

Laser Safety

Training Manual



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Use of this Manual

For Faculty:

You are responsible for the state of your laboratory. Please make sure that all new members to your lab read and understand the material in this manual. Have a copy left in each room that actually houses a laser.

For Students:

Your eyes are not replaceable. Read through this manual and do the calculations for your own lab. Talk to your fellow group members about the safety issues in your own lab.

Remember, safety is everyone's responsibility.

Please note the following important disclaimer. THIS MANUAL IS NOT AN OFFICIAL TRAINING DOCUMENT. NO CLAIM IS MADE AS TO THE ACCURACY OR COMPLETENESS OF IT'S CONTENTS. The examples here are derived from the American National Standard for Safe Use of Lasers: you should turn to this or other references for further examples, or if your particular situation involves factors not described here. If you do not feel confident in correctly assessing your laser and devising appropriate work practices, do not hesitate to seek help. If your colleagues cannot assist you, then the University's Laser Safety Officer should be able to provide assistance directly or indirectly to answer your questions. You should also contact the Laser Safety Officer for administrative issues surrounding your laser, such as appropriate signs, installation, or significant modification of the system.

Important Terms and Abbreviations

ANSI

American National Standards Institute, online at <http://web.ansi.org/>

Cataract

A clouding and stiffening in the lens of the eye, which can be produced by long term or acute exposure to ultra-violet radiation. Cataracts can cause general deterioration of vision, loss of focus, or total blindness.

Cornea

The surface of the eye that accomplishes the initial focusing of light. The cornea is transparent to visible and near-infrared radiation, but absorbs both ultra-violet and infrared light. Damage to the cornea can result in blurred or distorted vision.

Fovea

The point on the retina that corresponds to the central field of vision. The fovea has the highest density of light-receptive cells of any part of the retina. Damage to the fovea can lead to a blind spot in the central field of vision.

Glaucoma

An increase in internal pressure within the eye. Glaucoma can be caused by disease, acute heating of the eye's internal fluids, or in response to trauma (such as a severe blow to the eye). Glaucoma may cause blind spots or loss of peripheral vision.

Irradiance, E

Power incident upon a surface, measured in $\text{W}\cdot\text{cm}^{-2}$. Synonym: *power density*.

Keratitis

Inflammation to the cornea, characterized by dullness and the loss of transparency.

Laser

Light Amplification by Stimulated Emission of Radiation: a device that produces light by this process. In comparison to other light sources, laser radiation is highly collimated, coherent, monochromatic and intense.

Laser System

A laboratory apparatus that includes a laser and its power source, modifying apparatus such as doublers, dyes or OPOs, and all optics, instruments and objects which deflect, focus, or absorb the laser beam.

Macula

An oval depression on the retina, lateral and slightly below the optic disk. The macula is the general center of vision, and contains the fovea.

MPE

Maximum Permissible Exposure: the highest level of laser radiation that may be incident upon the eye (or skin) without having an adverse effect. The MPE depends on both the wavelength of light and duration of exposure.

NHZ

Nominal Hazard Zone: the area surrounding a laser system within which the power of the beam exceeds the MPE. A different NHZ will exist for different powers, setups, and application of the laser system, as well as level of protection used (such as laser goggles, curtains, etc.).

Optic Disk

The area on the retina corresponding to the entrance of the optic nerve, also known as the blind spot.

Optic Nerve

The bundle of nerves that attach the retina to the brain. Damage to the optic nerve can lead to total blindness.

Pupil

The aperture of the eye. The pupil controls the total level of light that is passes onto the retina. The pupil of an average adult may dilate to a diameter of 7 mm.

Radiant exposure, H

Energy incident upon a surface, measured in $\text{J}\cdot\text{cm}^{-2}$.

Retina

The inner surface of the rear of the eye, covered by blood vessels and light-sensitive cells. The retina absorbs light in the visible and near-infrared regions of the electromagnetic spectrum.

Principles of Laser Action & Use

Properties of Laser Radiation

A discussion of the principle of the laser phenomenon is not necessary for the purposes of this manual. It is sufficient to recognize the generic design of a laser. A central solid rod or chamber of gas forms the laser cavity. The medium within the cavity is induced to lase by excitation from a conventional light source, i.e. powerful flash lamps. The laser radiation is generated by multiple reflections from high quality mirrors at either end of the cavity. The laser radiation is finally emitted at one end, either continuously (CW lasers) by having one mirror slightly less perfect than the other, or in short pulses by means of a Q-switch or similar device. The important properties of laser radiation from a safety perspective are that it is highly collimated, monochromatic and intense.

In addition to the laser itself, a laser system will contain a number of other components. A power source is necessary to provide the high voltage and power required by the pump. After leaving the cavity, the beam may be redirected or modified by optics such as lenses, filters, mirrors or other devices. The beam will usually interact with a sample (solution, surface, molecular beam, etc.), often with its own particular housing, before arriving either at a detector (power meter, PMT) or a beam-stop.

Common Types of Lasers

Lasers can be roughly grouped according to the lasing material used, as this is the primary factor that determines the frequency of light emitted. Gas lasers are particularly versatile in this regard. Excimer lasers have a cavity filled by a mixture of inert and reactive gasses. These lasers output light in the UV range. Other types of gas lasers output light in the visible region (e.g. He-Ne, He-Cd, Argon ion). The carbon dioxide laser produces a population inversion within the vibrational states of CO₂, and outputs light in the mid-IR.

Solid state lasers are generally crystalline materials doped with a metal ion. These lasers produce radiation in the visible and near-IR (e.g. Nd:YAG, Ti-sapphire, Ruby). Diode lasers use the production of electrons at a p-n junction to output light in the visible region.

Finally, a number of devices exist for modifying the output of a laser. In particular, frequency doubler, laser dyes and OPOs can be used in conjunction with a laser to produce laser radiation at almost any frequency.

Although lasers are commonly acknowledged by their users to be dangerous devices, they are by no means unique. Conventional sources of light such as the Sun, photocopiers, and oxy-acetylene torches are also hazardous to the eyes. Scientists who take precautions with lasers are no different from welders, surveyors or mountaineers who take precautions against developing welder's flash, cataracts, or snow-blindness.

Classification of Lasers

As well as classification according to their frequency, lasers are classified according to the power of light they are able to admit. The American National Standard for Safe Use of Lasers defines four major classes of laser systems, which help to guide users in developing appropriate safety guidelines. They are summarized below (for details consult the ANSI standard itself, see Appendix III – Further Information):

Class I:

A system that emits laser radiation but is safe under all circumstances of use. This includes devices such as CD players and laser pointers. The significant word is “emits” – a class I laser system often contains a laser operating at a dangerous power level, but is deemed safe because the beam is completely enclosed (your CD player is safe to use, but may be unsafe to repair without appropriate safety measures).

Class II:

CW visible lasers emitting radiation with a power less than 1 mW. A class II laser system is not intended for continuous viewing, but in the case of incidental exposure a user is protected by their natural aversion response (the blink reflex). Hence the class II classification is for visible lasers only.

Class III:

This class includes visible & non-visible, CW & pulsed systems that exceed class I and class II limits. The delineations of this class are rather complicated, but for visible lasers they are those that emit less than 0.5 W in 0.25 s. In general, direct viewing or specular reflections from a class III laser may be hazardous, but not diffuse reflections, or exposure of the skin.

Class IV:

The most hazardous class, class IV laser systems are those which exceed all the previous limits. Class IV laser systems produce hazardous emissions in less time than you can blink. Both specular and diffuse reflections from a class IV laser may be dangerous; it can represent a hazard to the skin, and may also a fire hazard.

The class III category is further subdivided into class IIIA and class IIIB according to the laser power. The different levels of laser classification dictate differing levels of responsibility on the part of the user regarding, operation, safety measures, and reporting. All class IIIB and class IV lasers must be registered according to the Illinois Department of Nuclear Safety Lasers System Act.

Effects of Laser Radiation

Anatomy of the Eye

Besides providing one of your most precious senses, your eye is a remarkable optical device. The basic elements of the human eye are illustrated in Figure 1. The cornea is a thin layer of tissue that forms the outer surface of the eye. Besides providing protection, the cornea is responsible for 70% of the eye's refractive power.. Behind the cornea is the iris, a ring of muscle that controls the size of the eye's aperture, or pupil.

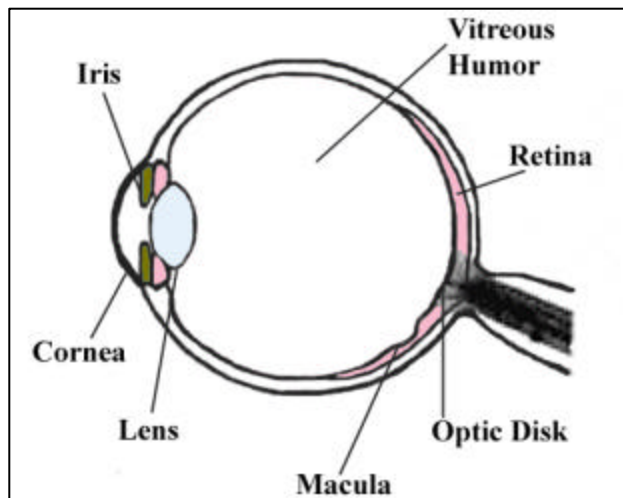


Figure 1: Anatomy of the human eye

Light admitted through the pupil passes through the lens, which accomplishes the fine focusing of light onto the rear of the eye. Although the cornea provides the majority of refractive power, it is the lens of the eye that provides us with the ability of variable focus. Light transmitted by the lens passes through the inner volume of the eye, which is filled with a slightly viscous fluid called the vitreous humor. The lens focuses the light onto the rear inner surface of the eye, called the retina. The retina is layer of photosensitive cells and blood vessels, which respond to the light with a flood of neurotransmitters. The photoreceptive cells come in two varieties: rod cells which are responsible for overall visual acuity, and cone cells which provide color vision.

The photoreceptive cells of the retina are largely concentrated in a region called the macula, and within this a particular point called the fovea is the actual center of vision. Close to the macula is the optic disk, the point at which the optic nerve leaves the eye and travels back to the brain. Since this region is largely devoid of actual photoreceptors it is also know as the blind spot. Responses from the retina travel back along the optic nerve to the brain for signal processing

Optical Properties of the Eye

The different constituents of the eye have distinct optical properties, which determine how they are affected by laser radiation. Most UV radiation is absorbed by the cornea. This means that the energy of this radiation is absorbed at a surface rather than a volume such as inner fluid of the eye. However, this radiation is unfocussed. Near-UV (312-390 nm) is absorbed by both the cornea and the lens.

Visible light is transmitted by the cornea, lens and vitreous humor, and is absorbed by the retina. A given amount of energy in the visible spectrum will have far

greater impact on the function of the eye than for other wavelengths. This is due to two factors, a) the retina is a thin surface, whereas the other parts of the eye occupy a finite volume, and b) the frontal sections of the eye act to focus an incident beam to a point on the retinal surface. In other words, energy that would be absorbed by all of the cornea, lens or humor, is absorbed by only a few cells if it impinges on the retina. Importantly though, visible light is absorbed by the photoreceptors themselves, which triggers a nervous response to the brain.

Near-IR (700-1400 nm) radiation is also absorbed by the retina. However, the actual photoreceptors in retinal cells are not sensitive to this radiation, which is instead absorbed by the general tissue. This means that Near-IR radiation does not evoke a nervous response – a bright source of Near-IR light will not cause you to blink. This is particularly significant to the hazards presented by some lasers.

The vitreous humor also begins to absorb radiation in the near-IR, although it is generally not the major absorbing species. In the mid-IR, both the lens and cornea absorb radiation, while in the far-IR the cornea becomes opaque once more.

Effects of Laser Radiation on the Eye

Laser radiation can damage the eye in two different ways – specific absorption by essential tissues, and heating/ablation of tissue layers by nonspecific absorption. The same effects that are used in a controlled manner by laser surgeons to improve vision can, in the case of uncontrolled exposure, lead to loss of focus, blind spots, or even total blindness.

An excess of radiation absorbed by the cornea (UV & far-IR) will result in *keratitis* – tissue scarring that causes loss of focus, blind spots and general decrease in vision. Light absorbed by the lens (near-UV and mid-IR) results in *cataracts*, in which the proteins within the lens denature, causing the lens to become cloudy and less pliable. Cataracts can lead to general visual degradation and also loss of the ability to focus. In severe cases, both keratitis and cataracts may cause complete blindness.

The most delicate region of the eye is the retina, which is also the most crucial to vision. Excessive powers of visible and near-IR radiation can damage the retina in several ways. The *ablation* of a section of the retina will produce a blind spot in that region of vision, as well as hemorrhaging of blood vessels that will produce floating spots or a bloody haze due to contamination of the vitreous humor. A particular hazard is the eye's reflex to focus any bright source upon the fovea, where it will produce a large central blind spot and significant loss of color and night vision. However, off-center exposure can be just as hazardous due to the risk of striking the optic nerve. Damage to the optic nerve can result in total blindness.

IR radiation can damage the eye through thermal heating, with a number of consequences. Sudden heating and consequent expansion of the vitreous humor leads to an increase in the eye's internal pressure, a condition known as *glaucoma*. This may in turn damage cells upon the retina or other internal surfaces of the eye. Heating or

ablation may cause a sudden flow of blood into the vitreous humor, at which time it will spontaneously contract. This may cause segments of the retina to be tear away from the wall of the eye, referred to as *retinal detachment*. Retinal detachment can lead to severe visual impairment, even total blindness

It should be noted that the damage caused by excessive irradiation is not always apparent to the user. Only visible light, which activates the retinal photoreceptors, will transmit a message to the brain that a light source exists. Thus Near-IR radiation is particularly dangerous, because it is focused on the retina, but is not subject to the aversion reflex experienced with a bright visible source. You may be completely unaware of the hazard until a soft but audible ‘pop’ indicates the ablation of your retina!

Effects of Laser Radiation on the Skin

The skin is also an extremely important organ, but thankfully it is much less susceptible to EM radiation damage than the eye. For instance, the safe limit for irradiance of the eye to visible laser radiation over 10 s is $1 \text{ m W}\cdot\text{cm}^{-2}$; the safe limit for the skin over the same time period is $1 \text{ W}\cdot\text{cm}^{-2}$.

In the interests of brevity, the skin hazards posed by lasers will not be further considered in this manual. However, it is worth remembering that UV radiation is the main cause of malignant tumors in the skin, and that many class IV lasers are powerful enough to produce a local burn on the skin. In other words, you should not heedlessly expose your skin to a high power laser. However, if you take care to establish work procedures that provide adequate protection for your eyes, you will generally provide adequate protection for you skin as well.

Acoustic Effects

Lasers can cause a localized vaporization of tissue, which in turn can create a mechanical shockwave that can be propagated through the surrounding tissue. These shockwaves can cause an actual tearing of tissue.

Photochemical Effects

Laser light can also cause changes to the chemistry of cells, which may result in changes to tissue.

Why should I worry about Laser Safety?

There are several reasons why research scientists must be especially aware of the hazardous nature of lasers:

Power:

Compared with lasers operating in a commercial or industrial setting, research lasers are far more likely to be high power devices, as researchers continually probe the edges of knowledge. Almost without exception, the lasers found in the Chemistry Department Research labs are class IV devices.

Modification:

A research laser system, unlike one designed for a specific industrial or commercial purpose, is subject to constant modification in order to perform different experiments. This means that safety measures designed for the system's initial use may, as time goes by, become obsolete or inadequate, while new safety concerns may appear. A research laser requires constant attention to maintain a safe working environment.

Multiple Users:

A research laser is often used by several people in different modes, arrangements and power levels. Poor communication and different safety standards between users can lead to an unsafe work environment.

Complacency:

Despite the fact that researchers are generally more intelligent and competent than other laser users, they have the same accident rate. This is because familiarity with the system leads to a state of complacency concerning safety. Experience and intelligence are NOT safety measures: laser goggles and beam stops are.

Non-Beam Hazards

Besides the hazardous nature of laser radiation, to be discussed subsequently, it is worth remembering the other hazards that may be associated with lasers:

Electrical Hazards:

Lasers are electrical devices that operate at high voltage and high power. Do not attempt maintenance upon a laser without taking appropriate measures against the danger of electrocution.

Compressed Gas Hazards:

Gas Lasers, especially excimer lasers, use compressed gasses, including corrosive gases such as HCl. Make sure all gas cylinders are well secured, and the regulators well maintained.

Flammability Hazards:

Class IV lasers are sufficiently powerful to ignite flammable materials such as paper, cloth, and solvents that may be used in an experiment.

Explosion Hazards:

Focusing a class IV laser can produce a beam powerful enough to ionize air. This can cause flammable vapors or liquids that may explode, or optics to heat to the point of shattering. Take this into consideration when focusing a beam.

Chemical Hazards:

Many lasers systems may use laser dyes to modify the wavelength of the output wavelength of the laser. These dyes are often carcinogenic and/or toxic. Many gases used in lasers are also hazardous to inhale, either specifically or due to the risk of asphyxiation.

Optical Hazards:

Besides the laser radiation itself, lasers contain very powerful sources of incoherent light, such as discharge tubes or pumping lamps. This light is also strong enough to cause permanent damage to the eye.

Am I Safe? The Important Definitions

Given the enormous range of wavelengths, power levels and exposure times that may be experienced with laser, how do you know when a given exposure is dangerous? The answer lies in the large amount of experiments that have been performed by researchers like you to determine the effect of laser radiation on the eye for various wavelengths, power levels, and exposure times. This has provided detailed knowledge of what total energies will, under a particular set of conditions, cause a biological effect.

This vast store of information has been collated by a number of government and non-government organizations to produce tables of information. They have also been the source for the American National Standard for the Safe Use of Lasers (ANSI Z136.1). Unfortunately, like most technical standards, the information in this standard is difficult to assimilate at first reading. To begin to use the information that is provided for your benefit, you must first understand the following definitions.

The Accessible Emission Limit (AEL)

The primary measurement of a laser's hazard potential is the Accessible Emission Limit (AEL), which defines the maximum total power of radiation that can be emitted from a laser of a particular class. Assuming a linear additive effect for radiation absorbed by the, the minimum irradiance known to cause a biological effect is converted into a power level for the length of time defined by a given class.

As AELs are mainly used for classification of a laser, they are not immediately useful to a user who wants to know if his/her particular setup is safe. However, you can use the classification scheme to help you make very simple decisions. For instance, if you always keep your power level below that required of a class II device, you can be assured that accidental exposure to the beam will not be hazardous to you. For visible lasers, this means keeping the average power below 1 mW for start up or alignment procedures.

The Maximum Permissible Exposure (MPE)

The single most useful number in laser safety calculations is the Maximum Permissible Exposure (MPE). This is the minimum irradiance or radiant exposure that may be **incident upon the eye** (or the skin) without causing biological damage. The MPE is related to the AEL by the limiting aperture of the eye, which is itself a function of wavelength and exposure time. To make things simple, the MPE is tabulated separately: for a specific safety calculation it should be the first table you turn to. One caution: the actual value of the MPE is occasionally dependent on some correction factors, which are separately tabulated.

The Nominal Hazard Zone (NHZ)

The other major definition for laser safety calculations is the Nominal Hazard Zone (NHZ). This is a distance within which the irradiance of a beam is greater than the MPE. Besides being specific to a given wavelength and time of exposure, a different NHZ can be defined for the beam's path to your eye – direct viewing, specular reflectance, or diffuse reflectance.

The NHZ is a practical definition; it has a specific shape around your particular laboratory apparatus (for instance, assuming your lab has no windows and a solid door, the NHZ will in the worst case scenario be the floor area of the lab itself). In other words, the NHZ for you will be derived at the end of your safety calculations, and thereafter will be most useful to you for planning control measures in your laboratory.

The Laser Safety Officer (LSO)

The ANSI standard contains much more than tables of information and explanations of the appropriate safety calculations. It also contains all sorts of regulations for appropriate safety measures, procedures and controls associated with lasers in an institutional setting. To manage all these administrative aspects of laser use, the standard recommends that institutions with significant numbers of operating lasers should appoint a specific person to be the Laser Safety Officer (LSO) to oversee the safe operation of lasers within a particular department of organization.

According to the ANSI standard, “Only personnel who are trained in laser safety, optical engineering, or physics are suited to perform the detailed hazard evaluation computations or the classification of laser or laser system.” However, in many cases the Laser Safety Officer may not be such a person! In this case they may choose to delegate such responsibilities to the appropriate persons. Even if they are appropriately trained, the LSO may not be able to effectively respond to a constantly changing laboratory laser system. As graduate students and faculty in a physical sciences department at a prestigious research university, YOU should qualify as someone who is suited to perform laser safety calculations. Also, given that you may be using and modifying your laser on a daily basis, it is unrealistic to think that someone else will make sure it is safe – you must be responsible for your own safety.

Principle of Laser Safety Evaluation

The basic method for evaluating the safety (or otherwise) of your specific laser system is to calculate the maximum irradiance that an unprotected eye might experience while the system is operating in a particular manner, and check whether it is less than the MPE. This involves thinking about all the different circumstances that may occur – accidentally viewing the beam directly while aligning an optic, catching a chance reflection while changing the optical setup, and so on. This might sound tortuous, but is really quite simple if you quickly determine what are the worst-case scenarios for any exposure.

Assuming you find that the irradiance in a particular situation is greater than the MPE. You then determine the NHZ for that particular situation. For example, the NHZ for a diffuse reflectance may be within 1 m of the laser itself, but the NHZ for direct viewing may include the entire laboratory. Within the NHZ, you then calculate the necessary OD for a set of laser goggles that will reduce the irradiance at the eye below the MPE. You can also take action to reduce the NHZ, such as enclosing the beam path or changing the design of the laser system. Finally, you should develop a set of consistent set of lab practices with your colleagues to ensure that everyone operates the system in a manner that is safe for both themselves and others.

Before proceeding, let us summarize right now the most common causes of accidents in research labs (as obtained from actual case histories). They are:

- (1) not wearing appropriate safety goggles,
- (2) not reducing power for alignment procedures, or the power increased unbeknownst to the user,
- (3) stray beams left uncontained by beam stops or other barriers.

If you are not addressing the three items above, you are currently operating your laser in an unsafe manner. For those who believe that an eye injury won't happen to them, a case history of an actual accident is provided in Appendix II. Don't wait until after the accident to make excuses or blame someone else. Change your work practices now!

MPEs and Safety Calculations

Useful Approximations:

The tables in Appendix I may look bewildering, but they are worth learning to use. The values listed in the tables are the maximum safe energy that may be incident upon the eye. As the tables illustrate, this energy is a rather complicated function of wavelength and the duration of exposure. In some places a single value suffices for a broad range of conditions. In other cases, notably those of visible and near-infrared radiation during ordinary time-periods of exposure, the MPE should be calculated on a case-by-case basis. For these purposes, it is worth using the following assumptions:

1. Limiting time of inadvertent exposure to visible radiation = 0.25 s (the blink reflex)
2. Limiting time of inadvertent exposure to UV or NIR radiation = 10 s (natural eye motion)
3. Limiting time of exposure for intentional viewing = 10^2 s (i.e. during laser alignment)
4. Limiting time of long-term exposure = 3×10^4 s (24 hrs)

You might think the estimated exposure time of 100 s for a procedure such as alignment is ridiculous. However, even if you are wise enough to use indirect methods such as burn paper or power meters to align your beam, it is entirely possible that you will look in the same direction for 100 s during an alignment procedure. The 100 s exposure time includes the possibility of unbeknownst exposure to a stray beam while performing an operation on your laser system. Once you have determined MPE relevant to particular application, you must calculate the level of incident radiation at your eye under a variety of circumstances. Important parameters for such calculations are the optical path length from laser output to the eye, the beam diameter and divergence, the limiting aperture of the eye, whether the beam is viewed as a point or extended source, and whether a reflection is considered specular or diffuse.

Important Conventions

Before calculating actual numbers, you have to be sure you have the right starting values and units. The three big numbers found in laser manuals are the beam diameter a , the beam divergence f , and the radiant energy Q or radiant power Φ . These values appear in safety calculations, where they have the units of cm, radians, J and W respectively. The central quantities in a laser safety calculation however, are the radiant exposure H (measured in $\text{J}\cdot\text{cm}^{-2}$) and the irradiance E (measured in $\text{W}\cdot\text{cm}^{-2}$). These values are less common in the front of laser manuals. There may also be some confusion depending on the profile of your beam and the choice of beam diameter.

The most common profile of a laser beam is a Gaussian profile. The diameter a of a Gaussian beam be specified according the $1/e$ or $1/e^2$ point. Laser manufacturers may often use the $1/e^2$ definition since this area encompasses 90% of the total beam energy. However, safety calculations use the $1/e$ diameter, so check which one you are using. The two diameters have a simple relation $a(1/e^2) = \sqrt{2}a(1/e)$.

Your beam may not have a Gaussian profile. Another common profile is the top hat, in which the beams radiant exposure is equal for all points within the beam diameter. This mode makes the beam diameter very easy to define, and also the irradiance. For a beam with a top hat profile, beam diameter a , and radiant power Φ :

$$E_0 = \frac{4\Phi}{\pi a^2}$$

The subscript for E identifies it as the maximum irradiance, i.e. at zero distance from the lasers exit port. The radiant exposure is calculated from this by dividing H by the appropriate exposure time or pulse duration.

For a Gaussian beam, the central irradiance will be different from the average irradiance over the area within the beam diameter. However, the MPE is not determined according to the peak irradiance of the beam, it is determined by averaging the incident power of the beam over an area defined by the *limiting aperture* of the eye. For visible light this limiting aperture is the diameter of a fully dilated pupil, which is 7 mm. For non-visible radiation other limiting apertures are defined as follows:

Spectral Region	Period of Exposure (s)	Aperture Diameter (mm)
180 to 400 nm	10^{-9} to 0.25	1.0
	0.25 to 3×10^4	3.5
400 to 1400 nm	10^{-9} to 3×10^4	7.0
1400 nm to 100 μm	10^{-9} to 0.25	1.0
	10 to 3×10^4	3.5
100 to 1000 μm	10^{-9} to 3×10^4	11.0

If the diameter of your beam is similar to the limiting aperture for your wavelength, you may calculate the irradiance assuming your beam has a top hat profile, using the following equation:

$$E_0 = \frac{4\Phi}{\pi [\max(a, D_f)]^2}$$

In which Φ is the total radiant power of the beam, a is the beam diameter (measured at $1/e$ of the peak irradiance), and D_f is the limiting aperture at the appropriate wavelength.

1. CW and Single Pulse MPEs

Example 1.1:

Q: Determine the MPE for accidental direct exposure to a visible laser.

A: The time to use for “accidental exposure” in the visible region is 0.25 s, the blink reflex. Visible lasers are those that emit light of wavelengths between 400 and 700 nm. From Table 3, we find:

$$MPE = 1.8t^{3/4} \times 10^{-3} \text{ J} \cdot \text{cm}^{-2}$$

For $t = 0.25$ s, this is equal to a radiant exposure $H = 0.636 \text{ mJ} \cdot \text{cm}^{-2}$. If we want the MPE in terms of irradiance, we use the formula:

$$\begin{aligned} E &= \frac{H}{t} \\ &= \frac{0.636}{0.25} \\ &= 2.55 \text{ mW} \cdot \text{cm}^{-2} \end{aligned}$$

Finally, if we consider the limiting aperture of the eye in the visible region, 7 mm, then the area over which the visible radiation will be viewed is $\pi/4 \times 0.7^2 = 0.385 \text{ cm}^2$. Hence the maximum flux of a visible laser to avoid harm due accidental exposure should be $2.55 \times 0.385 = 1.0 \text{ mW}$. As you may recall, this is the upper power limit for a class II laser device.

Example 1.2:

Q: Calculate the MPE for intentional, direct ocular exposure to the fundamental mode of a CW Nd:YAG laser.

A: The fundamental mode of a Nd:YAG laser is at 1064 nm. The appropriate value is read directly from Table 3: For intentional viewing, take the time of exposure to be 100 s, so the MPE is $5C_C \times 10^{-3} \text{ W} \cdot \text{cm}^{-2}$, or $5 \text{ mW} \cdot \text{cm}^{-2}$ ($C_C = 1.0$ for 1050 to 1150 nm).

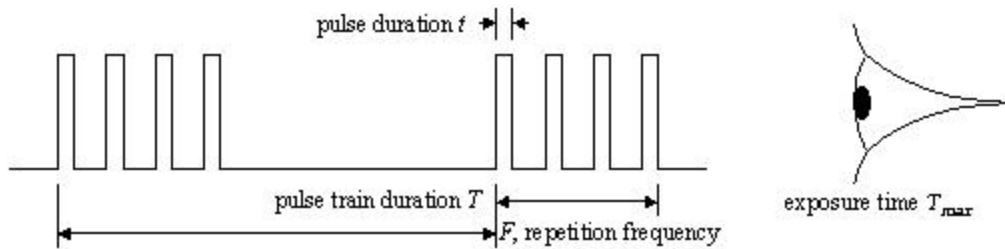
Example 1.3:

Q: Calculate the MPE for accidental exposure to a Xe:Cl excimer laser.

A: The wavelength of emission from a Xe:Cl excimer is 308 nm. Since this is invisible to the human eye, the time period for accidental exposure should be take as 10 s. From Table 2, the MPE is $40 \text{ mJ} \cdot \text{cm}^{-2}$. Note from Table 2 that this MPE applies to all exposure times. Unlike the visible and near-IR region, where the eye can tolerate a small but constant irradiance, in the UV radiation damage is cumulative. Thus the longer the exposure time, the lower the safe operating power.

2. Repetitively Pulsed Lasers

The most common lasers in research today are pulsed lasers, due to their higher peak energies. Because of its high peak intensity, the MPE from a pulsed laser is more complicated than for an equivalent continuous source. To determine the correct MPE for a given train of pulses you must know the pulse repetition frequency (F), the duration of a single pulse (t), the total duration of a train of pulses (T), and the total exposure time T_{max} .



There are three rules that limit the MPE per pulse for a train of laser pulses:

1. The MPE/pulse is limited to the MPE for any single pulse (single pulse limit).
2. The MPE/pulse is limited to the MPE for all exposure times between T and T_{max} , divided by the number of pulses n during that time period (average power limit).
3. The MPE/pulse is limited to the MPE for a single pulse multiplied by $n^{-1/4}$, where n is the number of pulses that occur during the period of exposure T_{max} (repetitive pulse limit).

Above a critical frequency (>55 kHz for visible lasers) rule 2 gives the lowest value. In other cases all three limits should be checked.

Ex. 2.1

Q: Calculate the MPE for a XeCl excimer laser (308 nm), with a pulse length $t = 20$ ns, operating at a frequency $F = 120$ Hz.

A: Assume an exposure time of 10 s (no blink reflex). Now check each of the three limits:

1. The MPE for a single pulse of 20 ns at 308 nm, found in Table 2, is the lower of $0.56 t^{1/4}$ and $40 \text{ mJ}\cdot\text{cm}^{-2}$. In this case, the MPE for a single pulse is given by $0.56 \cdot (2 \times 10^{-8})^{1/4} = 6.7 \text{ mJ}\cdot\text{cm}^{-2}$.

2. The MPE of a continuous source for a 10 s exposure, found in Table 2, is $40 \text{ mJ}\cdot\text{cm}^{-2}$. The total number of pulses $n = 1200$, so the MPE per pulse $= \frac{40}{1200} = 33 \text{ mJ}\cdot\text{cm}^{-2}$
3. Using the MPE for a single pulse $= 6.7 \text{ mJ}\cdot\text{cm}^{-2}$ (from limit 1), and the number of pulses in 10 s $n = 1200$ (from limit 2), the calculated MPE per pulse $= \frac{6.7}{\sqrt[4]{1200}} = \frac{6.7}{5.89} = 1.1 \text{ mJ}\cdot\text{cm}^{-2}$

So the MPE/pulse is defined by limit 2, and is $33 \text{ mJ}\cdot\text{cm}^{-2}$. To express this in terms of irradiance, multiply the result by the repetition frequency F :

$$\begin{aligned} E &= \frac{H}{t} \\ &= 3.3 \cdot 10^{-5} \times \frac{120}{1} \\ &= 4 \text{ mW}\cdot\text{cm}^{-2} \end{aligned}$$

Ex. 2.2

Q: Calculate the MPE for accidental exposure to a pulsed Nd:YAG laser operating in its doubled mode of 532 nm, with an pulse length $t = 1 \text{ ns}$ and a repetition frequency $F = 20 \text{ Hz}$.

A: Assume an exposure time of 0.25 s (blink reflex)

1. The MPE for a single pulse of 1 ns at 532 nm, found in Table 3, is $0.5 \text{ mJ}\cdot\text{cm}^{-2}$.
2. The MPE of a continuous source for a 0.25 s exposure, found in Table 2, is $0.636 \text{ mJ}\cdot\text{cm}^{-2}$. The total number of pulses $n = 5$, so the MPE per pulse $= \frac{0.636}{5} = 0.13 \text{ mJ}\cdot\text{cm}^{-2}$
3. Using the MPE for a single pulse $= 0.5 \text{ mJ}\cdot\text{cm}^{-2}$ (from limit 1), and the number of pulses in 0.25 s $n = 5$ (from limit 2), the calculated MPE per pulse $= \frac{0.5}{\sqrt[4]{5}} = 0.33 \text{ mJ}\cdot\text{cm}^{-2}$

Hence the MPE/pulse is defined by limit 3, and is $0.33 \text{ mJ}\cdot\text{cm}^{-2}$. To express this in terms of irradiance, multiply the result by the repetition frequency F :

$$\begin{aligned}
 E &= \frac{H}{t} \\
 &= 3.3 \cdot 10^{-4} \times \frac{20}{1} \\
 &= 6.7 \text{ mW} \cdot \text{cm}^{-2}
 \end{aligned}$$

Note that the magnitude of this MPE is several hundred times lower than for an equivalent CW laser (compare to exercise 1.1).

3a. Extended Source Viewing

If a laser beam has a high divergence, or is viewed at a close distance relative to the beam diameter, the image formed by the beam upon the retina may not be a point. In this case, the laser is an extended source and the MPE should be corrected accordingly. Extended source MPEs are applied only in the spectral region 400 to 1400 nm, and where the angle subtended by the eye to capture the entire beam is greater than a minimum angle specified for differing exposure times:

Exposure Time (s)	Angle α_{\min} (mrad)
= 0.7	1.5
0.7 – 10	$2t^{3/4}$
= 10	11

If the laser beam subtends an angle greater than the minimum for particular viewing circumstances, then the MPE should be multiplied by the factor α/α_{\min} . Extended source viewing may apply in cases such as viewing a beam after passing through an optic, or viewing a diffuse reflection at close distance. However, since an extended source correction factor increases the MPE, it is generally sufficient to perform your calculations simply assuming a point source (worst case scenario).

3b. Diffuse Reflections

The major feature of class IV lasers such as those found in research laboratories is the fact that even diffuse reflections can be hazardous. Thus it is important to understand how to calculate the power of a diffusely reflected laser beam.

The flux of energy through a point at a given distance and angle from a diffusely reflecting surface is:

$$H = \frac{r_l Q \cos q_n}{pr^2}$$

where r_l is the reflectance at the wavelength in question, Q is the energy of the incident beam, q_n is the angle of observation with respect to the normal, and r is the distance from

the point of reflection to the point of observation. For safety calculations this equation can be greatly simplified by assuming $r_l = \cos q_n = 1$.

Ex. 3.1

Q: A user (sans safety glasses) observes a diffuse reflection from a CW Nd:YAG laser operating at 532 nm with an energy of 2 W. The distance is 40 cm and the angle of observation 20° to the normal. Is the user safe?

A: Assuming an exposure time of 0.25 s, the $MPE = 0.636 \text{ mJ} \cdot \text{cm}^{-2}$. Assume a perfect reflector ($r = 1$) and ignore the angle of observation. The energy observed by the user is:

$$H = \frac{0.5}{3.14 \times (40)^2} = 9.95 \times 10^{-5} = 0.1 \text{ mJ} \cdot \text{cm}^{-2}$$

Yes, the user is safe.

Ex. 3.2

Q: Let the diameter of the beam at the surface of the reflector $a = 8 \text{ mm}$. Is the beam observed as an extended source?

A: To determine the angle subtended by the beam's image at the point of observation, we require the distance ($r = 40 \text{ cm}$) the angle ($q = 20^\circ$) and the beam diameter (0.8 cm). The angle subtended is given by:

$$a = \frac{D \cdot \cos q}{r} = \frac{0.8}{40} \times 0.94 = 19 \text{ mrad}$$

Yes, the beam does represent an extended source. The correct MPE is actually $0.636 \times 19/1.5 = 8.06 \text{ mJ} \cdot \text{cm}^{-2}$. Note that the above equation only holds for small angle in which $\sin q \sim q$.

4. Nominal Hazard Zones

Having determined the MPE for a specific laser operating in a specific mode, you can now define a Nominal Hazard Zone (NHZ), the area around your laser within which the beam exceeds the MPE. To do this you need to know how your beam diameter changes with distance. A Gaussian beam actually changes its diameter according to a hyperbolic function, with the minimum diameter occurring at the *beam waist*. However, for safety calculations you can use one of two approximations. For lasers in which the beam waist is at or in front of the exit port, the diameter D of a Gaussian beam at a given distance r is given by the following formula:

$$D = \sqrt{a^2 + (r - r_0)^2 f^2}$$

Where a is the beam diameter at the exit port, and f is the beam divergence. Depending on the situation, you may further simplify this equation by dropping the r_0 (waist close to exit port), a (large distance r), or the whole thing (for a large diameter, low divergence, and short distance, $D \sim a$). In cases where the beam waist is behind the exit port, it may be more appropriate to use a linear approximation:

$$D = a + rf$$

Ex. 4.1

Q: A frequency-doubled CW Nd:YAG has a Gaussian beam diameter $a = 1 \text{ cm}$ ($1/e^2$), divergence $f = 0.5 \text{ mrad}$, and a power $\Phi = 2 \text{ W}$. Assume the beam waist is close to the exit port. What is the Nominal Hazard Zone (NHZ) for accidental direct viewing of this beam?

A: The question does not specify the wavelength or operating mode of the laser. We will use the MPEs from the previous exercises for a frequency doubled Nd:YAG, operating at 532 nm. For a CW laser as in exercise 1.1, radiant exposure $MPE:H = 0.636 \text{ mJ}\cdot\text{cm}^{-2}$, irradiance $MPE:E = 2.55 \text{ mW}\cdot\text{cm}^{-2}$. For a pulsed Nd:YAG such as in exercise 2.2 (pulse duration $t = 1 \text{ ns}$, repetition frequency $F = 20 \text{ Hz}$), the $MPE/\text{pulse} = 0.33 \text{ mJ}\cdot\text{cm}^{-2}$, $MPE:E = 6.7 \text{ mW}\cdot\text{cm}^{-2}$.

The first step is to calculate E_0 for our laser. Firstly we have to correct the beam diameter a to be at the $1/e$ point of the laser, $a(1/e) = a(1/e^2) \div \sqrt{2} = 0.71 \text{ cm}$. Since this is the same as the limiting aperture defined for the wavelength range 400 to 1400 nm, we may determine E_0 assuming a top hat profile for the beam:

$$\begin{aligned} E_0 &= \frac{4F}{p[\max(a, D_f)]^2} \\ &= \frac{4 \times 2}{p \times 0.7^2} \\ &= 5.20 \text{ W}\cdot\text{cm}^2 \end{aligned}$$

The irradiance is inversely proportional to the beam diameter squared. Thus we may use the relation:

$$\frac{E_0}{MPE} = \frac{(D_{\text{NHZ}})^2}{a^2}$$

Since the beam waist is near the exit port, and considerable expansion of the beam will have to occur to satisfy the equation above, we will make the approximation $D = fr$, and calculate r_{NHZ} for the CW case:

$$\begin{aligned}\frac{E_0}{MPE} &= \frac{(fr_{\text{NHZ}})^2}{a^2} \\ r_{\text{NHZ}} &= \frac{a}{f} \sqrt{\frac{E_0}{MPE}} \\ &= \frac{0.7}{5 \times 10^{-4}} \sqrt{\frac{5.2}{2.55 \times 10^{-3}}} \\ &= 632 \text{ m}\end{aligned}$$

Remember that the default units of r_{NHZ} are cm, so you will often need to convert to some sensible units at the end of the calculation.

It would be useful to derive a formula so that one may calculate the NHZ directly from the variables Φ , f and a , since these are generally reported in laser manuals. If the beam waist is close to the exit port, the irradiance E of a Gaussian beam at a given distance r is given by the following formula:

$$E = \frac{4F}{p(a^2 + f^2 r^2)}$$

Once the MPE has been determined, we can rearrange this equation to solve for the distance r_{NHZ} :

$$r_{\text{NHZ}} = \frac{1}{f} \sqrt{\frac{4F}{p \cdot MPE} - a^2}$$

Where the MPE is given in terms of irradiance ($\text{W} \cdot \text{cm}^{-2}$). If the MPE is used in units of radiant exposure ($\text{J} \cdot \text{cm}^{-2}$), then the appropriate measurement for the beam is the radiant energy Q .

Ex. 4.2

Q: A frequency-doubled pulsed Nd:YAG laser is operating with pulse duration $t = 1$ ns, repetition frequency $F = 20$ Hz. Other beam parameters are identical to those in the previous exercise. What is the Nominal Hazard Zone (NHZ) for accidental direct viewing of this beam?

A: The MPE for this laser was found in exercise 2.2, $\text{MPE/pulse} = 0.33 \text{ mJ} \cdot \text{cm}^{-2}$. The radiant energy per pulse for this laser $Q = \Phi/F = 0.1$ J. Using the equation derived above:

$$\begin{aligned}
 r_{\text{NHZ}} &= \frac{1}{f} \sqrt{\left(\frac{4Q}{\mathbf{p} \cdot \text{MPE}} - a^2 \right)} \\
 &= \frac{1}{5 \times 10^{-4}} \sqrt{\frac{4 \times 0.1}{\mathbf{p} \times 3.3 \times 10^{-7}} - 0.7^2} \\
 &= 12.4 \text{ km}
 \end{aligned}$$

It would be unsafe to operate this laser outdoors without first notifying the local air traffic control!

Ex. 4.3

Q: Calculate the radius of the Nominal Hazard Zone for the diffuse reflection in exercise 3.1.

A: Simply rearrange the diffuse reflection equation to solve for r , substituting the MPE for H . Once again assume $r_l = \cos \mathbf{q}_n = 1$.

$$r_{\text{NHZ}} = \sqrt{\frac{0.5}{3.14 \times (6.36 \times 10^{-4})}} = \sqrt{250} = 15.8 \text{ cm}$$

Protective Eyewear

As the calculations above should demonstrate, the majority of applications of lasers in a research setting will involve levels of radiation that are extremely hazardous to ones eyes. One of the common ways a direct user of a laser system protects him/herself is by wearing protective eyewear, or laser goggles.

However, many people do not bother to check whether their eyewear is appropriate to their application. On one extreme, a user may wear goggles that are appropriate for alignment procedures but will not protect against intrabeam exposure at full power. At the other extreme, a user may wear goggles that have much higher optical density than is necessary. This can be just as hazardous, because the lack of vision while wearing such goggles will tempt users to take them off, or may cause the user to make other mistakes that endanger his health.

Fortunately, once you understand how to calculate the MPE for a particular situation, determining the correct eyewear is easy. Simply calculate the radiant exposure or irradiance of the beam under the circumstances of your experiment, calculate the corresponding MPE, and take the logarithm of the quotient:

$$OD = \log_{10} \frac{H}{\text{MPE}:H} = \log_{10} \frac{E}{\text{MPE}:E}$$

The OD obtained is the minimum required to protect your eyes. Round **up** to the nearest value that is commercially available. Laser goggles are expensive but your eyes

are worth more. In some cases it may be appropriate to have two sets of goggles available, one with a low OD that provide maximum visibility during alignment and low power operation, and another with a high OD for full power applications.

Ex. 5.1

Q: Calculate the appropriate OD of laser goggles for use with the two Nd:YAG lasers in exercises 4.1 and 4.2.

A: The maximum irradiance for both these lasers was determined in exercise 4.1, $E_0 = 5.2 \text{ Wcm}^{-2}$. The MPE for each laser, in units of irradiance, were calculated in exercises 1.1 and 2.2 respectively.

For the CW case:

$$\log_{10} \frac{E}{MPE:E} = \frac{5.2}{2.55 \times 10^{-3}} = 3.3 \Rightarrow \text{OD} = 4$$

For the pulsed case:

$$\log_{10} \frac{E}{MPE:E} = \frac{5.2}{6.7 \times 10^{-6}} = 5.9 \Rightarrow \text{OD} = 6$$

Laser goggles are not always sold at all optical densities. A pair of laser goggles with OD = 6 at 532 nm would be appropriate for both these lasers.

A common attitude amongst researchers is that laser goggles are the first line of defense against hazardous laser radiation. This is not true. The first line of defense against hazardous radiation is a solid opaque barrier, i.e. a wall! Although laser goggles are of great importance, there are a number of other ways in which you can, and should, make your laboratory a safe and efficient work environment. These will be discussed in the next chapter.

Finally, one should not forget that the high optical density of laser goggles is due to their capacity to absorb laser radiation, but laser goggles also have a specific heat capacity and a melting point. There have been several recorded cases where a user sustained drastic and permanent injury when the beam they chose to look at melted through their laser goggles! Treat laser goggles as a last line of defense against injury, not your one and only safeguard.

Designing a Safe Laboratory

A safe laboratory arises from two principle actions. The first is thought and planning in the layout of the laboratory – position of the laser in relation to exits, internal barriers such as screens and curtains that isolate the laser from other parts of the room, and appropriate warnings and controls at the exits such as signs, lights, and/or interlocks. The second is a cooperative effort amongst the users to communicate about their use of the laser system – establishing a protocol for using the system, entering and leaving the room while the laser is in operation, and keeping all informed on changes made to the system and times it will be in use.

There are many different ways to achieve a safe laboratory, and what is appropriate depends strongly on the individual laboratory. What follows is a short list of ideas that may stimulate thought on how to design and use your own laser system:

Planning Elements:

- Install a laser so that it points away from any exits, be they doors or windows. A laboratory wall is the most sturdy and permanent beam stop.
- Enclose the path of the laser beam. This may involve using metal pipes or boxes over the optics, shield walls around the table, or even a completely self-contained enclosure within the laboratory. The more you can do to contain the entire laser system, the safer your laboratory.
- Make your laser lab a single-use room, so that no one need enter while the laser is operating except those directly involved in the experiment. If this is not possible, enclose the laser system within the room itself by using partition walls or ceiling-to-floor-curtains. It is acceptable to make them of a combustible material – the smell of burning cloth and appearance of smoke can be a useful indicator of where beam stops are necessary.
- Keep the number of usable entrances to a minimum (i.e. one), as this will stop you having to duplicate warning signs, lights, curtains, etc. The entrance should be well shielded from the laser system by walls or curtains so that someone who accidentally enters the lab is not in immediate danger. Always have protective eyewear on hand at the entrance to the lab – don't make people walk through a hazardous area to retrieve them.
- All entrances to a laser laboratory must be clearly marked by warning signs appropriate to the laser's class. They should be large, scary, preferably multilingual, and describe the power and wavelengths of the radiation generated by your laser.
- In addition to warning signs, it is highly desirable to construct additional control measures at the entrance to a laser lab. These may include

warning lights, intercom systems, and door interlocks that trigger an emergency shutdown in case of unauthorized access. Each control has both advantages and disadvantages: discuss within your group what is appropriate for your system.

- Perform the calculations described above to determine the Nominal Hazard Zones (NHZs) within your lab. This is a practical calculation, so it will be dependent on the situation. For instance, if the laser system is in a self-contained enclosure within the lab and if all users follow the correct work practices, then the NHZ may be only a small area within the lab. However, if the laser is not well contained, or if the control measures designed for it such as laser curtains are removed, the entire room is likely to be within the NHZ.
- You can establish different NHZs for different levels of protection. For instance, for a user wearing OD 3 laser goggles, the NHZ for intrabeam viewing may be a zone of several m around the laser. However, a user wearing OD 6 laser goggles may be safe at any distance, i.e. $r_{\text{NHZ}} = 0$. In this way, you can design a safe multipurpose laboratory in which different users of the lab take different precautions, without having to adhere to draconian or unnecessary safety rules.

Safe Work Practices

The points above were aimed at safety planning in establishing a laboratory. However, these measures are only effective if the users follow appropriate precautions and standing rules when operating in the lab. Here are few examples of good work practice.

- All people in the immediate vicinity of an operating laser should wear protective eyewear appropriate to the lasers operating mode. That means anyone within a line of sight of the laser, which may include around corners if appropriate precautions to avoid stray reflections have not been taken. Keep your laser goggles in one clearly visible place, preferably next to the entrance of the lab.
- Never look directly into a laser beam, even if you have determined it is safe to do so. You might be wrong. Use indirect methods such as burn paper or power meters to find the beam on the laser table. Remember that even diffuse reflectance from a class IV laser can be hazardous.
- Cut off all paths with beam-stops. The more you can track and contain stray reflections, the simpler and more effective will be your other protective barriers. Keep all the beams in a single plane on your table. Take care when handling optics to keep them in the same plane as the beam, to avoid stray reflections bouncing around the room.

- Reduce the operating power of your laser whenever possible. Aim to work in a mode such that the actual exposure to you (accounting for the OD of laser goggles, if you wear them) is significantly **below** the MPE.
- Keep track of all the beam paths on your laser table, not just the main one of interest. For instance, after a frequency-doubling stage, there is commonly a significant amount of power remaining at the fundamental frequency. You should take account of each beam, preferably separating them early and stopping the one that is not of interest.
- Laser tables are commonly built to facilitate work by a standing person, i.e. just above waist height. Unfortunately this is also around the eye level of a seated person. Removing chairs and stools from around your laser table (even the whole room if practical) will help ensure that your eyes will never lie in the same plane as the beam.
- Establish a common protocol for entering and leaving the lab. For instance, someone wishing to enter a lab with the laser running should knock loudly and wait for the user inside to admit them, rather than walking in unannounced. The main benefit of a door interlock that must be overridden from inside is to enforce this type of work practice. Installing a phone or intercom within the lab can also help users communicate without having to walk in and out of the lab.
- Keep everyone informed on changes made to the laser system, and where possible develop standard methods of operation that all users will follow. For instance, a standard start and shutdown procedure, or a prescribed operating power for procedures carried out by multiple users of the system. This will not only make your lab more safe, but more efficient and productive.

The points above are by no means an exhaustive list, nor will they be appropriate to every situation. Think about your own system, the safety measures currently in place, and how you might improve them. You will find that designing a safe laboratory is a simple task, and well worth the effort.

Safety is everyone's responsibility. If you see a laboratory or a user that is manifestly unsafe, there is no harm in voicing your concerns. A laboratory is a fluid environment with constantly changing instruments and people. Take the time to instruct new members of the lab in safe work practices. Also be willing to review your safety measures from time to time – has the lasers power output been increased, has the system configuration changed, is there something that could be done more effectively or more easily? With a few simple rules and a willingness to abide by them, it is easy to make your lab a safe and enjoyable environment in which to work.

Appendix I - reference tables

The tables printed are all adapted from the 2000 American National Standard for the Safe Use of Lasers, first published in 1993. The most recent edition of this standard, ANSI Z136.1 2000, is available in the Chemistry Library. Wavelength ranges are of the form $\lambda_{\min} = \lambda < \lambda_{\max}$. All MPE values are in $\text{J} \cdot \text{cm}^2$ unless otherwise indicated.

Correction Factor	Wavelength Range (nm)	Value
C_A	400 to 700	1.0
C_A	700 to 1050	$10^{0.002(\lambda - 700)}$
C_A	1050 to 1400	5.0
C_B	400 to 450	1.0
C_B	450 to 600	$10^{0.02(\lambda - 450)}$
C_C	1050 to 1150	1.0
C_C	1150 to 1200	$10^{0.018(\lambda - 1150)}$
C_C	1200 to 1400	8.0
C_P^{**}	400 to 1400	$n^{-1/4}$
T_I	450 to 500	$10^{0.02(\lambda - 550)}$

**Use of the pulsed laser correction factor is dependent on pulse repetition frequency (F).

Wavelength (nm)	Exposure Duration (s)	
	10^{-9} to 3×10^4	
180 to 302	3×10^{-3}	
303	4×10^{-3}	
304	6×10^{-3}	
305	10×10^{-3}	
306	16×10^{-3}	
307	25×10^{-3}	
308	40×10^{-3}	
309	63×10^{-3}	
310	0.1	
311	0.16	
312	0.25	
313	0.40	
314	0.63	
Wavelength (nm)	Exposure Duration (s)	
	10^{-9} to 10	10 to 3×10^4
315 to 400	$0.56 t^{1/4}$	1.0

*for wavelengths <315 nm, value is as listed or $0.56 t^{1/4}$, whichever is lower.

Table 3a: Vis/NIR MPE's[†]				
Wavelength (nm)	Exposure Duration (s)			
	10^{-13} to 10^{-11}	10^{-11} to 10^{-9}	10^{-9} to 18×10^{-6}	18×10^{-6} to 10
400 to 700	1.5×10^{-8}	$2.7t^{3/4}$	5.0×10^{-7}	$1.8t^{3/4} \times 10^{-3}$
700 to 1050	$1.5C_A \times 10^{-8}$	$2.7C_A t^{3/4}$	$5.0C_A \times 10^{-7}$	$1.8C_A t^{3/4} \times 10^{-3}$
1050 to 1400	$1.5C_C \times 10^{-7}$	$27.0C_C t^{3/4}$	$5.0C_C \times 10^{-6}$	$9.0C_C t^{3/4} \times 10^{-3}$

Table 3b: Vis/NIR MPE's[†]			
Wavelength (nm)	Exposure Duration (s)		
	10 to T_1	T_1 to 100	100 to 3×10^4
400 to 450	1×10^{-2}		$C_B \times 10^{-4} \text{ W} \cdot \text{cm}^{-2}$
450 to 500	$1 \times 10^{-3} \text{ W} \cdot \text{cm}^{-2}$	$C_B \times 10^{-2}$	
500 to 700	$1 \times 10^{-3} \text{ W} \cdot \text{cm}^{-2}$		
700 to 1050	$C_A \times 10^{-3} \text{ W} \cdot \text{cm}^{-2}$		
1050 to 1400	$5.0C_C \times 10^{-3} \text{ W} \cdot \text{cm}^{-2}$		

[†]for multiple pulses apply correction factor C_P

Table 4: IR MPE's[‡]			
Wavelength (nm)	Exposure Duration (s)		
	10^{-9} to 10^{-3}	10^{-3} to 10	10 to 3×10^4
1400 to 1500	0.1	$0.56t^{1/4}$	0.1 $\text{W} \cdot \text{cm}^{-2}$
1500 to 1800	1.0		
1800 to 2600	0.1	$0.56t^{1/4}$	
Wavelength (nm)	Exposure Duration (s)		
	10^{-9} to 10^{-7}	10^{-7} to 10	10 to 3×10^4
≥ 2600	10×10^{-2}	$0.56t^{1/4}$	0.1 $\text{W} \cdot \text{cm}^{-2}$

[‡]for multiple pulses apply correction factor C_P

Appendix II – Case History

This case was printed in the November 1981 issue of *Laser Focus*:

‘A Naval Research Laboratory chemist who was struck in the eye with a laser beam this summer is still suffering from the injury. The victim, who requested his name not be printed, was hit by 585-nanometer dye laser light that had reflected off an angle-turned frequency doubler when he bent over to adjust a stepper-motor drive. Although his vision has gradually improved, he told *Laser Focus* he lost much of the high-resolution capability in the eye

The chemist, who’s worked with lasers for five years and considers himself a “laser jock”, was “amazed” by how little laser energy it took to do so much harm. Measurements made after the accident showed that the pulse back-reflected off the frequency doubler carried only about 25 microjoules. But that was enough to punch a hole through multiple layers of eye tissue and to cause hemorrhaging. The result was a blood blister over the macula lutea, the part of the eye that provides visual acuity and which is necessary for tasks such as reading. The pulse energy could have been much higher – close to two millijoules – if the NRL group had not earlier taken steps to suppress amplified spontaneous emission in the dye amplifier chain, the victim said.

A surprising – and unsettling – discovery after the accident was how little the doctors knew about laser eye injuries. According to the injured, even retinal specialists were often reduced to guessing during treatment.

The NRL researcher said he never saw a flash when the laser beam struck the eye. “I bent over and all of a sudden I couldn’t see,” he recalled. *He wasn’t wearing safety glasses at the time*, which he said was common practice in the lab. One reason was that the laser – a YAG-pumped dye system – was run by computer and seldom needed adjustments which required close eye proximity to the beam. Also, he pointed out, laser systems that simultaneously produce numerous beams at wavelengths from the ultraviolet to the infrared are difficult to guard against. Since no single pair of goggles will block out all beams, many lab workers chose to wear none at all. And in a darkened laser room, glasses that protect the wearer from laser light also obscure vision enough to raise the possibility of other hazards, such as hitting your head or tripping over cables.

The injured chemist criticized laser manufacturers for their method of compliance with Bureau of Radiological Health safety rules. Lasers are built in such a way “that to use one you’ve usually got to partly disassemble it,” he said. “Laser companies should design their product so that it can be adjusted and used while complying with BRH rules.” He also had harsh words for the maker of the frequency doubler that reflected into his eye. “A \$10 beam-stop on that doubler could have prevented this whole thing from happening,” he said.’

