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Laser Beam Control and Applications

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Comparison of different beam diameter definitions to characterise thermal damage of the eye

Karl Schulmeister*, Reinhard Gilber, Florian Edthofer, Bernhard Seiser and Georg Vees
ARC Seibersdorf research, A-2444 Seibersdorf, Austria

ABSTRACT

To assign a diameter to a beam profile which does not feature an actual perimeter presents a formidable problem. Traditionally, different beam diameter criteria are used which, however, depending on the beam profile, may yield drastically different results. The second moment method has been standardised by ISO, however, it also has some limitations. While a certain diameter criterion may have advantageous properties for instance for describing the propagating beam, it may not be appropriate for other ‘applications’ such as scaling the thermal damage threshold or for calculating the power that passes through an aperture. We discuss the latter two on the basis of some example profiles which show that the second moment diameter is in these cases not an appropriate parameter.

For laser safety, where the exposure limit for the eye (MPE) is stated as a function of what could be referred to as the ‘thermal beam diameter’, a diameter criterion is needed that yields a correct value for this parameter for any arbitrary size and shape of the beam profile at the retina. A procedure is proposed that can be applied to determine a ‘thermal damage parameter’ for a given beam profile. This procedure is checked against thermal model calculations of the damage threshold. It is also shown that the power that passes through an aperture (such as the pupil of the eye) can be seriously underestimated when using the second moment diameter for non-Gaussian beams.

Keywords: beam diameter, second moment, laser safety, apparent source, thermal damage, aperture, maximum permissible exposure, ISO 11146, IEC 60825-1, ANSI Z136.1

1. INTRODUCTION

The potential for a laser beam that is incident on the a given tissue - such as the retina of the eye - to induce thermal damage does not only depend on the irradiance level, but also on the diameter of the irradiated spot. Smaller spots cool better in radial direction than larger spots, which is why larger spots where the center is not cooled in radial direction, as it is surrounded by heated areas, have a lower damage threshold. This is not only known for tissue, but is also relevant for instance in integrity testing of laser guards and laser protective eye wear. Thus the discussions in this paper should also relate to some extent to other fields where the laser beam thermally interacts with matter.

The basic problem is to assign a ‘diameter’ to an arbitrary laser irradiance profile, where most laser profiles do not have a clearly defined edge but rather extend (in theory) to infinity. This single diameter parameter (circular symmetry is used here for simplicity) has to be able to portray the profile in an appropriate way, with the challenge that the information that is presented by the actual irradiance profile has to be condensed down to one number. It is not surprising that several diameter criteria are in practical use, but only one, the second moment diameter, is internationally standardized [1]. We would like to argue that while the second moment diameter has certain special properties, it also can grossly misrepresent the thermal impact of a given profile as well as grossly misrepresent the power that passes through an aperture. Both can have serious consequences when characterizing potential eye damage for which the fractional power that passes through the pupil of the eye (for a beam that is larger than the pupil of the eye) is relevant, as well as the thermal diameter of the retinal image, which in safety standards [2, 3, 4] is referred to as “angular subtense of the apparent source” (a multiple misnomer, by the way, in the view of the authors [5]).

In international laser safety documents of ICNIRP [1,2] and IEC 60825-1 [3], as well as national standards such as ANSI Z136.1 [4], the retinal thermal exposure limits (maximum permissible exposure, MPE) are stated relative to the value that is applicable to small sources, i.e. to minimal retinal image sizes. For larger image sizes (see figure 1), the

* karl.schulmeister@arcs.ac.at www.healthphysics.at/laser_e

retinal thermal MPE scales with the ‘angular subtense of the apparent source’ α . It follows that α describes the relative thermal hazard level for a given level of power that enters the eye and that is subsequently distributed over the retinal image (as the basic MPE is specified in terms of averaged corneal exposure which is directly related to the power that passes through an 7 mm aperture) [6]. Retinal irradiance profiles that, for a given pulse duration and wavelength, have the same damage threshold (ED-50 value) associated with them, should also ideally be assigned the same parameter α . In that sense the parameter α should be understood as ‘thermally effective diameter’ of the retinal image profile.

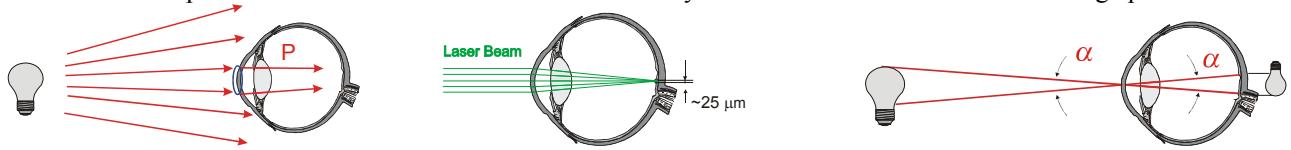


Figure 1. The power that enters the eye (through the pupil as the aperture) and the area over which this power is spread on the retina are the two important factors to assess for a safety of optical radiation that can damage the retina.

2. IRRADIANCE PROFILE DIAMETER DEFINITIONS

The problem of assigning one or more parameters to a given beam profile is not unique to laser safety. For general laser beam characterization purposes, criteria have been developed to define the diameter of an irradiance distribution which does not have a clearly defined perimeter, as is the case for all but top-hat (constant irradiance) profiles. For other profiles, there is no actual ‘natural’ diameter, and any criterion that assigns one or more parameters to characterize the extent of the irradiance profile will have to be scrutinized in terms of its usefulness and appropriateness depending on the way that parameter is subsequently used.

2.1 ‘Traditional’ beam diameter definitions

Often, the beam diameter is defined as the diameter d_x (assuming circular geometry for this simplified discussion) of a circle that encircles some percentage x of the total power that is contained within the irradiance profile. Common levels used in this context are 63 % of the total power ($1-1/e$), or 87 % ($1-1/e^2$). For a Gaussian beam profile, the d_{63} diameter is identical to the position of the irradiance profile where the local irradiance level is a factor of $1/e$ (i.e. 37 %) of the peak irradiance level, and the d_{87} (or to be more precise, the $d_{86.5}$) diameter is identical to the position where the local irradiance is a factor $1/e^2$ (i.e. 13.5 %) of the central maximum level. For a Gaussian, the $1/e^2$ diameter is a factor $\sqrt{2}$ larger as the $1/e$ diameter, and thus the area encircled by the diameters scales with a factor of 2.

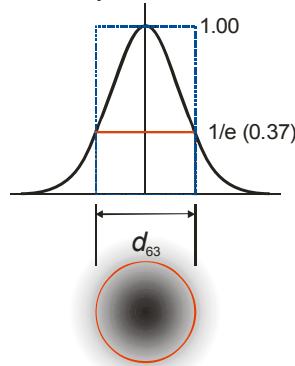


Figure 2. Diameter definition for a Gaussian beam profile often used for NOHD calculations.
The diameter that encircles 63 % of the total power that is contained in the beam is at the irradiance level which is a factor of 0.37 of the peak irradiance.

For laser safety hazard distance (NOHD) calculations based on the assumption of a Gaussian beam profile, the diameter criterion based on the 63 % power content (or the $1/e$ irradiance level) is used, as this diameter criterion for a Gaussian beam profile produces the maximum peak irradiance level, when the total power that is contained within the beam profile is divided by the ‘63 %-area’ (see figure 2). Thus the Gaussian beam can be represented, in a worst-case simplification, by a beam with a top-hat irradiance profile which has the peak irradiance level of the Gaussian as the

top-hat-irradiance-level and the diameter of the top-hat profile is the d_{63} diameter. This peak irradiance level can be directly compared with MPE levels to determine the NOHD of Gaussian laser beam (when the d_{63} diameter is larger than the 7 mm averaging aperture).

2.2 The second moment beam diameter

In recent years, a more general beam diameter definition was developed, mainly within a European standardization research network for the characterization of laser beams (CHOCLAB). The so called ‘second moment’ diameter (2M), which is standardized in ISO 11 146 [1], has the distinct advantage that as long as the beam diameter for any (not only Gaussian) beam is determined by the second moment technique, then simple beam propagation formalisms developed for beam propagation of Gaussian beams (such as the ABCD law) also apply to any beam profile. For a propagating beam, the 2M diameter behaves in the same way as an ‘embedded’ Gaussian beam which has a correspondingly smaller diameter (the ratio between the two being $\sqrt{M^2}$, the beam propagation ratio), see figure 3.

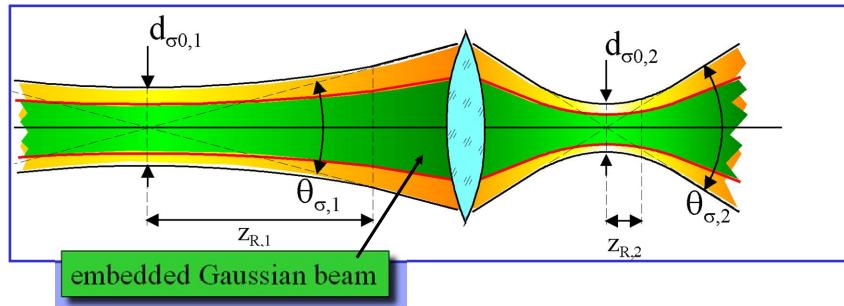


Figure 3. The second moment diameter, d_σ , follows the same laws of propagation as an embedded Gaussian beam which is a factor of $\sqrt{M^2}$ smaller than the 2M diameter of the actual laser beam. Figure courtesy B. Eppich, TU Berlin.

The second moment (2M) beam diameter as a characteristic parameter associated to an irradiance distribution is very similar in principle to the statistical standard deviation of a distribution of data points or the moment of inertia (where the first moment would be the center of gravity) of a distribution of mass points. All of these have the property to weigh the contribution of points (of mass, or irradiance) with the square of the distance of that point to the center. For a Gaussian beam profile this produces a 2M diameter is identical to the $1/e^2$ diameter, however, for other profiles it deviates substantially from other diameter definitions (other beam diameter definitions, however, do not lend the property that they can be used with simple beam propagation formalism).

The 2M technique, depending on the beam profile, may produce diameter values which obviously do not appropriately describe the profile in terms of ‘thermally distinctive’ features. For instance, while it was shown that the 2M method even describes the beam propagation of the beam emitted by a laser stack (i.e. a beam emitted from an array of individual sources), it is obvious that the 2M diameter can not be used to describe the thermal impact of such a source when it is imaged onto the retina or onto a workpiece. Figure 4 shows the second moment profile envelope of two distinct sources, such as of an array.

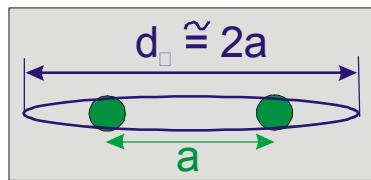


Figure 4. A second moment diameter d_σ can be associated to a profile consisting of two small top-hat profiles, however, the diameter in the horizontal direction is not likely to be a good representation of the spatial extent, nor in particular of the thermally relevant dimensions of the irradiance profile.

Due to the weighting with the square of the distance to the center, the 2M ‘beam diameter’ D_σ for the two spots is about double the distance a between the spots (for small spot diameters D). The exact formula is $D_\sigma = \sqrt{D^2 + (2a)^2}$. According to IEC 60825-1, the appropriate way to deal with multiple sources for laser safety issues is to analyze the individual sources separately (provided they are further apart than α_{min}), which means that α is derived from the single

spot diameter and the power that is associated to one spot (P) is used to characterize the potential for thermal damage. This is also intuitive, since the thermal impact will be associated to every spot individually, at least when they are far enough apart. To use the 2M beam diameter to characterize the beam diameter would grossly underestimate the local irradiance level which exists in the two hot-spots, if it were assumed that the beam profile (not knowing its real profile) is Gaussian and the diameter of that Gaussian is equal to the 2M diameter as shown above – but this is exactly what would be done when the 2M diameter would be used for such a source. We would like to propose a ‘image analysis’ method which in most cases should yield an appropriate ‘thermal damage’ diameter, as described in subsection 2.3 with two examples in Section 3.

However, not only the diameter characterizing the retinal image, α , would be grossly overestimated using the 2M diameter, also the power that can enter the eye (or pass through a pupil or other aperture) would be grossly wrong when using formulas that assume a Gaussian beam with the second moment diameter propagating through space. A Gaussian beam with the 2M diameter as shown in figure 4 by the blue ellipse, and a total power of $2P$ would, for apertures with a diameter for instance equal to the top hat diameter D yield a much lower power passing through the aperture than one of the top-hat beams passing through the aperture. Thus if the 2M diameter and divergence would for instance be used to determine the NOHD in the typical simplified way, the NOHD could be seriously underestimated as for the actual case, namely two individual beams, a correspondingly higher power could pass through the pupil of the eye. This is further discussed in Section 4.

2.3 The ‘maximum thermal hazard’ (MTH) method

There is an ‘image analysis’ method implied in the laser safety standard for the analysis of multiple sources, and we would like to argue that this method can be generalized for non-homogeneous (i.e. non-top hat) irradiance profiles. The principle is to analyze a non-homogeneous source in respect to the most hazardous combination of power contained within a certain part of the source image and the angular subtense of that part of the source (the ‘width’ or ‘diameter’ of a certain part of the source). The partial power is compared to the emission or exposure limit, and the angular subtense is used to calculate the exposure or emission limit. In the strict sense, all but a constant irradiance profile (a top-hat profile) could be considered as non-uniform source. The most hazardous combination of power within an area of the image and the diameter of that area is the one where the ratio of (power within area)/(diameter of area) is maximum.

In practice, this technique lends itself to the evaluation of CCD images, where the signal of each pixel is characteristic of the local image irradiance. Parts of the image can be integrated up over an area (an evaluation ‘window’) which varies both in size and position on the image. The evaluation area, or ‘window’ is chosen as rectangular here, in order to simplify algorithms, but may also be circular (a rectangular evaluation area yields the more conservative results, as for the same characteristic diameter, the power that is contained in a rectangle is larger than the power contained in a circle of the same diameter). The width and the length of the rectangle is limited to small values by the value that corresponds to $\alpha_{\min} = 1.5$ mrad (which in terms of a CCD image is equivalent to a certain number of pixels) and to large values by $\alpha_{\max} = 100$ mrad. The parameter equivalent to α in the laser safety MPE values, for a non-circular case (or non-square case) is determined by the arithmetic mean, as usual for ‘oblong’ sources and as described in IEC 60825-1. Each evaluated area contains a certain partial power P_i and has a certain ‘diameter’ δ_i associated with it, for instance as shown for $i=1$ with white lines in figure 5.

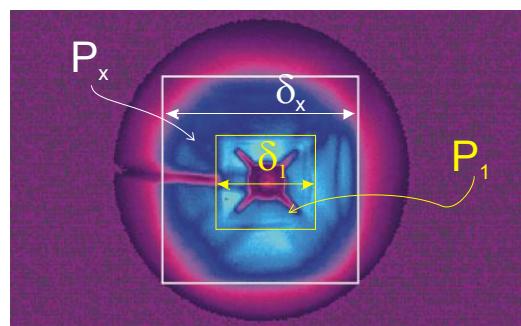


Figure 5. ‘Maximum thermal hazard’ (MTH) analysis of an image that was produced by a LED in terms of most hazardous combination of power contained within an area and characteristic diameter of that area.

The relevant ‘most hazardous’ evaluation window is the one with the maximum ratio of P_i / δ_i which corresponds to the maximum relative level of thermal hazard. For the example of the image of the LED shown in figure 5, this most critical area is shown in white, and the corresponding level of partial power P_x is then used in the comparison to the exposure limit or product emission limit, while the ‘diameter’ δ_x of the critical part of the image is transformed into an angular subtense and is used as value of α to determine the MPE or the emission limit. This principle is equivalent to analyzing multiple sources as described in the appendix of IEC 60825-1 where the power that is contained in individual sources is related to the angular subtense of the partial source and different combinations of sources are analyzed (usually it is simple to show that the single source is always the most critical one except when the sources are very close together). The method as proposed here is a generalization of the method given in IEC 60825-1 for discrete assemblies of sources to inhomogeneous images.

When this ‘maximum thermal hazard’ (MTH) method is applied to a Gaussian beam profile, then a diameter which encircles 72 % of the total power results, i.e. a diameter which in size is between the d_{63} and the d_{87} diameter. However, for a comparison of the diameter definitions it needs to be considered, that in contrast to the usual application of the d_{63} diameter for the determination of α , for the MTH method, it is not the total power that is compared to the exposure limit or emission limit, but only 72 % of the total power (or rather, of the power that is measured through the applicable aperture and with an open field of view).

3. THERMAL ANALYSIS OF IMAGE PROFILES

In the following, the diameter criteria as discussed in section 2 are applied to two image profiles. Results of a finite difference thermal damage model are presented for comparison with the ‘thermal’ diameter criteria. Since the top-hat distribution is the only distribution with a clearly defined diameter, it is taken as the basis for the comparison with other profiles. The principle of comparison is shown with an example: assume that for a top-hat profile with an outer diameter of 25 μm ($\alpha = 1.5$ mrad, i.e. a minimum retinal spot size), the intraocular damage threshold (ED-50) equals 1 μJ for a given pulse duration and wavelength. The threshold for a larger top-hat shaped distribution will be larger, for example for an outer diameter which equals 250 μm ($\alpha = 15$ mrad), the threshold could be 100 μJ . The ideal criterion for the determination of α for an arbitrary retinal profile is one which produces a value of $\alpha = 15$ mrad as “thermally characteristic angle” for any profile which also has a threshold of 100 μJ .

3.1 Top-Hat

Even for a top-hat profile there is some uncertainty of how to define the diameter in the laser safety community: if the 63 % criterion is applied to a top-hat profile, it yields a ‘diameter’ which is less than the diameter of the top-hat profile, which does appear overcritical to many. The 2M, the 1/e and the MTH method all yield the top-hat diameter as the ‘diameter’. Since a number of experimentally determined thresholds were obtained with a (close-to) top-hat irradiance profile (for instance by aperturing out the central part of the beam to obtain a smaller diameter), and due to the safety factor between the animal threshold data and the MPE, it should be justifiable to use the outer diameter of the top-hat, and it should not be necessary to us a value less than that, such as would result from the 63 % criterion.

3.2 ‘1 over r^2

With some specialized information transmission laser products, a retinal irradiance profile can be produced which can be described approximately with an irradiance distribution that decreases with the inverse square of the distance to the center of the distribution, and is therefore, here, referred to as the ‘ $1/r^2$ ’ distribution. The central part of the distribution, which would otherwise tend towards infinity, is approximated by a top-hat profile with a typical value of about 1.5 mrad, as shown in figure 6. It is noted that the second moment diameter is not defined for a distribution which falls with the rate of $1/r^2$.

Figure 6 also shows the results of the application of the different ‘diameter’ criteria: the MTH diameter happens to be identical to the diameter where the local irradiance is 1/e from the maximum, so that $\alpha = 2.4$ mrad when the central top hat portion has a diameter of 1.5 mrad (when a circular evaluation window, and not a square one, is used, as the MTH diameter was calculated analytically in this case). When the total beam power is defined as the one within an angle of 100 mrad, then the 63 % diameter- α equals 17.6 mrad.

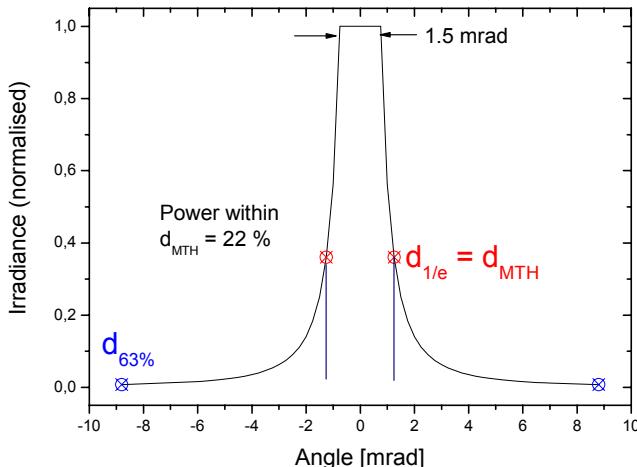


Figure 6 For a retinal irradiance profile that is described by a ‘inverse of distance to the center squared’ dependence with a central top-hat portion, the maximum thermal hazard (MTH) method yields the same diameter d_{MTH} as the $1/e$ diameter definition, however, this diameter only contains 22 % of the total power which is compared to the limit.

This is good example to show the difference between the $1/e$ and the 63 % criterion when applied to non-Gaussian profiles: the 63 % results in α that is a factor 7.3 higher than the $1/e$ diameter criterion (it should be mentioned at this point that the 63 % is often quoted to be contained in the IEC 60825-1:2001 laser safety standard, although there it is defined to be used for the beam diameter, not necessarily the retinal image profile diameter, while the $1/e$ method is favored by the ANSI Z136 standard).

The MTH-diameter can not be directly compared to the $1/e$ or the 63 % diameter, as the MTH-method implies that only the power (or energy) that is contained within the critical area is compared with the exposure limit. When this concept is adopted for the comparison with calculated retinal damage thresholds, then the calculated threshold for the $1/r^2$ profile for a given d_{MTH} is multiplied by a factor 0.22, since for the $1/r^2$ profile, only 22 % of the total power is within d_{MTH} . This reduced value is compared to the threshold that is calculated for a top-hat profile that has the same diameter as d_{MTH} . A computer model based on a finite difference method was used to solve the heat flow equation as basis for thermal damage predictions of the human retina. Thresholds for pulse durations between 10 μs and 100 ms were calculated and are summarized in table 1 (for optical properties that are typical for visible wavelengths).

Table 1 Comparison of calculated top-hat retinal damage thresholds with thresholds for the $1/r^2$ profile shown in figure 6 for a number of pulse durations between 10 μs and 100 ms. The MTH method yields an analysis which is a factor of between 1.2 and 1.5 not ‘conservative enough’.

	Top Hat Threshold for d_{MTH}	Threshold for $1/r^2$ profile	Reduction of $1/r^2$ profile threshold to 22 %	Factor Top-Hat threshold higher than reduced threshold
	μJ	μJ	μJ	
10 μs	6	20	4	1,3
100 μs	7	23	5	1,3
1 ms	12	44	10	1,2
10 ms	55	180	40	1,4
100 ms	370	1100	242	1,5

The results shown in Table 1 indicate that the MTH-method yields acceptable results in that it produces a ratio of the adjusted thresholds which is between a factor of 1.2 and 1.5 – ideally it should be 1 or somewhat less than 1 to be somewhat on the conservative side. The application of the $1/e$ diameter (where the total power of the beam is compared to the limit) would be a factor of between 3.0 and 3.7 too conservative, which would err on the safe side. However, the 63 % diameter criterion would underestimate the hazard by a factor of at least 2.

3.3 Far field of instable resonator

The profile produced in the far field of an instable resonator, is shown in figure 7. This distribution is the Fourier transform of a ring-shaped profile, which is the near field profile of an instable resonator, and features a sharp peak in the middle, and a broad ‘shoulder’ of ‘higher frequencies’ (i.e. at larger angles) with relatively small intensity levels. Due to these outer lying components of the distribution, the second moment diameter also comes out to be very large when compared to the other diameter criteria, which are all shown in figure 7.

Again, the MTH method diameter is very similar to the $1/e$ diameter, but again it needs to be kept in mind that the MTH method involves only a part of the total power that is contained in the distribution, which for the case of the distribution shown in figure 10 is 31 %. The 63 % diameter is a factor of 7 larger than the $1/e$ diameter.

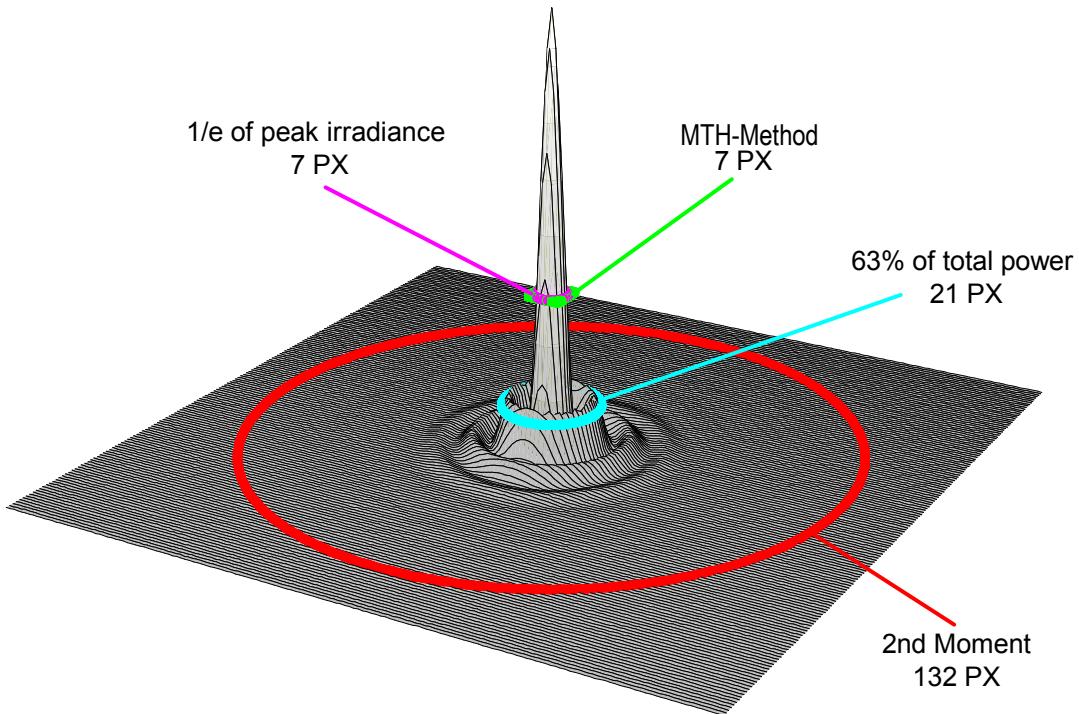


Figure 7. The far field irradiance distribution of an unstable resonator. The different diameter criteria are given in units of ‘pixels’ (such as those from a CCD camera).

This distribution can be considered a classic example where the second moment method yields a diameter which can not be considered as characteristic of the geometrical extent of the distribution in a practical sense [7]. This was also the reason why the application of the 2M method for instable resonators was not included in the scope of the original version of the ISO 11 146 standard. However, in later versions of the standard, this limitation of the scope was lifted. It seems clear from this discussion that to base the parameter α on the second moment for this distribution would grossly underestimate the risk for retinal thermal damage. The second moment diameter is a factor 19 larger than the $1/e$ and MTH diameter, and a factor 6 larger than the 63 % diameter.

The results of the finite difference based thermal damage model are summarized in Table 2. The MTH-method appears to be a good method to characterize the thermal retinal hazard for all calculated pulse durations and geometrical scaling factors of the distribution. For the smallest scaling factor, i.e. the smallest distribution, the MTH method results in an evaluation which is a factor 2 too conservative for pulse duration less than about 1 ms, while in the other cases it is often ‘exact’ but never a factor of more than 1.4 ‘not conservative enough’.

Table 2. Comparison of calculated damage threshold data for top-hat distributions with the threshold data calculated for the far field distribution of an instable resonator.

Pulse duration	d_{MTH}	top hat threshold for d_{MTH}	threshold farfield	threshold farfield with 31 % reduction	Factor Top-Hat threshold higher than reduced threshold
	μm	μJ	μJ	μJ	
10 μs	17,5	1,0	6,3	2,0	0,5
	35	4,3	12,5	3,9	1,1
	70	17,0	40,7	12,6	1,3
100 μs	17,5	1,2	7,5	2,3	0,5
	35	4,8	14,5	4,5	1,1
	70	19,5	45,5	14,1	1,4
1ms	17,5	3,3	17,1	5,3	0,6
	35	9,4	30,7	9,5	1,0
	70	29,0	79,9	24,8	1,2
10 ms	17,5	24,0	80,1	24,8	1,0
	35	47,0	135,0	41,9	1,1
	70	97,0	278,0	86,2	1,1
100 ms	17,5	182,0	536,0	166,2	1,1
	35	327,0	830,0	257,3	1,3
	70	587,0	1530,0	474,3	1,2

4. POWER PASSING THROUGH AN APERTURE

When the power that passes through an aperture has to be calculated and the information on the actual beam irradiance profile at the aperture is not available, then usually a Gaussian is assumed and the following simple equation is used:

$$\eta = 1 - \exp[-2(D_{ap} / d_{beam})^2] \quad \text{Eq. 1.}$$

where η is the fraction of the total power or energy passing through an aperture of diameter D_{ap} . The value used as the beam diameter is determined according to the $1/e^2$ or the d_{87} criteria, which for Gaussian beam profile is the same as the second moment diameter d_σ (and then Equation 1 is valid and accurate). However, as shown already in the previous section, depending on the beam profile, for non-Gaussian profiles, these diameter parameters can be grossly different. Since it is only the second moment diameter which is defined in an international standard, and it is the only one where the beam envelope defined as the second moment diameter propagates according to the same rules as a Gaussian, it can be expected that the second moment diameter will find wider application also for calculating the power that passes through an aperture. As was already indicated for the example of a multiple beam above, the power that actually passes through an aperture in comparison to the power that is calculated with Equation 1 which assumes that a Gaussian beam with diameter d_σ is incident on the aperture, can be seriously underestimated.

The following subsections compare the power P_{real} that actually passes through an aperture with diameter D_{ap} (all apertures are centered) with the power P_{Gauss} that would be calculated to pass through an aperture when the beam profile at the aperture were to be assumed Gaussian and the second moment diameter d_σ of the profile were used. This is shown schematically in figure 8.

Figure 8 shows the cross-sectional irradiance profile of the far-field of an unstable resonator as well as a Gaussian profile with the second moment diameter that is the same as the second moment diameter as the far-field profile, and both profiles contain the same total power within the profile. The peak irradiance of the far-field profile is not shown due to scaling reasons - this already indicates that if the diameter of the "test" aperture D_{ap} is small enough, the power that actually passes through this aperture for the far-field profile can be very much larger than the power that is calculated with Eq. 1 assuming a Gaussian profile.

It is also noted that the second moment diameter of the profiles that feature some diffraction effects (i.e. all but the fibre) are not very well defined: the 2M diameter depends critically on the outlying components and extending the range over which the 2M diameter is determined can lead – for the same given distribution – to a significant increase of the 2M diameter. The distributions below (with the exception of the fibre) were all calculated up to a certain radial range. It can well be that for larger ranges, the 2M diameters would become larger. In practice this can happen when a CCD camera is used for experimentally determining the 2M diameter where outer-lying components are not sufficiently accounted for. It also may lead to the conclusion that the 2M diameter should not be applied to such distributions, which might include Gaussian beams where diffraction occurs following the placement of an aperture into the beam.

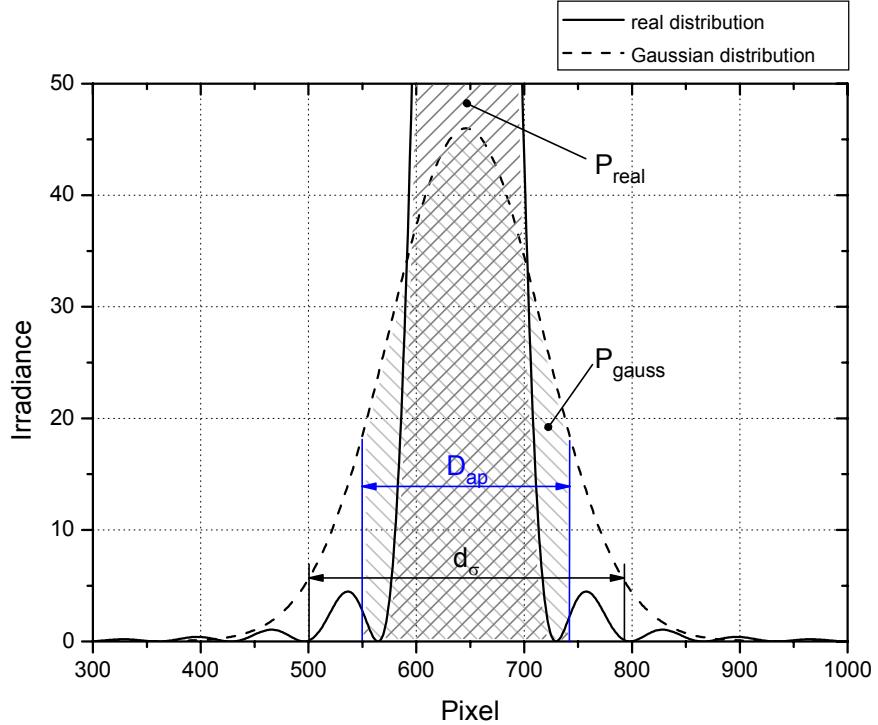
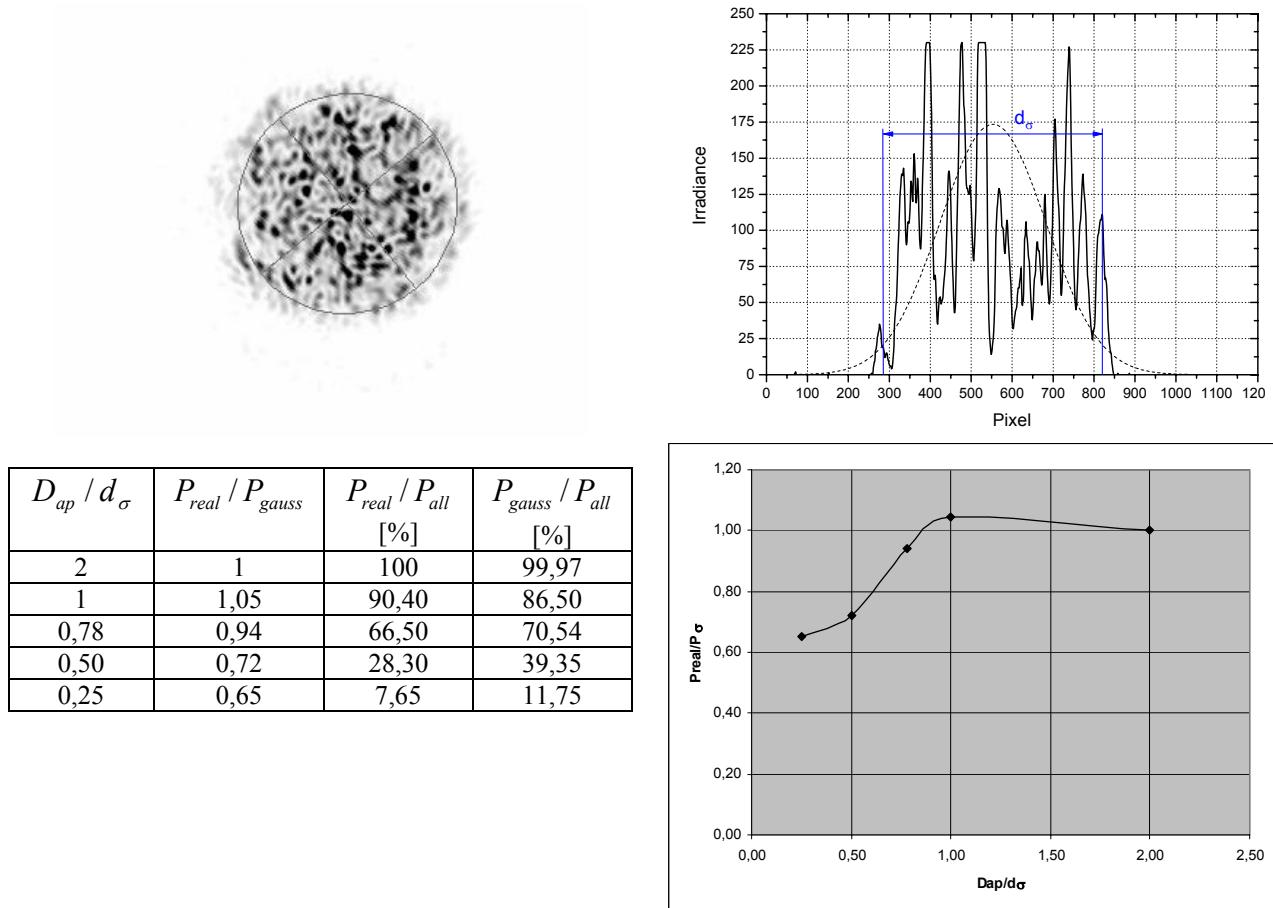


Figure 8. The far field irradiance profile of an unstable resonator and the irradiance profile of a Gaussian beam with the same total power and the same second moment diameter.

In the tables of the following examples, we have listed a number of ratios for the diameter of the aperture relative to the second moment beam diameter, starting from a factor 2 where the ‘test’ aperture is twice a wide as the 2M diameter of the distribution, to a factor of 0.25, i.e. where the aperture is a factor of 4 smaller than the 2M diameter. The second column gives the ratios of the ratio of the actual power that passes through the aperture relative to the calculated one, assuming a Gaussian profile. The third column lists the ratio of the power passing through the aperture relative to the total power of the beam. The figure to the right of the tables plots the Power ratio as a function of the aperture diameter/2M diameter ratio.

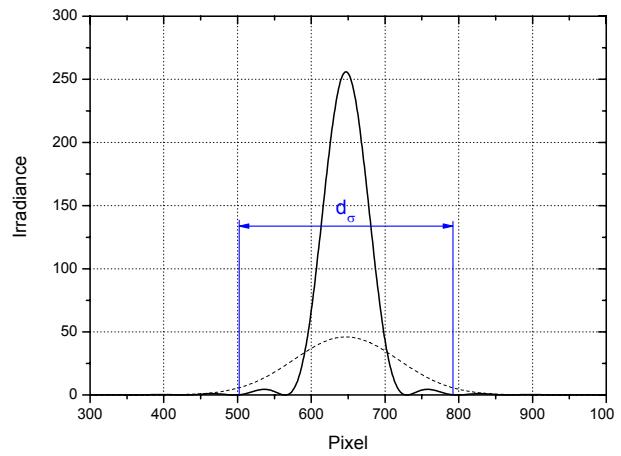
Distribution 1: output of a fiber with a core diameter of 300µm (measured)



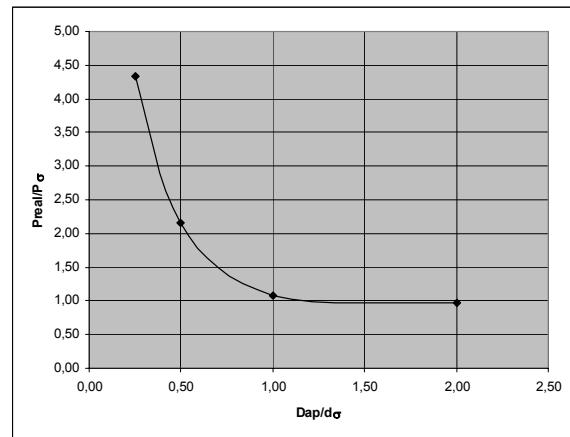
Distribution 2: diffraction of a homogeneous plane wave at a circular aperture, considered in the far field

$$I_x = I_o \left[\frac{2J_1(x)}{x} \right]^2$$

$$x = \frac{\pi D}{\lambda} \sin(\theta)$$



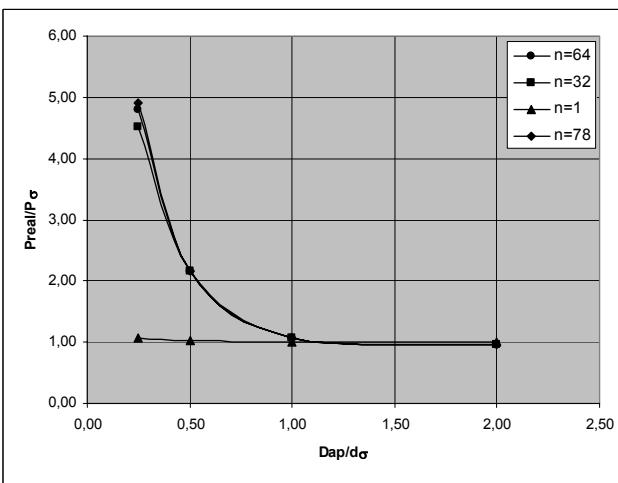
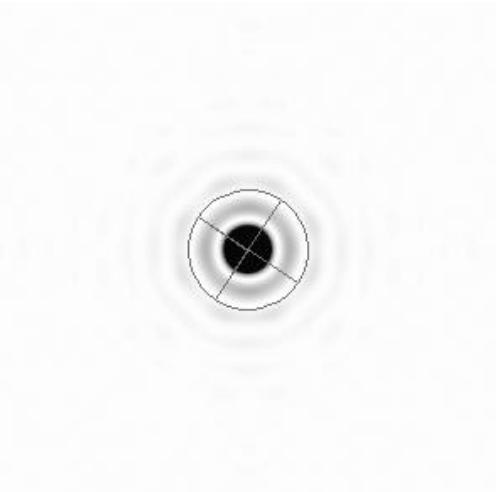
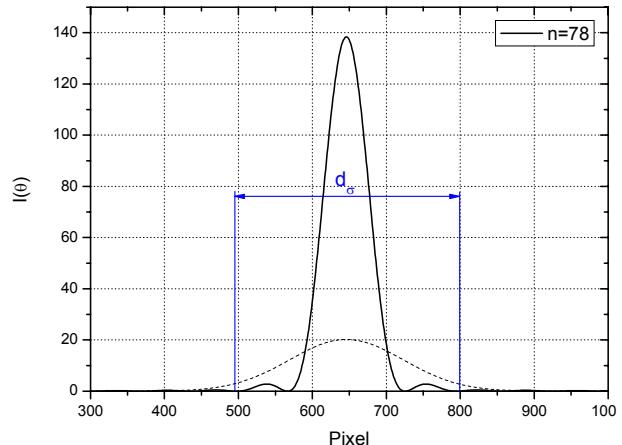
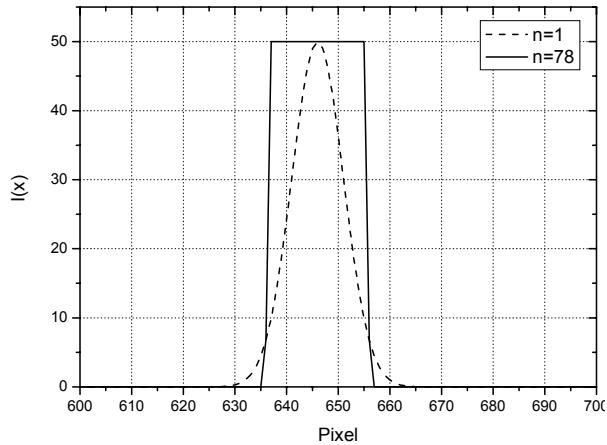
D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
3	0,99	98,65	100
2	0,97	97,05	99,97
1	1,07	92,70	86,50
0,50	2,16	85,00	39,35
0,25	4,33	50,90	11,75



Distribution 3: Fourier transformation (i.e. far field) of a super Gaussian field

$$I(x) = I_o e^{-2(x/w_0)^{2n}}$$

$$I(\theta) = F_{x \rightarrow \theta} \{ I_o e^{-2(x/w_0)^{2n}} \}$$



n=1:

D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
2	1	100	99,97
1	1	86,9	86,50
0,5	1,03	40,40	39,35
0,25	1,06	12,50	11,75

n=32:

D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
2	0,97	97	99,97
1	1,07	92,70	86,50
0,5	2,16	85,20	39,37
0,25	4,52	53,10	11,75

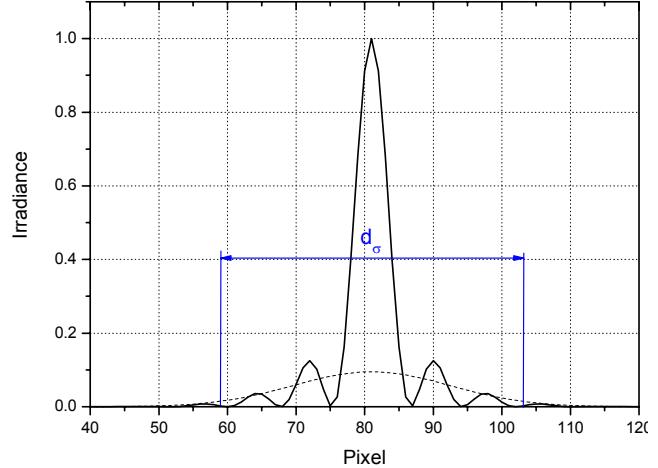
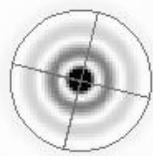
n=64:

D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
2	0,97	96,80	99,97
1	1,07	92,20	86,50
0,5	2,16	84,80	39,35
0,25	4,81	56,50	11,75

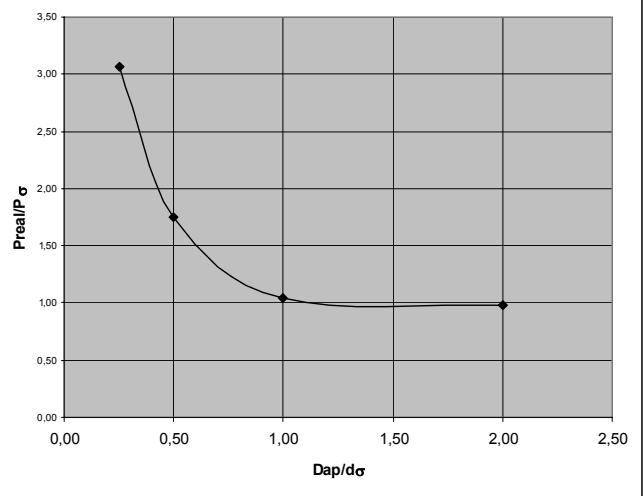
n=78:

D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
2	0,97	96,80	99,97
1	1,06	92,10	86,50
0,5	2,15	84,70	39,35
0,25	4,91	57,70	11,75

Distribution 5: far field of an instable resonator



D_{ap} / d_σ	P_{real} / P_{gauss}	P_{real} / P_{all} [%]	P_{gauss} / P_{all} [%]
2	0,98	97,59	99,97
1	1,04	90,35	86,47
0,50	1,75	68,86	39,35
0,25	3,07	36,04	11,75



5. CONCLUSIONS

It is pointed out that the parameter α , which is the parameter that scales the retinal thermal damage threshold and MPE, needs to be interpreted in the sense of a ‘thermally equivalent diameter’ of the retinal irradiance distribution, rather than a beam diameter in the usual optical sense. Different beam ‘diameter’ criteria were applied to a number of types of retinal irradiance profile shapes. The d_{63} method and the 1/e method, that are often used (as stated in the IEC 60825-1 and ANSI Z136.1 laser safety standards), as well as the standardized method of the second moment (2M) diameter are compared with a ‘maximum thermal hazard’ MTH-method that is proposed as a general method for the evaluation of retinal irradiance profiles. The criteria were applied to a profile described by a $1/r^2$ dependence and the far field profile of an unstable resonator. It is obvious that the second moment can not be used to characterize the scaling of thermal damage thresholds for these examples.

When the second moment diameter is used to calculate the power that passes through an aperture, we note that for the same diameter ratios, the ratio of actual power over calculated power that passes through the aperture is approximately the same (in the range of 3 to 5) for most studied types of beam profiles. Assuming a Gaussian beam profile and using 2M diameters can seriously underestimate the power that passes through an aperture. The 2M diameter for beams which contain some diffraction also critically depends on the range of the evaluation area used to determine the 2M diameter.

6. SUMMARY

The practical application of different diameter criteria were critically discussed for the case of thermal damage thresholds and for calculating the power that passes through an aperture. It is shown that the second moment diameter may not yield appropriate results, depending on the profile. Unfortunately, these limitations are not discussed in the ISO standard on beam diameter definition.

ACKNOWLEDGEMENTS

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