Lasers, Eyeballs, and *Cohabitation*

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When you are little, your parents and teachers tell you not to look at the Sun: it will blind you. They were right, and you've clearly learned the lesson. As it turns out, the Sun is the "kinder blinder." It takes a few moments to cause permanent damage to your retina, long enough for your reflexes to close your eyes, avert your gaze, and save your vision.

Most research lasers are unkind and unforgiving. Our Ti:sapphire laser pulses 1000 times per second. Before your reflexes can kick in, your eye would absorb many pulses, any one of which may have enough energy to destroy the portion of your retina upon which it is focused. Like any piece of dangerous equipment (automobiles, high-voltage circuits, radioactive sources), you need to understand the hazards and how to avoid them before you begin working in the laboratory.

The following provides a brief introduction to lasers in general, and our laser in particular. Besides discussing some of the optical physics of lasers, it concentrates on how your eye responds to light and how it can be damaged by laser beam. A second document summarizing safe operating procedures accompanies this one, and concludes with an informed consent form. As you work through this document, feel free to ask questions and make comments. Also, please work the exercises to gain familiarity with the magnitudes involved.

1. How the Laser Operates

A laser produces an extremely bright beam by channeling the optical emission of an excited medium into a nearly **collimated** (parallel) beam. Because of the small cross section of the beam, a 5–mW HeNe laser beam is much brighter than a 100–W light bulb, despite being 4 orders of magnitude weaker in average power.

Our Ti:sapphire laser is really 4 lasers combined. The Millennia diode laser produces an infrared beam that is frequency doubled into the green to provide the pump beam for the femtosecond oscillator. A sapphire crystal doped with titanium ions absorbs this green pump light, putting Ti^{3+} ions that absorb a pump photon in an excited state. The ions lose some of the energy of the exciting photon to lattice vibrations, so that they are ready to radiate in the red and near-infrared spectral region. The absorption and emission bands

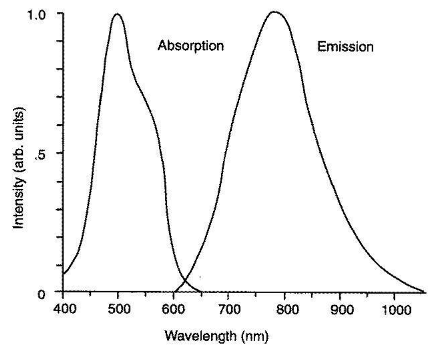


Figure 1: Absorption and emission spectrum of Ti:sapphire. The emission peak of Ti^{3+} ions in sapphire is extraordinarily broad, with a full width at half maximum of nearly 200 nm. This broad spectrum allows Ti:sapphire lasers and amplifiers to produce extremely short pulses of light.

of titanium-doped sapphire are shown in Fig. 1.

The spontaneous radiation from excited Ti^{3+} ions in the Ti:sapphire rod heads out in all directions; a few lucky photons head towards the spherical mirrors M_2 and M_3 in the

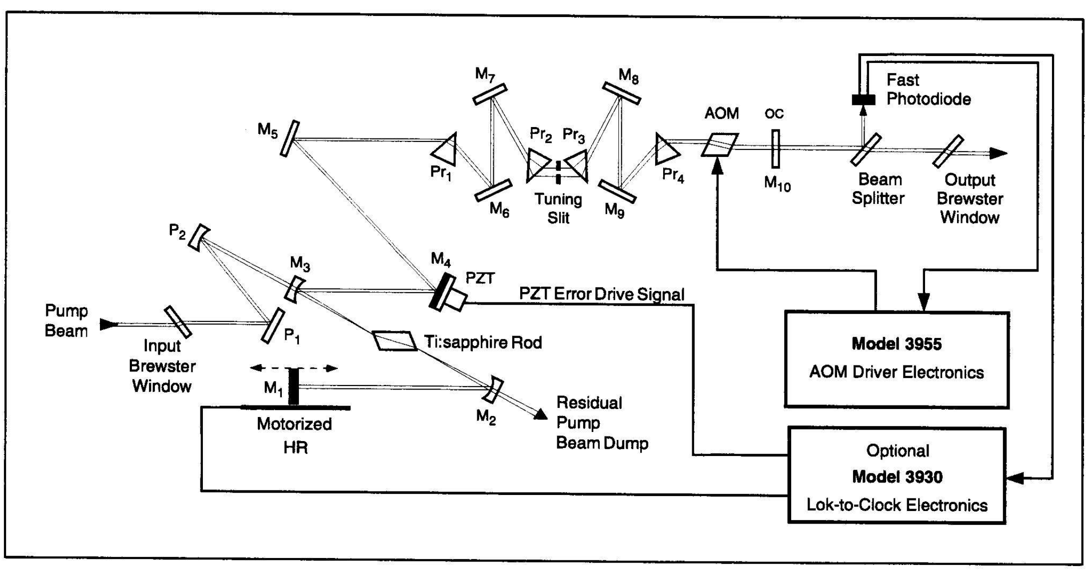


Figure 2: Layout of the Tsunami femtosecond oscillator.

right direction to reach the ends of the cavity at M_1 and the output coupler M_{10}, which redirect them back to the crystal. (See Figure 2.) On a second pass through the crystal, they may stimulate Ti^{3+} to radiate into the same optical mode, in phase with the passing beam, thereby swelling its intensity. If after a complete round trip through the optical cavity, the spontaneous photon arrives back at its point of departure with greater intensity than when it started (if the cavity has "net gain"), then the intensity in this mode builds exponentially.

A general feature of exponential growth is that it tends to be very unfair: the winner takes all. For a gain medium such as Ti:sapphire, each Ti^{3+} may radiate in a wide band of wavelengths, although the gain cross section peaks at a particular wavelength. Other things being equal, this wavelength would come to dominate the beam. However, mirrors and other optical elements in a cavity influence the net gain profile, as well. Most importantly in our Tsunami femtosecond oscillator, a pair of prisms provides **negative group-velocity dispersion**, which compensates the normal (positive) dispersion of the sapphire crystal. In normal dispersion, red frequencies move faster than blue frequencies ($n_{\text{blue}} > n_{\text{red}}$). This tends to make pulses disperse with time. By providing just enough compensation to make sure that all wavelengths in the emission band of Ti^{3+} take approximately the same time to complete one round trip, the prism pair makes it possible to generate short pulses and to use a much broader region of the emission spectrum than would be possible if the laser is allowed to "oscillate cw" (*cw* stands for "continuous wave" and is the opposite of "pulsed").

Dispersion compensation is generally not enough to make short pulses; in addition, the oscillator needs some incentive to pulse. In the case of Ti:sapphire lasers, this comes from Kerr-lens mode-locking. When the intensity in the sapphire crystal is higher, the index of refraction increases. Light bends toward regions of higher index of refraction (think how a converging lens works), so when the intensity is higher, the beam inside the crystal becomes tighter, making the intensity even higher. This positive feedback works against normal diffraction to raise the intensity in the gain region, where it serves to increase the efficiency with which the beam extracts energy from the Ti:sapphire crystal. The nonlinear focusing effect provides the incentive for the oscillator to operate in a pulsed mode, since intense light is more effective at extracting energy.

The duration of the pulses that leave the cavity at each bounce off the slightly transmitting **output coupler** depends on how well dispersion is compensated; in our case the pulses are about 35 fs in duration.

Exercise 1.1 Using the Heisenberg uncertainty principle,

$$\Delta E\,\Delta t \geq \frac{\hbar}{2} \quad \longrightarrow \quad \Delta\nu\,\tau \geq \frac{1}{4\pi}$$

where τ is the (approximate) pulse duration, estimate the bandwidth $\Delta\nu$ required to produce a pulse duration of 50 fs. Convert your answer to a wavelength range, centered on 800 nm.

To make a more careful estimate of the relationship between pulse duration and bandwidth, we can approximate the temporal profile of the pulse as a Gaussian

$$I(t) = Ce^{-t^2/\tau^2} \tag{1}$$

The constant τ is the $1/e$ half width of the pulse, which is smaller than the full width at half maximum (FWHM) that is easy to estimate visually.

Exercise 1.2 Show that $t_{\text{FWHM}} = \tau\sqrt{\ln 8}$.

The quantity Δt that figures in the Heisenberg uncertainty relation is given by

$$\Delta t = \frac{\int_{-\infty}^{\infty} I(t) t^2\, dt}{\int_{-\infty}^{\infty} I(t)\, dt} \tag{2}$$

Exercise 1.3 Using the expressions

$$\int_{-\infty}^{\infty} e^{-\alpha x^2}\, dx = \sqrt{\pi/\alpha} \tag{3}$$

$$\int_{-\infty}^{\infty} x^2 e^{-\alpha x^2}\, dx = -\frac{\partial}{\partial\alpha}\int_{-\infty}^{\infty} e^{-\alpha x^2}\, dx = \frac{1}{2}\sqrt{\pi}\alpha^{-3/2} \tag{4}$$

show that $\Delta t = \tau/\sqrt{2}$ for a Gaussian pulse.

A simple result for Gaussian pulses is that the Fourier transform of a Gaussian pulse is also a Gaussian pulse. That means that for a "transform-limited" Gaussian pulse, the frequency spectrum has the same Gaussian form as the temporal profile (although centered around a nonzero value of carrier frequency). Thus

$$I(\omega) = C' e^{-(\omega-\omega_0)^2/\Omega^2}$$

Exercise 1.4 Combine the results above to show that the time-bandwidth product, using FWHM for each, leads to the following relationship for Gaussian pulses:

$$t_{\text{FWHM}}\omega_{\text{FWHM}} \geq \ln 8$$

and use this to refine your estimate for bandwidth required to produce a 35-fs Gaussian pulse. Also estimate, using Figure 1, the minimum pulse duration one can in principle obtain from a Ti:sapphire laser.

The Tsunami operates at about 82 MHz, emitting a pulse each time the single pancake of light in the cavity arrives at the output coupler. Since light moves at about 1 foot per nanosecond, the cavity length is about 12 feet. The average power out of this laser is roughly 500 mW.

Exercise 1.5 Estimate the pulse energy and peak power out of the Tsunami.

1.1 Amplifier

Virtually all of those millions of pulses are thrown away each second. A thousand lucky ones make it into the Spitfire regenerative amplifier, which is pumped by the Evolution laser at a repetition rate of 1 kHz. These are stretched by a pair of gratings to produce a pulse of much greater duration than the 50-fs seed pulse, but having precisely the same spectral width. Furthermore, the chirp of the pulse is linear: as we move across the spectrum of the seed pulse the different frequency components are delayed in a linearly increasing fashion. This will be important when it comes time to put them back together to recover a short (amplified) pulse at the end of the amplifier.

> A cautionary note: never touch a grating. They cannot be cleaned, and any oil from your finger will seriously degrade a grating.

The purpose of stretching the input pulse is to avoid extreme intensities within the amplifier, where they can easily destroy the Ti:sapphire crystal. Once a seed pulse has been thoroughly stretched, it is injected into the amplifier cavity, where it passes repeatedly through the excited Ti:sapphire crystal, extracting gain at each pass. Eventually, the gain of the crystal is depleted and the pulse begins to lose energy on each successive round trip. Before that happens, we would like to switch the pulse out of the cavity for us to use.

Both the seed pulse's entry into the cavity, and the amplified pulse's switch out of the cavity come about via Pockels cells, which cause the plane of polarization of the light to rotate when a high-voltage signal is applied to them. This causes beams to reflect from surfaces that they otherwise pass through. The timing electronics is responsible for

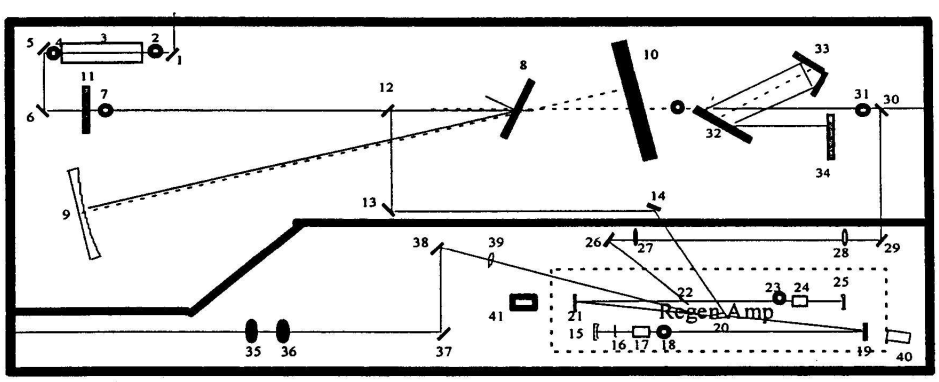


Figure 3: Layout of the SpitFire regenerative amplifier. (1) input mirror; (8) stretcher grating; (10) stretcher dielectric retroreflector; (14) mirror coupling into regen cavity, delimited by mirrors (15) and (25); (32) compressor grating.

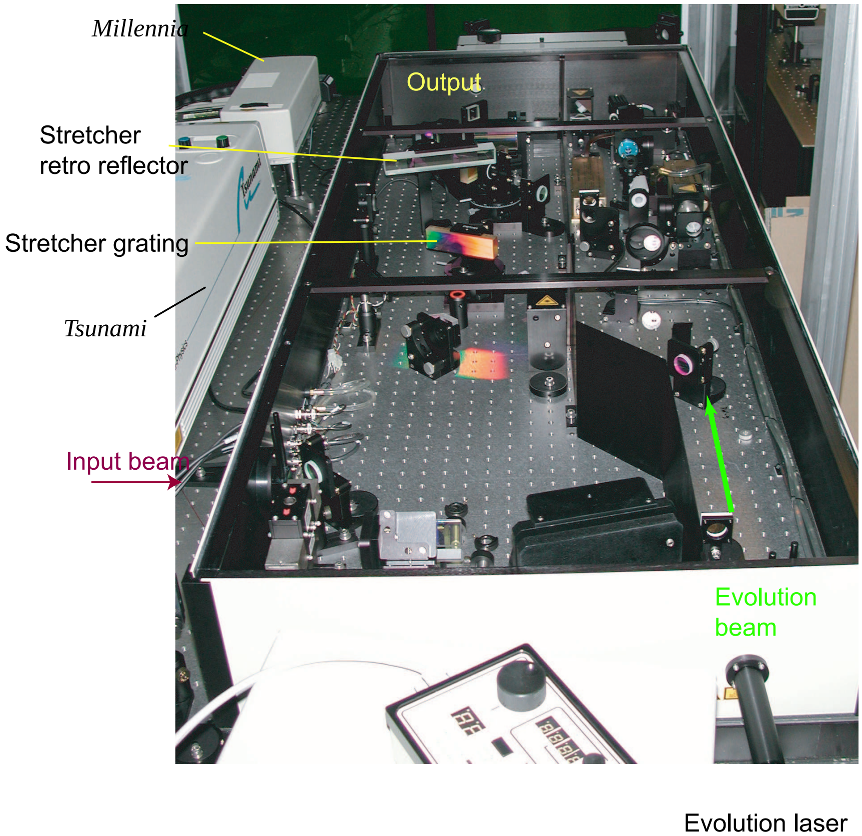
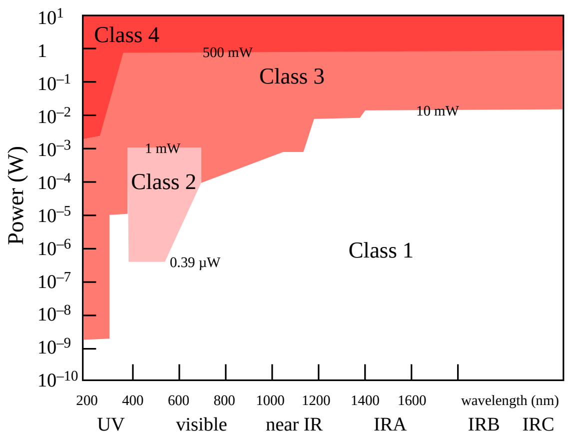


Figure 4: SpitFire regenerative amplifier.

synchronizing the pulse train from the Tsunami, the excitation pulses from the Evolution, and the two Pockels cells, providing variable delays and locking between the Evolution and the Tsunami.

Once the pulse has been switched out of the regenerative amplifier cavity, it is compressed with another pair of gratings to put the red and blue ends of the spectrum back on top of one another. This seldom leads to quite so short a pulse as the seed, and we typically obtain about 50 fs for the output pulse duration. The average output power is about 800 mW (which is only slightly higher than the average output power of the Tsunami oscillator). This means that we have traded repetition rate for pulse energy in going through the regenerative amplifier.

Exercise 1.6 Estimate the peak power of the output pulse of the amplifier.



Source: Sécurité Laser, 2001

Figure 5: Lasers are classed according to their wavelength and power. The weakest beams are designated Class 1, and are generally safe under all circumstances. There are few such lasers! They have powers below 0.39 μW, which is about 1000 times weaker than a typical helium-neon laser. Higher-numbered classes are progressively more dangerous. Our Ti:sapphire laser is a class 4 laser.

2. Classification of Lasers

Lasers are classified according to the danger their beams pose to the skin and eyes. The following table, and Figure 5, show how power and wavelength get mapped into classes. Class 1 lasers are so weak that they are safe under all circumstances. I'm not sure that I have ever met such a laser.

All four of the lasers in our setup are Class 4 lasers, meaning that they are very dangerous. They can cause burns to the skin and permanent blindness.

Class 1	$P \leq 0.39\ \mu\text{W}$	incapable of causing damage, and considered safe under all circumstances; e.g., some laseer printers
Class 2	$0.39\ \mu\text{W} \leq P \leq 1\ \text{mW}$	visible emission that is weak enough that the normal blink response protects the eye; no danger for an exposure of less than 0.25 seconds
Class 3A	$1\ \text{mW} \leq P \leq 5\ \text{mW}$	Do not look into the beam, especially through an optical instrument
Class 3B	$5\ \text{mW} < P \leq 0.5\ \text{W}$	
Class 4	$P > 0.5\ \text{W}$	Dangerous to both the eye and the skin, either by a direct beam or a diffusely scattered one

3. Eye safety

The retina is the sensor responsible for the translation of visible photons into chemical signals that can be sent down the optic nerve to the brain for processing into vision. The retina must cope with a tremendous range in signal strength, from darkness to bright sunlight, over ten orders of magnitude. Perhaps not surprisingly, bright (indirect) sunlight is about the maximum our eyes can handle; the minimum depends on the individual and the wavelength, but under optimal conditions the human eye can detect a signal of just a few photons.

Because the eye includes a high-quality lens, the "optical gain" of the eye is quite high, up to about half a million. This means that the intensity on the retina may be hundreds of thousands of times greater than the intensity of the beam that arrives at the eye. For a uniform beam focused by a lens of focal length f and diameter ϕ, the central region of the Airy pattern in the focal plane has a radius given by

$$r = 1.22 \frac{\lambda f}{\phi} \qquad (5)$$

Exercise 3.1 Estimate the factor by which the intensity of a uniform beam is increased on focusing by a human eye.

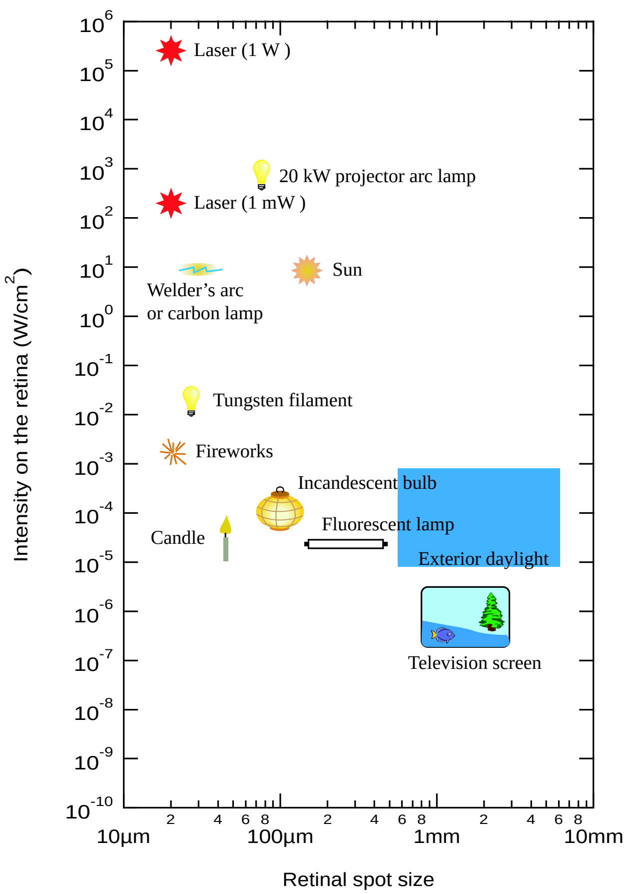


Figure 6: Approximate intensities on the retina of various common sources of illumination.

The danger a laser beam poses to the eye depends on its average power, wavelength, and size. Depending on the wavelength, the light may be absorbed by the front layer of tissue, may pass through all tissues of the eye, including the retina, without coming to a focus, or may be focused on the retina. Figure 7 shows the intensity on the retina of various sources of light. Two issues are at play: the tightness of the focus and the power of the

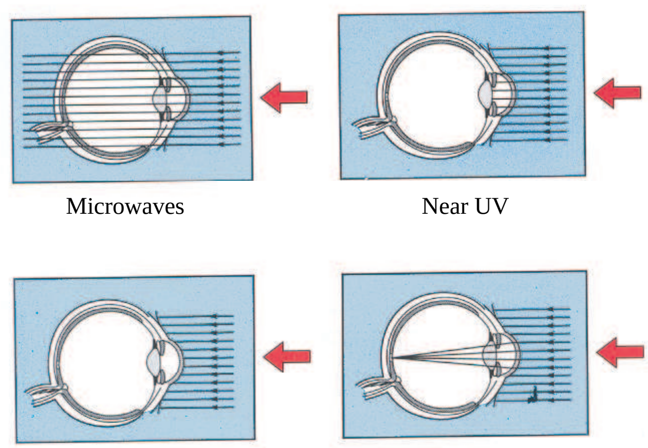


Figure 7: How the eye absorbs different wavelengths of light.

source. For a diffuse source such as a fluorescent tube, the total amount of light emitted may be significant, but the source extends over a large area, so that the concentration of power on any location of the retina is small. Because a laser beam tends to be very nearly collimated (parallel), the focal spot on the retina for a relaxed eye focused at infinity is very small, making the intensity (power per unit area) high enough to cause damage.

How the eye becomes damaged depends upon details of the laser source and the exposure the retina receives. The main mechanisms are heating (often explosive, accompanied by a blast that detaches the retina) and photochemical degradation. I have yet to speak with a doctor or laser safety expert who can give me a convincing assessment of which mechanisms operate when an eye is blinded by looking too long at the Sun. However, with a laser beam the mechanism is often easier to determine.

The first consideration is wavelength. As shown in Fig. 7, which eye tissues absorb laser light depends on the wavelength.

- In the microwave region, as well as in the x-ray region, the radiation passes unfocused through all tissues of the eye and on into the cranial cavity.

- Light in the far UV (roughly 100–315 nm) and the far IR ($\lambda > 1.4\ \mu$m) is absorbed in the outer layer of the eye, the **cornea**, where it can cause burns and permanent damage of the corneal tissue. When slightly damaged, such as when scratched, the cornea is the fast part of the body to heal. It heals by producing new cells at the periphery of the eye, and these migrate to the damaged region and replace damaged cells, which are sloughed off by tears. When the "active" regions where new cells are produced become damaged, no healing of the cornea can take place. In some cases, it is possible to transplant a healthy cornea to restore sight; in others this fails by rejection of the transplanted tissue.

- Light in the near UV penetrates the cornea but is absorbed in the lens, where it can cause a degradation of the proteins of the lens that turns them cloudy and opaque. This condition is called a cataract; before the hazards of UV exposure were well understood, many atomic physicists working with UV sources, including Hg lamps, developed cataracts and had to have cataract surgery to replace the lenses of their eyes. My boss at JILA, Alan Gallagher, had to have both his lenses replaced for just this reason.
- In the visible and near infrared spectral region, which includes the spectrum of the Ti:sapphire laser and the undoubled Nd:YAG laser (which is truly invisible, unlike the Ti:sapphire), light is well focused by the cornea and lens onto the retina, leading to very high intensities at the focal spot. **This kind of laser is the most dangerous for permanent retinal damage.**

With an intense, pulsed laser in the visible or near IR, a single shot from the laser may be sufficient to destroy a patch at the focal spot and in the surrounding area. If the beam arrives straight on, as shown in Figure 3., the region of the retina that is damaged is called the **fovea**, which is the region responsible for visual acuity and detailed color vision. In this region of the retina, which is only about 100 μm across, the density of the cones responsible for color vision is greatest, leading to the greatest resolution and clarity in the entire visual field of view.

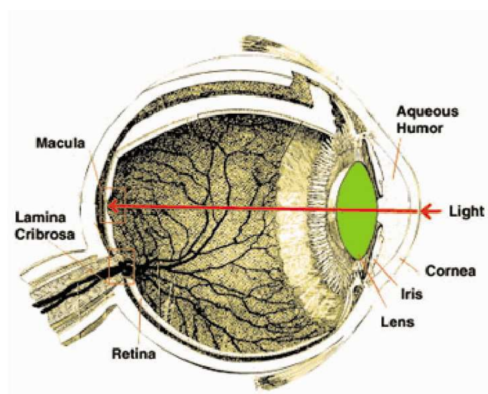


Figure 8: Schematic of the eyeball, showing the fovea in the center of the macula, and the optic nerve placed somewhat off the main axis.

The optic nerve leaves the eye in a region 1.5 mm or so below the fovea. If this region is destroyed by a laser shot, the eye is irreparably blinded. Laser spots on other regions of the retina, such as arise by misdirected laser beams and stray reflections that enter the eye away from the forward direction, tend not to be as severe as hits to the fovea and optic nerve. Typically, a region surrounding the spot is damaged and goes blind. It is also common that with the laser heating of the retinal cells, blood vessels explode and blood enters the **vitreous humor** (the fluid that fills the eyeball between the lens and the retina). Those who have suffered such laser shots describe how terrifying it is to see one's vision streaked with blood as though shot in battle. Chunks of retinal tissue can float around in the vitreous humor for years, clouding vision and causing "holes" in one's field of vision that wander around. According to Prof. Donnelly's personal experience, floaters can persist for years and can be more annoying than the permanent blind spots.

For a Ti:sapphire laser pulse lasting less than 1 ns, the maximum permissible exposure to the **cornea** in a single pulse is given by the expression

$$P_{\max} = 5 \times 10^6 \, C_4 \text{ W m}^{-2} \tag{6}$$

$$C_4 = 10^{0.002(\lambda - 700)} \tag{7}$$

where wavelength is in nanometers. This gives $P_{\max} \approx 8 \text{ MW/m}^2$. However, our laser does not produce single pulses, but a steady train of pulses at 1 kHz. The exposure taken by the cornea in an "incident" will depend on the reaction time of the victim. For an exposure of t seconds, the maximum permissible **fluence** (energy per unit area) is given by

$$F_{\max} = 18 \text{ J/m}^2 C_4 t^{0.75} \tag{8}$$

where C_4 has the same definition as above.

Exercise 3.2 How many times greater than the maximum permissible exposure level is the beam coming out of our regenerative amplifier during an exposure of 50 ms?

4. Upshot

Laser physics is enormously rich and varied, and lasers have become an absolute commonplace with CD players and laser pointers. The dangers should not intimidate us but sober us. This exposition should persuade you of the positively enormous risks of careless behavior in a laser laboratory. One thoughtless mistake can destroy an eye. That eye might be yours, or it might belong to someone else in the room. Most experiments involve teamwork, and it is therefore essential that everyone understand the risks and dangers, and that we all work to minimize them.

Safe Practices

Now that you are convinced that the equipment is dangerous, it is time to learn how to operate it safely.

1. **Always wear laser glasses or goggles.** This is the cardinal rule for the laboratory. From the time the laser is started up until it is shut down, safety glasses must be on. **Failure to follow it is grounds for permanent expulsion from the laboratory and group.** No professor wants to make a telephone call to a student's parents explaining why their child is now blind in one eye.

2. **Keep the beam parallel to the table.** In most circumstances, the beam can remain at the same height above the table throughout an optical setup. In rare situations, it may be necessary to use a periscope to change the height of the beam, or to rotate its polarization. These are potential hazards. When the beam moves vertically, it has a chance of missing a mirror and either bouncing off the table or heading straight up into an eye.

3. **Keep your head above the beam plane.** Even with safety glasses on, do not put your head at beam level. If you must pick something up off the floor, train yourself to close your eyes as you pass through the beam plane, regardless of your safety glasses.

4. **Block any beam that you are not using.** If you are working elsewhere in the laboratory and don't need the beam on your setup, block the beam as close to the source as possible without disturbing others' work.

5. **Fasten optics securely.** A leading cause of accidents is the stray reflection from a mirror, lens, or other optic that is moved into our out of the beam, by accident or on purpose. Block the beam, insert the optic, verify its position with the beam briefly using the IR viewer, and fasten the optic/mount firmly to the table before unblocking the beam.

6. **Eliminate stray reflections.** Because our laser is so intense, even the stray reflection from a portion of the beam is sufficient to blind. Carefully track down stray beams using the IR viewer and/or an IR-sensitive card. Use beam blocks, black paper, iris diaphragms, and glass filters to remove them.

7. **Ask.** When in doubt about the operation of any piece of laboratory equipment, ask another student or a professor.

8. **Assume the worst.** When you enter the laboratory, assume the laser is on, not off.

9. **Get instruction.** Before operating a new piece of equipment, have someone show you have it works and explain potential problems. Read the manual. It may take you several times watching the procedure before you are ready to handle it on your own. This is normal. I watched folks in France perform the start-up procedure plenty of times before I was ready to make more than trivial adjustments. No shame there.

10. **Think!** It takes one split-second misstep to destroy an eye. If you are tired and having a hard time concentrating, it is time to pack up for the day. Accidents can happen at any time, but when you're tired or doing something unfamiliar they are much more likely. When it doubt, discretion is the better part of valor. **Think!**

Informed Consent

The purpose of this document has been to acquaint you with the hazards of working with lasers and to help you learn how to work safely with the laser. When you work alone on a laser, you alone are at risk. Usually, more than one person is present in a laser laboratory, either collaborating on a single setup or working on independent experiments with independent beams. In this case, you are responsible for your safety and the safety of others in the room.

I have read this document, worked the exercises, and understand the hazards of the 1-kHz Ti:sapphire laser system. I have studied the list of safe operating procedures and consent to follow them. I understand that I will be permanently removed from the laboratory for failure to use appropriate laser safety glasses.

Signature: ______________________________

Name: ______________________________

Date: ______________