# Quantum Eraser &
# Sirah Credo Dye Pulsed Laser

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# Chapter 1

# Quantum Eraser

## 1.1 Principle

A Mach-Zehnder-interferometer is illuminated with a laser beam. Circular interference fringes appear on the screens behind the interferometer. If polarization filters with opposite polarization planes are placed in the two interferometer paths the interference patterns disappear. Placing another polarizer before one of the screens causes the pattern to reappear. Electromagnetic radiation can be described both in terms of propagating waves, as well as particles (photons). The experiment illustrates this duality by showing how interference patterns can be explained on the basis of both classical wave mechanics and quantum physics.

## 1.2 Tasks

1. Set up the experiment and observe the interference pattern on the screen.
2. Change the polarization of the beams with the PF1 and PF2 polarizers and observe the influence on the interference pattern.
3. Use the third polarizer PF3 to cancel the polarization of the light in the two beams, and observe the reappearance of the interference pattern.

## 1.3 Equipment

| Equipment | |
|---|---|
| Laser | 1 |
| Surface mirror | 3 |
| Adjusting support for mirrows | 3 |
| Beam splitter | 2 |
| Adjust support for beam splitter | 2 |
| Beam stoppers | 2 |
| Screen 150 mm × 150 mm | 2 |
| Glass lens in mounting, f = +20 mm | 1 |
| Lens holder for base plate | 1 |
| Polarisation filter for base plate | 3 |
| Magnetic foot for base plate | 10 |

## 1.4 Set-up and Procedure

**Caution!**

The laser module is a class 2 laser, which does not require any protective eyewear. However, to avoid injury, do not look directly into the laser beam.

In this experiment a Mach-Zehnder Interferometer is used to split a light beam into two parts, send them along two different paths where they can be subjected to individual treatment and then to reunify the two beams again and observe interference effects (See Fig.1.1). Since the precise alignment of the Interferometer is crucial the individual steps will be described in the following and illustrated with photographs. In the final set-up shown in Fig. 1.2 the position of all the optical elements can been seen along with the names and abbreviations used for them in this set-up guide.

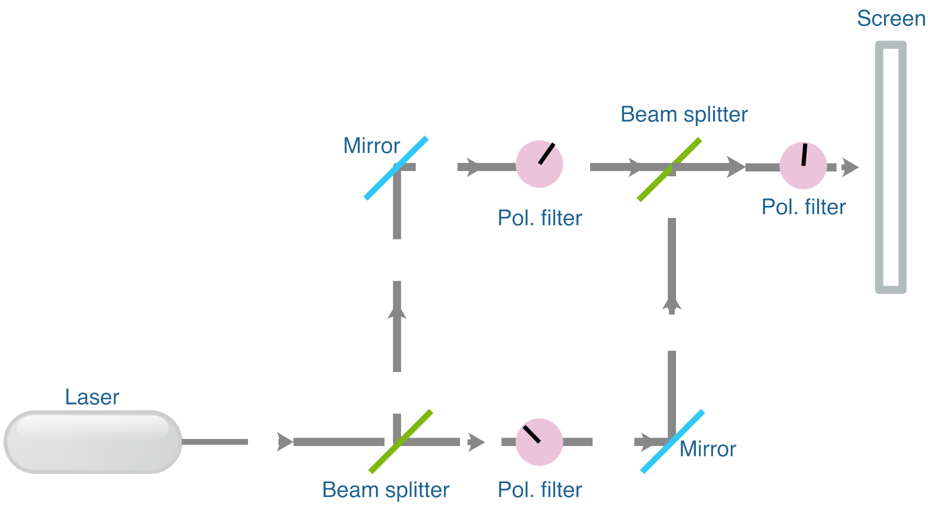



Figure 1.1: Schematic diagram of the optical paths.

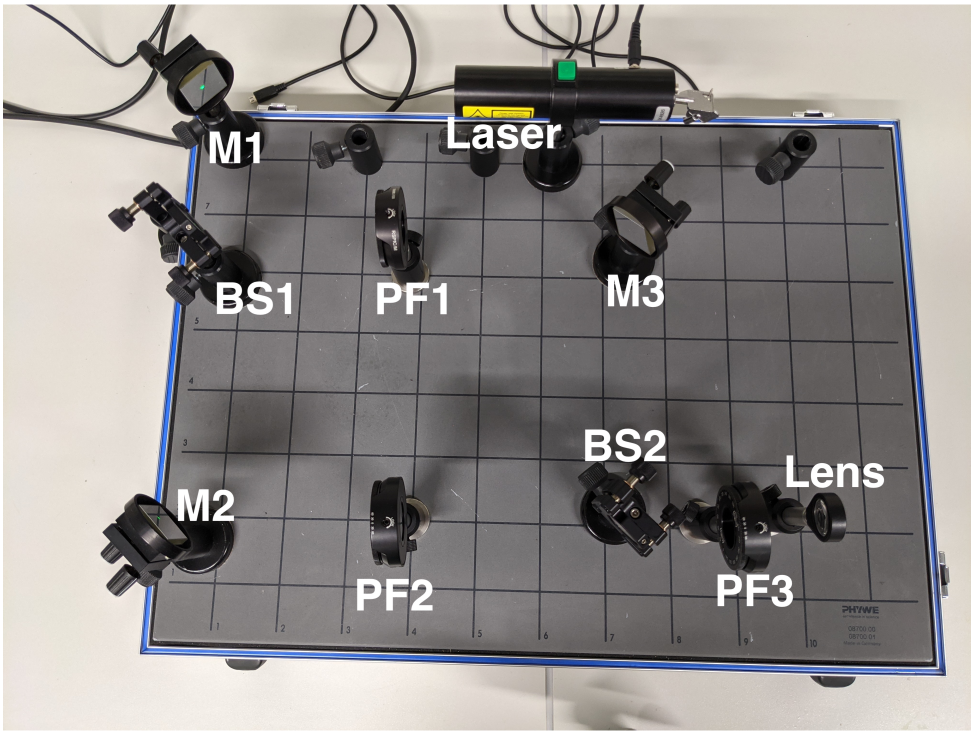



Figure 1.2: Final setup.

- Fix the laser to the optical base plate and direct the beam with the mirror M1 to the left corner. Since the laser is not perfectly straight, this mirror will allows us to bring the beam parallel to the base plate. (Fig. 1.3).
- In this step the beam from mirror M1 will be adjusted to have a straight path. Place the two beam stoppers in the edge along the line 1 one close to the mirror and the other one far away. Adjust the laser path to hit the edge of both stoppers and then

bring the laser to the same height in both stoppers. Write down the height. (Fig. 1.4).

- Now that the beam is parallel to the base plate place the beam splitter BS1 in front of mirror M1. Use the stoppers like the step before to align the beam with one of the lines of the base plate. (Fig 1.5)
- The mirrors M2, M3 and beam splitter BS2 are positioned as shown in Fig. 1.6 so that the indicated light-path forms. One should make sure that the coated side of the beam splitter BS1 is located on the side pointing towards mirror M2 and the coated side of beam splitter BS2 points toward mirror the screen. The beams should preferably travel parallel to the lines on the base plate and strike the optical elements in the centre, this can be done with the same procedure explained before, using the beam stoppers as reference.
- The goal of this step is to achieve a perfect coincidence of the pairs of beams going from the beam splitter BS2 to the screens. Initially on both screens two bright points will be visible. With the adjustment screws at mirror M2 and M3, and the splitter BS2 these points can be brought to coincide on one of the two screens. If the two dots appear in different heights on one of the screens while they coincide on the other one, this can be corrected by tilting the beam splitter BS2.
- The expansion lens is brought into position between the BS2 and the screens. The interference pattern visible on both screens (Fig. 1.7a and 1.7b).
- Finally, the three polarizing filters PF1, PF2, PF3 can be placed. Fig. 1.2 show the complete setup.

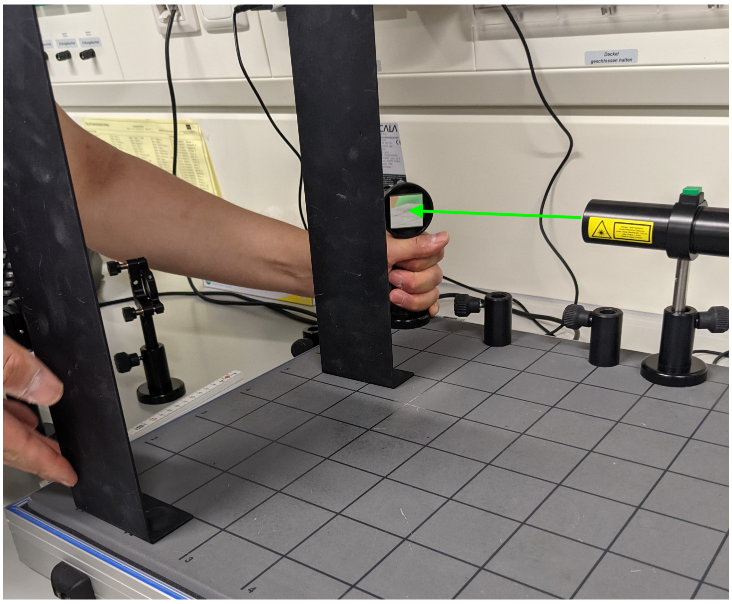


Figure 1.3: Laser directed to the center of mirror M1

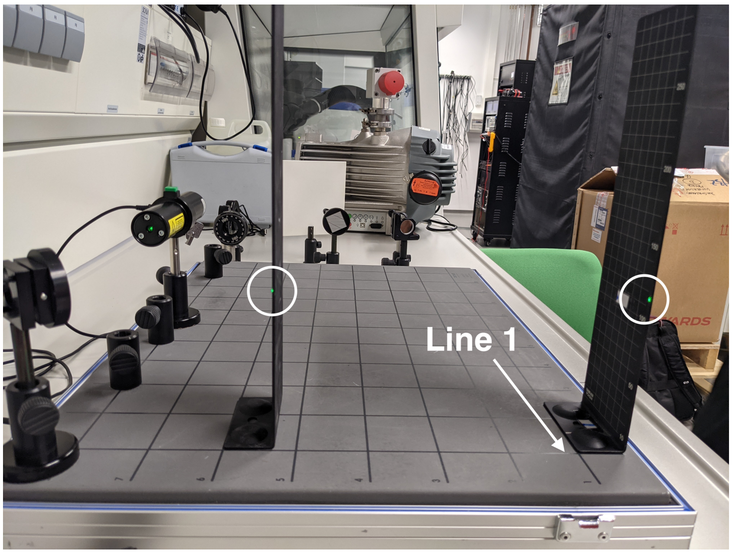



Figure 1.4: Laser aligned with line 1 using the beam stoppers

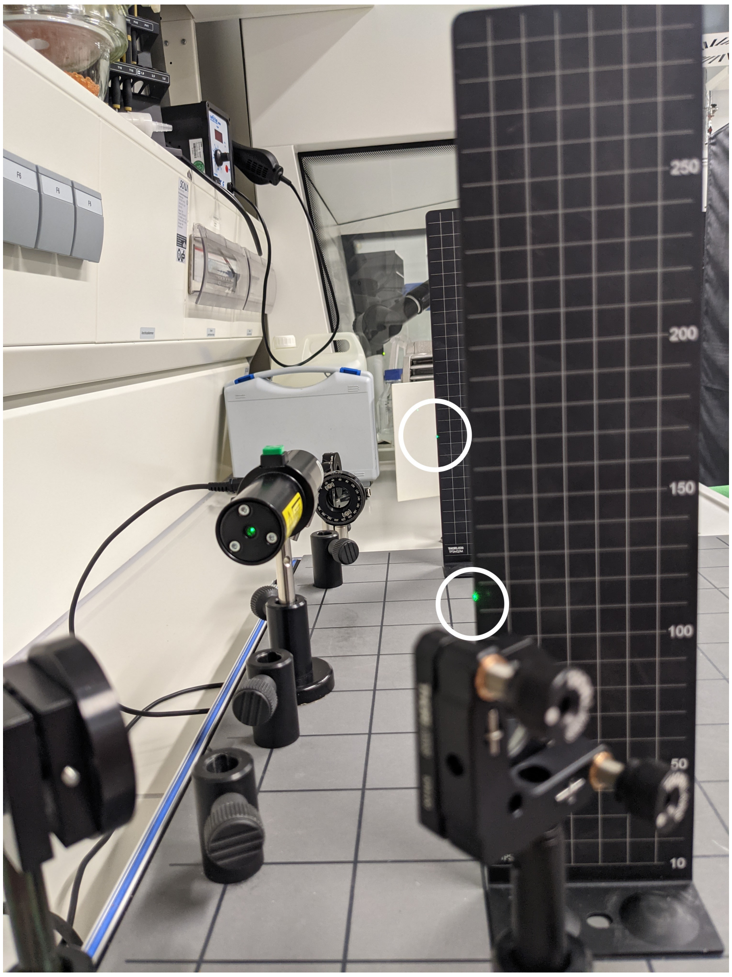



Figure 1.5: Laser beam from beam splitter being aligned in line 3 of the base plate.

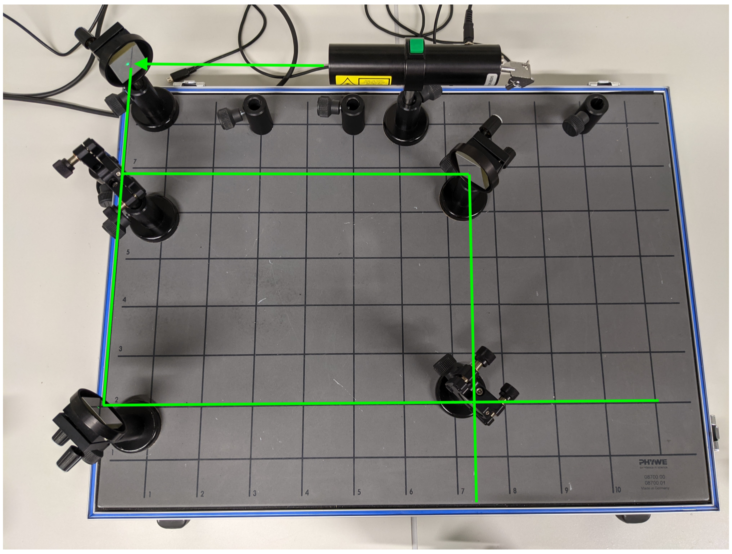
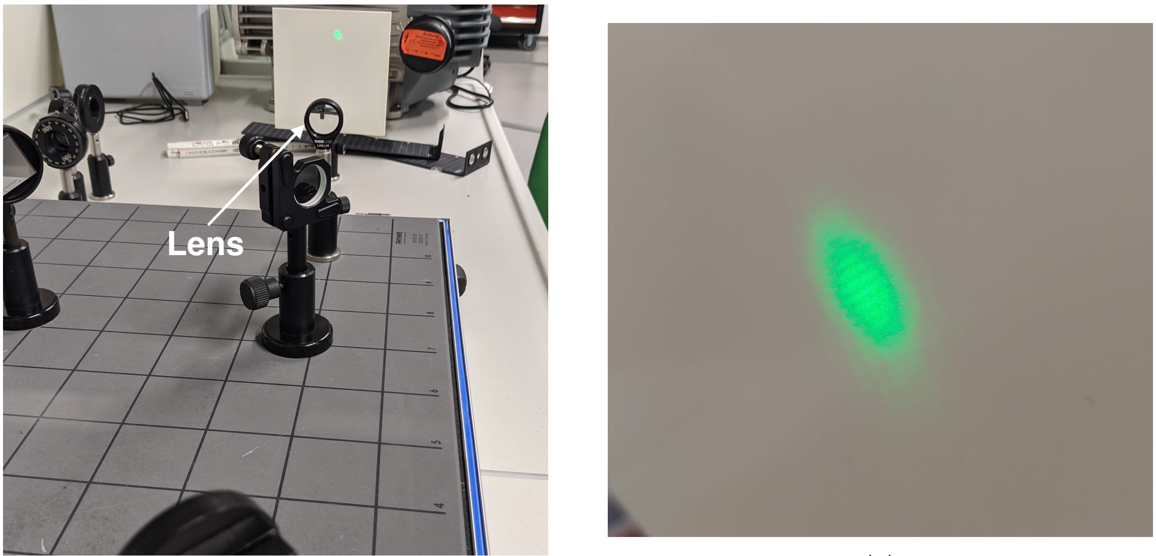


Figure 1.6: Correct set-up of the mirrors and the beam splitters.




(a) (b)

Figure 1.7: (a) Lens to expand the beam to be able to see the (b) interference pattern

Having set the experiment as described above, block one of the two paths in the interferometer: a relatively homogeneous spot is visible on the screens. If you now open the blocked path, the spot does not become brighter everywhere, but there are regions (fringes) where the brightness drops.

Shift the polarizing filter PF3 out of beam path. The polarizing filters PF1 and PF2 are oriented so that light passing them has the same polarization. Under these circumstances interference rings are visible on both screens.

If you rotate PF1 so that light passing it is polarized perpendicular to light passing PF2, the interference effect on both screens vanishes. The next step is to introduce the polarizing filter PF3 and orientate it at an angle of 45 degrees with respect to PF1 and PF2. The interference pattern is visible again on the screen SC1 behind PF3.

## 1.5 Theory and Evaluation

### 1.5.1 Classical physics - wave interference

Wave interference is the superposition of two or more waves that results in a new wave pattern. The resultant displacement at a point is equal to the vector sum of the displacements of different waves at that point. To illustrate this principle, let us assume two sinusoidal waves of the same wavelength interfere with each other. If the phase-shift between them is zero, in other words, if at any given point their amplitudes are the same, the overall amplitude will be double that of each wave (constructive interference). If, on the other hand, their phases are shifted by half a period, they will cancel each other out (destructive interference). Fig. 1.8 illustrates this example. Most electromagnetic waves can be well approximated by plane waves, that is waves with infinitely long and wide wave fronts. For such electromagnetic waves, it follows from Maxwell's equations that the electric and magnetic field are perpendicular to the direction of propagation and to each other.

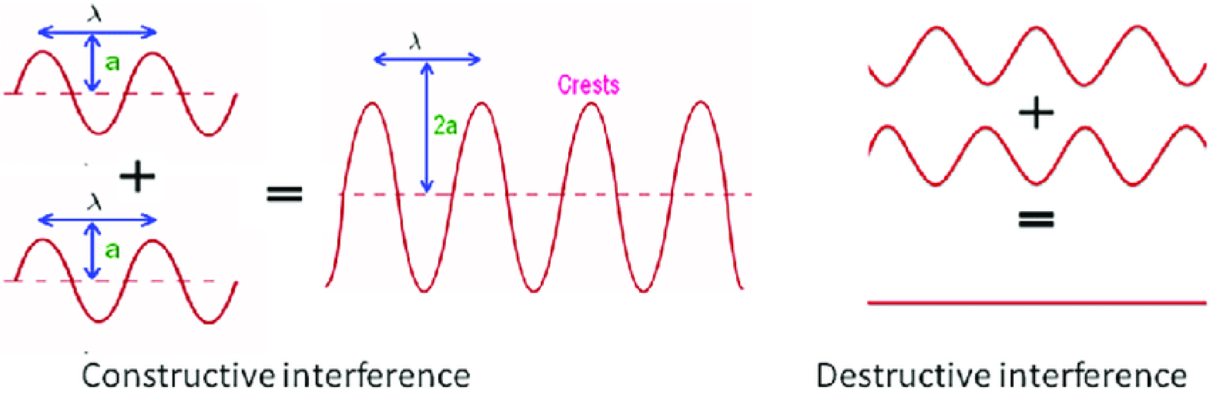



Figure 1.8: Illustration of wave interference.

Electromagnetic waves exhibit a property called polarization, which describes the orientation of their oscillations. Conventionally, when considering polarization, only the electric field vector is described and the magnetic field is ignored, since it is perpendicular to the electric field and proportional to it. If we divide the electric field vector into x and y components, a polarization of a wave tells us how those components change in time. In other words, a polarization state of an electromagnetic wave is the shape traced out in a fixed plane by the electric vector as such a plane wave passes over it (Fig. 1.9). Important fact is that electromagnetic waves of different polarization do not interfere with each other.

The laser in the experiment produces coherent electromagnetic radiation, i.e. electromagnetic waves with the same frequency, polarization and phase. The beam is split into two, and the polarization of each beam can be changed separately by adjusting

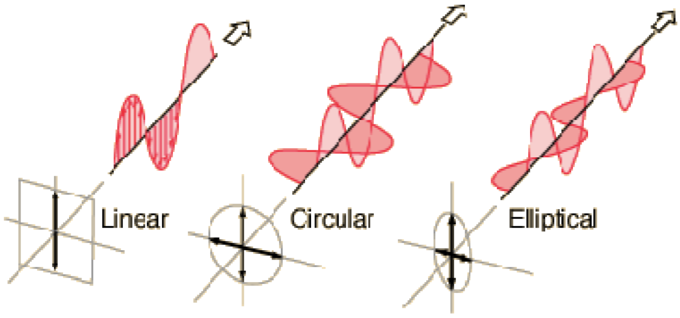



Figure 1.9: Schematic representation of electromagnetic waves and their polarization.

the polarizers PF1 and PF2. Hence, if we set the polarization of both beams to be the same (equivalent to removing the polarizes from the beam paths), we ob- serve the interference pattern on the screens. The bright fringes are the locations where the incoming beams interfere constructively, hence producing higher amplitude than without the interference effect, while the dark fringes are the locations where destructive interference takes place, and the radiation from the two beams cancels each other out. When we use the polarizers PF1 and PF2 to set different polarizations for each beam, the interference pattern disappears, since electromagnetic waves of different polarization do not interfere. We can now use the third polarizer, PF3, to recover the interference fringes by setting it at an angle of 45°with respect to the polarizers PF1 and PF2. In doing so, we again bring the two beams to the same polarization, and they interfere.

### 1.5.2 Quantum physics - the quantum eraser

The experiment can also be interpreted by a quantum theory. Hence, we now consider the electromagnetic radiation to consist of photons. Note, that this does not mean that we can think of photons as rigid spheres. Actually, in mathematical terms, a state of a system (a photon for example) in quantum mechanics is described by a complex wave function$\Psi(x,t)$ (also called a state vector in a complex vector space), belonging to a complex separable Hilbert space, and is governed by the Schrödinger equation (Eq. 1.1)

$$i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \hat{\mathbf{H}}\Psi(x,t) \tag{1.1}$$

where i is the complex number, $\hbar$ is the reduced Planck constant and $\hat{\mathbf{H}}$ is the Hamiltonian operator.

The wave function $\Psi(x,t)$ is a rather abstract mathematical object and does not represent an observable, that is, a quantity we can actually measure. What we can obtain from the quantum theory is a probability density of an observable, which is given by the amplitude of the wave function. Hence, we can calculate the probability of finding a particle at a given position in space, or having a given momentum, or energy, etc. Therefore, even though we talk about particles, the quantum theory describes them as wave packets, and what we actually obtain are “clouds” of probability. For example, if we calculate a position of a photon, the result will be a region in space where the probability is non-zero, and not a single location, as in classical physics. What this means is that, from the quantum point of view, the particle is every- where in the region where the calculated probability is non-zero. Additionally, the probability is given only by the amplitude of the wave function, while the phase encodes information about the interference between quantum states. This gives rise to the wave-like behavior of quantum states. For example, if there are two ways for a photon to travel, as in the quantum eraser experiment, and both are equally probable (we cannot measure which path the photon actually takes), both of these quantum states interfere with each other and result in the fringe pattern we observe.

Contrary to classical mechanics, the quantum theory does not allow for accurate simultaneous predictions of conjugate variables, like position and momentum, time and energy (frequency). This is known as the uncertainty principle (Eq. 1.2, for position and momentum)

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{1.2}$$

where $\Delta x$ and $\Delta p$ are the uncertainty of position and momentum, respectively. Hence, a minimum exists for the product of the uncertainties, and the more precisely one property is measured, the less precisely the other can be measured. Now let us interpret the experiments using quantum physics. Even though the laser produces many photons that travel through the setup simultaneously, the truly amazing fact is that the result is the same (interference pattern is formed) even when we sent one photon at the time. From the quantum- mechanical point of view, the photon has non-zero probabilities of travelling along both paths in the setup, therefore it travels simultaneously along both paths and interferes with itself ! Both states (photon travelling along path a and path b) coexist and have the same probabilities, and the wave function is a superposition of those states, which results in the interference pattern. When we use the polarization filters PF1 and PF2 to prescribe polarization information on the photon (opposite polarizations for each path), the wave function changes (and hence the probabilities of finding the photon along the two paths) and removes the ability of the photon to interfere with itself. What it means is that, by polarizing the photon, we are able to tell which path it travelled (the probability becomes one for one path and zero for the other) and hence only one state exists. Thus the interference pattern disappears. When we erase the polarization information with the third polarizer (PF3), the probability of finding a photon at a given lo- cation at the detector (screen) results again from a superposition of the two equally probable quantum states (photon travelling along path a and path b), and hence forms the interference pattern. Thus the name “quantum eraser”.

# Chapter 2

# Sirah Credo Dye Laser Tuning

## 2.1 Principle

When working with a laser system, it is desirable to understand at least the basic principles of its operation and related aspects. These are described in the following.

A laser is a device that generates an intense beam of coherent monochromatic light (or other electromagnetic radiation) by stimulated emission of photons from excited atoms or molecules (medium). In the case of the pulsed dye laser, the medium is a laser-active dye in a liquid solvent, this dye is contained in a cell or cuvette of aproximately 0.5 x 0.5 x 2 cm in size. The Sirah laser have two dye cells, the Resonator and the Amplifier. Laser dyes have a limited lifetime as they tend to be chemically modified during laser operation over longer times. Therefore, the dye solution has to be replaced with respect to the life time of the used dye. Note also that many dyes and the used solvents are poisonous, making necessary a careful handling.

Laser dyes can be optically pumped, in our lab we pump the laser with a Q-switched Nd:YAG laser at 532 nm that has a maximum power of 90W. In the Resonator cell the dye absorb the light from the pump laser and emit light of longer wavelengths (in our case in the red).

As it is difficult to obtain a high pulse energy and all other desirable properties (beam quality, emission bandwidth, etc.) directly from a dye laser oscillator, our Sirah dye laser system contain a laser Resonator and one Amplifier stage.

Here, the wavelength-tunable Resonator produces pulses with relatively low energy, but good beam quality and spectral purity, and the amplifiers serve essentially to increase the pulse energy. The laser Resonator contains a dye cell and diffraction gratings (see Figure 2.1) within an optical resonator, where light can circulate, whereas the laser light does only a single pass through each amplifier stage. The interaction of oscillator and amplifiers involves some non-trivial aspects. Therefore, optimum performance requires that all components are optimally adjusted. System optimization must begin with the oscillator and end with the last amplifier stage. Errors made in one stage can usually not be fully compensated by optimizing further stages.

### 2.1.1 Amplified Spontaneous Emission (ASE)

A pumped laser gain medium inevitably exhibits some spontaneous emission. This means that some light is emitted even if no signal light (to be amplified) impinges the pumped gain medium. If the laser gain is high, the resulting fluorescence is also strongly amplified – particularly in certain directions, such as the "long" direction of a pumped region. Therefore, the ASE light is also somewhat directional, although substantially less than a laser beam. Other characteristics are that ASE has a much broader optical bandwidth (frequency range) than the laser emission, a lower degree of polarization, and usually also a different temporal profile.

ASE is particularly strong in pulsed dye laser systems, because (a) such systems have a high laser gain, (b) the dyes can emit in a broad optical bandwidth, and (c) the build-up of laser radiation in a dye laser oscillator takes a few nanoseconds, during which the wanted laser radiation cannot saturate the gain and in that way reduce the ASE power.

ASE has essentially two negative implications on laser operation and applications of the laser light: ASE extracts some of the stored energy, i.e., it leads to lower output pulse energies in the wanted laser beam. ASE light may "contaminate" the laser beam, if it cannot be removed in some way, and can then have detrimental effects on the application.

## 2.2 Tasks

Learn how to tune the dye laser and its operation.

## 2.3 Optical Setup

**Warning!**

The Sirah Dye Laser is a class IV laser, which require protective eyewear. Avoid wearing reflective jewellery while using the laser. Under no circumstances look into the laser output.

The optical setup of the Sirah dye laser is sketched in Figure 2.1. The laser resonator consists of the output coupler mirror OC, the dye cell $DC_{RES}$, the prism expander PE, the grazing-incidence grating G and the wavelength tuning mirror TM. The laser beam exiting the resonator passes two turning prisms. Before entering the amplifier $DC_{Amp}$ the telescopic lenses $L_i$ adapt the laser beam diameter for the amplification in the second installed dye cell. Then the amplified beam is send to the laser aperture of the Credo-Dye laser system.

Our dye laser has a frequency conversion unit (FCU) installed, including beam shift compensation and wavelength separation between the generated UV light and the fundamental of the Credo-Dye laser.

The incoming pump energy is distributed in the pump volumes of resonator and amplifier by the beamsplitter BS and the mirror $M_3$, which are adjustable by the operator. The mirrors $M_1$ and $M_2$ constitute a factory set time delay for the pump beam between resonator and amplifier. The pump beam is focused on the dye cells by the cylindrical lenses $C_1$ and $C_2$, adjustable by the operator.

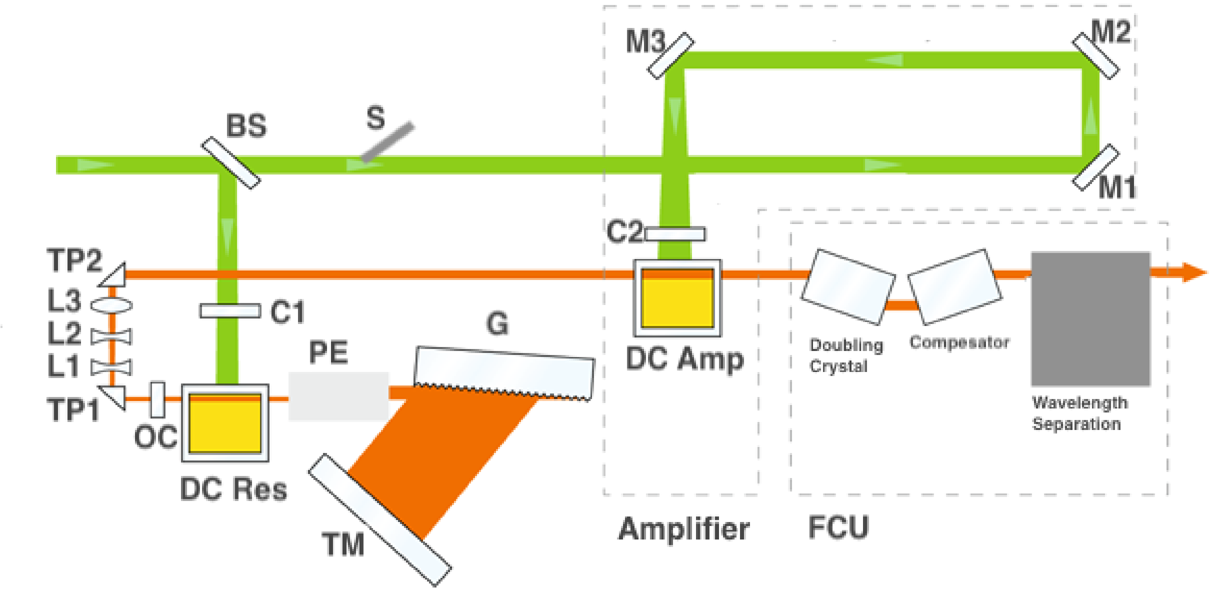



Figure 2.1: Sirah Credo optical layout

## 2.4 Tuning Procedure

For the alignment, you need to operate your pump laser with a pulse energy as low as possible, so that safety hazards are minimized and (for a green pump beam) you can properly see the beam scattered on a card (without being dazzled).

1. Close the shutter S. Remove the cover plates of the dye laser, the cover plates of the pump optics and the acrylic covers. Remove the dye cell $DC_{Res}$ and $DC_{Amp}$. Now you have to place the beamtool 1 onto the baser plate centric in front of the beamsplitter BS Fig. 2.2. Switch on the low power pump beam, and verify if the beam hits the center of the beamtool's 58 mm mark. Now check the position of the pump beam on the beam splitter BS itself, by inserting a card in the pump beam close to the beamsplitter's front side. Verify that the pump hits the beamsplitter near its left edge, and approximately centrically in the vertical direction Fig. 2.3.

2. Insert your card in the pump laser beam behind the beamsplitter BS, but in front of the shutter S. Check that the pump beam profile is not cut by the beamsplitter BS or its mount.

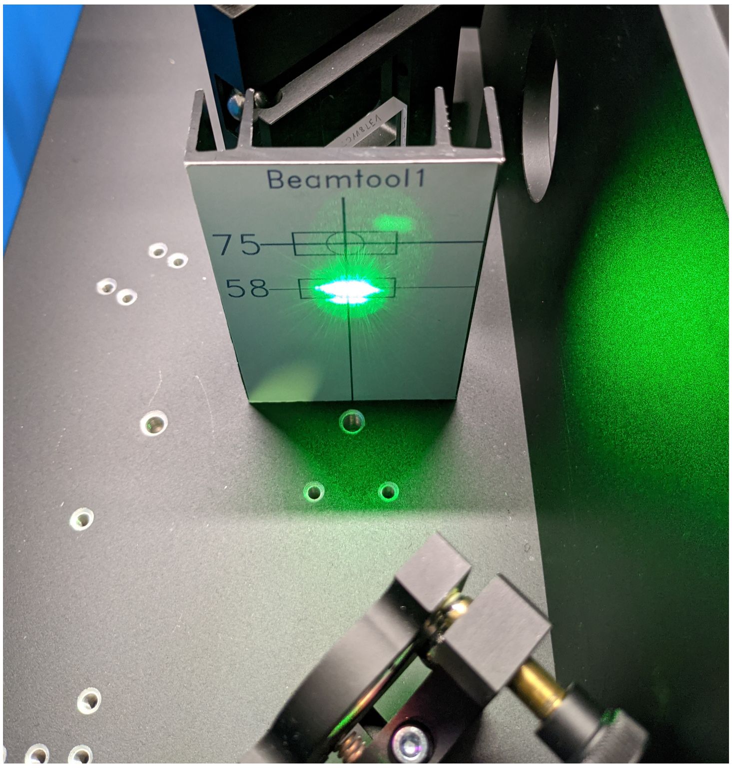



Figure 2.2: Checking pump's beam position on the beam splitter: Beamsplitter BS with beamtool 1

3. Open the shutter S and position the beamtool 1 centric in front of M1. As before, verify if the beam hits the centre of the beamtool and also check with a card, that the beam hits the centre of the mirror M1.

4. The mirror M1 and M2 guide the laser light stepwise higher onto the centre of mirror M3. Insert a card in front of mirror M3 and verify if the pump beam finds the centre of this mirror too.

5. Finally, you should check the position of the pump beam on the dye cells. Put beamtool "Resonator"in the resonator's dye cell mount. You will see the focused resonator pump beam on the tool located approximately in the centre of the dye cell's position Fig. 2.4.

6. Open the shutter S and repeat step 5 for the amplifier's pump beam by using the beamtool "Amplifier" Fig. 2.5.

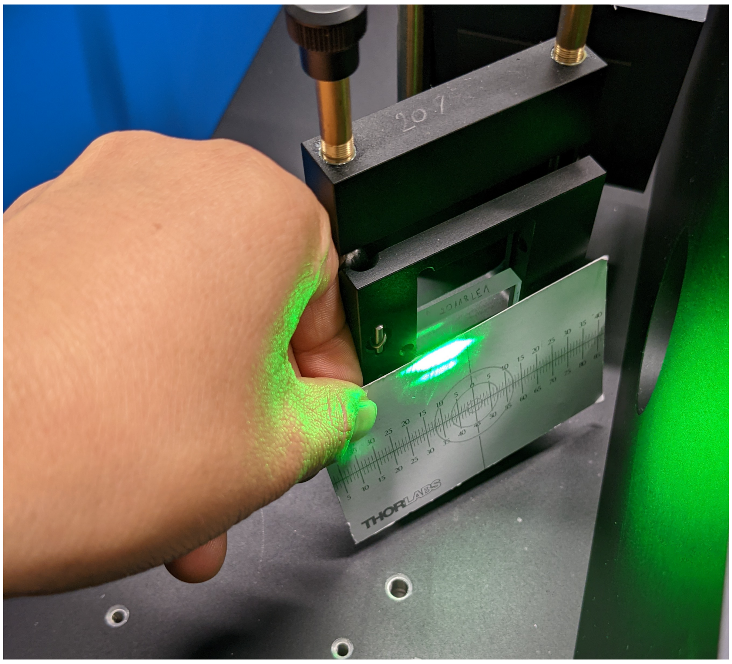



Figure 2.3: Checking pump's beam position on the beam splitter: Use a card to check the beam position on the beamsplitter itself

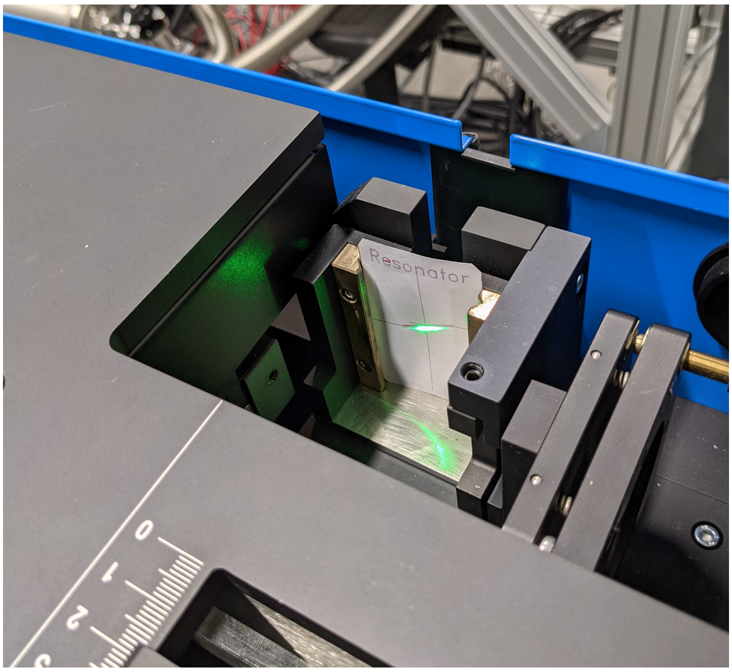



Figure 2.4: Checking pump's beam position on the resonator: Use the beamtool "Resonator" to align the beam with the beamtool.

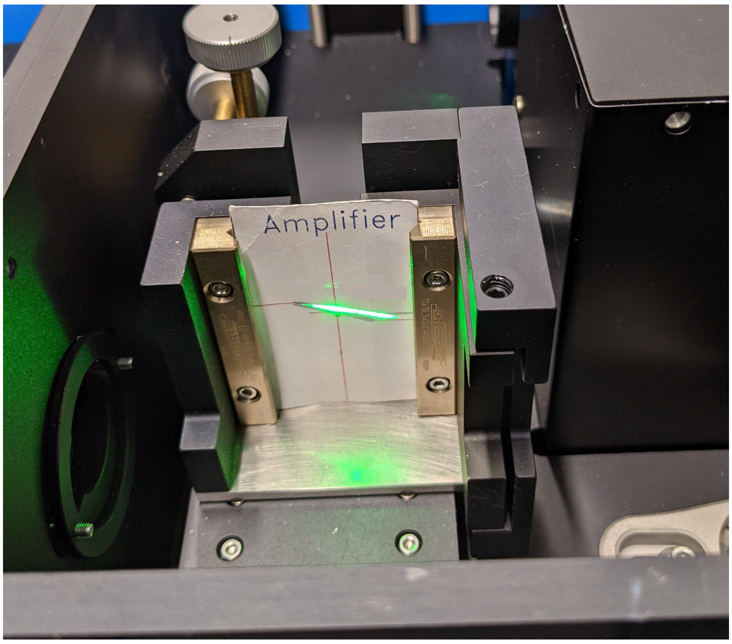


Figure 2.5: Checking pump's beam position on the resonator: Use the beamtool "Amplifier" to align the beam with the beamtool.