ILSC® 2019 Conference Proceedings

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Reference information for this proceedings paper

Citation: ILSC 2019, 202 (2019); doi: 10.2351/1.5118564
Title: Computer modelling to support laser safety analysis of pulse trains with varying peak power and pulse duration
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Proceeding of the International Laser Safety Conference, March 18-21, 2019 USA
Paper 202, Pages 66-72
Published by the Laser Institute of America, 2019, Orlando, Florida, USA

Computer Modelling to Support Laser Safety Analysis of Pulse Trains with Varying Peak Power and Pulse Duration

Paper # 202

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Abstract

Neither the international laser safety standard IEC 60825-1 Edition 3.0 nor the standard ANSI Z136.1-2014 provide specific rules on how to apply the pulse reduction factor C_5 (resp. C_P) to irregular pulse trains, featuring both varying peak power as well as varying pulse duration. Without specific guidance, the analysis has to be performed based on restrictive approaches, such as counting all pulses and giving them the same weight, even the ones with smaller peak power and lower energy. Preliminary work, presented at the ILSC 2017, focused on pulse trains with varying peak power. The present study provides guidance on how to analyze irregular pulse patterns - both in terms of peak power and pulse duration - in a less restrictive way.

Introduction

In 2014, the third edition of IEC 60825-1 was published [1] as well as a new edition of ANSI Z136.1 [2]. For pulse durations longer than 5 µs in the wavelength range of 400 nm to 1050 nm and pulse duration longer than 13 µs in the range of 1050 nm 1400 nm, the rules of how to apply maximum permissible emission limits (MPEs) and accessible emission limits (AELs) to multiple pulses in both documents are equivalent. The rules for the analysis of multiple pulses for pulse durations less than the above mentioned values differ, since in IEC 60825-1, a factor C_5 less than 1 applies for time bases longer than 0.25 s, while in ANSI Z136.1-2014 there is no reduction of the single pulse AEL that applies to pulse durations shorter than given above. In the following, we will only refer to IEC 60825-1 Edition 3.0, but the discussion also applies to ANSI Z136.1-2014.

The changes of IEC 60825-1 Edition 3.0 with respect to earlier editions were reviewed in an ILSC 2013 paper [3] as well as in a White Paper [4]. Specific issues related to the analysis of multiple pulses and discussed in 2015 [5] were published in an Interpretation Sheet for IEC 60825-1 Edition 3.0.

The present paper relates to the rules laid down in subclause 4.3 f) of IEC 60825-1 which describe how classification of products with pulsed emission (or scanned emission that leads to a pulsed accessible emission pattern) has to be performed. As in previous editions, three criteria are given which have to be considered in parallel, i.e. it depends on the specific emission pattern which of the three criteria is the most restrictive one that limits the emission of a certain product to remain within a certain safety class (such as Class 1). The present discussion relates to the reduction factor C_5 and therefore to limits that can be associated with retinal thermal hazards (wavelength range of 400 nm to 1400 nm). The three criteria that have to be applied (i.e. all have to be assessed and be complied with) can be described as follows:

1) Single pulse criterion

The accessible emission (AE) of each single pulse has to be below the single pulse AEL, where the AEL is determined for the corresponding pulse duration.

2) Average power criterion

The accessible emission expressed as average power (averaged over a certain time period) has to be below the AEL applicable for that averaging duration. For regular emission patterns (constant pulse duration, period and energy per pulse) the critical averaging duration is always equal to T_2 for Class 1 and equal to 0.25 s for Class 2. For irregular emission patterns, the averaging time period has to be varied, i.e. the AE and the AEL are both determined for some averaging time window that is varied both in terms of duration as well as in terms of temporal position within the pulse train. It was shown in reference [5] that the average power rule is equivalent to comparing integrated energy to the AEL expressed as energy; also Criterion 2) can be seen as extension of Criterion 1) when the shortest "averaging duration" used is the duration of a single pulse.

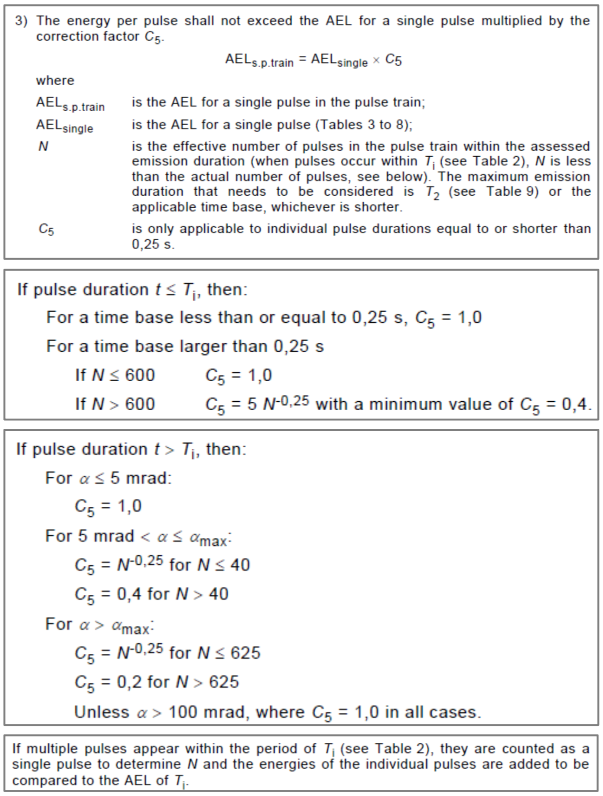
3) Reduced single pulse criterion

Criterion 3) calls for the application of C_5 (see rules for determination of C_5 below) to reduce the single pulse AEL, i.e. a more restrictive version of Criterion 1) (or the same for the case where $C_5 = 1$). As a basic rule, C_5 is a function of N and N is the number of pulses within T_2 (or 0.25 s for Class 2). This factor C_5 is applied to reduce the single pulse AEL, and the AE of every single pulse has to be below this reduced AEL. While applying this rule on regular pulse train is straightforward, for irregular pulse trains there is the added complexity that groups of pulses have to be treated as "effective pulses", and N would then be the number of occurrences of the group within T_2. The AEL and AE is then determined for the group, i.e. the AEL is determined for the group duration and AE is the energy per group. This rule can be seen as an extension of the average power rule when for each averaging duration, the region within the averaging duration is considered as an "effective pulse", but additionally to just comparing the energy within the group to the AEL applicable for the group duration, that AEL is reduced by the factor C_5 derived from the number of "effective pulses" within T_2.

While in the current standard wording, for Criterion 3) it is not specifically noted to apply C_5 in case of pulse groups, based on basic biophysical reasoning (particularly if there is negligible cooling between the pulses within the pulse group) it is necessary to apply Criterion 3) not only to individual pulses but also to pulse groups (in ANSI Z136.1-2014 the grouping is specifically included in the wording). The necessity of the application of C_5 to groups of pulses is also expressed in the Interpretation Sheet I-SH 1 for IEC 60825-1 Ed. 3.0 [6].

In contrast to earlier editions of IEC 60825-1 as well as ANSI Z136.1, this grouping became necessary for the 2014 editions of the two standards, because in the latest edition, for emission durations longer than T_i, the reduction factor C_5 (C_P in ANSI) is limited to 0.2 (equivalent to only counting a maximum of 625 pulses) for apparent sources larger than α_{max} and to 0.4 (equivalent to only counting a maximum of 40 pulses) for apparent sources between 5 mrad and α_{max}. This limitation of the "extent" of the reduction of the AEL by the factor C_5 did not exist in earlier standards and as a consequence, considering individual pulses only (no grouping) and counting the number of individual pulses (compared to the number of pulse groups, the number of the individual pulses is always larger) the resulting C_5 applied to the AEL of individual pulses was always more restrictive as compared to considering a number of neighboring pulses as one effective pulse.

The following is a replication of the rules regarding C_5 currently specified in IEC 60825-1 Edition 3.0.



3) The energy per pulse shall not exceed the AEL for a single pulse multiplied by the correction factor C_5.

$$AEL_{s.p.train} = AEL_{single} \times C_5$$

where

$AEL_{s.p.train}$ is the AEL for a single pulse in the pulse train;
AEL_{single} is the AEL for a single pulse (Tables 3 to 8);
N is the effective number of pulses in the pulse train within the assessed emission duration (when pulses occur within T_i (see Table 2), N is less than the actual number of pulses, see below). The maximum emission duration that needs to be considered is T_2 (see Table 9) or the applicable time base, whichever is shorter.
C_5 is only applicable to individual pulse durations equal to or shorter than 0,25 s.

If pulse duration $t \leq T_i$, then:
For a time base less than or equal to 0,25 s, $C_5 = 1,0$
For a time base larger than 0,25 s
If $N \leq 600$ $C_5 = 1,0$
If $N > 600$ $C_5 = 5\ N^{-0,25}$ with a minimum value of $C_5 = 0,4$.

If pulse duration $t > T_i$, then:
For $\alpha \leq 5$ mrad:
$C_5 = 1,0$
For 5 mrad $< \alpha \leq \alpha_{max}$:
$C_5 = N^{-0,25}$ for $N \leq 40$
$C_5 = 0,4$ for $N > 40$
For $\alpha > \alpha_{max}$:
$C_5 = N^{-0,25}$ for $N \leq 625$
$C_5 = 0,2$ for $N > 625$
Unless $\alpha > 100$ mrad, where $C_5 = 1,0$ in all cases.

If multiple pulses appear within the period of T_i (see Table 2), they are counted as a single pulse to determine N and the energies of the individual pulses are added to be compared to the AEL of T_i.

Proposal for "Partial N"

The work presented in 2017 [7] focused on the analysis of irregular pulse patterns for which the pulse duration was kept constant throughout the emission, i.e. the repetitively pulsed emission was irregular in the sense that the peak power and possibly the pulse period varied from pulse to pulse. In such case, it was proposed to specify the interpretation of the parameter N in a way that would loosen the overly restrictive definition of N, currently interpreted as the number of actual pulses. The idea was to count pulses according to their relative peak power, so that only the pulse with highest peak power counts as 1 while the other pulses count as a fraction of the highest peak power corresponding to their relative power. The rationale for that proposal lied in the non-linearity of the purely thermal damage mechanism with peak power for pulses with duration longer than 5 µs. This method for determining N can already be applied for product classification according to IEC 60825-

1:2014 since the publication of the interpretation sheet I-SH 1.

Following upon that work, we now propose to generalize the concept to irregular pulse trains, for which both peak power and pulse duration can vary from pulse to pulse. As basic prerequisite for such attempt, it was decided that a practicable method for interpreting the parameter N shall be in accordance with all existing classification rules. In other words, this proposal was made in the spirit of providing guidance for the analysis of complex emissions without having to modify the current classification scheme.

The parameter N is currently defined as the "effective number of pulses" and it is proposed to interpret this term as follows: N is the ratio of energy within T_2 (or time base, whichever is shorter) to energy of a single physical pulse or group of pulses under consideration for AEL_{single}. Such definition would be indeed consistent with the existing rules:

- for emissions with varying peak power and constant pulse duration where N was interpreted as a ratio of peak power, see 6 g) of I-SH 1
- for emissions with constant peak power and pulse duration (referred to as "non-uniform" repetitive pulse patterns) where the analysis of pulse groups or subgroups was clarified (e.g. regarding the pulse duration or pulse group duration applicable to determine AEL_{single})

and would also provide a solid definition of *N* in the general case where both peak power and pulse duration can vary. Noticeably, the fact that the period between two consecutive pulses can also vary does not require additional consideration since N is defined as a ratio of energy. Similarly, the repetition of identical pulse groups does not necessitate any additional definition since absolutely any combination of consecutive pulses can be investigated to determine AEL_{single} and the correction factor C_5 without having to decide what constitutes a repetitive pulse group or how identical consecutive pulse groups can be or whether the pulse duration can satisfy the adjective "constant" or not.

According to the above mentioned interpretation, N is unconditionally equal or greater than 1 regardless of the pulse or group of pulses considered. The duration of the pulse or group of pulses is as before used to calculate the value of α_{max} in order to determine the partial accessible emission (and C_6) and also what calculation rule for C_5 and thus $AEL_{s.p.train}$ has to be applied.

The arbitrary emission shown in Figure *1* is intended to illustrate the calculation steps for deriving $AEL_{s.p.train}$. Assuming a top hat circular beam with a source size (or angular subtense of the apparent source) of 10 mrad, the most restrictive classification rule for that emission would be found according to the "reduced pulse criterion" applied to the first pulse for which:

- pulse duration $t_1 = 1$ ms
- $\alpha_{max} = 6.3$ mrad (thus $\alpha > \alpha_{max}$)
- $C_6 = 6.3 / 1.5$
- $AEL_{single} = 700 \cdot C_6 \cdot t^{0.75} = 16.6\ \mu J$
- Total energy $Q_{emission} = 50\ \mu J$
- Energy of first pulse $Q_1 = 10\ \mu J$
- $N = 50 / 10 = 5$ (ratio of $Q_{emission}$ to Q_1)
- $C_5 = N^{-0.25} = 0.67$
- $AEL_{s.p.train} = 11.1\ \mu J$
- $AE_1 = 10 \cdot (6.3/10)^2 = 4\ \mu J$
- $AE_1 / AEL_{s.p.train} = 0.36$

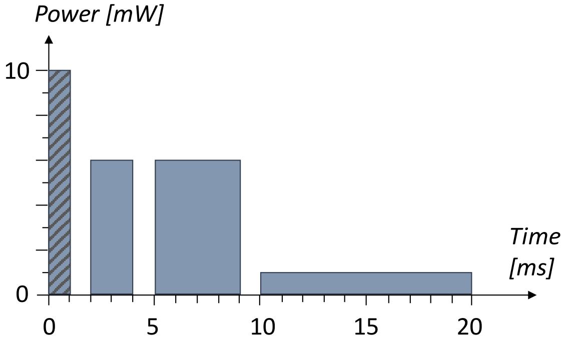


Figure 1. Arbitrary emission constitutive of an irregular pulse pattern (see text for details)

For the exact same emission associated with a source size of 40 mrad, the most restrictive result is still found for the "reduced pulse criterion" but for a group consisting of the first three pulses, i.e. for a group duration of 9 ms, for which N = 1.24. This basic example demonstrates the application of the parameter N based on relative energy instead of an actual number of pulses and the dependence of results on other laser parameters (especially pulse period and source size) due to the time-dependent α_{max}.

As in our previous work, the general validity of this interpretation of the parameter N was investigated by generating a large database of irregular pulse trains and calculating the injury threshold for each emission individually. By applying the classification rules referred to as "single pulse", "average power" and "reduced single pulse" with the proposed interpretation of N, it was possible to calculate for each emission the ratio of injury threshold to MPE and validate the proposed interpretation of N.

Similarly to the method provided in I-SH 1 for the analysis of irregular pulse trains with constant pulse duration, the interpretation of N proposed for the general case is accompanied by a threshold set to 5% of the highest peak power in the emission, level below which individual pulses can be ignored for the calculation of N.

We note that, while the normative scope of IEC 60825-1 is product classification on the basis of the accessible emission (AE) and accessible emission limits (AEL) for the different classes, the underlying basis of the AELs for Class 1 and Class 2 are the maximum permissible exposure limits (MPE) for the eye. For the same evaluation duration (emission duration for AEL, exposure duration for MPE) and for the same wavelength and retinal spot size, the numerical values for the AELs are the same as for the MPE when the MPE is expressed as "energy through aperture" (in Edition 3 of IEC 60825-1, MPE values are presented both in terms of radiant exposure as well as in terms of energy through aperture). In the following, for the comparison of injury thresholds against limits, we will be referring to MPEs in terms of "energy through aperture", but the discussion applies also to the analysis based on AEL for Class 1.

Materials and Methods

A computer model, validated against in-vivo non-human primate experiments [8], was used to predict thermally induced injury thresholds (THR) of the retina for a series of irregular pulse trains. The THR were then compared to maximum permissible exposures (MPE) according to Annex A of IEC 60825-1, equivalent to the classification rules of IEC 60825-1 Edition 3.0 (subclause 4.3.f). The parameter C_5 was determined with the interpretation of N as described above. The ratio of THR to MPE, here referred to as reduction factor (RF), was used as the main figure of merit to evaluate the validity of the proposed rule. As discussed in [7], a RF equal to or greater than 2 was considered as satisfactory for validating the proposed method since no RF < 2 was found for single pulses in the thermal regime.

The computer model being optimized to predict injury thresholds for non-human primates, it was necessary to make the following adaptations in order to be on the safe side when calculating THR for the human eye:

- The size of a minimum visible lesion was reduced from 50 μm to 20 μm in order to account for the fact that such small lesions of the retinal pigmented epithelium might be vision impairing even if undetected by ophthalmoscopic means [9],

- the retinal image diameter was calculated by multiplying the angular subtense of the apparent source by the focal length of the eye, i.e. optical aberrations of any kind were disregarded,

- the air equivalent focal length of the relaxed human eye was set to 16.68 mm (see Le Grand full theoretical relaxed eye in [10])

According to this model, the resulting injury threshold (THR) is a prediction of the experimental ED_{50} level, i.e. the total intraocular energy required to induce a minimum visible lesion to the retina with a probability of 50% (valuable discussion in [11]). It is emphasized that the above adjustments do not relate to the actual injury threshold seen in human subjects but are merely a set of worst-case assumptions adopted for the purpose of safety. Whenever exposure conditions and endpoints were comparable, injury thresholds for humans were shown to be consistently higher than for non-human primates [12]. All THR were calculated at a wavelength of 530 nm, where the RF is known to be the lowest for single pulses in the range of 400 nm to 1400 nm (results not shown). All source sizes for which the C_5 parameter can be smaller than 1 were investigated (5 mrad < $\alpha \leq$ 100 mrad).

Given the complex relationships between laser parameters, injury thresholds and MPEs, there is no such thing as "the" worst-case emission that could be used to validate a general definition of N. This obstacle was circumvented by generating a database of 15000 theoretical exposures in order to cover all conceivable irregular pulse trains as best possible.

Pulse trains were generated using a set of random numbers associated with various variables involved in the definition of a pulse train (such as pulse width, pulse period, peak power, number of pulses in a pulse pattern, number of patterns, etc.). The following list offers an overview of the most relevant variables and ranges of values used to generate exposures:

- pulse duration between 10 μs and 250 ms
- duty cycle (from pulse to pulse and between patterns) between 10% and 95%
- number of pulses per pattern between 1 and 5000
- number of patterns per exposure between 1 and 500 (the number of pulses per exposure being limited to 5000 and the exposure duration being limited to 10 s for technical reasons)
- peak power between 1% and 100% (varied from pulse to pulse or modulated according to various rules)

The database generated in this manner was considered to represent an extensive set of realistic exposure scenarios and, in view of its size and variety, to include the most hazardous ones. Figure 2 illustrates the potential of this pseudorandomized generation process. In some extreme cases, the exposure consisted of a single pulse, or an irregular pattern with constant pulse duration, or even a uniform pulse pattern.

For each exposure, the MPE was calculated according to the existing "single pulse", "average power" and "reduced single pulse" criteria, only the parameter C_5 was calculated using the proposed interpretation of N. For each exposure, the MPE value calculated for the most restrictive criterion was used to be compared with the injury threshold for that exposure (see previous work [7] for details about this calculation).

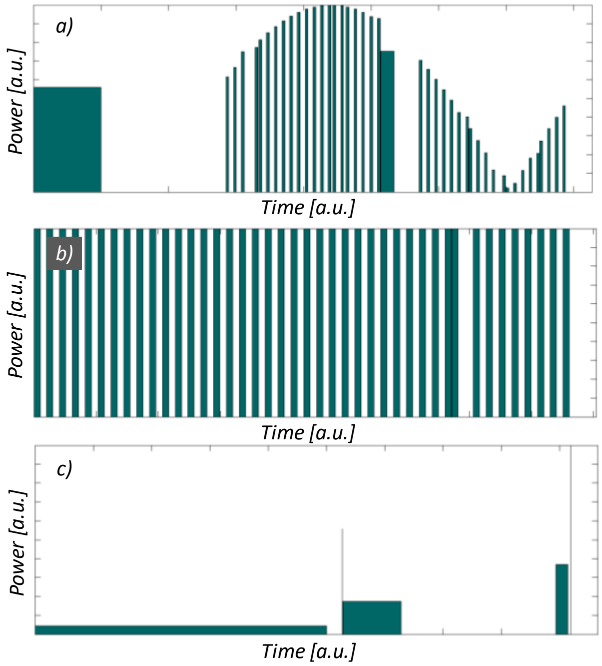


Figure 2. Illustration of three pulse trains (a is #19, b is #6026 and c is #13613) generated to simulate possible exposures for the purpose of safety analysis

Results

For each source size, the 15000 exposures were analyzed altogether in terms of RF, the distribution of which is shown in Figure *3*. It appears that the RF was mostly concentrated between 2 and 10 with a median value comprised between 3.3 and 5.7 for the different source sizes investigated. Most importantly, the lowest RF found for this database of 15000 exposures was often found to pertain to an exposure consisting of a single pulse. Whenever an irregular pulse pattern was found to feature a RF smaller than the RF of a single pulse, the analysis was scrutinized. It appears that such result was always found for relatively large source sizes (40 mrad and 70 mrad) and exposures featuring a significant amount of pulses with relatively low peak power, as shown in example c) of Figure 2 and where "average power" was the most restrictive criterion.

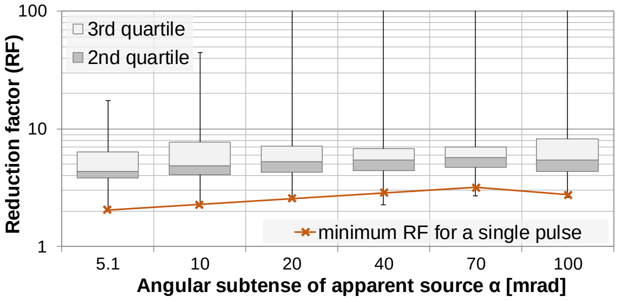


Figure 3. Distribution of RFs for various values of α (lower bar: minimum RF, upper bar: 99% quantile) and for each value of α also the minimum RF obtained for a single pulse (cross)

The data shown in

Figure *4* pertains to the results obtained for a source size of 10 mrad. The top diagram shows that a significant fraction of relatively low RFs follow the base line for single pulses (annotation #) for durations longer than 2.5 ms, precisely the duration corresponding to α_{max} for a source size of 10 mrad. For relatively long emission durations approaching 10 s, the RF can be lower than the base line for CW, where the "average power" criterion becomes limiting and where the effect of neglecting pulses with peak power below 5% of the highest peak power becomes noticeable (annotation $). Finally, the bottom diagrams illustrate the importance of considering pulse groups, limited to time windows of 250 ms, when evaluating complex pulse trains. It shows that pulse groups can encompass hundreds of physical pulses (annotation *) while the reduction factor remains below the median value, indicating that the interpretation of N as relative energy of pulses (or pulses groups) coupled with pulse grouping can actually loosen the resulting AEL to some extent without sacrificing safety.

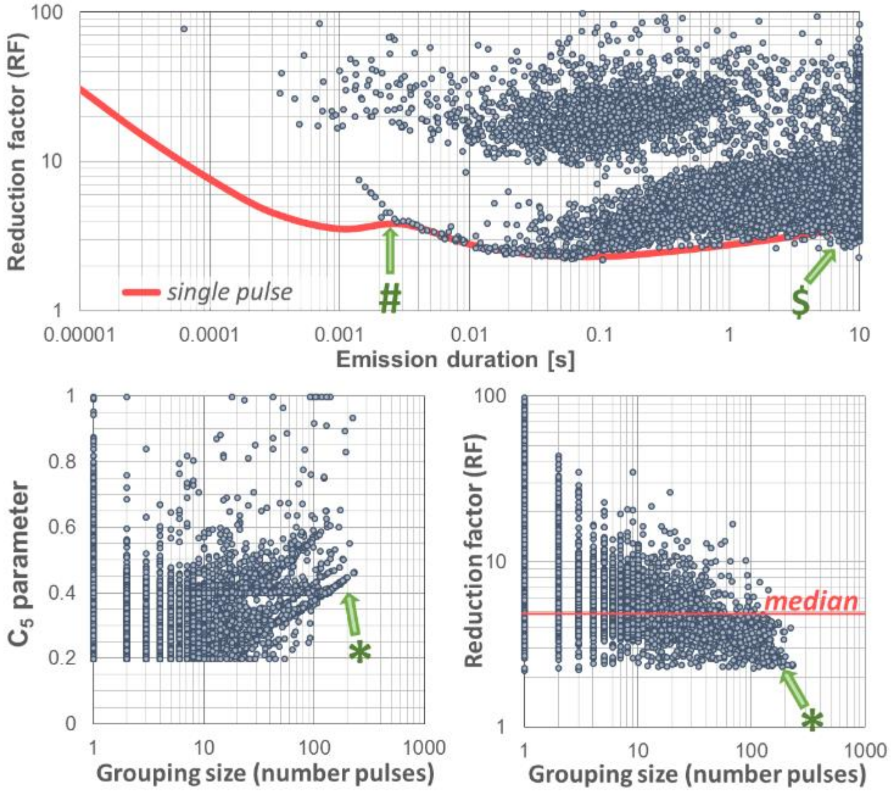


Figure 4. Distribution of RFs (results for 10 mrad) as a function of simulated emission duration along with other results related to the number of physical pulses grouped for the purpose of analysis/classification (see text for annotations #, $ and *)

Conclusion

The purpose of this study was to verify if a more general and less restrictive interpretation of the parameter N – used in laser safety standards for analyzing repetitively pulsed emissions – could be used as guidance for future classification of complex pulse trains. The simulations carried out in this study for the pulse duration regime governed by thermal mechanisms support the concept of a “partial energy” or “partial N” where counting the number of pulses is no longer defined on the basis of the number of physical pulses but rather on their relative energy within the emission. This interpretation is considered as being a significant improvement in the sense that it is a generalization of the current definition. It can be applied regardless of the “properties” of the emission, making specific guidance dedicated to regular pulse groups or pulse trains with constant pulse width obsolete. Furthermore, it harmonizes the C_5 and average power methods in their definition. Indeed, the average power method is already defined in such terms in IEC 60825-1 for irregular pulse patterns: *“For irregular pulse patterns (including varying pulse energies), T has to be varied between T_i (…) and the time base*”.

Apart from a few restrictions (e.g. the impossibility to predict injury thresholds for pulses shorter than T_i by means of a thermal model) and the need for additional data to confirm the conclusions, this study shows that the concept of partial energy is valid. Future work will extend simulations to emission durations up to 100 s (time base for Class 1) and investigate the possibility of applying the same interpretation of N for pulses shorter than T_i.

The empirical approach chosen in this study was motivated by the idea that irregular pulse patterns encompass a variety of parameters and are by definition difficult to anticipate. Real-life laser applications already show that the emission can be modulated in very different ways and because of the non-linearity of injury thresholds with source size, exposure duration and the complexity of the rules leading to AEL values, the generation of a large amount of pseudo-random patterns (with as little bias as possible) was assumed to be the most appropriate option. This approach also allowed to apply a computer model dedicated to the prediction of injury threshold levels of the retina – data that cannot be gained by experimental means given the virtually infinite number of possible exposures – with the aim of demonstrating the negligible risk for injury associated with the accessible emission levels for Class 1 in IEC 60825-1. With the assumption that a safety margin (or “reduction factor”) of 2 is sufficient, this study could support future developments of the multiple-pulse analysis methods promulgated by ICNIRP [6] as well as ANSI and IEC classification.

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Citation: ILSC **2019**, 202 (2019); doi: 10.2351/1.5118564
View online: https://doi.org/10.2351/1.5118564
View Table of Contents: https://lia.scitation.org/toc/ils/2019/1
Published by the Laser Institute of America