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**Fabrice Manns**
**Per G. Söderberg**
**Arthur Ho**
**Bruce E. Stuck**
**Michael Belkin**
*Editors*

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# Criteria for the determination of the 'thermal' retinal image diameter

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

## ABSTRACT

For a given power entering the eye, the level of retinal thermal hazard depends on the retinal image size over which that power is distributed. Maximum permissible exposure limits are given in terms of the angular subtense of the apparent source $\alpha$, which describes the diameter of the retinal image. Since this parameter scales the retinal thermal exposure limits (MPE), it is a direct measure of the relative thermal hazard of different retinal images, and thus should be seen as 'thermally effective' rather than 'optical' diameter of the retinal image. From the method given in IEC 60825-1 for the analysis of non-uniform sources, a general method for the analysis of non-top hat profiles was derived and is suggested as general analysis method for the angular subtense of the apparent source for a given image. This and other criteria are compared with the results of thermal models.

**Keywords:** laser safety, hazard analysis, product classification, apparent source, angular subtense, retinal thermal injury, maximum permissible exposure, allowable emission limit, IEC 60825-1, ANSI Z136.1

## 1. INTRODUCTION

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 retinal thermal MPE scales with the 'angular subtense of the apparent source' $\alpha$ (see also [5] in these proceedings and [6]). It follows that $\alpha$ describes the relative thermal hazard level for a given level of power that enters the eye and that 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). 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 $\alpha$. In that sense the parameter $\alpha$ should be understood as 'thermally effective diameter' of the retinal image profile.

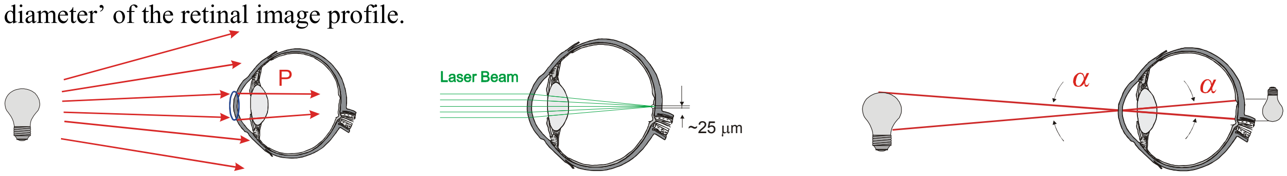


**Figure 1.** The power that enters the eye and the area over which it is spread on the retina are the two important factors to assess for a safety of optical radiation that can damage the retina.

## 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. The only irradiance profile (be it the irradiance incident on a surface such as the retina or be it the irradiance profile at different positions in the beam) that exhibits a clearly defined diameter is a top hat profile. 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

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



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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.

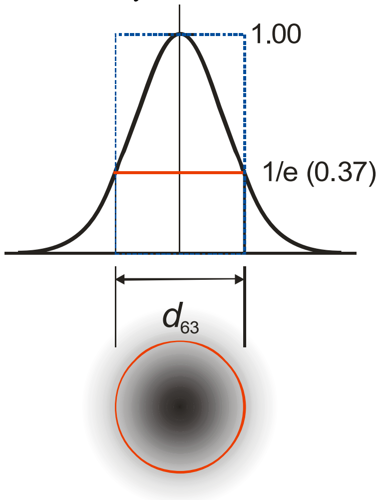


**Figure 2**. Diameter definition for a Gaussian beam profile often used for NOHD calculations. The diameter that encircles 63 % of the total power that is contained in the beam is at the irradiance level which is a factor of 0.37 of the peak irradiance.

For laser safety 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). The origin of this definition needs to be kept in mind (characterizing the worst case level of optical radiation that can *enter the eye* or pass through a measurement aperture) and it can not be automatically assumed that this is also an appropriate definition when it comes to characterizing the thermal damage potential of an arbitrary *retinal* irradiance profile. It also needs to be kept in mind that the two forms of the diameter definition, i.e. the '1/e of peak irradiance' and the $d_{63}$ are identical for Gaussian beam profiles only, while they may well give substantially different results for non-Gaussian beams, as will be shown below.

**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 [7], has the distinct advantage that as long as the beam diameter for any (not only Gaussian) beam is determined and defined by the second moment technique, then simple beam propagation formalisms developed for beam propagation of Gaussian beams (such as the ABCD law) can be used.

The second moment (2M) beam diameter as a characteristic parameter associate 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 which is identical to the $1/e^2$ diameter, however, for other profiles it deviates substantially from other diameter definitions (which can not be used to characterize the beam propagation, i.e. the evolvement of the beam diameter with distance, of a non-Gaussian beam).

The 2M technique, depending on the beam profile, may produce diameter values which obviously do not describe the profile in terms of 'thermally distinctive' features very well. It can also seriously underestimate the power that passes through an aperture when the formula that applies for Gaussian beams is used to calculate the power that passes through an aperture and the diameter of the beam is determined with the 2M method. 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 for laser safety analysis for the case of individual sources. Figure 3 shows the second moment profile envelope of two distinct sources or beams.

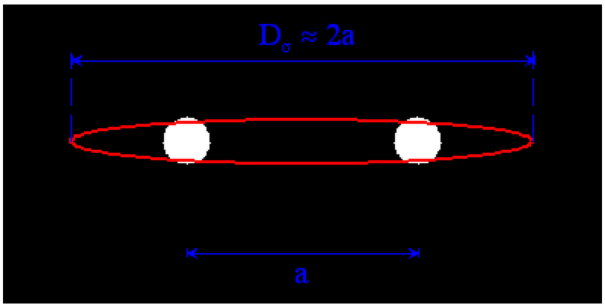


**Figure 3.** A second moment diameter can be associated to a profile consisting of two small top-hat profiles, however, the diameter in the horizontal direction is not likely to be a good representation of the spatial extent, nor in particular of the thermally relevant dimensions of the irradiance profile.

Due to the weighting with the square of the distance to the center, the 2M 'beam diameter' $D_\sigma$ 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 such sources for laser safety issues is to analyse the sources separately (provided they are further apart than $\alpha_{min}$), which means that $\alpha$ is derived from the single spot diameter and the power that is emitted from one spot is used to determine the accessible emission level or exposure level. To use the 2M beam diameters for safety purposes would grossly overestimate the parameter $\alpha$ and could therefore seriously underestimate the hazard. However, not only the diameter characterizing the retinal image, $\alpha$, would be grossly overestimated using the 2M diameter, also the power that can enter the eye (or pass through a pupil) would be grossly wrong when using formulas that assume a Gaussian beam propagating through space. A Gaussian beam with the 2M diameter as shown in figure 3 by the red ellipse, and a total power that is equal to the one that is contained in the two top-hat portions of the image 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 could actually yield should one of them pass 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.

**2.3 The 'maximum thermal hazard' (MTH) method**

There is an alternative method implied in the laser safety standard for the safety analysis of multiple sources, and we would like to argue that this method can be generalised for non-homogeneous (i.e. non-top hat) irradiance profiles. The principle is to analyse 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 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 $\alpha$ 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' $\delta_i$ associated with it, for instance as shown for i=1 with white lines in figure 3.

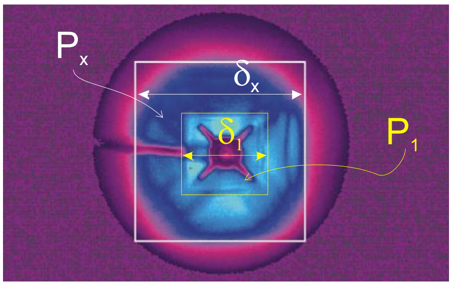


**Figure 4.** 'Maximum thermal hazard' (MTH) analysis of an image that was produced by a LED in terms of most hazardous combination of power contained within an area and characteristic diameter of that area δ.

The relevant 'most hazardous' evaluation window is the one with the maximum ratio of $P_i$ / $\delta_i$ which corresponds to the maximum relative level of thermal hazard. For the example of the image of the LED shown in figure 4, 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' $\delta_x$ of the critical part of the image is transformed into an angular subtense and is used as value of $\alpha$ 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 analysed (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 d63 diameter for the determination of a, 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. ANALYSIS OF IMAGE PROFILES

In the following, the diameter criteria as discussed in section 2 are applied to a number of image profiles. Results of a finite difference thermal damage model and the 'Thompson-Gerstman' model [8] 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 $\alpha$ 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 Gaussian

As the zero order beam features a Gaussian profile, many threshold studies have been performed with Gaussian beams. Care needs to be taken when analysing these data, as some studies state the $1/e^2$ diameter as the 'diameter' of the spot size diameter, while others use the 1/e diameter. The application of different criteria to Gaussian beam profiles is discussed in section 2.

The 'Thompson-Gerstman' thermal damage model [8] was used to calculate retinal damage thresholds for both Gaussian retinal irradiance profiles as well as top-hat profiles. The ratios of the thresholds, when specified as intro-ocular energy, are shown in figure 5 as function of 'diameter' for a range of pulse durations. Here, the 'diameter' for the Gaussian exposure profiles is the 1/e (=63 %) diameter. For short pulses, the 1/e diameter definition of the Gaussian compares well with the top-hat thresholds (within 10 %). This can be expected, as in this pulse duration regime, the peak irradiance is directly related to the threshold for damage, and the 1/e diameter criterion is designed to yield the same peak irradiance for the Gaussian as a top-hat profile with the same diameter. For small spots and longer pulse durations, the deviation for the 1/e definition is of the order of 40 % (the threshold of the Gaussian spot is higher than the threshold of the top-hat) but this deviation is reduced for larger spot sizes. When the MTH-Method is used to determine the 'thermal diameter' of the Gaussian exposures, the effect is that the ratio is reduced by about 30- 40 % for exposure durations longer than 1 ms, so that the small spot data fit very well and for the larger spots, the threshold for the Gaussian is underestimated by a factor of about 20-30 %. At this point of the study, awaiting more detailed model data and comparisons with experimental threshold data, it could be said that both the 1/e = 63 % and the MTH-Method yield acceptable results.

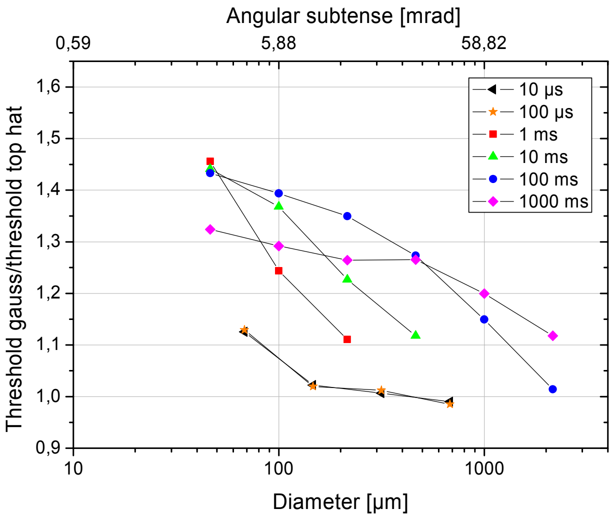


**Figure 5.** Comparison of calculated thermal damage threshold data for top-hat and Gaussian beam profiles as function of 'Diameter' where the diameter of the Gaussian profile is taken to be the 1/e (= 63%) value.

### 3.3 Ring profile

A rather rare type of retinal irradiance profile, which was, however, used in one animal experiment study [9], is the annular- or ring-shaped profile. In the experimental study it was produced by imaging a ring shaped aperture that was placed in the beam, in practice it might be encountered when one images the near field of an instable resonator or if there is some ring shaped mirror around an emitter, as is for instance the case for LEDs (while for an LED there is also the square chip in the center of the ring shaped cup). The profile is characterized by the outer diameter and the diameter of the inner 'obstruction'. We have used a parameter x to describe the ratio of the inner diameter over the outer diameter, so that a value of x = 0.3 would characterize a rather 'thick' ring where only 9 % of the area as compared to a top-hat would be 'obstructed' in the center, and x = 0.9 would be a thin ring where 81 % of the area of the top hat would be obstructed. Threshold model calculations were performed with a Thompson-Gerstman model for a number of outer diameters, for pulse durations between 10 µs and 1 s and for a range of obstruction ratios of x between 0.3 and 0.9 (optical parameters that are typical for visible wavelengths were used).

For pulse duration of 10 µs, the model calculations, for outer diameters between 147 µm and 681 µm showed that the threshold for ring shaped profiles is directly related to the retinal irradiance and otherwise independent of the ring size. This was to be expected for pulse duration in the thermal confinement regime, where damage occurs before heat flow can have an effect on the temperature profile. The ratios of the calculated ring threshold data over the top-hat data for all modeled outer ring diameters and factors of x lie within 1 % of the ratios of the irradiance values for the respective ring and the top-hat profile (figure 6). A ring with x = 0.9 has a factor of 5 (the inverse of 1-0.81) lower threshold than a top-hat with the same outer diameter and the same total energy contained within the profile, because the irradiance in the ring is a factor 5 higher than for the top-hat. It follows that the criterion for the determination of $\alpha$ should reflect that the ring is more hazardous than a top-hat for the same outer diameter and thus would have to assign the ring a correspondingly smaller value of $\alpha$. Another way of solving this issue is to reduce $\alpha_{max}$ for pulses in the thermal confinement regime to be the same as $\alpha_{min}$ so that the MPE would in effect be directly related to the retinal local irradiance (or radiant exposure) level (see Jack Lund et al, these proceedings [10]). The MTH-method would then simply search for the area of highest local irradiance in the image (averaged over $\alpha_{min}$) and is the method of choice in this case.

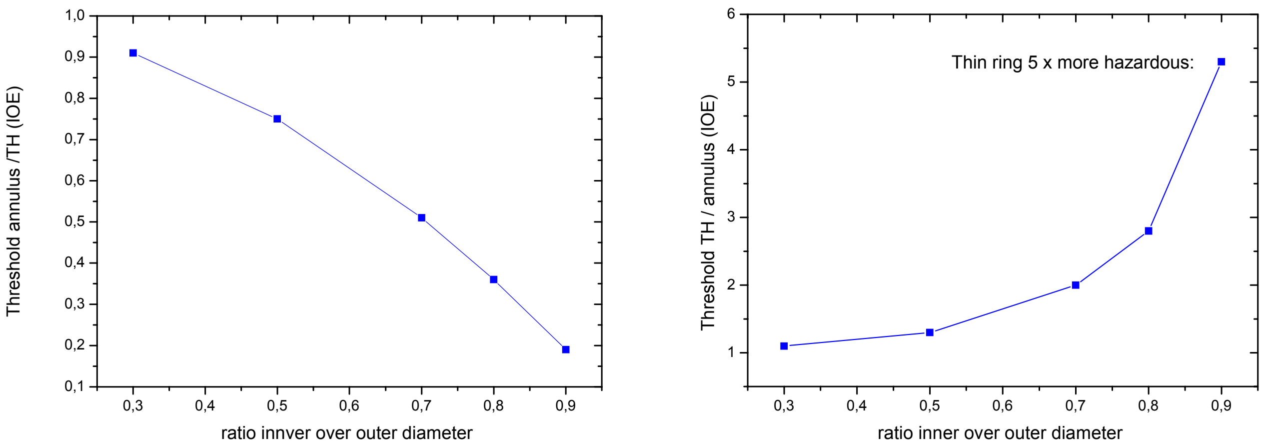


Figure 6. Ratio of threshold (in terms of energy per pulse passing through the pupil or incident on the retina) for an annulus profile over a top-hat profile with the same outer diameter (left) and the inverse thresholds ratio on the right. The left hand side ratio is identical to the ratio of the irradiance levels that exist on the retina for a ring with varying thickness. The right hand side graph is a figure of how much the ring is 'more hazardous' than a top hat with the same outer diameter.

For longer pulse durations, the direct relationship between the retinal irradiance level and the threshold for damage does no longer apply. The model data show interesting trends, as for longer pulses and small-to-medium sized rings, the ring can show a higher threshold (i.e. be less hazardous) than the top-hat with the same outer diameter, i.e. for this case, the appropriate criterion for the determination of $\alpha$ as the 'thermally effective diameter' would have to produce a value of $\alpha$ that is larger as the outer diameter of the ring (which is an example where a criterion similar to the 2M method might be appropriate, as the 2M diameter of a ring is by up to a factor 1.4 larger than the ring). The MTH-method, as long as the ring is with $\alpha_{max}$, yields the outer diameter as $\alpha$. The results of the thermal model are shown in figure 7 for two different outer diameters.

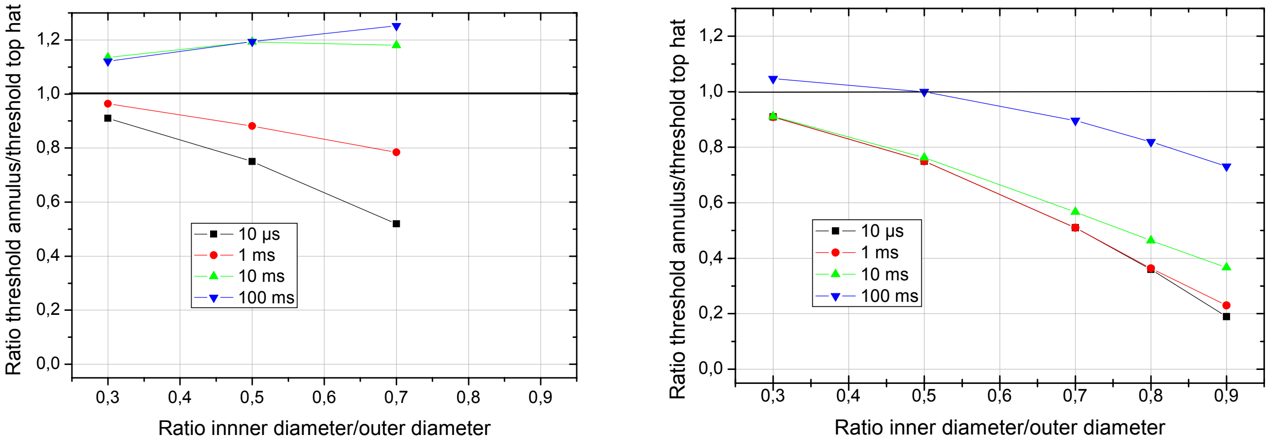


Figure 8. Ratio of the calculated threshold for an annulus as a function of the diameter ratio x, for a number of pulse durations. Left, for an outer diameter of 150 µm, right, for an outer diameter of 680 µm. A threshold ratio above 1 means that the ring is less hazardous than the top-hat profile, even though it has a larger retinal irradiance than the corresponding top-hat profile. For the smaller outer diameter (left), the maximum value of x was only 0.7, as for larger values of x, the ring would have become thinner than what is usually assumed as to be the minimal ratinal image size.

At the time of writing, the temperature-time history was not studied in sufficient detail to explain the threshold behavior of the ring vs. the top-hat profiles, but a factor that can make the ring less hazardous for longer pulse durations is that for the ring, the radial cooling takes place also towards the center. Also there does not seem to be simple ‘diameter’ criterion which would account for the relative differences between a top –hat and a ring for all pulse durations and outer ring diameters, although the effect of a time dependent $\alpha_{max}$ for the evaluation window of the MTH-method is still to be tested for the application of the ring data shown above.

### 3.4 ‘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 9.

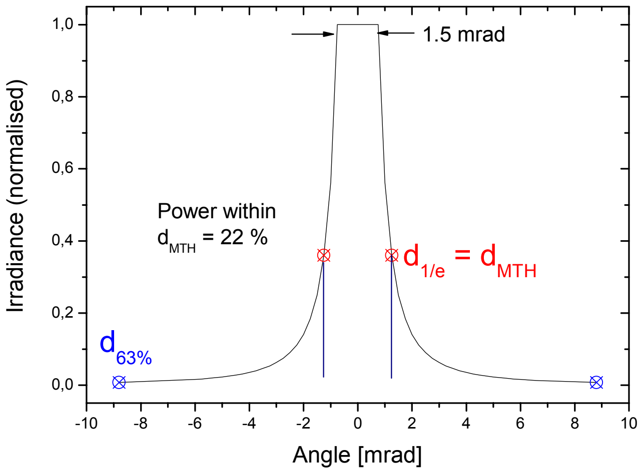


**Figure 9** For a retinal irradiance profile that is described by a ‘inverse of distance to the center squared’ dependence with a central top-hat portion, the maximum thermal hazard (MTH) method yields the same diameter $d_{MTH}$ as the 1/e diameter definition, however, this diameter only contains 22 % of the total power which is compared to the limit.

Figure 9 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-$\alpha$ equals 17.6 mrad. 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 $\alpha$ 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. Thresholds for pulse durations between 10 µs and 100 ms were calculated and are summarised in table 1 (again for optical properties that are typical for visible wavelengths).

Table 1 Comparison of calculated top-hat thresholds with thresholds for the $1/r^2$ profile shown in figure 9 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. It is noted that the second moment diameter is not defined for a distribution which falls with the rate of $1/r^2$.

### 3.5 Far field of instable resonator

The profile produced in the far field of an instable resonator, is shown in figure 10. 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 10.

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.

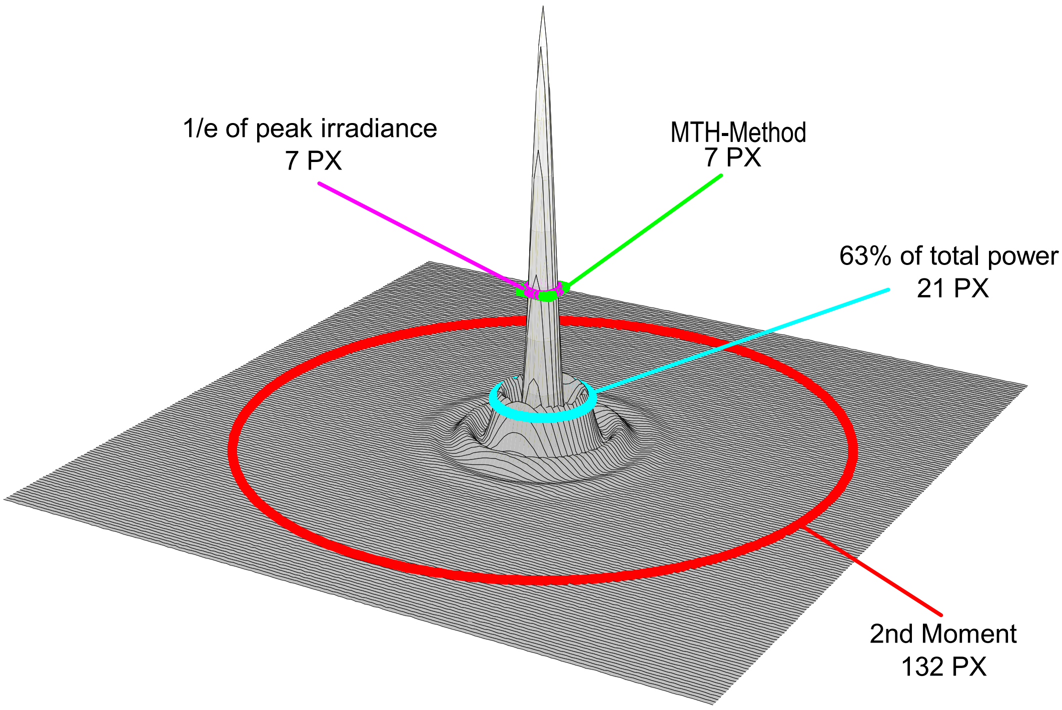


Figure 10. The far field irradiance distribution of an unstable resonator. The different diameter criteria are given in units of 'pixels' (such as those from a CCD camera).

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 [11]. This was also the reason why the application of the 2M method was not included in the scope of the original version of the ISO 11 146 standard but in later versions of the standard, this limitation of the scope was lifted. It seems clear from this discussion that to base the parameter $\alpha$ on the second moment for this distribution would grossly underestimate the risk for retinal thermal damage. Additionally, when the 2M diameter is used and a Gaussian beam profile is assumed for the calculation of how much power passes through an aperture, if the aperture is of the size of the central peak, the power that passes through this aperture in the far field of an unstable resonator can be grossly underestimated - the peak irradiance of the Gaussian with the same 2M diameter as shown for far field of the instable resonator is a factor of 180 smaller than the peak irradiance of the far field of the unstable resonator!

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. SUMMARY AND CONCLUSIONS

It is pointed out that the parameter $\alpha$, which is the parameter that scales the retinal thermal 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 where 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 contained in some way in the IEC 60825-1 and ANSI Z136.1 laser safety standard, as well as the standardized method of the second moment diameter are compared with a 'maximum thermal hazard' MTH-method that is proposed in this paper as a general method for the evaluation of retinal irradiance profiles. The criteria were applied to Gaussian, top hat and ring shaped profiles, as well as a profile described by a$1/r^2$ dependence and the far field profile of an unstable resonator. For each profile, thermal damage models were applied for a number of pulse durations and profile sizes.

The $d_{63}$ criterion does not appear appropriate in all cases, as it can underestimate the hazard by producing values of $\alpha$ which are somewhat too large. The 1/e criterion produces values of $\alpha$ which are conservative, sometimes by a factor of 3, but has the problem that it is not unambiguous (unique) in that for a highly structured profile it might well be that there are more than one positions where the local irradiance falls to below 1/e of the peak irradiance. The second moment method, while it is the only method that is actually well studied for beam propagation purposes and is also standardized, is in many cases completely unacceptable as basis for the determination of $\alpha$. The proposed MTH-method appears to yield acceptable results for all profiles and pulse durations that were analysed, with the exception for some cases of ring shaped profiles. Additional profile types, including non-circularly symmetrical profiles, are also to be used for thermal modelling and for a more general verification of the MTH-method in future studies to back up the proposal of the MTH-method to be specified in IEC 60825-1.

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