INTERNATIONAL STANDARD

ISO 11670

Second edition
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Lasers and laser-related equipment — Test methods for laser beam parameters — Beam positional stability

Lasers et équipements associés aux lasers — Méthodes d'essai des paramètres du faisceau laser — Stabilité de visée du faisceau

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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

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

ISO 11670 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

This second edition cancels and replaces the first edition (ISO 11670:1999), Clauses 3 and 9 of which have been technically revised. Annexes A and B have been added.

Introduction

The centre of a laser beam is defined as the centroid or first-order spatial moment of the power density distribution. The current propagation axis of a beam is then the straight line connecting two centroids measured at two different planes simultaneously in a uniform, homogeneous medium. Beam axis instability may be characterized by transverse displacements and angular movements that are either monotonic, periodic or stochastic in time.

The movement of a laser beam may be randomly distributed and uniform in amplitude in all directions. In general, the beam may move a greater amount in one direction. If one direction predominates, the procedures specified in this International Standard can be used to identify that dominant direction (the beam x-axis) and its azimuthal location relative to the axes of the laboratory system.

This International Standard provides general principles for the measurement of these quantities. In addition, definitions of terminology and symbols to be used in referring to beam position are provided.

Lasers and laser-related equipment — Test methods for laser beam parameters — Beam positional stability

1 Scope

This International Standard specifies methods for determining laser beam positional as well as angular stability. The test methods given in this International Standard are intended to be used for the testing and characterization of lasers.

2 Normative references

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

ISO 11145:2001, *Optics and optical instruments — Lasers 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*

IEC 61040:1990, *Power and energy measuring detectors, instruments and equipment for laser radiation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61040, ISO 11145 and ISO 11146 and the following apply.

3.1
angular movement
α_x, α_y
angular movement of the laser beam in the x-z and y-z planes, respectively

NOTE These quantities are defined in the beam axis system x,y,z. If the ratio of the quantity in the x direction to that in the y direction does not exceed 1,15:1, the quantity is regarded as rotationally symmetric and only one number may be given. The symbol α without index is used in that case.

3.2
beam angular stability
$\delta\alpha_x$, $\delta\alpha_y$
twice the standard deviation of the measured angular movement

NOTE These quantities are defined in the beam axis system x,y,z. If the ratio of the quantity in the x direction to that in the y direction does not exceed 1,15:1, the quantity is regarded as rotationally symmetric and only one number may be given. The symbol $\delta\alpha$ without index is used in that case.

3.3
pivot
point of intersection of all momentary beam axes with the z-axis

NOTE The measurement of the pivot is not a subject of this International Standard, because it does not necessarily exist.

3.4
transverse displacement
a_x, a_y
distance of transverse displacement of the laser beam in the x- and y-directions, respectively

NOTE 1 These quantities are defined in the beam axis system x,y,z. If the ratio of the quantity in the x direction to that in the y direction does not exceed 1,15:1, the quantity is regarded as rotationally symmetric and only one number may be given. The symbol a without index is used in that case.

NOTE 2 The measurement of the transverse displacement is not a subject of this International Standard.

3.5
beam positional movement
positional movement of the centroid of the laser beam in the plane z'

NOTE The positional movement at plane z' results from the superposition of transverse displacement and/or angular movement of the laser beam.

3.6
beam positional stability
$\Delta_x(z')$, $\Delta_y(z')$
four times the standard deviation of the measured beam positional movement at plane z'

NOTE These quantities are defined in the beam axis system x,y,z. If the ratio of the quantity in the x direction to that in the y direction does not exceed 1,15:1, the quantity is regarded as rotationally symmetric and only one number may be given. The symbol $\Delta(z')$ without index is used in that case.

3.7
relative beam angular stability
$\delta\alpha_{\text{rel},x}$, $\delta\alpha_{\text{rel},y}$, $\delta\alpha_{\text{rel,}}$
beam angular stability divided by the divergence angle

NOTE For elliptical beams, an effective divergence angle $\theta_{\text{eff}} = \sqrt{\frac{1}{2}\left(\theta_x^2 + \theta_y^2\right)}$ should be used, since the principal axes of the beam positional stability in general will not coincide with the principal axes of the laser beam propagation.

3.8
relative beam positional stability
$\Delta_{\text{rel},x}\,(z')$, $\Delta_{\text{rel},y}\,(z')$, $\Delta_{\text{rel,}}\,(z')$
beam positional stability at plane z' divided by the beam diameter at plane z'

NOTE For elliptical beams, an effective beam diameter $d_{\text{eff}} = \sqrt{\frac{1}{2}\left(d_x^2 + d_y^2\right)}$ should be used, since the principal axes of the beam positional stability in general will not coincide with the principal axes of the laser beam propagation.

3.9
beam stability parameter product
S_x, S_y, S
The product of the minimum beam positional stability along the propagation and the beam angular stability

NOTE In a way similar to the beam diameter, the beam positional stability, as defined in sub-clause 3.6, obeys a hyperbolic propagation law. Thus, the propagation of the absolute beam stability can be completely characterized by three parameters: the position z_0 of the minimum value of the beam positional stability, the minimum value of the beam positional stability Δ_0 and the beam angular stability α. The position z_0 of the minimum value of the beam positional stability in general does not coincide with the waist position of the laser beam. See Annex A for further details.

3.10
beam positional change from cold start
difference in beam position from the position noted immediately upon turning on a turned-off, ambient-temperature-equilibrated laser and the position noted after that laser has operated for longer than the warm-up time

3.11
short-term stability
stability within a time interval of 1 s

3.12
medium-term stability
stability within a time interval of 1 min

3.13
long-term stability
stability within a time interval of 1 h

4 Coordinate systems and beam axis

4.1 Beam axis distribution

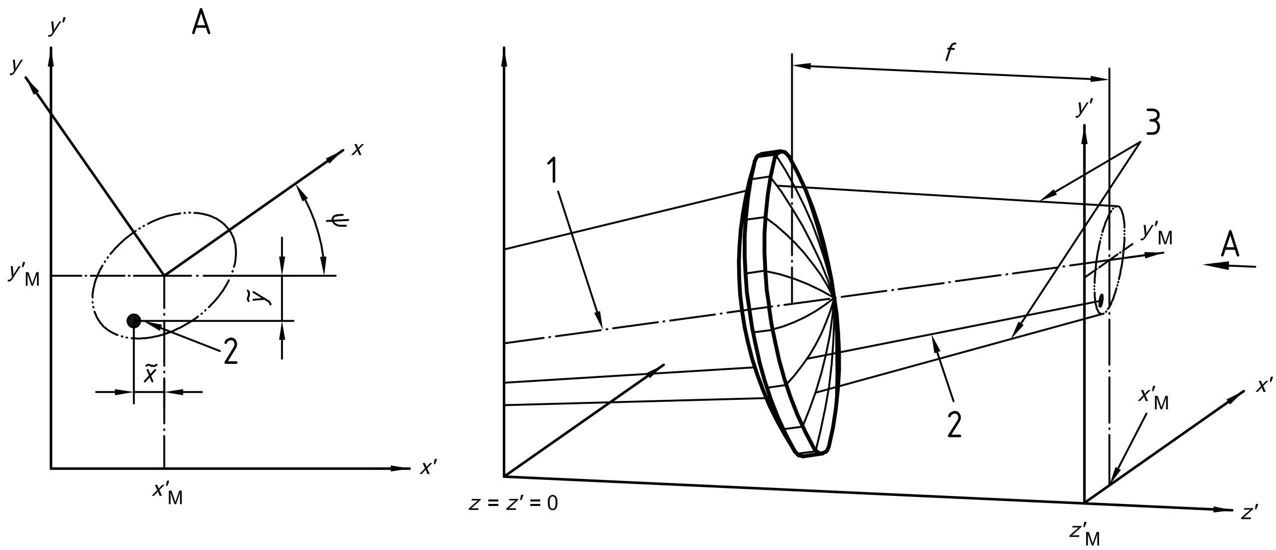
The distribution of the beam axes (as defined in ISO 11145) is obtained from a significant number ($n \geqslant$ 1 000) of measurements of the beam axis direction.

The movement of the beam axis can be described by means of the standard deviation of this beam axis distribution. This standard deviation can vary in different directions. This means that the amplitude of the beam movement can be greater in one dominant direction than in another, and that the distribution of beam axis movements is not necessarily radially symmetric.

4.2 Coordinate systems

4.2.1 General

All coordinate systems are defined as right-handed.



Key

1 average direction of the beam propagation axes

2 beam axis (for one measurement)

3 two times the standard deviation of the beam axis distribution

Figure 1 — Coordinate systems x',y',z' and x,y,z

4.2.2 Laboratory system

The x', y' and z' axes define the orthogonal space directions in the laboratory system. The origin of the z'-axis is in a reference (x'-y')-plane defined by the laser manufacturer (e.g. the front of the laser enclosure), so that the beam propagates approximately (less than 10° deviation) along the z'-axis.

4.2.3 Beam axis system

A second orthogonal coordinate system, the beam axis system, is defined in the following way:

— the z-axis is the average direction of the beam propagation axis (first-order spatial moment of the beam axis distribution), which shall be determined after the laser has reached a steady state;

— the x-axis is the direction of maximum amplitude of movement of the asymmetric beam axis distribution in the far-field;

NOTE The asymmetric beam axis distribution is not to be confused with the asymmetric beam power distribution function.

— the origin of the beam axis system coincides with the origin of the laboratory system.

4.2.4 Azimuth angle

The azimuth angle, ψ, is the angle by which the beam x-axis is rotated with respect to the laboratory system x'-axis.

4.2.5 Transformation of coordinates

The transformation of the n measured coordinates of the laboratory system (x',y',z') into the beam axis system (x,y,z) shall be performed using the following equations for the translational and rotational transformations (see Figure 1, where subscript M indicates the coordinates in the measuring plane):

a) First step (calculation of x'_{M} and y'_{M})

$$x'_{\mathrm{M}} = \frac{\sum_i x'_i}{n} \tag{1}$$

$$y'_{\mathrm{M}} = \frac{\sum_i y'_i}{n} \tag{2}$$

where $i = 1$ to n.

b) Second step (translation):

$$\widetilde{x} = x' - x'_{\mathrm{M}} \tag{3}$$

$$\widetilde{y} = y' - y'_{\mathrm{M}} \tag{4}$$

c) Third step (rotation around the z axis):

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \begin{pmatrix} \widetilde{x} \\ \widetilde{y} \end{pmatrix} \tag{5}$$

where

$$\psi = \frac{1}{2} \arctan \left(\frac{2 s_{\widetilde{x}\widetilde{y}}^{2}}{s_{\widetilde{x}}^{2} - s_{\widetilde{y}}^{2}} \right) \tag{6}$$

$$s_{\widetilde{x}}^{2} = \frac{\sum_i \left(x'_i - x'_{\mathrm{M}}\right)^2}{n-1} \tag{7}$$

$$s_{\tilde{y}}^{2} = \frac{\sum_{i} \left(y'_{i} - y'_{\mathrm{M}} \right)^{2}}{n-1} \tag{8}$$

$$s_{\tilde{xy}}^{2} = \frac{\sum_{i} \left(x'_{i} - x'_{\mathrm{M}} \right) \left(y'_{i} - y'_{\mathrm{M}} \right)}{n-1} \tag{9}$$

where $i = 1$ to n.

5 Test principles

5.1 Beam positional stability

The beam positional stability is measured directly or in the image plane of an imaging element. The movement of the centroid of the beam is determined using a position-sensitive detector. The position of the centroid of the beam (as measured by the first-order spatial moment of the power density distribution function in the x,y,z system) indicates the instantaneous position of the beam axis in the laboratory x',y',z' system. The beam positional stability can be calculated from the standard deviation of the variation of the centroid position over the appropriate short, medium or long time scale.

5.2 Beam angular stability

The beam angular stability is measured in the focal plane of a focusing element. The movement of the centroid of the beam is determined using a position-sensitive detector. The position of the centroid of the beam (as measured by the first-order spatial moment of the power density distribution function in the x,y,z system) indicates the instantaneous direction of the beam axis in the laboratory x',y',z' system. The beam angular stability is calculated from the standard deviation of the variation of the centroid position over the appropriate short, medium or long time scale.

6 Measurement arrangement, test equipment and auxiliary devices

6.1 Preparation

The laser beam and the optical axis of the measuring system shall be coaxial.

The aperture of the optical system shall be such that it accommodates the entire cross-section of the laser beam. Clipping or diffraction loss shall contribute an increase of less than 1 % to the anticipated error of the final measurements. The optical elements (beam splitter, attenuator, imaging element, etc.) shall be mounted such that the optical axis runs through the geometrical centres. Care should be taken to avoid systematic errors. Reflections, external ambient and thermal radiation, air turbulence or thermal blooming are all potential sources of error.

The laser shall warm up according to the manufacturer's specification in order to achieve thermal equilibrium before measurements are started. The test equipment shall be in thermal equilibrium as well.

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 front of each optical component. The aperture which reduces the output signal by 5 % shall have a diameter less than 0,8 times the aperture of the optical component.

6.2 Control of environment

The optical bench or support system for the laser and measurement system should have an optomechanical stability that exceeds that of the laser under test by at least an order of magnitude. Measures should be taken to ensure that extraneous or systematic influences do not increase the anticipated probable error of the measurements by more than 10 %. These measures should include mechanical and acoustic isolation of the test facility, temperature stabilization of the laboratory and the laser cooling system (as specified by the manufacturer), shielding from extraneous electrical and optical noise and use of low-noise electronic equipment.

6.3 Detection system

For measurement of the beam positional stability, the first-order spatial moment of the power density distribution function shall be measured in accordance with ISO 11146. In particular, the provisions for the detector system apply for this International Standard. If the power density distribution function does not change from measurement to measurement, simpler detector systems may be used (e.g. lateral diodes, quadrant detector). The accuracy of the measurement is directly related to the spatial resolution of the detector system and its signal-to-noise ratio.

The radiation detector system shall be in accordance with IEC 61040:1990, Clauses 3 and 4 of which are particularly important. It shall be taken into account that only relative measurements are necessary. Furthermore, the following points should be noted.

— It shall be confirmed from the manufacturer's data or by measurement, that the output quantity of the detector system (e.g. voltage) is linearly dependent on the input quantity (laser power). Any wavelength dependency, non-linearity or non-uniformity of the detector or the electronic device shall be minimized or corrected by use of a calibration procedure.

— Care shall be taken to ascertain that the damage threshold (for irradiance, radiant exposure, power and energy) of the detector surface is not exceeded by the laser beam.

6.4 Beam-forming optics, optical attenuators, beam splitters, focusing elements

In the case where the cross-section of the laser beam is greater than the detector area, a suitable optical system shall be used to image the cross-sectional area of the laser beam onto the detector surface.

Optics shall be selected appropriate to wavelength.

Optical attenuators shall be used when the laser output power or the power 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. For use with high-power lasers, any high-power-induced deterioration of the laser beam shall be avoided.

The focusing system shall be in accordance with the requirements relating to the optics described above. In addition, the following requirements shall be met:

— the focusing system shall be aberration-free, i.e. the influence on the quantities to be measured shall be less than 20 % of the total error of the measurement without any aberration;

— the focal length and the location of its principal planes shall be known to within 1 % of the focal length;

— the aperture of the focusing system shall be selected such that it accommodates the entire cross-section of the laser beam and clipping or diffraction loss is smaller than 1 % of the anticipated probable error of the measurement.

None of the optical elements used shall significantly influence the relative power density distribution. When imaging the laser beam onto the detector surface, the change in magnification shall be taken into account during the evaluation procedure.

6.5 Calibration

A calibration procedure shall be performed before starting the measurement of the beam positional stability. This can be accomplished by simply making provision for displacing the position-sensitive detector by a known distance using an orthogonal pair of micrometer-driven linear slides.

7 Test procedures

7.1 General

Measurements shall be carried out at the operating conditions which are specified by the laser manufacturer for the type of laser being evaluated.

The beam shall be sampled at least 1 000 times during the measuring interval. The electrical frequency bandwidth of the detector, including the bandwidth of any succeeding amplifier and associated electronics, shall be three times higher than the inverse of the time difference between two measurements.

NOTE If camera-based systems are used for the measurement, the temporal bandwidth is limited by the frame repetition rate.

7.2 Beam positional stability

In order to measure the beam positional stability at the position z', the detection system shall be installed at location z' or location z' shall be imaged with magnification γ onto the detector surface. The movement of the beam axis shall be recorded within measuring times of 1 s (see 3.11), 1 min (see 3.12) or 1 h (see 3.13), respectively.

7.3 Beam angular stability

In order to measure the beam angular stability, the detector surface shall be placed in the focal plane of a focusing element. The movement of the beam axis shall be recorded within measuring times of 1 s (see 3.11), 1 min (see 3.12) or 1 h (see 3.13), respectively.

8 Evaluation

8.1 Beam positional stability

Evaluation of beam positional stability shall be performed in the following way.

a) The centroid at location z' shall be determined by

1) reading out a lateral-sensitive detector (see 6.3);

or by

2) calculating the first-order spatial moments of the power density distribution function

$$x_i' = \frac{\int \int xE\left(x,y\right) \mathrm{d}x \mathrm{d}y}{\int \int E\left(x,y\right) \mathrm{d}x \mathrm{d}y} \tag{10}$$

$$y_i' = \frac{\int \int yE\left(x,y\right) \mathrm{d}x \mathrm{d}y}{\int \int E\left(x,y\right) \mathrm{d}x \mathrm{d}y} \tag{11}$$

When using an imaging system, the imaging magnification shall be taken into account.

b) The coordinates x'_{M} and y'_{M} of the intersection of the beam axis with the plane of measurement in the laboratory system ($z' = z'_{\mathrm{M}}$) are given by

$$x'_{\mathrm{M}} = \frac{\sum_i x_i'}{n} \tag{12}$$

$$y'_{\mathrm{M}} = \frac{\sum_i y'_i}{n} \tag{13}$$

where $i = 1$ to n ($n \geqslant 1\,000$).

c) The x'_i and y'_i coordinates may be transformed into the beam axis system (x,y,z) according to 4.2.5 (translational and rotational transformation). The azimuth angle, ψ, shall be calculated and recorded.

$$\psi = \frac{1}{2} \arctan\left(\frac{2 s_{\widetilde{xy}}^{\;2}}{s_{\tilde{x}}^{\;2} - s_{\tilde{y}}^{\;2}}\right) \tag{14}$$

$$s_{\tilde{x}}^{\;2} = \frac{\sum_i \left(x'_i - x'_{\mathrm{M}}\right)^2}{n-1} \tag{15}$$

$$s_{\tilde{y}}^{\;2} = \frac{\sum_i \left(y'_i - y'_{\mathrm{M}}\right)^2}{n-1} \tag{16}$$

$$s_{\widetilde{xy}}^{\;2} = \frac{\sum_i \left(x'_i - x'_{\mathrm{M}}\right)\left(y'_i - y'_{\mathrm{M}}\right)}{n-1} \tag{17}$$

where $i = 1$ to n.

NOTE This angle ψ does not define the x-axis of the beam axis system in general, because the measurement is not performed in the far-field.

d) From these values (x_i,y_i) the standard deviations s_x, s_y and s can be calculated according to

$$s_x = \sqrt{\frac{\sum_i x_i^{\,2}}{n-1}} = \sqrt{\frac{\sum_i \left[\left(x'_i - x'_{\mathrm{M}}\right)\ \cos\psi + \left(y'_i - y'_{\mathrm{M}}\right)\ \sin\psi\right]^2}{n-1}} \tag{18}$$

$$s_y = \sqrt{\frac{\sum_i y_i^{\,2}}{n-1}} = \sqrt{\frac{\sum_i \left[-\left(x'_i - x'_{\mathrm{M}}\right) \sin\psi + \left(y'_i - y'_{\mathrm{M}}\right) \cos\psi\right]^2}{n-1}} \tag{19}$$

$$s = \sqrt{\frac{\sum_i x_i^{\,2}}{n-1}} \tag{20}$$

where

$$r_i^{\,2} = x_i^{\,2} + y_i^{\,2}$$

$$r_i^{\,2} = \left(x'_i - x'_{\mathrm{M}}\right)^2 + \left(y'_i - y'_{\mathrm{M}}\right)^2$$

e) The beam positional stability can be determined using the equations

$$\Delta_x\left(z\right) = 2\, s_x \tag{21}$$

$$\Delta_y\left(z\right) = 2\, s_y \tag{22}$$

$$\Delta\left(z\right) = \sqrt{2}\, s \tag{23}$$

8.2 Beam angular stability

The displacement in the focal plane $\zeta_{x'}$, $\zeta_{y'}$, ζ is correlated to the angular movement $\alpha_{x'}$, $\alpha_{y'}$, α in the following way:

$$\alpha_{x'} = \zeta_{x'}/f \tag{24}$$

$$\alpha_{y'} = \zeta_{y'}/f \tag{25}$$

$$\alpha = \zeta/f \tag{26}$$

The evaluation of the beam angular stability shall be performed in the following way.

a) The centroid in the focal plane shall be determined by

1) reading out a lateral-sensitive detector (see 6.3);

or by

2) calculating the first-order spatial moments of the power density distribution function

$$\zeta_{x'_i} = \frac{\int\int xE(x,y)\,\mathrm{d}x\mathrm{d}y}{\int\int E(x,y)\,\mathrm{d}x\mathrm{d}y} \tag{27}$$

$$\zeta_{y'_i} = \frac{\int\int yE(x,y)\,\mathrm{d}x\mathrm{d}y}{\int\int E(x,y)\,\mathrm{d}x\mathrm{d}y} \tag{28}$$

b) The coordinates $\zeta_{x'_\mathrm{M}}$ and $\zeta_{y'_\mathrm{M}}$ are given by

$$\zeta_{x'_\mathrm{M}} = \frac{\sum\limits_i \zeta_{x'_i}}{n} \tag{29}$$

$$\zeta_{y'_\mathrm{M}} = \frac{\sum\limits_i \zeta_{y'_i}}{n} \tag{30}$$

where $i = 1$ to n ($n \geqslant 1\,000$).

c) The $\zeta_{x'_i}$ and $\zeta_{y'_i}$ coordinates may be transformed into the beam axis system (x,y,z) according to 4.2.5 (translational and rotational transformation). The azimuth angle ψ' shall be calculated and recorded.

$$\psi' = \frac{1}{2}\arctan\left(\frac{2s_{\widetilde{xy}}^2}{s_{\tilde{x}}^2 - s_{\tilde{y}}^2}\right) \tag{31}$$

$$s_{\tilde{x}}^2 = \frac{\sum\limits_i \left(\zeta_{x'_i} - \zeta_{x'_\mathrm{M}}\right)^2}{n-1} \tag{32}$$

$$s_{\tilde{x}}^2 = \frac{\sum\limits_i \left(\zeta_{y'_i} - \zeta_{y'_\mathrm{M}}\right)^2}{n-1} \tag{33}$$

$$s_{\widetilde{xy}}^2 = \frac{\sum\limits_i \left(\zeta_{x'_i} - \zeta_{x'_\mathrm{M}}\right)\left(\zeta_{y'_i} - \zeta_{y'_\mathrm{M}}\right)}{n-1} \tag{34}$$

where $i = 1$ to n.

NOTE This angle ψ' defines the x-axis of the beam axis system.

d) From these values (ζ_{x_i}, ζ_{y_i}) the standard deviations $s_{\zeta x}$, $s_{\zeta y}$ and s_ζ can be calculated according to

$$s_{\zeta_x} = \sqrt{\frac{\sum\limits_i \zeta_{x_i}{}^2}{n-1}} = \sqrt{\frac{\sum\limits_i \left[\left(\zeta_{x'_i} - \zeta_{x'_\mathrm{M}}\right)\cos\psi' + \left(\zeta_{y'_i} - \zeta_{y'_\mathrm{M}}\right)\sin\psi'\right]^2}{n-1}} \tag{35}$$

$$s_{\zeta_y} = \sqrt{\frac{\sum_i {\zeta_{y_i}}^2}{n-1}} = \sqrt{\frac{\sum_i \left[-\left(\zeta_{x'_i} - \zeta_{x'_M}\right) \sin\psi' + \left(\zeta_{y'_i} - \zeta_{y'_M}\right) \cos\psi' \right]^2}{n-1}} \quad (36)$$

$$s_{\zeta} = \sqrt{\frac{\sum_i {\zeta_i}^2}{n-1}} \quad (37)$$

where

$${\zeta_i}^2 = {\zeta_{x_i}}^2 + {\zeta_{y_i}}^2 = \left(\zeta_{x'_i} - \zeta_{x'_M}\right)^2 + \left(\zeta_{y'_i} - \zeta_{y'_M}\right)^2$$

e) The beam angular stability can be determined using the equations

$$\delta\alpha_x = \frac{2 s_{\zeta_x}}{f} \quad (38)$$

$$\delta\alpha_y = \frac{2 s_{\zeta_y}}{f} \quad (39)$$

$$\delta\alpha = \frac{\sqrt{2} s_{\zeta}}{f} \quad (40)$$

where f is the focal length of the focusing element used.

9 Test report

The following information shall be included in the test report:

a) General information:

1) test has been performed according to ISO 11670:2003;

2) date of test;

3) name and address of test organization;

4) name of individual performing the test.

b) Information concerning the tested laser:

1) laser type;

2) manufacturer;

3) manufacturer's model designation;

4) serial number.

c) Test conditions:

1) laser wavelength tested at;

2) operating mode (continuous wave or pulsed);

3) laser parameter settings

— output power or energy;

— current or energy input;

— pulse energy;

— pulse duration;

— pulse repetition rate;

4) mode structure;

5) polarization;

6) environmental conditions.

d) Information concerning testing and evaluation:

1) test method used;

2) detector and sampling system:

— response time of the detector system;

— trigger delay of sampling (for pulsed lasers only);

— measuring time interval (for pulsed lasers only);

3) beam forming optics and attenuating method:

— type of attenuator;

— type of beam splitter;

— type of focusing element;

4) other optical components and devices used for the test (polarizer, monochromator, etc.);

5) other relevant parameters or characteristics of the test which have to be chosen (aperture setting, reference plane, reference axis, laboratory system).

e) Test results:

1) Beam positional stability (according to 7.2)

Location, z

Stability conditions (optional)	Short		Medium		Long	
	Test value	Uncertainty	Test value	Uncertainty	Test value	Uncertainty
Beam positional stability, Δ						
Beam positional stability, Δ_x						
Beam positional stability, Δ_y						
Azimuth, ψ						

2) Beam angular stability (according to 7.3)

Stability conditions (optional)	Short		Medium		Long	
	Test value	Uncertainty	Test value	Uncertainty	Test value	Uncertainty
Beam angular stability, $\delta\alpha$						
Beam angular stability, $\delta\alpha_x$						
Beam angular stability, $\delta\alpha_y$						
Azimuth, ψ'						

Annex A
(informative)

Propagation of absolute beam stability

A.1 Introduction

In the following, the formulae for the propagation of the beam positional stability for the stigmatic case are given. All relations also hold for the simple astigmatic case if the beam axis system is used as coordinate system and the appropriate definitions are used [α_x, $\Delta_x(z')$ and α_y, $\Delta_y(z')$ instead of α, $\Delta(z')$].

It can be shown that the beam positional stability propagates in the same manner through optical systems as the beam diameter does. In free space the propagation law reads

$$\Delta^2(z) = \Delta_0^2 + (z - z_0)^2 \cdot \alpha^2$$

Thus, the propagation of the absolute beam stability can be completely characterized by three parameters: the position z_0 of the minimum value of the beam stability, the minimum value of the beam positional stability, Δ_0, and the beam angular stability, α. The position z_0 of the minimum value of the beam positional stability in general does not coincide with the waist position of the laser beam.

Most statements of ISO 11146 remain true when the term “beam diameter” is replaced by “absolute beam positional stability”.

The beam stability parameter product, S, which is defined as the product of the minimum beam positional stability along the propagation and the beam angular stability:

$$S = \alpha \cdot \Delta_0$$

is invariant by propagation through first order optical systems.

NOTE Unlike the beam propagation ratio, the lower limit of the beam stability parameter product is zero. A value of zero does not necessarily mean that the beam is stable in the near field and the far field.

A.2 Maximum and minimum relative beam positional stability

Another useful invariant quantity is the mixed parameter product P with

$$P = \sqrt{d_{\sigma 0}^2 \cdot \alpha^2 + \Delta\left(z_0\right)^2 \cdot \theta_\sigma^2} = \sqrt{d_\sigma\left(z_0\right)^2 \cdot \alpha^2 + \Delta_0^2 \cdot \theta_\sigma^2}$$

where

$d_{\sigma 0}$ is the beam waist diameter;

Δ_0 is the minimum value of the beam positional stability;

$d_\sigma(z_0)$ is the beam diameter at the position where the absolute beam positional stability has its minimum value;

$\Delta(z_0)$ is the value of the absolute beam positional stability in the waist of the beam.

The beam stability parameter product, S, and the mixed parameter product, P, can be used to calculate the minimum and maximum relative beam positional stability that the beam can take on. Since all involved quantities are invariant quantities, the minimum and maximum relative beam positional stabilities are as well. The minimum relative beam positional stability is given by

$$\Delta_{\text{rel,min}} = \sqrt{\frac{1}{2}\left[\left(\frac{P}{D \cdot \theta}\right)^2 - \sqrt{\left(\frac{P}{D \cdot \theta}\right)^4 - 4\left(\frac{S}{D \cdot \theta}\right)^2}\right]}$$

and the maximum relative beam stability is given by

$$\Delta_{\text{rel,max}} = \sqrt{\frac{1}{2}\left[\left(\frac{P}{D \cdot \theta}\right)^2 + \sqrt{\left(\frac{P}{D \cdot \theta}\right)^4 - 4\left(\frac{S}{D \cdot \theta}\right)^2}\right]}$$

A.3 Measurement procedure and evaluation

The determination of the position, z_0 of the minimum value of the beam positional stability, the minimum value of beam positional stability, Δ_0, the beam angular stability, α, and the beam stability parameter product is analogous to the combined determination of laser beam propagation parameters as described in Clauses 9 and 10 of ISO 11146:1999.

The provisions of ISO 11146:1999 Clauses 9 and 10, directly hold if the following substitutions are made:

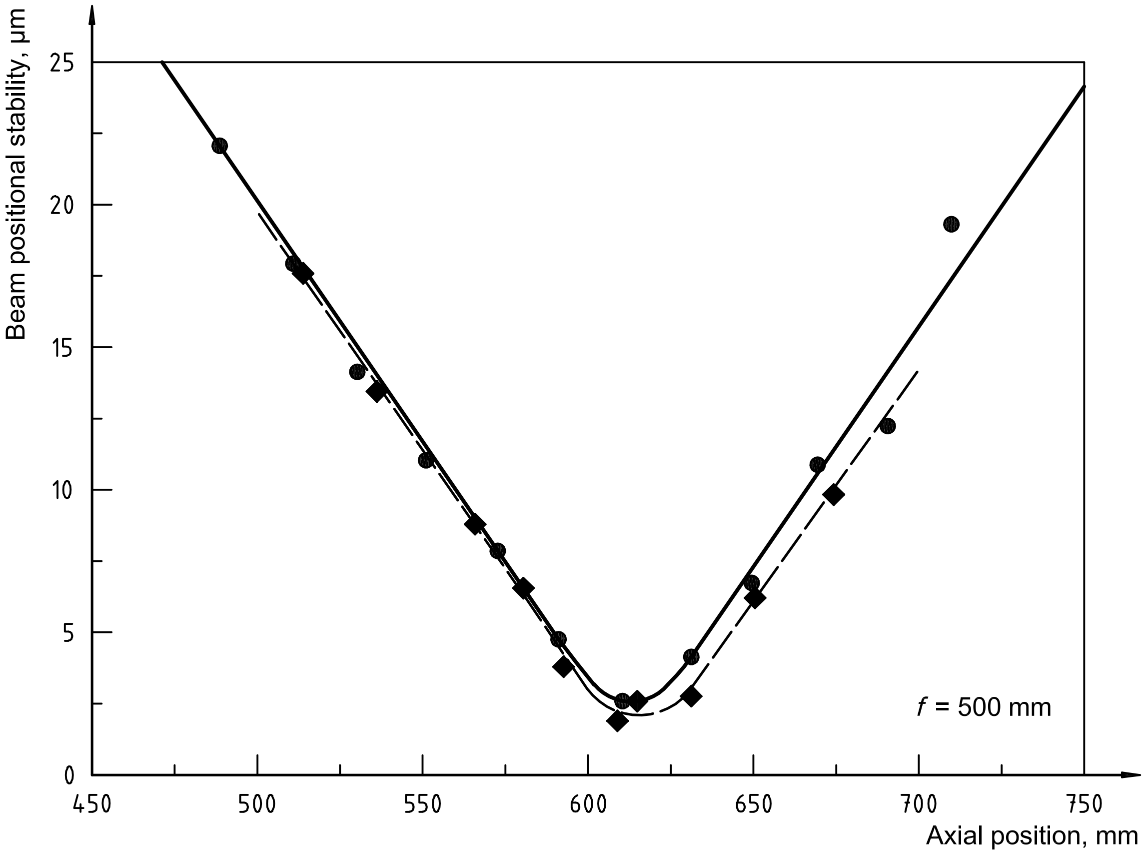
— waist diameter by minimum value of the beam positional stability;

— waist position by position of the minimum value of the beam positional stability;

— divergence angle by beam angular stability;

— and times-diffraction-limit factor (beam propagation ratio in the revision of ISO 11146:1999) by beam stability parameter product.

As an example, the measured beam positional stability along the propagation and the fitted hyperbola are shown in Figure A.1. The beam source was an industrial Q-switch Nd: YAG-laser; for the measurements two different CCD-camera systems have been used.



Key

- ● No. 9, CCD-camera
- ——— No. 9, CCD-camera (fit)
- ◆ No. 11, CCD-camera
- — — — No. 11, CCD-camera (fit)

Figure A.1 — Beam positional stability of a Q-switched Nd: YAG-laser measured with two different CCD-camera systems along the propagation

Annex B
(informative)

Decoupling of short- and long-term fluctuations

Most lasers show temporal fluctuations on different time scales. Besides very fast fluctuations (for example pulse-to-pulse variations), there might occur additional variations on a longer time scale. These beam fluctuations are usually mixed up within the measurement of the beam pointing stability.

In order to eliminate the long-term drift from the measurements, one of the two following equivalent high-pass filtering procedures can be chosen:

a) Fourier transform method:

The measured data is Fourier transformed. If f_m denotes the frequency of the short term variations, frequencies above $2f_\mathrm{m}$ are to be cut-off and the inverse Fourier transform is to be applied.

b) "Running-average" subtraction:

A "running average" of the measured data is calculated, according to

$$\widetilde{x}_j = \frac{1}{2c\,\frac{f_\mathrm{m}}{f_\mathrm{s}} + 1} \cdot \sum_{i=j-c\frac{f_\mathrm{m}}{f_\mathrm{s}}}^{j+c\frac{f_\mathrm{m}}{f_\mathrm{s}}} x_i$$

and subtracted from the measured data. f_s denotes the sampling frequency and f_m the frequency of the short-term variations. The constant factor, c, should be chosen to be greater than 2. Additionally, c/f_m has to be chosen smaller than 0,2 times the time constant of the long term fluctuations, which is to be eliminated.

Applying one of these procedures is to be noted in the test report.

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