Journal of Laser Applications

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Cite as: J. Laser Appl. **32**, 032027 (2020); https://doi.org/10.2351/7.0000017
Submitted: 18 February 2020 . Accepted: 27 July 2020 . Published Online: 19 August 2020

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Journal of Laser Applications ARTICLE scitation.org/journal/jla

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Published Online: 19 August 2020

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Mathieu Jean,[1] Karl Schulmeister,[1] Sebastian Kotzur,[2,3] and Annette Frederiksen[4]

AFFILIATIONS

[1]Seibersdorf Labor GmbH, Laser, LED and Lamp Safety, 2444 Seibersdorf, Austria
[2]Robert Bosch GmbH, Corporate Research, 71272 Renningen, Germany
[3]Institute for Ophthalmic Research, Eberhard Karls University of Tübingen, 72076 Tübingen, Germany
[4]Robert Bosch GmbH, Chassis Systems Control, 71701 Schwieberdingen, Germany

ABSTRACT

The current laser safety standards do not address specifically how to account for repetitively pulsed lasers with irregular pulse trains. Variations in peak power, pulse duration, and duty cycle within a pulse train pose a number of problems when it comes to product classification or to assess the hazard of a given exposure. This study proposes to analyze irregular pulse trains by generalizing the determination of the number of pulses N used in the IEC 60825-1 or n in the ANSI Z136.1 standard. The proposed method for the determination of N applies to emission durations longer than 5 µs and was validated by generating a large number of theoretical pulse patterns and by comparing the retinal injury threshold, determined with a computer model, with the applicable emission limit. For 18 000 different pulse patterns, the ratio of the injury threshold to the emission limit was never less than 2, which is commonly considered as a sufficient safety margin. The smallest safety margin found for regular pulse patterns also equals 2. This study validates an analysis method for irregular pulse trains that can be included in the standards by simple generalization of the determination of the parameter N.

Key words: laser safety, retinal damage, computer model, pulse train, classification, IEC 60825-1, ANSI Z136.1

I. INTRODUCTION

For irregular pulse trains, one or more of the following parameters varies: the energy per pulse, the pulse duration, or the pulse interval. Irregular pulse trains are common to many types of laser products. For instance, for scanned emission, such as found in many lidars and 3D cameras, that scans both horizontally and vertically, even a continuous (nonpulsed) emission results in an irregular ocular exposure as a consequence of the stationary circular aperture representing the pupil of the eye. Products with stationary beams can also feature emission with varying pulse durations or peak power, for instance, range finders optimized to operate at different distance ranges. The proposed method is not relevant for the case of regular pulse patterns that are, for example, possible for ophthalmic instruments with scanned beams where the beam is not clipped by the pupil of the eye (e.g., Maxwellian view).

In 2014, the third edition of IEC 60825-1[1] and a new edition of ANSI Z136.1[2] were published. In both standards, the rules of how to apply maximum permissible exposure (MPE) values or accessible emission limits (AELs) to repetitively pulsed lasers are identical for pulse or emission durations longer than the parameter T_i or t_{min}, symbols used in IEC 60825-1 and ANSI Z136.1, respectively. This parameter is equal to 5 µs in the wavelength range of 400 to 1050 nm and equal to 13 µs between 1050 and 1400 nm (see subclause 4.3 f) in IEC 60825-1:2014; 8.2.3 and Table 6c in ANSI Z136.1-2014. The two standards differ only for pulse durations shorter than T_i (or t_{min}), where the correction factor C_5 is applied in the IEC 60825-1 standard, while there is no such correction in the ANSI Z136.1 standard. In the following, we will only refer to the IEC 60825-1 standard, but the discussion applies to both standards. The pulse duration domain less than 5 µs is, however, not in the scope of the present work.

The changes of IEC 60825-1:2014 in comparison to earlier editions were reviewed in a white paper.[3] Specific issues related to the analysis of repetitively pulsed emissions were addressed in a proceeding paper[4] and published in an Interpretation Sheet (ISH1) for IEC 60825-1 in 2017.[5] The analysis of a repetitively pulsed emission relies on the application of three rules (or criteria), often referred to as single pulse, average power, and reduced pulse criterion. These criteria are concomitant in order to cover different biophysical aspects, and the most restrictive result is defined as the highest ratio of accessible emission (AE) to AEL. In IEC 60825-1, the term accessible emission, AE, is used to refer to the quantity that is compared against the AEL, and when the AE is smaller than the respective AEL (such as for class 1) for all conditions required in the standard, the product is assigned the respective class, such as Class 1. The specific term AE is used to highlight that there is a range of rules to consider for the determination of AE, such as with specific aperture stop diameters and angles of acceptance. The main interest of this paper is the classification of a laser product such as Class 1 for wavelengths between 400 and 1400 nm where the retinal thermal AEL applies, as shown in Eq. (1) for the visible wavelength range and emission durations t between 5 μs and T_2,

$$\mathrm{AEL}\ [\mathrm{J}] = 7\times 10^{-4}\, C_6 t^{0.75}, \tag{1}$$

where

$$T_2\ [\mathrm{s}] = \begin{cases} 10 & \text{if } \alpha \le \alpha_{\min} \\ 100 & \text{if } \alpha > 100\ \mathrm{mrad}\,. \\ 10\times 10^{(\alpha-\alpha_{\min})/98.5} & \text{otherwise} \end{cases} \tag{2}$$

Therefore, when we refer to AEL, the retinal thermal AEL for Class 1 is meant, unless otherwise noted. The analysis, in principle, is equivalent for classification of laser products as Class 2, where the maximum emission duration to be considered is limited to the time base of 0.25 s. In this paper, for the application of the method to Class 2, the time base of 0.25 s has to be used whenever we refer to T_2 (the emission duration from which onward the AEL is a constant power value). The parameter T_2 is a function of the angular subtense of the image of the apparent source α as shown in Eq. (2) where $\alpha_{\min} = 1.5$ mrad.

The following gives a brief overview of the three pulse evaluation criteria that apply to the classification as Class 1 in the retinal thermal regime.

A. Single pulse criterion (criterion 1)

The accessible emission of a pulse has to be below AEL(t) for the duration t of that pulse, $\mathrm{AEL}_{\mathrm{single}}(t)$. In the case of an irregular pulse train (in the following, the abbreviation IPT is used), each and every pulse must be compared against the applicable AEL(t).

B. Average power criterion (criterion 2)

The accessible emission AE(t), determined as average power, averaged over duration t, is compared against AEL(t) applicable for that duration t. In IEC 60825-1, the symbol $\mathrm{AEL}_{\mathrm{T}}$ is used, where T is the averaging duration. For regular pulse patterns, i.e., a pattern that fulfills three conditions, namely constant pulse duration, constant energy per pulse, and constant pulse interval (i.e., constant pulse frequency), the most restrictive averaging duration is always T_2. In the case of an IPT, the averaging duration t must be varied between T_{i} and T_2 in order to verify that AE(t) is below AEL(t) for all averaging durations and temporal positions of the averaging time-window within T_2. In the case of an emission where the temporal irregularity extends over periods that are longer than T_2, it is also necessary to shift the averaging time-window of T_2 so as to find the most restrictive ratio of AE(t) to AEL(t). We note that to compare the average power (averaged over a certain duration t) against AEL(t) expressed as power is equivalent to compare the energy within that time t against AEL(t) expressed as energy, i.e., the ratio of AE(t)/AEL(t) does not change.

C. Reduced pulse criterion (criterion 3)

The accessible emission of a pulse, or that of a group of pulses, has to be below $\mathrm{AEL}_{\mathrm{s.p.train}}(t)$ for the duration t of that pulse or pulse group. $\mathrm{AEL}_{\mathrm{s.p.train}}(t)$ can be understood as reduced single pulse AEL and is the product of $\mathrm{AEL}_{\mathrm{single}}(t)$ and a correction factor C_5 (referred to as C_{P} in ANSI Z136.1). C_5 varies between 0.2 and 1, depending on the parameter N (referred to as the "effective number of pulses") determined for the time period T_2. The specific formula to use for C_5 also depends on the applicable emission duration t (i.e., the duration of a pulse or of a group of pulses) and the angular subtense of the image of the apparent source α as illustrated in Eq. (3) for $t > T_i$ (see additional details in Clause 4.3 f) of IEC 60825-1:2014 as well as the discussion by Schulmeister,[4]

$$C_5 = \begin{cases} 1 & \text{if } \alpha \le 5\ \mathrm{mrad} \text{ or } \alpha > 100\ \mathrm{mrad}, \\ \max(0.4, N^{-0.25}) & \text{if } 5\ \mathrm{mrad} < \alpha \le \alpha_{\max}, \\ \max(0.2, N^{-0.25}) & \text{if } \alpha > \alpha_{\max}. \end{cases} \tag{3}$$

For regular pulse patterns, the application of the reduced pulse criterion (referred to as criterion 3) is based on the number of pulses within T_2 and the energy per pulse, where it is not necessary to consider groups of pulses as if they were pulses. For an IPT, additionally to considering single pulses for criterion (criterion 3), groups of pulses have to be analyzed, i.e., each group is treated as an "effective pulse" (see also ISH1).[5] For such an analysis of groups of pulses, the duration of the group is used to determine $\mathrm{AEL}_{\mathrm{single}}(t)$. The accessible emission is the energy within that group, and N is the number of groups within T_2. As a general method, the emission duration t for which accessible emission and AEL(t) are determined can be seen as a time window over which the energy is summed up. There is no specific term and symbol used in the current edition of IEC 60825-1, and we will refer here to the evaluation duration Δt. Thus, AE is the energy summed up within Δt, and the sum has to be below $\mathrm{AEL}_{\mathrm{s.p.train}}(\Delta t)$. Since the limiting angular subtense $\alpha_{\max}(\Delta t)$ is also determined with Δt, the value of α in C_6 ($C_6 = \alpha/\alpha_{\min}$) as well as the angle of acceptance for the determination of AE can vary depending on the value of Δt (see, for instance, Schulmeister[6] for a detailed discussion on these parameters of the standard). In the general scheme, the evaluation duration Δt is varied both in terms of the temporal start position within the pulse train and in terms of the duration (between T_{i} and 0.25 s; emission durations longer than 0.25 s are not considered as pulses, and C_5 is not applied). Without specific rules how to determine N for an IPT, each pulse or pulse group has to be counted, irrespective of how small the peak power or energy is compared to the other pulses (or pulse groups) in the pulse train.

Thus, when each pulse is counted as 1, the parameter N does not reflect the fact that pulses with relatively low peak power are inherently less hazardous as a consequence of the lower energy deposition rate. Some effort has been done in the past years for the laser safety standards to better address the issue of irregular pulsed emissions. In the specific case of constant pulse duration and varying peak power,[7] specific guidance has been published in an IEC document[5] as a complement to IEC 60825-1 edition 3.0. It specifies that N can be determined based on the fraction of the relative peak powers of the pulses. This is, however, not applicable in the general case where both peak power and pulse duration vary.

The present study intends to demonstrate that irregular pulse trains can be properly evaluated when the parameter N is determined as the ratio of the energy within T_2 to the energy within the evaluation duration Δt (see detailed discussion of the method in Sec. II A). The intention behind this proposal is to provide a solution that does not require any modification of the existing classification rules and is applicable to any pulse train with pulses in the thermal damage mechanism regime, i.e., for pulse durations longer than T_i. Since the computer model employed for validation is not applicable for the regime where the damage mechanism is microcavitation,[8] at this point in time it is unfortunately not possible to assess if the proposed method is also valid for the case that the emission contains pulses with duration shorter than T_i.

II. MATERIALS AND METHODS

A. Analysis method to be validated

The parameter N used to calculate the correction factor C_5 in IEC 60825-1 (or n and C_P in ANSI Z136.1) is referred to as the "effective number of pulses" (this term implies that N is not necessarily the actual number of pulses within the specified evaluation period). In the following, we refer to T_2 as the period to determine N, which is applicable for classification as Class 1 laser product. For the case that the time base equals 0.25 s, i.e., for Class 2 classification, T_2 has to be replaced accordingly. It is proposed, for future editions of IEC 60825-1, to determine N [see Eq. (4)] by the ratio of energy Q_{T_2} within the emission duration T_2 to energy $Q_{\Delta t}$ within the evaluation duration Δt (representing a pulse or a group of pulses within T_2),

$$N = \frac{Q_{T_2}}{Q_{\Delta t}}. \quad (4)$$

As is already the general requirement to analyze groups of pulses as "effective pulses" (see Interpretation Sheet 1),[5] both the duration of Δt and the temporal position within T_2 (the start time of Δt) must be varied to cover individual pulses but also groups of pulses up to a duration of 0.25 s (the maximum duration to be considered for a pulse or a group of pulses). Thus, for irregular pulse trains, this method of considering the energy within a certain evaluation period to encompass single pulses but also groups of pulses (here given the symbol Δt and to be varied in temporal start position and duration) is already necessary, based on IEC 60825-1:2014 and the associated Interpretation Sheet ISH1.[5] The difference to the existing required method is that N is not equal to the number of pulses or pulse groups but is determined in a more general way. Thus, we emphasize that for this method, for irregular pulse trains, N is not the number of pulses or the number of pulse groups within T_2, and we, therefore, in the following also avoid using that terminology and refer to the parameter N only—as the parameter relevant for the determination of C_5. It is also apparent that the numerical value of N determined with the proposed method, for irregular pulse trains, is different to when N is the number of pulses or the number of pulse groups within T_2. In order to facilitate the use of symbols and the flow of reading, the symbol N is used and not a different symbol. It is pointed out, however, that for pulse trains with constant energy per pulse Q (or groups of pulses with constant energy per group), the value of N determined by the proposed method is equal to the number of pulses (or pulse groups, respectively), because the total energy within T_2 is $Q_{T_2} = N \cdot Q$.

For a simple pulse pattern, the choice of the evaluation durations can be based on the pattern at hand, but it can also be automated by a computer program to analyze the pulse train data. We note that the variation of the evaluation duration Δt in terms of start time and duration is equivalent to the requirement for the average power criterion to vary the averaging duration. The evaluation duration Δt is used to calculate the accessible emission limit $\mathrm{AEL}_{\mathrm{single}}(\Delta t)$ as well as $\alpha_{\max}(\Delta t)$, which is relevant for the determination of C_6 and of the accessible emission. The value of N that is determined for a specific duration and position of Δt is used to calculate C_5 and $\mathrm{AEL}_{\mathrm{s.p.train}}(\Delta t)$ for that evaluation duration. The energy $Q_{\Delta t}$ can be seen as the accessible emission AE that applies to the evaluation duration that is analyzed, although for the determination of N as a ratio, a relative value can be used instead of the absolute value of $\mathrm{AE}(\Delta t)$. As is the general classification principle, AE has to be below $\mathrm{AEL}_{\mathrm{s.p.train}}$ for all durations and positions of Δt within T_2. This can also be understood as the process to determine the evaluation duration Δt which features the maximum ratio of AE/AEL, and this particular evaluation duration is then used for classification according to the reduced pulse criterion.

We note that for the determination of N based on our proposal, the field-of-view (i.e., the angle of acceptance) must be identical for both components of the fraction. In other words, both Q_{T_2} and $Q_{\Delta t}$ must be determined for the same angle of acceptance. For a stationary retinal image, the choice of the field-of-view does not affect the energy ratio, i.e., it is possible to use a field of view that is larger than the image of the apparent source, also referred to as an open field of view.

In the case of pulses defined by a rectangular temporal function, the above formula can be rewritten as

$$N = \frac{\sum_{k=1}^{K} P_k \cdot t_k}{\sum_{m=1}^{M} P_m \cdot t_m}, \quad (5)$$

where K is the number of pulses within T_2 and M is the number of pulses within the evaluation duration, Δt. Thus, M pulses within Δt are a subset of the K pulses within T_2. P_k and P_m are the respective peak powers, and t_k and t_m are the respective pulse durations of the rectangular temporal functions. For this method to determine N, it is proposed to neglect all pulses with a relative peak power below 5% of the highest peak power when determining Q_{T_2} and $Q_{\Delta t}$ and when selecting the interval Δt, i.e., these pulses are purely removed from the AEL analysis. All existing classification rules, criteria, and parameters given in IEC 60825-1:2014 are applicable. The method

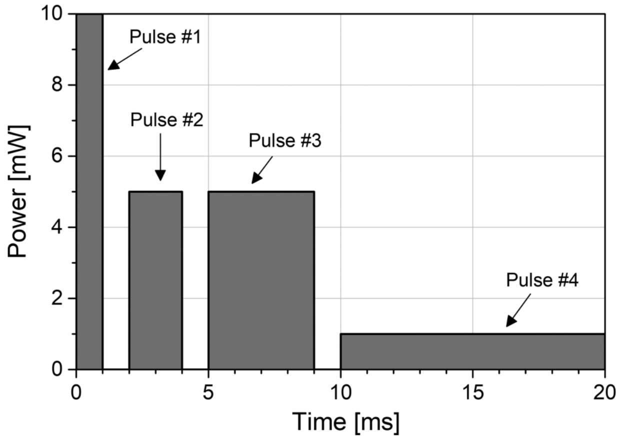

FIG. 1. Arbitrary example of an irregular pulse pattern, consisting of four pulses within T_2.

can also be applied for an MPE analysis as described in Annex A of IEC 60825-1 or for an analysis based on ANSI Z136.1.

The arbitrary pulse pattern shown in Fig. 1 is used to illustrate the calculation steps for deriving $\mathrm{AEL}_{\mathrm{s.p.train}}(\Delta t)$. The angular subtense of the image of the apparent source is assumed to be equal to 10 mrad, and the profile is circular and homogeneous, i.e., top-hat. The evaluation duration Δt is varied to apply to each pulse, as well as to groups of pulses. It is assumed that besides the four pulses shown in Fig. 1, there are no other pulses within T_2. For each choice of the evaluation duration Δt (and start position), $\mathrm{AEL}_{\mathrm{single}}(\Delta t)$ is determined for that duration Δt, also considering the limitation of $\alpha_{\max}(\Delta t)$ and in turn C_6 that depends on the choice of the duration of Δt. For instance, for the first pulse with a pulse duration of 1 ms, $\alpha_{\max}(\Delta t) = 6.3$ mrad. For each chosen evaluation duration, $\mathrm{AEL}_{\mathrm{single}}(\Delta t)$ is reduced by C_5 to obtain $\mathrm{AEL}_{\mathrm{s.p.train}}(\Delta t)$, where C_5 is determined as the ratio of the energy in the total pulse pattern Q_{T_2} (taken here as 50 μJ) to the energy within the evaluation duration $Q_{\Delta t}$. For the first, second, or fourth pulse, $Q_{\Delta t}$ equals 10 μJ, and therefore, N is in those cases 50/10 μJ = 5. For the third pulse, $N = 50/20$ μJ = 2.5. To determine N, the values of Q_{T_2} and $Q_{\Delta t}$ are assessed here in terms of the total intraocular energy, i.e., with an open field view. The same ratio would result when, for instance, an angle of acceptance equal to $\alpha_{\max}(\Delta t)$, or any other angle of acceptance, was applied. We note that, in this example, for applying Δt to the first, second, or fourth pulse, it results in a value of N larger than the actual number of pulses in the pulse pattern. Also groups of pulses need to be analyzed, such as the first and second pulses as a group, resulting in $N = 50/20$ μJ = 2.5. The AE for the respective evaluation duration Δt is the sum of the pulse energies within Δt and within the angle of acceptance equal to $\alpha_{\max}(\Delta t)$. Comparing all ratios of AE to AEL (for all possible evaluation durations and start positions) identifies the first pulse as critical for the reduced pulse criterion, i.e., criterion 3. All parameters relevant to this calculation are detailed in Table I for several evaluation durations (not all applicable choices of the evaluation duration are shown). Application of other classification rules shows that criterion 3 is the most restrictive one in this example.

For the exact same pulse pattern but with an angular subtense of the image of the apparent source of 40 mrad, the most restrictive result is still found for the reduced pulse criterion, but in this case for the group consisting of the first three pulses, i.e., for an evaluation duration of 9 ms, for which $N = 1.25$. These examples demonstrate

TABLE I. Application of the reduced pulse criterion to the pulse pattern shown in Fig. 1 for several evaluation durations and according to the proposed definition of N (example for an angular subtense of the image of the apparent source of 10 mrad and a wavelength in the visible wavelength range). For the determination of N, both numerator and denominator were taken as the total energy passing through the 7 mm aperture stop, i.e., determined with an open field of view (FOV) not limited to $\alpha_{\max}$. The same ratio would result when any other field of view was used, such as $\alpha_{\max}$.

Parameter	Pulse No. 1	Pulse No. 2	Pulse No. 3	Pulse Nos. 1 and 2	Pulse Nos. 2 and 3	Pulse Nos. 1 to 3
Evaluation duration, Δt (ms)	1	2	4	4	7	9
$\alpha_{\max}(\Delta t)$ (mrad)	6.3	8.9	12.6	12.6	16.7	19.0
C_6	6.3/1.5 = 4.2	6.0	6.7	6.7	6.7	6.7
$\mathrm{AEL}_{\mathrm{single}}(\Delta t)$ (μJ)	$7\times10^{-4}\cdot C_6\cdot t_1^{0.75}$ J = 16.6 μJ	39.5	74.2	74.2	112.9	136.4
Energy Q_{T2} open FOV (μJ)	50	50	50	50	50	50
Energy $Q_{\Delta t}$ open FOV (μJ)	10	10	20	20	30	40
N	50/10 = 5	5	2.5	2.5	1.67	1.25
C_5	$N^{-0.25} = 0.67$	0.67	0.80	0.80	0.88	0.95
$\mathrm{AEL}_{\mathrm{s.p.train}}(\Delta t)$ (μJ)	11.1	26.4	59.0	59.0	99.4	129.0
$\mathrm{AE}(\Delta t)$ (μJ)	10 μJ (6.3 mrad/10 mrad)^2 = 4 μJ [see Eq. (6)]	8	20	20	30	40
$\mathrm{AE}/\mathrm{AEL}_{\mathrm{s.p.train}}$	**0.36**[a]	0.30	0.34	0.34	0.30	0.31

[a]In this example, the most restrictive (highest) AE/AEL ratio was found for pulse No. 1.

the application of the parameter N based on relative energy instead of an actual number of pulses, as well as the dependence of the result on other characteristics (especially, pulse period and source size) due to the time-dependent parameter $\alpha_{max}(\Delta t)$.

B. Validation strategy

In order to test the above definition of N and ensure that all applicable IPTs can be properly assessed under one simple definition, it was decided to adopt an empirical approach. This approach was justified by the number of parameters that characterize an IPT and that have an impact on the injury threshold, namely, pulse duration, peak power, duty cycle, and the number of pulses. A wide variety of possible emission patterns result that can neither be validated analytically nor by applying general biophysical principles. However, general biophysical principles were used to design the proposed definition of N on the grounds that thermally induced injuries are nonlinear both with pulse energy and with pulse duration. The relationship between injury buildup and pulse energy can be modeled by the Arrhenius integral and is illustrated in the following example. Let us consider a pulse pattern that consists of two thermally independent pulses (i.e., sufficient cooling between pulses) of equal duration and the second pulse having half the peak power of the first one. Thus, the second pulse has 33% of the total energy of the group. The Arrhenius integral with strong nonlinearity of injury with temperature dictates that the second pulse will contribute considerably less than 33% to the injury buildup, i.e., considerably less than its energy relative to the total pattern energy. Since the factor C_5 is given as $N^{-0.25}$, the authors were inclined to believe that nonlinearity of the Arrhenius integral would not be outweighed by the relaxation of C_5 resulting from N being <2 in this example. The previously published work on IPT with constant pulse duration[7] supports this reasoning. Furthermore, the time-dependence of AEL (AEL proportional to $t^{0.75}$) similarly favors a definition of N based on relative energy since the time-dependence of thermally induced injuries on pulse duration is shallower than $t^{0.75}$. It is, however, not possible to demonstrate conclusively the validity of the proposed method on that basis only.

Consequently, a large number of hypothetical emissions were generated and a computer model that was developed to predict retinal injury thresholds (THRs) in the thermal regime was used to compare the THR to the applicable AELs for every single emission. The success of the proposed definition for N was measured by the ratio of THR to AEL and referred to as the reduction factor (RF). It is commonly accepted in the laser safety community[9,10] that the RF shall not be smaller than two, i.e., the accessible emission limit shall be at least a factor of 2 below the injury threshold expressed as ED_{50} level in order for laser products classified as Class 1 to be interpreted as safe.

C. Database

A computer program was written in order to generate a large database of pulse patterns, organized into five series for a total of 18 000 pulse patterns. The generation was based on a set of parameters that define the pulse pattern (see Table II). The value of a parameter was determined by a random number generated in the unit interval [0,1] and then scaled to the interval set for the respective parameter. An interval can be either continuous or discretized. The distribution of random numbers was governed according to one of the following six weighting functions: uniform (1), linear decrease (2), linear increase (3), exponential decrease (4), exponential increase (5), or parabolic (6). All parameters and the weighting of their respective random number are summarized in Table II. The most relevant parameters are also illustrated in Fig. 2.

The total duration of the pulse pattern and the total number of pulses are not input parameters for the pulse pattern generation and are, therefore, not associated with a random number. If the pulse pattern generated by the computer program exceeds the maximum values set for either the pulse pattern duration or the

TABLE II. List of parameters used to generate pulse patterns and the range of values for the five series. For each parameter, the type of weighting function of the random number is indicated in parentheses.

Parameter	Series 1	Series 2	Series 3	Series 4	Series 5
Pulse pattern duration (s)	10^{-5}–10	10^{-5}–10	10^{-5}–10	10^{-5}–10	10^{-5}–T_2
Number of subpatterns[a]	1–50 (2)	1–200 (2)	1–1000 (2)	1–1000 (2)	100–1000 (1)
Number of pulses per subpattern	1–200 (2)	1–200 (2)	1–500 (2)	1–200 (2)	1–200 (2)
Total number of pulses	1–1000	1–3000	1–5000	1–5000	1–5000
Pulse duration[b] (s)	10^{-5}–0.1 (1)	10^{-5}–0.1 (1)	10^{-4}–0.1 (1)	10^{-5}–0.1 (6)	10^{-5}–0.1 (6)
Probability of change for pulse duration (%)	0–100 (1)	0–100 (1)	0–50 (2)	0–100 (2)	0–100 (2)
Magnitude of change for pulse duration [log(t)]	0–4 (2)	0–4 (2)	0–3 (2)	0–4 (6)	0–4 (6)
Pulse-to-pulse duty cycle (PPDC) (%)	10–95 (3)	10–95 (3)	10–95 (3)	10–95 (3)	10–95 (3)
Probability of change in PPDC (%)	0–100 (1)	0–100 (1)	0–100 (1)	0–100 (1)	0–100 (1)
Peak power envelop	1–5 (1)	1–5 (1)	5 (1)	6 (1)	6 (1)
Envelop periodicity[c]	0–1 (1)	0–1 (1)	0–1 (1)	0–1 (1)	0–1 (1)
Number of envelop cycles	0.5–10 (4)	0.5–10 (4)	0.5–10 (1)	0.5–10 (1)	0.5–10 (1)

[a]A pulse pattern consists of the assembly of numerous subpatterns.
[b]The pulse duration was discretized with three values per order of magnitude (1, 2, and 4 times 10^x).
[c]The periodicity of the peak power envelop is either anchored to the subpattern duration (0) or to the duration of 1 s (1).

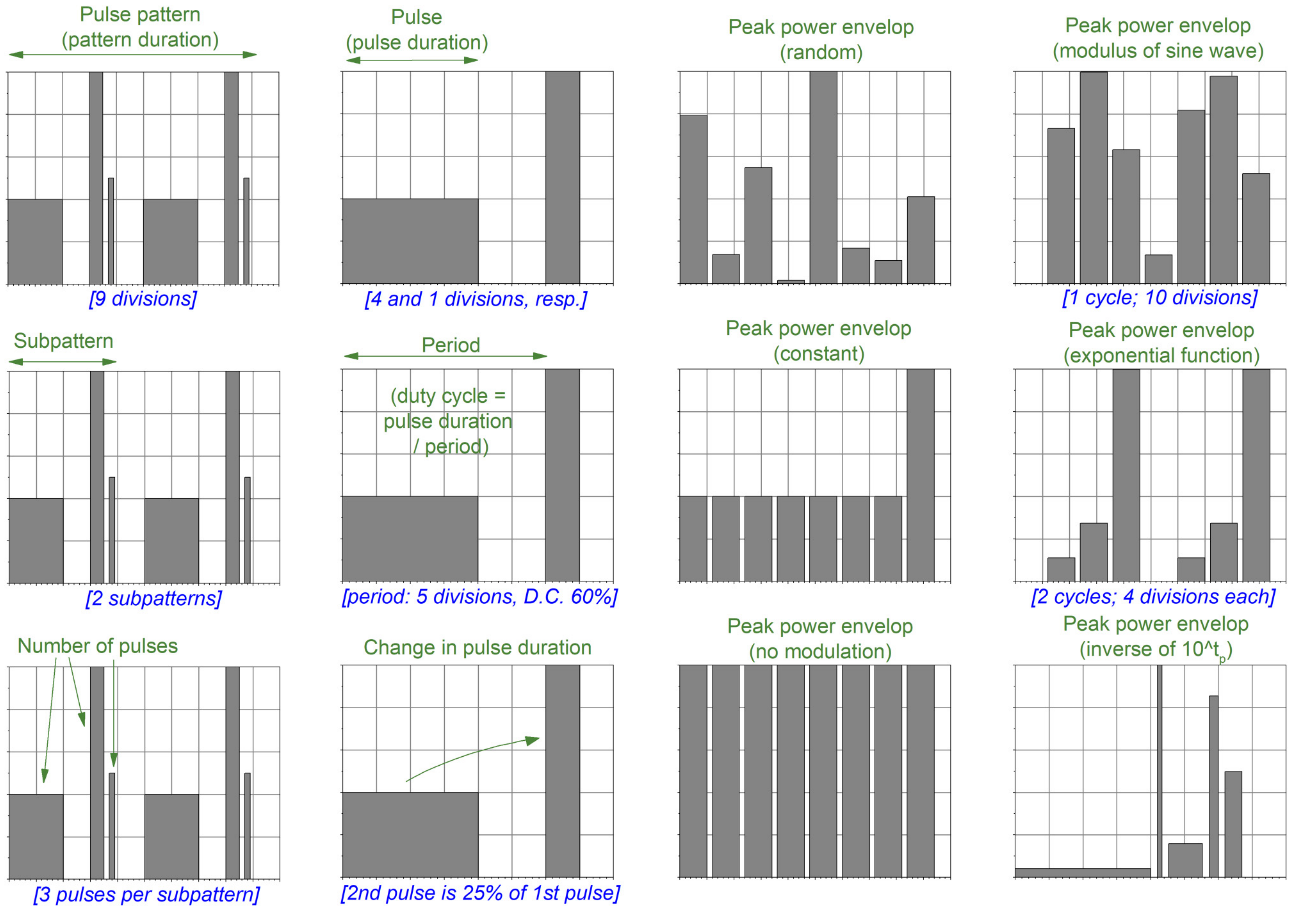

FIG. 2. Illustration of various parameters and conventions used for the generation of pulse patterns; time on the abscissa and power on the ordinate (for each subplot, the parameter is indicated at the top and the corresponding numerical value corresponding to the example at hand at the bottom).

total number of pulses, then the pulse pattern is shortened accordingly. For instance, in series 1, the pulse pattern cannot last longer than 10 s or contain more than 1000 pulses.

Most of the parameters are set at the beginning of the generation process and apply to the whole pattern. However, the two parameters "probability of change in pulse duration" and "probability of change in PPDC" were designed to control whether or not the pulse duration or the duty cycle can change between two consecutive pulses. In this case, a random number of value x in the unit interval [0,1] is generated for each pulse of the pattern and compared to the fixed value X of the respective "probability of change" (PoC) parameter. If $x < X$, then the pulse duration or the duty cycle is allowed to change. This additional procedure allows the generation of pulse patterns with constant pulse duration (e.g., when $X \to 0$) or even regular pulse patterns (when $X \to 0$ for both PoC parameters and peak power envelop of type 3, 5, or 6). The overall duration of the created pulse patterns also varies: pulse patterns can be of duration T_2, but they can also be shorter, some only consist of a few pulses. While short pulse trains do not occur very often for the classification of products, they might occur in an MPE analysis, for instance, for a laser located on a moving platform.

Finally, the relative peak power of each pulse (peak power envelop in the unit interval [0,1]) can take one of the six following forms: random (1), absolute magnitude of a sine function (2), constant (3, in this case, all pulses but the last one have the same peak power; the last pulse of the pattern is set to 1), exponential (4), no modulation (5, all pulses have the same peak power), or inversely proportional to 10 to the power of the pulse duration (6). The maximum peak power within emission is normalized to 1. The temporal pulse shape was invariably rectangular (constant peak power during the pulse duration). Four pulse patterns generated in this manner are shown in Fig. 3 to illustrate the range of types of pulse patterns obtained by the pseudorandomized generation process.

The number and the variation of pulse patterns are believed to provide a sufficient basis for a general validation of the proposed method.

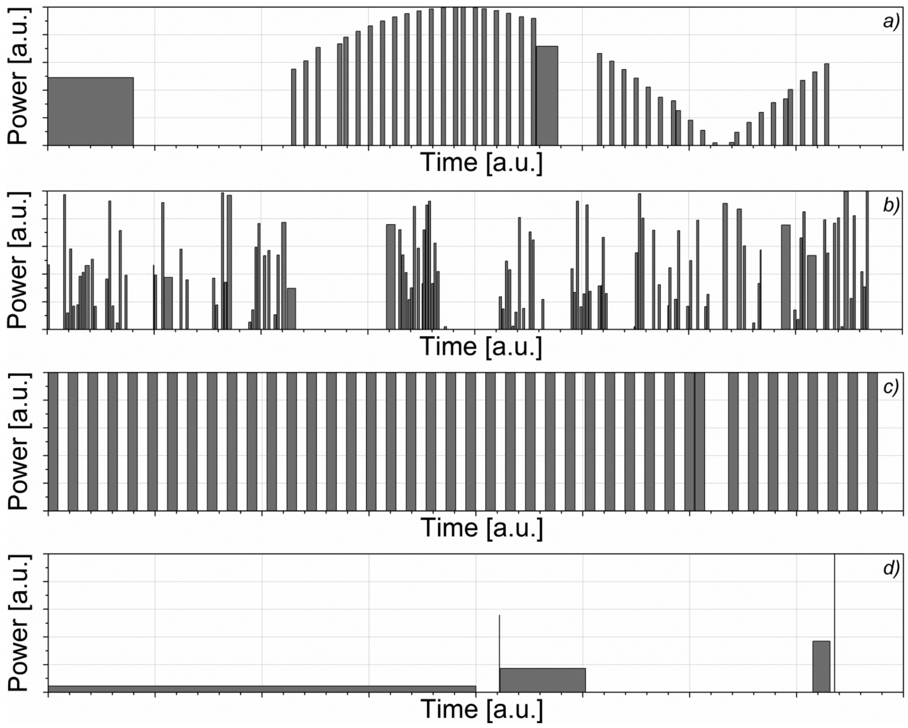

FIG. 3. Four pulse trains chosen arbitrarily in the database for their varied characteristics: No. 19 exhibits a sine envelop as well as occasionally variable duty cycle and pulse duration (a), No. 5732 exhibits constantly varying duty cycle and random peak power (b), No. 6026 is almost regular with constant peak power and constant pulse duration (c), and No. 13613 contains both short and long pulses (d).

D. Retinal injury thresholds

THRs of the retina were predicted by a computer model[10] that was validated against *in vivo* experiments on nonhuman primates. The model is based on bulk homogeneous heating of the retina and, therefore, applies to thermal injury. The finite-element method is used to solve the heat conduction equation in a layered environment representing the retinal tissues, and the Arrhenius equation is applied to the temperature history in order to determine the injury threshold level within the RPE layer. Heating of individual melanosomes, which is relevant in the nanosecond and short microsecond regime, cannot be modeled, and therefore, the injury thresholds related to microcavitation (see Ref. 8) cannot be predicted. Consequently, the validity of the computer model is restricted to pulse durations longer than about 100 µs. For completeness, pulse durations in the transition range (of 10, 20, and 40 µs) were included in the calculations. According to this model, the resulting 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% (see discussion in Ref. 11). In the case of a pulse pattern, the predicted THR is expressed in units of energy and defined for the entire pulse pattern. THR is the intraocular energy level required to reach $\Omega = 1$ in the Arrhenius integral. In order to obtain THR for the human eye, the following adaptations from the nonhuman primate model were made:

(1) The air equivalent focal length of the relaxed human eye was set to 16.68 mm (see Le Grand full theoretical relaxed eye in Ref. 12),
(2) the retinal image diameter was calculated by multiplying the angular subtense of the image of the apparent source by the focal length of the eye, thus disregarding optical aberrations and scattering of any kind, and
(3) the minimum retinal spot diameter was set to 25 µm and the minimum visible lesion diameter was set equal 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.[13]

It is emphasized that the above adjustments are a set of conservative assumptions. Whenever exposure conditions and endpoints were comparable, injury thresholds for humans were shown to be consistently higher than for nonhuman primates.[14] The THR was calculated for each of the 18 000 emissions and for six different values of the angular subtense of the image of the apparent source α in the range between 5 and 100 mrad where the reduction factor C_5 applies. The irradiance distribution of the image of the apparent source was taken to be constant and circular, i.e., a top-hat distribution. All THRs were calculated at a wavelength of 530 nm, where the RF for retinal thermal injury is the lowest, as shown in Fig. 4. For $\alpha = 5$ and 10 mrad, the reduction factor can reach values lower than 2.5, with minimum values of 2.1 and 2.3, respectively. The results obtained for wavelengths above 1200 nm are considered irrelevant to this study since the RF is mainly governed by the correction factor C_7 (or C_C in ANSI Z136.1).

E. RF calculation

The figure of merit used to evaluate and validate the tested hypothesis is the ratio of THR to the accessible emission limit (AEL), referred to as the RF. The AEL to be compared with the

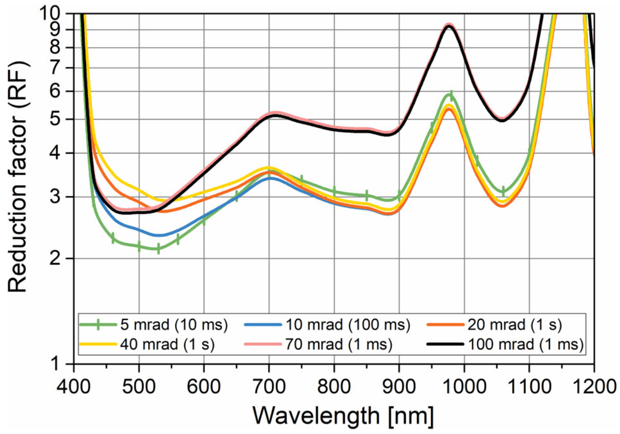

FIG. 4. Ratio of the predicted injury threshold, THR, to AEL of Class 1 as a function of wavelength for 5 mrad < $\alpha \le 100$ mrad for single pulses (for each value of α, the pulse duration was the one associated with the lowest THR/AEL ratio).

THR is the one for which the ratio of AE to AEL is the highest, considering the different criteria to be applied in the case of repetitively pulsed lasers.

Since we are working with theoretical emissions, there is no actual AE. However, the AE/AEL ratios can be calculated with a simulated AE on the basis of the angular subtense of the image of the apparent source α and for an arbitrary maximum peak power level P within the pulse pattern, as shown in Eq. (6) for M consecutive pulses within Δt. This definition applies to any pulse or groups of pulses and, therefore, to all classification rules. In the case of the reduced pulse criterion, pulse grouping is limited to a maximum grouping duration of 0.25 s and in the case of the average power criterion to T_2 for Class 1 or 0.25 s for class 2. In Eq. (6), power P_m is defined as the peak power passing through the 7 mm aperture stop (not limited by a field of view), so that $P_m \cdot t_m$ can be considered as total intraocular energy, the energy per pulse passing through the 7 mm aperture stop. It is necessary to take into account that for the case that the image of the apparent source is larger than α_{max}, the angle of acceptance for the determination of AE is limited to α_{max}, so that AE is smaller than the total energy that passes through the 7 mm aperture stop. For a top-hat distribution of the retinal image, the reduction factor is equal to the square of the ratio of α_{max} over α. A detailed discussion of the correction is given by Schulmeister *et al.*,[15]

$$\begin{cases} AE = \sum_{m=1}^{M} P_m \cdot t_m & \text{for } \alpha \le \alpha_{max}, \\ AE = \left[\dfrac{\alpha_{max}}{\alpha}\right]^2 \sum_{m=1}^{M} P_m \cdot t_m & \text{for } \alpha > \alpha_{max}. \end{cases} \tag{6}$$

The first step in the validation for a given pulse pattern is to determine the most restrictive AEL, i.e., the AEL that is associated with the largest ratio of AE to AEL, based on the variation of the evaluation duration Δt (in terms of duration as well as the start position) as well as for all multiple pulse criteria. We note that, as given in IEC 60825-1, AEL(Δt) is determined with a factor C_6 where the value of α is limited to $\alpha_{max}(\Delta t)$ and AE(Δt) is determined as given in Eq. (6). In the second step, the most restrictive AEL is compared with the THR. Since the THR is defined for the entire pulse pattern and it is not possible to extract a "sub-THR" for a subset of pulses, it is necessary to scale the AEL to the entire pulse pattern. The scaling takes into account the energy outside the duration Δt, which is the duration for which the AEL(Δt) applies. The scaling factor is equal to the ratio of energy Q_{T_2} (the sum of the energies of the pulses within T_2; the pulse train can also be shorter than T_2) and energy $Q_{\Delta t}$ within the evaluation duration (that was identified as the critical evaluation duration in the first step). Also, for the case that the retinal image is larger than $\alpha_{max}(\Delta t)$, the scaled AEL (Δt) is increased by the ratio of $[\alpha/\alpha_{max}(\Delta t)]^2$ as shown in Eq. (7). For an analysis based on IEC 60825-1, the inverse of this factor is applied to reduce AE [compare Eq. (6)], where AE(Δt) is defined as the energy passing through the defined field of view, which is limited to $\alpha_{max}(\Delta t)$. The increase factor applied to AEL(Δt) considers that AEL(Δt) is to be compared against the THR, and the THR is defined as total intraocular energy (the energy passing through the pupil of the eye) and not as energy within the angle of acceptance equal to $\alpha_{max}(\Delta t)$. That is, this factor increases the AEL(Δt) to a level that is applicable to the total energy entering the 7 mm aperture stop (see also Ref. 15). A reader familiar with ANSI Z136.1 will note that the AEL increase factor used here follows the same concept as increasing C_E beyond α_{max} with α^2 and comparing the respective MPE (or AEL) against the total energy passing through the 7 mm aperture. In Eq. (7), the term Q_{T_2} refers to the energy for the entire pulse pattern, of duration up to T_2, for which the injury threshold is defined,

$$\begin{cases} \text{AEL}_{7\,\text{mm}\_T_2} = \text{AEL} \cdot \dfrac{Q_{T_2}}{Q_{\Delta t}} & \text{for } \alpha \le \alpha_{max}, \\ \text{AEL}_{7\,\text{mm}\_T_2} = \text{AEL} \cdot \dfrac{Q_{T_2}}{Q_{\Delta t}} \cdot \left[\dfrac{\alpha}{\alpha_{max}}\right]^2 & \text{for } \alpha > \alpha_{max}. \end{cases} \tag{7}$$

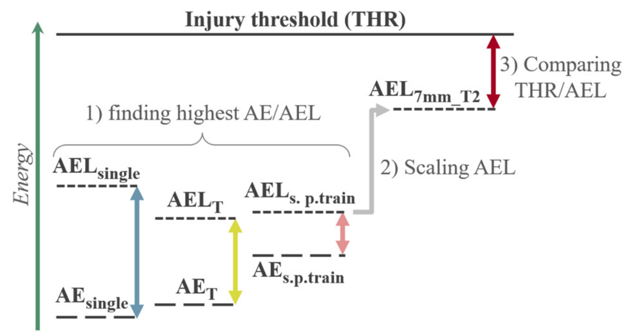

FIG. 5. Illustration of the relationship between AEs, AELs, and THR in the case of a repetitively pulsed emission. For the validation of the proposed method to determine C_5 for a given pattern, the AEL with the largest ratio of AE/AEL is identified first, then that AEL is scaled to a value that is applicable to the total intraocular energy within the pulse pattern; finally, the scaled AEL can be compared against the injury threshold for the pulse pattern that was determined with the computer model.

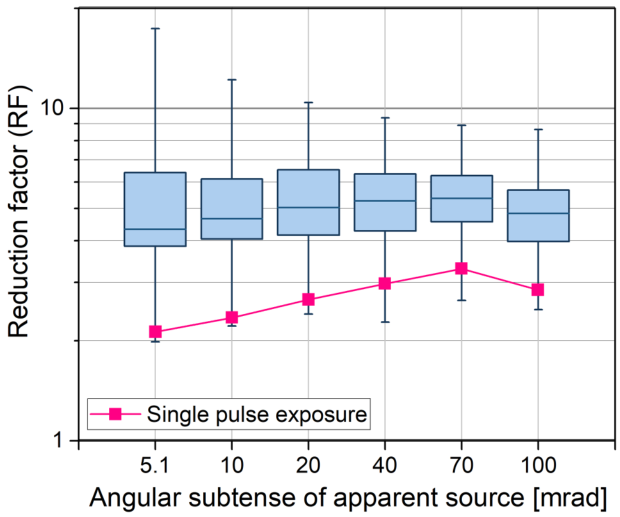

FIG. 6. Distribution of RFs for the database of 18 000 emissions and various values of α; the lower and upper bars represent the minimum value and 99th percentile, respectively; the box limits represent the first quartile, median value, and third quartile (a minimum value of $\alpha = 5.1$ mrad was used, since $C_5 = 1$ for $\alpha \leq 5$ mrad).

The diagram shown in Fig. 5 schematically demonstrates the process of AEL calculation and the comparison with the THR.

III. RESULTS

The distribution of RF is illustrated in Fig. 6 and reported in Table III as a function of α for the 18 000 computer-generated pulse patterns in the range of angular subtenses of the image of the apparent source α where the correction factor C_5 is applicable. It can be seen that the RF was consistently equal to or larger than 2 with an overall median value of 5.

For most values of α, the minimum RF corresponds closely to the lowest RF found for a single pulse. However, in some cases, the RF found for an irregular pulse train is somewhat lower than that of a single pulse. This outcome was found for a specific type of pulse pattern containing a few short pulses (typically less than 100 μs) combined with a series of longer pulses with relative low peak power. An example is shown in Fig. 7, where the pulses with relative peak power below 5% of the highest peak power are neglected for the determination of N and the most restrictive AEL was either found for the reduced pulse criterion with a low value

TABLE III. Summary statistics of the RF distribution obtained for irregular pulse trains.

Parameter	5.1 mrad	10 mrad	20 mrad	40 mrad	70 mrad	100 mrad
99th percentile	17.4	12.2	10.4	9.4	8.9	8.6
Third quartile	6.4	6.1	6.5	6.4	6.3	5.7
Median	4.3	4.7	5.0	5.3	5.4	4.8
First quartile	3.9	4.0	4.2	4.3	4.6	4
Minimum RF	2.0	2.2	2.4	2.3	2.6	2.5
Min. RF (single pulse[a])	2.1	2.3	2.6	2.9	3.3	2.8

[a]Restricted to emission durations between 10 μs and 100 s.

for N (typically less than 10) or for the average power criterion, mostly for long pulse patterns and large retinal images (typically above 20 mrad).

The tendency of the average power criterion to govern long pulse patterns, lasting between approximately 10 s and up to T_2 is evident in Fig. 8(a), where it concerns 0.10% of the 18 000 emissions for $\alpha = 20$ mrad (and up to 1.4% for $\alpha = 100$ mrad).

Additionally, it is worth mentioning that the time where $\alpha = \alpha_{\max}$—here referred to as $t_{alphamax}$ and equal to 10 ms for $\alpha = 20$ mrad—can be identified in the diagram of Fig. 8(b). When the reduced pulse criterion is the most restrictive, the RF was found to be the lowest for a pulse duration or group duration equal to $t_{alphamax}$. The grouping of pulses is approximately evenly distributed on both sides of $t_{alphamax}$ and ranging from a single pulse (see, e.g., point clouds at 100 or 200 μs) to pulse groups up to 0.25 s. The results obtained for other values of α show similar trends.

In order to quantify the impact of the reduced pulse criterion, the fourth series (randomly chosen, 3000 emissions for each of the six values of α) was analyzed only with the single pulse and the average power criterion, i.e., setting $C_5 = 1$ invariably. As illustrated in Fig. 9, the RF is significantly lower, with a minimum value of 1.3. In the absence of reduced pulse criterion, 12% of the simulated emissions were associated with a value of RF lower than 2. This can be considered as not sufficiently restrictive.

Finally, the impact of the proposed 5% relative power limit for calculating N was investigated by running the RF analysis with the reduced pulse criterion but without the 5% limit. For the results obtained for the fourth series, when the 5% limit was not applied, the minimum RF was increased from 2.1 to 2.2 and the median RF from 5.4 to 5.6. The impact of the 5% limit was mostly restricted to long pulse patterns lasting around 10 s or longer. These results validate the proposal to neglect pulses with peak power less than 5% of

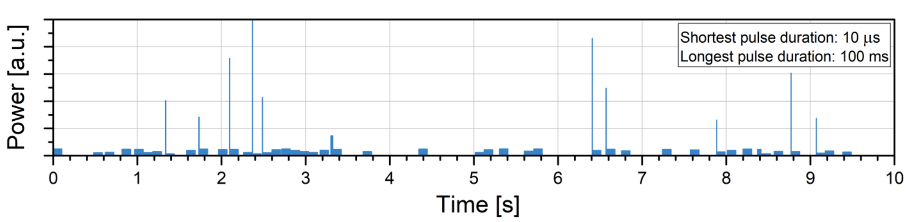

FIG. 7. Illustration of a typical emission (emission No. 12783) leading to a lower RF (in this case, RF = 2.7) than the lowest RF obtained for a single pulse with $\alpha = 70$ mrad.

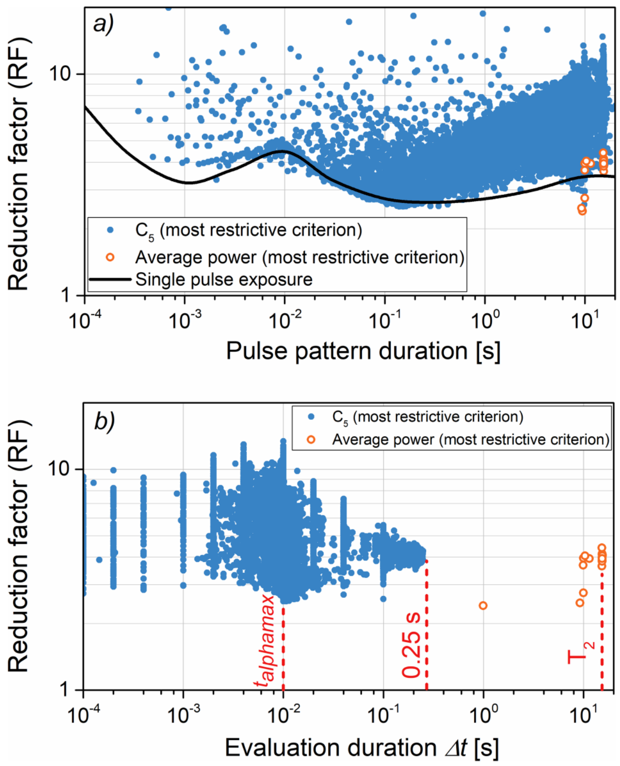

FIG. 8. Distribution of RF for $\alpha = 20$ mrad as a function of (a) pulse pattern duration and (b) the evaluation duration found for the most restrictive AE/AEL ratio (open orange circles and blue circles for pulse patterns restricted by the average power or the reduced pulse criterion, respectively).

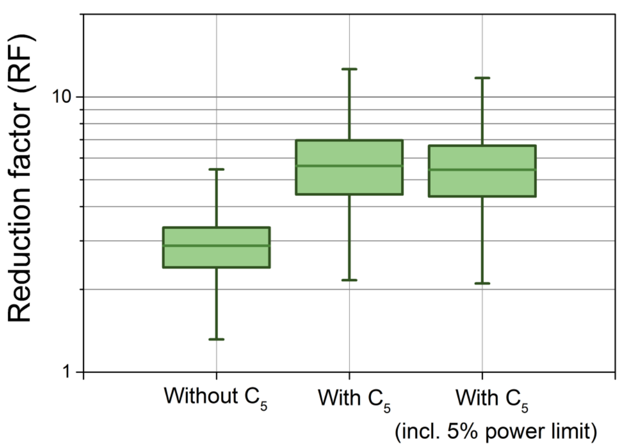

FIG. 9. Distribution of RFs for the fourth series of pulse patterns according to various analysis schemes (the lower and upper bars represent the minimum value and 99th percentile, respectively; the box limits represent the first quartile, median value, and third quartile); see text for more details.

the maximum, again noting that at this point in time, the method is validated for pulse durations in the thermal regime.

IV. CONCLUSIONS

The safety concerns related to exposure to multiple pulses arose in the 1970s, and the first edition of the ANSI standard adopted a correction factor to lower the exposure limit according to the repetition frequency and in later editions according to the number of pulses. By applying the current AELs (or MPEs) and the analysis method in IEC 60825-1 and ANSI Z136.1, it is proposed to revise the definition of N for the determination of the correction factor C_5. To that end, the parameter N is interpreted as a ratio of energy, namely, the ratio between the energy within the duration T_2 (or shorter time bases or exposure durations) and the energy within the evaluation duration Δt used to derive AEL(Δt) of a single pulse.

For regular pulse patterns, this definition (or interpretation) of the parameter N results in the same analysis as for the classic understanding of N, since the ratio of energy within T_2 to the energy of a single pulse is exactly equal to the number of pulses within T_2. Similarly, for irregular pulse patterns with constant pulse duration and varying peak power, the proposed definition of N is consistent with the interpretation based on the relative peak power of ISH1:2017. Furthermore, this interpretation allows both accessible emission and accessible emission limits to be determined for any train of pulses. This applies regardless of the irregularity of the temporal emission but provided that the pulse pattern does not contain pulses shorter than T_i since the computer model used to predict retinal injury thresholds can only predict injuries that are thermal in nature. At this point in time, the conclusions of this study cannot be extrapolated to other damage mechanisms, particularly, damage due to microcavitation in the nanosecond pulse duration regime. The question of whether the proposed interpretation of N can be applied to pulses shorter than the breakpoint T_i remains to be answered.

In the thermal regime, the results obtained with the proposed analysis method demonstrate that the retinal injury threshold is invariably at least a factor of 2 above the applicable AEL of Class 1. This margin, which is also found for single pulses, is believed to be sufficient in order to qualify emissions that do not exceed the AELs of Class 1 and Class 2 as safe. When the proposed method is applied for classification as Class 3R, we see that the predicted injury thresholds may be exceeded, but this also applies to regular pulse trains and is not an effect of the proposed method. The number and variety of possible temporal emissions investigated here allow the conclusion that the proposed interpretation of N is generally applicable in the thermal regime.

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