Art versus Science: Audience Scanning with Lasers

By Greg Makhov, chair ILDA laser safety committee

There are opposing viewpoints about audience scanning with lasers. Simply put, the artistic approach to audience scanning is based on the idea that the laser is a lighting effect, and that the brightness of the lighting effect is set by eye, for the best look. This will take into account the distance from the source, fog density, and competing light. It is a ***subjective*** approach. For example, setting the volume level of a sound reinforcement system is normally done by ear.

The scientific approach to audience scanning involves calculations and measurements, comparing the exposure with the safe exposure limit, without regard to the artistic consequences (such as the effect being too dim). It may ensure safety, but may not ensure effectiveness. This is an ***objective*** approach. Adjusting an instrument, such as an X-ray machine, is normally done using a set of measurements.

Much of this has to do with the perceived hazardous nature of the equipment being adjusted. Lighting systems and sound systems are generally not considered hazardous in their intended operation, and one can clearly see (or hear) their correct operation. Lasers and X-ray machines are considered hazardous, and some aspects of their correct operation are invisible to normal human senses, so a more precise approach is indicated to ensure proper and safe operation.

What's Wrong with a Subjective Approach? Sound Reinforcement Example

In most temporary show environments, the audio technician does not use a decibel meter to set the amplitude of the sound system. While most audio techs are well familiar with the concept of hearing damage from high volume levels, little or no thought goes into the practice of ensuring that this damage potential does not occur. Short bursts of feedback can reach painful sound pressure levels almost instantaneously. Also, little consideration is given for audience proximity to the sound stacks. While the mixing console may be 50 to 100 meters from the main stacks, the audience members may be as little as 1 meter in front of the stacks. Sound Pressure falls off following the inverse square law, as does light, so a person twice as close to the source will receive four times the Sound Pressure Level (+6 dB).

Over the past 50 years, as high power sound systems have become increasingly common at entertainment events, there are numerous studies that have demonstrated hearing loss in persons who regularly attend such events. This is an established fact, not a hypothesis, yet most audio techs take no measures to ensure that this type of damage is not inflicted upon their audiences. It does not take a big sound system to cause this type of injury, just a matter of proximity. One's hearing can be damaged by a small sound system in a bar or a club just as readily as by a stadium capacity system at a major concert.

Moreover, the audio technicians who set up and adjust such systems all too frequently have hearing damage themselves, which leads to compensation by adjusting the sound system even louder.

The Objective Approach - *Science*!

The Basics of Laser Measurement

A beam of laser light can be measured in terms of energy (**Joules**) or power (**Watts**). These can be interchanged if we know the time during which the laser beam emits (1 second, 1 hour, etc.) A 1 Joule per second laser is a 1 Watt laser, and a 1 Watt laser emits 1 Joule each second.

Generally, when a laser emits continuously, we refer to the output in terms of Watts. If the laser emits for less than 1 second (such as a pulsed laser, which may emit in milli- or microseconds), we will often refer to the output in terms of Joules. However, any laser can be described in either unit, and for some laser exposures, we may find one unit more appropriate than the other. Some repetitively pulsed lasers are rated in Watts of average power, whereas a brief exposure to a CW laser may be described in millijoules.

A second important concept is the concentration of the power or energy. To explain the concept, consider the case of sunlight. Direct sunlight feels warm on your skin. However, sunlight passed through a magnifying glass and onto your arm will burn the skin (rather quickly!). The difference lies in the concentration of the light.

The concentration of power is known as **Irradiance**, and the concentration of energy is known as **Radiant Exposure**. These are usually given in Watts/centimeter squared and Joules/centimeter squared respectively. These units are probably the best measure of a laser beam as far as damage potential is concerned. We cannot answer the question of whether a 20 Watt laser beam will cause injury, but we can assuredly answer that a 636 Watts/centimeter squared beam will burn your hand (636 W/cm^2 = 20 W/0.0314 cm^2, or a 20 Watt beam with a 2 mm beam diameter). A 20 Watt laser beam that is 10 meters in diameter is merely a bright, directional light; the same power in a 2 millimeter beam has a burning intensity. *Same power, different irradiance.*

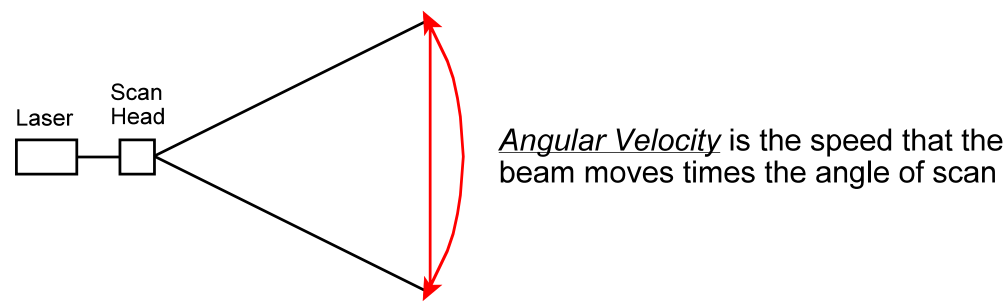
Scanning Beam - Division by Time

Beam scanning is changing the pointing direction of the laser beam over time. It can be very slow or very fast, over a small angle or a large angle. Scanning can also be performed by a variety of technologies; polygon scanners, galvanometer scanners, rotating prisms, and rotating HDGs (holographic diffraction gratings) can all serve as scanning devices. Some of these devices can scan lines, other scan circles or complex patterns. Some can start and stop very rapidly, some can take minutes to speed up or slow down.

Measuring Beam Deflection

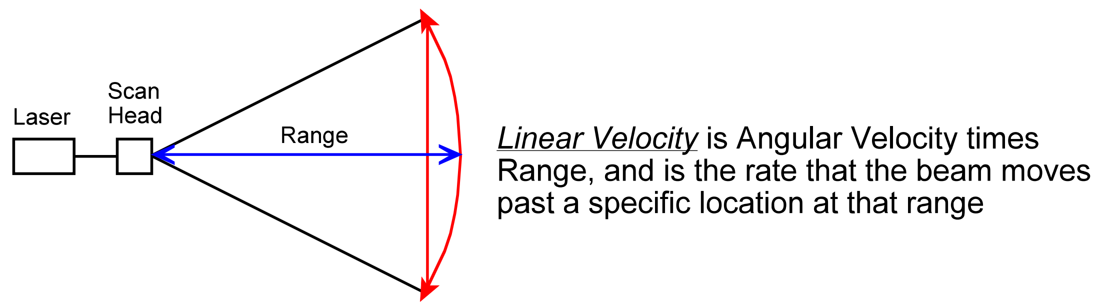
For our first example, let us imagine a scanning device that deflects the beam over an arc of 1 Radian (about 57 degrees) in 1/100 of 1 second (10 milliseconds). To keep our example simple, we will only look at a single direction of scan, not a reciprocal motion. We will also assume that the beam has a constant velocity. If the scan is repetitive, we can say that this scan occurs 100 times per second, or that the scan has a radial velocity of 100 radians per second (1 radian angle times 100 scans per second). This is defined as the **Angular Velocity**.

Example 1



For our second example, let us assume that the distance from the scanning device is 10 meters (1000 centimeters). From this additional information, we can determine two results: the length of the scan path (at 10 meters) and the **Linear Velocity** of the scanning beam. With a 1 radian scan angle and a distance of 10 meters, the scan path length is equal to the angle (in radians) times the distance (1 radian x 10 meters distance = 10 meter path). Since we know that the scan rate is 100 scans per second, and the beam moves over a path of 10 meters in each scan, the Linear Velocity is equal to the 100 scans per second times the path length of 10 meters, or 1000 meters per second .

Example 2

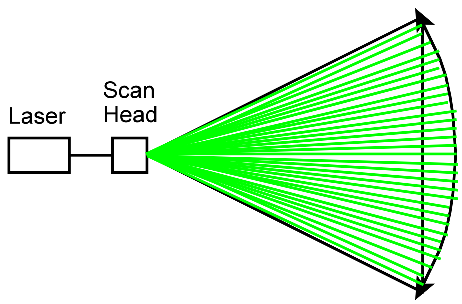


In our third example, we will use a given value of 1 centimeter for the beam diameter. If we compare the 1 cm diameter and the path length of the scan of 1000 cm, we can say that the path length is 1000 times the diameter of the beam. Moreover, since we know that this path length is traversed by the beam 100 times per second, the beam will cross its own diameter of 1cm in (1000 cm x 100 scans per second) 1/100,000 of a second, and will be scanned 100 times in 1 second.

One could accurately describe the scanned line as dividing the power of the beam over the path length of the scan, or that at any one beam diameter location on the line, an average power that is 1/1000 of the peak power would be present. However, the actual power incident in any 1 cm diameter of the path length as the beam passes that point will be the peak power of the beam (1 W).

Another way of looking at the example is taking into account the amount of time that the beam is at any one location. If the scan is repeated 100 times per second, and the path length is 1000 centimeters, then the scan rate is 100,000 centimeters per second. Hence, the beam will only be at a single location (1 cm across) for 1/100,000 of a second or 10 microseconds. With 100 scans per second, each location will be revisited 100 times in a second, so the total time spent at one location is 100 x 10 microseconds = 1 millisecond, for each second of scan.

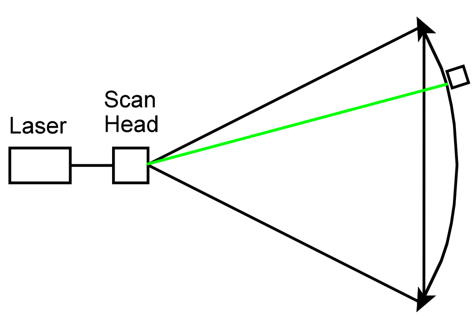
Example 3



Energy at one location can be reduced by scanning, where the power is "spread out" over the scan path

For our fourth example, let us assume that the laser is 1 Watt in power. If we take the concept of dividing the power over the area of the scan path, the average beam power will be 1 milliwatt per centimeter. Also, if we multiply the power of the laser with the time of exposure (1 Watt x 10 microseconds) , the energy per exposure is 10 microjoules per pulse. However, with a 100 pulses per second, the energy per second is (100 x 10 microjoules) 1 millijoule per second (which is 1 milliwatt).

Example 4



Average Power is the energy of the beam at one location per second

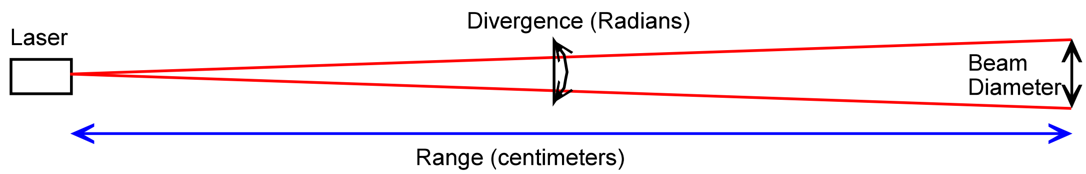
Distance and Divergence: Irradiance

Another measure of a laser beam is the rate at which it spreads out, or diverges. While the divergence of a laser is an inherent property of the particular laser cavity, it can be modified by external optics, such as a collimator or telescope.

The standard unit of measure for divergence is the radian, and usually laser beam divergence is in units of milliradians. A typical Argon gas laser may have a divergence of 1 milliradian, where a high power Nd:YAG laser may have a divergence of 10 milliradians.

If we know the divergence of the laser, and the range to a target, we can easily predict the spot size (diameter) of the beam on the target. From this we can obtain the area of the beam at the target, and finally the irradiance.

Example 5



Beam Diameter at a distance is the divergence of the beam times the range

Let us use our previous example value of a 10 meter distance from the laser to the target. If we neglect the initial size of the laser beam (it is usually very small), a 1 milliradian beam will have a spot size of 1 cm at 10 meters (.001 radians x 1000 cm = 1 cm). The basic formula is:

Divergence x Range = Diameter

(divergence is in radians, and the range and diameter are generally in centimeters)

Next, we can find the area of the beam, by going back to high school geometry. The basic formula for area of the circular beam is:

3.14 x (beam diameter)^2 / 4 ***or*** **0.785 x (beam diameter)^2**

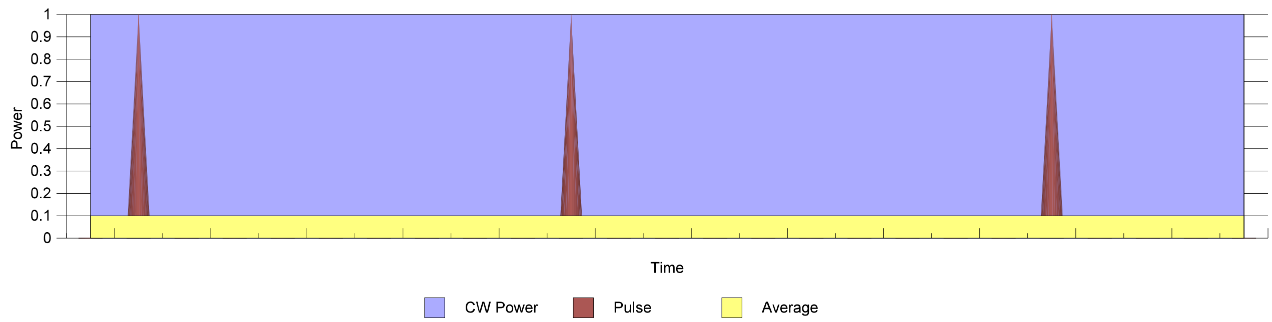
If our beam is 1 cm in diameter, then we have 0.785 x (1cm)^2 = 0.785 cm^2 of beam area.

Since we have 1 Watt of power, the irradiance of the beam is 1W / 0.785cm^2 = 1.27 W/cm^2. This is our *concentration* of power at 10 meters distance.

Irradiance and Radiant Exposure

We can now combine the results of our calculations to give an accurate picture of the exposure of our scanning beam. We calculated in Example 4 that the single pulse duration (time to cross a beam diameter) was 10 microseconds, and we calculated in Example 5 that the irradiance of the beam was 1.27 W/cm^2.

Example 6

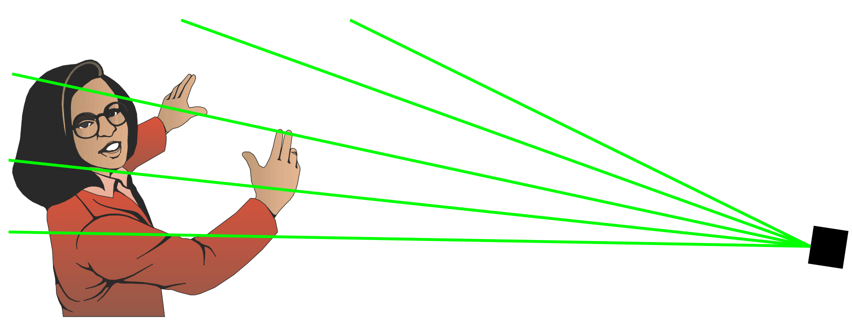


To find the radiant exposure for a single pulse, we take 1.27 W/cm^2 times the 10 microseconds of exposure, and arrive at 12.7 microjoules/cm^2. 100 successive pulses (a second's worth of energy) adds to a total of 1.27 millijoules/cm^2. This is also equivalent to an average irradiance of 1.27 milliwatts/cm^2.

OK, we have some numbers, but is this Safe?

To determine safety, we have to consult one of the safety standards, such as the ANSI Z136.1, or the IEC 60825-1. As a result of many years of biological studies of laser exposures, scientists have arrived at a Maximum Permissible Exposure, below which level an injury is unlikely to occur. It is important to note that the MPE says nothing about viewing comfort. An exposure of even a small fraction of the MPE can still be dazzlingly bright and irritating.

We have to consider three exposure conditions to reasonably ensure the safety of the exposure, the first being the ***Single Pulse Limit***. In Example 6, we found that a single pass of the beam resulted in an exposure of 12.7 microjoules/cm^2 over a duration of 10 microseconds. If we lookup the MPE for a 10 microsecond exposure to a visible laser, the value given is 0.5 x 10^{-6} Joules /cm^2, or 0.5 microjoules/cm^2. Our single pulse exposure is about ***25 times*** this value! This is **not a safe exposure**, not even for a single pulse.



Herein lies the Confusion

In Example 4, we concluded that the average power per centimeter diameter with a 1 Watt beam scanning over a 10 meter path at 100 times per second was about 1 millijoule per second or 1 milliwatt average. From our most basic understanding of safety, 1 milliwatt of power seems to be safe. This is the general rationale that is used to imply that audience scanning is a safe practice, in that scanning reduces the intensity proportionally to the path length. Yet, when we compare the single pulse radiant exposure with the Single Pulse Limit (MPE) then the exposure is 25 times what is permissible.

Safe Exposure is not just about average power! A scanning beam is not equal to a dispersed or diffracted beam, and should not be compared as such.

<u>**The Three Rules of Exposure**</u>

Rule 1: Single Pulse Limit: The scanning beam must be within the MPE for a single pulse exposure.

Rule 2: Average Power Limit: The scanning beam's average power must be within the MPE for the entire exposure event.

Rule 3: Repetitive Pulse Limit: The Single Pulse MPE is corrected by the number of pulses during the exposure, using $n^{-1/4}$ as the correction factor, where n is the number of pulses during the 0.25 second aversion response time (for visible lasers). The single pulse exposure must be within the repetitive pulse limit.

To be a safe exposure, the laser beam must not exceed <u>***any***</u> of these three limits.

A "Safe" Example?

Since our 1 W beam at 10 meters was 25 times the single pulse limit, let's be conservative and adjust our irradiance down by a factor of 100, to a value of 12.7 milliwatts/cm^2. We can do this by increasing the divergence of the beam, taking this parameter from 1 milliradian to 10 milliradians. Our power and scanning parameters will remain the same.

However, our pulse width will increase, since our beam diameter is now 10 times larger. Rather than 10 microseconds, the pulse width will be 100 microseconds.

The Radiant Exposure becomes 0.0127 x 100 μsec = 1.27 x 10^{-6} or 1.27 microjoules/cm^2. The exposure is less than the single pulse limit of 1.8 microjoules/cm^2 (based on 100 μsec exposure), and passes the first test.

Single pulse exposure = 1.27 μJ/cm^2 < 1.8 μJ/cm^2 Single Pulse Limit - Good!

Since we have a repetition of 100 scans per second, our average power is 100 times the single pulse energy, or 127 microjoules/cm^2/second, which is equal to 127 microwatts /cm^2. The average power limit for 1 second (from the tables) is 1.8 milliwatts / cm^2. The exposure is about 14 times less than the limit, and passes the second test.

Average power exposure = 127 μW/cm^2 < 1.8 mW/cm^2 Average Power Limit (1 Sec) -Good!

The final test is the Repetitive Pulse Limit. Since we have 25 pulses in 1/4 of a second, the correction factor C_p is $25^{-1/4} = 0.45$, which is then multiplied with the single pulse limit of 1.8 microjoules /cm^2, becoming 0.81 microjoules/cm^2. However, our exposure level of 1.27 microjoules /cm^2 is greater than this value.

Single pulse exposure = 1.27 μJ/cm^2 > 0.81 μJ/cm^2 Repetitive Pulse Limit. - Bad!

So, even with a 50 times reduction in Irradiance, we are still not safe, by a factor of about 1.5, but at least we are close.

Now What?

Our simplest solution now is to reduce the power to about 630 milliwatts (to decrease our single pulse exposure below the Repetitive Pulse Limit), with the total exposure limited to 25 pulses and 1/4 second. We could try to limit the number of pulses, but to meet our exposure limit, this would need to have a maximum of 4 pulses at the 1 watt power to stay below the limit.

Summary

- 630 milliwatts power (reduced from 1 Watt)
- 10 milliradians divergence (increased from 1 milliradian)
- 100 microsecond pulse width (increased from divergence)
- 10 centimeter beam diameter (increased from divergence)
- 8.0 mW/cm^2 average irradiance (reduced from 12.7 mW/cm^2)
- 10 meter range
- 100 pulses per second
- 0.25 second exposure time
- MPR *"n"* = 100 *0.25 sec = 25
- Single Pulse Exposure = 0.8 microjoules/cm^2
- Average Power Exposure = 80 microwatts/cm^2

Conclusion

To achieve an exposure within the MPE, it was necessary to reduce the beam power and increase the beam divergence. The limiting factor became Rule 3: Repetitive Pulse Limit. However, this exposure must be limited to 1/4 of a second.

But is it artistically effective?

A 630 milliwatt beam scanning over a 60 degree angle at 10 meters distance will be substantially visible if the room is filled with smoke and the laser is the primary light source. This fan effect would need to cross the eyes in 1/4 second. However, with insufficient smoke or competitive lighting, the temptation to "turn it up" is strong, to allow the laser effect to work successfully in a less optimal environment.

But I adjust lights by eye, why can't I adjust a safe level for the laser by eye?

The human eye is an amazing optical instrument, one that has yet to be equaled by any man-made device. It has over 100 million detectors, can accurately detect light images over 12 decades of intensity, and can discriminate between wavelengths only a few nanometers apart. You can see a single photon!

However, it is not a measuring device. It cannot be calibrated, and is poor at absolute measures of intensity. It is relatively slow in response, and can readily be damaged by intense light sources. If I damage my $2000 meter, I have to pay the repair costs; if I damage my eye, the repair costs are impossible.

In attempting to judge the brightness of a light source, human vision accomplishes this best by comparison. If you had a laser effect that was calibrated as a safe exposure, and you compared it with an unknown effect of the same nature (scan pattern, wavelength, divergence), you could probably match the average power with some degree of accuracy. However, you cannot see the refresh rate, duty cycle, or individual pulse energy, all of which are factors in a safe exposure. At best, you could only meet one of the three Rules for exposure.

Moreover, since the eye has a response curve (the photopic response curve) where it is less sensitive in blue and red spectral regions, and more sensitive in the green and yellow regions, one can incorrectly assess the brightness of the laser through a normal aspect of human vision. Just because the blue laser effect appears dim does not mean that the effect is a lower power than the green laser effect, or that it is safe.

Finally, with bright light sources, a phenomenon called *bleaching* occurs, where the light causes the retina to lose its sensitivity. Extreme bleaching is perceived as afterimages or blindspots, and remains until the retina regains normal sensitivity, generally over several minutes. Trying to view a bright light source and judge it will almost inevitably produce this effect, and result in very poor measurements. Imagine trying to judge the brightness of a candle by staring at it.

Can Audience Scanning be Safe and Effective?

The answer to both questions is yes, provided that care is taken to ensure that the exposure is controlled, and that the environment is optimized for the effect. Visually effective shows are certainly possible, but not against competing light, or with insufficient fog. Safe shows are possible, if care is taken to measure and calibrate the exposure, and proper equipment is used to protect against over exposure.

The task is not easy. To be visually effective, the beams need to be close to the MPE. Consequently, the measurements, procedures, and control measures must be accurate and responsive. Consider that the difference between the brightness of the beam as it passes through the air, and the brightness when it enters the eye is about 1 Million to 1, and this should provide an idea as to the magnitude of the problem. Audience scanning is not about intentional retinal illumination. This is really a side effect, in that there is not a current means of shuttering the beam at those times that it crossed the retina. In lieu of a "ocular blanking technology", we *put up with* retinal illumination to allow effects to be in close proximity to the eye, and to surround the viewer.

Just imagine trying to watch an interesting show while someone keeps taking a flash photograph of you. At best, this will be annoying. Repeated scanning of laser beams across the eyes of the audience produces the same effect. It makes it very difficult to see the rest of the show - especially if you need a few seconds for your eyes to recover each time. Think of your "Customers"!

BUSTING LASER MYTHS

Myths about Audience Scanning

1 "A scanning beam is safe; it spreads the beam power out over the entire scan path."
WRONG - this is an average power argument, neglecting single and repetitive pulse issues.

2 "Faster scanning makes it safer; the beam crosses the eye faster so less energy is present."
WRONG - Faster scanning means more pulses per second, and the repetitive pulse correction will negate any advantage. This would only apply if there was a single exposure (one scan only).

3 "It looks dim, so it is safe."
WRONG - it may be dim because of wavelength or low average power. The eye cannot measure the exposure with any degree of accuracy. It is easily possible to misjudge by a factor of 10 or more.

4 " It doesn't look any brighter than a laser pointer, so it must be ok."
WRONG - This is an average power comparison again, and a laser pointer (5 mW) is only safe for the time it takes to react (0.25 second).

5 "Audience Scanning is illegal in the United States."
WRONG - Audience Scanning is a condition in the Variance Application form for Laser Lightshows and Displays, and has been approved on at least two applications.

6 “Audience Scanning is allowed in Europe.”

WRONG - The same standards apply in almost all parts of the world. The implementation of these standards may not *appear* to be as restrictive as in the United States.

7 “A scanfail device will ensure that it is safe.”

WRONG - A scanfail device is required for all audience scanning applications. However, it does not automatically make your show safe, as current devices do not measure or control the exposure level.

8 “There has never been an injury with audience scanning.”

WRONG - At best, the injuries that have occurred have been poorly documented. Just as with hearing loss, the nature of the injuries may not be immediately apparent.

9 “The power is the same at any distance because laser beams don’t spread out.”

WRONG - All lasers beams diverge (spread out). Audience scanning becomes safer with distance, and more dangerous with proximity. It must be measured at the closest audience proximity.

10 “A pulsed laser can be used for audience scanning, just like a CW laser.”

WRONG - Most pulsed lasers have such extremely short pulse durations that scanning does not affect the exposure, and the single pulse energies are usually 10 to 100 times the MPE. Only at extreme ranges could pulsed lasers be used safely.

11 “My insurance company will cover me if someone claims an eye injury from audience scanning.”

WRONG - Insurance companies consider accepted information about risks. Since the MPE values are internationally agreed, any intentional exposures above these values may invalidate your insurance.

12 “Audience Scanning will never be safe”

WRONG - It is a matter of technique and approach. Even top laser safety experts agree on this.