3. Background for the Research

3.1 Introduction

There are a number of applications for lasers in the entertainment and display industry. The examples described here represent a cross section of these applications and are events where the author was involved either as the laser safety adviser to the enforcing authority or attended at the request of the organisers or venue operator. The involvement was at the start of the research.

There is currently no published comprehensive review of the laser systems used by the entertainment industry in the UK. This puts the enforcing officer at a disadvantage in that s/he may not be familiar with the technology and have no reference to turn to. At the start of this research the laser companies were reluctant to reveal details of the hardware used. This was justified by them on the basis of fierce competition within the UK. This approach appears to be different from that in the United States and Canada where standardisation has been encouraged and shows are transferred between companies on magnetic tape. Laser F/X International have recently published a guide to the equipment used in North America (Roberts, 1996), but this does not cover the safety aspects of individual components in any detail.

3.1.1 Details of Laser Display Systems

An outline block diagram of a simple laser display system is presented in figure 3.1.

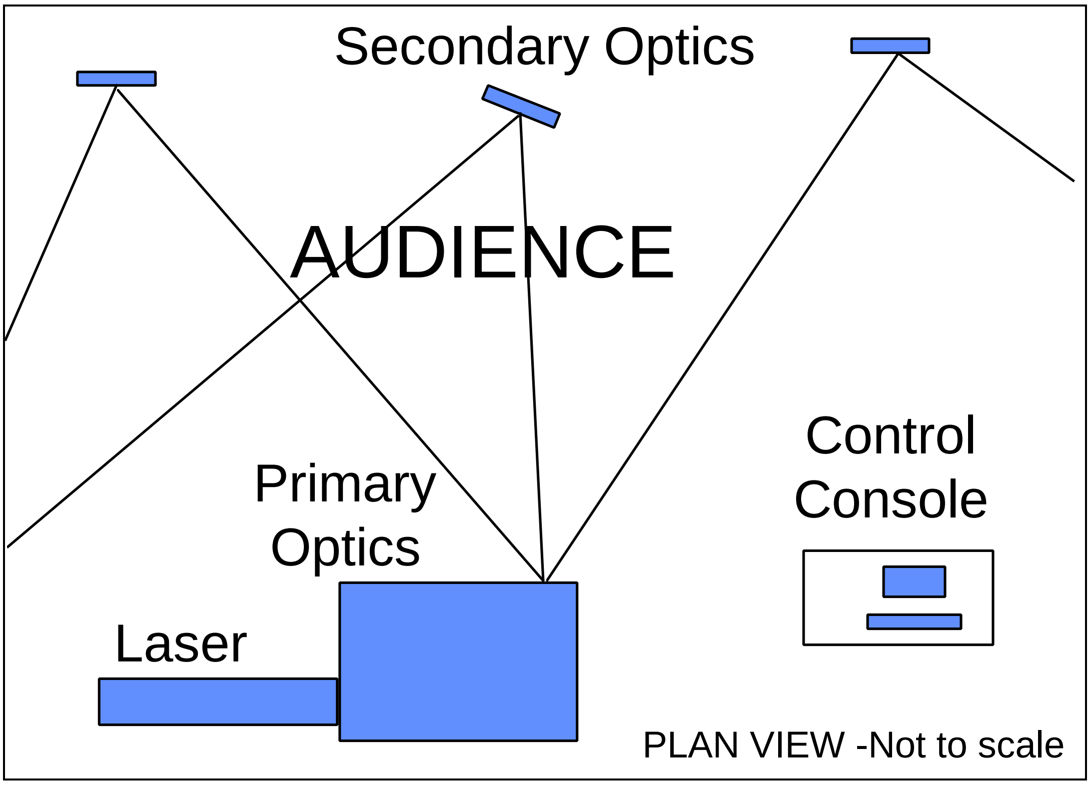

Figure 3.1 Simple Laser Display System

In order to use laser radiation for entertainment, it is necessary to have laser beams that are visible. This means that the radiation should be within the wavelength range 400 to 780 nm, and a proportion of the beam needs to enter the eye to stimulate the optical sensors on the retina. The eye does not respond equally to all wavelengths. Therefore, in order to achieve the same level of "brightness", different irradiance levels on the retina are required. The absolute luminosity curve for the eye's photopic (high light level) response is presented in figure 3.2 on a linear/log scale to emphasise the contribution at the visible wavelength extremes (after Anderson 1989). Combining visible radiation of different wavelengths produces white light. Since the mixture relies on the visual perception of the light, it is important that the irradiances on the retina are matched to the inverse of the curve in figure 3.2. The use of multiple colours is more important for graphical images than for beam effects. These are discussed in more detail below.

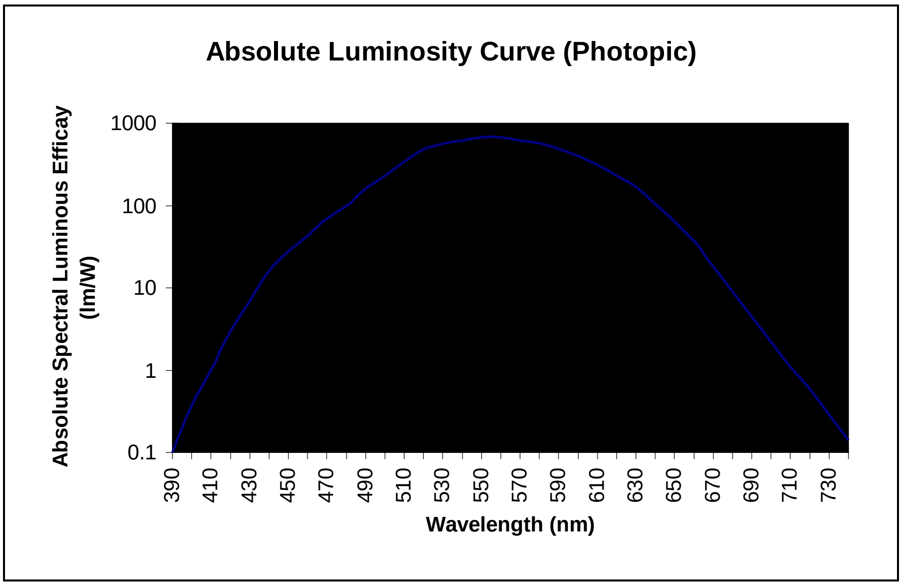

Figure 3.2 Absolute Luminosity Curve (Photopic)

A number of different types of laser are used in the entertainment industry. The types described here are restricted to those which emit laser radiation in the visible part of the electromagnetic spectrum. It is unlikely that lasers emitting infrared radiation will be employed but it is accepted that there may be some experimentation with lasers emitting ultraviolet radiation (UVR). UVR can be used to induce fluorescence in certain materials, including cosmetics. However, the collimated nature of laser radiation is a disadvantage for such applications.

There is limited information about the number of lasers used in the entertainment industry but there is an indication of the number of units sold per year from the annual review and forecast covering all laser applications published by Laser Focus World. The information relating to entertainment also covers laser pointers, laser-based information displays, display holograms and laser projection systems. The data from the 1995, 1996, 1997 and 1998 review and forecasts are presented in table 3.1 for world-wide sales (Anderson 1995, 1996, 1997 and 1998). All other categories were zero. It was recognised that China and Asia represent growing entertainment markets.

Diode lasers, including laser pointers, have not been included in this table. The data was collected by contacting manufacturers throughout the world. However, it is known that a number of laser display companies are using metal vapour lasers whereas the data in table 3.1 suggests that these have moved out of favour. The sudden growth of diode-pumped solid state lasers is ably demonstrated.

Table 3.1 only considers lasers sold new into the entertainment industry and also probably ignores small manufacturing bases. A number of the lasers used in the entertainment industry move into the sector as second hand products from other industries. There are also a small number of dedicated manufacturing bases. However, the latter probably represent less than ten units per year in the UK, although most of these are solid state lasers.

Table 3.1 Laser Focus World Review and Forecast of Worldwide Laser Sales (Units)

	1994 (Actual)	1995 (Actual)	1996 (Actual)	1997 (Actual)	1998 (Forecast)
Solid State - Lamp Pumped	40	50	15	20	25
Solid State - Diode Pumped	0	0	20	50	90
Ion < 1W	316	207	154	200	200
Ion > 1W	257	289	305	286	299
He-Cd	20	25	0	0	0
He-Ne	5500	7000	7750	5000	5000
Metal Vapour	5	0	0	0	0
Total	6138	7571	8244	5556	5614

This section reviews some of the laser display systems used and is based on discussions with a number of laser companies. Although there was a belief that they all had unique systems, they were all very similar in concept, if not in detail. The safety issues associated with the various components of the laser display are presented. Further details of the equipment used are contained in Appendix 1.

3.1.1.1 Lasers

Table 3.1 shows the types of lasers sold for use in the entertainment industry. Each have safety issues associated with them (see table 3.3). The wavelengths used for entertainment applications from each type of laser are summarised in table 3.2.

Table 3.2 - Principal Wavelengths from Lasers Used in Entertainment

Type of Laser	Principal Entertainment Wavelengths (nm)
Solid State - Lamp or Diode Pumped Nd:YAG (frequency doubled)	 532
Ion Argon-ion Krypton-ion Mixed Gas or "white light"	 457.9, 476.5, 488.0, 514.5 406.7, 413.1, 468.0, 530.9, 568.2, 647.1, 676.4 457.9, 476.5, 488.0, 514.5, 530.9, 568.2, 647.1, 676.4
He-Cd	441.6, 537.8, 636.0
He-Ne	543.5, 594.1, 604.0, 611.9, 632.8, 640.1
Metal Vapour Copper Vapour Gold Vapour	 510.6, 578.2 628.0
Dye Lasers	Various
Semiconductor Lasers	Various

As has already been discussed in 3.1.1, the eye's response, in terms of how bright a light source is for a fixed irradiance, depends on the wavelength. White light can be generated by mixing the wavelengths either from a single laser or two or more lasers. However, in order to achieve true white light (as perceived by the eye) it is necessary to mix the irradiances at each wavelength in inverse proportion to the photopic response of the eye. There are essentially two types of visible effect that are produced: beams in the air and graphical images. Usually, the effects are mutually exclusive, ie with graphical images it is preferable not to have the beams visible in the air; and with beam effects it is generally undesirable to see the eventual target site of the beams.

The safety issues associated with each of the types of laser in table 3.2 are summarised in table 3.3. Some of the hazards will only be accessible during maintenance or servicing of the laser. However, since these operations are routinely carried out by staff from the laser companies it is important that they are included here.

Table 3.3 - Hazards Associated with Entertainment Lasers (in Addition to Visible Laser

Type of Laser	Invisible Laser Radiation	Incoherent Optical Radiation	High Voltages	Weight	Moving Parts	Coolant	X-Rays	T
Solid State - Lamp pumped	▤	▤	▤	▤	▤	▤		
Solid State - Diode Pumped	▤			▤	▤	▤		
Ion			▤	▤	▤	▤		
He-Cd	▤		▤	▤	▤	▤		
He-Ne			▤					
Metal Vapour			▤	▤	▤	▤	▤	
Dye	▤(?)	▤(?)	▤	▤	▤	▤		
Semiconductor	▤(?)			▤(?)				

Key: ▤ this hazard generally exists for this type of laser.

▤(?) depends on the specific type of laser. The hazards associated with dye lasers may be due to the pumping laser

The typical mode of operation and current maximum radiant powers for typical entertainment lasers are summarised in table 3.4.

Table 3.4 Summary of Common Entertainment Lasers

Laser	Mode of Operation	Radiant Power Range (in Entertainment)
Helium-Neon	Continuous	< 1 mW to 75 mW
Argon-ion	Continuous	50 mW to 50 W
Krypton-ion	Continuous	50 mW to 5 W
Mixed Gas	Continuous	50 mW to 5 W
Helium-Cadmium	Continuous	up to 150 mW
Copper Vapour	Pulsed	up to 100 W average
Gold Vapour	Pulsed	up to 5 W average
Neodymium:YAG (frequency doubled)	Continuous or Q-switched	up to 50 W average
Semiconductor	Continuous	up to 5 W (array)

It is possible that other lasers could be used for entertainment applications but the list considered in this section represents the majority of the types of lasers in use today. The continuous development of the semiconductor laser will mean that three-colour semiconductor products will eventually come on to the market.

As described in the previous chapter, laser radiation safety appears to be well addressed, with information to assess the magnitude of the hazard given in the current British Standard (BSI, 1994). In order to make the assessment for a given laser, the following information will be required:

- wavelength;
- radiant power or energy;
- pulse characteristics;
- beam divergence; and
- initial beam diameter.

There may be some inconsistencies in the way some of this data is presented by manufacturers. The beam is generally assumed to have a Gaussian profile. The beam diameter may be quoted at the 1/e or $1/e^2$ points. The divergence may be quoted as a full or half angle. It is also possible that some lasers will have a beam waist outside the laser aperture.

3.1.1.2 Associated Equipment

A semiconductor laser may be a complete unit, including all power sources. Most of the other lasers will at least have an electrical power cable which needs to be connected to an electricity supply. Lasers, such as the argon-ion laser, may consist of a laser head, an “exciter” unit, which provides the necessary high voltages, a control module, cooling water supply and all of the associated cables and pipework to connect the various parts together.

A summary of the equipment associated with running an entertainment laser is presented in table 3.5, along with the resultant hazards.

Table 3.5 Hazards from Associated Equipment

Equipment, etc	Hazards
Generator	Noise, High Voltages (may be three-phase supply), Fuel, Heat, Fumes, Weight
Laser Exciter	High Voltages, Weight
Control Module	Uncontrolled Access
Cooling Plant	Noise, Water/Coolant, Pressure, Heat, Weight
Water Storage Tanks	Weight, Water (potential risk of drowning)
Support Stand	Weight, Stability
Electrical Cables/Control Cables	High Voltages, Trip Hazards
Cooling Pipes	Trip Hazards, Pressure, Water/Coolant

3.1.1.3 Optical Systems

The laser may be used without any other optical components to produce a display. However, it is more likely that the beam will be directed through optical systems to produce various visual effects.

There are three optical systems which need to be considered:

- the transfer of the beam from the laser to one or a number of primary optical processing systems;
- primary optical processing, normally within an optical bench; and
- secondary optics, normally mounted around the venue and including the final target site(s) for the laser beam(s).

Any one of the optical systems can alter the characteristics of the laser beam, including the temporal characteristics, the radiant power or energy, beam diameter and beam divergence.

The transfer of the beam from the laser to the primary optical system may be through the open air, through a beam tube or through a fibre optic cable. The laser may be mounted within an enclosure with the primary optical system, it may be coupled directly to the enclosure, or may be remote.

The optical systems may contain a number of components which may also alter the characteristics of the beam. Typical components are summarised in table 3.6. Further descriptions of the individual components are given in Appendix 1.

Table 3.6 Summary of Components in Optical Systems

Component	Characteristics
Beam Dump	May be a specific absorber block, local shielding within the primary optical system or part of the venue structure. Essentially, the place where the beam is terminated. May be the place where reflected beams from, for example, dichroic filters are dumped. Should be sufficient to cope with the maximum irradiance likely to be encountered at that position.
Beam Scanners	Deflect beam under control. May be mirror mounted on motor shaft, galvanometer pairs or acousto-optic modulators. Used to generate aerial beam effects and images on screens. Can be considered a moving form of the plane mirror.
Beam Splitters	An incoming beam is split into two beams. The split may be 50-50, or any other ratio. Can be used to generate more than one effect simultaneously from a single laser beam.
Beam Stop	Generally, a mechanical shutter placed in the beam path. May be activated by a solenoid. May be switched out of the beam path at the start of a show and back in at the end of the show.
Colour Selectors	May be dichroic mirrors or a polychromatic acousto-optic modulator. The dichroic mirrors may be mounted on rotary actuators. Consideration has to be given to the unwanted portion of the beam.
Diffraction Grating	May be transmission or reflection. May have zero order suppressed. Beam power effectively split over a greater area.
Effects Wheel	May contain a number of optical components such as diffraction gratings, and also a straight through position. The wheel rotates under control to select the different positions.
Lenses	May be used to focus or diverge the laser beam. May be used as part of the Z-Blanking system or to increase the beam divergence at the exit aperture of the primary optical system. The use of a lens anywhere in the beam path will suggest that the beam divergence provided by the manufacturer of the laser will not be valid for the beam after the lens. The use of a convex lens may produce a focal point external to the aperture from the primary optical system
Luminaires	Glass or plastic which influences the path of the beam. Shower glass or other optically transmitting material which has a surface texture is generally used. A prism or a polychromatic acousto-optic modulator may be used to split the colours before passing through the luminaire.
Masking Plates	Physical blanking plates which may be located at the exit apertures of the primary optical system to restrict the possible beam paths to avoid exposure, for example, of the audience. May also be incorporated into secondary optical components to reduce the effect of unplanned component movement.
Mirror Balls	A secondary optical component which has multiple facets of either plane or diffraction mirrors. The facets may be of similar dimensions to the laser beam, in which case the beam is scanned across the mirror ball, or the beam may be diverged through a lens to fill the mirror ball.

Table 3.6 Summary of Components in Optical Systems (continued)

Component	Characteristics
Plane Mirrors	Front or rear silvered mirrors. Assume total reflection with all beam characteristics except direction conserved.
Projection Screens	May be a standard projection screen or may be any other surface, including buildings, trees and clouds, on which the laser beam is projected. The projection screen may have reflecting surfaces or may transmit a proportion of the incident beam.
Rotary Actuators	Usually has something mounted on an arm which is introduced into the beam under control. Can be used to switch beam paths, block beam paths and remove specific wavelengths from the laser beam.
Z-Blanking	Generally either a galvanometer or an acousto-optic modulator which switches the beam on and off under control. Used so that the beam position can be moved without being seen.

3.1.1.4 Control Systems

The laser display is usually controlled by one of three methods: manually, programmable controller, computer-based controller. The controller generally does not control the laser itself: this was considered in 3.1.1.2. However, it will control all of the primary optical system and possibly secondary optics. It may control associated equipment such as smoke generators, electric screens, water screens, etc. Programmable controls are considered here to include systems which incorporate a tape player to present pre-recorded laser shows. The controller will be linked to the equipment it is intended to control. This may be by wire, fibre optic cable link or by radio/infrared free-in-air link. Each of these will have safety issues associated with them. The trend towards computer control and digital communications may provide the opportunity for increased fault tolerance but also provides the opportunity for communication over greater distances via network systems. This may result in global control of many laser displays in different countries at the same time from a central point. This approach is already used for permanent small-scale laser displays in shopping malls. These are generally used to display textual images and logos and are programmed from a central location (Lissack, 1995).

A summary of the safety issues associated with the control systems is presented in table 3.7.

Table 3.7 Safety Issues from Control Systems

Item	Safety Issues
Manual Controller	Degree of operator control. Potential for pressing wrong button. Ability to alter show from what has been agreed.
Programmable Controller	Programming errors.
Computer-based Controller	Computer failures. Interference from other equipment. Programming errors.
Communication Channels	Loss of communication. Interference with communication.
Operator	Training. Degree of control. Pressure of work (stress).
Power Supplies	Failure. Malfunction. What happens to optical systems under these circumstances? High voltages.

3.2 Lasers in Entertainment

A number of applications of lasers in entertainment were reviewed to consider whether the conclusions from chapter 2 were valid, ie laser radiation issues were readily addressed using the guidance and standards available and that the main safety issues related to the non-beam aspects and practical risk assessment.

It was necessary to analyse each of the events using a common format. This would also highlight areas which needed further investigation. A description of each of the events studied is presented in Appendix B.

The inclusion of an event in this chapter does not necessarily imply that the public were exposed to an unacceptable risk. Of equal concern was whether the laser company could quantify the hazards and therefore make a judgement about the magnitude of any risks. As already stated in Chapter 1, the average family attending an event provided for their entertainment assumes that their safety is assured.

Each of the events is identified by a letter (A-H), for reference in the summary table. An outline of the events is presented in table 3.8

Table 3.8 Outline of Laser Events

Event	Description
A	Outdoor Classical Laser and Firework Concert
B	Outdoor Classical Laser and Firework Concert
C	Outdoor Display at a Marina
D	Drive-In Movie and Laser Show
E	Trade Exhibition
F	Trade Conference
G	Medical Laser Exhibition
H	Laser Tag Game

3.3 Analysis of Laser Events

Factors of interest in analysing the events described in Appendix B include whether the event could be assessed in advance, ie whether adequate documentation was available; whether the event could be assessed on the day, but before the start time of the event; and whether the risks were adequately assessed and/or controlled.

None of the laser companies involved in the events were able to supply adequate information in advance to enable a judgement to be made. Although an appendix 3 to PM19 was supplied for seven of the eight events, the information was either not appropriate, incomplete or wrong. In all these cases, the companies considered that the information they had supplied was adequate and events had been approved in the past on the basis of similar paperwork.

Some of the assessments were carried out with either Environmental Health Officers or venue safety managers. They did not understand the information they were being provided with. In all cases, proactive consideration of safety was considered by the laser company staff to be detrimental to their work. There appeared to be an ethos that raising safety issues would imply an unacceptable risk and this was not what the promoters wished to hear.
There were several cases of the actual event not matching the paperwork provided. In one case (event A), the arrangement for the stage was changed on the day. At another (event C) further construction work took place after the initial assessment, which altered the risks.

Practical preparation and planning prior to the events appeared to be limited. It was usual for the equipment to arrive on site and then to be constructed into a laser display system using a range of components. Generally, inadequate time was allowed for construction and alignment to take place.

At most of the events, audience exposure to the laser radiation was either planned or reasonably foreseeable. None of the laser companies had the ability to assess the magnitude of the hazard, or the risk of injuries taking place. All laser companies were experienced, in that they had undertaken many events previously. They appeared to rely on a lack of reported incidents from previous events to justify the lack of risk.

Whilst the quantification of the laser radiation hazard was an obvious issue, the associated hazards often had more immediate impact. Outdoor events in particular suffered the problems from trying to operate essentially laboratory equipment in a relatively hostile environment. Water and electrical power were always a problem. Since they are so vital to the operation of the laser display, and must be an issue at most outdoor laser events, it was astonishing how surprised the laser company staff appeared to be that they experienced problems.

The enforcing officer or venue safety manager generally did not have experience of assessing laser events. However, rather than consider the issues they should have been familiar with, such as electrical and mechanical safety, they considered the laser event to be completely different. The laser radiation safety issue may have been minor compared with the risk of electrocution and working at height.

The laser companies were normally working alongside other sectors of the industry, such as fireworks companies, stage construction companies, and lighting and sound engineers. These sectors generally presented a professional (to the uninitiated) image with good preparation and equipment that appeared to be designed and constructed for the environment in which they were intended to work. The staff from these other companies generally considered the laser companies to present an amateur image and, in some cases, considered them a danger to everyone working in the vicinity.

None of the events fully complied with the requirements of PM19.

3.4 Conclusions

Table 3.9 summarises the eight events assessed and brings together the common factors which needed to be investigated further. Consideration is given to the paperwork supplied by the laser company, such as the PM19 Appendix 3 (HSE 1980).

The selected examples reported here demonstrate that exposure in contravention of the then Health and Safety Executive Guidance was occurring. There were no events attended by the author where everything was satisfactory. There was a wide range of knowledge amongst Environmental Health Officers (EHOs). The laser companies have been known to use this to their advantage. However, further research was required to identify the extent of the involvement of EHOs with laser displays. It would not be reasonable to expect EHOs to be experts in assessing laser displays if they are rarely required to assess them. A more effective use of public money would be to seek assistance from a third party when necessary. It was necessary to survey the enforcing officers to determined the extent of their involvement in laser displays. However, it was found that all of the EHOs had expertise in the non-laser-radiation hazards, but because they were dealing with a laser product did not always use this expertise to work through the problem systematically. They saw the use of lasers as being special.

The stage at which the EHO became involved in the event, and the stage at which they sought external advice, also had a bearing on how the final event could be influenced to ensure that the risks were minimised.

The human factor has been shown to be a major component in the display events discussed, but engineering and administrative controls were also found to be inadequate.

It was clear that some of the laser companies wished to provide shows with the risk to everyone minimised. However, their technical ability to do this was limited. In other instances, the desire to expose personnel directly with the laser radiation was driven by the perceived customer desire for this. It is likely that this ethos will only be overcome by the laser companies demonstrating that they can produce more effective shows without the need for the beams to go into audience areas. This requires an understanding of the eye's response to laser radiation in terms of visual perception rather than health effects.

A common comment from the laser display operators was that the enforcing officers did not understand the 'special' problems associated with the laser display industry. Equally, the enforcing officers considered the laser display companies unhelpful. The root of the problem appeared to be an inconsistent approach to assessing laser displays throughout the UK, possibly due to the lack of specific legislation. This was generating friction because operators found it difficult to understand why a show could be considered acceptable in one location, but not in another. There was also no recognised approach to either tackling or assessing the risks from the activity.

It is obvious from these assessments that there is a wide gulf between the laser display companies and the enforcing officers.

The methodology used to progress an improvement to the level of laser safety was to understand the tasks involved in putting on a laser display (including an understanding of the technology), identify whether it was possible to develop a protocol for identifying the hazards, quantifying these hazards, assessing the risks and presenting the conclusions.

Table 3.9 Summary of Common Factors from the Laser Events

Event	A	B	C	D	E	F	G	H
EHO Experienced?	N*	?	N*	N*	N/A	N/A	N/A	N/A
Collaboration?	P	P	P	P	N	N	P	N
Risk Assessment?	N	N	N	N	N	N	N	N
Training - use	Y	Y	Y	Y	N/A	Y	N/A	N/A
Training - safety	N	N	N	N	N	N	N	N
Mechanical Stability	N	N	N	Y	N	Y	N/A	N/A
Goggles Available	N	Y	N	N	N/A	N	N/A	N
Written Procedures	N	N	N	N	N	N	N	N
Laser Controlled Area Marked?	N	N	N	N	N/A	N	N/A	N/A
App 3 PM19 Supplied?	Y	Y	Y	Y	Y	Y	Y	N
App 3 PM19 Adequate?	N	N	N	N	N	N	N	N/A
EMC Problem?	Y	N	N	N	N/A	N	N/A	N
Operation/control problem?	Y	Y	Y	Y	N/A	Y	N/A	N/A
Human Factors problem?	Y	Y	Y	Y	Y	Y	Y	Y

Notes: Y = Yes, N = No, ? = not known, P = Partial, N/A = not applicable
*laser safety support provided at the request of the EHO