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Fixed minor typos

Scanning Audiences at Laser Shows: Theory, Practice and a Proposal

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Abstract

For more than three decades, the technique of "audience scanning" has been routinely used at laser light shows outside of the United States. Visible beams from continuous-wave lasers are projected towards viewers, to put them inside cones, fans and other moving light shapes set to music. Over 109 million persons have attended audience scanning shows, collectively experiencing 11 billion laser pulses to their eyes. Most commonly, irradiance levels have not been measured by operators; instead they have been set by eye to look "OK". Since MPE-level irradiance at the audience is somewhat dim, most shows have exceeded the MPE. Estimated irradiance levels range from 5-10 times the MPE, to 100 times or more.

Despite the fact that there have been 11 billion pulses, many well above the MPE, in 30 years there has been only a handful of proven or even claimed reports of injuries from deliberate audience scanning with continuous-wave lasers. A number of possible reasons are presented, including the distance to the audience (e.g., higher beam divergence than in laboratory accidents), the use of moving beams, the pupil being more closed than regulations anticipate, and viewers who actively take action to reduce exposure.

Audience scanning lasers are often found in venues such as discos where patrons enjoy riskier-than-normal activities. This includes hearing-damaging sound levels, alcohol consumption (sometimes to excess), smoking, and even potential consumption of illegal drugs. Patrons self-manage the risk; they can move farther from the speakers or use earplugs; they can avoid alcohol, smoking etc. Similarly, if an audience scanning show is uncomfortable and/or above the MPE, patrons can and do avoid direct exposure by glancing away, blinking, blocking the direct beam, moving farther from the lasers, etc. This is one of the reasons why there have been so few injury reports in the past 30 years.

However, there are too many shows which far exceed the MPE. ILDA therefore proposes changes it believes would significantly increase safety, while still allowing crowd-pleasing brightness levels. All shows would be required to accurately measure their irradiance. Shows below the MPE would remain legal as they are now. Shows up to 10 times the MPE would be permissible if the audience was cautioned via signs and announcements (e.g., "Extra-bright lasers are in use; avoid direct eye exposure"), if scan-fail circuits are used, and if show

producers accept stricter liability. Shows greater than 10 times the MPE would no longer be allowed. It is expected that conservative venues (corporate shows, theme parks) would remain with current below-the-MPE shows, while discos, nightclubs and rock concerts would prefer brighter, more exciting "10x" shows.

Version History

Version 1 of this paper was published in the *Proceedings of the 2009 International Laser Safety Conference (ILSC)*.

Version 2.2 (Feb. 2009) has a slightly different title, a longer abstract, more photos, and some new and expanded sections.

Version 2.3 (April 20 2010) includes estimated numbers of persons exposed to audience scanning. The estimates were in the PowerPoint slides presented in March 2009 at the ILSC but did not make it into this paper until version 2.3. Version 2.3 also includes updated information on sources of laser show eye injury reports, plus an emphasized recommendation to videotape Level 2 shows.

Version 2.4 (April 23 2010) adds details from the 1996 laser show incident study. It also adds highlighting of key passages, to help those who may not have time to read the entire paper.

Version 2.5 (November 12 2010) corrects a few typos and rewords a few sentences to make them clearer.

Version 2.6 (also November 12 2010) adds a box discussing injury claims from the July 2009 Tomorrowland festival in Belgium. This discussion was not included in the original paper (Version 1) submitted to ILSC early in 2009.

Version 2.6a (November 15 2010) corrects a few typos found in Version 2.6, and adds details about the irradiance of the Tomorrowland festival's lasers. Did some additional editing for clarity, and added two new footnotes.

Version 2.7 (April 23 2011) adds information about three Israelis injured by pulsed YAG lasers at a show. Two had no long-term vision effect, and one had a "minor" vision effect (20/35 vision).

Version 2.8 (August 20, 2012) fixes some minor typos.

The most up-to-date version of this paper is always available at the ILDA website www.laserist.org; search the site for "Safety links and articles".

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Introduction

One of the most exciting and beautiful visual experiences one can have is to be inside an audience scanning laser show set to music. A typical show might start off with a cone of light that expands to encompass the audience. The solid-color cone fades to become striped, with areas of light and dark. Each stripe becomes a different color of the rainbow. The cone begins to shrink vertically until it is a thin plane of laser light. Because the plane is only a few centimeters thick, a slice of theatrical fog can be seen swirling throughout the plane. Suddenly, alternate stripes move up and down, like a giant keyboard being played. Then, from two side projectors, mirror-image beams create mid-air sculptures made of intangible laser light. As these sculptures change instantly on the beat of the music, the center projector sweeps planes, cones, waves and other shapes through the audience.

The experience has been compared to being inside a fireworks show, or being in a "swimming pool filled with light." Unlike watching a movie screen or TV projection, audience scanning shows reach out and touch spectators, including them inside the spectacular visuals. The closest non-laser experience would be when theatrical lights at a pop concert sweep over an audience. But the laser images are much more precise and varied. Under computer control, any shape and any beam pattern can be created, and the show can have endlessly changing patterns of color, and of light and dark.

The uniqueness of being inside "digital" light is why audience scanning is the most popular and common type of laser show being done today. Every night, in discos, nightclubs, and concert venues across the world, tens of thousands of willing patrons are deliberately scanned with laser light.

Defining "Audience Scanning"

The term "audience scanning", as used in this paper, means continuous-wave, visible laser light that is intentionally aimed into audience areas to create mid-air beam effects. Note these important points and caveats:

Audience scanning is not intended for direct eye exposure

Audience scanning is ***not*** done in order to directly expose viewers' eyes to laser light. Direct eye exposure is a by-product of audience scanning – it is not the intended function.

If practical technology existed to detect and avoid viewers' eyes, laser show producers would use it. Since it does not, producers continue to create audience scanning shows that, as a by-product, include direct eye exposures.

Audience scanning means deliberate exposure only

This paper only discusses intentional, deliberate exposure of audiences to laser light. It does ***not*** include accidental exposures where the laser was never intended to enter an audience area. Also, it also does not include exposures to technicians, performers, workers or other non-public persons who may be exposed to laser light.

This is an important distinction. We are not discussing overall laser show accident rates -- only incidents involving deliberate exposure of an audience to laser light.

Audience scanning only uses continuous-wave lasers

Audience scanning should ***never*** be done with pulsed lasers such as Q-switched YAGs and copper-vapor lasers.[1] Since the laser's power is packed into a short pulse, the potential for injury is much greater, compared with using an equivalent continuous-wave laser.

There have been at least three accidents where pulsed lasers were mistakenly used for audience scanning. We discuss these elsewhere in this paper. However, we do not count pulsed-laser incidents as "audience scanning" accidents since our contention is that intentional, deliberate audience scanning must be done using only continuous-wave lasers.

Audience scanning only uses visible lasers

There is no point in using non-visible lasers to create mid-air effects. For this reason, we restrict ourselves to the effects of laser light in the visible spectrum.

[1] The official position of the International Laser Display Association is that "pulsed lasers should never be used for audence scanning...The only exception would be under very special conditions that have been reviewed and confirmed by a qualified and experienced laser safety specialist. Two examples of special conditions: 1) Substantial distances (many miles) are involved or 2) The pulse repetition rate is extremely high, such as 80 MHz. Even under these special conditions, a comprehensive analysis must be done by a highly qualified expert." See www.laserist.org/safety-basics.htm, item 9.

How Audience Scanning Shows are Created

This paper discusses the most common type of audience scanning show: using non-resonant galvanometer scanners under computer control. A laser beam is bounced off of a tiny (3 x 5 mm) mirror on one scanner to create horizontal movement. This horizontal line is then bounced off a second mirror on a second scanner which creates vertical movement. The result is the ability to place the laser "dot" anywhere in a square area (scan field).

A projector uses two galvanometer scanners, one for horizontal (X-axis) and one for vertical (Y-axis). The photo shows two General Scanning model G-120 scanners. The laser beam enters from the right, is deflected first by the X-axis mirror and then by the Y-axis mirror, and finally exits towards the viewer or projection screen. Photo courtesy Pangolin Laser Systems Inc.

The scanners are controlled by a computer. The laser show creator uses specialized graphics software to draw a path for the laser beam to follow. This is essentially a "connect-the-dots" drawing. It is internally represented in the computer as a series of points with X and Y coordinates. The software steps through the coordinates; hardware turns them into voltages using a digital-to-analog converter. The X and Y voltages are sent to the scanner amplifiers which condition the signals before sending them to the X- and Y-axis scanners. In addition, each XY point can be assigned a color and/or intensity.

For audience scanning laser shows, the computer-controlled graphics are usually simple shapes such as lines, waves, circles, and squares. The projector is aimed towards the audience, and theatrical fog or haze is added to the air. Viewers see flat planes, wavy planes, cones and pyramids of light which emanate from the projector.

It is also possible to "turn the projector around" to draw more complex shapes onto a viewing screen. This results in a graphics laser show, where logos, words and complex animations are projected onto the screen or other surface.

Lowering power in the audience area

One successful technique, to reduce audience exposure yet have an aesthetically pleasing display, is to use higher power beams outside the audience zone. (In the U.S., beams must be kept 3 meters vertically and 2.5 meters laterally from the point of closest audience access.)

As a fan, cone or other effect comes down into the audience, the power of the audience-scanned part is reduced. Conceptually, the simplest technique is to use a neutral density filter that intercepts beams going below the audience "horizon." More commonly, software automatically reduces the laser output power when the beam is below the audience horizon. The use of software gives more flexibility in defining which areas have reduced power levels, and how far the power is reduced in those areas.

This can be an effective technique. Although the beam is being dimmed, it is also coming closer to the viewer which causes it to appear brighter. These two effects tend to cancel out. As the beam sweeps down into the audience, the brightness reduction is often not noticeable.

Safety Implications

In an audience scanning show, shapes are scanned into an audience. When the beam crosses a viewer's eye, the eye sees a series of pulses. If the shape remains static (e.g., a non-moving cone) and the eye is at a fixed location, the pulses will be at a fixed frequency and amplitude for that particular shape. The Maximum Permissible Exposure (MPE) can be calculated as a multiple-pulse exposure.

However, this is a simple case. During an audience scanning laser show, many different shapes are created. At any giving viewing location, each time an effect crosses the eye, the scan frequency (pulse rate) and the color/intensity may be different.

This is what makes safety analysis so challenging. Unlike high-inertia or resonant scanners which have fixed frequencies and amplitudes, galvanometer scanners produce variable frequency and amplitude pulses.

Exposure parameters during a show

During a typical audience scanning show, a person may be exposed to the direct laser beam on the order of one or two dozen times. In other words, there are about 12 to 24 times the viewer sees a "flash" as a direct beam enters their eye.

Because the beam is being scanned, a typical flash is composed of five to ten pulses, each typically less than one millisecond.

The nominal laser power used for audience scanning is in the range of 0.5 to about 5 Watts. Due to losses in the projector from scan mirrors, steering mirrors, and color/intensity control devices, the beam power at the projector aperture can be about half of the nominal laser power.

After the aperture, a lens can be used to diverge the beam. The larger beam decreases the irradiance, thus making the beam safer. Whether it is capable of causing injury depends of course on many factors which are discussed later in this paper.

Estimated Exposures

We estimate that there have been at least 109 million person-exposures to audience scanning, over the past 30 years. (One person at one audience scanning show or event is one "person-exposure". The same person may go to another show on a different night; although they are still one person, this is now two "person-exposures".)

We further estimate that audiences' eyes have experienced at least 11 billion laser pulses over the past 30 years.

These figures are based on the following assumptions:

- 100 nightclubs/discos worldwide, with 100 people nightly: 10,000 person-exposures per day
- 10,000 x 365 days equals 3,650,000 person-exposures per year
- **109,500,000 person-exposures over the past 30 years**
- The beam crosses an eye an average of 20 times per show

- During each crossing event the beam is being scanned (e.g, in a circle, line or other shape) so the eye experiences each scan as a pulse[2]
- To be conservative, say there are only 5 pulses per crossing event
- 100 pulses per show x 109,500,000 person-exposures equals **10,950,000,000 pulses to eyes over 30 years.**

We believe these figures to be conservative, so the actual number of persons and pulses is probably much higher.

Very Few Reported Injuries

If you told a laser safety expert that you wanted to use multi-watt lasers to deliver 11 billion pulses to millions of ordinary persons, he or she would be concerned, to say the least. Certainly injuries would be likely if a person was working in close proximity to a Class 3 or 4 laser, as in a laboratory or industrial setting. Yet in the history of audience scanning laser shows, there have been just a handful of eye injury reports. We looked in four places for these reports: a 1996 study, general press reports, scientific papers, and Rockwell Laser Industries' database.

1996 study

A 1996 study[3] commissioned to look for audience scanning incidents found only five reported accidents (claimed or actual eye injury). One was due to "deliberately staring" at a disco laser beam, three were of undetermined severity, and one had an unusual, short-lived effect (the person felt "a very strong brief pain in his entire body" when the beam hit, but later reported no vision loss or subsequent ill effects).

The study commented that although the number of reports was low, it "seems within the proper order of magnitude". This was based in part on the fact that reported laser incidents in general are relatively rare. For example, the Rockwell Laser Industries online *Laser Accident Database*[4] lists an average of 16 injurious laser beam incidents per year, for all laser activity worldwide.[5]

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[2] These "scanned pulses," created when a scanned continuous-wave laser beam passes over the eye, are distinguished from pulses created by a pulsed laser. As stated in this paper, pulsed lasers should not be used for audience scanning.

[3] Murphy, P. *Is Deliberate Audience Scanning Unsafe?* Proceedings of the 1997 International Laser Safety Conference, Vol. 3, pp. 493-502. From the paper: "We hired a professional research firm, with ten years of experience. The firm's clients include National Geographic Society, Hughes Corporation, Citicorp, University of California, [and] Sony Pictures…. The firm searched for incidents and accidents from the following sources: Electronic and library search of medical, legal, safety databases; Incident lists from Rockwell Laser Industries and Greg Makhov; CDRH data for U.S. audience scanning; [and] Original research. The original research consisted of telephone and e-mail interviews with 24 regulators, laserists, and safety professionals in Australia, Canada, England, Germany, Malaysia, Mexico, South Africa, Taiwan and the U.S."

[4] Rockwell Laser Industries. *Laser Accident Database*. Available online at www.rli.com/resources/accident.aspx. Accessed April 2010.

[5] The Rockwell online database was analyzed in April 2010. The online version contains 417 incidents from 1964 to 2001, with most in the 1980s and 1990s. The average number of incidents for the top ten years (those with the most incidents) was 22.6 per year. However, only 71% of incidents resulted in eye or skin injury from exposure to laser beams. The rest were non-injurious exposures, injury from non-beam hazards such as electrical shock, or damage to inanimate objects. Thus, the laser beam injury rate for the top ten years is 22.6 x 0.71 or 16.0 incidents per year.

The study analysis also discussed whether incidents and accidents are underreported:

> "Some critics assume that most or all accidents and incidents would be covered up. However, it would seem difficult to hide every report, if significant numbers of audience members are being severely injured. Disco- or concert-goers hit by lasers, who experience significant vision loss, would be likely to contact someone -- venue operators, law enforcement, medical personnel, lawyers (even outside the litigious U.S.), government officials and regulators, laser operators and/or the media. At least some of these reports should have filtered back to those interviewed in the study.
>
> "If we have to venture a number for the underreporting rate, 90% seems supportable. One researcher claims only 10% of all laser accidents are reported.[6] This is echoed by R. James Rockwell, who feels a 90% underreporting rate seems within the correct order of magnitude."[7]

If 9 out of 10 accidents do not become public, this means there were roughly 50 injuries in the study's timespan of 1964-1996. Even this is a surprisingly low number, considering that over 50 million people viewed audience scanning shows during the same period.

It is also surprisingly low compared to injury rates for other entertainment-related activities. For example, amusement park ride incidents caused roughly 72,000 injuries and 44 fatalities over a single decade, in the U.S. alone.[8]

Injury reports in the general press

Laser show injuries are newsworthy. For example, a July 2008 pulsed laser incident in Moscow, made headlines worldwide, including being a front page story on news websites such as MSNBC.com and CNN.com. Almost two years later, a Google search turns up about 50 stories in English about this incident.[9]

Beyond the Moscow incident, however, there are almost no other items listed in Google's search results.[10] Note that these results include not only news stories, but also any other blog posts, forum messages, tweets, etc. where someone might complain about a laser show

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[6] Bauman, N. *Laser Accidents: Why only 10% get reported.* Laser Medicine & Surgery News and Advances, August 1988, p. 1-7. As footnoted in Murphy, I*s Deliberate Audience Scanning Unsafe?* op. cit.

[7] Personal communication, April 9, 1997, to Patrick Murphy. As footnoted in Murphy, *Is Deliberate Audience Scanning Unsafe?* op. cit.

[8] Levinson, M.S. *Amusement Ride-Related Injuries and Deaths in the United States: 2005 Update*, U.S. Consumer Product Safety Commission. Ten-year injury estimates calculated using Table A1, p. 13, taking the average number of injuries per year for the eight listed years, and extrapolating to a ten-year period. Death estimates based on "an average of 4.4 estimated fatalities per year", p. 7.

[9] Forty-three results were found from a Google search conducted April 20 2010, using the search words *laser blinds Moscow ravers aquamarine festival - jewelry*, limited to pages added July-September 2008. Note that this is a very restricted search. Using other terms would bring up additional stories about the Moscow show that do not include all the search words. However, such a search also brings up more non-related stories; the above term is better to quickly find pertinent stories.

[10] Try a search for the following: *"laser show" retina -Russia -Russian -Moscow*. Using the dash (minus sign) causes the search to ignore results from the Moscow incident. Note that there are only a handful of actual injury reports in the 1,430 results found. Similarly, replace "retina" with "injury". Again, very few of the 4,130 results are actual cases or reports of injury to audience members.

causing eye problems. This helps indicate that there is not a significant problem even with claimed or unproven injuries, let alone actual injury reports.

Injury reports in the scientific press

Using Google Scholar to search for reports in medical and scientific journals[11] returns just three reports of laser show injuries:

- A 1998 German paper by H.G. Sachs about one person with vision defect and scotoma after exposure at a disco.[12] It is not clear if the show was using deliberate audience scanning with a continuous wave laser, or if it was an unintended, accidental exposure.

- A 2007 article about a pulsed YAG exposure to three Israeli laser show patrons where the lesions resolved within six months.[13] [14] Recall that pulsed lasers should not be used for audience scanning, so this incident does not apply to the laser usage we are discussing in this paper.

- A 2009 paper from Turkish doctors.[15] Two men in their 20s reported injuries from a “laser machine … placed at about 1.5 m height and 2-3 m away from the two men who did not intentionally stare at the laser light source.” (The paper states that the laser was 4.95 mW, which seems very low -- laser pointer strength -- to cause extrafoveal lesions from an unintentional non-staring exposure. Perhaps the laser was mislabeled, or there was some other cause of the lesions.)

The references for these papers also indicate that the scientific literature is very thin. The 2007 paper notes that, “to our knowledge, only one case of eye injury during a laser show has been reported previously”; this may be the 1998 case mentioned above. The 2008 paper, in turn, says that “reports on retinal injury due to show lasers are few in literature” and only lists the 1998 and 2007 papers as previous incidents.

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[11] The Google Scholar search phrase giving the most pertient results was very broad: *“laser show” injury*

[12] Sachs HG and others from Regensburg University and TUV Bayern. *Eye Inuries During a Laser Show*, Klin Monbl Augenheilkd, March 1998, 212(3): 13-5. Original article in German.

[13] Shneck Marina MD and others at the Department of Ophthalmology, Soroka University Medical Center, Ben-Gurion University of the Negev. *Retinal Laser Injury During a Laser Show.* Retinal Cases & Brief Reports: Volume 1(3) Summer 2007, pp 178-181

[14] Noam Sapiens, research consultant at NSLS Consulting, told us that he had spoken with the three Israelis. He said two of them had “no long term effect” and that one had a “minor vision effect of 20/35 vision”.

[15] Aras C and others from the Cerrahpasa Medical School and Dunya Eye Hospital, both in Istanbul, Turkey. *Inadvertent Laser-Induced Retinal Injury Following a Recreational Laser Show.* Clinical & Experimental Ophthalmology, Vol. 37, Issue 5, pp 529-530, received October 26 2008, accepted April 29 2008, published online July 12 2009.

Rockwell Laser Industries database

A fourth source of injury reports is the Rockwell Laser Industries online *Laser Accident Database*. Below is a complete list of all Rockwell cases in the "entertainment" category where audience members were injured:[16]

- Case #36: **Eye irritation** following laser show. 1980.
- Cases #33 and 134: **Temporary sore eyes** (red, bloodshot, irritated) after observing 30-minute laser demonstration. Treatment was not sought. 1980.
- Case #183: **Temporary vision loss** after beer cans were tossed into beams (which were not scanning on the audience), reflecting the laser light into the audience. 1992.
- Case #350: **Retinal scotoma** produced while watching laser show (beam hit into eye). 1997.
- Case #400. **Nineteen disco dancers partially blinded** in Bulgaria. 1999. Other reports have stated this was caused by illegal use of a pulsed (not CW) laser. *As discussed below, pulsed lasers such as Q-switched Nd:YAG should never be used for audience scanning, so this is an exceptional situation.*

Thus, the Rockwell Laser Industries database contains only one injury from deliberate audience scanning caused by a continuous wave laser, case #350. This is the same case as the 1998 paper by Sachs from Germany described in the previous section.

Pulsed lasers not included in this discussion

Rockwell case #400, of the nineteen disco dancers in Bulgaria, brings up an important point. Pulsed lasers should not be used for audience scanning applications. This includes lasers such as Q-switched Nd:YAG and copper vapor. The powerful pulses increase the potential hazard. This in turn makes it more difficult to properly analyze the safety hazards of beams which are also being scanned (pulses on top of pulses).

For example, a 40W argon (continuous wave) and a 40W Nd:YAG (pulsed) both emit the same amount of energy. However, each 600 nanosecond YAG pulse has 70 times the energy as the argon's beam, during the pulse duration.

There have been only three reported accidents in the past 30 years where multiple audience members have suffered confirmed eye injuries. In all three cases, pulsed lasers were used:

- In Israel around 2007, three teenagers in a club were injured. (They may have been intentionally staring at the beam.) As a result of the accident, Israel now requires specific laser training for show operators.
- In Bulgaria in 1999, 19 disco dancers were partially blinded, as listed in Rockwell case #400.

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[16] Rockwell's database includes 12 other "entertainment" cases not related to injuries from deliberate audience scanning. These include incidents where light show technicians were injured during alignment, where pilots were illuminated, or where the audience was unintentionally illuminated but no injuries were reported.

- Near Moscow in July 2008, approximately 30 persons who attended the Aquamarine Open Air Festival went to hospitals and clinics complaining of problems with their eyes.[17] A Russian laserist who spoke with the doctor who did the examinations stated that "normal sight was restored in all but four of those injured." The four have "spots or other noticeable injuries."[18]

Because of the increased hazard, the International Laser Display Association requires its members to affirm that they will not scan audiences with pulsed lasers. Throughout this document, the term "audience scanning" is meant to include only the deliberate (non-accidental) use of visible, continuous-wave lasers.

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[17] July 5 2008 Russian Incident, International Laser Display Association webpage available online at www.laserist.org/2008-07_Russian-incident.htm. There are numerous other online sources with accounts of this incident. A video news report from a Russian TV station, with footage of the incident, clearly shows the dotted lines characteristic of scanning with a pulsed laser. The video is at http://news.ntv.ru/136097.

[18] Timofeyev, A., Presentation at the 2009 ILDA Conference, Sept. 9 2008. A summary is online at www.laserist.org/c2008-report.htm; scroll down to "ILDA Safety Workshop." Dr. Timofeyev is with Orion-Art Production International in Moscow.

Update: Tomorrowland festival incident, July 2009

Since the above sections were written in early 2009, there has been another widely-reported incident, which turned out to be caused due to audience misuse of laser pointers.

In late July 2009, two persons said they were injured by laser beams at the Tomorrowland electronic music dance festival, held July 25-26 in Boom, Belgium. Initial news reports on August 4 implied that the injuries were caused by lasers from the extensive light show presented at the festival. However, authorities concluded on September 2 that the injuries were caused by misuse of laser pointers by audience members.

Even before hearing details of the show, it seemed unlikely that the laser show caused the two injuries. The first clue was that only 2 out of 90,000 attendees were injured. If the laser show was unsafe, one would expect many more injuries since the lasers scan onto thousands of audience members.

The laser show producers had never had an incident in 20 years. They were using up-to-date techniques such as software beam attenuation maps which automatically reduce the power of beams going into pre-defined audience areas. The laser beams were monitored and operated normally throughout both evenings.

Calculations based on the laser beam power, divergence, and diameter, plus the software beam attenuation map settings, show that the irradiance was at most 50 mW/cm2 at the closest audience distance (30 meters from the laser projector). At a distance of 50 meters, the irradiance would be about 10 mW/cm2. These levels are well below the 100 mW/cm2 maximum level, recommended by the International Laser Display Association [later in this paper] for shows intended for discos, nightclubs and festivals.

In contrast, laser pointers were in wide use throughout the crowd. The irradiance of a 200 mW laser pointer at 3 meter distance would be 1,020 mW/cm^2, or 20 to 100 times more powerful than the laser light show laser. The pointer could also be misused to give a longer exposure time than the laser light show laser. The Tomorrowland laser show producer said that at other shows he has seen audience members deliberately shining lasers onto other people's faces.

Additional information about this incident is available at www.laserist.org/2009-07_Belgian-incident.htm.

Summary: Just a handful of cases

To summarize the previous section, it is possible to find only a handful of injuries due to deliberate audience scanning using continuous-wave lasers. Given that millions of people have been exposed to billions of pulses, this is a remarkable result.

Could this be due to laser shows being at or below the MPE? As it turns out, real-world exposures probably far exceed what would normally be considered safe -- which makes the handful of injury reports even more remarkable.

Real-world Exposures Well Over the MPE

Current laser safety guidelines and regulations intend for the irradiance at the point of closest audience access to be below the MPE. However, Greg Makhov (ILDA Safety Committee chair), John O'Hagan (U.K. Health Protection Agency), James Stewart (Laser Visuals safety consultancy), Geoff Jones (former chair of the European Laser Association) and many others involved with laser displays state that they have routinely experienced shows which are clearly well over the MPE. In 1996, Jones stated that levels "10, 20 or even 100 times the MPE have been used."[19] Makhov estimates that shows are routinely 25 to 100 times over the MPE.[20]

Thus, most real-world laser shows are above the MPE, and many of these shows are far above the MPE (20x to 100x).

In fact, as discussed below, shows which are at or below the MPE tend to have dim and fuzzy beams. It is the natural tendency of a show producer to "turn up the brightness" and "make it sharper", coupled with a feeling that "it's safe enough" which leads to shows that are well above the MPE.

If most shows are above the MPE, and some shows are *very* far above the MPE, then why are there so few injury reports?

Definition of "Injury"

In order to report a real or suspected injury, a person must notice a change in their vision.[21] Thus, by definition, a reported injury would be due to a noticeable change.

It can be argued that audience scanning causes changes in the eye which are not noticed by the subject, but which are detectable during a detailed examination. For purposes of this paper, we shall call these "changes" but not "injuries." If the change is not noticed (except during an eye exam), it has no adverse effect on vision and we would not define it as an "injury."

We are not aware of any studies undertaken to find retinal changes in people who attend audience scanning laser shows. Therefore, the primary resource for estimating any harm from such shows comes from injury reports. Since there are remarkably few such reports, this leads

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[19] Jones, Geoff, quoted in the 1996 study of audience scanning injury reports which is referenced in Murphy P., Is *Deliberate Audience Scanning Unsafe?*, op. cit. At the time Jones was chair of the British Entertainment Laser Association which later became the European Laser Association.

[20] Makhov did a detailed analysis of a show he attended. The projector had a nominal output of 3 Watts; due to color palette limiting and projector inefficiency, "a less conservative measure might suggest that only 1 Watt was projected at any one time." Divergence was 1 milliradian, and he was located 25 meters away. For a static beam at this distance, the irradiance was 162 mW/cm^2, or 65 times the average power MPE.

Fortunately, the show was well-designed with no static beams in the audience. As will be seen later in this paper, the fact that the beam was scanning means the single-pulse MPE is more relevant. Makhov's calculations indicate the exposure at his location was 16 times the single-pulse MPE.

Performers were much closer to the laser – about 10 meters. At this distance, the exposure was 75 times the single-pulse MPE.

[21] This assumes the injury claim is not made under false pretenses; for example, to try and get a settlement for a pre-existing injury.

to the conclusion that audience scanning laser shows are not a significant hazard -- despite many or perhaps most shows being done at levels well beyond the MPE.

Potential Injury-Preventing Mechanisms

There are a number of reasons why deliberate audience scanning at laser shows is causing far fewer injury reports than one might initially expect:

MPEs have a built-in safety factor to prevent changes. MPE levels are set roughly 10 times below the level at which a change could be detected in 50% of typical human eyes. Thus, if a person is exposed to a level of 10 times the MPE, there is still only roughly a 50% chance that a detectable change to the retina will occur.

MPEs have an even higher safety factor to prevent noticeable injuries. MPE irradiance levels are intended by definition to prevent changes to the eye. These changes may only be detected during an eye exam, or by laboratory tests under controlled pre- and post-exposure conditions. It would take even higher irradiance levels to cause spots or vision problems which a person would notice on their own, in their everyday life.

This raises the possibility that laser shows over the MPE may, theoretically, be causing changes in some eyes (detectable with careful examination) but are not so far over the MPE as to cause noticeable or reportable vision problems.

Viewers are not always looking at the laser source. In a disco or concert situation, the focus is not usually exclusively at the laser source. Therefore, direct laser light will either miss those looking away from the source, or will enter the eye at an oblique angle and be focused on the periphery of vision.

Aversion response helps avoid serious injuries. The natural aversion response to bright light causes viewers to blink and/or move their head if light entering the eye is too bright. This reduces the potential harm from exposures longer than the nominal 1/4 second aversion response time.

Avoidance response helps avoid minor injuries. In addition to the sudden aversion response, viewers also take more subtle, often subconscious avoidance actions if the light is too bright. This has been routinely observed at shows with bright lasers. As an effect is about to cross a viewer's face, they will move their head slightly, glance down, squint and/or blink.

Blocking the beam avoids any exposure. We have seen viewers deliberately position themselves so another person's head, a column, or a similar obstacle blocks the direct beams coming from the projector. In such a case, most of the show can still be enjoyed.

Less light is entering the eye than standards anticipate. Laser safety standards are based upon a dark-adapted pupil size of 7 mm. However, most displays are not viewed as a single beam in total darkness. The pupil is constricted a bit, making a pupil size of 4-5 mm more likely. At 5 mm, the pupil lets in only about 50% as much light as at 7 mm, and the pulse width is decreased by 30%. Both factors lead to a significant hazard reduction.

The pupil is relatively far from the laser source. In laboratory and industrial accidents, the pupil is often within a meter or two of the laser source. In most displays the audience is much further away. This gives the beam more room to diverge.

There is a small chance of hitting a pupil. The total pupil area of 100 persons in a nightclub (scan field of 10 x 10 meters) is roughly 1/25000 of the total area scanned by the laser. Thus, any randomly positioned static beam (e.g., scan failure) would have only a 1/25000 chance of directly hitting a pupil.

Only part of the audience is at the closest (most hazardous) distance from the laser. The MPE is calculated for the closest audience members. However, most viewers are farther away. They receive less light energy for two reasons: 1) the beam diverges more and 2) the linear velocity of a scanned beam increases with distance. Depending on the crowd depth, the beam power may be significantly reduced for audience members who are not in front.

Avoidance response

Viewers' avoidance response should be discussed further, as this is an important factor.

When the authors attend audience scanning shows, we watch the audience to see how they are reacting to the show. Often, as beams approach a person's face, the person will move their head or upper body in the opposite direction. This reduces the exposure time. Other mechanisms seen are glancing or blinking as the beam approaches the eye.

An avoidance response is more subtle than the 1/4 second aversion response which occurs when bright light is flashed in an eye. The glance away and the blink are not severe. But like the aversion response, the avoidance response may be involuntary -- viewers are not consciously aware of moving slightly to avoid the beam.

In a few cases, viewers deliberately position themselves so an object such as another person's head or a column is blocking the direct beams coming from the projector. The viewer can also use their own hand to block the beam. Even if the direct beams are blocked, most of the show (the area outside of the blocked object) can still be enjoyed.

An interesting line of research would be to videotape viewers during audience scanning shows of various powers and pattern designs. In shows which are too bright, many viewers will be seen using avoidance techniques.

Let us now turn to the question of how best to measure the light exposure at viewers' eyes, and the effect that scanning the laser beam has on the exposure.

Pulsed MPE is More Relevant For Scanned Effects

For a show which meets laser safety guidelines, irradiance at the closest point of audience access should be at or below the MPE. However, it is not accurate to use the average power MPE.

As described earlier, by scanning the beam, the exposure is reduced from 1/4 second (until the aversion response kicks in), to a shorter time on the order of a millisecond or less. A laser being scanned in a circle, to create a cone of light, is effectively a pulsed source for the viewer who has the circle cross their eye. The viewer may experience one flash if the scanned pattern continues moving past their eye, or they may experience multiple flashes if the scanned pattern remains at their eye location and they do not move their head. The MPE then must be calculated as both a single pulse and as a multiple pulse.

The major challenge in analyzing show safety is that a show is composed of hundreds of effects. In addition, viewers' eyes may be located anywhere in the scan field. Even if there were a "magic" exposure meter that could measure MPE at a single location, the show would have to be repeated dozens of times with the meter at different locations, just to give a first-order approximation of the show's safety.

Fortunately, one of the co-authors (Makhov) has developed a way to dramatically simplify measurement of audience scanning shows

Calculating Scanning Parameters

Makhov has done extensive studies of scanning parameters. He has determined the basic parameters for audience scanning shows.[22] This analysis indicates that by scanning the beam, the allowable exposure is from 4 to a maximum of 10 times greater than if the beam were static. Here is how he reached this conclusion:

- By examining the computer signal sent to the galvanometer scanners, the minimum velocity of a moving effect is found to be on the order of 10 radians per second. The maximum velocity is about 1000 radians per second. The minimum distance from a projector is about 1 meter (in a small club or disco), while the practical maximum range is 10,000 meters.
- Given that linear velocity equals angular velocity (10 to 1000 radians per second) times range (1 to 10000 meters), the range of possible linear velocities (beam crossing a viewer's eye) is from 10 meters per second to 10,000,000 meters per second. Makhov states that this is "a large but manageable area."[23]
- From this, the range of pulse durations can be calculated. Assuming a 1 milliradian divergence – which is tight for laser projectors – the pulse duration is the beam diameter divided by the linear velocity. The range of pulse durations is 2 milliseconds to 1 microsecond.

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[22] Makhov, G. & Benner, W.R. *A Safety System for Audience Scanning Displays*. Presentation at the 2009 ILDA Conference, Sept. 9 2008. The PowerPoint slides are available from Makhov in PDF format.

[23] Ibid. Quotes in this section are from Makhov's PowerPoint slides.

This is mostly within the range of Thermal MPE values ranging from 10 seconds to 18 microseconds. The MPE for the pulse is therefore $1.8 \times t^{3/4} \times 10^{-3}$ J/cm^2.

A table of MPE values for various exposure times is derived:

Exposure time	MPE
1.0 second	1.8 mW/cm^2
0.25 second	2.5 mW/cm^2
0.01 second	5.6 mW/cm^2
0.001 second	10 mW/cm^2
18 microseconds	27 mW/cm^2

Table 1. *MPEs for selected exposure times*

Makhov first notes that a person exposed to bright light will have an aversion response. The accepted value is 0.25 second. After this time, the person has blinked and/or turned away. So, 1/4 second is the longest exposure duration needing to be considered.

Next, Makhov notes that "from 1/4 second to 1 millisecond, average MPE increases only by a factor of 4" and "from 1/4 second to 18 microseconds, average MPE increases by a factor of 10."

The result of this analysis is that by scanning the beam, the allowable pulsed MPE is increased only by a relatively small factor relative to the average power MPE. Said another way, if a static, unmoving continuous-wave beam is "safe" (below the average power MPE), then scanning the beam as in a typical light show allows the power to be increased about 4 to 10 times higher and still be "safe" (below the now-applicable single-pulse MPE limit).

Makhov concludes "Since the increase in MPE as a function of scanning is small (only 4 to 10 times), scanning parameters are a *minor* factor. To stay within the MPE, the accessible irradiance is the *major* factor." (Emphasis in the original.) This finding, that the increase in MPE due to scanning is about a factor of four, is echoed by laser safety expert John O'Hagan. He states "our experience with a range of moving effects is that scanning instead of static beams only makes the beams 'safer' by about a factor of 3-5." [24]

This leads to two important conclusions:

- **Show measurement is vastly simplified.** The show operator only needs to measure the accessible exposure at the point of closest audience access. If the operator sets the power of a static beam in the audience area to 10 mW/cm^2 (four times the 2.5 mW/cm^2 average power MPE), this will approximate the single-pulse MPE limit for the audience scanning portion of the show. This simplification assumes the show has been designed so effects are kept moving, and the scanned shapes are smooth with no "hot spots".

[24] O'Hagan, J. *Laser Roundtable Panel: Audience Scanning and Safety*, conducted by ILDA. Available at http://www.laserist.org/laserist2008/roundtable.htm

- **Increasing the beam divergence allows power and visibility to be increased.** Show operators can increase the laser power, and thus the beam visibility, by increasing the beam divergence. The key is to keep the irradiance under the MPE. The best technique is to use a beam with 5 to 10 milliradian divergence. Beyond about 10 milliradians, the beam becomes too fat and fuzzy. In Makhov's view, a show using "a high divergence beam with more power 'looks better' than a low divergence beam with less power."

Other Safety Steps

Some laser show producers attempt to increase safety by automated means. For example, electronic circuits can be used which terminate laser output if scanning stops. This does not affect the overall exposure – whether scanned beams are above or below the MPE – but it does protect against a failure that could cause static beams to enter the audience.

Such "scan-fail" circuits monitor the velocity signal at the galvanometer. To provide safety, the scan fail detection circuit needs to cut off the laser within at least 10 milliseconds, and preferably within 1 millisecond. Not all commercially-available circuits have such a fast response.[25] Scan-fail devices can have other drawbacks as well:

- Many audience scanning shows use full-power beams for non-audience areas, with a lower power being used in the audience area. Most scan-fail circuits look at the scanner velocity without regard to beam location. They will erroneously cut off any static beam effects that might be used in the safe, non-audience area.

- Scan-fail circuits may not detect when the beam is moving but the effect is unsafe. A simple example is a shape consisting of two dots. The laser scans between the dots, so the circuit sees it as having velocity. Yet it may not be safe to have essentially two stationary beams, each with 50% of the projector output power.

More sophisticated systems have been developed. To give one example, Pangolin Laser Systems' "Professional Audience Safety System" meets the demanding requirements of the U.S. Center for Devices and Radiological Health (CDRH), which reviews American laser show projectors and show setups. PASS uses redundant analog circuits "to continually monitor the laser power, scanner signals, and other projector-related parameters .... in a very intelligent way so as not to destroy the intended visual effect."[26]

Other companies market devices intended for audience scanning use. To give two examples, LOBO electronic GmbH has a "Laser Safety Measurement System" used to measure audience exposure, while Greek company Eye-Magic produces the "IRIS Safe" scan-fail circuit which has provisions for allowing full-power beams over the audience while monitoring and protecting beams in the audience.

Anyone intending to use scan-fail circuits and/or monitoring systems for audience scanning needs to understand their capabilities and limitations. Such systems are not yet at the "set and

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[25] Any functioning scan-fail circuit is better than nothing. Even if the response time is slower than 10 milliseconds, it is likely to be much faster than a human operator can notice failure and shut off the beam.

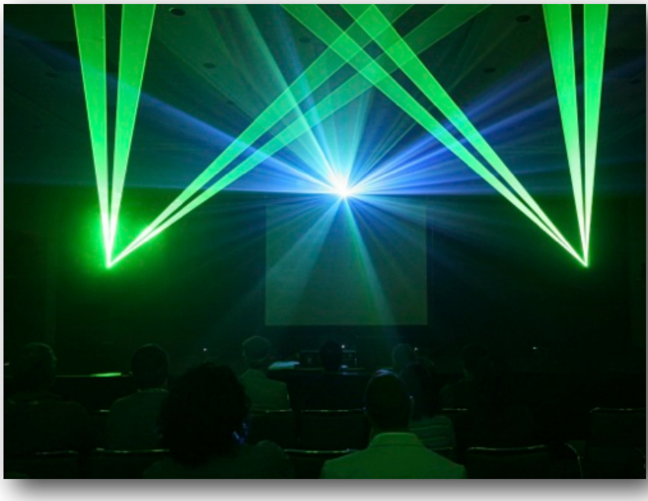
[26] Pangolin webpage "PASS: Professional Audience Safety System" at http://www.pangolin.com/PASS/index.htm. Accessed Feb. 9 2009.

forget” stage. And the laser show still needs to be designed with audience scanning in mind (e.g., no static beams in the audience area).

The Problem with Audience Scanning at the MPE

Thus far, we have described how audience scanning can be done, relatively easily, within the MPE.

The problem with this is that the effects are relatively dim. They need to be viewed in a space that is almost completely dark. The increased beam divergence causes “fuzzy” beams with soft planes and cones of light. Some feel that the show is less exciting to audiences.



In the photo at right,[27] beams above the audience have powers above the MPE. Beams going into the audience are below the MPE. The difference in brightness is readily apparent. The green beams above are bright, sharp and well-defined. The blue beams are soft (due to using a lens to increase beam divergence), and the portion of the beams which are in the audience are also dim (due to using software which lowers irradiance when the beams are below a specified height).

This illustrates the primary reason why so many shows are well above the MPE: they look brighter, like the top of the photo above, instead of dimmer, like the bottom half. Beams above the MPE are brighter and sharper, and thus more impressive and enjoyable.

Just as people turn up the volume when they hear a song they really like, laser show producers increase the power to make the show more exciting. Unfortunately, most show producers do not measure their shows, or they rely on incorrect “seat of the pants” assumptions, so they have no real idea of how far above the MPE they are scanning.

An important secondary reason shows are well above the MPE is the paucity of injury reports. If audience members were to complain to show producers or venue owners about the lights being

[27] Photo taken at the Nov. 2007 ILDA Laser Theater, during the Lighting Dimensions International trade show in Orlando. This was one of the first public demonstrations of CDRH-approved audience scanning using the Pangolin Professional Audience Safety System.

too bright, or if they were to file injury claims, this would lead to changes. No one wants to present shows which are unpopular or could lead to costly legal actions.[28]

Is it possible to "turn up the volume" of laser shows? Are there some shows where this is more acceptable than others? Said another way, are the regulatory limits of audience exposure that might be acceptable for a family theme park ride, insufficient for a different audience such as those attending nightclubs, rock concerts and raves?

This leads to a discussion of how people evaluate and even seek out risk, in their leisure activities.

Risk Assessment for Leisure Activities

All of us have participated in potentially injurious activities; for example, playing sports, going hiking or camping outdoors, riding bicycles, etc. Most of us have experienced some sort of injury at times, ranging from cuts and bruises to broken bones or possibly worse. Serious injuries requiring medical attention are common. In the United States alone, "approximately 3.7 million ED [emergency department] visits occur each year for injuries related to participation in sports and recreation."[29]

Usually, the injury eventually heals. Often there is a scar, skin blemish or other detectable remnant of the injury. Despite incurring visible injuries, we continue to play sports, go camping, ride a bicycle, etc. Minor injuries are a normal and accepted part of doing interesting, enjoyable things in life.

This is not to argue that changes or even injuries to an eye due to laser exposure should be cavalierly accepted. The point is that everything we do has a risk/benefit ratio. Individuals choose activities based on their personal risk assessment. The goal is to manage and minimize the risk, not to eliminate the activity or water it down to bland nothingness (e.g., allowing only touch football, staying indoors, or requiring outboard training wheels on all bicycles).

In the case of audience scanning shows, if there has been only a handful of reported injuries in 30 years, then this risk might be considered to be within the "normal and accepted part of doing interesting, enjoyable things in life."

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[28] In July 2008, after widespread news accounts of the injuries caused by the Aquamarine rave near Moscow, many ILDA members were contacted by concerned clients. Clients wanted to know if the ILDA members' shows were actually safe (e.g., not using pulsed lasers as Aquamarine did).

More relevant for this discussion, clients were also very concerned whether the shows were perceived as safe by audience members. A few clients cancelled already-contracted for shows, because they felt that audiences would fear the laser beams. Note that just one reported incident was able to cause skittishness and cancellations. Clearly, clients would not want audience scanning laser shows if they or their audiences perceived the shows as unsafe.

[29] U.S. Centers for Disease Control Injury Center. *Preventing Injuries in Sports, Recreation, and Exercise.* Available online at http://www.cdc.gov/Ncipc/pub-res/research_agenda/05_sports.htm. To give another example, the U.S. CPSC estimates that in one year (1998) there were more than 1,000,000 "medically-attended" sports-related injuries to persons in just one age group, "baby boomers" aged 35-54. CPSC data from *Baby Boomer Sports Injuries*, 2000. U.S. Consumer Product Safety Commission, p. 2. Available online at http://www.cpsc.gov/library/boomer.pdf

Audience perception of laser show risk

People clearly enjoy viewing audience scanning laser shows. At entertainment trade fairs we attend, often the largest crowds can be found at the stands of laser show companies who perform elaborate audience scanning shows every hour, as shown in the photos in the Introduction section and at right.

Certainly the audience is aware that lasers are being used. From exposure to movies and TV shows, they may have a preconception of lasers as dangerous, devastating weapons, able to disable or kill with a single blast. Anecdotal evidence from messages on Internet blogs and forums where laser exposure is discussed, makes it clear that the general public is well aware that laser beams can easily cause eye injuries.[30]

Yet audience members willingly stand in an area where they are scanned one or two dozen times with bright laser beams. The reason for this behavior is that viewers are making a risk assessment. They subconsciously evaluate a number of risk factors. They are "voting with their feet" that the risk is low compared with the benefit of seeing a spectacular show. Factors being considered include:[31]

- **Voluntary exposure vs. involuntary:** "Can I choose to watch the laser show, or is this something I am required to do?"
- **Single-person injury vs. multiple persons:** "If an injury occurs, will it happen to one or a few audience members, or to everyone at once?"
- **Common vs. unusual:** "Is the danger from something I'm familiar with ('don't look into the sun'), or is the danger from something I dread such as nuclear radiation?"
- **Non-fatal vs. fatal:** "What is the worst that can happen to me? Will I die?"
- **Immediate vs. delayed:** "If there is an injury, will I notice it immediately, or will it occur hours or days later?"
- **Controllable vs. uncontrollable:** "How much control do I have over the risk? Can I leave or take other action such as turning away or masking the direct beam?"
- **New vs. old:** "Is this something novel that I'm not familiar with? Or have I heard about and seen laser shows so I am generally aware of the risks?"

[30] They may not know details regarding parameters such as power, irradiance, exposure time, etc. They also may not realize other potential dangers, such as distracting or flashblinding pilots with laser pointers. But they certainly are aware that laser beams are an eye hazard and should be avoided.

[31] These factors are adapted from Paul Slovic's book *The Perception of Risk*, Earthscan Publications Ltd., 2000.

- **Known vs. unknown:** "Have I read about injuries, or potential safety concerns? Or have I never seen anything about laser show injuries or hazards?"

Clearly, they assess laser show risk as low or else they would not remain in the audience area. Based on the small number of injury reports, there is a high probability that they are correct.

Analogies with similar risky activities

Audience scanning laser shows are most popular in venues such as discos, nightclubs, raves and rock concerts, where patrons willingly participate in activities which feature a number of potential or actual risk factors:

- **Sound systems can be painfully loud** and are known to cause hearing damage. It is common for patrons to have "ringing ears" the morning after exposure to loud music, indicating hearing damage. In fact, a single evening too close to a speaker can cause permanent hearing damage. Yet there is no move to have completely ear-safe volume levels at all musical performances. Patrons have determined that the potential loss of hearing is not as important to them as the enjoyment of loud levels of sound.

- **Alcohol consumption is widespread.** Often, it is consumed to excess.

- **Smoking is commonly allowed** in many countries.

- **Drugs may be illegally consumed,** especially at raves.

- **Patrons may engage in risky behavior after the show**, such as inebriated driving.

This is not to suggest that "anything goes" with laser power levels, just because "anything goes" with sound levels or alcohol consumption. But it should be recognized that those who patronize discos, nightclubs, raves, concerts, etc. willingly accept a certain level of increased risk.

Risk can be desirable

In fact, the risk may be part of the attraction. People sometimes enjoy things which are not 100% healthy for them. This makes a key point:

> **People understand, accept, and even seek out reasonable risk. A disco or nightclub with moderate, OSHA-approved sound levels, that serves only soft drinks, will have very few patrons.**

The parallel with laser shows is clear. Shows with dim, fuzzy, below-the-MPE beams will excite few viewers. Audiences are proven to seek out higher power shows; for example, at industry trade shows where competing exhibitors run demonstration laser shows.

Patrons can accept and control risks

Another important point is that patrons have significant control over risks. If high sound levels are a concern, they can turn away from the speakers, move to the back of the room, or wear earplugs. If they prefer not to drink or smoke, patrons can abstain.

Similarly, if a person wants to avoid laser exposure, they can move their head, glance away or blink as direct beams approach them (these actions may be involuntary and unnoticed), they can block the direct beam with their hand, or they can stand outside the audience scanning zone. In the latter two cases, they still enjoy most of the show while having no direct exposure.

ILDA believes that patron-initiated risk assessment and management is an important factor responsible for the lack of eye injury reports, even from shows that are well over the MPE.

Finding the Right Balance

The International Laser Display Association has wrestled for years to balance safety, artistic, and commercial concerns. Given the choice of two shows, one with fuzzy beams below the MPE, and one with bright, thin beams above the MPE, viewers and clients will prefer the latter. (If a show is too far above the MPE – too bright – it becomes unpleasant to experience the direct beams. Even then, there are plenty of audience members who will attend such shows, perhaps because they compensate by taking avoidance actions when the beam comes near.)

At ILDA's annual conferences, which generally alternate between North America and Europe/Asia, the association has seesawed. U.S. conference hosts have presented CDRH-legal, below-the-MPE displays which exasperated European members ("You ruined my show! No one could see the effects!"). In Europe, conference hosts have done rehearsals at below-the-MPE levels to satisfy ILDA's safety efforts, but then they turned up the power significantly for the performance, to match how the shows were presented in their original form.

ILDA's position on audience scanning

ILDA currently has the following position on audience scanning:

- **Shows with audience exposure below the MPE** should be encouraged whenever possible. However, these tend to be dim and fuzzy which makes them less artistically satisfying (and less commercially viable).

- **Shows with audience exposure somewhat above the MPE** are safe in the empirical sense of leading to very few (if any) legitimate reports or claims of injuries. Significant reasons were listed earlier; these include: less laser light entering the eyes than is assumed under current standards; actions taken by audience members to reduce exposure, and the built-in safety margins of the MPE concept. Audiences enjoy these shows, and they are probably the most common type of show done worldwide.

- **Shows with audience exposure significantly above the MPE** should be completely banned. These shows are uncomfortable for audiences, they reflect a lack of concern and/or knowledge about safety issues, they may be causing changes and perhaps injuries (though still very minor, given the lack of reports), and they are not good for the image of responsible laser show operation. Unfortunately, there are far too many shows where the MPE is clearly being exceeded by a factor of 25 to 100 or more.

We also note that too many laser show producers do not accurately know how much power they are putting out. They use seat-of-the-pants methods to essentially say "well, this show does not look too bright to me."

As one way to help improve safety, ILDA has developed a list of basic principles of laser show safety. All members are required to affirm that they have "read, understand and acknowledge" the principles.[32] Principle 8 states that audience scanning should be done in accordance with applicable laws, regulations and standards; Principle 9 states that pulsed lasers should not be used; and Principle 10 states that scanning must be done only with appropriate knowledge and measurements.

A New Approach to Audience Scanning

Based on the totality of information presented in this paper, ILDA is therefore proposing a new approach which leads to greater overall safety than today's situation. We suggest that there be two types of audience scanning shows:

- **Shows with audience exposure below the MPE** would of course be allowed, just as they are today.
- A new category of show would allow **shows with audience exposure levels up to ten times the MPE**, under specified conditions which include safe show content, accurate measurements of the beam, cautionary warnings to the audience, and increased liability exposure. In exchange for this, audience scanning would be banned at any level above ten times the MPE.

This could be considered a compromise between those who want only MPE-level shows, and those who feel that today's higher-than-MPE shows are effectively safe. A key benefit of this proposal is that all shows would have to be measured, to accurately know the show's power. Any really high powered show (greater than 10x the MPE) would be banned completely.

We call the first type of show "Level 1" and the second type "Level 2". Here are details:

Level 1 Show: Below the MPE (similar to current practice)

A "Level 1" show does not exceed the MPE limits. A quick and easy-to-measure approximation is to set each laser projector so it does not exceed 10 mW/cm^2 in the audience area, when measured as a static beam at maximum show power, at the point of closest audience access.

A scan-fail circuit should be required which can detect and terminate a static beam in the audience area within 1 millisecond. There must be a trained laser show operator continually monitoring the show who will shut down the beam in cases of scan failure or other increased hazard. For increased flexibility, a more advanced analysis can be performed, taking into account scanning speed and patterns, effective scan-fail safeguards, automated monitoring, or other means as long as equivalent or better safety is provided.

A Level 1 show does not need to have any signage or other indication for audience members that lasers are in use.

Since the MPE concept is embodied in many countries' laser laws, such shows would by definition be legal. If there is any litigation against the laser show company (e.g., by someone claiming an injury), and the laser show company can demonstrate that they took accurate measurements correctly indicating their static beam was within the stated Level 1 limits, then

[32] The principles are available online at www.laserist.org/safety-basics.htm.

the burden of proof is on those bringing the suit to prove that the injury was caused by the laser show.

Level 2 Show: Greater power in return for greater responsibility

A “Level 2” show is allowed to exceed the MPE limits by a factor of ten. Specifically, the exposure limit is raised to 100 mW/cm^2 for a static beam in the audience area. As with Level 1, there must be a scan-fail circuit, and the show must be continuously monitored by a trained laser show operator.

A Level 2 show must post signage with wording such as “Caution: Extra-bright laser lights in use. Avoid direct exposure to beams.”[33] If audio announcements are normally made before the event (such as at a concert), then there must also be an audio warning to the audience such as “Extra-bright lasers will be used. Do not stare directly into the beams.”[34]

If there is legal action against the laser show company, the burden of proof is on the laser show company to demonstrate that 1) they were no greater than 10 times the MPE and 2) that the laser show did not cause the claimed injury.

As part of this proof, it is highly recommended that Level 2 shows be video recorded. The video should include pre-show setup activities such as measuring the beam power. Power levels and results should be called out so that the audio of this activity is captured on the recording. The entire scannable laser area should be recorded during scanning activity. This may require a wide-angle lens, or multiple cameras. Ideally, a camera should be at each projector location so that it can “see” what the beam is hitting. All video footage should be kept for at least 30 days. Industrial security camera equipment and recorders may be appropriate for this purpose.

Such video footage could be invaluable in refuting false claims. A person could be asked where in the audience he or she was standing. Since beam power measurements had been made and videotaped, it would be relatively easy to calculate the maximum power at that location. To give another example, if audience members were aiming their own laser pointers at each other, the video should show this type of misuse as well. Even the fact of recording the show’s laser activity helps demonstrate that the producer is safety conscious and has nothing to hide.

Choosing between Level 1 and Level 2

Certainly, there will be venues and clients which are “scared off” by the Level 2 requirements. For example, corporate clients and amusement parks may be more comfortable with Level 1 shows. This is fine; Level 2 is intended for discos, nightclubs, concerts and other venues where audiences may already be accepting (or even welcoming) a higher level of risk and a greater degree of personal risk management.

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[33] This is similar to the warning signs that are posted at amusement parks, such as “Ride at your own risk. Persons with heart conditions or a fear of heights spaces should not go on this ride”. The signs give additional information to willing participants, without preventing everyone from riding. The signs may also help in liability cases, to demonstrate that participants were warned in advance of the risks.

[34] Such warnings may have real benefits. In the few cases where an audience member had a proven, severe eye injury, often a key factor is that the person deliberately stared into a beam. (This may be due to intoxication or simply to poor judgment.) Warning signs and announcements are one way to help reduce even these small number of cases.

Non-measured shows are not permitted

It is important to note a corollary of the above proposal. All audience scanning shows must be measured. It does not matter which Level, 1 or 2, is in use; the irradiance at the audience must be accurately known before the show starts.

This is a significant improvement over current practice, where many audience scanning shows are not adequately evaluated. The laser power is simply adjusted until “it looks good”. Under the Level 1/Level 2 proposal, no audience scanning is permitted unless the power is known.

Simplifying Audience Scanning Projectors

The Level 1/Level 2 requirements may be relatively easy for full-time laser show professionals to achieve. They have, or can easily gain, knowledge of how to accurately measure the static beam and how to adjust the projector to achieve the required limits.

However, this is not so easy for users of increasingly popular mass-produced laser projectors that run off the DMX standard used by lighting consoles. Such a person may be a mobile DJ or a disco owner who goes to eBay or other Internet sources to purchase a “plug-and-play” DMX laser projector. They may not be aware of, or want to comply with, restrictions on audience scanning. Since the laser projector looks and works like a standard lighting instrument, the buyer may aim it at the audience in the same way.

To help improve safety in this situation, ILDA proposes that laser projectors can have an optional user-activated audience scanning mode. This can be done by sliding a lens in front of the output, by electronic controls, or by any other means so that the maximum laser power is known at a given distance from the projector. The projector will have a permanent label stating the distance, such as “Approved for Level 1 audience scanning when lens is inserted and laser is at least X meters from the closest point of audience access.” Also, when in audience scanning mode, a scan-fail circuit capable of detecting and terminating laser output within 1 millisecond would be required.

There may need to be an upper limit on the output power of such a “consumer-level” laser projector.[35] It is intended for discos, nightclubs, hotel ballrooms and other relatively small venues where someone with limited laser knowledge might install a mass-produced laser in the same way they buy and install a lighting instrument. It is not intended for concerts, stadium shows and other venues requiring high powered lasers.

Other considerations for audience scanning projectors

Here are some additional implementation notes:

- The distance requirement stated on the label is for the laser with the power turned up to maximum. The user of course may turn down the power if desired.
- A projector may come preset with no user safety adjustments other than turning down the beam power. In such a case, the labeling is simple (see example immediately above).

[35] ILDA has not at this time considered what might be a reasonable upper limit. A very rough approximation might be 500 milliwatts.

- A projector may be user-adjustable to give options such as unrestricted output, Level 1 at 30 meters output, and/or Level 2 at 30 meters output. Such adjustability is acceptable as long as it is made clear to the user what the closest acceptable Level 1/Level 2 distance is to the audience, in each mode.
- The end-user is legally responsible for correct implementation. For audience scanning, they shall not operate the laser at a closer distance than what is indicated on the laser projector.

One advantage of this system is that it makes it much easier for non-experts such as a disco owner to check whether an installation is safe. They merely note the indicated distance on the projector, and measure to the point of closest audience access. (For a full safety inspection, the beam irradiance should of course be measured directly.)

Putting Level 1/Level 2 Into Action

Initial enactment of the Level 1/Level 2 proposal does not have to be done on a formal basis. Those involved can take the following steps:

- **Laser show producers** can measure their shows to know the irradiance they are using. They can increase divergence to 5-10 milliradians in the audience area, to allow more power while keeping the average power irradiance below 10 mW/cm^2 (or 100 mW/cm^2 for Level 2 shows) at the point of closest audience access. They can use safety hardware; at a minimum there should be a scan-fail safeguard capable of terminating a static laser beam within 1 millisecond. If doing a Level 2-type show, they can provide caution signs and work out any audio announcements with the venue. They should also record all laser activity, including pre-show measurements.
- **Laser show clients and venue operators** can require that shows be done in accordance with Level 1 or Level 2 -- whichever is more appropriate and comfortable for the client/venue. Because regulators may not always know about or be able to enforce audience scanning limits, the client and/or venue may have more influence over the light levels used for their shows.
- **Regulators** should focus on shows which are significantly over the MPE. Shows which slightly over (defined here as 10x the MPE) should be permitted if Level 2 steps such as caution signs are taken. This can take the form of an informal enforcement policy.
- **ILDA** should present a formal Level 1/Level 2 policy to standards-making bodies such as IEC and ANSI. The policy can be reviewed and modified, and if consensus is reached, be incorporated into the appropriate standard.

Future Research Directions

ILDA believes that the current state of knowledge about injury rates, audience-initiated avoidance behavior, and risk assessment is sufficient to justify the Level 1/Level 2 proposal as increasing the already safe (non-injurious) practice of audience scanning.

However, additional evidence is always welcomed. This can include the following:

- A more extensive **search** to try to find any additional injury reports.
- **Survey** persons leaving audience scanning laser shows. Ask if they notice any visual impairments. Follow-up a few days later to see if lasting changes are reported. Of course, there may be problems. For example, a person may start to notice normal eye defects, such as floaters, or they may have had a pre-existing visual impairment not due to laser exposure. The survey gives directions for follow-up research, but should not be relied on alone as an indicator of audience scanning effects.
- A **medical study** can be conducted of persons who frequent audience scanning laser shows. This can be done independently to see if there are detectable changes to their eyes, or it can be done in conjunction with the above survey to further examine any reported visual impairments. If numerous or unusual changes are found, a comparison study with a control group should be done.
- **Videotaping**, for later analysis, viewers as they watch audience scanning laser shows. This allows study of viewers' avoidance behaviors. One good location to do this is at a trade fair where a number of laser show companies have demonstration shows. Often there is a wide variation between shows' brightness levels. Avoidance behaviors at "soft" shows, closer to the MPE can be compared with behaviors at "harder" shows that may have uncomfortable light levels.

If such studies show that there are significant changes or visual impairments from audience scanning, then of course the issue needs to be reexamined. Until then, ILDA's position remains that the Level 1/Level 2 proposal is a safe and reasonable compromise leading to an overall reduction in audience exposure.

Summary

In an audience scanning laser show, viewers are surrounded by beautiful, futuristic light patterns, moving to music. As an unintended side effect, laser light scans across viewers eyes roughly one or two dozen times per show. We estimate that, in 30 years of audience scanning laser shows, there have been at least 109 million person-exposures[36] to 11 billion scanned pulses from continuous-wave laser light.

The irradiance at the point of closest viewer access should be below the lowest (safest) applicable MPE: average, single-pulse or multiple-pulse. However, MPE-level effects tend to be dim and fuzzy.

For this reason, many shows are over the MPE -- often by a factor of 25 to 100 times or more. Fortunately, despite over 109 million person-exposures, injury claims are very rare. They are rare both on an absolute scale and when compared to injury claims from other leisure activities such as amusement park rides or recreational sports.

It is likely that there are a number of mechanisms that reduce exposure below that which is assumed by current standards and regulations. These include the distance to the audience (e.g., higher beam divergence than in laboratory accidents), the use of moving beams, the pupil

[36] As explained earlier in this paper, one person being exposed at a single show or event. A single person may attend multiple shows or events, thus creating multiple "person-exposures".

being more closed than regulations anticipate, and viewers who actively take action to reduce exposure.

By analyzing shows, it can be shown that scanning reduces the exposure by 4 to 10 times compared with the same beam in a static condition. This is because the scanned beam is seen as pulses as it crosses the eye. Thus the single-pulse or multiple-pulse MPE applies.

This knowledge makes it much easier to set up a safe audience scanning show, by measuring the static beam at the point of closest audience access. Beam power is lowered (or, preferably, divergence is increased) until the irradiance is four times that of the static MPE. (Additional analysis can be done to confirm that effects do not have hot spots, that any scan-fail circuit works as intended, etc.)

ILDA recognizes the tension between those wanting MPE-level dim and fuzzy shows, and those wanting to continue doing brighter, more impressive (and commercially viable) shows. We note that current shows (even those well over the MPE) do not appear to be causing significant numbers of injuries. Our assertion is that there are mechanisms which reduce exposure (avoidance, smaller pupil, etc.). Also, risk acceptance by the audience is a key factor. Many audience scanning shows take place in environments where risks such as loud music and drinking are accepted and even sought out.

ILDA therefore proposes allowing “Level 2” shows which can be up to 10 times the MPE, if patrons are cautioned to avoid direct viewing and if liability burden of proof is on the operator. Shows above 10 times the MPE would be prohibited.

Finally, ILDA proposes a method for “plug and play” mass-produced laser projectors to have an audience scanning mode which is easy for just about anyone to understand and implement.

ILDA understands that these proposals may not find their way into standards and regulations -- certainly not anytime soon. ILDA may modify the proposal based on additional comments, analysis and research. But we put forward these observations in the hope that they can stimulate some interest and discussion among everyone involved: laser show producers, clients hiring laser shows, laser safety experts, and regulators.

About the Authors

Patrick Murphy is executive director of the International Laser Display Association. ILDA has 150 members in 38 countries that are involved with laser shows and displays. Murphy holds a BA in laser art and technology and an MBA degree. In 2004, he received ILDA’s Career Achievement Award for innovation in laser software and for work in the 1990s as ILDA Airspace Issues Coordinator. He would like to thank William R. Benner Jr. for sharing his knowledge and insight into audience scanning safety considerations.

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