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WHITE PAPER

Extended Source AEL Analysis of Scanned Laser Emission for IEC 60825-1

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CONTENT

1 SUMMARY

This white paper discusses the classification of scanned laser emission, as defined in the international laser product safety standard IEC 60825-1:2014. The emphasis lies on the AEL analysis of a scanning product as Class 1 in the retinal thermal hazard regime of 400 nm to 1400 nm, particularly the classification as extended source. Issues related to faults are not discussed. The systematic approach for an AEL analysis presented in this white paper should also be useful for extended apparent sources when they do not originate from scanned emission.

A scanned emission can result from scanning one or more beams with one or more mirrors, but also for an array when the elements of the array are emitting at different times.

For a well collimated beam, the retinal image for accommodation to infinity is small. For a mirror-scanner, for accommodation to infinity, this small retinal image scans across the retina with the same angular scanning speed as the beam in real space. Similarly, accommodation to the apparent location of an array produces a time-varying retinal image pattern when different elements of the array emit at different times. In this white paper, we use the abbreviation TVRI for time-varying retinal image patterns, i.e. time-varying retinal image irradiance distributions. The distinctive feature of a TVRI is that different parts of the image vary in time differently. There is no established terminology, and other terms could be non-stationary retinal image, or dynamic retinal image. It is also common in laser safety to refer to the apparent source instead of the retinal image, such as non-stationary apparent source, although that can lead to misconceptions.

For a mirror scanner, at sufficiently close distances, for accommodation to the mirror, the retinal image is extended (depending on the distance to the mirror) but stationary on retina, i.e. incident on the same location of the retina. It depends on the beam parameters and scanning parameters whether accommodation to infinity or accommodation to the mirror is more restrictive in terms of limiting the emission to Class 1 levels.

An AEL analysis for the example of a scanning mirror demonstrates the importance of considering both accommodation to infinity and accommodation to the pivot point (i.e. the mirror) of the emitted beam. The example also shows that it is important to not only perform the AEL analysis at a distance of 100 mm from the pivot point but also further away, as required by IEC 60825-1:2014 for the extended analysis. For scanners, often a distance further than 100 mm is the most restrictive one. That is, the distance where the ratio of accessible emission to the AEL is maximum, is found at some distance further than 100 mm from the pivot point.

So far, a detailed discussion of how to analyse TVRI (such as scanned retinal images) is not available, neither in IEC 60825-1:2014, IEC TR 60825-13:2011 (which is based on Edition 2 of IEC 60825-1), nor in other publications.

The method discussed in this white paper follows the general principles and requirements of IEC 60825-1:2014, such as that the accessible emission (AE) has to be below the AEL for all emission durations, as well as that the retinal image has to be analysed with varying angles of acceptances, in the sense of an image analysis. The multi-pulse reduction factor C_5 is applied in a more general way as compared to the recommendations found in the Interpretation Sheet 1 on IEC 60825-1: the "long-term" α that is used to decide which C_5 to apply, is determined for the long-term averaged retinal image irradiance pattern. Also, for TVRI it seems prudent to include C_5 in the retinal image analysis (variation of the angle of acceptance) for the determination of AE/AEL.

It should be noted that the method described in this white paper is not to be interpreted as definitive in terms of a formal guidance of how to perform an AEL analysis for scanned retinal emission to achieve Class 1 classification. The paper discusses a *possible* way of analysis that is seen by the author as compliant with the generic principles of IEC 60825-1. There might

be alternative methods that are also compliant with the principles of IEC 60825-1. It also should be noted that the method as discussed has not been compared against injury thresholds and therefore relies on an appropriate safety margin between the AEL of Class 1 when the generic principles as given in IEC 60825-1 are applied.

Finally, even for extended retinal images that do not vary in time (i.e. stationary retinal images) can an AEL analysis be complex and involved, particularly for pulsed emission. To apply the extended analysis as discussed in subclause 5.4.3 of IEC 60825-1 is optional. It is possible to assume that the retinal image is small and to base the classification on this simplified worst-case assumption (5.4.2 “Default (simplified) evaluation”). The difference in terms of analysis effort is often substantial. The advantage of investing the effort into an extended analysis is that a higher emission level is permitted for Class 1 or Class 2, resulting for instance in a wider detection range for pattern projection 3D cameras, or a better visibility for line alignment lasers, as examples for extended sources with stationary beams.

For *time-varying* retinal images, such as from scanners, the difference in complexity and effort for the analysis - but also in terms of permitted emission level - is even more pronounced. When the reader of this white paper is frustrated by the effort, it should be kept in mind that it is also valid to classify a scanner based on a stationary beam, which has the advantage that a scanning safeguard is not necessary to cover faults of the scanning mechanism. The analysis for the stationary beam can be done as extended source, in case the beam qualifies as an extended source (such as a line laser), or again with the simplified default analysis assuming a small retinal image. This is the simplest but also the most restrictive analysis and classification. The next level is to consider the scanning of the beam across the 7 mm aperture stop to result in a pulsed accessible emission (i.e. one pass across the aperture stop results in a pulse, or in a group of pulses when the emission from the laser is pulsed), but to assume a minimum and stationary retinal image. This method is still drastically less complex and less cumbersome as compared to the analysis of a scanned emission as extended source, but permits a higher emission level as compared to the assumption of a non-scanned beam.

2 GENERAL ISSUES

Congruent with ISO and IEC standard regulations, a decimal comma is used in this paper, in contrast to the usual usage of a decimal point for texts in English language (i.e. ½ = 0,5 in this paper, and not 0.5). Abbreviations used in this white paper are summarised in Table 1

Table 1. Abbreviations used in this white paper.

AE	Accessible emission. Whenever the text refers to AE, the accessible emission determined with the rules defined for Class 1 and the retinal thermal limit is meant.
AEL	Accessible emission limit. Whenever the text refers to the AEL, the AEL of Class 1 is meant, unless otherwise noted.
FOV	Field of view; the FOV is defined by the angle of acceptance in vertical and horizontal direction, respectively.
FWHM	Full width at half maximum; definition of the emission duration for a pulse, or pulse train, to be determined with the half-peak power points.
MRP	Most restrictive position; position where the ratio AE/AEL is maximum.
TVRI	Time varying retinal image; a scanned retinal image or otherwise time-varying retinal image profile.

The discussion refers to IEC 60825-1:2014, i.e. Edition 3.0 of IEC 60825-1 [1]. Whenever the text of this paper refers to IEC 60825-1, Edition 3.0 is meant. Sometimes the text only refers to "the standard".

For scanning emission, the application of Condition 1 of Table 10 is not required in the current edition[1] of IEC 60825-1, only Condition 3, which in the wavelength range of interest is given as 7 mm aperture stop at distances of 100 mm from the reference point and further. Thus, all of the discussion in this White Paper refers to Condition 3 in the wavelength range of 400 nm to 1400 nm. The emphasis will be on retinal thermal limits. The analysis for retinal photochemical limits as additional limit for Class 1 classification in the blue and green wavelength range is relatively straightforward and will be included in the example of an array.

With "AEL analysis", the determination of the accessible emission (AE) and the determination of the AEL, both for the case of extended retinal images, is meant. The AE is determined with a 7 mm aperture stop and an imaging system to mimic the eye. The imaging system is necessary to achieve different accommodation distances of the eye and to determine the respective retinal images. These retinal images then need to be analysed.

"Accommodation" refers to the eye imaging different object distances. Therefore, the accommodation distance is the same as what is referred to object distance in optics. The image distance in the human eye is normalised to 17 mm for an equivalent air-filled eye. Accommodation in the human eye is affected by adjustment of the focal length of the lens. The standard defines accommodation to be varied between 100 mm in front of the location of the 7 mm aperture stop, to infinity. When infinity is imaged (referred to also as accommodation

[1] Condition 1 might be required to be applied in future editions of IEC 60825-1.

to infinity) the focal length of the lens system of the eye equals 17 mm. For accommodation to 100 mm in front of the eye, the focal length of an air-filled eye equals 14,53 mm, resulting in the image being located 17 mm behind the lens system of the eye. For a measurement setup with a lens and a CCD camera to record the image (or other types of detectors in the image plane), the focal length of the lens is fixed, and is usually larger than in the human eye. In this case, the adjustment of the accommodation has to be achieved by variation of the image distance, i.e. the distance between the CCD camera and the lens. A 7 mm aperture stop is to be placed on the lens of this "artificial eye".

IEC 60825-1:2014 for the wavelength range of 1250 nm to 1400 nm requires that the AEL is limited to Class 3B (see the footnote in the AEL tables). Similarly, in subclause 7.13, a warning label is required if Class 3B levels are exceeded at the closest point of human access. These additional issues are not in the scope of this white paper, but see for instance reference [2].

It is assumed that pulse durations are longer than 10 ps, so that the constant AEL up to T_i can be used. In order to simplify the text, instead of referring to T_i in the general way, the wavelength range of 400 nm to 1050 nm is implied so that the text can refer to 5 µs.

For information on Amendment A11:2021 to EN 60825-1:2014, see our white paper [3] under this link. With the exception of emission in the wavelength range of 1250 nm to 1400 nm, amendment A11 does not feature requirements that are relevant for scanners.

Discussion of compliance with EN 50689:2021 for consumer laser products in Europe [4] is not in the scope of this white paper. EN 50689:2021 is discussed in our respective white paper [5] (link).

3 DEFINITIONS AND EXAMPLES OF SCANNED EMISSION

3.1 Scanning laser radiation

Definition 3.98 of IEC 60825-1 defines “scanning laser radiation” in the following way:

> laser radiation having a time-varying direction, origin or pattern of propagation with respect to a stationary frame of reference

Scanning laser radiation that is discussed in this white paper have a time-varying direction, such as affected by mirrors or when an array is projected.

The definition 3.98 includes products where the whole laser product is moving, such as a laser product mounted on a car or a drone. This type of scanning laser radiation is not in the scope of the discussion of this white paper. IEC Technical Committee 76 is working on a Technical Specification IEC TS 60825-19 that deals with these types of products, referred to as moving platforms.

The determination of the class of the product, i.e. the determination of the AE and AEL can be based on the scanning nature of the emission, producing a pulsed accessible emission when the beam scans across the 7 mm aperture stop. Alternatively, as worst-case simplified assumption, the classification can be based on a hypothetical stationary beam. The result of accounting for the scanning nature of the emission is that measurement Condition 1, which simulates accessible emission through binoculars and small telescopes, does not need to be applied according to the current and previous edition of IEC 60825-1 (this might change in future editions of the standard). Another result is that a scanning safeguard is necessary (subclause 6.11) to cover the case of reasonably foreseeable faults of the scanning nature of the emission.

When the scanning nature of the beam is accounted for in the classification of the product, then there is the choice of either applying the “Default (simplified) evaluation” (subclause 5.4.2 of the standard) with α = 1,5 mrad and C_6 = 1, or to perform an analysis as extended source (subclause 5.4.3), i.e. an analysis as extended source, including of the TVRI.

3.2 Reference point

The reference point is the point associated to a laser product used to determine the distance of the 7 mm aperture stop. For a setup to determine the retinal image, the 7 mm aperture stop is located on the imaging lens for that setup. In practice, often the energy pattern passing through the 7 mm aperture stop is determined with a radiometer and/or oscilloscope and the retinal image information is used as *relative* retinal irradiance pattern to determine both the angular subtense α needed for the AEL, as well as the effect of a limited angle of acceptance on the AE. **In any case, the location to determine the AEL and the AE has to be always seen in pairs, i.e. the same location and orientation**.

Table 11 of IEC 60825-1 lists reference points for Condition 3.

For “Scanned emission (including scanned line lasers)”, the reference point is the “Scanning vertex (pivot point of the scanning beam)”.

Thus, for the example of a mirror effecting the scanning, the location of the mirror is the pivot point of the scanning beam and thus the reference point. When the product features a lens to modify the scanning angle, a virtual location of the mirror, as virtual pivot point of the emitted beams results. The pivot point is found by extending the emitted beams into virtual space and identifying the location where they cross over (see subsequent subchapter).

For an array being projected, the pivot point, and therefore the reference point for the determination of the classification distance, is the exit pupil of the projection lens. This will be discussed further below in the subchapter on projected arrays.

3.3 Mirror scanner

Figure 1 shows the schematic of a collimated beam being scanned by a mirror. In this figure, the eye is assumed to accommodate to infinity. The eye is shown here as representative of the imaging system to determine the retinal irradiance pattern, consisting of an imaging lens (in the eye the combination of cornea and lens), the aperture stop (in the eye, the pupil), and an imaging plane (in the eye, the retina). For classification, instead of the pupil, a 7 mm aperture stop is defined.

When the angular scan range of the beam that is incident on the eye is larger than the 7 mm aperture stop, then scanning across the 7 mm aperture stop results in a pulsed accessible emission pattern in terms of power detected as function of time behind the 7 mm aperture stop. Additionally, the laser emission is often pulsed in its own right, resulting in groups of pulses detected through the 7 mm aperture stop.

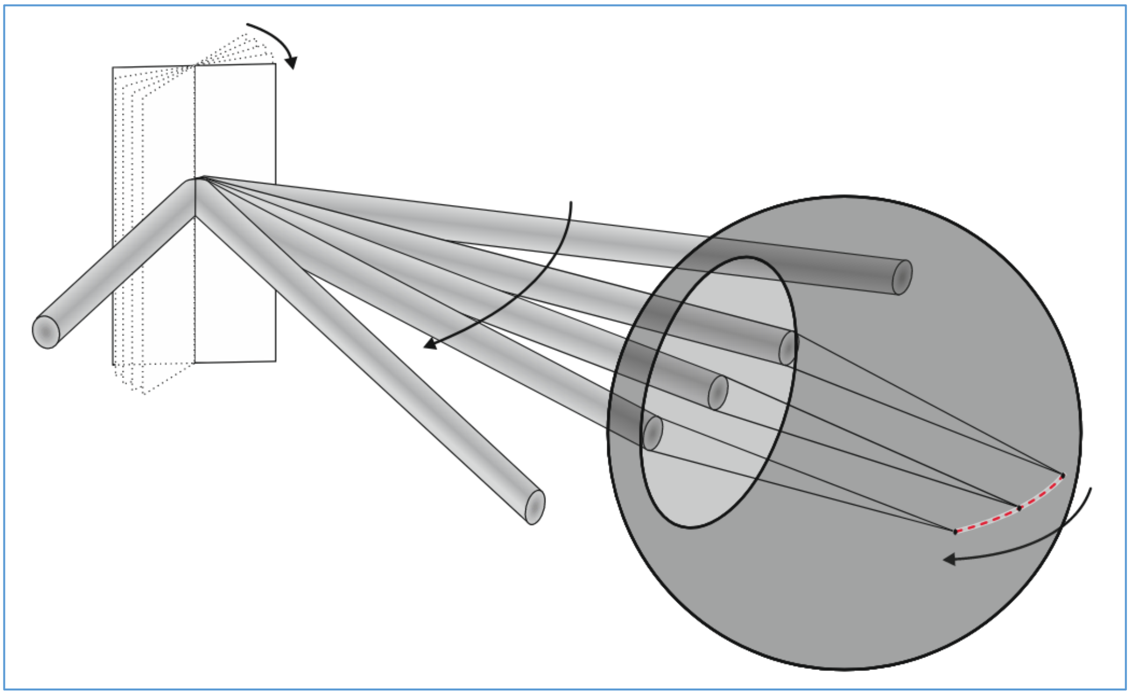

Figure 1. Schematic showing a collimated beam scanned by a mirror, and a conceptual eye for accommodation to infinity. For a collimated laser beam, a minimum retinal image results for accommodation to infinity. The scan path across the retina is shown by a red dashed line.

For accommodation to infinity, or generally for accommodation to distances beyond the mirror, the eye extends the beam "information" that is available from the beam that is incident on the eye to beyond the mirror into virtual space. This is schematically shown in Figure 2.

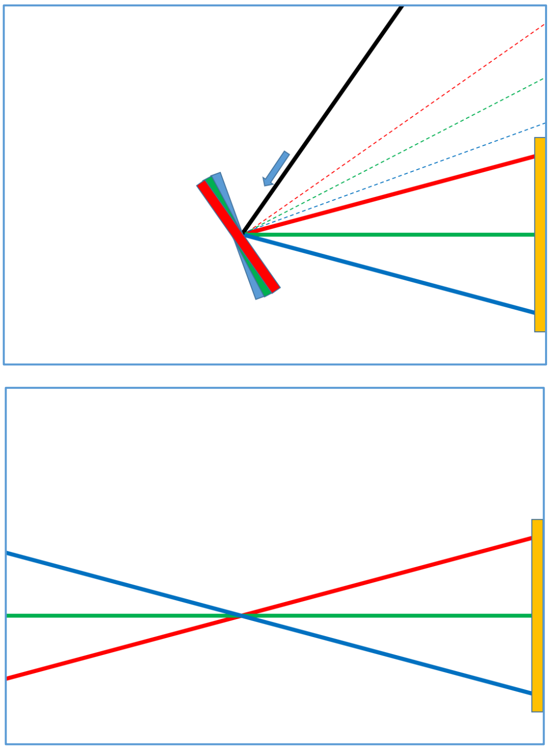

Figure 2. On the top, the black coloured beam is incident on the mirror. The different mirror positions and respective reflected beams are shown with varying colours. For each, the dashed line is the normal to the mirror surface. The beams that are incident on the eye (the location of the aperture stop is indicated by the orange bar) provide the only “information” that is available to the eye in order to form the retinal image. Thus, for accommodation to beyond the mirror, one can imagine that the eye extends the beams beyond the location of the mirror into virtual space, as shown in the bottom figure. The location of the pivot point is where the beams cross over.

For accommodation to infinity, the angular distribution of the retinal irradiance pattern is equal to the angular distribution of the beams in virtual space behind the mirror (for a detailed discussion, see [6]). This applies both to the scanning angular speed as well as to the retinal image associated to the beam, that is scanning across the retina. The angular distribution of the beam behind the mirror in virtual space is the same as the angular distribution of the actual beam in real space. In other words (when the same criteria for the angle determination are used, such as the 1/e points for a Gaussian profile), the angular subtense of the retinal image associated to the beam is equal to the divergence of the beam (see Figure 1 in reference [6]). For a sufficiently well collimated laser beam, the angular subtense of the retinal image, also referred to as angular subtense of the apparent source α, is equal to α_{min}. This (small) retinal irradiance profile scans across the retina with the same angular speed as the beam that scans across the 7 mm aperture stop. For a well collimated beam with a diameter small compared to the 7 mm aperture stop, such as for example 1 mm, the angular extent of the scan path on the retina is equal to the angle that the 7 mm aperture stop subtends as seen from the pivot point (compare again Figure 1 of [6]). For instance, for a distance of 100 mm from the pivot point, the 7 mm aperture stop subtends 70 mrad and that is at the same time the angular subtense of the extent of scan path on the retina. This relationship has the same origin as the 7 mm aperture stop determining the angular extent of the line image of a line laser for accommodation to infinity, as discussed in reference [6]. When the beam that is incident on the 7 mm aperture stop is larger than the aperture stop and partially incoherent, the scan path can be wider than the limitation by the 7 mm aperture stop, i.e. it can be wider than 70 mrad at 100 mm distance.

It was always recognised (see for instance Henderson Schulmeister 2004 [7]) that in the general case the scan path cannot be used to determine the parameter α for the AEL determination. For emission in the visible wavelength range, to look into a scanned collimated beam that is for instance scanning horizontally (the power level being reduced to levels for comfortable viewing and safety) is misleading in terms of angular subtense of the retinal image. When looking into the scanner from close distance, the eye accommodates to infinity and the visual perception is a line, as the temporarily averaged retinal irradiance profile. However, this line cannot not be used to determine the value of α for the classification of the product. In terms of temperature rise in the retina, there is a substantial difference between a small irradiance profile scanning across the retina, such as along a line path, as compared to a line shaped irradiance profile with the same line length and total power entering the eye. Unless the scan speed is extremely fast, the retinal irradiance and the temperature increase for an actual line shaped profile is much smaller as compared the retinal irradiance and the temperature increase for a minimum retinal image that is scanning across the retina (for the same power entering the 7 mm aperture stop). To explain this issue in simple terms, the comparison with a laser spot welder is used: for welding, the beam is focused onto the workpiece and scanned, rather than projecting a line shaped laser profile onto the workpiece.

The case for accommodation to the mirror is schematically shown in Figure 3. The irradiance profile that is present at the location of accommodation is the basis for the retinal image. For a more detailed discussion of extended sources, see for instance our ILSC 2015 paper [8]. In short, where the eye accommodates to is the location of the virtual object, resulting in a respective retinal image, with due consideration of the potential effect of the 7 mm aperture stop on the retinal image [6]. Due to the 7 mm aperture stop, in some cases, the retinal image irradiance profile is *NOT* equivalent to the irradiance profile at the location of accommodation. This is then an example where the term "angular subtense of the apparent source" for the parameter α can be misleading, and it should be really referred to the *retinal image* for the determination of α rather than the apparent source. The term angular subtense of the apparent source is still not incorrect when "apparent source" is understood as some hypothetical object at the location of accommodation that results in the respective retinal image. However, such a work-around for an inappropriate term can be avoided in the next edition of IEC 60825-1 when the term "angular subtense of the image of the apparent source" is used, or "angular subtense of the retinal image".

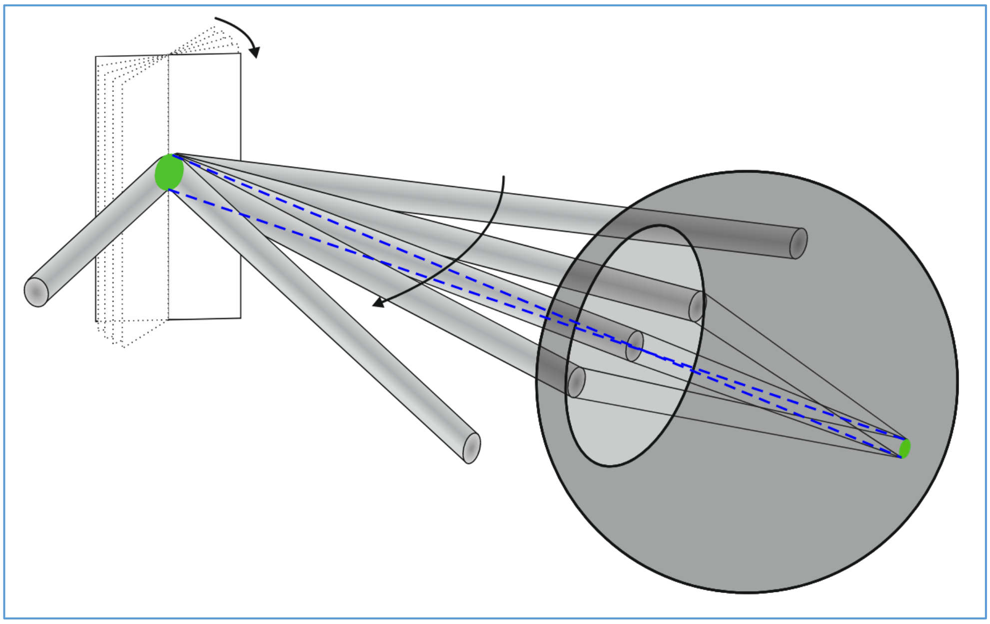

Figure 3. The same emission as in Figure 1, but now the eye is assumed to accommodate to the mirror.

In Figure 3, for accommodation to the mirror, the case of the laser beam being smaller than the aperture stop is shown, so that the retinal irradiance profile is the conjugate of the irradiance profile at the mirror. In this sense, when applying the appropriate diameter definition, α is both the angular subtense of the apparent source (which is the irradiance profile at the location of the mirror) and of the image. When the diameter of the irradiance profile at the mirror (assumed to be a top-hat irradiance profile so that diameter definition discussion can be avoided) is for instance equal to 1 mm, then for a distance of 100 mm between the 7 mm aperture stop and the mirror, α = 1 mm/100 mm = 10 mrad. When the irradiance profile at the 7 mm aperture stop is larger than the aperture stop, the aperture stop in many cases (not always) affects the retinal image. The irradiance profile at the retina is then smaller than for the case that the aperture stop and lens is larger than the beam. In this case, α cannot be calculated simply with the extent of the irradiance profile at the mirror but needs to be determined by measurement or ray tracing with due consideration of the effect of the 7 mm aperture stop. The potential impact of the 7 mm aperture stop on the retinal image is discussed in more detail with the example of three beams in the 2015 ILSC paper [8] and for partially coherent beams in the 2019 ILSC paper [6].

Accommodation to the pivot point is the only location in the beam path where accommodation to this location results in a stationary retinal image, i.e. not moving across the retina. In some systems, such as when the reflecting surface is not coincident with the rotation axis and the beam is incident towards the edge of the mirror, there is no actual pivot point in the strict sense, where all the reflected beam cross over and where accommodation to that position results in a completely stationary retinal image. In other words, the location where the beam is reflected might “wobble” around to some degree (in scanning direction but also in terms of distance to the 7 mm aperture stop). However, usually this effect is relatively small and in order to reduce complexity it is advantageous to assume in the analysis that there *is* a pivot point and the retinal image is stationary. In principle, the wobbling effect could be analysed based on the principle below of varying the accommodation of the eye and to perform the respective multi-step analysis for the resulting TVRI.

It depends on the beam parameters and the scanning parameters whether accommodation to the pivot point or accommodation to infinity is associated to the more restrictive ratio of AE to AEL and thus limits the permitted emission level for the product to be Class 1. For a systematic analysis that covers all variations, also accommodation to in-between infinity and 100 mm should be considered.

In an analysis as extended source, it is important to also consider distances further than 100 mm from the reference point. This will be shown in an example in chapter 6.

3.4 Array

3.4.1 Array without projection lens

An array is a classic example of an extended source where variation of the angle of acceptance is needed for the AE/AEL analysis. Figure 4 shows the array that is found as example in the Interpretation Sheet 1 to IEC 60825-1.

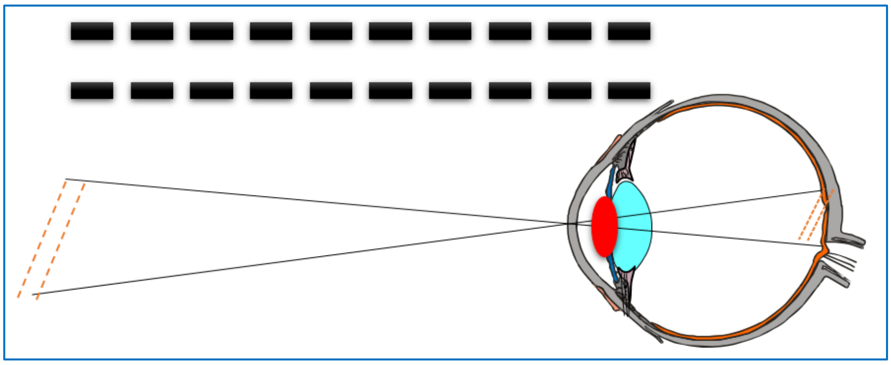

Figure 4. Example of an array used in IEC 825-1:1993 and Interpretation Sheet ISH1:2017. When the eye accommodates to the location of the array, the retinal image is produced accordingly (here shown very schematically and assuming that the pupil does not reduce the extent of the array).

3.4.2 Projecting one element – the classic lighthouse design

Figure 4 shows an array without optics as part of the product. In this case, accommodation to the actual location of the array elements produces the respective retinal array pattern.

An array can also be located in the focal plane of a projection lens to produce more or less collimated beams, shown in the following figures. In this case, the optical (apparent) location of the array is some distance behind the projection lens. The classic arrangement to produce an optimised collimation is to locate the emitter in the focal plane of the projection lens, as shown in Figure 5.

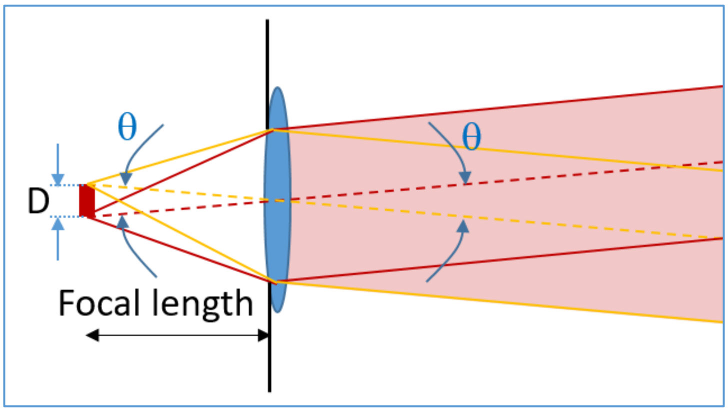

Figure 5. Placing a source of optical radiation in the focal plane of a projection lens produces an emitted beam with minimum divergence.

An ideal setup moves the apparent location of the emitter to infinity, since the rays that originate from a given point on the source are emitted as parallel rays when passing through the projection lens. Therefore, the source irradiance pattern (which is also referred to as exitance pattern) is translated to a correlating angular pattern of the emitted beam. Such a projection assembly is first discussed based on the example of just one element. This is a classic set-up for search lights and light houses for more than 200 years (with parabolic reflector designs already in the 18th century[2]), where the goal is to produce a beam with minimum divergence angle. When the source of light (such as a diffuse lightbulb) is placed in the focal plane of the lens, the divergence of the emitted beam θ is equal to the angular subtense subtended by the source as seen from the projection lens θ, i.e. it is given by the

[2] https://uslhs.org/reflectors

dimension of the source D and the focal length of the lens f, using the small-angle simplified determination of the subtended angle:

$$\theta = \frac{D}{f}$$

Since in the projected beam, the rays that originate from a given point of the source are all parallel, looking into the beam and accommodating to infinity results in a retinal image where the pattern of the image is the same as the pattern of the projected source (which can be an array) – at least when sufficiently close to the projection lens. This is shown in Figure 6, where for demonstration purposes, also rays that do not pass through the cornea and lens are shown to be focused onto one point on the retina.

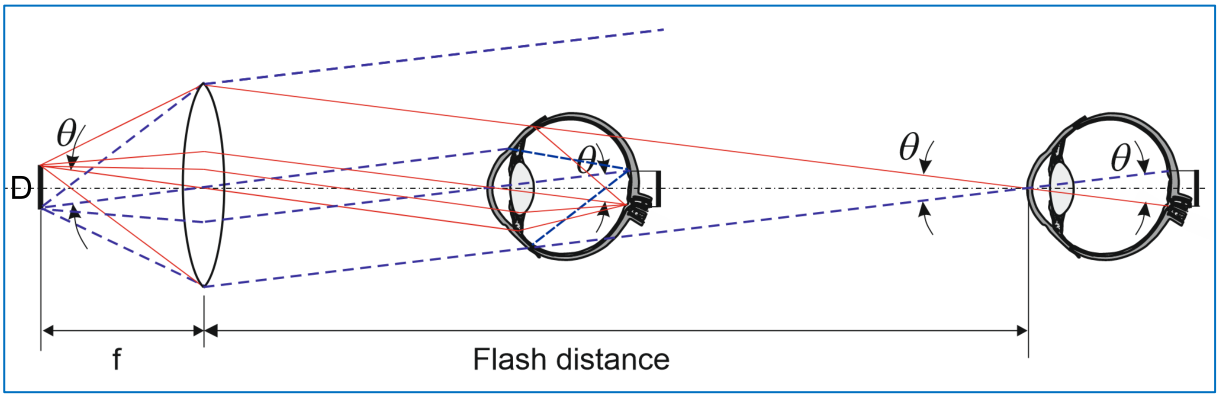

Figure 6. For sufficiently close distances, accommodation to infinity produces a retinal image with the same angular extent and retinal irradiance pattern as the angular extent of the source as seen from the projection lens.

It is a very interesting feature of such a projection setup that for sufficiently close distances, the angular subtense of the retinal image θ is equal to the divergence of the beam θ and is independent of the distance to the projection lens. In Figure 6, the eye shown on the right edge of the figure is at the distance where the angle subtended by the projection lens is equal to the angle subtended by the image θ. This is called the flash distance, or the distance from which onwards the lens is "flashed". This term comes from the fact that at the flash distance, the lens is fully filled with the image of the source. From that distance onwards, the image extent is given by the lens rather than by the projected source. The drawing and discussion use the lens extent for simplicity, while in real projection optics there is an aperture stop associated to the projection optics, and the image of the aperture stop is referred to as the exit pupil. Thus, for real projection optics, the exit pupil is relevant in terms of flash distance, defined as distance where the exit pupil appears under the same angle as the projected source. In that sense, it is the exit pupil that is flashed and not the lens. For a more complete discussion it also needs to be considered that the above is strictly accurate only for a very small pupil of the eye. For a finite pupil diameter, or 7 mm aperture stop for an artificial eye setup, at the flash distance, rays with a somewhat larger angle as shown still pass through the 7 mm aperture stop. Thus, the actual distance where the retinal image starts to get smaller is somewhat further out; it is at the location where the rays shown pass through the *edge* of the aperture stop (at the defined flash distance, they pass through the *centre* of the aperture stop). When considering the image profile at the flash distance, when the aperture stop is smaller than the projected beam, the image irradiance profile will not be the same as the profile of the projected source of optical radiation. That is, in an idealised case for a homogenous projected profile, at the flash distance the edge of the retinal image will have half the irradiance (or "brightness") as compared to the centre of the image. To achieve a homogenous retinal image (constant retinal irradiance), the eye would have to be somewhat within the flash distance, so that the 7 mm aperture stop is fully within the two edge rays (red and dashed blue) shown.

3.4.3 *Projected array*

In the previous subchapter it was shown for one source element placed in the focal plane of a lens, that the angular distribution of the emitted beam (the divergence) is equal to angular power distribution of the source seen from the projection lens. Furthermore, for sufficiently close distances, the angular power distribution on the retina, for accommodation to infinity, is equal to the angular power distribution of the source. This can also be translated to an array being placed in the focal plane of the projection lens. Each element of the array then is associated to a beam in the same way as discussed above and as shown in Figure 7. What for one beam (one source element) applied to the angular distribution of the emission being related to the angular distribution of the source as seen from the projection lens, applies now to the two beams and the two elements.

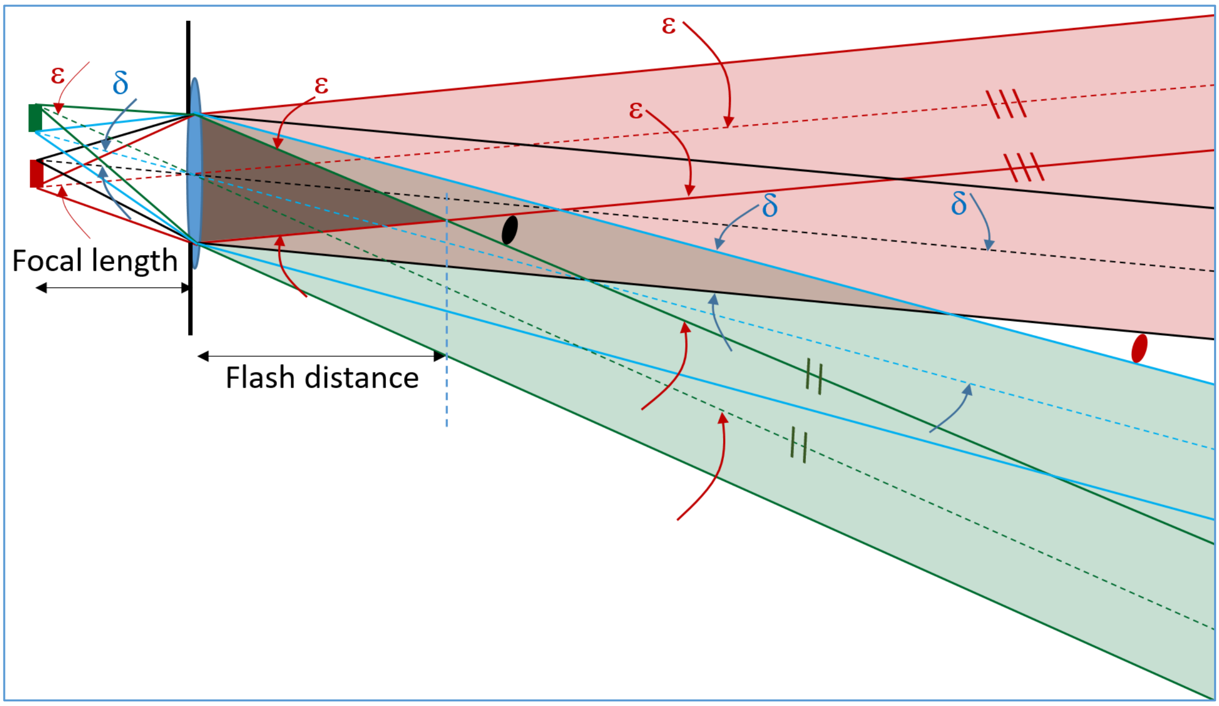

Figure 7. Example of an array consisting of two elements.

We use the symbol ε for the angular extent of the array, i.e. the angle subtended by the outside edges of the two elements. The flash distance for the array is the distance where the exit pupil (the image of the aperture stop) appears under an angle equal to ε. In the figure, the dark-shaded zone within the flash distance marks the region where the retinal image is comprised of the whole array. When the 7 mm aperture stop is located fully within the dark shaded area, the irradiance profile of the retinal image (again of course for accommodation to infinity) is the same as the projected profile of the array elements.

When the aperture stop is located exactly at the flash distance, the ray bundles associated to the edge points of the array (red lines for the lower edge and green lines for the upper edge) cover half the aperture stop. Therefore, the irradiance of the edge of the retinal image is half of the maximum irradiance which is achieved when the ray bundle associated to the respective part of the image covers the 7 mm aperture stop fully (compare discussion for the single element).

Due to the finite diameter of an aperture stop, somewhat further distances are necessary (indicated by a small black disk in the figure) so that the retinal image actually becomes smaller than the source profile, i.e. so that no part of the ray bundle associated to the edges of the array pass through the aperture stop. In other words, for the distance shown by the small black disk and further distances, the outer parts of the two elements are lost for the retinal image formation.

The angle δ in the figure above denotes the overlap regions of the two beams. This angle is the same as the angle spanned by the innermost edges of the two elements as seen from the projection lens. Due to the finite diameter of the aperture stop, here indicated with a small red disk, the distance where it is possible (depending on the lateral location of the aperture stop) that no element is imaged, is somewhat further out.

3.4.4 Time-varying retinal image

The following pertains to a projected array and accommodation to infinity, or to an array of emitting elements without projection lens, and accommodation to the plane of the array elements.

When all the elements of the array emit at the same time, the array elements imaged onto the retina are also on and off at the same time. This is then a common retinal image where the relative distribution within the retinal irradiance pattern does not vary over time. When the emission of the whole array is pulsed, the retinal irradiance pattern is of course also pulsed, but all the retinal images of the elements are pulsed in the same way, i.e. on and off at the same time. This can be referred to as a stationary retinal image, or constant retinal image. Such an emission is also the classical example (see for instance Interpretation Sheet 1, ISH1 [9] figure 1) for the application of the image analysis to determine the field of view which is associated to the maximum AE/AEL ratio.

When the array elements are not all emitting at the same time but, for instance, consecutively, the retinal irradiance distribution within the image varies with time, what is referred to in this white paper as time-varying retinal image (TVRI). It can be also thought of as a time-varying retinal irradiance distribution in terms of different parts of the retinal irradiance profile vary differently in time.

Such an emission is also a "scanning laser radiation" in the sense of the standard definition 3.78. For an array without projection optics, the origin of the laser beams associated to the array elements varies in time. For an array placed in the focal plane of a projection lens, the direction of the emitted beams varies in time, very similar in principle of the beams of a scanner with a mirror.

The array could be made up of elements arranged in a line with some distance between the elements of the array, which translates to the respective angular separation of the images of the elements on the retina. The elements could emit pulses one after the other with a certain period. In this case, the retinal irradiance pattern is very similar to that of a beam scanned by a mirror where the emission is pulsed with some period, particularly when the pulse duration is in the nanosecond regime so that there is negligible scanning during the pulse. The angular separation of the retinal images associated to the pulses depends on the angular scanning speed of the beam and the pulse period. This is in principle equivalent to the angular and temporal separation of the retinal exposure from an array where the array elements emit with a certain period.

3.4.5 Reference point

For a scanner using a mirror, the pivot point of the scanned beam is the location of the mirror. Consequently, the mirror is the reference point for the determination of the distance of the 7 mm aperture stop. For projected arrays, there are similarities to mirror scanners also in terms of the pivot point. As discussed above, placing an array in the focal plane of the projection lens produces one emitted beam per array element. The emission angle (i.e. the direction) of the respective beam is determined by the angular position of the source element. For a projected array, the pivot point of the collection of beams is where the beams cross over, and that location is the projection lens, or more accurately the exit pupil of the projection lens. The situation with respect to the pivot point is equivalent to the case of a mirror when the eye accommodates to behind the mirror, the beams are extended by the eye into virtual space behind the mirror. The mirror is the location where for the eye, the beams cross over (compare Figure 2). For a projected array, the eye extends the beams that are associated to each element beyond the exit pupil. With this concept it can be derived that the cross-over point (the pivot point) for the beams emitted from an array projector is the exit pupil of the projection lens.

For the collection of all the beams seen together, the exit pupil is equivalent to a beam waist, which is the generic reference point in IEC 60825-1 in case no other specific reference point is applicable. When the exit pupil is the location of the beam waist for the collection of emitted beams, the exit pupil is then also an appropriate reference point even when the array is not "scanning". That is, for a projected array where all the elements emit at the same time and produce a constant (not varying in time) retinal image for accommodation to infinity, the exit pupil of the projection lens is the reference point[3] in the sense of IEC 60825-1.

In the same way as for a mirror scanner, accommodation to the mirror is associated to a stationary retinal image, so is accommodation to the exit pupil for a projected array associated to a stationary retinal image. That is, even for the case that not all elements emit at the same time (for accommodation to infinity resulting in a time-varying image pattern on the retina), accommodation to the exit pupil of the projecting lens produces a stationary image, at least in a simplified idealised analysis. The retinal image can be understood as the conjugate of the irradiance profile at the location of the exit pupil. In other words, for accommodation to the exit pupil, the irradiance profile of the exit pupil is the apparent source. In reality the exit pupil might not be filled in the same way for different array elements, so that variation of the emitting elements might result in a time-varying exit pupil irradiance pattern. For a worst-case simplified analysis this can be neglected.

[3] As a side note, the exit pupil of the projector is also the reference point and location of the virtual beam waist for image projectors, such as cinema projectors as defined in IEC 62471-5.

4 GENERAL AEL ANALYSIS PRINCIPLES

4.1 Introduction

In the following subchapters, general and underlying principles of an AEL analysis are discussed. The analysis in principle can be performed via calculations and ray tracing simulation, or via measurements.

The fundamental and somewhat obvious principle is that for all possible and relevant variations, the AE has to be below the respective AEL. It is of vital importance to always see the AE and the AEL as a pair. For instance, the AE has to be determined at the same location in the beam as the AEL. Also in terms of temporal parameters, the AE is determined for the same emission duration as is the AEL.

The requirement

AE < AEL

can also be written as

$$\frac{AE(\text{variation} - i)}{AEL(\text{variation} - i)} < 1$$

which emphasises that the AE and AEL need to be seen in pairs and the AE needs to be smaller than the AEL for all relevant variations, here given the index *i*.

The fundamental variations that apply to both constant as well as time-varying retinal images are discussed in the following subchapters.

4.2 Vary emission duration, application of C_5

4.2.1 The term "emission duration"

One of the fundamental variations is the variation of the emission duration. This can be found in subclause 4.3 e) "Time bases" of IEC 60825-1:

> Every possible emission duration within the time base shall be considered when determining the class of a product. This means that the emission level of a single pulse shall be compared to the AEL applicable to the duration of the pulse, etc.

The term "emission duration" deserves some discussion. The "emission duration" is not the duration that the product is actually emitting in terms of being switched on and then after some time being switched off. The term emission duration refers to the value of *t* that is used to determine the AEL(*t*). That is, the AEL depends on the parameter with the symbol *t* and the name of that parameter is "emission duration". The upper range of *t* to be considered is the time base. The emission duration can therefore be equal to the duration of one pulse, it can be equal to the duration of groups of pulses, it can be equal to T_2, or it can be equal to the time base.

The emission duration is not only relevant as value to determine the AEL(*t*), but it is also the duration for which the accessible emission, AE, is determined. This is discussed further in the subsequent subchapter.

When only the retinal thermal limit is of concern, then it is not relevant to consider emission durations above T_2, since the AEL when expressed as power remains constant for emission durations longer than T_2 and the AE expressed as average power will usually also remain the same for averaging durations above T_2.

4.2.2 AE and AEL are both determined for a given emission duration

> CAVEAT: The following three subchapters discuss the generic relationship between the AE and AEL with respect to the emission duration. The discussion applies **accurately and in a simple way only to <u>rectangular</u> temporal pulse shapes**. For the case of non-rectangular temporal pulse shapes, the AE needs to be determined for a somewhat longer duration to include the energy in the trailing edges, as will be discussed further in subchapter 4.2.5.

When the emission duration is varied, the AE is determined for the same emission duration as the AEL. For instance, for the comparison with AEL(T_2) given as power, the AE is the average power, averaged over T_2. Somewhat more generally valid, both the AEL and the AE are expressed as energy. Then, AE is the energy within the emission duration. Mathematically this is expressed as integration of the time dependent power $P(t)$ over the emission duration. Often the emission duration that is considered contains several pulses with known energy per pulse, detected through the respective aperture stop and field of view. In this case, the AE is the sum of the energy of the pulses within the emission duration.

Due to this nature of integrating the power within the emission duration or adding the energy within the emission duration, a more intuitive symbol for the emission duration is Δt.

AE(Δt) is then the energy within Δt detected with the appropriate aperture stop and field of view. The AE(Δt) needs to be below the AEL(Δt), both determined for the same Δt (see subchapter 4.2.5 for the case of non-rectangular pulses). We note that for the analysis based on requirement 3) of 4.3 f) of the standard, the single-pulse AEL(Δt) is understood as to be reduced by C_5.

The AE and AEL do not only depend directly on the emission duration as a parameter, but also indirectly, because $\alpha_{max}(\Delta t)$ is also determined for the same Δt, limiting both the angle of acceptance (the field of view) for the determination of the AE as well as the value of C_6 as parameter of the AEL. Furthermore, the value of C_5 as parameter of the AEL depends on the value of Δt as well as in some cases on $\alpha_{max}(\Delta t)$.

In that sense, the term "AEL analysis" should be understood rather as an AEL *and* AE analysis, with the AEL and the AE always seen as a pair – not only in terms of choice of emission duration but also for the other variation parameters described further below. The term AEL-AE analysis, or AE/AEL analysis is probably better suited.

4.2.3 Variation of the temporal analysis window

For the general case of irregular pulse trains, not only the duration of Δt is relevant and needs to be varied, but also the temporal location of Δt within the emission pattern. This is demonstrated in Figure 8 for an exemplary emission pattern with varying pulse durations and peak power values. The orange arrows indicate different temporal locations of Δt (i.e. different starting times) and different durations of Δt (not all possible and potentially relevant choices of Δt are shown).

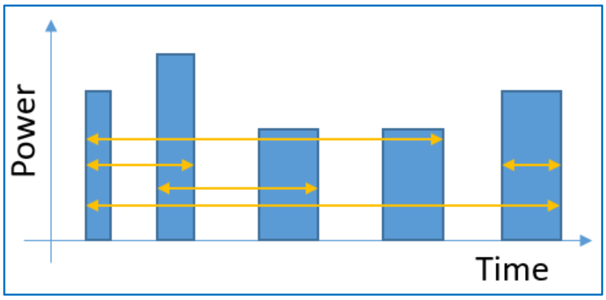

Figure 8. Example of a pulsed accessible emission and a selection of possible locations and durations of the emission duration Δt.

Thus, in the general case (but assuming rectangular temporal pulse shapes, see 4.2.5), the given choice of emission duration Δt has a start time t_1 and an end time t_2 so that

$$t_2 - t_1 = \Delta t$$

To express the variation of the duration and the start time of the emission duration, the index j can be added: Δt_j.

Instead of the term emission duration, one can think of Δt also as ***temporal analysis window*** that is moved across the emission pattern and also varied in duration.

Described mathematically and assuming rectangular pulse profiles, the AE expressed as energy is the integral of the power as function of t between the start and end times:

$$AE(t_2 - t_1) = \int_{t_1}^{t_2} P(t)\ dt$$

For comparison against the AEL expressed as power (such as for AEL(T_2)), the average power is easily obtained by

$$AE_{av\_P}(\Delta t) = \frac{AE(\Delta t)}{\Delta t} = \frac{\int_{t_1}^{t_2} P(t)\ dt}{t_2 - t_1}$$

The retinal thermal AEL for emission durations below T_2 and for the photochemical retinal AEL below 100 s are given as energy, so that the respective AE is also expressed as energy. Both the AEL and AE can, however, also be expressed as power. The $\mathrm{AEL_P}$ in power is obtained by dividing the energy-AEL by Δt:

$$AEL_P(\Delta t) = \frac{AEL(\Delta t)}{\Delta t}$$

to be compared against the accessible emission that is then power averaged over Δt.

This is a nice example that the ratio AE/AEL is relevant, which is identical and independent whether all is expressed as power or as energy. For the power-case, both the AE and the AEL expressed as energy are divided by Δt:

$$\frac{AE_{av\_P}(\Delta t)}{AEL_P(\Delta t)} = \frac{\frac{AE(\Delta t)}{\Delta t}}{\frac{AEL(\Delta t)}{\Delta t}} = \frac{AE(\Delta t)}{AEL(\Delta t)}$$

4.2.4 Application of C_5

The variation of the emission duration between the duration of one pulse and up to the time base already covers requirements 1) and 2) of the repetitive-pulse analysis requirements given in 4.3 f) of the standard. Requirement 1) refers to the energy of a single pulse to be below the AEL for the single pulse, and requirement 2) refers to the average power within T to be below the AEL(T). Where the standard uses the symbol T for the averaging duration, here we use Δt. We note that the average power is derived from the energy within T simply by dividing the energy by T (see formulas above).

For the retinal thermal limits, also requirement 3) of 4.3 f) needs to be considered, which for emission durations up to 0,25 s (emission durations above 0,25 s are not considered as pulses) in effect replaces both requirement 1) and requirement 2). Requirement 3) expresses that the single-pulse AEL(Δt), obtained from the AEL tables needs to be multiplied with the factor C_5. For the analysis of actual pulses, requirement 3) is either more restrictive than or equivalent to (when $C_5 = 1$) requirement 1). As is specified in ISH1 [9], the factor C_5 also needs to be applied to groups of pulses, where one group is referred to as "effective pulse". In other words, the choice of Δt also needs to encompass two or more pulses as groups of pulses. Then, AE(Δt) is the accessible energy for that group (again with minor adjustment for the case of non-rectangular pulse shapes, see next subchapter), while AEL(Δt) is determined for the respective group duration – and AEL(Δt) needs to be multiplied with C_5 determined from the number N of how often the respective pulse group occurs within T_2. With this application to groups of pulses, requirement 3) is either more restrictive than or equivalent to (when $C_5 = 1$) requirement 2).

As a conclusion, for emission durations < 0,25 s, where C_5 needs to be applied, it is sufficient to only consider requirement 3) - requirements 1) and 2) are covered or are less restrictive.

For emission durations equal to or larger than 0,25 s, C_5 does not apply and only the average power rule is relevant. Since AE_{av_P} as average power is usually constant for averaging durations longer than 0,25 s, and the AEL_P expressed as power decreases from $\Delta t = 0{,}25$ s down to T_2, it is sufficient to only consider averaging durations of T_2 (or 0,25 s for Class 2 classification).

The application of C_5 for irregular pulse trains is often a challenge. The principle of the variation of the start point and duration of the temporal analysis window, Δt, is relatively straightforward and in the general case simply covers all kind of combination of pulses as "effective pulses". However, C_5 also needs to be applied to the respective AEL(Δt). For irregular pulse patterns and a systematic variation of Δt it is currently not defined satisfactorily how the number of "effective pulses" N is to be determined when the temporal emission pattern is so irregular that the respective group of pulses does not repeat. A detailed discussion on the current and possible future methods to analyse irregular pulse trains is not in the scope of this white paper. Some discussion can be found in our 2015 ILSC [10] and in reference [11]. ISH1 provides guidance that for constant pulse durations but varying peak powers, N can be determined as a fraction of the pulse's peak power compared to the maximum peak power in the pulse train. The applicability of this method is somewhat limited due to the requirement that the pulse durations all have to be the same. In the paper [11], a generalised method is proposed which would lend itself very well for the systematic analysis of irregular pulse trains. According to the proposed method, the parameter N is the ratio of the total accessible energy within T_2 over the accessible energy within the temporal analysis window Δt. The method was validated in the thermal retinal injury domain by use of a computer model. Unfortunately, this method is not formally available at this point in time in the sense of strict compliance with IEC 60825-1, since it is referenced neither in IEC 60825-1:2014 nor in ISH1. Also, it should be kept in mind that the validation with the computer model does not apply to nanosecond pulses and potential injury based on microcavity formation.

Some more comments for the application of C_5 for TVRI are found further below in subchapter 4.5.7. In practice, the lack of a method to determine N in the general case of the variation of Δt is often solved by the worst-case values of C_5 of either 0,4 or 0,2, which for the emission duration regime above 5 µs is reached at very low numbers of N. Thus, to simply assume the worst-case value of N also solves the problem of how to determine N. Another worst-case simplified approach is to determine N by division of T_2 by Δt. Irrespective of the pulse pattern, this is the number how often the temporal analysis window would fit into T_2. Due to the minimum values of C_5, this approach lends itself to rather long values of Δt. It can be made somewhat less restrictive when there are longer sections without any detectable accessible energy, which need not be considered to determine N.

The application of C_5 in the emission duration regime above 5 µs is another example of the substantial difference between a simplified analysis, assuming $\alpha = \alpha_{min}$, and an extended analysis. For the simplified analysis, in this emission duration regime, $C_5 = 1$ so that only the single pulse and the average power requirement need to be applied and analysed.

4.2.5 Non-rectangular temporal pulse shapes

The systematic scheme presented in the previous subchapters of determining both the AEL(Δt) as well as AE(Δt) for the same duration Δt in the accurate sense only applies for the case of rectangular temporal pulse shapes. For non-rectangular pulse shapes, the scheme needs to be adjusted.

As mentioned above, the term *emission duration* is used for the symbol Δt for which the AEL(Δt) is determined (here we use the symbol Δt, the standard uses the symbol *t)*. For *rectangular* temporal pulse shapes (see Figure 9), when the AE of the pulse is compared against the respective AEL(Δt), it is evident what the “pulse duration” is to be used as value for Δt.

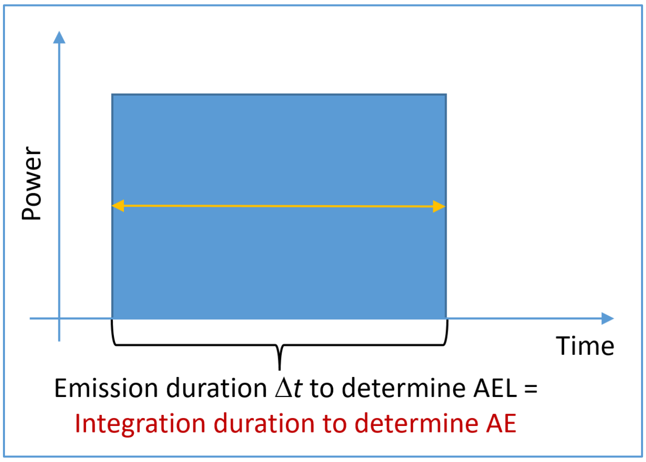

Figure 9. Example of a pulse with rectangular temporal pulse shape. The accessible energy is determined by integration of the power over the duration of the pulse, marked with an orange arrow. This is also the emission duration used to determine the AEL.

For a rectangular pulse shape, the emission duration to determine the AEL is the same as the integration duration to determine the accessible energy AE of the pulse. The same applies for groups of rectangular pulses as shown in Figure 10. When this group of pulses is analysed as one effective pulse (which is necessary both based on requirement 2) and 3) of 3.4 f) of the standard), the duration of the group is simply given by the outer edges of the first and last pulse, and this duration is used as emission duration to determine the AEL. The same duration is used to determine the accessible energy for the group of pulses, i.e.

AE = $Q_1 + Q_2 + Q_3$.

Therefore, the formalism AE(Δt) < AEL(Δt) as used in the previous subchapters is applicable for a group of pulses with rectangular temporal pulse shapes.

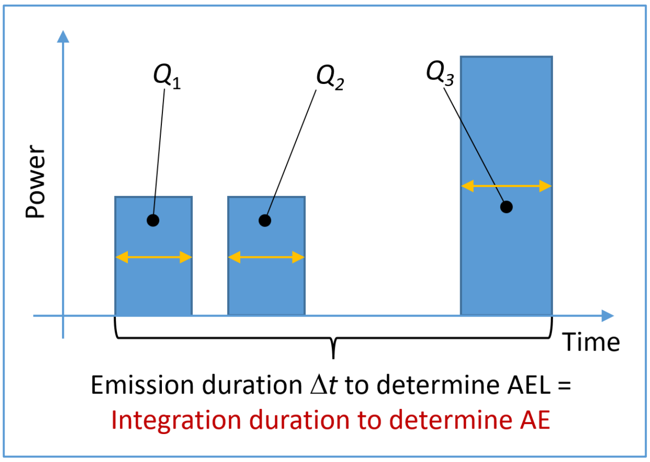

Figure 10. Example of a group of pulses with rectangular pulse shapes, analysed as one effective pulse.

The scheme needs to be adjusted for non-rectangular pulse shapes, due to the definition of emission duration (3.33) in the standard, which is based on the half-peak power points:

> 3.33
>
> **Emission duration**
>
> For a train of pulses (or subsections of a train of pulses), this is the duration between the first half-peak power point of the leading pulse and the last half-peak power point of the trailing pulse.

This is shown for a triangular pulse shape in Figure 11.

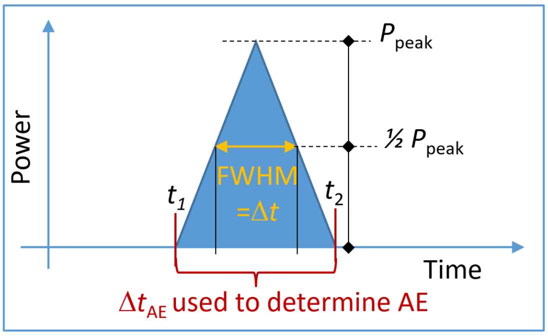

Figure 11. Example of a triangular temporal pulse shape, where the AEL is determined based on the FWHM but the AE is determined for the whole pulse, not just for the FWHM.

For non-rectangular temporal pulse shapes, there is no obvious pulse duration that can be based on “temporal edges” – some criterion needs to be defined in the same way as there is no obvious beam diameter for a gaussian beam profile or any other non-top-hat beam profile. For a laser safety analysis, in the current edition of IEC 60825-1, the half-peak power points are given as definition for the emission duration (3.33) and the pulse duration (3.69). That is, for a given pulse, the peak power needs to be determined as well as the temporal locations where the power equals half the peak power. The common term *full - width at half maximum* (FWHM) is used here, although this term is not used in IEC 60825-1. The standard defines to use the FWHM as emission duration to determine the AEL, i.e. AEL(t = FWHM). For a non-rectangular temporal pulse shape, such as a triangular temporal pulse shape (shown in Figure 11), the FWHM is shorter than the overall emission of the pulse in terms of the power as function of time being above zero. The AEL is calculated with the FWHM, but the AE is not limited to the energy within the FWHM – rather, the AE is the *total* energy in the pulse, including the sections outside of the FWHM[4]. The symbols used in this white paper are Δt for the emission duration (which for a single pulse is the same as the FWHM) to determine the AEL, while Δt_{AE} is used as symbol for the integration duration of the AE, i.e.

$$AE(\Delta t_{AE}) = \int_{t_1}^{t_2} P(t)\ dt$$

We see that for non-rectangular pulse shapes, the integration range Δt_{AE} is somewhat larger than the emission duration Δt determined with the half-peak power points.

The generally valid comparison of AE with the respective AEL is therefore:

$AE(\Delta t_{AE}) < AEL(\Delta t)$.

It is interesting to see what the difference to a scheme is where the AE is integrated over the same duration as used to determine the AEL, and varying that duration $\Delta\tau$ to find the maximum ratio of $AE(\Delta\tau)$ /$AEL(\Delta\tau)$. In such a scheme, the AE is only the energy that is found within $\Delta\tau$, and $\Delta\tau$ is systematically varied. The $AEL(\Delta\tau)$ for emission durations above 5 µs increases with $\Delta\tau^{0,75}$, i.e. less than linear. For a triangular pulse shape, the energy within the integration range (centred around the peak) increases linearly with $\Delta\tau$. The maximum of the ratio $AE(\Delta\tau)$ /$AEL(\Delta\tau)$ is therefore reached when $\Delta\tau = \Delta t_{AE}$ and the AE is equal to the total energy within the pulse. This is the same AE as for the case of the method given in the current standard, but the $AEL(\Delta t = \text{FWHM})$ is somewhat smaller than $AEL(\Delta t_{AE})$ and therefore the ratio of

$AE(\Delta t_{AE})$ / $AEL(\Delta t = \text{FWHM})$ is somewhat more restrictive overall. Since the AE is the same, the difference comes from the AEL value, where $AEL(\Delta t_{AE})$ is a factor of $2^{0,75} = 1,68$ higher than $AEL(\Delta t = \text{FWHM})$. Considering this factor for the example of a triangular pulse, it does not appear justified to argue for the application of a $AE(\Delta\tau)$ /$AEL(\Delta\tau)$ maximisation scheme via variation of $\Delta\tau$ for the AEL analysis of a pulse (it might be justifiable for the analysis of multiple pulses based on requirement 3 of 4.3 f) when the factor C_5 is sufficiently conservative). When the pulse duration is in the regime outside the thermal confinement regime, the temperature rise in the retina is related to the peak power to a higher degree as related to the energy per pulse. The smaller AEL, being based on the FWHM, reflects that a triangular pulse produces a temperature that is higher than the temperature produced by a rectangular pulse with the same energy but a pulse duration equal to Δt_{AE}, which would have half the peak power of the peak power of the triangular pulse.

The above discussion applied to a single pulse. Requirement 2) of 4.3 f) requires that the average power with emission duration T (to use the symbol of the standard) needs to be below the $AEL(T)$. The standard does not specify the exact conditions of how to determine the average power for a pulse train with non-rectangular temporal pulse shapes.

Requirement 3) of 4.3 f) extends the single pulse AEL requirement by multiplication with C_5, which also needs to be applied to groups of pulses (see ISH1), i.e. treating a group of pulses as effective pulse. The single effective pulse $AEL(\Delta t)$ is then determined for the emission duration Δt equal to the duration of the group of pulses. Definition number 3.33 “emission duration” of the standard provides the method of how to determine the emission duration for a group of pulses (see Figure 12 for an example): the emission duration Δt assigned to the group is given by the half-peak power points of the outward edges of the first and last pulse, indicated with green dots in Figure 12.

[4] That the AE is the total energy in the pulse and not just the energy within the half-peak power points is not specifically stated in the current version of the standard, but it is an obvious issue based on biophysics understanding and determination of experimental animal injury thresholds as basis for the AELs for Class 1.

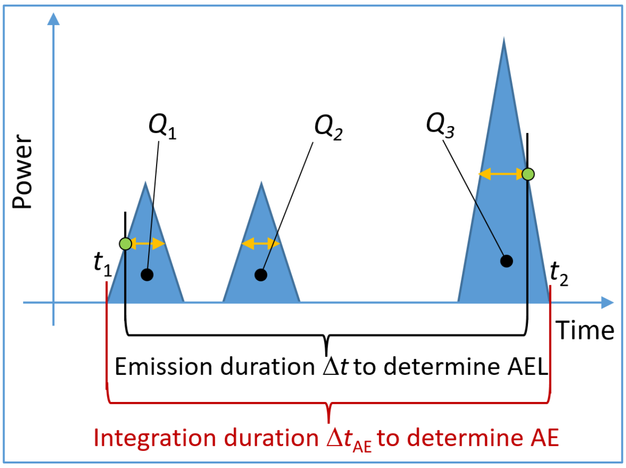

Figure 12. Example of a group of pulses treated as one effective pulse, where the AEL is determined with the emission duration based on the half-peak power points, but the integration duration for the determination of the AE is longer to capture the full energy of the pulse group.

For a single triangular pulse, we have discussed that for the determination of the AE it cannot be supported to take only the energy within the FWHM as AE, but the total energy of the pulse needs to be compared against the AEL(FWHM). By extension, it appears consistent to apply the concept also for requirement 2) and requirement 3) of 4.3 f). For the case of a pulse train, the AE is the sum of the energies of the pulses that make up the pulse train, not only the energy within the emission duration that is used to determine the AEL. That is, the consistent determination of the AE is AE = Q_1 + Q_2 + Q_3. Therefore, the integration duration Δt_{AE} to determine the AE is somewhat wider than the emission duration Δt that is used to determine[5] the corresponding AEL(Δt):

$$AE(\Delta t_{AE}) = \int_{t_1}^{t_2} P(t)\ dt$$

The average power AE_{av_P} for this group of pulses is determined by the total energy in the pulse group, i.e. including outside of the half-peak power points, and the averaging duration is the integration duration Δt_{AE}, not the emission duration Δt:

$$AE_{av\_P}(\Delta t_{AE}) = \frac{Q_1 + Q_2 + Q_3}{\Delta t_{AE}}$$

The choice of the averaging duration of Δt_{AE} becomes evident when we consider two triangular pulses next to each other (Figure 13), where the average power level of the two pulses, shown as yellow shaded rectangle, is equal to the half-peak power level.

[5] The emission duration Δt is also used to determine $\alpha_{max}((\Delta t)$.

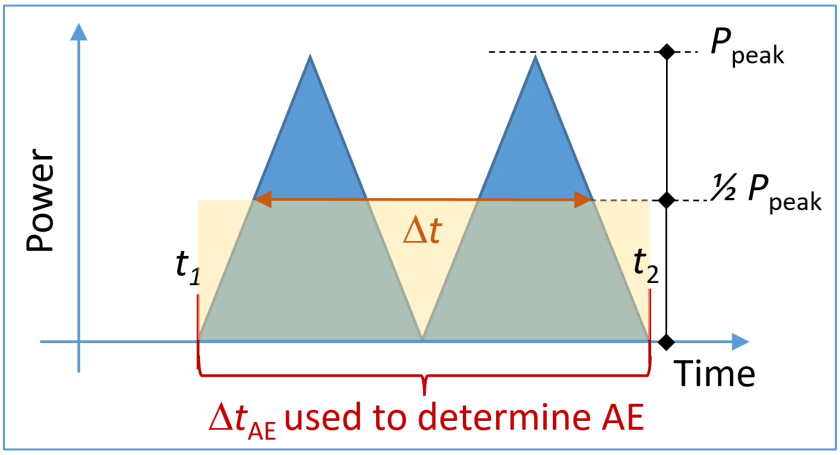

Figure 13. The average power for two triangular pulses next to each other is equal to half the peak power and obtained by averaging over Δt_{AE}. This is consistent with the average power of one triangular pulse.

When the AEL is expressed as power quantity to be compared against the AE expressed as average power AE_{av_P}, it is important to determine the energy AEL (i.e. as given in the AEL tables) with the emission duration Δt and not with the longer integration duration Δt_{AE}. To be consistent with the determination of the average power AE from the energy AE, the power AEL_P is obtained via division by the integration duration Δt_{AE}. In formulas this means:

$$AEL_P(\Delta t) = \frac{AEL(\Delta t)}{\Delta t_{AE}}$$

Overall, this is then consistent with the concept that both the accessible emission limit and the accessible emission can be expressed as energy or as power values. The overall comparison (the ratio) is identical:

$$\frac{AE_{av\_P}(\Delta t_{AE})}{AEL_P(\Delta t)} = \frac{\dfrac{AE(\Delta t_{AE})}{\Delta t_{AE}}}{\dfrac{AEL(\Delta t)}{\Delta t_{AE}}} = \frac{AE(\Delta t_{AE})}{AEL(\Delta t)}$$

For requirement 2), the average power requirement, the wording and the symbols used in the standard in 4.3 f) would also be consistent with determining the AEL(T) for the averaging duration and determining the average power as averaged over T and using the energy only within T and not including the parts of the first and last pulse which is outside of the half-peak power points. The standard does not specify the exact method of how to determine the average power. For requirement 3), being originally based on the single pulse AEL, there seems to be less freedom of interpretation of how the energy per pulse, or the energy per pulse group, is determined. When the method discussed in this subsection (i.e. including the energy of the first and last pulse that is located outside of Δt) is applied for all three multiple pulse criteria, this is on the one hand on the conservative side (which appears prudent for some short pulse groups where a significant portion of the energy can be outside of the half-peak power points) and on the other hand it has the advantage that the same method is applied for all three requirements, so that requirement 3) is sufficient to analyse, since it is either identical with the other two requirements (for C_5 = 1) or more restrictive.

We summarise that for non-rectangular pulse profiles, an analysis that is accurate and compliant with the current standard requires the AE to include the energy outside of the emission duration (which is based on the half-peak power points). Without further scientific studies on the injury threshold, considering the potential loss of safety margin, it does not appear justified to perform an AEL analysis with a scheme based on the ratio AE(Δt) /AEL(Δt)

with a systematic variation of Δt, where the AE is only the energy within the integration duration Δt and the AEL(Δt) is based on an emission duration equal to the integration duration. This is somewhat unfortunate, because the latter would lend itself for a relatively simple automated analysis by a computer program.

For non-rectangular temporal pulse profiles to be fully compliant with the standard method and at the same time use the AE(Δt) /AEL(Δt) scheme with systematic variation of Δt, the potential difference could be considered with a correction factor, or by performing an analysis where the actual pulse shapes are replaced by worst-case simplified rectangular pulses - for the case of triangular pulses the appropriate replacement is simply a rectangular pulse with the same peak power and a duration equal to the FWHM of the triangular pulse.

4.2.6 Systematic variation of temporal analysis window

The above method of variation of duration and temporal location of Δt (for non-rectangular profiles with due consideration of the energy outside of Δt) can be seen as generally applicable method in the sense of an automated AEL analysis, where two program loops vary both the duration and the starting point of the temporal analysis window Δt. This variation of the emission duration can in principle be applied irrespective of the actual emission pattern.

Of course, in practice, when the analysis is not performed by a computer program but by a human with an understanding of the dependencies of the AE and the AEL on emission duration, it is not necessary to analyse *all* possible emission durations. Such an analysis will be limited to relevant ones. For instance, for emission durations between 5 µs and T_2, when the analysis window Δt is increased into a temporal regime where no emission takes place, then the AE (as energy within Δt) remains constant but AEL(Δt) increases. It is evident that such a variation of Δt is not relevant and cannot lead to a higher value of AE/AEL.

4.2.7 Notes on the discontinuity at 5 µs

The only aspect that needs discussion for a systematic variation of Δt, is the discontinuity of C_5 at Δt = 5 µs. For emission durations up to including 5 µs, C_5 is independent of α and limited to a minimum of 0,4. Due to the underlying injury mechanism in the nanosecond regime, this C_5 can be referred to as the “micro-cavity” C_5. For emission durations exceeding 5 µs, C_5 depends on α and the worst-case reduction factor, which often applies also for scanners, is C_5 = 0,2. Due to the underlying injury mechanism, this C_5 can be referred to as the “thermal” C_5. The discontinuity of C_5 at 5 µs has also been commented in ISH1. When the scheme is to systematically vary Δt – independently from the actual emission pattern – then the discontinuity at 5 µs requires some additional discussion. After all, for a systematic variation of Δt, which could be applied independently of the actual pulse pattern, Δt = 5,1 µs would also have to be considered, including for cases where the pulse duration is in the nanosecond regime. It is argued that in practice the actual pulse pattern is considered, and the AE of a nanosecond pulse is compared against the AEL determined with the microcavity C_5, not the thermal C_5that would be applicable for Δt = 5,1 µs, for instance. Such an analysis it not implied in the definition of C_5, and is therefore not necessary to apply for a systematic variation of Δt. In other words, even when the scheme is to systematically vary the emission duration, this variation can be done based on the actual pulse pattern to encompass actual pulses at the start and end of the temporal analysis window, as schematically shown in Figure 8. This is discussed in the following with an example.

The AEL for single pulses (i.e. without C_5) is almost the same for Δt = 5 µs and Δt = 5,1 µs. Let us assume the emission consists of pulses where the pulse duration is in the nanosecond regime. These pulses are emitted in groups of two pulses with for instance 20 µs separation between the two pulses, and some longer separation of these two-pulse groups. It is clear that the AE of each of the nanosecond pulses needs to be below the AEL that is a constant energy value up to Δt = 5 µs, and the respective micro-cavity C_5 is applied (limited to 0,4 which applies when N > 24415). It is also clear that the AE of the two nanosecond pulses together, considered as an effective pulse, needs to be below the AEL for Δt = 20 µs where the thermal C_5 is applied. The thermal C_5, for values of α above 5 mrad for 625 pulses within T_2 assumes the worst-case value of C_5 = 0,2. Depending on the value of C_5 for each of the two emission durations and other factors (such as an angular separation of the two pulses for TVRI), one pulse or the group of two pulses is associated to a more restrictive (higher) AE to AEL ratio. So far, the analysis is intuitive. What would not be done in an AEL analysis is to compare the AE of one nanosecond pulse with the AEL determined for Δt = 5,1 µs, which would lead to the application of the respective potentially lower thermal C_5 = 0,2 to the nanosecond pulse. With the lower limit of 0,2, the thermal C_5 could be more restrictive than applying the micro-cavity C_5 that is applicable to Δt = 5 µs. In principle, when the scheme that the AE needs to be below the AEL for "all emission durations" is followed in a strict systematic approach regardless of the actual pulse pattern, then Δt = 5,1 µs *would* have to be applied even to a nanosecond pulse. However, the analysis does not have to be done regardless of the actual pulse pattern, and it is neither noted in IEC 60825-1 nor in an interpretation sheet to do so. In a "normal" AEL analysis, it is obvious that only the AEL for 5 µs with the respective microcavitation C_5 is applied to a nanosecond pulse, or to several nanosecond pulses within 5 µs. Therefore, it is also argued that an "unnatural" emission duration of a little bit above Δt = 5 µs does not have to be applied for a pattern of well-defined pulses that are separated by more than 5 µs, even though the generic requirement that the AE needs to be below the AEL for all Δt is at the heart of the method applied to analyse TVRI to systematically vary the emission duration irrespective of the actual pattern of the accessible emission. Such a systematic variation can and should still be based on the actual pulse pattern and it is not necessary to include temporal analysis windows that start or end at a time in the pulse train where this is no emission.

Also, biophysically it is not necessary to apply the thermal C_5 to emission durations of 5 µs and less, due to the relatively large safety margin (i.e. reduction factor) for a single pulse with a pulse duration in the regime of 5 µs. In the 2014 update of IEC 60825-1 (based on the ICNIRP 2013 update [12]), the single-pulse AEL for t = 5 µs was reduced by a factor of 2,5 compared to the earlier limit. The AEL needed to be reduced based on new injury threshold studies performed in the nanosecond regime [13]. The reduction of the AEL in the microsecond regime resulted in an enlargement of the reduction factor, which be validated with the injury threshold for a pulse duration of 3 µs [13]. This was the basis for not applying the thermal C_5 (with a minimum value of 0,2) in the emission duration regime of 5 µs.

4.3 Vary location of assessment

Besides the variation of the temporal analysis window, discussed in the previous subchapter, it is evident that the location of the AE/AEL assessment within the spatial emission field also needs to be varied. This variation of location is meant in terms of laterally within the emission pattern for a given distance to the reference point (i.e. not just in the centre of the emission) as well as, for classification as extended source, in terms of distance to the reference point. For measurement Condition 3, for extended sources, it is specified that the analysis is to be performed at 100 mm from the reference point (unless the closest point of human access is further than 100 mm from the reference point) but also at further distances.

Again, the complexity and effort of the analysis can be reduced greatly with a simplified analysis (C_6 = 1) where only a distance of 100 mm from the reference point needs to be considered.

Again, it is important to note that both the AE and the AEL are determined in pairs for one given location. This location is basically the location of the 7 mm aperture stop. When an assessment as extended source is performed, it is necessary to determine the equivalence of the retinal image, and then the 7 mm aperture stop is located on the imaging lens that mimics the imaging properties of the eye.

In terms of distance, IEC 60825-1 refers to the most restrictive position (MRP) which is the position in the beam where the ratio AE/AEL is maximum. When the AE is below the AEL at the MRP (for all emission durations - different emission durations might be associated to different MRP) then the product can be assigned to the respective class. This approach is of course equivalent to say that the AE needs to be below the AEL for all distances equal to and further than 100 mm from the reference point, if accessible. Since also lateral variations of the position of the determination of AE and AEL need to be considered, the term position, or location does not only refer to the distance to the reference point but also the location variation laterally.

Our ILSC 2015 paper [8] discusses an example with three beams where the AE/AEL ratio becomes more restrictive when moving some distance away from the cross-over point of the beams. The cross-over point of the beams is equivalent to a beam waist. That distances further than 100 mm can have a higher AE/AEL ratio than for 100 mm is also common for scanned emission, as will be shown in the example in chapter 6.

As was the case for the variation of the emission duration, also for the variation of the location can be considered as a systematic variation. Experimentally, linear motor stages with radiometers and/or an imaging system lend themselves for a systematic variation of the location of the determination of relevant parameters. When the nature of the emission is well known and the AE and AEL dependencies are understood, it is again possible to exclude some distances or locations which are surely not relevant in terms of value of AE/AEL. For instance, in many cases, particularly for stationary retinal images, it is evident that 100 mm from the reference point is the most restrictive distance, and it is not necessary to consider further distances. When scanners are analysed as extended sources, it is often found that the most restrictive distance is further than 100 mm (a fact that is often overlooked).

4.4 Vary accommodation

4.4.1 Summary of what accommodation means

The human eye is an optical imaging system just as for instance photo-cameras. The human eye varies the accommodation by adjustment of the focal length of the lens. For the emmetropic eye, when the lens is relaxed, the eye accommodates to infinity. This means that an object that is located at infinity (or at least very far away) is imaged onto the retina as the image plane. In this case, the focal plane is coincident with the location of the retina, i.e. the image distance i is equal to the focal length f of the eye's lens system (which consists of the cornea and the lens). When the optical power of the lens in the eye increases in the process of accommodation to a certain distance closer than infinity, the focal length decreases and a closer object at distance o, is imaged onto the retina.

An example is shown in Figure 14 for the case of a projector, where the accommodation was chosen to image the exit pupil of the projector. The image on the right was measured with a CCD camera where the different colours correlate with the irradiance in the image. When performing measurements, the variation of accommodation is achieved by adjusting the distance i between the lens and the CCD camera.

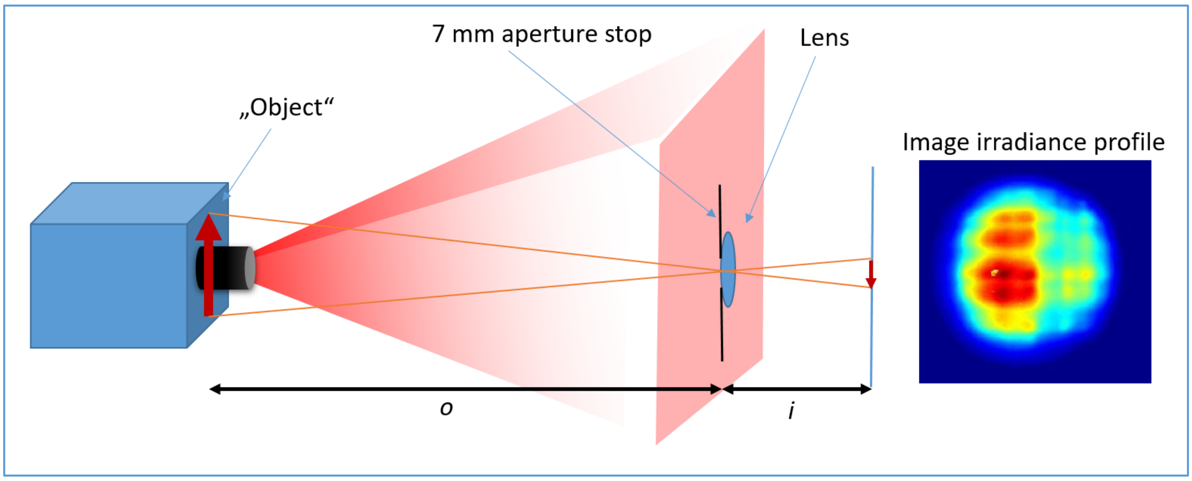

Figure 14. Example for a measurement setup to determine the retinal irradiance pattern, in this case for accommodation to the exit pupil of a projector. The image irradiance profile is shown on the right, enlarged as well as turned into the plane of the paper.

The respective parameters are related by the well-known formula:

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i}$$

The term accommodation distance is equivalent to what the object distance *o* is in optics. That is, depending on the focal length of the imaging system *f* and the image distance *i*, a certain object distance is imaged. For laser safety in IEC 60825-1, the closest point of accommodation to consider is 100 mm in front of the “eye”.

The principle of imaging a certain object distance also applies to laser radiation where the “object” that is imaged needs to be seen in a more abstract way. This is where the term “apparent source” comes in, which, however, due to the potential impact of the pupil on the retinal image size, can no longer be considered as an ideal term [6]. Examples of accommodation to infinity and of accommodation to the mirror of a scanner were already given in subchapter 3.3.

For laser radiation, for a given accommodation distance, the irradiance profile that is located at this distance is imaged onto the retina, with due consideration of the potential effect that the aperture stop might have on the retinal image.

Further discussion on the issue of “apparent source” can for instance be found in the following publications of our group, which can be downloaded freely from the Seibersdorf Laboratories website (this list of publications needs to be seen in terms of temporal development of a better understanding of the issues over time[6]).

- “The Apparent Source” – A Multiple Misnomer [14], ILSC 2005
- Comparison of different beam diameter definitions to characterize thermal damage of the eye, [15], Proc. SPIE 6101 2006

[6] For instance, when a more detailed discussion in IEC TC 76 on the apparent source and beam propagation started at the end of the 20th century, the 2nd moment diameter was proposed by ISO TC 172 members to be also used for laser safety purposes. The author of this white paper also refers to the 2nd moment in the book “Laser Safety” published in 2004. Soon afterwards, this was found inappropriate in some cases, as discussed in our proceeding papers of 2005.

- Classification of extended source products according to IEC 60825-1 [8] ILSC 2015
- Notes on the determination of the angular subtense of the apparent source in laser safety [6], ILSC 2019

4.4.2 *Principle of variation of accommodation*

Additionally to the variation of the distance to the reference point (as well as laterally within the emission field), and the variation of the emission duration, for each measurement location, the accommodation has to be varied. As is the case for the variation of the emission duration or the variation of the distance, when the nature of the product and the dependencies of the AE and AEL is well understood, it is not necessary to actually perform the analysis for varying accommodation distances when it is evident that a certain accommodation distance is the most restrictive one.

For the analysis as extended source, for a given location of the 7 mm aperture stop in the beam, the energy that passes through the 7 mm aperture stop is not necessarily the AE, because the AE is determined through a given angle of acceptance, which might be smaller than the retinal image (see subsequent subchapter). The energy that passes through the 7 mm aperture stop is equivalent to the energy that enters the eye, or the experimental imaging set-up mimicking the eye. This quantity depends on the location in the beam, but not on the accommodation of the eye. Varying the accommodation distances between infinity and 100 mm in front of the eye leads to varying retinal images, which means that the energy that passes through the 7 mm aperture stop is distributed across the retina depending on the accommodation.

Simple examples where it is evident which accommodation produces the maximum AE/AEL ratio are:

- Well collimated non-astigmatic and non-scanned beams: accommodation to infinity produces the minimum retinal image diameter.
- Non-astigmatic and non-scanned beams with large divergence: accommodation to the beam waist.
- Diffuse reflection or diffuse transmission produces spatially incoherent radiation and accommodation to the diffuse surface is the worst case.

The term "the apparent source" is discussed in more detail in the papers listed above. For a given location of the eye (or the measurement imaging system) in the beam, and for a given emission duration, "the apparent source" can be understood as to be located at that distance of accommodation (optical object distance) which produces the retinal image with the most restrictive ratio AE/AEL. That is, other retinal images, associated to accommodation to different locations, have a lower AE/AEL. It is interesting to note that for a given location in the beam, the worst case accommodation (and therefore the location of "the apparent source") can depend on the chosen emission duration, particularly for TVRI. It is possible that for emission durations longer than 10 seconds (in the domain of T_2), accommodation to infinity is associated with the worst-case AE/AEL, while for an emission duration equal to 5 µs, accommodation to the mirror results in the worst-case AE/AEL.

Since

- location
- accommodation and
- emission duration

are systematically varied in the method promulgated in this white paper, there will be one combination of these three which overall results in the most restrictive, i.e. maximum, ratio of

AE/AEL. As long as this is less than 1, the product can be assigned the respective class (the topic of emission under fault is not in the scope of this white paper).

There are examples where it depends on the emission parameters which accommodation state is the most restrictive one, i.e. where it is not evident without further analysis what (for a given location in the beam and a given emission duration) the most restrictive accommodation is:

- For a stationary line laser, for a small beam diameter at the line shaping optics, accommodation to the beam shaping optics (which is also the reference point in Table 11 of IEC 60825-1) is usually worst-case; for a large enough beam diameter at the line shaping optics, accommodation to infinity may be the worst-case.
- For a diffractive optic element (DOE) producing some emission pattern, for a small beam diameter at the DOE, accommodation to the DOE can be the restrictive accommodation location; for larger irradiance patterns at the DOE and/or for a strong zero order transmission, accommodation to infinity can be more restrictive.
- For scanned laser emission, for a small irradiance profile on the mirror, accommodation to the mirror can be the restrictive case, for a large irradiance profile on the mirror, accommodation to infinity can be more restrictive than accommodation to the mirror (the scan pattern and speed of course also play a role).

4.5 Image analysis

4.5.1 Terms: field stop, angle of acceptance, FOV

The analysis of the equivalent of the retinal image is at the centre of the AE/AEL analysis of extended sources. Information about the image distribution can be obtained by measurement with a lens that mimics the cornea-lens system of the eye, equipped with a circular 7 mm aperture stop. Usually, a lens with a focal length larger than the eye is used. This is valid since the image analysis is performed in terms of angular subtense and not in terms of extent in mm or µm. A CCD camera can be used in this artificial eye to mimic the retina, particularly for retinal images that do not vary in time. For TVRI, a CCD camera usually lacks the possibility to determine the dependence on time and provides information about the temporarily averaged retinal image irradiance profile. It is also possible to place a field stop in the image plane and position a radiometer, particularly a time-resolving power meter behind the field stop. The retinal image can also be obtained by ray tracing, again with due consideration of the potential effects of the 7 mm aperture stop on the retinal image.

In the beginning of this subchapter some terms will be discussed. The angle of acceptance is the angle that is subtended by a field stop placed in the image plane as seen from the imaging lens of the (artificial) eye, see Figure 15. The field stop in the image plane defines the field of view (FOV) in the sense of a two-dimensional solid angle property. The angle of acceptance γ_x and γ_y is usually used to refer to the horizontal and vertical angular extent (or the angular diameter when circular) of the FOV. These two angular subtenses are correspondingly related to the horizontal length d_x and the vertical length d_y of the field stop.

$$\gamma_x = \frac{d_x}{i} \qquad \gamma_y = \frac{d_y}{i}$$

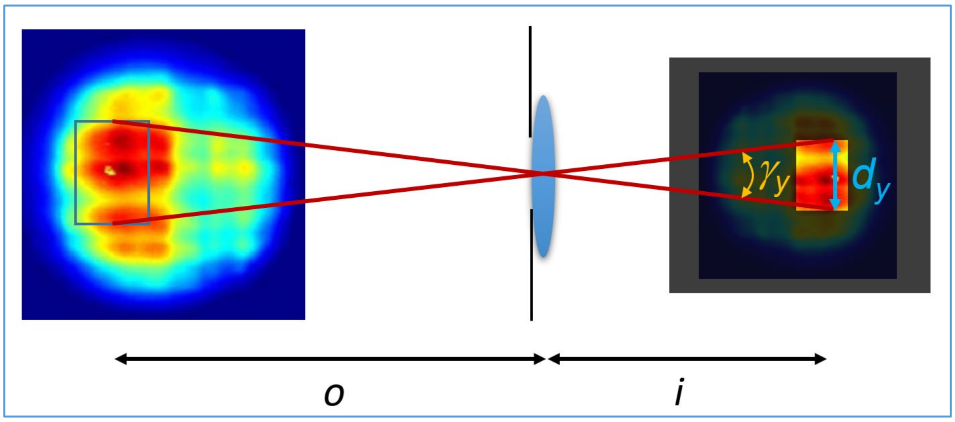

Figure 15. Schematic showing a rectangular field stop placed in the image plane, defining a rectangular field of view. The vertical extent d_y of the field stop defines the vertical angle of acceptance γ_y. The CCD image is used in this figure to also represent the source image, which in this case is valid since the radiation was spatially incoherent so that the 7 mm aperture stop did not have an effect on the retinal image. The retinal image plane and the object plane are shown flipped by 90°, which is why the horizontal angle of acceptance cannot be properly sketched. The field stop is shown semi-transparent but in reality would fully block radiation outside of the field stop.

The field stop can be an actual hardware field stop, or it can be a software field stop when the matrix information of the CCD camera is analysed by software.

For a non-circular or non-quadratic field stop, it is not really accurate to refer to "the angle of acceptance γ" as is done in the current edition or IEC 60825-1 in subsection 4.3d). A better term would be the FOV understood as two-dimensional property.

The more general approach for non-circular and non-square FOVs is to refer to the horizontal and vertical angle of acceptance γ_x and γ_y. The principle is that each dimension is varied between α_{min} and $\alpha_{max}(\Delta t)$, i.e.

$\alpha_{min} \leq \gamma_x \leq \alpha_{max}(\Delta t)$, and $\alpha_{min} \leq \gamma_y \leq \alpha_{max}(\Delta t)$.

The respective FOV is used to determine the accessible emission AE. At the same time, the horizontal and vertical angular subtense of the field stop is used to determine α for C_6 in the AEL. For this step, α_x is set equal to γ_x and α_y is set equal to γ_y. The parameter α for C_6 is then obtained as the mean:

$$\alpha = \frac{\alpha_x + \alpha_y}{2} .$$

This approach avoids using the symbol γ (which would have to be an average of the x and y extent of the FOV) and reflects the difference between the FOV to determine the AE and α as factor for the AEL.

4.5.2 Retinal irradiance pattern

A given location of the artificial eye in the emission field and a given accommodation state of the artificial eye results in a certain retinal irradiance profile at the retina - or for experimental determination, more generally, in the image plane. When x and y are the coordinates in the image plane, and t is the time, then for each location of the 7 mm aperture stop in the emission field and for each accommodation, a retinal irradiance pattern $E_{ret}(t,x,y)$ is given as spatial pattern in x and y but also varying in time t (unless it is a non-scanned cw emission). This irradiance profile information is the basis to determine both the accessible emission as well as parameters relevant for the AEL, namely C_6, but also C_5. While the retinal irradiance with units of W m^{-2} and as function of x and y with dimensions of length is the easiest conceptually, it has to be kept in mind that the analysis method for extended sources as well as the parameter α is defined in terms of angular quantities. This is more generally valid and also lends itself for the case that the analysis is done experimentally with a fixed focal length imaging system and a variable image distance *i*. In this case it is important to perform the analysis in terms of angle and not in terms of *x* and y coordinates in the image plane. The transformation of angular quantities in radian and distance quantities in mm is done simply via $x = \gamma_x \cdot i$ and $y = \gamma_y \cdot i$. The small angle approximation was used which is usually sufficiently accurate. Therefore, in the general case, it is not really the retinal irradiance as power per area that is analysed but the power per solid angle in W sr^{-1}. For simplicity, in this white paper, the discussion will refer to retinal irradiance with coordinates *x* and *y*, implying a transformation into angular quantities where necessary.

For a retinal image that does not vary in time, the *t*-dependence of the retinal irradiance profile can be associated to the whole irradiance profile. In this case, the retinal irradiance pattern is constant in terms of relative distribution across *x* and *y*, but the whole pattern can be "on" or "off" or modulated depending on the temporal power pattern passing through the 7 mm aperture stop. However, scanned emission or imaging arrays can lead to time-varying retinal images, where the retinal irradiance distribution within the image changes with time. That is, the *t*-dependence of the retinal irradiance pattern is not the same for all points in the retina. This is what is referred to here as time-varying retinal image (TVRI). This is also discussed somewhat further in chapter 5.

4.5.3 What the standard says

The analysis of the retinal irradiance pattern can be understood as a kind of image analysis. The rules for the image analysis are given in subclause 4.3 d) of IEC 60825-1 "Non-uniform, non-circular or multiple apparent sources".

A somewhat shortened version reads as follows:

> The 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 α subtended in each scenario. For the evaluation of assemblies of points or for partial areas, the angle of acceptance γ is to be varied in each dimension between α_{min} and α_{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 α 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 α_{max} or less than α_{min} shall be limited to α_{max} or α_{min} respectively, prior to calculating the mean.

The text in the standard refers to "every single point", to "various assemblies of points" and to "partial areas". The generic requirement is the variation of the angle of acceptance in each dimension, between α_{min} and α_{max}, where α_{max} is given by the choice of emission duration that is analysed. This is the more complete and generalised version of what is referred to as "partial areas" in the text of the standard, referring to areas of the retinal image. With this systematic variation of the angle of acceptance, consideration of "every single point" and "various assemblies of points" is included.

The method of image analysis as given in the standard was also discussed in the ILSC 2015 proceedings paper [8].

4.5.4 Variation of FOV

Note that not only the horizontal and vertical extent of the angle of acceptance has to be varied, but also the location within the retinal image profile. If necessary, also a rotation of the orientation is to be considered. This variation of the location (such as of the lower left corner of the FOV), together with the variation of the extent, can be expressed by adding the index *k* to the symbols, i.e. $\gamma_{x\text{-}k}$ and $\gamma_{y\text{-}k}$.

4.5.5 The FOV determines the AE

Whatever energy passes through the chosen field of view within the chosen temporal evaluation window Δt_j is then the accessible emission (but see subchapter on emission duration above; we continue with the simplification of rectangular temporal pulse shapes, so that the AE can be determined with the emission duration Δt, see 4.2.5)

AE(Δt_j, $\gamma_{x\text{-}k}$, $\gamma_{y\text{-}k}$).

It is evident that when the retinal irradiance profile is larger than the chosen FOV, the AE is smaller than the energy that passes through the 7 mm aperture stop. In this sense, the wording used in the current version of 4.3 d) of "partial accessible emission" is not fully appropriate, because it is not a "partial" AE that is determined through the FOV against the AEL, it is *the* AE (at least for the respective FOV). It is rather that the AE as energy passing through the FOV might be a *partial* energy compared to what passes in total through the 7 mm aperture stop.

4.5.6 Steps of the image analysis

The image analysis in the emission duration regime of longer than 0,25 s and particularly in the regime of T_2 is somewhat different and calls for a more detailed discussion in subchapter 4.5.8 and following subchapters.

For emission durations less than 0,25 s it is important to note that for the image analysis, the relevant emission duration Δt has to be chosen as a first step. This is necessary because $\alpha_{max}(\Delta t)$ limits the maximum extent of the FOV in each dimension, and thus the maximum FOV depends on Δt. For this step it is not necessary to choose the starting time of Δt, since this step is only about the determination of $\alpha_{max}(\Delta t)$.

Following this first step, the location as well as the horizontal and vertical extent of the FOV is varied, up to $\alpha_{max}(\Delta t)$, and possibly also a rotation needs to be considered. These can all be considered as individual loops when the image analysis is programmed.

The goal of this image analysis, performed for a given retinal irradiance profile $E_{ret}(t,x,y)$ and a certain choice of Δt_j, is to determine the worst-case location and extent of the field of view. In other words, for a given choice of Δt_j, the variation of $\gamma_{x\text{-}k}$, $\gamma_{y\text{-}k}$ will identify a specific $\gamma_{x\text{-}k}$ and a specific $\gamma_{y\text{-}k}$ which is associated to the maximum ratio of AE to AEL.

For retinal images that do not vary in time, the extent and location of the FOV in the retinal image does not have an influence on the temporal pulse pattern (power as function of time) that is detected through the FOV. For TVRI, however, different extents and locations of the FOV often result in different temporal patterns. Figure 16 shows the example of a retinal image that is an array of 8 by 3 elements. Each element has an extent of 2 mrad by 2 mrad, and the elements are separated by 1 mrad spacing edge to edge. The elements are pulsed consecutively with a period of 10 µs in the order shown by the numbers. The 24 pulses from the 24 elements, often called a frame, repeats itself with some give frame frequency. The pulse duration per element is assumed to be in the nanosecond regime. In this case, the scan path during the pulse is negligible, and an array pattern could also be created by a two-dimensional scanner and accommodation to infinity.

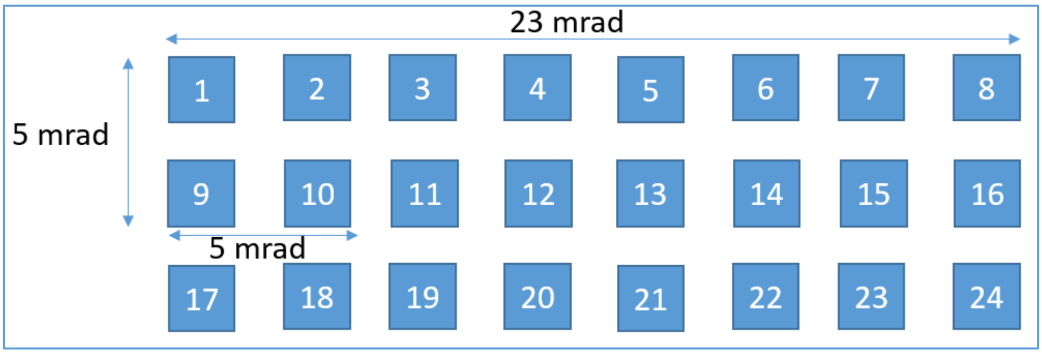

Figure 16. Example for a retinal image pattern created either by imaging an array or potentially also for accommodation to infinity with a two-dimensional scanner.

The horizontal overall extent of the array is equal to 23 mrad. When the emission duration that is analysed is longer than 13,3 ms, α_{max} is larger than 23 mrad and the maximum FOV encompasses all array elements. The pulse pattern that is detected through a FOV equal to or larger than 23 mrad is shown in Figure 17 as uppermost pulse pattern. For scaling purposes, it is assumed for Figure 17 that there is no pause between the frames.

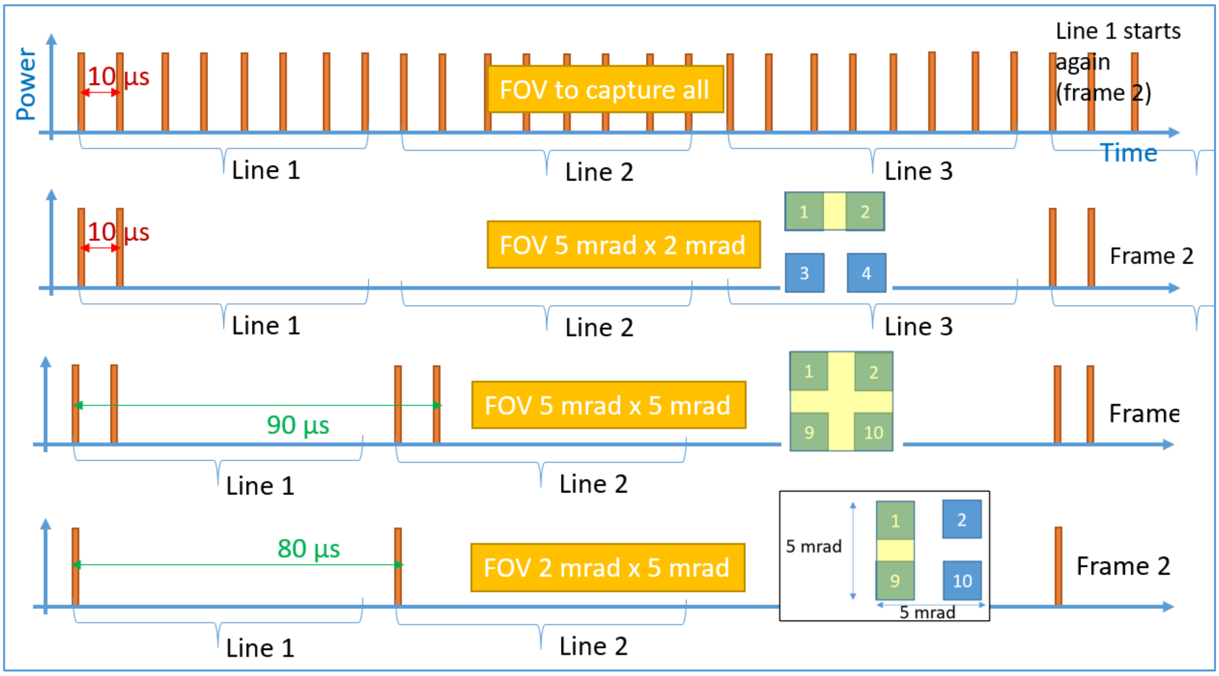

Figure 17. Example of pulse patterns detected through different FOVs. It is assumed that the second frame starts right after the first frame has ended. The top shows the pattern when the FOV encompasses the whole array. The second pattern is detected through a horizontal 5 mrad x 2 mrad FOV encompassing element 1 and 2. The third pattern passes through a FOV of 5 mrad x 5 mrad, encompassing 2 x 2 elements. The bottom shows the pattern for a vertical 2 mrad x 5 mrad FOV.

When emission durations up to 625 µs are analysed, the field of view is limited in each dimension to α_{max} = 5 mrad. Depending on the chosen FOV, the pulse pattern detected through the FOV varies. The respective pattern needs to be analysed in terms of AE and AEL analysis.

The example shows that for TVRI it can be advantageous to conceptually chose a certain α_{max}, such as 5 mrad, as a first step, and then consider what associated maximum emission duration results, which for 5 mrad is up to 625 µs. This means that per chosen FOV, the pulse pattern can be analysed based on the actual pulses being separated by 10 µs, but also by considering various groupings, such as for the 5 mrad x 5 mrad FOV to consider four pulses that pass through the FOV per frame as a group with an effective pulse duration of 90 µs (neglecting the duration of one pulse here), as shown in the third line of Figure 17. For a chosen α_{max} = 5 mrad, the maximum grouping duration is 625 µs.

The AE-AEL analysis for the array can be found in subchapter 4.6.

4.5.7 For TVRI: application of C_5 in the image analysis

The image analysis method defined in 4.3 d) of the standard requires the ratio of AE and AEL to be maximised.

For multiple pulses, 4.3 f) Requirement 3) states that the single-pulse AEL needs to be reduced by C_5. ISH1 provides guidance that for the image analysis of a given image (associated to a certain accommodation state), it is not necessary to apply C_5 to the AEL when determining the FOV with the maximum ratio of AE to AEL. In other words, according to ISH1, the image analysis of a given retinal irradiance profile is performed without the application of C_5.

For a retinal image that does not vary in time, the image analysis is relatively straightforward and results in an AE-AEL pair for each retinal image which has the maximum ratio, per given emission duration. Per location of the eye in the emission field, the accommodation has to be varied. Thus, per location, and per emission duration, a list of AE-AEL pairs results from the variation of the accommodation, one from each considered accommodation. Per emission duration, the maximum out of this list is selected and is then assigned to the respective location. Thus, for a given emission duration, each location has then an associated most restrictive AE/AEL ratio, originating from the worst-case accommodation. According to the guidance of the ISH1, it is only when different locations are compared that the "location-AEL" is multiplied with C_5 in order to determine the overall maximum ratio of AE/AEL (now the AEL containing C_5) for the respective choice of emission duration. Actually, it is not necessary to formally identify the *maximum* AE/AEL ratio for the different locations and emission durations, i.e. it is not necessary to compare AE/AEL ratios. The fundamental requirement is that for all relevant variations of location and emission duration, the AE needs to be below the respective AEL, i.e. all variations have to be associated to a ratio of AE/AEL less than 1. This is the more general and generic requirement, and it is not necessary to determine the maximum ratio - unless additional information is of interest, such as what the MRP is, or what the margin to the AEL is for a potential increase of the emission of the product.

One aspect in the development of the method described in this white paper was how to properly apply the factor C_5 when the analysed retinal irradiance pattern varies with time, i.e. a TVRI. After careful consideration of possible scenarios, the recommendation in this white paper is to **include C_5 already at the level of the image analysis**, i.e. for the variation of the FOV. The reason is that for TVRI, the number of pulses of one part of the retinal image (such as when an array is imaged, of one array element) might be associated to a smaller energy per pulse as compared to another element, but might emit with a higher repetition rate, thus overall being biologically more restrictive. When C_5 were not to be applied in the variation of the FOV, only the energy per pulse would be relevant and the result of the image analysis would be the element with the higher energy per pulse (the average power criterion only covers cases with sufficiently high repetition rates).

While this recommendation to apply C_5 in the image analysis to a degree deviates from the guidance found in ISH1, it is consistent with the following NOTE 3 of subclause 5.4.3 of IEC 60825-1 which requires "due consideration of repetitive nature of the accessible emission determined with the respective angle of acceptance".

> NOTE 3 For laser products emitting a scanned beam, depending on the accommodation condition to image the apparent source, a scanning beam can result in the image of the apparent source being scanned across the retina, resulting in a moving apparent source. If a moving apparent source is to be accounted for in the classification, the classification of the product is based on the evaluation method described here for extended sources (in contrast to the simplified analysis where a small source is assumed to be stationary). The moving apparent source is to be evaluated as described in 4.3. d) with due consideration of the repetitive pulse nature of the accessible emission determined with the respective angle of acceptance.

In practice it depends on the scan pattern on the retina and the pulsing scheme if the inclusion of C_5 in the image analysis makes a difference (and creates substantial added complexity) or not. The simplified worst-case approach of assuming the minimum value of C_5 (i.e. 0,2 for emission durations above 5 µs and 0,4 for emission durations less than or equal to 5 µs) also obviates the necessity to include C_5 in the image analysis (see subchapter 4.2.4 for comments on the analysis of irregular pulse patterns and worst-case simplifications).

The array in the previous subchapter is a good example for the potential impact of the FOV on the number of (effective) pulses, as can be seen in Figure 17. Further below we will present the respective AE-AEL analysis for this array.

4.5.8 Determination of $T_2(\alpha)$ – method

For emission durations $\Delta t \geq 0{,}25$ s, the parameter α_{max} is constant and equals 100 mrad. This emission duration regime can be referred to as long-term regime. This is the emission duration regime where C_5 no longer applies and the only requirement for pulsed emission is the average power requirement 2) of 4.3 f). For Class 1, when retinal photochemical limits apply, the retinal image needs to be scanned with a given FOV (that depends on the emission duration for emission durations longer than 100 s) for the location of maximum AE. For the retinal photochemical limits, there is no need to perform an image analysis to maximise the AE/AEL ratio, since the AEL does not depend on α.

For Class 1 based on the retinal thermal limit, for the average power criterion, it is usually sufficient to consider the AEL(T_2). However, T_2 depends on α as well as C_6 depends on α. The appropriate α, which can be referred to α_{T2}, if found via variation of the angle of acceptance in each dimension between 1,5 mrad and 100 mrad, where the variation includes also the location of the field of view in the retinal image. The principle of the image analysis is the same as for emission durations less than 0,25 s. The difference is that in the image analysis for $\Delta t <$ 0,25 s, the choice of Δt determines $\alpha_{max}(\Delta t)$, which limits the maximum extent of the angle of acceptance $\gamma_{x\text{-}k}$ and $\gamma_{y\text{-}k}$. The image analysis in the regime of $\Delta t = T_2(\alpha)$ is somewhat different because α_{max} equals a constant value of 100 mrad and the AEL depends not only on $C_6(\alpha)$ but also on $T_2(\alpha)$. Therefore, it is the choice of $\gamma_{x\text{-}k}$ and $\gamma_{y\text{-}k}$ that determines $T_2(\alpha)$ via $\alpha_x = \gamma_x$ and $\alpha_y = \gamma_y$. Thus, there is no need to "choose" Δt as a first step, it is rather that the choice of the extent of the FOV results in a certain value of $T_2(\alpha)$. The image analysis, based on the variation of the FOV, is performed to maximise

AE(γ_x, γ_y) / AEL($C_6(\alpha)$,$T_2(\alpha)$).

The image analysis can be done by expressing both the AE and the AEL in terms of power (AE then being the average power passing through the FOV) or both in terms of energy within T_2. The FOV that is associated to the maximum of the above ratio is the basis for the parameters α_x and α_y. The respective average angular subtense of the apparent source, as solution of the image analysis, can be referred to as α_{T2}. The average power requirement is fulfilled when the AE determined with critical FOV is below the AEL($C_6(\alpha_{T2})$,$T_2(\alpha_{T2})$). The process will be demonstrated for the array example in subchapter 0.

For Class 2 and Class 3R in the visible wavelength range, the time base equals 0,25 s and the AEL only depends on $C_6(\alpha)$ and not on $T_2(\alpha)$. Performance of an image analysis to determine the maximum ratio of AE/AEL result in a respective "long term" α for the time base of 0,25 s, for which the symbol $\alpha_{0,25s}$ could be used.

4.5.9 Determination of $T_2(\alpha)$ – importance for C_5

The issues discussed in the following are also a topic in ISH1 [9], but in substantially condensed form. The European amendment A11:2021 to EN 60825-1:2014 [3] features a somewhat longer version of the IEC ISH1 in Annex ZB. Since A11:2021 was developed some time after the IEC ISH1 and there was the option for more text than permitted for an interpretation sheet, Annex ZB in A11:2021 provides some additional information, particularly for the issues discussed in this subchapter.

The long-term average power image analysis described in the previous subchapter is not only an important AEL criterion in its own right, but for Class 1 yields α_{T2} and $T_2(\alpha_{T2})$ which are relevant for the application of C_5 to single-pulse AELs for emission durations less than 0,25 s. When the time base is 0,25 s, it is $\alpha_{0,25s}$ which is relevant which C_5 value is applied. The respective α is referred to in Annex ZB of A11:2021 as "long-term" α. To use a dedicated and common symbol for this long-term α, the symbol α_{TB} is used here. The subscript *TB* is representative of "time base".

For Class 1, $T_2(\alpha_{T2})$ is important because N is the number of pulses, or number of pulse groups, in T_2. When the time base is 0,25 s, N is the number of pulses, or the number pulse groups, in 0,25 s.

The long-term α, referred to here as α_{TB} jointly for Class 1 and when the time base is 0,25 s, is a critical parameter that determines the minimum value of the thermal C_5. For the thermal C_5 (i.e. for emission durations longer than 5 µs) subclause 4.3 f) of the standard features several cases, as shown in the following with adjusted symbols.

> C_5 is only applicable to emission durations shorter Δt than 0,25 s.
>
> > Note by the author: this is consistent with the definition of "pulsed laser" (3.70) where only emission durations *less than* 0,25 s are considered as a pulse. Not applying C_5 to an emission duration of *equal* to 0,25 s helps the alternative presentation of the last condition where C_5 = 1 for retinal images larger than 100 mrad, as further commented below.
>
> For $\alpha_{TB} \leq$ 5 mrad:
> $C_5 = 1,0$
>
> For 5 mrad $< \alpha_{TB} \leq \alpha_{max}(\Delta t)$:
> $C_5 = N^{-0,25}$ for $N \leq 40$
> $C_5 = 0,4$ for $N > 40$
>
> For $\alpha_{TB} > \alpha_{max}(\Delta t)$:
> $C_5 = N^{-0,25}$ for $N \leq 625$
> $C_5 = 0,2$ for $N > 625$
>
> For α_{TB} = 100 mrad: C_5 = 1,0.

The standard text of subclause 4.3 refers to α, while here the symbol α_{TB} is used.

Besides the symbol α_{TB}, the way this subsection of 4.3 f) is reproduced here deviates from the respective subsection of IEC 60825-1 by writing $\alpha_{max}(\Delta t)$ rather than just α_{max}, in order to clarify that α_{max} is determined for the respective emission duration, as the duration of the temporal analysis window (such as the pulse duration or pulse group duration).

If the discussion would be only for Class 1, it would be more intuitive to use the symbol α_{T2} rather than α_{TB}. After all, α_{T2} is the result of the process of variation the FOV to determine the accessible emission AE and maximising AE / AEL($C_6(\alpha)$,$T_2(\alpha)$). Thus, the duration T_2 to determine the number of effective pulses N is directly linked to α_{T2}. The parameter α_{T2} is the result of the image analysis and is also used in the inequalities of subclause 4.3 f). The time base for Class 1 is 100 s or 30 000 s for intentional long-term viewing. In the retinal hazard wavelength range, the latter is only relevant with respect to the retinal photochemical limit. For the retinal thermal limit, the AEL remains a constant power value for emission durations above T_2. Thus, as power level, the AEL for the time base of 100 s, AEL(t = 100 s) is equal to the AEL for the emission duration being equal to T_2: AEL(t = T_2 (α_{T2})). In that sense, an image analysis performed for t = 100 s is the same as an image analysis based on maximising AE / AEL($C_6(\alpha)$,$T_2(\alpha)$), although it is less intuitive to think about 100 s rather than T_2. Thus, for Class 1, $\alpha_{TB} = \alpha_{T2}$. For Class 2 and visible-emission Class 3R, α_{TB} can be thought of as $\alpha_{0,25s}$.

As a summary of the above and as introduction to the subsequent discussion, relevant text of Annex ZB.2.4 of A11:2021 is presented:

> To determine $T_2(\alpha)$ and in the criteria of 4.3 f) 3) "For $\alpha \leq 5$ mrad", "For 5 mrad < $\alpha \leq \alpha_{max}$", and, "For $\alpha > \alpha_{max}$", the quantity α is equal to the "long-term" α, i.e. equal to α as determined for a time base of 0,25 s or equal to the value of α of $T_2(\alpha)$. In the determination of this "long-term" α (applying the method specified in 4.3 d)), α_{max} = 100 mrad. That is, for T_2 and these inequalities, α is not limited to a value of $\alpha_{max}(t)$ smaller than 100 mrad and is therefore the same as the value that applies for the determination of C_6 for the time base of 0,25 s or 100 s, as applicable.
>
> As is generally defined (see 4.3 d)) the arithmetic mean is applied to determine α, i.e. it is not necessary that both dimensions satisfy the criterion "For $\alpha \leq 5$ mrad" independently.
>
> For the criterion "Unless α > 100 mrad", the angular subtense of the apparent source α is not restricted by α_{max}. For non-uniform (oblong, rectangular, or linear) sources, the inequality needs to be satisfied by both angular dimensions of the source in order for C_5 = 1 to apply. The value of α determined with α_{max} = 100 mrad (i.e. the "long-term" α) can also be used for this criterion, alternatively: in this case the criterion is written as "Unless α = 100 mrad", because for α to become exactly equal to 100 mrad, when applying α_{max} = 100 mrad, the image of the apparent source has to be larger than 100 mrad in both dimensions.
>
> Since the "long-term" α is needed for the inequalities in 4.3 f) 3) to determine the applicable C_5, the usual sequence is as follows.
>
> An analysis of the image of the apparent source is performed as given in 4.3 d) while either using AEL(t = 0,25 s), or AEL(t = $T_2(\alpha)$), depending on the time base. The angle of acceptance (as dimensions of the field of view) is varied between 1,5 mrad and 100 mrad in each dimension. Each field of view is associated to a certain value of T_2 and therefore AEL(t = T_2). The accessible emission is also determined for the respective field of view. The result of the process to vary the field of view is the "long-term" α that is associated to the field of view that produces the maximum ratio of AE to AEL. For the case of classification as Class 1, this process to determine the "long-term" α at the same time determines the value of $T_2(\alpha)$. This "long-term" α is used for C_6 for AEL(t = 0,25 s), or AEL(t = $T_2(\alpha)$), respectively, as well as the associated field of view to determine the AE for the comparison with these AEL.
>
> Following this step of the determination of the "long-term" α, all applicable shorter emission durations have to be analysed. For the analysis of emission durations less than 0,25 s, the "long-term" α is used to determine the appropriate C_5 in the equalities of 4.3 f) 3). $T_2(\alpha)$ is also relevant for the determination of N within $T_2(\alpha)$ or the time base, whichever is shorter.

The following picks up on the sentence of Annex ZB.2.4 marked with blue font and is the basis for the adjusted presentation of the C_5 requirements compared to 4.3 f) of the standard.

In the requirements for C_5 above, the final condition was written as

For α_{TB} = 100 mrad: C_5 = 1,0

instead of what is found in the standard:

Unless $\alpha > 100$ mrad, where C_5 = 1,0 in all cases.

The background is that in the image analysis to determine α_{TB} the field of view is limited to α_{max} = 100 mrad. Consequently, α_{TB} can never exceed 100 mrad. For this final condition, the symbol α used in the current version of the standard is more like a generic symbol for the retinal image dimension of an "unlimited α", or an "open α", i.e. apparently not limited to 100 mrad for this last condition. It was clarified in Annex ZB.2.4 of A11:2021 that α_{TB} (where α_{max} = 100 mrad is applied in the image analysis) can only be *exactly equal* to 100 mrad when both dimensions of the retinal image are either exactly 100 mrad (which is unlikely) or both dimensions of the retinal image are larger than 100 mrad. Thus, the condition of an unlimited α > 100 mrad is equivalent to the condition α_{TB} = 100 mrad – with the exception of the theoretical case that the retinal image has dimensions of exactly 100 mrad in both dimensions, because the current standard text refers to

Unless $\alpha > 100$ mrad

and not to

Unless $\alpha \geq 100$ mrad.

The condition of α = 100 mrad is consistent with the interpretation found in Annex ZB.2.4 of A11:2021.

Related to this adjusted presentation of the last condition, we take C_5 to apply to emission durations up to, *but not equal to 0,25 s*. This is based on the definition of pulsed laser (definition 3.70 of the standard). When emissions that last *exactly* 0,25 s are not considered as a pulse, then it stands to reason not to apply C_5. Thus, the definition of pulsed laser in the current edition of the standard is somewhat inconsistent with 4.3 f) where C_5 is applied "equal to or shorter than 0,25 s":

> C_5 is only applicable to individual pulse durations equal to or shorter than 0,25 s.

This difference of not applying C_5 to emission durations of *exactly* 0,25 s appears to be nit-picking, but it is necessary to avoid a logical inconsistency when we propose here to represent the last inequality of the standard as "For α_{TB} = 100 mrad". When we exclude the application of C_5 to an emission duration of exactly Δt = 0,25 s, then $\alpha_{max}(\Delta t)$ will also not be exactly equal to 100 mrad, i.e. $\alpha_{max}(\Delta t)$ will always be smaller than 100 mrad. This is relevant for the case that the retinal image in the long-term emission duration domain is larger than 100 mrad in both dimensions, i.e. when α_{TB} = 100 mrad. If we would permit that $\alpha_{max}(\Delta t)$ reaches exactly 100 mrad, and α_{TB} = 100 mrad, then the following would be true and C_5 would be less than 0,4, which is conflict with the final condition "For α_{TB} = 100 mrad" which is also true.

For 5 mrad $< \alpha_{TB} \leq \alpha_{max}(\Delta t)$:
C_5 = 0,4 for $N > 40$

4.5.10 Determination of $T_2(\alpha)$ – for TVRI

To perform an image analysis based on AEL(T_2) is also the first step for the case of TVRI[7]. For TVRI, the determination of $T_2(\alpha_{T2})$ with the method presented here is based on the **average retinal irradiance pattern, averaged over T_2.** Due to the averaging over time, the average irradiance pattern is not varying with time. In other words, the average irradiance pattern, averaged over at least 10 seconds is stationary in the sense of the average irradiance distribution within the image not varying over time.

As an example, we assume a well collimated beam with a diameter small compared to the 7 mm aperture stop with a two-dimensional scan pattern, such as a mirror scanning a beam both left and right but also up and down. For accommodation to infinity, the scan pattern on the retina consists of a minimum spot scanned over the respective area of the retina (limited in extent by the 7 mm aperture stop). For instance, for 100 mm distance from the scanning mirror, if the scan width is larger than the 7 mm aperture stop, the extent of the retina covered by the scan will be a circular area of 70 mrad angular subtense. The average retinal irradiance pattern (averaged over T_2) extends over 70 mrad, and does not vary in time, i.e. does not move and can be considered as stationary. For sufficiently dense scan paths, an image analysis that varies the FOV between 1,5 mrad and 100 mrad will result in 70 mrad as the worst-case FOV, i.e. as the FOV that features the maximum ratio of AE/AEL($T_2(\alpha_{T2})$). In the same way, for the case of imaging an array such as discussed in subchapter 4.5.6 above, the retinal image irradiance averaged over T_2 does not vary in time and can be considered as stationary. T_2 is then based on the classic image analysis of an array as discussed in ISH1 where it depends on the number of array elements and the spacing of the array elements whether an individual array element is associated to the maximum ratio of AE to AEL or the whole array. When the overall array is sufficiently large, and the elements are spaced sufficiently close together, then the maximum ratio of AE/AEL($T_2(\alpha_{T2})$) is found for the whole array. The array elements shown in subchapter 4.5.6 are sufficiently close together to result in the whole array being the solution of the image analysis for the determination of $T_2(\alpha_{T2})$).

The reader who is familiar with the ISH1 might point out that the ISH1 (see following text) can be interpreted differently when the ISH1 refers to the “stationary” retinal image.

> For the determination of the applicable value of C_5 in an analysis of moving apparent sources (originating from scanned emission when not accommodating to the pivot point or vertex) the value of α in the respective inequalities relating to the choice of C_5 in 4.3 f) 3) is determined for the *stationary* apparent source and the respective accommodation condition that is analysed (such as accommodation to infinity).

When the actual retinal image is time-varying, such as for the example of the array above, it is questionable what the “stationary” mode of such an array should be. One interpretation of a stationary rather than a TVRI is that all elements of the array emit at the same time. Such an image pattern would be equivalent in most cases to the pattern resulting from long-term averaging.

For the case of a collimated beam that is scanned via a mirror, for accommodation to infinity, when the mirror is assumed to be stationary, the retinal image of the apparent source would also not move. For a well collimated beam, the angular subtense of the retinal image in this case is less than 5 mrad and the thermal C_5 would consequently be equal to unity. The method discussed in this white paper, however, for the determination of α_{T2} is not based on stationary mirrors but on the long-term average of the retinal irradiance pattern associated to the retinal scan pattern. For the array example above, T_2 =13,7 s results from the 23 mrad x 8 mrad outer

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[7] This subchapter refers to Class 1 and T_2. However, the same general principle applies for Class 2 and visible-emission Class 3R where the AEL is determined for the time base of 0,25 seconds.

extent of the array and the corresponding thermal C_5 is less than 1. The long-term average irradiance pattern also does not change with time and is “stationary”.

There are cases where the scan pattern and/or image of the beam profile at infinity is larger than 100 mrad in both dimensions even for the case that the effect of the 7 mm aperture stop is duly considered. In this case, $C_5 = 1$. However, in these cases the most restrictive distance to the reference point is usually where one or both dimensions of the scan pattern become less than 100 mrad and then C_5 becomes smaller than 1.

That the criterion which C_5 to apply is based on the long-term average irradiance pattern is also consistent with heating of the retina from scan to scan or from frame to frame for the example of the array above, or for the example of a 2D scan and accommodation to infinity. While each short pulse per array element causes some temperature increase, which will cool off quickly, the background temperature increase that results for emission durations in the regime of tens and hundreds of milliseconds will be equivalent to that of a retinal image of the extent of 23 mrad x 8 mrad. This background temperature will gradually increase from frame to frame and the temperature increase from the individual pulses sit on top of that background temperature. This can be understood based on heat flow being relatively slow. With the thermal diffusivity of water D_{th}, which represents retinal tissue well, a simple thermal diffusion law predicts[8] that it takes a heating wave about 1 ms to cover δ = 1,5 mrad, and 5 ms to cover 3 mrad. It takes roughly 100 ms to cover half the horizontal extent of the array. Thus, the heat wave originating from one element will reach the heat wave of the neighbouring elements in the millisecond regime, evening out the temperature profile within the array. The centre of the array will, however, only be cooled laterally in the regime of 100 ms so that until that time, the background temperature in the centre of the array will gradually increase. Because one given array element in the centre of the array is surrounded by other elements, the radial cooling of this central array is compromised by the neighbouring elements. Thus, the background temperature will be much higher for the array as compared to a single array element. Thermally, as a background temperature, it is clearly the whole array and the relevant average irradiance that is relevant. The situation is equivalent for the case of a scan pattern on the retina resulting from mirror scanners. It is this background heating that for extended retinal images necessitates the reduction factor C_5 as it is defined in IEC 60825-1, and to base the value of α_{TB} for the C_5 inequalities on the long-term average irradiance pattern. As mentioned, due to the long-term averaging, this irradiance pattern is also stationary.

Some background information on the development of the ISH1 is also relevant for the respective paragraph discussed here. When the ISH1 was available as final draft, experts of the IEC technical committee TC 76 requested the IEC central office that this paragraph be removed. However, due to procedural reasons, the paragraph was not removed. When the content of ISH1 on the European level was included in an informative annex of A11:2021 to EN 60825-1:2014, this paragraph was not included.

4.5.11 Summary of image analysis

The following summarises what was discussed in this subsection 4.5. The wording “image analysis” refers to the AE/AEL analysis of a given retinal irradiance pattern $E_{ret}(t,x,y)$. This irradiance pattern depends on the location of the 7 mm aperture stop (as representative location of the eye) in the emission field, as well as on the accommodation state, which needs to be varied per location of the 7 mm aperture stop.

[8] D_{th} = 0,26 mm^2 s^{-1}; $\delta \cdot i \approx 2\sqrt{D_{th} \cdot t}$ where i is the image distance of the eye of 0,017 m (i.e. $\delta \cdot i$ is diffusion length in mm)

In terms of variation, the location of the 7 mm aperture stop can be associated to three dimensions, i.e. distance to the reference point as well as lateral coordinates. Usually it is sufficient and worst-case to align the plane of 7 mm aperture stop normally as indicated in Figure 18. The variation of the location can be represented by the index *m*, keeping in mind that the variation is three-dimensional.

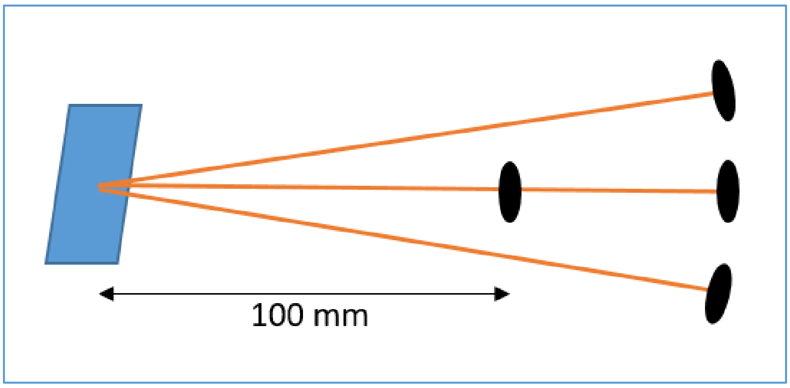

Figure 18. Schematic to demonstrate examples of the location of the 7 mm aperture in the emission field.

For each location *m*, the accommodation location has to be varied. This is the location in front of the eye associated to the optical object distance that is imaged onto the retina. This one-dimensional variation can be given the index *a*.

These parameter variations create a collection of retinal irradiance patterns than then all need to be analysed. The retinal irradiance pattern $E_{ret}(t,x,y)_{m,a}$ not only depends on the retinal coordinates *x* and *y* but in the general case, also on time.

The accessible emission AE is the energy that passes through the chosen field of view within the emission duration[9] $\Delta t = t_2 - t_1$. The FOV is defined by $\gamma_{x\text{-}k}$ and $\gamma_{y\text{-}k}$. Since the angle of acceptance is an angular quantity, and the irradiance coordinates are spatial quantities, the transformation of $x = \gamma_x \cdot i$ and $y = \gamma_y \cdot i$ is implied where *i* is the distance between the image and the imaging lens (using the small angle approximation for simplicity).

Thus, mathematically, the AE (as energy) is equal to

$$AE(t_2 - t_1, \gamma_{x-k}, \gamma_{y-k})_{m,a} = \int_{t_1}^{t_2} \int_{\gamma_{x1}}^{\gamma_{x2}} \int_{\gamma_{y1}}^{\gamma_{y2}} E(t,x,y)_{m,a} \; d\gamma_x \; d\gamma_y \; dt$$

This can also be written in two steps where first the irradiance is integrated over the FOV to result in a temporal power pattern *P*(t) (equivalent to a pulse pattern), such as shown in Figure 17 for the array example.

$$P(t)_{k,m,a} = \int_{\gamma_{x1}}^{\gamma_{x2}} \int_{\gamma_{y1}}^{\gamma_{y2}} E(t,x,y)_{m,a} \, d\gamma_x \, d\gamma_y$$

Here the index *k* was used to represent the variation of the location and the extent of the FOV, i.e. of γ_{x1}, γ_{x2}, γ_{y1}, γ_{y2}. The practical measurement can be done with a field stop placed in the image plane, and a photodetector and radiometer behind the field stop that can record the

[9] We remind the reader of the discussion in subchapter 4.2.5 that for non-rectangular pulse shapes, the AE needs to be determined over a somewhat wider integration range than the emission duration, because the emission duration is defined based on the half-peak power points of the temporal power profile.

power as function of time. Depending on the extent and location of the field stop, varying accessible emission patterns will be determined, as shown in Figure 17. **Note that for a given FOV it is not relevant where in the FOV the emission takes place and if the irradiance profile within the FOV is time-varying or stationary.** In other words, for the emission *within* the FOV it does not matter if the emission is stationary or time-varying. The time-varying nature of the retinal irradiance pattern is accounted for by varying the FOV.

For a given FOV, the pulse pattern is then analysed in terms of varying temporal analysis window (emission duration $\Delta t = t_2 - t_1$) to obtain the respective energy that passes through the chosen FOV within the chosen emission duration. The variation of the start point t_1 and the duration of the temporal analysis window $\Delta t_j = t_2 - t_1$ is expressed by the index j:

$$AE_{j,k,m,a} = \int_{t_1}^{t_2} P(t)_{k,m,a}\, dt$$

In the same way as the location information within the FOV is not available and not relevant, so is the temporal pattern within Δt_j not relevant. The energy of the pulses within Δt_j are added up to determine the AE for that emission duration.

To summarise, each FOV_k has the following associated parameters:

1) For a TVRI (obtained for location m and accommodation a), different locations and extents of the FOV_k within the retinal image will result in different temporal patterns $P(t)_{k,m,a}$ of the laser radiation passing through the FOV_k. For a stationary retinal image, the temporal pattern does not depend on the location and extent of the FOV, and only the absolute value of the energy per pulse depends on the location and extent of the FOV (see next item).

2) The extent of the FOV is varied in each dimension between 1,5 mrad and $\alpha_{max}(\Delta t)$.

3) The AE for the chosen FOV_k and Δt_j is the energy that passes through the FOV_k within Δt_j (if pulses occur within Δt_j, AE the sum of the energy within Δt_j). Thus, as a quantity we have

   $AE(\Delta t_j, FOV_k)_{m,a}$ which can also be written as $AE_{j,k,m,a}$

4) The angular extent of the FOV_k is used to determine α for C_6, as factor of the single pulse $AEL(\Delta t_j, C_6(\alpha_k)$; $\alpha_x = \gamma_x$ and $\alpha_y = \gamma_y$. The symbol α_k is used as the average of α_x and α_y derived from FOV_k.

5) ISH1 provides the guidance not to apply C_5 in the image analysis. As the more general case, for TVRI it appears necessary to apply C_5 to the single pulse AEL already at the level of the image analysis. For TVRI, C_5 not only depends on the chosen emission duration that is taken as effective pulse duration Δt_j, but also on the FOV. Analysis of the pulse pattern $P(t)_{k,m,a}$ detected through the respective FOV_k, for a given emission duration Δt_j results in the value of $C_5(\Delta t_j, FOV_k)_{m,a}$. Note that because the temporal power pattern depends on the chosen FOV_k, also C_5 depends on the chosen FOV_k (see examples above).
   It is implied here that as a first step, for Class 1 classification, an image analysis to determine $T_2(\alpha_{T2})_{m,a}$ was performed for the respective retinal irradiance pattern, as information needed to determine C_5. For Class 2 or visible-emission Class 3R, the image analysis is performed with the respective $AEL(t = 0{,}25\text{ s}, C_6(\alpha))$.

6) The AEL is then $AEL(\Delta t_j, C_6(\alpha_k), C_5(\Delta t_j, FOV_k))_{m,a}$ noting that C_5 also depends on T_2 and α_{T2} determined for location m and accommodation a.

Note that the image analysis refers to the analysis of one given retinal irradiance pattern $E_{ret}(t,x,y)$. Per given location in the beam (the index *m* is used to denote the respective variation) and per given accommodation state (index *a*) we have the respective $E_{ret}(t,x,y)_{m,a}$.

The concept of a generalised image analysis - that can also be used to analyse TVRI - is to vary, for a given $E_{ret}(t,x,y)_{m,a}$ both the FOV_k and the emission duration Δt_j, to ensure that for all variations the AE is below the AEL.

For a systematic overview of the analysis steps, see chapter 5.

4.6 AE-AEL analysis for the array example

4.6.1 Introduction

In this subchapter, a numerical AE-AEL analysis for classification as Class 1 is provided for the array example that was described in 4.5.6. It is assumed that the emitting elements of the array are located in the focal plane of a projection lens, thus optically moving the apparent source for the array into infinity. Within the flash distance, for accommodation to infinity, the angular subtense of the image of the array does not change, and for simplicity we assume that this is the case for 100 mm distance from the projection lens (or more accurately, from the exit pupil of the projection assembly). This is the basis for performing an AE-AEL analysis only for 100 mm distance from the reference point, and not further. Additional accommodation states also do not need to be analysed when it is assumed that the exit pupil of the projection system is sufficiently large so that it is evident that accommodation to the exit pupil is less restrictive than accommodation to infinity.

The wavelength is assumed to be in the blue wavelength range so that the photochemical retinal limit is also relevant. The emphasis, however, is on the retinal thermal limit. The analysis based on the retinal thermal limit for the visible wavelength range is the same for wavelengths up to 1050 nm when all the AEL values are scaled with the correction factor C_4.

As described in 4.5.6, the pulse associated to one array element is in the nanosecond regime, and the period for the pulse from array element to array element is 10 µs. The term *frame* is used for one emission of all 24 elements, which takes 23 x 10 µs = 230 µs (always neglecting the pulse duration of the last nanosecond pulse). In the example calculations, the frame frequency will be varied from 10 Hz to 1000 Hz.

4.6.2 Photochemical retinal limit

The analysis for the photochemical retinal limit depends on the time base. For a time base of 100 s, the analysis angle of acceptance γ_{ph} equals 11 mrad. For a time base of 30 000 s, the analysis angle of acceptance γ_{ph} equals 110 mrad.

Figure 19 shows that four elements happen to extend over 11 mrad. The vertical extent of the array is less than 11 mrad and thus fully fits into a 11 mrad FOV. The shaded region shows a square FOV, which can be used as worst-case simplification. A circular FOV with an angular diameter of 11 mrad is permitted, which is shown as red circle, but is more complex to analyse.

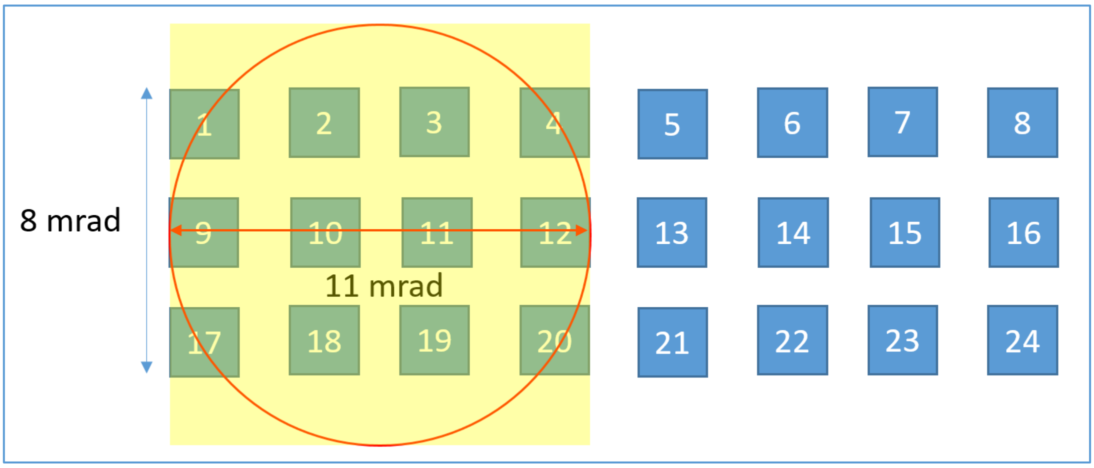

Figure 19. The AE for the retinal photochemical AEL analysis for a time base of 100 s is determined with an angle of acceptance of 11 mrad.

The analysis is relatively simple since only the average power detected through the FOV needs to be compared against the AEL_P of 0,039 mW, which applies both for 100 and for 30 000 s time base.

We take the simple worst-case of a square 11 mrad FOV and note that twelve array elements are located within the FOV. Thus, per array element, the $AEL_{P\_element}$ (to be compared to the average power passing through the 7 mm aperture stop per element) is limited to

0,039 mW /12 = 3,25 µW.

For the time base of 30 000 s, the whole array fits into 110 mrad and therefore the $AEL_{P\_element}$ per element equals

0,039 mW/ 24 = 1,19 µW.

Each element emits once per frame. For a given frame frequency *f*, the $AEL_{Q\_element}$ per array element expressed as energy per pulse is calculated with:

$$AEL_{Q\_element} = \frac{AE_{P\_element}}{f}$$

The resulting values are shown in Table 2 for a number of frame frequencies. These can be compared against the equivalent values based on the different retinal thermal AEL requirements.

Table 2. AEL values for Class 1 based on the **retinal photochemical limit**. The AEL in blue font is expressed as energy per pulse per array element.

			Frame Frequency		
		$AEL_{P\_element}$	10 Hz	100 Hz	1000 Hz
FOV	Elements in FOV	µW	$AEL_{Q\_element}$ in nJ		
11 mrad	12	3,25	325,0	32,5	3,3
110 mrad	24	1,63	162,5	16,3	1,6

4.6.3 T_2 analysis

For the average power requirement 2) of 4.3 f) in the emission duration regime above 0,25 s, the most restrictive emission duration is equal to T_2. However, T_2 depends on α. An array is a classic example for the variation of the FOV to encompass one element, or several elements (up to the maximum number of elements that fit into the FOV limited by α_{max}).

For an emission where all array elements feature the same average power, and the elements are sufficiently closely spaced, it is always the complete array that is associated to the maximum AE/AEL ratio. The critical spacing distance also depends on the number of the elements, i.e. larger arrays have a larger critical spacing. The FOV is limited by α_{max} = 100 mrad, so that the whole array fits into the maximum angle of acceptance.

In Table 3, all possible arrangements are analysed, starting with a FOV that is equal to the extent of one element, etc. Each FOV results in the respective value of α, which is a factor both for C_6 as well as for T_2. An arbitrary average power per array element passing through the 7 mm aperture stop of equal to 1 mW is used. Thus, the whole array has an AE as average power of 24 mW.

As expected, the maximum AE/AEL ratio is found for the overall array, resulting in a T_2 (α_{T2}) = 13,9 s. This is based on the linear increase of the AE with increasing number of elements in the FOV, but a less than linear increase of the AEL with increasing α.

Table 3. Variation of the FOV reveals that the maximum AE/AEL ratio is found for a FOV that encompasses the whole array.

Rows in FOV	Lines in FOV	FOV Hor.	FOV Vert.	α	C_6	T_2	AEL(T_2, C_6)	AE average power	AE/AEL
		mrad	mrad	mrad		s	mW	mW	
1	1	2	2	2,0	1,33	10,1	0,52	1	1,9
2	1	5	2	3,5	2,33	10,5	0,91	2	2,2
3	1	8	2	5,0	3,33	10,9	1,29	3	2,3
4	1	11	2	6,5	4,33	11,2	1,66	4	2,4
5	1	14	2	8,0	5,33	11,6	2,02	5	2,5
6	1	17	2	9,5	6,33	12,1	2,38	6	2,5
7	1	20	2	11,0	7,33	12,5	2,73	7	2,6
8	1	23	2	12,5	8,33	12,9	3,08	8	2,6
1	2	2	5	3,5	2,33	10,5	0,91	2	2,2
2	2	5	5	5,0	3,33	10,9	1,29	4	3,1
3	2	8	5	6,5	4,33	11,2	1,66	6	3,6
4	2	11	5	8,0	5,33	11,6	2,02	8	4,0
5	2	14	5	9,5	6,33	12,1	2,38	10	4,2
6	2	17	5	11,0	7,33	12,5	2,73	12	4,4
7	2	20	5	12,5	8,33	12,9	3,08	14	4,6
8	2	23	5	14,0	9,33	13,4	3,42	16	4,7
1	3	2	8	5,0	3,33	10,9	1,29	3	2,3
2	3	5	8	6,5	4,33	11,2	1,66	6	3,6
3	3	8	8	8,0	5,33	11,6	2,02	9	4,5
4	3	11	8	9,5	6,33	12,1	2,38	12	5,0
5	3	14	8	11,0	7,33	12,5	2,73	15	5,5
6	3	17	8	12,5	8,33	12,9	3,08	18	5,9
7	3	20	8	14,0	9,33	13,4	3,42	21	6,1
8	3	23	8	15,5	10,33	13,9	3,75	24	6,4

We see that the maximum AE/AEL ratio is 6,4 where the AE is the average power of the whole array, i.e. 24 mW. Thus, an average power level per array element of 1 mW was a factor of 6,4 too high. For one element, the permitted average power to pass through the 7 mm aperture stop equals 1 mW / 6,4 = 156 µW (this can also be obtained by dividing the AEL of 3,75 mW by 24). To compare with the requirements in the pulsed regime, we convert the AEL expressed as average power per element into energy per pulse per array element. In the same way as for the photochemical retinal limit, the AEL expressed as energy per pulse and per array element depends on the frame frequency and is shown in Table 4.

Table 4. The AEL expressed as energy per pulse per array element, based on the retinal thermal long-term average power requirement, i.e. based on **AEL(T_2).**

	Frame Frequency		
$AEL_{P\_element}$	10 Hz	100 Hz	1000 Hz
µW	$AEL_{Q\_element}$ in nJ		
156	15617	1562	156

We note that for the average power analysis and the associated image analysis in the emission duration regime longer than 0,25 s, it makes no difference if the array elements emit sequentially or all at the same time with the frame frequency.

When the emission is in the blue wavelength range, the photochemical retinal Class 1 limit is, as expected, significantly more restrictive than the retinal thermal Class 1 limit that applies to the long-term average power.

4.6.4 Emission duration: 5 µs

The individual pulse duration is in the nanosecond regime and there is one pulse within an emission duration of 5 µs. For the wavelength range up to 1050 nm, the single-pulse AEL is a constant energy value of 77 $C_6 \cdot C_4$ nJ for emission durations less than and equal to 5 µs. The microcavity C_5 applies based on the number of accessible pulses within T_2. For an emission duration of 5 µs, the FOV has to be varied between 1,5 mrad and 5 mrad in each dimension. For a 2 mrad x 2 mrad FOV, there is one array element within the FOV, and consequently one pulse per frame will be detected through the FOV (see Figure 17). For a 2 mrad x 5 mrad FOV, there are two pulses within the FOV per frame, resulting in double the number of pulses with a potentially reduced value of C_5 when analysing the pulse pattern with Δt = 5 µs. At the same time, the larger FOV is associated to a larger C_6. For a FOV of 5 mrad x 5 mrad, there are four pulses passing through the FOV per frame.

For the example of the array, when the elements of the 8 x 3 array emit consecutively, the pulse period is 10 µs and there is no pause between frames (f = 4167 Hz), the number of frames within T_2 = 13,9 s is already so high that the microcavity C_5 reaches its minimum at C_5 = 0,4. Consequently an increase of FOV from 2 mrad to 5 mrad has no effect on C_5. In this case it is evident that for an emission duration of 5 µs, the FOV with 2 mrad x 2 mrad with C_6 = 1,33 is the most restrictive case (the AE in all cases is the energy that passes through the 7 mm aperture stop per pulse, since this analysis is for Δt = 5 µs). To have an example where C_5 depends on the FOV, we can assume that after the pulse of the 24th element, there is a pause until the next frame starts again with element number 1. For instance, we can assume a frame frequency of 100 Hz so that there are 1371 frames within T_2.

For a frame frequency of 100 Hz, the following Table 5 shows the respective three cases of varying the FOV for a given emission duration $\Delta t \leq$ 5 µs (so that the actual number of pulses is used to determine N, and the AE is the energy for one pulse of an element passing through a 7 mm aperture stop).

Table 5. AEL values for the AEL applicable to the nanosecond pulses, based on $\Delta t \leq$ 5 µs and the microcavity C_5 for an angle of acceptance between 2 mrad and 5 mrad.

FOV – horiz.	FOV – vert.	Number of accessible pulses per frame	Pulses N in T_2	Microcavity C_5	α	C_6	$AEL_{Q\_element}$
mrad	mrad				mrad		nJ
2	2	1	1387	0,82	2,00	1,33	84
2 5	5 2	2	2774	0,69	3,25	2,33	124
5	5	4	5549	0,58	5,00	3,33	149

We see that for increasing FOV, the decrease of C_5 is less pronounced than the increase in C_6, so that the most restrictive AEL is that for the minimum FOV. Thus, the result of this image analysis for $\Delta t \leq$ 5 µs is α = 2 mrad and the AEL that applies to each pulse is equal to 84 nJ.

The finding that a FOV of 2 mrad x 2 mrad produces the maximum AE/AEL ratio also applies to other frame frequencies. Table 6 shows the results for varying frame frequencies.

Table 6. The AEL per nanosecond pulse for emission durations **$\Delta t \leq 5$ µs.**

Frame Frequency		
10 Hz	100 Hz	1000 Hz
$AEL_{Q\_element}$ in nJ		
103	84	47

For the chosen frame frequencies, this criterion is more restrictive than the long-term average power requirement for an emission duration of T_2.

4.6.5 Emission durations between 5 µs and 625 µs

The determination of the number of accessible pulses of the previous subchapter was based on an emission duration Δt = 5 µs. Each nanosecond pulse that passed through the respective FOV was counted as one pulse for the determination of N for C_5.

Longer emission durations also need to be analysed where two or more pulses are considered as a group, i.e. as one effective pulse. The thermal C_5 applies in this emission duration regime, so that α_{T2} = 15,5 mrad becomes relevant in terms of which C_5 to apply. For emission durations up to 6 ms, α_{T2} is larger than α_{max} and therefore the following applies:

For $\alpha_{TB} > \alpha_{max}(\Delta t)$:
$C_5 = N^{-0,25}$ for $N \leq 625$
$C_5 = 0,2$ for $N > 625$

N is in this case the number of *effective* pulses, i.e. the number of how often the pulse group is detected within T_2 through the respective FOV. Up to a grouping duration of Δt = 625 µs, the same choices of FOVs as shown in Figure 17 apply. We can see that for the horizontal 5 mrad x 2 mrad and the 5 mrad x 5 mrad FOV, 10 µs as group duration is associated to two pulses as a group. This group repeats with the frame frequency for the case of the horizontal 5 mrad x 2 mrad FOV, and twice per frame for the 5 mrad x 5 mrad FOV. Thus, for the emission duration of 10 µs, we have two scenarios:

- 5 mrad x 5 mrad FOV with two groups per frame
- 5 mrad x 2 mrad with one group per frame, associated to a smaller α but also smaller N and potentially higher C_5 as compared to the 5 mrad x 5 mrad case.

For the group of two pulses as effective pulse, the AE is twice the AE of a single pulse.

C_5 only makes a difference between the two cases when N is less than 625, as otherwise C_5 = 0,2 and the smaller FOV is then apparently the more restrictive one. For the frame frequency f = 10 Hz, there are 139 frames within T_2. Table 7 summarises the relevant values and shows that the 5 mrad x 2 mrad has the lower AEL_{group} value. This finding also applies for higher frame frequencies where C_5 reaches the lower limit of 0,2.

Table 7. AEL values for a group of two pulses with Δt = 10 µs for a frame frequency f = 10 Hz.

FOV	α	N	C_5	AEL_{group}	$AEL_{Q\_element}$
5 mrad x 5 mrad	5,0 mrad	278	0,25	102 nJ	51 nJ
5 mrad x 2 mrad	3,5 mrad	139	0,29	85 nJ	42 nJ

In order to compare against other requirements, Table 8 shows the AEL that applies per nanosecond pulse per array element for varying frame rates.

Table 8. The AEL per nanosecond pulse for the emission duration **Δt = 10 µs.**

Frame Frequency		
10 Hz	100 Hz	1000 Hz
$AEL_{Q\_element}$ in nJ		
42	29	29

The AEL per nanosecond pulse and per array element is notably more restrictive than for emission durations $\Delta t \leq 5$ µs calculated in the previous subchapter. For the group of two pulses, the AE is twice as high, and C_5 is also more restrictive. This compensates for the 10 µs single pulse AEL being a factor of 1,68 higher than the AEL for 5 µs, and that the worst case α for Δt = 10 µs is a factor of 1,75 larger than for Δt = 10 µs.

Another example for a grouping duration for the 5 mrad x 5 mrad FOV is Δt = 90 µs with four pulses as a group. For this group, the AE is four times the single-pulse AE, N is determined with one occurrence per frame, and the AEL is determined for Δt = 90 µs. With C_6 = 3,33, the single effective pulse AEL = 2,16 µJ. For higher frame frequencies, C_5 = 0,2 so that the AEL applicable to the group of four pulses equals 431 nJ. When this is divided by 4, we obtain $AEL_{Q\_element}$ = 108 nJ. We see that the limitation based on a four-pulse group and Δt = 90 µs is notably less restrictive than the two-pulse group and Δt = 10 µs. There is no need to check the case of Δt = 80 µs for a vertical 2 mrad x 5 mrad FOV because it has two pulses (as for Δt = 10 µs), but the AEL is much higher.

A maximum FOV of 5 mrad is associated to a maximum emission duration of 625 µs. This permits groups of two or more frames. However, due to the limited increase of the AE compared to the increase of the AEL, we can assume that this is not more restrictive than the groupings already analysed. Larger maximum FOV are possible for longer emission durations, which will be discussed in the next subchapter.

4.6.6 Emission durations for larger FOV

A FOV of 5 mrad encompasses 2 elements in a row and two lines. A FOV of 8 mrad is needed to encompass 3 full elements in a row and all of the three lines fully. The associated emission duration to result in α_{max} = 8 mrad is Δt = 1,6 ms. For a FOV of 8 mrad x 8 mrad, there are nine pulses passing through the FOV per frame. The AEL and the AE needs to be determined for Δt = 1,6 ms. Of course, also longer grouping durations are associated to a FOV permitted to be 8 mrad x 8 mrad, although 8 mrad is then not the maximum FOV. Smaller FOV that encompass 2 x 2 elements were discussed in the previous subchapter.

For a frame frequency of f = 1000 Hz, the period of the frames is equal to 1 ms. The duration between the first pulse of one frame and last pulse of the next frame equals 1,23 ms. This means that the pulses associated to two frames, i.e. 18 pulses fit into the emission duration of Δt = 1,6 ms.

We note that the chosen emission duration is longer than the pulse pattern that passes through the FOV. The same number of pulses would fit into an emission duration of Δt = 1,23 ms. However, α_{max}(1,23 ms) = 7,0 mrad so that not the whole 3 x 3 subarray fits into the smaller FOV (see).

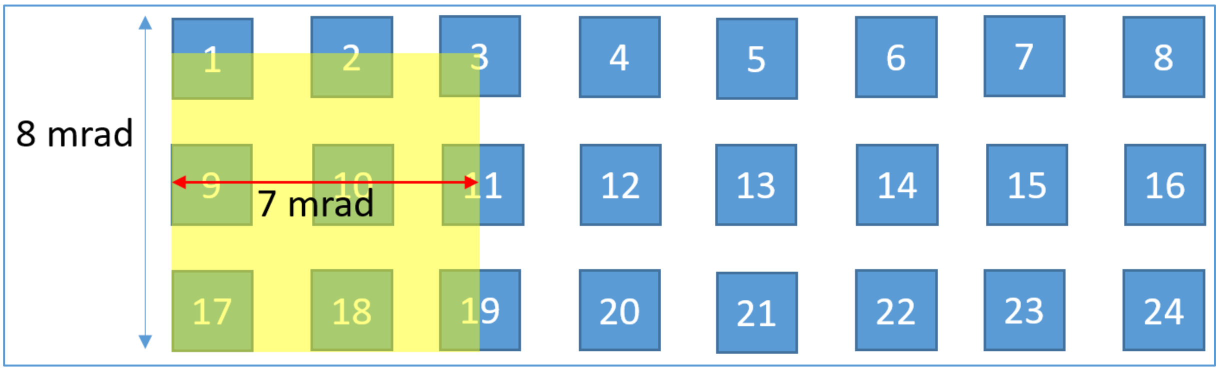

Figure 20. For a 7 mrad x 7 mrad FOV, a smaller AE passes through the FOV as compared to a FOV with 8 mrad x 8 mrad.

For a FOV of 7 mrad x 7 mrad, due to the partial array elements, the AE is a factor of 1,44 smaller than the full 8 mrad x 8 mrad subarray. The AEL for Δt = 1,23 ms is a factor of 1,22 smaller than for Δt = 1,6 ms. Thus, overall, the AE/AEL ratio for a FOV of 8 mrad x 8 mrad and the emission duration of Δt = 1,6 ms is more restrictive.

For f = 1000 Hz, with the emission of two frames fitting into Δt = 1,6 ms, there are 13872 frames in T_2, and N = 6936. This is significantly larger than 625 and therefore C_5 = 0,2. With α = 8 mrad, C_6 = 5,33. The AEL that applies to each time analysis window of Δt = 1,6 ms is therefore equal to $C_5 \cdot C_6\ \ 7 \cdot 10^{-4}\ \ 0{,}0016^{0{,}75}$ J = 5,97 µJ. Since there are two frames that make up the AE associated to Δt = 1,6 ms, and per frame 9 pulses, we need to divide this AEL by 18 to obtain the limitation of the AE per array element and per pulse of $AEL_{Q\_element}$ = 331 nJ. This is significantly less restrictive than for the shorter emission durations treated in the previous subchapters.

A similar analysis can be performed for a FOV of 11 mrad which encompasses a 4 x 3 subarray. The emission duration associated to α_{max} = 11 mrad is Δt = 3,0 ms. The pulses of three frames (taking 2,23 ms) fit into this emission duration. The value of $AEL_{Q\_element}$ = 318 nJ is a little bit more restrictive as for Δt = 1,6 ms, but not significantly.

For FOV that extend further, to encompass more elements in horizontal direction, and the corresponding longer emission durations to enable the larger FOV, the overall trend continues, with the exception of the trend of C_5. To encompass 5 elements, α_{max} = 14 mrad so that α_T = 15,5 mrad is larger than α_{max} and C_5 = 0,2, as in the analysis for the narrower FOV. However, to encompass 6 elements, α_{max} = 17 mrad so that α_{T2} = 15,5 mrad is now smaller than α_{max} and C_5 = 0,4. This makes FOV values of 17 mrad and above less restrictive than smaller FOV. The worst case FOV therefore is a FOV of 14 mrad, to encompass the 5 elements of a row, Δt = 4,9 ms. Pulses of 5 frames fit into this emission duration. The value of $AEL_{Q\_element}$ = 253 nJ is still significantly less restrictive than for Δt = 10 µs.

Thus, overall, the criterion that limits the accessible emission of the array, in terms of energy per pulse passing through the 7 mm aperture stop, is to take two pulses as a group with Δt = 10 µs.

5 SYSTEMATIC OVERVIEW OF ANALYSIS

In the previous chapter, the details of the parameter variation were discussed. Here, a summary and systematic overview is provided. The principle of the variations is the same for TVRI and for retinal image patterns that do not vary with time. However, for TVRI, some level of interpretation is necessary with respect to the determination of C_5.

One of the two main variations is the variation of the location of the eye[10] in the emission field, both in terms of distance but also laterally. Additionally, per location, a variation of the accommodation of the eye is required for the analysis of extended sources. It is not relevant in what order the variations are considered, when the two variations are seen as loops in an algorithm. When it can be concluded from general parameter dependencies that only accommodation to infinity and to the pivot point are the two relevant accommodations, then it lends itself that accommodation is the top variation level, and for each accommodation state, the distance to the reference point (or more generally, the location of the eye in the emission field) is varied. This is also done in the example in the subsequent chapter.

For each combination of location (index *m*) and accommodation (index *a*), a respective retinal irradiance pattern $E_{ret}(t,x,y)_{m,a}$ is obtained (see the note in subchapter 4.5.2 on the implied transformation to angular quantities). This concept is schematically shown in Figure 21.

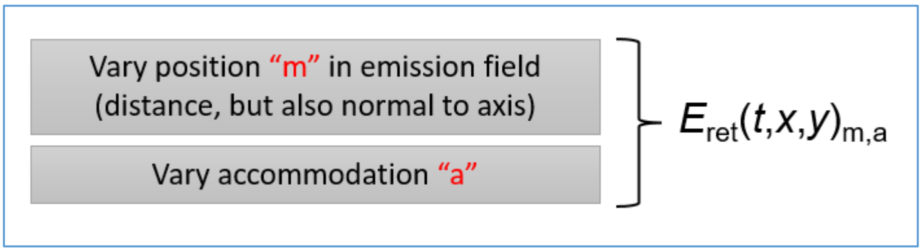

Figure 21. Diagram showing the variation of both the location of the eye in the emission field as well as, for each location, the accommodation distance. It is not relevant in which hierarchy the variation is performed: it can also be conceptualised as varying the location for a given accommodation.

For the case of a retinal image pattern that is *not varying in time*, such as typically for accommodation to the pivot point of the scanner, the time-dependence applies to the whole image irradiance pattern, so that the relative distribution within the retinal irradiance pattern is constant in time.

For the case of a TVRI (such as common for accommodation to infinity), different parts of the retinal image exhibit different temporal variations. The retinal irradiance distribution $E_{ret}(t,x,y)_{m,a}$ is then also a function of time in the sense that different parts of the image (different x, y coordinates) have different $E_{ret}(t)_{m,a}$ patterns.

For each location *m* and accommodation *a*, the retinal irradiance pattern needs to be analysed by variation of the angle of acceptance in each dimension γ_x, γ_y, as given in 4.3 d) of IEC 60825-1. The angle of acceptance values in each dimension, γ_x, γ_y, define the field of view (FOV). The relationship of the extent of the FOV with the emission duration is discussed further below. The respective FOV_k (using index *k* for a variation of both dimensions and location) is associated to a power pattern $P(t)_{k,m,a}$ passing through the FOV:

$$P(t)_{k,m,a} = \int_{\gamma_{x1}}^{\gamma_{x2}} \int_{\gamma_{y1}}^{\gamma_{y2}} E(t,x,y)_{m,a} \, d\gamma_x \, d\gamma_y$$

[10] The term „eye" is meant in an abstract way as an instrument used to determine the accessible emission via an imaging system. The location of the 7 mm aperture stop, placed at the imaging lens, is the reference location for the eye, and the image is detected at the image distance. Such a system can be realised with actual hardware, but also in a ray tracing model.

The resulting temporal power pattern, or pulse pattern, is analysed as any other pulse pattern according to the rules of 4.3 f) of IEC 60825-1, with a variation of the temporal analysis window.

For the analysis for emission durations less than 0,25 s it is necessary to perform an image analysis in the regime of T_2 first, since the respective parameters of $T_2(\alpha_{T2})$ are needed for the determination of C_5 that is applied to the AEL(Δt).

We assume in the following for simplicity that the pulses that pass through the FOV have a rectangular temporal shape. In this case, the emission duration Δt that is used to determine the AEL(Δt) is the same as the integration duration to determine the accessible emission. For non-rectangular temporal pulse shapes, the emission duration Δt is based on the half-peak power points of the outermost pulses in the considered pulse group or of the half-peak power points of the single pulse. In this case, as discussed in detail in subchapter 4.2.5, the integration duration Δt_{AE} for the determination of the AE needs to be a little wider than the emission duration Δt in order to encompass also the partial energy of the first and the last pulse outside of the half-peak power points. For rectangular temporal pulse shapes, the integration duration Δt_{AE} to determine the AE is the same as the emission duration to determine the respective AEL(Δt).

The choice of Δt_j (an index j is used to denote the variation both in terms of starting time of the temporal analysis window as well as the duration) results in the respective accessible emission as energy within

$\Delta t_j = t_2 - t_1$

$$AE_{j,k,m,a} = \int_{t_1}^{t_2} P(t)_{k,m,a}\, dt$$

Per chosen Δt_j, it needs to be considered that the FOV is limited in each dimension to a maximum extent given by $\alpha_{max}(\Delta t_j)$. Due to this limitation of the FOV, the variation of the FOV and the variation of the temporal analysis window (i.e. emission duration) is not independent. When the top-level variation is the emission duration, then per emission duration the variation of the FOV is limited to $\alpha_{max}(\Delta t)$. It is also possible to see the variation of the FOV as the top-level variation. In this case, γ_x and γ_y is varied each between 1,5 mrad and 100 mrad. The larger of the two dimensions is related to the minimum applicable emission duration Δt_{min} when per FOV$_k$ (including also a variation of the location in the retinal image, not just the extent) the emission duration Δt_j is varied to analyse the pattern $P(t)_{k,m,a}$ determined to pass through the FOV$_k$. The relationship of the angle of acceptance (the larger of γ_x and γ_y) with the minimum emission duration is via the formula for $\alpha_{max}(\Delta t)$:

$\alpha_{max} = \gamma_{(x,y)max} = 200\sqrt{\Delta t}$ which can be solved for Δt:

$\Delta t_{min} = \left(\dfrac{\gamma_{(x,y)max}}{200} \right)^2$ for the case that $\gamma_{x,y}$ is larger than 5 mrad.

For the case that both γ_x and $\gamma_y \leq 5$ mrad, there is no limitation on the minimum emission duration that is to be considered.

For instance, when the FOV is 100 mrad in one dimension, then this implies that $\alpha_{max} = 100$ mrad, which is the case only for emission durations of 0,25 s and above. Consequently, for a FOV of 100 mrad (as the maximum of the two dimensions), emission durations less than $\Delta t_{min} = 0{,}25$ s need not be considered in the analysis of the pulse pattern passing through the FOV. For the case of the maximum extent of the FOV being equal to 5 mrad or less, the whole range of emission durations need to be considered, since this FOV is then smaller or equal to the smallest α_{max}. For cases such as the array discussed above, the author finds the concept of first choosing the FOV and then varying the emission duration as the more intuitive one. Depending on the FOV, a certain accessible pulse pattern is detected, i.e. power as function of time. Such a pulse pattern is then analysed as any pulse pattern based on 4.3 f) of the standard, which includes treating groups of pulses as effective pulses and considering different group durations. For the third requirement of 4.3 f), C_5 is applied to the single-pulse AEL, where N is the number of pulses, or the number of pulse groups within T_2.

We come back to the variation of the FOV and its relationship to the emission duration Δt. We note that each dimension of the FOV is varied between $\alpha_{\min}$ and $\alpha_{\max}(\Delta t)$, i.e.

$\alpha_{\min} \leq \gamma_x \leq \alpha_{\max}(\Delta t_j)$, and $\alpha_{\min} \leq \gamma_y \leq \alpha_{\max}(\Delta t_j)$.

The respective FOV_k is used to determine the pulse pattern that passes through the FOV, and upon integration over Δt_j, the $AE_{j,k,m,a}$. At the same time, the horizontal and vertical angular subtense of the field stop FOV_k is used to determine α for C_6 in the AEL. For this step, α_x is set equal to γ_x and α_y is set equal to γ_y. The parameter α for C_6 is then obtained as the mean:

$$\alpha = \frac{\alpha_x + \alpha_y}{2} .$$

Because a is derived from the extent of the field stop FOV_k, the parameter α also receives the index k, i.e. α_k.

The variation of the temporal analysis window and variation of the FOV in the sense of an image analysis, as well as the resulting AE and AEL values, can be graphically represented as shown in the following figures.

As a first step (Figure 22), for Class 1 classification based on the retinal thermal limits, the variation of the FOV is performed to determine $T_2(\alpha_{T2})$, limiting the maximum extent of the FOV in each dimension to 100 mrad and using the temporarily averaged[11] retinal irradiance $E_{av}(x,y)_{m,a}$ as basis.

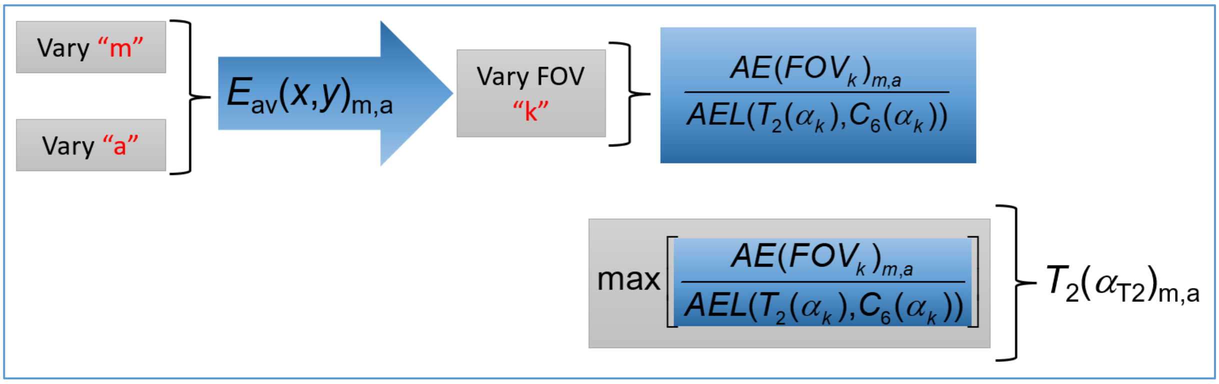

Figure 22. Diagram showing the concept of determination of $T_2(\alpha_{T2})$ for the time-averaged retinal irradiance pattern (obtained in location m and for accommodation a) via variation of the FOV.

The accessible emission is assumed to be given as average power passing through the chosen FOV_k. The AEL is given as power and depends via T_2 as well as via C_6 on the value of α. When the extent of the FOV_k is characterised by the plain angles γ_x and γ_y, then $\alpha_x = \gamma_x$ and $\alpha_y = \gamma_y$ and the symbol α_k is used as the average of α_x and α_y derived from FOV_k. Thus, as

[11] Strictly speaking averaged over T_2; however, usually the average irradiance pattern does not depend on the averaging duration in this regime of at least 10 seconds, thus there is only one average irradiance pattern that can be used for the $T_2(\alpha)$ analysis.

discussed in more detail in 4.5.8, variation of the FOV automatically results in the corresponding value of T_2. Therefore, in this analysis, it is not necessary to independently vary the temporal analysis window. The maximum of the ratio AE/AEL associated to the different FOV results in one value of $T_2(\alpha_{T2})$ for each retinal image pattern, i.e. for each variation of the location *m* and the accommodation *a*.

The information of $T_2(\alpha_{T2})_{m,a}$ is needed as input parameter in the image analysis for emission durations less than 0,25 s, where C_5 applies to the AEL(Δt_j), and where *N* is the number of effective pulses in T_2 and $\alpha_{TB} = \alpha_{T2}$ is the relevant quantity for the inequalities in 4.3 f). We note that the method described is based on the *average power* passing through the chosen FOV, averaged over long-term emission durations (formally over T_2, but in practice, the average power does not depend on the averaging durations in the regime above 10 seconds). The method is thus based on the *average* retinal irradiance pattern. The average retinal irradiance pattern can be considered as stationary in character, i.e. does not vary within the image over time. When the scan is effected by mirrors, this means that the mirror is scanning as designed, and not stationary. We see this as the appropriate method to choose the values of C_5, and it is consistent with the European version of the interpretation sheet of Annex ZB in amendment A11:2021 to EN 60825-1:2014

The step above for Class 1 is performed in an equivalent way for Class 2 and visible - emission Class 3R, as shown in the following Figure 23 (AE is the average power, averaged over 0,25 seconds and the AEL is also expressed as power quantity).

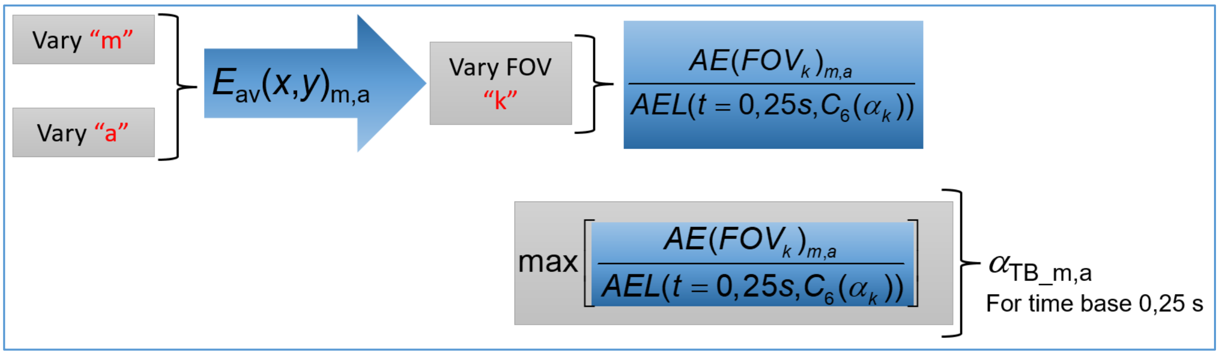

Figure 23. For Class 2 and visible-emission Class 3R, the image analysis is performed for an emission duration equal to the time base of 0,25 s.

The following scheme (Figure 24) for Class 1 applies[12] to temporal analysis windows Δt_j (also referred to as emission durations) up to, but not including T_2. C_5 applies to the AEL for emission durations Δt_j less than 0,25 s. Note that C_5 is applied to the AEL(Δt) as part of the image analysis process effected by the variation of the FOV. This is the more general applicable method for analysis of TVRI as compared to applying C_5 at the higher variation level of the variation of locations in the emission field.

Both the AE and the AEL are given as energy. We note that it is sufficient to vary Δt_j and apply requirement 3 of 4.3 f), i.e. the C_5 criterion, since this is either equivalent to or more restrictive than the single pulse requirement and the average power requirement of 4.3 f).

The laser product can be assigned Class 1 when for all relevant variations, the AE is below the respective AEL, i.e. AE/AEL < 1. Note that for the classification it is not necessary to determine the combination of *location – accommodation – FOV – temporal analysis window*

[12] For Class 2 and visible-emission Class 3R, the concept applies to emission duration < 0,25 s.

which features the maximum AE/AEL ratio. It is sufficient that all variations feature a ratio of AE/AEL < 1. However, knowledge of the maximum AE/AEL ratio provides the information about the margin between AE and AEL, which is helpful for instance for considering faults.

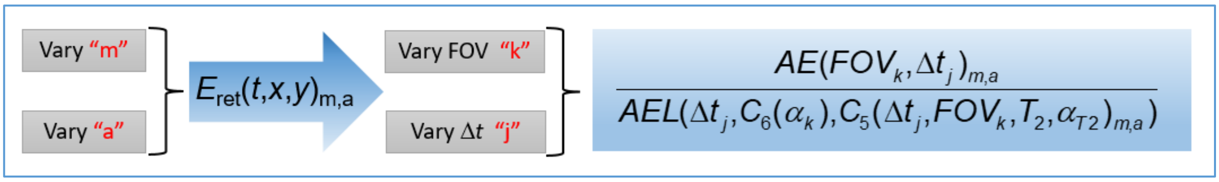

Figure 24. Diagram showing all variations applicable to emission durations up to T_2. Note that C_5 depends on $T_2(\alpha_{T2})_{m,a}$ that was the result of image analysis for a given location and accommodation discussed above.

The different variation levels might be tedious for the case of TVRI, but the analysis method follows the generally applicable requirements of IEC 60825-1 and in principle is relatively straightforward. The two issues where the discussed method applies the basic requirements of IEC 60825-1 in a way that might be seen as different to the interpretation sheet ISH1 (noting that ISH1 is not a normative document) are the determination of $T_2(\alpha_{T2})$ for the time-averaged retinal irradiance pattern (averaged over T_2; the averaging results in a stationary retinal image, discussed in subchapter 4.5.10) and the application of C_5 at the image analysis level (discussed in subchapter 4.5.7). The approach presented here appears prudent for an analysis method that can be considered to follow the requirements of IEC 60825-1 in a generally applicable and conservative way. As mentioned in the summary (chapter 1), there might well be other analysis methods for TVRI that can also be seen as consistent with IEC 60825-1.

With respect to the tediousness of the presented analysis method for TVRI, it is emphasised that there are several options for a simplified worst-case analysis, such as setting C_5 to the worst-case minimum value. The most extreme worst-case simplification is to assume that the emission is not scanning and/or producing a small retinal image.

In some cases, due the step functions in C_5, the variation of parameters is counter-intuitive compared to biophysics principles. The interpretations sheet ISH1 provides guidance for some relevant cases. There might be the motivation to base a classification analysis on some simplifying assumptions with respect to the emission pattern for the TVRI. Due to the discontinuities in the AEL rules, such a simplified assumed emission might be associated to higher permitted emission level as compared to the actual pattern when the analysis is performed as discussed in this white paper. One could be tempted to argue with bioeffect principles that the simplified emission assumption is justified and "cannot be more hazardous" than the actual emission, and therefore valid for a classification and compliance with IEC 60825-1. However, when the chosen simplification is not specifically mentioned in the ISH1 nor in IEC 60825-1, then it needs to be validated that the simplification can be used as a basis for classification as Class 1. After all, a simplification has to be on the cautious side, i.e. worst-case to be valid. For standard compliance, the quantitative criterion to validate a "worst-case" assumption is not bioeffects principles but is to perform an AE/AEL analysis for the actual emission vs. an AE/AEL analysis for the simplification. The simplification can only be seen as a validated and appropriate basis for classification when the AE/AEL for the worst-case assumption is closer to unity as compared to the AE/AEL of the actual emission.

6 MIRROR SCAN EXAMPLE

6.1 Basic parameters

The following simple example demonstrates the application of the method to analyse scanned emission as an extended source.

The example is based on a rotating collimated laser beam with a diameter of 2 mm and an assumed top-hat profile (i.e. circular constant irradiance profile). The rotation is over the full circle, which can be affected for instance by a rotating mirror where the angle of the mirror surface is at 45° with respect to the laser beam incident from below the mirror (Figure 25).

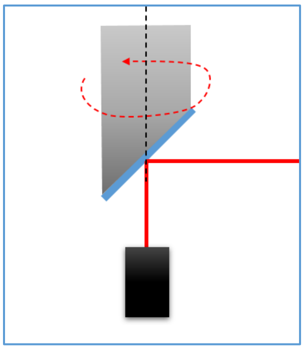

Figure 25. A possible assembly to results in a 360° rotating collimated laser beam.

Figure 26 shows the basic concept of the 7 mm aperture stop located in the rotating beam. Each pass of the beam across the 7 mm aperture stop creates a pulsed accessible emission that is detected through the 7 mm aperture stop.

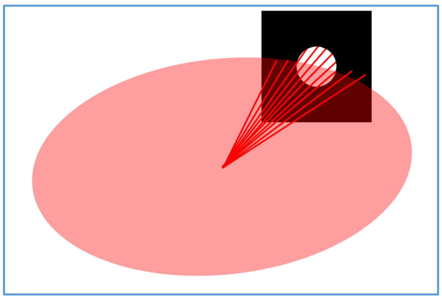

Figure 26. Schematic for collimated laser beam passing across the 7 mm aperture stop.

The collimation is assumed to be sufficiently small (smaller than 1,5 mrad) so that the beam diameter can be taken as constant in the distance range of interest and the angular subtense of the retinal image for accommodation to infinity is equal to α_{min} = 1,5 mrad.

The wavelength is assumed to be in the visible wavelength range and a classification as **Class 2** is desired. The emission is assumed to be continuous wave with a power of **5 mW**. The angular speed of the beam depends on the rotation frequency. For 10 rotations over 2 π sr per second (i.e. f = 10 Hz), the angular speed of the beam equals 62,38 rad s^{-1}.

We organise the AE-AEL analysis into the two big blocks of accommodation to infinity and accommodation to the mirror. Per accommodation state, we chose the emission duration as the next sub-level in the analysis. Per emission duration, we perform the AE-AEL analysis for a number of distances.

6.2 Accommodation to the mirror

6.2.1 Discussion of the retinal image

For accommodation to the mirror, the retinal image is not moving, and the retinal image irradiance pattern is equivalent to the scaled irradiance pattern at the location of the mirror. Thus, when the beam has a top-hat irradiance profile with a diameter of 2 mm, at 100 mm from the mirror α = 20 mrad, when not limited by α_{max}.

6.2.2 Emission duration 0,25 s

For a stationary retinal image with a top-hat profile, it is not necessary to vary the FOV to determine the worst-case AE/AEL ratio since it is apparent that the FOV that encompasses the top-hat profile is the most restrictive one. One of the classification criteria is the AEL for Δt = 0,25 s applied to the average power AE. Table 9 shows the AE-AEL analysis for distances between 100 mm and 2100 mm from the mirror. The calculation is relatively straightforward. From the angular speed ω the speed v at the respective distance L is calculated with:

$v = \omega \cdot L$

From this, the pass duration of the beam across the centre of the 7 mm aperture stop can be calculated. For a 2 mm beam diameter and a 7 mm aperture stop, it sufficiently accurate to neglect that the aperture is circular. The accessible energy per pass can be calculated simply by multiplication of the pass duration by the power of the beam. Multiplication by the rotation frequency gives the AE as average power. Due to the low frequency, the average power is relatively small and the AE/AEL ratio is well below unity (the values shown in the table are scaled with a factor of 1000). There is no dependence of the AE/AEL as function of distance as long as α > 1,5 mrad, because both the AE (derived from the pass duration across the 7 mm aperture stop) as well as C_6 scale with 1/L.

We have also highlighted the distance of 399 mm, where $\alpha_{0,25s}$ is marginally above 5 mrad, which will be relevant for applying the thermal C_5 for shorter emission durations.

Table 9. AE-AEL analysis for accommodation to the mirror for the emission duration equal **0,25 s**.

1	Distance to mirror	mm	100	150	200	300	399	400	1000	2000	2100
2	$\alpha_{0,25s}$	mrad	20,00	13,33	10,00	6,67	5,01	5,00	2,00	1,50	1,50
3	C_6		13,3	8,9	6,7	4,4	3,3	3,3	1,3	1,0	1,0
4	AEL(0,25s)	W	0,0132	0,0088	0,0066	0,0044	0,0033	0,0033	0,0013	0,0010	0,0010
5	Speed at distance	m s^{-1}	6,28	9,42	12,57	18,85	25,07	25,13	62,83	125,66	131,95
6	Duration to pass 7 mm aperture stop	s	1,1E-03	7,4E-04	5,6E-04	3,7E-04	2,8E-04	2,8E-04	1,1E-04	5,6E-05	5,3E-05
7		ms	1,11	0,74	0,56	0,37	0,28	0,28	0,11	0,06	0,05
8	Accessible energy per	J	5,6E-06	3,7E-06	2,8E-06	1,9E-06	1,4E-06	1,4E-06	5,6E-07	2,8E-07	2,7E-07
9	AE as average power	W	5,6E-05	3,7E-05	2,8E-05	1,9E-05	1,4E-05	1,4E-05	5,6E-06	2,8E-06	2,7E-06
10	AE/AEL x 1000		4,22	4,22	4,22	4,22	4,22	4,22	4,22	2,81	2,68

6.2.3 Emission duration equal to the pass duration across the aperture stop

The scan across the aperture stop produces a pulsed accessible emission. For a non-moving retinal image, the obvious choice for the emission duration to analyse the pulsed emission is the pulse duration, which is equal to the pass duration across the centre of the 7 mm aperture stop. The rotation frequency gives the number of pulses N within 0,25 s.

For distances up to 400 mm, the angular subtense of the retinal image is larger than $\alpha_{max}(\Delta t)$. Only the part that is within an angle of acceptance $\gamma = \alpha_{max}(\Delta t)$ is used to determine the AE per pulse. This is accounted for by determining the ratio of the area of the image and the FOV in line 6 of Table 10.

Table 10. AE-AEL analysis for accommodation to the mirror in the emission duration regime of **one pass duration**.

1	Distance to mirror	mm	100	150	200	300	399	400	1000	2000	2100
2	Number of pulses in 0,25 s		3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
3	Duration to pass 7 mm aperture stop	s	1,1E-03	7,4E-04	5,6E-04	3,7E-04	2,8E-04	2,8E-04	1,1E-04	5,6E-05	5,3E-05
4	α_{max} for pass duration	mrad	6,68	5,45	5,00	5,00	5,00	5,00	5,00	5,00	5,00
5	α limited to α_{max}	mrad	6,68	5,45	5,00	5,00	5,00	5,00	2,00	1,50	1,50
6	Ratio area retinal image larger than area field		9,0	6,0	4,0	1,8	1,0	1,0	1,0	1,0	1,0
7	C_6		4,5	3,6	3,3	3,3	3,3	3,3	1,3	1,0	1,0
8	C_5		0,76	0,76	0,76	0,76	0,76	1,00	1,00	1,00	1,00
9	AEL per pulse	J	1,4E-05	8,7E-06	6,4E-06	4,7E-06	3,8E-06	5,0E-06	1,0E-06	4,5E-07	4,4E-07
10	Energy through 7 mm aperture stop per pass	J	5,6E-06	3,7E-06	2,8E-06	1,9E-06	1,4E-06	1,4E-06	5,6E-07	2,8E-07	2,7E-07
11	AE (energy within α_{max})	J	6,2E-07	6,2E-07	7,0E-07	1,0E-06	1,4E-06	1,4E-06	5,6E-07	2,8E-07	2,7E-07
12	AE/AEL		0,04	0,07	0,11	0,22	0,36	0,28	0,55	0,62	0,61

For the distances of 100 mm and 150 mm we observe that the AE (line 11) is constant. This is based on the reduction of the energy per pulse with the inverse of the pass duration, and the area of the FOV increasing linearly with the pass duration. These two factors cancel each other out as long as the retinal image is larger than the angle of acceptance.

The emission duration is in the regime where the thermal C_5 applies. For distances up to 399 mm, $\alpha_{0,25s}$ (from Table 9) is larger than the value of α_{max} listed in Table 10 determined with the respective pass duration. Therefore, the following C_5 requirement applies:

For $\alpha_{TB} > \alpha_{max}(\Delta t)$:
$C_5 = N^{-0,25}$ for $N \leq 625$
$C_5 = 0,2$ for $N > 625$

The AEL becomes smaller with increasing distances and reaches a local minimum at 399 mm. Consequently, the AE/AEL ratio reaches a local maximum of 0,36 at 399 mm. At this distance there is a discontinuity, since at 400 mm $\alpha_{0,25s}$ becomes equal to 5 mrad and $C_5 = 1$. However, it needs to be considered that the AE/AEL maximum at 399 mm is only *local* maximum. For distances of 400 mm and further, $C_5 = 1$, but C_6 continues to decrease within increasing distance. Due to the *t*-dependence of the AEL, the AEL decreases to a larger degree than the AE does. The maximum AE/AEL ratio of 0,61 is therefore reached for a distance of 2000 mm where α becomes equal to 1,5 mrad. This is an example where it is important not to stop the distance variation at a local maximum. For the case of classification as Class 1, where N is larger and C_5 at the distance of 399 mm is smaller, 399 mm is also overall the MRP.

This trend is often found for scanned emission and accommodation to the mirror, i.e. that the MRP is either where α_{TB} is marginally less than 5 mrad or equal to 1,5 mrad. It is therefore important to vary the analysis distance and not only analyse at 100 mm distance from the mirror.

Due to the simple nature of the pulsed accessible emission with a constant pulse frequency of 10 Hz it is not necessary to consider groups of pulses and other emission durations.

For accommodation to the mirror, for a beam diameter of 2 mm, we conclude that for a power of 5 mW, the AE is a factor of more than 1,62 below the AEL, for the most restrictive distance.

We also note that the permitted emission depends on the diameter of the beam at the mirror. For the case that the beam diameter equals 1,5 mm, the MRP where α = 1,5 mrad is found at 1000 mm distance, and the AE/AEL is equal to 0,73.

6.3 Accommodation to infinity

6.3.1 Discussion of the retinal image

For accommodation to infinity, the retinal image is small, i.e. α = 1,5 mrad, and scans across the retina with the same angular speed as the beam in real space. The angular subtense of the scan path on the retina is given by the angular subtense of the 7 mm aperture stop as seen from the mirror, such as 70 mrad for a distance of 100 mm from the mirror (see for instance discussion in our ILSC 2019 paper [6] on this). The application of the FOV is schematically shown in Figure 27 for an angle of acceptance of 5 mrad in scan duration and 1,5 mrad in vertical direction. With the given angular speed of the laser beam, the scan duration across the FOV can be calculated. The FOV “cuts out” part of the scan path, defining the AE as energy within the FOV. This energy can be calculated by multiplying the power in the beam by the scan duration across the FOV. The extent of the FOV also determines the value of α:

$$\alpha = \frac{1{,}5\,\text{mrad} + 5\,\text{mrad}}{2}$$

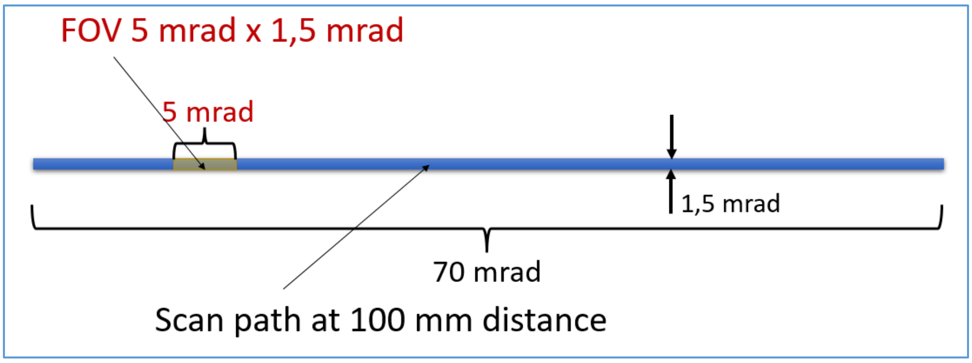

Figure 27. The blue thin rectangle depicts the path of the minimum retinal image across the retina for the example of a distance of 100 mm from the mirror. An example of a FOV is also shown.

6.3.2 Emission duration 0,25 s

As a first step, we perform an image analysis to determine the value of $\alpha_{0,25s}$ for a distance of 100 mm from the mirror. At 100 mm distance, the scan path covers an angle of 70 mrad. The angle of acceptance in the scan direction is varied between 1,5 mrad in the first column and 70 mrad in the last column of Table 11, respectively. The duration to scan the respective angle of acceptance (line 8) is needed to calculate the AE within the angle of acceptance. There is no need to apply C_5 in this image analysis, since C_5 does not depend on the choice of the angle of acceptance. The maximum ratio of AE/AEL is found for an angle of acceptance of 70 mrad, i.e. the full scan path. This result of the image analysis also applies for further distances and correspondingly shorter scan paths.

Table 11. Variation of the angle of acceptance to determine the worst-case AE/AEL ratio. Here for a distance of 100 mm from the mirror.

1	Angle of acceptance in scanning direction	mrad	1,5	2	3	4	5	30	70
2	Angle of acceptance-vertical	mrad	1,5	1,5	1,5	1,5	1,5	1,5	1,5
3	α	mrad	1,5	1,75	2,25	2,75	3,25	15,75	35,75
4	C_6		1,0	1,2	1,5	1,8	2,2	10,5	23,8
5	AEL	W	1,0E-03	1,2E-03	1,5E-03	1,8E-03	2,2E-03	1,1E-02	2,4E-02
6		mW	1,00	1,17	1,50	1,83	2,17	10,50	23,83
7	Duration to scan angle of acceptance	s	2,4E-05	3,2E-05	4,8E-05	6,4E-05	8,0E-05	4,8E-04	1,1E-03
8	Accessible emission as energy per scan	J	1,2E-07	1,6E-07	2,4E-07	3,2E-07	4,0E-07	2,4E-06	5,6E-06
9	Accessible emission as average power	W	1,2E-06	1,6E-06	2,4E-06	3,2E-06	4,0E-06	2,4E-05	5,6E-05
10	AE/AEL		0,0012	0,0014	0,0016	0,0017	0,0018	0,0023	0,0023

With this finding we can perform the AEL analysis for the emission duration equal to 0,25 s that applies to the AE expressed as average power, reproduced in Table 12. Note that the AE/AEL ratio is scaled with a factor of 1000.

Table 12. The AE-AEL analysis for accommodation to infinity and an emission duration of 0,25 s, applicable to the average power-AE.

1	Distance to mirror	mm	100	150	200	300	399	400	1000	2000	2100
2	Speed at distance	m s^{-1}	6,28	9,42	12,57	18,85	25,07	25,13	62,83	125,66	131,95
3	Duration to pass 7 mm aperture stop	s	1,1E-03	7,4E-04	5,6E-04	3,7E-04	2,8E-04	2,8E-04	1,1E-04	5,6E-05	5,3E-05
4		ms	1,11	0,74	0,56	0,37	0,28	0,28	0,11	0,06	0,05
5	Angular subtense of scan on retina	mrad	70,0	46,7	35,0	23,3	17,5	17,5	7,0	3,5	3,3
6	$\alpha_{0,25s}$	mrad	35,8	24,1	18,3	12,4	9,5	9,5	4,3	2,5	2,4
7	C_6		23,8	16,1	12,2	8,3	6,3	6,3	2,8	1,7	1,6
8	AEL(0,25s)	W	0,0238	0,0161	0,0122	0,0083	0,0063	0,0063	0,0028	0,0017	0,0016
9	Accessible energy per scan	J	5,6E-06	3,7E-06	2,8E-06	1,9E-06	1,4E-06	1,4E-06	5,6E-07	2,8E-07	2,7E-07
10	AE as average power	W	5,6E-05	3,7E-05	2,8E-05	1,9E-05	1,4E-05	1,4E-05	5,6E-06	2,8E-06	2,7E-06
11	AE/AEL x 1000		2,34	2,31	2,29	2,24	2,20	2,20	1,97	1,67	1,65

The maximum ratio of AE/AEL is found for a distance of 100 mm from the mirror, but with a substantial margin between the AE and the AEL.

6.3.3 Emission duration given by the pass duration across the aperture stop

The scan across the 7 mm aperture stop produces a pulsed accessible emission detected through the aperture stop. The duration of one scan across the centre of 7 mm aperture stop lends itself as choice for the emission duration Δt. We see in Table 9 above that for a distance of 100 mm from the mirror, the pass duration across the 7 mm aperture stop equals 1,11 ms. The associated value of $\alpha_{max}(\Delta t)$ = 6,7 mrad. The scan path subtends 70 mrad. Therefore, the angle of acceptance limited by 6,7 mrad is only part of the scan path, and the beam takes

106 µs to scan across 6,7 mrad. This partial scan path is used to determine the AE. Therefore, the AE is derived for the energy within 106 µs while the AEL is determined for 1,11 ms and is correspondingly large. Clearly this choice of emission duration is not relevant for the AE-AEL analysis.

6.3.4 Emission duration less than 625 µs

We shift our interest to the emission duration regime less than 625 µs, where the angle of acceptance is limited by 5 mrad and the scan duration across the angle of acceptance is also in the same regime so that there is less discrepancy between the scan duration across the FOV that determines the AE and the duration used to determine the AEL.

As a first step, an image analysis has to be performed to determine if an angle of acceptance in scan direction of 5 is most restrictive, or a smaller one. For this analysis it is not necessary to vary the angle of acceptance for a given emission duration, since it is obvious that for a given emission duration, to reduce the FOV reduces the AE to a larger degree than the AEL is reduced by the reduction of α. Therefore, for a given angle of acceptance, we chose the scan duration across the angle of acceptance as emission duration to determine the AEL. That is, for an angle of acceptance equal to 1,5 mrad, Δt = 23,9 µs, for an angle of acceptance equal to 5 mrad, Δt = 79,6 µs, respectively. This can be seen as an optimised image analysis that combines the variation of the FOV with the variation of the emission duration.

Table 13 shows that the maximum AE/AEL ratio is found for the smallest angle of acceptance of 1,5 mrad.

Table 13. Variation of the angle of acceptance to determine the worst-case AE/AEL ratio for the case of α_{max}= 5 mrad. The scan duration across the FOV is used as emission duration.

Angle of acceptance	mrad	1,50	2,00	3,00	4,00	5,00
Pass duration across FOV	s	2,4E-05	3,2E-05	4,8E-05	6,4E-05	8,0E-05
α	mrad	1,50	1,75	2,25	2,75	3,25
AEL single pulse	J	2,4E-07	3,5E-07	6,0E-07	9,1E-07	1,3E-06
AE per pass	J	1,2E-07	1,6E-07	2,4E-07	3,2E-07	4,0E-07
AE/AEL		0,50	0,46	0,40	0,35	0,31

With the finding of Table 13 we use an angle of acceptance of 1,5 mrad to determine α and the scan duration of 23,9 µs to determine the AE. That is, the emission duration for the pulse analysis is the same for all distances. The AE-AEL analysis is given in Table 14.

Since $\alpha_{0,25s}$ is derived from the scan path (see Table 12), in the distance regime up to about 800 mm $\alpha_{0,25s}$ is larger than α_{max} = 5 mrad. The following C_5 requirement applies for distances between 100 mm and about 800 mm:

For $\alpha_{TB} > \alpha_{max}(\Delta t)$:
$C_5 = N^{-0,25}$ for $N \leq 625$
$C_5 = 0,2$ for $N > 625$

For larger distances, $\alpha_{0,25s} \leq 5$ mrad and $C_5 = 1$.

Table 14. AE-AEL analysis for the emission duration equal to the scan duration across a 1,5 mrad angle of acceptance.

Distance to mirror	mm	100	150	200	300	399	400	1000	2000	2100
Number of pulses in 0,25 s		3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
Duration to pass across 1,5 mrad	s	2,4E-05	2,4E-05	2,4E-05	2,4E-05	2,4E-05	2,4E-05	2,4E-05	2,4E-05	2,4E-05
	µs	23,9	23,9	23,9	23,9	23,9	23,9	23,9	23,9	23,9
Result of image analysis: α	mrad	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
C_6		1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
C_5		0,76	0,76	0,76	0,76	0,76	0,76	1,00	1,00	1,00
AEL per pulse	J	1,8E-07	1,8E-07	1,8E-07	1,8E-07	1,8E-07	1,8E-07	2,4E-07	2,4E-07	2,4E-07
AE per pulse	J	1,2E-07	1,2E-07	1,2E-07	1,2E-07	1,2E-07	1,2E-07	1,2E-07	1,2E-07	1,2E-07
AE/AEL		0,66	0,66	0,66	0,66	0,66	0,66	0,50	0,50	0,50

Since the AE as well as the AEL for distances to about 800 mm does not depend on the distance, the AE/AEL ratio is constant and equal to 0,66.

We note that accommodation to the mirror, for the beam diameter of 2 mm at the mirror, was somewhat less restrictive (AE/AEL = 0,61) than accommodation to infinity. Other accommodation states are not analysed in the scope of this white paper.

6.3.5 Conclusion

For the analysis as extended source presented here for the chosen emission parameters, the maximum AE/AEL ratio is found for the pulse analysis in the regime of less than 625 µs and accommodation to infinity. For 5 mW power of the beam, the AE/AEL ratio for classification as Class 2 was equal to 0,66. In other words, when the power is increased to **7,6 mW**, the AE is equal to the AEL for classification as Class 2.

The restriction on the emission level based on accommodation to the mirror depends on the beam diameter at the mirror. When the beam diameter is for instance equal to 1,5 mm, the maximum AE/AEL ratio for accommodation to the mirror is found to be equal to 0,73. This is more restrictive than the AE/AEL ratio for accommodation to infinity, which does not depend on the beam diameter at the mirror. This is an example for the dependence on the emission parameters such as beam diameter at the mirror and scan pattern, whether accommodation to the mirror or accommodation to infinity is more restrictive.

It is also interesting to compare the finding for the beam diameter of 2 mm with an AE-AEL analysis which accounts for the scan of the beam across the 7 mm aperture stop, but assumes a minimum non-moving retinal image, where C_6 = 1 and C_5 = 1. This is the concept of the "Default (simplified) evaluation" described in subclause 5.4.2 of IEC 60825-1. For the analysis as pulse pattern, the AEL and the AE is based on the emission duration equal to the pass duration across the 7 mm aperture stop. The permitted power level where the AE is found to be equal to the AEL is equal to **3,8 mW**. The power level permitted when the emission is analysed as extended source (i.e. as TVRI) is a factor of 2 higher.

When the beam is assumed to be stationary (not scanned across the 7 mm aperture stop), the permitted emission for Class 2 is equal to **1 mW**.

7 MEET THE AUTHOR

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Dr. Schulmeister is a member of the ICNIRP Scientific Expert Group and was a member of the Main Commission for the 2013 revision of the ICNIRP Exposure Limit Guidelines. He served as the project leader for the development of IEC 60825-1:2014 as well as of the CENELEC amendment A11:2021 to EN 60825-1. He is member of the ANSI Z136 Technical Subcommittee "Laser Bioeffects" and Fellow of the Laser Institute of America.

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https://laser-led-lamp-safety.seibersdorf-laboratories.at/downloads

See also:

Linkedin

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