3 Extrapolation method

A distribution diagram of damaged and undamaged regions can be generated on the basis of a test with a reduced number of data points. In the extrapolation method, S-on-1 test procedures are performed covering a range of numbers of pulses per test site that is appropriate for determining, by extrapolation, the S-on-1 damage threshold for a defined large number of pulses. A slightly modified test procedure (see 4.3.3) is performed for a selected set of data points. In this method, the number of pulses $S$ is varied during the test procedure, and it shall be selected such that a significant number of sites are irradiated with the selected number of pulses $S$. The irradiation of an individual test site is stopped after the defined number of pulses has been reached or damage has been detected. The result of this irradiation protocol is a set of data points ($Q_{tp}$, $S$, state of damage) represented by the energy of the typical pulse, the selected number of pulses, and the state of damage, respectively. For specimens which show self-quenching damage mechanisms, the extrapolation method can also be used in damage-testing facilities without an online damage detection system. In this case, each site is subjected to the selected number of pulses independently of the state of damage.




**Key**

X number of pulses

Y energy density, in joules per square centimetre

1 90 % LIDT

2 50 % LIDT

3 10 % LIDT

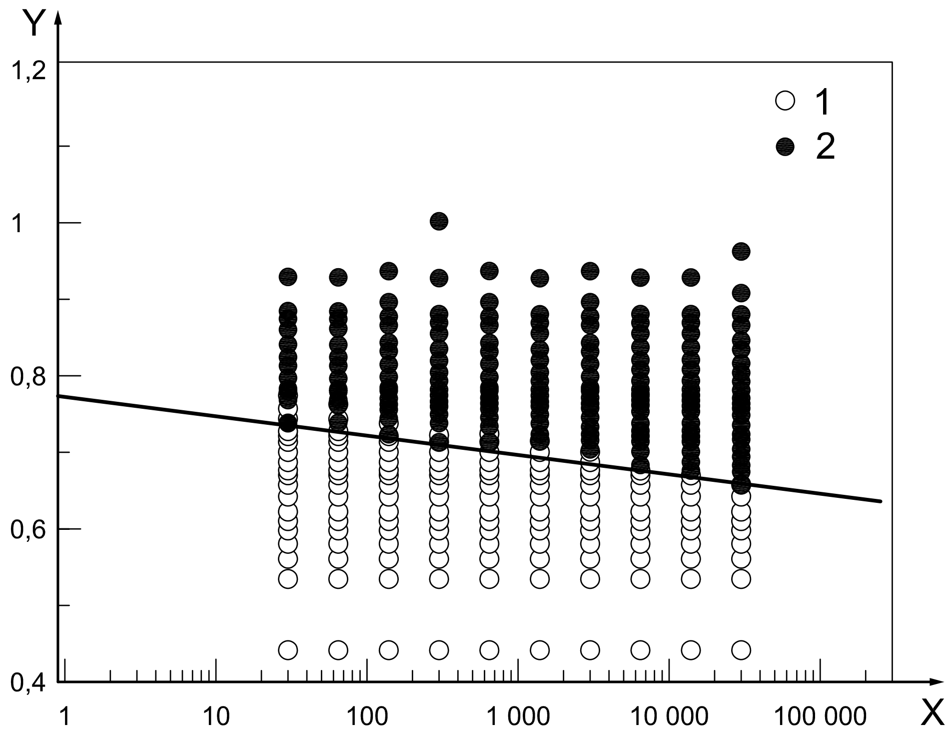
NOTE The test conditions were as follows: $\tau_{eff}$ = 130 fs, $d_{T,eff}$ = 87 µm, $\lambda$ = 780 nm, $f_p$ = 1 kHz, specimen: HR mirror ($Ta_2O_5/SiO_2$) for 780 nm.

**Figure 3 — Characteristic damage curve**

For each data point, the energy value $Q_{tp}$ is converted into the unit of energy density or power density and plotted as a graph presenting this value versus the number of pulses. By separating the data points with respect to the state of damage, the damaged and undamaged regions are indicated by the graph. This distribution diagram (see Figure 4) makes it possible to give an approximate estimation of the threshold energy density for large numbers of pulses.

NOTE Compared to the method using the characteristic damage curve, the extrapolation method is based on a considerably smaller number of S-on-1 test procedures, and it can be performed on one specimen. Although the reliability of the extrapolation method is limited, it might be sufficient for quality control of a production process already certified by a complete damage-probability test or as part of the preparation for extended damage testing. 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 also be deduced from the data file of the characteristic damage curve.

A particular data point $(Q_{tp}, S)_x$ with no damage can be considered to be an indication that no damage is likely to occur for lower pulse numbers $S$ for the energy value $Q_{tp,x}$. As a consequence, symbols indicating no damage can be plotted in the distribution diagram for all other selected values of $S$ which are lower than the pulse number $S_x$. A particular data point $(Q_{tp}, N_{min})_x$ with damage can be considered to be an indication that damage is likely to occur for all higher pulse numbers $S$ for the energy value $Q_{tp,x}$. As a consequence, symbols indicating damage can be plotted in the distribution diagram for all other selected values of $S$ which are higher than the pulse number $N_{min,x}$. Technical considerations or the statistical damage behaviour of the specimen might restrict the lowest number of $N_{min}$ which is detectable in a measurement facility. As indicated in Figure 4, a separation line can be drawn to indicate the energy/pulse regime with no damage of the specimen.




**Key**

X number of pulses

Y energy density, in joules per square centimetre

1 undamaged sites

2 damaged sites

NOTE The test conditions were as follows: $\tau_{eff}$ = 130 fs, $d_{T,eff}$ = 87 µm, $\lambda$ = 780 nm, $f_p$ = 1 kHz, specimen: HR mirror ($TiO_2/SiO_2$) for 780 nm.

**Figure 4 — Distribution diagram showing damaged and undamaged regions**

## 5 Accuracy

Prepare the calibration error budget outlined in ISO 21254-1 to determine the overall accuracy of the measurement facility. Variations in the pulse repetition rate, total energy or beam power, spatial profile and temporal profile shall be included in the error budget.

## 6 Test report

### 6.1 General

For the purpose of documenting and presenting the measurement data, the test report shall include the information specified in ISO 21254-1:2011, Clause 8, items a) to c), and the results for the type of test which was performed.

### 6.2 1-on-1 test

Information on the test result:

a) a Nomarski micrograph of a typical damaged test site, choosing a pulse energy or beam power in the damage-probability range between 20 % and 80 %;

b) a graph of the type shown in Figure 1;

c) the result of the test, given as $H_{th}$ or $E_{th}$ or $F_{th}$;

d) the total number of sites used for the test, $N_{ts}$.

It is recommended that a test report containing the test specifications and the test results be written and supplied to the customer. An example of such a test report is given in Annex B.

### 6.3 S-on-1 test

Information on the test result:

a) at least one Nomarski micrograph of a typical damaged test site, choosing a pulse energy in the damage-probability range between 20 % and 80 % for each number of pulses per site;

b) a graph of the kind shown in Figure 3 with data points joined by lines for S-on-1 damage-probability data or a graph of the kind shown in Figure 4.

In the event of changes in the damage mechanisms with the number of pulses, include a brief statement on the damage behaviour observed.

If possible, the supplier or the laboratory shall supply to the customer a test report containing the test specifications and the test results. An example of such a test report is given in Annex D.

# Annex A
(informative)

# Example of a measurement procedure (1-on-1 test)

## A.1 General

This annex describes an example of a measurement procedure for a 1-on-1 test. The basic structure of the procedure consists of three steps.

In the first (initialization) step, the fundamental parameters of the test are calculated or defined. The initialization may also include a binary search routine for an estimation of the actual damage threshold and for a determination of the energy density intervals for testing. In the initialization procedure, the fundamental test parameters are specified on the basis of the intended application and information available from former tests on specimens of similar design and materials.

In the second step, the specimen is interrogated and the data collected.

In the final step, the data collected are analysed and an estimate of the damage threshold and its uncertainty are calculated.

## A.2 Initialization of the measurement procedure

### A.2.1 Total number of test sites, $N_{ts}$

From the area $A_{opt}$ of the specimen available for the damage test, the beam diameter $d_{T,eff}$ and the separation of the test sites in terms of the laser beam diameter $d_{sep}$, the total number $N_{ts}$ of test sites can be determined. If a rectangular array of test sites is assumed, the total number of sites is given by:

$$N_{ts} = \frac{4A_{opt}}{(d_{sep}d_{T,eff})^2} \tag{A.1}$$

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

$$N_{ts} = \frac{8A_{opt}}{\sqrt{3}(d_{sep}d_{T,eff})^2} \tag{A.2}$$

In this HCP arrangement, all next-neighbour test sites are $d_{sep} \cdot d_{T,eff}$ apart. As minimum conditions for the damage frequency method, the value of $N_{ts}$ should exceed 75 and $d_{sep}$ should range between 1,25 and 5 for a beam with a Gaussian spatial distribution.

### A.2.2 Number of fluence steps, $n_{steps}$, probability resolution, $P_{res}$, number of damage sites, $n_{sites}$

Figure A.1 is used to determine the values of the probability resolution, $P_{res}$, and the number of sites to be damaged per fluence level, $n_{sites}$, for a given value of $N_{ts}$. For a given value of $N_{ts}$, the range of possible values of $P_{res}$ and $n_{sites}$ can be seen by following the contour for the value of $N_{ts}$ from left to right. For a sufficiently large value of $N_{ts}$, there is a large number of possible values for $P_{res}$ and $n_{sites}$, allowing great flexibility in the design of the test. For smaller values of $N_{ts}$, the choice of design is more limited.

If there is a history or suspicion of a tail of low probability, then the tester should opt for the smallest acceptable value of $P_{res}$. This will ensure, to the greatest extent possible, that a low-probability tail of this kind is seen by the interrogation protocol. If there is no history of, or concern over, a low-probability tail, then the preferred choice would be for $n_{sites}$ to have the largest possible value. The choice of a large value for $n_{sites}$ leads to the most accurate determination of the damage probability allowed in a particular area available for the test [see Equations (A.5) and (A.6)].

After the selection of $P_{res}$, Figure A.2 is used to determine the number of fluence levels, or fluence steps, used in the test, $n_{steps}$. The value of $n_{steps}$ is read directly off the curve in Figure A.2.

EXAMPLE Selection of $n_{sites}$ and $P_{res}$

Consider a test with 200 sites. The $n_{sites}$ contour for 200 allows values of $n_{sites}$ from 1 to 5 and corresponding values of $P_{res}$ from approximately 0,06 to 0,15. If there is concern over a low-probability tail, then the lower values of $P_{res}$, which allow more fluence levels to be interrogated, are recommended. If this concern is not present, then a higher value for $P_{res}$ is the preferred choice, because it will give higher accuracy in measuring of the damage probability.

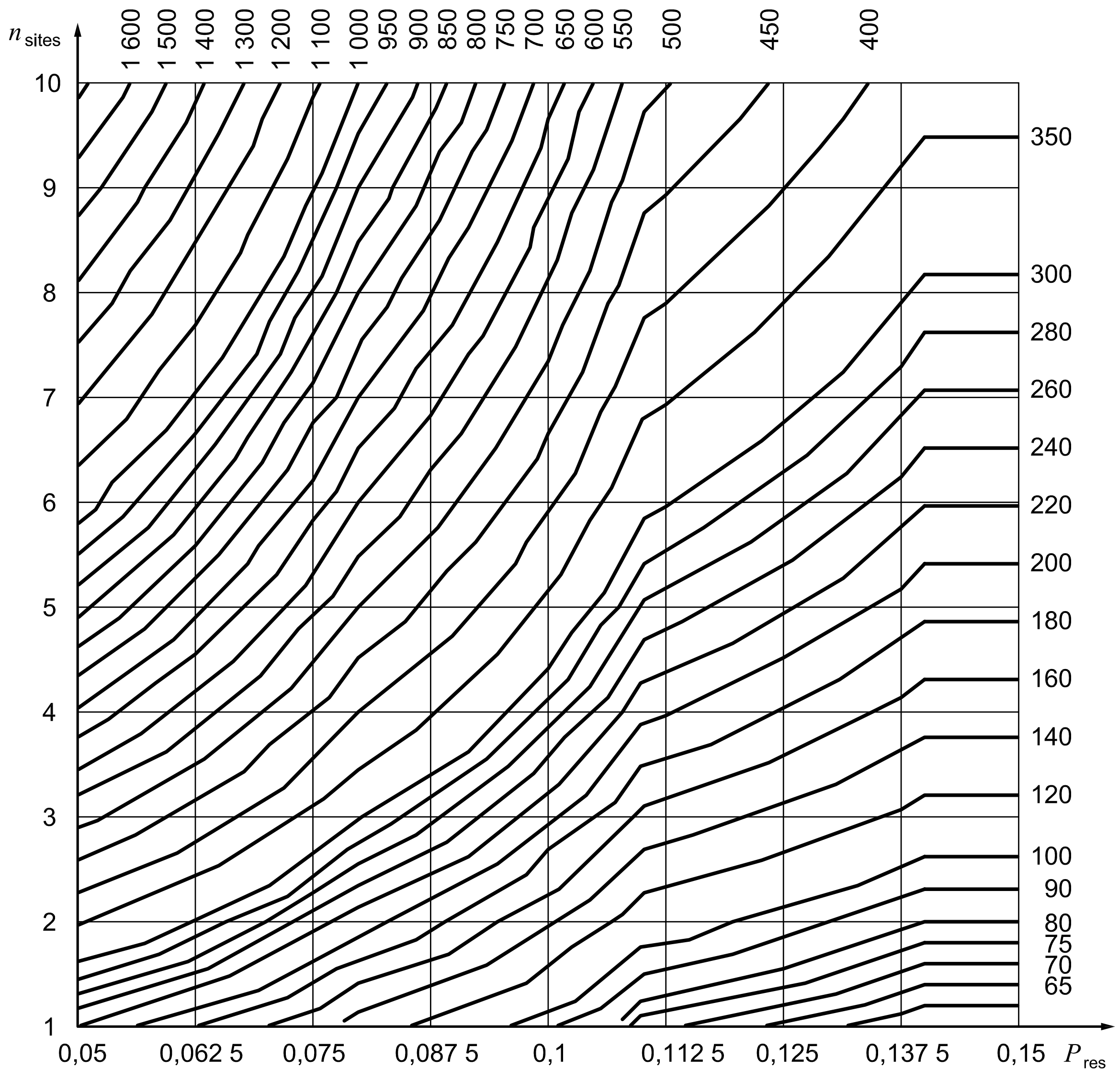



**Figure A.1 — Contour plot of $N_{ts}$**

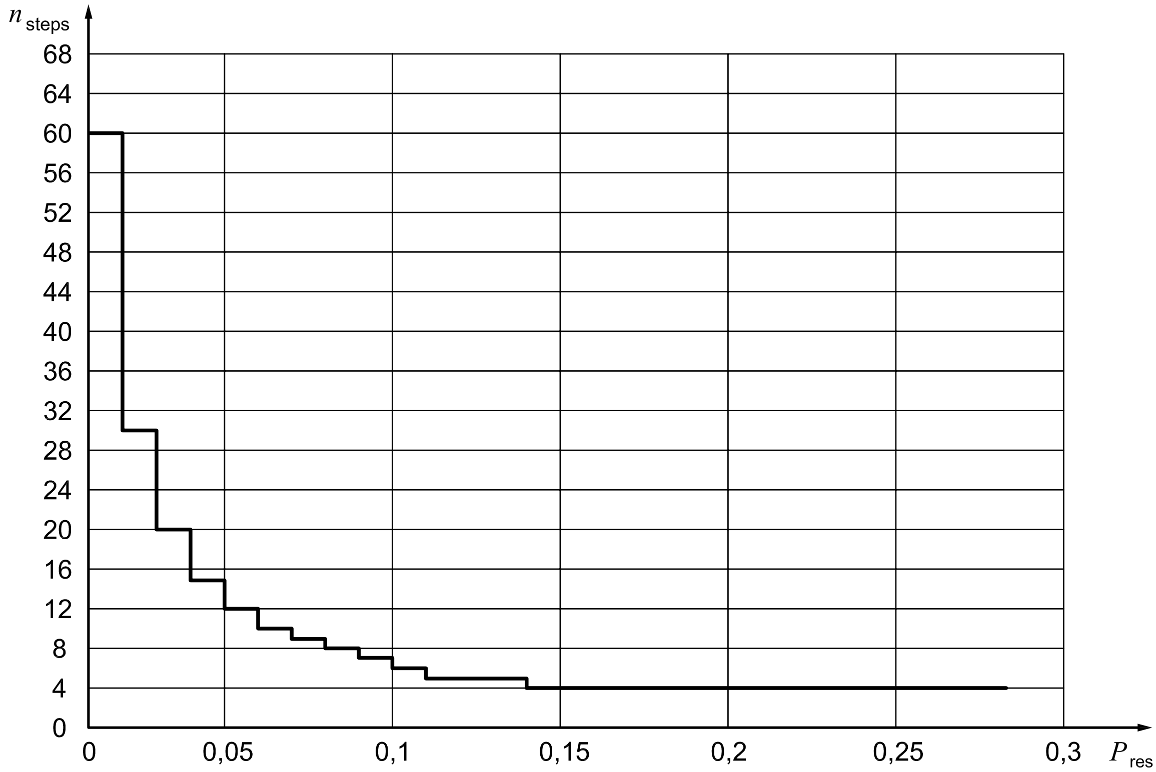



**Figure A.2 — Plot of $P_{res}$ versus $n_{steps}$**

### A.2.3 Top and bottom energy density levels, $H_{top}$ and $H_{bottom}$

The top and bottom energy density levels, $H_{top}$ and $H_{bottom}$, can be estimated from historical data available from previous damage tests on comparable specimens. The value of $H_{top}$ corresponds to an energy density value with approximately 60 % damage probability. The value of $H_{bottom}$ is near, but above, the estimated threshold. If historical data are not available, the values of $H_{top}$ and $H_{bottom}$ can be determined by a binary search routine, which is performed on the actual test area. A minimum number of 15 test sites should be used for this binary search routine. For large test areas with $N_{ts} > 150$, it is permissible to employ one-tenth of the total number of sites, $N_{ts}$, for this initial binary search.

### A.2.4 Resolution of energy density, $\delta H$

The energy density resolution is defined by the equation:

$$\delta H = \frac{H_{top} - H_{bottom}}{n_{steps}} \quad \text{(A.3)}$$

where $n_{steps}$ has been determined as described in A.2.2.

## A.3 Test routine

The algorithm for the irradiation sequence of the specimen is illustrated in Figure A.3. The initial energy density level $H_1$ is $H_{top}$. After interrogation of the first site, the state of damage is detected and recorded. The variables $n_i^{d}$ and $n_i^{nd}$ are counting variables for the number of sites damaged and not damaged, respectively, at the selected energy density level $H_i$. Irradiation of the sample at the $i$th level continues until at least 12 sites have been interrogated and $n_i^{d} = n_{sites}$ or $n_i^{nd} = 3/P_{res}$ without observation of a single damage site. When the irradiation is complete at the $i$th level and $n_{sites}$ sites have been damaged, the energy density level is decreased by $\delta H$. If $3/P_{res}$ shots at $H_i$ are taken without observation of a single damage site, the energy density level for the next value of $i$ is increased by 0,5$\delta H$ and by $\delta H$ for each level thereafter. This procedure is repeated until the whole test area has been used.

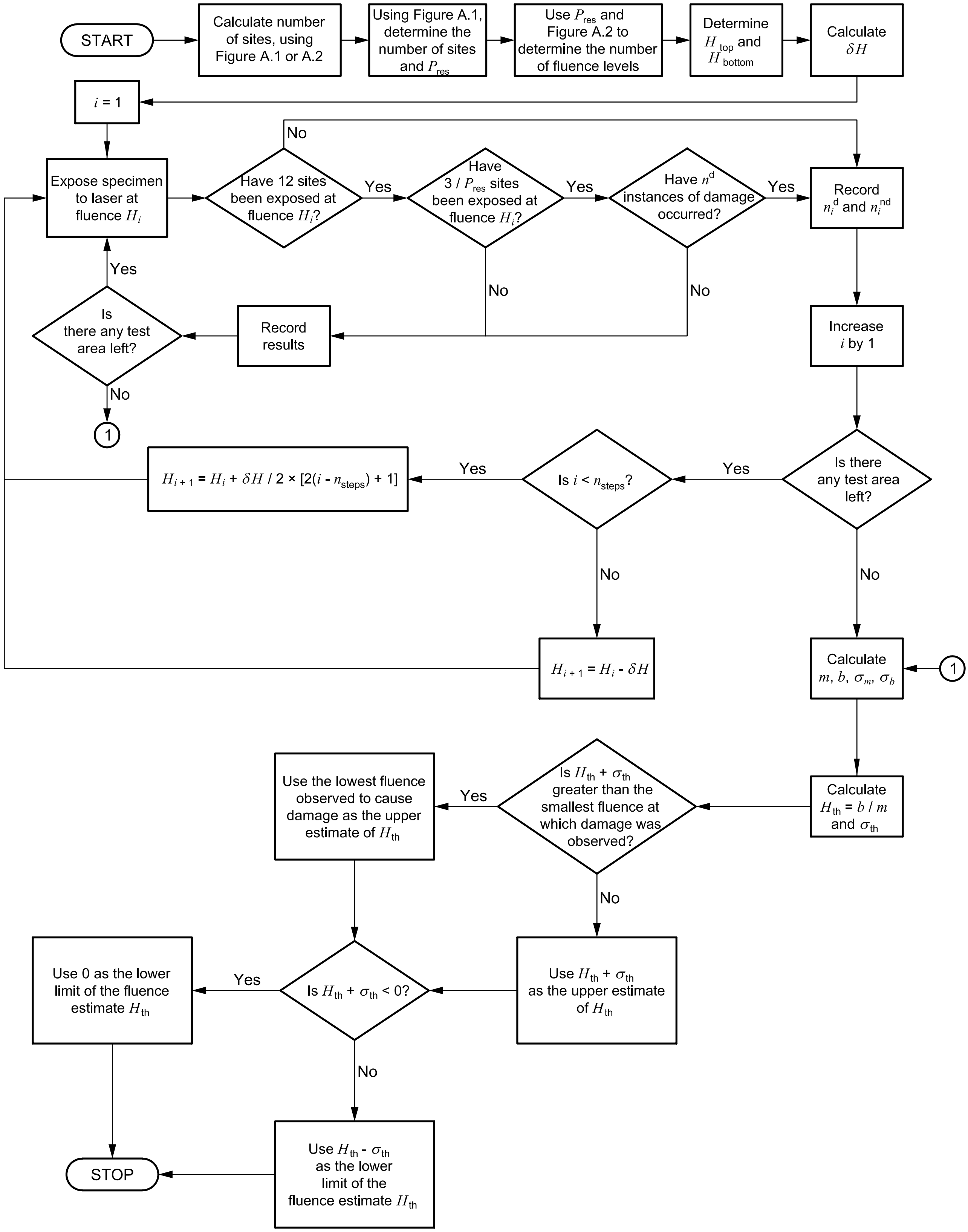



**Figure A.3 — Flow chart for test**

## A.4 Evaluation of the test results

The final step of the algorithm consists of an evaluation of the data stored during the test routine, as discussed below. For the determination of the damage threshold and the uncertainty in the result of the test, linear extrapolation of the measured damage probabilities is performed. For each energy density level $H_i$, the observed damage probability $P_i$ is calculated from the equation:

$$P_i = \frac{n_i^{\text{d}}}{n_i^{\text{d}} + n_i^{\text{nd}}} \tag{A.4}$$

where $n_i^{\text{d}} + n_i^{\text{nd}}$ is the total number of sites exposed to achieve $n_i^{\text{d}}$ damaged sites.

The uncertainty for each point $i$ in the data set is estimated using Equation (A.5) or Equation A.6):

$$\sigma_i = \sqrt{\frac{n_i^{\text{nd}}}{n_i^{\text{d}}\left(n_i^{\text{d}} + n_i^{\text{nd}}\right)} + \varepsilon_{\text{f}}^2} \qquad \text{when } n^{\text{d}} > 0 \tag{A.5}$$

$$\sigma_i = \sqrt{\varepsilon_{\text{f}}^2} \qquad \text{when } n^{\text{d}} = 0 \tag{A.6}$$

where $\varepsilon_{\text{f}}$ is the fractional uncertainty in the measured energy density.

The slope $m$ and intercept $b$ of the weighted linear fit to the measured damage-probability curve are calculated using Equations (A.7) and (A.8) and Equation (A.9), respectively:

$$m = \frac{1}{\Delta}\left[\left(\sum_i \frac{1}{\sigma_i^2}\right)\left(\sum_i \frac{P_i H_i}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)\left(\sum_i \frac{P_i}{\sigma_i^2}\right)\right] \tag{A.7}$$

where

$$\Delta = \left(\sum_i \frac{1}{\sigma_i^2}\right)\left(\sum_i \frac{H_i^2}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)^2 \tag{A.8}$$

and

$$b = \frac{1}{\Delta}\left[\left(\sum_i \frac{H_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{P_i}{\sigma_i^2}\right) - \left(\sum_i \frac{H_i}{\sigma_i^2}\right)\left(\sum_i \frac{P_i H_i}{\sigma_i^2}\right)\right] \tag{A.9}$$

The damage threshold is determined by the expression:

$$H_{\text{th}} = -\frac{b}{m} \tag{A.10}$$

The calculated threshold should be both positive and less than or equal to the lowest observed energy density causing damage. If the value of $H_{\text{th}}$ is not positive, the reported threshold should be given as the lowest observed energy density causing damage. Further, if any additional test sites are available, a binary search for the threshold should be conducted, with highest energy density in this search being the lowest energy density corresponding to damage observed when making the measurement.

The uncertainty in the threshold is determined using Equations (A.11) and (A.12) and Equation (A.13):

$$\sigma_{\text{th}} = \frac{1}{m^2}\sqrt{b^2\sigma_m^2 + m^2\sigma_b^2} \qquad \text{(A.11)}$$

where

$$\sigma_b = \sqrt{\frac{1}{\Delta}\sum\frac{H_i^2}{\sigma_i^2}} \qquad \text{(A.12)}$$

and

$$\sigma_m = \sqrt{\frac{1}{\Delta}\sum\frac{1}{\sigma_i^2}} \qquad \text{(A.13)}$$

The lower limit of the estimated threshold $H_{\text{th}} - \sigma_{\text{th}}$ should be positive and less than or equal to the lowest observed energy density causing damage. If either of these conditions is not fulfilled for the lower limit, then it should be replaced by 0.

# Annex B
(informative)

# Example of a test report for a 1-on-1 test

## Measurement of laser-induced damage threshold by a 1-on-1 test in accordance with ISO 21254-2

**Test institute**

Name of institute:

Tester/date: dd/mm/yyyy

**Specimen**

Type of specimen: Original part, HR at 1 064 nm on BK7 glass

Manufacturer:

Storage, cleaning: No special requirements

Specification: Highly reflective mirror, $R > 99{,}5$ % at 1 064 nm, 0 rad angle of incidence, standard coating for normal use

Part identification number:

Date of production: Coating run #1187 of dd/mm/yyyy

**Test specification**

Pulsed Nd:YAG laser consisting of an electro-optically Q-switched oscillator and an optically isolated amplifier stage. Single transversal and longitudinal mode operation. Focusing by a biconvex lens with a beam f-number of 300.

**Laser parameters**

Wavelength: 1 064 nm

Angle of incidence: 0 rad

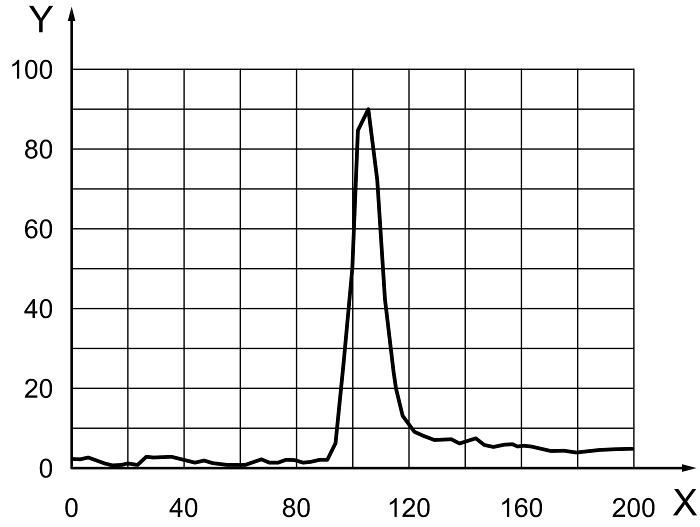
Polarization state: linear

Minimum time between shots: 5 s

Effective beam diameter in target plane: 0,34 mm

Pulse duration: 12 ns

Effective pulse duration: 12,7 ns

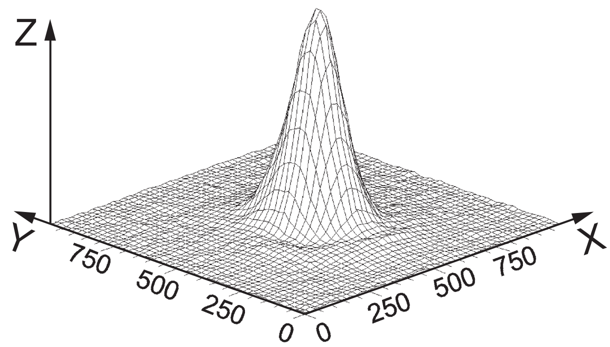



**Key**

X time, in nanoseconds

Y power, in arbitrary units

**Figure B.1 — Temporal profile**




**Key**

X length scale, in micrometres

Y length scale, in micrometres

Z power, in arbitrary units

**Figure B.2 — Spatial profile**

**Error budget**

a) Random variations:

| | |
|---|---|
| Pulse-to-pulse energy stability | ±3 % |
| Pulse-to-pulse spatial-profile stability | ±5 % |
| Pulse-to-pulse temporal-profile stability | ±8 % |

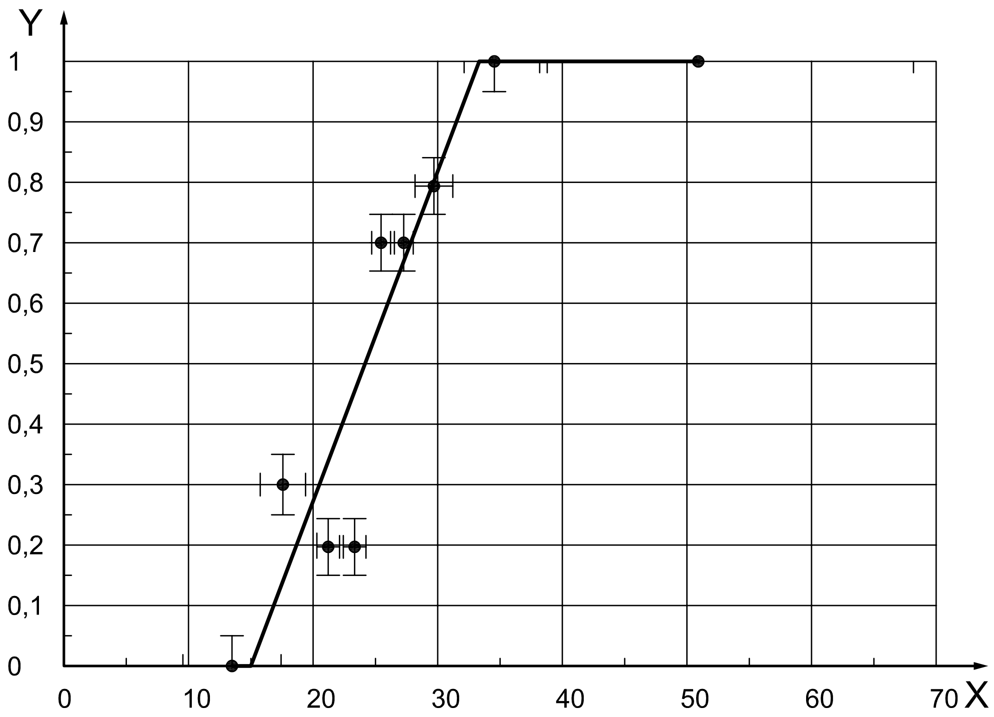
b) Systematic variations:

| | |
|---|---|
| Calorimeter calibration | ±5 % |
| Calorimeter-energy monitor correlation | ±2 % |
| Overall energy density measurement reproducibility | ±12,2 % |
| Overall energy density measurement uncertainty | ±10,4 % |

**Test procedure**

| | |
|---|---|
| Number of shots per specimen: | 25 |
| Arrangement of test sites: | 5 × 5 matrix |
| Minimum distance between sites: | 3 mm |
| Number of specimens tested: | 5 |
| Total number of sites for the test: | 125 |
| Damage detection: | online scatter measurement, online image processor |
| Storage of the specimen: | manufacturer's box, normal room conditions |
| Test environment: | clean, filtered air |
| Cleaning: | dusted off with dry nitrogen |

**Test results**

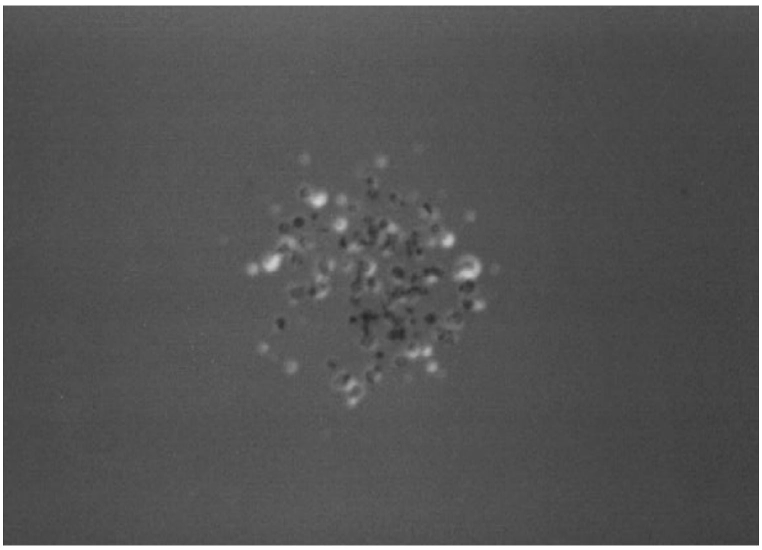



**Key**

X pulse energy density, in joules per square centimetre

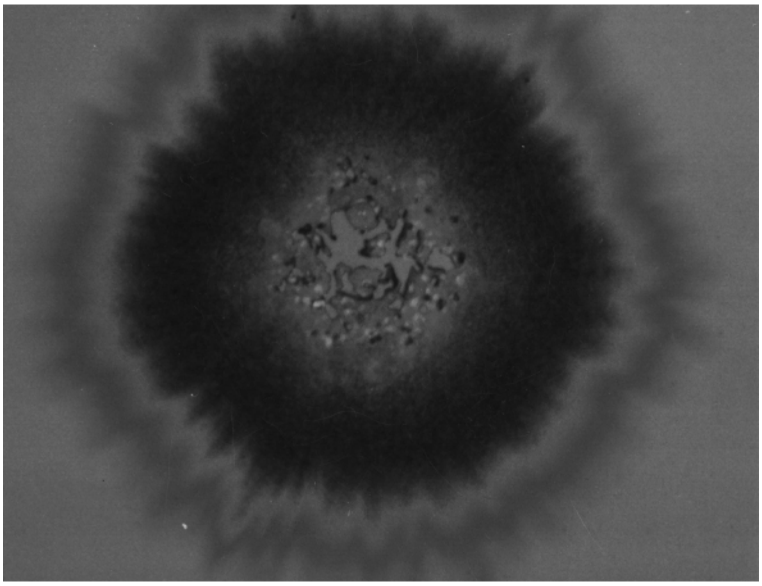
Y probability of damage

**Figure B.3 — Damage-probability plot, damage threshold 15,1 J/cm²**



NOTE Damage induced by inclusions in the coating. Contribution from absorption-induced damage at higher energy density levels.

**Figure B.4 — Nomarski micrograph for an energy density of 19 J/cm²**



NOTE Damage induced by inclusions in the coating. Contribution from absorption-induced damage at higher energy density levels.

**Figure B.5 — Nomarski micrograph for an energy density of 30 J/cm$^2$**

# Annex C
(informative)

# Example of a measurement procedure (S-on-1 test)

## C.1 General

This annex describes an example of a measurement procedure developed for a special laser-induced damage threshold measurement facility with a high-repetition-rate Nd:YAG laser. The basic structure of the procedure is oriented towards efficient determination of the laser-induced damage threshold using the 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 to provide an approximate estimate of the damage threshold. In the next step, the sites on the specimen surface are interrogated and the data 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 specimen surface. For this purpose, an individual model for the damage probability as a function of the energy density has to be included in the calculation. In the present example, this model is based on a logistic regression of binary data. However, any statistical or physical model can be employed to simulate the damage behaviour. The final step in the test procedure described in this example is the evaluation of the collected data and the computation of the damage-probability curve.

## C.2 Initialization of the measurement procedure

### C.2.1 Test parameters

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

The definitions given in Table C.1 apply to the test procedure described in this example.

**Table C.1 — Definitions of symbols used in the test procedure**

| Symbol | Meaning |
|---|---|
| $N_\mathrm{L}$ | minimum number of pulses for data evaluation: $0 < N_\mathrm{L} < S$ |
| $A_\mathrm{opt}$ | area of the specimen available for the damage test |
| $d_\mathrm{sep}$ | separation of test sites in terms of beam diameter $d_\mathrm{T,eff}$ (physical separation of test sites divided by the beam diameter) |
| $d_Q$ | minimum width of interval between energy classes |
| $P_N(Q)$ | probability of damage after $N$ pulses (specific model) |
| $\delta_N$ | uncertainty in the fit $P_N(Q)$ |

### C.2.2 Total number of sites for the test $N_\mathrm{ts}$

From the area $A_\mathrm{opt}$ of the specimen available for the damage test, the beam diameter $d_\mathrm{T,eff}$ and the separation of the test sites in terms of the laser beam diameter $d_\mathrm{sep}$, the total number $N_\mathrm{ts}$ of test sites can be determined. Assuming that the dimensions of the area available for the test are large compared to the separation of the test sites, the following approximations may be made.

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

$$N_{ts} = \frac{A_{opt}}{(d_{sep} d_{T,eff})^2} \tag{C.1}$$

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

$$N_{ts} = \frac{2}{\sqrt{3}} \frac{A_{opt}}{(d_{sep} d_{T,eff})^2} \tag{C.2}$$

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

### C.2.3 Minimum number of pulses $N_L$

The minimum number of pulses per site is selected according to the intended application of the specimens and the pulse-counting and switching uncertainty of the online damage detection system. In most S-on-1 damage threshold measurements, $N_L = 1$ will be preferred because this value 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 kilohertz regime. Also, for laser components in special applications with restricted operating conditions, a higher value of $N_L$ might be an advantage. The maximum number of pulses per site $S$ is dependent on the accuracy required for the extrapolation of the characteristic damage curve to high pulse numbers, and it is restricted by the need for a measurement time which is reasonable for the damage test.

### C.2.4 Energy resolution $\delta Q$

The energy resolution $\delta Q$ should be selected according to the energy reproducibility of the test laser in conjunction with the attenuation system.

### C.2.5 Fitting function $P_N(Q)$ and uncertainty $\delta_N$

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 function $P_N(Q)$ is a function of energy density and includes, besides the number of pulses $N$, a set of characteristic parameters. The uncertainty $\delta_N$ 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 is utilized:

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

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

## C.3 Initial test

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

## C.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 probability of damage $P_N(Q)$ to the specimen surface as a function of the pulse number $N$ and the energy $Q$. It might be based on the description of damage mechanisms or statistical algorithms specific to the actual type of specimen. The fitting parameters of this model are recalculated after each interrogation of the specimen. By evaluating the damage behaviour predicted by the recalculated model, the energy value $Q_{N\mathrm{S}}$ for the following test site is determined. The main criterion for the determination of this energy value is the improvement in the uncertainties $\delta_{N\mathrm{L}}$ and $\delta_{N\mathrm{P}}$ for the damage probabilities $P_{N\mathrm{L}}(Q)$ and $P_{N\mathrm{P}}(Q)$. These steps are repeated until the whole test area has been used or the required uncertainty in the characteristic damage curve has been reached.

The initial fitting parameters are computed using the data from the initial test routine.

**Step 1**: Initialization [see Equation (C.2)].

**Step 2**: For pulse numbers $N_\mathrm{L}$ and $S$, compute the damage probability fit curves $P_{N\mathrm{L}}(Q)$ and $P_{N\mathrm{P}}(Q)$ and their uncertainties $\delta_{N\mathrm{L}}$ and $\delta_{N\mathrm{P}}$ by fitting to the currently available set of data.

In the example given above [see Equation (C.3)], the parameter sets ($a_{N\mathrm{P}}$, $b_{N\mathrm{P}}$) and ($a_{N\mathrm{L}}$, $b_{N\mathrm{L}}$) have to be calculated independently for both numbers of pulses. An iteration procedure for this special case is given in Clause C.2.

**Step 3**: The value of an auxiliary variable $n$ is determined. The variable $n$ may take the value of $N_\mathrm{L}$ or $S$, depending which of the two corresponding uncertainties $\delta_{N\mathrm{L}}$ and $\delta_{N\mathrm{P}}$ is the higher, as follows:

$$n = \begin{cases} N_\mathrm{L} & \text{if } \delta_{N\mathrm{L}} > \delta_{N\mathrm{P}} \\ N_\mathrm{P} & \text{in all other cases} \end{cases} \tag{C.4}$$

The energy range between $Q_\mathrm{L}$ and $Q_\mathrm{H}$, indicating the increase in damage probability from $P_n(Q_\mathrm{L}) = 5$ % to $P_n(Q_\mathrm{H}) = 95$ %, is divided into a series of intervals, as follows:

$$[Q_\mathrm{L} + i \cdot d_Q,\ Q_\mathrm{L} + (i+1) \cdot d_Q) \tag{C.5}$$

where $i$ is a counting variable for the open interval [$Q_\mathrm{L}$, $d_Q$, $i$).

The width of the interval $d_Q$ is given by the maximum of the resolution $\delta Q$ and the energy range divided by the square root of $N_\mathrm{ts}$.

$$d_Q = \max\left( \delta Q, \frac{Q_\mathrm{H} - Q_\mathrm{L}}{\sqrt{N_\mathrm{ts}}} \right) \tag{C.6}$$

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

$$Q_\mathrm{L} = \max\left( -\frac{a_n + 2{,}94}{b_n}, 0 \right) \text{ and } Q_\mathrm{H} = \max\left( -\frac{a_n - 2{,}94}{b_n}, 0 \right) \tag{C.7}$$

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

**Step 4**: Select at random one interval [$Q_\mathrm{L}$, $d_Q$, $r$] from those with the minimum numbers of data points collected in the preceding interrogations. The energy value $Q_{N\mathrm{S}}$ for the next site is given by the position of this interval:

$$Q_{N\mathrm{S}} = Q_\mathrm{L} + (r + 0{,}5) \cdot d_Q \tag{C.8}$$

**Step 5**: Subject the next site to the calculated energy $Q_{N\mathrm{S}}$. If test sites are left, go back to step 1. If not, stop the measurement cycle and start the evaluation of the data collected.

## C.5 Evaluation of the results

In the final step of the algorithm, a procedure for the evaluation of the data stored during the test routine is performed in accordance with 4.3.4.2.

# Annex D
(informative)

# Example of a test report for an S-on-1 test

## Measurement of laser-induced damage threshold by an S-on-1 test in accordance with ISO 21254-2

**Test institute**

| | |
|---|---|
| Name of institute: | |
| Tester/date: | XXXXXX dd/mm/yyyy |
| Order No.: | 12345 |

**Specimen**

Type of specimen:

Manufacturer/supplier:

Part identification number:

Storage/cleaning procedure:

Specification:

Date of production:

**Test equipment**

### Beam source

| | |
|---|---|
| Type: | Q-switched laser |
| Manufacturer: | |
| Model: | Spectron SL456-10[1)] |

### Power meter

| | |
|---|---|
| Manufacturer: | Coherent, Inc. |
| Model: | J-50MB-YAG[2)] |
| Calibration due date: | mm/yyyy |

1) Spectron SL456-10 is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

2) J-50MB-YAG is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

**Online power measurement**

Pulse energy measured by an Si photodiode during irradiation, signal calibrated by making a measurement with the power meter before and after irradiation, linear interpolation of the heating power.

**Laser parameters**

| | |
|---|---|
| Wavelength: | 1 064 nm |
| Operating mode: | pulsed |
| Pulse repetition frequency: | 10 Hz |
| Source parameter settings: | |
| Output energy: | up to 50 mJ |
| Pulse duration (FWHM): | 10 ns |
| Pulse duration (effective): | 11 ns |
| Vacuum conditions: | |
| Conditioning: | — |
| Laser irradiation: | at atmospheric |
| Pump system: | |
| Turbo pump: | — |
| Rough pump: | — |

**Measurement specifications**

| | |
|---|---|
| Beam diameter in the target plane ($e^{-2}$): | 365 µm (normal incidence) |
| Beam diameter in the target plane (effective): | 258 µm (normal incidence) |
| Spatial beam profile: | near-Gaussian |
| Angle of incidence: | $0° \pm 1°$ |
| Polarization: | linear |
| Number of test sites: | >150 |
| Test site matrix: | hexagonal close-packed |
| Distance between test sites: | 1,5 mm |
| Online detection system: | scattered light |
| Offline detection system: | Nomarski microscopy (magnification 50×, 100×, 200×, 500×) |
| Environmental conditions: | |
| Cleaning: | |
| Mounting of optical components: | commercial kinematic mount |

**Comments**

**Error budget**

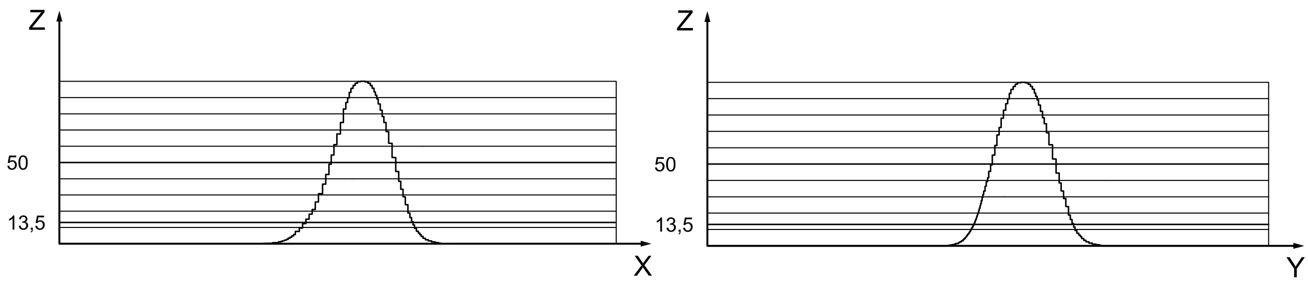
a) Random variations:

| | |
|---|---|
| Pulse-to-pulse energy stability: | 5 % |
| Pulse-to-pulse spatial-profile stability: | 5 % |
| Pulse-to-pulse temporal-profile stability: | 10 % |

b) Systematic variations:

| | |
|---|---|
| Calibration of the energy monitor: | 10 % |
| Online energy monitor: | 8 % |
| Reproducibility: | 25 % |

**Spatial beam profile at specimen position**




**Key**

X length scale, in arbitrary units

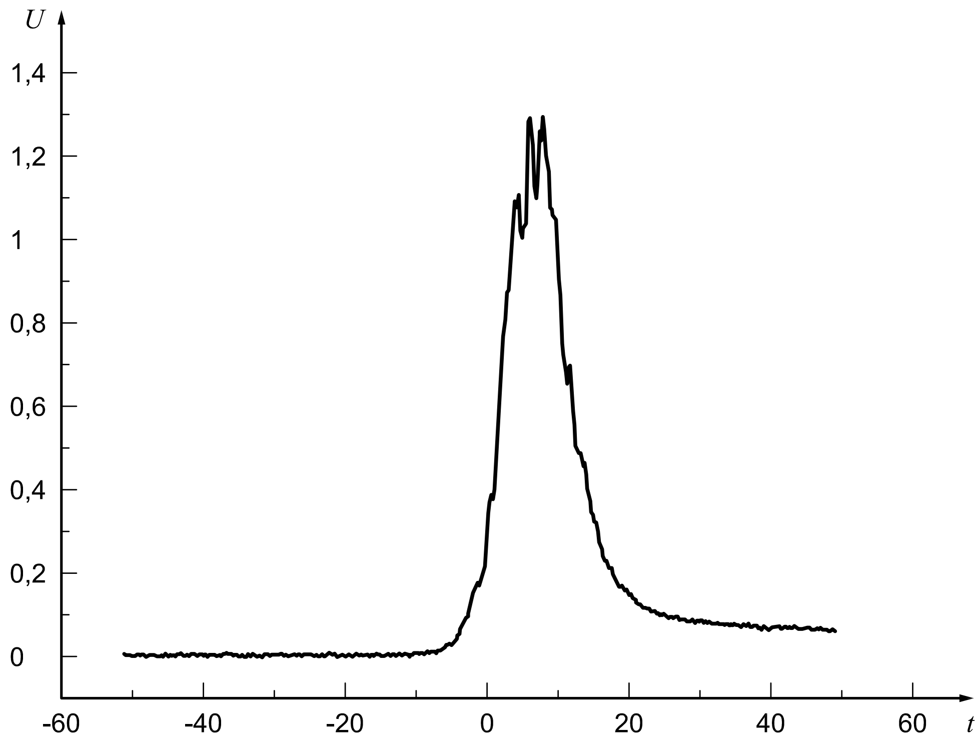
Y length scale, in arbitrary units

Z amplitude, in percent of full scale

NOTE $d_{86,5} = \sqrt{388\ \mu\text{m} \cdot 344\ \mu\text{m}} = 365\ \mu\text{m}$; $d_{\text{T,eff}} = \frac{1}{\sqrt{2}} d_{86,5} = 258\ \mu\text{m}$

**Figure D.1 — Spatial profile**

**Temporal beam profile at specimen position**




**Key**

*U* amplitude, in arbitrary units

*t* time, in nanoseconds

NOTE Pulse duration (FWHM) = 10 ns; pulse width (effective) = 11 ns.

**Figure D.2 — Temporal profile**

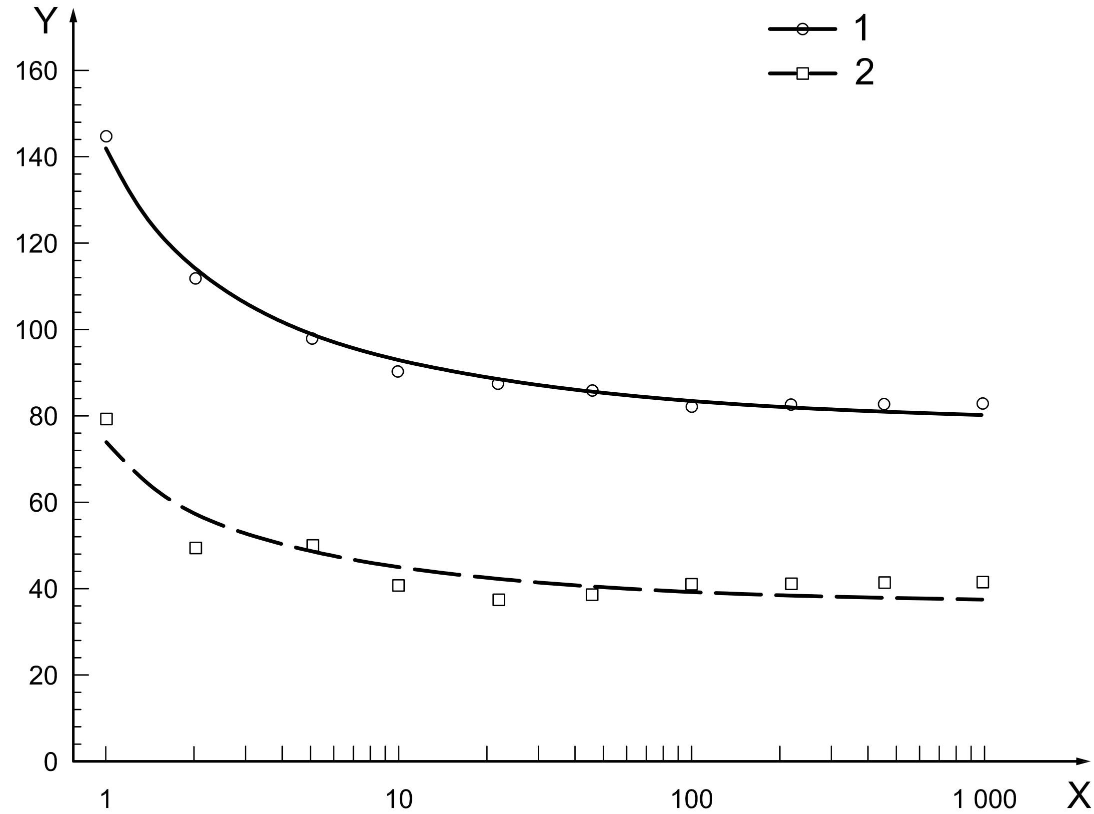
<u>**Test results**</u>

**Specimen**: Specimen 1

Manufacturer:

Specimen type:

**Characteristic damage curve**




**Key**

X number of pulses

Y energy-density threshold value, in joules per square centimetre

1 50 % threshold value

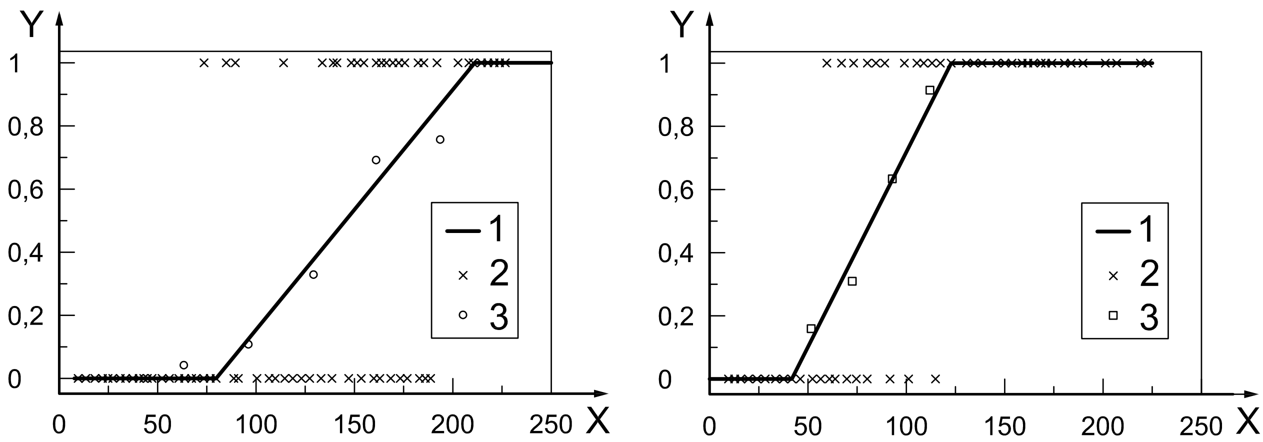
2 0 % threshold value

**Figure D.3 — Characteristic damage curve for specimen 1**

**Table D.1 — LIDT values for two different LIDT levels**

| Number of pulses | 50 % LIDT<br>J/cm$^2$ | 0 % LIDT<br>J/cm$^2$ |
|---|---|---|
| 1 | 144,5 | 79,4 |
| 2 | 112,1 | 49,5 |
| 5 | 98,0 | 50,0 |
| 10 | 90,4 | 40,8 |
| 22 | 87,4 | 37,4 |
| 46 | 85,7 | 38,6 |
| 100 | 82,1 | 40,9 |
| 220 | 82,1 | 40,9 |
| 460 | 82,1 | 40,9 |
| 1 000 | 82,1 | 40,9 |

**Damage-probability plots**




**Key**

X energy density, in joules per square centimetre

Y probability of damage

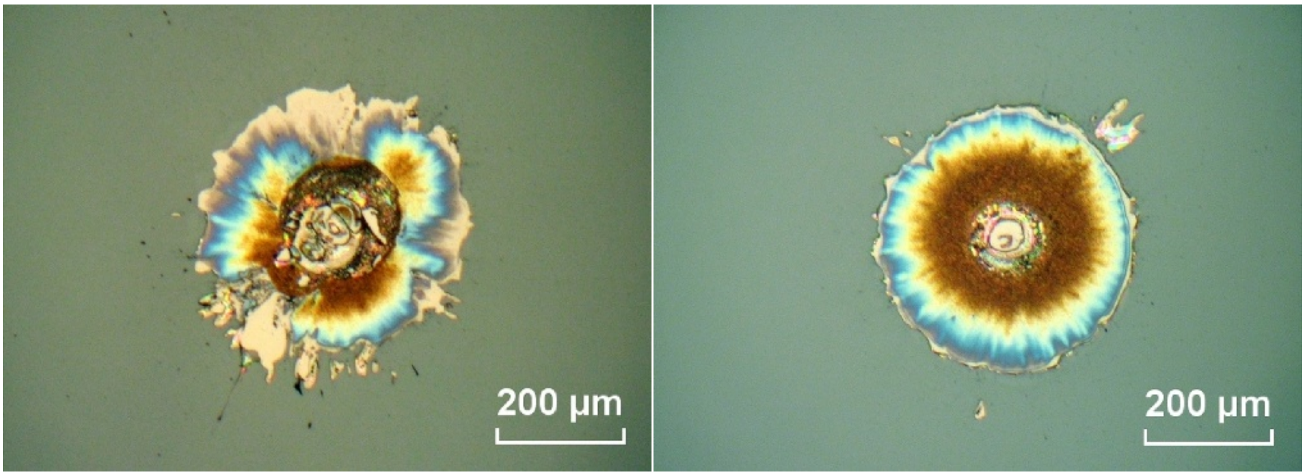
1 linear fit of probability

2 test data

3 probability of damage

**Figure D.4 — Damage-probability plots for specimen 1 for two different LIDT levels**

**Damage morphologies**




**a) Damaged coating of specimen 1 at position 95 (energy density 60,1 J/cm$^2$, damage after 5 pulses)**

**b) Damaged coating of specimen 1 at position 11 (energy density 90,1 J/cm$^2$, damage after 1 pulse)**

**Figure D.5 — Typical damage morphologies for specimen 1 at two spot sites after different numbers of pulses**

# Annex E
(informative)

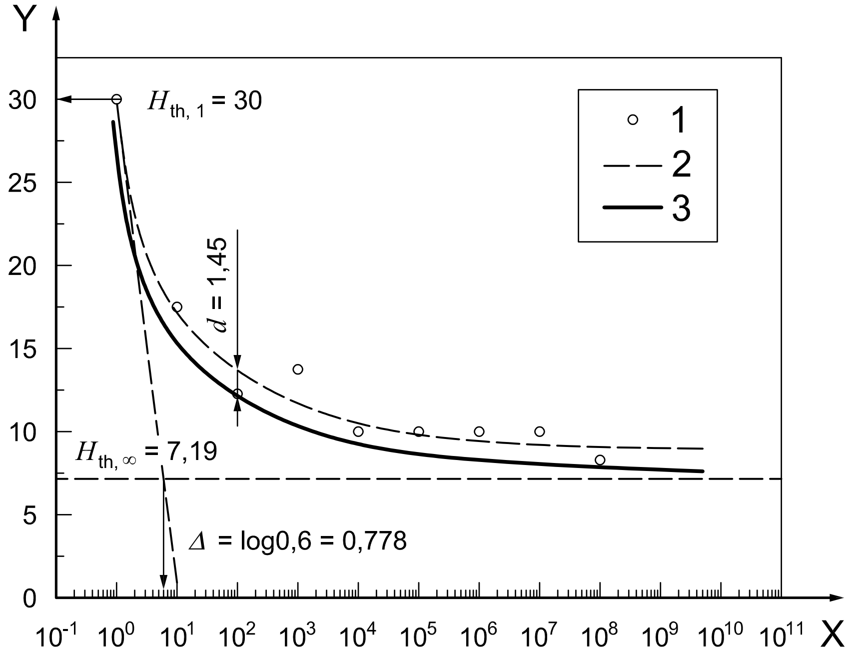
## Extrapolation method for S-on-1 tests

This annex gives an equation which allows the S-on-1 test damage threshold $H_{th}$ to be extrapolated to large numbers $N$ of pulses. The extrapolation model is based on three fitting parameters $H_{th,1}$, $H_{th,\infty}$ and $\Delta$ which can be considered to be parameters characteristic of the damage behaviour:

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

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

EXAMPLE Consider the data collected for a typical coating given in Figure E.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 define the safe operations limit. The displacement $d = 1{,}45$ corresponds to the intercept of the displaced characteristic damage curve with the lowest damage threshold measured for 100 pulses.




**Key**

X number of pulses $N$

Y S-on-1 test LIDT, in arbitrary units

1 data

2 fit

3 shifted fit

**Figure E.1 — Measured S-on-1 test damage threshold as a function of pulse number $N$, with fit in accordance with Equation (E.1) (laser mirror, 248 nm)**

# Annex F
(informative)

## Conversion of damage data into defect densities

This annex describes the calculations used to transform damage-probability curves into damage densities as a function of energy density. This procedure permits high accuracy and repeatability to be obtained and provides reproducible and comparable measurements for several facilities, whatever beam size and profile are used. The data reduction procedure is described for surface damage in Reference [6]. The paper also deals with the determination of damage density error bars that make possible the comparison of two similar, but physically distinct, samples.

Interaction between materials defects is neglected. Thus, if defects inducing damage at a given energy density $H$ are randomly distributed, the defect density $D(H)$ follows Poisson's law. Then, on a given surface area $A$, the damage probability $P(H,A)$ and defect density $D(H)$ are related by the following equation:

$$P(H,A) = 1 - \exp\left[-D(H)A\right] \quad \text{(F.1)}$$

By extension, it is possible to write damage test results in terms of probability. The Gaussian beam equivalent area $A_{\mathrm{eq,g}}$ is defined. If $\delta_{\mathrm{m}}$ is the measured damage density, then the damage probability is given by:

$$P = 1 - \exp\left(-\delta_{\mathrm{m}} A_{\mathrm{eq,g}}\right) \quad \text{(F.2)}$$

The measured damage density is therefore given by:

$$\delta_{\mathrm{m}} = -\frac{\ln(1-P)}{A_{\mathrm{eq,g}}} \quad \text{(F.3)}$$

When a spatially Gaussian beam is used, the absolute damage density can be expressed as the logarithmic derivative of the measured density $\delta_{\mathrm{m}}$:

$$D(H_i) = H_i \frac{\mathrm{d}\delta_{\mathrm{m}}(H_i)}{\mathrm{d}H_i} \quad \text{(F.4)}$$

The experimental curve of $\delta_{\mathrm{m}}(H_i)$ can often be fitted by a power law of the energy density:

$$\delta_{\mathrm{m}}(H_i) = \alpha (H_i)^{\beta} \quad \text{(F.5)}$$

where $\alpha$ and $\beta$ are calculated from the best fit of the measurements.

From Equations (F.4) and (F.5), the absolute damage density is obtained:

$$D(H_i) = \beta \delta_{\mathrm{m}}(H_i) \quad \text{(F.6)}$$

in other words:

$$D(H_i) = \beta \left(-\frac{\ln(1-P)}{A_{\mathrm{eq,g}}}\right) \quad \text{(F.7)}$$

If $P << 1$, then the relationship given in Equation (F.7) is equivalent to:

$$D(H_i) = \beta \frac{P}{A_{\text{eq,g}}} \tag{F.8}$$

As described in Annex A, for each energy density level $H_i$, the observed damage probability $P_i$ is given by the equation:

$$P_i = \frac{n_i^{\text{d}}}{n_i^{\text{d}} + n_i^{\text{nd}}} \tag{F.9}$$

where $\left(n_i^{\text{d}} + n_i^{\text{nd}}\right)$ is the total number of exposed sites and $n_i^{\text{d}}$ the number of damage sites.

The total scanned area $A_{\text{total}}$ is then equal to $\left(n_i^{\text{d}} + n_i^{\text{nd}}\right) \times A_{\text{eq,g}}$, which is used to determine the measured damage density:

$$\delta_{\text{m}}(H_i) = \frac{n_i^{\text{d}}}{\left(n_i^{\text{d}} + n_i^{\text{nd}}\right) A_{\text{eq,g}}} \tag{F.10}$$

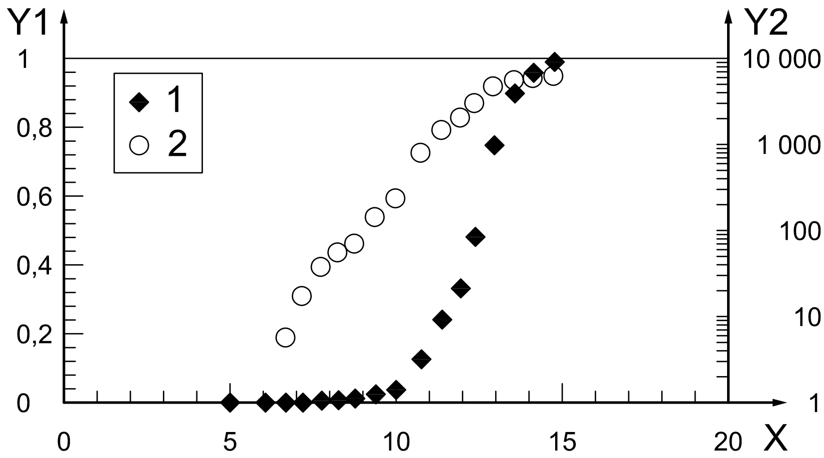
Finally, the absolute damage density given in Equation (F.7) is:

$$D(H_i) = \beta \frac{n_i^{\text{d}}}{\left(n_i^{\text{d}} + n_i^{\text{nd}}\right) A_{\text{eq,g}}} \tag{F.11}$$

In order to determine the absolute damage density, the number of damage sites, the Gaussian beam equivalent area and then the exponent $\beta$ obtained from power-law fitting of experimental data have to be measured. For a top-hat beam, the absolute damage density is given directly by Equation (F.10) where the area of the beam is used as $A_{\text{eq}}$.

Figure F.1 is an example of results obtained on a fused-silica component tested at 355 nm. The beam diameter is 0,4 mm at 1/e. The results are from a 1-on-1 test, using the method described in 4.2. The damage probability is first obtained as a function of the pulse energy density (bold diamonds). The damage density (empty circles) is then calculated using Equation (F.7).

In the case of bulk damage, it is straightforward, considering the total volume illuminated $V_{\text{eq,g}}$, to obtain the same kinds of relationships between damage probability and bulk defect density.




**Key**

X pulse-energy density, in joules per square centimetre

Y1 damage probability

Y2 damage density (number of occurrences of damage per square centimetre)

1 damage probability

2 damage density

**Figure F.1 — Damage-probability and damage-density plots [damage-density data obtained from Equation (F.7)]**

# Bibliography

[1] ISO 10110-7, *Optics and photonics — Preparation of drawings for optical elements and systems — Part 7: Surface imperfection tolerances*

[2] ISO 15367-1, *Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront — Part 1: Terminology and fundamental aspects*

[3] ISO 15367-2, *Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront — Part 2: Shack-Hartmann sensors*

[4] ISO 21254-3, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 3: Assurance of laser power (energy) handling capabilities*

[5] ISO/TR 21254-4, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 4: Inspection, detection and measurement*

[6] LAMAIGNÈRE, L., *et al*, An accurate, repeatable, and well characterized measurement of laser damage density of optical materials, *Rev. Sci. Instr.*, **78**, 103105 (2007)

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