5. Quantifying the Laser Radiation Hazard

5.1 Introduction

In many laser display situations there is the potential for exposure to laser radiation. Although there is a great deal of guidance on how to assess laser radiation exposure in the literature (see Chapter 2) this is identified as the one specific area where there is most concern and controversy. Murphy (1997) and Jones (1997) both consider that the practice of audience scanning presents little risk of injury. This is one side of the argument and, it can be argued, is based on at least ten years of practical experience of audience scanning throughout the world. However, the maximum permissible exposure (MPE) levels published in the current laser safety standard in the UK (BSI 1994) are based on considerable research since the first successful demonstration of the laser. UK safety legislation can use the MPE values as a metric against which the risk can be judged: if the MPE is not exceeded then the risk is acceptable, if it is exceeded the risk becomes more unacceptable as the degree of excess is increased.

The former UK guidelines on the use of lasers for entertainment (HSE 1980) included a proforma (appendix 3) which required the laser display company to provide calculations or measurements of exposure levels. In the author’s experience such information is either not provided or does not relate to the specific event. It is this lack of information and perceived ability to assess the magnitude of the laser radiation hazard which is of greater concern than whether actual injuries are occurring.

This chapter describes the theoretical and practical assessment of the laser radiation hazard, so-called quantification of the hazard. This process should form an important part of the planning stage of any event. A laser company ought to be capable of undertaking such assessments where the risk of exposure to the hazard is more than remote. This will include the manufacture of the laser product at the company's premises, alignment on site and any reasonably foreseeable audience exposure situations, including intended audience scanning.

Comparisons need to be made with published values for maximum permissible exposure (MPE). The values in BS EN 60825-1: 1994 (BSI 1994) will be used throughout.

5.2 Primary Laser Beam

Generally, the worst case condition will be exposure to the full radiant power of the laser beam as it exits from the laser aperture. In order to compare the exposure situation with the MPE the following parameters are required (assuming the laser radiation is emitted as a continuous wave (cw)):

- wavelength
- radiant power
- beam diameter
- exposure duration

If the laser radiation is emitted as a single pulse or a train of pulses then the radiant energy, pulse duration and (if appropriate) pulse repetition rate are required.

The MPE is given in terms of irradiance (W m^{-2}) or radiant exposure (J m^{-2}). For visible laser radiation (400 to 700 nm) BS EN 60825-1 uses a limiting aperture of 7mm: if the actual beam diameter is less than 7 mm then the actual radiant power is averaged over a disc of 7 mm diameter. Therefore, in these situations the biological irradiance is less than the physical irradiance. A description of the rationale for this can be found in, for example, Sliney and Wolbarsht (1980, pages 241-242).

It can be reasonably assumed that any exposure to the primary laser beam will be accidental for most of the applications of lasers for display purposes. The exception may be laser tag games. For a single accidental exposure, the primary protection measure, if the exposure is to the eye, will be the aversion response comprising the blink reflex and violent movement of the head. The laser safety standards assume this process in completed within 0.25 s.

5.2.1 Accidental Exposure to a CW Beam

For exposure durations up to 10 s the MPE is independent of wavelength over the wavelength region 400 to 700 nm. For a single accidental exposure the exposure duration can be considered to be 0.25 s (Sliney and Wolbarsht 1980, p 223). Therefore the MPE (taken from Table 6 of BS EN 60825-1) is:

$$MPE = 18\ t^{0.75}\ C_6\ J\ m^{-2} \qquad 5.1$$

C_6 is a correction factor to be used where the beam is viewed as an extended source and therefore can be set to 1 here. Substituting for t = 0.25 s, the MPE = 6.36 J m^{-2}. This is converted to an irradiance by dividing by the exposure duration, t, to give 25.4 W m^{-2}. If the beam diameter (defined in BS EN 60825-1 as the smallest circle which contains 63% of the total laser power (sub-clause 3.10)) is less than or equal to 7 mm then the maximum radiant power to not exceed the MPE can be calculated:

$$\begin{aligned} P_{\max} &= MPE \text{ x } Area\ of\ beam \\ &= 25.4 \text{ x } \frac{p}{4}\,(0.007\,)^2 \qquad 5.2 \\ &= 0.001\ W\ or\ 1\ mW \end{aligned}$$

Therefore, if the radiant power of a cw laser beam exceeds 1 mW, the MPE will be exceeded during an accidental exposure if the beam diameter is less than or equal to 7 mm. The MPE for exposure durations from 1 ns to 18 µs is 5 x 10^{-3} J m^{-2} or 5 x 10^{-3}/t W m^{-2}.

The time to exceed the MPE as a function of radiant power into a 7 mm aperture is presented in figure 5.1. It can be seen that even at 10 mW, the time to exceed the MPE is about 25 µs. At 5 W, which is typical of many laser display systems, the time to exceed the MPE is about 40 ns. Any control measure designed to protect the eyes of someone working within the region where the beam diameter is up to 7 mm will have to act within 40 ns for a 5 W laser.

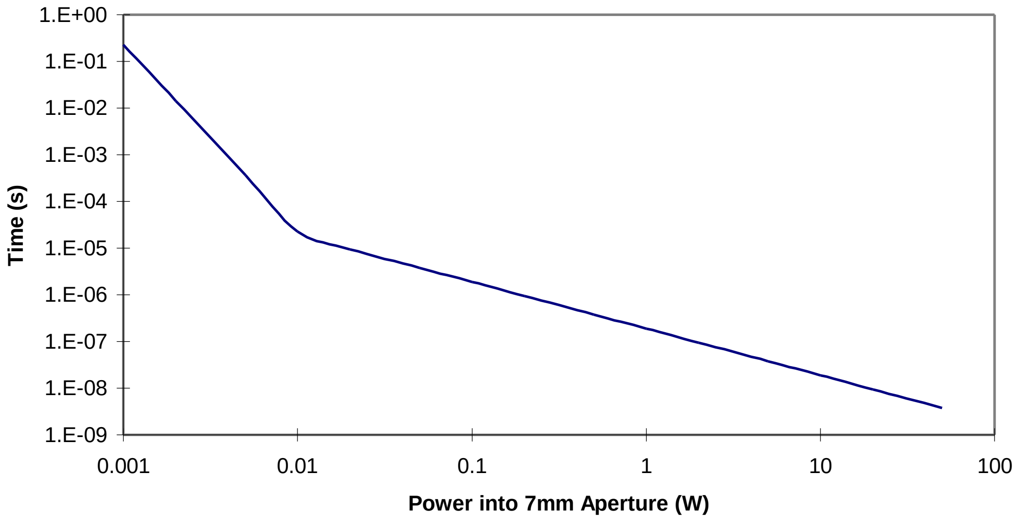


Figure 5.1 Time to Exceed MPE as a Function of Power

A similar assessment can be undertaken for the skin. It is accepted that skin injuries may be considered a tolerable occupational hazard by employees of the laser company but they will not be tolerable to, for example, the audience. The skin MPE values from BS EN 60825-1 are 200 J m^{-2} from 1 ns to 100 ns, and 1.1 x 10^{4} t$^{0.25}$ J m^{-2} from 100 ns to 10 s. For exposure durations of 10 s or longer, the skin MPE is 2000 W m^{-2}. All of these values are constant with wavelength over the region 400 to 700 nm.

The duration of an accidental exposure to the skin is less easy to define. One consideration is how long someone remains in the same position, another will be the type of activity they are carrying out. Exposure durations of either 10 s or 100 s could be justified. The limiting aperture for the skin over the visible wavelength region is 3.5 mm (BSI 1994, Table 7). For both 10 s and 100 s the MPE is the same - 2000 W m^{-2}. The maximum radiant power into 3.5 mm from this MPE is 19 mW. The time to exceed the relevant MPE as a function of radiant power into 3.5 mm is presented in figure 5.2. For a 5 W laser, the maximum exposure duration is about 6 ms.

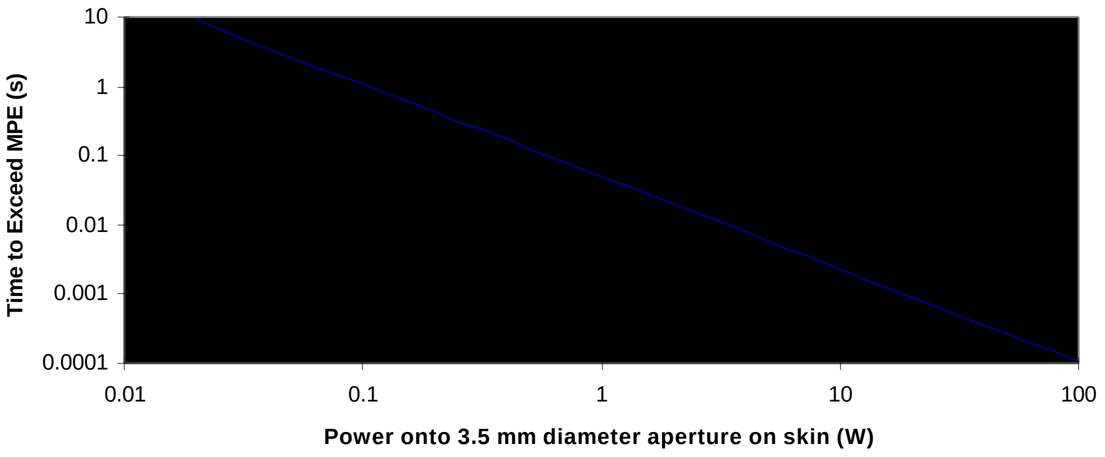


Figure 5.2 Time to Exceed MPE as a Function of Power on Skin

5.2.2 Accidental Exposure to a Single Pulse

If the laser emits a single pulse of laser radiation, where the duration of the pulse (defined as the time between the half peak power points at the leading and trailing edges of a pulse (BS EN 60825-1 sub-clause 3.60)) is 0.25 s or less, the treatment of the MPE is similar to the cw situation except that the pulse duration is used for the exposure duration. It is then possible to calculate if an exposure to the pulse, either received in the eye or on the skin, will exceed the MPE.

5.2.3 Accidental Exposure to a Train of Pulses

Exposure to a train (or series) of pulses could result from the output of a pulsed laser or a scanned pattern. BS EN 60825-1 requires a three-stage process to determine the applicable MPE (sub-clause 13.3) for laser radiation in the visible region where the target is the eye. The analysis here will be carried out for pulsed laser emission: scanned beams will be considered later.

Two pulsed lasers are likely to gain prominence in the entertainment industry: the copper vapour laser (inherently pulsed); and the neodymium:YAG which is occasionally used Q-switched.

The three stages for determining the MPE are as follows:

1. determine the MPE for a single pulse
2. apply a correction factor to the single pulse MPE (termed C_5 in BS EN 60825-1) which is $N^{-0.25}$, where N is the number of pulses in the exposure duration. This will reduce the single pulse MPE and the resultant is termed the "reduced single pulse MPE"
3. determine the MPE for the exposure duration (termed the "average MPE") and apply this to each pulse.

The applicable MPE is the most restrictive of the three. However, if the MPE falls below what would have been applicable for continuous exposure at the same peak power then the MPE for continuous exposure may be used. An example of this would be exposure to a pulsed laser with a peak pulse radiant power of 0.95 mW for an exposure duration of 0.25 s. The reduced single pulse MPE could be more restrictive than what would have been applicable had the beam been on all of the time.

Typical operating parameters for a copper vapour laser are (Hecht 1992):

Pulse duration:	10 ns
Pulse rate:	10 kHz

The exposure duration will depend on the circumstances. Here, an accidental exposure of someone close to the laser will be considered, such as the laser operator during alignment. Therefore, it will be reasonable to assume 0.25 s. This exposure duration will be termed T, whereas the pulse duration will be t. The first stage is to calculate the MPE for the single pulse. Table 6 of BS EN 60825-1 gives an MPE of 5×10^{-3} J m^{-2} for intrabeam viewing, for a 10 ns pulse. The number of pulses, N, in T is given by the pulse rate (in Hz) divided by 4, which equals 2500. $N^{-0.25} = 0.1414$. Therefore, the reduced single pulse MPE = $0.1414 \times 5 \times 10^{-3} = 7.07 \times 10^{-4}$ J m^{-2}. The average MPE for an exposure duration of 0.25 s is $18 \times T^{0.75} = 6.36$ J m^{-2}. This is divided between the individual pulses, ie 6.36/N = 6.36/2500 which gives 2.54×10^{-3} J m^{-2}. It can be seen that the most restrictive MPE is the reduced single pulse MPE ie, 7.07×10^{-4} J m^{-2}.

The initial beam diameters from copper vapour lasers tend to be in the region of 20 to 80 mm. Therefore, they will already be larger than the limiting aperture of 7 mm. Assuming a beam diameter of 20 mm, with the energy distributed equally across the diameter of the beam, it is possible to determine the maximum radiant exposure that can be emitted before the MPE is exceeded. This is determined from the MPE multiplied by the area of the beam (since the beam diameter is greater than 7 mm): $7.07 \times 10^{-4} \times p/4 \times$

$(0.02)^2 = 2.22 \times 10^{-7}$ J. For a pulse duration of 10 ns, this represents a peak power of 22.2 W. This should be compared with typical devices which produce a peak power of 250 kW or over 10,000 times greater. Therefore, it can be concluded that an exposure to the primary beam from a copper vapour laser is likely to cause serious eye damage in a short period of time.

Many suppliers of pulsed lasers quote average power and not peak pulse power. Using the above example, the average power would be quoted as 25 W, or just above the MPE. No account would be taken of the high peak power delivered in each 10 ns pulse. It is therefore important for those who use pulsed output lasers to understand the significance of the average power compared with the peak power. A failure to understand this issue could result in persons exposed to the beam being at considerable risk of eye injuries: it is like being sprayed by a machine gun which, if it is scanned past you MAY not result in injury (or worse). However, if the bullet (pulse) happens to occur where the person is, the probability of interaction is high. Expressing the output of the laser in terms of energy per pulse, and a knowledge of the area, will permit a direct comparison with the appropriate MPE per pulse.

It is concluded that pulsed lasers should not be used for entertainment applications unless adequate control measures are in place to ensure that people cannot be exposed to the beam.

5.3 Nominal Ocular Hazard Distance

An important part of the risk assessment for the use of lasers in the entertainment industry is the distance at which they present a risk of exceeding the MPE, and therefore the risk of injury. Generally, the eye is the critical organ and therefore the analysis here will concentrate on the distance at which the irradiance or radiant exposure equals the MPE, the so-called nominal ocular hazard distance (NOHD). A similar analysis is required where the skin is the critical organ, for example during alignment work where protective eyewear is worn or for some performer exposures.

The NOHD is calculated from a knowledge of the applicable MPE, the beam divergence, the initial beam diameter and the radiant power or energy of the laser. The MPE and the output of the laser must be in similar quantities, ie if the MPE is in terms of irradiance, the output of the laser must be in terms of radiant power.

In general the diameter, d, of the laser beam at a distance, D, from the aperture is given by the expression:

$$d = a + \phi D \qquad 5.3$$

where a is the initial beam diameter and Φ is the full angle beam divergence. This expression is valid where Φ is small and measured in radians such that $\tan(\Phi) \approx \Phi$. The irradiance at distance D is determined from the radiant power, P, divided by the area of the beam at D:

$$Irradiance = \frac{P}{\frac{\pi}{4}d^2} \qquad 5.4$$

At the NOHD, the irradiance will equal the MPE. Therefore, by substituting for d from equation 5.3, and rearranging with D = NOHD:

$$NOHD = \frac{\sqrt{\frac{4\ x\ P}{p\ x\ MPE}} - a}{f} \qquad 5.5$$

Equation 5.5 can be used to determine the NOHD for any laser used in the entertainment industry provided all of the parameters are known. Therefore, it is fundamental to any risk assessment that these parameters are known or reasonable worst-case assumptions can be made. No account is taken here of the effect of air, or smoke, attenuation. The former can generally be ignored over the distances used in entertainment applications. Smoke or vapour effects may attenuate the laser radiation but the effect may not be consistent with time. For these reason it is recommended that no correction factor is applied.

NOHD values for a number of parameters are presented in Table 5.1 for a single accidental exposure to a cw beam. The applicable MPE is 25.4 W m^{-2}. The initial beam diameter, a, has been set to zero since, with the distances generally involved, this represents a small error on the side of safety.

Table 5.1 NOHD as a Function of Radiant Power and Beam Divergence for a Single Accidental Exposure to a cw Beam

Radiant Power → Divergence ↓	100 mW	1 W	10 W
1 mrad	71 m	224 m	708 m
2 mrad	36 m	112 m	354 m
5 mrad	15 m	45 m	142 m

The figure of 224 m at a radiant power of 1 W with a beam divergence of 1 mrad can be used to relate to the NOHD at any other radiant power and divergence (assuming that the effect of the initial beam diameter can be neglected). First the NOHD should be corrected for the actual radiant power by multiplying the distance by the square root of the actual radiant power (measured in watts). This is then divided by the actual beam divergence in milliradians. Therefore, the NOHD for a 10 W laser with a beam divergence of 5 milliradians is 224 x v10/ 5 = 142 m, which agrees with the figure in Table 5.1. Note that the NOHD should always be rounded up. Generally, this will be to the nearest metre.

The NOHD calculations demonstrate that lasers typically used in the entertainment industry present a risk of eye injury over considerable distances, often comparable or greater than the dimensions of the venue. In military applications where laser beams are intended to travel considerable distances, for example for missile guidance or range-finding, corrections factors have to be applied for air attenuation of the beam and potential scintillation (Sliney and Wolbarsht 1980, Chapter 13). These are not considered appropriate for the entertainment industry since the uncertainties do not justify the effort in determining the correction factors.

5.4 Nominal Skin Hazard Distance

Generally, the eye is the critical organ when considering exposure to visible laser radiation. However, there may be circumstances where the eye is protected, for example by protective eyewear, or where performers may be intentionally exposed on the body, well away from the eyes. It is therefore important to quantify the hazard under such exposure conditions.

MPE values for the skin are presented in Table 8 of BS EN 60825-1. As described above, an accidental exposure duration to a cw laser beam is less easy to define than for the eye exposure situation. A reasonable value to use is 10 s since it is unlikely that anyone would normally stay in a fixed position for longer than this under the exposure conditions considered. A member of the audience may remain stationary for the duration of the show, but this is unlikely. However, for this critical group the risk to the eyes is likely to be greater than that to the skin.

The MPE for a single 10 s accidental exposure to a visible laser beam is 2000 W m^{-2}. Equation 5.5 can be re-written for the nominal skin hazard distance (NSHD) and the data is presented in Table 5.2 using similar parameters to Table 5.1.

Table 5.2 NSHD as a Function of Radiant Power and Beam Divergence for a Single Accidental Exposure to a cw beam

Radiant Power→ Divergence↓	100 mW	1 W	10 W
1 mrad	8 m	26 m	80 m
2 mrad	4 m	13 m	40 m
5 mrad	2 m	6 m	16 m

Again, the reference value of NSHD for 1 W and 1 milliradian can be used to determine the NSHD at other radiant powers and divergences if the initial beam diameter can be ignored.

5.5 Scanned Laser Beams

5.5.1 Introduction

As described in appendix A, graphical images are produced by a number of methods, but most commonly by the action of two mirrors on orthogonally-mounted galvanometers. A scanned laser beam will appear as a pulse of laser radiation as it passes the eye. If the scan parameters are known then the level of exposure to scanned beams can be assessed. This can be followed through to a calculation of NOHD and NSHD for each effect. The assessment of the scanned effects assumes that the scanning system is operating correctly. If any single failure mode could result in a stationary laser beam then the NOHD and NSHD should be based on the direct beam assessments in 5.2 to 5.4, above.

In many cases the exact parameters for a given scanned effect will not be known. Where they are known, they may only relate to a single part of the scanned effect. The analyses presented in this section will assume parameters in order to present the quantification process.

5.5.2 Methods

A theoretical analysis of scanned laser beams is developed and this is compared with measurements from a number of actual scan patterns.

5.5.3 Cone Scan from a Cone Spinner

The simplest, and most reproducible, scanned effect is that produced from a laser beam incident on a mirror mounted on the end of the shaft of a rotating motor. The scanned image will be a circle on a screen and will be perceived as a cone if the beam is made visible in the environment. It is recognised that similar effects can be produced by the use of, for example, galvanometers. However, as will be discussed later, the analysis of the exposure conditions can be more involved than with a cone spinner.

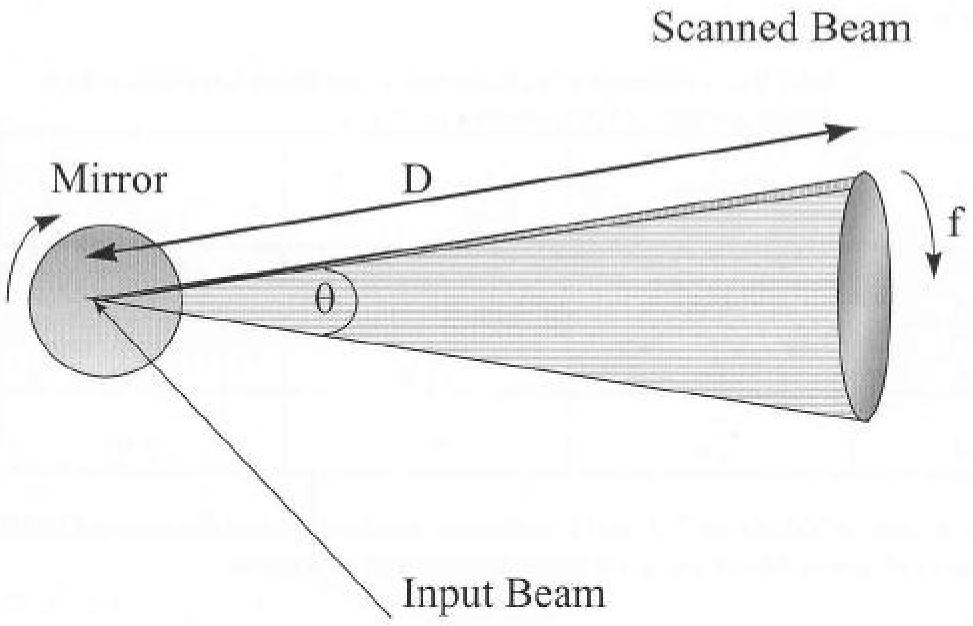


Figure 5.3 Cone Spinner

A diagram of the geometry of the exposure condition from a cone spinner is shown in figure 5.3. Relevant parameters are:

radiant power of the laser, P (W)
beam divergence, from the mirror, ? (radians)
initial beam diameter, at the mirror, a (m)
scan speed, f (Hz)
scan full angle, ? (degrees)
distance of interest, D (m)
maximum permissible exposure, MPE (W m^{-2})

The exposure condition, or time of exposure, needs to be determined at D, assuming a limiting aperture for the eye of 7 mm.

The diameter of the beam at distance, D, is given by equation 5.3. The irradiance at D is given by:

$$Irradiance = \frac{4\,x\,P}{p(a + D\,f)^2} \tag{5.6}$$

The beam will trace out a circular path at D. The diameter of the scan is given by D sin(T). The approximation of taking the sine of the scan full angle, as shown in figure 5.3 represents an error of less than 1% up to a scan full angle of 16°. Therefore, the circumference of the scanned pattern will be:

$$Circumference = p\,D\,\sin(\Theta) \tag{5.7}$$

The speed of the beam will be f multiplied by the circumference. The exposure duration can then be determined, ie the time taken for the beam of the given diameter to cross a 7 mm aperture. The total exposure duration will be the time taken to travel 7 mm plus the diameter of the beam, the largest duration generally being when the centre section of the beam passes the aperture. However, the beam diameter has already been quoted using an assumption, ie, for a Gaussian beam profile, the point at which the irradiance reaches 1/e of the central peak value (BS EN 60825-1 sub-clause 3.10). The pulse duration is defined as the time between the half peak power points on the leading and trailing edges of a pulse (BS EN 60825-1 sub-clause 3.60). If the pulses had been produced from, for example, a pulsed laser, then the rise time of the pulse is generally short compared with the pulse duration. However, in the scanned example, the rise time may be comparable with the pulse duration. The following argument justifies the use of the full width at half maximum (FWHM) value in most circumstances.

Assuming the beam profile is such that the irradiance is constant, ie a flat-topped beam with a square cross section, and that the beam is larger than the detector, which also has a square cross-section, the exposure situation will be as presented in figure 5.4. The signal will increase linearly as the beam leading edge is scanned across the detector. Whilst the detector is completely covered by the beam, the detector output will be constant and then fall linearly as the trailing edge passes over the detector. Taking the FWHM points and projecting them down to the time axis, the area outside the FWHM points equals the area deficit between the FWHM points and the peak value. Therefore, it would be reasonable to assume that the exposure consisted of a pulse at the peak power for the FWHM exposure duration.

Figure 5.4 Irradiance as a Function of Time for a Square Profile Beam

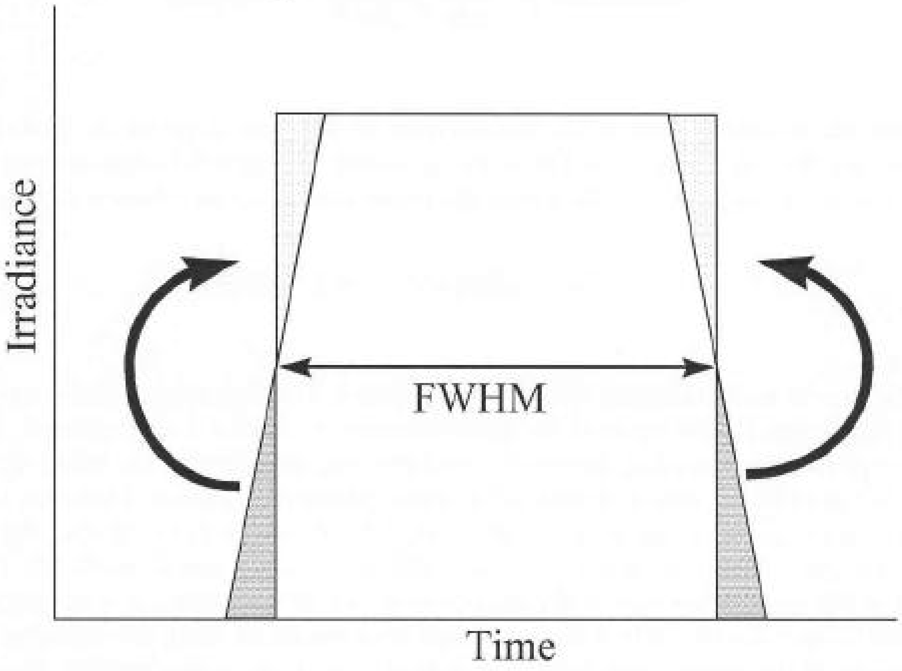
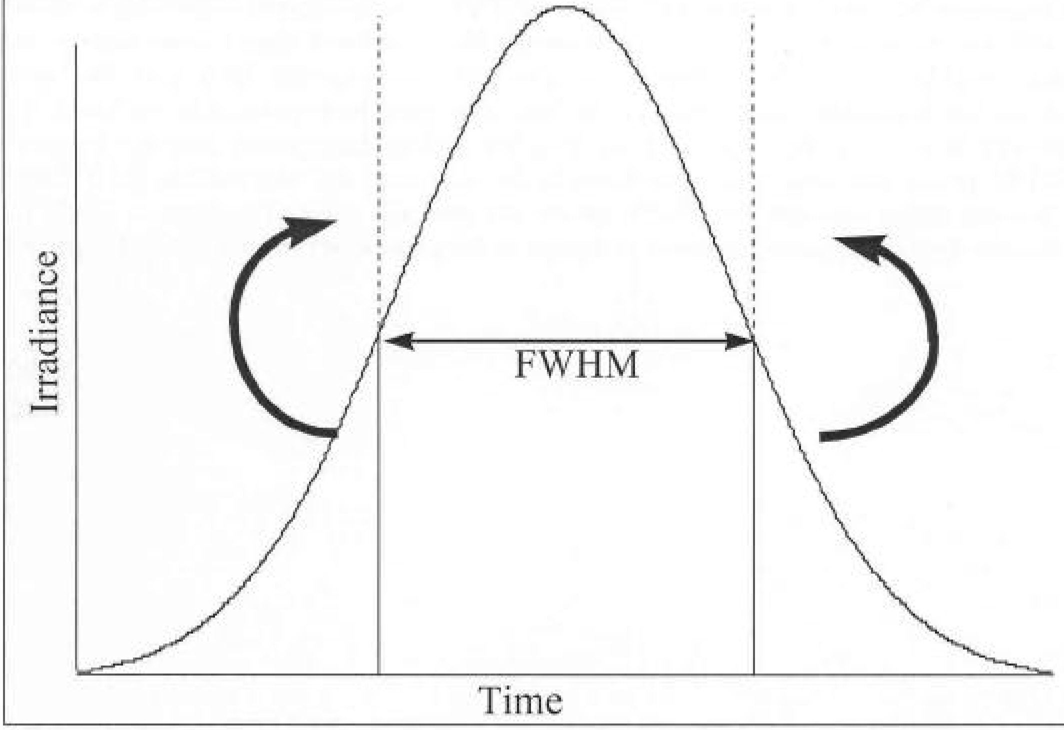


Figure 5.5 Gaussian Beam Across Small Detector



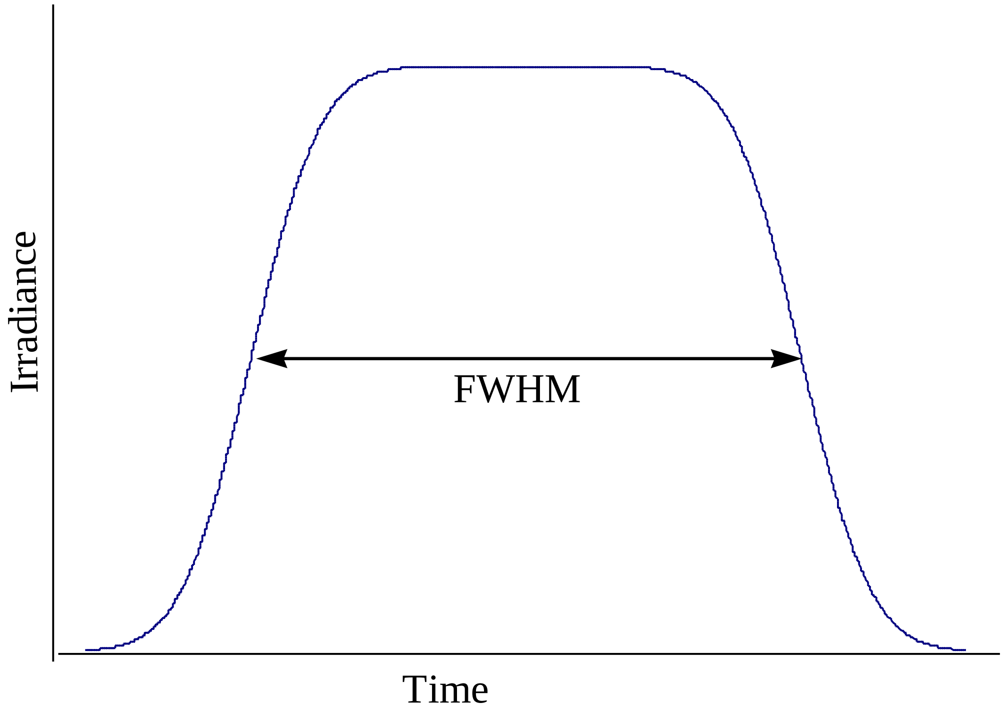
In the actual exposure situation where the beam profile is either Gaussian or a more complex mode, and the detector has a circular cross-section, a similar argument can be used (figure 5.5). The area from the half maximum out to the 3 σ point is approximately 34% greater than the area deficit between the half maximum point and the peak. The use of a detector which is much smaller than the beam width is an effective beam profiling tool when the beam is scanned across the detector face.

If the diameter of the laser beam is much smaller than the diameter of the detector, then the irradiance will be constant as a function of time while the beam crosses the detector (assuming a constant spatial response) even though the beam profile is not flat. The leading and trailing edge of the irradiance as the beam enters the detector aperture and exits from the aperture should approximate the integral of the beam profile. Figure 5.6 is a plot of a Gaussian curve (normal distribution) integrated from 3 σ to -3 σ to simulate the beam passing onto the detector, a constant region where the whole of the beam (within ±3 σ) passes across the face of the detector and then the inverse of the integral as the beam crosses the edge of the detector. This simulation assumes a beam diameter, specified at the 1/e points, which is 28% of the diameter of the detector. The linear speed of a scanned beam can be determined from the FWHM and the diameter of the detector aperture, ie v = diameter/FWHM or FWHM = diameter/v. In general, the exposure time per pulse, t (the FWHM), will be:

$$t = \frac{d}{v} \qquad 5.8$$

d is the diameter of the larger of the beam and the measurement aperture. Where the diameter of the beam and the measurement aperture are the same then this value is used. Note that the relevant beam diameter here is the half-power points and not the 1/e or 1/e^2 which may be specified in the manufacturer's literature. For a Gaussian beam profile, the diameter at the 1/e point is 20% larger than the diameter at the half-power point: the 1/e^2 point is 70% larger.

Figure 5.6 Gaussian Profile, Beam Smaller Than Detector



The MPE for the cone spinner can now be evaluated from the scan parameters. At the closest distances likely to be accessible by members of the public the laser beam diameter is probably going to be greater than the diameter of a nominal 7 mm diameter detector. Therefore, t, the exposure duration of each pass of the beam equals the beam diameter (at the 50% points) divided by the beam speed. The circumference, C, of the scan at a distance D (figure 5.3) is given by equation 5.7. The speed is given by fC, where f is the scan frequency in Hz. Therefore, t follows from:

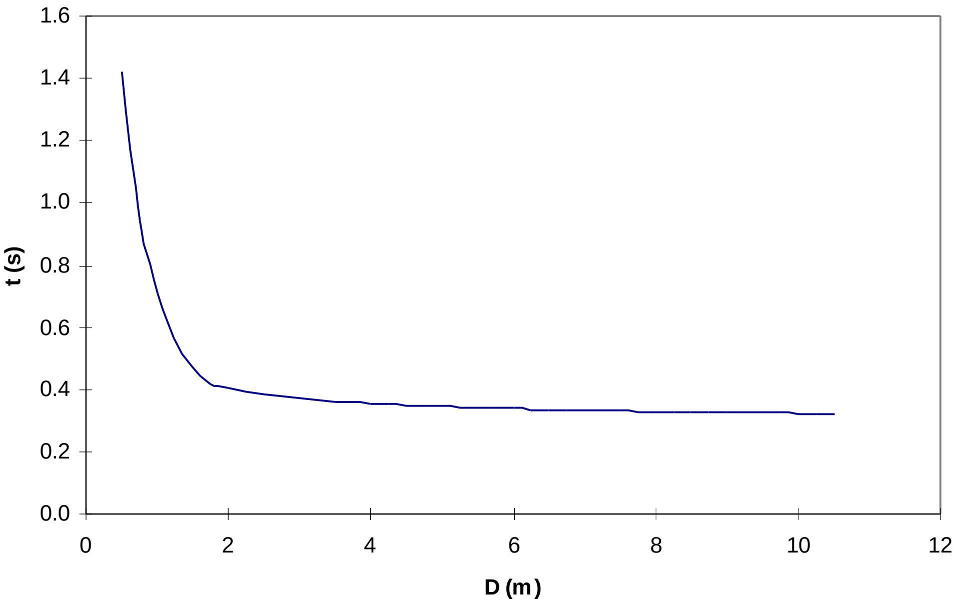
$$t = \frac{d}{fC} \qquad 5.9$$

where d is the beam diameter at distance D. Substituting for d from equation 5.3 and C from equation 5.7:

$$t = \frac{a + D\Phi}{pfD\sin(\Theta)} \qquad 5.10$$

A scan rate of 30 Hz should result in a solid image with no flicker. Assuming a scan angle of 3°, an initial beam diameter of 0.002 m and a beam divergence of 0.003 radians, t as a function of D can be plotted, as presented in figure 5.7. A 7 mm diameter detector is assumed, which means that 0.007 is used on the top of equation 5.10 instead of a + Dφ until a + Dφ = 0.007, ie at D = 1.67 m in this example.

Figure 5.7 t as a Function of D



It can be seen that t is approaching a constant value. This will be within 1% of the value for D = ∞ when D = a/0.01φ. For the example above, this occurs when D = 67 m. The MPE can be determined by substituting the value for t into equation 5.1. However, the MPE can also be expressed in terms of irradiance by dividing by t. Assuming a value of 1 for C_6 the MPE for distances where d > 7 mm can be rewritten as:

$$MPE = 18\left(\frac{pfD\sin(\Theta)}{a + \Phi D}\right)^{0.25} \text{ W m}^{-2} \qquad 5.11$$

The maximum radiant power permitted without exceeding the MPE can be determined by multiplying the MPE by the area of the 7 mm aperture (equation 5.2):

$$P_{\max} = \frac{18p}{4}\left(\frac{pfD\sin(\Theta)}{a+\Phi D}\right)^{0.25}(0.007)^2 \quad \text{W} \qquad 5.12$$

This suggests that the maximum power can be increased proportional to $f^{0.25}$. However, as stated in 5.2.3, the MPE must be modified when the recipient is exposed to a train of pulses. For 18 µs ≤ t ≤ 0.25 s, the applicable MPE will generally be the reduced single pulse MPE, ie the single pulse MPE multiplied by the factor $N^{-0.25}$. N is the number of pulses in the duration of interest, termed T. For an accidental exposure it would be appropriate to use 0.25 s. However, for audience scanning where the exposure is intentional it would be appropriate to use a longer duration. Where the actual duration of the effect is known, this could be used. However, for practical purposes the maximum exposure duration is unlikely to be greater than 10 s.

N is equal to fT. Therefore, $N^{-0.25} = 1/(fT)^{0.25}$. Substituting this into equation 5.12 gives the maximum peak power permitted into a 7 mm aperture, in a train of pulses:

$$P_{\max} = \frac{18p}{4}\left(\frac{pfD\sin(\Theta)}{fT(a+\Phi D)}\right)^{0.25}(0.007)^2 \qquad \text{W} \qquad 5.13$$

It can be seen that f now cancels out and the maximum peak power becomes independent of scan rate and proportional to $T^{-0.25}$. Therefore, considering an exposure duration of 10 s as opposed to 0.25 s only decreases the permitted power by about a factor of 2.5.

If the scan rate is increased sufficiently to bring t to below 18 µs, the relevant MPE will be the average MPE. The equivalent equation is:

$$P_{\max} = \frac{p}{4}\frac{18T^{-0.25}}{ft}(0.007)^2 \qquad \text{W} \qquad 5.14$$

Substituting for t from equation 5.10:

$$P_{\max} = \frac{p^2}{4}18T^{-0.25}\,\frac{(0.007)^2}{(a+\Phi D)}\,D\sin(\Theta) \qquad \text{W} \qquad 5.15$$

This again shows that the maximum peak power is independent of the scan speed. However, a check should also be made to ensure that the reduced single pulse MPE is not more restrictive. These results are extremely significant. A major argument used by laser display companies is that the risk of eye damage is decreased by increasing the scan speed with any control measure acting before the scan slowed below some (unspecified) value. This argument can only be used if increasing the scan speed does not increase N. A spreadsheet to demonstrate how the scan speed can be used by stalling the scanner for a period of time after each scan and reduce the exposure to below the MPE has been developed (Walker 1997). However, this spreadsheet uses the assumption that the beam can be scanned faster than commercially available scanners will permit, and the beam is assumed to be parked and blanked for a significant proportion of the scan frame. Such effects are unlikely to be visually acceptable, even if the scanner technology did exist.

5.5.4 Measurement of Scanned Beams

As identified in Chapter 3, it was normally difficult to obtain information on the laser beam characteristics. The manufacturer's data on the radiant power and the beam divergence for a laser may be altered by the optical systems employed to manipulate the beam. In order to theoretically assess exposure to beams, as described in the previous section with a simple cone spinner, it is necessary to know the scan rate, beam divergence, scan angle, initial beam diameter and the radiant power of the laser.

The use of proprietary laser power meters to assess scanned beams can lead to significant errors. As shown in 5.2.3, it is important to know the energy per pulse or the peak power. Commercial energy meters are not generally sensitive enough to detect the energy in a 5 W beam scanned across a 7 mm aperture in 10 - 100 µs. Depending on the design of a power meter, it may indicate true average power or, for modern digital sampling detectors, widely varying powers. This is due to the resultant signals at the sampling times being either during an actual exposure of the detector or during the period between exposures. Power meters such as the Coherent Fieldmaster with a silicon LM2 head present an erratic answer which, to the skilled user, indicates that the result is not reliable.

In order to evaluate scanned beams it was necessary to use a basic design of detector which consisted of a silicon photodiode, transimpedence amplifier and an oscilloscope. Two detectors were principally used for this research: a Centronics 50 mm^2 diameter photodiode with a 7 mm diameter circular aperture mask, for direct comparison with the MPE and a Hamamatsu S2858-01 detector with integral transimpedance amplifier for beam profiling. This technique proved a very effective alternative to commercial beam profiling equipment which scans across the beam.

Equation 5.10 shows that the time of scan across a 7 mm aperture is a function of many of the required parameters for input to the comparison with the MPE. If the scan time measurement can be made at a number of distances from the effective source it is possible to determine these parameters.

A nominal 1.3 mW helium-neon laser emitting a green beam (543.5) (Gre-Ne) was input to a Maplin scanner (cone spinner) driven from a custom power supply. One of the two motors in the scanning unit was driven and the laser beam scanned until the resultant image formed a solid circle on a screen. The Centronic detector was used to measure the scan time, t, as a function of distance from the scanning mirror.

5.5.5 Results

The detector voltage as a function of time is plotted in figure 5.8 for distances of 2.5 m to 7 m in 0.5 m intervals; figure 5.9 for 7 m to 19 m in 1 m intervals and figure 5.10 for 15 m to 19 m.

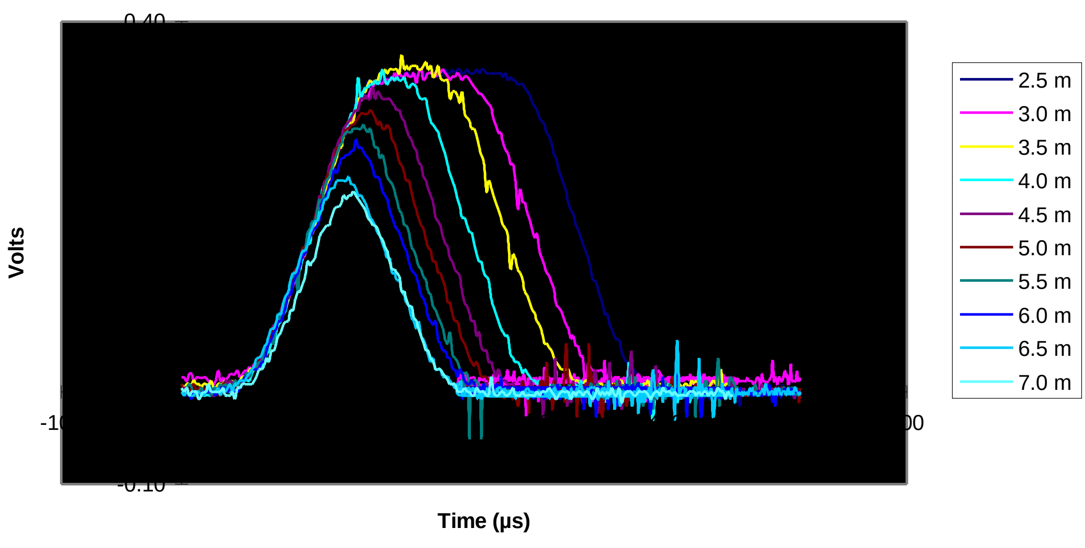


Figure 5.8 Maplin Scanner Gre-Ne Laser 2.5 to 7 m

It can clearly be seen in figure 5.8 that the laser beam was smaller than the detector diameter at distances from 2.5 to 4 m since the detector output is constant for a period of time. This plateau is reduced as the distance increases and the beam diameter increases. At about 4.5 m the beam diameter is approximately the same size as the detector aperture. As the distance is increased beyond 4.5 m the amplitude of the detector voltage decreases as a reducing proportion of the beam enters the detector. For comparison with the Standard (BSI 1994), the beam diameter is defined at the 1/e point, ie the largest aperture which collects 63% of the beam. The maximum voltage recorded when the total beam was collected was 0.35 V. Therefore, 63% of the beam will be collected when the peak voltage is 0.22 V. This represents a distance of between 6 and 7 m. The specification for the Gre-Ne laser gives an initial beam diameter of 1 mm and a beam divergence of 1 milliradian. From this, the beam diameter would be 7 mm at 6 m. This is consistent with the observed value.

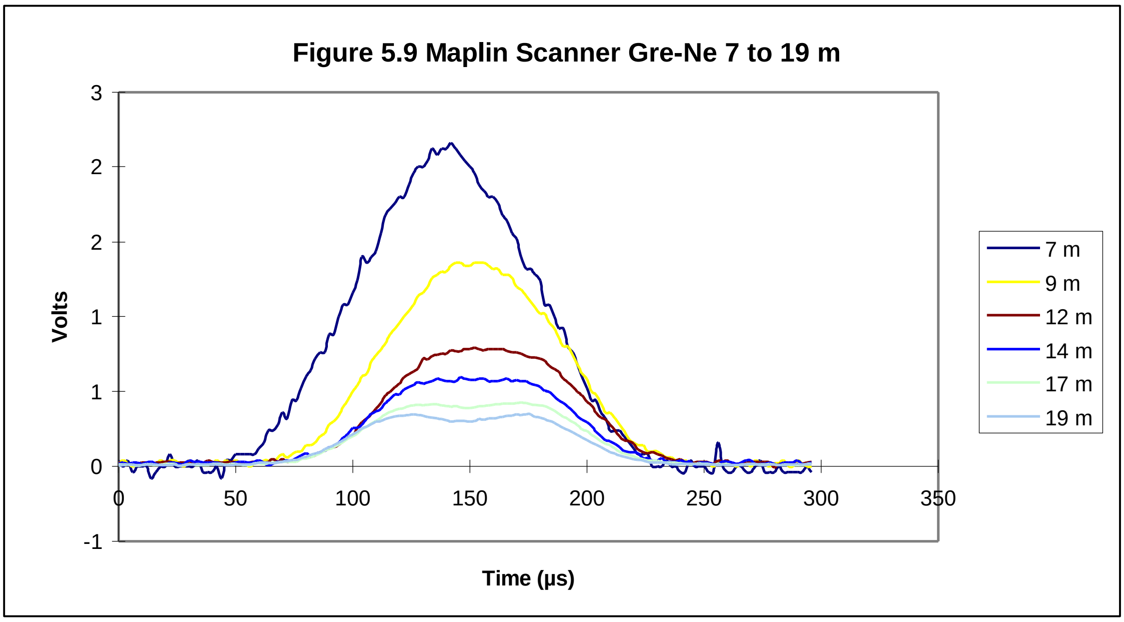


Figure 5.9 Maplin Scanner Gre-Ne 7 to 19 m

The gain of the detector was increased by a factor of about 10 when the distance was increased to 8 m. The 7 m response is multiplied by 10 and replotted in figure 5.9. It can be seen on this figure that the amplitude of the pulse seen by the detector continues to decrease with increasing distance as the detector samples a smaller segment of the beam as it scans past. It is interesting that some structure starts to appear in the pulse shape at distances from 17 m. Therefore, the pulses are replotted in figure 5.10. At 19 m, the theoretical beam diameter is 20 mm, or about three times the diameter of the detector. The Gre-Ne was understood to have a TEM_{00} mode structure and therefore should have been producing a gaussian beam profile. To confirm this, a proprietary beam profiling device using a CCD camera connected to a laptop computer was used to analyse the beam. This device focussed the incoming beam onto a 256 x 256 CCD array and produced an output from each element from 0 to 255. This confirmed that the Gre-Ne was operating in TEM_{11} mode and that the pulse shape seen by the detector as the beam scanned past was a section through this TEM_{11} profile.

Figure 5.10 Maplin Scanner Gre-Ne 15 to 19 m

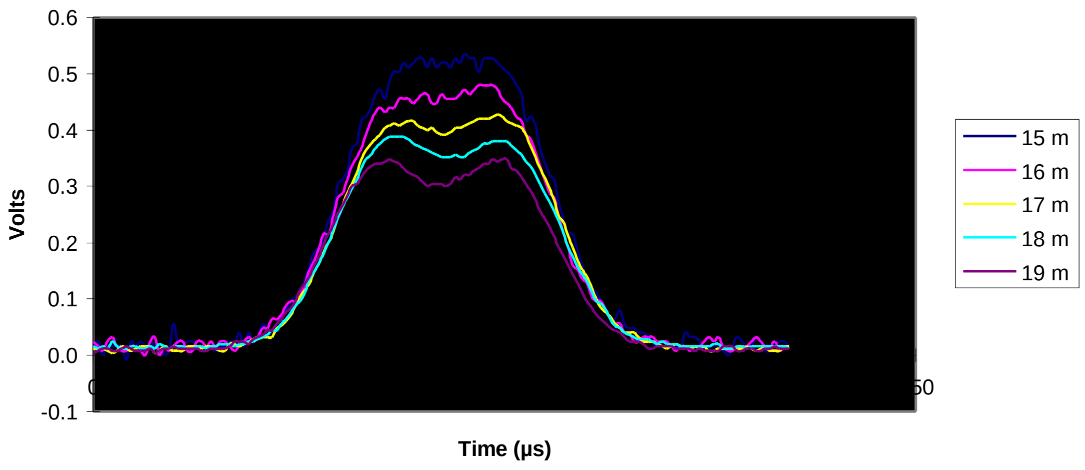
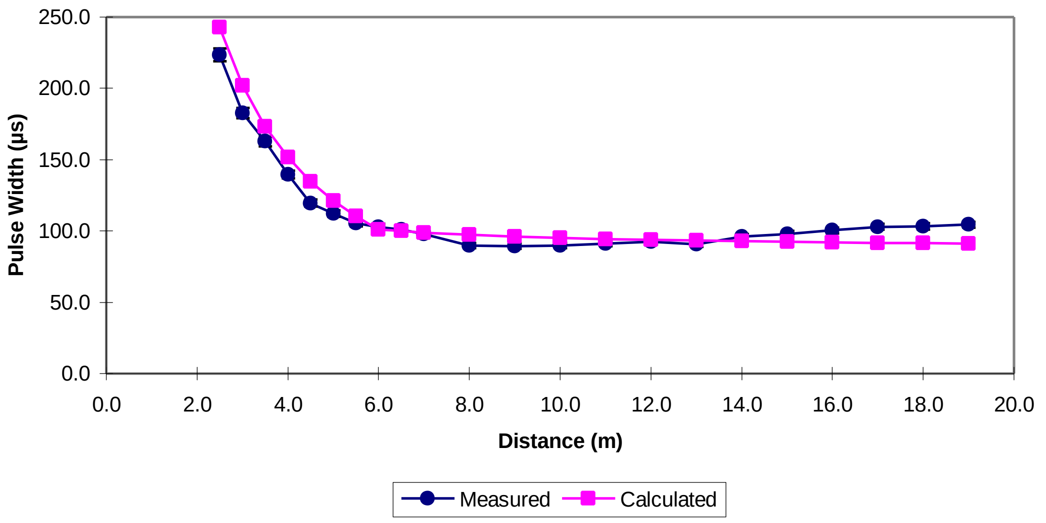


Figure 5.11 Comparison of Measured and Calculated Pulse Widths



The pulse width as a function of distance is plotted in figure 5.11. It was possible to determine the scan rate at each distance by increasing the delay on the oscilloscope trigger until the next pulse was seen. The scan rate was determined by the inverse of the time between peaks. During the course of the 22 measurements the mean scan rate was 37.6 Hz (standard deviation 0.4 Hz). Using this value for f, a beam divergence of 1 milliradian, an initial beam diameter of 1 mm and a full scan angle, ϑ, of 5.6° (determined from measuring the diameter of the scan pattern as a function of distance, D) it was possible to calculate the pulse width using equation 5.10 and these values are also plotted on figure 5.11.

It is of note that the pulse width reaches a constant value once the beam diameter is greater than the diameter of the detector. Essentially, the beam forms a constant proportion of the scanned circle as a function of distance. The minor deviation between the measured and calculated values at increasing distance is considered to be due to the increasing importance of the tails of the beam profile as smaller percentage segments of the total beam are scanned across the detector.

5.5.6 Discussion

Since a cone scan is one of the most popular audience scanning effects, the results from this analysis are extremely significant. A typical laser installation will be using a laser with a radiant power of 4 W, a beam divergence of 3 milliradians, and an initial beam diameter of 2 mm. Assuming a Gaussian beam profile, it is possible to calculate the NOHD for a cone for a given scan angle. As has already been shown, the pulse duration reaches a constant value with increasing distance, but the proportion of the beam entering the nominal 7 mm diameter aperture decreases because of the beam divergence. One way of reducing the NOHD, of course, is to increase the beam divergence. The closest point of access for the audience should be greater than the NOHD. Therefore a balance should be struck between the closest reasonable point of access and the beam divergence.

Table 5.3 NOHD (m) for a Cone Scan as a function of Divergence and Scan Angle

Divergence (milliradians)→ Scan Angle (degrees)↓	1	2	3	4	5	10	20
1	248.6	135.6	95.1	73.9	60.8	33.2	18.1
2	228.0	124.3	87.2	67.8	55.8	30.4	16.6
3	216.8	118.2	82.9	64.4	53.0	28.9	15.8
4	209.1	114.0	80.0	62.2	51.1	27.9	15.2
5	203.4	110.9	77.8	60.5	49.7	27.1	14.8
6	198.8	108.4	76.0	59.1	48.6	26.5	14.5
7	195.0	106.3	74.6	58.0	47.7	26.0	14.2
8	191.8	104.6	73.3	57.0	46.9	25.6	13.9
9	189.0	103.1	72.3	56.2	46.2	25.2	13.7
10	186.6	101.7	71.3	55.5	45.6	24.9	13.6

The influence of the scan angle and the beam divergence on the NOHD for a 4 W cw laser are presented in table 5.3. This has been calculated by setting equation 5.11 as equal to the irradiance for a 4 W beam and solving for D equals the NOHD with the approximation that the initial beam diameter is zero (equation 5.16):

$$NOHD = \sqrt{\frac{4P_o}{18p\Phi^2}\left(\frac{T\Phi}{2p\sin(\Theta)}\right)^{0.25}} \quad \text{m} \qquad 5.16$$

It can be seen from table 5.3 that doubling the divergence reduces the NOHD by about 50%. However, doubling the scan angle only reduces the NOHD by about 8%. This demonstrates the effectiveness of increasing the divergence for beams which may enter the audience area.

These results show that it is possible to determine the exposure condition when the laser beam is scanning at a constant speed. However, scanned effects are generally not produced using spinning mirrors, they are produced by pairs of galvanometers under programme control. The images will range in complexity from circles and straight lines through to sophisticated graphical representations. An introduction to the format of the data and the representations of the images is presented in Appendix A.

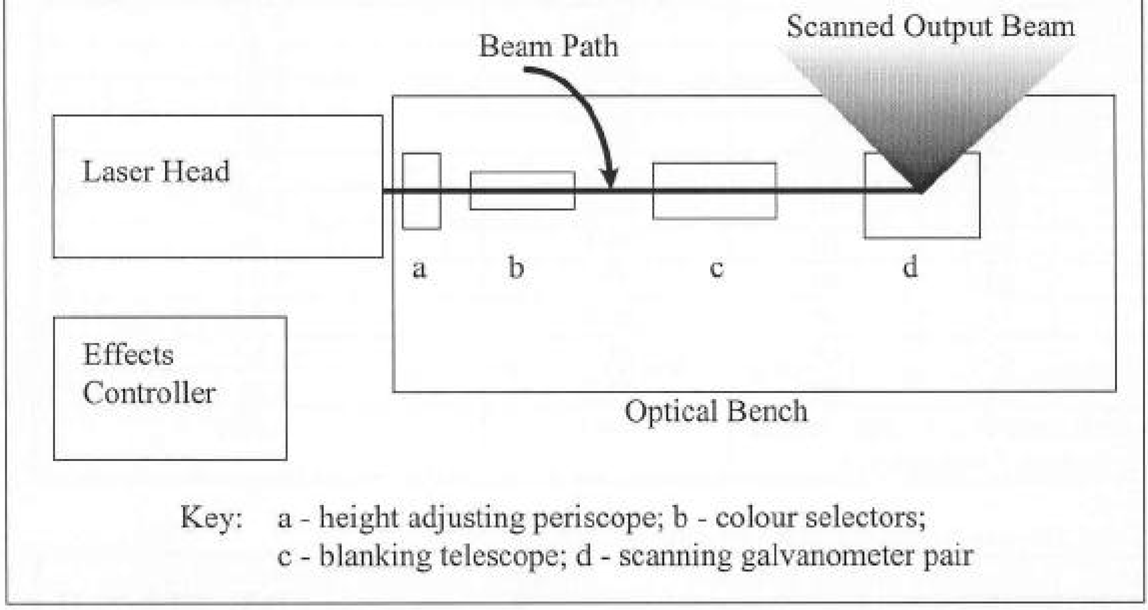
5.6 Measurements on Proprietary Scanning System

A proprietary laser display system was loaned by a laser display company and measurements made under laboratory conditions to determine the characteristics of scanned images. A schematic of the laser and the primary optical system is presented in figure 5.12.

5.6.1 Measurement Method

Measurements were undertaken using the 7 mm diameter photodiode, transimpedence amplifier and oscilloscope arrangement used in 5.5.1. In addition, a custom thermopile detector was used to determine average power (Corder 1997).

Figure 5.12 Proprietary Laser Display System



An air-cooled argon ion laser was used as the source. The radiant power of the static beam was 6.48 mW, measured using a calibrated Coherent Fieldmaster with an LM-2 detector. The power output from the laser was 7.90 mW, representing a loss of 18% of the input beam through the optical system. The beam diameter was 5 mm at the measurement position (3.95 m from the scanner to the detectors). The irradiance was calculated by averaging the radiant power over a 7 mm limiting aperture and was 168.4 W m^{-2}. Measurement of the radiant power requires the drive signal to the blanking telescope to be disconnected or the mirror moved out of the beam path. Many patterns generated by the control system include an element of blanking. As described earlier, measurements using a sampling power meter will be in error for beams which do not have a constant irradiance with time.

The assessed scan pattern was a cone, which was collapsed, ie x was fixed, to produce a flat (or line) scan in the vertical plane. Measurements were made at 11 positions along the scan using the photodiode to determine the duration of each ‘pulse’ as the laser beam scanned past the detector and the number of pulses per second; and the thermopile detector to determine the average irradiance. The measured pulse duration per scan from the photodiode detector is presented in table 5.4. The thermopile detector results are presented in table 5.5. Examples of the output voltage as a function of time from the photodiode are presented in figure 5.13 at the end of the scan (position 1 - left end of scan pattern in figure A.3) and figure 5.14 for the positions away from the end of the scan. It is significant that a person located at either end of the scan would receive half the number of pulses as a person at any other point along the scan. At the mid-position, the spacing between the pulses should be equal.

5.6.2 Results

The scan refresh rate was determined from the time between pulses at the end of the scan and was found to be 120 Hz. Therefore, at the ends of the scan, a person would be exposed 120 times per second and elsewhere in the scan at 240 times per second, in the absence of any aversion response. Assuming the natural aversion response and an accidental exposure, then it would be reasonable to assume an exposure duration of 0.25 s. The number of pulses received, N, would then be the above figures divided by 4.

Table 5.4 Measured exposure duration per scan from photodiode detector

Position	t (μs)	N for 0.25 s exposure	Reduced single pulse MPE	Maximum radiant power into 7 mm to not exceed MPE (mW)
1 (end)	366	30	55.6	2.14
2	78.6	60	68.7	2.64
3	50.0	60	76.9	2.96
4	36.8	60	83.0	3.20
5	30.0	60	87.4	3.36
6	26.1	60	90.5	3.48
7	26.2	60	90.4	3.48
8	26.4	60	90.2	3.47
9	24.9	60	91.6	3.52
10	24.7	60	91.7	3.53
11	25.2	60	91.3	3.51
Measured irradiance and radiant power through 7 mm aperture			168.4	6.48

Table 5.5 Thermopile detector measurements

Position	Measured average irradiance	Measured irradiance divided by $MPE_{average}$
1	21.5	0.85
2	5.63	0.22
3	3.60	0.14
4	2.70	0.11
5	2.18	0.09
6	1.90	0.07
7	1.83	0.07
8	1.83	0.07
9	1.63	0.06
10	1.50	0.06
11	1.53	0.06

5.6.3 Discussion

The results in table 5.4 demonstrate that the maximum power into a 7 mm aperture is of the order of a few mW. Even at 6.48 mW, the MPE will be exceeded at any position along the scan pattern. This can be compared with the MPE for the static beam, which would be 1 mW for a 0.25 s accidental exposure. However, if the average power is measured and compared with the average MPE, as in table 5.5, then it implies that the scan pattern is safe and also that the ‘safety margin’ between the end of the scan pattern and the middle (positions 1 and 10) increases by a factor of 14.

Figure 5.13 Photodiode Output at Position 1 of Flat Scan

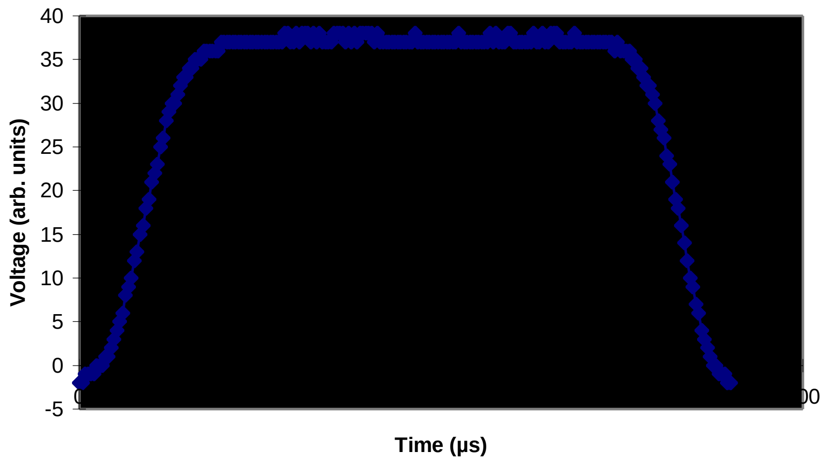
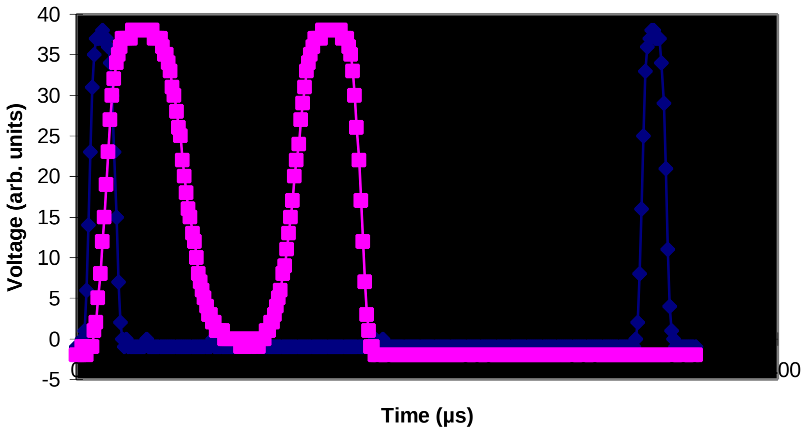


Figure 5.14 Photodiode Output Showing Twin Passes of Beam



The twin pulses close to position 1 in figure 5.14 clearly show the beam slowing down as it crosses the detector the first time and then accelerating away from a stationary position during the second pass. The times between 20 and 80% of peak value are 35 µs rise, 68 µs fall, for the first peak and 58 µs rise and 28 µs fall for the second peak. In comparison, the two pulses at position 3 are symmetrical.

An inspection of the photodiode output as a function of time on the oscilloscope presents the opportunity to understand the nature of the scanned pattern. During the study of the time between successive pulses the plot presented in figure 5.15 was obtained.

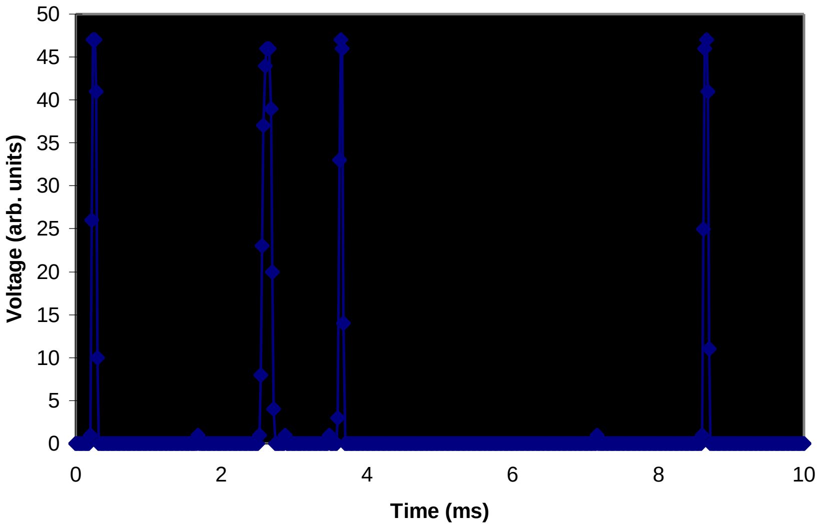


Figure 5.15 Photodiode Output. Position with 3 Pulses per Cycle

Figure 5.15 shows three peaks per scan cycle. The fourth peak occurs about 8.3 ms after the first pulse representing the 120 Hz refresh rate. It was initially thought that the three peaks were an artefact of the oscilloscope but further inspection of the scan pattern on the screen showed a small section of the pattern which was brighter to the eye. A plot of the x,y,z data to the driver boards of the scanners and z-blanking showed that there was an overlap of the scan pattern. It appears that the scan pattern had been digitised by hand (as a circle) and the engineer had put in a small overlap to ensure that there was no gap in the circular pattern. The scan was then blanked to allow the scanners to return to the start position and recommence the scan.

The respective times of exposure to the first three pulses (full width, half maximum) in figure 5.15 were approximately 64, 140 and 60 µs. There is no clear guidance on how to assess multiple pulses of different durations. However, it would be reasonable to assume that the MPE would be somewhere between that applicable for three pulses of 60 µs duration per cycle and three of 140 µs duration. In both cases, N, for a 0.25 s accidental exposure, will be 90. From section 5.2.3, the reduced single pulse MPE will be 66.39 and 53.73 W m^{-2} for the 60 and 140 µs pulses, respectively. Therefore, the maximum power into a 7 mm aperture is between 2.61 and 2.12 mW. By comparison with table 5.4 it can be seen that the small overlap region may present a greater hazard than any other part of the scan pattern.

This exercise demonstrates the importance of using the correct measurement instrument to undertake the measurements and the importance of applying the correct MPE (Corder, O’Hagan and Tyrer 1997, O’Hagan, Corder and Tyrer 1998). From position 11 in table 5.5, it can be seen that the average irradiance would suggest a safety margin of about a factor of 16. However, the same position in table 5.4 shows that the MPE was actually exceeded by a factor of 2. Therefore, the error in this one position is about a factor of 32.

Most scanned laser effects will be more complex than flat or cone scans. They may also move and change size with time. Indeed, many scanned effects will be animations. Although most complex graphical images will be projected onto screens away from the audience, the patterns used to scan across the audience as beam effects, are generated in an identical manner. A number of effects from a proprietary laser display system were assessed at a number of positions in the scan pattern to determine the maximum radiant power into a 7 mm aperture to keep below the MPE.

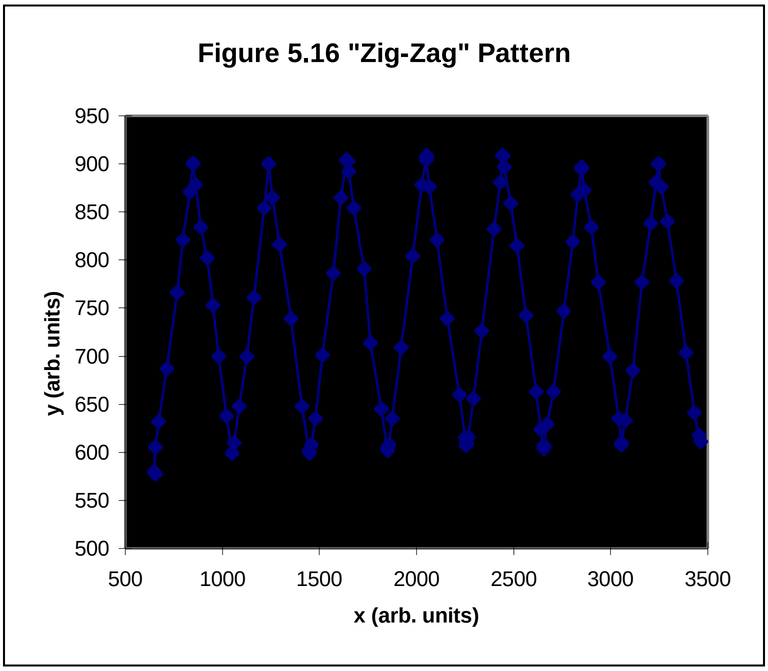
5.7 Zig-Zag Pattern

The x-y data for a zig-zag pattern is presented in figure 5.16. If the value of y is kept constant then the scanned pattern will appear as a number of fingers of light in space. Figure 5.17 shows the scan drive signals as a function of time. The inertia of the galvanometers will mean that the actual movement of the laser beam will not precisely follow the drive instructions, but it is still likely that the beam will reduce speed, if not stop, at the horizontal positions on the plot in figure 5.17.

5.7.1 Measurements

Using the photodiode detector, measurements were made along the scan pattern to determine the exposure duration of a 7 mm aperture. The beam diameter at the detector position was 5 mm, the scan width was 0.72 m and the distance between the visibly brighter regions of the pattern projected on to a screen was about 53 mm.

5.7.2 Results



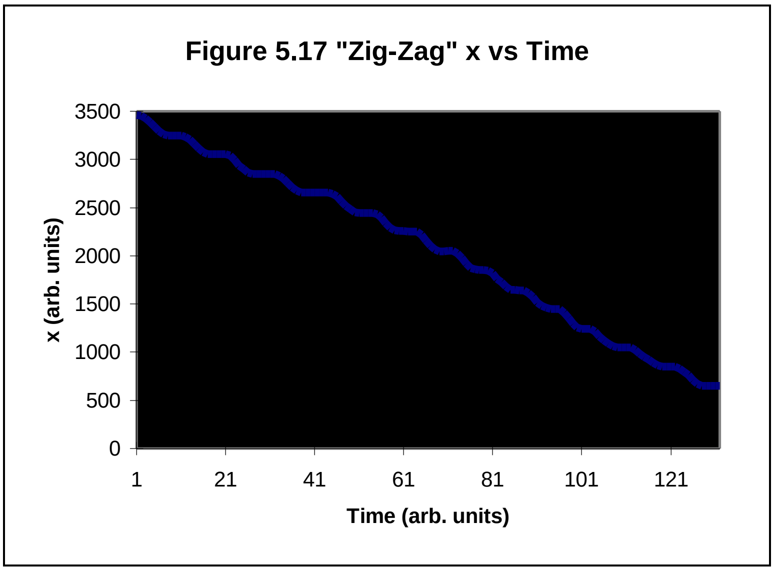


Figure 5.17 "Zig-Zag" x vs Time

The full width half maximum values for the measured pulsed durations are presented in figure 5.18. There appears to be a trend of increasing pulse duration at the dwell points but the durations at the intermediate points (approximately 40 µs) suggest that the speed at these points is relatively constant across the width of the scan pattern. The measured exposure durations can be used to determine maximum irradiances at these positions to comply with the MPE. Using the minimum (45.8 µs) and the maximum (289.8 µs) this gives a maximum irradiance of 219 and 138 Wm^{-2}, respectively, for a single pass of the beam. Assuming a scan rate of 100 Hz, and an aversion response time of 0.25 s, the irradiances reduce to 97.9 and 61.7 Wm^{-2}. These represent 3.9 and 2.4 mW into a 7 mm aperture.

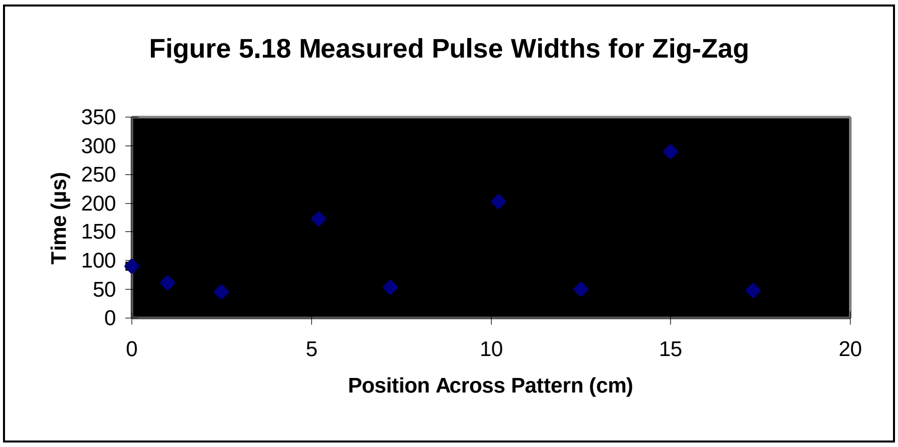


Figure 5.18 Measured Pulse Widths for Zig-Zag

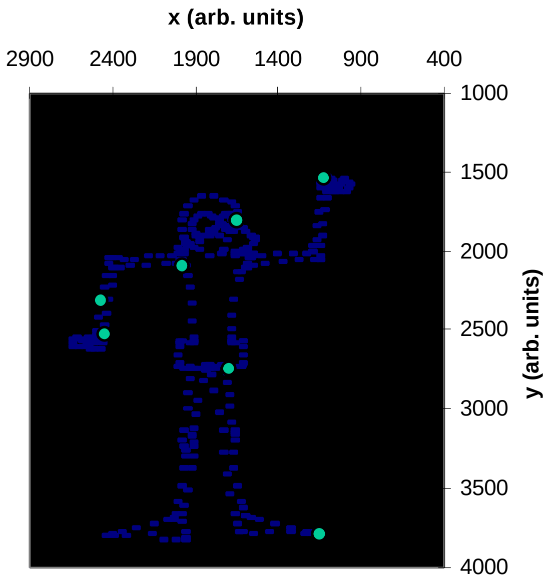
5.8 Complex Graphical Pattern

The zig-zag pattern is relatively straightforward - each position on the scan pattern is visited by the beam in a single pass across. Many images are complex and created by re-visiting the same position a number of times. Such images may also be animated. The graphical image in figure 5.19 is a single frame from the library of a commercial laser display system. The figure (Cuddles) performs an Egyptian dance. Some parts of the image are blanked so that the detail around the eye, for example, is clearer than implied from the x-y data alone.

5.8.1 Measurements

Measurements were made at a number of positions on the single frame (1 to 7 marked on figure 5.19) to determine the irradiance as a function of time, averaged over a 7 mm aperture. The laser beam diameter (as determined by eye) was 4 mm at the measurement position. The graphical image was 0.35 m from finger tip to finger tip and 0.46 m from the top of the head to the base of the feet.

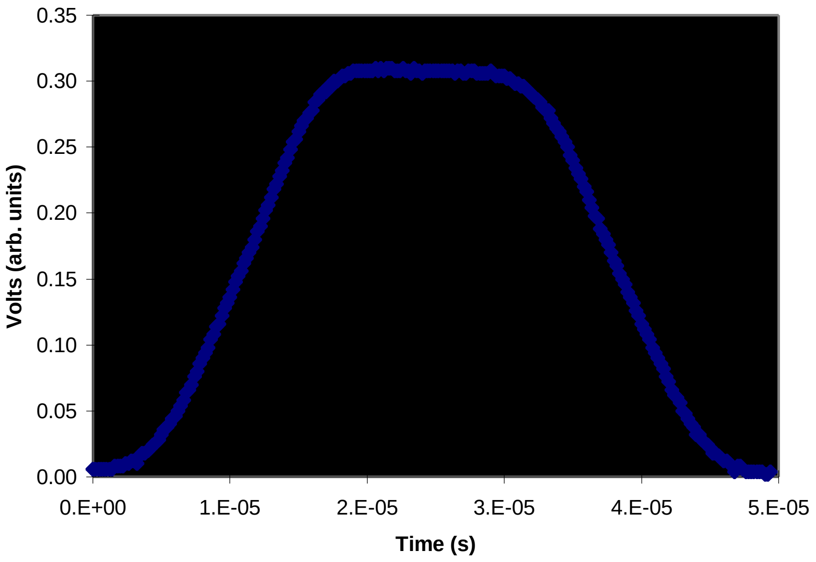
Figure 5.19 "Cuddles" x-y data



5.8.2 Results

The detector output as a function of time is presented in figures 5.20 to 5.26 for positions 1 to 7, respectively.

Figure 5.20 Cuddles Position 1



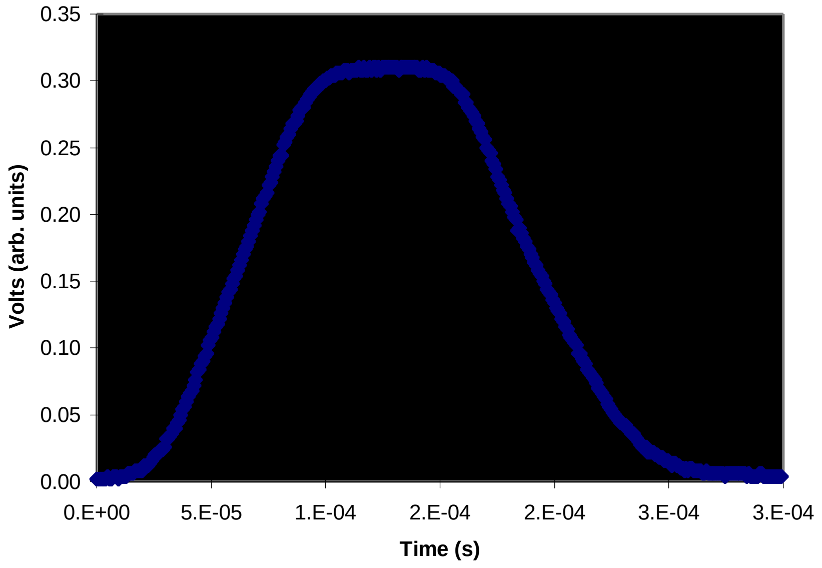


Figure 5.21 Cuddles Position 2

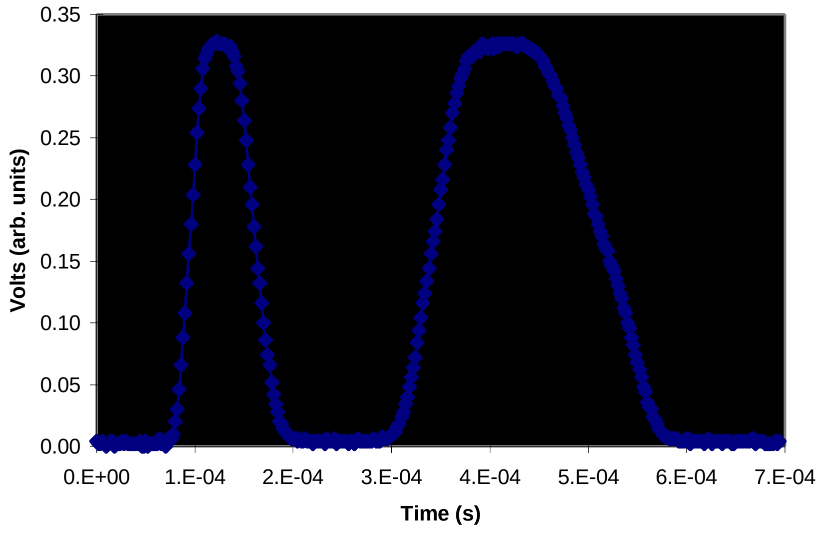


Figure 5.22 Cuddles Position 3

Figure 5.23 Cuddles Position 4

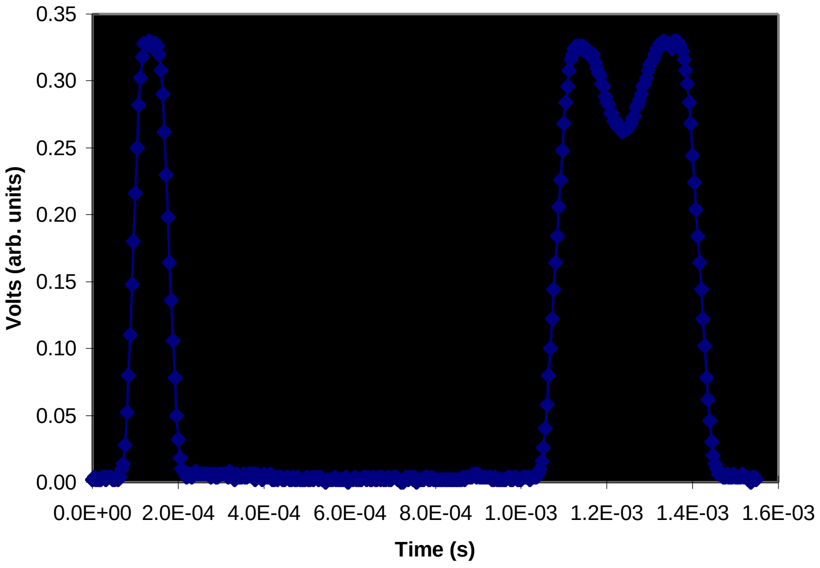


Figure 5.24 Cuddles Position 5

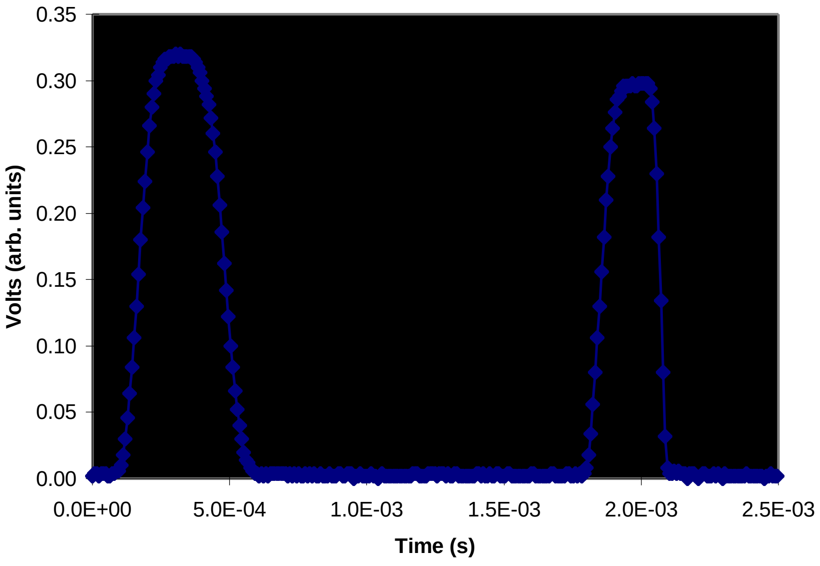


Figure 5.25 Cuddles Position 6

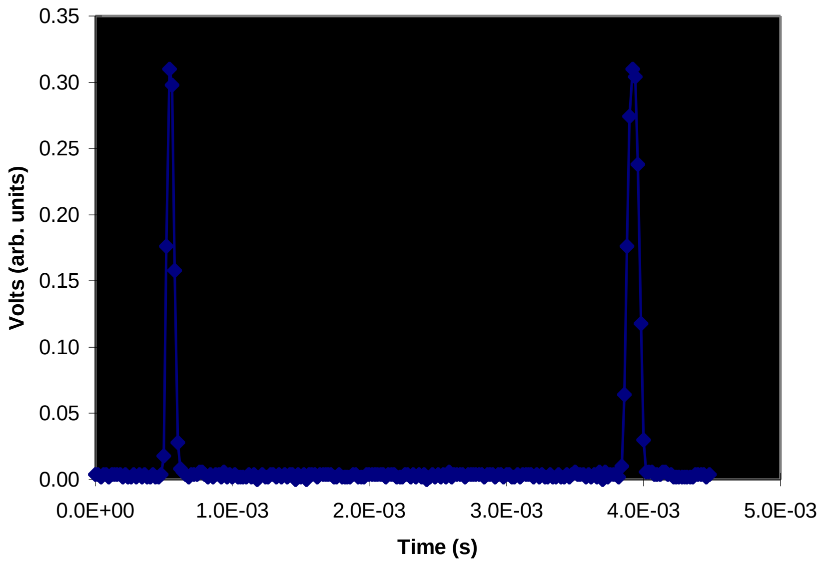


Figure 5.26 Cuddles Position 7

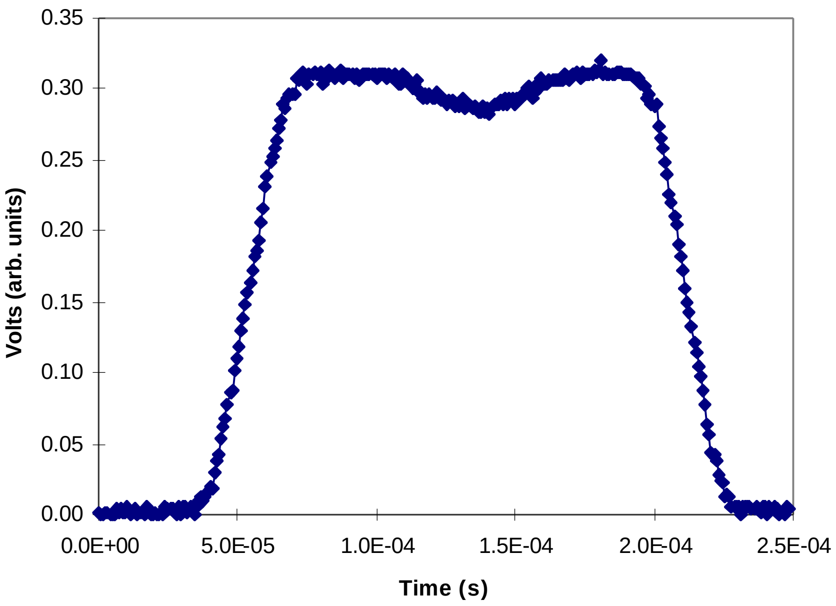


Table 5.6 Analysis of Cuddles Scan Pattern

Position	No. of Pulses per Frame	Pulse Width (μs)	MPE$_{single}$ (W m^{-2})	P$_{single}$ (mW)	MPE$_{train}$ (W m^{-2})	P$_{train}$ (mW)
1. Straight of arm	1 (33 Hz)	28	247	9.5	146	5.6
2. Right hand	1 (33 Hz)	133	167	6.4	98	3.8
3. Right armpit	2 (33 Hz)	67	198	7.6	117	4.5
		174	156	6.0	92	3.5
If both pulses same	(66 Hz)	174	156	6.0	77	2.9
If pulses combined	(33 Hz)	241	144	5.5	85	3.2
4. Eye	2 (33 Hz)	86	186	7.1	110	4.2
		340	132	5.1	78	3.0
If both pulses same	(66 Hz)	340	132	5.1	65	2.5
If pulses combined	(33 Hz)	426	125	4.8	73	2.8
5. Left hand	2 (33 Hz)	310	135	5.2	80	3.0
		220	147	5.6	87	3.3
If both pulses same	(66 Hz)	310	135	5.2	67	2.5
If pulses combined	(33 Hz)	530	118	4.5	69	2.6
6. Top of leg	2 (33 Hz)	59	205	7.9	121	4.6
		99	180	6.9	106	4.0
If both pulses same	(66 Hz)	99	180	6.9	89	3.4
If pulses combined	(33 Hz)	158	160	6.1	94	3.6
7. Left toe	1 (33 Hz)	159	160	6.1	94	3.6

5.8.3 Discussion

The pulse data was analysed for each position. The pulse width was taken as the full width half maximum for each pulse. Where the pulse was not resolved at the half maximum it was treated as a single pulse. The time to the next pulse, or pulse group, as appropriate was determined to ensure that all of the pulses in the single scan of the image had been identified. The refresh rate for the scan was 33 Hz.

As stated in 5.5.2, there is no guidance within the British or International Standard on how to analyse groups of pulses where the time interval between the pulses is not a constant value. Therefore, for positions 3 to 6, which all were visited more than once during a scan cycle, the MPE was calculated using the following options: each pulse was analysed independent of the other pulse; both pulses were assumed to have the pulse width of the longer duration pulse; and it was assumed that there was only one pulse per scan cycle of duration equal to the sum of the duration of the individual pulses. This is presented in table 5.6. The final column of table 5.6 gives the maximum power averaged over a 7 mm aperture in order not to exceed the MPE. The range of pulse widths is from 28 to 530 μs, but the power limit only ranges from 2.5 to 5.6 mW. This result supports the argument presented with the simple scan pattern (table 5.3) that the power averaged over 7 mm diameter apertures for compliance with the MPE must be much lower than the radiant powers of the lasers typically used in the entertainment industry.

5.9 Conclusions

Measurement of the characteristics of the laser beams used in laser displays is important for quantifying the laser radiation hazard. This is required as input to the risk assessment. Generally, if the irradiance is less than the maximum permissible exposure then the risk of injury is low. As the irradiance is increased above the MPE then the risk of injury increases. This takes no account of other sub-threshold effects such as dazzle, distraction and after-images. For a seated audience such effects may not be significant.

However, if the laser beams extend beyond the confines of the venue then such effects may be important, for example pilots and drivers of motor vehicles may be at particular risk.

Many lasers used in the entertainment industry are Class 3B or Class 4 and the radiant powers may be 20 W or more. Lasers with radiant powers of the order of 5 W are routinely used for audience scanning. It is important to appreciate that, with a scanned laser beam, the peak power is incident on the target for a period of time. For many years, assessments of audience scanning effects have been carried out using laser power meters which, at best, give an indication of average power and may not respond at all, thus giving the impression that the exposure condition is well below the MPE. It is therefore extremely important for either scanned effects to be analysed properly, or for worst case assumptions to be made. The latter includes measurement of the stationary beams at the closest audience locations.

It is possible to predict the irradiance conditions for simple scanned patterns, such as cones. The analysis presented in this chapter was supported by measurements of an actual scan pattern to demonstrate that the speed of the scan had no effect on the MPE. This result is extremely significant. Many laser display companies are under the impression that their scan patterns are safe because they scan at speed. However, many of these companies are not able to quantify their scan parameters and generally do not have laser irradiance/power measuring equipment which will respond to the scanned beams. The results from the thermopile detector demonstrate how the use of an average power meter can be misleading. Average power is not the appropriate quantity for comparison with the MPE.

Measurements of the pulse duration, ie the exposure of a theoretical 7 mm diameter ‘eye’ was used to determine the applicable MPE, generally the reduced single pulse MPE or the $\mathrm{MPE}_{\mathrm{train}}$, and the maximum radiant power permitted through this aperture was determined from the pulse duration and number per scan, or frame. In all cases this radiant power was less than 10 mW. Where the scan rate was low such that the pulse width reached 0.5 ms, the maximum radiant power was 2.5 mW. This should be compared with the MPE for a static beam, which would be 1 mW for a single accidental exposure assuming the 0.25 s aversion response.

The conclusion is that the assessment of scanned beams can be greatly simplified by measuring the power of a static beam through a 7 mm diameter aperture. If this is 1 mW or less then the MPE will not be exceeded at any position in the scan pattern. This can probably be increased to 2 mW for most scan patterns (see table 5.4) but any further increase will require significant effort to analyse each scan pattern, including any failure modes.

Limiting audience scanning beams to 2 mW into a 7 mm aperture can be achieved by using a low power laser such that the radiant power of the laser is less than 2 mW. This will limit the effectiveness of the beam effect where audience scanning is not required. Therefore a more effective control measure will be to increase divergence, and therefore, the diameter of a higher power laser beam such that the power entering the 7 mm diameter aperture is less than 2 mW. This could be achieved by the use of a lens. Another advantage of this approach is that the lens could be mounted at an aperture used for audience scanning. Other apertures from the optical system could be used for other effects, but these would need to be blanked to ensure that the beam could not stray into occupied areas. It would also be possible to combine two apertures to produce a scan pattern. For example, a cone scan could be generated by the top section projected overhead as a well collimated beam through one aperture whilst the lower section, which was projected into the audience passes through a different aperture, close to the first, but incorporating a lens.

Diffractive elements are becoming widely available which generate complex images. These allow laser effects to be produced, such as flat patterns, cones and cartoon characters without scanning the laser beam. Such elements could be rotated and selected, for example by mounting into a rotating cassette. Since the beam is not scanned, the peak radiant power is much lower and is truly averaged over the pattern. Such effects are currently limited since they need to take account of the size of the venue, etc. However, devices are currently being developed which will allow a diffractive element to be active and programmable to produce the desired effect.

In summary:

1. Audience scanning is currently carried out without adequate quantification of the hazard.
2. Analysis of beam effects is complicated for anything other than simple scan patterns.
3. Increasing the speed of a scan pattern does not make it safer.
4. Measurements of scan patterns are not made with appropriate instrumentation. Such measurements need to determine the duration of exposure for each scan pass the eye, the peak irradiance averaged over the 7 mm diameter eye, and the number of exposures within a suitable time frame, 0.25 s, say.
5. The analysis of complex scan patterns demonstrates that the maximum power into a 7 mm aperture is less than a factor of ten above the MPE for a static beam, and often only a factor of two greater.
6. The analysis can be simplified by assessing static beams only.

These conclusions are significant for putting the laser radiation hazard into context with other hazards which may be present at a laser display.