PD IEC/TR 60825-13:2011

Safety of laser products

Part 13: Measurements for classification of laser products

National foreword

This Published Document is the UK implementation of IEC/TR 60825-13:2011. It supersedes PD IEC/TR 60825-13:2006 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee EPL/76, Optical radiation safety and laser equipment.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

ISBN 978 0 580 64542 6

ICS 31.260

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

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 November 2011.

Amendments issued since publication

Amd. No.	Date	Text affected

PD IEC/TR 60825-13:2011

IEC/TR 60825-13

Edition 2.0 2011-10

TECHNICAL REPORT

colour inside

Safety of laser products –
Part 13: Measurements for classification of laser products

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE XB

ICS 31.260

ISBN 978-2-88912-741-2

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

SAFETY OF LASER PRODUCTS –

Part 13: Measurements for classification of laser products

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 60825-13, which is a technical report, has been prepared by IEC technical committee 76: Optical radiation safety and laser equipment.

This second edition cancels and replaces the first edition of IEC 60825-13, published in 2006. It constitutes a technical revision.

The main changes with respect to the previous edition are as follows:

Minor changes and additions have been made in the definitions, classification flow has been updated, apparent source sections have been clarified, scanning has been updated, and more examples and useful conversions have been added to the annexes.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
76/424/DTR	76/447/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

This technical report is to be used in conjunction with IEC 60825-1:2007.

A list of all parts of the IEC 60825 series, published under the general title *Safety of laser products,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

SAFETY OF LASER PRODUCTS –

Part 13: Measurements for classification of laser products

1 Scope

This part of IEC 60825 provides manufacturers, test houses, safety personnel, and others with practical guidance on methods to perform radiometric measurements or analyses to establish the emission level of laser energy in accordance with IEC 60825-1:2007 (herein referred to as “the standard”). The measurement procedures described in this technical report are intended as guidance for classification of laser products in accordance with that standard. Other procedures are acceptable if they are better or more appropriate.

Information is provided for calculating accessible emission limits (AELs) and maximum permissible exposures (MPEs), since some parameters used in calculating the limits are dependent upon other measured quantities.

This document is intended to apply to lasers, including extended sources and laser arrays. Users of this document should be aware that the procedures described herein for extended source viewing conditions may yield more conservative results than when using more rigorous methods.

NOTE Work continues on more complex source evaluations and will be provided as international agreement on the methods is reached.

2 Normative references

The following referenced document is 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.

IEC 60825-1:2007, *Safety of laser products – Part 1: Equipment classification and requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC 60825-1:2007 as well as the following terms and definitions apply.

3.1
angular velocity
speed of a scanning beam in radians per second

3.2
beam profile
irradiance distribution of a beam cross-section

3.3
beam waist
minimum diameter of an axis-symmetric beam

Note 1 to entry: For non-symmetric beams, there may be a beam waist along each major axis, each located at a different distance from the source.

3.4
charge-coupled device
CCD
self-scanning semiconductor imaging device that utilizes metal-oxide semiconductor (MOS) technology, surface storage, and information transfer

3.5
critical frequency
pulse repetition frequency above which a pulsed laser can be modelled as CW for the purposes of laser hazard evaluation

3.6
Gaussian beam profile
profile of a laser beam which is operated in the lowest transverse mode, TEM_{00}

NOTE 1 to entry: A Gaussian beam profile may also be produced by passing non-TEM_{00} laser beams through beam shaping optical elements.

3.7
measurement aperture
aperture used for classification of a laser to determine the power or energy that is compared to the AEL for each class

3.8
pulse repetition frequency
PRF
number of pulses occurring per second, expressed in hertz (Hz)

3.9
Q-switch
device for producing very short, high peak power laser pulses by enhancing the storage and dumping of energy in and out of the lasing medium, respectively

3.10
Q-switched laser
aser that emits short, high-power pulses by means of a Q-switch

3.11
Rayleigh length
Z_r
distance from the beam waist in the direction of propagation for which the beam diameter or beam widths are equal to $\sqrt{2}$ times that at the beam waist

NOTE 1 to entry: Rayleigh length is often referred to as ½ the confocal parameter.

3.12
responsivity
R
ratio of the output of a detector to the corresponding input expressed as $R = O/I$, where O is the detector's electrical output and I is the optical power or energy input

3.13
Ultrashort pulse laser
laser that emits pulses shorter than 100 fs and can contain a relatively large spectral content

4 Applicability

4.1 General

This report is intended to be used as a reference guide by (but not limited to) manufacturers, testing laboratories, safety officers, and officials of industrial or governmental authorities. This report also contains interpretations of the standard pertaining to measurement matters and provides supplemental explanatory material.

4.2 Initial considerations

Before attempting to make radiometric measurements for the purpose of product classification or compliance with the other applicable requirements of the standard, there are several parameters of the laser that must first be determined.

a) Emission wavelength(s)

   Lasers may emit radiation at one or more distinct wavelengths.

   The emission wavelength, wavelengths, or spectral wavelength distribution can typically be obtained from the manufacturer of the laser. Depending on the type of laser, the manufacturer may specify a wavelength range rather than a single value. Otherwise, the emission wavelength, wavelengths or spectral distribution can be determined by measurement, which is beyond the scope of this technical report. See 7.1 for assessing the accessible emission limit (AEL) for multiple wavelengths.

b) Time mode of operation

   The time mode of operation refers to the rate at which the energy is emitted. Some lasers emit continuous wave (CW) radiation; other lasers emit energy as pulses of radiation. Pulsed lasers may be single pulsed, Q-switched, repetitively pulsed, or mode locked. Scanned or modulated CW radiation at a fixed location also results in a train of pulses.

   In addition, the pulse train may be encoded, but have an average duty factor (emission time as a fraction of elapsed time, expressed as a decimal fraction or percentage).

c) Reasonably foreseeable single fault conditions

   The standard specifies that tests shall be performed under each and every reasonably foreseeable single fault condition. It is the responsibility of the manufacturer to ensure that the accessible radiation does not exceed the AEL of the assigned class under all such conditions.

d) Measurement uncertainties

   It is important to consider potential sources of error in measurement of laser radiation. Clause 5 of this technical report addresses measurement uncertainties.

e) Collateral radiation (see the standard for definition of collateral radiation)

   Collateral radiation entering the measurement aperture may affect measured values of power or energy and pulse duration. Test personnel should ensure that the measurement setup blocks or accounts for collateral radiation that would otherwise reach the detector.

f) Product configuration

   If measurements are being made for the purpose of classification, then all controls and settings listed in the operation, maintenance and service instructions must be adjusted in combination to result in the maximum accessible level of radiation. Measurements are also required with the use of accessories that may increase the radiation hazard (for example, collimating optics) which are supplied or offered by the manufacturer of the laser product for use with the product.

   NOTE This includes any configuration of the product, which it is possible to attain without using tools or defeating an interlock including configurations and settings against which the operation and maintenance instructions contain warnings. For example, when optical elements such as filters, diffusers or lenses in the optical path of the laser beam can be removed without tools, the product is to be tested in the configuration which results in the highest hazard level. The instruction by the manufacturer not to remove the optical elements cannot justify classification as a lower class. Classification is based on the engineering design of the product and cannot be based on appropriate behaviour of the user.

If measurements are being made to determine the requirements for safety interlocks, labels and information for the user, then the product must be evaluated under the configurations applicable for each of the defined categories of use (operation, maintenance, and service) in accordance with the standard.

IEC technical committee 76 (TC 76) recognises the existence of equivalent measurement procedures, which could yield results that are as valid as the procedures described in this technical report. This report describes measurement procedures that are adequate to meet the measurement requirements of the standard when measurements are needed. In many cases actual radiometric measurements may not be necessary, and compliance with the requirements of the standard can be determined from an analysis of a well-characterised source and the design of the actual product.

Measurements of accessible emission levels must be made at points in space to which human access is possible during operation and maintenance, as applicable. (For example, if operation may require removal of portions of the protective housing and defeat of safety interlocks, measurements must be made at points accessible in that product configuration.) Therefore, under some circumstances it may be necessary to partially disassemble a product to undertake measurements at the required measurement location, particularly when considering reasonably foreseeable single fault conditions. Where a final laser product contains other laser products or systems, it is the final product that is subject to the provisions of the standard.

Measurements must be made with the measuring instrument detector so positioned and so oriented with respect to the laser product as to result in the maximum detection of radiation by the instrument. That is, the detector may have to be moved or the angle changed to obtain a maximum reading on the meter. Appropriate provision must be made to avoid or to eliminate the contribution of collateral radiation to the measurement. For example, it may be necessary to take measurements some distance away from a laser system's output to avoid corrupting the data with radiation from flash lamps or pump diodes/diode lasers. As another example, it may be necessary to filter collateral radiation out with a line filter.

5 Instrumentation requirements

Measurement instruments to be used should comply with the latest edition of IEC 61040. Which instrument class (between class 1 and class 20 giving the approximate value of the possible measurement uncertainty) is to be used depends on the measurement accuracy needed.

Where instruments not fully compliant with IEC 61040 are used, the individual contributions of different parameters to the total measurement uncertainty have to be evaluated separately. The main points to be considered are those given in IEC 61040:

- change of responsivity with time;
- non-uniformity of responsivity over the detector surface;
- change of responsivity during irradiation;
- temperature dependence of responsivity;
- dependence of responsivity on the angle of incidence;
- non-linearity;
- wavelength dependence of responsivity;
- polarisation dependence of responsivity;
- errors in averaging of repetitively pulsed radiation over time;
- zero drift;
- calibration uncertainty.

Calibrations should be traceable to national standards.

Tests for the determination of measurement uncertainties of the instrument should be done according to IEC 61040.

For measurement uncertainties of CCD arrays and cameras see ISO 11146-3.

6 Classification flow

Known or measured parameters of the product enable calculation of AELs and measurement conditions. In addition, fault conditions that increase the hazard must be analysed. Then, a product emission measurement (or several different measurements) will determine if the emission is within the AEL of the class under consideration.

Tables 4 to 9 in the standard provide the accessible emission limits. These tables have rows for the wavelength ranges and columns for the emission durations. Within each row and column entry, there exist one or more formulas containing parameters that are defined in Table 10 in the standard.

The classification flow is illustrated in Figures 1 and 2. The initial approach is to use the default simplified evaluation from 9.3.2 in the standard. It considers the beam to be emitted from a small (point) source with C_6 = 1, a conservative approach if the apparent source size is not known. If the product output appears to be generated by an extended source and is in the 400 nm – 1400 nm range, and if the class determined by the simplified evaluation is not acceptable, then one can alternately determine the class using the more complex evaluation. This involves using additional parameters, including the angular subtense α as a function of distance and the measurement acceptance angle γ_p for the visible photochemical hazard.

First determine whether the laser is pulsed or continuous wave. If the pulse duration is greater than 0,25 s, the laser is considered continuous wave. For a continuous wave laser, refer to the flowchart in Figure 1, and for a pulsed laser, refer to the flowchart in Figure 2.

Next, the wavelength must be determined.

If the laser is pulsed or scanned, the pulse width (PW) and pulse repetition frequency (PRF) must also be determined.

Determine the applicable class or classes. For instance, for a low power application not in the 400 nm – 700 nm region, Class 1, Class 1M and Class 3R might be considered. For a visible wavelength source, Class 1, Class 1M, Class 2, Class 2M and Class 3R might be considered.

Next, the classification time base must be established. This can be determined in terms of default values (8.3e) in the standard), or determined from the definition of the T_2 parameter (Table 10 in the standard), or from considering the particular temporal output properties of the product in question.

This information is needed to locate the row and column entries of Tables 4 to 9 in the standard containing the formula or formulas of interest, and thus to determine the AELs.

Next, the measurement conditions must be determined (9.3 and Table 11 of the standard). For a pulsed laser, several conditions given in 8.3f) of the standard must be evaluated to ensure all fall within the AEL.

Once the AEL has been determined, the output data should be evaluated. The output data may be provided by the manufacturer or measured directly. If output data are provided by the manufacturer, it must be confirmed that the measurements were performed in accordance with Clause 9 of the standard. If the accessible emission is less than the AEL, the laser may be assigned to that class. For a pulsed laser, the AEL of the class applies for all emission durations within the time base.

If the accessible emission is not less than the AEL, a higher class AEL should be chosen and assessed. This is repeated until the AEL is not exceeded or the laser product is assigned to Class 4.

The system must be evaluated in accordance with the standard to insure that a reasonably forseeable single fault cannot cause the laser to emit radiation higher than the AEL for the assigned class. If this criterion is met, the laser classification is known.

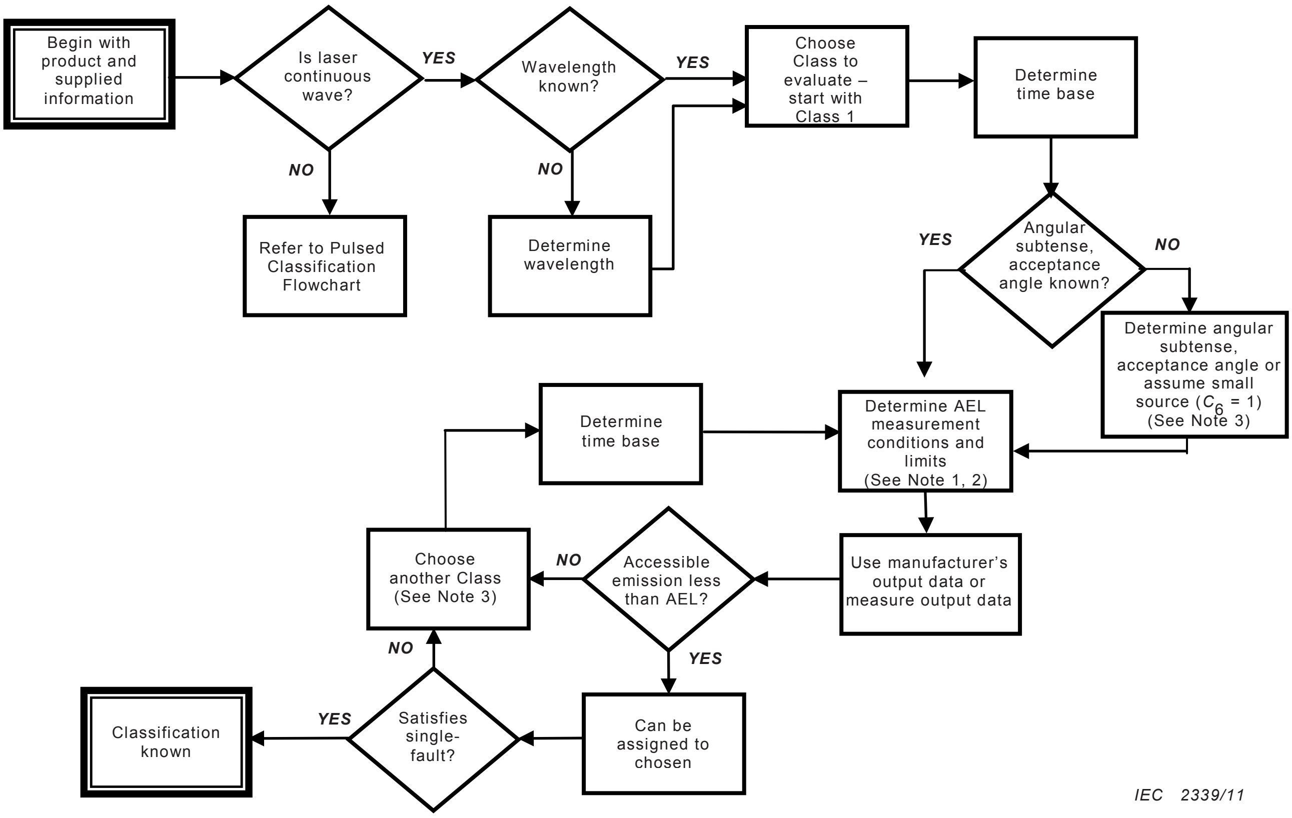


Figure 1 – Continuous wave laser classification flow

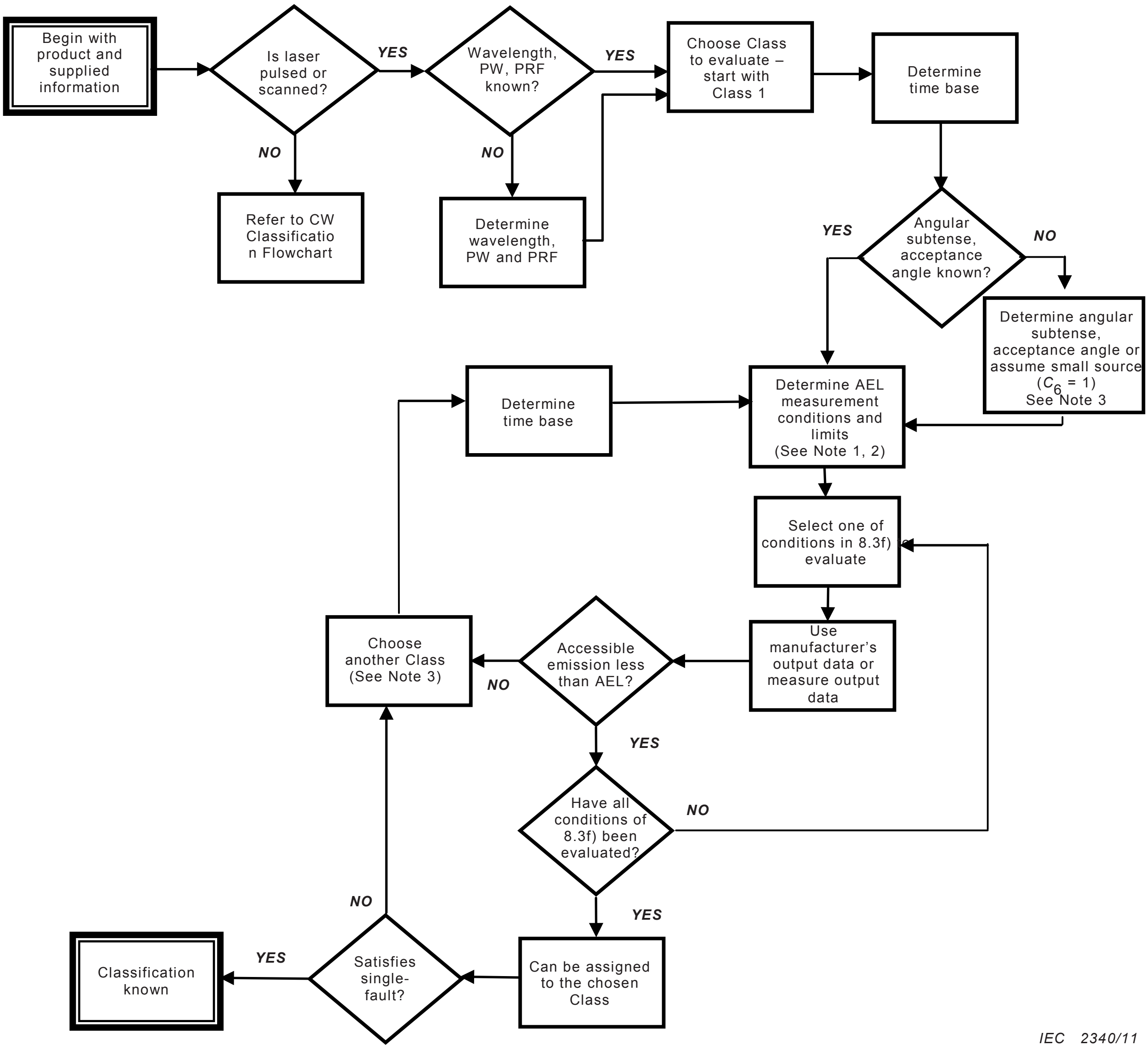


Figure 2 – Pulsed laser classification flow

NOTE 1 There may be more than one condition to be met if a product is to be assigned a certain class. For instance, in the wavelength region 400 nm – 600 nm, neither the thermal nor photochemical limit (each with its own measurement conditions) should be exceeded for a class to apply. Also, if a product has a pulsed output, none of the three limits (single pulse, pulse train and average power) may be exceeded.

NOTE 2 If using an extended source, the AEL will be a function of distance from the source. The most hazardous distance must be used for classification.

NOTE 3 If Class 1 or Class 2 requirements are not satisfied, it is appropriate to evaluate product emission using the Class 1M or Class 2M requirements. If a product emission satisfies the Class 1M or Class 2M requirements, it is not necessary to satisfy the Class 3R requirements.

7 Parameters for calculation of accessible emission limits

7.1 Wavelength (λ)

7.1.1 Wavelength determination

It is usually not necessary to determine this parameter to great accuracy. In general, biological hazards are not strong functions of wavelength. There are several exceptions (refer to Figure 3):

a) 302,5 nm – 315 nm region: over this range, the T_1 and C_2 parameters change significantly;

b) 450 nm – 600 nm region: over this range, the photochemical hazard decreases by a factor of 1 000;

c) 1 150 nm – 1 200 nm region: over this range, the thermal hazard decreases by a factor of eight;

d) 400 nm: at wavelengths greater than 400 nm, the hazard is mainly retinal; at shorter wavelengths, it is mainly non-retinal;

e) 1 400 nm; at wavelengths greater than 1 400 nm, the hazard is mainly non-retinal; at shorter wavelengths, it is mainly retinal.

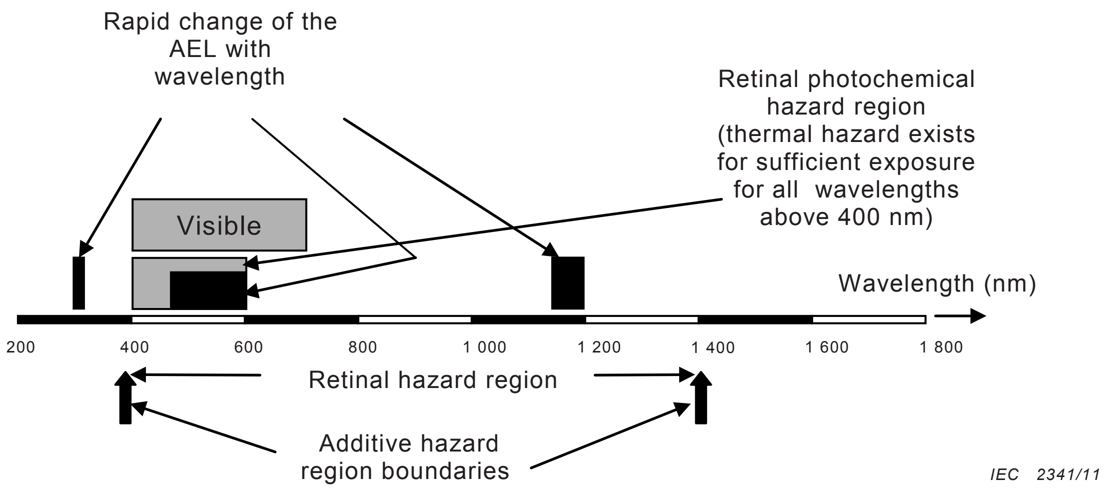


Figure 3 – Important wavelengths and wavelength ranges

For a narrow laser line, a wavelength provided by the manufacturer will likely be all that is necessary, and the remainder of 7.1 as well as 7.2 and 7.3 below need not be considered.

If the range of possible wavelengths (product-to-product variation) is a sizeable fraction of a), b) or c) above, either the most hazardous (shortest) wavelength may be used, or the wavelength may be measured for a given product.

In regions a), b) or c), a piece-wise summation may be required, determining the limit at several wavelengths and weighting by the output associated with that wavelength. This is discussed in detail below in subclauses 7.2.2 and 7.3.

Additive refers to hazards that must be considered together. For instance, multiple emissions less than 400 nm, or between 400 nm and 1 400 nm, or greater than 1 400 nm are additive. For spectrally broad or multiple emissions in each region, the hazards are additive, and a piecewise summation must be performed, as described in item b) of 8.3 of the standard. If a product emits wavelengths in two of these ranges (e.g., 700 nm and 1 500 nm), then the two wavelengths should be considered separately using the relevant AELs for each wavelength. For classification purposes, the higher class will apply.

For lasers whose possible range of output wavelength or output spectrum includes wavelengths greater than 1 400 nm and/or less than 400 nm, special considerations should be made with regard to the AEL. The hazards on either side of the boundary wavelengths are different, and the effects are different. To be assigned a given class, the power or energy in each spectral region must be less than each corresponding AEL.

Measurement or determination of the wavelength parameter is fundamental to laser hazard evaluations and laser classification. The wavelength must be identified to decide on which type of power or energy meter is to be employed. Some radiometers have detector elements that respond very efficiently in the visible and near-infrared, but have little to no responsivity in the far-infrared or ultraviolet and vice versa. Additionally, the appropriate application of exposure limits is dependant upon wavelength as well. In most cases, direct measurement of the operating wavelength of a laser is not necessary. This is usually specified by the manufacturer with more than a reasonable amount of certainty.

For lasers that can emit more than one wavelength, or emit near either limit of the retinal hazard region, determination of the emission spectrum is of utmost importance. Measurement of wavelength or spectral emission can be accomplished by techniques using a variety of equipment. Optical spectrum analyzers and similar instruments, such as wavemeters, offer the easiest operation. Most of these devices simply sample the beam and give a digital readout of the wavelength or spectrum. Some have geometrical and field of view limitations, but are usually very reliable. Monochromators, especially if manually operated, can be a little more labour intensive and time consuming, but are also very dependable and accurate. Optical filters, such as narrow band pass filters can also be considered as another option but they do have some limitations. Employment of these filters requires prior knowledge of approximately what wavelength is expected. Also, for multiple wavelength lasers or lasers with a broad emission, use of filters for wavelength or spectral emission determination can be quite cumbersome, if not futile.

7.1.2 Ocular hazard regions

The thermal hazard exists for sufficient exposure at all wavelengths above 400 nm.

The retinal photochemical hazard is only a consideration from 400 nm to 600 nm, and for exposure times greater than 1 s.

The hazard regions are broken down as follows:

- 180 nm to 400 nm. The hazard is mainly photochemical and non-retinal for CW exposure and thermal for pulsed exposure. (The standard does not address wavelengths shorter than 180 nm);
- 400 nm to 600 nm. In this range, both thermal and photochemical hazards must be considered. For the photochemical hazard, emission times of less than 10 s (or 1 s for the wavelength region 400 to 484 nm with apparent sources between 1,5 and 82 mrad) need not be considered;
- 400 nm to 1 400 nm. In this range, the retinal hazard region, the hazard to the retina predominates;
- 1 400 nm to 1 mm. At wavelengths greater than 1 400 nm the penetration depth of the radiation is much smaller than for wavelengths between 400 nm and 1 400 nm. The hazard is thermal but mainly non-retinal.

7.2 Multiple wavelength sources

7.2.1 General

The term multiple wavelength sources refers to a source that emits radiation in two or more discrete wavelengths. Multiple line lasers clearly fall into this category. These different wavelengths may fall into different hazard regions of the spectrum resulting in different biological effects and need to be accounted for independently. See 7.1.1, 7.1.2, and Figure 3.

Ultrashort pulse lasers can contain a relatively large wavelength bandwidth. The wavelength bandwidth for these lasers should be evaluated with the procedure in 7.3 if the AEL or MPE limit varies more than 10 % for the wavelength band of the laser pulse.

7.2.2 Single hazard region

For several sources emitting simultaneously at different wavelengths whose radiation produces the same type of hazard, a weighted sum must be used to determine whether the product meets or exceeds the AEL for a given class. For a single wavelength the criterion may be stated as:

If $P_{\text{meas}} < AEL$,
then the product does not exceed the class limit

where P_{meas} is the measured power (or energy or other quantity specified), and *AEL* is the class power (or energy or other quantity specified) limit. This can be restated as:

If $P_{\text{meas}} / AEL < 1$,
then the product does not exceed the class limit.

In this form, this can be extended to two wavelengths:

If $P_{\text{meas}}(\lambda_1) / AEL(\lambda_1) + P_{\text{meas}}(\lambda_2) / AEL(\lambda_2) < 1$,
then the product does not exceed the class limit.

For more than two wavelengths, this can be extended to a general summation:

If $\sum [P_{\text{meas}}(\lambda_i) / AEL(\lambda_i)] < 1$,
$i = 1,2,3\ldots$
then the product does not exceed the class limit.

This only applies to one type of hazard at a time (i.e., photochemical and thermal hazards are treated separately).

NOTE While the thermal hazard limit values are different for the visible range (400 nm to 700 nm) and the near infrared range (700 nm to 1 400 nm), the time bases (either the emission duration *t* or the calculated parameter T_2) are the same. Thus, the summation formula above still applies.

7.2.3 Two or more hazard regions

If a product emits two different wavelengths, and they are not in the same hazard region (e.g., λ_1 = 300 nm and λ_2 = 430 nm), each wavelength is to be treated separately:

If $P_{\text{meas}}(\lambda_1) < AEL(\lambda_1)$ and $P_{\text{meas}}(\lambda_2) < AEL(\lambda_2)$,
then the product does not exceed the class limit.

If either condition is not satisfied, comparison with the AEL of higher classes should be considered.

7.3 Spectrally broad sources

7.3.1 General

Some lasers (e.g., ultrashort-pulse lasers) have an appreciable spectral width. The implications of this are that classification may require assessment in more than one spectral region.

7.3.2 Spectral regions with small variation of the AEL with wavelength

If the spectral output of the emitter does not include any of spectral regions a), b) or c) or the boundary wavelengths of d) or e) (see 7.1 above), the distribution can be approximated by a single wavelength.

a) If the AEL does not vary with wavelength, any choice of wavelength within the emitter spectrum is equivalent.

b) If the AEL varies slowly with wavelength, and the emitter wavelength spectrum is contained within one spectral range in the limit table, the limit for the peak or centre of the distribution can be calculated, including shorter wavelengths corresponding to 10 % of peak irradiance of the distribution. If the AEL difference is less than about 1 %, the peak or centre wavelength may be used. A conservative approach is to use the most restrictive wavelength concerned.

7.3.3 Spectral regions with large variation of the AEL with wavelength (302,5 nm - 315 nm, 450 nm – 600 nm and 1 150 nm – 1 200 nm)

If the emitter has some or all of its spectral output in the three regions in which the limits vary greatly with wavelength, two approaches may be used.

a) Calculate the AEL using the lower wavelength boundary for the appropriate region. Since AELs for shorter wavelengths are almost always more restrictive than AELs for longer wavelengths, this simple and conservative approach may be used. However, this may result in a limit that is overly restrictive. If the AEL calculated is acceptable (e.g., the product is Class 1 with this assumption), no further calculations are needed.

b) Calculate the sum of the measured power divided by the AEL as a function of wavelength. Use the general summation in 7.2.2 above.

   Assume, for instance, a source with a triangular spectral distribution, which has a lower wavelength limit of 400 nm, a peak at 460 nm, and an upper wavelength limit of 520 nm. The AEL from 400 nm to 450 nm is constant. Above 450 nm, the AEL increases exponentially with the C_3 factor. If:

$$P_{meas}(400\text{ nm} < \lambda < 450\text{ nm}) \,/\, AEL\,(400\text{ nm} < \lambda < 450\text{ nm}) + \sum_{450<\lambda_i<520\text{ nm}} [P_{meas}(\lambda_i) \,/\, AEL(\lambda_i)] < 1$$

   then the applicable AEL is not exceeded.

7.3.4 Spectral regions containing hazard-type boundaries (near 400 nm and 1 400 nm)

If the output spectral distribution includes a hazard region boundary (400 nm and 1 400 nm), the output in each region is independent. Follow the procedure of 7.2.3 and 7.3.3 for each spectral region, if necessary.

7.3.5 Very broad sources

A determination of power or energy per unit wavelength is required. If this information is not available from the manufacturer, spectral measurements should be performed. It is beyond the scope of this document to detail this here. Some information on broadband source measurements is provided in IEC 62471.

If a laser product does not emit radiation below 315 nm, calculations can be simplified. The following information is needed to account for portions of the spectrum where biological reactions vary with wavelength (see section 7.1.1):

a) total power or energy between 315 nm and 400 nm measured as required by the standard (P_a or Q_a);

b) total power or energy between 400 nm and 700 nm measured as required by the standard for thermal limits (P_b or Q_b);

c) total power or energy between 400 nm and 450 nm measured as required by the standard for photochemical limits (P_c or Q_c);

d) power spectral distribution or energy spectral distribution from 450 nm to 600 nm measured as required by the standard for photochemical limits ($P_d(\lambda)$ or $Q_d(\lambda)$);

e) power or energy spectral distribution from 700 nm to the long wavelength limit of the distribution measured as required by the standard for thermal limits ($P_e(\lambda)$ or $Q_e(\lambda)$).

While the procedure applies to both power and energy, only power (P) will be used here.

– Choose an AEL. (Refer to Clause 9 of the standard for formulas and instructions on calculating limits.)
– Calculate the ultraviolet limit AEL_a, and the ratio $R_a = (P_a / AEL_a)$.
– Calculate the visible thermal limit AEL_b, and the ratio $R_b = (P_b / AEL_b)$.
– Calculate the visible photochemical limit AEL_c for 400 nm < λ < 450 nm and $AEL_d(\lambda)$ for the range 450 nm < λ < 600 nm. Sum ratios:

$$R_{cd} = P_c / AEL_c + \sum_{450<\lambda_i<600\text{ nm}} [P_d(\lambda_i) / AEL_d(\lambda_i)]$$

– Calculate the infrared thermal limit $AEL_e(\lambda)$ for 700 nm to the long wavelength end of the range. Sum ratios:

$$R_e = \sum_{700\text{ nm}<\lambda_i<\lambda_{max}} [P_e(\lambda_i) / AEL_e(\lambda_i)]$$

The product is assigned to the lowest laser class for which ALL of the following are true:

$R_a < 1,0$;

$R_b + R_e < 1,0$; and

$R_{cd} < 1,0$

7.4 Source temporal characteristics

7.4.1 General

If the product emits radiation continuously and with constant power, the analysis is straightforward. The emission time must be determined, either specified in the standard as a fixed duration, or specified by a calculated duration (i.e., T_2 is a function of apparent source size or source angular subtense). This allows the applicable AEL to be calculated. For such products, the remainder of 7.4 need not be considered.

7.4.2 Sources with limited "ON" time

If a product can emit radiation only for a limited period of time that is less than the time basis for that class specified in the standard, the shorter time can be used to calculate the applicable AEL. Shorter emission times result in higher peak power limits. Note that it is necessary to consider the AEL for all time durations up to the time base for classification.

7.4.3 Periodic or constant duty factor sources

7.4.3.1 General

Some products contain sources that produce a regular series of pulses, or an encoded (irregular) series. The irregular series may be considered as a regular series if the maximum duty factor is known. Duty factor here refers to the fraction or percentage of time the source is emitting.

For 3 µs long pulses at 120 pulses per second, the duty factor is $120 \times 3 \times 10^{-6}/1$ or 0,036 %.

For an encoded series of pulses, using a pulse train of 120 possible pulse positions of 3 µs long pulses every second with a 50 % encoding rate (50 % of the pulse positions contain a pulse, and 50 % do not), the duty factor is $0,5 \times 120 \times 3 \times 10^{-6}/1$ or 0,018 %.

Also, refer to Table 3 in the standard (time durations T_i below which pulse groups are summed) for further information on how to calculate limits. The pulse rate, duty factor, encoding duty factor and Table 3, along with the tables for the AELs, are needed to calculate the effective pulse power and duration, as well as the effective pulse rate.

Three limits must be considered:

a) the limit for a single pulse, based on the pulse width;

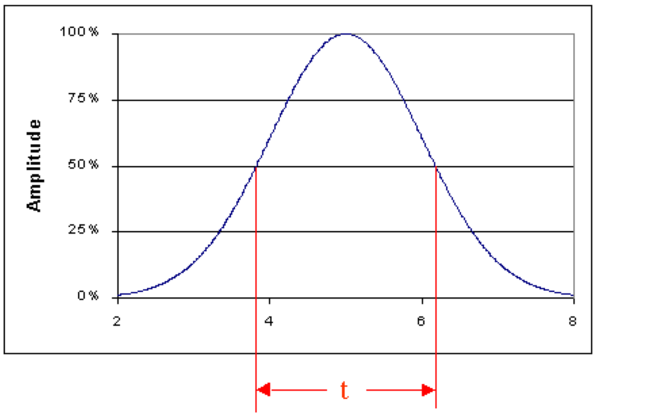
b) the limit for the average power for the specified or calculated classification time base;

c) the limit for the average pulse energy from pulses within a pulse train, taking account of C_5.

Item f) of 8.3.of the standard specifies that the most restrictive of requirements a), b), and c) be applied when determining the AEL for repetitively pulsed or modulated lasers for thermal limits for wavelengths of 400 nm and above. Requirement c) applies a correction factor to the single pulse AEL based on the number of pulses emitted during the applicable time base or T_2, whichever is shorter.

7.4.3.2 Pulse duration

The standard defines the pulse duration as the time increment measured between the half peak power points at the leading and trailing edges of the pulse. Therefore, the duration of interest is the time interval between the point, on the leading edge, at which the amplitude reaches 50 % of the peak value and the point, on the trailing edge, that the amplitude returns to the same value (see Figure 4).



IEC 2342/11

Figure 4 – Pulse duration definition

The pulse duration, *t*, can be accurately determined using a measurement instrument consisting of a photosensitive detector and an oscilloscope or similar device. The measurement instrument is subject to the following requirements.

a) The time response or frequency response of the entire measurement set-up must be sufficient to measure the duration accurately.

b) The radiation to be measured must be sufficiently spread over the active area of the detector such that there will be neither local saturation points nor local variations in sensitivity of the detector.

c) The radiant exposure or irradiance of the radiation must not exceed the maximum specified for the measurement instrument.

Additionally, the detector should be matched to the wavelength of the laser and should have a time constant at least ten times less than the pulse rise time. These are often referred to as fast detectors. Resistance should be decreased to shorten the time constant for this measurement. A 50 Ω terminator is a standard connector for this application that matches the resistance of the cable to then give a true pulse width. Some modern digital oscilloscopes have various terminations built in and are listed in the menu. Place the detector in the beam and set the triggering for the start of the upslope of the pulse. When a suitable trace has been obtained, the pulse width is measured at the full width half maximum of the leading upslope and trailing down slope of the pulse.

Single pulsed, Q-switched, mode-locked, and repetitively pulsed or scanning lasers all require some knowledge of pulse duration in order to classify the product. In the case of scanned radiation, pulse duration should be determined at all accessible positions in the scan pattern. This is necessary because, depending on the type of deflector, the beam speed may not be constant over the entire length of the scan line. For scanning products that incorporate a laser operating in continuous wave (CW) mode, the pulse duration depends on beam diameter and beam speed. For scanning products that incorporate a pulsed or modulated laser, the modulation frequency, the beam diameter, and the scan velocity should be considered in product classification and in emission duration calculations. Additionally, for a scanning beam the pulse duration will depend on measurement distance. For an extended source, this may include determining pulse durations as well as other parameters at different measurement distances in order to find the most hazardous distance.

7.4.3.3 Pulse repetition frequency

Oscilloscopes are most often used to measure the pulse repetition frequency (PRF), however these measurements may not be trivial. Many factors can lead to erroneous readings or not being able to detect the laser pulse train at all. As with power or energy measurements, oscilloscopes use a detector to convert the optical signal to an electrical signal. It is important in this measurement also to match the detector’s spectral responsivity to the wavelength of the laser. Care should be taken, for saturation can occur as with power and energy measurements. Additionally, having a prior knowledge of the approximate PRF will aid in setting the time domain of the oscilloscope. Measurements of this sort require proper termination of the cable that leads from the detector to the oscilloscope to ensure that the pulses are able to be measured by the scope. Most scopes are default set to a megaohm resistance which is more than sufficient. Some radiometers have the capability to measure PRF; once again it is important to ensure the manufacturer’s specifications of the instrument are understood. Other instruments such as frequency or pulse counters can also be used to determine the PRF.

Lasers that emit pulse trains that consist of pulses that are not uniformly spaced involve a bit more attention. Triggering of the oscilloscope becomes an issue. Rather than sampling continuously which produces overlapping traces a single trace will be needed. Overlapping traces might suggest a higher pulse count than what is reality which will lead to error in the calculations.

7.4.4 Sources with amplitude variation

If pulses are not "flat-top" (constant amplitude during the pulse ON time, see Figure 5 below), detailed analysis of the pulse structure may be required.

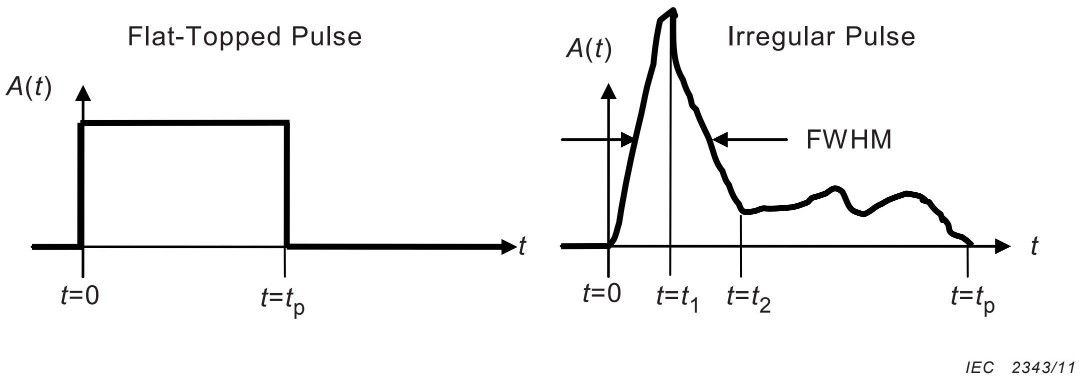


Figure 5 – Flat-topped and irregular pulses

For the flat-top pulse, a simplified analysis is possible; only pulse amplitude *A(t)* and pulse duration t_p should be considered.

For the second pulse, a piece-wise analysis may be necessary. For pulse energy, consider total energy from $t = 0$ to $t = t_1$, $t = 0$ to $t = t_2$ and $t = 0$ to $t = t_p$ as a minimum. For pulse duration, the peak must be captured with a suitable level of *A(t)*. Full width half maximum (FWHM) may be difficult to determine, and a conservative estimate as illustrated in Figure 5 using only the peak pulse may be necessary. Apply the evaluations in 7.4 to all of the incremental durations identified.

7.4.5 Sources with varying pulse durations or irregular pulses

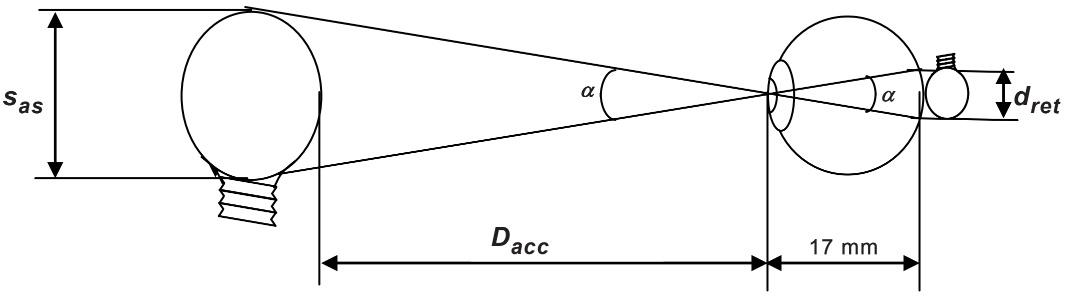
For trains of pulses with varying durations and/or varying amplitudes, the total-on-time-pulse (TOTP) method may be used as described in 8.3f)3)b) of the standard.

7.5 Angular subtense (α)

7.5.1 General

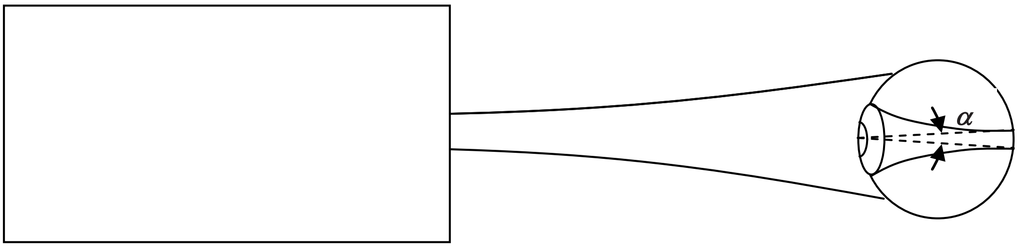
Within the thermal retinal hazard region (wavelength region 400 nm – 1 400 nm) the AELs depend on the angular subtense, α, of the apparent source, through the correction factor C_6 (see Tables 4-9 of the standard). The formula to be used to calculate the AEL depends on the value of T_2, and T_2 depends on α.

The apparent source is the real or virtual source object that forms the smallest retinal image for a given evaluation location of the retinal hazard. The angular subtense of the apparent source is determined by the smallest retinal image size that the eye can produce by accommodation (i.e., by varying the focal length of the eye lens). The angular subtense of the apparent source is used as a measure of the retinal image size. This angular subtense is the planar angle subtended by the diameter of the apparent source at the lens of the eye, see Figure 6a and 6b. The angular subtense of the apparent source may vary with position along the axis of the beam. With the exception of surface emitters (such as totally diffused transmitted or reflected beams or LEDs without lens caps or reflectors) the location of the apparent source is also a function of the position of the eye along the beam.



The example shows a beam transmission through, or reflection from, a diffuser such as a frosted light bulb where the light bulb is both the real source and the apparent source.

Figure 6a – Angular subtense (α) and apparent source size (s_{as}) of an incoherent or a diffuse source



This situation is more complex than for a simple source such as in Figure 6a, and both the angular subtense and the location of the apparent source typically change with the position in the beam.

Figure 6b – Angular subtense of a general laser beam at one position in the beam

Figure 6 – Angular subtense

The same power or energy spread over a larger retinal spot, in most cases, reduces the retinal hazard, as expressed by C_6. Therefore, this can be an important parameter for intermediate ($1,5 < \alpha < 100$ mrad) and large ($\alpha > 100$ mrad) individual sources and for arrays of sources. However, it is often unnecessary to determine the angular subtense and C_6 can be assumed to be equal to one (1). This provides the most conservative assessment. A laser hazard or classification assessment should always start with the assumption that $C_6 = 1$. If this is sufficient, i.e., the AEL values of the assumed laser Class are not exceeded, there is no need to perform any further analysis.

Most single lasers without beam modifying optics are small sources, $C_6 = 1$, and the location of the apparent source is not significant for laser safety. For these products, the remainder of 7.5 need not be considered.

For a general laser beam, the determination of α, and thus the use of $C_6 > 1$, is treated in 7.5.3.

For surface emitters, such as diffusely transmitted or reflected laser beams or bare laser diodes (without modifying optics), a simplified analysis can be used, as described in 7.5.3.3.

The special case of source arrays with the assumption that each individual source is small ($\alpha_s \leq 1,5$ mrad), is analysed in 7.5.4. Simple sources with non-circular emission patterns are illustrated in 7.5.4.5. Some considerations that apply specifically to the evaluation of scanning lasers are described in 7.8.

7.5.2 Location of the reference point

For small sources, or for all sources when assuming C_6 = 1, the accessible emission level can be measured at a predetermined distance from a reference point. The reference points are listed in Table 1 below. For the case of diffuse sources and semiconductor or large area emitters without modifying optics, the reference points for determination of the accessible emission level in Table 1 are valid also for measurements of intermediate and large sources using $C_6 > 1$.

Table 1 – Reference points

Type of product	Reference point
Semiconductor emitters (laser diodes, superluminescent diodes)	Physical location of the emitting chip
Scanned emission (including scanned line lasers)	Scanning vertex (pivot point of the scanning beam)
Line laser	Focal point of the line (vertex of the fan angle)
Output of fibre	Fibre tip
Diffuse sources	Surface of diffuser
Others	Beam waist

NOTE 1 If the reference point is located inside the protective housing (i.e., is not accessible) at a distance from the closest point of human access further than the measurement distance specified in the standard, the measurement must be carried out at the closest point of human access.

The technique for estimating the location of the beam waist given below may be used for small sources and Gaussian beams. A necessary condition for this estimation to be valid is that the analysis is performed at a position outside the Rayleigh range where ray optics applies, so that the far field divergence can (and should) be used.

NOTE 2 Information on apparent source location can be found in Enrico Galbiati: “Evaluation of the apparent source in laser safety”. (See Bibliography).

Choose a convenient reference plane (and make sure that the divergence is constant, i.e. the reference plane is in the far field). Determine the far field divergence angle, θ. The beam waist is located at a distance r from the reference plane (see Figure 7):

$$r = (d) / (2 \tan(\theta / 2)),$$

where r is the distance from the reference plane to the virtual point of focus of a small source.

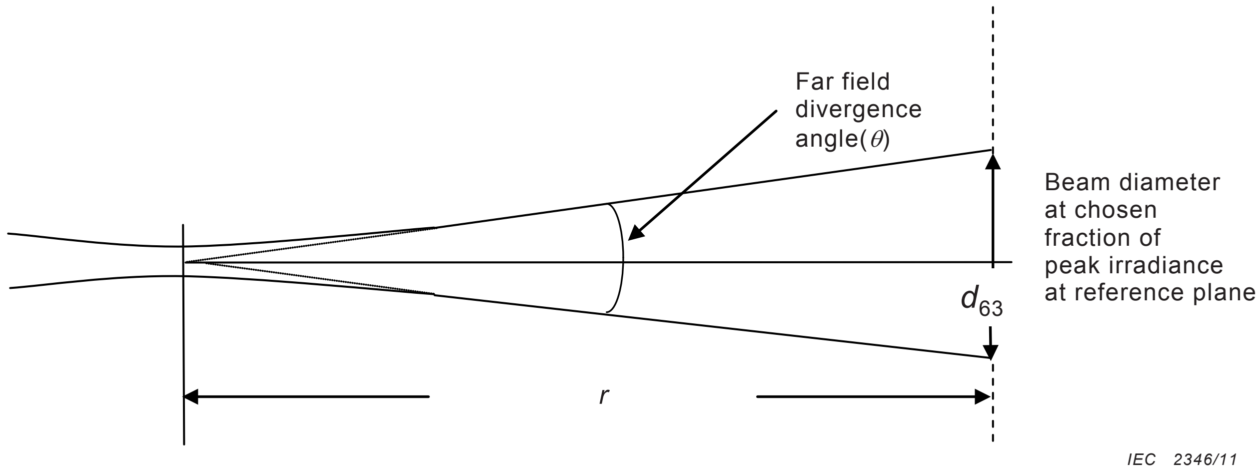


Figure 7 – Location of beam waist for a Gaussian beam

In some cases (e.g., for line lasers with cylindrical lenses, or general astigmatic beams) multiple beam waists may exist. For line lasers, see Table 1. For an astigmatic beam with separate beam waists in × and y (perpendicular to the optical axis), both beam waist locations and an intermediate point should be analysed. The worst case should be used.

Scanning beams are analysed further in 7.8.

7.5.3 Methods for determining angular subtense (α)

7.5.3.1 General

There are several suggested methods for determining the angular subtense of the apparent source. The different methods provide various degrees of accuracy and obviously various amounts of effort and cost. The method used is determined by the amount of accuracy needed, i.e., the proximity to the MPEs or AELs, and for some cases, the complexity of the case. The following methods discussed in this report are listed in order of increasing complexity:

a) conservative default method (7.5.3.2);
b) method used for simple sources such as surface emitters or totally diffused beams (7.5.3.3);
c) method to measure angular subtense used for arbitrary sources (7.5.3.4);
d) beam propagation method (7.5.3.5);

7.5.3.2 Conservative default method

If α is not known, and there is no method available to make an experimental evaluation, either a reasonable estimate may be made that can be quantitatively justified or a conservative default value may be chosen.

The default value for α is 1,5 mrad; below this value there is no change in the AEL. This results in C_6 = 1,0 and T_2 = 10 s. While limits calculated in this manner may be artificially low, it is a safe method to employ. As pointed out above, it is a good routine to always attempt this method as a first approximation. Often, no further analysis is needed.

7.5.3.3 Method used for surface emitters or diffused beams

For surface emitters, such as diffusely transmitted or reflected laser beams, a simplified analysis can be used. For these sources the real source is the same as the apparent source and therefore the size of the real source can be used to determine the angular subtense. Therefore, s_{as} in Figure 6a becomes equal to the diameter of the real source, and D_{acc}, the accommodation distance of the eye to the source, becomes equal to the real distance between the eye and the source. The equation below can be used to determine α:

$$\alpha = 2 \tan^{-1}(s_{as} / 2\ D_{acc}) = 2 \tan^{-1}(d_s / 2\ r),$$

where $\tan^{-1}$ is the inverse of the tangential trigonometric function. If α is sufficiently small, the trigonometric function can be simplified:

$$\alpha \sim (d_s / r),$$

where d_s is the diameter of the surface emitter and r is the distance between the surface emitter and the eye (or measurement aperture).

With the use of optics (e.g., integral lens, projection lens or reflector), the apparent source size and location are changed. This requires more detailed analysis, which is addressed in the next subclause.

7.5.3.4 Method used for arbitrary sources

A general method to determine the angular subtense α is to image the apparent source plane onto a detector plane, see Figure 8a. The object plane (being imaged) is the plane of the apparent source (which may contain either a physical source object or a wavefront).

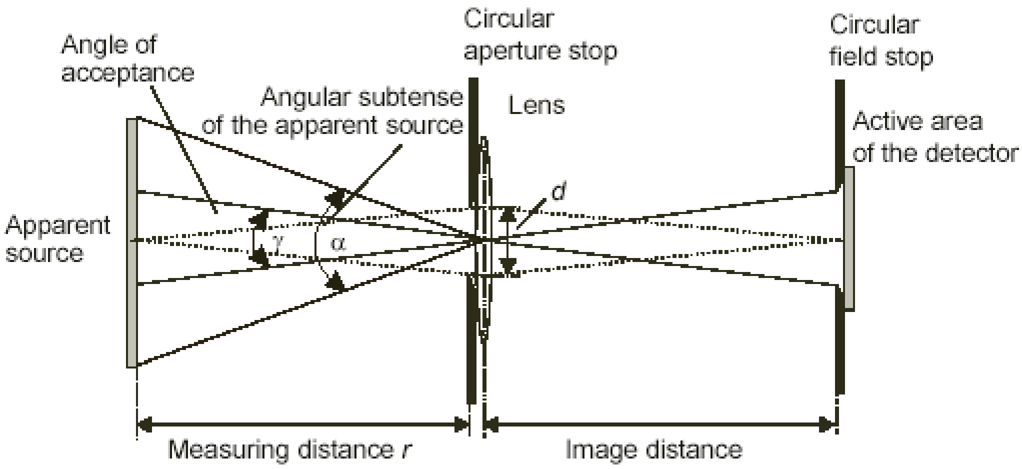


Figure 8a – Measurement set-up with source imaging

The correct image plane is where the smallest (or most hazardous) image is obtained (assuming that image is located beyond the focal point of the lens).

NOTE Changing the imaging distance is equivalent to imaging different source object planes, since each image plane corresponds to a “conjugate” object plane. This is almost equivalent to when the eye changes the focal length of its lens to image different object planes onto the retina – except in the eye the image distance is fixed and the focal length of the lens changes. Since variable focal length lenses are still being produced with small diameters only, it is easier to keep the focal length fixed and vary the image distance.

For objects at far distances and for parallel rays, the normal eye would form a sharp image on the retina while relaxed. If the object is at closer distance or the ray bundle is diverging, the eye will accommodate and decrease the focal length of its lens to make a sharp image on the retina. However, if a converging beam or ray bundle is incident on the eye, the eye cannot make the focal length of the relaxed eye smaller and therefore it cannot form a sharp image on the retina. Therefore, image distances shorter than the focal length of the imaging lens do not have to be considered when determining α. However, if there is a sharp image closer than the focal plane of the imaging lens, this indicates that the laser product has an external focus or beam waist. By the location of the image plane, the approximate plane of the external focus can be determined. The external focus should then be treated as the source plane and measurements be made with the external focus as the object source.

NOTE For complicated optical sources (e.g,. incorporating diffractive or holographic optical elements, or cylinder lenses) there may exist several foci (apparent sources) along the optical axis. They may all need to be evaluated to find the most hazardous viewing distance. Scanning systems face similar difficulties.

Determining source diameter:

The diameter of the source image is used to determine α as described in 7.5.3.3:

$$\alpha \sim (d_s / r) = (d_{si} / r_i),$$

where here d_{si} is the diameter of the imaged source and r_i is the image distance. (Note that the focal length of the lens is not required. However, for accurate measurements it should be noted that the image distance is to be measured from the second principal plane of the imaging lens. For thin lenses, this is just the centre of the lens, but for thick lenses, the second principal plane is the plane on the image side of the lens from which all the refraction occurs.) It is important to use a high quality lens to avoid errors caused by aberrations.

For a uniform (top-hat) distribution the diameter is easily determined from the outer extent of the beam. For all other distributions there may exist different definitions of the diameter, e.g., FWHM, 1/e diameter or $1/e^2$ diameter which all yield very different results. Therefore, in subclause 8.3.d, the standard stipulates the general method to be used for determining the angular subtense. It states that the most hazardous retinal spot area shall be used. In practice this means that:

1) for a given image distance, the angle of acceptance γ, is varied thus defining a varying area of acceptance.
2) for every value of γ the emission (energy or radiant exposure), $Q(\gamma)$, within the defined area is measured.
3) AEL is determined for every γ, setting $\alpha=\gamma$.
4) a “hazard factor” is determined for every γ, hazard factor = $Q(\gamma)/AEL(\gamma)$.
5) The γ which gives the highest value of the hazard factor is the value of α to be used.

For a general source the irradiation pattern does not have to be circular symmetric. In some cases it may be more appropriate to vary the acceptance angle to get an elliptical or rectangular shaped area of acceptance. The procedure above is still valid; the area that gives the highest “hazard factor” will be the area defining the angular subtense. See 7.5.4 for further guidance for non-circular sources.

The acceptance angle γ can be varied by using a field stop with variable aperture diameter. The position of the aperture needs to be adjustable in the image plane and should be adjusted to give the maximum reading for every value of the field stop diameter (i.e., γ). For a source with an irregular shape a CCD array for image grabbing would be helpful, since it enables the use of image analysis. The process above could thus be programmed and performed on a single image. Care should be taken to eliminate stray light so that the beam size is not overestimated.

The acceptance angle γ must always be limited to a minimum of 1,5 mrad and maximum of 100 mrad. This may be used to specify the size of the detector or CCD array, the resolution of the field stop diameter steps or CCD array and the magnification of the imaging lens to be used.

If the plane of the apparent source is known and accessible, the measurement set-up shown in Figure 8b can be used.

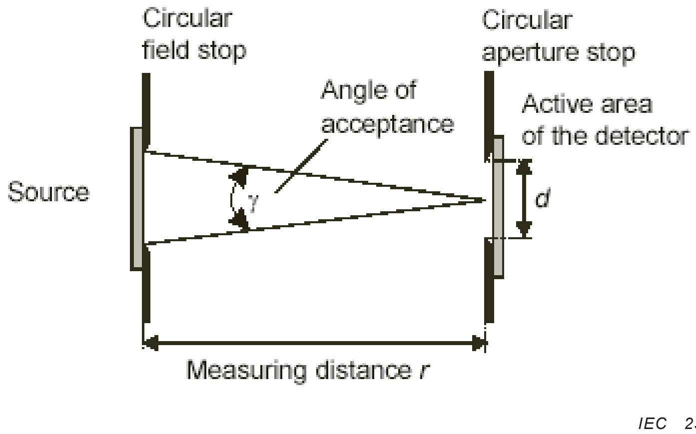


Figure 8b – Measurement set-up for accessible source

Figure 8 – Apparent source measurement set-ups

The worst-case measurement distance should be used for Condition 1 and Condition 3. Note that the location of the apparent source and the angular subtense may vary with the measurement distance. Thus, the location and size of the apparent source may have to be determined for every measurement distance. More information on this is available in the standard.

7.5.3.5 Beam propagation method

This method is based on wave optics rather than ray optics. One important finding of this approach is that the most hazardous viewing distance can be greater than 100 mm. A detailed analysis of this method is beyond the scope of this document. The 2nd moment method cannot be used since it is known to provide a serious underestimate of the risk both for determining the size of α and the aperture throughput.

7.5.4 Multiple sources and simple non-circular beams

7.5.4.1 General

Not all laser products have a single emitter or circular emission pattern. Multi-source examples are multi-channel fibre optic transmitters, multi-element signs and signals, multi-segment signs and characters, and other laser arrays. Simple sources (e.g. diffused beams) can have arbitrary shapes but still be easily treated if they are homogeneous (see 7.5.4.5). For a simple source such as a diffused beam, the emitting source is the same as the apparent source, regarding both location and size.

In theory, with multiple emitters, all combinations should be considered to determine the most hazardous set. One small bright source may or may not be the worst case. Similarly, all the sources taken together may or may not be the most hazardous.

In reality, not all combinations need be considered as some would obviously have less source density. Also, if all sources are intended to be equally bright, the analysis can frequently be simplified.

Linear arrays are easier to analyse than two-dimensional arrays. Nonetheless, it is possible to do the two dimensional analysis to determine the most hazardous case.

7.5.4.2 Procedure

Start with a single source. In array applications the single source is often a small source (C_6 = 1). If that is not the case, the same technique can be used, taking into account the finite size of the single source.

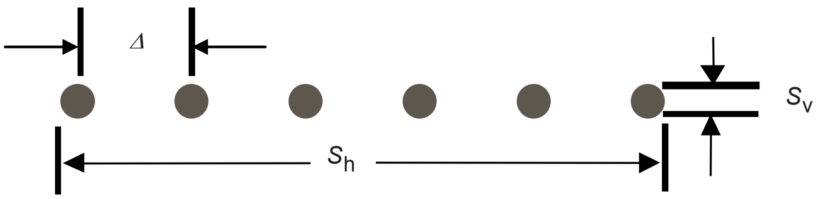
Determine the sequence of sources to be analysed. For each case, determine the angular subtense of the combination of sources (see below). This will allow calculation of the AEL for each case. For the analysis of a combination of small sources, the location of the apparent source can be approximated as the location of the actual source array (at all positions in the beams) and the actual spacing between the individual sources is used to calculate the angular subtense (see Figure 9). Only array sizes up to the field of view corresponding to α_{max} = 100 mrad in either direction need to be considered.

Then a measurement of the accessible emission (power through the specified measurement diameter) is done for each combination of sources, and compared to the calculated AEL for that configuration. The field of view (or acceptance cone) is limited in the measurement set-up (using a variable field aperture) so that only the sources considered for each case contribute to the measured power (see Figures 10a and 10b).

7.5.4.3 Angular subtense of a linear array

For simplicity, assume a linear array of identical sources with identical spacing (see Figure 9). If either of these assumptions is not applicable, the analysis is more complicated. If the array is two-dimensional and the spacing is different in the two directions, the parameter Δ becomes Δ_x and Δ_y. This analysis applies to outputs in the retinal hazard spectral region only (400 nm to 1 400 nm).

Figure 9 illustrates how to determine the angular subtense of a linear array of sources. Assuming the individual sources to be small, the angular subtense is calculated from the source array dimensions. Division by the measurement distance *r* (see Figures 10a and 10b) gives the angular subtense for each orthogonal dimension. The equivalent α value is calculated by averaging the two orthogonal α's, α_v and α_h. With almost all fibre cores and most laser apparent sources being smaller than 0,15 mm (corresponding to a minimum α value of 1,5 mrad at 100 mm distance) the default minimum value is often used in the calculation for S_v. According to the standard, the angular subtense in each orthogonal direction (α_v or α_h) is always limited to be ≥ α_{min} (and ≤ α_{max}) before calculating the arithmetic mean, α, of the array.



IEC 2349/11

Δ = center-to-center spacing

n = number of sources being evaluated

S_0 = single source size

S_v = vertical size = S_0 or 1,5 mrad, whichever is larger

S_h = horizontal size = [S_0 + (n - 1) × Δ] or 1,5 mrad, whichever is larger

$\alpha_v = S_v / r$ *and* $\alpha_h = S_h / r$

$\alpha = (\alpha_v + \alpha_h) / 2$

Figure 9 – Linear array apparent source size

Values of T_2 and C_6 can be determined from α for each combination of sources. Using these values and the C_4 and C_7 parameters derived from the emission wavelength, the AEL per source can be calculated. If the evaluation position is in the far field and the beam from each single source can be assumed to be a Gaussian beam, the beam diameter of a single source at each distance can be determined from the beam divergence, and the fraction of the emitted power collected in a 7 mm aperture can be calculated using the coupling parameter (see 7.8.8). This can be used to determine the allowable power per channel for each combination, and the minimum value would be the most restrictive case.

An example of a four source one-dimensional array of fibre optic sources with the same average power and equal spacing is shown in Table 2. The most restrictive case will be determined by the minimum ratio of AEL / *P* in the last column.

Table 2 – Four source array

Number of sources *n*	**Apparent source size** mm	**Angular subtense** mrad	**AEL of evaluated Class** mW	**Accessible emission** mW	**AEL / Power Ratio**
1	$s_{v1} = s_{h1} = s_0$	$\alpha_{v1} = \alpha_{h1} = \alpha_1 = s_0 / r$;	AEL_1	P_1	AEL_1 / P_1
2	$s_{v2} = s_0$; $s_{h2} = s_0 + \Delta$	$\alpha_{v2} = s_{v2} / r$; $\alpha_{h2} = s_{h2} / r$; $\alpha_2 = (\alpha_{v2}+\alpha_{h2}) / 2$	AEL_2	P_2	AEL_2 / P_2
3	$s_{v3} = s_0$; $s_{h3} = s_0+2\Delta$	$\alpha_{v3} = s_{v3} / r$; $\alpha_{h3} = s_{h3} / r$; $\alpha_3 = (\alpha_{v3}+\alpha_{h3}) / 2$	AEL_3	P_3	AEL_3 / P_3
4	$s_{v4} = s_0$; $s_{h4} = s_0+3\Delta$	$\alpha_{v4} = s_{v4} / r$; $\alpha_{h4} = s_{h4} / r$; $\alpha_4 = (\alpha_{v4}+\alpha_{h4}) / 2$	AEL_4	P_4	AEL_4 / P_4

If the power or energy varies between individual sources or the sources are not equally spaced, the number of cases to analyze is increased. For example, there will be three possible combinations of two sources within a four source array. Geometry and similarity between sources will determine the possible degree of simplification.

The division of the paired values of the AEL of the evaluated class over the accessible emission (*P*) must be greater than one for all evaluated cases. Then, the product can be assigned to the evaluated class.

7.5.4.4 Complexities of multiple source arrays

For the case of *n* sources, all cases from 1 source to *n* sources must be considered to determine the most restrictive limit. Usually the simplifying assumption is made that all sources emit the same average power as the peak source. That will be assumed here. If that is not the case, the analysis may be more complicated, but possibly worth doing so that the calculated most restrictive condition is not overly restrictive. If the array is two-dimensional (not constrained to lie on a straight or curved line), there may be several arrangements for a certain intermediate number (between 1 and *n*) to be considered.

Cases to be evaluated are determined by considering a variable circular aperture at the emission plane. The minimum source emission aperture diameter contains one source. The maximum emission source aperture diameter corresponds to an acceptance full angle at the 7 mm measurement aperture of 100 mrad. Determine α from the source array dimensions of the case to be evaluated, and measure the accessible emission through the 7 mm aperture. The AEL corresponding to the α of this case is compared to the measured accessible emission. The accessible emission must not exceed the AEL of the assigned class for any possible combination of sources.

NOTE If 7 mm is not the specified measurement aperture for this evaluation (e.g., using Condition 1 for an array of collimated sources), use the appropriate aperture and distance.

See Figures 10a and 10b below for the measurement geometry. Calculations depend on the angular subtense, α (of the combination of sources to be evaluated). Thus, determination of the appropriate α values is critical for the multi-source case. Considering each single source as a small source, α corresponds to the acceptance cone of Figure 10a or Figure 10b. (For the single source case, assuming the minimum default value of α = 1,5 is sufficient.)

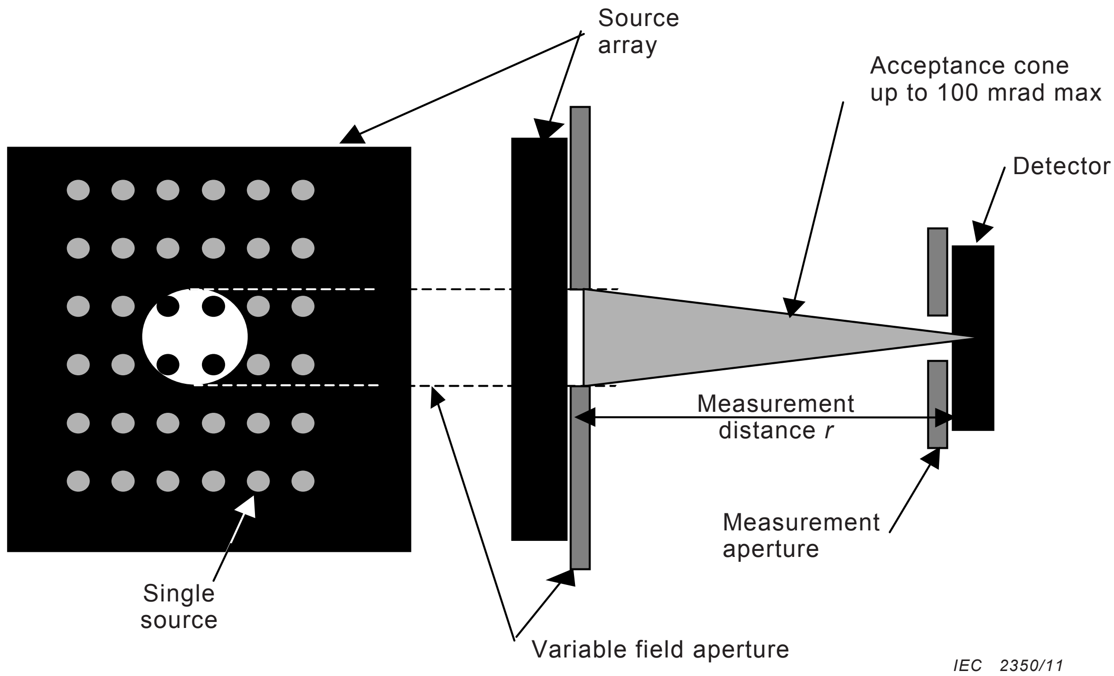


Figure 10a – Measurement geometry for an accessible source

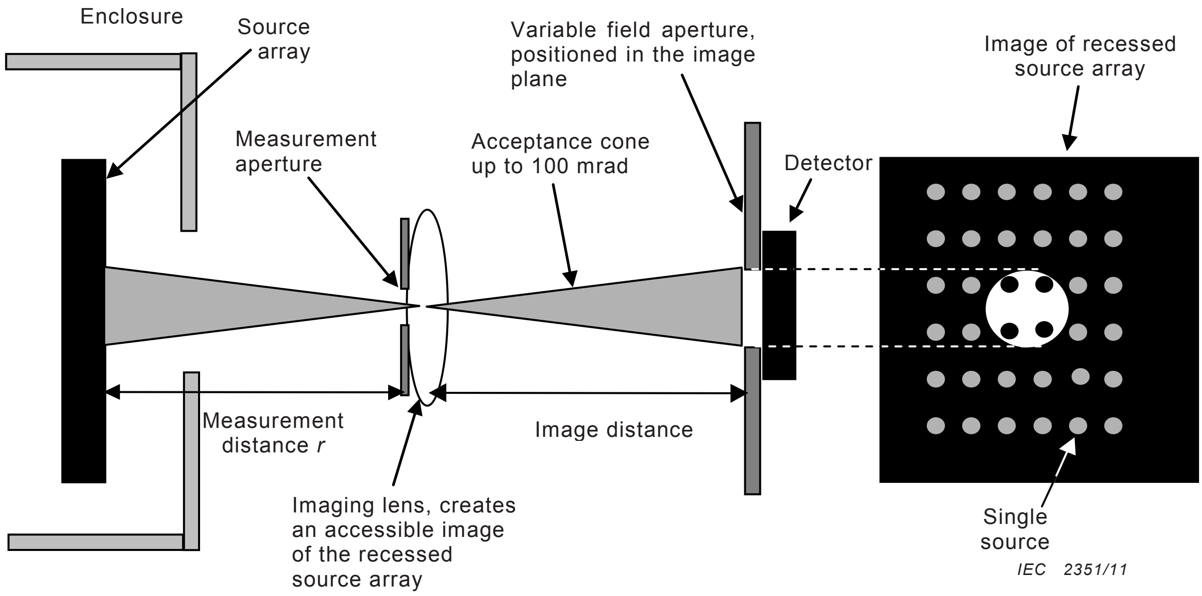


Figure 10b – Measurement geometry for a recessed source

Figure 10 – Measurement geometries

a) For an extended source, it can be shown that Condition 3 in the standard (IEC 60825-1:2007) will be more restrictive than Condition 2. Thus the angular subtense of the apparent source (α) can be determined by dividing the (average) dimensions of the source by the measurement distance of 100 mm (see Figures 9 and 10).

b) It is then necessary to measure or calculate the power collected in the measurement aperture for the array configuration being evaluated. If a measurement is not convenient and if the (1/e) beam divergence from the source is known, calculate the diameter of the beam pattern at the measurement aperture. If the divergence is not known, the angular subtense of a single source could be used as a conservative minimum value. Then calculate the fraction of that beam which would be collected in the 7 mm aperture. (See 7.8.8 for the coupling parameter). If the beam would overfill that aperture, then the fraction not transmitted should also be accounted for in determining the total allowable power.

c) Based on the fraction of the beam that would be collected in the 7 mm aperture and the value of α, we can calculate estimates for the class limits and the total allowable power for each assumed configuration. The class limit for the array will be determined by the configuration in which the total allowable power divided by the number of sources is a minimum.

7.5.4.5 Simple non-circular sources

So far only circular symmetric sources have been considered. If the source is non-circular, the effective angular subtense is given by:

$$\alpha_{x+y} = (\alpha_x + \alpha_y) / 2$$

where α_x and α_y are the angular subtenses along the two orthogonal directions, as shown below in Figure 11.

The angular subtense that is greater than α_{max} or less than α_{min} is to be limited to α_{max} or α_{min}, respectively, prior to calculating the mean.

For a rectangular source, α_x and α_y are the long and short dimensions of the real sources.

For an elliptical source, α_x and α_y are twice the semi-major and semi-minor axes of the ellipse.

Measurement of the angular subtense can be accomplished using a similar procedure to that given in 7.5.4.3.

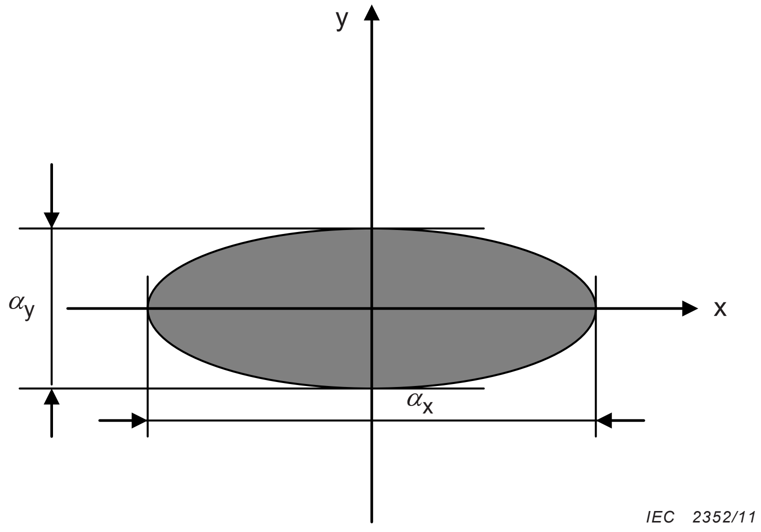


Figure 11 – Effective angular subtense of a simple non-circular source

7.6 Emission duration

7.6.1 General

In item e) of 8.3 in the standard, three classification time bases are specified:

a) 0,25 s for visible wavelengths for Classes 2, 2M and 3R;

b) 100 s for all except cases for which 1) and 3) apply;

c) 30 000 s for intentional long term viewing and for UV hazards.

An exception exists for the retinal hazard region of 400 nm to 1 400 nm for the thermal hazard only. If the parameter T_2 is specified in the appropriate box of the table giving the formulas for limits, calculate T_2, and use it if appropriate. T_2 ranges from 10 s for small sources to the default value of 100 s for large sources (see 8.3 f) of the standard).

7.6.2 Pulse duration

It is also often necessary to measure the duration of a single pulse as described in 7.4.3.2 for determination of the appropriate MPE or AEL limits. This is true for laser systems that emit laser radiation only in a single pulse mode or those that emit a series or train of pulses. Again, as with many of these laser parameters, the pulse width may be available from the manufacturer. If it is necessary to measure the pulse width an oscilloscope is the optimum choice of instrumentation.

7.6.3 Pulse repetition frequency

Determining the pulse repetition frequency (PRF) will be necessary to compute the number of pulses delivered during a given exposure time (or classification duration) and thus aid in determining C_5. This correction factor is then applied to the calculation of the proper MPE (or AEL). Once the PRF is determined, the number of pulses that occur during the exposure time is the product of the PRF and the exposure time (see 7.4.3.3 for a full discussion of PRF).

7.7 Measurement conditions

7.7.1 General

Certain measurement conditions apply to classification and others only to laser hazard evaluation. Those used for laser hazard evaluation are used in calculations of nominal ocular hazard distance (NOHD) and optical density (OD) required for protection.

7.7.2 Measurement conditions for classification

Refer to Table 11 in the standard for appropriate measurement apertures and locations.

Measurement conditions include:

a) diameter of the measurement aperture;

b) distance between measurement aperture and source or apparent source;

c) acceptance angle of radiation measurement device;

d) emission angle limit (angular subtense of the apparent source) of radiation to be measured.

Care should be taken to limit measured radiation to radiation in the main beam. Any off-axis radiation that reaches the detector via reflection or scattering from non-measurement system surfaces should be excluded.

For small sources with diameters significantly less than the limiting aperture, only a measurement of the total power is needed for classification.

For Condition 2 for small sources the measurement distance is 70 mm from the reference point. For emissions in the wavelength range of 400 nm to 1 400 nm, the need to perform measurements for Condition 2 (eye loupe viewing) can be greatly reduced by recognising that Condition 3 (unaided viewing) in many cases will be the most restrictive criterion.

If it can be shown that the apparent source is extended ($\alpha >$ 1,5 mrad) for unaided viewing at 100 mm distance from the reference point, Condition 2 does not have to be considered.

If the source is not extended for unaided viewing (i.e. the angular subtense of the apparent source is less than 1,5 mrad at 100 mm distance from the reference point), or if the angular subtense of the apparent source is not determined (default simplified evaluation), Condition 2 needs to be considered, as it could be more restrictive than Condition 3.

For the case that the optional application of Condition 2 for extended sources (Figure 5 of the standard) is considered, the following cases can be distinguished:

a) if the angular subtense of the apparent source is determined to be less than 1,5 mrad at 100 mm from the reference point, but appears extended ($\alpha >$1,5 mrad) using Condition 2 for extended sources (Figure 5 of the standard) (due to the magnification of the eye loupe), Condition 2 for extended sources may be less restrictive than the simplified Condition 2 and can be applied for the test. If Condition 2 for extended sources (per Figure 5 of the standard) is used, the corresponding angular subtense is also to be determined using this measurement setup. It should be noted that in this case Condition 3 (where C6 =1) can be more restrictive than Condition 2 for extended sources (Figure 5 of the standard) and has to be considered.
b) if the angular subtense of the apparent source is determined to be less than 1,5 mrad at 100 mm from the reference point, and is also less than 1,5 mrad using Condition 2 for extended sources (Figure 5 of the standard), the simplified Condition 2 (Table 11 of the standard) is applicable.

NOTE For the default (simplified) evaluation described in 9.3.2 of the standard, it is not necessary to determine the angular subtense of the apparent source. The apparent source can be assumed to be a small source to simplify the analysis, since this would be the most restrictive case. The simplified measurement conditions listed in Table 11 of the standard would apply.

For extended sources, the angular subtense of the apparent source is to be determined from the most hazardous measurement distance at greater than or equal to 100 mm from the apparent source for evaluations to satisfy Condition 3 of Table 11 of the standard and from a distance of 70 mm from the apparent source for evaluations to satisfy Condition 2. If the apparent source is recessed by more than the specified measurement distance according to the standard, the evaluation for Conditions 2 or 3 is to be at the closest point of human access. Angular subtense and accessible emission are paired values determined at the same distance.

For evaluations to satisfy Condition 1 of Table 11 of the standard, the specified minimum distance is 2 m from the closest point of human access. If angular subtense is to be used to calculate a value of $C_6 > 1$, all distances must be considered until the condition of maximum hazard is found. Under some Condition 1 evaluations, it is appropriate to multiply the angular subtense by a factor of 7 to account for a magnified image and the gain of typical optical aids. For these cases for Condition 1, the maximum angle over which laser energy need be collected would be (100 mrad) / 7 = 14,3 mrad. However, the multiplication factor may be less than 7 (see Clause 9 of the standard for more information on the multiplication factor).

Since the maximum acceptance angle for radiation measurements is 100 mrad for thermal evaluations and 110 mrad for photochemical evaluations, for large sources the energy from any portion of the source outside of those angles need not be collected.

7.7.3 Measurement conditions for hazard evaluation

7.7.3.1 General

Measurement conditions for hazard evaluation include power/energy measurements, irradiance and radiant exposure, beam diameter, and beam divergence at a minimum. The following subclauses provide information about these measurements.

7.7.3.2 Power/energy measurements

Another crucial parameter that needs to be measured for laser hazard evaluations and laser classification is the total radiant power, or total radiant energy, emitted by the laser in question. Radiant power, measured in watts, relates to lasers that have a continuous wave (CW) mode of operation where the rate of energy emitted is constant when plotted over time. Radiant energy, measured in joules, refers to lasers that emit in a single pulse or a series of pulses.

A radiometer, with its detector matched to the wavelength of the laser, is most often used to measure the radiant power or radiant energy. In some instances, a calorimeter would be the most effective device for measuring the radiant power or energy. When measuring the laser beam radiant power or radiant energy, the detector area should be larger than the beam area to ensure the entire beam is captured. This implies that prior knowledge of the approximate beam diameter is required. Most often the beam diameter is specified by the manufacturer. Visual inspection, with the naked eye for visible lasers and with infrared viewers, phosphorescent cards, or thermal liquid crystal sheets for lasers operating in the infrared or ultraviolet can also be used to determine the approximate beam diameter to detector area ratio.

The method of measurement of radiant energy for a single pulse laser is in essence the same as the method of measurement of radiant power, ensuring that the detector captures the entire beam. The energy per pulse of a laser that emits multiple pulses or a series of pulses can be measured directly using an energy meter or it can be calculated from the peak power and pulse width. The product of the peak power and pulse width results in an approximation of the area under the power over time curve. However, radiometers exist that can perform an integration of power over time which simplifies this measurement.

Although measurement of the radiant power and radiant energy appears to be very straightforward, potential errors can arise due to a variety of reasons. As previously mentioned, radiometric detectors are sensitive to only a portion of the optical spectrum. Using a detector to measure a laser that emits a wavelength that is at the limits of or outside the detector’s spectral responsivity will result in a reading that is probably lower than what is actually being emitted. Conversely, exceeding the detector manufacturer’s recommended maximum rating for average power or pulse energy will result in saturation of, or damage to, the detector which will also lead to low erroneous reading. A simple test for saturation is to reduce the input to the detector either using a neutral density filter or stopping down the beam via an aperture, by a factor of ten and determine if the reading corresponds accordingly. Quantum detectors are sometimes also limited by the pulse repetition frequency they can accept. If the pulse repetition of the laser is in excess of the detector manufacturer’s recommended maximum, saturation or damage can again occur.

7.7.3.3 Irradiance and radiant exposure

In some cases, it is impossible to capture the entire beam within the area of the detector. Depending on the application, the laser beam may be expanded such that the diameter is greater than the available detector. This situation is not necessarily adverse to the hazard analysis or classification. The MPEs are given in terms of irradiance or radiant exposure, so this type of measurement would offer a direct comparison. Some instruments are specifically designed to give readings in terms of irradiance and radiant exposure by dividing the power or energy collected by the active area of the detector. Irradiance and radiant exposure can also be calculated by dividing the reading from the detector (power or energy) by the area of the laser beam.

7.7.3.4 Beam diameter

Measuring beam diameter, at the output of the laser, is applicable when a hazard distance is to be assigned. The range equation considers this parameter in its determination of the nominal ocular hazard distance.

For laser beams with circular symmetry, an aperture technique can be used to determine beam diameter. A variable circular aperture centered on the optical axis of the beam is placed between the detector and the laser source. The aperture is opened to allow the total beam to pass through and a power or energy measurement is taken. The aperture is then reduced until 63,2 % of the total reading is achieved. The aperture diameter will then correspond to the 1/e diameter of the laser beam if the beam is of a Gaussian profile.

There is another aperture technique for beam diameter measurement that can be applied to Gaussian beams with circular symmetry. This method uses a small fixed circular aperture with diameter D_{fa} centered on the optical axis of the laser beam. Through this aperture a power measurement is taken yielding Φ_d. This is then represented as a ratio with respect to the total laser power as Φ_d / Φ_0. Assuming the beam has a Gaussian distribution and the ratio is less than 80 %, the beam diameter d can be approximated by

$$d_{63} = \sqrt{\frac{-D_{fa}^2}{\ln\left(1 - \frac{\Phi_d}{\Phi_0}\right)}}$$

For a top hat shaped distribution

$$d_{100} = D_{fa}\sqrt{\frac{\Phi_0}{\Phi_d}}$$

A measurement using a narrow slit scanned through the beam is another technique for determining the Gaussian beam diameter. To obtain the highest degree of accuracy, the slit width should be significantly smaller than the beam size. The slit is placed between the detector and the laser source. As the slit is scanned across the beam the detector reading is noted, the beam diameter is the distance between diametric points on the beam where the detector reading through the slit is 36,8 % of the maximum. This technique is useful for beams that are noncircular in profile when the scanning axis can be rotated to measure the beam diameters of the different axes.

A similar method employs a pinhole aperture instead of a slit. The principle is the same; a pinhole is placed between the laser and the detector. The irradiance reading through the aperture is monitored as the aperture is scanned across the beam. As with the slit technique, the beam diameter is the distance between the points on either side of the center of the beam where the irradiance readings are 36,8 % of the maximum reading taken from the center of the beam.

Instrumentation such as CCD cameras and pyroelectric arrays can also be employed to measure the beam diameter. These types of instruments sample the entire two dimensional cross section of the beam. Similar to the pinhole method this technique samples the entire beam profile at one plane location. Most of these devices are operated by computer and can be programmed to give the diameter at 1/e, $1/e^2$, or d_u points.

Visual inspection can yield a reasonably good estimation of the beam diameter. Placing a ruler in the beam near the exit and reading the measurement is the simplest approach. Of course if the laser is in the infrared, an infrared viewer will be needed to see the beam. An alternative would be to measure the scattered or emitted radiation from target material placed in the beam. These target materials could be phosphorescent cards, thermal liquid crystal sheets or simply a sheet of paper. Error is introduced in both methods due to the apparent size of the beam changing based on the amount of ambient light present at the time of measurement. For higher power lasers the burn or exposure pattern could be measured from the target material. Higher power lasers require the target material to be somewhat more robust depending on the power of the laser. Examples of such material could be photographic film, thermal paper, polycarbonate, acrylic, plexiglass forms of plastic, and a tongue depressor or similar piece of wood. Measuring these burn or exposure patterns is a little more precise than merely viewing the laser spot and measuring it, but is still not completely exact.

7.7.3.5 Beam divergence

Measuring the beam divergence is not always a necessary parameter for classification but for a complete hazard analysis, this parameter must be quantified, for it impacts the hazard distance calculations. There are a number of techniques used to determine the beam divergence. A few of these are described below.

a) One approach to divergence measurement is the two point diameter measurement technique. Measure the beam diameter at its smallest point either at the beam waist or close to the laser output aperture. Another diameter measurement is then taken at a point in the direction of propagation. The distance between the points is then measured. The square root of the squares of the difference of the diameters of the two points is determined and then divided by the distance of separation, which yields the divergence. This is expressed numerically for Gaussian beams by the following formulation.

$$\phi = \frac{\sqrt{(\mathrm{d}^2) - (\mathrm{d}_\mathrm{W}^2)}}{\mathrm{r} - \mathrm{r}_0},$$

where r_0 is the location of the beam waist.

b) A similar method is to choose two points along the axis of propagation where the beam diameter is much greater than the smallest diameter along the beam path (the smallest diameter being the beam waist or the diameter at the exit aperture). This region of the beam is called the far field. The diameters and separation distance of the chosen points are measured. The divergence is simply the difference of the diameters divided by the distance between the points. The equation below expresses this mathematically.

$$\phi = \frac{d2 - d1}{r_2 - r_1}$$

This is a rather straightforward simplistic method but it is not without pitfalls. To ensure accuracy, one must be in the far field as described above. The far field is the region of the beam where the irradiance values obey the inverse square law and decline with a $1/r^2$ dependence similar to an incoherent source. With some lasers this far field can be quite a distance from the laser exit aperture, sometimes kilometers away.

c) When space is an issue, another method of determining beam divergence for Gaussian laser beams is to employ a long focal length lens and an aperture. It is important to use a very high quality lens with a long focal length. The beam divergence can be calculated from the beam diameter of a focused laser beam at the focal point of the lens for the wavelength of the laser. The geometric focal length of the lens is dependant upon the particular wavelength in question. In some cases, for typical laser wavelengths, these focal lengths may be specified by the manufacturer. If, however, the focal length for a particular wavelength need be quantified, then a standard lamp and narrow pass filter may be used for this purpose. When the lamp is placed a certain distance s_1 from the lens, the image will appear at a distance s_2 from the other side of the lens. Once the image distance s_2 is determined, the lens maker's equation below can be used to calculate the focal length of the lens for that particular wavelength.

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f}$$

The physical set up for this measurement requires a lens be placed somewhere in front of the laser. Placement of the lens with regards to its focal length is not essential, however the lens should not be placed at the beam waist. A reference power or energy measurement should be taken of the laser beam after it is passed through the lens. This measurement should not be taken directly at the focal point, for damage to the detector is likely with a focused beam. A small aperture is then placed in the focal plane of the lens to measure the beam diameter. Note that the measurement is taken at the focal length of the lens, which is not necessarily where the smallest spot size is found. The energy passed through the aperture should measure 63,2 % of the reference reading to correspond to the 1/e points. Once the geometric focal length is known or determined and the focused beam diameter at the focal point is measured, the divergence can then be calculated using the following formulation.

$$\phi = \frac{d_{fp}}{f}$$

d) For lasers with a Gaussian profile and where space is not an issue, a simple technique using just a radiometer can be used for determining the beam divergence. For this method a total power or energy measurement must first be taken. Then in the far field, where the beam diameter is substantially greater than the initial beam diameter, a maximized irradiance or radiant exposure measurement, E_{max} or H_{max}, is taken. The irradiance measurement should be taken near the centre of the beam and the detector head should be significantly smaller than the beam diameter at this point. The following formulation relates the total power or energy value, Φ or Q, the maximized irradiance or radiant exposure, E_{max} or H_{max}, and the distance, r, at which the maximized irradiance measurement was taken to the divergence, ϕ.

$$\phi = \frac{\sqrt{\frac{4\Phi}{\pi E_{max}}}}{r} \quad \text{or} \quad \phi = \frac{\sqrt{\frac{4Q}{\pi H_{max}}}}{r}$$

7.8 Scanning beams

7.8.1 General

In many applications, a simple calculation assuming $C_6 = 1$ and a pulse duration corresponding to the beam scanning across the full measurement aperture at a distance of 100 mm from the vertex of the scanning beam results in classification that meets the manufacturer’s requirements. If a less restrictive limit is desired, this subclause outlines a method to determine a more accurate AEL that may allow a lower classification or more output power in the same classification. Annex A includes examples for scanning beams.

NOTE As specified in 9.3 of the standard, Condition 1 and Condition 2 do not apply to scanning beams.

7.8.2 Stationary angular subtense (α_s)

If we assume the scanning system is disabled and the eye is focused at a particular distance, Z, the stationary angular subtense is the subtended angle of the beam diameter (d) at distance Z. Figure 12 shows an optical layout for a disabled scanning system where the location of the point being imaged by the eye is beyond the vertex of the scanning beam.

$$\alpha_s = d / Z$$

where

d = beam diameter at location of point of eye focus

Z = Distance from measurement aperture to location of point of eye focus

NOTE 1 The retinal image irradiance profile is only directly proportional to the beam irradiance profile at the point of accommodation when all of the rays that form the beam actually enter the aperture stop AP. In other cases, an "artificial eye" model or experimental setup must be used to determine the angular subtense.

NOTE 2 The angular subtense is determined in accordance with the standard, subclause 8.3.d); see also 7.5.3 of this technical report. For a Gaussian beam the diameter encircling 63 % of the energy, d_{63}, can be used to determine the angular subtense.

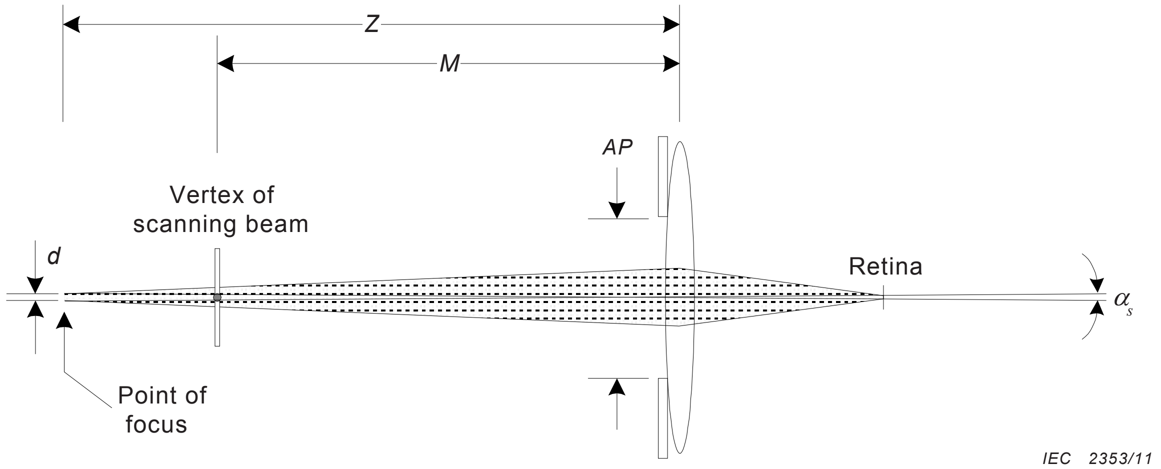


Figure 12 – Imaging a stationary apparent source located beyond the scanning beam vertex

7.8.3 Scanned pulse duration (T_p)

Figure 13 shows this optical system while scanning at two different times (t_0 and t_1) corresponding to when the centre of the beam has reached the edges of the measurement aperture (*AP*).

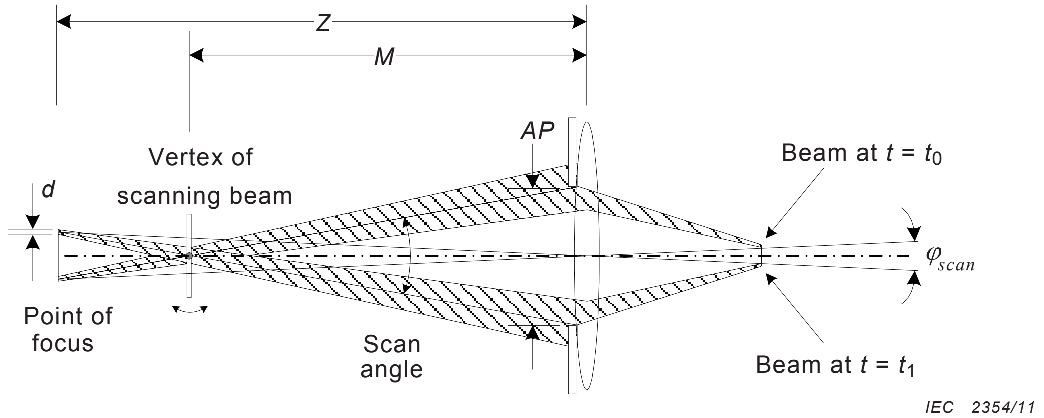


Figure 13 – Imaging a scanning apparent source located beyond the scanning beam vertex

NOTE 1 The scan element is shown as a transparent rather than reflective element in order to simplify the optical layout.

For constant angular velocity, the pulse duration used for classification is

$$T_p = t_1 - t_0 = \frac{\tan^{-1}(AP/M)}{\omega} \approx \frac{AP}{M\omega}$$

where

ω = angular velocity of the scanning beam in rad/s;

AP = measurement aperture diameter as defined in Table 11 of the standard (e.g., 7 mm for $\lambda < 1\,400$ nm);

M = distance from measurement aperture to scanning vertex.

NOTE 2 Since M is much larger than AP, a small angle approximation is used to simplify the equations.

As the distance from the scan element increases, the angle subtended by the measurement aperture decreases, resulting in decreased pulse duration. This may not be the case when the beam is larger than the measurement aperture or the scan velocity function is non-linear. See 7.4.3 and 7.6 regarding measurement of pulse duration and pulse repetition frequency.

7.8.4 Scanning angular subtense (α_{scan})

The scanning angular subtense, α_{scan}, is used to calculate C_6 for scanning beams where the scan angle covers a line or an area that is larger than the pupil. If the scan stays within the pupil, the beam can be treated as CW or a more elaborate analysis must be done. If the eye is not focussed on the scanning beam vertex, the beam forms a scan line on the retina, which subtends an angle of φ_{scan}. This is dependant on the measurement aperture size and distance and the point of eye focus:

$$\varphi_{scan} = \left| 2\tan^{-1}\left[\frac{AP}{2}\left(\frac{1}{M} - \frac{1}{Z}\right)\right]\right| \approx \left| AP\left(\frac{1}{M} - \frac{1}{Z}\right)\right|$$

NOTE 1 The scanning beam vertex is not necessarily at the surface of the scanning element, but often that is the case.

NOTE 2 This formula is valid regardless of which side of the scanning beam vertex the point of eye focus is located.

φ_{scan} cannot be used to define the angular subtense along the scanning direction for calculation of C_6 because for a brief time all of the energy is directed to a single point on the retina. However, for durations less than T_i as specified in Table 3 of the standard (e.g., 18×10^{-6} s for 400 nm $< \lambda <$ 1 050 nm), the hazard is not dependent on the beam shape and integration is allowed. Accordingly, the scanning angular subtense can be increased by φ_T, the portion of φ_{scan} corresponding to the movement of the beam on the retina during time T_i and given by the formula:

$$\varphi_T = \begin{cases} (T_i / T_p)\varphi_{scan} & T_p \geq T_i \\ \varphi_{scan} & T_p < T_i \end{cases}$$

Substituting equations for T_p and φ_{scan} yields:

$$\varphi_T = \begin{cases} T_i M\omega\left|\frac{1}{M} - \frac{1}{Z}\right| & T_p \geq T_i \\ AP\left|\frac{1}{M} - \frac{1}{Z}\right| & T_p < T_i \end{cases}$$

The scanning angular subtense α_{scan} is given by the formula:

$$\alpha_{scan} = \max[(\alpha_s + \varphi_T), \alpha_{min}]$$

where α_s is the stationary angular subtense along the scanning axis.

NOTE 3 If α_s is less than α_{min}, α_s is not replaced with α_{min}.

For any point of eye focus, C_6 can be calculated with the formula:

$$C_6 = \frac{\alpha_{nscan} + \alpha_{scan}}{2\alpha_{\min}}$$

where α_{scan} is the angular subtense along the non-scanning axis or $\alpha_{\min}$, whichever is larger.

7.8.5 Bi-directional scanning

If the scanning system is bi-directional, there is a location at the end of the scan line where the beam stops and reverses direction. If this point is accessible, it must be considered in determining the AEL. Since the angular velocity is non-linear, the pulse duration, T_{p}, is not given by the formula in 7.8.3 and must be measured or derived for the velocity as a function of angular position. In order to calculate C_6, φ_{T} should be measured or derived as the angle that the beam moves away from the endpoint in either time T_{i} / 2 or time T_{p} / 2, whichever is shorter. The duration is half because the beam reverses direction at the end of the scan line, while remaining in the same region on the retina. If the turn-around (zero-velocity) point is not accessible (e.g. it is clipped by some sort of beam block), then the end of the accessible scan line often has the slowest beam speed and, thereby, the longest pulse duration. In this case φ_{T} is still measured from the end of the accessible scan line but the measurement time is simply the shorter of T_i or T_{p}. For bi-directional scanning, the pulse duration depends on the position of the measurement aperture (*AP*) along the scan line. For a scanning mirror with sinusoidal oscillation, and the measurement aperture *AP* located at the end (turn-around point) of the scan line, the pulse duration used for classification using a small angle approximation is:

$$T_p = \frac{1}{\pi f} cos^{-1}\left(1 - \frac{2AP}{\theta M}\right),$$

where:

f = scan frequency;

θ = full scan angle;

AP = measurement aperture diameter;

M = distance from measurement aperture to scanning vertex.

It should be noted that while sinusoidal motion is often assumed for a bidirectional scanning element, the true motion is dependent on the mechanism used and may vary from a true sinusoid. If the motion has been well characterized as sinusoidal, derived equations can easily be used to determine pulse duration. (See Appendix A for a sinusoidal scanning example.) For other situations direct measurement of the beam motion may be the preferred method.

If laser power is varied as a function of scanning angle, which may be done for some type of performance optimization such as improving brightness uniformity, then the position in the beam which produces the longest pulse duration might not correspond to the limiting AEL for the device. In this case the AEL must be determined as a function of scan angle (as well as distance from the scanner) and compared to the laser power. The highest ratio of power to AEL will be the limiting condition.

7.8.6 Number of scan lines in aperture (*n*)

In the case of multiple scan lines originating from a single point on a scanning element, scan line separation typically increases with increasing distance from the scanning element. The number of scan lines in the aperture affects the number of pulses in the pulse train during the applicable time base. The equation below expresses the number of pulses in the pulse train, *N*, as a function of pulse repetition frequency, the number of scan lines in the aperture, and the applicable time base.

$$N = (PRF)\cdot n\cdot T$$

where

N = the number of pulses in the pulse train during the applicable time base, or T_2, whichever is smaller;

PRF = pulse repetition frequency of a single scan line;

n = number of scan lines in aperture;

T = applicable time base or T_2, whichever is smaller.

In order to determine the proper number of scan lines to count as entering the aperture, the full aperture size need not be considered. For example, if at a certain distance two scan lines happen to be separated by 7 mm, counting two full pulse durations across the pupil would be overly restrictive, since the pupil is circular. For the case of two scan lines separated by 6 mm on a 7 mm aperture, two pulses are created, each of which is one half of the pulse duration of the pulse of a single line centered on the aperture. As such, a 6 mm maximum separation is a conservative basis for counting pulses which cross a 7 mm aperture. If a more accurate, less restrictive result is desired, the TOTP method of 8.3.f) 3) b) of the standard can be employed to determine the effective total pulse per repetition. Using that method, the duration of each individual pulse and its dependence on where the beam crosses the aperture are taken into consideration.

See 7.4.3 and 7.6 concerning measurement of pulse duration and pulse repetition frequency.

In scanning systems where multiple scan lines enter the pupil from different field sources, the corresponding images on the retina are at different locations. If these sources are separated by more than 100 mrad, they are considered to be independent and are treated as isolated sources. For angular separation less than 100 mrad, the AEL is calculated for each source individually, as well as all combinations of multiple sources to determine the most restrictive case. If multiple sources are considered as one irregular source, the number of pulses is the number of times the irregular pattern is formed. For example, if source A and source B have a combined C_6 value of $C_{6(A+B)}$ and both are simultaneously scanned across the measurement aperture N times during the measurement period, the AEL will refer to the sum of power from A and B reduced by the repetitive pulse criteria for N pulses, rather than $2 \times N$. See 8.3 of the standard concerning measurement of multiple and irregular sources.

7.8.7 Maximum hazard location

7.8.7.1 General

The maximum hazard location is where the combination of angular subtense, pulse duration, number of pulses, eye accommodation, and collected energy (or power) results in the most restrictive classification. Determining this location can be a complex process since the eye will seek to focus on different objects under different circumstances. Also, the particulars of a specific laser device may produce points of interest in the scanning field. For example, if the stationary beam is converging and exits the device with a size larger than the measurement aperture, the maximum hazard location may be farther away than would be the case if the distance were determined based on the full energy of the beam entering the eye. This would be due to a dependence of the coupling parameter on measurement distance (see 7.8.8). In the case of multiple scan lines, the distance just prior to the transition to fewer scan lines inside the measurement aperture may be the location of maximum hazard. Similarly, the maximum hazard location may be at a distance where the pulse duration equals a boundary value from Tables 4, 5, 7, or 8 of the standard (e.g. 18 μs in the thermal hazard region). When evaluating a distance to determine the most hazardous location, all of the variables are to be measured at that distance.

For specialized, complex scanning systems, variations of all parameters of the system need to be considered, including the focus of the eye, in order to find critical combination. For simple scanning beam systems, as a minimum, the following two cases should be examined for the maximum hazard condition. Also see the examples in Clause A.1 of Annex A.

7.8.7.2 Infinite focus (relaxed eye)

If α_{scan} is considered to calculate $C_6 > 1$, the condition where the eye is focussed at infinity is important to consider. In this case, $Z = \infty$ and α_s approaches the divergence angle, β, of the beam. This can be seen from the definition of α_s as d / Z. As the distance, Z, to the measurement plane goes to infinity, so will the spot size, d, measured in that plane. This yields the result that for measurement distances where T_p is greater than T_i, α_{scan} is not dependent on the distance from the scanning vertex, M, but is only dependent on T_i (from Table 3 of the standard) and the angular scan velocity.

$$\alpha_{scan} = \begin{cases} \max\left[(\beta + T_i\omega), \alpha_{min}\right] & T_p \geq T_i \\ \max\left[(\beta + AP/M), \alpha_{min}\right] & T_p < T_i \end{cases}$$

When T_p is less than T_i, the equation changes. The measurement distance at which the equation changes is $M = AP / T_i\ \omega$. If the minimum accessible measurement distance is less than this value, this range near the scanner will have an α_{scan} that varies only with distance M. If the angular velocity is less than $((\alpha_{min} - \beta) / T_i)$, then α_{scan} will equal α_{min} in this range. If the beam is astigmatic, α_{nscan} can be large enough to yield $C_6 > 1$, but the measurement distance of 100 mm is often the most hazardous condition. This can be checked by varying the measurement distance to find the worst case position.

7.8.7.3 Focus on scanning vertex

Another condition to evaluate is where the eye is focussed on the scanning vertex and the measurement aperture location is far enough away such that α_s and α_{nscan} are less than α_{min}. In this case $C_6 = 1$. The distance Z_0 is given by

$$Z_0 = d_{max} / 0{,}0015$$

where d_{max} is the larger of the two dimensions of the beam at the location of the scanning vertex.

7.8.8 Gaussian beam coupling parameter (η)

Regardless of the total amount of energy in the beam, only the energy passing through the limiting aperture at the given measurement distance should be included for classification.

Depending on the waist width and beam divergence, the beam may be larger than the measurement aperture at some or all positions along the accessible beam path. For non-Gaussian beams the power passing through an aperture should be measured directly.

For a symmetric Gaussian profile, the fraction of the total energy passing through a circular aperture centred on the beam is:

$$\eta = 1 - e^{-\left(AP/d_{ap}\right)^2}$$

where

AP = diameter of the measurement aperture;

d_{ap} = diameter of the beam at the aperture (as determined according to the standard, i.e., d_{63}).

7.8.9 Scan angle multiplication factor

In order to determine the proper pulse duration, short of measuring it directly at every point of interest, it is necessary to know the angular beam speed of a scanning device. It is quite common for the scanning element to be a rotating mirror or set of mirrors with a constant speed of rotation, but it is important not to confuse the mirror rotation speed with the angular beam speed. For the very simple case where the axis of rotation is perpendicular to the scanning plane the angular beam speed will be faster than the mirror rotation speed by a factor of 2. This factor is referred to as the scan angle multiplication (SAM) factor, and for a simple rotating mirror it will always be between 0 and 2.

Figure 14 shows the situation where the SAM factor would be different than 2. The SAM factor, K_{SAM}, can be determined mathematically using the following formula:

$$K_{SAM} = \cos\theta_i + \cos\theta_r$$

where θ_i and θ_r are the incidence and reflection angles as defined in Figure 14.

NOTE The SAM factor is not necessarily constant through a full 360° rotation of a mirror. As such this equation is only truly accurate at the symmetric center of sweep. Typically, however, full scan angles are somewhat limited by finite size of the facet and the SAM factor does not vary much. For wide angle sweeps care should be taken to determine variance of the beam speed.

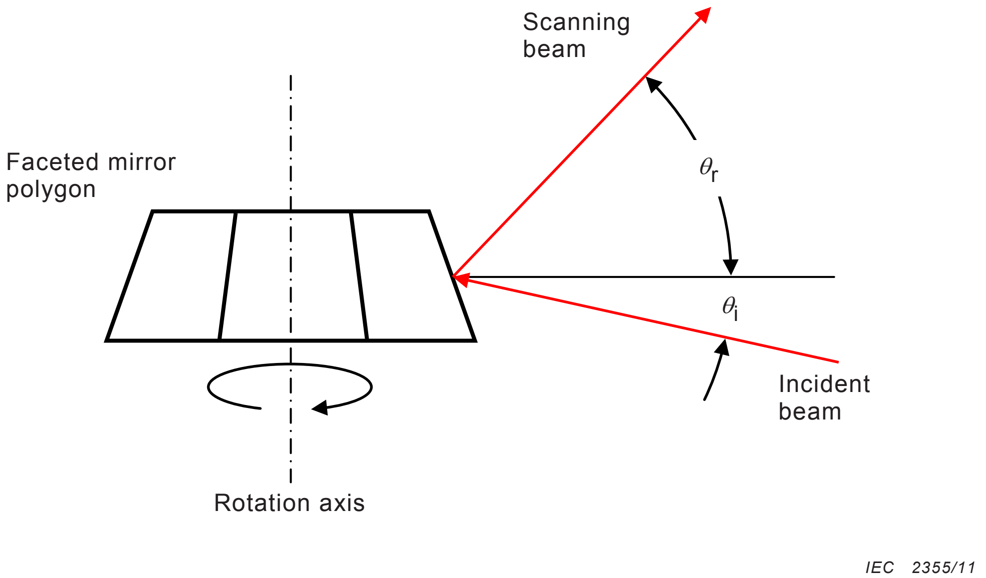


Figure 14 – Scanning mirror with an arbitrary scan angle multiplication factor

In many cases the different facets of the mirrored polygon will be tilted at different angles in order to produce a raster of lines. In such cases, each line will have a different beam speed as a result of the differing reflection angles. For tightly spaced rasters the difference will be small and the slowest speed may be used for all the lines, but for wider rasters independent calculation for each line may be appropriate.

Annex A
(informative)

Examples

A.1 Large source classification example

A.1.1 General

This example shows a method of classifying a product with a large apparent source (> 100 mrad). The energy is assumed to be uniformly emitted roughly perpendicular to a flat surface, and since no beam structure is present (i.e. the source is incoherent or totally diffused), the actual emission area is the apparent source. The assumed parameters are a circular source of diameter d and 1/e beam divergence Φ.

The analysis determines the total allowable power for Class 1. The analysis determines for different distances what fraction of the total energy is within the 100 mrad maximum collection angle, what fraction of that energy is collected by the measurement aperture, and the angular subtense of the apparent source. These parameters can then be used to determine the Class 1 AEL and then the total emitted power under both aided and unaided viewing conditions.

A.1.2 Limit for unaided viewing

A.1.2.1 Emitted collectable energy for unaided viewing

It is necessary to determine what fraction of the emitted energy is from a portion of the source within the maximum acceptance angle of δ = 100 mrad at the distance (r). Any emitted energy that is outside of a 100 mrad circle projected onto the source need not be considered. We can designate the fraction within 100 mrad as F_e.

There are two geometric conditions to consider:

For $r < 10\ d$, a 100 mrad circle projected onto the source is less than d in diameter, and:

$$F_e = \pi/4\ (0{,}1r)^2\ /(\pi/4\ d^2) = (0{,}1\ r/d)^2.$$

For $r \geq 10\ d$, the entire source is collected in a projected 100 mrad circle, and $F_e = 1$.

A.1.2.2 Angular subtense of source for unaided viewing

The value of α depends on the portion of the source being evaluated and the distance r from the source.

If $r < 10\ d$, then the source fills the collection angle then:

α = 100 mrad and C_6 = 100 / 1,5 = 66,7.

If $r \geq 10\ d$, then: $\alpha = d\ /\ r$ mrad, and $C_6 = 667\ d\ /\ r$.

A.1.2.3 Collected energy for unaided viewing

For $r < 10\ d$, the area of the diverging beam pattern at distance r from a portion of the source 0,1 r in diameter is approximately:

$A_r = \pi/4\ (\Phi\, r + 0{,}1\ r)^2 = 0{,}79\ (\Phi + 0{,}1)^2\ r^2$.

The fraction of that pattern collected in a 7 mm aperture is:

$F_c = 38{,}4\ \text{mm}^2\ /\ [0{,}79\ (\Phi + 0{,}1)^2\ r^2] = 49\ \text{mm}^2\ /\ [(\Phi + 0{,}1)^2\ r^2]$.

For $r \geq 10\ d$, the area of the diverging beam pattern at distance r from the full source is approximately:

$A_r = \pi/4\ (\Phi\, r + d)^2$.

The fraction of that pattern collected in a 7-mm aperture is:

$F_c = 38{,}4\ \text{mm}^2\ /\ [\pi/4\ (\Phi\, r + d)^2] = 49\ \text{mm}^2\ /\ (\Phi\, r + d)^2$.

Class 1 Criterion

Given a wavelength and a pulse duration, the energy limit can be calculated. For example, the energy limit for Class 1 from Table 5 of the standard for a wavelength from 700 nm – 1 050 nm is:

$E = 0{,}7\ C_4\ C_6\ T_2^{3/4}$ mJ.

This can be written in terms of power as:

$$AEL = E\ /\ T_2 = 0{,}7\ C_4\ C_6\ T_2^{3/4} \times 1\ /\ T_2 = 0{,}7\ C_4\ C_6\ /\ T_2^{1/4}\ \text{mW} \quad \text{(A.1)}$$

A.1.2.4 Total allowable power for unaided viewing

In order to determine the total allowable emitted power, it is necessary to use the correct values of T_2 and C_6 for the distance being evaluated. This analysis determines the angular subtense of the apparent source (α) at the measurement distance being evaluated for $r > 100$ mm, a conservative approach.

Using Equation (A.1), the total allowable emitted power at any distance can be determined, accounting for losses from the aperture stop and the field stop:

$$P_T = AEL\ /\ (F_e \times F_c) = 0{,}7\ C_4\ C_6\ /\ (F_e \times F_c \times T_2^{1/4})\ \text{mW} \quad \text{(A.2)}$$

A.1.3 Analysis for aided viewing

A.1.3.1 Approach

For evaluation of Condition 1, the approach used above for unaided viewing will be followed, with the following adjustments:

- the collection area for the 50 mm aperture is larger;
- the angular subtense of the source is increased by 7X due to the magnification of the optics;
- the acceptance angle for collection of the emitted energy is reduced to $\delta = 100\ /\ 7$ mrad due to the magnification of the optics;
- the minimum distance is 2 000 mm as specified in Table 11 of the standard.

A.1.3.2 Emitted collectable energy for aided viewing

There are two geometric conditions to consider:

For 2 000 mm < r < 70 d, a 100 / 7 mrad circle projected onto the source from a distance r is less than d in diameter, and the approximate fraction of the collected energy is:

$F_{ea} = \pi/4 \times (0,1\ r / 7)^2 / (\pi/4\ d^2) = (0,1\ r / 7\ d)^2$.

For $r \geq 70\ d$ the entire source is collected in a projected 100 / 7 mrad circle, and thus $F_{ea} = 1$.

A.1.3.3 Angular subtense of source for aided viewing

If 2 000 mm < r < 70 d, then:

$\alpha = 100$ mrad and $C_{6a} = 100 / 1,5 = 66,7$.

If $r \geq 70\ d$, then:

$\alpha = 70\ d / r$ rad, and $C_{6a} = 4670\ d / r$.

A.1.3.4 Collected energy for aided viewing

For $r < 70\ d$, the area of the diverging beam pattern at distance r from a portion of the source $0,1r/7$ in diameter is approximately:

$A_r = \pi/4\ (\Phi\ r + 0,1\ r / 7)^2 = 0,79\ (\Phi + 0,0143)^2\ r^2$

The fraction of that pattern collected in a 50 mm aperture is:

$F_{ca} = 1\ 960\ \text{mm}^2 / [0,79\ (\Phi + 0,0143)^2\ r^2] = 2\ 500\ \text{mm}^2 / [(\Phi + 0,0143)^2\ r^2]$.

For $r \geq 70\ d$, the area of the diverging beam pattern at distance r from the full source is approximately:

$A_r = \pi/4\ (\Phi\ r + d)^2$.

The fraction of that pattern collected in a 7 mm aperture is:

$F_{ca} = 1\ 960\ \text{mm}^2 / [\pi/4\ (\Phi\ r + d)^2] = 2\ 500\ \text{mm}^2 / (\Phi\ r + d)^2$.

A.1.3.5 Total allowable power for aided viewing

The total power is derived from the *AEL* using the form for Equation (A.2) but with the parameters for aided viewing at any distance is:

$$P_{Ta} = AEL / (F_{ea} \times F_{ca}) = 0,7\ C_4\ C_{6a} / (F_{ea} \times F_{ca} \times T_{2a}^{1/4})\ \text{mW}. \quad \text{(A.3)}$$

A.1.3.6 Total power allowed from the product

By determining the total emitted power at various distances under Condition 1 and under Condition 2, the minimum value at any distance can be established and used as the allowable power level for the product.

It is of interest to note that the limit under unaided viewing conditions will be constant for all distances of $r < 10\ d$, while the limit under aided viewing conditions will be constant for all distances of $r < 70\ d$. These constant values may or may not be the limiting criteria.

A.1.3.7 Sample result

If a source diameter d = 3 cm and a divergence value of θ = 0,05 rad are assumed, then the allowable power under Condition 3 for unaided viewing at the most restrictive distance of r < 30 cm is 0,61 W from Equation (A.2). The allowable power under Condition 1 at the most restrictive distance of r < 210 cm is 0,11 W from Equation (A.3). Thus the total emitted power allowed for Class 1 would be 0,11 W.

A.2 Scanning beam examples

A.2.1 Simple faceted mirror polygon

A red beam is scanned across a single line with a three-facet mirror spinning at 5 000 rpm. The facets are offset from the motor shaft by 20 mm and the scanning plane is perpendicular to the rotation axis of the polygon. The beam is nearly collimated (beam divergence less than α_{min}) and has an elliptical shape 1,0 mm by 0,5 mm (1/e scan and cross-scan, respectively) at the mirror facets. From the following choices determine the worst case AEL for Class 1:

a) focused on the scanning element, measuring at the nearest distance;

b) relaxed eye, measuring at the nearest distance;

c) focused on the scanning element, measuring at a distance where C_6 = 1;

d) focused on the scanning element, measuring at a distance where the pulse duration equals 18 µs.

For all cases repetitive pulsing requires determination of the AEL for clauses 1), 2), and 3) of 8.3.f) for condition 3 of Table 11 (investigation of conditions 1 and 2 is not necessary for scanning devices).

For a spinning facet wheel, the scanning vertex is typically at the surface of the facet. Measurement distances should be referenced to this point. Some minor shifting of the vertex will occur during the pulse, but this shift will only produce a slight blur of the spot which makes the calculated AEL more conservative.

Since the scanning plane is normal to the rotation axis, the SAM factor is 2 for all cases:

$K_{SAM} = 2{,}0 \quad \rightarrow \quad \omega = (5\,000 \text{ rpm})\ (2\pi / 60)\ (2{,}0) = 1\,047{,}2 \text{ rad/s}$

And since there are three identical facets on the spinning mirror, the pulse repetition frequency (PRF) is 3.

Case 1) Focused on the scanning element, measuring at the nearest distance

Since the scanning vertex is imaged, the beam does not scan across the retina. Assuming 100 mm from the scanning vertex is accessible, that is the appropriate value to use for both measurement and accommodation.

Z = 100 mm	M = 100 mm	d_{nscan} = 0,5 mm	d_{scan} = 1,0 mm
AP = 7,0mm	α_{nscan} = 5,0 mrad	α_s = 10,0 mrad	φ_{scan} = 0 mrad
φ_T = 0 mrad	α_{scan} = 10,0 mrad	α = 7,5 mrad	C_6 = 5,0
T_2 = 11,51 s	T_p = 66,9 µs	N = 2 876	C_5 = 0,137

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_p)^{0,25}$ W $\rightarrow$ $AEL_{1)}$ = 38,7 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4})\ (T_2)^{0,75}] / (N\ T_p)$ W $\rightarrow$ $AEL_{2)}$ = 114 mW

$AEL_{3)} = (AEL_{1)})\ C_5$ W ➔ $AEL_{3)}$ = 5,29 mW

Case 2) Relaxed eye, measuring at the nearest distance

For this case the accommodation distance goes to infinity. Because the beam is collimated $\beta = 0$. Accordingly, the cross-scan angular subtense goes to the limit of 1,5 mrad and $\alpha_{scan} = T_i\omega$.

$Z = \infty$	M = 100 mm	d_{nscan} = 0,5 mm	d_{scan} = 1,0 mm
AP = 7,0mm	α_{nscan} = 1,5 mrad	α_s = 0,0 mrad	φ_{scan} = 70 mrad
φ_T = 18,9 mrad	α_{scan} = 18,9 mrad	α = 10,2 mrad	C_6 = 6,78
T_2 = 12,25 s	T_p = 66,9 µs	N = 3 062	C_5 = 0,134

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_p)^{0,25}$ W ➔ $AEL_{1)}$ = 52,5 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4})\ (T_2)^{0,75}] / (N\ T_p)$ W ➔ $AEL_{2)}$ = 152 mW

$AEL_{3)} = (AEL_{1)})\ C_5$ W ➔ $AEL_{3)}$ = 7,06 mW

Case 3) Focused on the scanning element, measuring at a distance where $C_6 = 1$

To find the proper measurement distance the larger of the two beam dimensions is used. In this case the 1 mm beam dimension subtends 1,5 mrad at 667 mm. This value is used for both Z and M. Note that the shorter pulse duration changes the equation for $AEL_{1)}$.

Z = 667 mm	M = 667 mm	d_{nscan} = 0,5 mm	d_{scan} = 1,0 mm
AP = 7,0mm	α_{nscan} = 1,5 mrad	α_s = 1,5 mrad	φ_{scan} = 0 mrad
φ_T = 0 mrad	α_{scan} = 1,5 mrad	α = 1,5 mrad	C_6 = 1,0
T_2 = 10,0 s	T_p = 10,0 µs	N = 2 500	C_5 = 0,141

$AEL_{1)} = (C_6 \cdot 2 \times 10^{-7}) / (T_p)$ W ➔ $AEL_{1)}$ = 20,0 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4})\ (T_2)^{0,75}] / (N\ T_p)$ W ➔ $AEL_{2)}$ = 157 mW

$AEL_{3)} = (AEL_{1)})\ C_5$ W ➔ $AEL_{3)}$ = 2,82 mW

Case 4) Focused on the scanning element, measuring at a distance where the pulse duration equals 18 µs

For this final case the beam speed is used to determine the measurement distance. With a 7 mm aperture it is found that an 18 µs pulse is achieved at a distance of 371 mm. Using either equation for the AEL of the cases above will result in approximately the same limit (rounding of the coefficients causes a small difference).

Z = 371 mm	M = 371 mm	d_{nscan} = 0,5 mm	d_{scan} = 1,0 mm
AP = 7,0mm	α_{nscan} = 1,5 mrad	α_s = 2,69 mrad	φ_{scan} = 0 mrad

φ_T = 0 mrad α_{scan} = 2,69 mrad α = 2,10 mrad C_6 = 1,40

T_2 = 10,14 s T_p = 18,0 μs N = 2 535 C_5 = 0,141

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_p)^{0,25}$ W ➔ $AEL_{1)}$ = 15,0 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4}) (T_2)^{0,75}] / (N\ T_p)$ W ➔ $AEL_{2)}$ = 122 mW

$AEL_{3)} = (AEL_{1)})\ C_5$ W ➔ $AEL_{3)}$ = 2,12 mW

The maximum power allowed for Class 1 is 2,12 mW from case 4 since the most restrictive AEL must be used for classification. Note that these four cases may not be the only cases that need to be considered for any given application.

A.2.2 Scanning Raster

A faceted mirror polygon spinning at 1 000 rpm produces an evenly spaced raster of scan lines. The incident laser beam is 20° (θ_i) from normal to the rotational axis of the polygon. The reflection angles, θ_r, vary from 20° to 60° with one line every half a degree. The spot size at the facet is 0,4 mm and circular. Find the most limiting Class 1 AEL assuming it occurs when C_6 = 1 and the eye is focused on the scanning vertex.

Since this scanner produces a raster, multiple lines will enter the pupil up to a certain distance away from the scanning vertex. With a 7 mm aperture at 100 mm as many as 8 lines can cross the aperture within a single rotation of the polygon. The distance beyond which multiple lines no longer need to be considered is 688 mm (the distance at which 6 mm subtends half a degree). Since C_6 = 1 is achieved at 267 mm multiple lines will need to be considered.

Since all the lines are being generated by the same beam, each one will produce a single, temporally separate pulse. We will use the TOTP method to determine the effective pulse of the combined lines. At 267 mm the spacing between the raster lines is 2,33 mm. With this spacing either three or four lines will cross a 7 mm aperture. The two possible cases are shown in Figure A.1. The effective pulse width, T_{eff}, is the sum of the individual pulse widths of the n lines that cross the aperture and can be determined by adding up the total scan line length inside the aperture:

$$T_{eff} = \frac{\sum_{1}^{n} L_i}{7\,mm} T_1 = K_n T_1$$

where T_1 the pulse width of a single line. Upon examination of the two cases it is determined that K_n is larger for n = 3 at K_3 = 2,49 (compared to K_4 = 2,03). Therefore, the effective pulse for a single rotation of the polygon is $T_{eff} = 2{,}49 T_1$. This is not, however, the effective pulse of the full pulse train. The full pulse duration to use for classification, T_{TOTP}, is equal to T_{eff} times the number of pulses, N.

Now T_1 needs to be determined. For this we need to know the beam speed which is going to depend on where the aperture is in the raster pattern. The SAM factor will vary through the raster as the reflection angle changes. For the smallest reflection angle, 20°, K_{SAM} is 1,88; for the largest angle, 60°, K_{SAM} is 1,44. The smallest SAM factor will provide the slowest speed and hence the longest T_1, and therefore should be used. This results in a linear beam speed on the aperture of 40 200 mm/s and T_1 = 174 μs. This results in a single-rotation effective pulse duration, T_{eff}, of 434 μs which will be repeated once per rotation during the time base, T_2. This gives us all the information needed to calculate the AEL:

Z = 267 mm	M = 267 mm	d_{nscan} = 0,4 mm	d_{scan} = 0,4 mm
AP = 7,0mm	α_{nscan} = 1,5 mrad	α_s = 1,5 mrad	φ_{scan} = 0 mrad
φ_T = 0 mrad	α_{scan} = 1,5 mrad	α = 1,5 mrad	C_6 = 1,0
T_2 = 10,0 s	T_1 = 174 μs	T_{eff} = 434 μs	N = 167

$T_{TOTP} = N\ T_{eff}$ = 72,3 ms

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_1)^{0,25}$ W ➔ $AEL_{1)}$ = 6,09 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4})\ (T_2)^{0,75}] / (T_{TOTP})$ W ➔ $AEL_{2)}$ = 54,4 mW

$AEL_{3)} = [(C_6 \cdot 7 \times 10^{-4}) / (T_{TOTP})^{0,25}]$ W ➔ $AEL_{3)}$ = <u>1,35 mW</u>

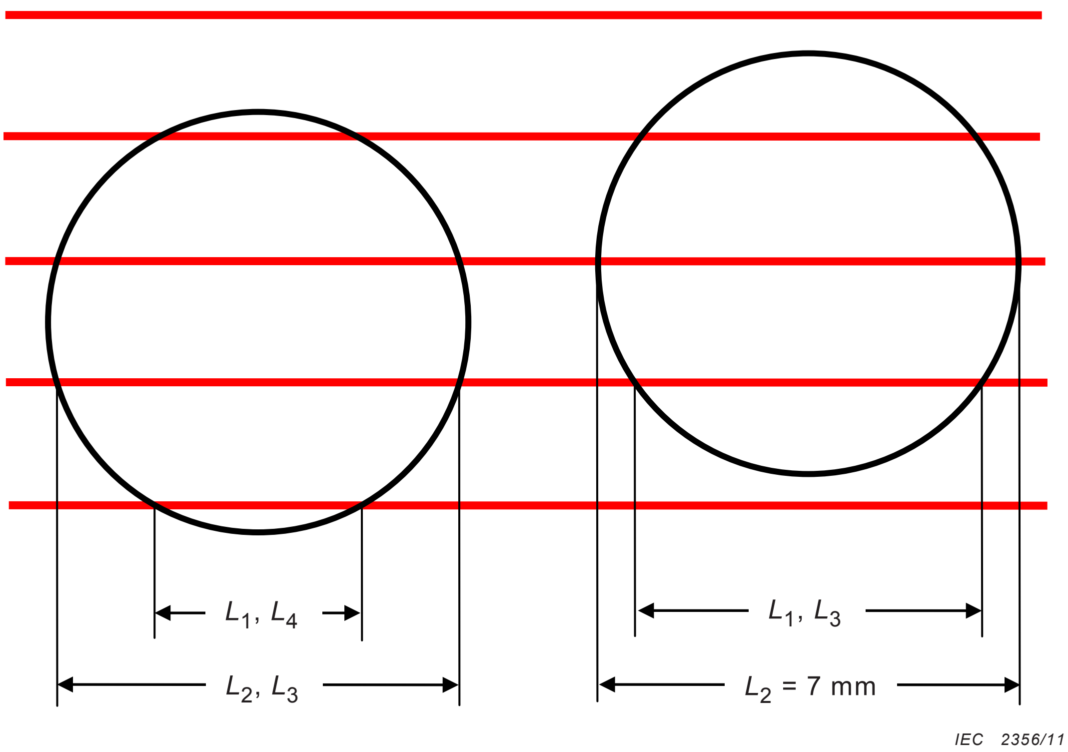


Figure A.1 – Multiple raster lines crossing the measurement aperture at distance from scanning vertex where C_6 = 1

A.2.3 Bi-directional scanning

An oscillating mirror is scanning a red laser beam with sinusoidal motion at a cycle frequency of 50 Hz with a full angular scan width of 60°. The size of the beam at the mirror is 0,8 mm and circular. Assuming that the worst condition occurs when the eye is focused on the mirror and located at the distance where C_6 = 1, what is the AEL for Class 1 if the full scan angle is accessible by the user? What is the AEL if the scan line is physically blocked such that only the central 50° of the scan is accessible?

In order to proceed, we need to define what is meant by “sinusoidal motion.” There are two reasonable definitions: 1) the angular position of the beam is defined by a sine function; 2) the motion of the spot projected on a screen is defined by a sine function. These two cases are the same for very small angles, but for larger sweep angles they differ.

For the first case the pulse duration is defined by the equation

$$T_p = \frac{1}{2\pi f}\left\{cos^{-1}\left[\frac{1}{\theta_{max}}\left(\theta_a - \frac{2AP}{M}\right)\right] - cos^{-1}\left(\frac{\theta_a}{\theta_{max}}\right)\right\} \quad \text{Eq. (A.4)}$$

where f is the frequency, θ_{max} is the full scan angle swept by the beam, θ_a is the accessible scan angle, and M is measured directly from the mirror to the aperture, AP. When θ_a is not equal to θ_{max} the pulse frequency is $2f$ due to the forward and backward sweep of the beam. When θ_a is set equal to θ_{max} the equation reduces to

$$T_p = \frac{1}{\pi f} cos^{-1}\left(1 - \frac{2AP}{\theta_{max} M}\right) \quad \text{Eq. (A.5)}$$

and the pulse frequency equals the cycle frequency due to two pulses merging into one when the turn-around point is exposed.

For the second type of sinusoidal motion the pulse duration is defined by the equation

$$T_p = \frac{1}{2\pi f}\left\{cos^{-1}\left[\frac{tan(\theta_a/2)}{tan(\theta_{max}/2)} - \frac{AP/cos(\theta_a/2 - AP/2M)}{M\,tan(\theta_{max}/2)}\right] - cos^{-1}\left[\frac{tan(\theta_a/2)}{tan(\theta_{max}/2)}\right]\right\} \quad \text{Eq. (A.6)}$$

where the variables are the same except M is the normal distance to the screen on which the beam is projected measured from the mirror. Again the pulse frequency is $2f$. When the full scan line is accessible the pulse frequency is f and the equation simplifies to

$$T_p = \frac{1}{\pi f} cos^{-1}\left[1 - \frac{AP/cos(\theta_{max}/2 - AP/2M)}{M\,tan(\theta_{max}/2)}\right]. \quad \text{Eq. (A.7)}$$

For the case of this example we will use sinusoidal angular motion, applying the first two equations. Equation (A.1.3.2) is used to determine the pulse duration for the fully accessible scan line. The aperture size, AP, is 7 mm, frequency, f, is 50 Hz, and θ_{max} is 60º (1,05 rad). The measurement distance, M, is 533 mm which results in an angular subtense of 1,5 mrad when focusing on the spot on the mirror. Substituting these into the equation yields T_p = 1,428 ms. With C_6 = 1 the time base, T_2, is 10 s for Class 1. The pulse frequency of 50 pulses per second results in 500 pulses in 10 s, yielding a C_5 factor of $(1/500)^{1/4}$ = 0,211. The AELs are determined from the standard:

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_p)^{0,25}$ W ➔ $AEL_{1)}$ = 3,60 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4}) / (T_2)^{0,25}] / (f\,T_p)$ W ➔ $AEL_{2)}$ = 5,51 mW

$AEL_{3)} = (AEL_{1)})\,C_5$ W ➔ $AEL_{3)}$ = 0,761 mW

Adding a beam block to reduce the accessible scan angle to 50º requires recalculating T_p using Eq. (A.1.3.1): T_p = 139,8 µs. The pulse duration has decreased by a factor of 10, but the pulse frequency has also doubled to 100 pulses per second, resulting in C_5 = 0,178. The new AEL’s are as follows:

$AEL_{1)} = (C_6 \cdot 7 \times 10^{-4}) / (T_p)^{0,25}$ W ➔ $AEL_{1)}$ = 6,44 mW

$AEL_{2)} = [(C_6 \cdot 7 \times 10^{-4}) / (T_2)^{0,25}] / (2\, f\, T_p)$ W ➔ $AEL_{2)}$ = 28,2 mW

$AEL_{3)} = (AEL_{1)})\, C_5$ W ➔ $AEL_{3)}$ = 1,14 mW

Thus, adding a beam block allows the laser power to be raised by about 50 %.

A.2.4 Laser projector classification

The projector uses a single mirror that oscillates in both horizontal and vertical directions. The mirror is scanning with sinusoidal motion in the horizontal direction at a cycle frequency of 18 000 Hz with a full angular scan width of 50°. The vertical is scanning at a 60 Hz rate. The scan pattern starts at the top corner, completes 480 lines, bidirectionally scanning down to the bottom, at which point there is retrace, or flyback, to the top starting position. This retrace takes exactly 20 % of the time, and lasers are turned off during this time. The size of the beam at the mirror is 0,9 mm and circular. The beam is assumed to be collimated. The beam power will be reduced as the beam is scanned from centre to edge to assure brightness uniformity and to assure that the AEL is met at all locations.

Definitions:

Z	=	Distance from measurement aperture to location of point of eye focus
M	=	Distance from measurement aperture to scanning vertex
AP	=	Measurement aperture diameter as defined in Table 10 of standard
d_{scan}	=	Beam diameter *in direction of scan* at location of point of eye focus (1/e)
d_{nscan}	=	Beam diameter *in direction orthogonal to scan* at location of point of eye focus (1/e)
f_{HSCAN}	=	Oscillation rate of scanning mirror in horizontal direction (Hz)
f_{VSCAN}	=	Vertical frame rate (Hz)
n	=	Number of scan lines in aperture per frame
T	=	Applicable time base (0,25 s for Class 2 laser radiation for λ = 400 nm to 700 nm)
N	=	Number of pulses in the pulse train during the applicable time base, or T_2, whichever is smaller
	=	$f_{VSCAN} \times n \times T$ For this example, the Class 2 time base of 0,25 s is used.
α_s	=	Stationary angular subtense along the scanning axis [$\alpha_s = d / Z$]
α_{scan}	=	Scanning angular subtense ($\alpha_{scan} = \max[(\alpha_s + \varphi_T), \alpha_{min}]$)
T_p	=	Scanned pulse duration in 7-mm aperture. This varies depending on the position of the aperture relative to the vertex of the scanning mirror and the rate of scanning mirror oscillation (f_{HSCAN}). Aperture located @ center of scan: T_{p_center} Aperture located @ end of scan: $T_{p\_scanend}$
T_i	=	Value from Table 3 of IEC 60825-1:2007, providing 'thermal confinement time' corresponding with λ range (e.g 18 × 10^{-6} s for 400 nm < λ < 1 050 nm).
φ_T	=	$(T_i / T_p) \times \varphi_{scan}$ If $T_p \geq T_i$
φ_T	=	φ_{scan} If $T_p < T_i$
φ_{scan}	=	angle of scan line on retina = $2 \times \tan^{-1}\{(AP / 2) \times [(1 / M) - (1 / Z)]\}$
$\pi/4$	=	the correction for scan time in a square to a circle

- **Horizontal geometry parameters**

f_{HSCAN} = 18 000 Hz

θ_{max} = Angular deflection of the scanned beam in the horizontal direction.

θ_{max} = 50,0 deg

H_{active} = Active part of horizontal line = 90 %

θ_{ah} = Horizontal accessible scan angle = $2 \times \tan^{-1}(H_{active} \times \tan(\theta_{max} / 2))$ = 45,5 deg

- **Vertical geometry parameters**

$$\text{aspect ratio} = 16H : 9V = \frac{Horz\_Active\_Scan}{Vert\_Active\_Scan}$$

f_{VSCAN} = 60 Hz

θ_{av} = Vertical accessible scan angle = $2 \times \tan^{-1}[1 / \text{aspect ratio} \times \tan(\theta_{ah} / 2)]$ = 26,6 deg

V_{res} = Vertical resolution = 480 lines

Beam characteristic

Combined red, green and blue beam of diameter 0,9 mm (1/e) at mirror

Accessible emission limit requirements

AEL_{single} = Requirement No. 1 for repetitively pulsed or modulated lasers, subclause 8.3 of the standard.
The exposure for any single pulse within a pulse train shall not exceed the AEL for a single pulse.

$AEL_{s.p.T}$ = Requirement No.2 for repetitively pulsed or modulated lasers, subclause 8.3 of the standard.
The average power for a pulse train of emission duration *T*, AEL_T shall not exceed the power corresponding to the AEL for a single pulse of duration *T*. (Note, for this example, the AEL_T is calculated using both the Class 2 time base, 0,25 s, and the pulse train exposure time in the aperture during one scanned frame).

$AEL_{s.p.train}$ = Requirement No.3 for repetitively pulsed or modulated lasers, subclause 8.3 of the standard.
The AEL is determined by the duration of the total-on-time-pulse (TOTP), which is the sum of all pulse durations within the emission duration or T_2, whichever is smaller.

Case 1) Focused on the scanning element, measuring at the nearest distance of 100 mm

Z = 100 mm M = 100 mm d_{scan} = 0,9 mm d_{nscan} = 0,9 mm
AP = 7,0 mm N = 1 087 φ_{scan} = 0 mrad T_{p_center} = 1,42 µs, $T_{p\_scanend}$= 2,62 µs
α_s = 9 mrad φ_T = 0 mrad α_{scan} = 9 mrad α_{nscan} = 9 mrad
$C_6 = (\alpha_{scan} + \alpha_{nscan}) / (2 \times \alpha_{min}) = 6$

Calculation of T_{p_center}:
θ_r = Half-angle of aperture at 100 mm = $\tan^{-1}((AP / 2) / M) = 2°$

$T_{p\_center} = 2 / (2 \times \pi \times f_{HSCAN}) \times \sin^{-1}(\theta_r / (\theta_{max} / 2) = 1{,}42$ µs

Calculation of $T_{p\_scanend}$:

$$T_p = \frac{1}{2\pi f}\left\{cos^{-1}\left[\frac{1}{\theta_{max}}\left(\theta_{ah} - \frac{2AP}{M}\right)\right] - cos^{-1}\left(\frac{\theta_{ah}}{\theta_{max}}\right)\right\}$$

$T_{p\_scanend}$ = 2,62 µs

Calculation of N:
$n = 2 \times \tan^{-1}[(AP / 2) / M] / \theta_{av} \times V_{res} = 72{,}4$

$N = n \times f_{VSCAN} \times T = 1\ 087$

t_7= pulse train exposure in aperture in one frame = $n \times 1 / (2 \times f_{HSCAN}) = 0{,}002$ s

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_center})$ W = 845 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}25)^{0{,}75}] / (T_{p\_center} \times \pi/4 \times N)$ W = 1 225 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}002)^{0{,}75}] / (T_{p\_center} \times \pi/4 \times n)$ W = 494 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0{,}75)} / (N^{(0{,}25)} \times T_{p\_center} \times \pi/4)$ W = 181 mW

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_scanend})$ W = 458 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}25)^{0{,}75}] / (T_{p\_scanend} \times \pi/4 \times N)$ W = 664 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}002)^{0{,}75}] / (T_{p\_scanend} \times \pi/4 \times n)$ W = 268 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0{,}75)} / (N^{(0{,}25)} \times T_{p\_scanend} \times \pi/4)$ W = 98 mW

Case 2) Relaxed eye (focused @ infinity), measuring to nearest distance of 100mm

$Z = \infty$ M = 100 mm d_{scan} = 0,9 mm d_{nscan} = 0,9 mm
AP = 7,0 mm N = 1 087 φ_{scan} = 70 mrad T_{p_center} = 1,42 µs, $T_{p\_scanend}$ = 2,62 µs
α_s = 9 mrad φ_T = 70 mrad α_{scan} = 70 mrad α_{nscan} = 1,5 mrad
$C_6 = (\alpha_{scan} + \alpha_{nscan}) / (2 \times \alpha_{min}) = 23{,}83$

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_center})$ W = 3 357 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}25)^{0{,}75}] / (T_{p\_center} \times \pi/4 \times N)$ W = 4 866 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}002)^{0{,}75}] / (T_{p\_center} \times \pi/4 \times n)$ W = 1 962 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0{,}75)} / (N^{(0{,}25)} \times T_{p\_center} \times \pi/4)$ W = 720 mW

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_scanend})$ W = 1 819 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}25)^{0{,}75}] / (T_{p\_scanend} \times \pi/4 \times N)$ W = 2 637 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0{,}002)^{0{,}75}] / (T_{p\_scanend} \times \pi/4 \times n)$ W = 1 063 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0{,}75)} / (N^{(0{,}25)} \times T_{p\_scanend} \times \pi/4)$ W = 390 mW

Case 3) Focused on the scanning element, measuring at a distance where C6 = 1

Calculating distance @ which C_6 = 1 (occurs when $\alpha_{scan} = d_{scan} / Z$ = 1,5mrad):
$Z = (d_{scan}$ / 1,5 mrad) = 0,9mm / 0,0015 = 600 mm

Z = 600 mm	M = 600 mm	d_{scan} = 0,9 mm	d_{nscan} = 0,9 mm
AP = 7,0 mm	N = 181	φ_{scan} = 0 mrad	T_{p_center} = 0,236 µs, $T_{p\_scanend}$= 0,535 µs
α_s = 1,5 mrad	φ_T = 0 mrad	α_{scan} = 1,5 mrad	α_{nscan} = 1,5 mrad

$C_6 = (\alpha_{scan} + \alpha_{nscan}) / (2 \times \alpha_{min}) = 1$

Calculation of N:
$n = 2 \times \tan^{-1}[(AP / 2) / M] / \theta_{av} \times V_{res} = 12,1$

$N = n \times f_{VSCAN} \times T = 181$

t_7= pulse train exposure in aperture= $n \times 1 / (2 \times f_{HSCAN})$ = 0,00034 s

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_center})$ W = 847 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0,25)^{0,75}] / (T_{p\_center} \times \pi/4 \times N)$ W = 7 377 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0,00034)^{0,75}] / (T_{p\_center} \times \pi/4 \times n)$ W = 775 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0,75)} / (N^{(0,25)} \times T_{p\_center} \times \pi/4)$ W = 285 mW

$AEL_{single} = (C_6 \times 2 \times 10^{-7}) / (T_{p\_scanend})$ W = 374 mW

$AEL_{s.p.T\ timebase} = [(C_6 \times 7 \times 10^{-4}) \times (0,25)^{0,75}] / (T_{p\_scanend} \times \pi/4 \times N)$ W = 3 254 mW

$AEL_{s.p.T\ time\ in\ aperture} = [(C_6 \times 7 \times 10^{-4}) \times (0,00034)^{0,75}] / (T_{p\_scanend} \times \pi/4 \times n)$ W = 342 mW

$AEL_{s.p.train} = (C_6 \times 7 \times 10^{-4}) \times (18 \times 10^{-6})^{(0,75)} / (N^{(0,25)} \times T_{p\_scanend} \times \pi/4)$ W = 126 mW

Conclusion: The most restrictive case is Case 1 with AEL= 181 mW at the centre of the scan and 98 mW at the edge of the scan for compliance with Class 2 per IEC 60825-1:2007.

A.3 Collimated laser diode example

A laser diode is placed at the focus of a lens in order to generate a collimated output of diameter d. What is the allowable Class 1 power for a CW beam emitting in the 400 nm to 1 400 nm range?

For that wavelength range, the Class 1 CW limit under the thermal criteria from Tables 4 & 5 of the standard is:

$$P = 0,7\ C_4\ C_6\ C_7\ /\ T_2^{1/4}\ \text{mW}.$$

Since the laser diode would be a small (point) source **even with the presence of the lens,** the size of the apparent source will be < 1,5 mrad. Thus the value of the extended source correction factor is the minimum value of C_6 = 1.

The time duration for classification of a small source is specified at the minimum value of T_2 = 10 s, and thus the allowable power becomes:

$$P = 0,7\ C_4 \times 1 \times C_7\ /\ 10^{1/4}\ \text{mW} = \mathbf{0,39\ C_4\ C_7\ mW}. \quad \text{(A.8)}$$

If the wavelength is in the 400 – 600 nm range, it is also necessary to evaluate the photochemical criteria for Class 1. That limit from Tables 4 & 5 of the standard is:

$$\mathbf{P = 39\ C_3\ \mu W}. \quad \text{(A.9)}$$

The values of C_3, C_4, and C_7 are determined by the emitted wavelength as defined in Table 10 of the standard.

The Class 1 power limit is to be compared with that which would be measured in a 7 mm aperture near the lens and in a 50 mm aperture at a distance of 2 m. So if the beam is less than 50 mm in diameter, all of the energy is collected and so that is also the total power allowed for Class 1. Note that if all of the energy can be collected in a 7 mm aperture, it is not necessary to make a measurement with a larger diameter detector.

If the beam has a diameter > 7 mm, then if the measured power in a 50 mm aperture at 2 m is above the limit, but the measured power in a 7 mm aperture is less than the limit, the product would be Class 1M.

Case 1: Consider a 3 mm diameter beam from the lens at 850 nm

At this wavelength, C_4 = 2 and C_7 = 1. The limit from Equation A.8 is:

$$P = 0{,}39 \times 2 \times 1 \text{ mW} = 0{,}78 \text{ mW}.$$

Since the wavelength is > 600 nm, the photochemical criteria does not apply and Equation A.9 is not needed. Thus the power limit is 0,78 mW, and since d < 50 mm, that is also the total allowable power.

Case 2: Consider a 3 mm diameter beam from the lens at 480 nm

At this wavelength, C_3 = 4, C_4 = 1 and C_7 = 1. The limit from Equation A.8 is:

$$P = 0{,}39 \times 1 \times 1 \text{ mW} = 0{,}39 \text{ mW}.$$

Since the wavelength is < 600 nm, the photochemical criteria must also be evaluated. From Equation (A.9):

$$P = 39\ C_3\ \mu\text{W} = 39 \times 4\ \mu\text{W} = 0{,}16 \text{ mW}.$$

Since the limit under Equation (A.9) is more restrictive, the allowable power is 0,16 mW.

Case 3: Consider a 20 mm diameter beam from the lens at 850 nm. What is the class for a 2 mW CW output?

The allowable power was determined in Case 1. For Class 1, the power must be < 0,78 mW in a 7 mm aperture near the lens and < 0,78 mW in a 50 mm aperture at 2 m. For Class 1M, that would be the total power allowed in a 7 mm aperture near the lens.

The Class 1 limit would be exceeded in the 50 mm aperture. However, the fraction of the 20 mm beam that is collected in a 7 mm aperture would be approximately $(7/20)^2$ = 0,12, or 0,12 × 2 mW = 0,24 mW. That value in a 7 mm aperture is less than the 0,78 mW limit, thus the output would be Class 1M.

Case 4: Consider a 3 mm diameter beam from the lens at 1 310 nm

At this wavelength, C_4 = 5 and C_7 = 8. The limit from Equation (A.8) is:

$$P = 0{,}39 \times 5 \times 8 \text{ mW} = 15{,}6 \text{ mW}.$$

Since the wavelength is > 600 nm, the photochemical criteria does not apply and Equation (A.9) is not needed. Thus the power limit is 15,6 mW, and since d < 50 mm, that is also the total allowable power.

A.4 Single mode fiber example

- **Diameter of a divergent beam**

The diameter of a divergent beam, d_{63}, at a distance *r* from the apparent source is required to perform AEL and MPE calculations involving an aperture. Most manufactures of divergent beam sources will specify the divergence in terms of a numerical aperture or *NA*. The *NA* of a point source is defined as the sine of one-half the divergence, ϕ, of the output beam, as measured at the 5 %-of-peak-irradiance points. That is

$$NA = \sin\frac{\phi}{2} \qquad \text{and} \qquad \frac{\phi}{2} = \arcsin(NA)$$

For a Gaussian beam, the beam diameter that corresponds to the 5 %-of-peak-irradiance points contains 95 % of the total power or energy. The beam diameter, d_{95}, at a distance *r* from the apparent source is given by:

$$d_{95} = d_{63} + 2 \cdot r \cdot \tan\frac{\phi}{2} = d_{63} + 2 \cdot r \cdot \tan[\arcsin(NA)]$$

Since d_{63} is of the order of a few tens of µm, it can be ignored in most situations. In addition, for safety calculations the beam diameter at the 63 % total power (or energy) points is used rather than the 95 % points. The conversion factor for a Gaussian beam is 1,7 (i.e., d_{95} / d_{63} = 1,7); hence, the beam diameter is approximated by:

$$d_{63} = \frac{d_{95}}{1{,}7} = \frac{2 \cdot r}{1{,}7}\tan[\arcsin(NA)] = \frac{2 \cdot r \cdot NA}{1{,}7}$$

A single-mode optical fibre is a special case of a point-type optical source. The divergence of a single-mode fibre is specified in terms of the fibre mode-field diameter, w_0, and the wavelength, λ, of the source. The beam diameter of a single-mode optical fibre, at a distance *r*, is approximated by:

$$d_{63} = \frac{2\sqrt{2} \cdot r \cdot \lambda}{\pi \cdot w_0}$$

where the wavelength, λ, is expressed in the same units as the mode-field diameter, w_0.

An optical fibre transmitter emitting at 1 300 nm is used for digital data transmission at a rate of 630 Mbits/s. The transmission code used is a balanced code and, therefore, the average power emitted is not data dependent. The transmitter assembly is pigtailed to a single mode fibre having a mode field diameter of 10 µm.

NOTE The mode field diameter, w_0, depends on the fibre type and the wavelength.

a) Determine the maximum average output power for Class 1M and Class 3R AELs.

b) Determine the maximum average output power for Class 1M and Class 3R AELs if the emitting wavelength is 1 550 nm.

Solution:

The output can be treated like a CW emission at a power level equal to the average emitted power due to the high data transmission rate and the balanced code.

a) **1 300 nm**

At a wavelength of 1 300 nm and a time base of 100 s, the maximum average emitted power for Class 1M and Class 3R is found as follows:

Class 1M

The time base used for a Class 1 system is 100 s. For a small source $\alpha < \alpha_{min}$, Table 4 of the standard indicates that the AEL for emission in the wavelength range 1 050 nm to 1 400 nm with an exposure duration in the range from 10 s to 3 × 10^4 s

$$P_{AEL} = 3{,}9 \times 10^{-4}\, C_4\, C_7 \text{ W}$$

where C_4 = 5 and C_7 = 8 therefore

$$P_{AEL} = 15{,}6 \text{ mW}$$

This aperture power is then corrected for the aperture coupling loss with the coupling parameter η to obtain the maximum emitted power level for the AEL condition. The coupling parameter depends upon the diameter of the beam at the distance the aperture is located from the source (100 mm, since measurement condition 3 is specified for class 1M; 70 mm will be used for Class 3R). For the single-mode fibre in this example the beam diameter is given by equation:

$$d_{63} = \frac{2\sqrt{2}r\lambda}{\pi\omega_0} = \frac{2{,}83 \times 100mm \times 1{,}3 \times 10^{-3}mm}{\pi \times 10 \times 10^{-3}mm} = 11{,}7mm$$

The fraction of the total emitted power (P_a) that passes through a 7 mm measurement aperture 100 mm from the source is:

$$P_a = \eta \times P_0 = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] \times P_0 = 0{,}301 \times P_0$$

The maximum emitted power corresponding to Class 1M ($P_{0,\text{max}}$) is

$$P_{0,\text{max}} = \frac{P_{AEL}}{\eta} = 51{,}8mW$$

Because 51,8 mW is less than the 500 mW limit for Class 3B, Class 1M = 51,8 mW.

Class 3R

At a wavelength of 1 300 nm and a time base of 100 s, Table 7 of the standard gives the small source $\alpha < \alpha_{min}$ AEL expression for total emitted power as

$$P_{AEL} = 2 \times 10^{-3}\, C_4\, C_7 \text{ W}$$

where C_4 = 5 and C_7 = 8, therefore

$$P_{AEL} = 2 \times 10^{-3} \times 5 \times 8 \text{ W} = 80 \text{ mW}$$

The value of the diameter d_{63} at the distance of 70 mm:

$$d_{63} = \frac{2\sqrt{2}r\lambda}{\pi\omega_0} = \frac{2{,}83 \times 70 \times 1{,}3 \times 10^{-3}}{\pi \times 10 \times 10^{-3}} = 8{,}20mm$$

The fraction of the total emitted power (P_a) that passes through a 7 mm measurement aperture 70 mm from the source is:

$$P_a = \eta \times P_0 = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] \times P_0 = 0{,}518 \times P_0$$

The maximum emitted power corresponding to Class 3R ($P_{0,max}$) is

$$P_{0,\max} = \frac{P_{AEL}}{\eta} = 155mW$$

Because 155 mW > 51,8 mW for Class 1M, Class 3R exists for this example. Therefore, for this example, the product can be any of the following classes based on the output power: Class 1, Class 1M, Class 3R, Class 3B or Class 4.

b) **1 550 nm**

Class 1M

If the same system is operated at 1 550 nm, then the procedure for performing the calculations is the same except that the AEL expression and apertures associated with the 1 550 nm wavelength are used.

Since we have a small-source $\alpha < \alpha_{min}$ and t = 100 s, then from Table 4 of the standard

$$P_{AEL} = 10 \text{ mW}$$

The beam diameter at 100 mm is:

$$d_{63} = \frac{2\sqrt{2}r\lambda}{\pi\omega_0} = \frac{2{,}83 \times 100 \times 1{,}55 \times 10^{-3}}{\pi \times 10 \times 10^{-3}} = 14{,}0mm$$

The fraction of the total emitted power (P_a) that passes through a 3,5 mm measurement aperture 100 mm from the source is:

$$P_a = \eta \times P_0 = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] \times P_0 = 0{,}061 \times P_0$$

The maximum emitted power corresponding to Class 1M ($P_{0,max}$) is

$$P_{0,\max} = \frac{P_{AEL}}{\eta} = 165mW$$

Because 165 mW is less than the 500 mW limit for Class 3B, Class 1M = 165 mW.

Class 3R

At a wavelength of 1 550 nm and a time base of 100 s Table 4 of the standard gives the small source $\alpha < \alpha_{min}$ AEL expression for total emitted power as

$$P_{AEL} = 5 \times 10^{-2} \text{ W} = 50 \text{ mW}$$

The value of the diameter d_{63} at the distance of 70 mm:

$$d_{63} = \frac{2\sqrt{2}r\lambda}{\pi\omega_0} = \frac{2{,}83 \cdot 70mm \cdot 1{,}55 \cdot 10^{-3}mm}{\pi \cdot 10 \cdot 10^{-3}mm} = 9{,}78mm$$

The fraction of the total emitted power (P_a) that passes through a 7 mm measurement aperture 70 mm from the source is:

$$P_a = \eta \cdot P_0 = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] \cdot P_0 = 0{,}401 \cdot P_0$$

The maximum emitted power corresponding to Class 3R ($P_{0,max}$) is

$$P_{0,\max} = \frac{P_{AEL}}{\eta} = 125mW$$

Because 165 mW for Class 1M > 125 mW, Class 3R does not exist for this example. Therefore, for this example, the product can only be the following classes based on the output power: Class 1, Class 1M, Class 3B or Class 4.

A.5 Beam waist example

Consider the following laser:

Wavelength	-	635 nm
PRF	-	1 Hz
Pulse width	-	500 ms
Radiant energy	-	0,98 mJ/pulse
Exit beam diameter	-	5 mm
Divergence	-	0,35 mrad

Sometimes the beam will slightly focus outside of the laser cavity before assuming its normal divergence. The focused beam or the focal point is called the “beam waist”. For a correct hazard evaluation the distance that the waist is from the exit port of the laser needs to be added to the calculated hazard distance.

As an example of how to measure and quantify a beam waist, let us examine the above laser. It is always a good idea to visually inspect the beam prior to initiating any measurement procedures. This is a good practice to incorporate into one's measurement procedure not only for detection of beam waist but to identify other beam abnormalities such as hot spots or dark areas where the beam has been "clipped" possibly by some internal component. During this visual inspection it is noticed that the laser spot seems to get smaller a few meters away from the laser's exit port. This is an indication that a beam waist is present. The overall measurement procedure will not vary but will require a more in-depth investigation of the beam diameter especially in the area of the beam waist.

Let us assume all of the other specified laser parameters have been verified using the measurement techniques listed in the text or in other examples. It is now time to examine the beam waist. Two values need to be determined. The first is the diameter of the beam waist. The second is the beam waist's location relative to the laser exit port.

Determining the diameter of the beam waist can be a rather painstaking endeavour, unless one is fortunate enough to find it on the first few attempts, for multiple beam diameter measurements must be taken in order to obtain the smallest diameter.

Using one of the techniques in 7.7.3.4, it was discovered a beam waist was located at 7 meters beyond the exit port of the laser and had a diameter of 3,5 mm.

Using the above parameters the MPE is 1,0 mW/cm^2 and the Class 1 AEL is 0,39 mW, making this laser a Class 3R laser system. Assuming no beam waist, a Gaussian circular beam, and using

$$\text{NOHD} = \frac{1}{\phi}\sqrt{\frac{4\Phi}{\pi MPE} - d^2}$$

will result in an NOHD of 43 m. However, using our determined beam waist diameter for *d* and recalculating yields an NOHD of 44 m then adding the 7 meters to account for the beam waist location yields a NOHD of 51 m.

A.6 Multiple wavelength laser example

A frequency doubled Nd:YAG laser operating at 1 064 nm and 532 nm with a uniform beam is to be used as part of a high altitude atmospheric imaging system. The parameters of this system are listed below:

	Laser 1	Laser 2
Wavelength, λ	1 064 nm	532 nm
Energy per pulse, Q	75 mJ	100 mJ
Divergence, ϕ	1 mrad	1 mrad
Pulse width	18 ns	18 ns
PRF	20 Hz	20 Hz
Beam diameter, d	1,5 cm	1,5 cm

Find the NOHD for this laser system (ignoring atmospheric attenuation since used at high altitudes).

Since we have energy with two wavelengths acting on the same tissue at the same time, the combined effects must be examined.

If H_1 / MPE_1 + H_2 / MPE_2 > 1, where H_i is the possible laser exposure and MPE_i is the maximum permissible exposure for each λ_i, then the maximum permissible exposure is exceeded.

$$H_i = \frac{4Q}{\pi a_i^2}$$

From this equation we find H_1 = 42,44 mJ/cm^2, and H_2 = 56,6 mJ/cm^2 . It can be found that $MPE_1 = 1{,}3 \times 10^{-6}$ J/cm^2, and $MPE_2 = 1{,}3 \times 10^{-7}$ J/cm^2. The result of H_1 / MPE_1 + H_2 / MPE_2 is much greater than 1, so the safe exposure limit is exceeded.

Let H_{eff} be the effective exposure level which is derived from the general laser range equation which computes the radiant exposure at any viewer distance. The equation for H_{eff} in the far field is given by

$$H_{eff} = \frac{1{,}27 e^{-\mu r}}{r^2} \sum_{i=1}^{N} S_i \frac{Q_i}{\phi_i^2}$$

where r is the distance away from the laser, μ is the atmospheric attenuation coefficient, and $S_i = MPE_{min} / MPE_i$ (MPE_{min} is the most conservative individual MPE found, in this case, MPE_2).

For λ_1 = 1064 nm, S_1 = 0,1, and for λ_2 = 532 nm, S_2 = 1.

The equation can be solved for NOHD, since r = NOHD when $H_{eff} = MPE_{min}$.

$$NOHD = \sqrt{\frac{1{,}27 e^{-\mu NOHD}}{MPE_{min}} \sum_{i=1}^{N} S_i \frac{Q_i}{\phi_i^2}}$$

Ignoring atmospheric attenuation gives

$$NOHD = \sqrt{\frac{1{,}27}{MPE_{min}} \left(S_1 \frac{Q_1}{\phi_1^2} + S_2 \frac{Q_2}{\phi_2^2} \right)}$$

Therefore, the NOHD for this system is approximately 10 km.

A.7 Linear array of laser fibres example

Consider a multi-fibre array with the following parameters:

Δ = center-to-center spacing = 250 μm

N = total number of sources = 12

S_o = single source size = 50 μm

S_v = vertical size = 50 μm → 150 μm

λ = 850 nm, so C_4 = 2 and C_7 = 1

Fiber NA = 0,2, for a 1/e divergence of 2 × 0,2 / 1,7 = 0,235 rad

n = number of sources being evaluated

S_h = horizontal size = $S_0 + (n - 1) \times \Delta = 50 + (n - 1) \times 250$

$\alpha_{\square} = S_v / r$ and $\alpha_h = S_h / r$

$\alpha = (\alpha_v + \alpha_h) / 2$ = {150 / 100 + [(50 + (n - 1) × 250)] / 100} / 2 mrad

for n > 1

What is the total emitted power allowed under the Class 1 limit?

$$AEL = 0,7\ C_4\ C_6\ /\ (T_2)^{1/4}\ \text{mW}.$$

It is necessary to consider configurations of the array up to a dimension of 1 cm (which corresponds to the maximum acceptance angle of 100 mrad at 100 mm).

Table A.1 – Number of source cases

n	α_h (mrad)	α_v (mrad)	α (mrad)	T_2 (s)	C_6	C_4	*AEL* (mW)	P_n (mW)	AEL / P_n
1	1,5	1,5	1,5	10	1	2	0,785	1 × *P*	0,785 / *P*
2	3,0	1,5	2,25	10,2	1,5	2	1,173	2 × *P*	**0,586 / *P***
3	5,5	1,5	3,50	10,5	2,33	2	1,811	3 × *P*	0,604 / *P*
4	8,0	1,5	4,75	10,8	3,17	2	2,440	4 × *P*	0,610 / *P*
8	18	1,5	9,75	12,1	6,5	2	4,865	8 × *P*	0,608 / *P*^
12	28	1,5	14,75	13,6	9,8	2	7,148	12 × *P*	0,596 / *P*^

Thus the most limiting case is the configuration of n = 2 sources, with a ratio of 0,586 / *P*. The above calculations assumed sources with identical power levels, but the P_n entries could be modified to accommodate different power levels.

If we assume that all of the sources emit from the same point, the diameter of the beam at the Class 1 measurement distance of 70 mm would be 2 *r NA* / 1,7 = 2 × 70 mm × 0,2 / 1,7 = 16,5 mm. Using the coupling formula in 7.8.8, the fraction collected in a 7 mm aperture would be 0,165. Thus the total power allowed from the 12-channel fibre would be:

$$P = 12\ \text{fibres} \times 0,586\ \text{mW per fiber} / 0,165 = 42,6\ \text{mW}.$$

The ratio of $AEL\ /\ P_i$ is shown as decreasing with increasing number of sources beyond a value of 5. In reality, the limit would slightly increase above that number, as the horizontal dimension of the source configuration would impact the diameter of the beam at the measurement distance (for the above calculation of the beam pattern at the measurement distance, the size of the source configuration was assumed to be zero).

A.8 Linear array of lasers example

Consider a multi laser array with the following parameters:

Δ = center-to-center spacing = 2 500 μm

N = total number of sources = 10

S_o = single source size = 50 μm

S_v = vertical size = 50 μm → 150 μm

λ = 850 nm, so C_4 = 2

Output *NA* = 0,2, for a 1/e divergence of 2 × 0,2 / 1,7 = 0,235 rad

n = number of sources being evaluated

S_h = horizontal size = $S_0 + (n - 1) \times \Delta = 50 + (n - 1) \times 2500$

$\alpha_\varpi = S_v / r$ *and* $\alpha_h = S_h / r$

$\alpha = (\alpha_v + \alpha_h) / 2 = \{150 / 100 + [(50 + (n - 1) \times 2500)]/100\}/2$ mrad

for $n > 1$

What is the total emitted power allowed under the Class 1M limit?

AEL = 0,7 C_4 C_6 / $(T_2)^{1/4}$ mW.

It is necessary to consider configurations of the array up to a dimension of 1 cm, or 4 sources (which corresponds to the maximum acceptance angle of 100 mrad at 100 mm).

Table A.2 – Number of source cases

n	α_h	α_v	α	T_2	C_6	C_4	*AEL*	P_n	*AEL* / P_n
	(mrad)	(mrad)	(mrad)	(s)			(mW)	(mW)	
1	1,5	1,5	1,5	10	1	2	0,785	1 × *P*	**0,79 / *P***
2	25,5	1,5	13,5	13,2	9	2	6,6	2 × *P*	3,3 / *P*
3	50,5	1,5	26	17,7	17,3	2	11,8	3 × *P*	3,9 / *P*
4	75,5	1,5	38,5	23,7	25,6	2	16,2	4 × *P*	4,1 / *P*

Thus the most limiting case is the configuration of n = 1 source, with a ratio of 0,79 / *P*. The above calculations assumed sources with identical power levels, but the P_n entries could be modified to accommodate different power levels.

The divergence of the beam at the Class 1M measurement distance of 100 mm would create a diameter of 2 *r NA* / 1,7 = 2 × 100 mm × 0,2 / 1,7 = 23,6 mm. Using the coupling formula in 7.8.8, the fraction collected in a 7 mm aperture would be

$$1 - e^{-\left[\left(7^2 / 23{,}6^2\right)\right]} = 0{,}084.$$

Thus the total power allowed from the 10-channel array would be:

P = 10 lasers × 0,79 mW per laser / 0,084 = 93,5 mW.

This example shows a method of classifying a product with a large apparent source (> 100 mrad). The energy is assumed to be uniformly emitted roughly perpendicular to a flat surface, and since no beam structure is present (i.e. the source is incoherent or totally diffused), the actual emission area is the apparent source. The assumed parameters are a circular source of diameter *d* and 1/e beam divergence Φ.

Annex B
(informative)

Useful conversions

B.1 Solid angle (Ω) and linear (full) angle (or divergence) (ϕ)

Small angle approximation: $\phi = (4\ \Omega/\pi)^{1/2}$ $\Omega = \pi/4\ \phi^2$

Exact formula: $\Omega = 2\pi(1 - \cos(\phi/2))$

B.2 Gaussian beam divergence or diameter

$D_{0,50}$ / $D_{1/e2}$ = 0,59 = 1 / 1,7, where $D_{0.50}$ is the diameter at half-irradiance points

$D_{1/e}$ / $D_{1/e2}$ = 0,71 = 1 / 1,4

$D_{0,50}$ / $D_{1/e}$ = 0,83 = 1 / 1,2

$D_{1/e}$ / $D_{0,95}$ = 0,59 = 1 / 1,7

B.3 Degrees and radians

Divide angle in degrees by 57,3 to get radians, or

multiply angle in degrees by 17,5 to get mrad.

B.4 Multimode fibre diameter

NA = sin(ϕ / 2) ϕ = 2 $\sin^{-1}$(*NA*) at 95 % points.

Diameter at distance *r* = 2 *r NA* / 1,7 at (1 - 1/e) points for Gaussian beams.

B.5 Single mode fibre diameter

Diameter at distance $r = 2 \times 2^{1/2}\ r\ \lambda / (\pi\ \omega_o)$ at 1/e points for mode field diameter ω_o and wavelength λ.

Bibliography

IEC 61040, *Power and energy measuring detectors, instruments and equipment for laser radiation*

IEC 62471, *Photobiological safety of lamps and lamp systems*

ISO 11554, *Optics and photonics – Lasers and laser-related equipment – Test methods for laser beam power, energy and temporal characteristics*

ISO 11146-3, *Lasers and laser-related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part 3: Intrinsic and geometrical laser beam classification, propagation and details of test methods*

GALBIATI, Enrico. Evaluation of the apparent source in laser safety. *Journal of Laser Applications* 2001,13: p.141-149

LYON, Terry. Hazard Analysis Technique for Multiple Wavelength Lasers. *Health Physics,* August 1985, 49(2):221-226

This page deliberately left blank

British Standards Institution (BSI)

BSI is the independent national body responsible for preparing British Standards and other standards-related publications, information and services. It presents the UK view on standards in Europe and at the international level.

It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001

BSI offers Members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Tel: +44 (0)20 8996 7669 Fax: +44 (0)20 8996 7001
Email: plus@bsigroup.com

Buying standards

You may buy PDF and hard copy versions of standards directly using a credit card from the BSI Shop on the website **www.bsigroup.com/shop.** In addition all orders for BSI, international and foreign standards publications can be addressed to BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001
Email: orders@bsigroup.com

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Knowledge Centre.

Tel: +44 (0)20 8996 7004 Fax: +44 (0)20 8996 7005
Email: knowledgecentre@bsigroup.com

Various BSI electronic information services are also available which give details on all its products and services.

Tel: +44 (0)20 8996 7111 Fax: +44 (0)20 8996 7048
Email: info@bsigroup.com

BSI Subscribing Members are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration.

Tel: +44 (0)20 8996 7002 Fax: +44 (0)20 8996 7001
Email: membership@bsigroup.com

Information regarding online access to British Standards via British Standards Online can be found at **www.bsigroup.com/BSOL**

Further information about BSI is available on the BSI website at **www.bsigroup.com/standards**

Copyright

Tel: +44 (0)20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

Tel +44 (0)20 8996 9001
Fax +44 (0)20 8996 7001
www.bsigroup.com/standards

raising standards worldwide™