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Optics and optical instruments — Lasers and laser-related equipment — Test methods for laser beam power [energy] density distribution

Optique et instruments d'optique — Lasers et équipements associés aux lasers — Méthodes d'essai de distribution de la densité de puissance [d'énergie] du faisceau laser

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Foreword

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

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

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

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

International Standard ISO 13694 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

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Introduction

Many applications of lasers involve using the near-field as well as the far-field power [energy] density distribution of the beam[1]. The power [energy] density distribution of a laser beam is characterized by the spatial distribution of irradiant power [energy] density with lateral displacement in a particular plane perpendicular to the direction of propagation. In general, the power [energy] density distribution of the beam changes along the direction of propagation. Depending on the power [energy], size, wavelength, polarization and coherence of the beam, different methods of measurement are applicable in different situations. Five methods are commonly used: camera arrays (1D and 2D), apertures, pinholes, slits and knife edges.

This International Standard provides definitions of terms and symbols to be used in referring to power density distribution, as well as requirements for its measurement. For pulsed lasers, the distribution of time-integrated power density (i.e. energy density) is the quantity most often measured.

According to ISO 11145, it is possible to use two different definitions for describing and measuring the laser beam diameter. One definition is based on the measurement of the encircled power [energy]; the other is based on determining the spatial moments of the power [energy] density distribution of the laser beam.

The use of spatial moments is necessary for calculating the beam propagation factor K and the times-diffraction-limit factor M^2 from measurements of the beam widths at different distances along the propagation axis. ISO 11146 describes this measurement procedure. For other applications, other definitions for the beam diameter may be used. For some quantities used in this International Standard, the first definition (encircled power [energy]) is more appropriate and easier to use.

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1) For the purposes of this International Standard, "near-field" is defined as the radiation field of a laser at a distance z from the beam waist which is less than the Rayleigh-length z_R. "Far-field" is defined in ISO 11145.

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Optics and optical instruments — Lasers and laser-related equipment — Test methods for laser beam power [energy] density distribution

1 Scope

This International Standard specifies methods by which the measurement of power [energy] density distribution is made and defines parameters for the characterization of the spatial properties of laser power [energy] density distribution functions at a given plane.

The methods given in this International Standard are intended to be used for the testing and characterization of both continuous wave (cw) and pulsed laser beams used in optics and optical instruments.

2 Normative references

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

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

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

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

IEC 61040:1990, *Power and energy measuring detectors — Instruments and equipment for laser radiation.*

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3 Terms and definitions

For the purposes of this International Standard, the terms and definitions given in ISO 11145 and IEC 61040 and the following apply.

3.1 Measured quantities

3.1.1
power density
$E(x,y,z)$
part of the beam power at location z which impinges on the area δA at the location (x,y) divided by the area δA

3.1.2
energy density
$H(x,y,z)$
<pulsed laser beam> part of the beam energy (time-integrated power) at location z which impinges on the area δA at the location (x,y) divided by the area δA

$$H(x,y,z) = \int E(x,y,z)\,\mathrm{d}t$$

3.1.3
power
$P(z)$
power in a continuous wave (cw) beam at location z

$$P(z) = \iint E(x,y,z)\,\mathrm{d}x\mathrm{d}y$$

3.1.4
pulse energy
$Q(z)$
energy in a pulsed beam at location z

$$Q(z) = \iint H(x,y,z)\,\mathrm{d}x\mathrm{d}y$$

3.1.5
maximum power [energy] density
$E_{\mathrm{max}}(z)$ [$H_{\mathrm{max}}(z)$]
maximum of the spatial power [energy] density distribution function $E(x,y,z)$ [$H(x,y,z)$] at location z

3.1.6
location of the maximum
$(x_{\mathrm{max}}, y_{\mathrm{max}}, z)$
location of $E_{\mathrm{max}}(z)$ or $H_{\mathrm{max}}(z)$ in the xy plane at location z

NOTE $(x_{\mathrm{max}}, y_{\mathrm{max}}, z)$ may not be uniquely defined when measuring with detectors having a high spatial resolution and a relatively small dynamic range.

3.1.7
threshold power [energy] density
$E_{\eta\mathrm{T}}(z)$ [$H_{\eta\mathrm{T}}(z)$]
a fraction η of the maximum power [energy] density at location z

$E_{\eta\mathrm{T}}(z) = \eta E_{\mathrm{max}}(z)$ for cw-beams;

$H_{\eta\mathrm{T}}(z) = \eta H_{\mathrm{max}}(z)$ for pulsed beams;

$0 \le \eta < 1$

NOTE Usually the value of η chosen is such that $E_{\eta\mathrm{T}}$ or $H_{\eta\mathrm{T}}$ is just greater than detector background noise peaks at the time of measurement. Subclause 9.3 describes background noise subtraction methods used to determine detector zero levels. Circumstances such as the application involved, distribution type, detector sensitivity, linearity, saturation, baseline, offset level, etc., may also dictate the choice of η.

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3.2 Characterizing parameters

3.2.1
effective power [energy]
$P_\eta(z)$ $[Q_\eta(z)]$
$P(z)$ $[Q(z)]$ evaluated by summing only over locations (x,y) for which $E(x,y) > E_{\eta\mathrm{T}}$ $[H(x,y) > H_{\eta\mathrm{T}}]$

3.2.2
fractional power [energy]
$f_\eta(z)$
fraction of the effective power [energy] for a given η to the total power [energy] in the distribution at location z

$$f_\eta(z) = \frac{P_\eta(z)}{P(z)} \quad \text{for cw-beams;}$$

$$f_\eta(z) = \frac{Q_\eta(z)}{Q(z)} \quad \text{for pulsed beams;}$$

$$0 \le f_\eta(z) \le 1$$

3.2.3
centre of gravity
centroid position
$(\overline{x}, \overline{y})$
first linear moments at location z

NOTE For a more detailed definition, see ISO 11145.

3.2.4
beam widths
$d_{\sigma x}(z)$, $d_{\sigma y}(z)$
widths $d_{\sigma x}(z)$ and $d_{\sigma y}(z)$ of the beam in the x and y directions at z, equal to four times the square root of the second linear moments of the power [energy] density distribution about the centroid

NOTE 1 For a more detailed definition, see ISO 11145 and ISO 11146.

NOTE 2 The provisions of ISO 11146 apply to definitions and measurement of:

a) second moment beam widths $d_{\sigma x}$ and $d_{\sigma y}$;

b) beam widths $d_{x,u}$ and $d_{y,u}$ in terms of the smallest centred slit width that transmits u % of the total power [energy] density (usually $u = 86{,}5$);

c) scanning narrow slit measurements of beam widths $d_{x,\mathrm{s}}$ and $d_{y,\mathrm{s}}$ in terms of the separation between positions where the transmitted power density is reduced to $0{,}135E_P$;

d) measurements of beam widths $d_{x,\mathrm{k}}$ and $d_{y,\mathrm{k}}$ in terms of the separation between $0{,}84P$ and $0{,}16P$ obscuration positions of a movable knife-edge;

e) correlation factors which relate these different definitions and methods for measuring beam widths.

3.2.5
beam ellipticity [eccentricity]
$\xi(z)$ $[e(z)]$
parameter for quantifying the circularity or squareness (aspect ratio) of a distribution at z

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beam ellipticity $\xi(z) = \frac{d_{\sigma y}}{d_{\sigma x}}$;

beam eccentricity $e(z) = \frac{\sqrt{d^2{}_{\sigma x} - d^2{}_{\sigma y}}}{d_{\sigma x}}$

where the direction of x is chosen to be along the major axis of the distribution so $d_{\sigma x} \geq d_{\sigma y}$.

NOTE If $e \leq 0{,}5$ or $\xi \geq 0{,}87$, rotationally symmetric distributions can be regarded as circular and rectangular-types as square.

3.2.6
beam cross-sectional area
$A_\sigma(z)$

$A_\sigma = \pi\, d_\sigma^2/4$ for beam with circular cross-section;

$A_\sigma = \pi/4\, d_{\sigma x}\, d_{\sigma y}$ for beam with elliptical cross-section

3.2.7
effective irradiation area
$A_\eta^{\mathrm{i}}(z)$
irradiation area at location z for which the power [energy] density exceeds the threshold power [energy] density

NOTE 1 To allow for distributions of all forms, for example hollow "donut" types, the effective irradiation area is not defined in terms of the beam widths $d_{\sigma x}$ or $d_{\sigma y}$.

NOTE 2 See threshold power [energy] density (3.1.7).

3.2.8
effective average power [energy] density
$E_\eta(z)$ [$H_\eta(z)$]
spatially averaged power [energy] density of the distribution at location z, defined as the weighted mean:

$E_\eta(z) = \frac{P_\eta}{A_\eta^{\mathrm{i}}}$ for cw-beams;

$H_\eta(z) = \frac{Q_\eta}{A_\eta^{\mathrm{i}}}$ for pulsed beams

NOTE $E_\eta(z)$ and $E_{\eta\mathrm{T}}(z)$ (see 3.1.7) refer to different parameters.

3.2.9
flatness factor
$F_\eta(z)$
ratio of the average power [energy] density to the maximum power [energy] density of the distribution at location z

$F_\eta(z) = \frac{E_\eta}{E_{\mathrm{max}}}$ for cw-beams;

$F_\eta(z) = \frac{H_\eta}{H_{\mathrm{max}}}$ for pulsed beams

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$0 < F_\eta \le 1$

NOTE For a power [energy] density distribution having a perfectly flat top $F_\eta = 1$.

3.2.10
beam uniformity
$U_\eta(z)$
normalized root mean square (r.m.s.) deviation of power [energy] density from its average value at location z

$$U_\eta = \frac{1}{E_\eta}\sqrt{\frac{1}{A_\eta^{\mathrm{i}}}\iint [E(x,y) - E_\eta]^2 \mathrm{d}x\mathrm{d}y} \quad \text{for cw-beams}$$

$$U_\eta = \frac{1}{H_\eta}\sqrt{\frac{1}{A_\eta^{\mathrm{i}}}\iint [H(x,y) - H_\eta]^2 \mathrm{d}x\mathrm{d}y} \quad \text{for pulsed beams}$$

NOTE 1 $U_\eta = 0$ indicates a completely uniform distribution having a profile with a flat top and vertical edges. U_η is expressed as either a fraction or a percentage.

NOTE 2 By using integration over the beam area between set threshold limits, this definition allows for arbitrarily shaped beam footprints to be quantified in terms of their uniformity. Hence uniformity measurements can be made for different fractions of the total beam power [energy] without specifically defining a windowing aperture or referring to the shape or size of the distribution. Thus using the equations in 3.2.2 and 3.2.10, statements such as: "Using a setting η = 0,3, 85 % of the beam power [energy] was found to have a uniformity of ± 4,5 % r.m.s. from its mean value at z" can be made without reference to the distribution shape, size, etc.

3.2.11
plateau uniformity
$U_P(z)$
⟨for distributions having a nearly flat-top profile⟩

$$U_P(z) = \frac{\Delta E_{\mathrm{FWHM}}}{E_{\mathrm{max}}} \quad \text{for cw-beams;}$$

$$U_P(z) = \frac{\Delta H_{\mathrm{FWHM}}}{H_{\mathrm{max}}} \quad \text{for pulsed beams}$$

where ΔE_{FWHM} [ΔH_{FWHM}] is the full-width at half-maximum (FWHM) of the peak near E_{max} [H_{max}] of the power [energy] density histogram $N(E_\mathrm{i})$ [$N(H_\mathrm{i})$], i.e. the number of (x,y) locations at which a given power [energy] density E_i [H_i] is recorded.

NOTE $0 < U_P(z) < 1$; $U_P(z) \to 0$ as distributions become more flat-topped.

3.2.12
edge steepness
$s(z)$
normalized difference between effective irradiation areas $A_{0,1}^{\mathrm{i}}(z)$ and $A_{0,9}^{\mathrm{i}}(z)$ with power [energy] density values above $0{,}1E_{\mathrm{max}}(z)$ [$0{,}1H_{\mathrm{max}}(z)$] and $0{,}9E_{\mathrm{max}}(z)$ [$0{,}9H_{\mathrm{max}}(z)$] respectively

$$s(z) = \frac{A_{0,1}^{\mathrm{i}}(z) - A_{0,9}^{\mathrm{i}}(z)}{A_{0,1}^{\mathrm{i}}(z)}$$

$0 < s(z) < 1$

NOTE $s(z) \to 0$ as the edges of the distribution become more vertical.

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Parameters E_{max}, E_{η}, P_{η}, A^{i}_{η}, F_{η}, U_{η}, and s are illustrated in Figure 1 for a uniform power density distribution in one dimension.

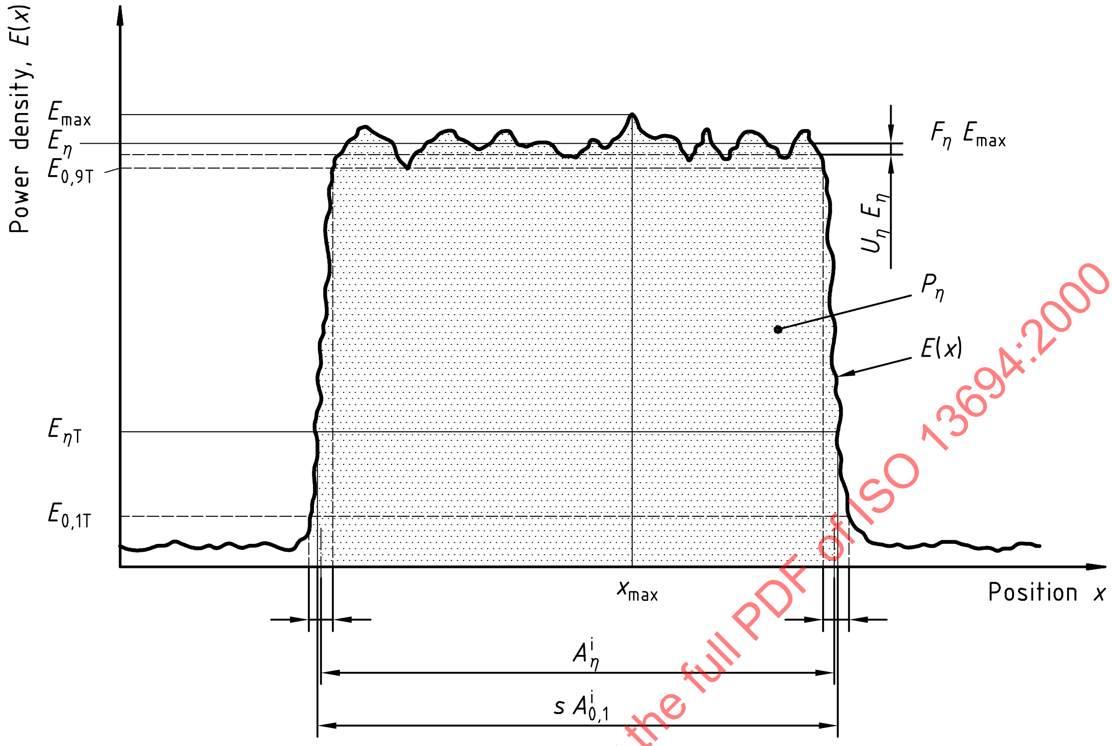

Figure 1 — Illustration for a uniform power density distribution $E(x)$ in one dimension

3.3 Distribution fitting

3.3.1
roughness of fit
R
maximum deviation of the theoretical fit to the measured distribution

$$R = \frac{\left| E_{ij} - E^{f}_{ij} \right|_{max}}{E_{max}}$$

where E^{f} is the fitted theoretical distribution

$0 \le R \le 1$

NOTE As $R \rightarrow 0$ the fit becomes better.

3.3.2
goodness of fit
G
parameter based upon Kolomogorov-Smirnov statistical test characterizing the fit between measured and theoretical distributions

$$G = \frac{1}{1 + \Delta\sqrt{N}}$$

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where

N is the total number of data points in the measured distribution.

Δ is the maximum deviation between measured and theoretical distributions of apertured powers (energies) truncated at $n \geq 10$ random locations (x_i, y_j) in the distribution:

$$\Delta = \frac{\left| P_{ij} - P_{ij}^{\mathrm{f}} \right|_{\max}}{P}$$

$$P_{ij} = \int_{\bar{x}-x_i}^{\bar{x}+x_i} \int_{\bar{y}-y_j}^{\bar{y}+y_j} E(x,y)\mathrm{d}x\mathrm{d}y \quad \text{and} \quad P_{ij}^{\mathrm{f}} = \int_{\bar{x}-x_i}^{\bar{x}+x_i} \int_{\bar{y}-y_j}^{\bar{y}+y_j} E^{\mathrm{f}}(x,y)\mathrm{d}x\mathrm{d}y$$

where E^{f} is the fitted theoretical distribution

$0 \leq G \leq 1$

NOTE As $G \to 1$ ($\Delta \to 0$) the quality of the fit becomes better.

4 Coordinate system

The x, y, z Cartesian axes define the orthogonal space directions in the beam axes system. The x and y axes are transverse to the beam and define the transverse plane. The beam propagates along the z axis. The origin of the z axis is in a reference xy plane defined by the laser manufacturer, e.g. the front of the laser enclosure. For elliptical beams, the principal axes of the distribution coincide with the x and y axes, respectively. In cases for which the principal axes of the distribution are rotated with respect to the laboratory coordinate system, the provisions of ISO 11146 describing coordinate rotation through an azimuth angle ϕ into the laboratory system shall apply.

5 Characterizing parameters derived from the measured spatial distribution

In definitions 3.2.1 to 3.2.12, summation integrals shall be computed over all locations (x,y) for which $E(x,y) > E_{\eta\mathrm{T}}$ or $H(x,y) > H_{\eta\mathrm{T}}$. This "threshold clipping" procedure for truncating summation integrals is different from the 99 % power [energy] spatial aperture truncation method used for calculating second-moment beam widths in ISO 11146. Before using threshold clipping it is necessary to apply proper background subtraction to the measured signal. According to the note in 3.1.7 usually the value of η is chosen such that $E_{\eta\mathrm{T}}$ or $H_{\eta\mathrm{T}}$ is just greater than detector background noise peaks at the time of measurements.

NOTE Since practical laser beams have a finite lateral size and detectors which measure their power density distribution a finite spatial resolution, definitions in this International Standard used for computations should more precisely contain discrete finite sums rather than continuous integrals. Finite integrals are used because they have a more compact form than summations and it is common practice to do so. For further information on the choice of practical integration limits, refer to 10.1.

6 Distribution fitting

6.1 General

For pulsed lasers, the following substitutions shall be made in the text of 3.3: power density E by energy density H, power P by energy Q and fitted theoretical distribution E^{f} by H^{f} respectively.

Testing for goodness of fit shall be carried out only over regions of the detector for which signal data has been registered. Values of $G < 0,5$ imply a poor fit which should be rejected.

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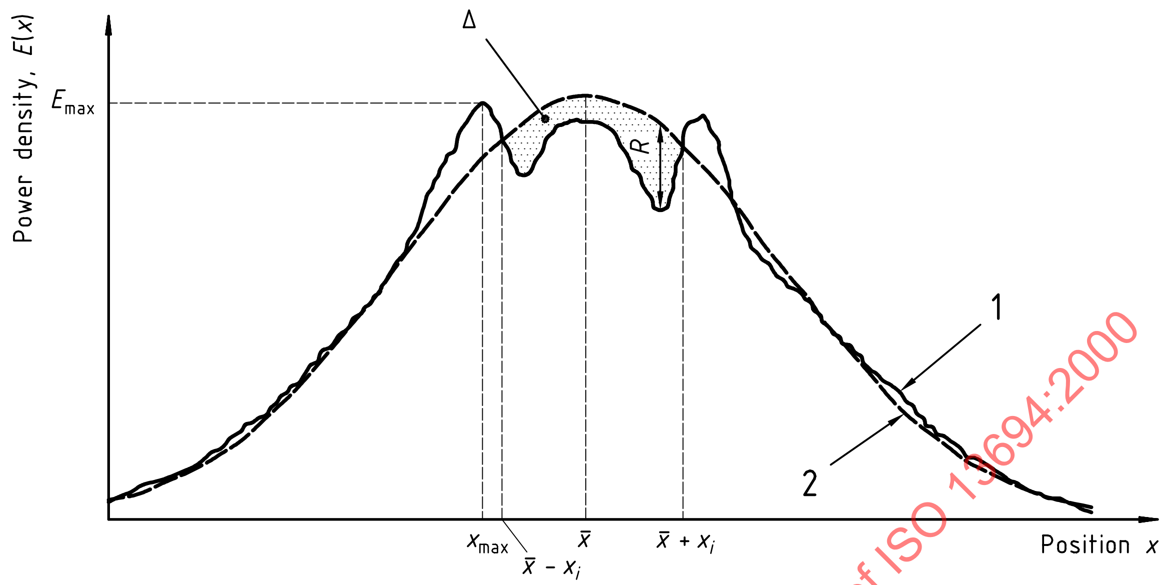
Figure 2 illustrates parameters R and $\varDelta$ for a power density distribution in one-dimension.



Key

1 $E(x)$ measured distribution

2 $E^f(x)$ theoretical Gaussian fit (R = 0,16; G = 0,81)

$\varDelta$ maximum difference in apertured powers

R maximum difference in power densities

Figure 2 — Example of Gaussian fitting to a measured distribution $E(x)$ in one-dimension

6.2 Fitting procedures

For fitting theoretical to measured distributions, the following approach is preferred to least-squared methods[2]. The measurement fixes five parameters: the centroid location $(\bar{x},\bar{y})$,beam widths $d_{\sigma x}$ and $d_{\sigma y}$ and total beam power [energy], P [Q]. These are then used as best estimates for the centre, standard deviation and normalization (area under the curve) respectively of the theoretical distribution $E^f(x,y)$

Examples of the functional form of common distributions which may be fitted are:

$$E^f(x,y) = E_0{}^f \mathrm{e}^{-\frac{1}{2}r^{2n}}$$

where $$E_0{}^f = \frac{16n^2 P}{2^{1/n}\Gamma^2(1/2n)d_{\sigma x}\, d_{\sigma y}}$$

and $$r^{2n} = \left[\left\{\frac{4(x-\bar{x})}{d_{\sigma x}}\right\}^2 + \left\{\frac{4(y-\bar{y})}{d_{\sigma y}}\right\}^2\right]^n$$

[2] Least-squared methods of fitting place equal weight on all regions of the distribution. For many distributions equal weighting of the wings and central region may not be appropriate.

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Gaussian: when order n = 1, so $E_0^{\mathrm{f}} = \dfrac{8P}{\pi d_{\sigma x} d_{\sigma y}}$

SuperGaussian: when order n = 2, 3,...

Donut and SuperDonut: $E^{\mathrm{f}}(x,y) = E_0^{\mathrm{f}} r^{2n} \mathrm{e}^{-\frac{1}{2} r^{2n}}$

Uniform (flat-top, top-hat or rectangular): $E^{\mathrm{f}}(x,y) = \dfrac{P}{A_\eta^{\mathrm{i}}}$ for locations (x,y) where $E(x,y) > E_{\mathrm{T}}$

= 0 elsewhere

For fitting uniform distributions, the value of A_η^{i} obtained for the measured distribution should be used.

Cross-sections of measured distributions shall be fitted using one-dimensional forms of these theoretical distributions. The linear and azimuthal coordinates of cross-sections shall then be stated.

7 Test principle

First the power [energy] density distribution $E(x,y)$ [or $H(x,y)$] at the location z is measured by positioning a spatially resolving detector of irradiance directly in the beam. The detector plane is either placed directly at z normal to the beam propagation direction or a suitable optical imaging system is used to relay the plane at z onto the detector. A stationary power [energy] density distribution is required to be measured. For lasers with temporally fluctuating beams an average power [energy] density shall be used. Following the measurement of $E(x,y)$ [or $H(x,y)$], parameters that characterize the beam power [energy] density distribution are then calculated from definitions given in 3.2.

8 Measurement arrangement and test equipment

8.1 General

For measuring the power [energy] density distribution of laser beams, any measuring device can be used which provides high spatial resolution and high dynamic range.

Methods commonly used to quantify laser beam power density distributions include 1D and 2D matrix camera arrays, single- and dual-axis scanning pinholes, single-axis scanning slits or knife edges, transmission through variable apertures (power-in-a-bucket measurements) and 2D densitometry by reflectance, fluorescence, phosphorescence, and film exposure.

8.2 Preparation

The laser beam and the optical axis of the measuring system should be coaxial. Suitable optical alignment devices are available for this purpose. Any pointing variations of the beam during the measurement period shall be verified not to affect the accuracy required of the measurement.

Optical elements such as beam splitters, attenuators, relay lenses shall be mounted such that the optical axis runs through their geometric centres. Care should be taken to avoid systematic errors. Reflections, external ambient light, thermal radiation or air draughts are all potential sources of error.

The field of view of the optical system shall be such that it accommodates the entire cross-section of the laser beam. Clipping or diffraction loss shall be smaller than 1 % of the total beam power or energy.

After the initial preparation is complete, an evaluation to determine if the entire laser beam reaches the detector surface shall be made. For testing this, apertures of different diameters can be introduced into the beam path in

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front of each optical component as well as the detector itself. The aperture which reduces the laser power by 5 % should have a diameter less than 0,8 times the aperture of the optical component.

8.3 Control of environment

Suitable measures, such as mechanical and acoustical isolation of the test set-up, shielding from extraneous radiation, temperature stabilization of the laboratory, choice of low-noise amplifiers, shall be taken to ensure that the contribution to the total probable error in the parameter to be measured is low.

Care should be taken to ensure that the atmospheric environment in high power [energy] laser beam paths does not contain gases or vapours that can absorb the laser radiation and cause thermal distortion to the beam power [energy] density distribution that is being measured.

8.4 Detector system

Measuring parameters of the power [energy] density distribution requires the use of a power [energy] meter having a high spatial resolution and signal-to-noise ratio for detecting radiation at the laser wavelength. The accuracy of the measurement is directly related to the spatial resolution of the detector system and its signal-to-noise ratio. The following points shall be observed and, where appropriate, recorded.

— The saturation level, the signal-to-noise ratio and the linearity of the detector system to the input laser power [energy] shall be determined from manufacturers' data or by measurement at the wavelength of the laser to be characterized. Any wavelength dependency, non-linearity or non-uniformity of the detector locally or across its aperture shall be minimized or corrected by use of a calibration procedure.

— The dynamic range of the sensor shall be greater than 100:1.

— To provide adequate spatial resolution, more than 2500 spatially non-overlapping (x,y) data points shall register a signal.

— Care shall be taken to ascertain the power [energy] density damage thresholds of the detector surface for the wavelength and pulse duration of interest, so that they are not exceeded by the laser beam.

— The provisions of ISO 11146 describing variable aperture, scanning slit and knife-edge methods for measuring beam widths apply also to measuring beam amplitude distributions at z.

— When using a scanning device to measure the power [energy] density distribution function, care shall be taken to ensure that the laser output is spatially and temporally stable during the complete scanning period.

— When measuring pulsed laser beams, to ensure beam parameters do not change during the sampling interval, the trigger time delay and sampling interval shall be measured and specified in the test report.

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8.5 Beam-forming optics, optical attenuators and beam splitters

If the cross-section of the laser beam is greater than the detector area or if the plane located at z is inaccessible to the detection system, a suitable optical system shall be used to image the cross-section area of the laser beam at z onto the detector surface. In such cases, the optical (de)magnification of the imaging system shall be recorded.

Optical components shall be selected appropriate to the laser wavelength and be free of aberration. An attenuator may be required to reduce the laser power [energy] density at the surface of the detector. Optical attenuators shall be used when the laser output power [energy] density exceeds the detector's working (linear) range or the damage threshold. Any wavelength, polarization and angular dependency, non-linearity or non-uniformity of the optical attenuator shall be minimized or corrected by use of a calibration procedure.

None of the optical elements used shall significantly influence the relative power [energy] density distribution. When imaging the laser beam onto the detector surface the (de)magnification factor shall be taken into account during the evaluation procedure.

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Care shall be taken to ensure that effects such as stray reflections, scattering or interference of the laser beam are not introduced by the detector or detection system at a level sufficient to affect the measured power [energy] density distribution. For example, in the case of matrix detectors such spurious effects may be introduced into the measurement by the sensor window – in which case an appropriate remedial measure would be either to apply antireflective coating or remove the window altogether.

9 Test procedures

9.1 Equipment preparation

If not defined otherwise by the manufacturer, a warm-up period of 1 h shall be allowed for both the laser and the sensor device before the measurements. Operating conditions shall be chosen as specified by the manufacturer.

Tuning between the detector output signal and the data acquisition electronics shall be performed by adjusting the background level in such a way that, after blocking the beam for all positions (x,y), a background signal $E_B(x,y) > 0$ or $H_B(x,y) > 0$ is registered.

In order to allow for compensation of positive and negative noise amplitudes in the computation of beam parameters (see 9.3.2), it should be checked that negative noise peaks in the signal are not clipped by the detection system.

The gain of the detector electronic readout system shall be adjusted to enable the full linear dynamic range of the measuring system to be used. Tuning of the signal height with respect to the dynamic range of the measuring system shall be performed by use of attenuators (see 8.5) and/or gain control of the detector electronics to ensure the signal-to-noise ratio is at least 100:1.

9.2 Detector calibration procedure

9.2.1 Spatial calibration

Spatial calibration shall be carried out, for example by placing an aperture or other obscuration of known size in the beam at z normal to the beam propagation direction and measuring its equivalent size as recorded on the detector. When relay optics are used to image the plane at z onto the detector surface, the size of obscuration chosen shall be such that diffraction effects in its image are effectively eliminated by the choice of resolving power of the imaging system. In arrangements that place the sensor head directly at z, the obscuration device shall be placed effectively in contact with the sensor so that edge diffraction effects are minimized.

9.2.2 Power [energy] calibration

If absolute values for the power [energy] density distribution are required, power [energy] calibration shall be achieved by first recording the uncalibrated distribution $E'(x,y)$ [or $H'(x,y)$] and then computing P', the uncalibrated total integral power density [Q', the uncalibrated total integral energy density]:

$$P' = \iint E'(x,y)\,\mathrm{d}x\mathrm{d}y$$ for cw-beams;

$$Q' = \iint H'(x,y)\,\mathrm{d}x\mathrm{d}y$$ for pulsed beams

An independent measurement of the total beam power P [pulse energy Q] in the distribution is then made using a suitably calibrated device placed at z. The provisions of IEC 61040 and ISO 11554 apply to single-element radiation detection systems and methods of measurement of beam power P and pulse energy Q at z. From this measurement, an absolute calibration of the power [energy] density distribution is provided:

$$E(x,y) = \frac{P}{P'}E'(x,y)$$ for cw-beams;

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$$H(x,y) = \frac{Q}{Q'} H'(x,y) \quad \text{for pulsed beams}$$

9.3 Data recording and noise correction

9.3.1 General

After unblocking the laser beam, the measured power [energy] density distribution $E_{\text{meas}}(x,y)$ [or $H_{\text{meas}}(x,y)$] shall be acquired and recorded. For pulsed lasers, the power density E shall be replaced by energy density H in the text of 9.3. In the case of pulsed lasers, care shall be taken that energy is accumulated during the full pulse duration.

At least 10 independent measurements in accordance with clauses 9 and 10 shall be made, and the values and respective standard deviations shall be calculated and given in the test report. For laser beam profiles which are temporally fluctuating, time-averaged measurements of the distribution may be made by averaging at least 10 individual recordings of $E_{\text{meas}}(x,y)$ or $H_{\text{meas}}(x,y)$.

Signals recorded as $E_{\text{meas}}(x,y)$ or $H_{\text{meas}}(x,y)$ can be divided into the sum of two parts: the "true" power [energy] density distribution $E(x,y)$ [or $H(x,y)$] generated by the beam under test and a possibly inhomogeneous background map $E_{\text{B}}(x,y)$ generated by other sources such as external or ambient radiation or by the sensor device itself:

$$E_{\text{meas}}(x,y) = E(x,y) + E_{\text{B}}(x,y)$$

For background correction provisions applied to parameters defined in 3.2.3 and 3.2.4, see ISO 11145 and ISO 11146. When evaluating the beam parameters defined in 3.2.1 and 3.2.2 and 3.2.7 to 3.2.14, procedures for background correction shall be applied to prevent noise in the wings of the distribution dominating the integrals (summations) involved. This correction shall be carried out by subtracting either a background map or an average background from the registered signal. For detection systems having a constant background level across the full area of the sensor, average background level subtraction correction can be used according to 9.3.3. In all other cases the subtraction of the complete background map as given in 9.3.2 is necessary.

9.3.2 Correction by background-map subtraction

Using the identical experimental arrangement, recording of a "dark image" background map $E_{\text{B}}(x,y)$ shall be carried out immediately prior to the acquisition of a power [energy] density distribution "signal map". For cw-lasers, the beam shall be blocked at the position in which the beam exits the laser enclosure; for pulsed lasers, data acquisition can be performed without triggering the laser.

Using background-map subtraction, the corrected distribution is given by:

$$E(x,y) = E_{\text{meas}}(x,y) - E_{\text{B}}(x,y)$$

NOTE In cases where temporally fluctuating residual ambient radiation is incident on the detector, which could distort the results, measurements of background and signal map should be performed in direct succession. For pulsed lasers or cw lasers with a fast shutter, this can be achieved using consecutive acquisition cycles of the detector system in combination with 'on-line' subtraction of the background.

As a result of the background subtraction, negative noise values may exist in the corrected power [energy] density distribution. These negative values shall be included in the further evaluation in order to allow compensation for positive and negative noise amplitudes.

Subtracting a background map does not always result in a baseline offset of zero. Even small baseline offsets can create large errors in the evaluation of parameters characterizing the measured power [energy] density distribution. Care shall be taken to minimize these baseline offset errors (see 10.2).

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9.3.3 Correction by average background subtraction

For detection systems having a constant background level across the complete area of the sensor, correction of measured distributions by average background level subtraction can be used.

An average detector background level $\overline{E}_{\mathrm{B}}$ across the area of the sensor is derived by recording and averaging across the detector at least $M \geq 10$ individual measurements of the background distribution $E_{\mathrm{B}}(x,y)$:

$$\overline{E}_{\mathrm{B}} = \frac{1}{MN} \sum_{i=1}^{N} \sum_{j=1}^{M} E_{\mathrm{B}\,i,j}$$

where N is the total number of individual (x,y) data recording points on the detector.

Using average background subtraction, the corrected distribution is given by:

$$E(x,y) = E_{\mathrm{meas}}(x,y) - \overline{E}_{\mathrm{B}}$$

10 Evaluation

10.1 Choice and optimization of integration limits

These provisions apply to the choice of integration limits for the summations involved in parameters describing the power [energy] density distribution defined in 3.2.1 and 3.2.2; 3.2.7 to 3.2.14; 3.3.3 and 3.3.4. For provisions applying to parameters defined in 3.2.3 and 3.2.4, see ISO 11145 and ISO 11146.

To within the desired measurement uncertainty, results of calculations of parameters characterizing the power [energy] density distribution shall be insensitive to the chosen threshold fraction η used for measurements. Insensitivity of calculations to the set threshold value $E_{\eta\mathrm{T}}$ or $H_{\eta\mathrm{T}}$ shall be checked by changing the value of η by 5 % to 10 %, e.g. from η = 0,01 to 0,011, and recomputing the parameter concerned. If a difference greater than the desired measurement uncertainty is obtained, another threshold value shall be chosen for the calculation. This procedure should be repeated until a value for η is found for which the computed parameter is stable.

Since all parameters defined in 3.2.7, 3.2.9 to 3.2.14 shall be insensitive to the laser power [pulse energy] used for measuring the power [energy] density distribution, self-consistency of the detection system may be verified by changing P [Q] uniformly across the xy plane at z and checking that recomputed values remain within the desired measurement uncertainty.

For example, $f_\eta = P_\eta/P$ [or Q_η/Q] in 3.2.2 shall be verified to have a value near unity and remain stable for small changes (say ~20 %) to the laser power [pulse energy] at z. By making a comparison with P [Q] measured using a separate calibrated beam power [energy] monitor placed at z, the validity of η used for the computation of P_η[Q_η] can be checked. Procedures for spatial and power [energy] calibration of the detection system are described in 9.2.1 and 9.2.2.

10.2 Control and optimization of background corrections

Corrected power [energy] density distributions shall be used for calculating the parameters defined in 3.2. It shall be checked, by variation of the threshold value, that the average background is properly nulled and parameters characterizing the power [energy] density distribution are sufficiently stable with regard to these variations.

The validity of the correction procedures used for background-map or average background subtraction shall be checked by varying between 5 % to 10 % the set value of $E_{\eta\mathrm{T}}$ or $H_{\eta\mathrm{T}}$ and recomputing parameters which characterize the power [energy] density distribution. If differences greater than the desired measurement uncertainty are obtained, an additional background correction optimization may be required. To within the desired measurement uncertainty, results of calculations of parameters characterizing the power [energy] density distribution should be insensitive to the chosen threshold fraction η used for measurements.

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