

Laser safety

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Apology

- Sorry about the horribly-formatted and text-heavy slides
- I wanted to write a document that is as stand-alone as possible, so that it can be read without the presenter
- The slide presentation will be improved in the future

Introduction

Course focus & things you should already know

Focus of this short course:

- Well-collimated laser beams inside laboratories (not medical, industrial or surveying situations).
- Quantum-optics research focus: complex optical setups, frequent setup changes, need to be up close with laser path. Shared and space-restricted workspaces.
- A key danger in our labs: collimated laser light focusing on retina causing permanent retinal damage.
- Emphasis on getting basic overview of physical processes that lead to injury from exposure to lasers
- Emphasis on understanding the basis of maximum permissible exposures: calculate them yourself and get feeling for thresholds.
- Much of information gained from laser safety course at NPL (uk) in Sep. 2016, given by Lasermet (www.lasermet.com) .

Things you should already know:

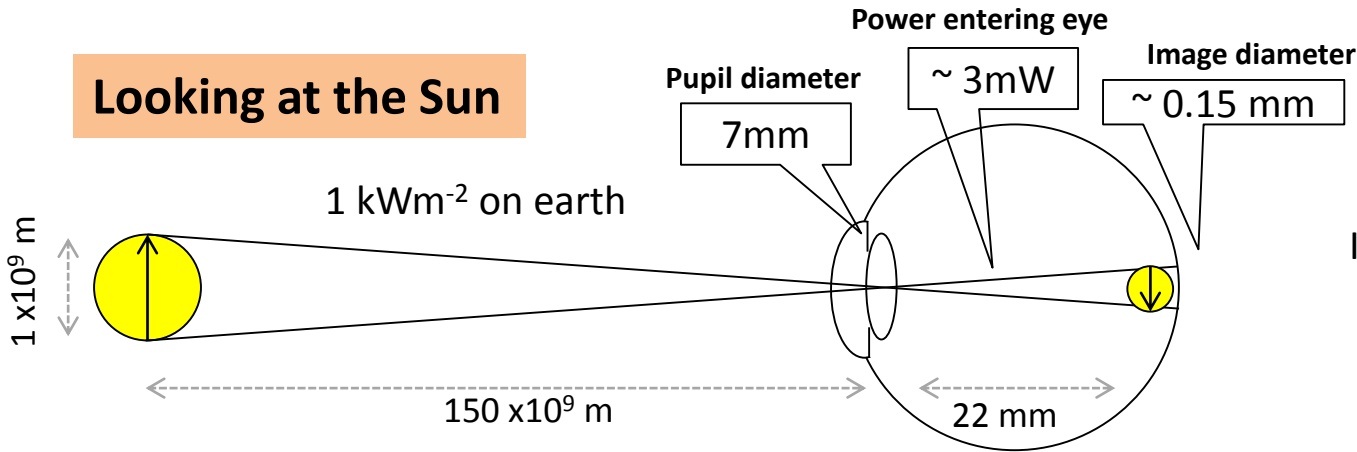
- Undergraduate level physics
 - e.g.
 - Basics of what a laser is, what it emits and how to quantify it (wavelength, frequency..)
 - Gaussian beams and basic optics
 - S.I. units & converting between them (energy J, power J/s, intensity J/s/m²)

Why learn about laser safety?

- Prevent accidents and ill-health. *Even with the blink reflex, a single direct 0.25s eye exposure to a 20mW visible or near IR laser beam will permanently damage your vision with high probability.*
- You and your employer have a moral & legal duty to take all reasonable steps to protect you and other people. *Otherwise an accident will shut down your lab and team spirit will suffer.*
- *You should be able to defend your laser safety approach if someone gets hurt. Could you, now?*
- *You may not know if you are doing it wrong. Possible to get away with bad laser safety for many years*
- *Quantum-optics research presents unusual and challenging laser safety situations. Vast number and range of powerful lasers with thousands of optical elements that are frequently rearranged by different people. Visitors coming in and out of lab. New laser systems arrive often and someone else sets it up.*
- *It only takes a little effort to be safe. Risks can be dramatically reduced without affecting your work significantly.*

1mW laser pointer vs. the sun

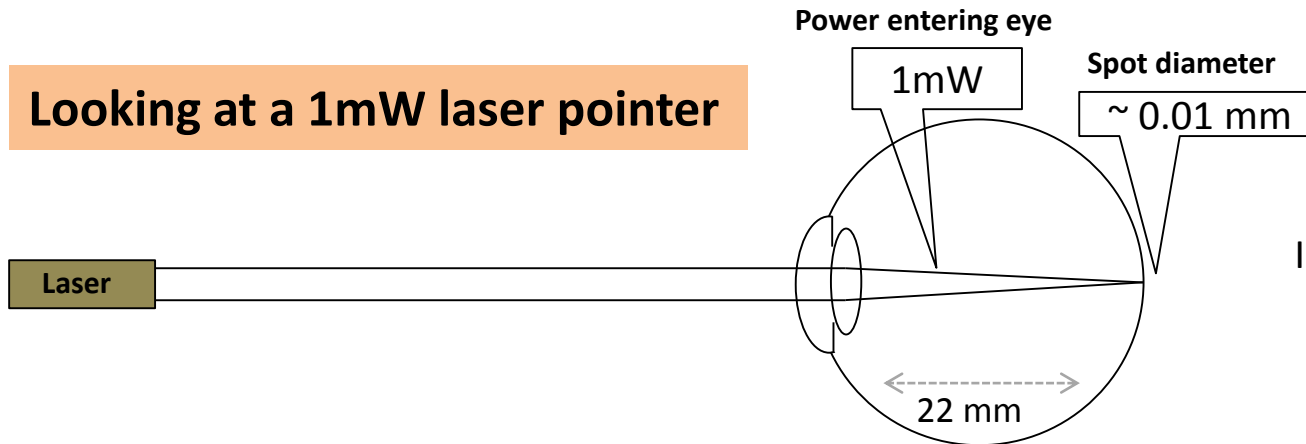
Looking at the Sun



Intensity of sun image on retina

$$I_{sun} \approx 2 \times 10^5 \text{ Wm}^{-2}$$

Looking at a 1mW laser pointer



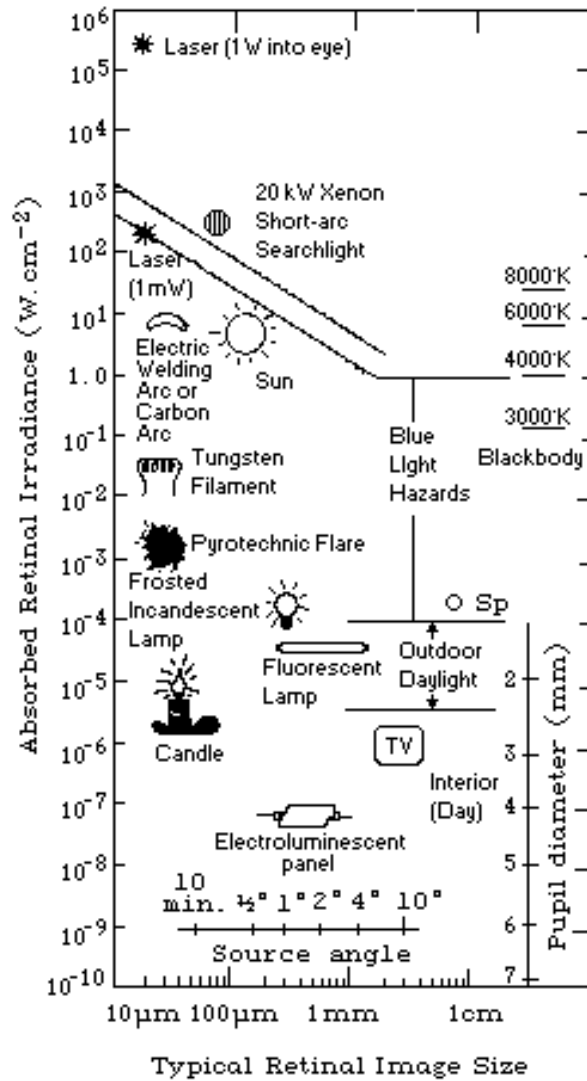
Intensity of laser spot on retina

$$I_{laser} \approx 1 \times 10^7 \text{ Wm}^{-2}$$

The retinal spot from a 1mW laser pointer is about 50 times more intense than the sun!

(Does not mean it produces 50 x more damage, more like 2 x, but still!)

A 1mW laser pointer vs. other intense sources



Credit: <http://www.inchem.org/documents/ehc/ehc/ehc23.htm>

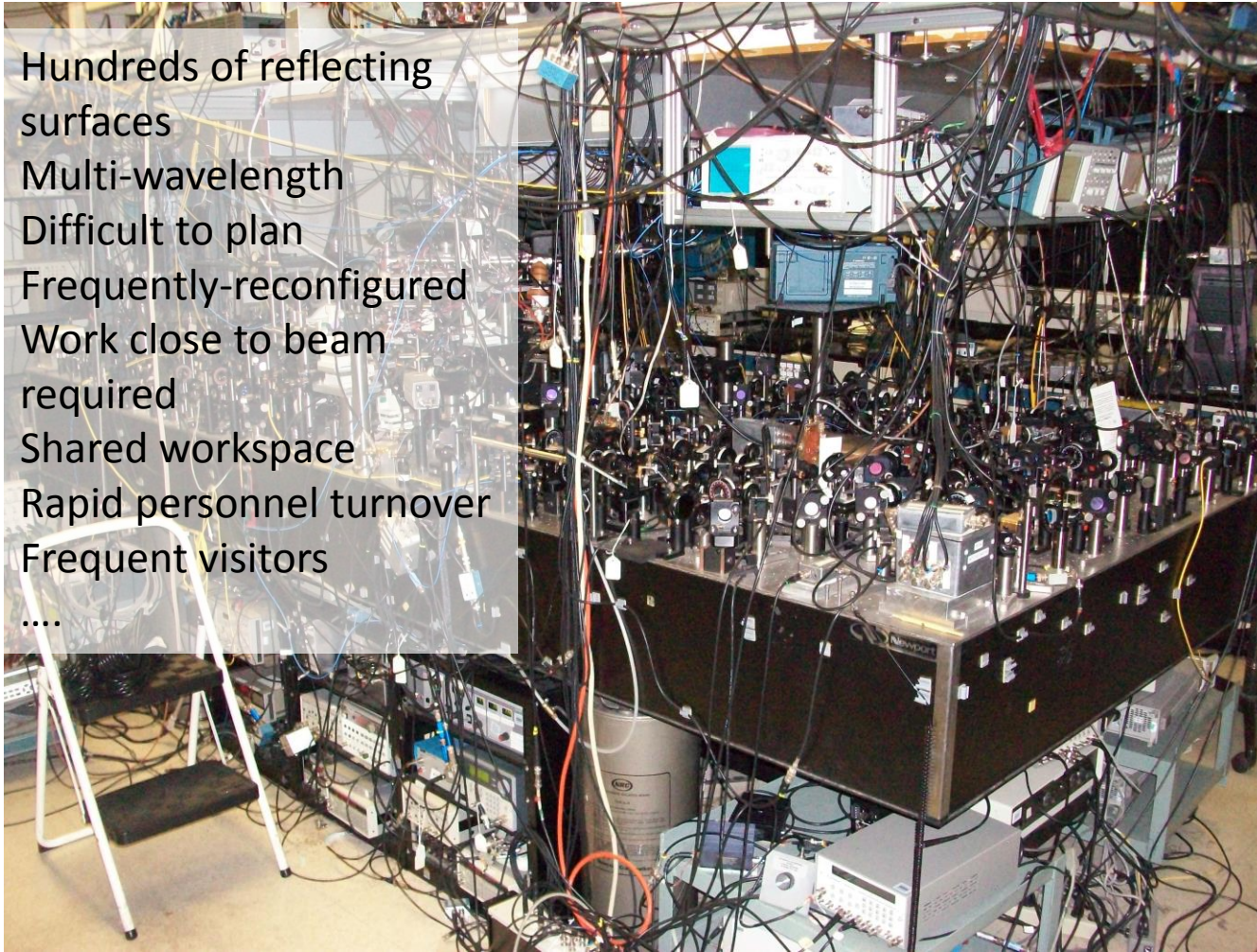
It only takes a moment....

- Los Alamos National Laboratory undergraduate student and staff scientist were working with a flash-lamp pumps, Q-switched Nd:YAG (1064nm) laser. The laser Q-switch was disabled, but the flash-lamps were left on. Injury caused permanent and irreversible damage to the fovea centralis of the student's eye, resulting in permanent vision impairment. The accident precipitated a multi-week shutdown of all scientific activity at the lab
- Brookhaven National Laboratory scientist was dissatisfied with the reduced visibility the goggles were causing, lifted the goggles to look at the experiment...A slight misalignment of the alexandrite laser (720nm to 860nm) caused the laser to be projected directly at the observer's eyes. Injury caused permanent vision impairment in both eyes. Additionally, all laser-related work was shut down for many weeks.

Laser safety challenges in atomic physics labs

Unusual laser safety challenges

- Hundreds of reflecting surfaces
- Multi-wavelength
- Difficult to plan
- Frequently-reconfigured
- Work close to beam required
- Shared workspace
- Rapid personnel turnover
- Frequent visitors
-



Class 4 Lasers in
Lab 1 @ IQOQI

375nm 70mW

393nm 1.5W

397nm 0.2W

397nm 1.5W

422nm 0.1W

532nm 10W

532nm 10W

729nm 1W

785nm 4W

785nm 0.1W

796nm 2W

844nm 1W

854nm 0.1W

1901nm 2W

We must be the experts and make it safe for us and other people

Overview of relevant literature and standards

Important documents

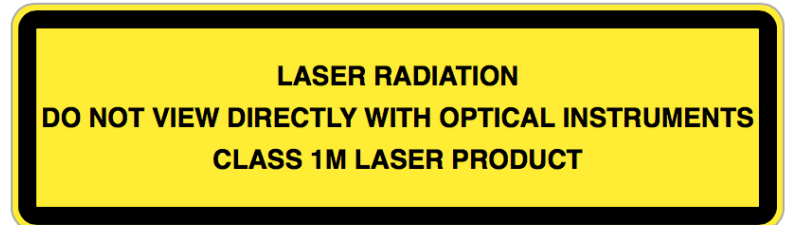
- In Europe we follow laser safety standards from the IEC:
 - The **International Electrotechnical Commission**, a non-profit, non-governmental international standards organization, prepare and publish international standards for all electrotechnology:
 - **Guide of best practice for laser *manufacture*: IEC 60825-1**
 - e.g. Laser classification, packaging and labeling information
 - **Guide of best practice for laser *user*: IEC 60825-14**
 - e.g. maximum permissible exposures to eye and skin
 - In 2014 both were revised e.g. new medical laser class '1C' introduced, and 1200-1400nm exposure limit revised to account for water absorption in eye.
 - The **IEC 60825-14.pdf document** is expensive but can often be downloaded by a cheeky internet search
- In Austria the AUVA (Allgemeine Unfallversicherungsanstalt - the Austrian Workers' Compensation Board) produce other laser safety documents broadly consistent with the above IEC documents. See their document: '**grundlagen der lasersicherheit**'
- **EN 207** is the European 'norm' for laser safety eyewear, which enables the identification of safe goggles (optical depth is not enough!) and I find it to be broadly consistent with IEC 60825-14.
- For nice overview of American Vs European documents see: <http://www.uvex-laservision.de/en/laser-knowledge/laser-safety-norms/>

Laser types and classification

Laser Classification

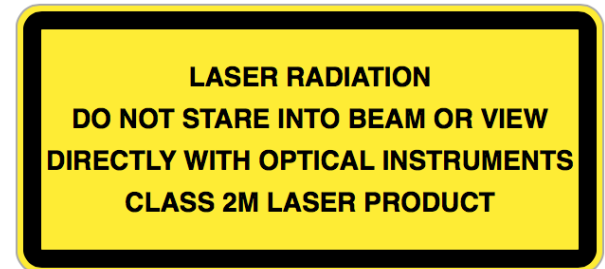
- **Class 1**: safe under all normal conditions of use.
 - Maximum permissible exposure (MPE) cannot be exceeded with eye or typical magnification optics
 - < 0.39 mW in visible regime (different otherwise)
 - Incorporated into many consumer products (CD players, laser printers)
 - Can be far more dangerous lasers inside

- **Class 1M**: safe under all normal conditions of use, except when viewed through optical instruments
 - Broad-diameter or highly-divergent beams can be focused into eye, resulting in greater than the maximum permissible exposure (MPE)



Laser Classification

- **Class 2:** safe because of the blink reflex limiting exposure to < 0.25 seconds.
 - Class therefore *only applies to visible lasers (400 - 700nm)*
 - Emitted power < 1mW
 - e.g. small laser pointer or barcode scanner
- **Class 2M:** safe because of the blink reflex, if not viewed through optical instruments



Required warning label
for all class 2 lasers or higher

Laser Classification

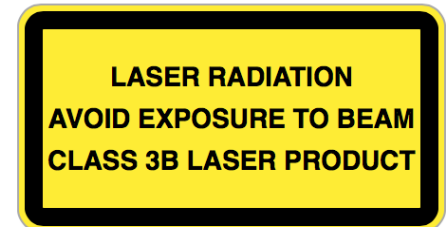
- **Class 3R:** MPE can be exceeded, but with low chance of injury.

- For visible lasers, < 5 mW emitted



- **Class 3B:** hazardous if the eye is exposed directly

- For visible lasers, < 500 mW emitted
- Must be equipped with key and interlock
- CD/DVD players contain 3B (whole thing class 1)
- Capable of starting fires and damaging skin
- No significant danger from diffuse (matt surfaces) reflections



Laser Classification

- **Class 4** can:
 - Can burn the skin
 - Can cause devastating and permanent eye damage as a result of direct or indirect beam viewing
 - Can ignite combustible materials, and thus may represent a fire risk.
 - All the above hazards may also apply to diffuse reflections of the beam, even from apparently matt surfaces – meaning that great care must be taken to control the beam path.
 - Class 4 lasers must be equipped with a key switch and a safety interlock. Most industrial, scientific, military, and medical lasers are in this category.



Laser Classification

- **Summary:**

- **Class 1 (1 and 1M).** Generally `totally safe', but don't magnify it or be surprised if it contains nasty lasers inside.
- **Class 2 (2 and 2M).** Blinks reflex saves you from these visible laser (don't stare!).
- **Class 3R ('restricted').** Avoid direct eye exposure altogether, but low chance of injury.
- **Class 3B.** Avoid direct eye exposure altogether, high chance of injury, but dont have to worry about diffuse reflections.
- **Class 4.** Capable of getting you every which way, even diffuse reflections and fires pose a severe hazard.

Overview of hazards when working with lasers

Overview: Hazards when working with lasers

Direct interaction between human and laser beam:

- Eyes & Skin ...much more about this later

Indirect interaction:

- Toxic substances

- E.g. dye lasers use organic dyes as lasing medium, usually in liquid form. Most dyes used are highly toxic and often carcinogenic. See also toxic gasses in Excimer lasers.

- Laser plumes

- Vapors, smoke, and particulate debris produced during laser ablation or vaporisation can be dangerous to human health

- Fire

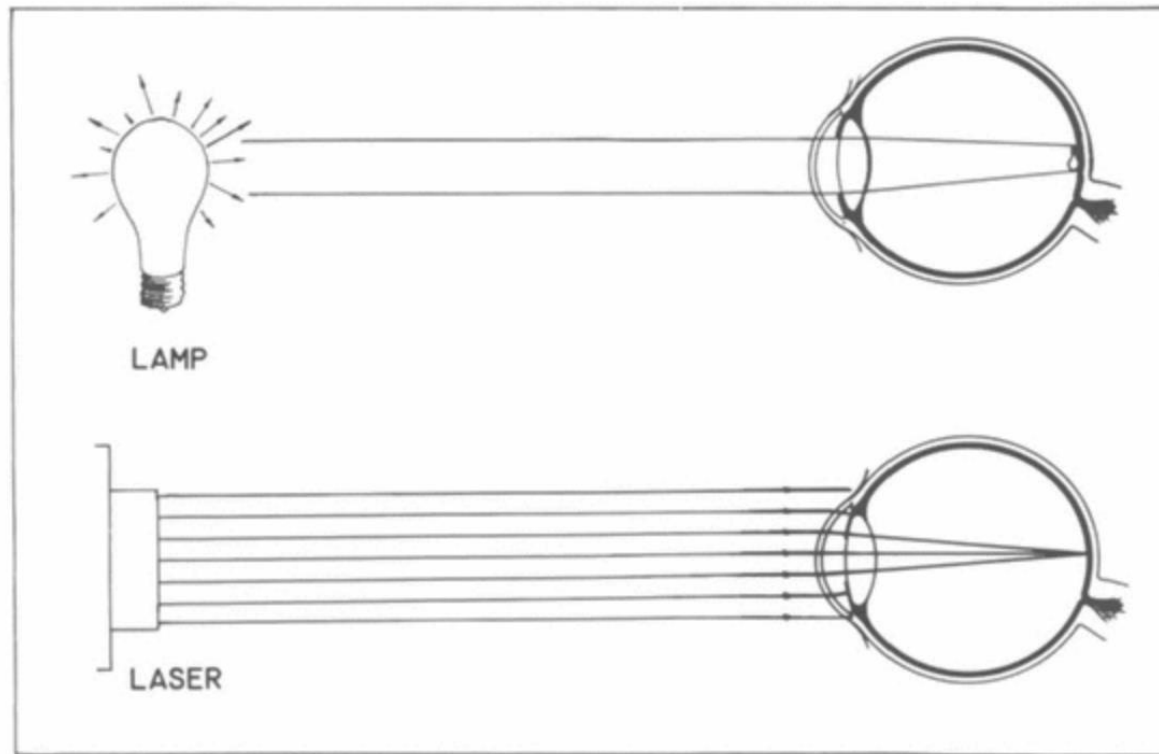
- Class 4 lasers (all the ones we have) can easily ignite combustible materials in their path

- Electrocutation

- Many lasers incorporate high voltage systems and can pose an electrocution hazard if improperly built or serviced.

Why are lasers so Hazardous to eyes?

e.g.



Large focal spot
(image of bulb filament)

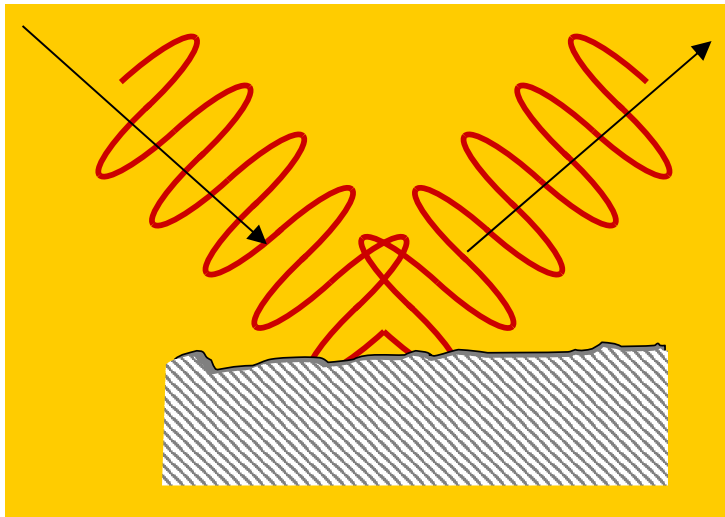
Microscopic focal spot
("Diffraction Limited")

The high collimation of a laser makes it far more dangerous to view than a conventional source. The laser will always focus to a much smaller spot than will an electric lamp or other incoherent source of light.

Graphic from Sloney DH and Trokel, S, 1993

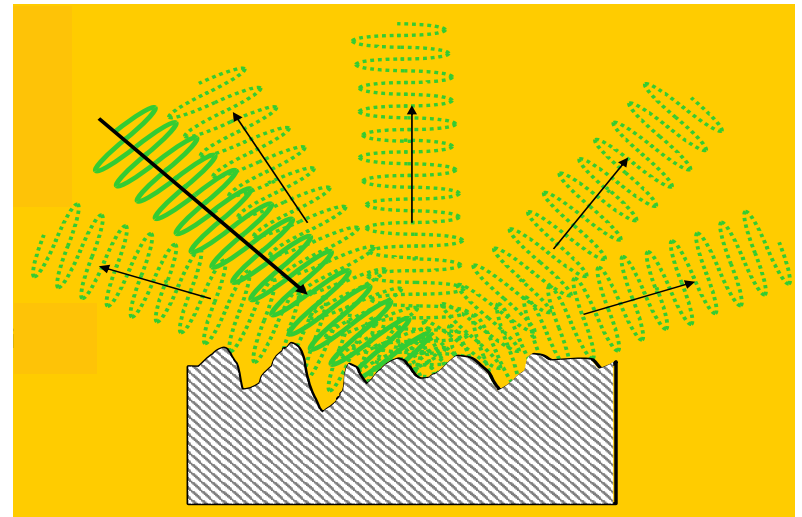
Unanticipated reflections are the number one retinal laser hazard

Specular reflection



Hazard for all lasers

Diffuse reflection



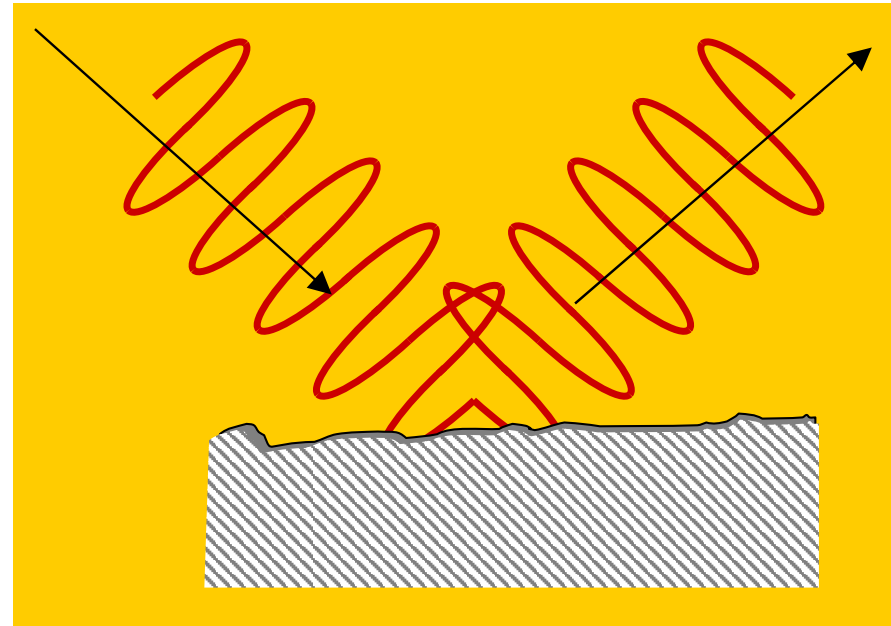
Hazard for class 4 lasers

NIST, Laser Safety Awareness, Joshua Hadler

Unanticipated reflections are the number one retinal laser hazard

Specular reflection:

- Mirror like surface, produces a collimated reflection containing most of the incident power
- The surface irregularities of the reflecting surface are generally smaller than the wavelength of light landing on it.
- Examples: Mirror, polished surface of a lens, glass surface, blade of screw driver still water.

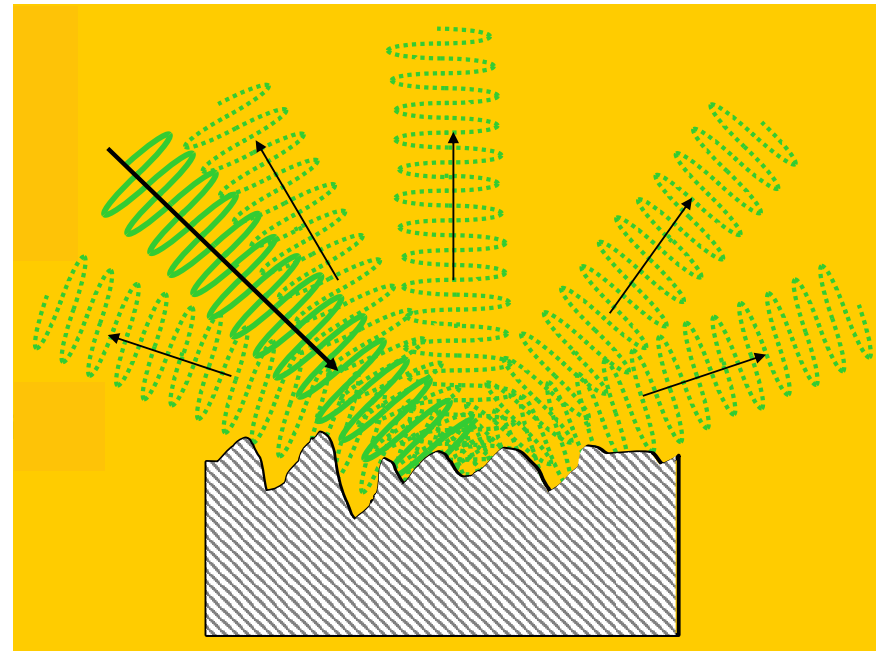


NIST, Laser Safety Awareness, Joshua Hadler

Unanticipated reflections are the number one retinal laser hazard

Diffuse reflection:

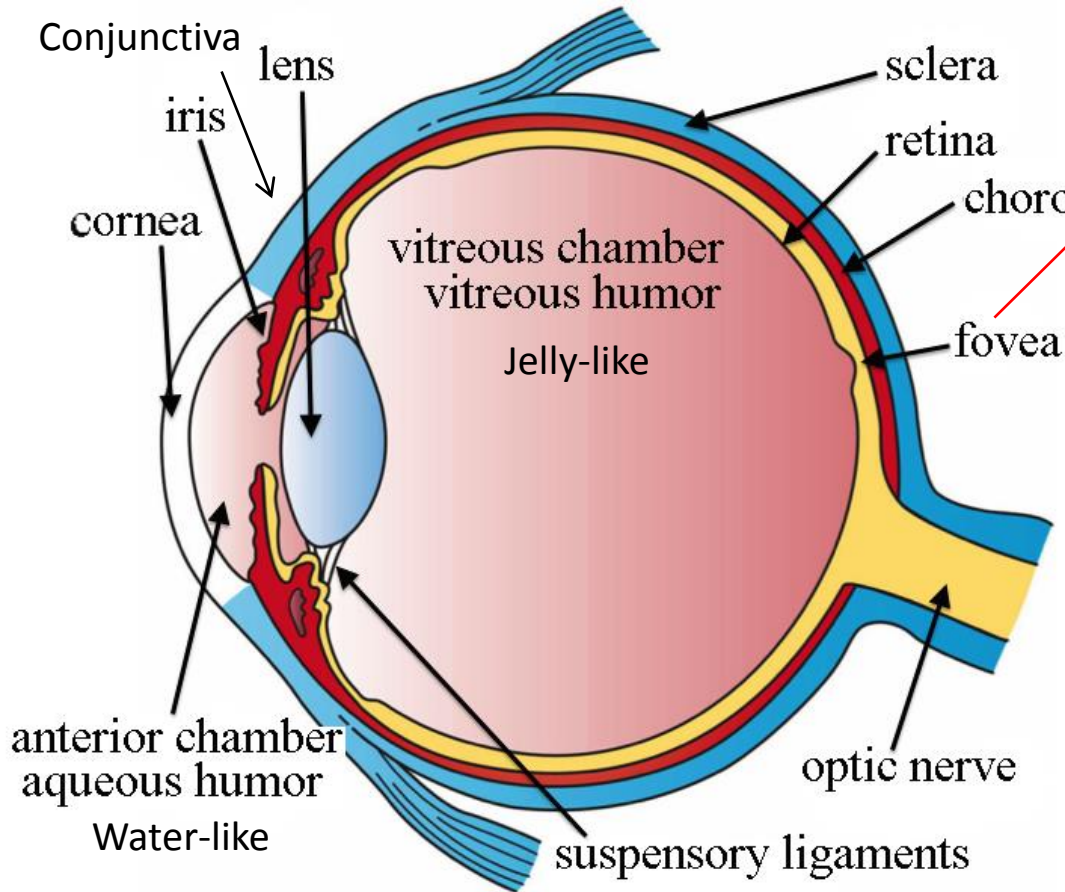
- Rough, scatters the incident beam in all directions.
- The surface irregularities of the reflecting surface are generally larger than the wavelength of light landing on it.
- Examples: Paper, matt finish paint, sand, wood, etc.
- A diffuse scatterer for visible light, can be a specular scatterer for IR light!



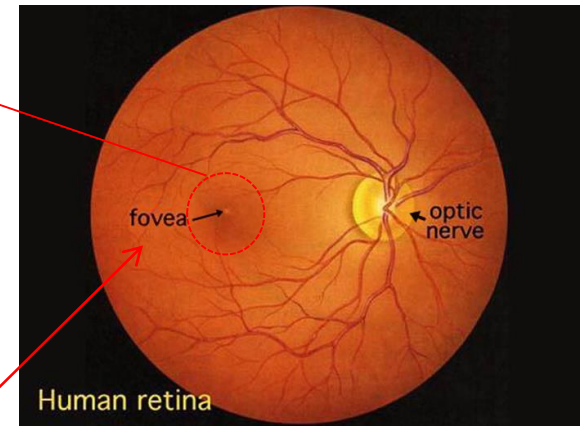
NIST, Laser Safety Awareness, Joshua Hadler

How laser beams interact with the skin and eyes

The human eye

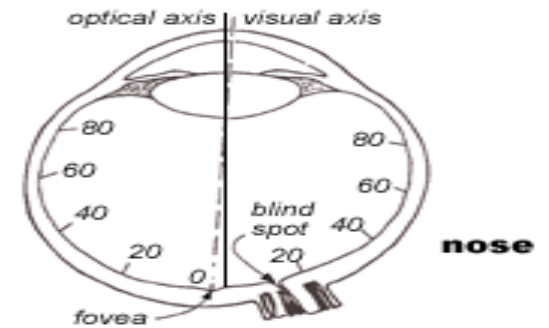


Macula



Human retina

Copyright © 2016 Webvision



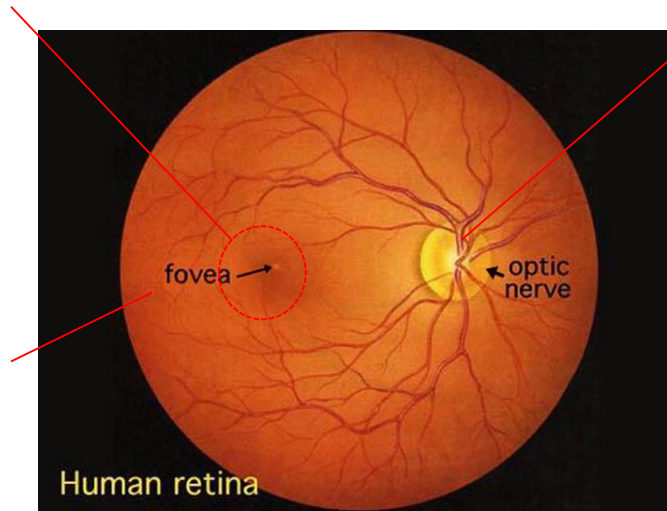
The Retina

The macula

- Darker area, few mm across
- Detailed vision occurs here
 - Damage here: v. bad
- Eye focuses images here

Contains **The fovea**

- Small pit, 300 μm across
- Densely-packed sensors (cones)
 - Highest resolution
- The eye moves continually to keep light from the object of interest falling on the fovea



Copyright © 2016 Webvision

The optic nerve

Information to brain
Blind spot
Damage here: unlikely, but v. bad.

The rest of the retina

Densely packed sensors (rods)
Rapid sensitivity
Motion sensing
Dark-adapted vision occurs here

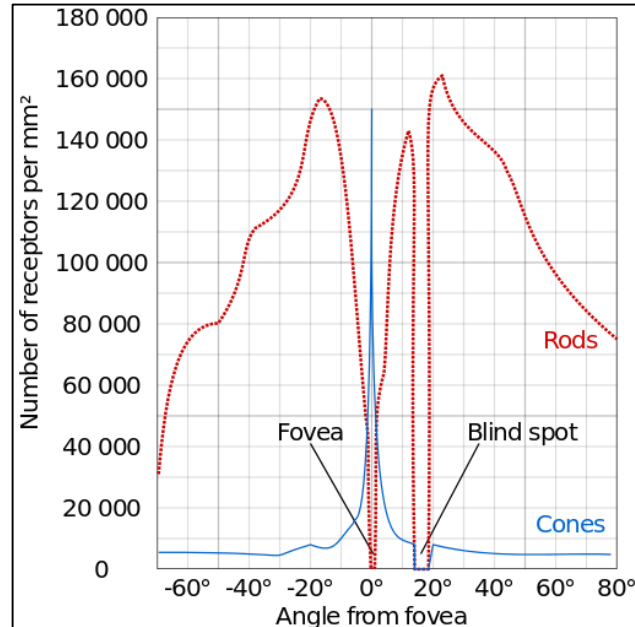
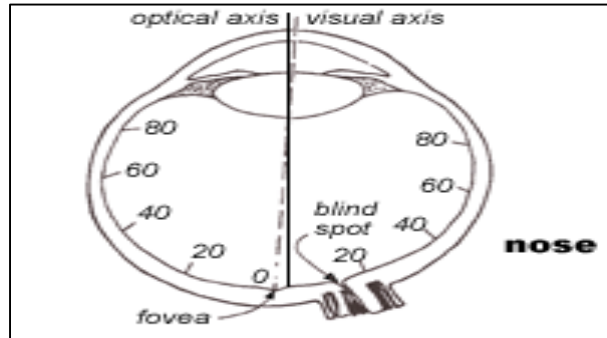
Retinal Photo sensors

Rods

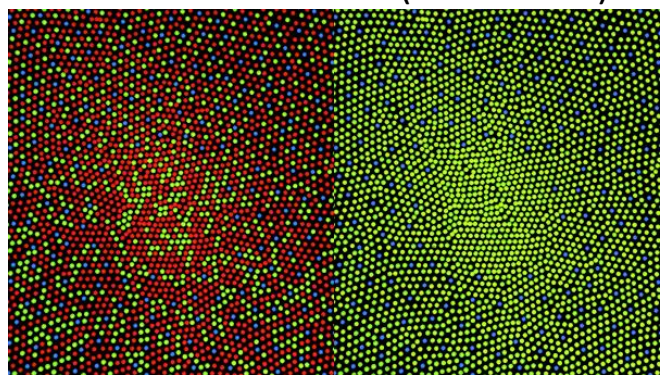
- Everywhere but Fovea.
- No color discrimination
- Low light vision
- Motion detection
- Peak sensitivity 498 nm

Cones

- Densely packed in Fovea
- 3 types: R(64%),G(34%),B(2%)
- Blue cones most sensitive (blue hazard) & not in fovea

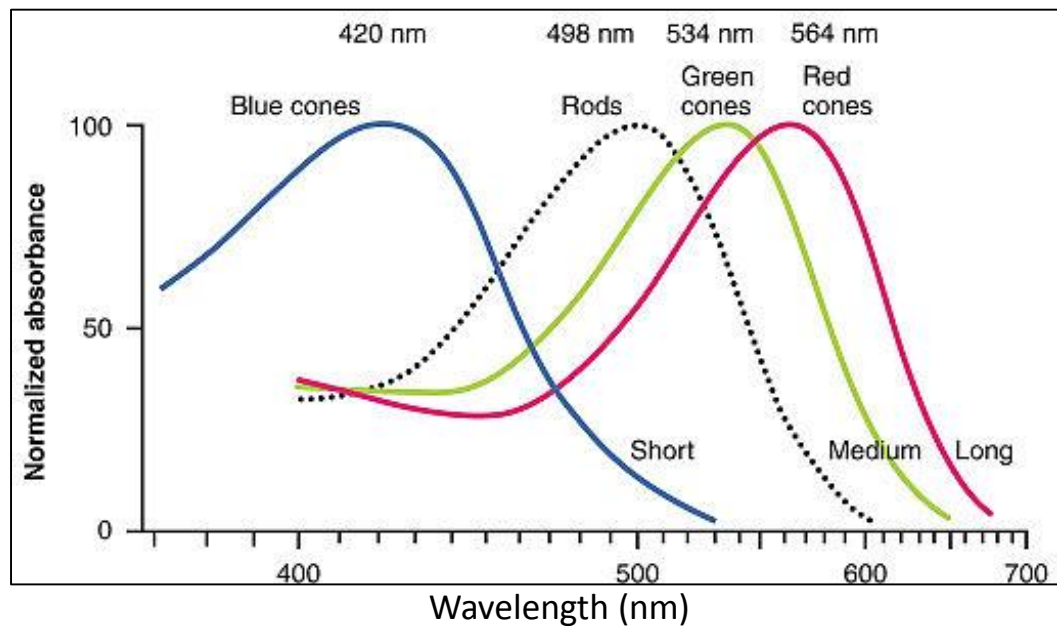


Cones cells in fovea (illustration)



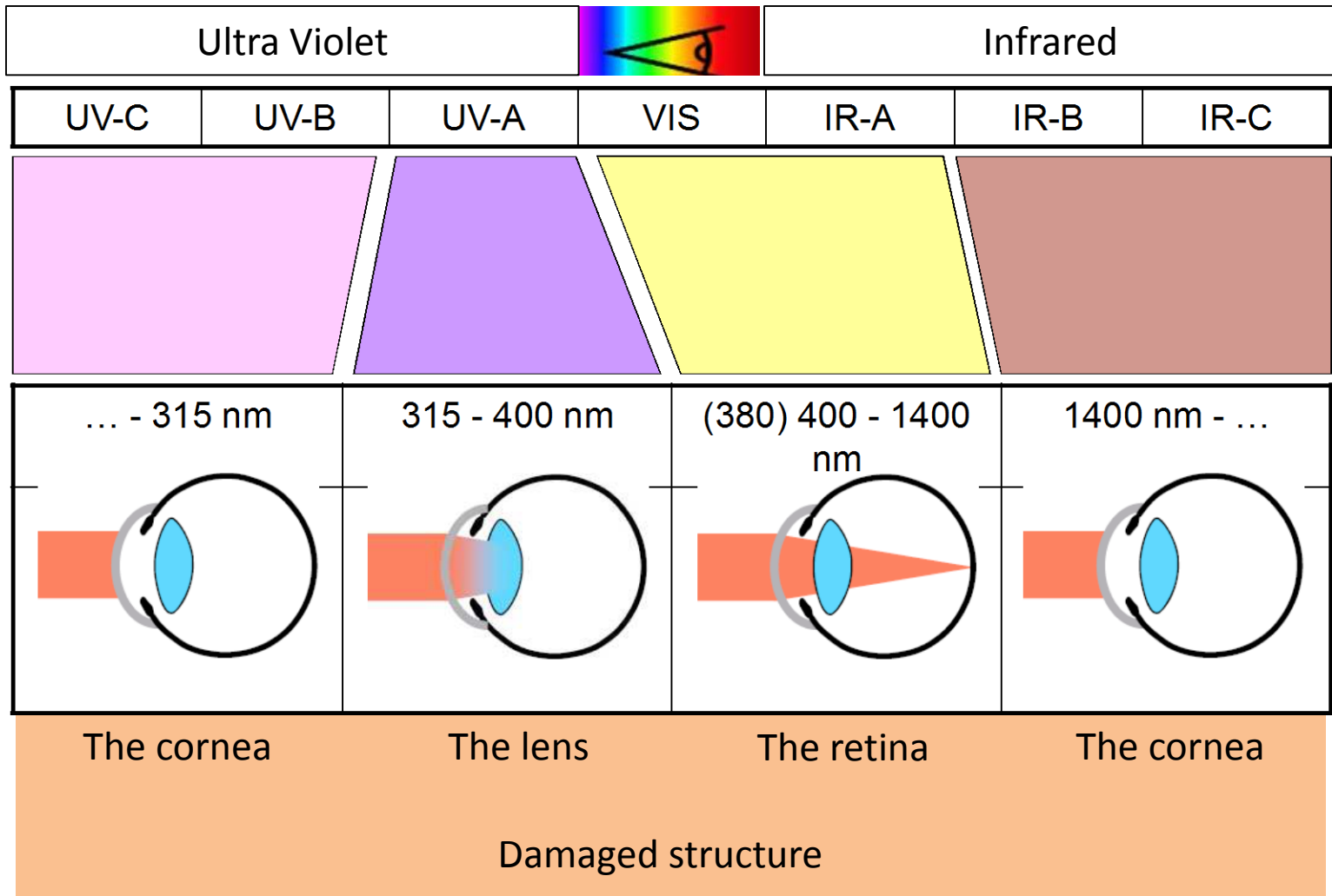
Normal

Color Blind



Wavelength selective damage of different cones:
<http://photobiology.info/Rozanowska.html>

Where different wavelengths get absorbed in the eye



© Emmerich Kitz AUVA

How to remember:

- UV, mid-IR and far-IR damage the front of the eye
- Visible and near-IR the back of the eye

Damage processes

Photochemical.

- Wavelength selective photon absorption by molecule leads to electronically excited state, leading the detrimental chemical changes (most relevant from 400-600 nm).
- Sunburn (skin and cornea) is photochemical process damaging cellular DNA
- Most common form of retinal damage caused by exposure to direct sunlight.
- Photochemistry involved in retinal photodamage is still rather poorly understood.
- With wavelength, can selectively damage the different cones via photochemical damage. Which photoreceptors (cones or rods) also depends on adjustment of eye before exposure (bright lab or dark lab, cones or rods affected).

Photothermal.

- Rate of light energy deposition is faster than thermal dissipation. Tissue temp goes up.
- Various stages of trouble (necrosis, boiling, desiccation, vaporization).
- Any light reaching retina can present thermal problem (in addition to photochemical damage between 400-600nm.)

Photomechanical

- Light energy is deposited faster than mechanical relaxation can occur
- Thermoelastic pressure wave produced, shear forces & cavitation destroy tissue
- Occurs for intense pulses shorter than 1ns

Examples of eye injuries caused by lasers

Image: NPL, UK



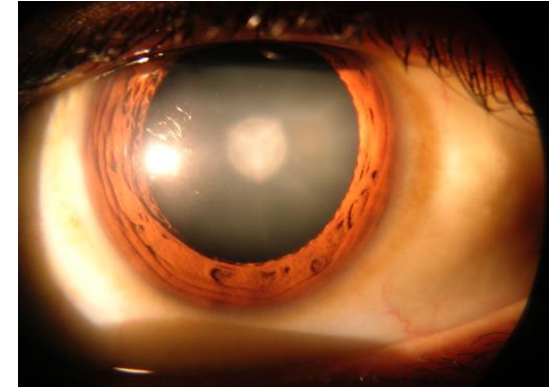
Localised corneal burn
UV or IR light

Image: Eddie314@ wikipedia



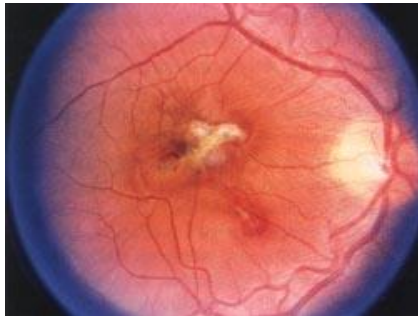
Photokeratitis
UV <315nm

Image: wikipedia

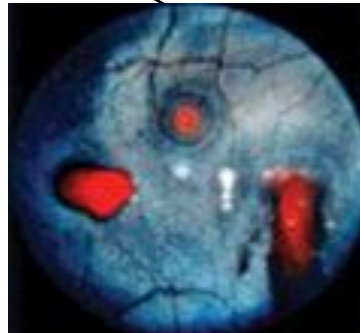


Cataract
315<UV<400

Images from Photonics Spectra, *In Laser Safety, Little Mistakes Can Have Big Consequences*. Kenneth Barat, LLNL, March 2005



Retina burn
400nm – 1400nm

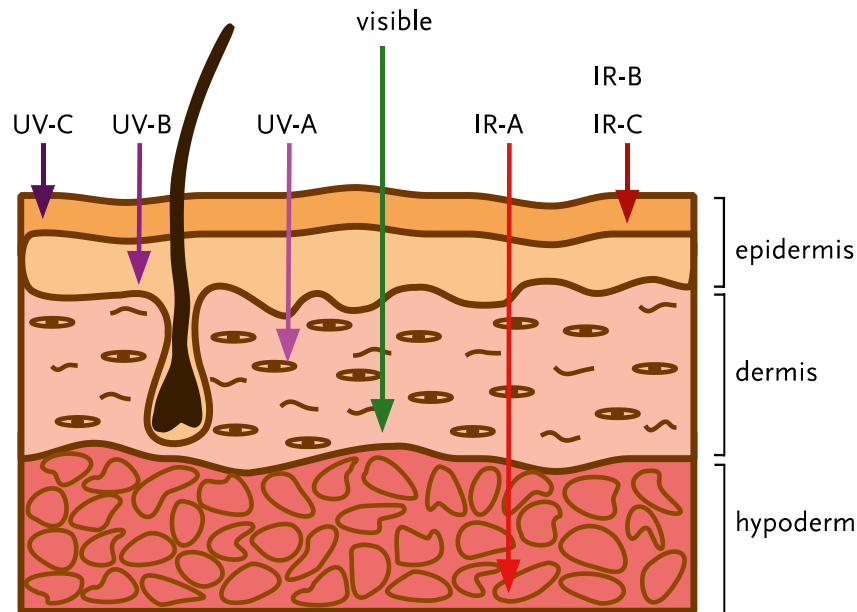


Retina burns
400nm – 1400nm

Can occur slowly due to accumulative damage from prolonged exposure to UV light (or very quickly due to UV)

Burns can occur quickly and from a wide variety of visible and invisible laser wavelengths. Typically permanent and irreversible damage

Skin penetration depth of optical radiation



Optical radiation hazards to the skin:

- Ultra Violet:** Skin burn, melanoma, accelerated skin aging, increased pigmentation.
- Visible:** Skin burn, photosensitive reactions, pigment darkening.
- Infrared:** Skin burn.

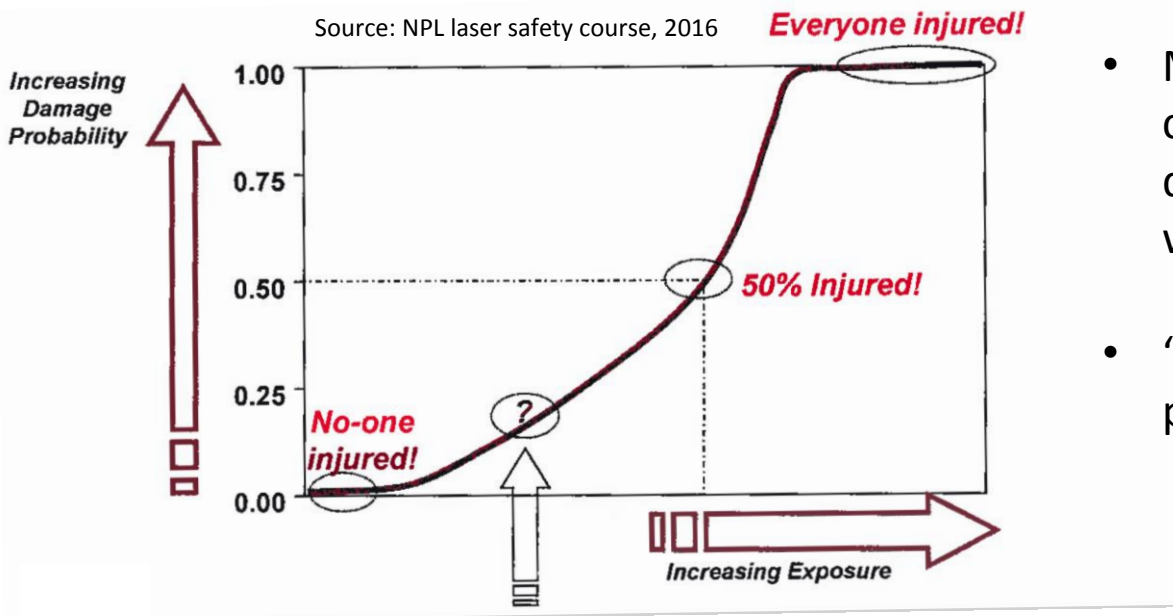
How much laser light is safe?

How much laser radiation is unlikely to cause damage?

- Limits on exposure to laser radiation during *accidental exposure*, that are currently deemed to be `safe', are captured by **'Maximum Permissible Exposures' (MPEs)**
- MPEs are published in tables by the IEC (60825-14.pdf). Most recent revision to date (2016) was in 2014.
- If you have an accident and are exposed to less than the MPE limit, then the probability of you suffering any damage is expected to be low.
- To identify the appropriate MPE for your situation you need to specify
 - Body part you are thinking about (eye or skin)
 - Laser wavelength and emission temporal profile (pulsed/CW)
 - Appropriate maximum accidental exposure time (set largely by laser wavelength)
- To understand and apply the MPE you need to know
 - Appropriate limiting aperture it applies to (model of relevant exposure area)
 - Underlying damage mechanism

Where MPEs come from

- Generic Dose Response Curve for Retinal Laser Exposure



- MPEs come from experiments collected by the IEC that determine statistical thresholds for when damage starts to occur
- “many tests done on US military personnel in 1960s”
-NPL laser safety course 2016

The MPEs are set at 10% of the exposure for which 50% of the people reported ‘injury’

MPE table for the EYE (*well-collimated laser beams*)

Table 5 – Maximum permissible exposure (MPE) at the cornea for direct exposure to laser radiation

10³

Wavelength λ in nm	Exposure time t in seconds (s)										
	10 ⁻¹³ to 10 ⁻¹¹	10 ⁻¹¹ to 10 ⁻⁹	10 ⁻⁹ to 10 ⁻⁷	10 ⁻⁷ to 1,8 × 10 ⁻⁵	1,8 × 10 ⁻⁵ to 5 × 10 ⁻⁵	5 × 10 ⁻⁵ to 1 × 10 ⁻³	1 × 10 ⁻³ to 10	10 to 10 ²	10 ² to 10⁴	10 ³ to 3 × 10 ⁴	
180 to 302,5	30 J·m ⁻²										
302,5 to 315	3 × 10 ¹⁰ W·m ⁻²		$(t \leq T_1)$ C ₁ J·m ⁻²				$(t > T_1)$ C ₂ J·m ⁻²		C ₂ J·m ⁻²		
315 to 400			C ₁ J·m ⁻²					10 ⁴ J m ⁻²		10 W m ⁻²	
400 to 450 ^a	1,5 × 10 ⁻⁴ J·m ⁻²	2,7 × 10 ⁴ t ^{0,75} J·m ⁻²	5 × 10 ⁻³ J·m ⁻²	18 t ^{0,75} J·m ⁻²			100 J·m ⁻²	C ₃ W·m ⁻²			
450 to 500 ^a							100 C ₃ J·m ⁻²				
500 to 700 ^a							10 W·m ⁻²				
700 to 1 050 ^a	1,5 × 10 ⁻⁴ C ₄ J·m ⁻²	2,7 × 10 ⁴ t ^{0,75} C ₄ J·m ⁻²	5 × 10 ⁻³ C ₄ J·m ⁻²	18 t ^{0,75} C ₄ J·m ⁻²			10 C ₄ C ₇ W·m ⁻²				
1 050 to 1 400 ^a	1,5 × 10 ⁻³ C ₇ J·m ⁻²	2,7 × 10 ⁵ t ^{0,75} C ₇ J·m ⁻²	5 × 10 ⁻² C ₇ J·m ⁻²		90 t ^{0,75} C ₇ J·m ⁻²						
1 400 to 1 500	10 ¹² W·m ⁻²		10 ³ J·m ⁻²			5 600 t ^{0,25} J·m ⁻²		1 000 W·m ⁻²			
1 500 to 1 800	10 ¹³ W·m ⁻²		10 ⁴ J·m ⁻²								
1 800 to 2 600	10 ¹² W·m ⁻²		10 ³ J·m ⁻²			5 600 t ^{0,25} J·m ⁻²					
2 600 to 10 ⁶	10 ¹¹ W·m ⁻²		100 J·m ⁻²	5 600 t ^{0,25} J·m ⁻²							

NOTE 1 For correction factors and units, see Table 8.

NOTE 2 The MPEs for exposure times below 10⁻⁹ s and for wavelengths less than 400 nm and greater than 1 400 nm have been derived by calculating the equivalent irradiance from the radiant exposure limits at 10⁻⁹ s. The MPEs for exposure times below 10⁻¹³ s at all wavelengths are set to be equal to the equivalent irradiance values of the MPEs at 10⁻¹³ s.

^a The MPEs given in this table for the wavelength range 400 to 1 400 nm (the retinal hazard region) apply to apparent source sizes no greater than 1,5 mrad. (This covers the direct viewing of most single laser sources.) Increased limits that are applicable to larger sources (such as certain multiple sources or diffuse reflections) are given in Table 6.

^b In the wavelength range between 450 nm and 500 nm, dual limits apply for exposure durations from 10 to 100 s and the exposure must not exceed either limit applicable.

- For each λ and time, there is an MPE
- **Only one MPE applies to any given situation.** You have to determine it. Let's call it the **MPE limit**
- Two other tables (skin & extended sources)
- Reference made to additional 'correction factor' table ('C' numbers)
- Note different units (Wm⁻² or Jm⁻²)
- Suspect Wm⁻² means thermal limit while Jm⁻² means non thermal limit

MPE table for the EYE (collimated laser beams, apparent source size < 1.5 mrad)

Table 5 – Maximum permissible exposure (MPE) at the cornea for direct exposure to laser radiation

Wavelength λ in nm	Exposure time t in											
	10^{-13} to 10^{-11}	10^{-11} to 10^{-9}	10^{-9} to 10^{-7}	10^{-7} to $1,8 \times 10^{-5}$	$1,8 \times 10^{-5}$ to 5×10^{-5}	5×10^{-5} to 1×10^{-3}	1×10^{-3} to 10	10 to 10^2	10^2 to 10^4	10^3 to 3×10^4		
180 to 302,5							$30 \text{ J}\cdot\text{m}^{-2}$					
302,5 to 315	$3 \times 10^{10} \text{ W}\cdot\text{m}^{-2}$		$(t \leq T_1)$				$C_2 \text{ J}\cdot\text{m}^{-2}$		$C_2 \text{ J}\cdot\text{m}^{-2}$			
315 to 400			$C_1 \text{ J}\cdot\text{m}^{-2}$				$(t > T_1)$		$10^4 \text{ J}\cdot\text{m}^{-2}$		$10 \text{ W}\cdot\text{m}^{-2}$	
400 to 450 ^a	$1,5 \times 10^{-4} \text{ J}\cdot\text{m}^{-2}$		$2,7 \times 10^4 t^{0,75} \text{ J}\cdot\text{m}^{-2}$		$5 \times 10^{-3} \text{ J}\cdot\text{m}^{-2}$		$18 t^{0,75} \text{ J}\cdot\text{m}^{-2}$		$100 \text{ J}\cdot\text{m}^{-2}$		$C_3 \text{ W}\cdot\text{m}^{-2}$	
450 to 500 ^a									$100 C_3 \text{ J}\cdot\text{m}^{-2}$			
500 to 700 ^a							$6.3 \text{ J}\cdot\text{m}^{-2}$		$10 \text{ W}\cdot\text{m}^{-2}$			
700 to 1 050 ^a	$1,5 \times 10^{-4} C_4 \text{ J}\cdot\text{m}^{-2}$		$2,7 \times 10^4 t^{0,75} C_4 \text{ J}\cdot\text{m}^{-2}$		$5 \times 10^{-3} C_4 \text{ J}\cdot\text{m}^{-2}$		$18 t^{0,75} C_4 \text{ J}\cdot\text{m}^{-2}$		$10 C_4 C_7 \text{ W}\cdot\text{m}^{-2}$			
1 050 to 1 400 ^a	$1,5 \times 10^{-3} C_7 \text{ J}\cdot\text{m}^{-2}$		$2,7 \times 10^5 t^{0,75} C_7 \text{ J}\cdot\text{m}^{-2}$		$5 \times 10^{-2} C_7 \text{ J}\cdot\text{m}^{-2}$		$90 t^{0,75} C_7 \text{ J}\cdot\text{m}^{-2}$					
1 400 to 1 500	$10^{12} \text{ W}\cdot\text{m}^{-2}$				$10^3 \text{ J}\cdot\text{m}^{-2}$		$5 600 t^{0,25} \text{ J}\cdot\text{m}^{-2}$		$1 000 \text{ W}\cdot\text{m}^{-2}$			
1 500 to 1 800	$10^{13} \text{ W}\cdot\text{m}^{-2}$				$10^4 \text{ J}\cdot\text{m}^{-2}$							
1 800 to 2 600	$10^{12} \text{ W}\cdot\text{m}^{-2}$				$10^3 \text{ J}\cdot\text{m}^{-2}$		$5 600 t^{0,25} \text{ J}\cdot\text{m}^{-2}$					
2 600 to 10^6	$10^{11} \text{ W}\cdot\text{m}^{-2}$		$100 \text{ J}\cdot\text{m}^{-2}$		$5 600 t^{0,25} \text{ J}\cdot\text{m}^{-2}$							

NOTE 1 For correction factors and units, see Table 8.

NOTE 2 The MPEs for exposure times below 10^{-9} s and for wavelengths less than 400 nm and greater than 1 400 nm have been derived by calculating the equivalent irradiance from the radiant exposure limits at 10^{-9} s. The MPEs for exposure times below 10^{-13} s at all wavelengths are set to be equal to the equivalent irradiance values of the MPEs at 10^{-13} s.

^a The MPEs given in this table for the wavelength range 400 to 1 400 nm (the retinal hazard region) apply to apparent source sizes no greater than 1,5 mrad. (This covers the direct viewing of most single laser sources.) Increased limits that are applicable to larger sources (such as certain multiple sources or diffuse reflections) are given in Table 6.

^b In the wavelength range between 450 nm and 500 nm, dual limits apply for exposure durations from 10 to 100 s and the exposure must not exceed either limit applicable.

- For each λ and time, there is an MPE
- **Only one MPE applies to any given situation.** You have to determine it. Let's call it the **MPE limit**
- Two other tables (skin & extended sources)
- Reference made to additional 'correction factor' table ('C' numbers)
- Note different units ($\text{W}\cdot\text{m}^{-2}$ or $\text{J}\cdot\text{m}^{-2}$)
- Suspect $\text{W}\cdot\text{m}^{-2}$ means thermal limit while $\text{J}\cdot\text{m}^{-2}$ means non thermal limit

Identifying the MPE limit for given situation

- Need to identify the appropriate accidental exposure time

Excerpt from 60825-14.pdf:

The exposure duration used in determining the MPE should be based on the **maximum duration of accidental exposure that could reasonably be expected to occur**, taking into account the wavelength of laser emission and the conditions under which the laser might be used.

Under worst-case conditions of accidental exposure, 100 s may be used as the maximum duration of exposure for laser radiation at wavelengths above 400 nm, and 30 000 s for wavelengths below 400 nm where longer-term photochemical effects may be initiated. This longer time-base is applicable in circumstances where repeated or prolonged exposure to ultraviolet radiation could occur without an immediate apparent effect, but is clearly not realistic in the case of direct accidental exposure to a high-power ultraviolet laser beam where immediate and obvious injury would be caused.

For accidental exposure to visible laser radiation (400 nm – 700 nm) where purposeful staring is not intended or anticipated, the aversion response time of 0,25 s may be used.

Wavelength	Accident time	Comment
< 400 nm (UV)	8 hrs	Sitting all day in scattering, accumulative damage
	100 s	Accidental exposure to invisible light
400 – 700 nm (visible)	0.25 s	Blink reflex
> 700 nm (IR)	100 s	Accidental exposure to invisible light

- For CW light, you can now read off the appropriate MPE value

What does the MPE mean?

- No more than the MPE may pass through a certain aperture right at the front of the eye (cornea), or skin, during the accidental exposure time

Table 2 – The diameter of the limiting aperture applicable to measurements of irradiance and radiant exposure (t is the exposure duration)

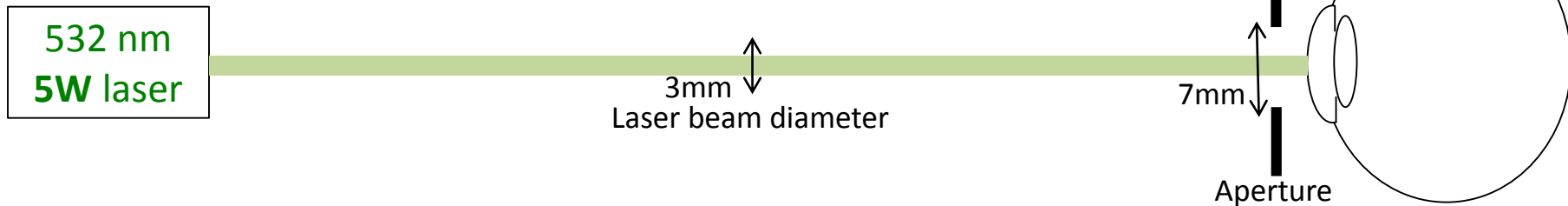
Spectral region nm	Aperture diameter for	
	Eye mm	Skin mm
180 to 400	1	3,5
≥ 400 to 1 400	7	3,5
$\geq 1\ 400$ to 10^5	1 for $t \leq 0,35$ s 1,5 $t^{3/8}$ for $0,35$ s $< t < 10$ s 3,5 for $t \geq 10$ s	3,5
$\geq 10^5$ to 10^6	11	11

- The MPE relates to the value of the exposure (Jm^{-2} or Wm^{-2}) when **averaged** over a circular area called the limiting aperture.
Implication: does not depend on how the light goes through the limiting aperture.
- Plan to change MPE presentation in future (2016 60825 docs revision)*

Example MPE calculation for the eye, 1

- 532 nm collimated CW laser
 - Damage to retina (photochemical and thermal effects)
 - Max accidental exposure time = 0.25 s (blink reflex triggered)
 - MPE limit = 6.3 Jm^{-2}
 - Limiting aperture with 7 mm diameter and area A)
 - ↳ ➤ No more than $(6.3 \times A)$ Joules = 0.24 mJ, through aperture during 0.25 s
 - ↳ ➤ I prefer to convert to power. 0.24 mJ for 0.25s is a little less than 1mW
 - ↳ ➤ If you blink, a 1mW green CW laser beam hitting your eye reaches MPE
 - ↳ ➤ **Take steps to ensure no more than 1mW can ever hit your eye!**

- **Application to a particular situation:** direct hit from collimated beam



- What to do?
 - 1. Eliminate, as far as is reasonable, the possibility of such an accident occurring
 - 2. Wear OD4 goggles (LB5) when working with this laser (factor 10000 reduction)

Example MPE calculation for the eye, 2

- 729nm collimated CW laser
 - Damage to retina (thermal only, as far as seems to be known)
 - Max accidental exposure time = 100 s
 - MPE limit = 11.5 Wm^{-2}
 - Limiting aperture = 7 mm diameter and area A
 - So no more than $11.5 \times A$ Watts = 0.44 mW should pass through aperture for 100s
 - 0.44mW is continuous MPE power limit for 100s exposure (valid from 10s to 8hrs)
 - Implication: Retina doesn't heat up appreciably at this power (can continuously dissipate heat deposited by laser well enough)
 - **Take steps to ensure that no more than 0.44mW can ever hit your eye!**

Pulsed lasers

For exact (confusing) wording or rules see 60825-14.pdf page 28)

The MPE is determined by the most restrictive of (up to) three requirements

Ben's first-level summary:

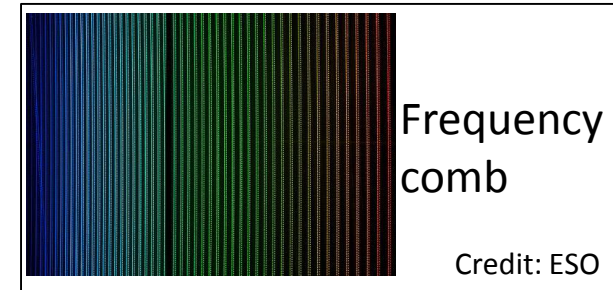
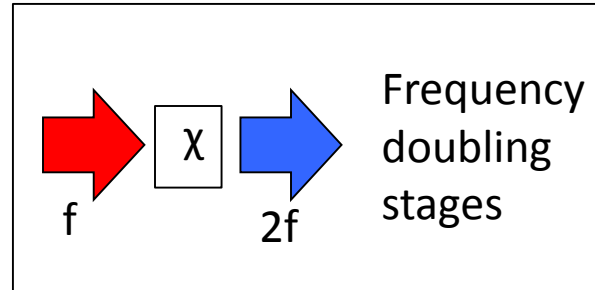
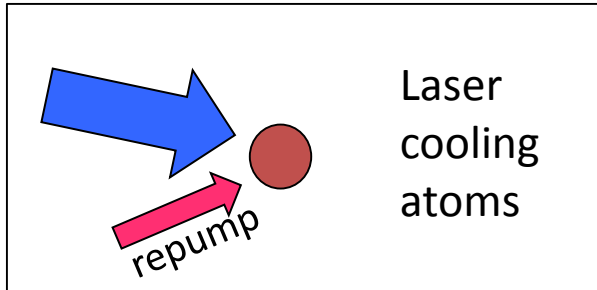
1. The energy for any single pulse in a train must not exceed the MPE for a single pulse *(The wording here is to take into account that trains could contain different pulses shapes and energies)*
1. The total energy from a pulse train of duration T shall not exceed the MPE for a single pulse of exposure duration T. *(Here T is the maximum foreseen accidental exposure time, assessed the same as for CW lasers. This MPE is the same as treating the laser as CW)*
1. The energy in any single pulse in a pulse train of length T shall not exceed the MPE for a single pulse multiplied by the correction factor C5. *(This correction factor aims to takes into account that the cumulative effect of N sequential pulses is worse than N x that of a single pulse.)*

Requirement 3 does not apply for wavelengths > 400 nm (only 1 and 2 apply)
(because requirements 3 only applies to thermal damage processes, not photochemical)

Brief summary:

1. No single pulse alone should cause damage
2. The effective CW power during the 'accidental max exposure time' should not cause damage
3. The cumulative effect of pulses during the 'accidental exposure time' should not cause damage

Multi-wavelength situations



- Reducing each wavelength below its individual MPE is rarely sufficient.
- Example: the MPE power limits for CW 854nm and 866nm are both 0.7mW. It is not OK to have 0.7mW of each hitting the eye simultaneously. In each case, the damage processes is thermal and to the retina. Effects are additive. The total power should therefore be no more than 0.7mW.
- The 60825-14.pdf has the definitive information on this potentially complex topic.
- Consider that wavelengths that damage the same body part in the same way will be additive. For example some UV and IR both affect the front of the eye.
- May need goggles with suitable level of protection for both wavelengths simultaneously (challenge to retain sufficient visibility to work)

MPE summary and remarks

- It is important to assess the maximum level of exposure that could arise in your lab under all foreseeable conditions and then relate this to the MPE.
- Take all reasonable measures to ensure that $> \text{MPE}$ does not occur (self-learning, training, shields, curtains, no loose optics,, goggles).
- Exposure to below MPE can still be uncomfortable and extremely distracting: secondary hazards (crash the plane or knock over some optics)
- It is not OK to intentionally expose yourself even to less than the MPE.
- The MPE values take into account current understanding of many physical effects e.g. increased chance of eye damage in blue spectral region ('blue hazard')


MPE summary and remarks

- For extended radiation sources (e.g. diffuse radiation spots, laser arrays) there are slightly more relaxed MPEs for 400nm to 1400nm as images are formed on the retina (table 7 60825-14.pdf).
- Don't get eye/skin near tight focuses! (non-linear crystals, ...).
- For > 400nm CW lasers, take measures to ensure that no more than 0.4mW ever hits your eye and no more than 10mW hits your skin.
- For 315 – 400nm CW lasers, the numbers are similar for few second accidental exposures. For longer exposures you need to consider accumulative damage and think rather in terms of doses (like nuclear radiation and sun exposure) that come into play at much smaller power levels (a few ten microns or much less could be your daily max accidental dose).

How to be safer (rules, standards and tips)

Hierarchy of Risk Controls

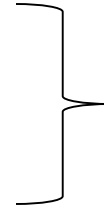
- Eliminate the hazard
 - Do we need lasers? (yes, for some things)
 - Do we really need such a high power laser?
- Reduce the hazard
 - Reduce the laser beam power
 - Spend money on more efficient optics and fibers
- Remove the person from hazard
 - Remote desktop, strict access policies
- Contain hazard by enclosure
 - Curtains, barriers, beam containers, fibers
- Reduce employee exposure
 - Build longterm-stable experiments for minimal maintenance.
 - Limit lab time.
 - Spend money on low-power beam visualisation devices
- Implement Safe Systems of work
 - Clear floor policy, permits to work...
- Personal protective equipment
 - Goggles, gloves..

- 
1. Eliminate
 2. Reduce
 3. Protect

Types of laser safety control

- Engineering controls

- e.g. Interlocks on door, physical enclosure
- Installed shields, beam blocks, curtains...
- Experimental design



- Powerful, as don't rely much on user behavior.
- Shields around optical tables are one of most important safety mechanism we have.
- Catch user error

- Administrative controls

- Local rules and procedures
- User registers, warning signs
- Training, permits to work



- Reply on user behavior and need continual updating
- Needs dedicated supervision

- Personal protective equipment

- Goggles and gloves



- Heavily rely on user behavior
- Will be used incorrectly at some point
- Great danger if used incorrectly
- Last line of defense

How to be safe: examples of engineering controls

*Most laser safety mistakes that we
make are caught by engineering
controls*

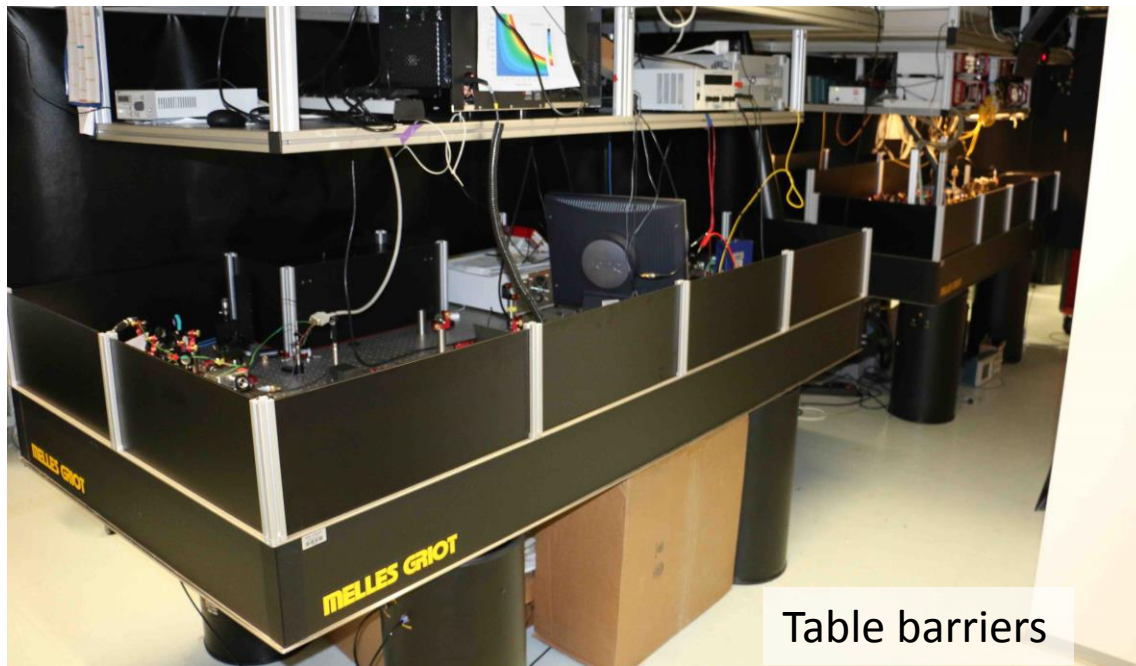
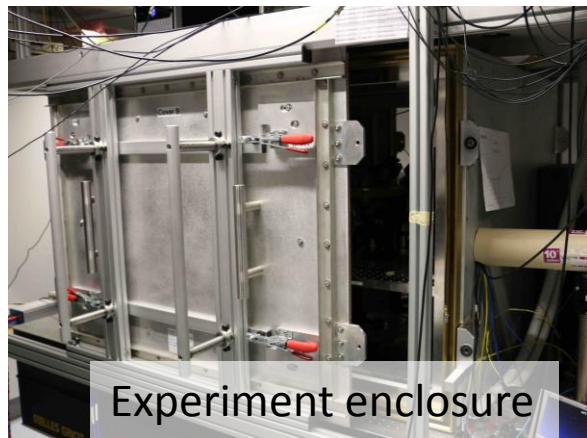
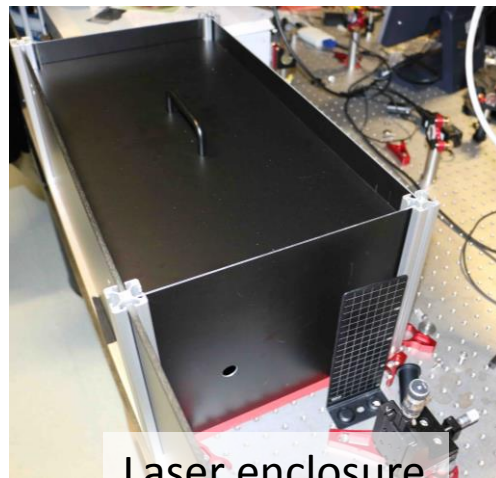


Table barriers



Experiment enclosure



Laser enclosure



Workspace enclosure

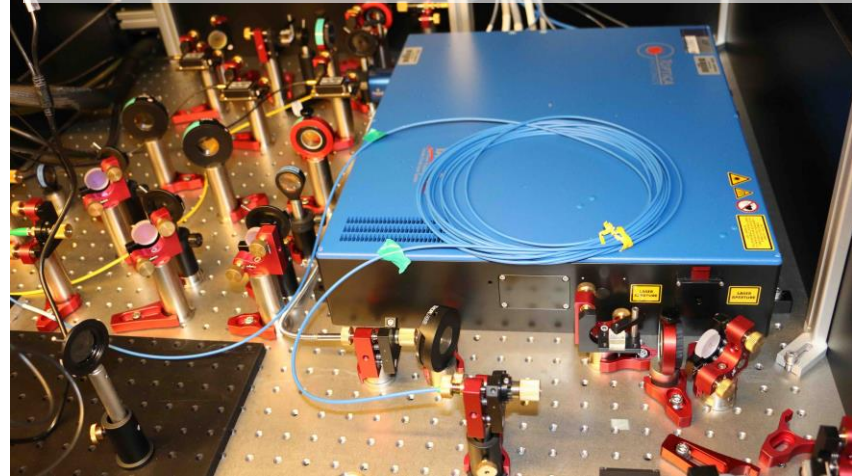
How to be safe: engineering controls. Examples

Most laser safety mistakes that we make are caught by engineering controls

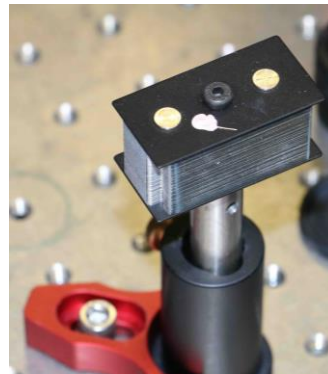
Fiber coupling (fiber-coupled lasers)



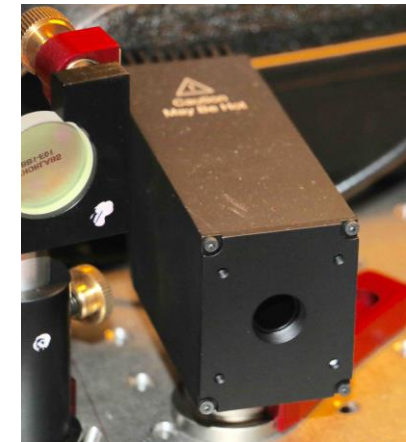
Fiber de-coupling (e.g. laser-fiber-setup)



Fixed beam heights



Visible to NIR low power beam block



UV high power beam block

Administrative controls: signs and lights

“Signs must include this symbol



and should indicate type of hazard(s), the restrictions on access that are in force and the precautions to be adopted on entry. Useful to include name of person responsible for area and from whom further information can be obtained.”

“Illuminated warning signs may be used on the outside of laser controlled areas, to indicate when the laser(s) are in use. They should clearly indicate when safe and when not, to enter the area

Quotes from: [60825-14.pdf](#) page 41 & 42

High resolution digital version of the above symbol can be downloaded from https://en.wikipedia.org/wiki/Laser_safety

Administrative controls: signs and lights

Based on that, I would suggest having the following 4 things on the outside of lab doors:



Official sign of most dangerous laser present (carefully designed)

LASERS IN THIS LAB			
Class	Wave length	Type & Power	Goggles required
4	532 nm Visible	4W CW	OD4, LB5
4	1550 nm Invisible	4W pulsed	OD5, LB5
....

Entry rules	
1	If laser sign is illuminated then knock, but do not enter without permission
1	If laser sign not illuminated then knock, enter and speak
1	No bags & please don't touch tables



← Laser-in-operation illuminated sign
 Questions: is it automatic or manual? What do you want it to mean when it is on/off?

Keep signage to absolute minimum, up-to-date, take down old signs, clearly visible and legible (Austrian AUVA says: text, bordering and symbols must be black on yellow background for all warning signs). Max one temporary sign to notify users of changes.

Administrative controls: lab policies

Example policies:

- Clear floor and walk-way
- No unsecured optics/optomechanics on the tables
- No optics inserted into live beams
- All laser barriers must be inserted if you leave the room
- Two people present when working with high voltage (>50V)
- Requirement to attend laser-safety course & pass test every 2 years
- Visitor policies (see earlier)
- Do not remove laser safety barriers unless absolutely necessary
- All accidents or near-accidents must be reported (see later)
- Group leader must approve people to work on certain equipment

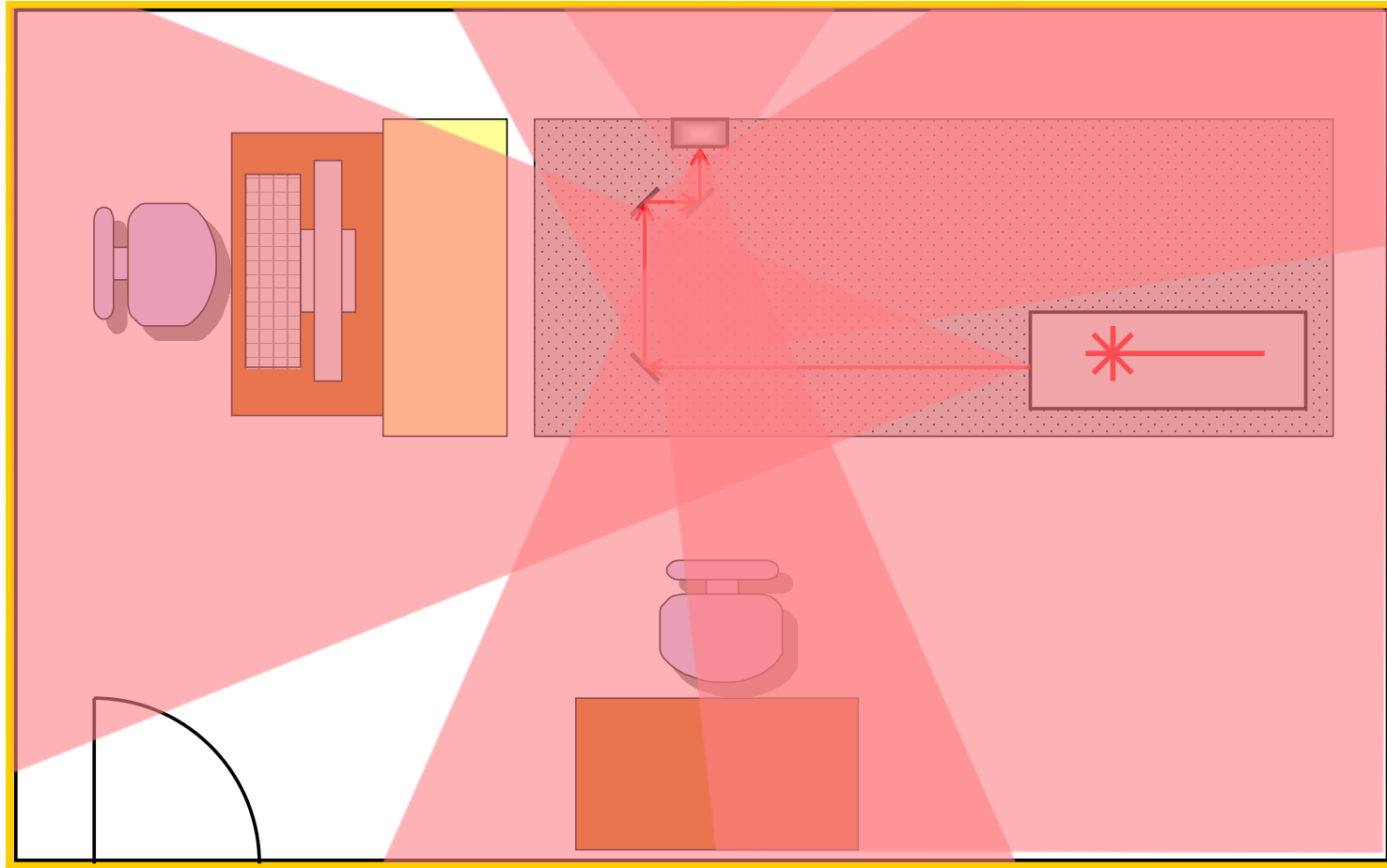
Policies must be strictly enforced or they become redundant

Suggested location for lab policy list: inside lab door

Laser Control Area (LCA)

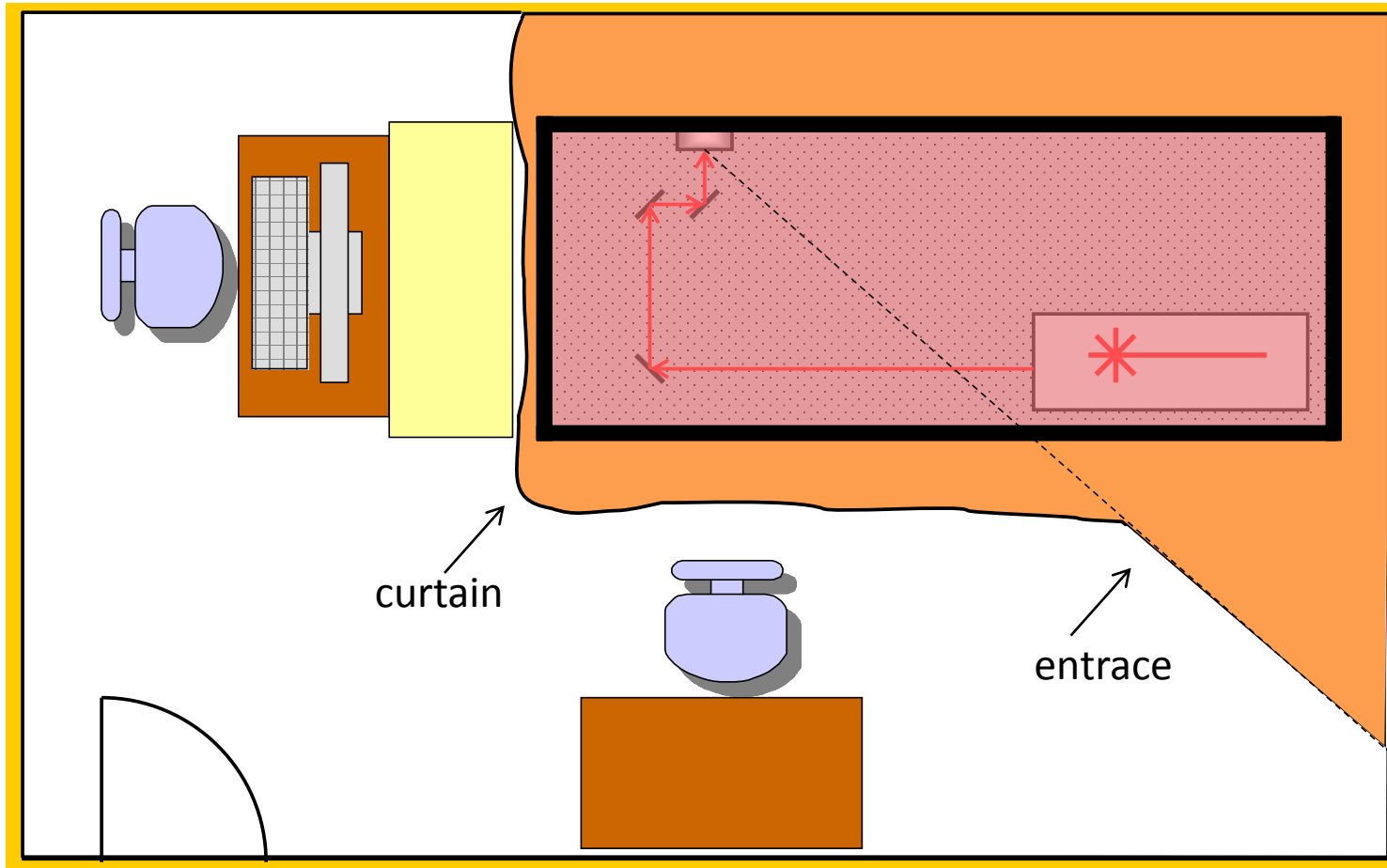
- The LCA is considered to be the area within which there is the **possibility** for there to exist accessible laser emissions in excess of the Maximum Permissible Exposure (MPE) limit for that given laser.
- Protective laser eye wear is to be worn whenever you are inside the LCA
- An LCA is considered to be both an engineering control as well as an administrative control (things are installed but also you need to behave correctly).

Laser Control Area (LCA)



- Even simple “conventional” optical layouts can potentially expose large areas of the lab room to laser light in excess of the MPE.
- Only a small angular change of the laser beam, or of one optical element, could radically change the beam path.
- Even the outside hallway could also be affected.

Laser Control Area (LCA)



- Table-edge barriers prevent problems at beam-height
- Laser safety curtain prevents problems at all heights and is retractable for greater flexibility
- Entrance/Exit chosen to avoid exposure to working areas.
- Beam-path enclosures could also be used to eliminate the risk to people inside curtain

Safely setting up and working with optical experiments (tips)

- Think about LCA when you are working on a setup. It is not OK to risk other people.
- Remove watches and other wrist/hand jewelry
- Low power alignment and buy low power detectors, filters, cameras, imaging cards.
- Don't put optics into beam
- Get a good supply of suitable beam blocks
- Think about what it would take for uncontrolled beams to occur: (look around, see if cables are hanging loose, think about choice to put beam on the edge of mirror (how far downstream is it?). Is a barrier missing?)
- Keep your workspace clear
- Leave space between optics to make beam analysis straightforward
- Install calibrated photodiodes to monitor system without the need to insert a power meter
- Secure loose cables and objects from above that could fall into the beam

Safely setting up and working with optical experiments (tips)

- Consider using efficient optical fiber decoupling of optical setups (if the 1st part misaligns, the 2nd part wont)
- Make stable systems that minimize the need for realignment. If having to realign a lot, then change the system.
- Could you easily add an enclosure, beam tubes, housing, lid? Who can help you with that? Talk to the workshop about possibilities, they have done most things many times.
- Watch out for cavities and 'filters' back reflecting
- Lock down power distribution control systems (e.g. waveplate + PBS), think when you change them!
- How is power being determined in your setup, could it be increased by accident? How?
- Is your beam stop absorbing (best), causing diffuse (worse) or specular reflections (worse still), flammable (horrible)?
- Don't use inappropriate materials for a beam block. Raise the standard of your temporary solutions. (black card may be 'OK' for a few mW, but if someone turns up the power later.....)
- Do you really need to output e.g. 2W from the laser, when you only need a few mW for the experiment?

General lab behavior

- Don't spend anytime with eyes open at standard beam height.
- If you are sitting and can see a mirror, then there is a problem. Fix it.
- A clear and tidy lab and workspace is important. It can be achieved by clearing up promptly after yourself and devoting time each day to tidy up in general (before/after lunch?).
- Be aware that new people will probably pick up your bad laser safety habits. Fix them.
- Don't accidentally bully people who raise concerns about laser safety
- Take time to think about laser safety when making a change in the lab
- Think about other people who aren't wearing goggles
- Never leave the lab with dangerous situation for other people

Put a list up on the door listing basic lab behaviors and enforce them.

Personal protective ware (goggles and gloves)

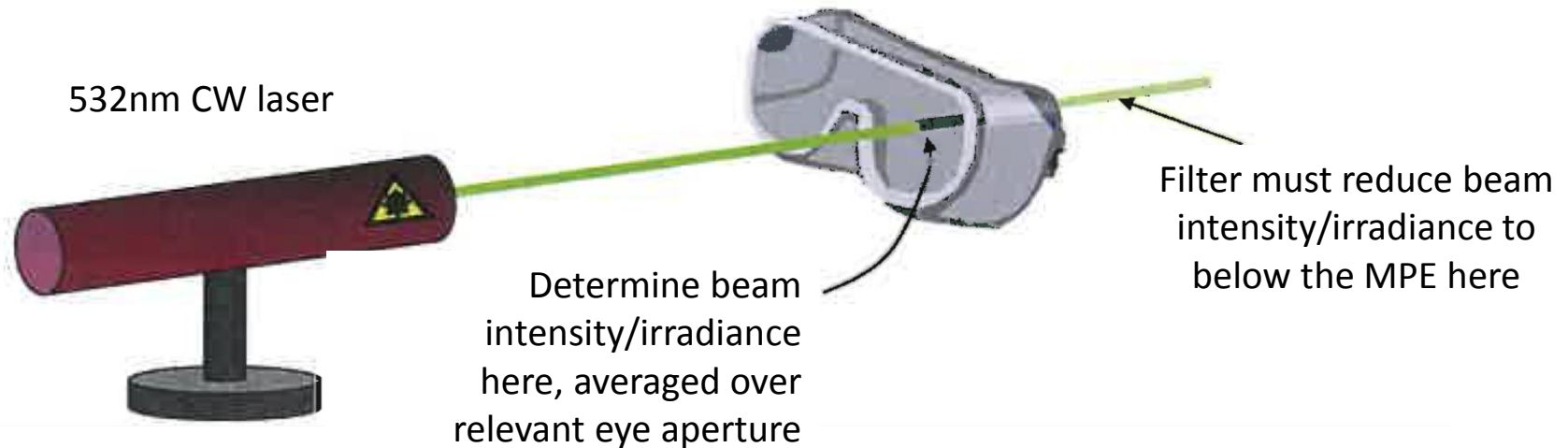
Laser safety goggles: the official word

Paraphrased from 60825-14 doc, pg 44:

- Where appropriate, laser protective eyewear should be worn in laser controlled areas.
- Only when not reasonably practicable to provide protection by other means
 - Cannot fully enclose laser system
 - Risk assessment confirms goggle suitability.
- If required then they are compulsory
 - Personnel cannot refuse to wear it!
- Laser safety eyewear standards
 - EN 207 'laser eye protectors'
 - EN 208 'adjustment laser eye protectors'
- Protective eyewear must:
 1. Reduce the maximum reasonably foreseeable laser exposure to below the MPE limit ('safe' level).
 2. Be capable of withstanding the maximum reasonably foreseeable laser exposure long enough for corrective action to be taken to terminate exposure (10 seconds).
 3. Allow the wearer to use the eyewear without discomfort or any significant degradation in vision.
- Goggles are designed to protect against accidental exposure. Not for deliberate viewing!
- Using the wrong goggles increases the danger significantly

Goggle criteria: sufficient optical depth

- Laser goggles aim to filter transmitted laser radiation via absorption (or reflection).

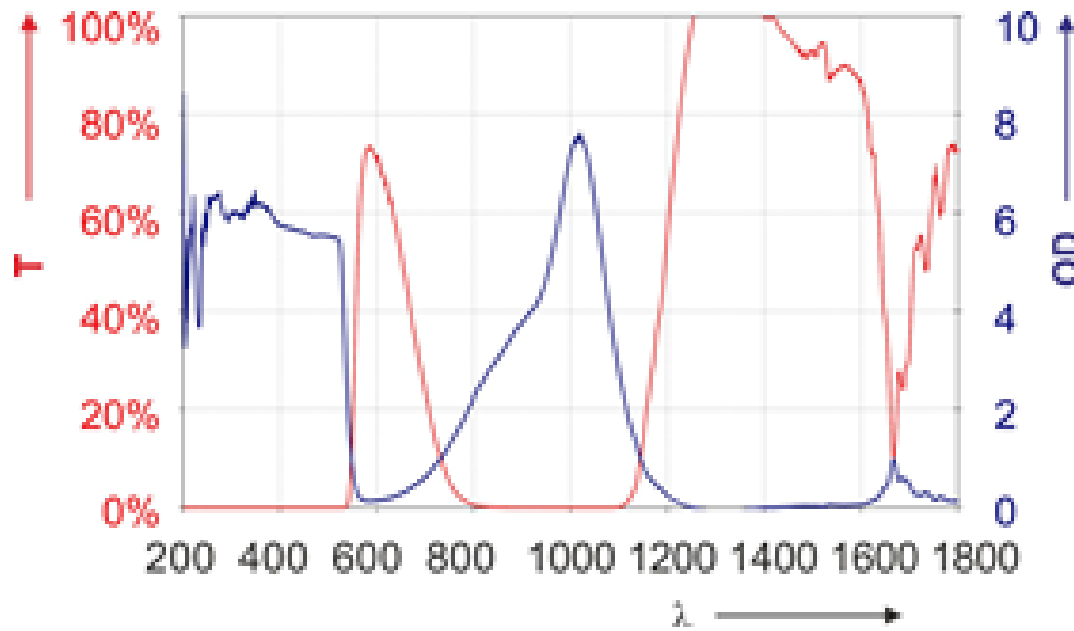


$$\text{Filter Optical Density OD} = \text{Log}_{10} \left[\frac{\text{Incident beam Int./Irr.}}{\text{MPE}} \right]$$

Example: 1 W 532nm CW laser, 2 mm beam diameter.

MPE(532nm, CW, 0.25s) = 6.3 Jm^{-2} through a 7mm diameter aperture, corresponding to a power of 1mW. All 5W would go through a 7mm aperture, so the laser power needs to be reduced 5000 times by the goggles. Therefore the required OD at 532nm is at least 4.

Goggle criteria: sufficient optical depth

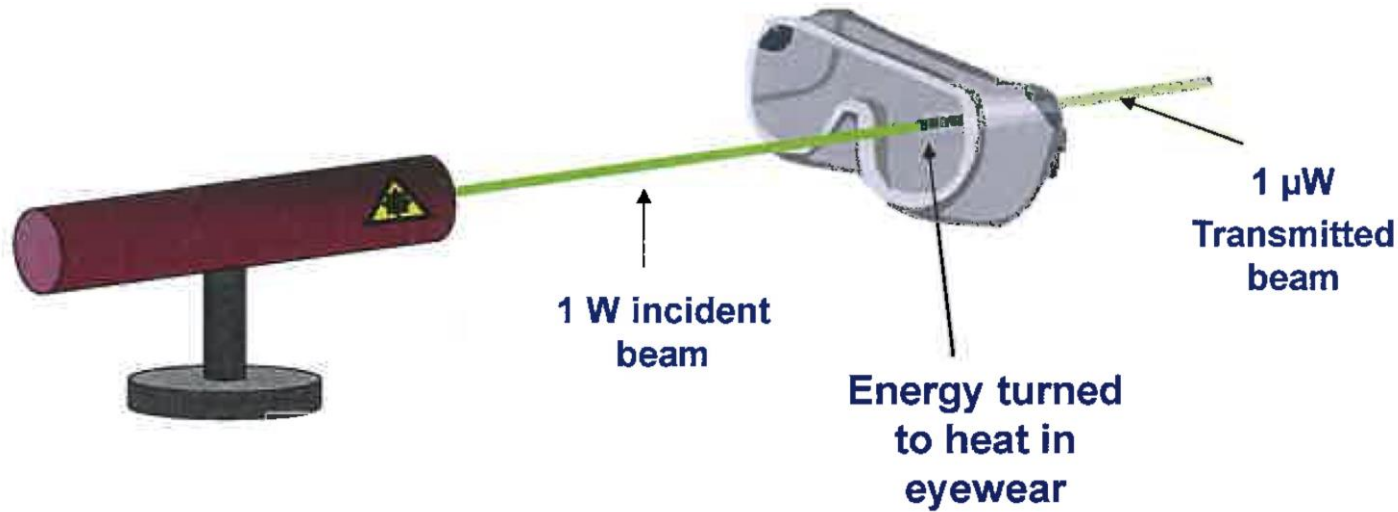


(Image needs to be replaced. I have emailed Michael Lindauer at LaserVision Austria)

- OD 4+ at 532nm (confirmed from detailed specifications on request, or on goggles)
- So eyewear **could** be suitable (audience question: why might it not be?)
- Note that the filtering is strongly wavelength dependent
- High visible light transmission (40% specified online)

Goggles criteria: withstanding damage

- Optical depth is not enough to specify the eyewear



Laser beam can cause ignition and/or damage to the eyewear

This is the primary reason for the EN 207 standard, which tells you the max. intensity for which you have at least 10 seconds before failure to provide promised optical depth.



Laser safety goggles: EN207 norm

EN 207 is the European norm for laser safety eyewear. Any laser eye protection sold within the European Community must be certified and labeled with the CE mark. According to this standard, laser safety glasses should not only absorb laser light of a given wavelength, but they should also be able to withstand a direct hit from the laser without breaking or melting. In this respect, the European norm is more strict than the American norm (ANSI Z 136) that only regulates the required optical density. More precisely, the safety glasses should be able to withstand a continuous wave laser for 10 seconds, or 100 pulses for a pulsed laser.

See e.g.

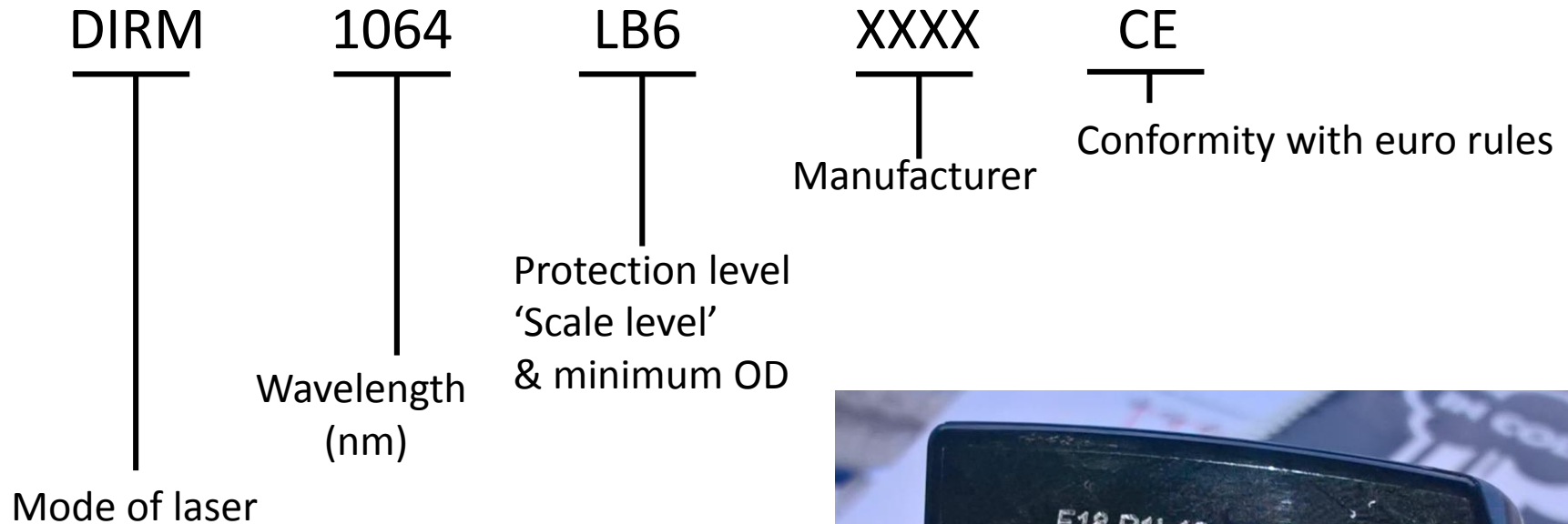
https://en.wikipedia.org/wiki/EN_207 for explanation

<http://www.edmundoptics.com/document/download/396278> for much better table

What the norm tells you about your European-bought goggles:

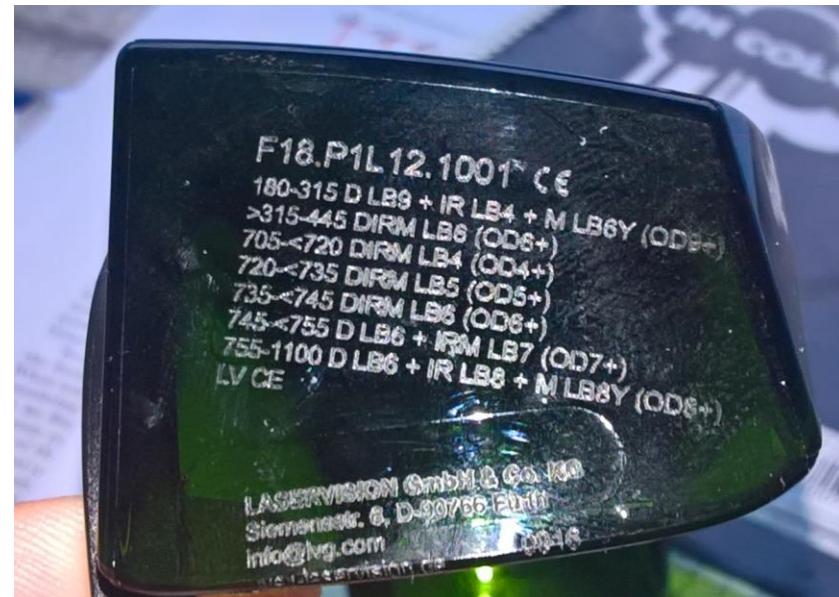
- The meaning of the symbols on the goggles
- **What the maximum intensity is that your goggles can stand**

Laser safety goggles: EN207 norm labeling



EN 207 specifies four laser working modes:

Working mode	Letter	Pulse length
Continuous wave	D	> 0.25 s
Pulsed mode	I	1 μ s–0.25 s
Giant pulsed mode	R	1 ns–1 μ s
Modelocked	M	< 1 ns



Laser safety goggles: EN207 norm

Now labeled as 'LB', e.g. LB3

(Table from Edmund Optics download)

EN207 – Classification and Specifications of filters and eye protection against Laser										
Scale number	Max spectral transmittance At Laser Wavelength	Maximum power (E) and/or energy (H) density in the wavelength range								
		180nm to 315nm			>315nm to 1400nm			>1400nm to 1000 microns		
		D W/m ²	I,R J/m ²	M W/m ²	D W/m ²	I,R J/m ²	M J/m ²	D W/m ²	I,R J/m ²	M W/m ²
L1	10 ⁻¹	10 ⁻²	3x10 ²	3x10 ¹¹	10 ²	5x10 ⁻²	1.5x10 ⁻³	10 ⁴	10 ³	10 ¹²
L2	10 ⁻²	10 ⁻¹	3x10 ³	3x10 ¹²	10 ³	5x10 ⁻¹	1.5x10 ⁻²	10 ⁵	10 ⁴	10 ¹³
L3	10 ⁻³	1	3x10 ⁴	3x10 ¹³	10 ⁴	5	0.15	10 ⁶	10 ⁵	10 ¹⁴
L4	10 ⁻⁴	10	3x10 ⁵	3x10 ¹⁴	10 ⁵	50	1.5	10 ⁷	10 ⁶	10 ¹⁵
L5	10 ⁻⁵	10 ²	3x10 ⁶	3x10 ¹⁵	10 ⁶	5x10 ²	15	10 ⁸	10 ⁷	10 ¹⁶
L6	10 ⁻⁶	10 ³	3x10 ⁷	3x10 ¹⁶	10 ⁷	5x10 ³	1.5x10 ²	10 ⁹	10 ⁸	10 ¹⁷
L7	10 ⁻⁷	10 ⁴	3x10 ⁸	3x10 ¹⁷	10 ⁸	5x10 ⁴	1.5x10 ³	10 ¹⁰	10 ⁹	10 ¹⁸
L8	10 ⁻⁸	10 ⁵	3x10 ⁹	3x10 ¹⁸	10 ⁹	5x10 ⁵	1.5x10 ⁴	10 ¹¹	10 ¹⁰	10 ¹⁹
L9	10 ⁻⁹	10 ⁶	3x10 ¹⁰	3x10 ¹⁹	10 ¹⁰	5x10 ⁶	1.5x10 ⁵	10 ¹²	10 ¹¹	10 ²⁰
L10	10 ⁻¹⁰	10 ⁷	3x10 ¹¹	3x10 ²⁰	10 ¹¹	5x10 ⁷	1.5x10 ⁶	10 ¹³	10 ¹²	10 ²¹

Example: consider goggles with the label '**D LB4 532nm**'. From table one finds:

- Max spectral (energy) transmittance of 10⁻⁴ (min OD4)
- Maximum power density before goggle damage of 10⁺⁵ Wm⁻² (e.g. 0.31W, 2mm diam. beam)

Watch out! These goggles have sufficient attenuation to take a 1W 532nm CW (D) 2mm diam. beam to below the MPE eye limit, but the goggles are not designed to withstand this much intensity! For that much intensity (3.2x10⁵ Wm⁻²) one needs LB5

How to determine if you have the right goggles for a given laser

- It is everyone's responsibility to make sure that the correct goggles are present and clearly labeled (e.g. main λ and \approx max power)
- Ok, but are the ones I picked up from the bench suitable?
 - Determine/look up the MPE eye limit for your laser wavelength and type (e.g. CW)
 - Assess the maximum foreseeable accidental exposure intensity that could occur (e.g. direct hit of full power collimated beam. Laser should be labeled with its max power)
 - Ensure LB level is sufficient for goggles to tolerate such an accident
 - Ensure goggle OD is sufficient at your wavelength to reduce transmission to below the MPE
 - Check that the goggles are comfortable, fit well and do not significantly impede you carrying out your work (e.g. can't see well enough). If not, find and order better ones.

Gloves

To protect your hands e.g. when adjusting optics near beams that can damage the skin

- Micro watt level UV
- Milli watt level visible & IR

e.g.

LaserVision gloves: Laser resistance of 4.7 W/cm^2 @ 1064



- Laser resistance of 4.7 W/cm^2 @ 1064 before exceeding MPE for skin

Spot the mistakes

How many mistakes can you spot?



Final remarks

More laser safety advice and discussion:

- Talk to your assistant and other colleagues
- Blatt group laser safety
 - IQOQI: Ben Lanyon, Ext. 4724, ben.lanyon@uibk.ac.at
 - UIBK: Yves Colombe, Ext. 52465, yves.colombe@uibk.ac.at
 - Report all accidents and near-accidents to us both via email.
 - We are not trained laser safety officers but are happy to share our knowledge and experiences
- Refresh your laser safety knowledge every year or at least every two years.
 - Repeat the course and tests
 - At least it will bring it back to the forefront of your mind
 - It is a rapidly developing field and we must keep up

Final key note

- **Laser safety is a shared responsibility**
 - Everyone with access has a duty of care for their own safety as well as other personnel
 - Don't think it is someone else's responsibility
 - Take ownership of the problem: it's the grown up thing to do.
- **If in any doubt**
 - Stop what you are doing and ask for advice
 - Don't guess your way around a laser
- **Don't...**
 - leave the system in an unsafe condition, ever
 - Ignore or override safety features
 - Assume that an established experiment is laser safe
- **Do...**
 - Take your time
 - Keep your knowledge and awareness up-to-date
 - Check other peoples work for laser safety
 - Ask other people to check your work

This table is for CW laser light only, different rules apply for pulsed lasers

Table that I made presenting MPE

Values for a range of wavelengths:

Useful on the inside Of lab door, or perhaps next to the laser goggles.

Perhaps also include the EN207 table for goggles and reminder of symbols?

Conclusion of this table: Let's ensure that the CW laser power that could ever foreseeably hit the front of an eye is less than 1mW, and less than 10mW for the skin.

Calculated by Ben Lanyon, 1.11.2016 using IEC 60825-14 standards. Specifically, tables 5 (eyes) and 7 (skin). Could contain errors. A digital version (excel) can be found here: anna-c704.uibk.ac.at/all/LaserSafety/labdoortable_lanyon102016_lab1IQOQ/LAB1_lasertable

CW Laser	Max. accidental exposure for the EYE			Max. accidental exposure for the SKIN	
	Max. foreseeable accidental exposure duration	Relevant aperture diameter at eye front (mm)	Maximum power at front of EYE (through aperture in 3rd column, for the greater time than in 2nd)	Relevant aperture diameter on skin (mm)	Max power for 10 sec exposure over 3.5mm diameter spot (mW)
275	8hrs (10 ³)	1	0.7mW (2.3µW)	3.5	0.028
375	8hrs (10 ³)	1	8µW (0.8mW)	3.5	9
393	8hrs (10 ³)	1	8µW (0.8mW) ^b	3.5	9
397	8hrs (10 ³)	1	8µW (0.8mW) ^b	3.5	9
422	0.25 ³	7	0.9mW	3.5	19
532	0.25 ³	7	0.9mW	3.5	19
729	100 ³	7	0.4mW ^c	3.5	21
785	100 ³	7	0.5mW	3.5	28
785	100 ³	7	0.5mW	3.5	28
796	100 ³	7	0.6mW	3.5	29
844	100 ³	7	0.7mW	3.5	37
854	100 ³	7	0.7mW	3.5	39
866	100 ³	7	0.8mW	3.5	41
1901	100 ³	3.5	9.6mW	3.5	9

^aThis power is calculated in the following way. Consider the document 60825-14.pdf from the IEC, table 5 page 9. This table contains the maximum permissible exposures (W/m² or mW/m²) for collimated laser light. Rows are different wavelengths, columns are different exposure times. The exposure time choice is discussed on page 28, basically 0.25 seconds for visible 400-700nm, 8 hours for 700nm and 100s for >700nm. This allows the table element to be found. Each element gives either W/m² or mW/m². The former requires the time gain to convert to W/m². Once you have that then you need to know that this W/m² is the MPE through a well-defined aperture. The appropriate aperture is given in table 2 on page 25. Once you have the W/m², then multiply by the aperture area to get W. This is the maximum total power that is allowed to go through that aperture, when placed at the front of the eye. If the full pupil diameter in the visible regime (7mm) because this light will get focused onto the retina by the eye's smallest spots given by the largest possible input beam diameter. For 400nm and 1400nm, the light doesn't make it to the retina. Now smaller apertures taken at the front of the eye will trigger a bigger diameter input beam with the same power would not necessarily make things worse, as it would for the visible case).

END OF SLIDES!

Now please do the worksheet

- Divide up into groups of approximately 3
- Each person writes up answer separately.
- Hand in work, with name on, before you leave

Spare slides/notes

Why lasers are dangerous.

Extended non-collimated light sources (e.g. light bulb or the sun)

- Only fraction of emitted light enters eye

- Eye creates an extended image of source on retina

- Broad spectrum, little energy concentration at nasty wavelengths

- Pupil contraction and blink reflex triggered to help save sight

Collimated laser beam

- All or most of energy can enter eye, changing little with distance from source

- Eye creates near diffraction limited spot on retina

- Narrow spectrum, all energy can be concentrated at nasty wavelengths

- Many lasers do not trigger pupil contraction and blink reflex

- Pulsed lasers can destroy your vision in 1nS or less.

Standards and where they come from

- Europe:
 - laser manufacture standards 60825-1
 - ...how to classify a laser and how it should be labeled
 - User Laser safety standards 60825-14
 - ...determine maximum permissible exposures of body to laser.
 - specific focus on personal protective ware: EN207 and EN208
 - ...goggles required for given laser wavelength and power.
- Austrian derivative:
- American standards: