Laser Safety Training Guide

PRINCETON UNIVERSITY

Environmental Health and Safety

http://www.princeton.edu/ehs

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LASER SAFETY TRAINING GUIDE

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Section 1: LASER FUNDAMENTALS

Introduction

The word *laser* is an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers are used as research aides in many departments at Princeton University.

In this document, the word laser will be limited to electromagnetic radiation-emitting devices using light amplification by stimulated emission of radiation at wavelengths from 180 nanometers to 1 millimeter. The electromagnetic spectrum includes energy ranging from gamma rays to electricity. *Figure 1* illustrates the total electromagnetic spectrum and wavelengths of the various regions.

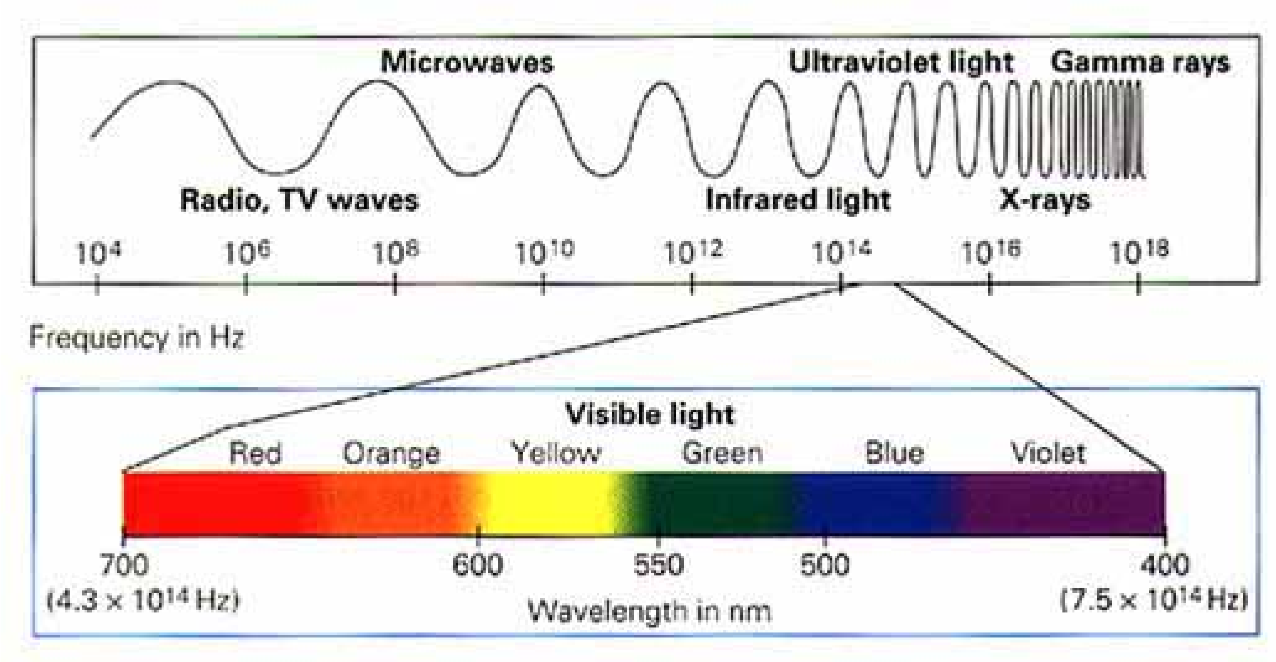


Figure 1. Electromagnetic Spectrum

The primary wavelengths for lasers used at Princeton University include the ultraviolet, visible and infrared regions of the spectrum. Ultraviolet radiation for lasers consists of wavelengths between 180 and 400 nanometers (nm). The visible region consists of radiation with wavelengths between 400 and 700 nm. This is the portion we call visible light. The infrared region of the spectrum consists of radiation with wavelengths between 700 nm and 1 mm.

The color or wavelength of light being emitted depends on the type of lasing material being used. For example, if a Neodymium:Yttrium Aluminum Garnet (Nd:YAG) crystal is used as the lasing material, light with a wavelength of 1064 nm will be emitted. Table 1 illustrates various types of material currently used for lasing and the wavelengths that are emitted by that type of laser. Note that certain materials and gases are capable of emitting more than one wavelength. The wavelength of the light emitted in this case is dependent on the optical configuration of the laser.

Table 1. Common Lasers and Their Wavelengths

LASER TYPE	WAVELENGTH (in nanometers)
Argon Fluoride	193
Xenon Chloride	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Frequency doubled Nd:YAG	532
Helium Neon	543, 594, 612, and 632.8
Krypton	337.5 - 799.3 (647.1 - 676.4 most used)
Ruby	694.3
Laser Diodes	630 - 950
Ti:Sapphire	690 - 960
Nd:YAG	1064
Hydrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Monoxide	5000 - 6000
Carbon Dioxide	10600

Laser Theory and Operation

A laser generates a beam of very intense light. The major difference between laser light and light generated by white light sources (such as a light bulb) is that laser light is monochromatic, directional and coherent. **Monochromatic** means that all of the light produced by the laser is of a single wavelength. White light is a combination of all visible wavelengths (400 - 700 nm). **Directional** means that the beam of light has very low divergence. Light from a conventional source, such as a light bulb diverges, spreading in all directions, as illustrated in *Figure 2*. The intensity may be large at the source, but it decreases rapidly as an observer moves away from the source.

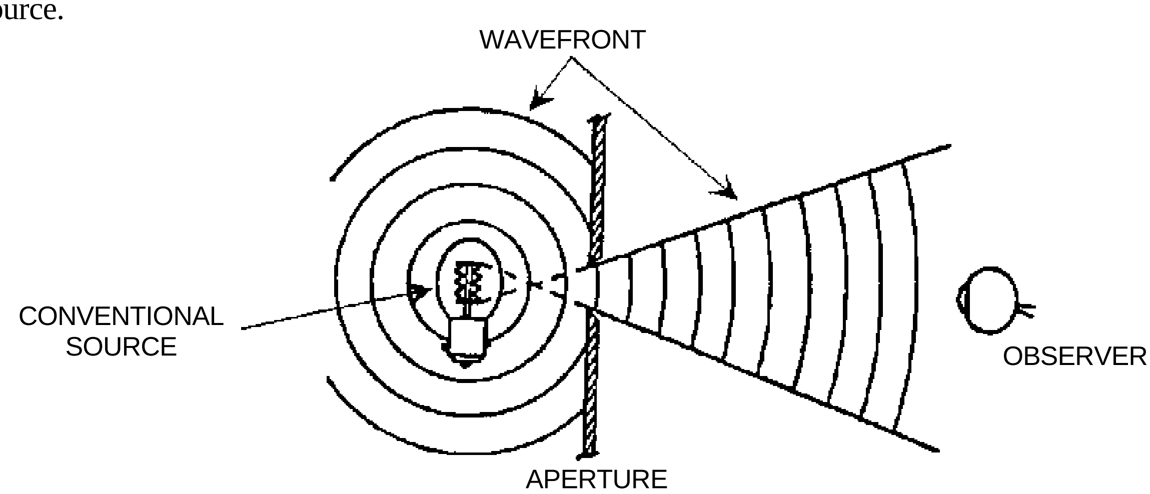


Figure 2. Divergence of Conventional Light Source

In contrast, the output of a laser, as shown in *Figure 3*, has a very small divergence and can maintain high beam intensities over long ranges. Thus, relatively low power lasers are able to project more energy at a single wavelength within a narrow beam than can be obtained from much more powerful conventional light sources.

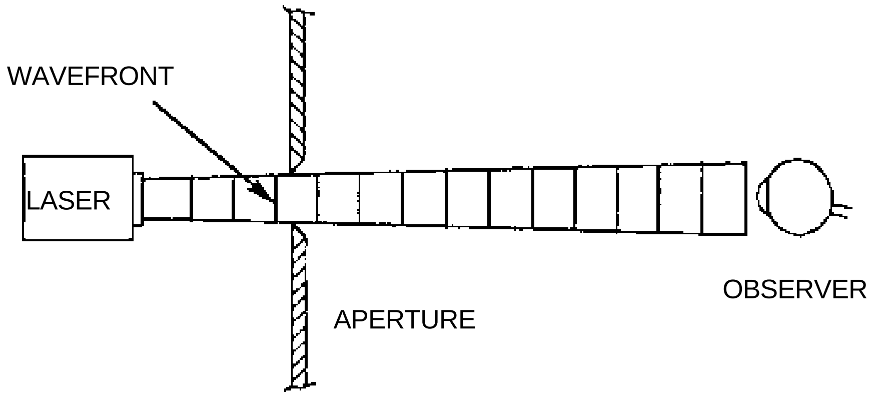


Figure 3. Divergence of Laser Source

Coherent means that the waves of light are in phase with each other. A light bulb produces many wavelengths, making it incoherent.

Figure 4. Incoherent light bulb vs. coherent laser.

Components of a Laser

Figure 5 illustrates the basic components of the laser including the *lasing material*, *pump source or excitation medium*, *optical cavity and output coupler*.

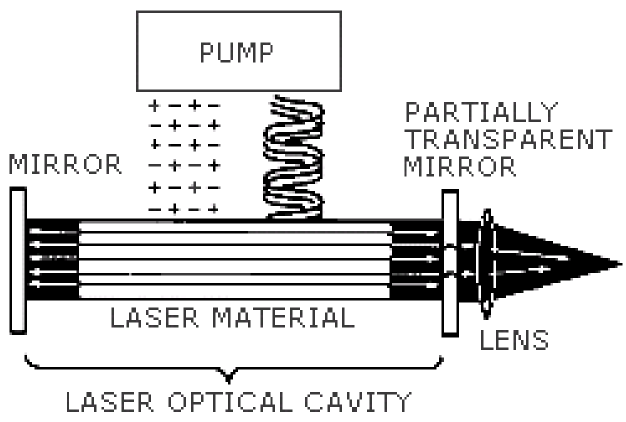


Figure 5. Solid State Laser Diagram

The lasing material can be a solid, liquid, gas or semiconductor, and can emit light in all directions. The pump source is typically electricity from a power supply, lamp or flashtube, but may also be another laser. It is very common in Princeton University laboratories to use one laser to pump another.

The *excitation medium* is used to excite the lasing material, causing it to emit light. The *optical cavity* contains mirrors at each end that reflect this light and cause it to bounce between the mirrors. As a result, the energy from the excitation medium is amplified in the form of light. Some of the light passes through the *output coupler*, usually a semi-transparent mirror at one end of the cavity. The resulting beam is then ready to use for any of hundreds of applications.

The laser output may be steady, as in *continuous wave (CW)* lasers, or *pulsed*. A Q-switch in the optical path is a method of providing laser pulses of an extremely short time duration. The Q-switch may use a rotating prism, a pockels cell or a shutter device to create the pulse. Q-switched lasers may produce a high-peak-power laser pulse of a few nanoseconds duration.

A continuous wave laser has a steady power output, measured in *watts (W).* For pulsed lasers, the output generally refers to energy, rather than power. The radiant energy is a function of time and is measured in *joules (J)*. Two terms are often used to when measuring or calculating exposure to laser radiation. *Radiant Exposure* is the radiant energy divided by the area of the surface the beam strikes. It is expressed in J/cm^2. *Irradiance* is the radiant power striking a surface divided by the area of the surface over which the radiant power is distributed. It is expressed in W/cm^2. For repetitively pulsed lasers, the pulse repetition rate (PRR) and pulse width are important in evaluating biological effects.

Types of Lasers

The **laser diode** is a light emitting diode that uses an optical cavity to amplify the light emitted from the energy band gap that exists in semiconductors (See *Figure 6*.). They can be tuned to different wavelengths by varying the applied current, temperature or magnetic field.

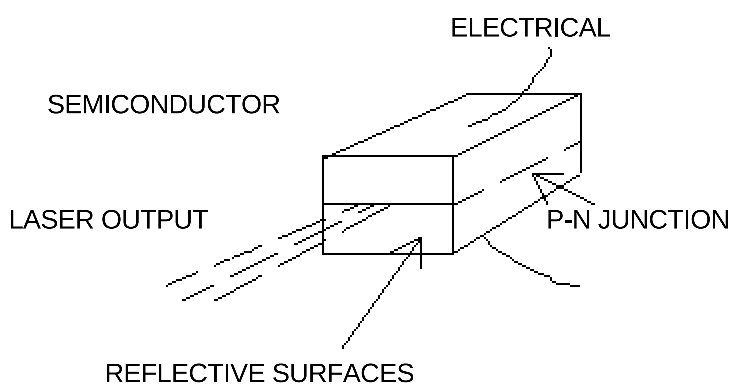


Figure 6. Semiconductor laser diagram

Gas lasers consist of a gas filled tube placed in the laser cavity as shown in *Figure 7*. A voltage (the external pump source) is applied to the tube to excite the atoms in the gas to a population inversion. The light emitted from this type of laser is normally continuous wave (CW). One should note that if Brewster angle windows are attached to the gas discharge tube, some laser radiation may be reflected out the side of the laser cavity. Large gas lasers known as gas dynamic lasers use a combustion chamber and supersonic nozzle for population inversion.

GAS DISCHARGE TUBE OUTPUT MIRROR

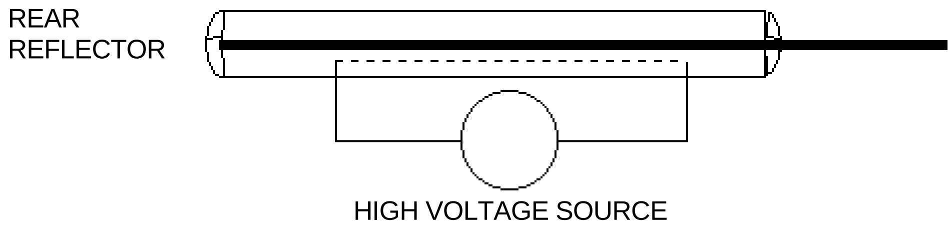


Figure 7. Gas laser diagram

Dye lasers employ an active material in a liquid suspension. The dye cell contains the lasing medium. These lasers are popular because they may be tuned to several wavelengths by changing the chemical composition of the dye. Many of the commonly used dyes or liquid suspensions are toxic.

Free electron lasers such as in *Figure 8* have the ability to generate wavelengths from the microwave to the X-ray region. They operate by having an electron beam in an optical cavity pass through a wiggler magnetic field. The change in direction exerted by the magnetic field on the electrons causes them to emit photons.

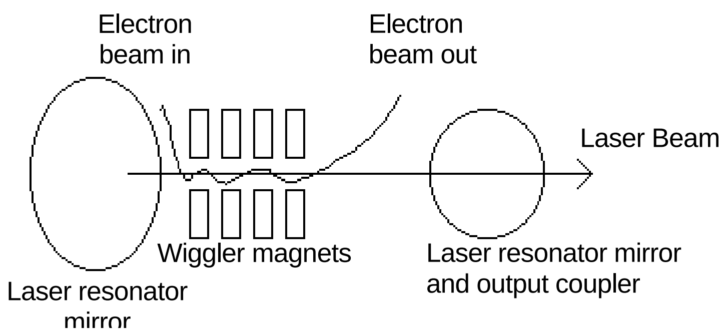


Figure 8. Free Electron Laser Diagram

Section 2: LASER HAZARDS

The hazards of lasers may be separated into two general categories – beam-related hazards to eyes and skin and non-beam hazards, such as electrical and chemical hazards.

Beam-Related Hazards

Improperly used laser devices are potentially dangerous. Effects can range from mild skin burns to irreversible injury to the skin and eye. The biological damage caused by lasers is produced through thermal, acoustical and photochemical processes.

Thermal effects are caused by a rise in temperature following absorption of laser energy. The severity of the damage is dependent upon several factors, including exposure duration, wavelength of the beam, energy of the beam, and the area and type of tissue exposed to the beam.

Acoustical effects result from a mechanical shockwave, propagated through tissue, ultimately damaging the tissue. This happens when the laser beam causes localized vaporization of tissue, causing the shockwave analogous to ripples in water from throwing a rock into a pond.

Beam exposure may also cause photochemical effects when photons interact with tissue cells. A change in cell chemistry may result in damage or change to tissue. Photochemical effects depend greatly on wavelength. *Table 2* summarizes the probable biological effects of exposure of eyes and skin to different wavelengths.

Table 2. Summary of Laser Biological Effects

Photo-biological Spectral Domain	Eye	Skin
Ultraviolet C (200 nm - 280 nm)	Photokeratitis	Erythema (sunburn), skin cancer, accelerated skin aging
Ultraviolet B (280 nm - 315 nm)	Photokeratitis	Increased pigmentation
Ultraviolet A (315 nm - 400 nm)	Photochemical cataract	Pigment darkening, skin burn
Visible (400 nm - 780 nm)	Photochemical and thermal retinal injury	Pigment darkening, photosensitive reactions, skin burn
Infrared A (780 nm - 1400 nm)	Cataract and retinal burn	Skin burn
Infrared B (1.4μm - 3.0 μm)	Corneal burn, aqueous flare, cataract	Skin burn
Infrared C (3.0 μm - 1000 μm)	Corneal burn only	Skin burn

Types of Beam Exposure

Exposure to the laser beam is not limited to direct beam exposure. Particularly for high powered lasers, exposure to beam reflections may be just as damaging as exposure to the primary beam.

Intrabeam exposure means that the eye or skin is exposed directly to all or part of the laser beam. The eye or skin is exposed to the full irradiance or radiant exposure possible.

Specular reflections from mirror surfaces can be nearly as harmful as exposure to the direct beam, particularly if the surface is flat. Curved mirror-like surfaces will widen the beam such that while the exposed eye or skin does not absorb the full impact of the beam, there is a larger area for possible exposure.

A diffuse surface is a surface that will reflect the laser beam in many directions. Mirror-like surfaces that are not completely flat, such as jewelry or metal tools may cause ***diffuse reflections*** of the beam. These reflections do not carry the full power or energy of the primary beam, but may still be harmful, particularly for high powered lasers. Diffuse reflections from Class 4 lasers are capable of initiating fires.

Whether a surface is a diffuse reflector or a specular reflector will depend upon the wavelength of the beam. A surface that would be a diffuse reflector for a visible laser may be a specular reflector for an infrared laser beam.

Eye

The major danger of laser light is hazards from beams entering the eye. The eye is the organ most sensitive to light. Just as a magnifying glass can be used to focus the sun and burn wood, the lens in the human eye focuses the laser beam into a tiny spot than can burn the retina. A laser beam with low divergence entering the eye can be focused down to an area 10 to 20 microns in diameter.

The laws of thermodynamics do not limit the power of lasers. The second law states that the temperature of a surface heated by a beam from a thermal source of radiation cannot exceed the temperature of the source beam. The laser is a non-thermal source and is able to generate temperatures far greater than its own. A 30 mW laser operating at room temperature is capable of producing enough energy (when focused) to instantly burn through paper.

Per the law of the conservation of energy, the energy density (measure of energy per unit of area) of the laser beam increases as the spot size decreases. This means that the energy of a laser beam can be intensified up to 100,000 times by the focusing action of the eye. If the irradiance entering the eye is 1 mW/cm^2, the irradiance at the retina will be 100 W/cm^2. Thus, even a low power laser in the milliwatt range can cause a burn if focused directly onto the retina.

NEVER point a laser at someone's eyes no matter how low the power of the laser.

Structure of the Eye

Damage to the eye is dependent upon the wavelength of the beam. In order to understand the possible health effects, it is important to understand the functions of the major parts of the human eye.

The **cornea** is the transparent layer of tissue covering the eye. Damage to the outer cornea may be uncomfortable (like a gritty feeling) or painful, but will usually heal quickly. Damage to deeper layers of the cornea may cause permanent injury.

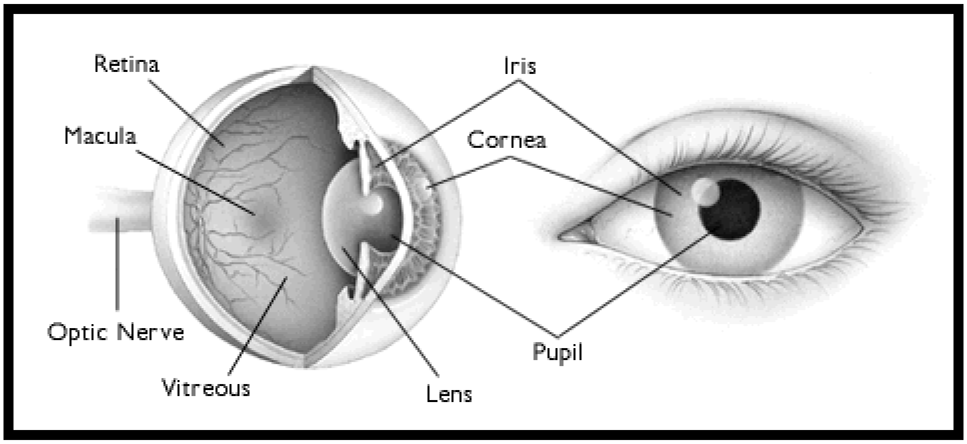


Figure 9. Cross section of the human eye.

The **lens** focuses light to form images onto the retina. Over time, the lens becomes less pliable, making it more difficult to focus on near objects. With age, the lens also becomes cloudy and eventually opacifies. This is known as a cataract. Every lens develops cataract eventually.

The part of the eye that provides the most acute vision is the **fovea** centralis (also called the **macula** lutea). This is a relatively small area of the **retina** (3 to 4%) that provides the most detailed and acute vision as well as color perception. This is why eyes move when you read or when you look as something; the image has to be focused on the fovea for detailed perception. The balance of the retina can perceive light and movement, but not detailed images (peripheral vision).

If a laser burn occurs on the fovea, most fine (reading and working) vision may be lost in an instant. If a laser burn occurs in the peripheral vision it may produce little or no effect on fine vision. Repeated retinal burns can lead to blindness.

Fortunately the eye has a self-defense mechanism -- the blink or aversion response. When a bright light hits the eye, the eye tends to blink or turn away from the light source (aversion) within a quarter of a second. This may defend the eye from damage where lower power lasers are involved, but cannot help where higher power lasers are concerned. With high power lasers, the damage can occur in less time than a quarter of a second.

Symptoms of a laser burn in the eye include a headache shortly after exposure, excessive watering of the eyes, and sudden appearance of *floaters* in your vision. Floaters are those swirling distortions that occur randomly in normal vision most often after a blink or when eyes have been closed for a couple of seconds. Floaters are caused by dead cell tissues that detach from the retina and choroid and float in the vitreous humor. Ophthalmologists often dismiss minor laser injuries as floaters due to the very difficult task of detecting minor retinal injuries. Minor corneal burns cause a gritty feeling, like sand in the eye.

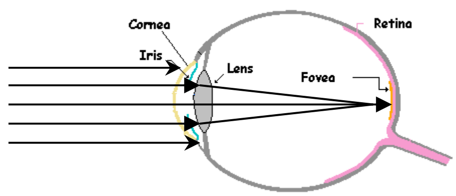
Several factors determine the degree of injury to the eye from laser light:

- **pupil size** - The shrinking of pupil diameter reduces the amount of total energy delivered to the retinal surface. Pupil size ranges from a 2 mm diameter in bright sun to an 8 mm diameter in darkness (night vision).
- **degree of pigmentation** - More pigment (melanin) results in more heat absorption.
- **size of retinal image** - The larger the size, the greater the damage because temperature equilibrium must be achieved to do damage. The rate of equilibrium formation is determined by the size of the image.
- **pulse duration** - The shorter the time (ns versus ms), the greater the chance of injury.
- **pulse repetition rate** - The faster the rate, the less chance for heat dissipation and recovery.
- **wavelength** - determines where the energy deposits and how much gets through the ocular media.

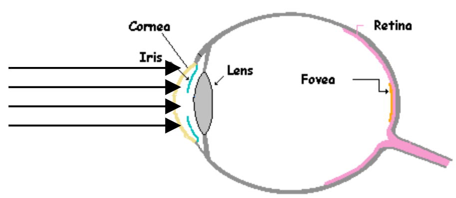
Eye Absorption Site vs. Wavelength

The wavelength determines where the laser energy is absorbed in the eye.

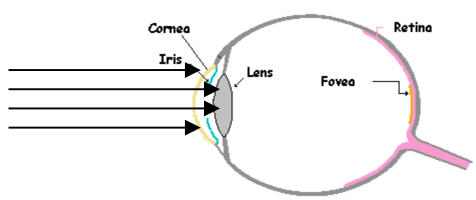
Visible and Near Infrared (400-1400 nm) penetrate the cornea and may be absorbed by the retina.



Mid and Far Infrared (1400 nm - 1 mm) and **Far-Ultraviolet (180 - 315 nm)** are absorbed by the cornea and may result in corneal burns.



Near-Ultraviolet (315-390 nm) is mostly absorbed by the lens and may cause early cataracts



Lasers in the visible and near infrared range of the spectrum have the greatest potential for retinal injury, as the cornea and the lens are transparent to those wavelengths and the lens can focus the laser energy onto the retina. The maximum absorption of laser energy onto the retina occurs in the range from 400 - 550 nm. Argon and YAG lasers operate in this range, making them the most hazardous lasers with respect to eye injuries. Wavelengths of less than 550 nm can cause a photochemical injury similar to sunburn. Photochemical effects are cumulative and result from long exposures (over 10 seconds) to diffuse or scattered light. *Table 3* summarizes the most likely effects of overexposure to various commonly used lasers.

Table 3. Summary of Bioeffects of Commonly Used Lasers

LASER TYPE	WAVELENGTH (μm)	BIOEFFECT Process	TISSUE EFFECTED			
			Skin	Cornea	Lens	Retina
CO_2	10.6	Thermal	X	X		
HFl	2.7	Thermal	X	X		
Erbium-YAG	1.54	Thermal	X	X		
Nd-YAG [a]	1.33	Thermal	X	X	X	X
Nd-YAG	1.06	Thermal	X			X
Gas (diode)	0.78-0.84	Thermal	[b]			X
He-Ne	0.633	Thermal	[b]			X
Ar	0.488-0.514	Thermal/ Photochemical	X			X[c]
XeFl	0.351	Photochemical	X	X		X
XeCl	0.308	Photochemical	X	X		

[a] Wavelength at 1.33μ or more common in some Nd-YAG lasers has demonstrated simultaneous cornea/lens/retina effects in biological research studies

[b] Power levels not normally sufficient to be considered a significant skin hazard

[c] Photochemical effects dominate for long-term exposures to retina (exposure times more than 10 seconds

Skin

Lasers can harm the skin via photochemical or thermal burns. Depending on the wavelength, the beam may penetrate both the epidermis and the dermis. The epidermis is the outermost living layer of skin. Far and Mid-ultraviolet (the actinic UV) are absorbed by the epidermis. Sunburn (reddening and blistering) may result from short-term exposure to the beam. UV exposure is also associated with an increased risk of developing skin cancer and premature aging (wrinkles, etc) of the skin.

Thermal burns to the skin are rare. They usually require exposure to high energy beams for an extended period of time. Carbon dioxide and other infrared lasers are most commonly associated with thermal burns, since this wavelength range may penetrate deeply into skin tissue. The resulting burn may be first degree (reddening), second degree (blistering) or third degree (charring).

Some individuals are photosensitive or may be taking prescription drugs that induce photosensitivity. Particular attention must be given to the effect of these (prescribed) drugs, including some antibiotics and fungicides, on the individual taking the medication and working with or around lasers.

Non-Beam Hazards

In addition to the hazards directly associated with exposure to the beam, ancillary hazards can be produced by compressed gas cylinders, cryogenic and toxic materials, ionizing radiation and electrical shock.

Electrical Hazards

The use of lasers or laser systems can present an electric shock hazard. This may occur from contact with exposed utility power utilization, device control, and power supply conductors operating at potentials of 50 volts or more. These exposures can occur during laser set-up or installation, maintenance and service, where equipment protective covers are often removed to allow access to active components as required for those activities. The effect can range from a minor tingle to serious personal injury or death. Protection against accidental contact with energized conductors by means of a barrier system is the primary methodology to prevent electrical shock.

Additional electrical safety requirements are imposed upon laser devices, systems and those who work with them by the federal Occupational Safety and Health Administration (OSHA), the National Electric Code and related state and local regulations. Individuals who repair or maintain lasers may require specialized electric safety-related work practices training. Contact the University Safety Engineer at 258-5294 for an electrical safety inspection and/or required training.

Another particular hazard is that high voltage electrical supplies and capacitors for lasers are often located close to cooling water pumps, lines, filters, etc. In the event of a spill or hose rupture, an extremely dangerous situation may result. During times of high humidity, over-cooling can lead to condensation which can have similar effects. A potentially lethal accident occurred at Princeton University when a graduate student opened a laser to wipe condensation from a tube.

The following are recommendations for preventing electrical shocks for lasers for all classifications:

1. All equipment should be installed in accordance with OSHA and the National Electrical Code.
2. All electrical equipment should be treated as if it were "live".
3. Working with or near live circuits should be avoided. Whenever possible, unplug the equipment before working on it.
4. A "buddy system" should be used when work on live electrical equipment is necessary, particularly after normal work hours or in isolated areas. Ideally, the person should be knowledgeable of first aid and CPR.
5. Rings and metallic watchbands should not be worn, nor should metallic pens, pencils, or rulers be used while one is working with electrical equipment.
6. Live circuits should be worked on using one hand, when it is possible to do so.
7. When one is working with electrical equipment, only tools with insulated handles should be used.
8. Electrical equipment that upon touch gives the slightest perception of current should be removed from service, tagged and repaired prior to further use.
9. When working with high voltages consider the floor conductive and grounded unless standing on a suitably insulated, dry matting normally used for electrical work.
10. Live electrical equipment should not be worked on when one is standing on a wet floor, or when the hands, feet or body is wet or perspiring.

11. Do not undertake hazardous activities when truly fatigued, emotionally stressed, or under the influence of medication that dulls or slows the mental and reflex processes.
12. Follow lockout/tagout procedures when working with hard-wired equipment.

Laser Generated Air Contaminants -- The "Plume"

This is a term used to refer to the "cloud" of contaminants created when there is an interaction between the beam and the target matter. These air contaminants are mostly associated with Class 3B and 4 lasers, and range from metallic fumes and dust, chemical fumes, and aerosols containing biological contaminants.

Some examples include:

- polycyclic aromatic hydrocarbons from mode burns on poly (methyl methacrylate) type polymers;
- hydrogen cyanide and benzene from cutting of aromatic polyamide fibers;
- fused silica from cutting quartz;
- heavy metals from etching;
- benzene from cutting polyvinyl chloride; and
- cyanide, formaldehyde and synthetic and natural fibers associated with other processes.

Special optical materials used for far infrared windows and lenses have been the source of potentially hazardous levels of airborne contaminants. For example, calcium telluride and zinc telluride will burn in the presence of oxygen when beam irradiance limits are exceeded. Exposure to cadmium oxide, tellurium and tellurium hexafluoride should also be controlled.

Exposure to these contaminants must be controlled to reduce exposure below acceptable OSHA permissible exposure limits. The material safety data sheet (MSDS) may be consulted to determine exposure information and permissible exposure limits. In general, there are three major control measures available: exhaust ventilation, respiratory protection, and isolation of the process.

Whenever possible, recirculation of plume should be avoided. Exhaust ventilation, including use of fume hoods should be used to control airborne contaminants.

Respiratory protection may be used to control brief exposures, or as an interim control measure until other administrative or engineering controls are implemented. Use of respirators must comply with the University Policy on Respiratory Protection. Contact the University Industrial Hygienist at 258-5294 if a respirator is needed.

The laser process may be isolated by physical barriers, master-slave manipulators, or remote control apparatus. This is particularly useful for laser welding or cutting of targets such as plastics, biological material, coated metals, and composite substrates.

Collateral and Plasma Radiation

Collateral radiation, i.e., radiation other than that associated with the primary laser beam, may be produced by system components such as power supplies, discharge lamps and plasma tubes. Such radiation may take the form of x-rays, UV, visible, infrared, microwave and radio-frequency radiation. "Home-built" lasers are again of particular concern and should be independently examined. In addition, when high power pulsed laser beams (peak irradiance of the order of 10^{12}

watts/cm^2) are focused on a target, a plasma is generated which may also emit collateral radiation. X-rays may be generated by electronic components of the laser system (e.g., high voltage vacuum tubes, usually greater than 15kV) and from laser-metal induced plasmas.

Fire Hazards

Class 4 laser systems represent a fire hazard. Enclosure of Class 3 laser beams can result in potential fire hazards if enclosure materials are likely to be exposed to irradiances exceeding 10 watts/cm^2. The use of flame retardant materials is encouraged.

Opaque laser barriers (e.g., curtains) can be used to block the laser beam from exiting the work area during certain operations. While these barriers can be designed to offer a range of protection, they normally cannot withstand high irradiance levels for more than a few seconds without some damage, including the production of smoke, open fire, or penetration. Users of commercially available laser barriers should obtain appropriate fire prevention information from the manufacturer.

Operator of Class 4 lasers should be aware of the ability of unprotected wire insulation and plastic tubing to ignite from intense reflected or scattered beams, particularly from lasers operating at invisible wavelengths.

Compressed Gases

Many hazardous gases are used in laser applications, including chlorine, fluorine, hydrogen chloride, and hydrogen fluoride. The use of mixtures with inert gases, rather than the pure gases is generally preferred. Hazardous gases should be stored in appropriately exhausted enclosures, with the gases permanently piped to the laser using the recommended metal tubing and fittings. An inert gas purge system and distinctive coloring of the pipes and fittings is also prudent.

Compressed gas cylinders should be secured from tipping. Other typical safety problems that arise when using compressed gases are:

- working with free-standing cylinders not isolated from personnel
- regulator disconnects, releasing contents to atmosphere
- no remove shutoff valve or provisions for purging gas before disconnect or reconnect
- labeled hazardous gas cylinders not maintained in appropriate exhausted enclosures
- gases of different categories (toxics, corrosives, flammable, oxidizers, inerts, high pressure and cryogenics) not stored separately

The departmental Chemical Hygiene Plan has additional information about safely handling compressed gases.

Laser Dyes

Laser dyes are complex fluorescent organic compounds which, when in solution with certain solvents, form a lasing medium for dye lasers. Certain dyes are highly toxic or carcinogenic. Since these dyes are typically changed frequently, special care must be taken when handling and preparing solutions, and during dye laser operation. The MSDS for dye compounds should be available to and reviewed by all potentially affected workers.

The use of dimethylsulfoxide (DMSO) as a solvent for cyanide dyes in dye lasers should be discontinued, if possible. The DMSO aids in the transport of dyes into the skin. If another solvent cannot be found, low permeability gloves should be worn by personnel any time a situation arises where contact with the solvent may occur.

Preparation of dye solutions should be conducted in a fume hood. Personal protective equipment, such as lab coats, appropriate gloves, and eye protection are necessary when preparing solutions.

Section 3: LASER HAZARD CLASSIFICATION

Lasers are classified according to their potential to cause biological damage. The pertinent parameters are:

- laser output energy or power
- radiation wavelengths
- exposure duration
- cross-sectional area of the laser beam at the point of interest.

In addition to these general parameters, lasers are classified in accordance with the *accessible emission limit* (AEL), which is the maximum accessible level of laser radiation permitted within a particular laser class.

The ANSI standard laser hazard classifications are used to signify the level of hazard inherent in a laser system and the extent of safety controls required. These range from Class 1 lasers (which are inherently safe for direct beam viewing under most conditions) to Class 4 lasers (which require the most strict controls). The laser classifications are described below:

Class 1 - Exempt Lasers

Class 1 laser cannot, under normal operating conditions, produce damaging radiation levels. These lasers must be labeled, but are exempt from the requirements of the Laser Safety Program. A laser printer is an example of a Class 1 laser.

Class 1M - Exempt Lasers

Class 1M laser cannot, under normal operating conditions, produce damaging radiation levels unless the beam is viewed with an optical instrument such as an eye-loupe (diverging beam) or a telescope (collimated beam). Such lasers must be labeled, but are exempt from the requirements of the Laser Safety Program other than to prevent potentially hazardous optically aided viewing.

Class 2 - Low Power Visible Lasers

Class 2 lasers are low power lasers or laser system in the visible range (400 - 700 nm wavelength) that may be viewed directly under carefully controlled exposure conditions. Because of the normal human aversion responses, these lasers do not normally present a hazard. A continuous wave (cw) HeNe laser above Class 1, but not exceeding 1 mW radiant power is an example of a Class 2 laser.

Class 2M - Low Power Visible Lasers

Class 2 lasers are low power lasers or laser system in the visible range (400 - 700 nm wavelength) that may be viewed directly under carefully controlled exposure conditions. Because of the normal human aversion responses, these lasers do not normally present a hazard, but may present some potential for hazard if viewed with certain optical aids.

Class 3 - Medium Power Lasers and Laser Systems

Class 3 lasers are medium power lasers or laser systems that require control measures to prevent viewing of the direct beam, but may also be hazardous under specular reflection viewing conditions. Class 3 lasers are normally not a diffuse reflection or fire hazard.

Class 3R (3a) denotes lasers or laser systems potentially hazardous under some direct and specular reflection viewing condition if the eye is appropriately focused and stable, but the probability of an actual injury is small. This laser will not pose either a fire hazard or diffuse-reflection hazard. They may present a hazard if viewed using collecting optics. Visible CW HeNe lasers above 1 mW, but not exceeding 5 mW radiant power, are examples of this class.

Class 3B denotes lasers or laser systems that may be hazardous under direct and specular reflection viewing conditions, but are normally not a diffuse reflection or fire hazard. Visible CW HeNe lasers above 5 mW, but not exceeding 500 mW radiant power, are examples of this class.

Class 4 - High Power Lasers and Laser Systems

Class 4 denotes a high power laser or laser system that is a hazard to the eye or skin from the direct beam, and may pose a diffuse reflection or fire hazard. Class 4 lasers may also produce laser generated air contaminants (LGAC) and hazardous plasma radiation. Class 4 lasers include all lasers in excess of Class 3 limitations.

Classification

Commercial lasers are classified and certified by the manufacturer. When a commercial laser is modified or when a new laser is constructed in the laboratory, it is the responsibility of the principal investigator to classify and label the laser per the ANSI Standard. EHS can assist in determining the appropriate classification. For a summary of typical laser classifications see Table C1, “Typical Laser Classification – Continuous Wave (CW) Point Source Lasers” and Table C2, “Typical Laser Classification – Single-Pulse Point Source Lasers.”

Section 4: Laser Control Measures

Individuals who operate lasers should follow the guidelines in this section to protect both themselves and others in the area. Supervisors and operators should be properly trained before working with or around Class 2, 3, and 4 lasers.

Features of a laser device, such as power output, beam diameter, pulse length, wavelength, beam path, beam divergence, and exposure duration determine the capability for injuring personnel. The potential for injury from use of a laser is determined by its classification; therefore, laser class also determines the control measures.

Concepts such are the *maximum permissible exposure* (MPE), *accessible exposure limit* (AEL), *optical density* (OD) and *nominal hazard zone* (NHZ) are important for the laser operator to use and understand.

Maximum Permissible Exposure (MPE)

MPE is the maximum level of laser radiation to which a person may be exposed without hazardous effects or biological changes in the eye or skin. The MPE is determined by the wavelength of laser, the energy involved, and the duration of the exposure. The ANSI 136.1 standard tables 5, 6, and 7 (see Appendix A) summarize the MPE for particular wavelengths and exposure durations.

MPE is a necessary parameter in determining the appropriate optical density and the nominal hazard zone.

Accessible Exposure Limit (AEL)

AEL is defined as the maximum accessible emission level permitted within a particular laser hazard class. The AEL value for various laser classes is determined by the product of the calculated MPE and the area of the limiting aperture.

Optical Density (OD)

The OD (absorbance) is used in the determination of the appropriate eye protection. OD is a logarithmic function defined by:

$$OD = \log_{10}\left[\frac{H_0}{MPE}\right]$$

Where H_0 is the anticipated worst case exposure conditions (in joules/cm^2 or watts/cm^2) and the MPE is expressed in the same units as H_0. The OD values for various lasers, computed for various appropriate exposure times, are listed below. Keep in mind that these values are for intrabeam viewing (worst case) only. Viewing Class 4 diffuse reflections (such as alignment tasks) requires, in general, less OD. These should be determined for each situation and would be dependent upon the laser parameters and viewing distance.

Table 4 provides a summary of optical density needed for particular lasers, based on the worst-case exposure duration.

Table 4. Optical Densities for Protective Eyewear for Various Laser Types

Laser Type/ Power	Wavelength (μm)	OD 0.25 seconds	OD 10 seconds	OD for 600 seconds	OD for 30,000 seconds
XeCl 50 watts	0.308[a]	---	6.2	8.0	9.7
XeFl 50 watts	0.351[a]	---	4.8	6.6	8.3
Argon 1.0 watt	0.514	3.0	3.4	5.2	6.4
Krypton 1.0 watt	0.530	3.0	3.4	5.2	6.4
Krypton 1.0 watt	0.568	3.0	3.4	4.9	6.1
HeNe 0.005 watt	0.633	0.7	1.1	1.7	2.9
Krypton 1.0 watt	0.647	3.0	3.4	3.9	5.0
GaAs 50 mW	0.840[c]	---	1.8	2.3	3.7
Nd:YAG 100 watt	1.064[a]	---	4.7	5.2	5.2
Nd:YAG (Q-switch)[b]	1.064[a]	---	4.5	5.0	5.4
Nd:YAG[c] 50 watts	1.33[a]	---	4.4	4.9	4.9
CO_2 1000 watts	10.6[a]	---	6.2	8.0	9.7

[a] Repetitively pulsed at 11 Hertz, 12 ns pulses, 20mJ/pulse
[b] OD for UV and FIR beams computed using 1 mm limiting aperture which presents a “worst case scenario. All visible/NIR computation assume 7 mm limiting aperture
[c] Nd:YAG operating at a less common 1.33 μm wavelength.
NOTE: All OD values determined using MPE criteria of ANSI Z-136.1

Nominal Hazard Zone (NHZ)

The NHZ relates to the space within which the level of direct, reflected, or scattered radiation during normal operation exceeds the appropriate MPE. Exposure levels beyond the NHZ are below the appropriate MPE level, thus no control measures are needed outside the NHZ. The NHZ may be calculated using the following formula:

$$NHZ = \frac{1}{\phi}\left[\left(\frac{4\Phi}{\pi * MPE}\right)^{\frac{1}{2}} - a\right]$$

Where ϕ is the emergent beam divergence measured in radians; Φ is the radiant power (total radiant power for continuous wave lasers or average radiant power of a pulsed laser) measured in watts; and *a* is the diameter of the emergent laser beam, in centimeters.

Control Measures by Laser Classification

Potential hazards exist to all individuals working near a laser system. Such individuals should be warned of the existence and location of lasers, and of the meaning of the warning labels for all classes of lasers. The purpose of control measures is to reduce the possibility of human exposure to hazardous laser radiation and non-beam hazards.

Particular attention should be given to the environment where the laser is used. This factor should be considered together with the class and application of the laser for determining the control measures to be applied. Basic elements to be considered are:

- number and class of lasers
- laser location
- presence (access) of uninformed, unprotected personnel
- permanence of beam paths
- presence of objects that may have specular surfaces or reflecting objects near the beam path
- use of optical devices such as lenses, microscopes, etc.

Control measures may be broken down to two types: *administrative controls*, such as signage, procedures, etc., and *engineering controls*, such as beam housings, shutters, etc. The following are general considerations for work with lasers, per laser hazard class. Table 5 on page 24 and 25 provides a summary of these control measures.

Class 1

Many Class 1 lasers are composed of more powerful lasers contained within a protective housing. If the Class 1 laser has an enclosed Class 3B or 4 laser, interlocks should be provided on any removable parts of the housing, or the laser should have a service access panel that is either interlocked or requires a tool for removal. If the protective housing is removed, control measures appropriate for the enclosed laser class shall be followed.

Class 1M

Class 1M lasers or lasers emitting beams in excess of the Class 1 AEL for aided viewing but do not exceed the Class 3B AEL, are exempt from any control measures other than to prevent potentially hazardous optically aided viewing. If optically aided viewing is to be conducted, control measures shall be followed to prevent exposure of laboratory personnel to levels in excess of the MPE for direct irradiation of the eye.

Class 2

The laser beam should not be purposefully directed toward the eye of any person. Alignment of the laser optical systems (mirrors, lenses, beam deflectors, etc.) should be performed in such a manner that the primary beam, or specular reflection of the primary beam, does not expose laboratory personnel to levels above the MPE for direct irradiation of the eye.

Work areas should be posted with a warning label or sign cautioning users to avoid staring into the beam or directing the beam toward the eye of individuals.

If the MPE is exceeded, design viewing portals and/or display screens to reduce exposure to acceptable levels.

If the Class 2 laser has an internal Class 3B or Class 4 laser, interlocks should be provided on any removable parts of the housing, or the laser should have a service access panel that is either interlocked or requires a specialized tool for removal. If the protective housing is removed, control measures appropriate for the enclosed laser class should be followed.

Class 2M

A Class 2M normally affords eye protection by the aversion response for unaided viewing; however, Class 2M is potentially hazardous if viewed with certain optical aids. If optically aided viewing is to be conducted, control measures shall be followed to prevent exposure of laboratory personnel to levels in excess of the MPE for direct irradiation of the eye.

Class 3R (3a)

The work area should be posted with a warning label or sign cautioning users to avoid staring into the beam or directing the beam toward the eye of individuals.

Removable parts of the housing and service access panels should have interlocks to prevent accidental exposure. A permanent beam stop or attenuator may also be used.

If the MPE is exceeded, design viewing portals and/or display screens to reduce exposure to acceptable levels. Alignment procedures should be designed to ensure the MPE is not exceeded.

Class 3B

These lasers are used in areas where entry by unauthorized individuals can be controlled. If an individual who has not been trained in laser safety must enter the area, the laser operator or supervisor should first instruct the individual as to safety requirements and must provide protective eyewear, if required.

If the entire beam is not enclosed or if a limited open beam exists, the laser operator, supervisor or laser safety officer should determine a Nominal Hazard Zone (NHZ). An alarm, warning light or verbal countdown should be used during use or start up of the laser.

The controlled area should

- have limited access to spectators,
- have beam stops to terminate potentially dangerous laser beams,
- be designed to reduce diffuse and specular reflections,
- have eye protection for all personnel,
- not have a laser beam at eye level,
- have restrictions on windows and doorways to reduce exposure to levels below the MPE, and
- require storage or disabling of the laser when it is not being used.

If the MPE is exceeded, design viewing portals and/or display screens to reduce exposure to acceptable levels. Alignment procedures and collecting optics should be designed to ensure the MPE is not exceeded.
Only authorized, trained individuals should service the laser. Approved, written standard operating, maintenance and service procedures should be developed and followed.

Class 4

In addition to the control measures described for Class 3B, Class 4 lasers should be operated by trained individuals in areas dedicated to their use. Failsafe interlocks should be used to prevent unexpected entry into the controlled area, and access should be limited by the laser operator to persons who have been instructed as to the safety procedures and who are wearing proper laser protection eyewear when the laser is capable of emission.

Laser operators are responsible for providing information and safety protection to untrained personnel who may enter the laser controlled areas as visitors.

The laser area should be

- restricted to authorized personnel only
- designed to allow for rapid emergency egress
- equipped with a device that allows for deactivation of the laser or reduction of the output to below the MPE
- designed to fulfill Class 3B controlled area requirements
- designed with entry safe controls
- designed such that the laser may be monitored and fired from a remote location
- (for pulsed systems) have interlocks designed to prevent firing of the laser by dumping the stored energy into a dummy load
- (for continuous wave systems) have interlocks designed to turn off the power supply or interrupt the beam by means of shutters.

The beam path must be free of specular reflective surfaces and combustible objects and the beam terminated in a non-combustible, non-reflective barrier or beam stop.

Warning Signs and Labels

All Class 2, 3 and 4 laser equipment must be labeled indicating hazard classification, output power/energy, lasing material or wavelength with words and symbols as indicated below:

- **Class 2 laser systems**:

  CAUTION, Laser Radiation – Do Not Stare Into Beam or View Directly With Optical Instruments (radiation may be replaced with "light" for systems operating at wavelengths greater than 400 nm and equal to or less than 700 nm)

- **Class 2M laser systems (Class 2 systems that exceed Class 2 AEL)**:

  DANGER, Laser Radiation – Do Not Stare into Beam or View Directly With Optical Instruments

- **Class 3R laser equipment:** DANGER, Laser Radiation (or laser symbol) - Avoid Direct Eye Exposure

- **Class 3B laser equipment:** DANGER, Laser Radiation (or laser symbol) - Avoid Direct Exposure to Beam

- **Class 4 laser equipment:** DANGER, Laser Radiation (or laser symbol) - Avoid Eye or Skin Exposure to Direct or Scattered Radiation

Labels and warning signs should be displayed conspicuously in areas where they would best serve to warn individuals of potential safety hazards. Normally, signs are posted at entryways to laser controlled areas and labels are affixed to the laser in a conspicuous location.

Additionally, the optical density of protective eyewear and wavelength shall be shown on the sign for a location requiring the use of eyewear. For lasers operating outside the visible range the word "Invisible" shall be placed prior to the words "Laser Radiation."

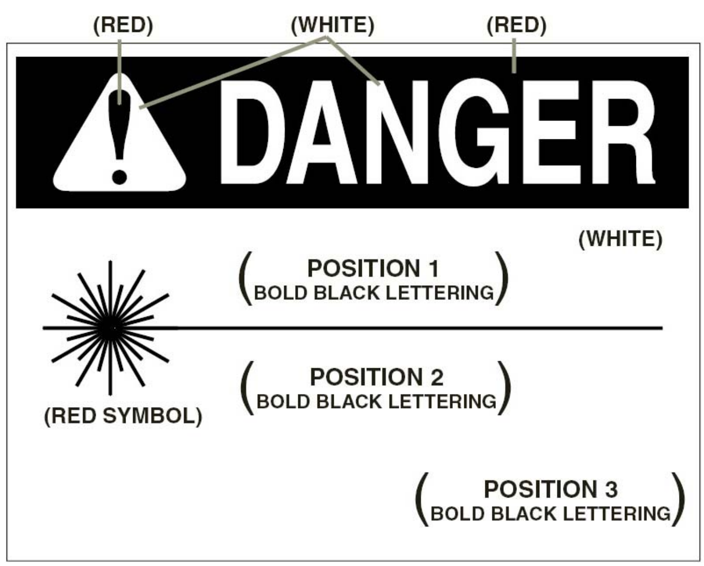


Table 5 Control Measures for the Four Laser Classes

Engineering Control Measures	**Classification**						
	1	1M	2	2M	3R	3B	4
Protective Housing (4.3.1)	X	X	X	X	X	X	X
Without Protective Housing (4.3.1.1)	LSO shall establish Alternative Controls						
Interlocks on Removable Protective Housings (4.3.2)	▽	▽	▽	▽	▽	X	X
Service Access Panel (4.3.3)	▽	▽	▽	▽	▽	X	X
Key Control (4.3.4)	—	—	—	—	—	•	X
Viewing Windows, Display Screens and Collecting Optics(4.3.5.1)	Assure viewing limited < MPE						
Collecting Optics (4.3.5.2)							
Fully Open Beam Path (4.3.6.1)	—	—	—	—	—	X NHZ	X NHZ
Limited Open Beam Path (4.3.6.2)	—	—	—	—	—	X NHZ	X NHZ
Enclosed Beam Path (4.3.6.3)	None is required if 4.3.1 and 4.3.2 fulfilled						
Remote Interlock Connector (4.3.7)	—	—	—	—	—	•	X
Beam Stop or Attenuator (4.3.8)	—	—	—	—	—	•	X
Activation Warning Systems (4.3.9.4)	—	—	—	—	—	•	X
Indoor Laser Controlled Area (4.3.10)	—	*	—	*	—	X NHZ	X NHZ
Class 3B Indoor Laser Controlled Area (4.3.10.1)	—	—	—	—	—	X	—
Class 4 Laser Controlled Area (4.3.10.2)	—	—	—	—	—	—	X
Outdoor Control Measures (4.3.11)	X	* NHZ	X NHZ	* NHZ	X NHZ	X NHZ	X NHZ
Laser in Navigable Airspace (4.3.11.2)	X	* NHZ	X NHZ	* NHZ	X NHZ	X NHZ	X NHZ
Temporary Laser Controlled Area (4.3.12)	▽ MPE	▽ MPE	▽ MPE	▽ MPE	▽ MPE	—	—
Controlled Operation (4.3.13)	—	—	—	—	—	—	•
Equipment Labels (4.3.14 and 4.7)	X	X	X	X	X	X	X
Laser Area Warning Signs and Activation Warnings (4.3.9)	—	—	—	—	•	X NHZ	X NHZ

LEGEND:
- X — Shall
- • — Should
- — — No requirement
- ▽ — Shall if enclosed Class 3B or Class 4
- MPE — Shall if MPE is exceeded
- NHZ — Nominal Hazard Zone analysis required
- * — May apply with use of optical aids

Table 10 Control Measures for the Four Laser Classes – Cont.

Administrative and Procedural Control Measures	Classification						
	1	1M	2	2M	3R	3B	4
Standard Operating Procedures (4.4.1)	—	—	—	—	—	•	X
Output Emission Limitations (4.4.2)	—	—	—	—	LSO Determination		
Education and Training (4.4.3)	—	•	•	•	•	X	X
Authorized Personnel (4.4.4)	—	*	—	*	—	X	X
Alignment Procedures (4.4.5)	∇	∇	∇	∇	∇	X	X
Protective Equipment (4.6)	—	*	—	*	—	•	X
Spectators (4.4.6)	—	*	—	*	—	•	X
Service Personnel (4.4.7)	∇	∇	∇	∇	∇	X	X
Demonstration with General Public (4.5.1)	—	*	X	*	X	X	X
Laser Optical Fiber Transmission Systems (4.5.2)	MPE	MPE	MPE	MPE	MPE	X	X
Laser Robotic Installations (4.5.3)	—	—	—	—	—	X NHZ	X NHZ
Protective Eyewear (4.6.2)	—	—	—	—	—	•	X
Window Protection (4.6.3)	—	—	—	—	—	X	X NHZ
Protective Barriers and Curtains (4.6.4)	—	—	—	—	—	•	•
Skin Protection (4.6.6)	—	—	—	—	—	X	X NHZ
Other Protective Equipment (4.6.7)	Use may be required						
Warning Signs and Labels (4.7) (Design Requirements)	—	—	•	•	•	X NHZ	X NHZ
Service Personnel (4.4.7)	LSO Determination						
Laser System Modifications (4.1.2)	LSO Determination						

LEGEND:
- X Shall
- • Should
- — No requirement
- ∇ Shall if enclosed Class 3B or Class 4
- MPE Shall if MPE is exceeded
- NHZ Nominal Hazard Zone analysis required
- * May apply with use of optical aids

Protective Equipment

Enclosure of the laser equipment or beam path is the preferred method of control, since the enclosure will isolate or minimize the hazard. When engineering controls do not provide adequate means to prevent access to direct or reflected beams at levels above the MPE, it may be necessary to use personal protective equipment. Note that use of personal protective equipment may have serious limitations when used as the only control measure with higher power Class 4 lasers or laser systems. The protective equipment may not adequately reduce or eliminate the hazard and may be damaged by the incident laser radiation.

Protective Eyewear

Protective eyewear is necessary for Class 3 and 4 laser use where irradiation of the eye is possible. Such eye protection should be used only at the wavelength and energy/power for which it is intended. Eye protection may include goggles, face shields, spectacles or prescription eyewear using special filter materials or reflective coatings (or a combination of both) to reduce exposure below the MPE. Eye protection may also be necessary to protect against physical or chemical hazards.

The following factors should be considered in selecting the appropriate laser protective eyewear:

- wavelength(s) of the laser output
- potential for multi-wavelength operation
- radiant exposure or irradiance levels for which protection (worst case) is required
- exposure time criteria
- MPE
- optical density (OD) requirement of the eyewear filter at laser output wavelength
- angular dependence of protection afforded
- visible light transmission requirement and assessment of the effect of the eyewear on the ability to perform tasks while wearing the eyewear
- need for side shield protection and peripheral vision
- radiant exposure or irradiance and the corresponding time factors at which laser safety eyewear damage (penetration) occurs, including transient bleaching
- need for prescription glasses
- comfort and fit
- degradation of absorbing media, such as photo bleaching
- strength of materials (resistance to mechanical shock or trauma)
- capability of the front surface to produce a hazardous specular reflection
- requirement for anti-fogging design or coatings

Laser Eye Protection Selection Process

1. **Determine the wavelength of the laser**. Eye protection is wavelength-specific. Eyewear that provides protection for CO_2 lasers will not necessarily protect against Nd:YAG lasers.
2. **Determine the maximum anticipated viewing duration.** Viewing duration usually fall into one of three categories:

   a) Unintentional, accidental exposure to **visible lasers** (400-700 nm), use **0.25 seconds**

   b) Unintentional, accidental viewing of **near infrared** (700-1000 nm) beams, use **10 seconds**

c) For all other lasers, use 600 seconds or laser on time, up to 8 hours.

3. **Determine the maximum irradiance or radiant exposure to which the eye may be exposed.** Consider the following:

   a) If the emergent beam is not focused down to a smaller spot and is greater than 7 mm in diameter, the emergent beam radiant exposure/irradiance may be considered the maximum intensity that could enter the eye.

   b) If the beam is focused after emerging from the laser or if the beam diameter is less than 7 mm, assume that all of the laser energy/power could enter the eye. In this case, use the columns titled *Maximum Output Power/Energy* in *Table 6.*

4. **Determine the optical density needed.**

5. **Select the type of eye protection needed.** Laser eye protection is available in the form of glasses and goggles. The lens may be made out of glass or crystalline filter material or plastic. Generally, glass or crystalline lenses are recommended for harsh environments, such as areas where solvents and corrosives are used.

6. **Test the eye protection.** Always check the integrity of the lens before use. At very high beam intensities, filter materials become bleached out or otherwise damaged. A continuous wave power exceeding 10 W can fracture glass and burn through plastics.

Table 6. Selecting Laser Eye Protection for Intrabeam Viewing for 400 - 1400 nm Wavelengths

Q-Switched (1 ns - 0.1 ms)		**Non-Q-Switched (0.4 ms - 10 ms)**		**CW Momentary View (0.25 s to 10 s)**		**CW Staring (more than 3 hours)**		**Attenuation**	
Max Output Energy (J)	Max. Beam Radiant Exposure (j/cm^2)	Max Laser Output Energy (J)	Max. Beam Radiant Exposure (J/cm^2)	Max Power Output (W)	Max Beam Irradiance (W/cm^2)	Max. Power Output (W)	Max. Beam Irradiance (W/cm^2)	Attenuation Factor	OD
10	20	100	200					10^8	8
1	2	10	20					10^7	7
10^{-1}	2×10^{-1}	1	2			1	2	10^6	6
10^{-2}	2×10^{-2}	10^{-1}	2×10^{-1}			10^{-1}	2×10^{-1}	10^5	5
10^{-3}	2×10^{-3}	10^{-2}	2×10^{-2}	10	20	10^{-2}	2×10^{-2}	10^4	4
10^{-4}	2×10^{-4}	10^{-3}	2×10^{-3}	1	2	10^{-3}	2×10^{-3}	10^3	3
10^{-5}	2×10^{-5}	10^{-4}	2×10^{-4}	10^{-1}	2×10^{-1}	10^{-4}	2×10^{-4}	10^2	2
10^{-6}	2×10^{-6}	10^{-5}	2×10^{-5}	10^{-2}	2×10^{-2}	10^{-5}	2×10^{-5}	10^1	1

Other Protective Equipment

It is important that protective equipment such as beam stops, shields, safety interlocks, and warning lights and horns be maintained in proper operating condition and be utilized whenever indicated to prevent harmful exposure to laser radiation.

Special Controls for Ultraviolet and Infrared Lasers

Since infrared (IR) and ultraviolet (UV) wavelengths are normally invisible, particular care must be taken when using these types of lasers. In addition to the recommended control measures that apply for each laser classification, the following should also be employed:

Infrared

1. The collimated beam from a Class 3 laser should be terminated by a highly absorbent backstop wherever practicable. Many surfaces which appear dull visually can act as reflectors of IR.
2. The beam from a Class 4 laser should be terminated in a fire resistant material wherever practicable. Periodic inspection of the absorbent material is required since many materials degrade with use.
3. Areas that are exposed to reflections from Class 3 or 4 lasers, at levels above the MPE, should be protected by appropriately screening the beam or target area with IR absorbent material. This material should be fire-resistant for use with Class 4 lasers.

Ultraviolet

1. Exposure to UV should be minimized by using shield material which attenuates the radiation to levels below the appropriate MPE for the specific wavelength.
2. Special attention should be given to the possibility of producing undesirable reactions in the presence of UV, for example, ozone formation.

Section 5: LASER SAFETY AT PRINCETON UNIVERSITY

Introduction

Most lasers used at Princeton University are capable of causing eye injury to anyone who looks directly into the beam or its reflections from a specular (mirror-like) surface. In addition, diffuse reflections of a high-power laser beam can produce permanent eye damage. High-power laser beams can burn exposed skin, ignite flammable materials, and heat materials that release hazardous fumes, gases, debris, or radiation. Equipment and optical apparatus required to produce and control laser energy may also introduce additional hazards associated with high voltage, high pressure, extremely low temperature materials (cryogenics), noise, collateral radiation, flammable materials, and toxic fluids. Thus, each proposed experiment or operation involving a laser must be evaluated to determine the hazards involved and the appropriate safety measures and controls required.

Laser Safety at Princeton University

The Laser Safety Program is administered by EHS, with the assistance of the Laser Safety Advisory Group. The Laser Advisory Group consists of faculty, staff and graduate students representing the major laser using departments on campus. The Assistant Radiation Safety Officer serves as the Laser Safety Officer for Princeton University and leads the Laser Advisory Group. EHS and the Laser Advisory Group recommend that individuals using lasers set up and operate laser facilities to meet the laser safety guidelines established by the American National Standards Institute (ANSI) standard ANSI Z136.1-2007, *American National Standard for the Safe Use of Lasers*.

The Laser Safety Program applies to individuals who operate or work in proximity to Class 2, Class 3 or Class 4 lasers.

Hazard Classification

Commercial lasers are classified and certified by the manufacturer. When a commercial laser is modified or when a new laser is constructed in the laboratory, it is the responsibility of the principal investigator to classify and label the laser per the ANSI Standard. EHS can assist in determining the appropriate classification. For a summary of typical laser classifications see Table C1, “Typical Laser Classification – Continuous Wave (CW) Point Source Lasers” and Table C2, “Typical Laser Classification – Single-Pulse Point Source Lasers.”

Medical Surveillance

Some individuals who operate or work in close proximity to particular Class 3B or Class 4 lasers or laser systems may receive a pre-assignment and a post-assignment eye examination performed by a consulting ophthalmologist. Results of the examinations are maintained by the Office of Occupational Medicine at McCosh Health Center. Contact the Laser Safety Officer for more information.

Training

Individuals who work with or in close proximity to Class 3 or Class 4 lasers must attend laser safety training provided by EHS. This training includes:

- fundamentals of laser operation

- biological effects of laser radiation on the eye and skin
- non-radiation hazards (e.g., fire hazards, chemical exposure)
- classification of lasers and laser systems
- control measures and personal protective equipment

Individuals who work with or in close proximity to Class 3B or Class 4 lasers receive additional training from EHS, including:

- relations of specular and diffuse reflections
- radiometric units and measurement devices
- maximum personal exposure levels or eye and skin under all conditions
- laser hazard evaluations and range equations

Roles and Responsibilities

Department

- Identify laser products that are covered by the ANSI Standard and establish procedures to ensure that the recommendations of the Standard are followed.
- Ensure individual who work with or around lasers have received the proper laser safety training.
- Establish a safety review procedure to determine that adequate hazard analyses and corrective actions have been completed for all applicable laser systems.

Supervisors

- Be knowledgeable of the education and training requirements for laser safety, the potential laser hazards and associated control measures for all lasers under their control.
- Report known or suspected accidents to EHS.
- Ensure that lasers under their control are not operated or modified without approval of the supervisor or principal investigator.
- Ensure that all administrative and engineering controls are followed.
- Maintain inventory control and a permanent record of the status of all Class 3B, and Class 4 lasers
- Ensure that individuals working with lasers have attended the general laser safety training and provide laser operators with training in the administrative, alignment and standard operating procedures.
- Classify and label any unclassified lasers
- Attend University's laser safety training programs.
- Ensure that laser workers are registered for the medical surveillance program.
- Notify EHS immediately in the event of an exposure to a Class 3 or Class 4 laser.
- Provide standard operating procedures (SOP), in accordance with ANSI Z136.1-2007 and any established University policy, for all laser operations involving Class 3 and Class 4 lasers detailing alignment, operation and maintenance procedures.

Purchasing Office

- Notify EHS when orders for Class 3 and Class 4 lasers are placed

EHS

- Review and approve the purchase of Class 3 and Class 4 lasers
- Provide assistance in evaluating and controlling hazards.
- Maintain records of lasers and laser operators.
- Conduct laser safety training.
- Participate in accident investigations involving lasers.
- Periodically audit the departmental Laser Safety Program.

Individual

- Attend laser safety training
- Be familiar with specific safety hazards of lasers which is being operated or working near.
- Follow standard operating procedures and comply with requirements established by the Laser Safety Committee, Laser Safety Officer and the supervisor.
- Use Class 3B or Class 4 lasers only if specifically authorized by the laser supervisor.
- Report known or suspected accidents to the supervisor and EHS.
- Inform spectators about and protect spectators from all potential laser hazards
- Register for the medical surveillance program

References

Contact the EHS at 258-5294 for more information. Pointers to several sources of laser safety information available via electronic media may be found at the EHS web page http://www.princeton.edu/ehs.

The following resources and training aids are available through EHS:

- ANSI Standard Z136.1-2007, *American National Standard for the Safe Use of Lasers*, 2007
- CFR Chapter I, Subpart J, Part 1040 - *Performance Standard for Light Emitting Products* (the Food and Drug Administration requirement document for light emitting products.
- Videocassette: *High Powered Lasers in the Lab*, Interactive Medica Communications, 1994
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- Mallow, Alex and Leon Chabot, *Laser Safety Handbook*, Van Nostrand Reinhold, 1978

Section 6: GLOSSARY

absorption

Radiation imparts some or all of its energy to any material through which it passes

accessible emission limit (AEL)

Maximum accessible emission level which is permissible in the appropriate laser class

accessible radiation

Laser radiation that can expose human eye or skin in normal usage

aperture

The opening through which laser radiation can pass

attenuation

The decrease in radiant flux as it passes through an absorbing or scattering medium

aversion response

Action, such as closing of the eye or movement of the head, to avoid exposure to laser light.

beam

A collection of rays which may be parallel, divergent, or convergent.

beam diameter

The distance between diametrically opposed points in that cross section of a beam where the power per unit area is 1/e times that of the peak power per unit area

beam divergence

The full angle of the beam spread between diametrically opposed 1/e irradiance points; usually measured in milliradians (1 milliradian = 3.4 minutes of arc)

continuous wave

The output of a laser, operated in a continuous rather than pulsed mode.

controlled area

An area where the occupancy and activity of those within is subject to control and supervision for the purpose of protection from laser radiation and related hazards.

cornea

The transparent outer coat of the human eye which covers the iris and the crystalline lens. The cornea is the main refracting element of the eye.

Diffuse reflection

Change of the spatial distribution of a beam of radiation when it is reflected in many directions by a surface or by a medium.

Embedded laser

A laser enclosed in a laser system, having an assigned class number higher than the inherent capability of the laser system. The laser system's lower classification is appropriate because of the engineering features that limit accessible emission.

Enclosed laser

A laser contained in a protective housing. Opening or removing the protective housing provides additional access to laser radiation above the applicable MPE. (An embedded laser is a type of enclosed laser.)

Energy (Q)

The capacity for doing work. Energy content is commonly used to characterize the output from pulsed lasers and is generally expressed in Joules (J).

Erythema

The medical term for redness of the skin due to congestion of the capillaries.

Failsafe interlock

An interlock where the failure of a single mechanical or electrical component of the interlock will cause the system to go into, or remain in, a safe mode.

Infrared radiation

Electromagnetic radiation with wavelengths that lie within the range 0.7μ to 1 mm.

Intrabeam viewing

The viewing condition whereby the eye is exposed to all or part of a laser beam

Iris

The circular pigmented membrane that lies behind the cornea of the human eye.

Irradiance (E)

Power per unit area, expressed in watts per square centimeter.

Joule (J)

A unit of energy (1 joule = 1 watt-second).

Laser

A device that produces an intense, coherent, directional beam of light by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for Light Amplification by Stimulated Emission of Radiation.

Laser Safety Officer

Individual with the authority to monitor and enforce the control of laser hazards and effect the knowledgeable evaluation and control of laser hazards.

Laser system

An assembly of electrical, mechanical and optical components that includes one or more lasers.

Macula

The small, uniquely pigmented and specialized area of the retina.

Maximum Permissible Exposure (MPE)

The level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin. MPE is expressed in terms of either radiant exposure (joules/cm^2) or irradiance (watts/cm^2).

Nominal Hazard Zone (NHZ)

Describes the space within which the level of the direct, reflected, or scattered radiation during normal operation exceeds the MPE. Exposure levels beyond the boundary of the NHZ are below the appropriate MPE level.

Ocular fundus

The back of the eye. May be seen through the pupil by use of an ophalmoscope.

Optical density (D_λ)

Logarithm to the base ten of the reciprocal of the transmittance: $D_\lambda = -\log_T$, where T is transmittance.

Power

The rate at which energy is emitted, transferred, or received, usually expressed in watts (joules per second). Also called radiant power.

PRR

Abbreviation for pulse repetition rate. (See repetitively pulsed laser.)

protective housing

An enclosure that surrounds a laser or laser system, preventing access to laser radiation above the applicable MPE level.

pulse duration

Duration of a laser pulse, usually measured as the time interval between the half-power points on the leading and trailing edges of the pulse.

Pulsed laser

A laser that delivers its energy in the form of a single pulse or a train of pulses which are less than or equal to 0.25 s.

Q-switch

Device that produces very short (~10-250 ns) intense laser pulses by enhancing the storage and dumping of electronic energy in and out of the lasing medium.

Q-switched laser

Laser that emits short (~10-250 ns), high power pulses by means of a Q-switch.

Radiant energy or flux (D)

Laser energy emitted, expressed in joules.

Radiant exposure (H)

Surface density of the radiant energy received, expressed in joules per cm^2.

Radiant power

Laser power emitted, expressed in watts

reflection

Deviation of radiation following incidence on a surface.

Repetitively pulsed laser

A laser with multiple pulses of radiant energy occurring in sequence with a PRR of 1 Hz.

Retina

The sensory membrane that receives the incident image formed by the cornea and lens of the human eye. The retina lines the inside of the eye.

Specular reflection

A mirror-like reflection.

Transmittance (T)

The ratio of total transmitted radiant power to total incident radiant power.

Ultraviolet Radiation

Electromagnetic radiation with wavelengths smaller than visible radiation.

viewing portal

An opening in an experimental system, allowing the user to observe the experimental chamber. All viewing portals and display screens included as an integral part of a laser system must incorporate a suitable means to maintain the laser radiation at the viewing position at or below the applicable MPE (eye safe) for all conditions of operation and maintenance. It is essential that the material used for viewing portals and display screens not support combustion or release toxic vapors following exposure to laser radiation.

Visible Radiation (light)

Electromagnetic radiation that can be detected by the human eye. This term is commonly used to describe wavelengths that lie in the range of 0.4 to 0.7 μm.

watt (W)

Unit of power or radiant flux (1 watt = 1 joule per second).

wavelength (γ)

The distance between two successive points on a periodic wave that have the same phase.

Appendix A: Selected ANSI Standard Tables

ANSI Table C1:	Typical Laser Classification - Continuous Wave Lasers
ANSI Table C2:	Typical Laser Classification - Single Pulse Lasers
ANSI Table 5:	Maximum Permissible Exposure for Ocular Exposure to a Laser Beam
ANSI Table 6:	Parameters and Correction Factors
ANSI Table 7:	Maximum Permissible Exposure for Skin Exposure to a Laser Beam

Table C1. Typical Laser Classification – Continuous Wave (CW) Point Source Lasers

Wavelength (µm)	Laser Type	Wavelength (µm)	Class 1 * (W)	Class 2 (W)	Class 3 ** (W)	Class 4 (W)
Ultraviolet						
0.180 to 0.280	Neodymium: YAG	0.266	$\leq 9.6 \times 10^{-9}$	None	> Class 1 but ≤ 0.5	> 0.5
	(Quadrupled)		for 8 hours			
	Argon	0.275				
Ultraviolet						
0.315 to 0.400	Helium-Cadmium	0.325				
	Argon	0.351, 0.363,	$\leq 3.2 \times 10^{-6}$	None	> Class 1 but ≤ 0.5	> 0.5
	Krypton	0.3507, 0.3564				
Visible						
0.400 to 0.700	Helium-Cadmium	0.4416 only	$\leq 4 \times 10^{-5}$			
	Argon (Visible)	0.457	$\leq 5 \times 10^{-5}$			
		0.476	$\leq 1 \times 10^{-4}$			
		0.488	$\leq 2 \times 10^{-4}$			
		0.514				
	Krypton	0.530				
	Neodymium: YAG		$\leq 4 \times 10^{-4}$			
	(Doubled)	0.532				
	Helium-Neon	0.543		> Class 1 but $\leq 1 \times 10^{-3}$	> Class 2 but ≤ 0.5	> 0.5
	Dye	0.400 - 0.500	$\leq 0.4\, C_B \times 10^{-4}$			
	Helium-Selenium	0.460 - 0.500				
	Dye	0.550 - 0.700				
	Helium-Neon	0.632				
	InGaAlP	0.670	$\leq 4 \times 10^{-4}$			
	Ti:Sapphire	0.350 – 0.500				
	Krypton	0.6471, 0.6764				
Near Infrared						
0.700 to 1.400	GaAlAs	0.780	$\leq 5.6 \times 10^{-4}$			
	GaAlAs	0.850	$\leq 7.7 \times 10^{-4}$			
	GaAs	0.905	$\leq 9.9 \times 10^{-4}$			
	Neodymium: YAG	1.064	$\leq 1.9 \times 10^{-3}$			
	Helium-Neon	1.080	$\leq 1.9 \times 10^{-3}$			
		1.152	$\leq 2.1 \times 10^{-3}$			
	InGaAsP	1.310	$\leq 1.5 \times 10^{-2}$			
Far Infrared						
1.400 to 10^3	InGaAsP	1.550		None	> Class 1 but ≤ 0.5	> 0.5
	Holmium	2.100				
	Erbium	2.940				
	Hydrogen Fluoride	2.600 - 3.00	$\leq 9.6 \times 10^{-3}$			
	Helium-Neon	3.390 only				
	Carbon Monoxide	5.000 - 5.500				
	Carbon Dioxide	10.6				
	Water Vapor	118	$\leq 9.5 \times 10^{-2}$			
	Hydrogen Cyanide	337				

* Assumes no mechanical or electrical design incorporated into laser system to prevent exposures from lasting up to T_{max} = 8 hours (one workday); otherwise the Class 1 AEL could be larger than tabulated.

** See 3.3.3.1 for definition of Class 3R.

Table C2. Typical Laser Classification – Single-Pulse Point Source Lasers

Wavelength (μm)	Laser Type	Wavelength (μm)	Pulse Duration (s)	Class 1 (J)	Class 3B (J)	Class 4 (J)
Ultraviolet						
0.180 to 0.400	Excimer (ArF)	0.193	20×10^{-9}	$\leq 2.4 \times 10^{-5}$		
	Excimer (KrF)	0.248	20×10^{-9}	$\leq 2.4 \times 10^{-5}$		
	Neodymium: YAG Q-switched (Quadrupled)	0.266	20×10^{-9}	$\leq 2.4 \times 10^{-5}$	> Class 1 but ≤ 0.125	> 0.125
	Excimer (XeCl)	0.308	20×10^{-9}	$\leq 5.3 \times 10^{-5}$		
	Nitrogen	0.337	20×10^{-9}	$\leq 5.3 \times 10^{-5}$		
	Excimer (XeF)	0.351	20×10^{-9}	$\leq 5.3 \times 10^{-5}$		
Visible						
0.400 to 0.700	Rhodamine 6G (Dye Laser)	0.450-0.650	1×10^{-6}			
	Copper Vapor	0.510, 0.578	2.5×10^{-9}			
	Neodymium: YAG (Doubled) (Q-switched)	0.532	20×10^{-9}	$\leq 1.9 \times 10^{-7}$	> Class 1 but ≤ 0.03	> 0.03
	Ruby (Q-switched)	0.6943	20×10^{-9}			
	Ruby (Long Pulse)	0.6943	1×10^{-3}	$\leq 3.9 \times 10^{-6}$		
Near Infrared						
0.700 to 1.4	Ti: Sapphire	0.700-1.000	6×10^{-6}	$\leq 1.9 \times 10^{-7}$		
	Alexandrite	0.720-0.800	1×10^{-4}	$\leq 7.6 \times 10^{-7}$	> Class 1 but ≤ 0.033**	> 0.033**
	Neodymium: YAG (Q-switched)	1.064	20×10^{-9}	$\leq 1.9 \times 10^{-6}$	>Class 1 but ≤ 0.125	> 0.125
Far Infrared	Erbium: Glass	1.540	10×10^{-9}	$\leq 7.9 \times 10^{-3}$		
1.400 to 10^3	Co: Magnesium-Fluoride	1.8-2.5	80×10^{-6}	$\leq 7.9 \times 10^{-4}$		
	Holmium	2.100	250×10^{-6}	$\leq 7.9 \times 10^{-4}$	> Class 1 but ≤ 0.125	> 0.125
	Hydrogen Fluoride	2.600-3.000	0.4×10^{-6}	$\leq 1.1 \times 10^{-4}$		
	Erbium	2.940	250×10^{-6}	$\leq 5.6 \times 10^{-4}$		
	Carbon Dioxide	10.6	100×10^{-9}	$\leq 7.9 \times 10^{-5}$		
	Carbon Dioxide	10.6	1×10^{-3}	$\leq 7.9 \times 10^{-4}$		

* Assuming that both eye and skin may be exposed, i.e., 1.0 mm beam (area of limiting aperture = 7.9×10^{-3} cm^2).

** Class 3B AEL varies from 0.033 to 0.480 J corresponding to wavelengths that vary from 0.720 to 0.800 μm.

Table 5a. Maximum Permissible Exposure (MPE) for Point Source Ocular Exposure to a Laser Beam †

Wavelength (μm)	Exposure Duration, t (s)	MPE ($J \cdot cm^{-2}$)	MPE ($W \cdot cm^{-2}$)	Notes
Ultraviolet				In the Dual Limit Wavelength Region (0.180 to 0.400 μm), the lower MPE considering photochemical and thermal effects must be chosen.
Dual Limits for λ between 0.180 and 0.400 μm				
Thermal				
0.180 to 0.400	10^{-9} to 10	$0.56\ t^{0.25}$		
Photochemical				
0.180 to 0.302	10^{-9} to 3×10^{4}	3×10^{-3}		See Tables 8a and 8b for limiting aperture and Table 9 for measurement aperture.
0.302 to 0.315	10^{-9} to 3×10^{4}	$10^{200(\lambda-0.295)} \times 10^{-4}$		
0.315 to 0.400	10 to 3×10^{4}	1.0		
Visible				
0.400 to 0.700	10^{-13} to 10^{-11}	1.5×10^{-8}		In the Wavelength Region (0.400 to 0.500 μm), T_1 determines whether the photochemical or thermal MPE is lower.
0.400 to 0.700	10^{-11} to 10^{-9}	$2.7\ t^{0.75}$		
0.400 to 0.700	10^{-9} to 18×10^{-6}	5.0×10^{-7}		
0.400 to 0.700	18×10^{-6} to 10	$1.8\ t^{0.75} \times 10^{-3}$		
0.500 to 0.700	10 to 3×10^{4}		1×10^{-3}	
Thermal				
0.450 to 0.500	10 to T_1		1×10^{-3}	For extended sources in the retinal hazard region (0.400 to 1.4 μm), see Table 5b.
Photochemical				
0.400 to 0.450	10 to 100	1×10^{-2}		See Table 6 and Figures 8 and 9 for correction factors C_A, C_B, C_C, C_P, C_E, and times T_1 and T_2.
0.450 to 0.500	T_1 to 100	$C_B \times 10^{-2}$		
0.400 to 0.500	100 to 3×10^{4}		$C_B \times 10^{-4}$	
Near Infrared				
0.700 to 1.050	10^{-13} to 10^{-11}	$1.5\ C_A \times 10^{-8}$		For repeated (pulsed) exposures, see Section 8.2.3. A correction factor, C_P applies to thermal limits, but not to photochemical limits.
0.700 to 1.050	10^{-11} to 10^{-9}	$2.7\ C_A\ t^{0.75}$		
0.700 to 1.050	10^{-9} to 18×10^{-6}	$5.0\ C_A \times 10^{-7}$		
0.700 to 1.050	18×10^{-6} to 10	$1.8\ C_A\ t^{0.75} \times 10^{-3}$		
0.700 to 1.050	10 to 3×10^{4}		$C_A \times 10^{-3}$	
1.050 to 1.400	10^{-13} to 10^{-11}	$1.5\ C_C \times 10^{-7}$		The wavelength region λ_1 to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$, e.g., 0.180 to 0.302 μm means $0.180 \leq \lambda < 0.302$ μm.
1.050 to 1.400	10^{-11} to 10^{-9}	$27.0\ C_C\ t^{0.75}$		
1.050 to 1.400	10^{-9} to 50×10^{-6}	$5.0\ C_C \times 10^{-6}$		
1.050 to 1.400	50×10^{-6} to 10	$9.0\ C_C\ t^{0.75} \times 10^{-3}$		
1.050 to 1.400	10 to 3×10^{4}		$5.0\ C_C \times 10^{-3}$	
Far Infrared				
1.400 to 1.500	10^{-9} to 10^{-3}	0.1		Note: The MPEs must be in the same units.
1.400 to 1.500	10^{-3} to 10	$0.56\ t^{0.25}$		
1.400 to 1.500	10 to 3×10^{4}		0.1	
1.500 to 1.800	10^{-9} to 10	1.0		
1.500 to 1.800	10 to 3×10^{4}		0.1	
1.800 to 2.600	10^{-9} to 10^{-3}	0.1		
1.800 to 2.600	10^{-3} to 10	$0.56\ t^{0.25}$		
1.800 to 2.600	10 to 3×10^{4}		0.1	
2.600 to 1000	10^{-9} to 10^{-7}	1×10^{-2}		
2.600 to 1000	10^{-7} to 10	$0.56\ t^{0.25}$		
2.600 to 1000	10 to 3×10^{4}		0.1	

Table 5b. Maximum Permissible Exposure (MPE) for Extended Source Ocular Exposure†

Wavelength (μm)	Exposure Duration, t (s)	MPE ($J \cdot cm^{-2}$) except as noted	MPE ($W \cdot cm^{-2}$) except as noted	Notes
Visible				
0.400 to 0.700	10^{-13} to 10^{-11}	$1.5\ C_E \times 10^{-8}$		(See Tables 8a and 9 for limiting apertures)
0.400 to 0.700	10^{-11} to 10^{-9}	$2.7\ C_E\ t^{0.75}$		
0.400 to 0.700	10^{-9} to 18×10^{-6}	$5.0\ C_E \times 10^{-7}$		
0.400 to 0.700	18×10^{-6} to 0.7	$1.8\ C_E\ t^{0.75} \times 10^{-3}$		
	Dual Limits for λ between 0.400 and 0.600 μ*m visible laser exposure for* $t > 0.7$ *s*			
Photochemical				
For $\alpha \le 11$mrad, the MPE is expressed as irradiance and radiant exposure*				
0.400 to 0.600	0.7 to 100	$C_B \times 10^{-2}$		(See Tables 8a and 9 for limiting apertures)
0.400 to 0.600	100 to 3×10^4		$C_B \times 10^{-4}$	
For $\alpha > 11$mrad, the MPE is expressed as radiance and integrated radiance*				
0.400 to 0.600	0.7 to 1×10^4	$100\ C_B\ J \cdot cm^{-2} \cdot sr^{-1}$		(See Table 8a for limiting cone angle γ)
0.400 to 0.600	1×10^4 to 3×10^4		$C_B \times 10^{-2}\ W \cdot cm^{-2} \cdot sr^{-1}$	
	and			
Thermal				
0.400 to 0.700	0.7 to T_2	$1.8\ C_E\ t^{0.75} \times 10^{-3}$		
0.400 to 0.700	T_2 to 3×10^4		$1.8\ C_E\ T_2^{-0.25} \times 10^{-3}$	
Near Infrared				
0.700 to 1.050	10^{-13} to 10^{-11}	$1.5\ C_A\ C_E \times 10^{-8}$		(See Tables 8a and 9 for limiting apertures)
0.700 to 1.050	10^{-11} to 10^{-9}	$2.7\ C_A\ C_E\ t^{0.75}$		
0.700 to 1.050	10^{-9} to 18×10^{-6}	$5.0\ C_A\ C_E \times 10^{-7}$		
0.700 to 1.050	18×10^{-6} to T_2	$1.8\ C_A\ C_E\ t^{0.75} \times 10^{-3}$		
0.700 to 1.050	T_2 to 3×10^4		$1.8\ C_A\ C_E\ T_2^{-0.25} \times 10^{-3}$	
1.050 to 1.400	10^{-13} to 10^{-11}	$1.5\ C_C\ C_E \times 10^{-7}$		
1.050 to 1.400	10^{-11} to 10^{-9}	$27.0\ C_C\ C_E\ t^{0.75}$		
1.050 to 1.400	10^{-9} to 50×10^{-6}	$5.0\ C_C\ C_E \times 10^{-6}$		
1.050 to 1.400	50×10^{-6} to T_2	$9.0\ C_C\ C_E\ t^{0.75} \times 10^{-3}$		
1.050 to 1.400	T_2 to 3×10^4		$9.0\ C_C\ C_E\ T_2^{-0.25} \times 10^{-3}$	

† See Table 6 and Figures 8, 9 and 13 for correction factors C_A, C_B, C_C, C_E, C_P, and times T_1 and T_2.

* For sources subtending an angle greater than 11 mrad, the limit may also be expressed as an integrated radiance $L_p = 100\ C_B\ J \cdot cm^{-2} \cdot sr^{-1}$ for $0.7\ s \le t < 10^4$ s and $L_e = C_B \times 10^{-2}\ W \cdot cm^{-2} \cdot sr^{-1}$ for $t \ge 10^4$ s as measured through a limiting cone angle γ. These correspond to values of $J \cdot cm^{-2}$ for 10 $s \le t < 100$ s and $W \cdot cm^{-2}$ for $t \ge 100$ s as measured through a limiting cone angle γ.

$\gamma = 11$ mrad for $0.7\ s \le t < 100$ s,
$\gamma = 1.1 \times t^{0.5}$ mrad for $100\ s \le t < 10^4$ s
$\gamma = 110$ mrad for $10^4\ s \le t < 3 \times 10^4$ s

See Figure 3 for γ and Appendix B7.2 for examples.

Note 1: For repeated (pulsed) exposures, see Section 8.2.3.
Note 2: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$, e.g., 1.180 to 1.302 μm means $1.180 \le \lambda < 1.302$ μm.
Note 3: Dual Limit Application: In the Dual Limit wavelength region (0.400 to 0.600 μm), the exposure limit is the lower value of the determined photochemical and thermal exposure limit.
Note 4: The MPEs must be in the same units.

Table 6. Parameters and Correction Factors

Parameters/ Correction Factors	Wavelength (μm)	Figure with Graphical Representation
$C_A = 1.0$	0.400 to 0.700	8a
$C_A = 10^{2(\lambda-0.700)}$	0.700 to 1.050	8a
$C_A = 5.0$	1.050 to 1.400	8a
$C_B = 1.0$	0.400 to 0.450	8c
$C_B = 10^{20(\lambda-0.450)}$	0.450 to 0.600	8c
$C_C = 1.0$	1.050 to 1.150	8b
$C_C = 10^{18(\lambda-1.150)}$	1.150 to 1.200	8b
$C_C = 8$	1.200 to 1.400	8b
$C_E = 1.0 \quad \alpha < \alpha_{min}$*	0.400 to 1.400	—
$C_E = \alpha / \alpha_{min} \quad \alpha_{min} \le \alpha \le \alpha_{max}$*	0.400 to 1.400	—
$C_E = \alpha^2 / (\alpha_{max}\,\alpha_{min}) \quad \alpha > \alpha_{max}$*	0.400 to 1.400	—
$C_P = n^{-0.25}$ **	0.180 to 1000	13
$T_1 = 10 \times 10^{20(\lambda-0.450)}$ ***	0.450 to 0.500	9a
$T_2 = 10 \times 10^{(\alpha-1.5)/98.5}$ ****	0.400 to 1.400	9b

* For wavelengths between 0.400 and 1.400 μm: $\alpha_{min} = 1.5$ mrad, and $\alpha_{max} = 100$ mrad

** See 8.2.3 for discussion of C_P and 8.2.3.2 for discussion of pulse repetition frequencies below 55 kHz (0.4 to 1.05 μm) and below 20 kHz (1.05 to 1.4 μm).

*** $T_1 = 10$ s for $\lambda = 0.450$ μm, and $T_1 = 100$ s for $\lambda = 0.500$ μm.

**** $T_2 = 10$ s for $\alpha < 1.5$ mrad, and $T_2 = 100$ s for $\alpha > 100$ mrad.

Note 1: Wavelengths must be expressed in micrometers and angles in milliradians for calculations.

Note 2: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$, e.g., 0.550 to 0.700 μm means $0.550 \le \lambda < 0.700$ μm.

Table 7. Maximum Permissible Exposure (MPE) for Skin Exposure to a Laser Beam

Wavelength (μm)	Exposure Duration, t (s)	MPE $(J \cdot cm^{-2})$ except as noted	MPE $(W \cdot cm^{-2})$ except as noted	Notes
Ultraviolet				
	Dual Limits for λ between 0.180 to 0.400 μm			In the Dual Limit Wavelength Region (0.180 to 0.400 μm), the lower MPE considering photochemical and thermal effects must be chosen.
Thermal				
0.180 to 0.400	10^{-9} to 10	$0.56\, t^{0.25}$		
Photochemical				
0.180 to 0.302	10^{-9} to 3×10^4	3×10^{-3}		
0.302 to 0.315	10^{-9} to 3×10^4	$10^{200(\lambda-0.295)} \times 10^{-4}$		3.5 mm limiting aperture applies for all wavelengths and exposure durations (see Table 8a).
0.315 to 0.400	10 to 10^3	1.0		
0.315 to 0.400	10^3 to 3×10^4		1×10^{-3}	
Visible and Near Infrared				The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$, e.g., 0.180 to 0.302 μm means $0.180 \le \lambda < 0.302$ μm.
0.400 to 1.400	10^{-9} to 10^{-7}	$2\, C_A \times 10^{-2}$		
0.400 to 1.400	10^{-7} to 10	$1.1\, C_A\, t^{0.25}$		
0.400 to 1.400	10 to 3×10^4		$0.2\, C_A$	
Far Infrared				
1.400 to 1.500	10^{-9} to 10^{-3}	0.1		The exposure duration t_1 to t_2 means $t_1 \le t < t_2$, e.g., 10 to 10^3 s means 10 s $\le t < 10^3$ s.
1.400 to 1.500	10^{-3} to 10	$0.56\, t^{0.25}$		
1.400 to 1.500	10 to 3×10^4		0.1	
1.500 to 1.800	10^{-9} to 10	1.0		
1.500 to 1.800	10 to 3×10^4		0.1	
1.800 to 2.600	10^{-9} to 10^{-3}	0.1		
1.800 to 2.600	10^{-3} to 10	$0.56\, t^{0.25}$		See Section 8.4.2 for large beam cross sections and Table 6 for correction factor C_A
1.800 to 2.600	10 to 3×10^4		0.1	
2.600 to 1000	10^{-9} to 10^{-7}	1×10^{-2}		
2.600 to 1000	10^{-7} to 10	$0.56\, t^{0.25}$		
2.600 to 1000	10 to 3×10^4		0.1	

Appendix B: Laser Safety Tips

- Locate beam at waist level or below. Don't place beam at eye level.
- Close and cover your eyes when stooping down around the beam (where you will pass by the beam at eye level).
- When leaning over a table, beware of beam directed upward.
- Enclose as much of the beam as possible.
- Don't direct beam toward doors or windows.
- Terminate beams or reflections with beam with fire-resistant beam stops. Anodized aluminum or aluminum painted black (which is not necessarily fire-resistant) can work well for this purpose.
- Use surfaces that minimize specular reflections.
- Locate controls so that the operator is not exposed to beam hazards.
- Make sure warning/indicator lights can be seen through protective filters.
- If you can see the beam through your laser eyewear, you are not fully protected.
- View applications remotely.
- Don't wear watches or reflective jewelry around Class 3B or 4 lasers.
- Don't wear neckties around Class 4 open beam lasers.
- In reality, all interlocks are defeatable.
- The best defense is good understanding of the hazards.

Alignment:

- Isolate process.
- Use lowest practical power.
- View diffuse reflections only.
- Use IR/UV viewing cards/eyewear.
- Where possible, use HeNe alignment lasers.

Appendix C

Laser Safety
Self-Audit Checklist

Building ______________________ Room __________ Principal Investigator ____________________

Audit Performed by ______________________________ Date _________

	Y	N	NA	COMMENTS
A. Administrative				
1. Lasers are classified appropriately (2, 2M, 3R, 3B, 4)				
2. Standard operating procedures are available				
3. Alignment procedures are available				
4. Viewing cards are used for alignment				
5. Laser users attended appropriate training				
6. Lasers are included in inventory				
B. Labeling and Posting				
1. Certification label present				
2. Class designation and appropriate warning label present				
3. Radiation output information on label				
4. Aperture label present				
5. Appropriate warning/danger sign at entrance to laser area				
6. Warning posted for invisible radiation				
C. Control Measures				
1. Protective housing present and in good condition				
2. Beam attenuator present				
3. Laser table below eye level				
4. Beam is enclosed as much as possible				
5. Beam not directed toward doors or windows				
6. Beams are terminated with fire-resistant beam stops				
7. Surfaces minimize specular reflections				
8. Controls are located so that the operator is not exposed to beam hazards				

	Y	N	NA	COMMENTS
. Personal Protective Equipment				
1. Eye protection is appropriate for wavelength				
2. Eye protection has adequate OD				
3. Warning/indicator lights can be seen through protective filters				
E. Class 3B and 4 Lasers				
1. Interlocks on protective housing				
2. Service access panel present				
3. Limited access to spectators				
4. Nominal hazard zone determined				
5. Operators do not wear watches or reflective jewelry while laser is operating				
6. Viewing portals present where MPE is exceeded				
F. Class 4 Lasers				
1. Failsafe interlocks at entry to controlled area				
2. Area restricted to authorized personnel				
3. Laser may be fired remotely				
4. If present, curtains are fire-resistant				
5. Area designed to allow rapid emergency egress				
6. **Pulsed –** interlocks designed to prevent firing of the laser by dumping the stored energy into a dummy load				
7. CW – interlocks designed to turn off power supply or interrupt the beam by means of shutters				
8. Operators know not to wear ties around the laser				
G. Non-Beam Hazards				
1. High voltage equipment appropriately grounded				
2. High voltage equipment located away from wet surfaces or water sources				
3. High voltage warning label in place				
4. Compressed gases secured				