MAXIMUM PERMISSIBLE EXPOSURE IN THE LASER DISPLAY SHOWS

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Contents

1 Introduction

In Laser display shows a safety concern is clearly involved. In fact, in most cases visible light beams are projected towards the audience, both in order to obtain “special effects” of various kind as well as aspects of the performance in itself, based often on music and laser.

Safety standards are based on IEC 60825-1, which is also the source of several occupational safety regulations for workers’ exposure to laser radiation.

The above mentioned Standard reports the Maximum Permissible Exposure (MPE) to laser radiation, for different exposure times and wavelengths. A specific guideline for laser display shows can be found in the IEC 60825-3 standard.

Laser beams are usually projected above the audience onto screen surfaces in order to create moving drawings or writings. In many cases, the visual effect is obtained by laser light scattering on fumes, atmospheric water vapour or even water jets.

Therefore, IEC 60825-3 states that when the beam is pointed in directions where audience may be present and even in a range 3 meters ahead of the public, it must comply with MPE. Furthermore, in a range between 3 and 5 meters above the public it cannot exceed 5*MPE. The International Laser Display Association (ILDA), gathers the most relevant companies that can deliver laser display shows, at the aim of maintaining high quality standards and safety for the public and the workers as well.

In 2009, ILDA safety experts released a report entitled “Scanning Audiences at Laser Shows: Theory, Practice and a Proposal” [1] dealing with the applicability of MPEs to laser shows.

Incidents in laser shows have been reported [2] after that report, even with very low levels (2 mW) and in professional laser shows.

In its site, ILDA claims that incidents reported in the literature have been caused by non-ILDA members or by laser pointers used by somebody in the audience (http://www.ilda.com/injury.html).

A Belgian medical team, in a 2011 paper [3] reports the case of two patients with eye injury after a laser show where "*the retina was exposed to eight different durations (0.5-64 seconds) of laser beam from a commercially available, handheld, class 3B green laser pointer (500 mW)*". In their conclusion the authors [3] state that *"is unlikely that laser pointers, even those of class 3B, can cause these ocular injuries"*.

In the present paper, (reporting the results of a work supported by one of the two Italian ILDA member), based on the performance of a Kvant Spectrum 30 laser show projector, some of the considerations reported in [1] will be reconsidered and a practical method to check for the compliance of a laser show with applicable MPE will be described.

It should be remarked that, even when scanning continuous wave lasers (CW) are used, in case of direct viewing of professional laser show projectors, the exposure of the audience in reality is to a pulsed beam. In fact, is a single laser beam that generates any pattern by moving among a given number of directions, normally referred to as "points". To account for these pulses is a key issue in the determination of MPE. It is remarked that different assumptions may lead to very different MPE values.

2 Laser source description

The Kvant Spectrum 30 laser produces multicolour laser effects using 3 diode CW laser sources combined in a single beam. To obtain a light of the desired colour, the intensities of the three fundamental colours, red, green and blue are controlled.

The maximum power of the three sources, as reported in the manual, are:

Red (637 nm),	8000 mW
Green (520 nm),	10000 mW
Blue (460 + 445 nm),	11000 mW

The three beams are then combined in a unique scanning system that projects the combined beam in a set sequence of directions in order to generate an image, as a sequence of dots. The combined beam has a dimension, declared at the laser aperture, of 6 X 5,5 mm and a 1 mrad divergence.

The persistence on the retina of the sequence of dots creates the effect of a drawing; the drawing can be still or, more often, in motion with changes of colour.

Definition and stability of the image depend on the scan rate, expressed in points per second (pps).

The ratio between the scan rate and the number of points composing the image, sets the number of image projected per second. When this number exceeds 20, the human eye can perceive only a still image and its shape can be varied continuously.

Low scan rates, for a given number of dots, generate images much bolded in some points or flickering. The scan rate is limited by the electro-mechanical characteristics of the mirrors moving system, and usually is a pre-set parameter.

The measurements carried out in this works used a scan rate SR = 30 kpps.

3 Experimental measurements and analysis of the data

3.1 Materials and methods

The wavelength of the radiation was found by measuring spectral irradiance *E(λ)* between 200 and 1000 nm by means of Ocean Optics HR 4000 spectroradiometer.

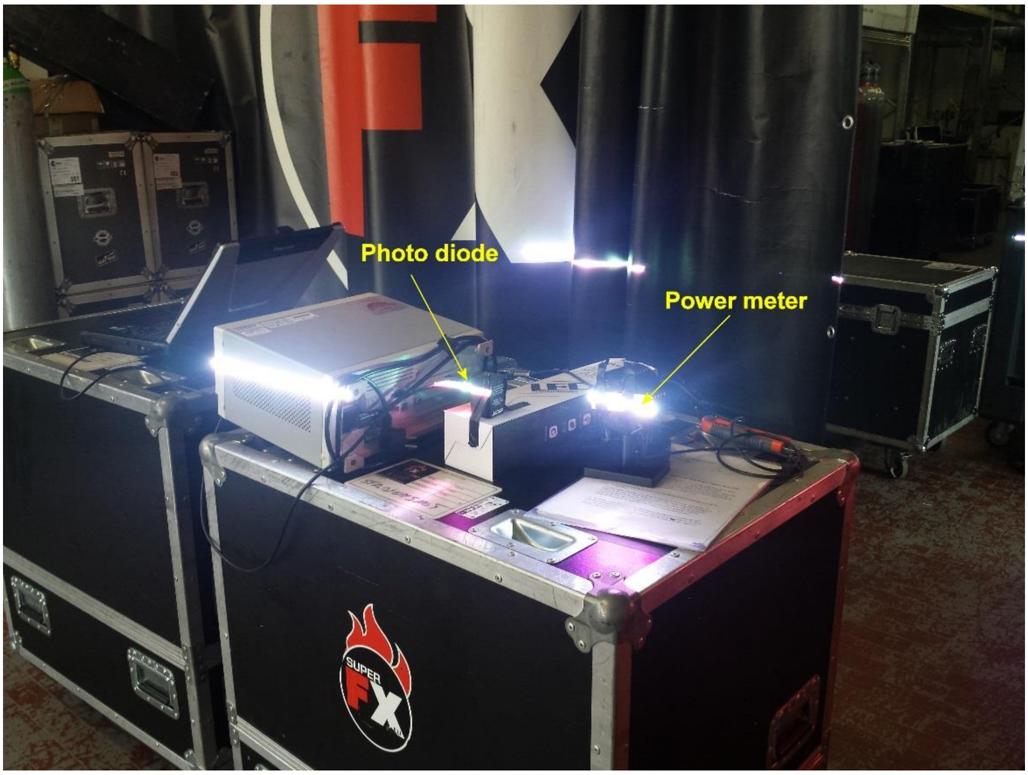
The irradiance was measured by scattering the laser radiation on a white diffuser produced by Bruel&Kjaer as white sample for lighting measurements.

Laser measurements were performed by placing in fixed position the following instruments:

- Power Meter Ophir Nova II with thermopile detector and flat response between 200 and 6000 nm;
- Digital Storage Oscilloscope Good Will GDS 2100, coupled to a photodiode to check the time trend of the pulses;

Figure 1 shows the two detectors enlightened by a still line generated by the laser.

Figure 1: detectors enlightened by a still line



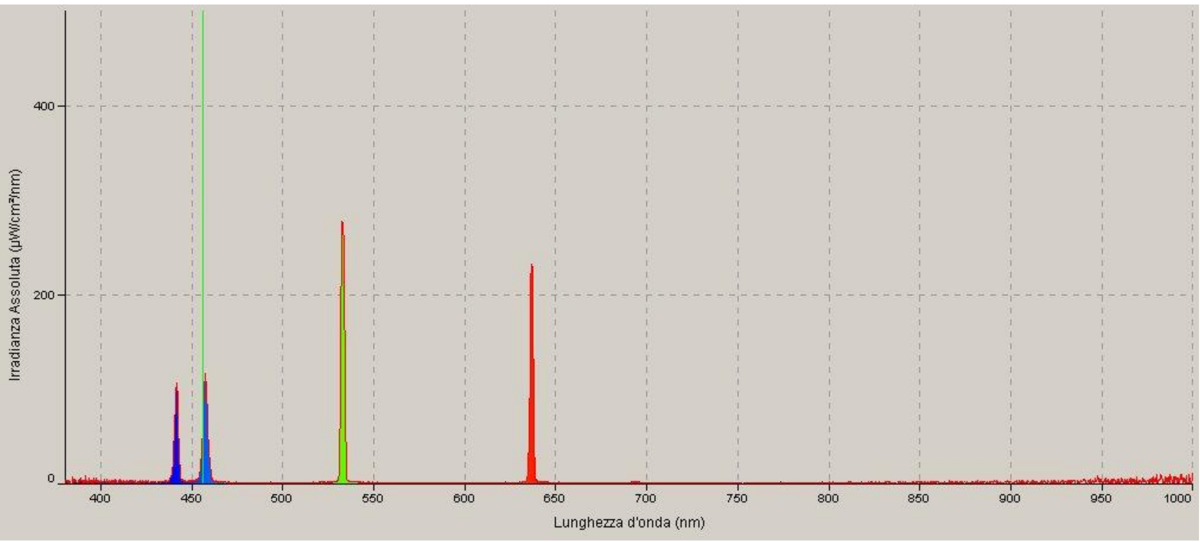
The photodiode has an effective area of 2 mm. The power meter 11 mm aperture was reduced, by a metal frame, in order to obtain a 7 mm aperture, corresponding to what is required by the standard to simulate the human pupil.

It must be pointed out that the power meter can measure the actual power incident on the pupil's area only averaging it for times greater than 1 s; the photodiode reports the time trend of the pulses but on a reduced surface. The photodiode cannot measure the actual incident power due to the dependence of the response from the wavelength.

3.2 Characterization measurements

Combining the three beams, a white light is obtained. Figure 2 shows the spectrum measured by scattering the laser on a white diffuser.

Figure 2: spectrum of the white beam



The resulting values of the wavelength comply with the data in the manual, included the double emission of the blue laser.

Table 1 reports the results obtained by concentrating the whole white beam, i.e. the sum of the three lasers, into the power meter's detector, without limiting frame and setting different values of the % power to 30 W.

The difference between the set power level and the measured output is within 10%.

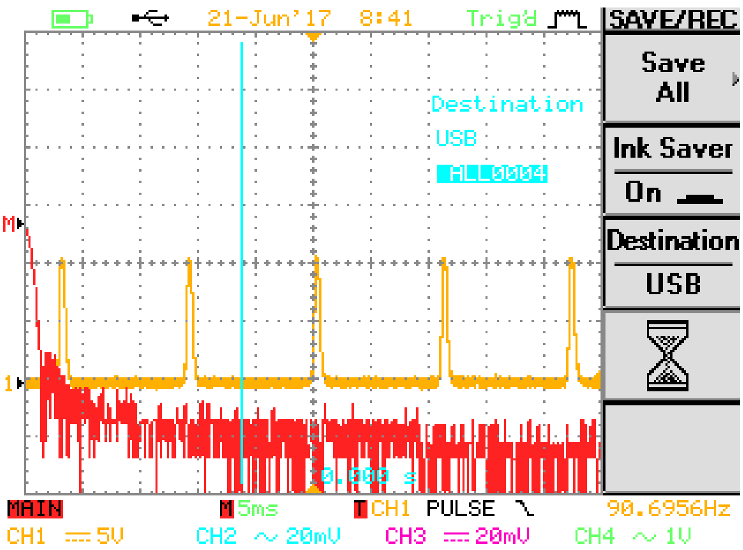
Table 1: difference between set power and real output obtained by concentrating the combined beam in a single spot

Set level	Measured power W	% difference
10%	2,83	-6
20%	5,6	-7
30%	8,36	-7
50%	13,7	-9
75%	20,32	-10
100%	26,57	-11
50%	13,79	-8

When the laser generates a line, the detector does no longer receive a continuous beam but a sequence of pulses, with a period corresponding to the time of laser aiming to the detector itself.

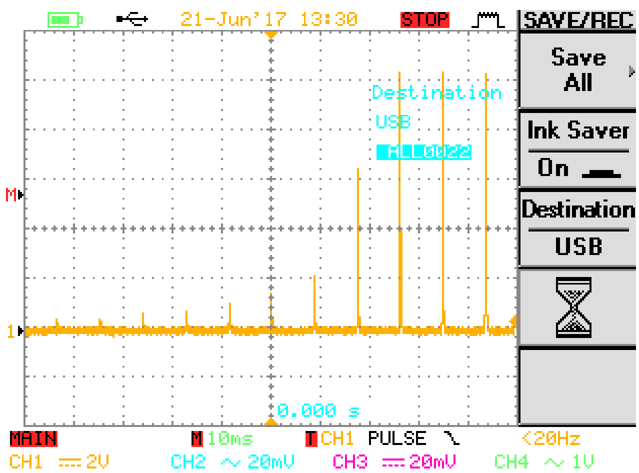
Figure 3 shows the time trend measured when a still line is kept on the photodiode, as in Figure 1; the line is made in this case of $N = 316$ points.

Figure 3: beam intensity vs time for a still line made of 316 points hitting the photodiode. The red line is the spectrum of the signal obtained by Finite Fourier Trasform



In Figure 4, the same 316 points line is kept in motion as in a normal show.

Figure 4: beam intensity vs time when a line made of 316 points is kept in motion across the photodiode.



The beam is still the one pertaining to a CW laser. However the power in a given direction arrives in pulses, since the same beam generates in sequence every dots in the line. The real absorbed power during a laser show is therefore a fraction of the beam power.

In the following, the exposures in a given direction will be for simplicity defined “pulses”, as the viewer in fixed position receives a pulsed beam, even if the emission is continuous.

The repetition frequency of such “pulses” is a function of the scan rate *SR* and of the number of the points generating the line:

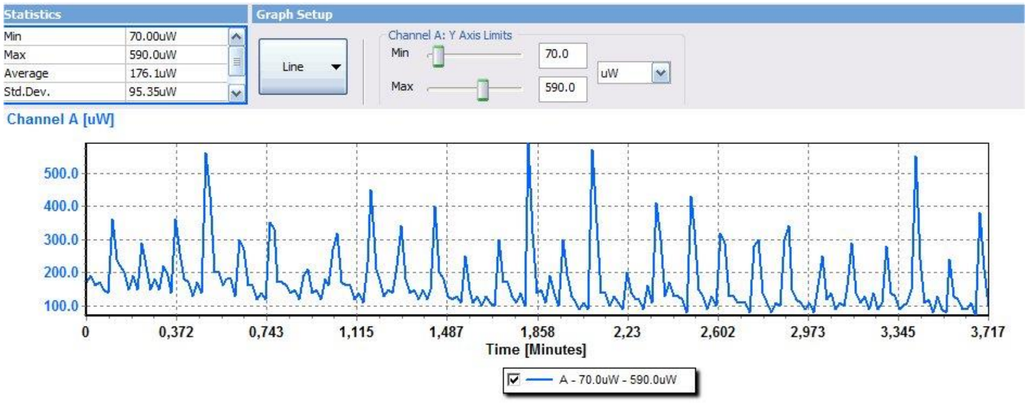
$$f = \frac{SR}{N} \quad (1)$$

The time interval between the pulses is therefore *1/f*; by posing *SR* = 30 kpps and *N* =316, a value of 11 ms is obtained, as reported in Figures 3 and 4.

In Figure 5 the time trend as measurable with the power meter with the line in motion is shown. The maximum power is not correctly displayed since the power meter cannot report an accurate measure due to the short time in which the laser hits the detector.

In the following, calculations to obtain reliable measures of the power output from a mean power measurement are reported.

Figure 5 : data detected by the power meter when the line moves across the detector.



3.3 Numerical estimates

The mean power P_m absorbed by an observer in fixed position is related to the peak power P_p by the relation

$$P_m = P_p \frac{T_{on}}{T_{off}} \quad (2)$$

where T_{on} and $T_{off} = 1/f$ are the pulse length and the time elapsed between two pulses.

The peak power, in this case, is the power value set for the continuous beam, made of the sum of the three beams.

T_{off} is the time interval between two pulses, as given in (1). T_{on}, instead is a key parameter involved in the power measurement. A precise estimate of this parameter is difficult, since it depends also on the laser spot dimension. A minimum value of T_{on} is given by the scan rate:

$$T_{on,min} = \frac{T_{off}}{N} = \frac{1}{SR} \quad (3)$$

It is in facts, the total time when the beam aims in other directions, divided by the number of points.

In general, the beam spot dimension, even with low divergence φ, increases when the distance from the source is increased:

$$d = a + r\varphi \quad (4)$$

By referring to the data reported in the manual, at the laser aperture the diagonal of a single dot is a = 8,1 mm; at a distance of 50 m (a conceivable value for typical shows), according to Eq. (4), the spot diagonal becomes d = 58 mm. An observer at 50 m receives the laser light until his/her pupil, with d_p = 7 mm, remains internal to the 58 mm wide spot: pulse duration will be therefore increased at least by a factor $\frac{d}{d_p}$.

This estimate holds only if the line is made of non-overlapping points; in reality the pulse duration should be increased due to the overlapping of the points. The points of a line projected at a distance r, in general, do not overlap if the length l of the line is such that

$$l >= N(a + r\varphi) \qquad (5)$$

Then, the maximum number of points required to generate a line of length l without overlapping of the points, by taking into account Equation (4) is given , by

$$N_{max} = \frac{l}{d} \qquad (6)$$

Since the power meter requires a certain time interval to provide reliable reading, it is advisable to make the measurement on a still drawing at a distance such that expression (5) holds, so that overlapping of the points is avoided.

On the other hand, even if the points do not overlap the laser spot on a target at distance r, is in motion with linear velocity

$$v = \omega r \; (7)$$

where ω is the angular velocity.

The beam divergence is estimated 1 mrad and *SR* = 30 kpps, so that the angular speed should imply that 30000 cones with 1 mrad aperture are spanned in one second. Therefore ω = 30 rad/s.

The spot dimension increases by receding from the source according to Eq.(4). An observer will view the beam during all the time that the beam spot rides a length *L*, equal to the pupil diameter increased by the ratio of the beam spot and the pupil diameter itself:

$$L = d_{p1} \frac{d}{d_{p0}} \quad (8)$$

The pulse duration then is

$$T_{on} = \frac{L}{v} = d_{p1} \frac{a + r\varphi}{d_{p0}} \frac{1}{\omega r} \qquad (9)$$

with some consequences that are worth to be emphasized.

On receding from the source, the pulse duration decreases as, for Equation (7), the speed of the spot increases with range. The spot diameter increases as well due to divergence but at high distance the term depending on the angular velocity causes the pulse duration to decrease with distance.

For naked eye viewing one has d_{p1}=d_{p0}=7 mm. On the contrary if the beam is observed with optical instruments (typically, the binoculars), d_{p1} is the diameter of the aperture of the instrument, that is normally > 7 mm. Therefore, by considering equations (9) and (2), the real power on the pupil is increased.

3.4 MPE and NOHD determination

Exposure limit values (ELVs) applicable to workers' exposure to laser radiation in European Union are fixed in the attachment XXXVI to 2006/25/EC Directive.

Those values are not applicable to general public exposure. However, the same values are reported as Maximum Permissible Exposure (MPE) in IEC Standard 60825-1:2007.

For general public exposure, it is more appropriate to refer to MPE values and to the definitions set in the updated IEC 608251:2014.

The Nominal Ocular Hazard Distance (NOHD), is the distance at which the irradiance or radiant exposure, due to the broadening of the beam, is reduced below the MPE.

A first key issue, for these calculations, is the choice of the viewing time: according to IEC 60825-1, for viewing times between 5 μs and 10 s it is given by

$$H_{MPE} = 18T^{0,75}C_6 \quad \mathrm{J/m^2} \quad (10)$$

The coefficient C_6, depends on the viewing angle and will be further discussed; however it is important to notice that equation (10) holds in the whole range between 400 and 700 nm, since, for T <10 s, thermal effect are dominant.

For larger viewing times, photochemical effects must also be considered so that dependence from wavelength is included as well. Therefore for times T< 10 s is possible to consider the three lasers generating the fundamental colours as a unique laser with 30 W maximum power. For visible lasers, incidental vision can be considered to be limited to T = 0,25 s by the natural reflex, and this is the viewing time normally considered in (10).

Neglecting the dimension of the source, *NOHD* is given by

$$NOHD = \frac{1}{\varphi}\sqrt{\frac{4P}{\pi MPE}} \quad (11)$$

If P is the power of the laser (in W) and MPE is expressed as irradiance in W/m^2, with the divergence φ in radians, the $NOHD$ in meters is obtained.

For a source of 8,1 mm width, at a distance > 5,4 m, the subtended angle is < 1,5 mrad, therefore C_6=1. The MPE for a continuous beam with 0,25 s of exposure time is 25 W/m^2. By substituting this value in equation (11), with the power and divergence declared in the manual, $NOHD$ = 1220 m as reported in the same manual.

The above reported calculation corresponds to concentrate the whole power of the beam in a single white dot as done in Table 1.

In this case all the points are overlapped and the application of the MPE for a CW beam could be suitable. However this is not a proper operational condition of a laser for a show. Indeed an observer at a given distance from the source is exposed to a pulsed beam with frequency SR/N and pulse duration depending from distance as in Eq.(9).

For pulsed beams, according to IEC 60825-1, it is necessary to compare the MPE obtained considering three different criteria:

a) A single pulse which duration T_{on},
b) The mean irradiance considering the pulses absorbed in 0,25 s,
c) The single pulse as in a) times a coefficient that takes into account the cumulative effect of the number of pulses absorbed in 0,25 s.

Table 2 shows this comparison for a line made of N = 316 points (f = 95 Hz), measured at 3,2 m from the source. The subtended angle is therefore α = 3,2 mrad, so C_6 = 1,7.

For α < 4 mrad, the 2014 version of IEC 60825-1 requires C_5 = 1, so at 3,2 m, the pulse train condition is the same as the single pulse, for wider angles, i.e.

closest to the source C_5 depends on the number of pulses as in former editions of the standard.

Table 2: comparison among different criteria for evaluation of pulsed laser

Condition	**Exposure time**	**MPE**	**MPE J/m²**	**MPE W/ m²**	**N of considered pulse**
Single pulse H_{sing}	118 us	$18*C_6*t^{0,75}$ J/m²	0,02	293	1
Mean irradiance	0,25 s	$18*C_6*t^{0,75}$ J/m²	0,27	2270	24
Pulse train, $H_{sing}*C_5$	118 us	$H_{sing}*C_5$	0,03	293	1

The criterion of mean irradiance is obtained by applying Eq. (10) and dividing by the number of pulses absorbed in 0,25 s at 95 Hz.

A result in W/m^2 is obtained dividing each pulse radiant exposure by T = 118 µs in order to compare homogenous quantities.

Even considering the most precautionary criterion, in this case the single pulse, the MPE is higher than the one obtained by considering a 0,25 s exposure to a CW beam.

The evaluation of *NOHD* cannot be performed analytically as in Eq.(11). In fact, as addressed above, MPE depends on subtended angle while the exposure time depends on the distance as well.

Table 3 shows an example of calculation of MPE and irradiance for an image made of 316 points generated at 30 kpps by a 30 W laser.

The calculation can be repeated increasing the viewing distance, where the irradiance falls below the MPE, then an esteem of the *NOHD* is obtained.

In the same Table 3 the MPEs values are reported, both as single pulse irradiance and as mean power on a 7 mm aperture.

By using a standard spreadsheet one can obtain a theoretical value of irradiance to be compared with actual values measured in relevant positions.

Table 3: MPE and expected irradiance at different distances from a source for a figure of 316 points generated at 30 kpps

Naked eye viewing distance , m	**Pulse duration, s**	**Mean power measurable with a 7 mm aperture, mW**	**MPE in mW on 7 mm aperture**	**MPE as single pulse irradiance W/m2**	**Mean irradiance on the spot W/m^2**	**MPE W/m^2 as mean irradiance**	**α, mrad**	**C_6**
0,1	2,75E-03	5645,91	19,40	1,93E+03	146706,1	504,0	81,39	54,26
0,2	1,39E-03	2789,11	5,82	1,15E+03	72473,5	151,2	40,70	27,13
0,4	7,12E-04	1361,89	1,76	6,77E+02	35388,0	45,8	20,35	13,57
0,8	3,72E-04	650,48	0,54	3,98E+02	16902,3	14,1	10,17	6,78
1,6	2,03E-04	298,52	0,38	5,11E+02	7757,0	9,9	5,09	3,39
3,2	1,18E-04	128,20	0,13	2,93E+02	3331,2	3,3	2,54	1,70
6,4	7,57E-05	49,99	0,05	1,93E+02	1299,0	1,4	1,27	1,00
12,8	5,45E-05	17,36	0,04	2,09E+02	451,0	1,1	0,64	1,00
25,6	4,39E-05	5,39	0,04	2,21E+02	139,9	0,9	0,32	1,00
51,2	3,86E-05	1,53E+00	3,22E-02	2,28E+02	39,8	0,8	0,16	1,00
102,4	3,60E-05	4,11E-01	3,06E-02	2,32E+02	10,7	0,8	0,08	1,00
204,8	3,47E-05	1,07E-01	2,97E-02	2,35E+02	2,8	0,8	0,0397	1,00
409,6	3,40E-05	2,72E-02	2,93E-02	2,36E+02	0,7	0,8	0,0199	1,00
819,2	3,37E-05	6,86E-03	2,91E-02	2,36E+02	0,2	0,8	0,0099	1,00
1638,4	3,35E-05	1,72E-03	2,90E-	2,37E+02	0,0	0,8	0,005	1,00

			02				0	
3276,8	3,34E-05	4,32E-04	2,89E-02	2,37E+02	0,0	0,8	0,0025	1,00

It can be noticed that, considering the beam motion as in the above discussion, the *NOHD* at the same 30 W power results < 400 m.

4 Discussion

For moving beam, the MPE does not depend on the avoidance response but on the actual exposure to a single pulse, that decreases when the distance is increased.

Therefore it is advisable to use a high number of points, in relation with the scan rate, avoiding points overlap. Only in the latter case, MPE approaches the value of 25 W/m^2, corresponding to continuous beam with full power.

Murphy and Makhof [1] seem to suggest that IEC MPEs are based on too precautionary assumptions, such as the 7 mm pupil aperture.

In principle this could be true for healthy workers, undergoing medical examination before exposure. It could be criticized, at variance, for general public, specially in shows with hundreds of attendants. For example, a dilatation of the pupil due to drug assumption could be expected.

The estimates addressed above can be easily assembled in a spreadsheet software, typically MS Excel. Then the power level of the show can be adjusted in order to comply with the real MPE values rather than increasing the CW MPE with some “rule of thumb.

Equations (2) and (9) prove that by observing the laser source with optical instruments the mean power on the eye is increased. The *NOHDs* evaluated with Table 3 should be increased at least by a factor $\sqrt{\frac{A}{d_p}}$ where A is the aperture of the lens of the instrument in mm.

In laser safety standards, “optical instruments”, normally means binoculars and telescopes. In the case of laser shows, attention must be paid to professional video and photo cameras with optical viewfinder. In fact, binoculars and telescopes are not so common among laser show audience, and can be prohibited without any consequence. At variance, to adjust the image through the optical viewfinder is a practice common among professionals and evolved amateurs. However in laser shows they should take pictures only with special clearance by the staff. Therefore, they should be warned that staring into beam could be harmful for their devices and, when using the optical viewfinder, for their eyes as well. Any professional camera has now the online-view option which is eye safe even if not detector safe.

Few accidents [1],[2] caused by laser shows, are reported in literature and none of them related to the use of cameras. However the calculations reported above show that probability of harms does exist, in particular when safety rules are not respected.

MPEs in Table 3 are reported as mean irradiance in order to simplify the comparison with measurements. By considering peak irradiance of laser shows, an observation about the conclusion of Boosten et al. [3] is however possible.

It should be remembered that only class 2 (< 1 mW) laser pointers are considered to be eye safe, due to the human avoidance response, therefore running a class 3B (< 500 mW) pointer among a crowd of people is, at least, an irresponsible behaviour.

A laser show projector, should be indeed operated by trained personnel capable to decrease the output power when scanning the audience. A laser pointer, whichever its power, is a hand held device that the user can only turn on and off. Moreover, the output power can be often higher than declared in the laser label, if any [4].

In order to compare different exposure situations, it is however possible to divide the actual irradiance at a given distance by the applicable MPE. This ratio is normally expressed by the logarithm with the aim at the calculation of protection glass requirements, which in this case are not applicable, unless in particular situation for the staff.

In Table 4 the irradiances experienced at 6,4 m from the laser source are calculated for a class 3B (500 mW) pointer and for the Kvant 30 spectrum laser show device, both at full power of 30 W and when reduced to 10 % power output.

Irradiance values are taken from Table 3 and converted to single pulse irradiances by inverting Equation (2).

Table 4: comparison of possible exposure at 6,4 m (point source condition, C_6 = 1) from a 0,5 W pointer and a laser show projector

	Irradiance W/m^2	**MPE W/m^2**	**Logaritmic ratio**
Laser pointer 0,5 W	4899	25	2,3
Kvant spectrum 30 W 30 kpps	180692	193	3,0
Kvants pectrum 3 W 30 kpps	18069	193	2,0

In all three cases, the MPE is exceeded. However even at 30 W, a laser show projector causes an exposure not so higher than a laser pointer.

When lowered at 10%, the show projector has still a power 3 times greater than a class 3B pointer. However the irradiance exceeds the MPE less than in the case of the pointer.

In case of injury, only a police investigation could establish where the subject was at the time of exposure and which sources were involved. Indeed, class 3B laser pointer are CW sources while, as seen above, laser show projectors cause normally pulsed exposures. However, it is clear that laser the risk from different sources cannot be assessed considering only the mean power.

5 Conclusions

The laser show operator, if properly educated and trained, can regulate laser power in order to comply with the MPEs.

Due to the beam motion, the MPE is a function of the scan rate and range of the show.

The CW MPE leads to a strong overestimation of the risk since the actual exposure involve a fast moving beam.

The use of video and photo cameras by the audience should undergo a clearance by the Laser Safety Officer.

If designed by a person with laser safety knowledge, a laser display show is safer than the use of hand held laser pointer, in particular when exceeding class 2.

6 Conflict disclosure

This paper is based on a laser safety assessment requested by Super FX S.r.l. (Travagliato, Brescia, Italy), an Italian special effects company, member of ILDA

7 References

[1] Patrick Murphy and Greg Makhov, *Scanning Audiences at Laser Shows: Theory, Practice and a Proposal* InternationalLaser DisplayAssociation2009 http://www.ilda.com/

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[3] Boosten K, Van Ginderdeuren R, Spileers W, et al. *Laser-induced retinal injury following a recreational laser show: two case reports and a clinicopathological study.* Bull SocBelgeOphtalmol. 2011;317:11–16.

[4] Hadler J., Tobares E., Dowell M. 04/2013 “*Random testing reveals excessive power in commercial laser pointers*” Journal of Laser Applications. Laser Institute of America, (3).