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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 des faisceaux laser — Stabilité de visée du faisceau

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Contents

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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.

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

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.

It is unlikely that the movement of a laser beam will 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 defines 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 testing and characterization of lasers.

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 — 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 International Standard, the terms and definitions found 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 stability
$\Delta_x(z')$, $\Delta_y(z')$
maximum transverse displacement and/or angular movement of the beam away from an average, steady-state position. The beam positional stability is determined by the movement of the centroid of the laser beam in the x'-y' plane at 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.

3.6
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

3.7
short-term stability
stability within a time interval of 1 s

3.8
medium-term stability
stability within a time interval of 1 min

3.9
long-term stability
stability within a time interval of 1 h

4 Coordinate systems and beam axis

4.1 Beam axis distribution

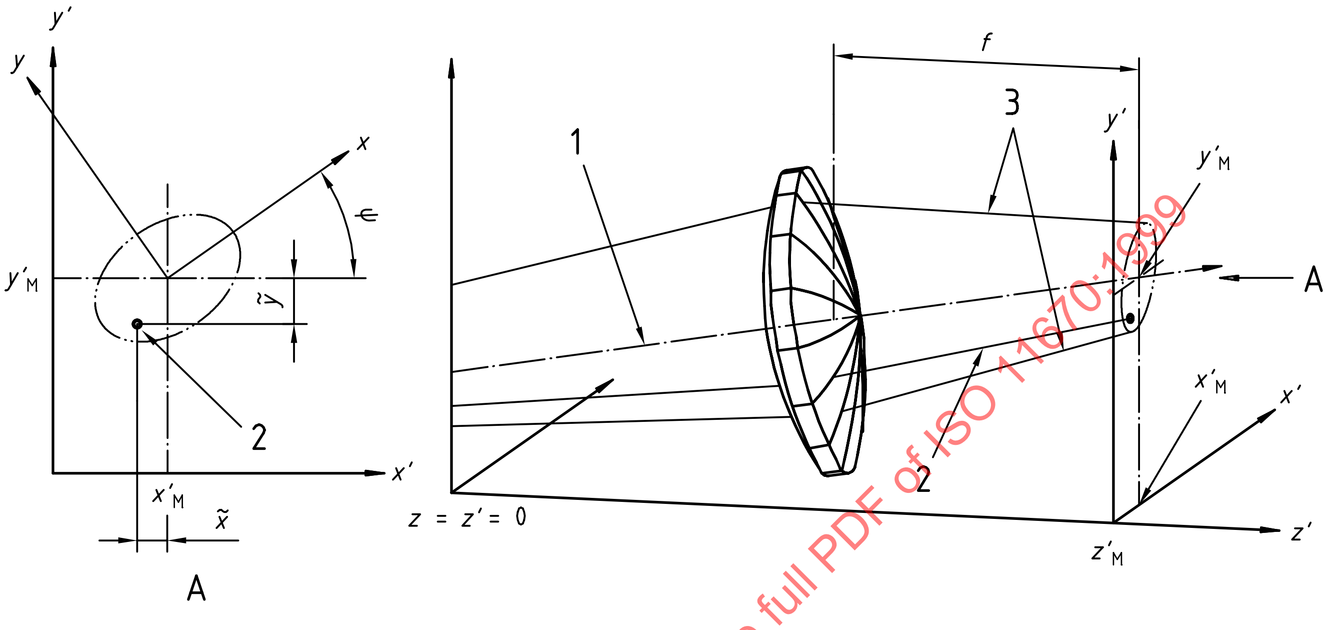
The distribution of the beam axes (as defined in ISO 11145) is obtained from a significant number ($n \geqslant 1\,000$) of measurements of the beam axis direction.

The movement of the beam axis can be described by means of the standard deviation of this beam axis distribution. This standard deviation can be different 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.



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 should not 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)

$$x'_M = \frac{\sum_i x'_i}{n} \tag{1}$$

$$y'_M = \frac{\sum_i y'_i}{n} \tag{2}$$

where i is 1 to n.

b) Second step (translation):

$$\tilde{x} = x' - x'_M \tag{3}$$

$$\tilde{y} = y' - y'_M \tag{4}$$

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

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

where

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

$$s_{\tilde{x}}^2 = \frac{\sum_i (x'_i - x'_M)^2}{n-1} \tag{7}$$

$$s_{\tilde{y}}^2 = \frac{\sum_i (y'_i - y'_M)^2}{n-1} \tag{8}$$

$$s_{\tilde{x}\tilde{y}}^2 = \frac{\sum_i (x'_i - x'_M)(y'_i - y'_M)}{n-1} \tag{9}$$

where i is 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 position of the beam axis in the laboratory x',y',z' system. The beam angular stability can be 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 should be coaxial. Suitable optical alignment devices are available for this purpose.

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 contribute an increase of less than 1 % to the anticipated probable 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.

Before measurements are started, the laser shall warm up for at least 1 h (if not otherwise stated by the manufacturer) to achieve thermal equilibrium.

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 % should 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 Detector 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 provisions of IEC 61040:1990 apply to the radiation detector system; clauses 3 and 4 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 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 the damage threshold (for irradiance, radiant exposure, power and energy) of the detector surface, so that it is not exceeded by the laser beam.

— When using a scanning device for determining the power density distribution function, care shall be taken to ensure that the laser output is spatially and temporally stable during the whole scanning period.

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

In case 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 conformance 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

Before the measurements are started, the laser shall warm up for at least 1 h (if not otherwise stated by the manufacturer) to achieve thermal equilibrium. 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 1000 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.

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 (for determination of short-term stability, see 3.7), 1 min (for determination of medium-term stability, see 3.8) or 1 h (for determination of long-term stability, see 3.9), 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 (for determination of short-term stability, see 3.7), 1 min (for determination of medium-term stability, see 3.8) or 1 h (for determination of long-term stability, see 3.9), 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

$$x'_i = \frac{\iint xE(x,y)\mathrm{d}x\,\mathrm{d}y}{E(x,y)\mathrm{d}x\,\mathrm{d}y} \tag{10}$$

$$y'_i = \frac{\iint yE(x,y)\mathrm{d}x\,\mathrm{d}y}{E(x,y)\mathrm{d}x\,\mathrm{d}y} \tag{11}$$

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 ($z' = z'_M$) are given by

$$x'_M = \frac{\sum_i x'_i}{n} \tag{12}$$

$$y'_M = \frac{\sum_i y'_i}{n} \tag{13}$$

where i is 1 to n ($n \geq 1000$).

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.

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

$$s_{\tilde{x}}^{\,2} = \frac{\sum_i (x'_i - x'_M)^2}{n-1} \tag{15}$$

$$s_{\tilde{y}}^{\,2} = \frac{\sum_i (y'_i - y'_M)^2}{n-1} \tag{16}$$

$$s_{\tilde{x}\tilde{y}}{}^2 = \frac{\sum_i (x'_i - x'_M)(y'_i - y'_M)}{n-1} \tag{17}$$

where i is 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

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

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

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

where

$$r_i^2 = x_i^2 + y_i^2$$

$$r_i^2 = (x'_i - x'_M)^2 + (y'_i - y'_M)^2$$

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

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

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

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

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

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

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

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

$$\zeta_{x'\mathrm{M}} = \frac{\sum_i \zeta_{xi'}}{n} \tag{29}$$

$$\zeta_{y'\mathrm{M}} = \frac{\sum_i \zeta_{yi'}}{n} \tag{30}$$

where i is 1 to n ($n \geq 1000$).

c) The $\zeta_{xi'}$ and $\zeta_{yi'}$ 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.

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

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

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

$$s_{\tilde{x}\tilde{y}}{}^2 = \frac{\sum_i \left(\zeta_{x'_i} - \zeta_{x'\mathrm{M}}\right)\left(\zeta_{y'_i} - \zeta_{y'\mathrm{M}}\right)}{n-1} \tag{34}$$

where i is 1 to n.

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

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

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

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

$$s_\zeta = \sqrt{\frac{\sum_i \zeta_i^{\,2}}{n-1}} \tag{37}$$

where

$$\zeta_i^{\,2} = \zeta_{x_i}^{\,2} + \zeta_{y_i}^{\,2}$$

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

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

$$\delta\alpha_x = \frac{2 s_{\zeta x}}{f} \tag{38}$$

$$\delta\alpha_y = \frac{2 s_{\zeta y}}{f} \tag{39}$$

$$\delta\alpha = \frac{\sqrt{2} s_\zeta}{f} \tag{40}$$

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

9 Test report

An example of a test report is given below.