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Karl Schulmeister, Bernhard Seiser, Johannes Husinsky, Mathieu Jean, Beate Fekete and Letizia Farmer

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DAMAGE THRESHOLDS FOR SCANNED EXPOSURE OF THE RETINA

Paper 301

Karl Schulmeister[1], Bernhard Seiser[1], Johannes Husinsky[1], Mathieu Jean[1], Beate Fekete[2], Letizia Farmer[2]

[1] Austrian Research Centers, Laser and Optical Radiation Test Lab, 2444 Seibersdorf, Austria
[2] Austrian Research Centers, Toxicology Department, 2444 Seibersdorf, Austria

Abstract

Laser products that emit scanned laser radiation produce a pulsed exposure of the eye, as well as, depending on the accommodation state of the eye, a scan pattern on the retina. IEC 60825-1 does not provide guidance on how to consider the scanned retinal exposure for product safety classification. We discuss the general approach for product classification based on retinal scanning. The hazard relative to the non-scanning case can be characterised with a retinal thermal injury model that was developed at the Austrian Research Centers Seibersdorf. Depending on the laser beam diameter on the deflector and the scan parameters, the allowed output power for "safe" laser classes such as Class 2 or Class 1 can be greatly increased when compared to the assumption of a non-scanning retinal exposure.

Introduction

When a laser beam is periodically reflected from a rotating mirror, pulsed exposure of the eye results, since the laser radiation moves over the pupil of the eye with a certain velocity. For a given scan speed, the pulse duration per exposure depends on the distance to the scanner. IEC 60825-1 provides exposure limits and emission limits for safety classification of products for pulsed exposure and methods on how to evaluate multiple pulse exposures [1]. The exposure to multiple pulses that results from laser scanners is relatively easy to evaluate when it assumed that the angular subtense of the apparent source (the angular subtense of the retinal exposure) is minimal, or C_6 in retinal exposure limits that apply to thermal injury of the retina, equals unity. The complete evaluation of the safety of the ocular exposure from a scanner is involved and currently, international standards do not provide for an appropriate analysis of scanned retinal exposure. We present the results of a retinal injury computer model that can be the basis for a complete safety evaluation or classification of laser products that emit scanned laser beams.

General Safety Evaluation Scheme of Laser Scanners

We restrict the discussion in this paper to wavelength ranges where retinal exposure is relevant, i.e. 400 nm to 1400 nm and to an analysis of potential thermal injury to the retina. For time basis (Class 1) and wavelength ranges (400 nm to about 600 nm) were photochemical retina injury has to be analysed additionally to retinal thermal exposure, the analysis is somewhat simpler since the retinal radiant exposure is relevant irrespective of the scan speed on the retina.

For a complete safety analysis or classification of a laser scanner, varying positions to the product as well as for each position, varying accommodation states of the eye need to be considered, as is required generally in the second edition of IEC 60825-1 for all products where C_6 is to assume a value larger than unity. This general approach was discussed in more detail by Schulmeister et al. [2] as well as by Henderson & Schulmeister [3]. The class of a product is to be determined at the "most restrictive position" where the ratio of "accessible emission" and "emission limit" is maximized. The "accessible emission" is given by the laser power pattern as function of time that is measured with a 7 mm diameter aperture and depends on the laser scanning parameters (power, beam diameter as function of distance, scanning speed, number of scans per second) and the "emission limit" depends on wavelength, pulse duration, number of pulses and the correction factor for extended retinal exposure, C_6.

It is important to consider that the classification of a laser scanner based on the scanning emission according to IEC 60825-1 is only permissible when the accessible emission does not exceed the emission limit even for reasonably foreseeable ***single fault conditions***. This means that there has to be a reliable automatic laser power reduction (or shut off) for the case that the scanner fails or reduces speed below a critical level.

In terms of an analysis of the retinal exposure, two distinct cases need to be considered, as discussed in more detail by Henderson & Schulmeister [4]: i) accommodation at infinity and ii) accommodation at the pivot point of the laser beam (i.e. the reflecting surface of the scanner). For a collimated laser beam, i) results in a small spot being scanned across the retina as schematically depicted in Figure 1 a) and 1 b). The closer the eye is to the scanner, the larger the scan length on the retina (see Figure 1a) and 1b). It is important to note that this *scan length can not* be used as length of the apparent source, as it is not a line that is projected onto the retina, but a moving spot, which is much more hazardous than an actual line.

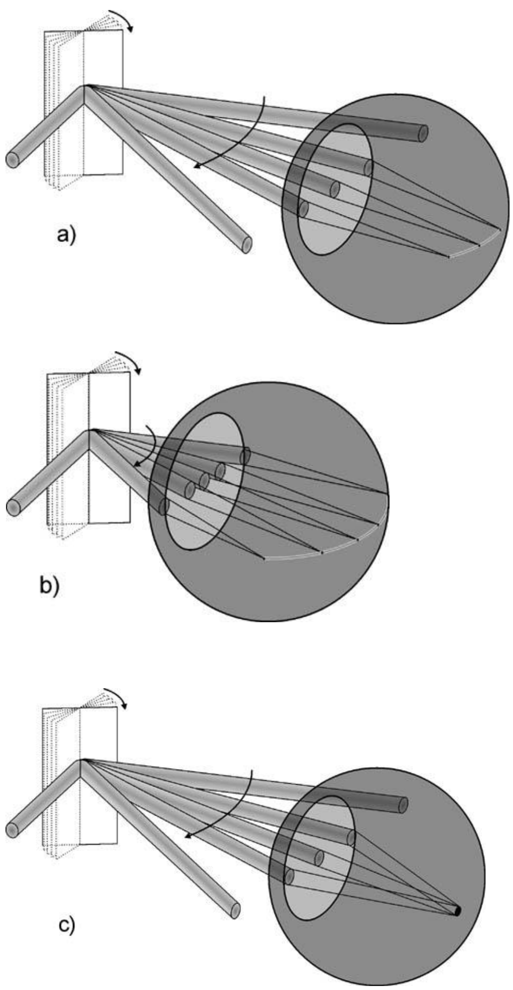

Figure 1. For a well collimated beam that is scanned across the pupil of the eye, if the eye accommodates to infinity, a minimal spot is formed on the retina which is scanned across the retina (a and b). If the eye accommodates onto the scanning mirror (c), then the beam that enters the eye is imaged onto the same spot on the retina, but the spot is usually larger as in cases a) and b). (adopted from Henderson & Schulmeister [4])

For the case that the scanner is not just performing 360° turns but only part of a circle and scanning "back and forth", particular attention needs to be given to the *turnaround points* of the scanning path: both the accessible emission (power pattern through pupil) is different as well as retinal exposure pattern is different when compared to "central" parts of the scan. It is shown later that even if the beam does not slow down before turning around (which would be possible with acousto-optical deflectors), retinal exposure is more hazardous for the turn-around time. The importance of the turn-around region is further increased if there is the beam is slowing down which is the case for deflectors with finite mass and when the turn around region is not blanked out.

In the second case, ii) where the eye accommodates onto the deflection point (see figure 1c), the eye images the beam profile that is incident on the deflecting surface. If the deflection position is on the turning axis of the mirror, the corresponding image on the retina will not scan. If the deflection point is some distance away from the turning axis, such as is the case for a polygon mirror, the image on the retina will also move, but to a far lesser extent as it will move when the eye accommodates to infinity. This accommodation condition often produces extended images on the retina, as for exposure distances of for instance 100 mm from the deflection point, a beam diameter that is larger than 0.15 mm will produce an angular subtense that is large than 1.5 mrad.

Up to now it was not possible to characterise a scanned exposure on the retina in terms of safety except for the case that the scan is faster than the thermal relaxation time, which is a regime where the damage level when specified in terms of energy per pulse does no longer depend on the pulse duration: while it is clear that scanned retinal exposure is "safer" than when it is assumed that the beam is not scanning across the retina, it was not characterised how much "safer" a scanned exposure is.

In the second part of the paper we review the results of a retinal thermal damage computer model that was developed for safety evaluations of scanned retinal exposures. With the results of a damage model, it is possible to perform a complete safety analysis of a laser scanner: it will depend on the scanning parameters and on the spot size on the deflection point whether the accommodation to infinity (case i) which produces a small spot but is scanned across the retina is more restrictive, or the accommodation on the deflection point which produces a larger spot but does not scan on the retina (case ii). Again it is noted that if the beam turns around (i.e. is scanning back and forth) and the turning phase is not blanked out, the analysis needs to give particular attention to exposure in the turn around part of the scan.

Without information on the hazard level of scanned exposure of the retina, it has to be assumed that the spot on the retina is not moving. That is, the scanning still produces a pulsed exposure as the beam scans across the pupil of the eye (or the aperture for measurement), but the spot on the retina, also for case i) has to be assumed as non-scanning. Since for a collimated beam, accommodation to infinity produces a minimal spot, this assumption will always result in the more critical situation when compared to case ii) (with the possible exception of very fast scans so that the scan duration, at least of part of the scan length on the retina, is less than 18 µs, the thermal relaxation time for wavelengths between 400 nm to 1050 nm, or 50 µs for 1050 nm to 1400 nm).

Thermal Retinal Injury Model

A thermal retinal injury model was developed at the Austrian Research Centers Seibersdorf that was validated with damage thresholds from both ex-vivo exposures as well as non-human primate exposures [5]. The model is available as tool for the safety evaluation of products where the methods given in IEC 60825-1 would have to be based on worst-case assumptions as for the case of scanned retinal exposure, or for the case of irregular multiple exposures (see Paper 303 of these proceedings) where currently no evaluation method is specified for the case of varying peak power.

The results of the injury model as reviewed here are in more detail discussed in reference [6] and apply to the wavelength of 532 nm and for top-hat retinal exposure profiles unless noted.

With the thermal retinal injury model, we have calculated damage thresholds for a number of scan speeds, retina spot sizes D and number of repetitions of scans. Since the center of the spot at time t = 0 is on top of the point where we consider the starting point x = 0 of our scan, the locations left of x = D/2 are not exposed to the full exposure duration as are points to the right of x = D/2 since for these latter points, the full beam profile scans across. This decreased exposure duration for edge points explains why the local damage threshold is higher than for the points in the scan which are more than a distance of D away, as shown in figure 2 and indicated by vertical lines.

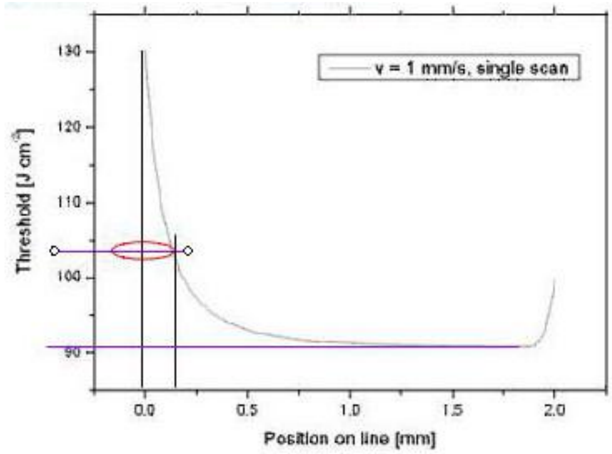

Figure 2. Local damage thresholds for a single scan with diameter of 288 µm top hat profile and a scanning speed of 1 mm/s and a scan length of 2 mm. Adopted from [6]

Beyond the second vertical line which marks the radius of the spot, the local damage threshold decreases further along the scan path due to the influence of the neighboring region on the scan line (the ones that were heated previously to the spot at the point x under consideration, i.e. to the left), where the temperature at spot x is higher due to this heated neighbors. The threshold at the end of the scan increases again due to a lower exposure duration of the end-region of the scan x = 2 mm (partial coverage by the beam), however, the heating effect of preheated neighbors results in a threshold at the final spot that is much lower than at the beginning of the scan (x = 0), where both have the same exposure duration. In the central part of the scan, however, the influence of the pre-heated neighboring area is not great, it is about 10 – 15 %. In spite of this influence of the neighboring area, we will see below that this central region can be treated quite well with an equivalent pulse duration approach, at least for the conditions investigated here.

For multiple scans, the situation at the endpoints is drastically different as can be seen in figure 3.

For a single scan, due to the relatively fast scan speed, there is practically no decrease of damage threshold along the line. However, for multiple scans, the end-regions exhibit drastically decreased damage thresholds not only compared to the case of a single scan but also compared to the central region of the scanned line. This is *not* due to a decrease of scan speed: we have assumed that the scan speed remains constant up to the turning point and then turns around within one time-step of modeling, which is thermally an instant turn around. The decrease of the threshold in the endpoints is rather due to the prolonged exposure since there is practically a doubling of the exposure duration as compared to the center of the line, with no cooling in between. The non-symmetric shape of the lines stem from the influence of heated neighbour regions, which lead to a higher temperature as compared to the single heated spot.

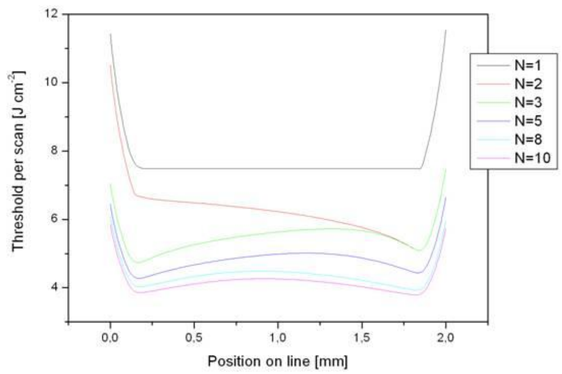

Figure 3. Local damage threshold for multiple scans, for a spot size of 288 µm top hat profile, and a scan speed of 100 mm/s (i.e. 100 times faster as in figure 2). N denotes the number of scans, where the scans where of alternating direction. Adopted from [6]

It is instructive to plot damage thresholds as function of scan speed (single scan) for four different Gaussian retinal irradiance profiles (1/e diameter), figure 4. It can be seen that for high scan speeds, the dependence of the damage threshold is linear with scan speed, which expresses that the fast scan has the same effect as a non-scanned line, i.e. the scan is fast enough so that thermally the scan path appears to be heated instantaneously and all points at the same time. For smaller spots, this critical time appears to occur at lower scan speeds than for large spots. On the slow scan speed end, the damage threshold approaches an almost horizontal line, which however can not be expected to become an actual horizontal line, since the non-scanned damage threshold also is still dependent on exposure duration when expressed as irradiance level, even though if it is a very weak dependence (approximately $t^{-0.1}$).

How much less hazardous (which could for instance be expressed by a correction factor similar to C_6 for extended sources) a scanned beam vs. non-scanning is, can not be derived from the plots such as Figure 4 if a non-scanned spot with a given pulse duration is compared with a scanned exposure where the total scan duration equals the pulse duration: the hazard of a scan depends strongly on scan speed (and spot diameter), but also on edge effects, and it is the scan speed and scan length together with the number of scans that is related to the total scan duration.

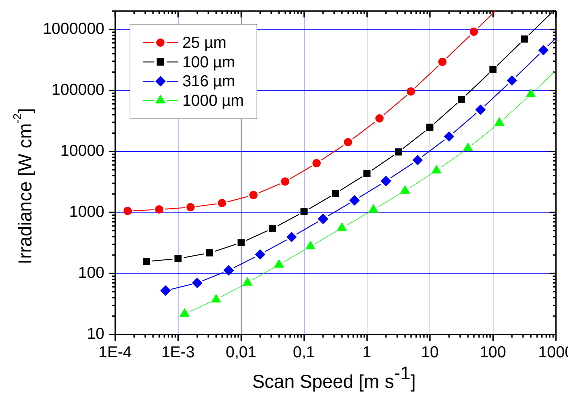

Figure 4. Calculated damage thresholds as function of scan speed for four different spot sizes for a Gaussian beam profile (1/e) for a single scan. Adopted from [6]

Conclusions and Summary

Provided that there is a reliable scanning safeguard, laser products that emit scanned laser radiation can be classified based on the accessible emission that is determined for the scanning laser beam. Depending on the accommodation state of the eye, retinal scanning can occur which is less hazardous than if the same exposure would occur without retina scanning. A thermal retinal injury model, for the first time, provides the tool for a complete safety analysis and classification based on retinal scanning motion. Depending on the laser beam diameter on the deflector and the scan parameters, the allowed output power for "safe" laser classes such as Class 2 or Class 1 can be greatly increased when compared to the assumption of a non-scanning retinal exposure.

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