Laser safety in the laser chemistry laboratory

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LASER = Light Amplification by Stimulated Emission of Radiation

- Lasers are **special light sources**, that
  - its **intensity obtained by amplification** of spontaneous radiation by stimulated emission,
  - can be quite **monochromatic**,
  - can be **tunable,**
  - can be quite **intensive**,
  - can be quite **effective** light source,
  - can provide **short**, or even **ultra-short light pulses**,
  - can be quite **coherent**,
  - can be **collimated**.

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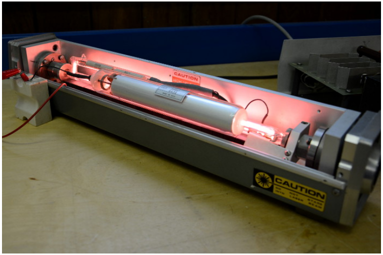
Different types of lasers

- A material **must be specially excited** (pumped) to be able to amplify an incident light beam.
- Lasers are **categorized on the pumping scheme** of the laser-active material:

  - gas lasers
  - solid-state lasers
  - dye lasers
  - diode lasers
  - chemical lasers
  - free-electron lasers



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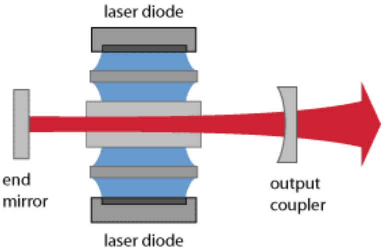

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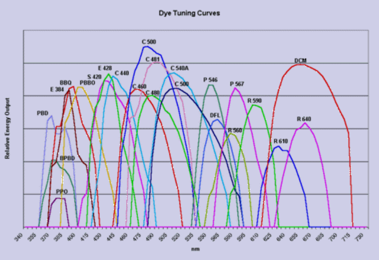

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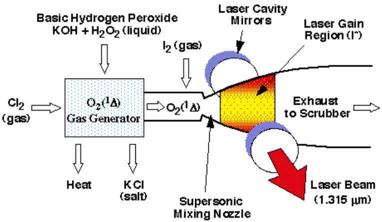

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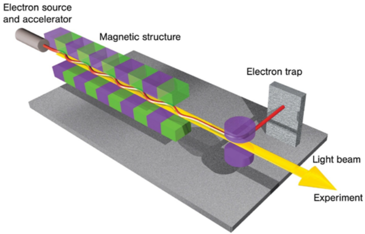

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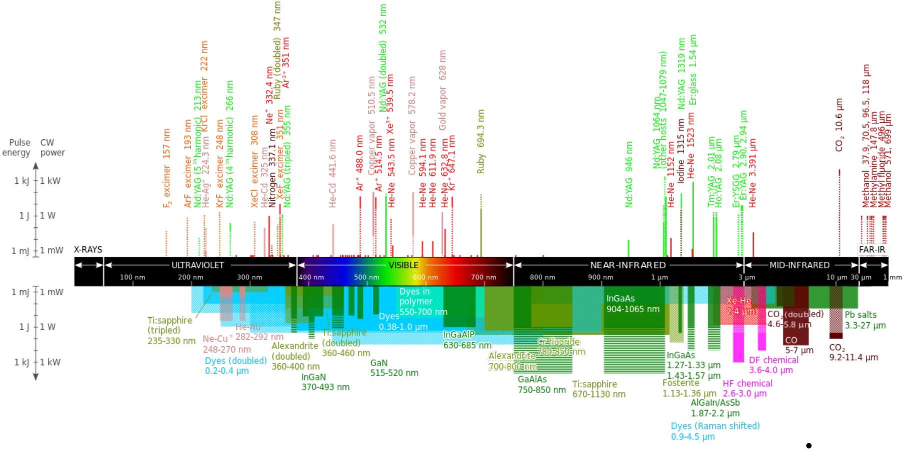
Wavelengths of commercially available lasers



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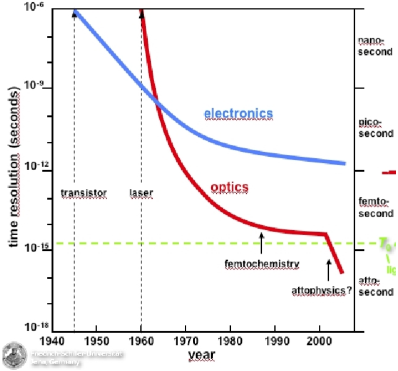
Ultrashort light pulses



- With ultra-short light pulses one can investigate dynamical properties of fundamental chemical processes.

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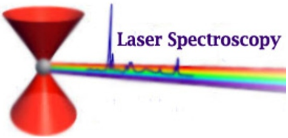
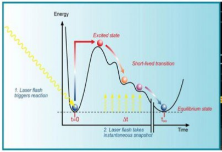
Why a laser can be useful in a chemistry laboratory?

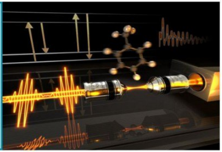
- **Laser-spectroscopy**



- **Photochemistry**

- **Dynamics of chemical processes – Femtochemistry**





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Planck's postulate

It states that the frequency of a photon absorbed or emitted during an electronic transition is related to the energy difference (ΔE) between the two energy levels involved in the transition:

$$\Delta E = h\nu$$

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Laser-spectroscopy

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Photochemistry

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Femtochemistry

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Laser hazards

- Safety is, or **should be**, an integral part of using laser technology.
- Laser hazards can result in **serious injury, even death**.

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Hazards for the eye and the skin

- The **chief concern** over laser use has always been the possibility of **eye injury**.
- While skin presents a greater target, it is **injury to one's eyes that drives laser safety**, funding, controls, and applications.
- The effect of laser radiation will **vary with the wavelength** and the part of the eye with which the beam interacts.
- In addition, biological effects from **direct exposure** and **diffuse-reflection** exposure will differ.

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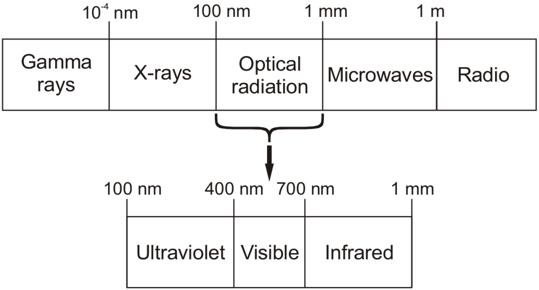
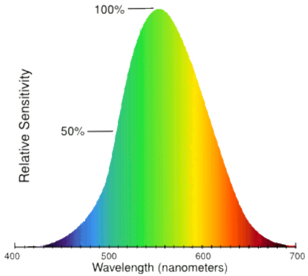
Optical radiation

- The Regulations lay down the minimum safety requirements for the exposure of workers to risks arising from **artificial optical radiation**.





- Optical radiation itself is just part of a more general kind of radiation known as electromagnetic (EM) radiation.

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The safety of laser technology

The concerns that arise over laser hazards and the need for having a formal and systematic approach to risk analysis and safety control really stem from **three unique aspects** of laser technology.

- **Laser hazards are not at all obvious**. The appearance of the laser equipment or even a knowledge of its output power may give little indication to an untrained person of its ability to cause injury.
- A person who is accidentally exposed to laser radiation **may be unaware** of this until a serious injury has been caused.
- Lasers can cause harm at a distance, sometimes at a considerable distance, from the laser equipment itself. There need be **no direct physical contact** with the laser itself.

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Laser safety should be a part of overall health and safety

- Laser safety **should not be seen in isolation**, however, but considered as part of an overall approach to health and safety, both in the workplace and amongst the public at large.
- It may at times **require specialist knowledge** and appear to be highly technical in nature.
- The aim is simply stated; to ensure that laser equipment is designed to be safe and that it is **used in a safe manner**.

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Exposure limits (EL)

- Maximum limits of safe exposure to laser radiation for both eyes and skin are issued by the **International Commission for Non-ionizing Radiation (ICNIRP)**.

- These limits, called **exposure limits** (ELs), are incorporated into **international laser safety standards** and also form the basis for **product classification**.

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International safety standards

- The IEC standard is adopted in Europe as EN 60825.

Reference	Title
IEC 60825-1	Equipment classification, requirements and user's guide
IEC 60825-2	Safety of optical fibre communication systems
IEC 60825-3	TR Guidance for laser displays and shows
IEC 60825-4	Laser guards
IEC 60825-5	TR Manufacturer's checklist for IEC 60825-1
IEC 60825-6	TS Safety of products with optical sources, exclusively used for visible information transmission to the human eye
IEC 60825-7	TS Safety of products emitting 'infrared' optical radiation, exclusively used for wireless 'free air' transmission and surveillance (NOHD $<$ 2.5 m)
IEC 60825-8	TR Guidelines for the safe use of medical laser equipment
IEC 60825-9	TR Compilation of maximum permissible exposure to incoherent optical radiation
IEC 60825-10	Laser safety application guidelines and explanatory notes

USA laser safety standards

Reference	Title
ANSI Z136.1	American National Standard for the Safe Use of Lasers
ANSI Z136.2	American National Standard for the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources
ANSI Z136.3	American National Standard for the Safe Use of Lasers in Health Care Facilities
ANSI Z136.5	American National Standard for the Safe Use of Lasers in Educational Institutions
ANSI Z136.6	American National Standard for the Safe Use of Lasers Outdoors

In USA all laser products sold or offered for sale have to be registered with **CDRH** (the Center for Devices and Radiological Health).
One important **difference** between IEC and US safety requirements is that both CDRH and ANSI laser safety standards generally exclude **LEDs**.

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Biological effects

- User **awareness** of potential laser-exposure hazards is essential for a successful laser safety program.
- As the type of potential injury can vary significantly as a function of the laser's wavelength and duration of exposure, it is useful to build a general awareness of the **biological effects**.

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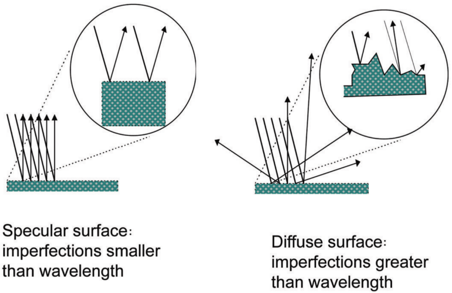
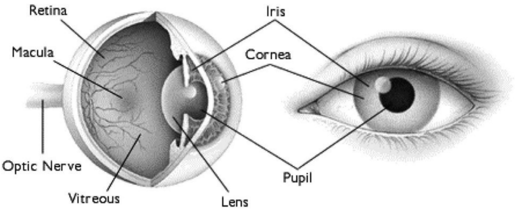
Direct exposure or diffuse reflection



One of the deciding factors on how hazardous a laser beam can be is the manner in which one is exposed to the beam.

Exposures to the eye

- Hazards from beams entering the eye are the major danger of laser radiation because **the eye is the organ that is most sensitive to light**.
- The **optics of the eye** can serve as a lens to focus laser light to be transmitted and **increase its intensity by four to five orders of magnitude**.



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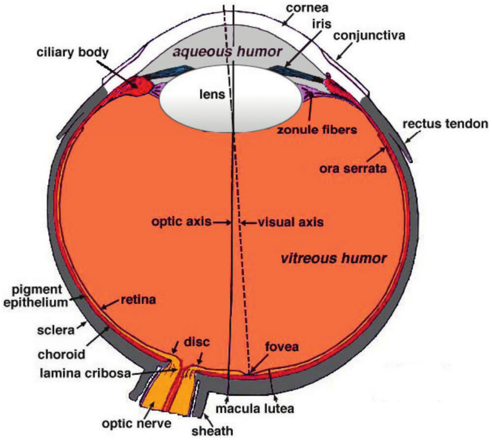
Light path through the eye

Light from an object enters the eye first through the clear cornea and then through the pupil, which is the circular aperture (opening) in the iris. Next, the light is converged by the lens, progresses through the gelatinous vitreous humor, and comes to a focus on the retina, creating an inverted image.



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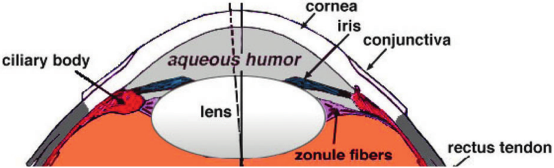
The cornea

The cornea is the transparent layer of tissue covering the eye.



Damage to the outer cornea may be uncomfortable or painful, but the cornea will usually heal quickly. Damage to deeper layers of the cornea may cause permanent injury. The cornea is the primary optical element responsible for much of the focusing power of the eye. Damage to the cornea may result in significant distortions in vision quality.

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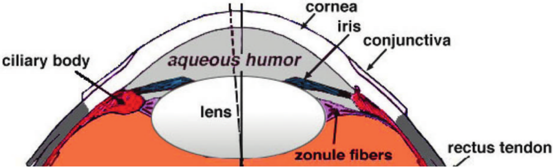
The lens of the eye

The lens of the eye provides a **varying focus** of light to form images onto the retina.



A few laser exposure conditions are known to cause an opacification or cloudiness of the lens. This is known as a **cataract**. Users of certain ultraviolet laser wavelengths in the **315–400 nm range** should be explicitly briefed on the dangers of such systems.

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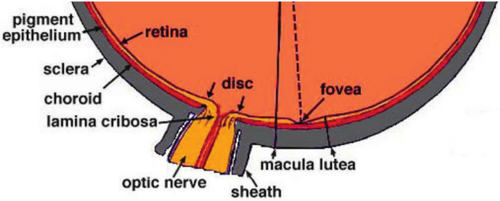
The retina

The retina is the inside wall of the eye; the part that provides the most acute vision is the **fovea centralis** (part of the macula lutea). This is a relatively small area of the retina (3–4%) that provides the most detailed and acute vision as well as color perception.



The remainder of the retina perceives light and movement.

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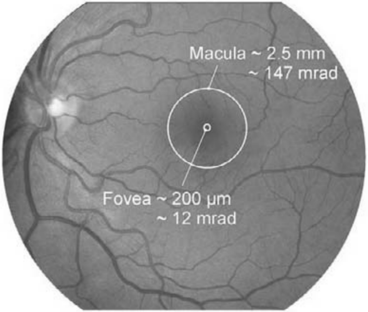
The retinal pigmented epithelium (RPE)

The retinal pigmented epithelium (RPE) is the portion of the retina that contains cells with melanin and other pigments that **strongly absorb visible and near infrared light**.



If laser damage occurs on the fovea, most fine (reading and working) vision may be lost. If a laser burn occurs in the part of the eye that creates peripheral vision, the burn may produce little or no effect on vision.

Retinal hazard bands

- A laser beam (400–1400 nm) with low divergence entering the eye can be focused down to an area 20–30 μm in diameter.
- The overall power that can reach the retina is limited by the transmission of the eye at the wavelength of the laser.
- The primary band that can reach the **retina with more than a few percent transmission** is termed the "retinal hazard region".
- In laser safety 400–700 nm is the wavelength range of visible light, and 700–1400 nm is the range of near-IR radiation. These regions correspond to retinal hazard bands.

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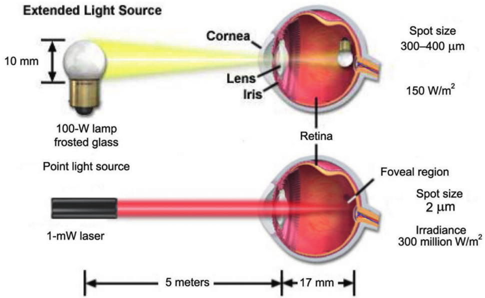
Laser hazard



The energy density (measure of energy per unit area) of a laser beam increases as 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 for visible and near-IR wavelengths.

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Even a weak laser beam can be dangerous

- If the irradiance entering the eye is 1 $\mathrm{mW/cm^2}$, the irradiance at the retina will apprach 100 $\mathrm{W/cm^2}$.
- Even a typical 4% reflection off of an uncoated optical element can be a serious eye hazard.
- Remember, a low-power laser in the milliwatt range can cause a burn if focused directly onto the retina.
- A 40-mW laser is capable of producing enough irradiance (when focused) to instantly burn through paper.

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Aversion response

- The eye has a self-defense mechanism called aversion response, which can be the closing of the eyelid or moving the head to avoid exposure to bright light.
- The aversion response is commonly assumed to occur within 0.25 sec and is only applicable to visible laser wavelengths.
- Such a time is commonly applied to laser hazard analysis for visible-wavelength-emitting lasers.
- The aversion response may defend the eye from damage where lower- power, continuous-wave lasers are involved, but cannot help where higher-power lasers are involved because with high-power lasers, the damage can occur in less time than 0.25 sec.

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Dazzle/startle effects

- Visible light exposure can cause potentially dangerous transient effects at exposure levels well below those that cause retinal injury.
- These effects may persist for the time of exposure, or well beyond.
- This sort of exposure can startle and distract the person exposed, causing them to lose focus on their activity.
- Visible light exposure can also yield afterimages and induce watering eyes and headaches.
- These are affected by ambient lighting conditions, with dim or dark lighting conditions being most significantly impacted.
- If possible, a well-lit area or experimental condition may lessen the effects, but may not always be practical.

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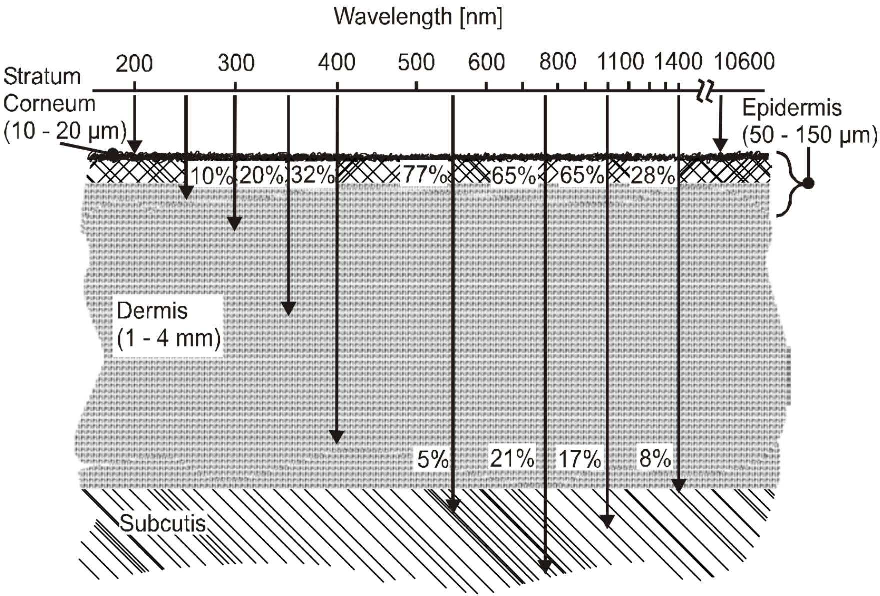
Structure of a human skin

- The **stratum corneum** is the outermost surface layer made up of dead skin cells. It has a thickness of about 10–20 μm.
- The **epidermis** is the outer layer of skin its thickness varies in different types of skin. It is the thinnest on the eyelids at 0.05 mm and the thickest on the palms and soles at 1.5 mm.
- The **dermis** also varies in thickness depending on the location of the skin. It is 0.3 mm on the eyelid and 3.0 mm on the back. The dermis is composed of three types of tissue that are present throughout—not in layers. The types of tissue are collagen, elastic tissue, and reticular fibers.
- The **subcutaneous tissue** is a layer of fat and connective tissue that houses large blood vessels and nerves. This layer is important in the regulation of temperature of the skin itself and the body. The size of this layer varies throughout the body and from person to person.

Light absorption in human skin



Skin Injury

- There is quite a variation in depth of penetration over the range of wavelengths, with the maximum occurring around 700–1200 nm.
- Injury thresholds resulting from skin exposure of less than 10 sec from far-IR and far-UV radiation are superficial and may involve changes to the outer dead layer of the skin.
- A temporary skin injury may be painful if sufficiently severe, but it will eventually heal, often without any sign of injury.
- Burns to larger areas of the skin are more serious, as they may lead to serious loss of body fluids.

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Photochemical injury

- **UV-B and UV-C**, often collectively referred to as "actinic UV," can cause erythema and blistering, since they are absorbed in the epidermis.
- **UV-C** (200–280 nm) is absorbed in the outer dead layers of the epidermis (stratum corneum).
- **UV-B** (280–315 nm) is most injurious to skin. It has an initial pigment-darkening effect followed by erythema if there is exposure to excessive levels. It is a component of sunlight that is thought to have carcinogenic effects on the skin. In addition to thermal injury, there is the possibility of radiation carcinogenesis , either directly on DNA or from effects on potential carcinogenic intracellular viruses.
- **UV-A** (315–400 nm) can cause hyperpigmentation and erythema to the skin.

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Biological effects by wavelength

Photobiological spectral domain	Eye effects	Skin effects
Ultraviolet-C (180 nm–0.280 μm)	Photokeratitis, cornea thermal injury	Erythema (sunburn), skin cancer
Ultraviolet-B (0.2800–0.315 μm)	Photokeratitis, cornea thermal injury	Accelerated skin aging, increased pigmentation
Ultraviolet-A (0.315–0.400 μm)	Photochemical UV cataract, thermal injury to anterior eye	Pigment darkening, skin burn
Visible (0.400–0.780 μm)	Photochemical and thermal retinal injury, photomechanical damage (short pulses)	Photosensitive reactions, skin burn
Infrared-A (0.780–1.400 μm)	Cataract, thermal retinal injury, photomechanical damage (short pulses)	Skin burn
Infrared-B (1.400–3.00 μm)	Corneal burn, aqueous flare, IR cataract, thermal injury to anterior eye	Skin burn
Infrared-C (3.00–1000 μm)	Corneal burn	Skin burn

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Classification

- The classification of a laser is **based on the concept of accessible emission limits** (AEL) that are defined for each laser class.
- This is usually a maximum power (in W) or energy (in J) that can be emitted in a specified wavelength range and exposure time that passes through a specified aperture stop at a specified distance. For infrared wavelengths above 4 μm, it is specified as a maximum power density (in W/m^2).
- It is the **responsibility of the manufacturer** to provide the **correct classification of a laser**, and to **equip the laser** with appropriate **warning labels** and **safety measures** as prescribed by the regulations.
- Safety measures used with the more powerful lasers include **key-controlled operation, warning lights** to indicate laser light emission, **a beam stop** or **attenuator**, and an electrical contact that the user can connect to an **emergency stop or interlock**.

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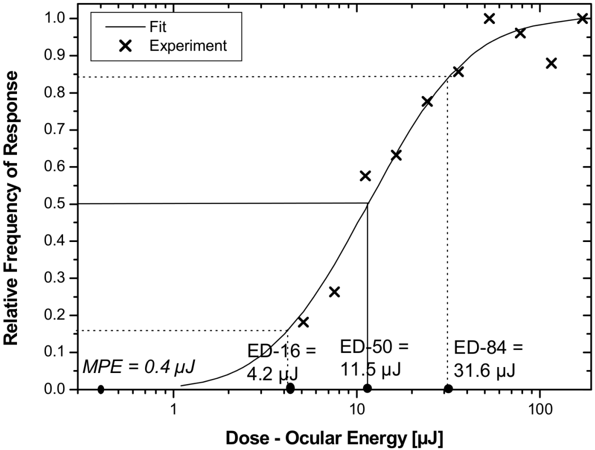
The concept exposure limits

The MPE (Maximal Permissible Exposure) is set well below the ED-50 to insure that there is practically zero risk when exposed at the MPE level.



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Hazard classes

Class	Hazard
Class 1	Safe under reasonably foreseeable conditions (Note: Class 1 lasers include high-power lasers that are fully enclosed, such that potentially hazardous radiation is not accessible during use).
Class 1M	Safe for the naked eye except if magnifying optics are used.
Class 2	Safe for short exposures (less than 0.25s). The eye is protected by the blink reflex.
Class 2M	Safe for short exposures (less than 0.25s). The eye is protected by the blink reflex except if magnifying optics are used.
Class 3R	Safe if handled with care, may be dangerous if mishandled. Risk is limited by the blink reflex and natural response to heating of the cornea for infrared radiation.
Class 3B	Direct viewing is hazardous. Protective eyewear is necessary if the beam is accessible. Safety interlocks are required to prevent access to hazardous laser radiation.
Class 4	Can burn the skin and cause permanent eye damage. Class 4 lasers can also present a fire hazard. Safety interlocks with manual reset are required to prevent access to hazardous laser radiation.

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Laser pointer safety

1 mW red pointer, 1 mrad 1 mW green pointer, 1 mrad	Class 2	"Do not stare into beam"
5 mW red pointer, 1 mrad 5 mW green pointer, 1 mrad	Class 3R	"Avoid direct eye exposure"
25 mW green handheld, 1 mrad 125 mW green handheld, 1 mrad 250 mW green handheld, 1 mrad	Class 3B	"Avoid exposure to beam"
500 mW green handheld, 1 mrad 1 W green handheld, 1 mrad 1W blue (445nm) handheld, 1 mrad	Class 4	"Avoid eye or skin exposure to direct or scattered radiation"

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Laser safety measures

Safety control measures for managing risk should be considered in accordance with the following sequence, with as much emphasis as possible being placed on the first, i.e. on engineering methods of control.

- **Engineering control measures.** These cover those engineering features incorporated in the laser product by the manufacturer together with any additional physical features, including enclosures and interlocks, that may by added by the user (by which is meant the user's organization) to the laser itself or included in the overall laser installation.
- **Administrative control measures**. Administrative control measures cover the overall safety policy of the organization (the 'local rules'), which include the appointment of a Laser Safety Officer, the use of warning signs, and the requirements for safety training (which are all discussed in the next chapter), as well as the designated procedures, often called standard operating procedures (SOPs), that have to be followed in the setting up, adjustment and operation of specific items of laser equipment.
- **Personal protection.** Only where a combination of engineering and administrative control measures cannot alone adequately control the risk should the adoption of personal protection (primarily but not only laser eye protection) be considered.

For individuals: general precautions

- The most obvious hazard is potential damage to eyesight.
- Lasers tend to be **extremely bright sources** of visible or invisible electromagnetic radiation.
- If suitable precautions are not taken, then permanent damage to the eyes is a distinct possibility.
- Skin damage is also another potential problem.
- The direct irradiation of skin by a highly intense laser can result in severe burns.
- However, even scattered radiation, especially in the ultraviolet, may need protecting against.

- **Many scientists involved with lasers agree on the following guidelines.**

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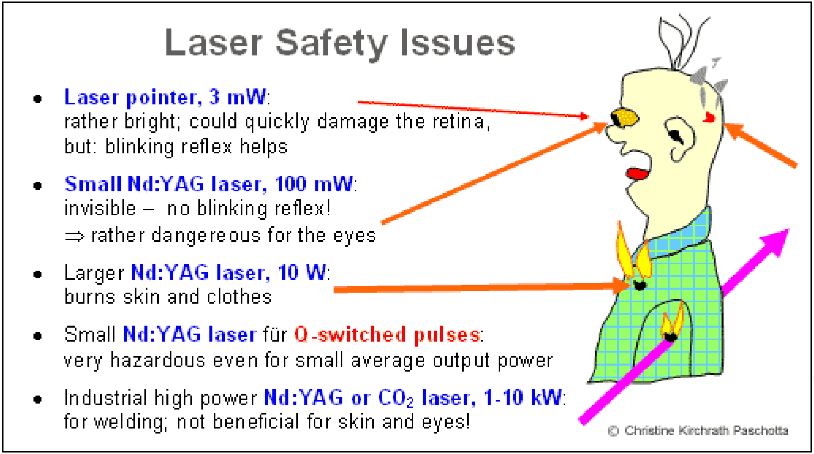
Aware of the risks

- Everyone who uses a laser should be aware of the risks. This awareness is not just a matter of time spent with lasers; to the contrary, long-term dealing with invisible risks (such as from infrared laser beams) tends to reduce risk awareness, rather than to sharpen it.



Never view direct light beams

Always use some screen or a paper to watch the beam position and shape. If is possible **use special viewers** that show the beam at different wavelength especially in the case of high power light beams.

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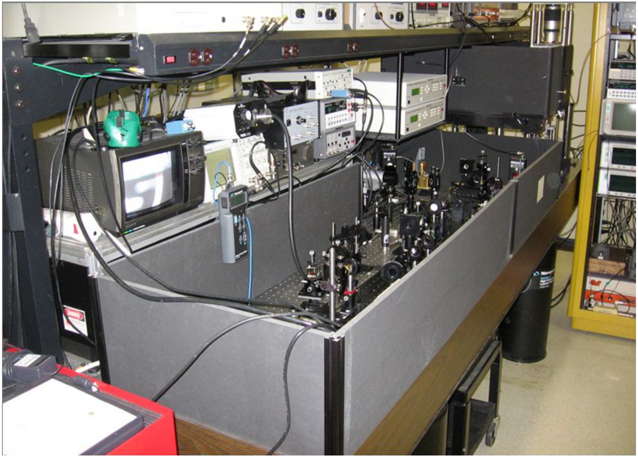
Experiments on an optical table

- Optical experiments should be carried out on an optical table with **all laser beams travelling in the horizontal plane only**, and all **beams should be stopped** at the edges of the table.



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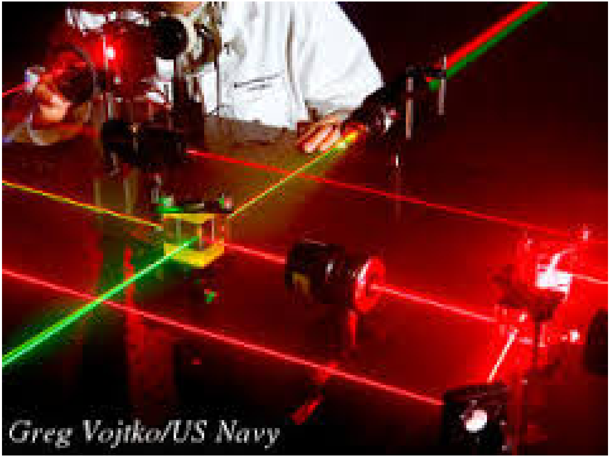
Never put eyes at the level of the horizontal plane of the setup

- Users should never put their eyes at the level of the horizontal plane where the beams are in case of reflected beams that leave the table.



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No watches and jewelry allowed in the laboratory

- Watches and other jewelry that might enter the optical plane should **not be allowed in the laboratory**.

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All non-optical objects should be matt finished

- All non-optical objects that are close to the optical plane should have a matte finish in order to **prevent specular reflections**.

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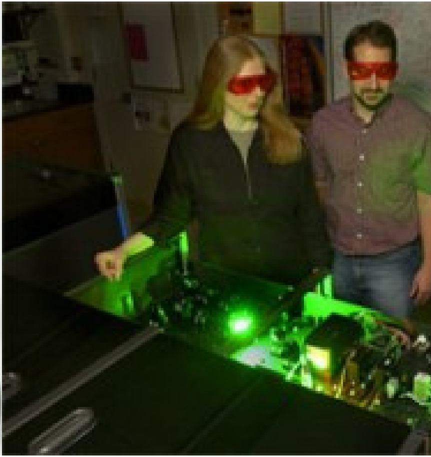
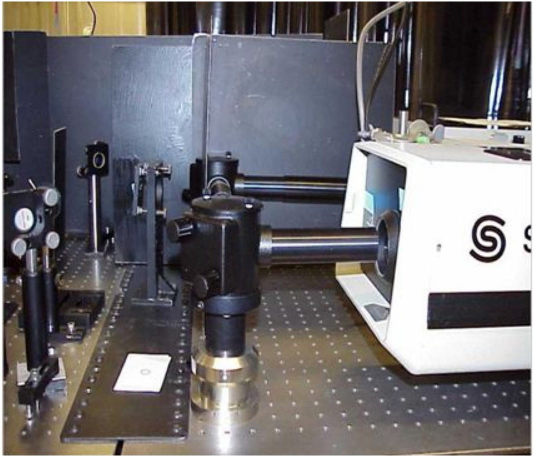
Adequate eye protection

- Adequate eye protection should always be required for everyone in the room if there is a significant risk for eye injury.



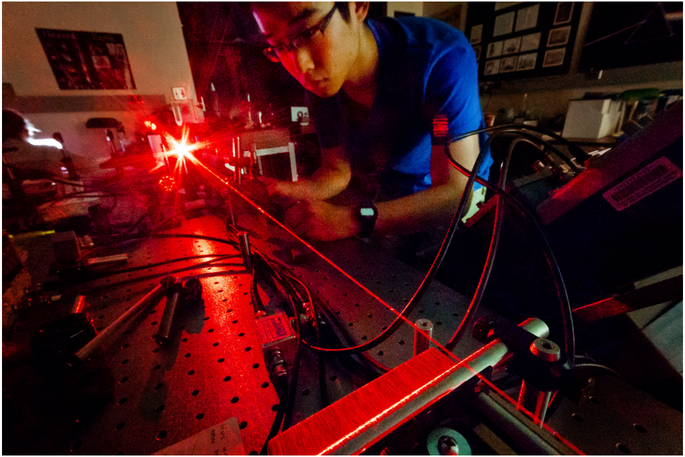
Beam guiding through opaque tubes

- High-intensity beams that can cause fire or skin damage (mainly from class 4 and ultraviolet lasers) and that are not frequently modified should be guided through opaque tubes.



Always use as small beam power as possible

- Alignment of beams and optical components should be performed **at a reduced beam power** whenever possible.



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Protective eyewear (goggles or spectacles)

- Eyewear must be selected for the specific type of laser, to block or attenuate in the **appropriate wavelength range**.
- Eyewear is rated for **optical density (OD)**, which is the base-10 logarithm of the attenuation factor by which the optical filter reduces beam power.
- The protective specifications (wavelengths and optical densities) are usually printed on the goggles, generally near the top of the unit. In the European Community, manufacturers are required by European standard **EN 207** to specify the maximum power rating rather than the optical density.

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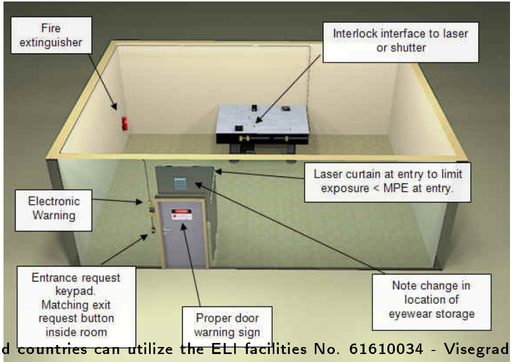
Interlocks and automatic shutdown

- Interlocks are circuits that stop the laser beam if some condition is not met, such as if the laser casing or a room door is open.
- Class 3B and 4 lasers typically must have a connection for an external interlock circuit.
- Many lasers are considered class 1 only because the light is contained within an interlocked enclosure, like DVD drives or portable CD players.



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Laser safety officer (LSO)

- **In many jurisdictions, organizations** that operate lasers are required to appoint a laser safety officer (LSO). The LSO is responsible for ensuring that safety regulations are followed by all other workers in the organization.
- From an ANSI and real-world point of view, you **cannot have laser safety without a person responsible for it**.
- If staff has **access to Class 3B or Class 4 lasers**, an LSO is required.
- The LSO does not need to perform all of the LSO duties; rather, he or she is responsible for seeing that they are all addressed.
- There are duties of LSO regardless of whether the LSO is **a part-time or full-time** staff person.

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References

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- Ken Barat: Laser Safety, Tools and training, CRC Press, 2009.
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- ICNIRP Guidelines, Health Physics, 431-40, 2000.
- ANSI Z136-1, American National Standard for Safe Use of Lasers (Florida:LIA), 2000.
- https://en.wikipedia.org/wiki/Laser_safety

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Thank you for your attention!

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