INTERNATIONAL STANDARD

ISO 11146

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Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor

Lasers et équipements associés aux lasers — Méthodes d'essai des paramètres des faisceaux laser — Largeurs du faisceau, angle de divergence et facteur de propagation 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 11146 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

Annexes A and B form a normative part of this International Standard. Annex C is for information only.

Introduction

Any radially symmetric laser beam requires three parameters for characterization:

a) location of the beam waist z_0;

b) waist diameter $d_{\sigma 0}$; and

c) the far-field divergence angle Θ_σ for the beam under test.

With these three values, one can predict the beam diameter at any plane along the propagation axis. To a first approximation (for divergence angles less than 0,8 rad), the beam propagates as

$$d_\sigma{}^2(z) = d_{\sigma 0}{}^2 + (z - z_0)^2 \cdot \Theta_\sigma{}^2 \tag{1}$$

The beam propagates according to equation (1) provided the second moments of the power (energy) density distribution function are used for the definition of beam widths and divergences. The propagation is described by a beam propagation factor K or a times-diffraction-limit factor M^2 which can be derived from the above basic data. The relationship between K and M^2, respectively, the actual waist diameter $d_{\sigma 0}$ and the divergence angle Θ_σ, is:

$$K = \frac{1}{M^2} = \frac{4\lambda_0}{\pi} \cdot \frac{1}{n \cdot d_{\sigma 0} \cdot \Theta_\sigma} = \frac{4\lambda}{\pi} \cdot \frac{1}{d_{\sigma 0} \cdot \Theta_\sigma} \tag{2}$$

where

K is the beam propagation factor;

M^2 is the times-diffraction-limit factor;

λ_0 is the wavelength in vacuum ;

λ is the wavelength in medium with index of refraction n,

Θ_σ is the divergence angle,

$d_{\sigma 0}$ is the waist diameter,

n is the index of refraction.

NOTE 1 The accuracy of measurement of beam propagation factors is expected to be in the region of 10 %. It is not consistent with divergence angles (full angle according to ISO 11145) above 0,8 rad.

The product

$$n \cdot d_{\sigma 0} \cdot \Theta_\sigma = \frac{4\lambda_0}{K\pi} = \frac{M^2 4\lambda_0}{\pi} \tag{3}$$

describes the propagation of laser beams and is invariant throughout the propagation of the beam as long as aberration-free and non-aperturing optical systems are used.

For non-radially symmetric beams, the values of seven parameters are required for characterization:

— locations of the beam waists z_{0x} and z_{0y}

— waist widths $d_{\sigma 0x}$ and $d_{\sigma 0y}$;

— far-field divergence angles $\Theta_{\sigma x}$ and $\Theta_{\sigma y}$; and

— azimuth angle φ between the x-axis of the beam axes system and the x'-axis of the laboratory system. The x-axis of the beam axes system coincides with the principal axis of the laser beam closest (within ±45°) to the arbitrary x' coordinate.

In analogy to equation (3), the propagation of non-radially symmetric beams, which are however still characterizable using two principal axes orthogonal to each other, can be described independently for the x- and y-axes using K_x and K_y as beam propagation factors, or M_x^2 and M_y^2 as times-diffraction-limit factors, respectively.

NOTE 2 Beams that suffer from general astigmatism (twisted beams) require three additional parameters for their characterization. The propagation in the x-z plane is not necessarily independent of the propagation characteristics in the y-z plane and not necessarily along the propagation path will a generally astigmatic beam exhibit a circular power density distribution. The measurement of generally astigmatic beams is outside the scope of this International Standard.

In this International Standard, the second moments of the power (energy) density distribution function are used for the determination of beam widths. However, there may be problems experienced in the direct measurement of this property in the beams from some laser sources. In this case, other indirect methods of measurement of second moment may be used as long as comparable results are achievable.

In annex A, three alternative methods for beam width measurement and their correlation with the method used in this International Standard are described. These methods are:

- Variable aperture method
- Moving knife-edge method
- Moving slit method

The problem of the dependence of the measuring result on the truncation limits of the integration has been investigated and evaluated by an international round robin carried out in 1997. The results of this round robin testing were taken into consideration in this document.

Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor

1 Scope

This International Standard specifies methods for measuring beam widths (diameter), divergence angles and beam propagation factors of laser beams.

These methods may not apply to highly diffractive beams such as those produced by unstable resonators or passing through hard-edged apertures.

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.*

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 given in ISO 11145 and IEC 61040, and the following apply:

3.1
energy density
$H(x,y)$
that part of the beam energy which impinges on the area δA at the location x, y divided by the area δA

3.2
power density
$E(x,y)$
that part of the beam power which impinges on the area δA at the location x, y divided by the area δA

3.3
beam waist locations
z_0, z_{0x}, z_{0y}
positions where beam widths reach their minimum values along the axis of propagation

See Figure 1.

NOTE The locations are expressed as the distances to the beam waists (inside or outside the resonator) from a reference plane defined by the manufacturer e.g. the front of the laser enclosure.

3.4
beam diameter
d_σ

$$d_\sigma(z) = 2\sqrt{2}\,\sigma(z) \tag{4}$$

where the second moment of the power density distribution function $E(x, y, z)$ of the beam at the location z is given by

$$\sigma^2(z) = \frac{\iint r^2 E(r,z) r \mathrm{d}r \mathrm{d}\varphi}{\iint E(r,z) r \mathrm{d}r \mathrm{d}\varphi} \tag{5}$$

where r is the distance to the centroid $(\bar{x}, \bar{y})$

and where the first moments give the coordinates of the centroid, i. e.

$$\bar{x} = \frac{\iint x E(x, y, z) \mathrm{d}x \mathrm{d}y}{\iint E(x, y, z) \mathrm{d}x \mathrm{d}y} \tag{6}$$

$$\bar{y} = \frac{\iint y E(x,y,z) \mathrm{d}x \mathrm{d}y}{\iint E(x,y,z) \mathrm{d}x \mathrm{d}y} \tag{7}$$

NOTE 1 In principle, integration is carried out over the whole x-y plane. In practice, the integration is performed over an area such that at least 99 % of the beam power (energy) is captured. Refer to practical limits in 6.4.

NOTE 2 The power density E is replaced by the energy density H for pulsed lasers.

NOTE 3 This definition differs from that given in ISO 11145:1994, for the reason that only beam propagation factors based on beam widths and divergence angles derived from the second moments of the power (energy) density distribution function allow calculation of the beam propagation. Other definitions of beam widths and divergence angles may be helpful for other applications, but must be shown to be equivalent to the second-order moment definition to be used for calculating the correct beam propagation.

3.5
beam widths
$d_{\sigma x}$; $d_{\sigma y}$

$$d_{\sigma x}(z) = 4\sigma_x(z) \tag{8}$$

$$d_{\sigma y}(z) = 4\sigma_y(z) \tag{9}$$

where the second moments of the power density distribution function $E(x, y, z)$ of the beam at the location z are given by

$$\sigma_x{}^2(z) = \frac{\iint (x-\bar{x})^2 E(x,y,z) \mathrm{d}x \mathrm{d}y}{\iint E(x,y,z) \mathrm{d}x \mathrm{d}y} \tag{10}$$

$$\sigma_y{}^2(z) = \frac{\iint (y-\bar{y})^2 E(x,y,z) \mathrm{d}x \mathrm{d}y}{\iint E(x,y,z) \mathrm{d}x \mathrm{d}y} \tag{11}$$

where $(x-\bar{x})$ and $(y-\bar{y})$ are the distances to the centroid $(\bar{x}, \bar{y})$

and where the first moments give the coordinates of the centroid, i. e.

$$\bar{x} = \frac{\iint x E(x,y,z)\mathrm{d}x\mathrm{d}y}{\iint E(x,y,z)\mathrm{d}x\mathrm{d}y} \tag{12}$$

$$\bar{y} = \frac{\iint y E(x,y,z)\mathrm{d}x\mathrm{d}y}{\iint E(x,y,z)\mathrm{d}x\mathrm{d}y} \tag{13}$$

NOTE 1 In principle, integration is carried out over the whole x-y plane. In practice, the integration is performed over an area such that at least 99 % of the beam power (energy) is captured. Refer to practical limits in 6.4.

NOTE 2 The power density E is replaced by the energy density H for pulsed lasers.

NOTE 3 This definition differs from that given in ISO 11145:1994, for the reason that only beam propagation factors based on beam widths and divergence angles derived from the second moments of the power (energy) density distribution function allow calculation of the beam propagation. Other definitions of beam widths and divergence angles may be helpful for other applications, but must be shown to be equivalent to the second-order moment definition to be used for calculating the correct beam propagation.

3.6
times-diffraction-limit factor
M^2
measure of how close the beam parameter product is to the diffraction limit of a perfect Gaussian beam

$$M^2 = \frac{\pi}{\lambda} \cdot \frac{d_{\sigma 0}\Theta_\sigma}{4} \tag{14}$$

4 Coordinate systems

4.1 General

The x, y and z 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 manufacturer, e.g. the front of the laser enclosure.

For elliptical beams, the principal planes of propagation, defined as xz and yz, are the planes containing the major and the minor axes, respectively, of the ellipse. See figure 1.

If the principle planes of propagation do not coincide with the $x'z$ and $y'z$ planes of the laboratory system x', y', z, then one of two equivalent procedures can be chosen:

4.2 Description in the beam axis system

If the azimuth of the beam axis system relative to the laboratory system is known, then the beam parameters can be measured directly in the beam axis system and the azimuth angle recorded with those measurements.

4.3 Description in the laboratory system

If the principal axes of the beam are not known, they can be determined by measuring the two second moments $\sigma_{x'}{}^2$, $\sigma_{y'}{}^2$ and the mixed moment $\sigma_{x'y'}{}^2$ of the beam distribution in the laboratory system. It is then possible to calculate the second moments in the beam axis system **and** the azimuth angle φ between the two systems.

The mixed moment is given by

$$\sigma_{x'y'}{}^2(z) = \frac{\iint (x'-\bar{x}')(y'-\bar{y}')E(x',y',z)\mathrm{d}x'\mathrm{d}y'}{\iint E(x',y',z)\mathrm{d}x'\mathrm{d}y'} \tag{15}$$

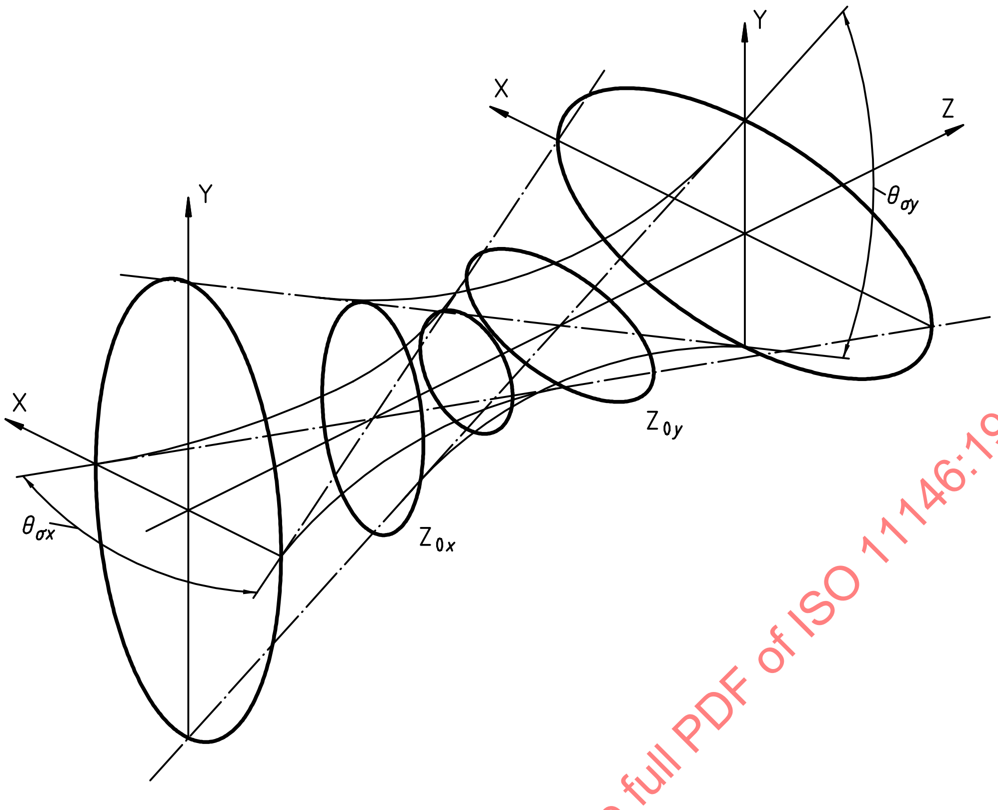


Figure 1 — Coordinates in the beam axis system

5 Test principles

5.1 Beam widths and beam diameter

For the determination of beam widths or diameter at location z, the power (energy) density distribution function of the laser beam shall be determined in the $x'y'$ plane at the location z. Additionally, the azimuth angle φ shall be determined.

From the measured cross-sectional distribution function, the first spatial moments $\bar{x},\bar{y}$ containing the beam axis are determined. In a second step, the second moments σ_x^2, σ_y^2 or σ^2 as well as the beam widths $d_{\sigma x}$, $d_{\sigma y}$ or the beam diameter d_σ are calculated. See equations (4) to (7) and (8) to (13), respectively.

5.2 Divergence angles

The determination of the divergence angles follows from measurements of the beam widths or the beam diameter:

First, the laser beam shall be transformed by an aberration-free focusing element. The beam diameter $d_{\sigma f}$ is then measured one focal length f away from the rear principal plane of the focusing element. The divergence angle of the laser beam before the focusing element is determined using the relationship

$$\Theta_\sigma = \frac{d_{\sigma f}}{f} \tag{16}$$

For non-radially symmetric beams, the divergence angles $\theta_{\sigma x}$ or $\theta_{\sigma y}$ in the xz or yz planes are determined by using the beam widths instead of the beam diameter.

5.3 Beam propagation factor and times-diffraction-limit factor, respectively

For the determination of the beam propagation factors K_x, K_y or K and the times-diffraction-limit factors M_x^2, M_y^2 or M^2, respectively, it is necessary to determine the waist widths $d_{\sigma 0x}$, $d_{\sigma 0y}$ or the waist diameter $d_{\sigma 0}$ and the related beam divergence angles $\theta_{\sigma x}$, $\theta_{\sigma y}$ or θ_{σ}.

5.4 Beam waist location, combined measurement of beam widths, beam divergence angle and beam propagation factor or times-diffraction-limit factor

For determination of the waist location the beam widths, data along the propagation axis shall be fit to a hyperbola as discussed in clause 9.

The other beam parameters can also be determined by this method.

6 Measurement arrangement and test equipment

6.1 General

The test is based on the measurement of the cross-sectional power (energy) density distribution function of the entire laser beam.

6.2 Preparation

The optical axis of the measuring system should be coaxial with the laser beam to be measured. Suitable optical alignment devices are available for this purpose (e.g. aligning lasers or steering mirrors).

The aperture of the optical system shall accommodate the entire cross-section of the laser beam. Clipping shall be smaller than 1 % of the total beam power or energy.

The attenuators or beam-forming optics shall be mounted such that the optical axis runs through the geometrical centres. Care should be taken to avoid systematic errors. Reflections, interference effects, external ambient light, thermal radiation or air draughts are all potential sources of error.

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 widths 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.

6.3 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 of the parameter to be measured is low.

Care should be taken to ensure that the atmospheric environment in high-power laser beam paths does not contain gases or vapours that can absorb the laser radiation and cause thermal distortion in the beam to be assessed.

6.4 Detector system

Measurement of the cross-sectional power (energy) density distribution function requires the use of a power (energy) meter with high spatial resolution and high signal-to-noise-ratio.

The accuracy of the measurement is directly related to the spatial resolution of the detector system and its signal-to-noise ratio. The latter is important for laser beams with low power (energy) densities at larger diameters (e.g. for diffracted parts of the laser beams).

In practice, noise in the wings of the density distribution function [either $E(x,y,z)$ or $H(x,y,z)$] may readily dominate the second moment integral. Thus it is usually necessary to subtract a background map (the detector response with the beam blocked) from the signal map in determining the experimental distribution function.

NOTE For example, consider calculating the second moment of a Gaussian beam at diameter $2w$. Truncating the integration at r/w = 1,9 clips off only 0,5 % of the value of the second moment. Assuming a 0,8 % peak-to-peak amplitude noise to simulate the real experimental profile, truncation within these limits is required to be reasonably assured of a ± 5 % uncertainty in the measured second moment.

The smallest spatial structures which are to be resolved should be sampled more than twice (sampling theorem). Therefore the detector resolution necessary for the measurement is directly correlated to the structures of the beam to be measured.

The provisions of IEC 61040:1990 apply to the radiation detector system; clauses 3 and 4 are particularly important. Furthermore, the following points should be noted.

— It shall be confirmed, from manufacturers' data or by measurement, that the output quantity of the detector system (e.g. the 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 thresholds of the detector surface so that they are 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.

— When measuring pulsed laser beams, the trigger time delay of sampling as well as the measuring time interval play an important role because the beam parameters may change during the pulse. Therefore it is necessary to specify these parameters in the test report.

6.5 Beam-forming optics and optical attenuators

If the beam cross-sectional area is greater than the detector area, a suitable optical system shall be used to reduce the beam cross-sectional area on the detector surface. The change in magnification shall be taken into account during the evaluation procedure.

Optics shall be selected appropriate to wavelength.

An attenuator may be required to reduce the laser power density at the surface of the detector.

Optical attenuators shall be used when the laser output-power or power density exceeds the detector's working (linear) range or the damage threshold. Any wavelength, polarization and angular dependency, non-linearity or non-uniformity, including thermal effects 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.

6.6 Focusing system

The focusing system for the divergence angle measurement shall conform with the requirements relating to the beam-forming optics given in 6.5. The total error contributed by the focusing system shall be less than 1 % of the beam width.

7 Beam widths and beam diameter measurement

7.1 Test procedure

Before the measurements are started, the laser shall warm up for at least 1 h (unless otherwise stated by the manufacturer) to achieve thermal equilibrium. The measurements shall be carried out at the operating conditions specified by the laser manufacturer for the type of laser being evaluated.

Repeat at least five times the measurement of the cross-sectional power (energy) density distribution function at each location z at which the beam widths are determined.

7.2 Evaluation

The following calculations are carried out using equations (4) to (7) and (15), given in 3.4 and 4.3.

Calculate the first moments of the power (energy) density distributions.

In the next step, calculate the second moments $\sigma_{x'}{}^2$ and $\sigma_{y'}{}^2$ as well as $\sigma_{x'y'}{}^2$ for each measurement.

Calculate the azimuth angle φ and the beam widths $d_{\sigma x}$ and $d_{\sigma y}$ using equations (17) to (20):

$$\varphi = \frac{1}{2}\arctan\left(2\sigma_{x'y'}{}^2 / (\sigma_{x'}{}^2 - \sigma_{y'}{}^2)\right) \tag{17}$$

$$d_{\sigma x}(z) = 4\sigma_x(z) = 2\sqrt{2}\left\{\left(\sigma_{x'}{}^2 + \sigma_{y'}{}^2\right) + \varepsilon\left[\left(\sigma_{x'}{}^2 - \sigma_{y'}{}^2\right)^2 + 4\,\sigma_{x'y'}{}^4\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{18}$$

$$d_{\sigma y}(z) = 4\sigma_y(z) = 2\sqrt{2}\left\{\left(\sigma_{x'}{}^2 + \sigma_{y'}{}^2\right) - \varepsilon\left[\left(\sigma_{x'}{}^2 - \sigma_{y'}{}^2\right)^2 + 4\,\sigma_{x'y'}{}^4\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \tag{19}$$

where

$$\varepsilon = \mathrm{sgn}\ (\sigma_{x'}{}^2 - \sigma_{y'}{}^2) = \frac{\sigma_{x'}{}^2 - \sigma_{y'}{}^2}{\left|\sigma_{x'}{}^2 - \sigma_{y'}{}^2\right|} \tag{20}$$

Perform these calculations for each measurement and calculate the mean values and the standard deviations for the beam widths and the azimuth angle.

If the ratio $d_{\sigma x}/d_{\sigma y}$ is smaller than 1,15:1, the beam may be considered circular at that measuring location and the equations for circular beams may be used (see 3.5).

8 Divergence angle measurement

8.1 Test procedure

Locate the focusing element in the beam path in such a way that its optical axis is coaxial with the laser beam to be measured.

Locate the measuring plane of the detector system one focal length away from the rear principal plane of the focusing element.

NOTE In general, this location is not identical with the waist location behind the focusing element.

Perform at least five measurements of the beam widths $d_{\sigma fx}$, $d_{\sigma fy}$ or the beam diameter $d_{\sigma f}$ at that location in accordance with clause 7.

8.2 Evaluation

NOTE The following equations are given explicitly only for the radially symmetric case, but equivalent expressions for the x and y parameters of non-circular beams are given in annex B.

Calculate the far-field divergence angle(s) of the unfocused beam according to

$$\Theta_\sigma = \frac{d_{\sigma f}}{f} \tag{21}$$

where

$d_{\sigma f}$ is the beam diameter one focal length away from the focusing element;

f is the focal length of the focusing element.

for each measurement and calculate the mean value(s) and the standard deviation(s) for the divergence angle(s).

9 Combined determination of laser beam propagation parameters

If the beam waist is accessible for direct measurement, the beam waist location and the standard deviation shall be determined by a hyperbolic fit to different measurements of the beam width along the propagation axis z. For this, at least 10 measurements shall be taken. Approximately half of the measurements shall be distributed within one Rayleigh length on either side of the beam waist, and approximately half of them shall be distributed beyond two Rayleigh lengths from the beam waist.

The hyperbolic fit to the measured diameters along the propagation can be expressed in the following way (for the equations given, see note in 8.2):

$$d_\sigma{}^2 = A + B \cdot z + C \cdot z^2 \tag{22}$$

When the coefficients A, B, C (or A_x, A_y, B_x, B_y, C_x, C_y; see annex B), of the hyperbola(e) have been found by appropriate numerical or statistical curve-fitting techniques (see note), the values of the beam waist diameter or widths and location(s) can be determined using:

$$z_0 = \frac{-B}{2C} \tag{23}$$

$$d_{\sigma 0} = \sqrt{A - \frac{B^2}{4C}} \tag{24}$$

NOTE It is advisable to weight the data points inversely proportional to the variance of the data points.

If the beam waist is not accessible for direct measurement, the same procedure shall be applied to an artificial waist created by using an aberration-free focusing element as defined in 6.6. According to Figure 2, the distance l from the focusing element to the reference plane, as well as the distances s_2 or s_{2x} and s_{2y} from the artificial waist to the rear principal plane of the focusing element, shall be determined. In addition, the beam widths $d_{\sigma 2}$ or $d_{\sigma 2x}$ and $d_{\sigma 2y}$ shall be determined at the artificial waist. From these data the waist location(s) of the original beam can be calculated using

$$z_0 = l - s_1 \tag{25}$$

(Symbols according to Figure 2.)

where s_1 (or s_{1x} and s_{1y}, see annex B) is determined using

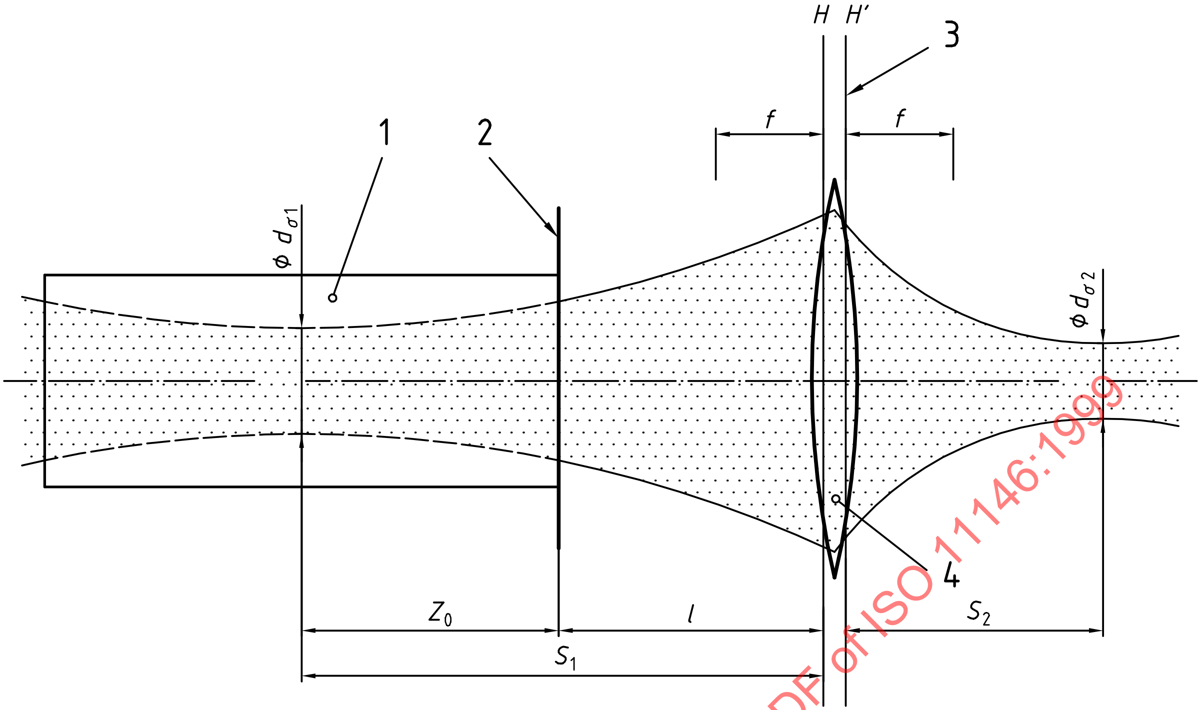
$$s_1 = \frac{f \cdot s_2 (s_2 - f) + f \cdot z_{R2}{}^2}{s_2{}^2 - 2 \cdot f \cdot s_2 + f^2 + z_{R2}{}^2} \tag{26}$$

and where

f is the focal length of the lens;

z_{R2} is the Rayleigh length of the artificial beam waist.

The Rayleigh length of the artificial waist z_{R2} can be determined by using the equations for the hyperbolic fit procedure (see clause 10).



Key

1 Laser
2 Reference plane
3 Rear principal plane
4 Focusing element

Figure 2 — Scheme for calculation of beam waist location(s)

The beam waist diameter or widths can be calculated in the following way (using the relationship $d_{\sigma 2} = V \cdot d_{\sigma 1}$, where V is the magnification):

$$d_{\sigma 1} = \frac{1}{V} d_{\sigma 2} \tag{27}$$

If s_1, s_{1x} or s_{1y} equal(s) f (the focal length of the lens), then:

$$V = \frac{z_{R2}}{f} \tag{28}$$

otherwise:

$$V = \left[\frac{f^2 + (f^4 - 4z_{R2}{}^2 \cdot (s_1 - f)^2)^{\frac{1}{2}}}{2 \cdot (s_1 - f)^2} \right]^{\frac{1}{2}} \tag{29}$$

10 Determination of beam propagation factor and times-diffraction-limit factor

As outlined in 5.3, it is necessary when determining the beam propagation factor K and the times-diffraction-limit factor M^2 to measure the beam waist widths or the beam waist diameter according to clause 7 and the related beam divergence angles according to clause 8. For the equations given see note in 8.2.

It is very important that the measurement(s) of the divergence angle(s) has to be performed for the same part of the beam for which the beam waist width is measured.

If the beam waist is not accessible directly, an artificial waist shall be created using an aberration-free focusing element, as defined in 6.6, and the measurements of the beam waist width(s) and the beam divergence angle(s) shall be performed for that part of the beam.

From these measurements, the beam propagation factor can be calculated using

$$K = \frac{1}{M^2} = \frac{4\lambda}{\pi} \cdot \frac{1}{d_{\sigma 0} \cdot \Theta_\sigma} \tag{30}$$

Using the standard deviations of the measurements of the beam waist widths and divergence angles, the standard deviation of the beam propagation factor shall be determined.

NOTE The waist location determination process described in clause 9 can also be used to determine the beam propagation factor and the times-diffraction-limit factor, respectively. The hyperbola-fitting process described there will reveal directly the beam waist widths as well as the propagation factors (times-diffraction-limit factors).

The hyperbolic fit to the measured diameters along the propagation can be expressed in the following way:

$$d_\sigma{}^2 = A + B \cdot z + C \cdot z^2 \tag{31}$$

When the coefficients A, B and C of the hyperbola have been found by appropriate numerical or statistical curve-fitting techniques (see note in clause 9), the values of the beam waist diameter and location, as well as the relevant beam propagation factor or times-diffraction-limit factor, can be determined using:

$$z_0 = \frac{-B}{2C} \tag{32}$$

$$d_{\sigma 0} = \sqrt{A - \frac{B^2}{4 \cdot C}} \tag{33}$$

and

$$K = \frac{1}{M^2} = \frac{4\lambda}{\pi} \cdot \frac{1}{\sqrt{A \cdot C - \frac{B^2}{4}}} \tag{34}$$

$$\Theta = \sqrt{C} \tag{35}$$

$$z_R = \frac{1}{C}\sqrt{A \cdot C - \frac{B^2}{4}} \tag{36}$$

11 Test report

a) Date ______________________ Name of tester __________________________

Name of test organization ____

b) Laser type _________________ Manufacturer ___________________________

Model ______________________ Serial # ________________________________

c) Wavelength ________________ Polarization ____________________________

Power or energy output ____

Current or energy input ____

Aperture setting _____________ Pulse repetition rate _____________________

Trigger time delay of sampling (for pulsed lasers only) _______________________

Measuring time interval (for pulsed lasers only) _____________________________

d) Other information ____

e) Reference plane chosen ____

f) Laboratory system x', y', z chosen ___________________________________

g) Test method used

Second moment ☐

Variable aperture ☐

Moving knife-edge ☐

Moving slit ☐

h) Azimuth angle φ ____

i) Beam widths or beam diameter (according to clause 7)

	Mean value	Standard deviation
Location z		
Beam diameter d_σ		
Beam width $d_{\sigma x}$		
Beam width $d_{\sigma y}$		

j) Divergence angle (according to clause 8)

Focusing element used ______________________________

Focal length ______________________________

	Mean value	Standard deviation
Divergence angle θ_σ		
Divergence angle $\theta_{\sigma x}$		
Divergence angle $\theta_{\sigma y}$		

k) Beam propagation parameters derived from hyperbolic fit (according to clauses 9 and 10)

	Mean value	Standard deviation
Waist location z_0		
Waist location z_{0x}		
Waist location z_{0y}		
Waist diameter d_0		
Waist width d_{0x}		
Waist width d_{0y}		
Divergence angle θ_σ		
Divergence angle $\theta_{\sigma x}$		
Divergence angle $\theta_{\sigma y}$		
☐ Beam propagation factor K ☐ Times-diffraction-limit factor M^2		

☐ Beam propagation factor K_x ☐ Times-diffraction-limit factor $M_x{}^2$		
☐ Beam propagation factor K_y ☐ Times-diffraction-limit factor $M_y{}^2$		

Annex A
(normative)

Alternative methods for beam width measurements

A.1 Introduction

If measurement equipment with sufficently high signal-to-noise ratio and a simultaneously high spatial resolution is not available, alternative methods, described in this annex, may be used. These methods allow measurement of beam width or beam diameter, with an accuracy which is acceptable in many cases, using rather simple equipment.

The methods described in this annex are not based on the determination of the second moments of the spatial power (energy) distribution function which is necessary in order to obtain a consistent propagation formalism.

It has been demonstrated, however, that at least for several cases (see note) there exists a correlation between the beam propagation factors and the times-diffraction-limit factors, respectively, determined with one of the alternative methods and the results of the method described in this International Standard.

This can be written as:

$$\frac{1}{\sqrt{K_\sigma}} = M_\sigma = c_i(M_i - 1) + 1 = c_i\left(\frac{1}{\sqrt{K_i}} - 1\right) + 1 \qquad \text{(A.1)}$$

where

K_i is the beam propagation factor according to alternative method i ;

M_i is the square root of the times-diffraction-limit factor according to alternative method i ;

c_i is the correlation factor (see below) between alternative method i and the standard method.

Alternative method	c_i
Variable aperture	1,14
Moving knife-edge	0,81
Moving slit	0,95

NOTE These c_i were verified for gas laser beams with stable resonator geometries and power up to 10 W (and for CO_2 laser beams up to 1 kW) and with M^2 up to $M^2 = 4$, for radially symmetric beams. For higher M^2 values and other types of lasers, the correlation factors need to be verified.

From this relationship between the beam propagation factors or the times-diffraction-limit factors, a K- or M^2-dependent correlation factor can be derived for the determination of the beam diameters (widths).

$$d_\sigma = d_i\sqrt{K_i}\left[c_i\left(\frac{1}{\sqrt{K_i}} - 1\right) + 1\right] \qquad \text{(A.2)}$$

or

$$d_\sigma = \frac{d_i}{M_i}\left[c_i\left(M_i - 1\right) + 1\right] \quad \text{(A.3)}$$

where d_i is the beam diameter or beam width according to alternative method i

A.2, A.3 and A.4 describe three alternative methods:

— Variable aperture method

— Moving knife-edge method

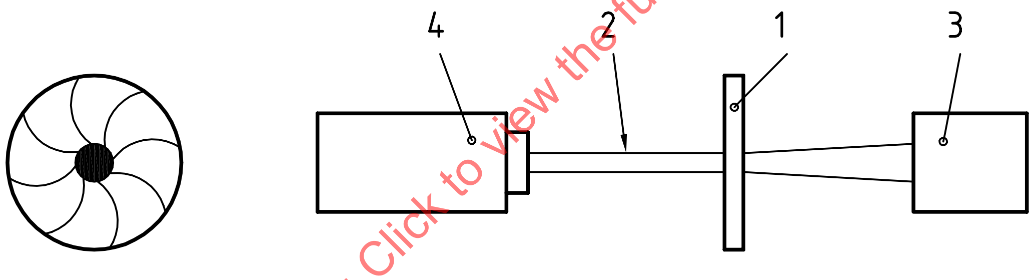
— Moving slit method

A.2 Variable aperture method

A.2.1 Test principle

A variable diaphragm located at the plane of measurement is used to determine the fraction of transmitted power (energy) as a function of the diameter of the aperture (compare Figure A.1). The uncorrected diameter of the beam is defined by the minimum aperture diameter which allows transmission of 86,5 % of the total beam power (energy). The beam diameter can be calculated using the equation given in A.2.5.

This method can only be used for beams with a ratio of principal axes not exceeding 1,15:1.



a) Axis (cut-away) view (detector side) **b) Top view**

Key

1 Variable diaphragm
2 Beam
3 Detector
4 Laser

Figure A.1 — Configuration for measuring variable-aperture beam width

A.2.2 Detector

The provisions of IEC 61040:1990 apply to the radiation detector; clauses 3 and 4 are particularly important. Furthermore, the following points should be noted.

— It shall be confirmed, from manufacturers' data or by measurement, that the output quantity of the detector system (e.g. the 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 thresholds (for irradiance, radiant exposure, power and energy) of the detector surface so that it is not exceeded by the laser beam.

— Sensitivity shall be uniform across the detector surface, and the detector shall not be sensitive to beam position within the measurement clear aperture.

— The detector size shall be chosen so that more than 99 % of the total laser power (energy) is captured by the detector.

A.2.3 Diaphragms/apertures

Select round diaphragms with diameters in steps such that the transmitted power (energy) is reduced by less than 5 % when changing from one size to the next.

Alternatively, it is permissible to use a variable diaphragm (iris) with calibrated aperture settings.

Diaphragms shall be constructed to maintain geometric shape during operation and absorption of the beam energy (may be water-cooled, reflective or use attenuation as in 6.5). For configuration, see Figure A.1.

A.2.4 Test procedure

Align the detector such that its measurement aperture is centred on the optical axis of the beam to be measured to at least 0,1 times the width to be measured (with its principal plane perpendicular to the propagation axis). Centring procedure: Reduce aperture to approximately 80 % power (energy) transmission and move aperture to maximum power (energy) transmission.

Verify that total beam power is incident on the detector surface. (Introduce a diaphragm coaxial to the beam at the detector surface, such that it covers or occludes the outer 30 % of the detector area. No measurable change in detected power should occur).

Record total power (P_0) or energy (Q_0).

Decrease aperture size in steps which cause 5 % or less decrease in detected power. Record at least the next aperture size greater (d_1) and the next aperture size smaller (d_2) than the aperture at the point at which power is reduced to 86,5 % of the original total power reading. At each of these size settings, record the respective power (P_1, P_2) or energy (Q_1, Q_2) readings.

A.2.5 Evaluation

Calculate the uncorrected beam diameter $d_{86,5}$ by linear interpolation between the known size apertures at the corresponding power (energy) level points above and below 86,5 % total power (energy).

$$d_{86.5} = d_1 + \left[\left(P_{86.5} - P_1 \right) \cdot \left(d_2 - d_1 \right) / \left(P_2 - P_1 \right) \right] \tag{A.4}$$

Calculate the corresponding d_σ by using the equation

$$d_\sigma = d_{86.5} \frac{1}{M_{86.5}} \left[1{,}14 \left(M_{86.5} - 1 \right) + 1 \right] \tag{A.5}$$

or

$$d_\sigma = d_{86.5} \sqrt{K_{86.5}} \left(1{,}14 \left(\frac{1}{\sqrt{K_{86.5}}} - 1 \right) + 1 \right) \tag{A.6}$$

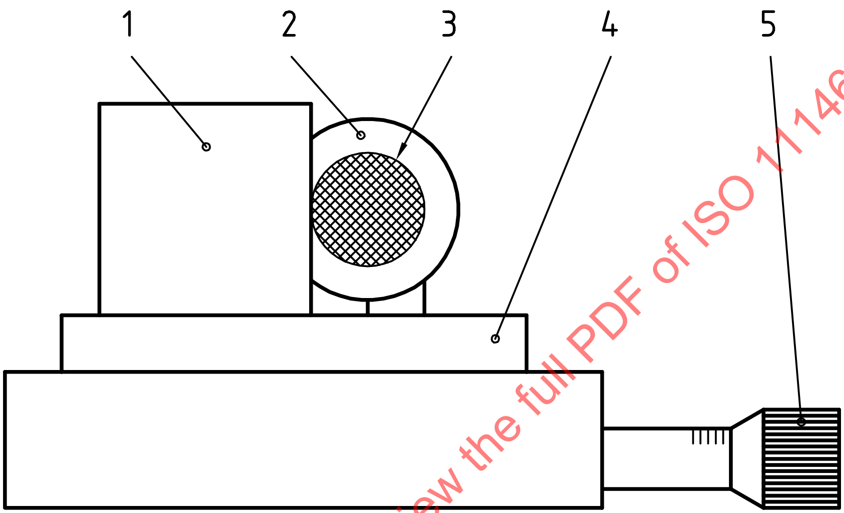
For limitations see note in A.1.

A.3 Moving knife-edge method

A.3.1 Test principle

A moving knife-edge is used to cut the beam in front of a fixed large-area detector so that the detector measures the transmitted power (energy) as a function of the edge position (see Figure A.2). The uncorrected beam width is given by twice the distance of the two knife-edge locations which are determined by 84 % and 16 % power (energy) transmission. The beam width can be calculated using the equations given in A.3.4.

When dealing with elliptical beams, the moving direction of the knife-edge shall be chosen to coincide with the two principal beam axes.



Key

1 Knife-edge

2 Photo cell collector

3 Beam

4 Translation stage

5 Micrometer

Figure A.2 — Configuration for measuring moving knife-edge beam width

A.3.2 Detector system

The requirements given in A.2.2 apply. The length of the knife-edge shall be chosen such that it covers at least the diameter of the sensitive detector area.

A.3.3 Test procedure for radially symmetric beams

The procedure for measuring width of radially symmetric beams is as follows.

Record the beam power (energy) with the knife-edge well out of the beam.

Move the translation stage until the x-axis knife-edge reduces the power (energy) transmitted to the power (energy) meter to 84 % of the initial power (energy) and record the position of the translation stage (x_1).

Continue moving the translation stage until only 16 % of the initial beam power (energy) is transmitted to the power (energy) meter and record the location of the translation stage (x_2).

A.3.4 Evaluation

Compute the uncorrected beam width d_k at this location according to equation (A.7):

$$d_k = 2 \cdot (x_2 - x_1) \tag{A.7}$$

where $(x_2 - x_1)$ is the absolute value of the difference in translation stage position readings.

Calculate the corresponding d_σ according to equation (A.8) or (A.9):

$$d_\sigma = d_k \cdot \frac{1}{M_k} \left[0{,}81 \left(M_k - 1 \right) + 1 \right] \tag{A.8}$$

or

$$d_\sigma = d_k \sqrt{K_k} \left[0{,}81 \left(\frac{1}{\sqrt{K_k}} - 1 \right) + 1 \right] \tag{A.9}$$

For limitations see note in A.1.

A.3.5 Test procedure for non-radially symmetric beams

Two measurements moving the knife-edge along the principal axes are necessary to obtain the beam widths $d_{\sigma x}$ and $d_{\sigma y}$ The procedure and evaluation are the same as given in A.3.3 and A.3.4.

The principal axes can be determined as follows:

a) Determine two orthogonal moving directions for which the uncorrected beam widths are equal.

b) Rotate these two directions by 45° to yield the principal axes.

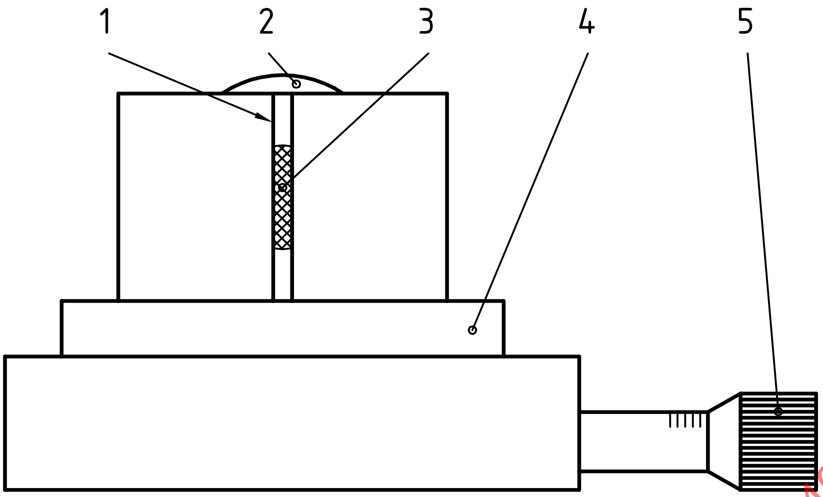
A.4 Moving slit method

A.4.1 Test principle

A slit mounted on a translation stage is used to cut the beam in front of a fixed large-area detector so that the detector measures the transmitted power (energy) as a function of the slit position (see Figure A.3). The uncorrected beam width is given by the distance of the two slit positions where the power (energy) is 13,5 % of the maximum transmitted power. The beam width can be calculated using the equations given in A.4.5.

When dealing with elliptical beams the moving direction of the slit shall be chosen to coincide with the two principle beam axes.

NOTE By using a strip detector, and moving the slit and detector together, very consistent results can be obtained on larger diameter beams.



Key

1 Moving slit
2 Photo cell collector
3 Beam
4 Translation stage
5 Micrometer

Figure A.3 — Moving slit beam-width measuring setup

A.4.2 Detector system

The requirements given in A.2.2 apply. The length of the slit shall be chosen such that it covers at least the diameter of the sensitive detector area.

A.4.3 Slit

The slit length to be used shall be not less than two times greater than the approximate beam width to be measured.

The slit width to be used shall be not more than 1/20 the approximated beam width to be measured.

A.4.4 Test procedure for radially symmetric beams

Position the slit through (perpendicular to the propagation axis of) the beam such that maximum total power (energy) is transmitted through the opening to the detector. Record this as reading 1.

Translate the slit laterally such that it allows only 13,5 % of the total (reading 1, above) power (energy) to pass, at one edge of the beam. Record the position (x_1) of the slit.

Translate the slit laterally in the opposing direction, such that it allows only 13,5 % of the total transmitted power (energy) to pass at the opposing edge of the beam. Record the location (x_2) of the slit.

A.4.5 Evaluation

The distance between the positions ($x_2 - x_1$) is the uncorrected beam width d_S.

Calculate the corresponding d_σ by using the equation

$$d_\sigma = d_S \cdot \frac{1}{M_S}\left[0{,}95\left(M_S - 1\right) + 1\right] \tag{A.10}$$

or

$$d_\sigma = d_S\sqrt{K_S}\left[0{,}95\left(\frac{1}{\sqrt{K_S}}-1\right)+1\right] \tag{A.11}$$

For limitations see note in A.1

A.4.6 Test procedure for non-radially symmetric beams

Two measurements moving the slit along the principal axes are necessary to obtain the beam widths $d_{\sigma x}$ and $d_{\sigma y}$.The procedure and evaluation are the same as given in A.4.4 and A.4.5.

The principal axes can be determined as follows.

a) Determine two orthogonal moving directions for which the uncorrected beam widths are equal.

b) Rotate these two directions by 45° to yield the principal axes.

Annex B
(normative)

Equations for non-circular beams

In the normative text of this International Standard, only the equations for the radially symmetric case are given. The equivalent expressions for the x and y parameters of non-circular beams are contained in this annex.

Referring to clause 8:

$$\Theta_{\sigma x} = \frac{d_{\sigma f x}}{f} \quad \text{(B.1)}$$

$$\Theta_{\sigma y} = \frac{d_{\sigma f y}}{f} \quad \text{(B.2)}$$

where $d_{\sigma f x}$, $d_{\sigma f y}$ are the beam widths one focal length away from the focusing element.

Referring to clause 9:

$$d_{\sigma x}{}^2 = A_x + B_x \cdot z + C_x \cdot z^2 \quad \text{(B.3)}$$

$$d_{\sigma y}{}^2 = A_y + B_y \cdot z + C_y \cdot z^2 \quad \text{(B.4)}$$

$$z_{0x} = \frac{-B_x}{2C_x} \quad \text{(B.5)}$$

$$z_{0y} = \frac{-B_y}{2C_y} \quad \text{(B.6)}$$

$$d_{\sigma 0x} = \sqrt{A_x - \frac{B_x{}^2}{4C_x}} \quad \text{(B.7)}$$

$$d_{\sigma 0y} = \sqrt{A_y - \frac{B_y{}^2}{4C_y}} \quad \text{(B.8)}$$

$$z_{0x} = l - s_{1x} \quad \text{(B.9)}$$

$$z_{0y} = l - s_{1y} \quad \text{(B.10)}$$

$$s_{1x} = \frac{f \cdot s_{2x}(s_{2x} - f) + f \cdot z_{\mathrm{R}x2}{}^2}{s_{2x}{}^2 - 2 \cdot f \cdot s_{2x} + f^2 + z_{\mathrm{R}x2}{}^2} \quad \text{(B.11)}$$

$$s_{1y} = \frac{f \cdot s_{2y}(s_{2y} - f) + f \cdot z_{\mathrm{R}y2}{}^2}{s_{2y}{}^2 - 2 \cdot f \cdot s_{2y} + f^2 + z_{\mathrm{R}y2}{}^2} \quad \text{(B.12)}$$