LASER SAFETY REQUIREMENTS

P D Morgan

Milkwood

Acknowledgements

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They are:

Martin Dunstan,

Chris Gowers,

Mark Kempenaars,

Keith Stammers.

Outline of Talk

Introduction

Laser Types

Hazards Associated with Lasers

Laser Classification

Control Measures for Lasers

Practical Examples of Safety Implementation

Example of Risk Assessment and Method Statement

Concluding Remarks

INTRODUCTION

Why is Laser Radiation Potentially Hazardous to the Eye? (1)

1) It is monochromatic. Unlike a white-light bulb, the emission from which extends over the whole of the visible spectrum, laser emission usually comprises a well-defined wavelength, with a very narrow wavelength spread. Sometimes, 2 or 3 lines are emitted.

2) It can be of very high power.

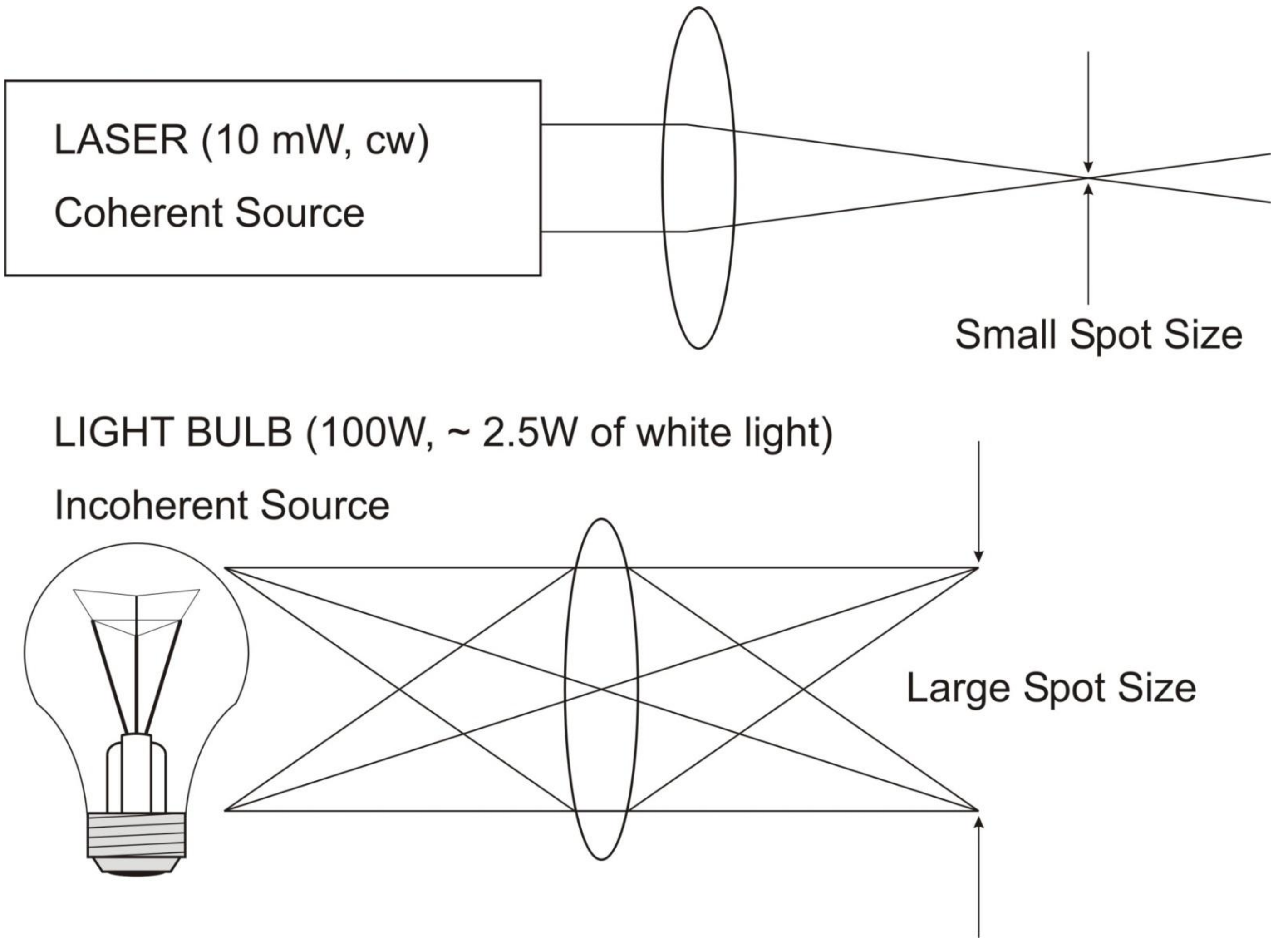
3) It is coherent. Photons are emitted from a light bulb independently of each other; there is no phase relationship between them. Laser radiation comprises photons that are emitted in phase. This produces spatial coherence across the beam wave-front. $I \alpha A^2$.

Why is Laser Radiation Potentially Hazardous to the Eye? (2)

4) It has low divergence. Where a resonant cavity is used, the laser radiation usually emerges from a small diameter aperture as an almost parallel beam. If allowed to fall on a target tens of metres distant, often the beam has not increased significantly in diameter - nor decreased significantly in intensity, This is unlike a light bulb which radiates in all directions, with an intensity that rapidly diminishes with distance - $1/R^2$.

These interrelated properties permit the focusing of laser beams to very small spot sizes, in some cases yielding extremely high intensities. Even lasers of modest power can be hazardous to skin and eyes. In the case of visible and near-infrared radiation the eyes are particularly vulnerable because of their ability to focus it onto the retina.

Why is Laser Radiation Potentially Hazardous to the Eye? (3)



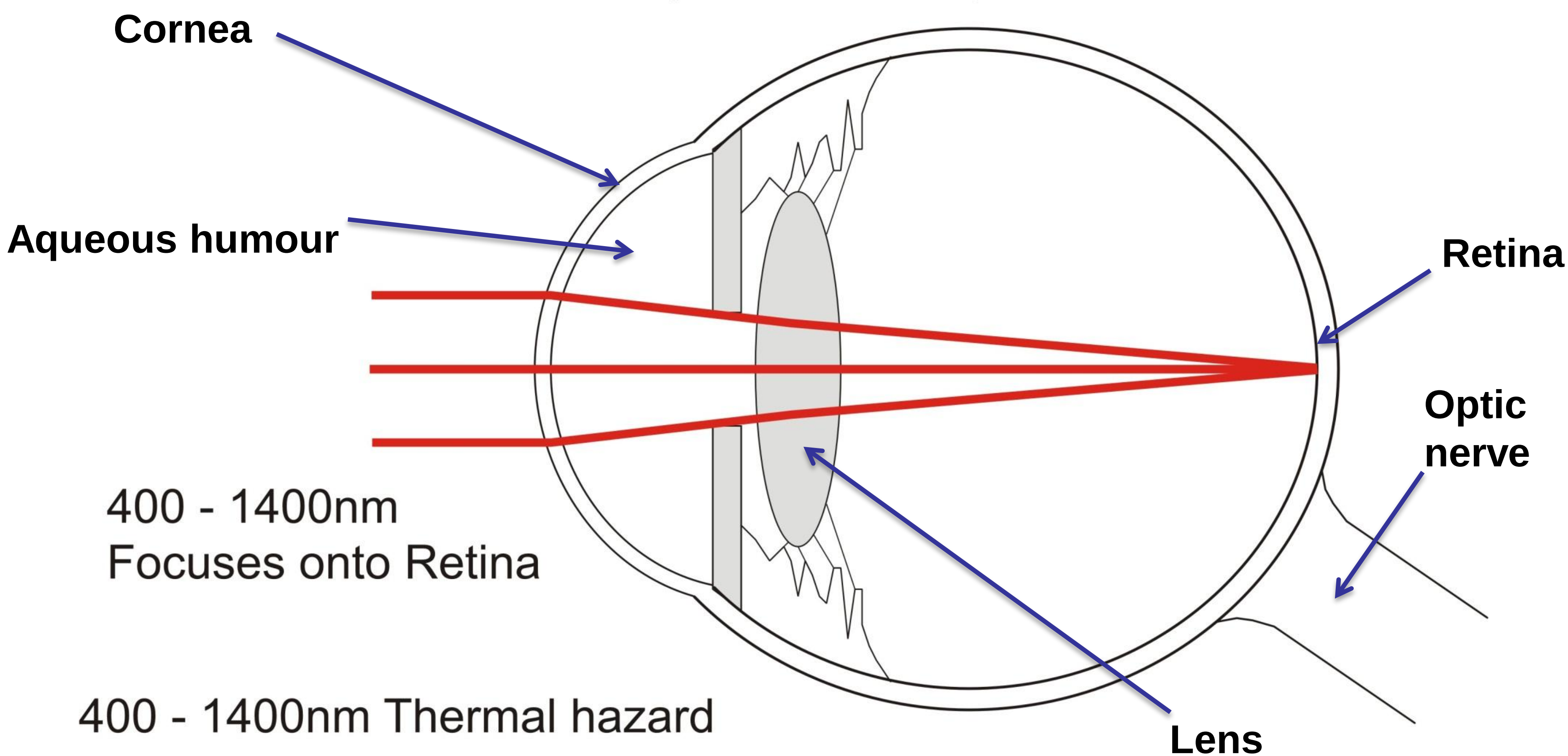
Whilst the retina in the human eye only records images in the wavelength range ~ 400 to 700 nm, the lens in the eye focuses radiation in the range 400 to 1400 nm onto the retina.

A visible laser beam exactly filling the fully-dilated pupil - 7 mm in diameter - will be focused onto the retina to a spot 500,000 times more intense than at the surface of the eye. Thus, a cw laser of power 10 mW has the potential to cause retinal damage - intensity increases from 26 mW cm^{-2} at surface of eye to 13 kW cm^{-2} on retina! (Statistics from UK eye hospitals indicate that 10 - 15 mW cw is power level in the visible at which signs of damage begin to appear, in an accidental exposure.)

NB: a laser emitting in the range 700 to 1400 nm (near IR region) is particularly hazardous, as the beam is invisible but is still sharply focused on the retina. In this wavelength range there is no aversion response (reflex action) - blinking and moving head - as protection.

The Retinal Hazard Region

Includes visible radiation (400 - 700nm) and near IR (700 - 1400nm)



400 - 1400nm
Focuses onto Retina

400 - 1400nm Thermal hazard

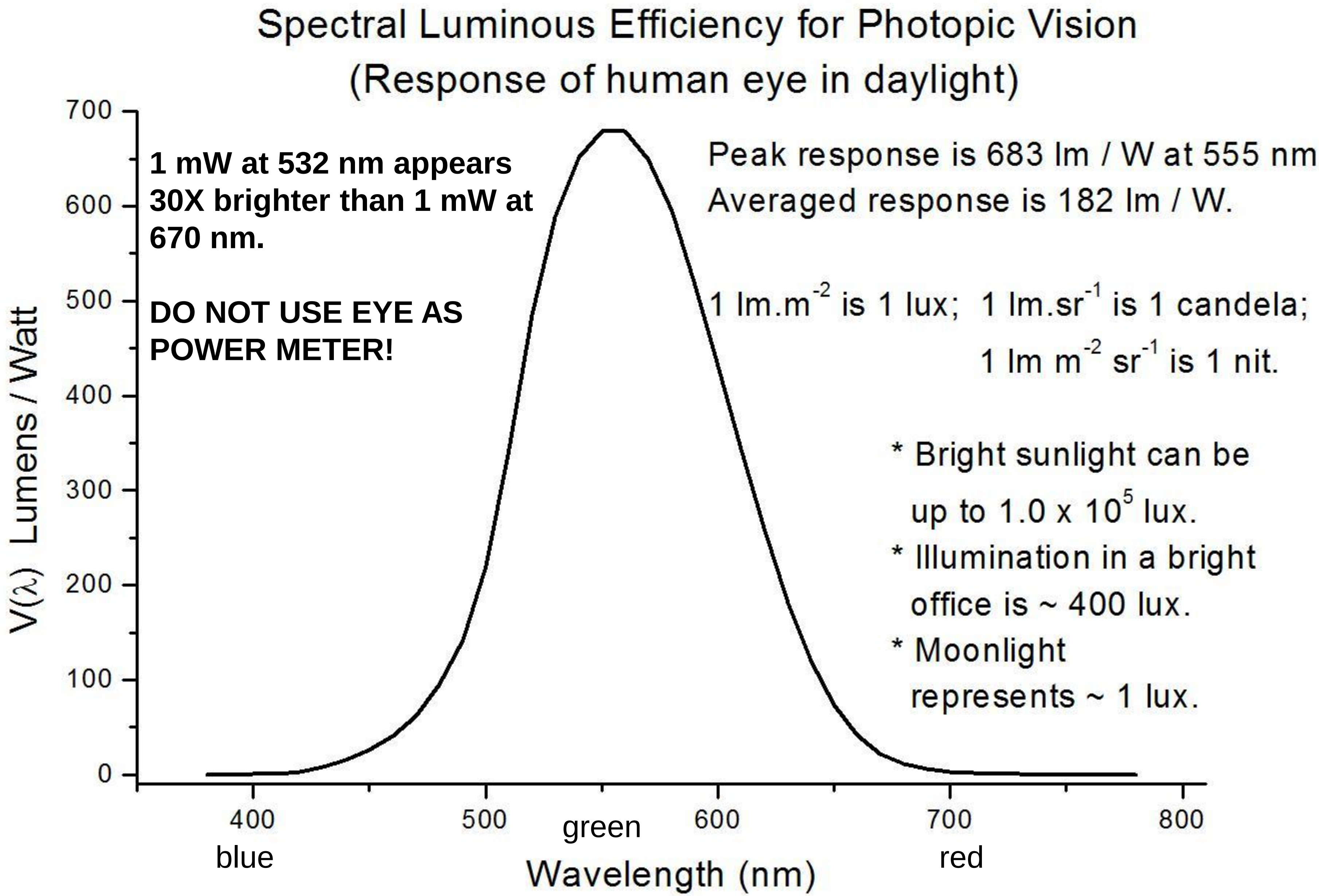
400 - 600nm Photochemical hazard

Ultraviolet Radiation and the Eye (100 - 400 nm)

UV-C (100 - 280nm): affects the cornea surface
UV-B (280 - 315 nm): absorbed by the cornea
UV-A (315 - 400 nm): affects the lens

Far-Infrared Radiation and the Eye (1400 nm - 1 mm)

The radiation affects the cornea and the aqueous humour



1 mW at 532 nm appears 30X brighter than 1 mW at 670 nm.

DO NOT USE EYE AS POWER METER!

TYPES OF LASERS ENCOUNTERED IN THE LABORATORY

TYPES OF LASERS ENCOUNTERED IN THE LAB (1)

Gas lasers - active medium is a gas excited by an electric discharge

DCN	196 μm	(250 mW cw)
CO_2	10.6 μm	(50 kW cw, GW pulsed)
He-Ne	633 nm	(100 mW cw)
Argon ion	488, 514 nm	(20 W cw)
Excimer	248 nm - KrF	(10 MW pulsed)

Solid-state lasers - active medium is a solid rod of transparent material excited by intense light from a xenon flash-lamp or from an array of laser diodes

Nd:YAG	1064, 532 (f x 2) nm	(TW pulsed, 100 W cw)
Nd:Glass	1064 nm	(GW pulsed)
Ruby	694 nm	(10 GW pulsed)

TYPES OF LASERS ENCOUNTERED IN THE LAB (2)

Dye lasers - active medium is a liquid (dye in solution), excited by a xenon flash-lamp or another laser

100+ dyes	300 - 1800 nm	(100 MW pulsed)

Semiconductor lasers - miniature devices comprising a p-n junction diode. Can be deceptively powerful. Many laser pointers are of this type, and they often pose the biggest headache for the Laser Safety Officer (LSO)!

GaAlAs	600 - 900 nm	(30 W cw)
InGaAsP	1100 - 1600 nm	(30 W cw)
InGaN	$\geq$ 405 nm	(500 mW cw)

LASER CLASSIFICATION

The Control of Artificial Optical Radiation at Work Regulations 2010 is a European Directive. Amongst other issues, it sets down legally-binding exposure limits for workers to laser radiation.

Otherwise, there are no legal requirements specifically for lasers. Within the EU, EN 60825 (Safety of Laser Products) in its various parts is widely adopted as the reference safety document. It represents standards of good practice. You may use your own approach to laser safety, if you so wish, but why reinvent the wheel?

Lasers, nevertheless, are regarded as equipment or machinery. As such, they are covered by many legal requirements, eg Provision and Use of Work Equipment Regulations; Manual Handling; Electricity at Work Regulations; Reportable Injuries, Diseases and Dangerous Occurrences Regulations; and Control of Substances Hazardous to Health. Apologies for UK bias.

Failure to seriously address laser safety could result - in the event of a significant incident - in the closure of the establishment by the competent Health and Safety Authority, as well as criminal proceedings being brought against those deemed to be negligent.

However, if you have made an honest attempt at addressing the issues, but have made a mistake, then you will be treated leniently and with sympathy.

LASER CLASSIFICATION ACCORDING TO EN 60825

Laser <u>products</u> are grouped into classes by their potential to cause harm to the human eye. The hazard is related to the wavelength, energy and pulse characteristics of the laser radiation, as well as the viewing conditions. The necessary safety measures are determined using this classification.

Seven classes of product are defined, based on the maximum power (or energy) to which anyone could be exposed during routine operation of the laser - not necessarily the total power or energy that the laser is emitting, which could be far higher.

Each Class is defined by an Accessible Emission Limit (AEL), ie the power or energy of the laser radiation that is accessible to the eye. It is not always straightforward to calculate the Accessible Emission, particularly for a train of laser pulses or for an array of laser diodes.

In order of increasing hazard, the Classes are: 1, 1M, 2, 2M, 3R, 3B and 4. If a laser system is modified its Class may change as a consequence - this should be kept in mind. Also, Class of system or product will very likely change if access panels removed, eg for servicing.

In the following simplified definitions, the term laser is used loosely to mean both system and product:

Class 1 Lasers which are safe under reasonably foreseeable conditions of operation. [AEL is 79 μW at 351 nm, 39 μW at 422 nm, 224 μW at 488 nm, 0.39 mW at 532 nm, 0.39 mW at 633 nm, 1.95 mW at 1064 nm and 9.6 mW at 10,600 nm, for cw beams (exposure duration 100 s).] Products with embedded lasers are often Class 1.

Class 1M Same AEL as for Class 1. Beam is highly divergent, or is collimated and of large diameter. Total beam power can be much higher than AEL, which is power passing through aperture of diameter 7 mm (pupil of eye) in the visible region. Aperture is wavelength dependent. May be hazardous if beam is observed using viewing aid.

Class 2 Lasers which emit between 400 and 700 nm. These pose bigger risk than Class 1 lasers, due to higher AEL - 1 mW for cw beam. Also, possibility of exposure dazzling or startling someone. Protection to eye against <u>accidental</u> exposure to cw beam is afforded by aversion response (blinking and moving head - assumed to take 0.25s). Generally considered safe, but deliberate direct viewing of beam is regarded as taking unnecessary risk and should be avoided.

Class 2M Same AEL as for Class 2, and same general comments. Beam is highly divergent, or is collimated and of large diameter. Total beam power can be much higher than AEL. Generally, not safe if viewing optics are used.

Class 3R Classed as medium power. In visible region (400 - 700 nm) AEL is 5 mW for cw beam, with assumed exposure 0.25 s. This is 5 x greater than AEL for Class 2 laser. At other wavelengths, AEL is up to 5 x greater than that for Class 1 laser. Because AELs for Classes 1 and 2 are quite conservative, accidental direct viewing of beam poses low risk of injury. Deliberate direct viewing of beam should always be avoided.

NB Class 3R laser pointers should not be used in lecture theatres. Too bright. In Australia such devices are classified as offensive weapons - $6,000 fine and / or 6 months in jail for possessing a Class 3R pointer!

Class 3B Classed as medium to high power. AEL is 500 mW for cw beam in wavelength range 315 nm to 1 mm. Direct viewing of beam usually hazardous. Viewing of diffuse reflections tolerable under strictly controlled conditions. May cause burning sensation, or burning, on skin.

Class 4 Classed as high power. AEL is greater than 500 mW, for cw beam in wavelength range above, but no upper limit. Direct viewing of beam and of specular (mirror like) or diffuse reflections always hazardous. Eye, skin, flesh and fire hazard.

EXAMPLES OF LABELLING UNDER EN 60825 (for Classes 2, 3B and 4)

Onus is on Manufacturer / Supplier to ensure correct labelling: black on yellow background with black border. However LSO should check!

NB	American classification system uses Roman Numerals, ie Class II, IV, etc. Slightly different from EU norm, but is accepted in EU.

LASER RADIATION
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION
CLASS 4 LASER PRODUCT

MAXIMUM OUTPUT < 1 mW
WAVELENGTH 630 - 680 nm
CLASSIFIED TO BS EN 60825-1: 1994

CAUTION - CLASS 3B LASER
RADIATION
WHEN OPEN AVOID EXPOSURE
TO BEAM

LASER APERTURE

HAZARDS ASSOCIATED WITH LASERS AND THEIR USE

HAZARDS ASSOCIATED WITH LASERS AND THEIR USE

The laser emission itself:

- at medium to high power, risk of severe damage to skin and flesh and, in the case of "visible" radiation, catastrophic damage to eyes.
- at low to medium power, secondary effects dominate: risk of injury caused by involuntary movement due to being startled by laser light (reflex action); consequences of being temporarily dazzled.

There is a maximum permissible exposure (MPE) for eyes and skin - which is wavelength dependent - either in terms of power or energy.

Collateral radiation from pump source. If it is another laser it will be of higher class (more powerful) than primary laser. Flash lamp UV.

X-rays - generated in e-beam lasers, HV thyratrons > 5kV, interaction of intense laser radiation with heavy metal targets.

EMI - from poorly shielded power supplies, rf-excited lasers.

High voltage and stored energy - risk of electrocution or severe burns, risk of fire in case of malfunction.

Xenon flash-lamps are not at atmospheric pressure - risk of implosion during handling (flying glass shards).

High temperatures and copious amounts of waste heat in large laser systems - problems associated with cooling.

Toxic, corrosive or carcinogenic chemicals - poisonous or corrosive gases, dyes.

Compressed-gas cylinders - risk of explosion.

Flammable gases; flammable liquids - used as solvents for dyes.

Risk of fire and toxic fumes - if powerful laser beams not correctly terminated.

Heavy equipment - risk of accidents whilst handling.

Trailing leads and cables - risk of trips and falls.

Whilst lasers have caused burns and eye damage to many users, laser radiation has never killed anybody - except in James Bond movies! However, people have died from electrocution, poisoning and cancer, through misuse, or misunderstanding, of lasers. Others have died in fires started by lasers and a few have been killed by power supplies toppling on them, whilst unloading from trucks.

CONTROL MEASURES

LASER RADIATION - HIERARCHY OF RISK CONTROL

(In general, this hierarchy is applicable to controlling other risks)

1. Eliminate

Is a laser needed in the first place?
Could another type of illumination be used?

2. Reduce

Do we really need such a powerful laser?
Using a Class 2 alignment laser at $\lambda = 532$ nm is more effective than using a Class 3R device at $\lambda = 670$ nm.

3. Engineering Controls

Interlocked laser access panels, beam guards, beam stops or dumps, low power alignment laser. Alternative: Laser in interlocked enclosure with enclosed beam paths - making it Class 1 product.

4. Administrative Controls
Trained users only, restricted access, key control, warning signs, risk assessment, written operating instructions, adverse incident procedures, audit of laser safety.

5. Personal Protective Equipment (the last line of defence)
If Maximum Permissible Exposure (MPE) exceeded:
Eyewear appropriate to laser type(s) and class(es)
Suitable protective gloves and clothing – fire proof!

CONTROL MEASURES FOR LASERS - EN 60825

Approval and Verification by Laser Safety Officer (LSO)

No laser to be purchased, used or brought onto site without prior approval of LSO. I wish!! Laser Class to be verified before first use.

Laser Responsible Officer (LRO)

An LRO is appointed for each laser of class 3R (non-visible only), 3B and 4, except for office products with embedded lasers - eg CD writer and reader in PC. LSO endorses appointment.

Registration (with LSO) of Laser & its Location

Required for each laser of class 2 and above, with exception of office products with embedded lasers.

Risk Assessment and Standing Orders (prepared by LRO)

Required for all Class 3B and 4 lasers - also for Class 3R lasers emitting non-visible radiation. Approval by LSO. To be displayed in prominent position. Contact details of LRO and LSO. List of authorised users. Contingency plans - nearest eye hospital with expertise in treating injuries caused by lasers, and how to get there.

Training of Laser Users

Required for all laser users operating devices of Class 2 and above. Training appropriate to class of laser used. For Class 2 lasers, simple training usually given by LSO (eg Why laser radiation is hazardous, "Do not point laser at people", "Do not deliberately stare into beam"). For Classes 3B and 4, specialist 3-day course may be more appropriate - in UK, Health Protection Agency together with U. of Loughborough.

Laser Controlled Areas (LCA)

For all Class 3B and 4 lasers. No laser of these classes should be operated other than in an LCA. Periodic inspection by LSO.

Enclosure of Beam Paths

Within LCA, beam paths for all Class 4 lasers to be enclosed. Also applies to Class 3B lasers, if practicable. Open beam paths should not be at head height - well above, or below. Fence off open beam paths with barriers or guards.

Beam Stops and Attenuators

For lasers of Classes 2, 2M and 3R, beam should be terminated by stop at end of useful length - to reduce unnecessary exposure. For all lasers of higher class, beam absorbers or dumps should define end of optical path - to prevent inadvertent potentially-harmful exposure.

Interlocked Access Doors to LCA

If doors inadvertently opened, laser emission should be terminated. Use commercially-available robust interlock switches.

Warning Signs at Entrance to LCA

Indicates Class of laser and nature of hazards. Prominently displayed. Authorised personnel only to enter.

Laser Emission Indicator

For Class 3R (non-visible only), 3B and 4 lasers, warning lights to indicate that laser is operating, interlocked with power supplies.

Laser Key Control

For Class 3B and 4 lasers, operating key to be removed and stored in key press when laser not in use. Only authorised users permitted to draw key from press.

Avoid Specular (mirror like) Reflections

For Class 3R (non-visible only), 3B and 4 lasers, particularly cw, remove watches and rings before moving hands near beam - assuming that $MPE_{\mathbf{skin}}$ is not exceeded - to avoid directing beam into eye. Ensure optical components in beam path are secure. If auxiliary components frequently placed in beam path - eg to use low-power alignment laser - use interlocks to prevent main laser operating with these components still in place. (Frequent cause of eye damage.)

Protective Eyewear - last line of defence

For Class 3B and 4 lasers, use eyewear whenever it is impracticable to reduce accessible laser irradiance below $MPE_{\mathbf{eye}}$ by engineering or administrative controls.

Protective Clothing - last line of defence

For Class 3B and 4 lasers, use suitable clothing (overalls and gloves) whenever it is impracticable to reduce accessible laser irradiance below $MPE_{\mathbf{skin}}$ by engineering or administrative controls. Care should be taken to select clothing that will not be set on fire by the laser beam!

We note that for cw lasers operating in the visible wavelength region - 400 to 700 nm - the Maximum Permissible Exposure (MPE) is 1 mW. Nevertheless, the safety margins on this limit are such that it is not regarded as necessary for users of Class 3R lasers - for which output in the visible regime can be up to 5 mW - to use protective eyeware.

If it is practicable, the approach outlined below is often the best solution for regular operation of high-power lasers.

Engineering Approach to Make Class 1 Laser Product

Make Laser Controlled Area light tight - with enclosed beam path to target. Operate laser remotely, external to LCA. For routine operation the product can be classified as Class 1, even with a Class 3B or 4 laser installed. Maintenance and servicing of laser now only operations where original classification still holds, with attendant controls and safeguards.

SUMMARY OF CONTROL MEASURES FOR LASERS UNDER EN 60825, ACCORDING TO CLASS

<table>
<tr><th>Requirements / Class</th><th>Class 1 & 1M</th><th>Class 2 & 2M</th><th>Class 3R</th><th>Class 3B</th><th>Class 4</th><th>Embedded laser *</th></tr>
<tr><td>Laser Responsible Officer</td><td colspan="2">No</td><td>Yes - (non visible only)</td><td colspan="3">Yes</td></tr>
<tr><td>Registration</td><td>No</td><td colspan="5">Yes</td></tr>
<tr><td>RA & Standing Orders</td><td colspan="2">No</td><td>Yes - (non visible only)</td><td colspan="3">Yes</td></tr>
<tr><td>Training</td><td>No</td><td colspan="5">Yes</td></tr>
<tr><td>Laser Controlled Area (LCA)</td><td colspan="3">No</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Enclosure of beam paths</td><td colspan="3">No</td><td>Yes where practicable</td><td>Yes</td><td></td></tr>
<tr><td>Beam stops or attenuators</td><td>No</td><td colspan="4">Yes</td><td></td></tr>
<tr><td>Interlocked access to LCA</td><td colspan="3">N / A</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Warning signs at LCA entrance</td><td colspan="3">N / A</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Laser emission indicator</td><td colspan="2">No</td><td>Yes - (non visible only)</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Laser key control</td><td colspan="3">No</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Avoid specular reflections</td><td colspan="2">No</td><td>Yes - (non visible only)</td><td colspan="2">Yes</td><td></td></tr>
<tr><td>Restriction on viewing aids</td><td colspan="2">Yes (for subclass M only)</td><td colspan="3">Yes</td><td></td></tr>
<tr><td>Protective eyewear required</td><td colspan="3">No</td><td colspan="2">Yes - if MPE exceeded</td><td></td></tr>
<tr><td>Protective clothing to be worn</td><td colspan="3">No</td><td>Possibly</td><td>Specific to Hazard</td><td></td></tr>
</table>

* [shaded box] = appropriate to class of product with embedded laser, ie 1, 1M, 2, 2M, 3R or 3B

PRACTICAL EXAMPLES OF SAFETY IMPLEMENTATION

The European Norm EN 60825, in its various parts, is not cast on tablets of stone. Occasional deviations are allowed. However, in all such deviations, and depending on the nature of the task in hand, the safety measures adopted should be such as to reduce the risks to As Low as Reasonably Practicable (ALARP). Note: it is not a requirement that risks be eliminated entirely, otherwise we would all have to pack up now and go home!

An example of a situation in which most of the recommended engineering controls cannot be implemented is to be found on weapons ranges used by fighter aircraft. They routinely use Class 4 lasers to illuminate targets on these ranges - there is no alternative but to permit open-beam work. Safety is then mostly ensured by adherence to strict administrative controls.

The target is placed in front of a substantial backstop, often a natural rise in the terrain, to define the limit of the laser beam. This is the only engineering control. In order to ensure the exclusion zone is empty, rigorous check-in and check-out procedures are followed.

Only when the ground in the exclusion zone around the target has been cleared of personnel is the aircraft permitted to start its approach run. In addition, the pilot is not authorised to fire the laser unless the aircraft is following the correct path and is over a designated section of the range.

AT JET, various safety measures have been put in place to deal with the lasers used for Thomson Scattering - all Class 4.

The lasers are located in a light-tight Enclosure situated in the Roof Laboratory. Each laser head is mounted in a light-tight cabinet. The laser beams emerging from the various heads are enclosed within light-tight tubes to the penetration into the Torus Hall beneath. Inside the Hall the laser beams are not enclosed. Within the Enclosure, each laser system is Class 1. Maintenance can be carried out on a laser whilst the others are operating.

PSACS (Personnel Safety and Access Control System), amongst other functions, ensures that when anyone is in the Torus Hall the laser path from the Roof Laboratory is closed at the penetration by a beam block, comprising a 10mm steel plate, operated by air pressure. Its position - open or closed - is fed back to PSACS by safety contact switches. PSACS is entirely hard-wired logic.

For periodic calibration, the system can be overridden using a special key. Thus, the shutter can be open whilst the personnel responsible for the diagnostic are in the Torus Hall (following strict administrative procedures and wearing the appropriate eyeware). Safety for others is ensured by those personnel in the Torus Hall holding the keys to all its access doors. In addition, the card-operated entrance turnstiles are set to “operator access” only. This way nobody else can get in, unless the operators allow them to do so.

Taking another example from JET, the FIR interferometer uses a cw 3B 10 mW laser emitting at 532 nm, for alignment of the various elements in the optical chain The laser is in a light-tight enclosure, together with the source DCN laser. The beam paths to the tokamak, some 85 m away, are also totally enclosed. For routine operation the system is Class 1.

However, there are several panels that need to be opened - one at a time and in sequence - at various points along the optical chain, in order to periodically align the components. This has the potential of exposing the operator to radiation from the alignment laser. Consequently, safety is ensured by a combination of an administrative control and an engineering control. The former, in essence, is a check list to ensure the engineering control is activated prior to overriding the panel interlocks and switching on the laser - as well as for other requirements.

The engineering control comprises a wheel at the laser output, on which are mounted six attenuators of different values. An appropriate attenuator is chosen so that the laser beam power in the region of activity is never more than 1 mW – the MPE. Thus, close to the output aperture of the alignment laser an attenuation of x10 is used. On the other hand, when working on elements at the end of the optical chain, by which point the laser beam has been split into twenty separate paths, no attenuation is required.

The only exception to the above would be during the installation of the alignment laser and the initial adjustment of its beam path. For this procedure suitable eyeware is worn, reducing the maximum power to which the eye could be exposed to 1 mW. The laser beam is of extremely-low divergence and has a very-high pointing accuracy. Once it is correctly aligned along the desired path, it is thereafter used as the absolute reference without needing further adjustment.

EXAMPLE OF RISK ASSESSMENT AND METHOD STATEMENT

Refer to hand-outs

CONCLUDING REMARKS

CONCLUDING REMARKS (1)

Familiarise yourselves with the Laser Classification system. Remember, that Classes 1 and 2 pose little risk if used correctly, whereas Classes 3R, 3B and 4 are increasingly more dangerous. The last two classes require particular care.

Before using any laser, check the labelling to establish its Class. Ensure you take appropriate precautions. Use the table on Slide 39 as a checklist. In particular, modifying the laser or performing routine maintenance tasks may very well result in the system moving to a higher class.

In dealing appropriately with the beam hazards, do not overlook the non-beam hazards associated with the laser - they are often much greater!

CONCLUDING REMARKS (2)

Beware of laser pointers in the wrong hands! A 1 mW laser emitting green light will certainly startle and dazzle, with possible nasty consequences - especially if you are up a ladder!

Avoid all unnecessary exposure to laser beams, even if irradiance is below the Maximum Permissible Exposure (MPE). There is evidence that regular exposure for long periods to visible laser radiation at levels well below the MPE reduces eye sensitivity (M Harris, Oxford Eye Hospital). Possibly due to photochemical damage?

The bottom line is that there is no substitute for proper training and suitable experience. All the rules in the world will not protect the uninitiated from eventual disaster!

CONCLUDING REMARKS (3)

Refer to EN 60825 for full details. However, its main focus is on hazards posed by laser beams. Non-beam hazards are only briefly mentioned.

If you have any issues or concerns, please contact me:

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