MAXIMUM PERMISSIBLE EXPOSURE TO LASER DISPLAY SHOWS

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Sommario

1 Introduction

Laser display shows pose a safety concern since they use visible beams projected towards the audience both as “special effects” in shows of various kind of perfomers and even as a performance in itself, based mainly on music and laser.

Applicable safety standards are based on IEC 60825-1, which is also the source of many occupational safety regulations of 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.

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

Therefore, IEC 60825-3 states that when the beam is pointed in a direction where audience may be present and even in a range 3 meters ahead of the public, it must comply with MPE; even, 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 able to deliver laser display shows with the aim at maintaining high quality standards and safety of 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] with considerations about the applicability of MPEs to laser shows.

Laser incidents in laser show have been reported after that work [2], even with power level very low (2 mW) compared with professional laser shows.

In its site, ILDA claims that accidents reported in literature have been caused by non ILDA members or by laser pointers used by 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, actually, "*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 they state that *"is unlikely that laser pointers, even those of class 3B, can cause these ocular injuries"*.

In this work, supported by one of the two Italian ILDA member, starting from the performance of a Kvant Spectrum 30 laser show projector, some of the considerations of Murphy and Makhof will be reconsidered and a practical method to check for the compliance of a laser show with applicable MPE is described.

It is in fact important to point out that, even if, for audience scanning, continuous wave lasers (CW) are in use; in case of direct viewing of a professional laser show projector, the exposure is actually to a pulsed beam. In facts, it is a same laser beam that generates any shape while moving between a fixed number of directions, normally referred to as "points".

The way to account for these pulses is a key issue in the determination of MPE; and 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, in order to obtain a light of the desired colour, by regulating the intensity of the three fundamental colours, red, green and blue.

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, in many cases 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 in one second, if this number exceeds 20, the human eye can perceive only a still image which shape can be varied continuously.

Too low scan rates, for a given number of dots, generate an image too 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.

Measurements in this works have been done with a scan rate *SR* = 30 kpps.

3 Assessment by measurements and calculations

3.1 Materials and methods

The wavelength of the radiation was found measuring spectral irradiance $E(\lambda)$ between 200 and 1000 nm by an Ocean Optics HR 4000 spectroradiometer.

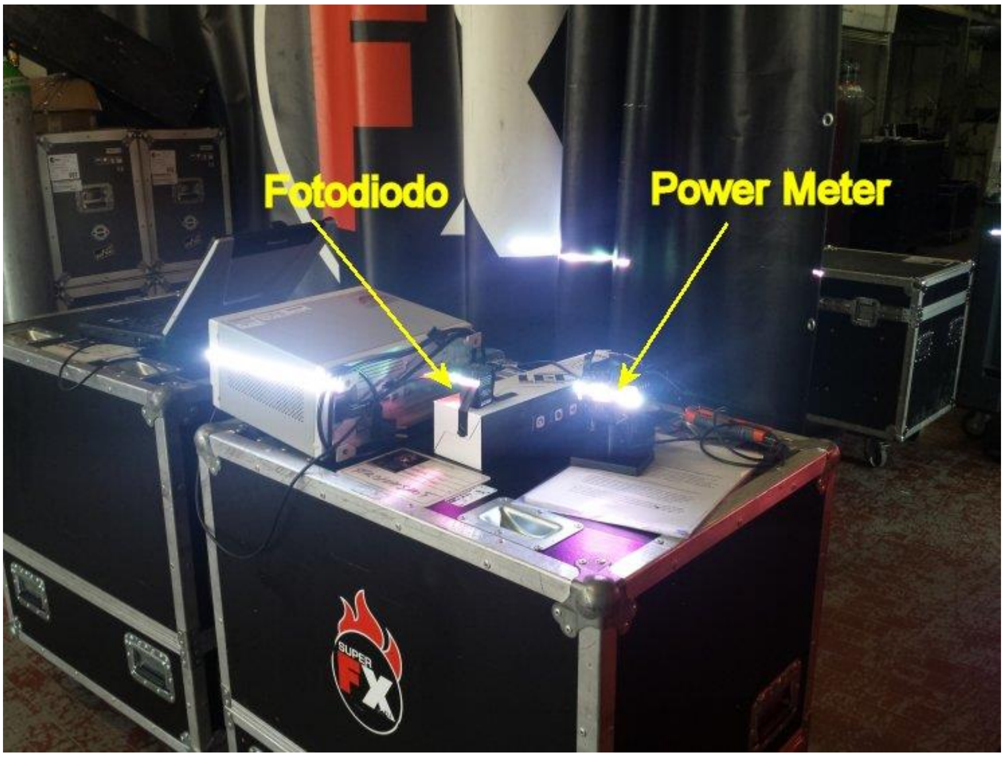
The irradiance was measured scattering the laser radiation on a white diffuser produced by Bruel & Kjaer as white sample for lighting measurements.

Laser measurements were done, setting up 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 curse 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



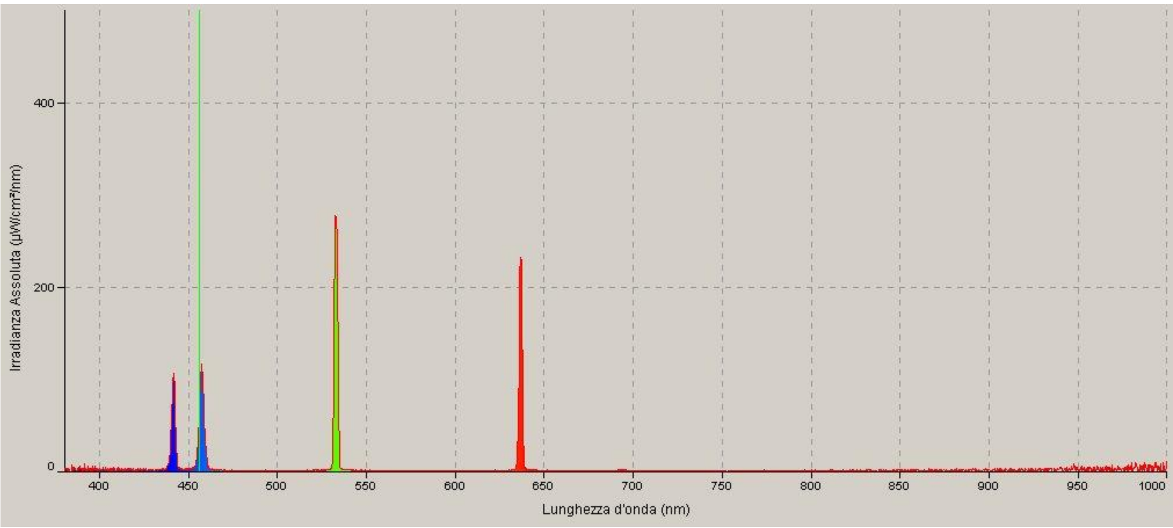
The photodiode has an effective area of 2 mm; the power meter 11 mm aperture was reduced, by a metal frame, in order to obtain a 7 mm aperture, corresponding to what is required by the standard to simulate the human pupil.

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 curse of the pulses but on a reduced surface. The photodiode, is neither able to 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 scattering the laser by 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.

In Table 1 are reported the results obtained 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 set power level and measured output is next to 10%.

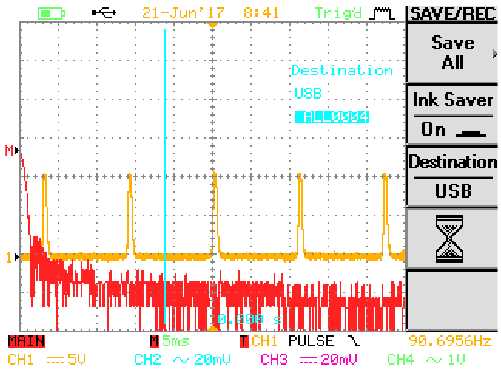
Table 1: difference between set power and actual output obtained by concentrating the combined beam in a single spot

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 when the laser aims at the detector itself.

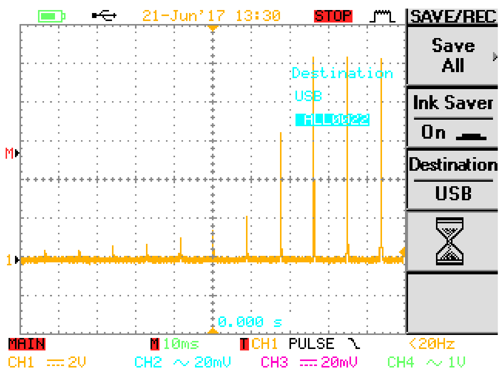
Figure 3 shows the time curse measured when a still line is kept on the photodiode, as in Figure 1; the line is made in this case of N = 316 points.

Figure 3: beam intensity vs time when a still line made of 316 points hits 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 that of a CW laser but the power in a given direction arrives in pulses as the same beam generates in sequence every dots in the line: the actually absorbed power during a laser show is therefore a fraction of the beam power.

In the followings, the exposures in a given direction will be for simplicity defined "pulses", as the viewer in fixed position sees a pulsed beam, even if 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:

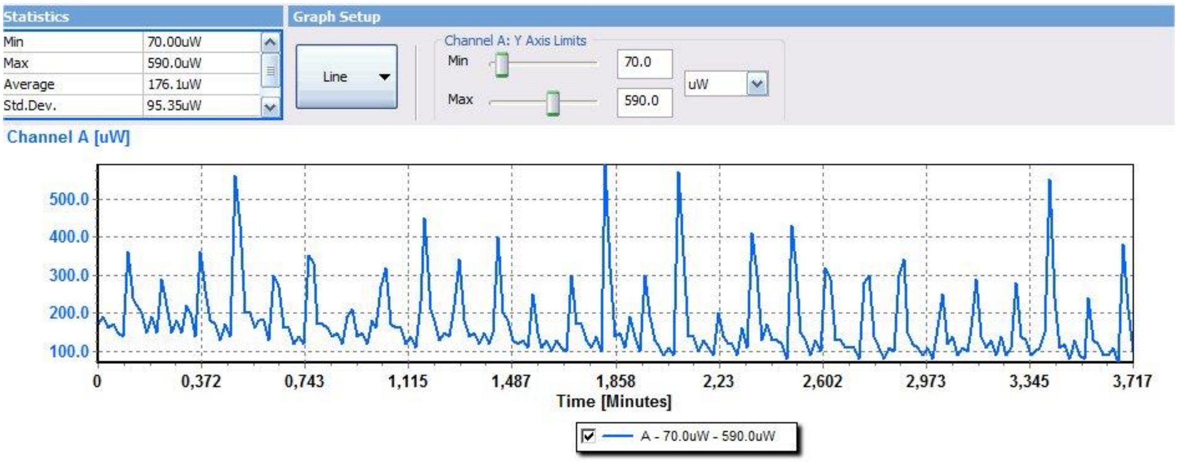
$$f = \frac{SR}{N} \qquad (1)$$

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 observable in figures 3 and 4.

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

In the followings, are reported useful calculations to obtain a reliable measure of the power output from a mean power measurement.

Figure 5 : measure obtained from the power meter when the line moves across the detector



3.3 Calculations

The mean power P_m absorbed by an observer in fixed position is bound 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 set value for the continuous beam made of the sum of the three beams.

T_{off} is the time interval between two pulses, given in (1); the value of T_{on}, instead is a key parameter of the power measurement and is difficult to obtain since it depends also on the laser spot dimension.

A minimum value of T_{on} is given by the scan rate:

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

Actually, it is given by the total time when the beam aims in other directions, divided by the number of points.

In general, beam spot dimension, even with low divergence, increases at increasing distances from the source:

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

Considering the data supplied in the manual, the diagonal of a single dot is, at the laser aperture, a = 8,1 mm; at 50 m distance (a reasonable value for typical shows), the spot diagonal reaches, according to (4), d = 58 mm. An observer at 50 m sees the laser 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 $\frac{d}{d_p}$.

The above reported discussion holds only if the line is mad of non-overlapping points; on the contrary the pulse duration increases 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

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

Then, the maximum number of points allowing to generate a line of length *l* without overlapping of the points, is given, considering expression (4), by

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

Due to the characteristic of power meter to require a certain time interval to give a reliable reading, it is advisable to make the measurement on a still drawing at a distance such that expression (5) holds in order to exclude overlapping of the points.

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

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

where ω is the angular speed.

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

The spot dimension increases receding from the source according to (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 is then

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

with some consequences that are worth to be noticed.

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 speed dominates, and in facts, the pulse duration decreases with distance.

In naked eye viewing, d_{p1}=d_{p0}=7 mm.

If instead 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, considering equations (9) and (2), the actual 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 attachment to 2006/25/EC Directive.
These 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, is more correct to use MPE values and definitions set in the just 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 is given by

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

The coefficient C6, 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 prevalent.

For larger viewing times, also photochemical effects must be considered so including a dependence from wavelength as well.

For times < 10 s, therefore, is actually 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 such 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 meter 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; substituting this value in equation (11), with 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 points are overlapped and the application of the MPE for a CW beam could be justified; however this is not a reasonable operation of a laser for a show.

Actually, 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 (9).

For pulsed beams, according to IEC 60825-1, it is due to compare the MPE obtained considering a single pulse which duration is T_{on}, the mean irradiance considering the pulses absorbed in 0,25 s, and the single pulse times a coefficient that takes into account the cumulative effect of the number of pulses absorbed in the exposure time.

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 applying equation (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 what is obtained considering a 0,25 s exposure to a CW beam.

The calculation of *NOHD* cannot be done analytically as in (11) since, as seen above, MPE depends on subtended angle and exposure time depends on 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 is repeated doubling the viewing distance, where the irradiance falls below the MPE, an esteem of the NOHD is obtained.

The same table reports the MPEs both as single pulse irradiance and as mean power on a 7 mm aperture.

Using a standard spreadsheet allows to have a theoretical value of irradiance to be compared with actual values measured, better on still effects, 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/m²**	**MPE W/m² 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-02	2,37E+02	0,0	0,8	0,0050	1,00
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

The MPE, for a moving beam, does not depend on the avoidance response but on the actual exposure to a single pulse that decreases at increasing distance.

Therefore it 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.

This could be theoretically true for healthy workers, undergoing medical examination before exposure, not for general public, specially in shows with hundreds of attendants. For example, a dilatation of the pupil due to drug assumption cannot be ruled out so easily.

Applying the relations shown above, which can be easily assembled in a spreadsheet software, typically MS Excel, the power level of the show can be adjusted in order to comply with the actual MPE rather than increasing the CW MPE with some "rule of thumb".

Equation (2) and (9) prove that observing the laser source with optical instruments increases the mean power on the eye. 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 facts, binoculars and telescopes are not so common among laser show audience, and can be prohibited without any consequence.

Instead, adjusting the image through the optical viewfinder is very common among professionals and evolved amateurs, however in laser show they should take pictures only with special clearance by the staff. Therefore, they could be noticed that staring into beam directly could be harmful for their devices and, if 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 a probability of causing harms there exists, in particular when safety rules are not observed.

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

As a premise, 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 actually operated by trained personnel able to lowering 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 if not in particular situation for thee staff.

In Table 4 the irradiances experienced at 6,4 m from the laser source are calculated for a class 3b (0,5 W) 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 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/m²	**MPE W/m²**	**Logaritmic ratio**
Laser pointer 0,5 W	4899	25	2,3
Kvant spectrum 30 W 30 kpps	180692	193	3,0
Kvant spectrum 3 W 30 kpps	18069	193	2,0

In all three cases, the MPE is exceeded but, 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 stilla power 3 times greater than a class 3B pointer but the irradiance exceed the MPE less than in the case of the pointer.

In case of injury, a police investigation would establish where the subject was at the time of exposure and which sources were involved but class 3b laser pointer are CW sources while, as seen above, laser show projector causes normally shorter exposures.

5 Conclusions

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

Considering the beam motion the. MPE is a function of the scan rate and range of the show and can be evaluated using laser parameters and a dedicated spreadsheat.

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* International Laser Display Association 2009 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 Soc Belge Ophtalmol. 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).