**ILSC® 2015 Conference Proceedings**

# Classification of extended source products according to IEC 60825-1

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**Reference information for this proceedings paper**

Title: *Classification of extended source products according to IEC 60825-1*

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Proceeding of the International Laser Safety Conference, March 23-26 2015, Albuquerque, New Mexico
Page 271-280

Published by the Laser Institute of America, 2015
Orlando, Florida, USA www.lia.org

# CLASSIFICATION OF EXTENDED SOURCE PRODUCTS ACCORDING TO IEC 60825-1

Paper #C101

***Reprint of conference proceedings with amendments***

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## Abstract

Since Edition 2 of IEC 60825-1, the classification of products such line lasers, scanners, DOE or others that produce an extended retinal image can be based either on a simplified analysis, assuming a small retinal image, or on an extended analysis, where the angular subtense of the apparent source needs to be characterized as well as the classification needs to be based on the "most restrictive position". Even though this concept is standardized for almost 10 years, uncertainties in the application are frequent and discussion of the concept in the form of examples should be helpful. It is emphasized that in many cases, there is not "one" apparent source associated to a given product, and that further distances can be more restrictive than closer distances, which is not intuitively known from conventional sources and is the very reason for the special procedure to be defined in IEC 60825-1.

## Introduction

### Historical Perspective

The concept of classification of extended sources defined in IEC 60825-1 Edition 2 (published in 2007) was discussed in a paper presented at the ILSC 2005 [1]. In the present paper, only a short summary is given of the concept as well as an example. The concept that was developed for the 2nd Edition of IEC 60825-1 was also maintained for Edition 3 of IEC 60825-1. In Edition 3 the parameter $\alpha_{max}$ became pulse duration dependent (see discussion in [2,3]) which further enhanced the significance of extended sources in terms of permitting higher emissions for the "safe" classes compared to an analysis assuming small sources and $C_6$=1.

The basic concept of extended sources was also described in the "Laser Safety" textbook [4] published at the end of 2003, including results of beam propagation modeling. The beam propagation model (a concept which was promoted for laser safety by Brooke Ward, an expert of ISO TC 172 working on beam propagation standardization [5]) was used for laser safety purposes in terms of calculating the power through the aperture and the angular subtense of the apparent source and to identify the most restrictive position (MRP; in some earlier publications this was referred to as the most hazardous position, MHP) and the most restrictive accommodation. The beam propagation model, where an analytical solution was developed by Enrico Galbiati [6], is very helpful to understand the basic principles and to show that further distances from the product can be more restrictive than closer ones. It also demonstrated that the *location* of the apparent source changes with the position in the beam, i.e. depends on where the analysis is performed. Consequently, the specification of Edition 1 of IEC 60825-1, "to perform the classification (including to determine $\alpha$) at 100 mm from the apparent source" was found to be logically flawed for extended source laser beams, because it implies that there is *one* specific given apparent source associated to the beam, independent from where it is determined. This is in more detailed discussed in the 2005 ILSC paper. In the "Laser Safety" book, published in 2003, the beam propagation method was promulgated also for non-Gaussian beam profiles, based on the work by ISO TC 172 and the 2nd moment definition of beam divergence and beam waist. However, further research into the 2nd moment definition in cooperation with Bernd Eppich from TU Berlin showed that for non-gaussian profiles, the 2nd moment diameter method can produce results that err to a severe degree [7]. Consequently it was necessary to conclude that the beam propagation model cannot be used to calculate $\alpha$ or the power that passes through the aperture for non-gaussian beam profiles (based on measurements of the 2nd moment beam divergence and beam waist as input parameters). The beam propagation model, as for instance discussed in the 2005 ILSC paper, is however, highly instructive to help understand and discuss the basic concept of the most restrictive position MRP. From the results of the model it can also be seen that for the retinal hazard wavelength range of 400 nm to 1400 nm, and $M^2$ = 1, i.e. for a zero order Gaussian beam, and also for $M^2$

values which are in the lower range, the solution is always that at the MRP the eye can accommodate to a position which results in a small source, i.e. $\alpha = \alpha_{min}$. Consequently, a high to medium quality beam (low $M^2$) is always to be classified as a small source, irrespective of the beam waist diameter and divergence. Only products such as arrays, "low quality" beams, line lasers, DOE, scanners and diffuse sources can represent extended sources, but for these, the $2^{nd}$ moment can err grossly when it comes to calculate the angular subtense and the power through the aperture from the $2^{nd}$ moment beam waist diameter and divergence and therefore the beam propagation model is of no practical value for specific products.

## Summary of Concept

For an understanding of the concept of classification of extended sources it is important to keep in mind that the critical quantity is not the AEL (implied here are AEL values that feature the factor $C_6$) alone but also the accessible emission AE, so that it is the ***ratio*** AE/AEL which is actually relevant for classification. This ratio could also be called "power to limit ratio", PLR, when it is appreciated that the AE and AEL can also be given as energy and not only as power.

For diffuse sources (i.e. a laser beam being incident from the back onto a diffusing material) it is clear from physical principles that the diffuse material, which completely scatters the laser radiation, can be considered the location of the apparent source, i.e. the smallest retinal image results (independently of the position of the eye in the radiative field) when the eye accommodates to the diffuse surface. If the diffusely emitting spot is large enough compared to the distance, it will present an extended source. This is the classical condition for extended sources for laser safety, i.e. a laser beam being incident on a diffuse surface contrary to viewing the (collimated) laser beam by looking into the laser beam. Consequently in some historical laser safety documents, small source conditions were also referred to as "intrabeam viewing" as at the time, contrary to nowadays, it was not appreciated that there are sources (such as line lasers) which also present an extended source for "intrabeam viewing". But diffuse sources are the simplest and best defined sources to discuss what an extended source is and how the angular subtense of the source is equal to the angular subtense of the retinal image, see Fig. 1.

According to IEC 60825-1 (starting with Edition 2) classification of laser products featuring extended sources is based on determining the angular subtense of the apparent source parameter α by variation of the accommodation of the measurement system that mimics the eye (between 100 mm in front of the eye and infinity) and variation of the position of the "eye" in the beam, starting with the prescribed minimal distance from the reference point, such as 100 mm from the scanning pivot point for condition 3 (the "unaided eye" condition).

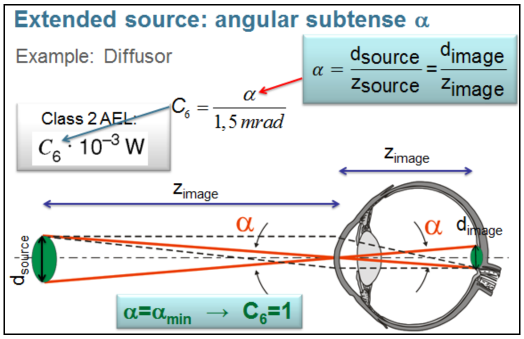



Fig. 1. Definition of α for the simple case of a diffuse source, assuming an air filled eye.

For each position in the beam, the accommodation of the "eye" (i.e. the measurement equipment used to mimic the eye) is varied to obtain different retinal images of the apparent source. Thus there is a series of retinal images for each position in the beam, and a series of positions in the beam making up a collection of retinal images. These images can be analyzed in a relative way (as pixel values) but they can also be calibrated in terms of laser power, where a certain pixel value of the CDD camera corresponds to a certain laser power value. Summing up over a part of the CCD array (over part of the image of the source) then results in the accessible emission (AE) that is associated to that area (as a partial power, i.e. a value equal to or smaller than what passes through the 7 mm aperture stop). The image analysis method specified in IEC 60825-1 to determine α and the respective AE will be discussed in more detail below. It is noted here that the image analysis method is – for each image, i.e. each accommodation state – also based on the concept of maximizing AE/AEL where the AE and AEL is determined for different parts of the image. The part of the image with the highest ratio of AE/AEL, for this image and accommodation state, is the solution of the image analysis and the result is for this image with index i the value of $\alpha_i$ and the partial power, $AE_i$. Thus, for one given position of the eye in the beam, the series of images obtained from varying the accommodation state has an associated list of $AE_i/AEL(\alpha_i)$ values. For the given position, the maximum ratio AE/AEL out of the list represents the critical accommodation and the respective "object" (which is typically virtual, except when it is a diffusor) is *for this position of the eye in the beam* the apparent source. It is noted that the apparent source can be different depending on the position in the beam, so that there is not necessarily "one" apparent source associated to a given product as it is for a diffusor.

More importantly, analyzing the ratio AE/AEL for different positions, where for each position the accommodation is varied to determine the worst case accommodation, further distances can be more critical than closer ones. Therefore, classification of extended sources requires varying the position of the "eye" in the beam. Thus the concept is that both the AE as well as the AEL is determined in pairs at various positions in the beam and for each position, for varying accommodation states. The Most Restrictive Position MRP (implying to consider the most restrictive accommodation) is identified where AE/AEL is maximum overall, i.e. for all relevant position in the beam and all relevant accommodation states, and this AE and AEL is then used for classification (Fig. 2).

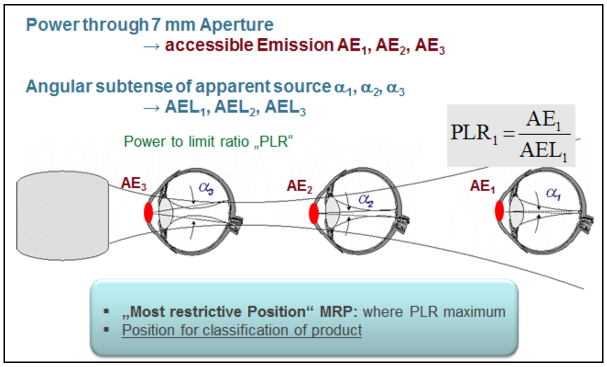



Fig. 2. Sketch of the concept of classification of extended sources according to IEC 60825-1. The eye represent the measurement system that is made up of an aperture stop, an imaging lens and a CCD camera, where for each position in the beam, the accommodation of the "eye" is varied by varying the distance between the CCD camera and the lens.

The advantage of this concept is that it is not necessary to discuss or determine "what" the apparent source of the product is, and often this is not possible because the location of the apparent source can depend on the position in the beam where it is determined (see Ref. [1]).

What is interesting to note is that while for sources such as diffusers, the MRP for Condition 3 is at 100 mm from the diffuser and further distances are less restrictive and the diffuser is always the apparent source, there are also cases where it becomes more restrictive (AE/AEL increases) to move away from the product, which is counterintuitive but possible and the classification method of extended sources considers this possibility. It is emphasized that to apply the extended analysis, i.e. to consider varying accommodation states from different positions in the beam is *optional*, as it is always permitted to assume that the source is a small source, then $C_6 = 1$ and the determination of the accessible emission can be simply determined at the given fixed minimal distance (such as 100 mm for Condition 3) measured from the reference point - this is referred to as the default simplified analysis. If the resulting classification is satisfactory, then it is not necessary to invest the effort to perform the full extended analysis. The extended analysis is an option to have significantly higher emission levels for the respective class (such as Class 1) as compared to the simplified analysis.

As was discussed in the paper of ILSC 2005, the retinal image is related to the irradiance profile in space at that position where the eye accommodates to. If the rays that make up the beam at the position where the eye is looking at, all enter the eye, then the retinal image is fully equivalent (in the optical sense of object and image) to the beam profile at the position where the eye is looking at. If some information (some rays) are lost by an obstacle in the beam or by the aperture of the "eye", then the image on the retina (on the CCD camera) will be different from the profile where the eye is looking at. This will be shown below with an example.

From this it can also be understood that the parameter $\alpha$ is only equivalent to the divergence of the beam (neglecting the problem of associating a value of $\alpha$ for non-gaussian beams here), when the eye accommodates to infinity. This can be understood considering that when the eye accommodates to infinity, the retina is in the focal plane of the eye's lens system and different positions on the retina are associated with imaging bundles of parallel rays that have varying incident angle. Thus the irradiance distribution on the retina characterizes the angular distribution of the beam, which is nothing else than the divergence.

It follows that the parameter $\alpha$ can never be larger than the divergence of the beam: since the parameter $\alpha$ has to be determined for all applicable states of accommodation, in case accommodating to a point closer than infinity results in a value of $\alpha$ larger than the divergence, then the eye just has to accommodate to infinity and then $\alpha$ equals the divergence.

## Field of view, Angle of Acceptance

The apparent source needs to be considered in terms of the retinal image, where another name for the retinal irradiance profile is "the image of the apparent source". In practice the image of the apparent source can be determined with a CCD camera and a lens with variable distance w.r.t. the CCD camera to mimic accommodation. If the CCD chip is in the focal plane of the lens, the accommodation is at infinity. It is not necessary to use a lens that has the same focal length as the human eye (which would be variable to accommodate) but it is necessary to use a 7 mm aperture for measurement Condition 3. In the CCD image, each pixel subtends a certain solid angle, and an area within the CCD image, when integrating power over that area, is equivalent to a certain field of view of the detector. This is equivalent to placing a field stop in the imaging plane, i.e. the field stop is realized by the integration area within the CCD image. The term used for the corresponding solid angle that is defined by the field stop is field of view (FOV), as it defines the solid angle in object space from which the system receives and detects radiation. The second relevant aperture is the aperture stop at the position of the lens, which is 7 mm for Condition 3. Together these two apertures define what part of the radiation is measured, which for laser safety classification is referred to as accessible emission AE. For additional discussion on imaging extended sources see for instance reference [8]. The plane angle that is spanned in one dimension in the image by the field of view is usually referred to as angle of acceptance and given the symbol $\gamma$. A rectangular FOV therefore has in terms of angle of acceptance an angular "length" $\gamma_x$ and "height" $\gamma_y$.

### Example

An interesting example that demonstrates the concept of the retinal image being related to the irradiance profile in space where the eye accommodates to, as well as that the MRP is some distance from the beam waist (which in effect is a cross-over point of three beams in the example below), is discussed in the following. The example device emits three collimated laser beams which cross over at some point in space. The laser beams can be assumed to be well collimated (i.e. divergence less than 1.5 mrad) with a beam diameter of for instance 1 mm at 1/e levels at the position where the beams cross.

First we discuss the retinal image when the eye is located in the arrangement so that all three beams pass through the aperture stop (pupil) of 7 mm, Fig. 3, assumed here to be 100 mm distance from the cross-over point.

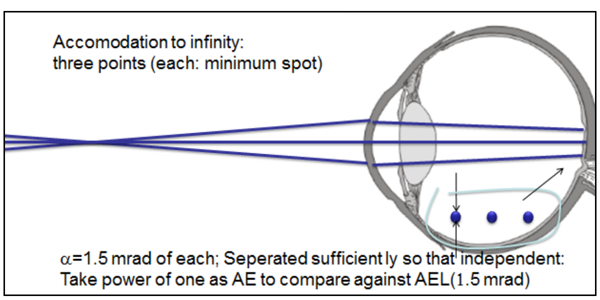



Fig. 3. Three collimated laser beams produce three small spots on the retina when the eye accommodates to infinity. The focusing for each beam onto a small spot on the retina is not shown.

When the eye accommodates to infinity, the retina is in the focal plane of the imaging system of the eye and each collimated beam is focused on the retina to a minimum spot, which is assumed to be 25 µm in diameter, i.e. $\alpha$ for each spot is equal to $\alpha_{min}$. This accommodation condition and position in the beam thus results in three small spots on the retina which are separated by the angular subtense that is equal to the angular separation of the beams in space. It depends on the spacing of the three spots if they are treated separately for laser safety, but usually they are (see analysis of array in next section below), so that the accessible emission here is the power of one beam that is 1/3 of the what totally enters the eye, and $C_6$ =1. The retinal image is here directly related to the irradiance profile in space at the position where the eye accommodates to, which is infinity.

Next (Fig. 4) we consider a position of the eye in the beam that is far enough away from the cross-over points so that the two outer beams no longer enter the eye, i.e. they are cut off by the 7 mm aperture. When the eye still accommodates to infinity, this will now produce one small spot on the retina. The laser safety analysis is the same as for the condition above, but the point here is that retinal image has changed. Thus this is an example where the retinal image is *not* directly related to the irradiance profile at the position in space where the eye accommodates to, because some "information" of the profile is lost due to the aperture.

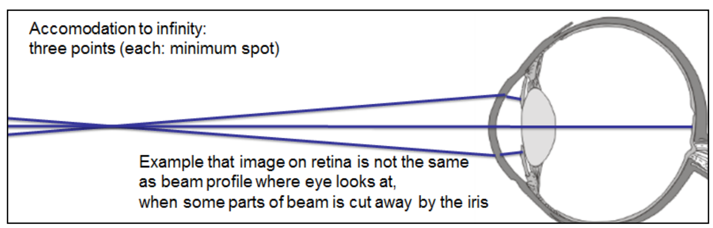



Fig. 4. Some further distance where the two outer beams are cut away by the 7 mm aperture.

The next analysis (Fig. 5) is for the case of 100 mm from the cross-over point, and the eye accommodating to the cross-over point. This means that the eye images the beam profile that is present at the cross-over point, which has a diameter of 1 mm diameter. This produces a value of $\alpha$ of 10 mrad and $C_6$ = 6.6. The image is thus one spot on the retina, but it has a diameter that is directly related to the diameter of the beam profile at the cross over point, and is an extended image. The accessible emission is a factor of 3 higher than in the above example (Fig. 3) where the eye accommodates to infinity. Due to the relatively large value of $C_6$, accommodation to the cross-over point at this distance is less restrictive than accommodation to infinity even though the AE is a factor of 3 higher, i.e. the ratio AE/AEL for accommodation to *infinity* is 1 over $C_6$ = 1 (1/1) and for accommodation to the cross-over point is 3 over $C_6$ = 6.6 which equals 0.45.

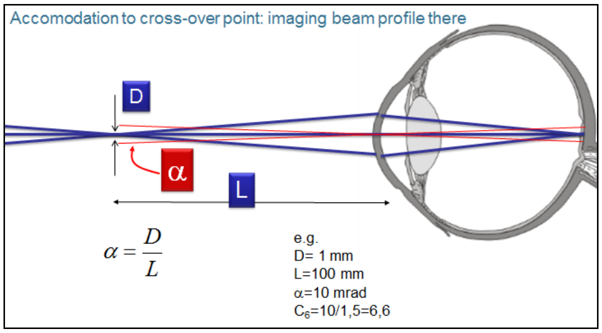



Fig 5. Accommodation to the cross-over point from 100 mm distance (eye not drawn to scale). The red lines are drawn at a wider angle than the diameter of the beam at the cross-over point to more clearly show the angular subtense of the source for this case.

When the eye moves further away, the image of the profile at the cross over point becomes smaller (and the AEL becomes smaller and more restrictive). As long as all beams pass through the 7 mm aperture, the accessible emission remains the same, and the ratio AE/AEL therefore becomes larger with further distance. This is a good example to understand how further distances from the product can be more restrictive: when the laser power that enters the eye remains the same or changes very little, but the angular subtense of the source when moving away becomes smaller, the ratio AE/AEL becomes greater. This was already learned from the beam propagation model and is also discussed in the Laser Safety textbook and in the 2005 ILSC presentation [1,4]. To the extreme, when the angular separation of the three beams is not great, the eye could move to a position of 660 mm from the cross over point, where the 1 mm profile is imaged onto a small spot, i.e. $\alpha$=1/660 = 1.5 mrad but all three beams still enter the eye, so this is a factor of 3 more restrictive (AE/AEL factor of 3 higher) as compared to the situation shown in Fig. 3. For the case of the beam angular separation not being that small that at 660 mm still all beams pass through the 7 mm aperture, the interesting position is the furthest position from the cross-over point where all three beams just pass through the aperture, and the eye accommodates to the cross-over point. Then the accessible emission is the power from all three lasers and $\alpha$ is correspondingly smaller as compared to closer positions. It depends where this position is and how large the beam diameter is at the cross-over point is, if this is the most critical condition or the condition where the eye accommodates to infinity. For instance, if all three beams still pass through the aperture at 300 mm from the cross-over point, then $C_6$ = 2.2 and AE/AEL = 3/2.2 = 1.36 and this position and accommodation condition would be more restrictive than shown in Fig. 3 where the ratio equals 1.

## Image Analysis to Determine α

The parameter $\alpha$ needs to be interpreted as a figure of merit that scales the retinal thermal AEL. Since the retinal image is an irradiance profile as a function of x and y axis, in order to determine the parameter $\alpha$, the two-dimensional irradiance information needs to be “collapsed” into one number. This calls for an image analysis.

Edition 1.2 of IEC 60825-1 in the appendix featured an example of an array of sources and how such an array was to be analyzed. An equivalent example is given in IEC TR 60825-14 (2004) as example B.9. The analysis is based on combining different parts of the apparent source (of the retinal image) and searching the most critical combination, which is nothing else then also searching for the combination with the maximum ratio of AE/AEL, where each combination features a certain AE (such as the power from a subassembly of 4 sources) and those four sources have a certain $\alpha$ associated to them, resulting in a certain AEL (the example was given for an MPE analysis, but the concept can be directly transferred to an AEL analysis where it is actually simpler as it is based on “power through the aperture”, or “power within a certain partial retinal image”).

It is noted that the figure shown in Edition 1.2 featured a circular aperture (see Fig. 6 below), but it is pointed out that this figure is the same as of Edition 1.0, and it appears to be an oversight that the figure was not adjusted to the method that is specified in the text of Edition 1.2, and also IEC TR 60825-14 (2004) still has that figure copied from Edition 1.0 of IEC 60825-1.

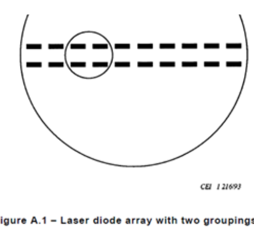



Fig. 6. Figure showing an arrangement of two rows of emitters with 10 emitters per row. The figure is to be understood as retinal image that needs to be analysed in terms of $\alpha$ and accessible emission that is compared against the AEL.

Under Edition 1.0, for an oblong apparent source such as a rectangular arrangement, $\alpha$ was not determined as the arithmetic mean, but $\alpha$ was defined to be taken as the *shortest* dimension, which in hindsight was needlessly restrictive. However, this explains why in Edition 1.0 the analysis area was shown as a circle in the figure. The text in Edition 1.2 and in IEC TR 60825-14 (2004), however, makes it clear that a *rectangular* field of view was intended, which is clear from the text just below the figure:

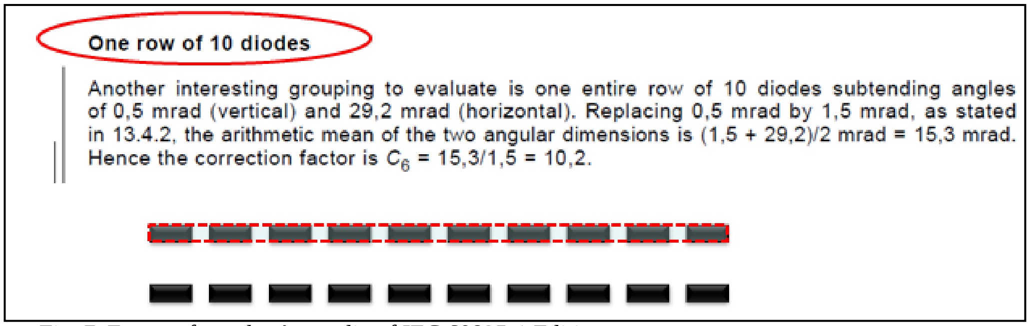



Fig. 7. Excerpt from the Appendix of IEC 60825-1 Edition 1.2 (the text). The sketch is not given with the red border in IEC 60825-1 but is added here to clarify which field of view is consistent with the text. With a circular FOV (shown in the figure in the example, copied from Edition 1.0) it would not be possible to select "one row of 10 diodes".

The method that is given in the example of Edition 1.2 and IEC TR 60825-14 (2004) is therefore to apply a varying field of view, i.e. varying areas of analysis within the image of the apparent source, to determine α for each area and the power that is associated with this area (a total power of "20 P" enters the eye or passes through the 7 mm measurement aperture, where P is the power that is associated as coming from one of the 20 sources). The method is summarized in Fig. 8.

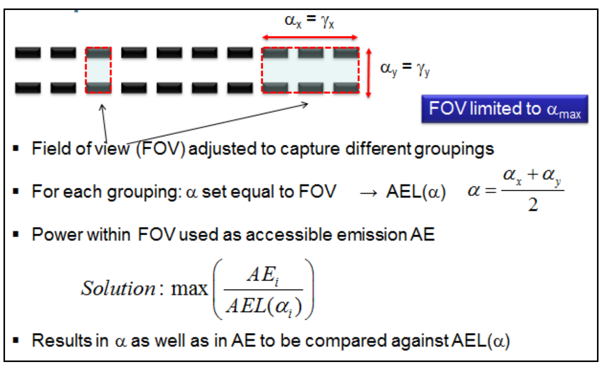



Fig. 8. Method defined by IEC 60825-1 Edition 1.2 and IEC TR 60825-14 in the Annex for the example of an array of sources.

It is important here that if the individual sources are far enough apart then the solution of the analysis is that one of the 20 sources results in the maximum AE/AEL then only the power that is associated to the one source is considered the accessible emission AE and is the quantity that is compared against the AEL where α is angular subtense of one element; in the example above that AE would be 1/20 of the power that passes through the 7 mm aperture stop.

For Edition 2 and Edition 3 of IEC 60825-1, the method defined in IEC 60825-1 was extended to apply that analysis method not only for arrays but generally for complex sources to determine - for a given retinal image of the source – both the parameter α as well as the accessible emission, which is the partial power that is within a field of view that is given by the critical integration area. For irregular sources, as was described by the example in IEC 60825-1 Edition 1.2 and by the example in IEC TR 60825-14 (2004), it is necessary to vary the angle of acceptance in each dimension, which results in effect in a rectangle as field stop. The method is in Edition 3 of IEC 60825-1 defined to analyze non-uniform or multiple apparent sources (Clause 4.3 d)) in the following way:

d) Non-uniform, non-circular or multiple apparent sources

For comparison with the thermal retinal limits, if:

– the wavelength range is from 400 nm to 1 400 nm; and

– the AEL depends on $C_6$

then if:

– the image of the apparent source does not have a uniform irradiance profile[3]; or

– the image of the apparent source consists of multiple points,

then measurements or evaluations shall be made for each of the following scenarios:

– for every single point; and

– for various assemblies of points; and

– for partial areas.

This is necessary in order to ensure that the AEL is not exceeded for each possible angle $\alpha$ subtended in each scenario. For the evaluation of assemblies of points or for partial areas, the angle of acceptance $\gamma$ is to be varied in each dimension between $\alpha_{min}$ and $\alpha_{max}$, i.e. $\alpha_{min} < \gamma < \alpha_{max}$, to determine the partial accessible emission associated with the respective scenario. For the comparison of these partial accessible emission levels with the respective AEL, the value of $\alpha$ is set equal to the angular subtense that is associated with the partial image of the apparent source.

Classification is to be based on the case where the ratio between:

– the partial accessible emission within a partial area over the angular subtense α of that area; and

– the corresponding AEL

is a maximum.

The angular subtense of a rectangular or linear source is determined by the arithmetic mean value of the two angular dimensions of the source. Any angular dimension that is greater than $\alpha_{max}$ or less than $\alpha_{min}$ shall be limited to $\alpha_{max}$ or $\alpha_{min}$ respectively, prior to calculating the mean.

## Circular Field Stop

It should be clarified that the method of maximising AE/AEL is not consistent with using only a circular field stop to determine α and the accessible emission, as it would in some cases result in values of α and AE that err too much on the unsafe side, as α would in this case always be the diameter of the circular FOV and would not be averaged for oblong sources (such a method would also not be consistent with the example given in IEC 60825-1 Edition 1.2 and IEC TR 60825-14 (2004) for the array).

In some scientific discussions it is pointed out that a circular FOV would be consistent with thermal heatflow which is argued to even out oblong irradiance patterns in terms of thermal profile. However, as can be shown with thermal modelling (thermal model validated against all applicable non-human primate data, see [9]), *at the threshold level*, the maximum temperature still occurs only within the exposed area and the injury, if it were to occur, would be located within the irradiated area only. It is only for super-threshold levels, i.e. exposure levels far exceeding the minimal lesion threshold, where the injured area were larger than the irradiated area. The thermal model was used to compare the injury threshold for 192 profiles (see these proceedings [10]) and two are shown in Fig. 9. It can be seen that the circular FOV (if it is used in terms of maximising AE/AEL and $\alpha$ is set equal to the diameter of the circular FOV) then the circular FOV always had a smaller safety margin. For 250 ms and 530 nm wavelength, in the extreme, the circular FOV had a safety margin of only 1.1 (which is difficult to justify as sufficient) while the rectangular FOV method, for the same profile (the profile which overall also produced the lowest safety margin for the rectangular FOV), had a safety margin of 1.6, which is not large but should be possible to justify as acceptable.

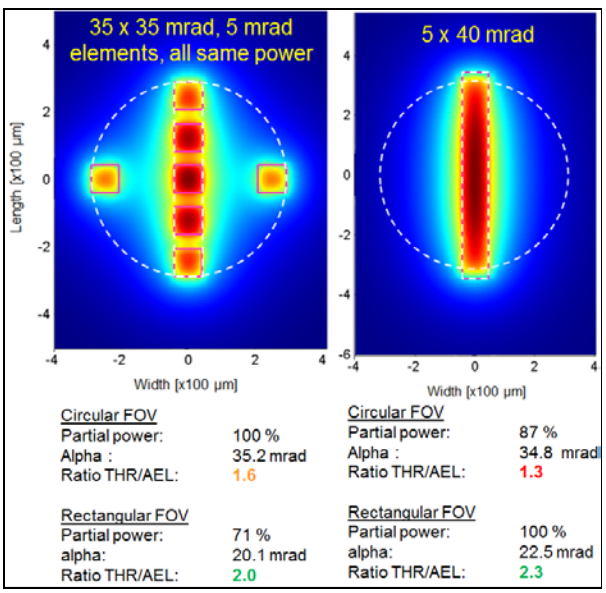



Fig. 9. Examples of two retinal images where the injury threshold were calculated (250 ms, 530 nm wavelength) and compared with the results of the $\alpha$ analysis using a circular FOV and a rectangular FOV (shown with white dashes).

To demonstrate the difference between using a circular aperture and a rectangular aperture (following the scheme given for the array as discussed above), we consider two bars with some length L such as 40 mrad and a minimal thickness, i.e. 1.5 mrad. The two bars are a distance D apart. Applying the rectangular method, we see that the PLR for <u>one</u> bar equals $PLR_1$ = 1/(L/2) = 2/L (neglicting the width against the length, so that $\alpha \approx L/2$ and assuming the power of one bar eqals 1) . The PLR for both bars is

$$PLR_2 = \frac{2}{\alpha} = \frac{2}{\frac{D+L}{2}} = \frac{2 \cdot 2}{D+L}$$

When we equate the two PLR, we find the critical distance D where for larger D, the two bars are treated seperately w.r.t. to AE and AEL and for shorter D, the two bars together are considered for the AE and AEL:

$\frac{2}{D+L} = \frac{1}{L}$ and we see that the critical distance D is L (having neglected the thickness of the bars, for a more accurate analysis this thickness would have to be added). Thus, if - according to the method using rectangular integration areas - the seperation of the two bars is wider than the length of the bar, they are treated seperately for the laser safety analysis.

When a circular FOV were to be used (Fig. 10), one case to analyse is a circle around one bar, with the power = 1, i.e. the PLR would be 1/L as L is the diameter of that circle.

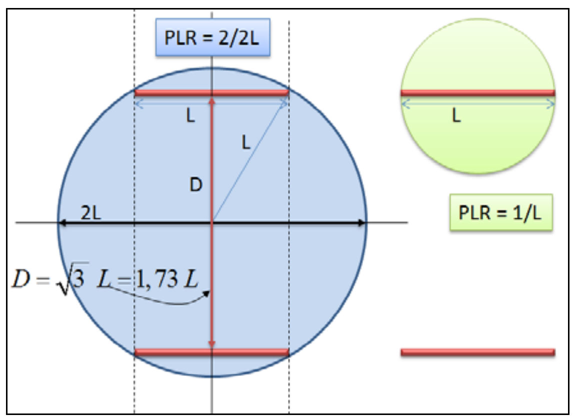



Fig. 10. Example of two bars with lenght L seperated by distance D. When analysed with a circular FOV they would need to be spaced by a distance 1.73 L to be treated as separate. This produces values of $\alpha$ which are too large and most likely do not have a sufficient safety margin.

For the case of a circle around the two bars it is easily seen (with a factor of two higher power within the circle) that the circle would have to have a diameter of 2L, to have the same PLR as the circle that fits around one bar. Only spacings of the bars larger than the corresponding value would result in one bar being more critical in terms of AE/AEL. With simple trigonometry, one can see, as shown in Fig. 10, that they would need to be spaced by a distance greater than D= √3 L = 1.73 L to be treated seperately, i.e. so that the AE/AEL for the case of circling both bars is less then the AE/AEL for case of circling one bar. This would be an example where the proponent of a circular FOV could say that $\alpha$ is to be determined in a second step, i.e. $\alpha$ is not the diameter of the circle, which would be 2L but in this case. For a method where $\alpha$ is determined in a second step, it would be obvious what the choice of $\alpha$ would be as there are clearly defined elements and borders and one would take (L+D)/2 as $\alpha$ (neglecting the width again). For the case that the distance of the bars is at the critical distance (or just a little closer) this value of $\alpha$ would be a factor of 1.35 higher (less restrictive) as for the rectangular critical distance of D = L. Also it should be noted that in many cases, the choice of $\alpha$ for the pattern within the circle is not so clear, as in reality patterns do not always have well defined borders and elements. Presently the author does not know of a generally applicable (when the elements are not so well defined) method to determine $\alpha$ as a second step, but it could be that there is one given in the paper in these proceedings by Dr. David Sliney on the topic of how to analyse irregular sources (ILSC 2015 Paper #602). The question then is if such a new method is in line with Clause 4.3 d) of IEC 60825-1 Edition 3. From the above example of the two bars - where the method with the rectangular FOV already has a rather small safety factor - for the circular FOV, the reduction of the safety margin by 1.5 when using the diameter of the FOV (2L) as $\alpha$ or when using the edge of the pattern $\alpha$ = (L+D)/2 by a factor 1.35 is producing a safety margin which is most likely not acceptable.

However, a circular field stop can be used also according to IEC 60825-1 when the retinal image is larger than $\alpha_{max}$, as the maximum dimension of the integration area is $\alpha_{max}$ and instead of using a square field of view with side “lengths” of $\alpha_{max}$, a circular field stop with a diameter of $\gamma = \alpha_{max}$ can be used, which is less restrictive. This is also the origin of Figure 1 in IEC 60825-1 Edition 3 (Fig. 11 here) where the field stop in the figure is “circular”.

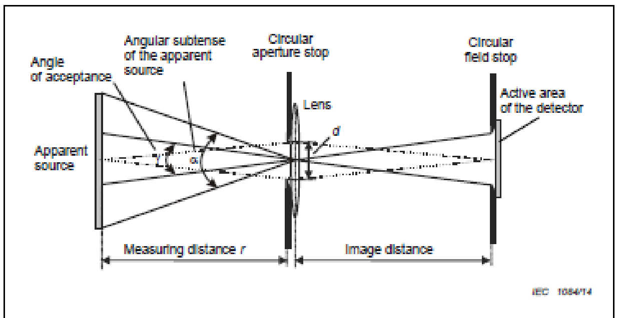



**Figure 1 – Measurement set-up to limit angle of acceptance by imaging the apparent source onto the plane of the field stop**

Fig. 11. Reproduction of Fig. 1 from IEC 60825-1 Ed 3.0.

A circular field stop is also intended to be used for the analysis with respect to the photochemical retinal hazard, where, however, only the maximum accessible emission is to be searched for that can be found with a given $\gamma_{ph}$ such as 11 mrad, and the AEL does not depend on a parameter associated to the retinal image size.

### Description of the image analysis method

#### Overview

The method defined in Clause 4.3 d of IEC 60825-1 Edition 3.0 is directly applicable to complex sources such as arrays, and is equivalent to the Example B.3 of IEC TR 60825-14 (2004), where different groups of diodes are analyzed as described also above, and the most restrictive grouping is applicable. Only a rectangular field stop is consistent with the text of this example; using a rectangular FOV with varying size and position within the image of the apparent source is also consistent with the requirement given in Clause 4.3 d where each analysis FOV is associated to a corresponding value of $\alpha$. When - as argued for in the paper and presentation by Dr. Sliney of these proceedings - a circular field stop were to be used and the position and diameter is varied to identify the maximum AE/AEL, the parameter $\alpha$ cannot be equal to the diameter of the circular FOV in the final determination of the AEL for the case that the image of the apparent source is not of circular symmetric shape (such as oblong sources or bars, arrays or other irregular sources); see above example of the two bars. In case a circular FOV is used to analyze non-circular image patterns in the sense of determining the maximum AE/AEL, the parameter $\alpha$ needs to be determined separately, i.e. in a second step. No guidance is given in the standard how this can be accomplished and to the knowledge of the author no guidance is available in the literature at the time of writing of this paper regarding how to determine $\alpha$ for irregular sources of arbitrary shape, as this “second step”, and how this ties together with the example that is given in IEC 60825-1 Edition 1.2 for arrays as the method that was used since then, and with the definition given in Clause 4.3 d) of IEC 60825-1.

As mentioned above, if the source is larger than the maximum field stop given by $\alpha_{max}$, then a circular field stop with a diameter equal to $\alpha_{max}$ can be used and $\alpha$ is set equal to $\alpha_{max}$, and the analysis method is reduced to moving the field stop across the image to identify the maximum accessible emission value.

In the following, the method that is consistent with Clause 4.3 d) and using rectangular FOVs is described in more detail. It is emphasized that alternative simplified methods to analyze the apparent source are permissible if it can be demonstrated that they are not less restrictive as the method as defined in Clause 4.3

d). The simplest one and most restrictive is to use the total accessible emission as determined with the aperture stop (or through a FOV which is equal to $\alpha_{max}$) and assume a small source. Another method is to neglect all parts of the image which are less than the 1/e value of the peak image irradiance and using the smallest of the remaining image feature to determine the size of $\alpha$, and using the total power as accessible emission.

For the case that the irradiance profile of the image is a Gaussian beam profile, according to definition 3.7 Note 1 to entry of IEC 60825-1, the $d_{63}$ beam diameter definition can be used to determine the value of $\alpha$ for this case. In this case, however, the total power (or energy; this distinction is not relevant for the present analysis and "power" or "irradiance" is generally used further on) that passes through the aperture stop is considered as the AE, i.e. there is not "partial AE" used in this case.

### Application of 4.3 d) for multiple or non-uniform image profiles

For multiple sources such as arrays or other complex sources, it is necessary to apply an analysis method which can be considered to be an image analysis method, which has the image irradiance profile as the "input" and the value of $\alpha$ and the value of the accessible emission that is compared against the AEL as the "output". It is noted that the power that passes through the aperture stop (i.e. 7 mm for measurement condition 3, placed at the imaging lens of the measurement system) is distributed across the image, so that the integral of the image irradiance profile across the whole image is equal to that power value. This is referred to here as $P_{total}$. The AE that is compared against the AEL can be equal to $P_{total}$ but for multiple or non-homogenious sources, it can also be smaller than $P_{total}$.

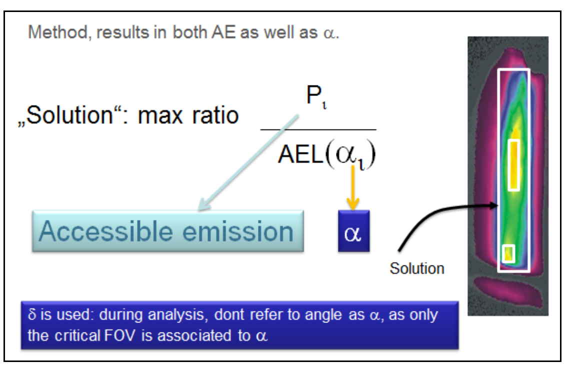



Fig. 12 Overview of image analysis method to identify the integration area (field of view) which features the maximum ratio of AE/AEL.

The analysis is specified in 4.3 d) to be based on varying the angle of acceptance $\gamma$ in each dimension (i.e. $\gamma_x$ and $\gamma_y$ when x and y are the coordinates in the image plane), in order to obtain a certain partial accessible emission that passes through the defined angle of acceptance. The angle of acceptance can be achieved by physical aperture stops, but more easily, when data from a camera is available, by considering certain integration areas in the image, which in 4.3 d) is referred to as partial image. Each integration area within the image is thus associated with an extent in x and y direction, as well as with a location within the overall image. The outer edges of the integration area are defined by the angle of acceptance, so that image areas outside of that range are not "accepted" in the measurement, which is nothing else than just integrating the irradiance distribution of the partial image within the integration area to obtain the partial power $P_k$ that is associated to the partial image with index *k*. The dimensions of the integration area that is defined by $\gamma_x$ and $\gamma_y$ is then also considered as angular subtense in the sense of $\alpha_x$ and $\alpha_y$ for the determination of the AEL($\alpha$) where $\alpha$ is the arithmetic mean, i.e. $\alpha = (\alpha_x + \alpha_y)/2$. Since at this stage different integration areas with index *k* are to be analyzed, this index is also used for the angular subtense that is subtended by the integration area. However, since $\alpha$ is really only the result of the image analysis as the angular subtense of the image that scales the retinal thermal AEL (i.e. it is the "thermal diameter" of the image), the usage of the symbol $\alpha$ is avoided for the variation of the integration area, because it is only the *critical* integration area that then produces the value of $\alpha$ that is associated to the image (as the solution of the image analysis). Here, for the process of identifying the critical integration area for the image by varying the position and dimensions of the integration areas, each integration area therefore has the associated angular subtense with symbol $\delta_k$ (and the critical one then has the angular subtense denoted with $\alpha$, which can be interpreted as the "thermal effective diameter" of the image)

The shape of the integration area is not specified in Clause 4.3 d) but in terms of achieving a certain integration area which is to be varied in each dimension, it is most practical to use integration areas that are limited by straight edges, which then form a rectangle in the general case. If the image profile is a top-hat or some other circular profile, it is also possible to use a circular integration area, which would for the same value of $\delta$ result in a smaller partial AE as compared to a square integration area and be less critical. According to Clause 4.3 d) the dimensions of the integration area (the integration rectangle) are to be varied in each dimension between $\alpha_{min}$ and $\alpha_{max}$. Also, the positions of the integration rectangles within the image have to be varied. This procedure thus results in a number of paired parameters of $P_k$ and $\delta_k$ for each integration area indexed *k*. The value of $\alpha$ associated to the respective image and the associated partial AE as the solution of the image analysis is obtained by identifying the integration area with the maximum ratio of $P_k/AEL(\delta_k)$. The principle is shown in the Fig. 13 and Fig. 14 below.

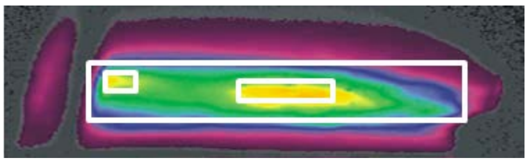


Fig. 13. Example of an image (irradiance level with false colours), showing three different integration areas. The integration areas are delimted by the angle of acceptance $\gamma_x$ and $\gamma_y$. Each has an associated value of partial power $P_k$ which is obtained by integration of the image irradiance inside of the angle of acceptance (also referred as the field of view).

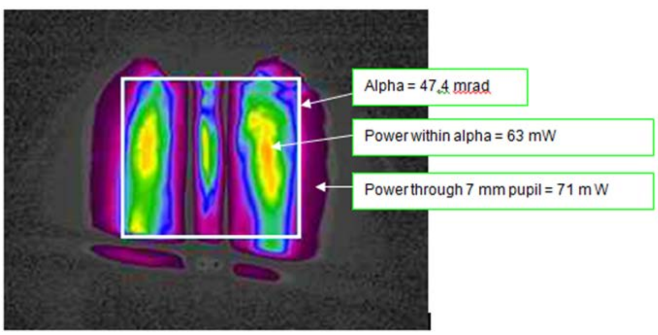
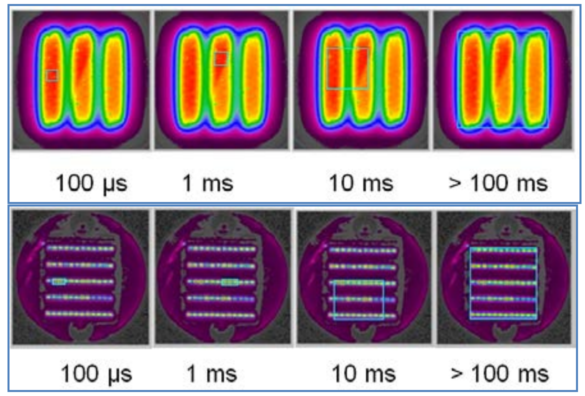



Fig. 14. Example of the result of an analysis, i.e. showing the critical rectangle which produces the maximum ratio of $P_k/AEL(\delta_k)$; this value is used as $\alpha$ associated with that image. Only the partial power inside the rectangle is used as AE (here called "power within alpha"), not the total power that passes through the 7 mm aperture.

This method appears somewhat complex, but it is a relatively simple method in principle and is the exact equivalence (applied generally to irregular retinal image profiles) of the method specified for solving the example of an array in edition 1.2 of IEC 60825-1, "complex diode array", Annex A.2-4 but also the same example in IEC TR 60825-14 (2004).

## Examples

Since $\alpha_{max}$ depends on the pulse duration (or temporal integration duration), the results of the image analysis for a given image irradiance profile can be different for different pulse durations. The following image series show the result of the critical rectangle for different pulse durations.




## Acknowledgment

We gratefully acknowledge funding of the comparison of the image analysis method with injury thresholds by LIPA, the Laser Illuminated Projector Association.

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