Laser Safety

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EUV

Modified from presentation by Henry C. Kapteyn, Steve Cundiff, Sterling Backus, and Margaret Murnane at JILA (NIST-CU)

Thanks also to Randy Bartels

Outline

- This is why laser safety is important
- Laser-related hazards
- Laser classification
- Eye hazards
- Optical protection
  - Maximum permissible exposure, calculating requirements
  - Laser-protective spectacles
- Issues in practical laser safety
  - Particular hazards (Ti:sapphire)
  - Past incidents
  - Minimizing risk: practical rules and tips

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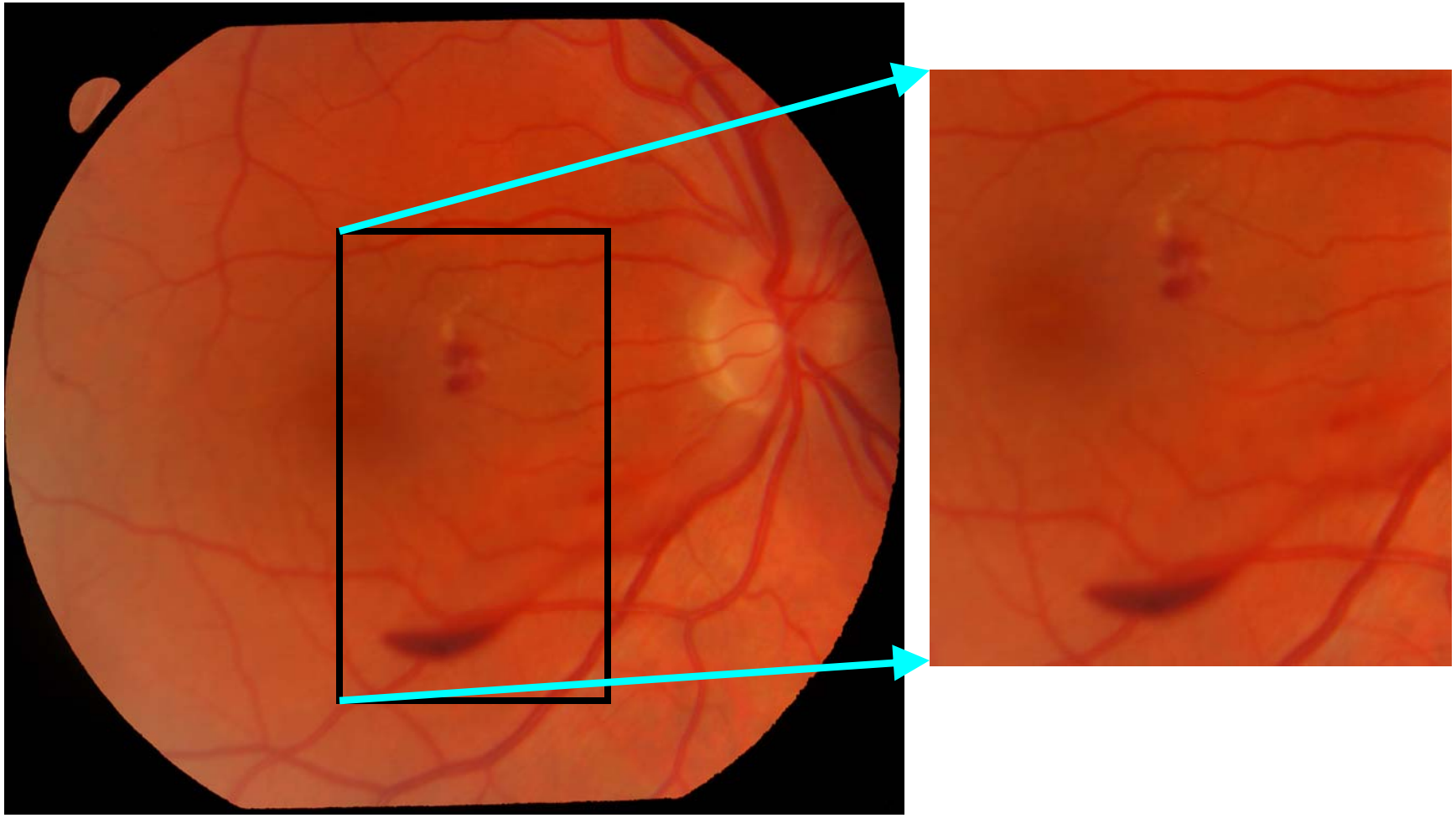
This is why laser safety is important: Retina Damage caused by ultrafast pulses



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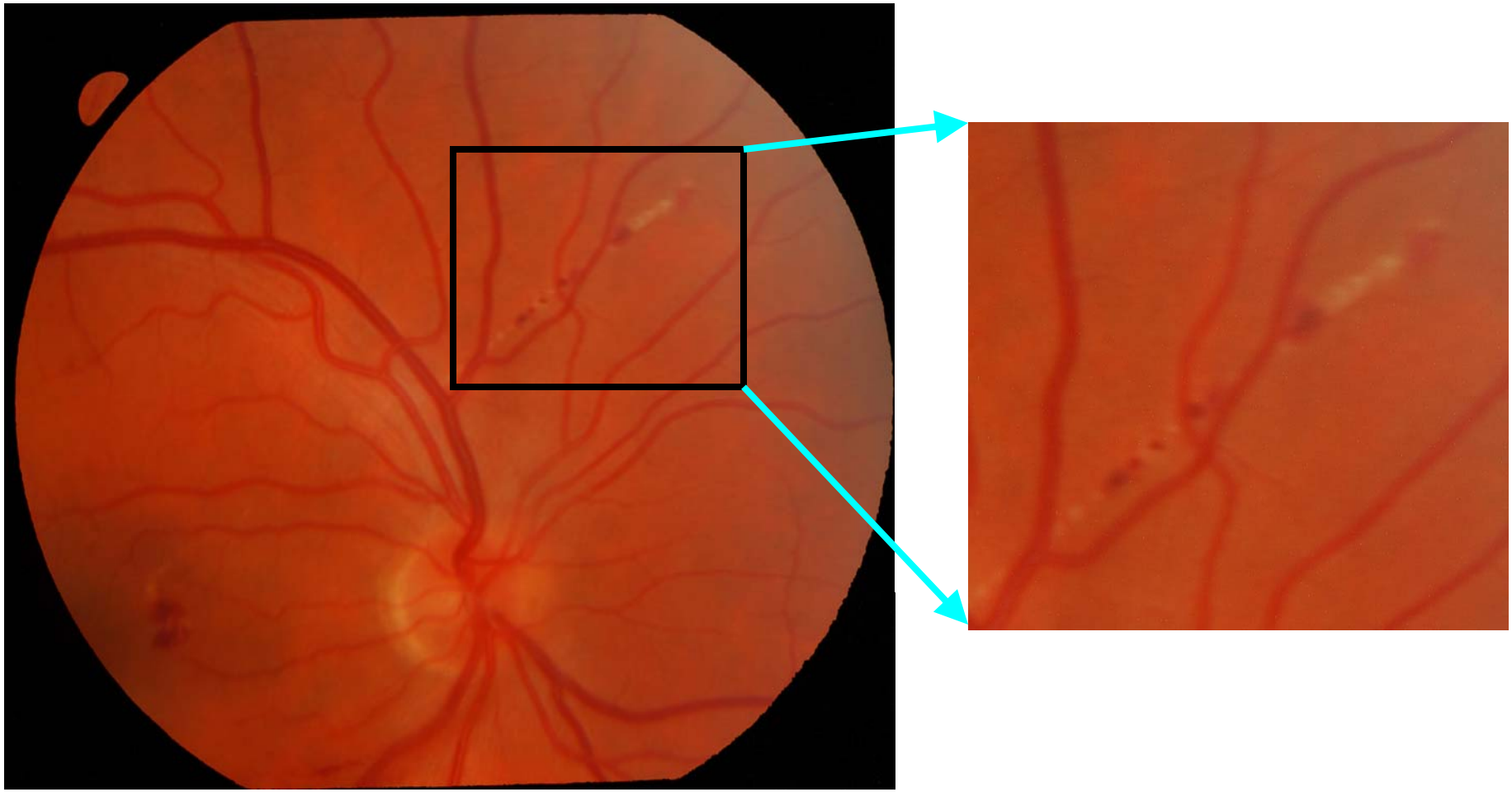
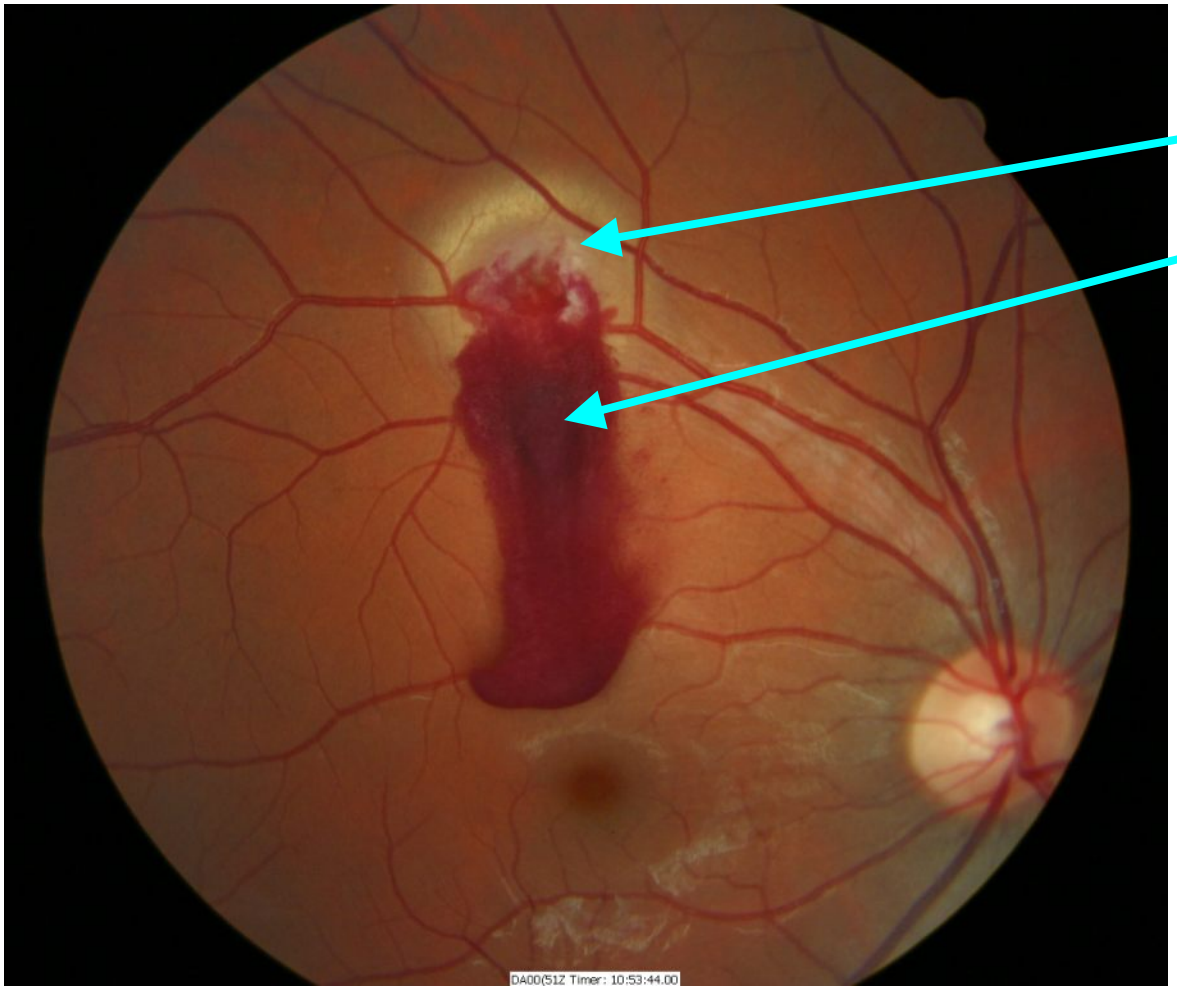


This is why laser safety is important:
Retina Damage caused by high energy laser pulse



Caused by 3mJ, 20ns infrared laser and failure to use protective eyewear

Lasers present several possible laboratory hazards

- High Voltage, current, power
  - Only “qualified personnel” should open box
  - At least one graduate-student death per year due to laser High Voltage
- Chemical Hazards
  - F_2 , Cl_2 gas
  - Explosion hazards
- Concentrated light:
  - Fire hazard
  - Skin, Clothing
  - EYE HAZARD

Laser hazard classification:

- Class 1
  - A Class 1 laser is considered safe based upon current medical knowledge. This class includes all lasers or laser systems which cannot emit levels of optical radiation above the exposure limits for the eye under any conditions.
  - There may be a more hazardous laser embedded in the enclosure of a Class 1 product, but no harmful radiation can escape the enclosure.
  - Examples:
    - CD-ROM players/drives

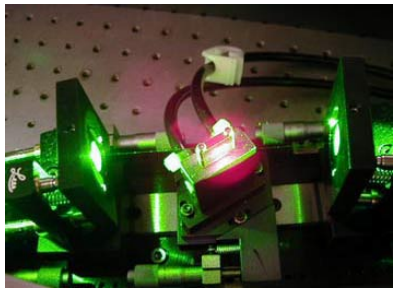
- Class 2
  - A Class 2 laser or laser system must emit a visible beam. A Class 2 laser will be too dazzling to stare into for extended periods.
  - Momentary viewing is not considered hazardous since the radiant power from this laser is less than the MPE (Maximum Permissible Exposure) for momentary exposure of 0.25 second or less.
  - Intentional extended viewing, however, *is* considered hazardous.
  - Example:
    - Supermarket scanners

Source: LIA Safety bulletin, www.laserinstitute.org/publications/safety_bulletin/laser_safety_info/

Laser hazard classification (cont):

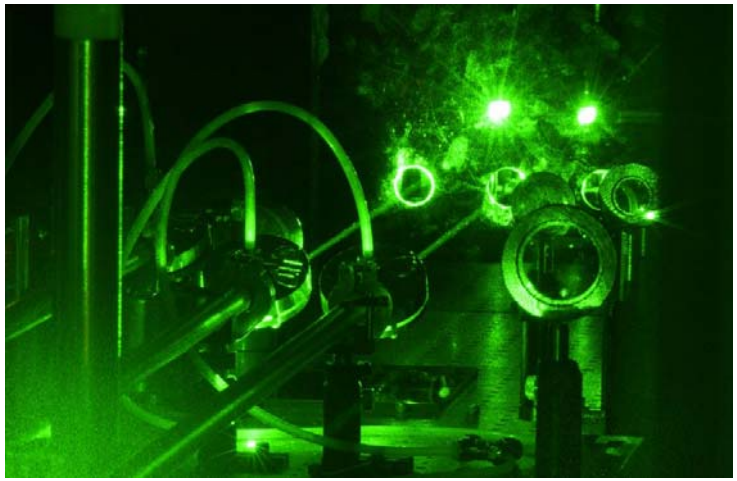
- Class 3
  - A Class 3 laser or laser system can emit any wavelength, but it cannot produce a diffuse (not mirror-like) reflection hazard unless focused or viewed for extended periods at close range.
  - It is also not considered a fire hazard or serious skin hazard.
  - Any continuous wave (CW) laser that is not Class 1 or Class 2 is a Class 3 device if its output power is 0.5 W or less.
  - Since the output beam of such a laser is definitely hazardous for direct viewing, control measures center on eliminating this possibility.
- Class 3a
  - Marginal eye hazard (~5 mW)
  - Examples:
    - 4 mW HeNe
    - Laserpointers

- Class 3b
  - Significant eye hazard (5-500 mW)
  - Example:
    - Ti:Sapphire oscillator in CW (output power between 350-450 mW)



Laser hazard classification (cont):

- Class 4
  - A Class 4 laser or laser system is any that exceeds the output limits (Accessible Emission Limits, AEL's) of a Class 3 device.
  - As would be expected, these lasers may be either a fire or skin hazard or a diffuse reflection hazard.
  - Very stringent control measures are required for a Class 4 laser or laser system.
  - Examples:
    - Verdi (532 nm, 5W)
    - Ti:Sapphire oscillator (modelocked)
    - Nd:YAG (532 nm) in CW as well as Q-switched
    - Amplified Spontaneous Emission



Output from a Q-switched Nd:YAG

Other considerations in classifying lasers:

- Other Considerations for continuous wave (CW) lasers
  - the average power output (Watts)
  - limiting exposure time inherent in the design

- For pulsed lasers
  - the total energy per pulse (Joules)
  - pulse duration
  - pulse repetition frequency
  - emergent beam radiant exposure are considered

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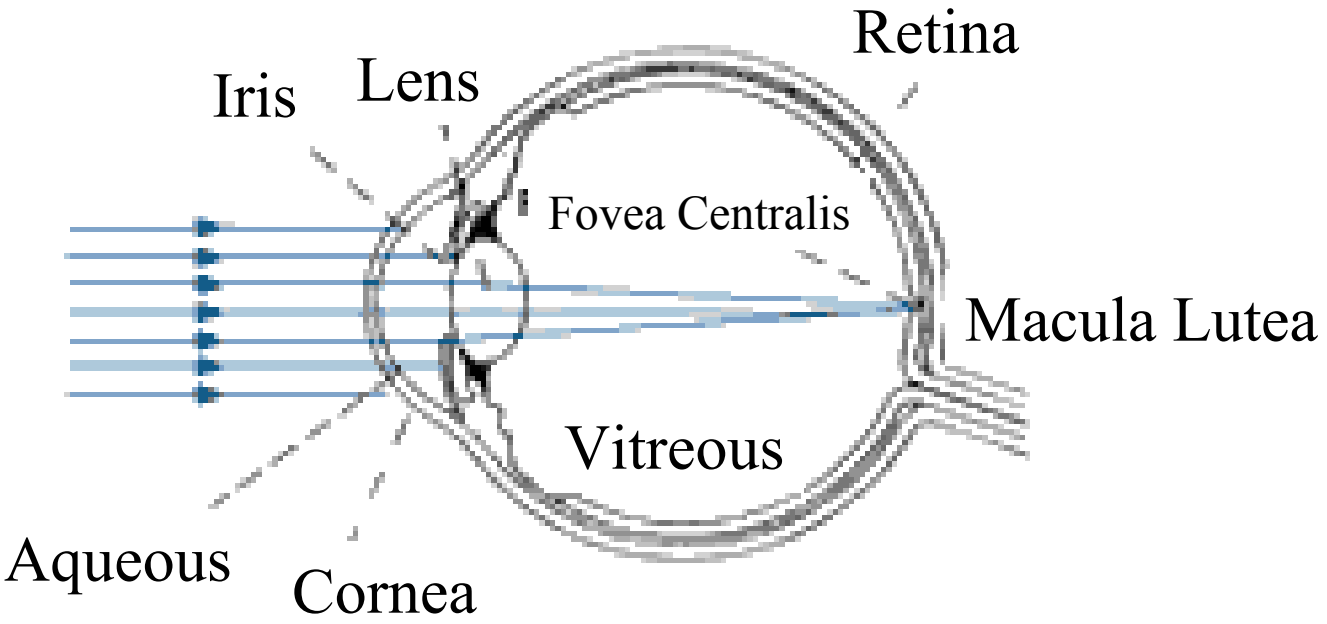
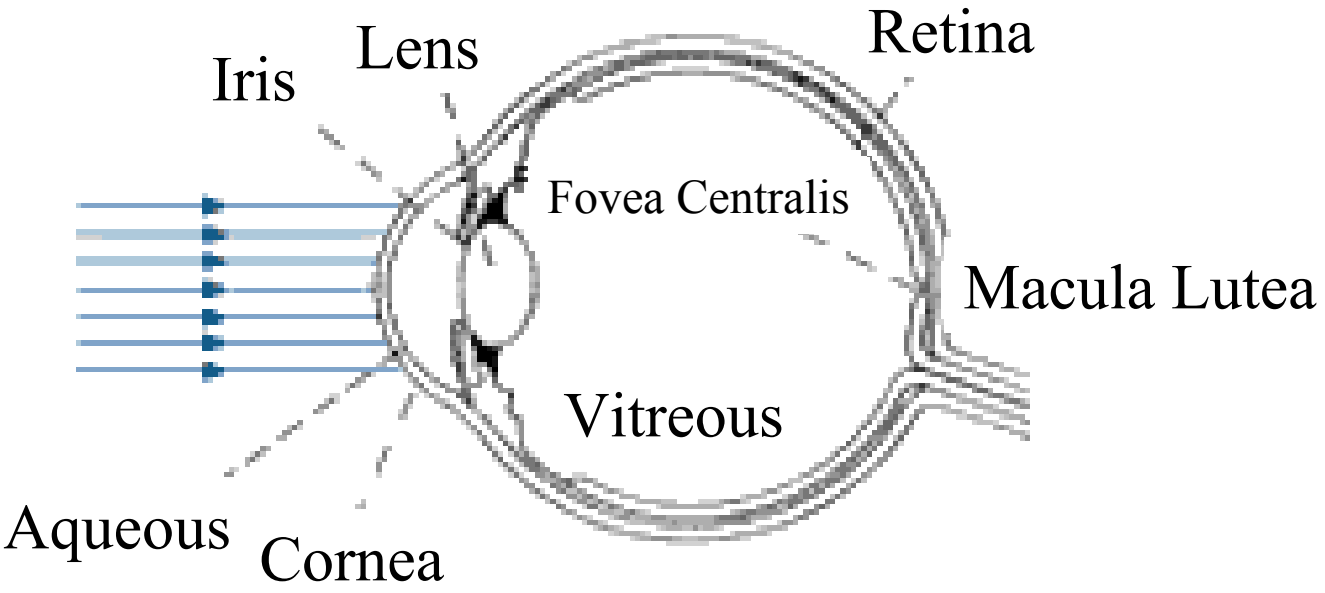
Degree of Hazard depends on wavelength:

- Most-hazardous: visible-NIR (400-1400 nm)
  - Eye is designed to focus visible light
  - An eye focused on the horizon or a far-away object will optimally focus a collimated beam



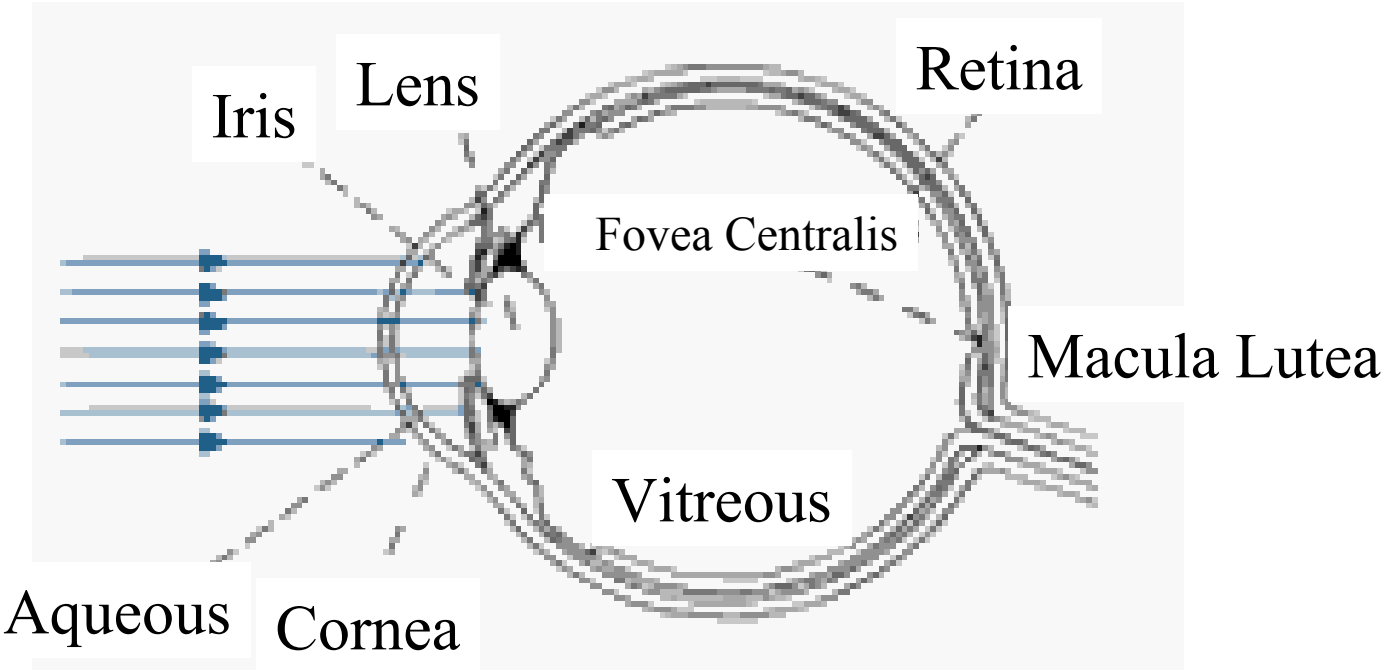
Degree of Hazard depends on wavelength (cont):

- Least Hazardous: Mid-infrared (>1400 nm), middle UV (180-315 nm)
  - Do not penetrate, do not present retinal hazard
  - UV light can do photochemical damage to cornea, skin



Degree of Hazard depends on wavelength (cont):

- Near UV (315-390 nm) presents internal damage hazard, but not to retina
- Skin Effects:
  - Erythema (sunburn), skin cancer and accelerated skin aging are produced by emissions in the 200 to 280 nm range. Increased pigmentation results from exposure to light with wavelengths of 280 to 400 nm.



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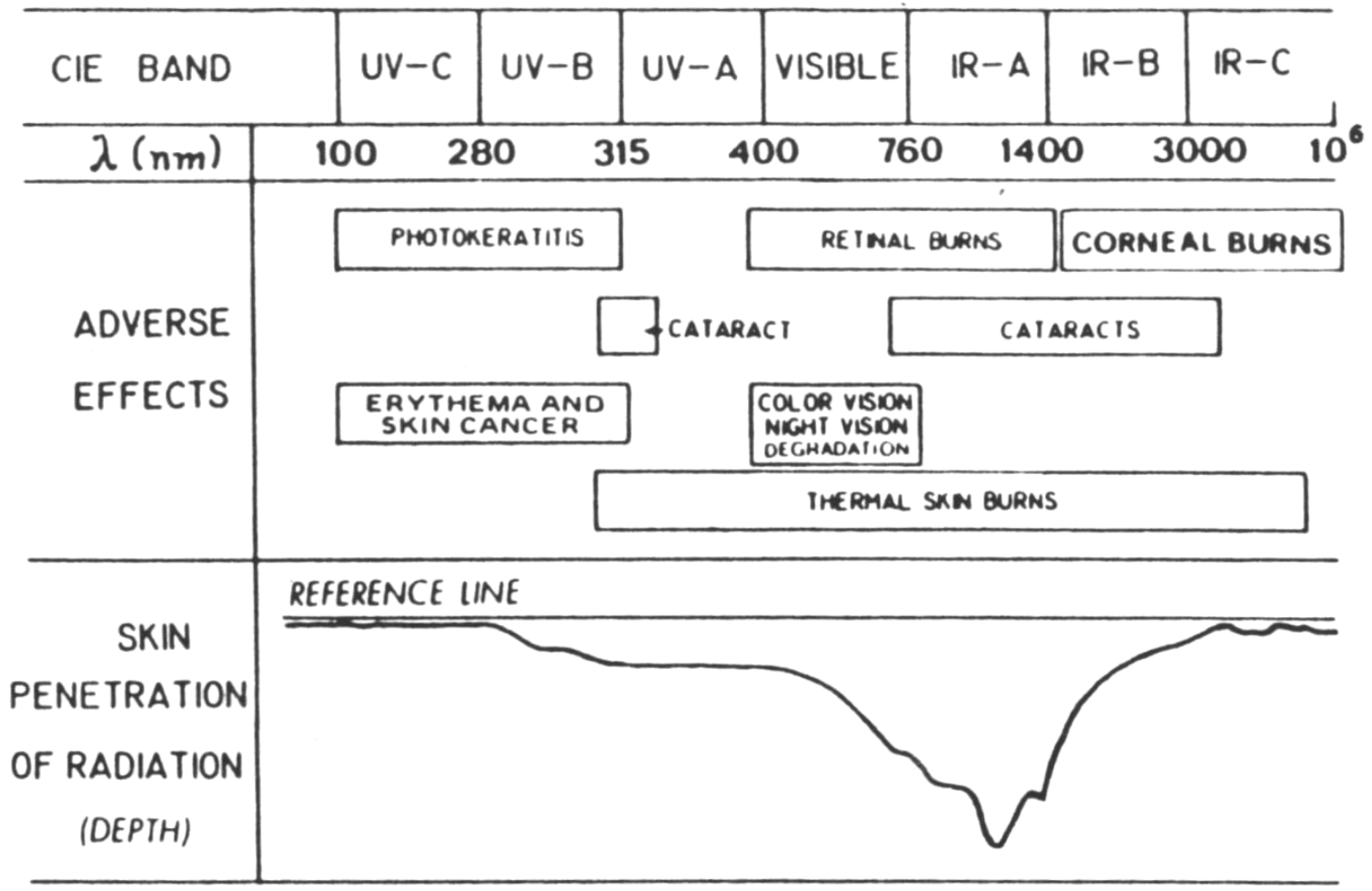
Summary: Hazards in different spectral regions.



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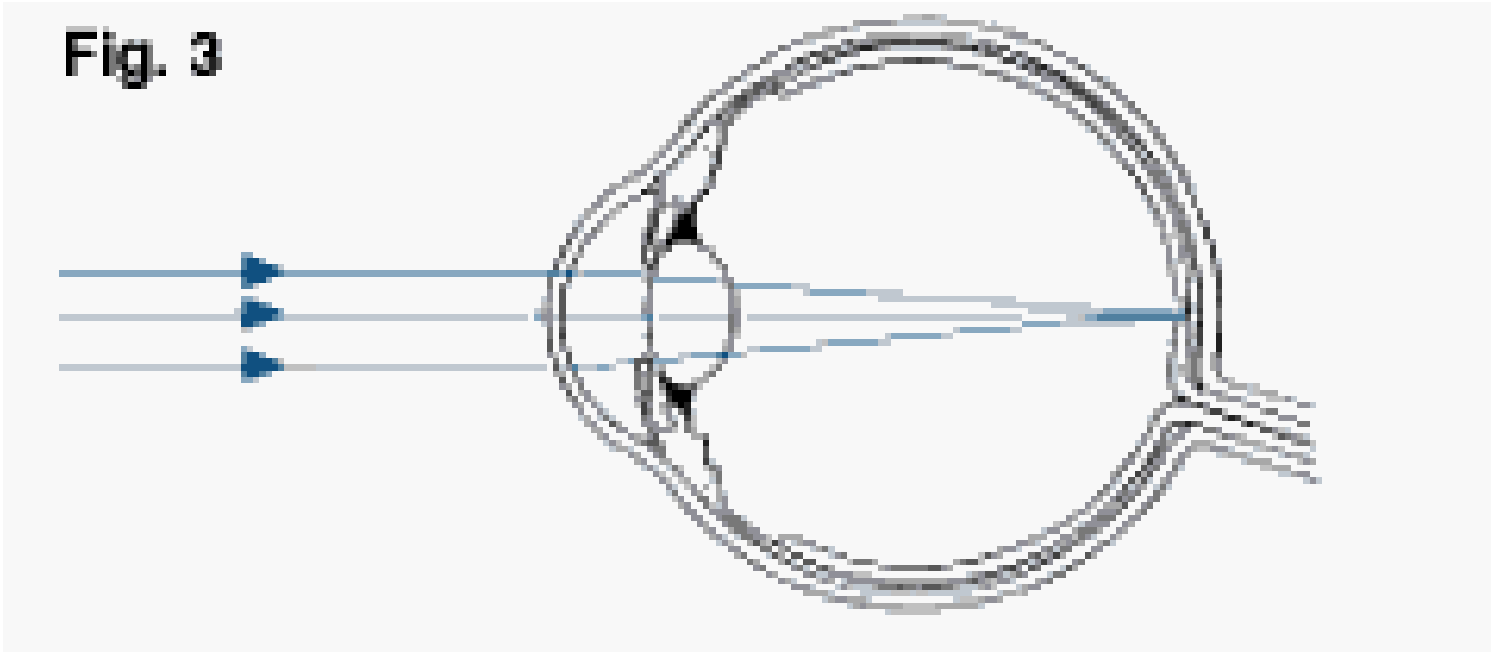
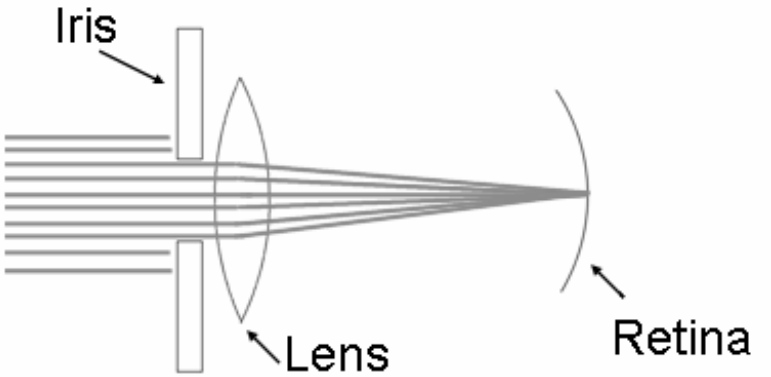
Focusing creates hazard even at low exposure:

- Intensity at the focal spot can be 10^6 times greater than intensity impinging on the iris



Comparison of "natural," laser eye hazard



- Eye basic parameters:
  - Focal length ~25 mm
  - Maximum size of iris 7 mm

- Staring at the sun:
  - 100 mW cm^{-2}, 10 mrad angle subtended
  - Iris in full sun ~2 mm diameter
  - Diameter of image on retina:

$$d_{retina} = 10 \bullet 10^{-3}\ radians \times\ 25\ \ mm = 0.25\ \ mm$$

  - Power into iris:

$$P_{iris} = 100\ \ mW\ \ cm^{-2} \times\ \ \pi(1\ \ mm)^2 =\ \ 3\ \ mW$$

  - Fluence:

$$F_{retina} = \frac{3\ \ mW}{\pi(.0125cm)^2} =\ \ 6\ \ W\ \ cm^{-2}$$

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1 mW He-Ne laser

- Collimated, diffraction-limited spot, beam 2 mm diameter
  - Eye is nearly diffraction-limited for d≤2 mm

$$d_{retina} = \frac{2\lambda f}{\pi r} = \frac{2 \bullet \left(633 \bullet 10^{-7} cm\right) \bullet 2.5 \ cm}{\pi \ 0.1 \ cm} = 10 \mu m$$

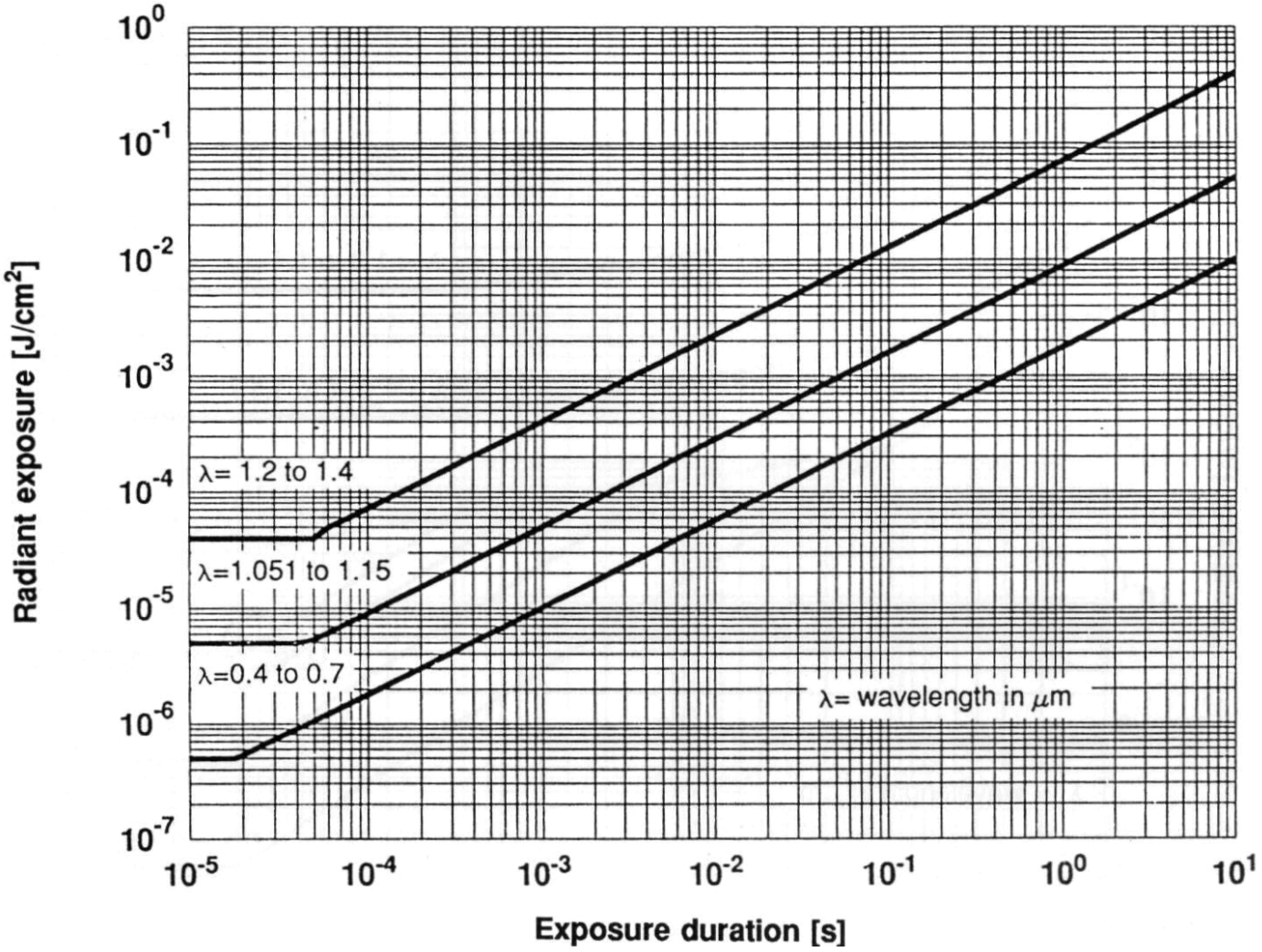
  - Fluence on retina:

$$F_{retina} = \frac{1 \ mW}{\pi \left(5 \bullet 10^{-4} cm\right)^2} = 1300 \ W \ cm^{-2}$$

  - **So staring into a 1mW He-Ne laser can result in about 200 times more fluence on your retina than staring at the sun**

Maximum Permissible Exposure

- Example from ANSI Z136.1-1993: American National Standard for Safe Use of Lasers (part of LIA Laser Hazard Evaluator Manual)



- Single pulse laser beam
- Exposure duration is FWHM
- Aversion response time ~ 0.25s
- Check reference for multiple pulse exposure

$$Cp = n^{-1/4}$$

Correction factor for multiple pulse exposure for visible and NIR laser

MPE: ps/fs ti:sapphire single pulse

- From graph, ~$0.5*10^{-6}$ J cm^{-2} @ 10^{-5} sec
  - 7 mm iris diameter = 0.385 cm^2
  - Pulse energy limit ~0.2 microjoules
    - = 2 *microwatts* @ 10 Hz
    - = 0.2 milliwatts @ 1 kHz
    - ~10^{-4} to 10^{-6} of full-beam energy

- Modelocked ti:sapphire laser ~5 nJ = 0.005 μJ /pulse
  - Treat as CW laser ~ 0.5 watt output power
  - 1 sec exposure ~$1.5*10^{-3}$ J cm^{-2}; $1.5*10^{-3}$ W cm^{-2}
  - 2 mm beam diameter -> 0.6 mW beam

Optical Density

- "Optical density" refers to transmission on log scale
  - OD 3 means 10^{-3} transmission
- Required OD:

$$OD_{req} = \log_{10}\left({laser\ energy(power)} \Big/ {MPE} \right)$$

- Example: CW ti:sapphire laser

$$OD_{req} = \log_{10}\left({500\ mW} \Big/ {0.6\ mW} \right) = 3$$

- 100 mJ ti:sapphire

$$OD_{req} = \log_{10}\left({0.1\ J} \Big/ {0.2 \bullet 10^{-6}\ J} \right) = 5.7$$

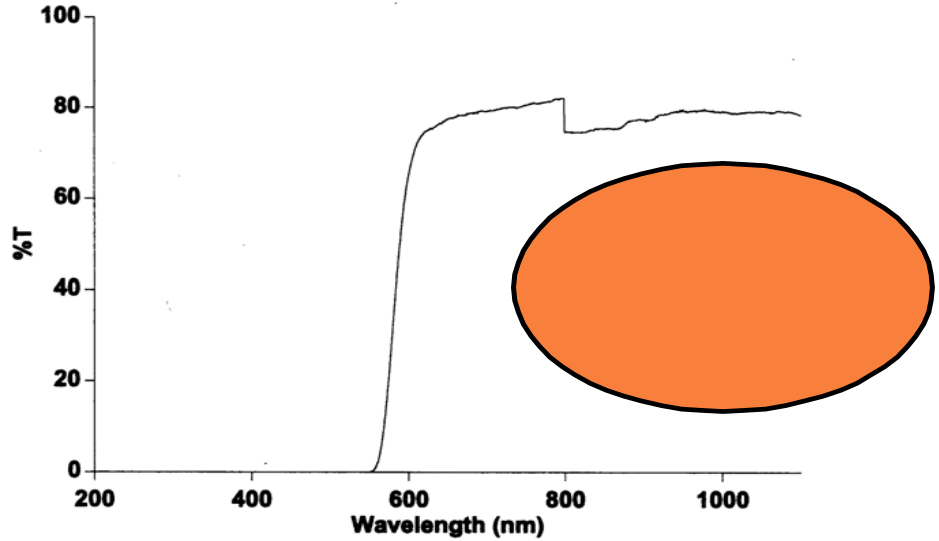
- 2J ti:sapphire

$$OD_{req} = \log_{10}\left({2\ J} \Big/ {0.2 \bullet 10^{-6}\ J} \right) = 7$$

  - If beam is larger than 7 mm dia, effective pulse energy can be reduced

Suitable protective eyewear for each laser:

I. 5-6W Verdi (532 nm), ~10W Argon laser (488 nm) and pulsed frequency doubled Nd:YAG (532 nm)
   - Pink or Orange plastic spectacles:

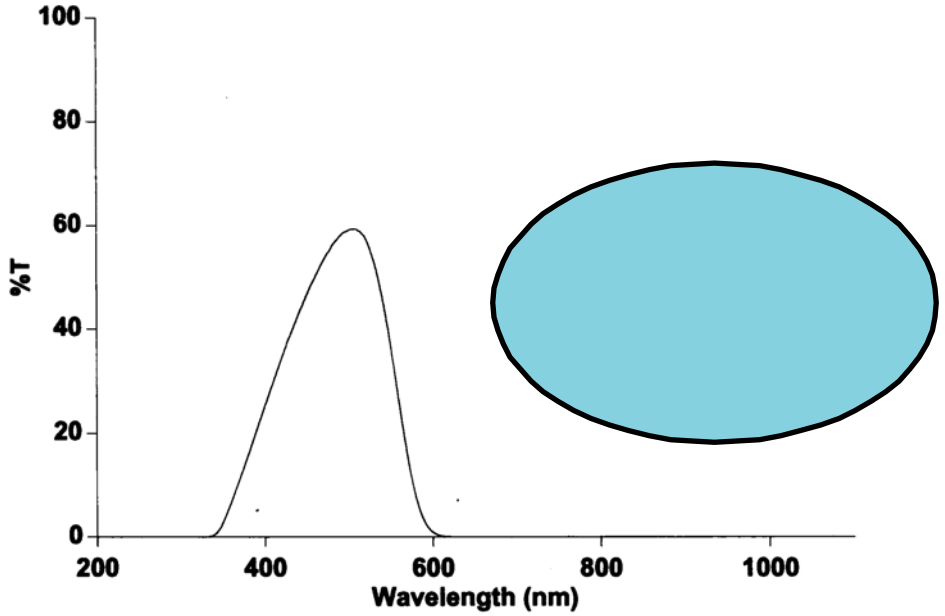


- reasonable usability
- OD is written on side of goggles usually
- No protection from Ti:sapphire
- Full protection for CW 488-532 nm laser radiation
  - Variations for 488 (argon) and 532 (doubled Nd:YAG) have varying protection at other wavelengths

Suitable protective eyewear for specific lasers (cont.):

II. Ti:Sapphire pulses as well as amplified Ti:Sapphire pulses (800 nm)

- BG-39 glass goggles:

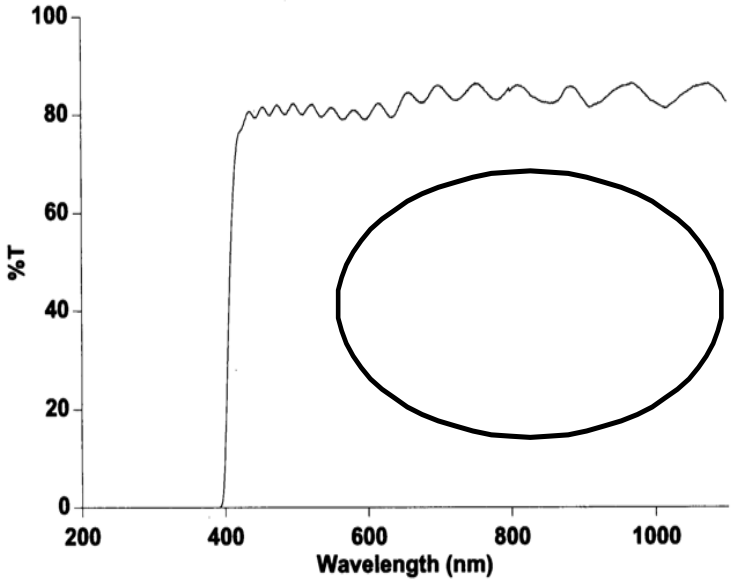


- Bluish glass
  - Very good usability
- Clearly-marked for protection in 700-1000 nm range
- Protection from Ti:sapphire laser radiation
  - Does *not* protect against pump laser light (488-532 nm)

Suitable protective eyewear for specific lasers (cont.):

III. Excimer (ArF, KrF, XeCl), 190 nm-360 nm, or CO_2 (10.6 micron) lasers

- Clear polycarbonate goggles:

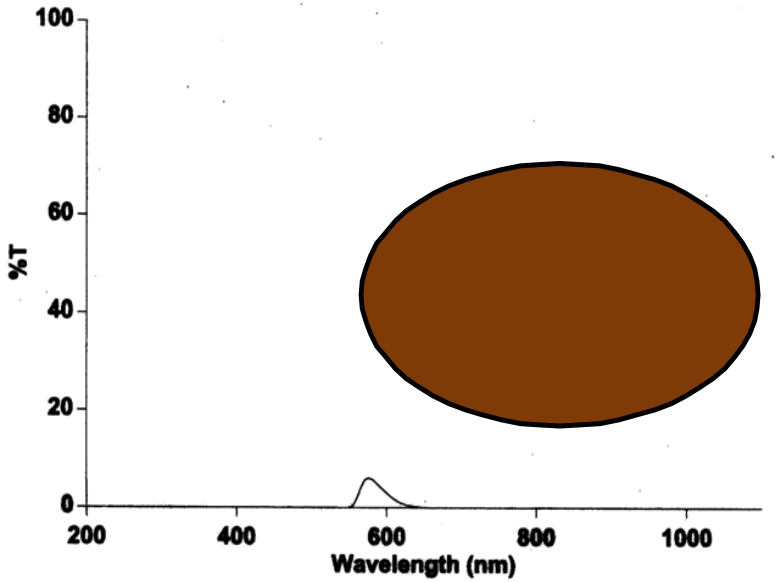


- Clear plastic
  - excellent usability
- Inexperienced students, visitors may believe that these goggles will protect them from visible radiation as well!

Suitable protective eyewear for specific lasers (cont.):

IV. Broadband protection: Excimer laser, CO_2 , Nd:YAG, doubled Nd:YAG

- "Laser-gard broad spectrum B":



- Brownish plastic
  - poor usability
- Full protection for 190-532 nm laser radiation
- Also some protection from Ti:sapphire

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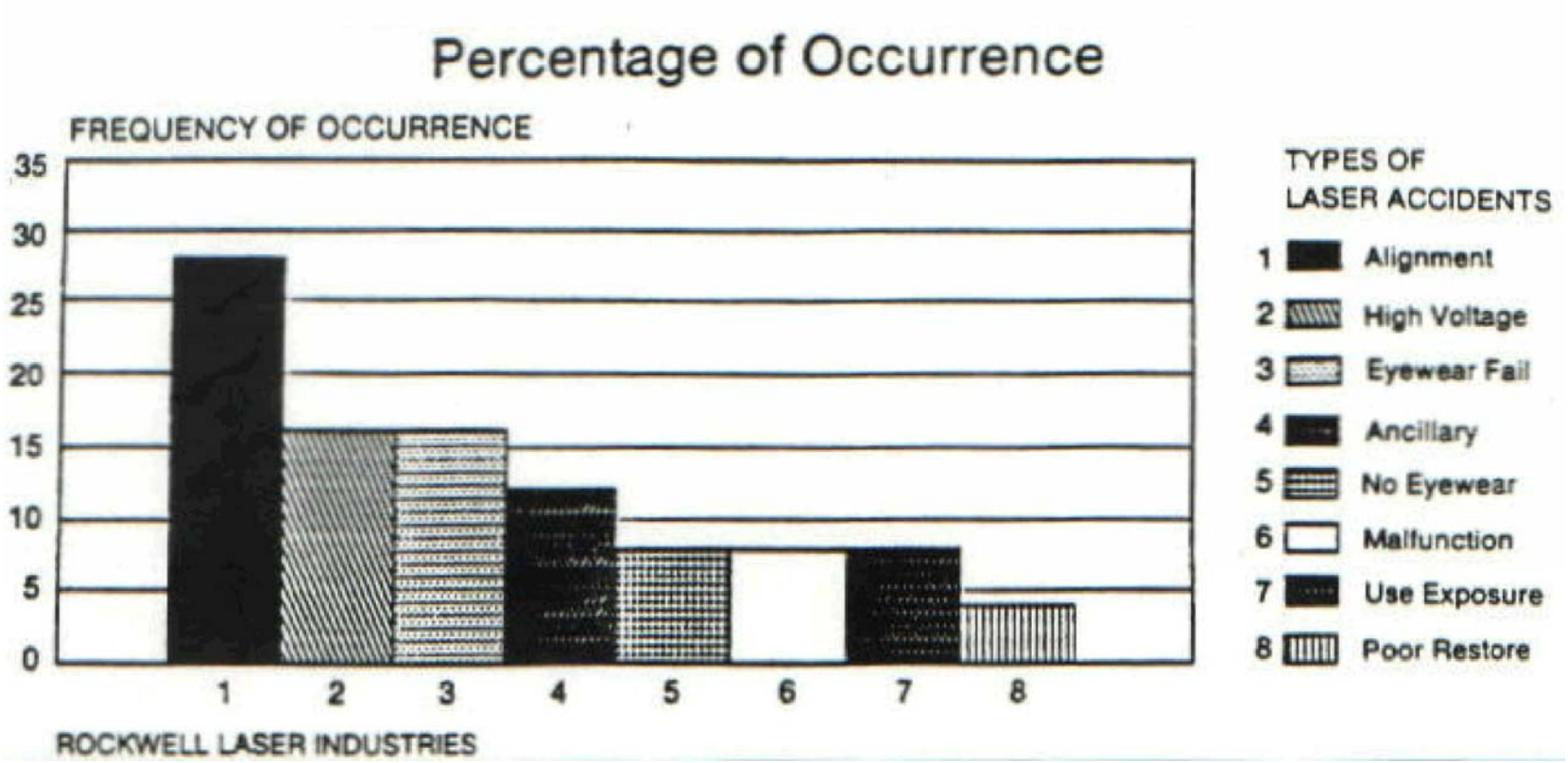
How accidents happen:



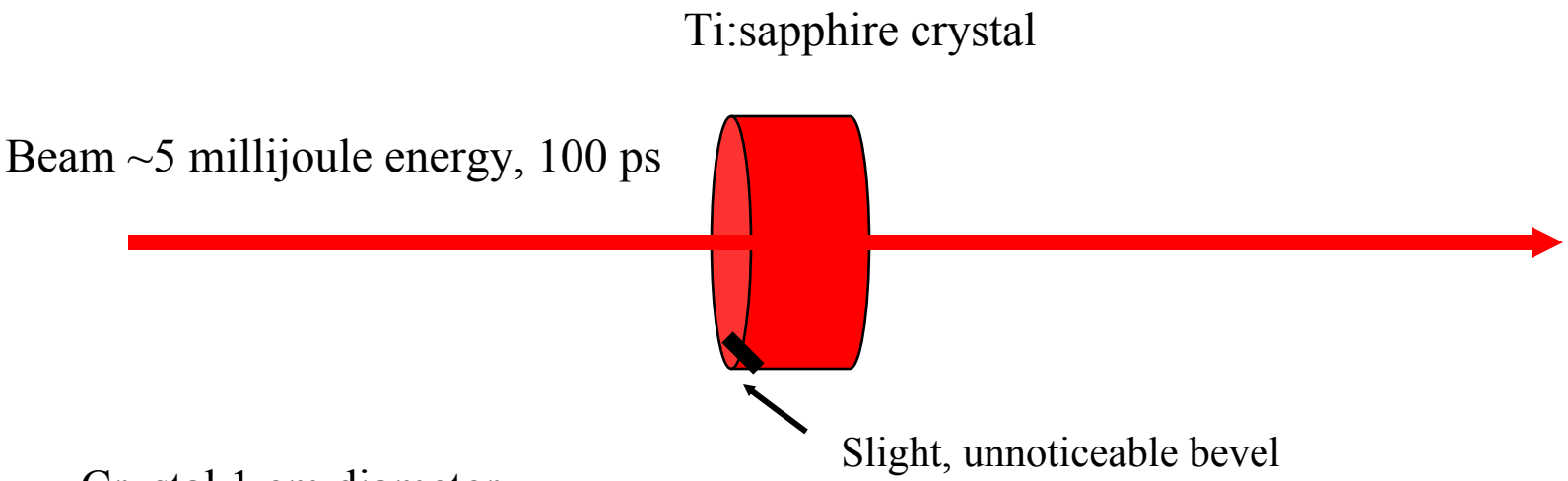
How accidents happen (cont.):

- New person not familiar with lasers, enters hazard area
  - Visitors
  - New students

- Someone *believes* they are familiar with laser safety considerations, then uses incorrect goggles that provide no protection
  - Visitor from another lab
  - Summer students, etc…

How accidents happen (cont):

- Experienced researcher "knows where all the beams are."
  - Unfortunately, not always true
  - Example incident: ti:sapphire amplifier



  - Crystal 1 cm diameter
  - Beam ~3-4 mm diameter ($1/e^2$)
  - All beams in plane of table
  - **Bevel deflected edge of beam upward into eye**
  - Wearing glasses for 532 nm, not 800 nm

How accidents happen (cont.):

- "Peeking" over top of spectacles
  - Often done unconsciously
  - Particular problem with common "50's" style spectacles
  - Ill-fitting spectacles

- Temporarily removed goggles to "see the beam"
  - Often not promptly refitted
  - Researcher is careful at first, but then forgets safety

- More than one person in lab
  - Elbow bumps a mirror mount, redirects beam

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How accidents happen (cont.):

- Working with broad spectrum and visible lasers is especially difficult:
  - Often so many colors are present at hazardous levels that full protection leaves little light to see with.
- Example: High peak-power Ti:sapphire lasers
  - Pulse repetition-rate 10 Hz-10 kHz
    - >10 Hz too fast to avoid multiple exposure
  - 10^{-4} -10^{-6} of total beam can cause eye damage
  - 800 nm wavelength is “visible” at high powers
    - Beam looks like a HeNe, is many, many times more hazardous
    - Nevertheless, tempting to remove spectacles
  - >20 known incidents
    - Most with level of seriousness similar to “eclipse blindness”
    - small blind spots
    - Even small spot serious when in *fovea centralis* ; 150 µm diameter

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Incidents:

- The following is an account written by a researcher who sustained permanent eye damage viewing the reflected light of a Class 4 neodymium YAG laser emitting a 6 millijoule, 10 nanosecond pulse at 1064 nanometers:

  - "When the beam struck my eye, I heard a distinct popping sound caused by a laser-induced explosion at the back of my eyeball. My vision was obscured almost immediately by streams of blood floating in the vitreous humor. It was like viewing the world through a round fish bowl full of glycerol into which a quart of blood and a handful of black pepper have been partially mixed."
    - Dr. C.D. Decker.

Incidents (cont.)

- The following is an account from an incident which occurred in 2001
  - "[Laser company rep] was just here installing a [pump laser] for the multipass amplifier. A bit of an accident occurred while the tech was characterizing the amplifier. I was walking past and he asked me a question...as I turned to face him I caught a reflection of the 3 mJ beam in my left eye. I wasn't even working on the system, but it goes to show that if you are in a lab you need to wear safety goggles. It ends up the service guy had taped a neutral density filter onto the input of an autocorrelator. So it shot the reflection, ~ 60 mW, up to my eye height. No pain, but quite a bit of damage. I have been seeing a retinal specialist and we don't yet know what is just blood on the retina and what is damage. I go back again tomorrow morning for another retinal scan. As of Monday, I had only 60% vision in my left eye. There is a dark streak going from 1 o'clock down to 8 o'clock. I'm keeping my fingers crossed."

Best Practices for Laboratory Laser Safety:

- Reliable protection depends on both protective equipment, *and* safe lab practices, particularly when broad spectrum lasers are in use:

- Experience: clear vision is also a safety issue
  - Seems a more-immediate problem than "improbable" laser exposure
  - Glasses tend to "migrate" from face

- Remind yourself and others to wear goggles

- Use light-tight or appropriately-tinted enclosures where possible
  - Example, enclosure to protect from 532 nm allows use of 800 nm spectacles

- Rigorously avoid procedures that might result in direct exposure

Best Practices for Laboratory Laser Safety (cont.):

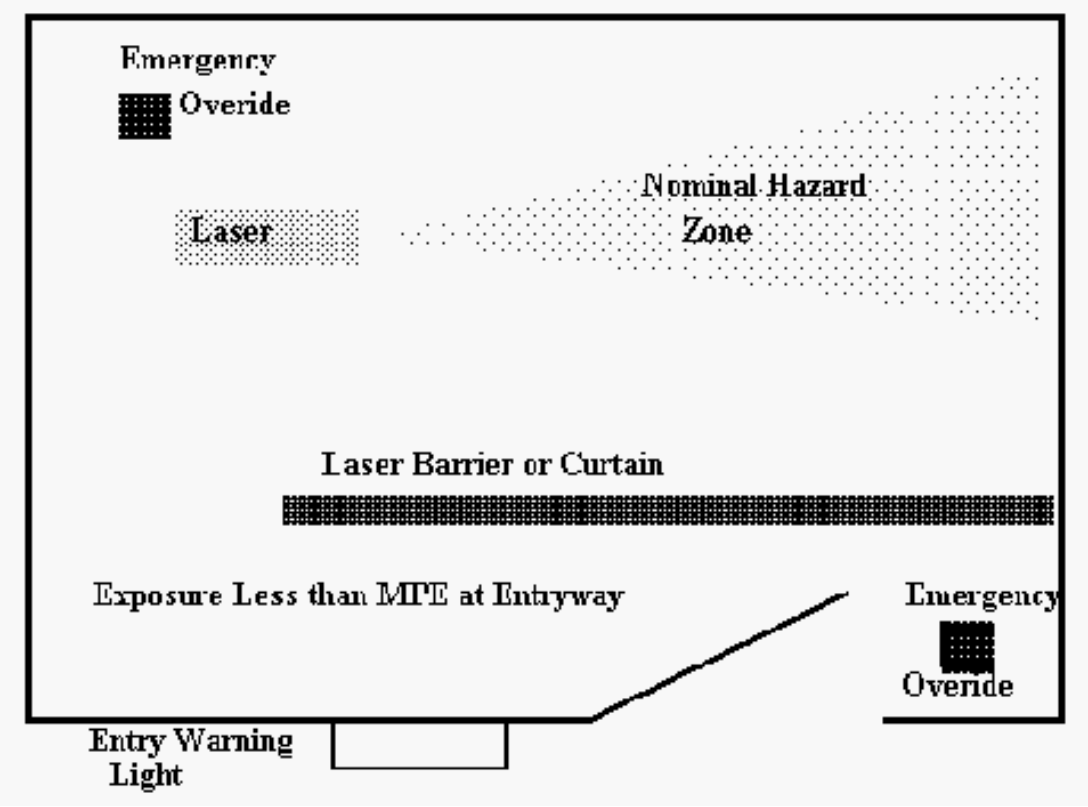
- Always *think* before doing, when aligning laser/optical systems
- KEEP THE LIGHTS ON
  - Smaller iris lets-through less light, focus is larger
- Don’t do involved alignment in an overly-fatigued state
- Block beam when inserting new optical elements
- EXTRA CARE:
  - Cells
  - Vacuum chambers
  - Lens surface reflections can go up
  - ND, Color filters can tilt upward

Best Practices for Laboratory Laser Safety (cont.):

- Avoid situations where the beam is, or might be deflected upward
  - i.e. beam steering, “flippers,” periscopes
- Use beam blocks for stray beams
  - Residual unreflected light from dielectric mirrors
- Avoid “eye level” beams
  - If necessary, fully enclose so that there is *no chance* of passing through beam
- Exercise caution when leaning down to beam-level
  - Always look away from table area when bending-down
  - Think twice before leaning to table level to get a better look at your experiment
- Be VERY CAUTIOUS using “IR cards”
  - Tilt downward

"Safe" room layout:

- Warning light
- Curtains, shields, beam blocks
  - Ideally, no beams should leave edge of table
- Use "high chairs" to avoid sitting with eyes at beam level
- Elevated computer tables



Laser safety resources:

- Laser Institute of America - http://www.laserinstitute.org
- OSHA Technical Manual, Section III, Ch. 6 – Laser Hazards –
  - http://www.osha-slc.gov/dts/osta/otm/otm_iii/otm_iii_6.html
- Rockwell Laser Industries (includes documentation on laser accidents)
  - http://www.rli.com/html/resources.html
- Eye safety tips from dermatologists
  - http://www.dermatology.org/laser/eyesafety.html
- Samples of university lab safety manuals
  - Iowa State University - http://www.ehs.iastate.edu/rs/lasers.htm
  - University of Illinois at Urbana-Champaign – http://www.ehs.uiuc.edu/~rad/laser
  - Oklahoma State Univ. – http://www.pp.okstate.edu/ehs/hazmat/labman/chapt6.htm

Resources (cont):

Books and Publications-

- American National Standard for Safe Use of Lasers, ANSI Standard Z136.1 - 1993
- CRC Handbook of Laser Science and Technology, Volume 1, Lasers and Masers - Ch. 6, “Laser Safety”, CRC Press, 1982.
- L. Matthews and G. Garcia, Laser and Eye Safety in the Laboratory, IEEE Press, Bellingham, WA, 1995.
- D.C. Winburn, Practical Laser Safety, Marcel Dekker, Inc., New York, 1985.
- D. Sliney and M. Wolbarsht, Safety with Lasers and Other Optical Sources: A Comprehensive Handbook, Plenum Press, New York, 1980.

The Laser Safety Officer

- ANSI Z136.1 specifies that any facility using Class 3b or Class 4 lasers or laser systems should designate a Laser Safety Officer to oversee safety for all operational, maintenance, and servicing situations.
- All Class 3b and Class 4 lasers are to have written Standard Operating Procedures (SOP). SOP's are to be written under the supervision of the Laser Supervisor and approved by the Laser Safety Officer. SOP's will contain the following information:
  - Operating procedures.
  - Maintenance procedures.
  - Service procedures.
  - Alignment procedures.
  - The Nominal Hazard Zone (NHZ) for the above procedures as defined by the Laser Safety Officer.
  - Protective eye ware and other personal protective equipment as prescribed by the laser safety officer.