INTERNATIONAL STANDARD

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

Part 2:
Threshold determination

Lasers et équipements associés aux lasers — Méthodes d'essai du seuil d'endommagement provoqué par laser —

Partie 2: Détermination du seuil

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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

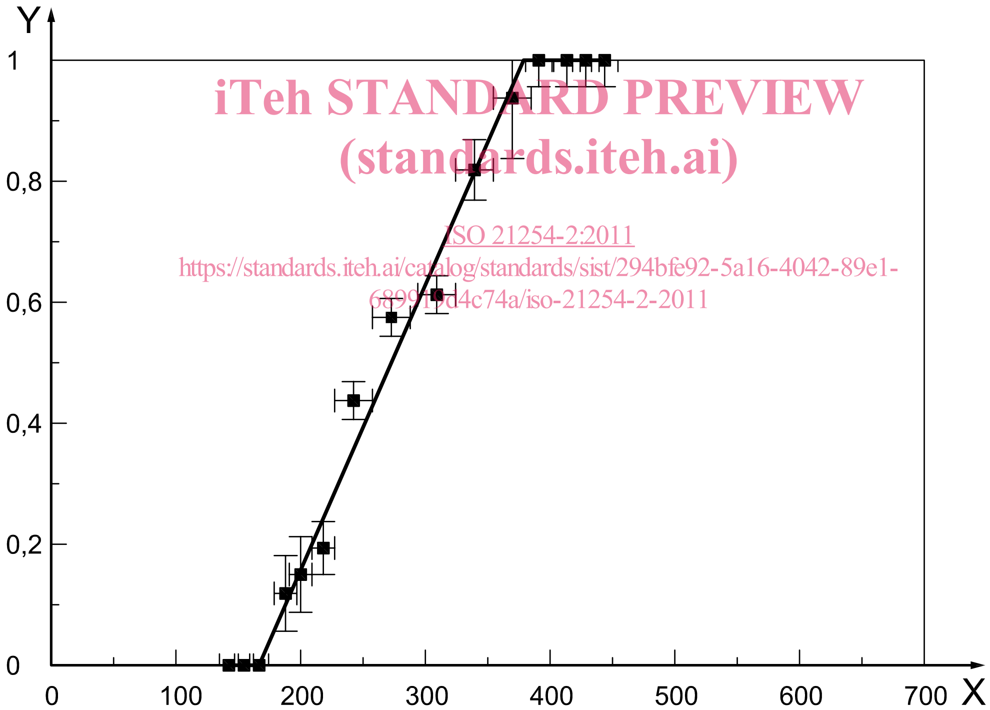
The test equipment shall be characterized by the parameters described in ISO 21254-1:2011, 6.2.6.5.

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, λ = 10,6 µm, τ_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_{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_{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_{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_{tp}, N_{min}), where $N_{min} \leqslant S$ in the case of damage,

(Q_{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:

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

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 ΔQ 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 ΔQ 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.

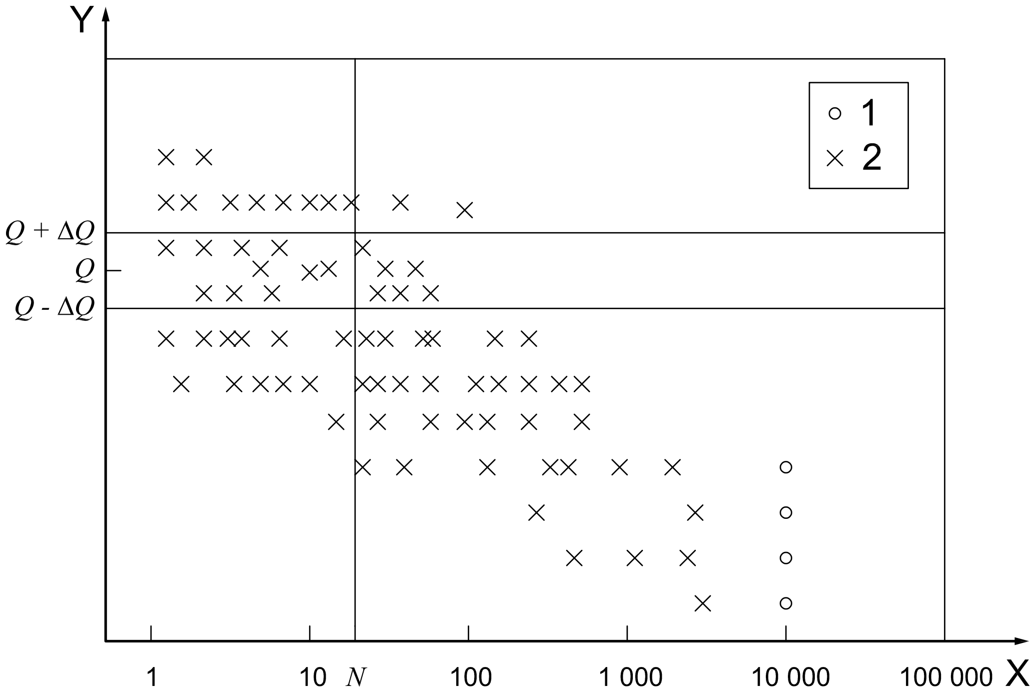
This procedure is repeated for other values of the energy Q to generate a data set of damage-probability values for the selected number N of pulses. The resulting data set represents discrete points on a damage-probability curve which is plotted versus the energy of the typical pulse. From this curve, 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

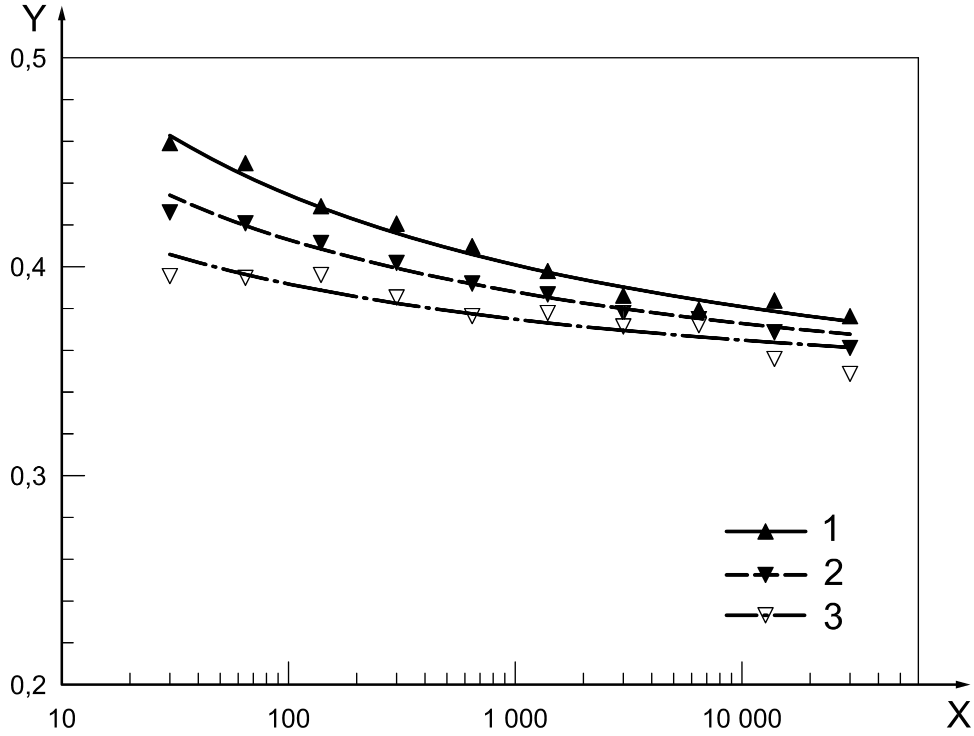
Figure 2 — Data points resulting from damage testing

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

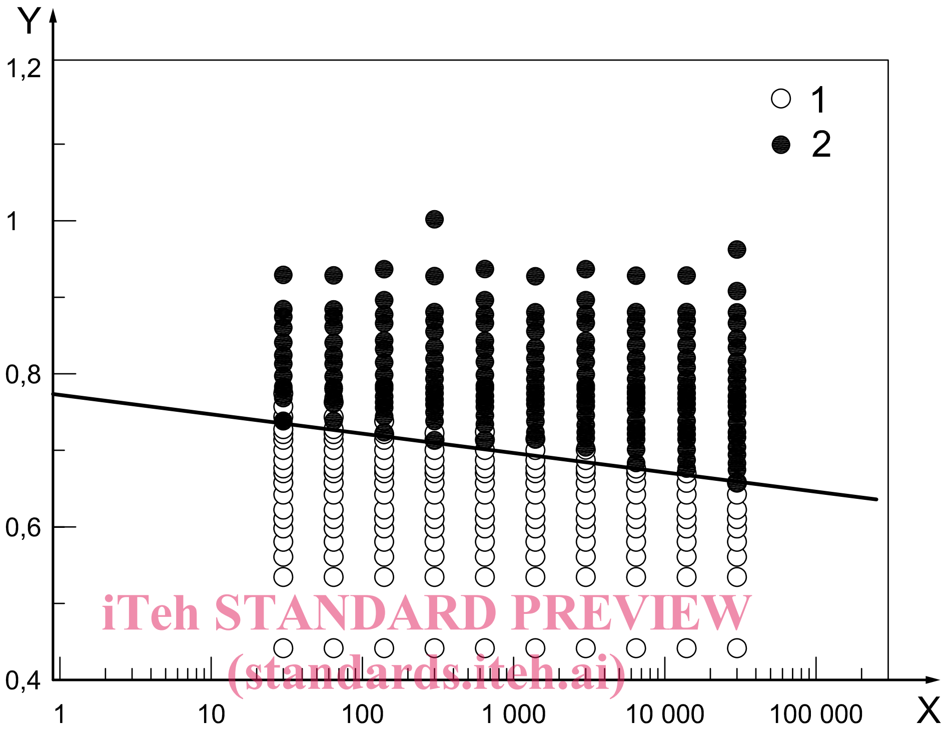
NOTE The test conditions were as follows: $\tau_{eff} = 130$ fs, $d_{T,eff} = 87$ µm, $\lambda = 780$ nm, $f_p = 1$ kHz, specimen: HR mirror (Ta_2O_5/SiO_2) for 780 nm.

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: τ_{eff} = 130 fs, $d_{T,eff}$ = 87 µm, λ = 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.