How to create a safe audience scanning laser show

Making laser light shows safe and enjoyable

By William R. Benner, Jr.

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Successfully determining the safety level of an Audience Scanning laser show requires not only the proper tools, but also an understanding of the theory behind safety exposure limits and the ability to correctly interpret measurement data. This article is intended to explain the basic concepts of Audience Scanning evaluation, along with a "hands on" approach to evaluating audience scanning effects within a laser show.

This article is based on a lot of research into audience scanning safety, and has also been reviewed by safety experts including **Greg Makhov, ILDA Safety Committee Chairman,** and **John O'Hagan of the UK National Radiological Protection Board.** Since the resources used in preparing this article have been mainly based in the United States and the United Kingdom, there is a possibility that in other countries, different analysis techniques can be used to evaluate beams projected into the audience. Moreover, in some countries such as Sweden, it is illegal to scan the audience with a laser beam. Because of this, you should seek the advice of local regulatory officials.

Before explaining how to evaluate a show, it might be good to answer a very fundamental question -- why go to the trouble of evaluating a show to make sure that it is safe? There are at least three answers to this question:

Reason #1. To avoid possible legal action

If someone is exposed to an unsafe show, it is possible the show will harm their vision. In climates of heavy litigation such as the United States, it is likely that this person would seek legal action against the venue owner and the show producer. If the show was determined to be operating at unsafe levels, it raises the probability of that person being awarded a claim of damages, even if the harm was not caused by the show. If on the other hand, shows were being done completely safely, no vision damage would occur. Even if someone decided to try frivolous legal action, it is unlikely that they would be able to collect a claim if the show is operating at safe levels.

Reason #2. Safe audience scanning shows are more enjoyable than unsafe ones

When operated at safe levels, audience scanning shows leave little or no afterimages, which makes the whole show enjoyable. You should test this yourself. The next time you have the opportunity to view audience scanning shows, pay particularly close attention to your vision as various effects cross your eyes. Effects that appear to leave a strong afterimage are not pleasant to experience and detract from the whole show. When this happens, your eyes will be too busy recovering from the last effect to enjoy the next one. However, effects that leave little or no afterimage are beautiful and fun to experience.

Reason #3. Because it can be done safely

As humans, if something seems difficult to achieve, we sometimes would rather avoid it instead of challenging it. As you start to learn about the many aspects of laser safety, it may seem as though there are far too many variables and formulas to calculate, which makes audience scanning safety hard to evaluate. Instead of seeking the help of safety experts, it is easier to simply deny that there is a safety problem. This article will first introduce some definitions of terminology, and then show you how to evaluate an audience scanning show.

Definitions of audience scanning terminology

Irradiance

Probably the **most important and fundamental concept to laser safety is irradiance**. This is a big word that simply means concentration of laser power per unit area. It can be found by dividing the power of the beam by the area that covers. For example, if a 1 watt beam covers a 1 square centimeter area, it has an irradiance of 1 watt per square centimeter. If that beam is allowed to diverge to cover a 2 square centimeter area, notice that it has expanded in both width and height. In this case the irradiance is 1 watt / 4cm (2cm high X 2cm wide) = 0.25 watts per square centimeter. Although the irradiance has greatly decreased because the beam has expanded to cover a larger area, the total beam power is still exactly 1 watt.

The reason that irradiance is so pivotal to laser safety is that for safety evaluation, your eye is considered to have a pupil diameter of 7mm. Any beam that enters your eye with a diameter of 7mm or smaller, will deliver the full power of that beam into your eye. However, if the beam is larger than 7mm, your eye will only be exposed to the portion of the beam which is allowed to enter the eye, so of 7mm. The ANSI Z136.1 Standard for Safe Use of Lasers uses watts per square centimeter as the unit of measure for safety evaluation. Some other standards use watts per square meter as the unit of measure.

Average power versus peak power

Lets say that you want to project the image of a circle onto a screen. There are at least two ways of producing that image:

- Directing a beam through an optical element such as a diffraction grating
- Directing a beam to a set of scanners which can rapidly draw the circle and make it appear solid. The reason that scanners can create the same solid image on a screen is because of a phenomenon called persistence of vision. If the diffraction grating and the scanners produce the same image, they will have the same brightness on the screen because they will be spreading the total laser power out around the screen by the same amount. At any one point along the circle, the average power may be 1000 times less than the power of the laser.

However, just because these images look the same, don't forget that in the case of the scanners, there is just one spot on the screen at any one point in time, and this spot has the entire power of the laser. If you place your eye at that point along the circle, and the beam diameter is 7mm or less, your eye will receive the total power of that laser each time the beam scans past your pupil. Using our 1 watt laser as an example, even though the average power is 1mW, the peak power that your eye will get is 1 watt! This peak power is the most hazardous and easiest overlooked element of audience scanning safety evaluation.

Pulses and multiple pulses

When a laser beam scans across the pupil, it is said to deliver a pulse of laser light to your eye. This is because as the beam scans past your eye, it will only enter your eye for a brief time depending on beam diameter and the scan rate. This pulse of light created by the scanned beam is similar to a pulse that is created by a beam that is not scanning, but is turned on for only a brief instant. The amount of time that the beam is on within your pupil is called the "pulse-width".

For audience scanning shows, this pulse-width is commonly 20 to 500 microseconds. When you project an effect such as a tunnel or sheet scan, this is done by continually scanning the tunnel or sheet to make them appear solid. As the beam crosses your eye, it will allow a pulse of light to enter your eye. Since the scanners will trace this effect many times to make it appear to be solid, your eye will receive multiple pulses of light. The reason that the concept of pulses and multiple pulses is important is because safety standards prescribe a maximum amount of light that you can be exposed to for a single pulse, and for multiple pulses.

How to evaluate an audience scanning show

Within this article we will discuss **how to evaluate a laser show** using manual calculations assisted by basic measurement tools. This requires the ability to project a stationary effect. Although your laser projector can be scanning an effect such as a sheet scan, tunnel or array of beams, the effect itself must remain stationary because a light detector has to be placed into the scanned beam effect to obtain an accurate measurement. For this reason, ADAT or other taped shows cannot be effectively evaluated using these techniques.

Tools needed for manual calculations assisted by basic measurements

Calibrated Laser Power Meter

You must use a **laser power meter** designed to measure static (non-moving and non-modulated) beams. Since the meter should be able to measure low light levels, the meter should use a silicon detector with flat spectral response. For ease in performing safety evaluations, you should use one with an active area of 1 cm2 (one square centimeter). Using this size detector is easier because if the beam fills or overfills this detector, the meter will be extraneously measuring irradiance (concentration of laser power) in watts per square centimeter. Although other detector sizes can be used, you would have to perform a calculation to convert units of measure. For simplicity, this article assumes that a 1cm2 detector will be used.

Fast silicon photodiode with amplifier

Fast silicon photodiodes are available from several vendors, including Hamamatsu, Centronic and UDT. Since these devices output a current instead of a voltage, an external amplifier must be used to facilitate connecting them to a scope. Alternatively, you can purchase a detector with a built-in amplifier such as the OSI series from Centronic. For audience scanning pulse-width measurement, the active area of the detector should be 7mm or greater. If it is greater than 7mm, you will need to make a mask with a 7mm hole and place it over the detector. This is called a limiting aperture. (7mm is the internationally recognized ocular pupil diameter to be used for safety evaluation.)

Oscilloscope

An oscilloscope will be used along with the fast silicon photodiode to measure the pulse-width and pulse repetition rate. Analog field scopes with a vertical bandwidth of 50MHz or greater will work fine. Digitizing oscilloscopes should be used with caution because sample aliasing can result if you are not careful.

Scientific calculator

Any calculator capable of doing exponents and powers of ten will work fine. Often, I use the Calculator program that comes with Microsoft Windows, (select "scientific" mode from the view menu).

Some technical skill...

Manual audience scanning safety evaluation is quite tedious and error prone. It requires knowledge and experience to use the tools specified above and should only be done by individuals who are technically adept.

Evaluating the laser show

After the equipment has been prepared, you should run the entire show several times to identify and list particularly bright and hazardous effects. Once these have been identified, evaluate each of them by doing the following:

Step 1.

Measure the laser beam irradiance at the closest point of audience access. To do this, project a non moving beam into the venue. (Ideally, this should be done back at the studio, with good prior knowledge of the show site. Do this at the venue only while the room is not occupied by non-laser people or audience members.) This beam must be the same color and power level as the effect being evaluated. Carefully place the detector head into the beam at the closest point of audience access. (Be aware that light can be reflected off of the detector head, particularly with silicon detectors. Make sure that this reflected light does not pose a hazard to others in the room.) Make sure that the beam overfills (or at least fills) the one centimeter detector area.

If the beam diameter is less than one centimeter, this is already an unsafe exposure unless you are using laser powers below 15mW. Record the value reported by the meter as "watts per square centimeter". For example, if the meter reads 7.5mW, you would record it as 7.5mW/cm2. Now 7.5mW may seem extremely low [see note 1]. Who would do a show with a 7.5mW beam? Why even measure a 7.5mW beam? The answer is that in step 1, the beam is not 7.5mW, its irradiance is 7.5mW per square centimeter. Hopefully the beam diameter would be greater than one centimeter, and the 7.5mW would be collected in the brightest portion of the larger beam. Tens of watts of actual beam power can be used provided that the beam diameter at the closest point of access is large enough to lower the irradiance to an acceptable level.

Step 2.

Measure the pulse-width of the effect as it crosses the eye. To do this, project the effect into the venue and carefully place the fast photodiode into the effect at the brightest place in the effect. (Again, be aware of stray reflections.) The brightest place will probably have multiple points in the image to hold the beam in place for accentuation (e.g. at a corner or anchor point). Using the oscilloscope, measure and record the pulse-width, adjusting the horizontal time base as needed. (Although there are many ways to define pulse-width, safety experts agree that the "Full-Width, Half-Maximum" points should be used. For example, if the pulse is 2 volts in amplitude, measure the width at the 1 volt point.) Depending on the effect, this will probably range from around 20 to 500 microseconds. (Make sure that the detector is not saturated during this measurement. If the pulse has a flat top, it could be saturated and you should use a neutral density optical filter to reduce the amount of light striking the detector.)

Step 3.

Measure the pulse repetition rate. To do this, simply increase the horizontal sweep time until you see two or more consecutive pulses, and measure the time between pulses. Using the scientific calculator, compute the repetition rate by taking the inverse of this time. For example, if you measure 16 milliseconds (0.016 seconds) between pulses, the pulse repetition rate would be 1 / 0.016 or 60H

Now that we have collected information about the effect, we will see how this effect stacks up agai the Maximum Permissible Exposure [MPE] prescribed by safety guidelines and government regulations.

Step 4.

Compute the single-pulse Maximum Permissible Exposure [MPE] for this effect. This is the safety guideline or government regulation prescribing the maximum amount of irradiance (laser power density) that is considered safe for a given pulse-width. To compute the single-pulse MPE [see note 1] (in Watts per square centimeter), raise the pulse-width (in seconds) to the 3/4 power, multiply the result by 0.0018 and divide the entire result by the pulsewidth (in seconds).

For example, if the pulse-width is 100 microseconds (0.000100 seconds) the calculation would be (0.000100) ¾ X .0018 / 0.000100 = 0.018 W/cm2 or 18 milliwatts per square centimeter. (To do this with the scientific calculator provided with Microsoft Windows, enter 0.0001, press the X^Y key, enter 0.75 (equivalent of 3/4), press *, enter 0.0018, press /, enter 0.0001, and press =.) If the irradiance measured in Step 1 is greater than the single-pulse MPE, stop right there -- the effect is not even safe for one pulse of laser light (one scan across your eye) and must not be performed before an audience.

Step 5.

Compute the multiple-pulse MPE for this effect. This is a reduced version of the single-pulse MPE, based on the number of pulses that the audience member will be exposed to. Basically, the more pulses of light that are received by the eye, the less light allowed per pulse. To compute the multiple-pulse MPE, multiply the exposure time (in seconds) by the pulse repetition rate, and raise this number to the -1/4 (negative one quarter) power. For example, if the exposure time is 1/4 second [see note 2] and the pulse repetition rate is 60Hz, the calculation would be (0.25 X 60) -1/4 = 0.508. (To do this with the scientific calculator provided with Microsoft Windows, press the (key, enter 0.25, press *, enter 60, press the) key.

This gives you the total number of pulses experienced during the exposure time. Then press the X^Y key, enter 0.25 and press the +/- key (equivalent of -1/4), and then press =.) You then multiply this factor by the single-pulse MPE to derive the multiple pulse MPE. In this example, it would be 0.018 X 0.508 = 0.0091 W/cm2 or 9.1 milliwatts per square centimeter. If the irradiance measured in Step 1 is greater than the multiple-pulse MPE, stop right there -- the effect is not safe for the exposure time and would have to be reduced and re-measured before performing before an audience.

Step 6.

Compute the average power delivered by this effect and compare it to the average MPE for the exposure time. To do this, multiply the irradiance measured in Step 1 by the pulse-width, multiplied by the pulse repetition rate. For example, if the irradiance is 7.5mW/cm2 and the pulse-width is 100 microseconds and the repetition rate is 60Hz, the calculation would be 0.0075 X 0.000100 X 60 = 0.000045 W/cm2 or 0.045 milliwatts per square centimeter average power. Using the calculation for single pulse MPE, we can find the average MPE for a 1/4 second exposure (since the exposure time is 1/4 second in this case) as 0.25 3/4 X .0018 / 0.25 = .00255 W/cm2 or 2.5 milliwatts per square centimeter. If the average power delivered by this effect is greater than the average MPE, this effect is not safe for that exposure time.

It is handy to have someone check your calculations. Mistakes can have an immediate effect on the audience, unlike calculating X-ray exposures where your mistakes manifest themselves 20 years later.

In order for the effect to be considered safe, it must not exceed any of the three MPE limits. In audience scanning shows, the multiple-pulse MPE will be the most restrictive and the average MPE will be the least restrictive. This particular example illustrated this as the single-pulse and average MPE were not exceeded but the multiple-pulse MPE was.

Score the Whole Show

The manual processes described above should be repeated for as many effects as possible. Or, if time is limited, you should measure the effects that pose the greatest hazard. These are ones which project only a few beams into the audience or project patterns which are small in size or look particularly bright. If an effect exceeds the MPE, you can reduce the laser power or brightness of the effect, or change the effect to decrease the pulse-width or number of pulses. You should also consider the "total MPE" of the entire show. If all of the effects in your show were barely below the MPE, the show as a whole would probably be above the MPE. Since you are calculating the MPE for only specific effects in the show, you must manually "score" the whole show. Unfortunately, at this time, nobody has developed a statistical method of arriving at this "total MPE". Until that time, err on the side of safety by reprogramming effects that are "on the edge".

Increasing divergence to reduce the irradiance

While reading this or performing measurements on your own show, you may realize that relatively l beam powers must be used if the beam diameter at the audience is small. This is because if the beam diameter is small, the irradiance is high. You can decrease the irradiance by increasing the beam diameter at the audience, which will allow substantially higher beam powers. To do this, you will have to use a lens or collimator. Multiple watts of laser power may be used if the irradiance is kept to a reasonable level by expanding the beam.

A simplified approach

After performing manual analysis over and over, on hundreds of effects and shows, it will be seen that in order for an Audience Scanning show to be safe, several factors need to be in place:

- The actual scanning and beam modulation need to happen at a rate fast enough to keep the pulse-width experienced by the eye around 1millisecond or faster.
- The maximum irradiance of a beam measured at the closest point of audience access needs to be somewhere between 5mW/cm2 and 10mW/cm2.

If you accept these two factors, then a simplified approach can be used to evaluate audience scanning safety. The simplified approach involves measuring the irradiance of a non-moving, non-modulated beam at the closest point of audience access, in a manor similar to Step 1 above. The beam must represent the highest power level that will ever be found in the audience, thus allowing you to gauge the maximum irradiance that will ever be experienced by the audience. For an RGB laser projector, this should be a white beam. Note that with modern software, it is often difficult to get a non-modulated beam, since most of the time, modern software will always be modulating the beam for some reason -- for example, during inter-frame blanking periods, whether an animation is being projected or not.

Therefore you must consult your software company to find out how to get a non-moving, non-modulated, and essentially full-power beam out of the software so that this measurement can be performed. Once the irradiance of a non-moving, non-modulated beam is measured, it must be between 5mW/cm2 and 10mW/cm2. If the beam power is higher, you will need to reduce the power coming out of the projector, or increase the divergence to achieve an irradiance level between

5mW/cm2 and 10mW/cm2. And of course, this simplified approach can only be used AS LONG AS a reliable system is in place to ensure that the two factors mentioned above are not violated under any circumstances.

(The rigorous mathematical basis for this simplified approach is not presented in this article, however, it should be noted that this is also the consensus of the Thesis on Audience Scanning Risk Assessment by John O'Hagan. The Theses can be consulted for more detailed information.)

Keeping the laser show safe

Just because the show passes all of the evaluations now, does not mean that it will stay that way. A number of things can happen to make the show unsafe. Examples of these include: sudden increases in beam power, and something about the projection system failing, stopping the scanning from occurring including computer, cabling or scanning system failure. You must consider reasonable failure modes and provide control measures (such as scan fail safeguards) to limit the consequences. Pangolin's PASS system was designed to monitor the projected beam power as well as the scanning system and other projector-related systems and ensure that these are operating within a safe level.

A Reward for Your Hard Work

The next time you have an opportunity to view audience scanning shows, pay particularly close attention to your vision as various effects cross your eyes. Effects that appear to leave a strong afterimage are not pleasant to experience and detract from the whole show. When this happens, your eyes will be too busy recovering from the last effect to enjoy the next one. However, effects that leave little or no afterimage are very beautiful and fun to experience. In this case, your eyes will say "Wow! I made it! And I can continue to enjoy the show!" It turns out that effects that exceed the MPE will generally cause afterimages, while effects which do not exceed the MPE will not. As artists, you can learn from the MPE measurements and create shows that are safe and enjoyable by all.

Audience Scanning Safety Endnotes

Note 1. Throughout this article, the MPE values expressed are from the ANSI Z136.1 Standard for Safe Use of Lasers. Although this is technically different from other international safety standards, the main difference for visible wavelengths is the units of measure. For example, while the ANSI standard uses Watts per square centimeter, some other standards use Watts per square Meter. However, these standards are surprisingly in agreement as to the actual "Exposure Limits". You should refer to the laser safety standard for your country and seek regulatory advice. In some countries such as Sweden, it is illegal to scan the audience with a laser beam.

Note 2. When determining the exposure time for an effect, you should take into account how long the effect will linger in place. For example, fan effects and tunnel effects that are moving will sweep past the eye very quickly, and thus, the exposure time would be very short -- perhaps on the order of just a single sweep. But fan effects and tunnel effects that are not moving will scan past the eye multiple times, causing a longer exposure time. When in doubt, a quarter second (0.25 seconds) may be used since humans will "avert" the beam (by blinking or turning their heads), and one quarter second is the universally-accepted natural aversion response within laser safety standards.

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