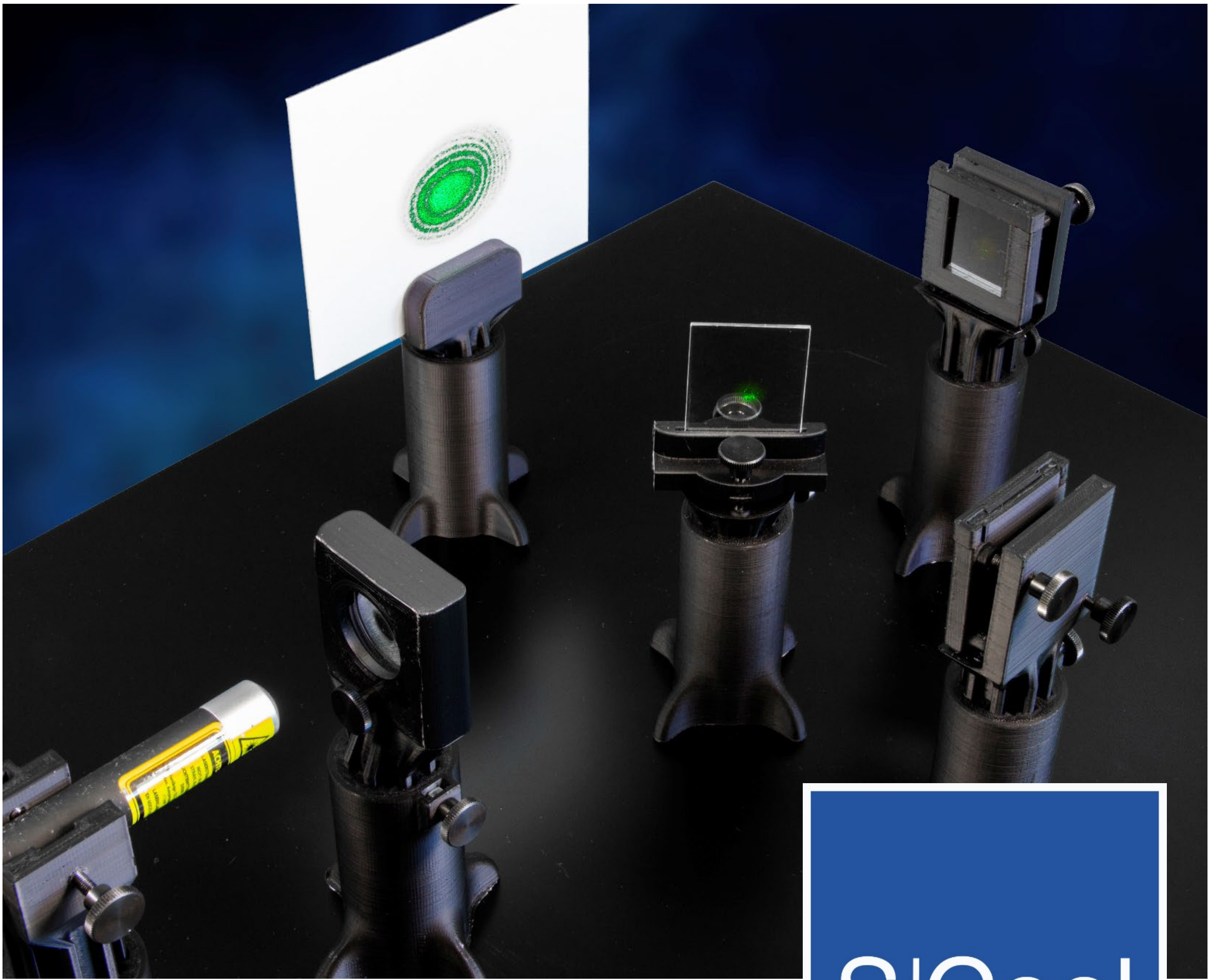


3D PRINTED LASERLAB

Assembly Instructions

fabian.bernstein@cern.ch

Contents

Bernstein, Fabian (2020). 3D printed Laserlab. Assembly Instructions. Version 1

More ideas for the classroom:

https://cern.ch/scoollab/classroom-activities

0) Introduction

Space, **time**, and **matter** are among the most fundamental concepts we rely on for structuring our understanding of the surrounding world. In the past, fundamental research has made the most astonishing discoveries on the nature of these and has shown that our everyday understanding cannot be quite right.

Many times, advances in our understanding are closely tied to sophisticated experiments, which are, however, often not accessible to a broader public. Now, with the growing popularity of 3D printers, many of those experiments can indeed be conducted at home, on your very desk.

In this line of reasoning, this project proposes a **Do-it-yourself 3D printed Laserlab**, which allows for **hands-on experimentation** in the realms of Special Relativity and General Relativity as well as Quantum Physics. Technically, the Laserlab consists of 3D printed optical mounts that are complemented by inexpensive components such as screws, magnets, or mirrors. Once assembled, they serve as building bricks for experimental setups, very much like those you would find in a professional photonics laboratory but for a fraction of the cost.

This manual is built on the premise that you have a fair knowledge of physics and that you know your way around with optical setups. It is meant to aid the assembly of the optical mounts and facilitate the setup of the experiments. Neither does it contain in-depth information on the underlying physics nor the educational uses cases of the proposed experiments.

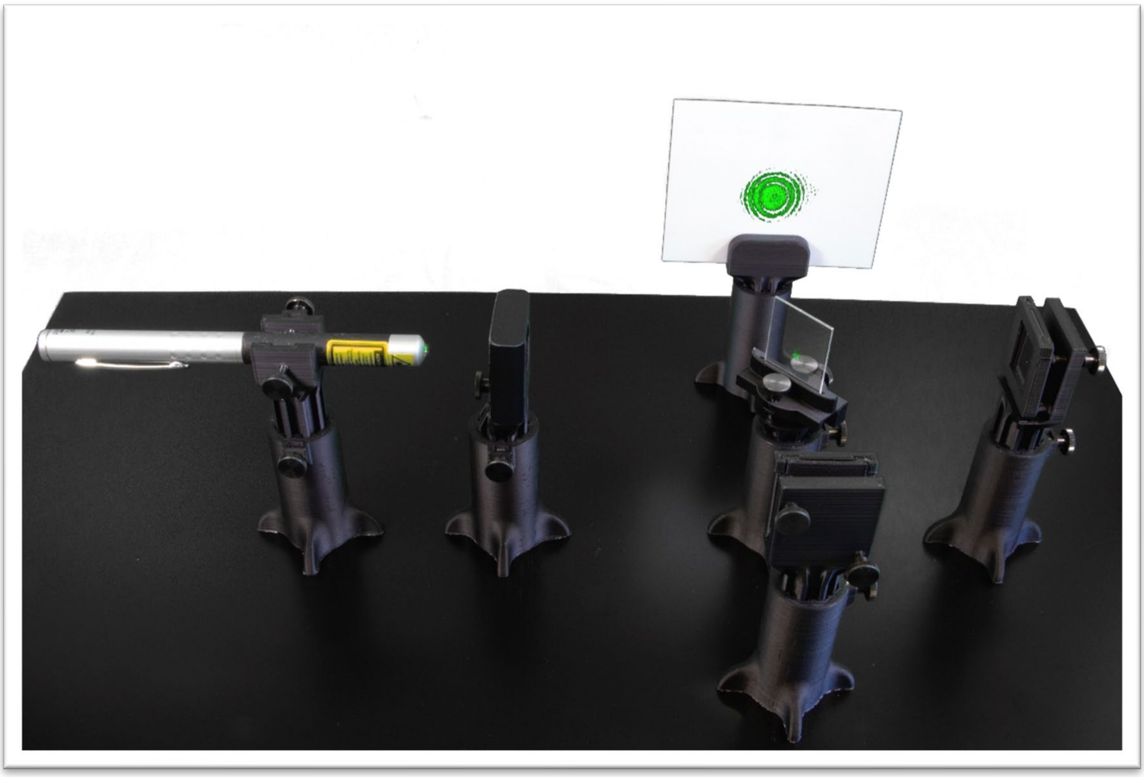
Health and Safety Warnings

Attention Laser Radiation

The experiments described in this manual make use of commonly available consumer laser pointers.
Be aware that laser pointers are not toys and can cause **serious health issues and eye damage! Do not stare into the beam!**

All laser safety restrictions set forth in the laser pointer's manual **and all governmental safety regulations apply.**

1) Michelson Interferometer (basic)



1.1) Physics Background

A Michelson interferometer is a sensitive optical device for detecting changes in the optical path length in one of the interferometer's arms. As Michelson-Morley experiment, Michelson interferometers have played a key role in exploring the foundations of Albert Einstein's theory of Special Relativity. In particular, the experimental discovery of the invariance of the speed of light is directly linked to the Michelson-Morley experiment. For more information on the Michelson-Morley experiment, see [1].

In recent times, Michelson interferometers have been utilized for detecting gravitational waves in large experimental facilities such as LIGO or Virgo. Further information on gravitational wave detectors can be found here [2].

In a Michelson interferometer, a laser beam is split equally onto two perpendicular mirrors by means of a beam splitter. Each partial beam is reflected, and both beams are subsequently superimposed on the far side of the beam splitter. Due to differences in the optical path length, an interference pattern can be observed at the screen. Since the wavelength of the light is rather short, a very slim shift of one of the mirrors (some tens of nanometers) will result in a noticeable alteration of the interference pattern.

For a more comprehensive explanation, see [3].

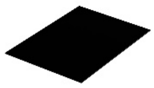
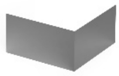
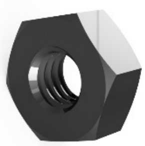
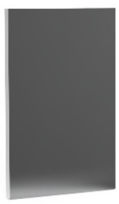
1.2) Technical Notes

- A Michelson interferometer is an extremely sensitive device that will detect relative changes in the optical path length of some 10 nanometers. Therefore, a solid table is required.
- Laser pointers feature different laser diodes with varying coherence lengths. If no interference pattern can be observed despite a careful setup, try a different laser pointer.

1.3) Required Materials & Mounts

A) 3D printed mounts		
Base	**Laser pointer Mount**	**Mirror Mount**
		
6x	1x	2x
Beamsplitter Mount	**Lens Mount**	**Screen Mount**
		
1x	1x	1x

B) Required materials

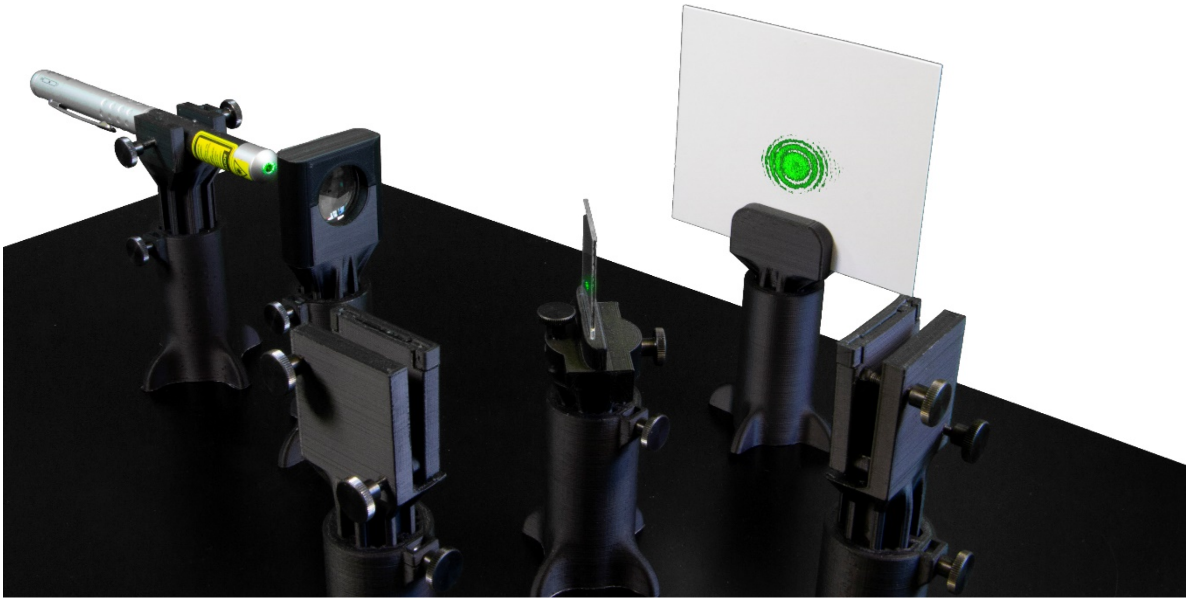
Steel plate	**Laser pointer**	**Neodym Magnet**
		
1x	1x	6x
Min. size: 420 x 300mm Recommended size: 600mm x 400 mm	Standard red or green consumer laser pointer Coherence length critical	15 x 15 x 8 mm
Knurled Screw	**Nut**	**Screen**
		
16x	11x	1x
M3, length: 12 mm	M3	Piece of cardboard, approx. 10 x 8 cm
Mirror	**Beamsplitter**	**Lens**
		
2x	1x	1x
30 x 20 x 1 mm front-coated	40 x 30 x 1 mm 50/50, non-polarizing	Convex glass lens (plastic works poorly) Ø = 25 mm, f = +45 mm

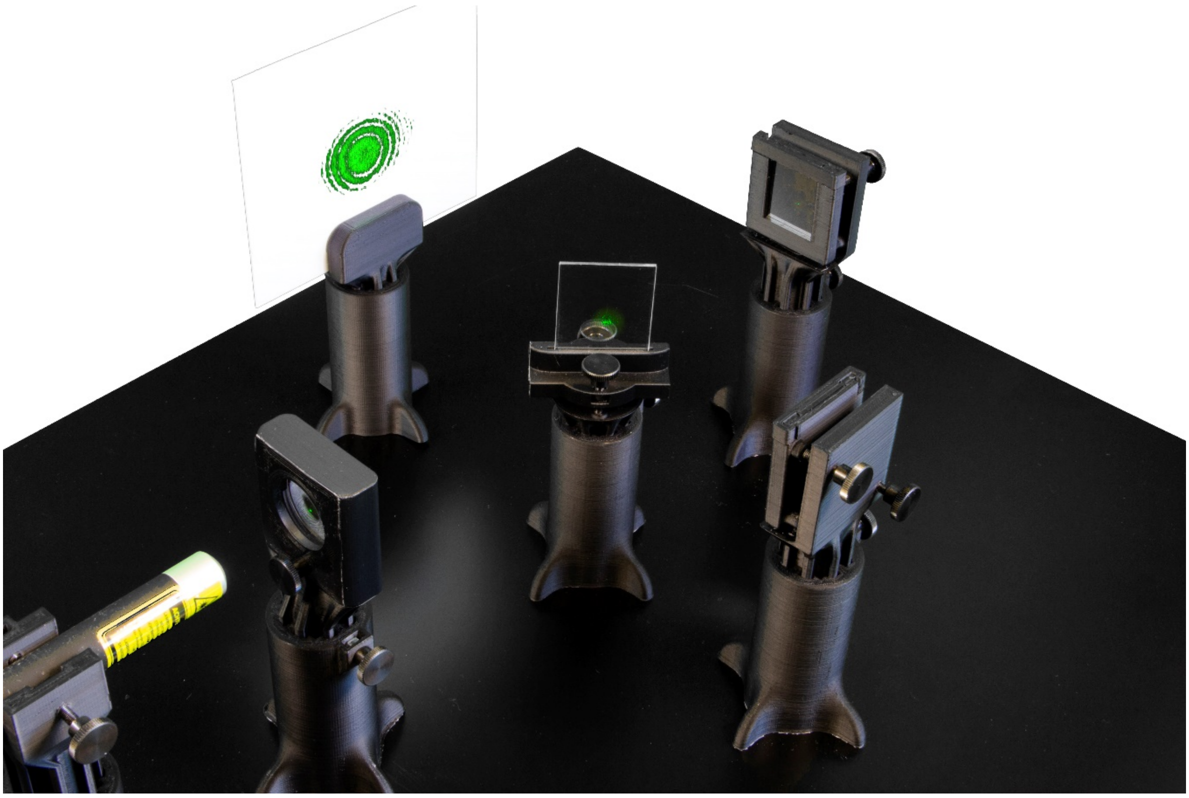
1.4) Setup

The setup of the Michelson interferometer is quite straightforward once all the mounts have been assembled. All mounts should stand firmly on the underlying steel base plate thanks to the magnets in the Base Mounts. To facilitate the assembly process, “cheat sheets” have been designed for all of the experiments. If printed on a DIN A3 sheet of paper and placed on the steel base plate, they will designate the positions of all mounts as well as the order in which they have to be placed. If no copy machine or large format printer is available, the cheat sheets will still give you an idea of where the mounts have to go.

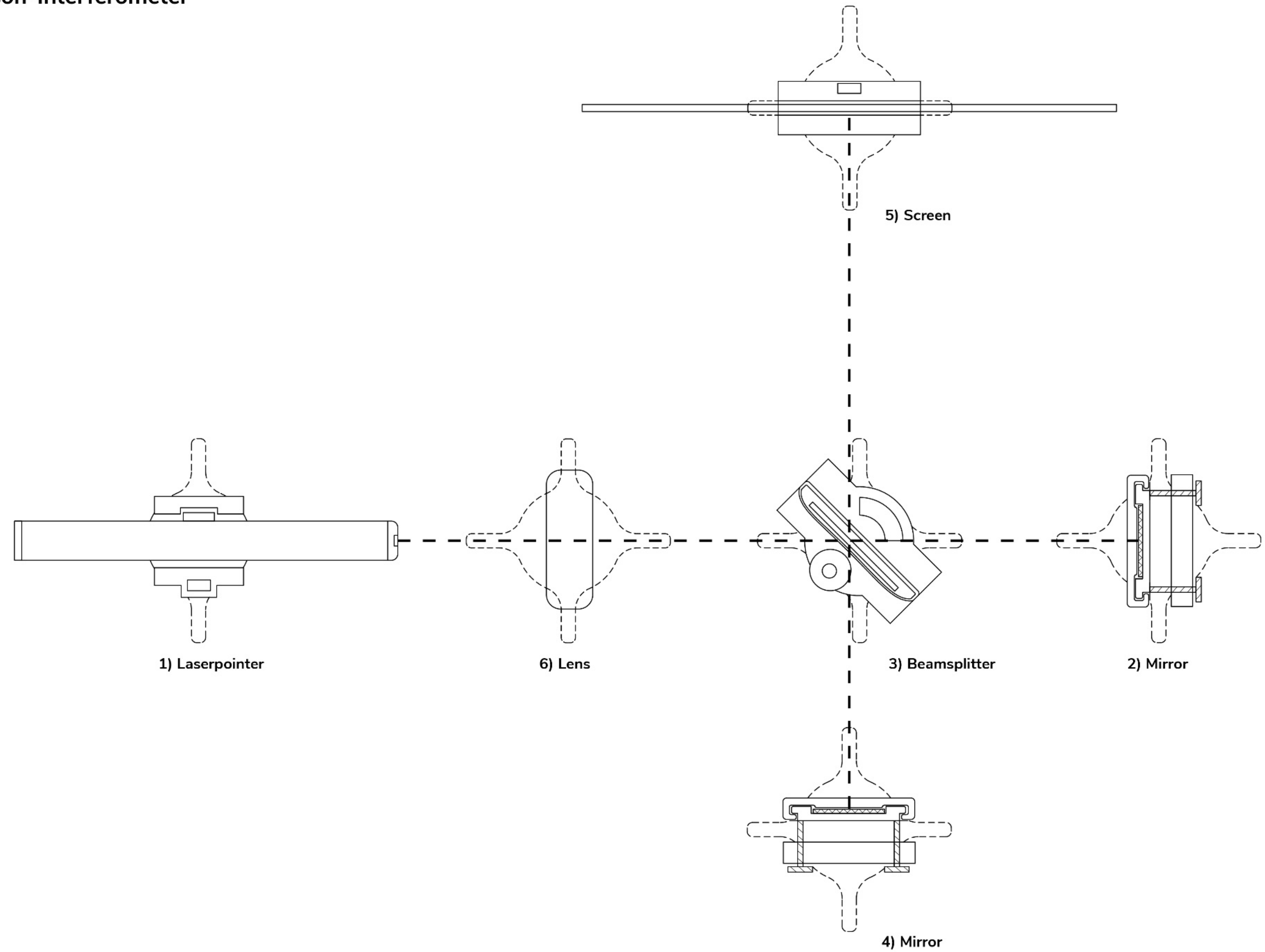
First, place the Laser pointer Mount 1) onto the steel base plate. The laser beam should travel horizontally, i. e. in parallel to the steel base plate. Second, place the Mirror Mount 2) onto the steel plate. Make sure that the laser beam is being reflected onto itself; that is, the reflection of the beam should reenter the laser pointer pinhole where the beam originates from. You can either turn the mount itself using the handles on the Base Mount or use the adjustment screws for the fine-tuning.

Place the Beamsplitter 3), the Mirror Mount 4), and the Screen Mount 5) on the base plate in such a way that the two partial beams are at a right angle. Turn the Mirror Mount 4) until the two spots are well aligned. The two spots should show a near-perfect overlap on the screen. Lastly, place the Lens Mount on the indicated position. Adjust the height of the lens so that the center of the beam on the screen stays where it has been before (without the lens). You should now be able to see the interference pattern. Use the fine-tuning screws on any of the mirrors to center the interference pattern on the screen.

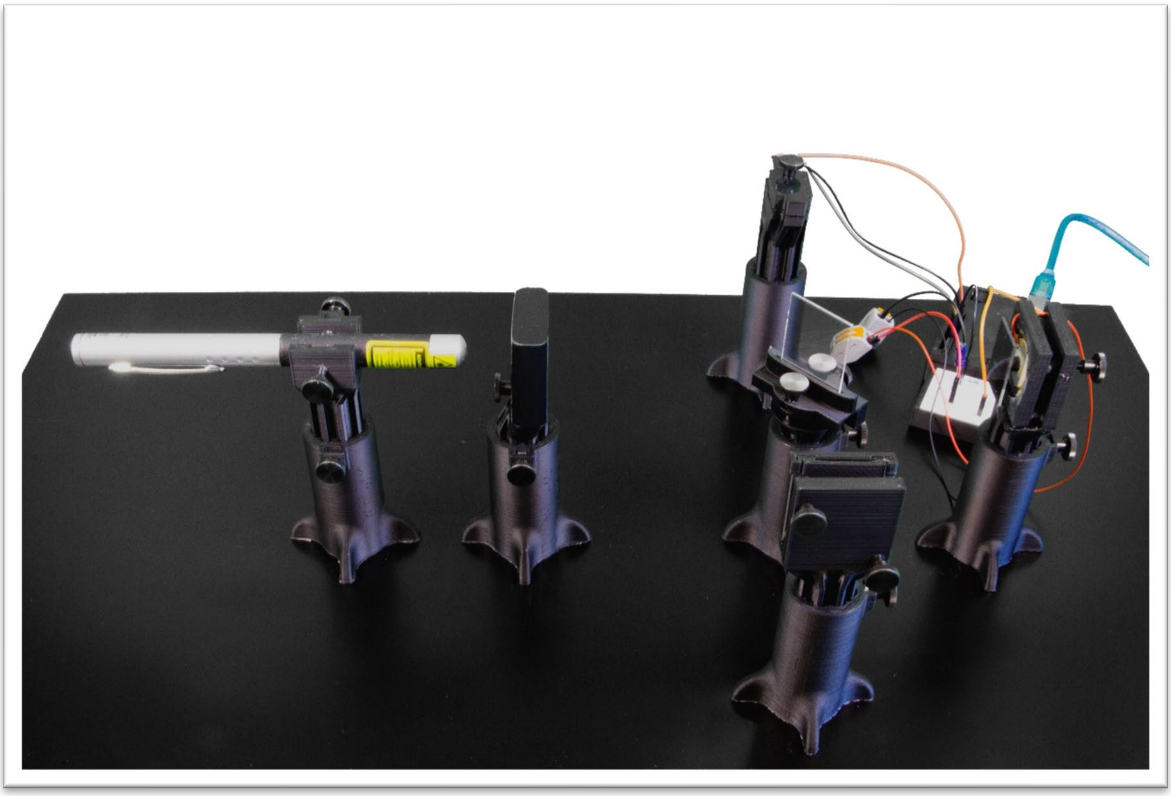




Michelson-Interferometer



2) Michelson Interferometer (advanced)



2.1) Physics Background

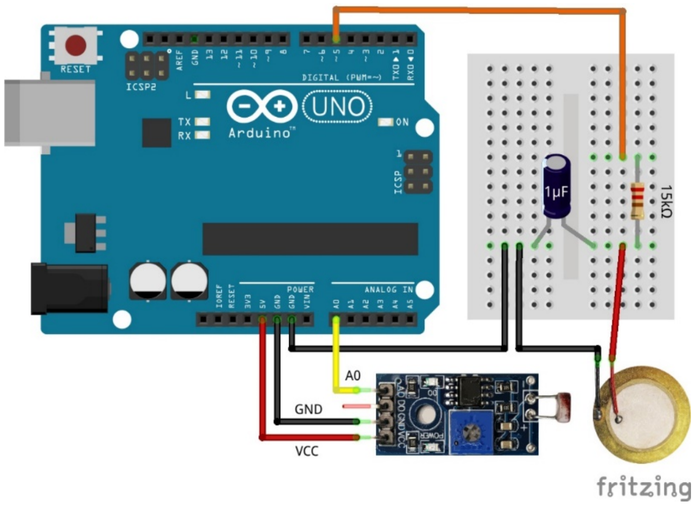
Two additions to the basic Michelson interferometer are proposed: On the one hand, you can use the piezo-driven Mirror Mount to displace one of the Mirrors by very small amounts (some 100 nm). This will result in shifting interference patterns, hence demonstrating how a Michelson interferometer can be used as a very sensitive detector. Gravitational-wave detectors such as LIGO and Virgo rely on detecting extremely small changes of the optical path length in one of the arms by exactly those interferometric means (more information here [3, 4, 5]).

To apply a voltage to the piezo, you can use pretty much any adjustable voltage source. For your convenience, we provide an Arduino sketch that allows for using an Arduino Uno to drive the piezo. However, since the Arduino Uno does not feature a Digital-Analog-Converter, a simple low pass filter has to be set up. More detail on this in the Technical Notes.

Secondly, it is possible to transform the setup from a qualitative to a quantitative experiment by means of a Light Dependent Resistor (LDR). To facilitate the measurement process, we have designed a custom LDR Mount which works with standard Arduino LDR modules. This way, the LDR can be directly connected to the Arduino using jumper wires, and the measured signal can be displayed in the Arduino IDE.

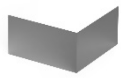
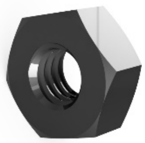
2.2) Technical Notes

- It is possible to use an Arduino Uno to drive the piezo and read out the LDR at the same time. If you want to do so, you will need a resistor (15 kΩ) and a capacitor (1 µF) to build a lowpass filter for driving the piezo (the Arduino Uno does not feature a Digital-to-analog converter and relies on Pulse Width Modulation (PWM) for generating quasi-analog voltages between 0 V and 5 V).
- If using an Arduino and the provided sketch, the wiring should be as follows:



- Note that the Light Dependent Resistor is optional – it's also instructive to see the interference pattern shifting on the screen while the voltage is being ramped up. However, if you want to quantify the displacement of the piezo / the mirror, you can use a standard Arduino LDR module (see Required materials) and the provided 3D printed LDR Mount.
- The provided sketch will drive the piezo and read data from the LDR at the same time. You can visualize the data in the Serial Plotter or copy and paste it from the Serial Monitor or use other means to transfer the data to your computer. In the Serial Plotter you will see the signal from the LDR as well as the analogWrite()-Value and the Voltage that is applied to the piezo. This way you can calculate the displacement of the piezo / mirror per Volt.

2.3) Required Materials & Mounts

A) Required materials		
Steel plate	**Laser pointer**	**Neodym Magnet**
		
1x	1x	6x
Min. size: 420 x 300mm Recommended size: 600mm x 400 mm	Standard red or green consumer laser pointer Coherence length critical	15 x 15 x 8 mm
Knurled Screw	**Nut**	**Screen**
		
16x	11x	1x
M3, length: 12 mm	M3	Piece of cardboard, approx. 10 x 8 cm
Mirror	**Beamsplitter**	**Lens**
		
2x	1x	1x
30 x 20 x 1 mm front-coated	40 x 30 x 1 mm 50/50, non-polarizing	Convex glass lens (plastic works poorly) Ø = 25 mm, f = +45 mm

Piezo Speaker	Arduino Microcontroller	Electronic components
 1x Simple piezo speaker Ø = 27 mm	1x 5V microcontroller e. g. Arduino Uno	1x Light-dependent resistor module 27 x 13 mm 1x capacitor 1µF 1x resistor 15kΩ 2x Splicing connector 2-conductor 1x mini breadboard Jumper Wires

B) 3D printed mounts

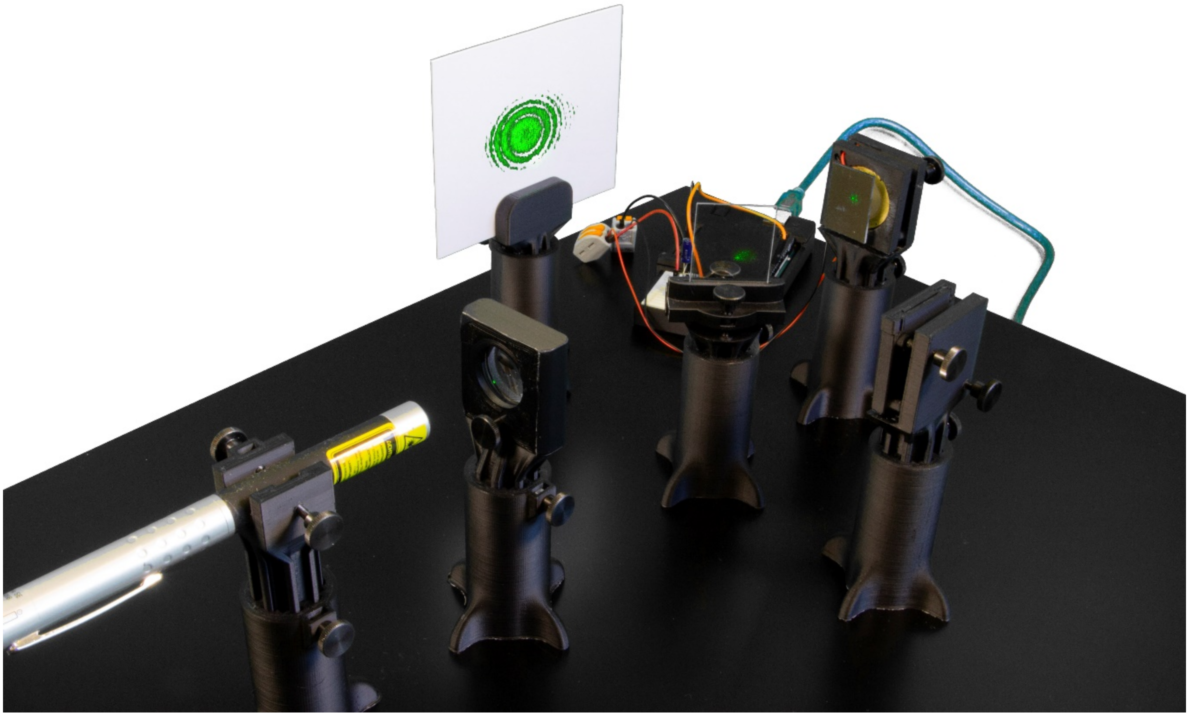
Base	Laser pointer Mount	Mirror Mount
		
6x	1x	1x
Beamsplitter Mount	**Lens Mount**	**Piezo Mirror Mount**
		
1x	1x	1x
Screen Mount	**Light Dependent Resistor Mount**	
		
1x	1x	

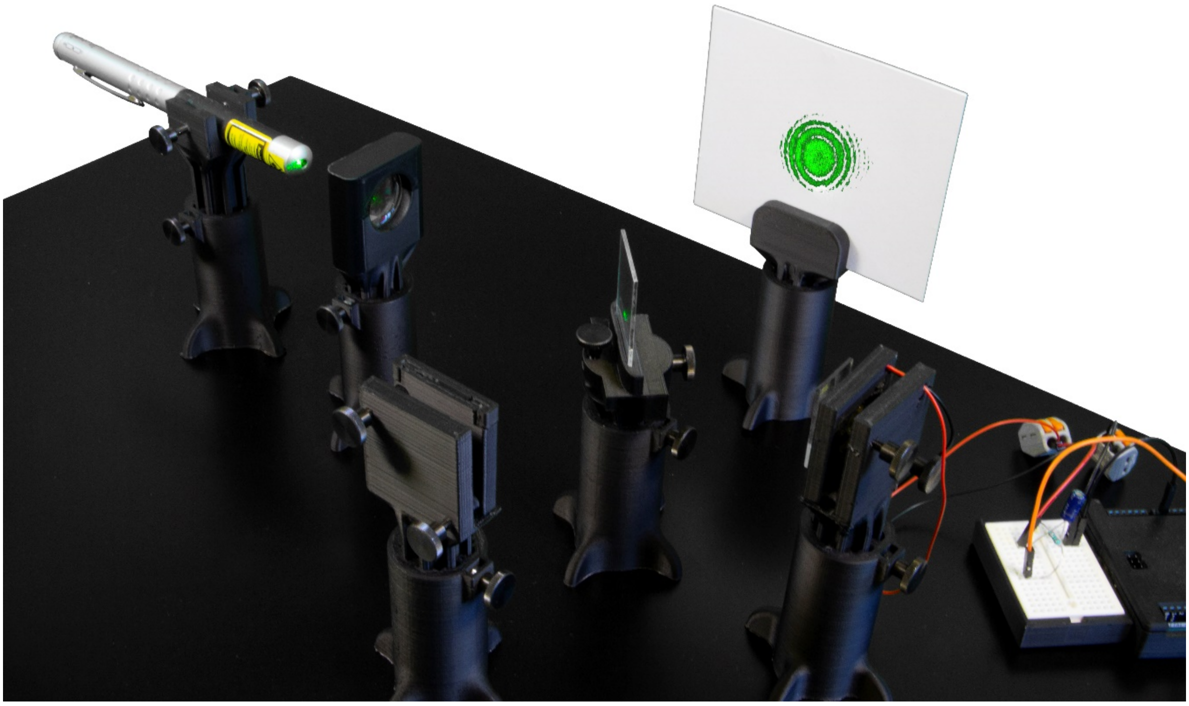
2.4) Setup

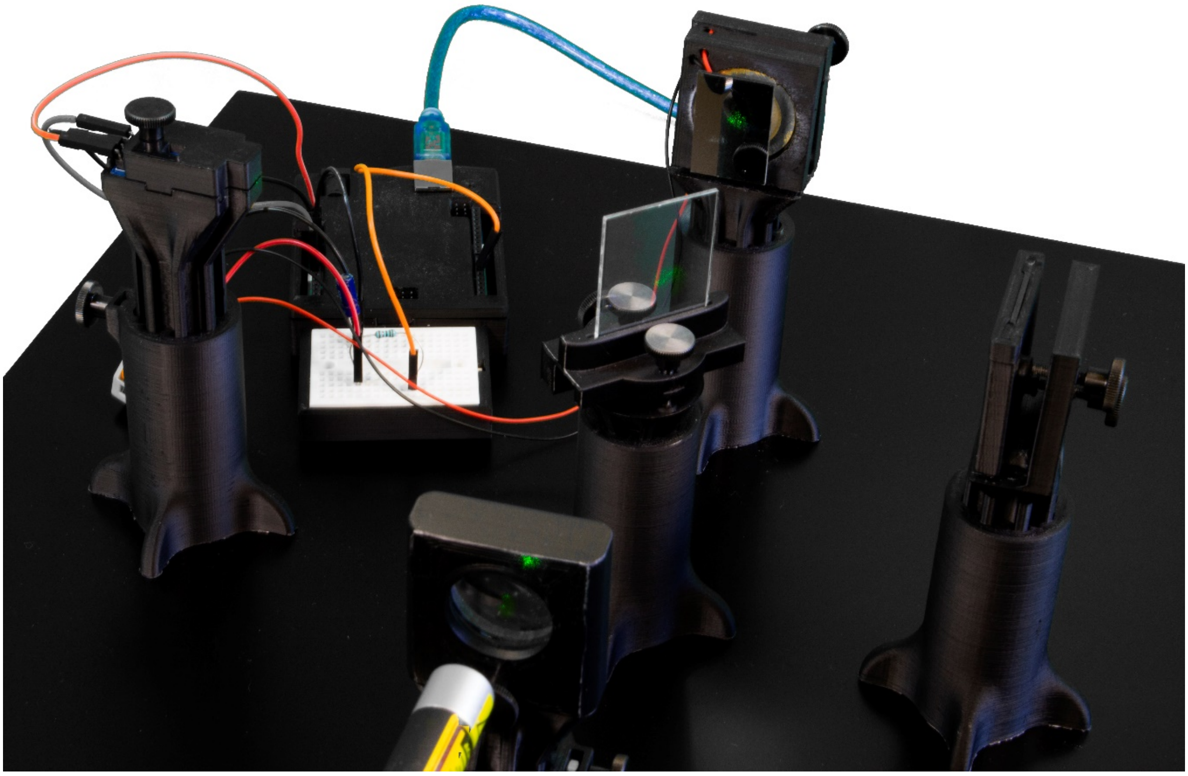
Setting up the advanced Michelson interferometer resembles the setup for the basic version. Make sure that the interference pattern is clearly visible before you move on to shifting the mirror with the piezo or replacing the screen by the LDR Mount.

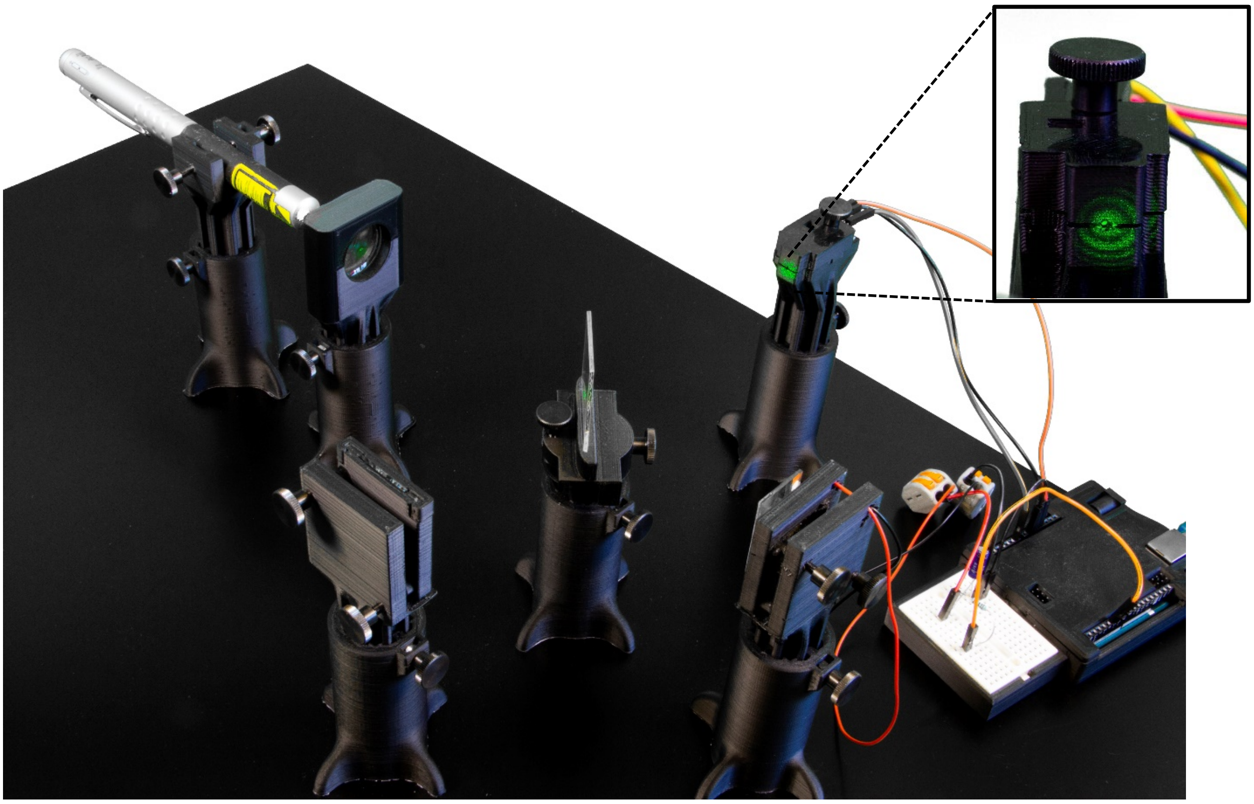
Once the interference pattern appears on the screen, apply a voltage (depending on the piezo – for a standard piezo speaker up to ±10V should be fine) to the piezo either using an adjustable power supply or an Arduino Uno. You should see the interference pattern moving if you alter the voltage. Since there is always some random movement of the mirrors, the shift introduced by the piezo and the random movement will both contribute to the variation of the interference pattern. The provided Arduino sketch will gradually ramp up the voltage from 0 V to +5 V and will then jump back to 0 V.

To measure the shift in the interference pattern, replace the screen by the LDR mount and align it in such a way that the center of the interference pattern is directly on the pinhole of the LDR mount. Once the LDR module is connected, the signal from the LDR can be displayed via the serial plotter in the Arduino IDE.

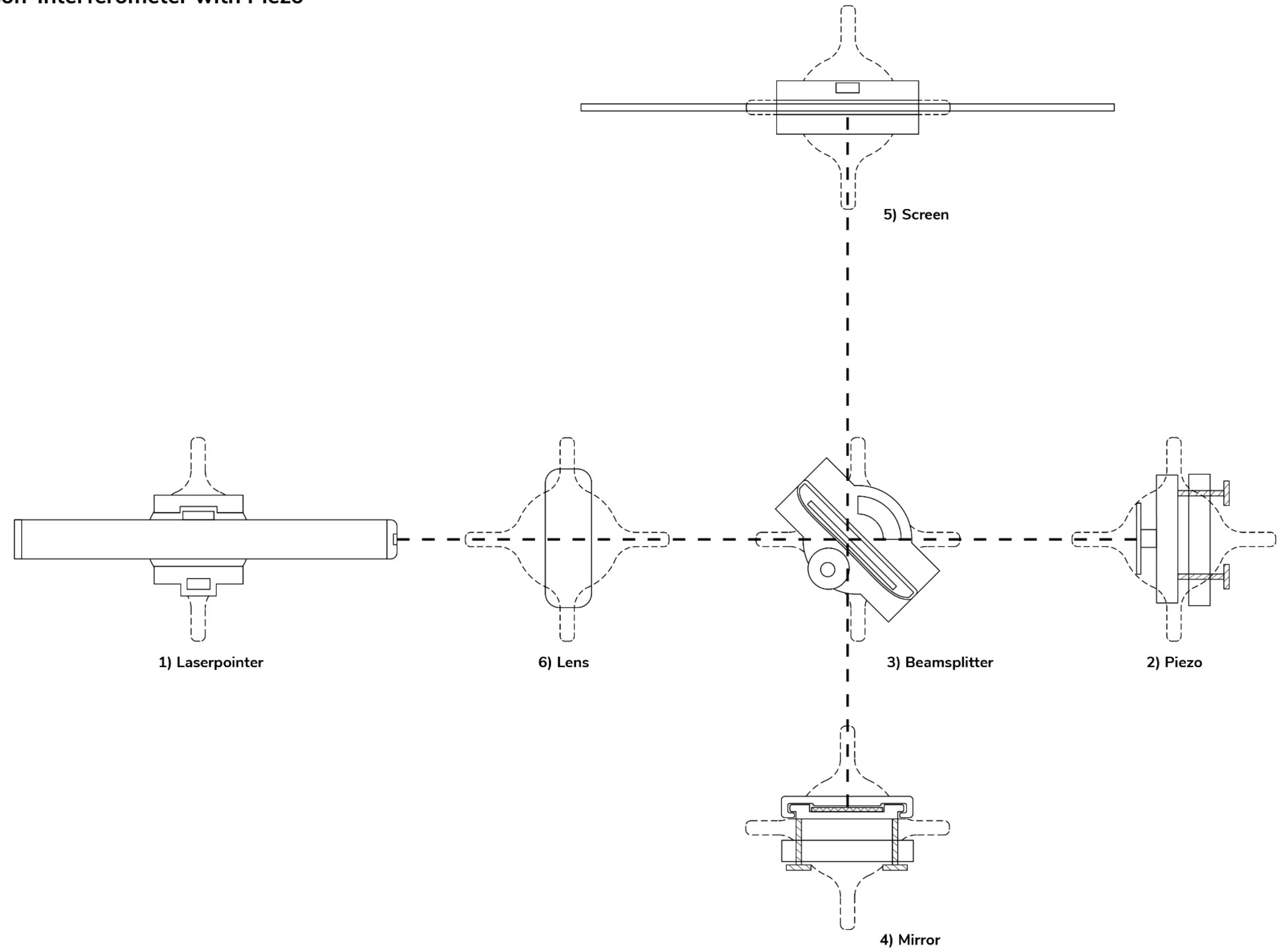




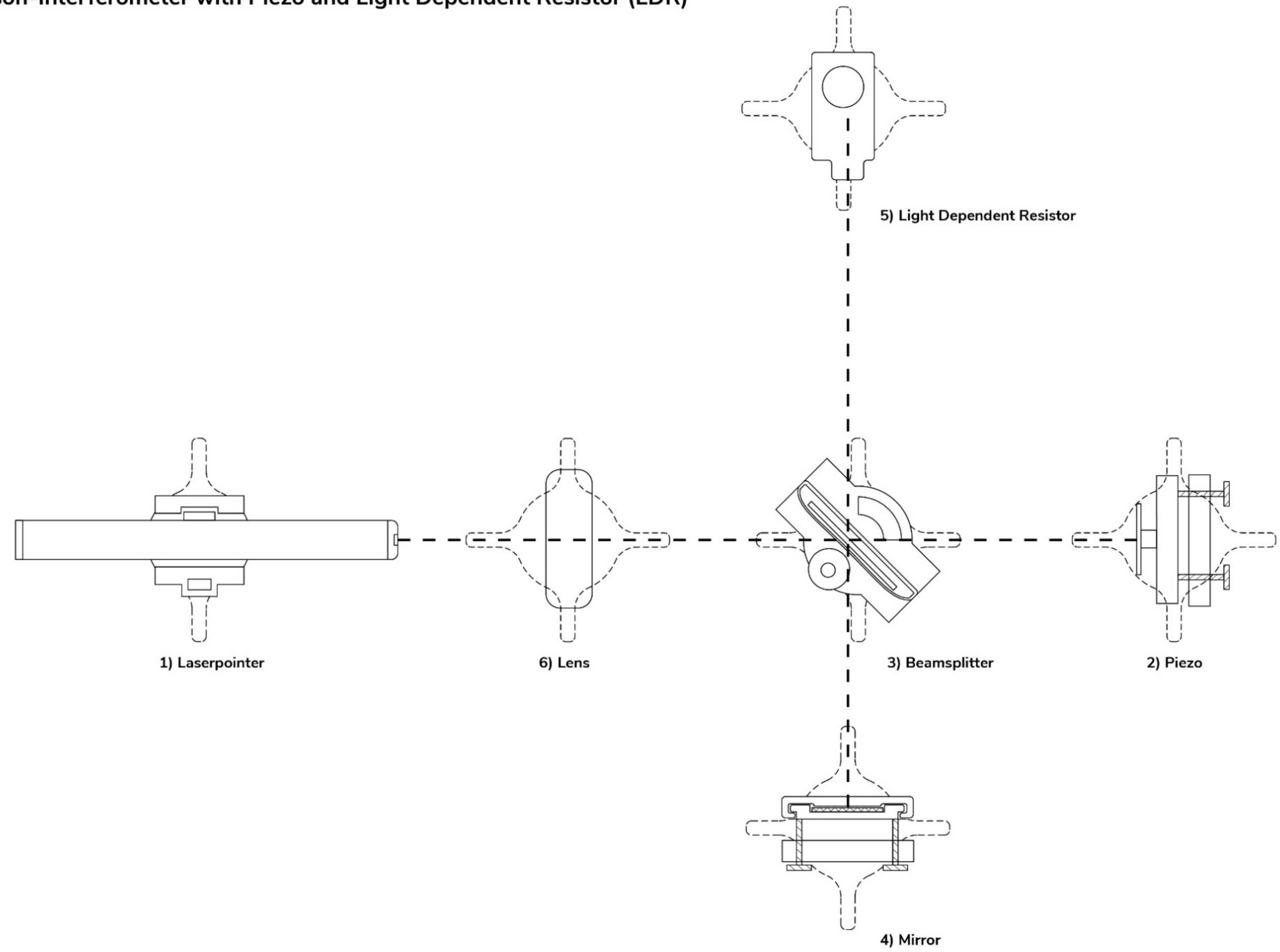




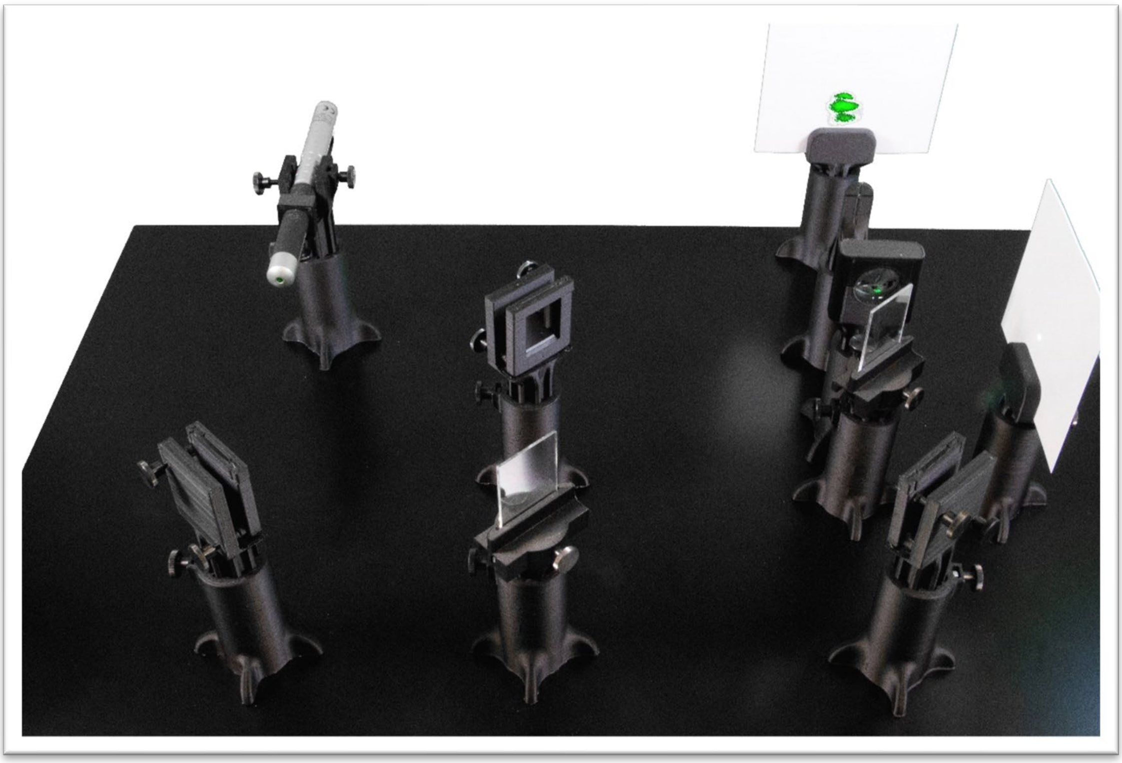
Michelson-Interferometer with Piezo



Michelson-Interferometer with Piezo and Light Dependent Resistor (LDR)



3) Mach-Zehnder-Interferometer



3.1) Physics Background

A Mach-Zehnder interferometer is a device that serves different purposes. It is commonly used to measure the density of different gases. In the scope of this lab, it is the starting point for setting up a Quantum Eraser.

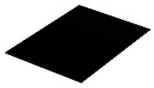
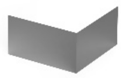
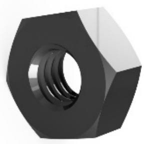
Like the Michelson interferometer, a Mach-Zehnder interferometer works by splitting a laser beam into two partial beams, which are later superimposed on a screen. However, unlike the Michelson interferometer, a Mach-Zehnder interferometer uses two beamsplitters with the interference patterns showing up on two screens.

3.2) Technical Notes

- Note that a Mach-Zehnder interferometer is significantly more challenging to set up than a Michelson interferometer. Therefore, prior experience with optical setups is strongly recommended, and only a rough outline of how to set up the experiment will be given.
- An additional 3D printed mount – the heightfinder – has been designed to facilitate the process as much as possible. The heightfinder helps to ensure that the beam always travels at the same height above the steel base plate (therefore staying horizontally at all times).
- It is advisable to place the lens directly in front of the screen rather than behind the laser pointer. This will result in the interference pattern being stripe-shaped rather than concentric.

3.3) Required Materials & Mounts

A) Required materials

Steel plate	**Laser pointer**	**Neodym Magnet**
		
1x	1x	10x
Min. size: 420 x 300mm Recommended size: 600mm x 400 mm	Standard red or green consumer laser pointer Coherence length critical	15 x 15 x 8 mm
Knurled Screw	**Nut**	**Screen**
		
25x	18x	2x
M3, length: 12 mm	M3	Piece of cardboard, approx. 10 x 8 cm
Mirror	**Beamsplitter**	**Lens**
		
3x	2x	1x
30 x 20 x 1 mm front-coated	40 x 30 x 1 mm 50/50, non-polarizing	Convex glass lens (plastic works poorly) Ø = 25 mm, f = +45 mm

B) 3D printed mounts

Base

10x

Laser pointer Mount

1x

Mirror Mount

3x

Beamsplitter Mount

2x

Lens Mount

1x

Screen Mount

2x

Heightfinder

1x

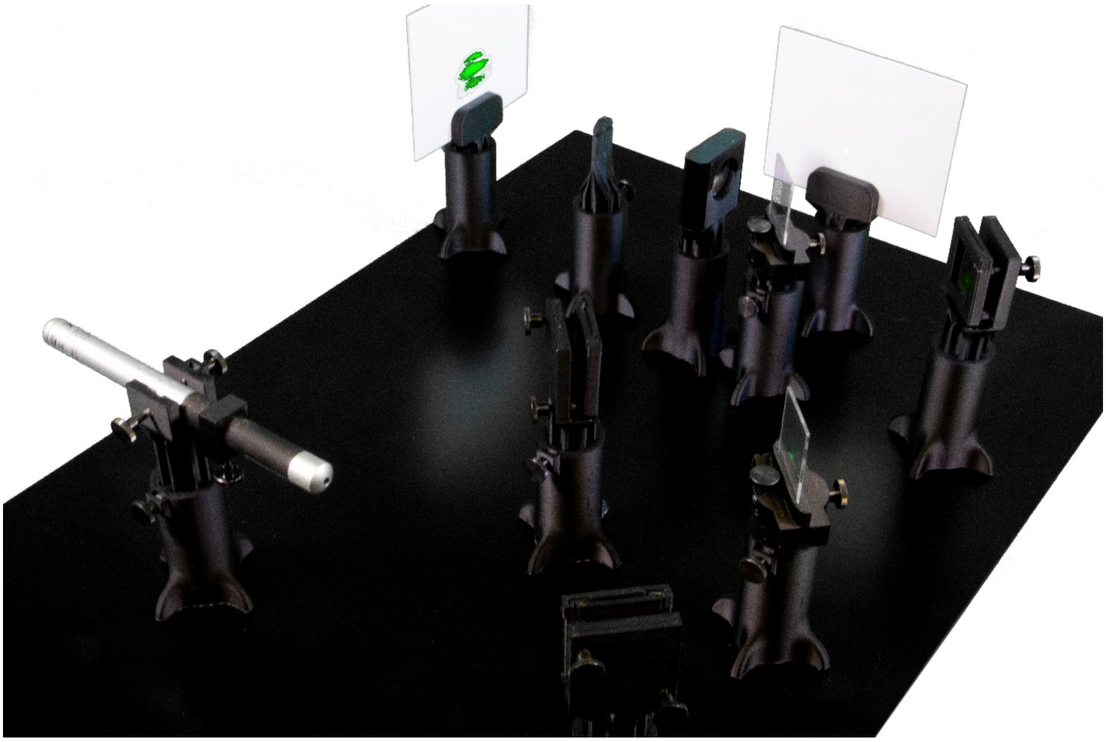
3.4) Setup

First, place the laser pointer 1) and the Mirror Mount 2) on the base plate. Place the heightfinder at the position 3a) and adjust the heightfinder and the Mirror 2) so that the laser beam passes through the pinhole of the heightfinder. The objective is that the laser beam should be exactly parallel to the steel base plate after hitting the Mirror 2).

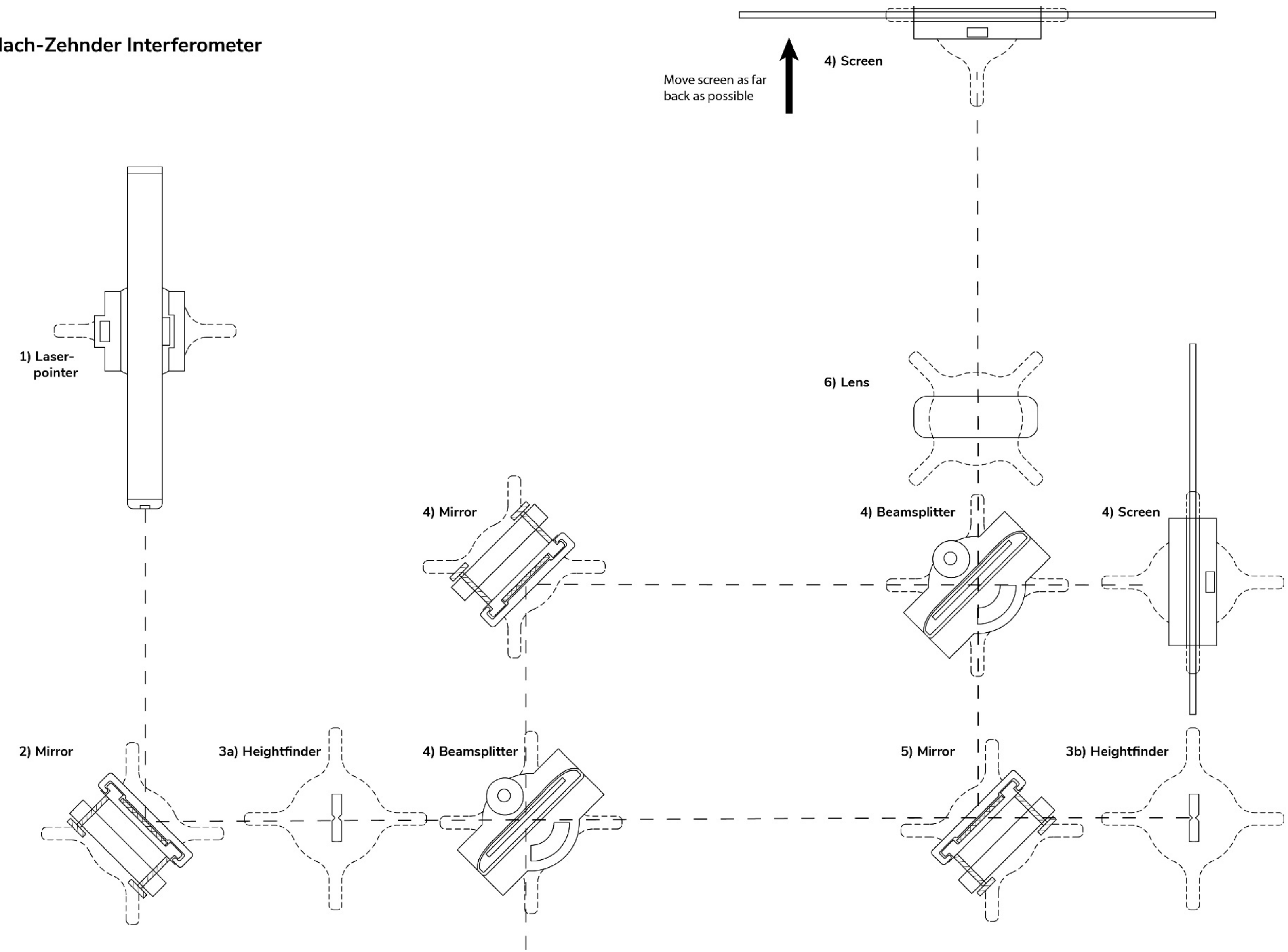
Next, place the heightfinder at position 3b) – the laser beam should ideally still stay on the pinhole. If this is not the case, iterate between position 3a) and 3b) adjust the height of the heigthfinder and the tilt of the Mirror 2) until this is accomplished.

Place the Beamsplitter Mounts, Mirror Mount 4) and screens 4) on the base plate. One of the screens should be as close as possible to the beamsplitter while the second screen should be as far back as possible. Place the Mirror Mount 5) on the base plate and adjust its position and tilt until the beam spots align on both screens simultaneously. This usually requires patience and perseverance.

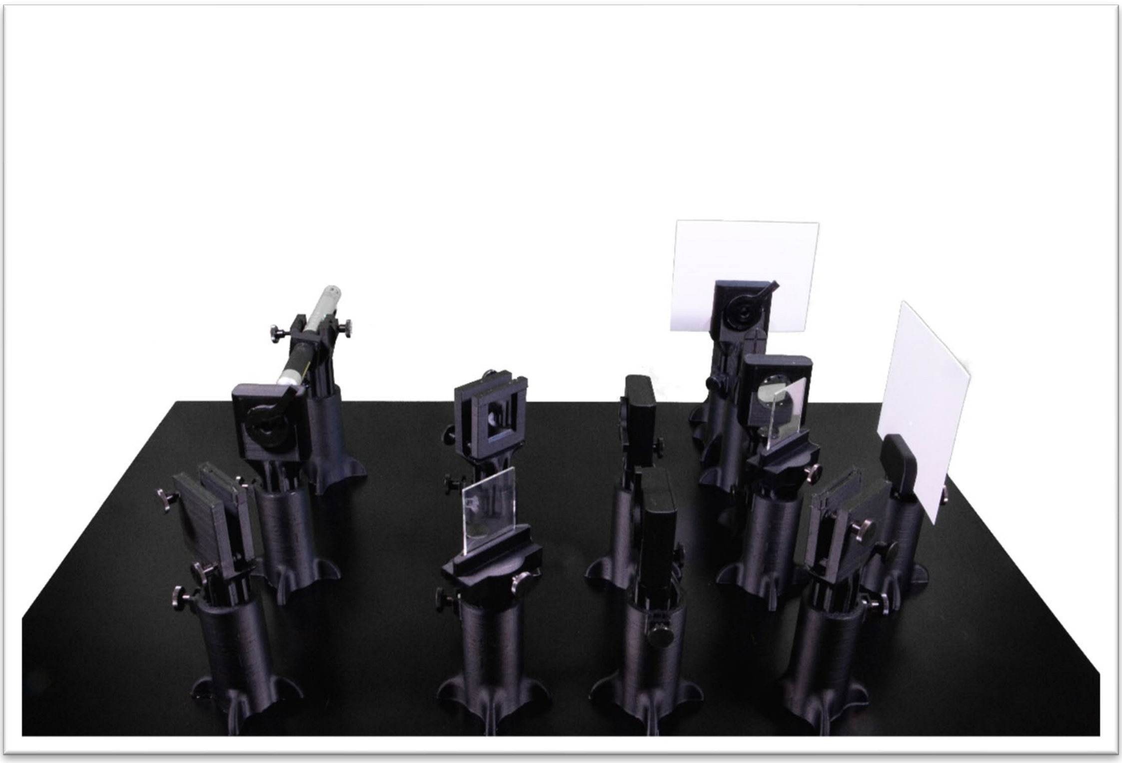
Once finished, place the Lens Mount 6) on the base plate. The interference pattern should now be clearly visible on the screen.



Mach-Zehnder Interferometer



4) Quantum Eraser



4.1) Physics Background

A Quantum Eraser is an educational experiment that demonstrates the properties of the quantum mechanical measurement process. Strictly speaking, the experiment can be explained in a classical manner – it is only once that one-photon sources are introduced (which is not feasible in most educational settings) that a quantum mechanical explanation becomes inevitable.

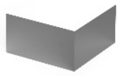
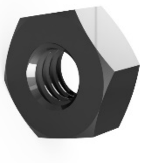
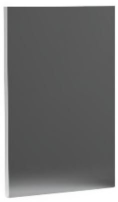
In a nutshell, the main idea is that interference on the screen can be observed as long as two indistinguishable paths from the light source to the screen are present. Once the paths are made distinguishable by introducing linear polarizers, interference will break down. However, interference can be restored by erasing the which-way-information using an additional polarizer (hence “Quantum Eraser”). A more detailed discussion can be found here [6,7].

4.2) Technical Notes

- As the Quantum Eraser is a Mach-Zehnder interferometer with additional linear polarizers, it is necessary to first successfully set up the Mach-Zehnder interferometer.

4.3) Required Materials & Mounts

A) Required materials

Steel plate	**Laser pointer**	**Neodym Magnet**
		
1x	1x	14x
Min. size: 420 x 300mm Recommended size: 600mm x 400 mm	Standard red or green consumer laser pointer Coherence length critical	15 x 15 x 8 mm
Knurled Screw	**Nut**	**Screen**
		
33x	26x	2x
M3, length: 12 mm	M3	Piece of cardboard, approx. 10 x 8 cm
Mirror	**Beamsplitter**	**Lens**
		
3x	2x	1x
30 x 20 x 1 mm front-coated	40 x 30 x 1 mm 50/50, non-polarizing	Convex glass lens (plastic works poorly) Ø = 25 mm, f = +45 mm

Linear Polarizing Film

4x

12 x 12 mm

B) 3D printed mounts

Base

14x

Laser pointer Mount

1x

Mirror Mount

3x

Beamsplitter Mount

2x

Lens Mount

1x

Screen Mount

2x

Heightfinder

1x

Polarizer Mount

4x

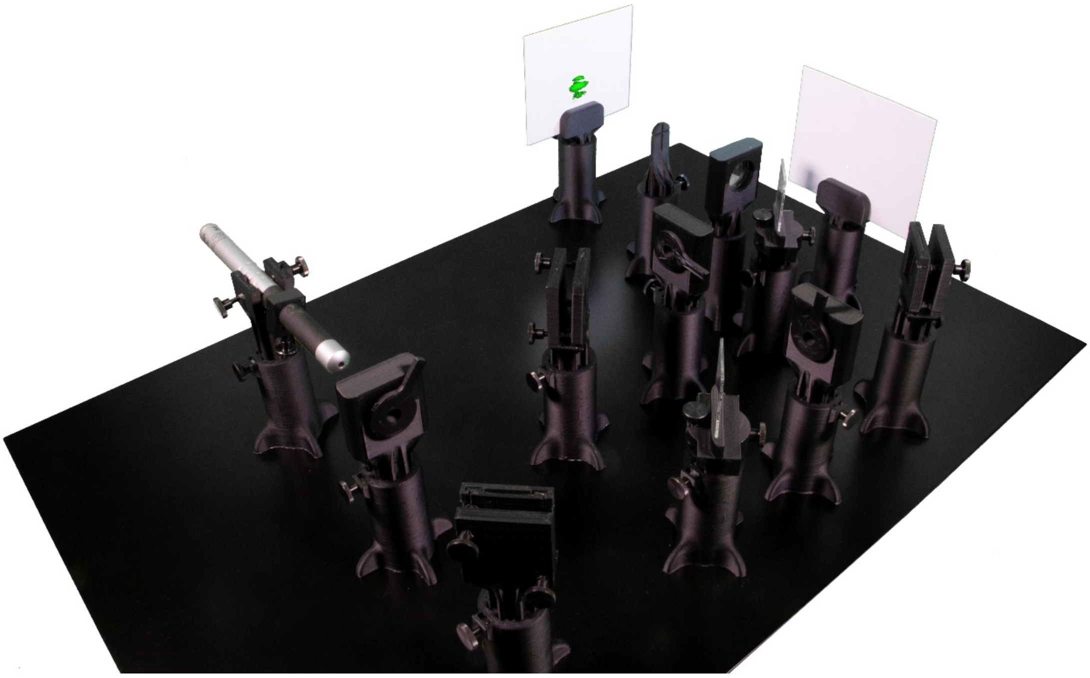
4.4) Setup

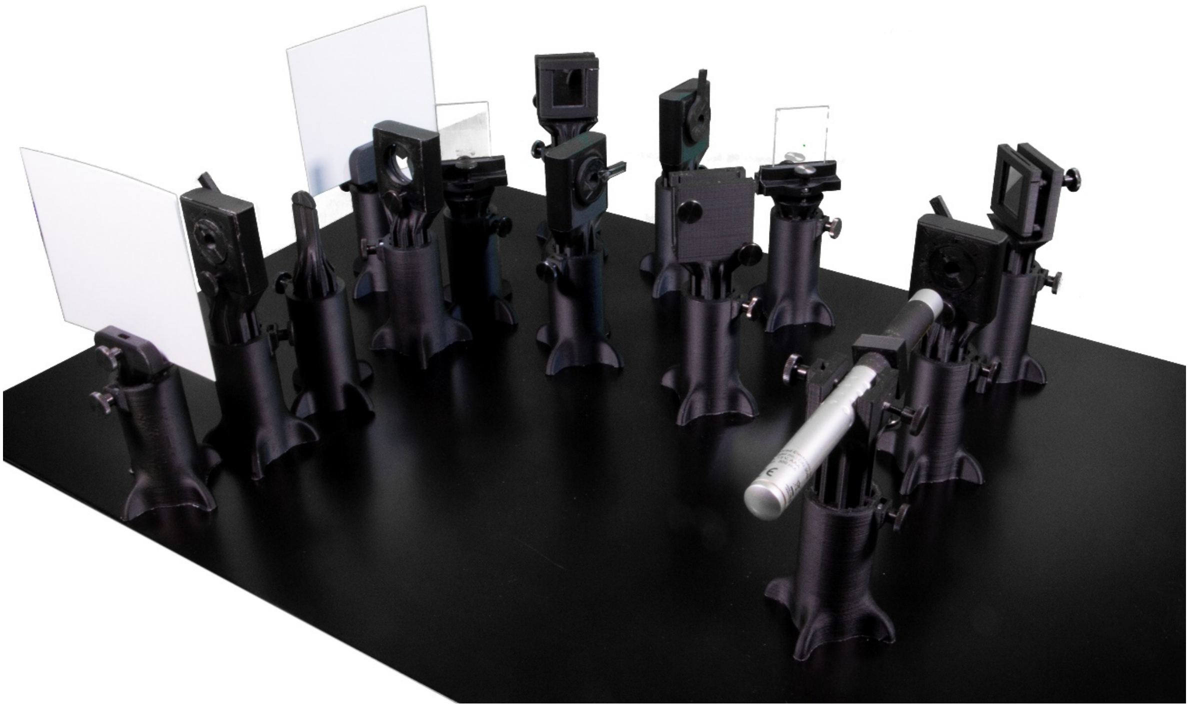
Light emitted by laser pointers is usually, to a varying extent, elliptically polarized. To achieve a maximum contrast of the interference pattern on the screen, it is advisable to insert a linear polarizer directly behind the laser pointer. This will generate a linearly polarized laser beam with a well-defined polarization axis.

All indications on the direction of rotation of the polarization axes are relative to this first polarizer, which is defined to be at 45°.

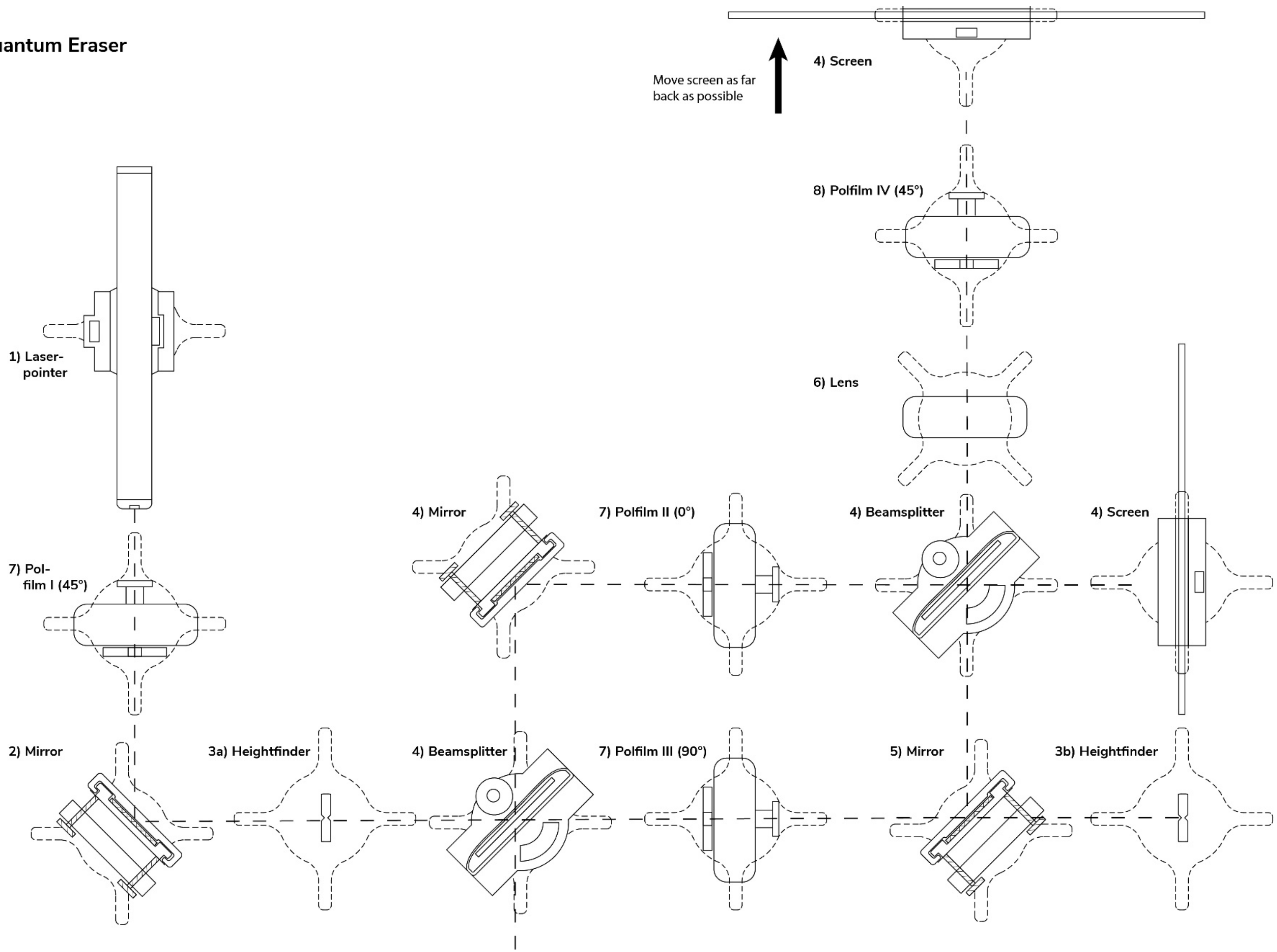
Once inserted, the interference pattern on the screen should not change dramatically since the two different paths through the Mach-Zehnder interferometer are still indistinguishable. If two additional polarizers (0° and 90°) are inserted at the indicated positions, the interference pattern will disappear. From a classical point of view, this is because of the Fresnel-Arago laws. From a quantum mechanical perspective, the two possible paths have now been made distinguishable since the polarizers mark the photons with “which-path-information.” This eliminates the interference pattern.

If the “which-path-information” is erased by inserting an additional polarizer at 45° directly before the screen, the interference pattern will reappear.





Quantum Eraser



Appendix A: Assembly of Optical Mounts

Base	Print settings / Remarks

Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Brim
Supports: No
Resolution: 0.2 mm

Printing with a brim is recommended to counteract possible warping issues, which will lead to reduced stability. To assemble the base, simply insert the neodymium magnet, put the nut in place, and use the knurled screw to fixate the specific mounts.

Laser pointer Mount

Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Skirt
Supports: No
Resolution: 0.2 mm

Insert the nut in the opening. One screw is for fixing the laser pointer while the second screw is used to permanently turn the laser pointer on. This screw does not require a nut since it will automatically draw a thread in the plastic.

Mirror Mount

Filament material: PLA, ABS (recommended)
Infill: 100%
Build Plate Adhesion: Skirt
Supports: Yes
Resolution: 0.2 mm

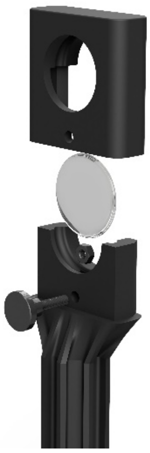
The Mirror Mount has to be printed with supports. ABS is superior to PLA since it does not lend itself to permanent deformation as easily. No nuts are required. Insert the mirror and hold it in place using the clip. One screw is for tilting the mirror up and down, the other one for tilting it left/right.

Beamsplitter Mount	Print settings / Remarks

Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Skirt
Supports: No
Resolution: 0.2 mm

Insert the nut into the opening of the lower part of the mount. Place the upper part onto it and fix it using the screw. Insert the beamsplitter while holding the upper part to prevent movement (it’s a press-fit and might be tight). Insert the second nut and the knurled screw for adjusting the beamsplitter tilt.

Lens Mount



Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Skirt
Supports: No
Resolution: 0.2 mm

Insert the nut into the opening, place the lens in the mount and fix it using the lid and the screw. The lens mount is designed for lenses with a diameter of 27 mm.

Screen Mount

Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Skirt
Supports: No
Resolution: 0.2 mm

Any cardboard piece can be used as a screen. Insert it into the mount and fix it using the nut and the screw.

Piezo Mirror Mount	Print settings / Remarks
	Filament material: PLA, ABS (recommended) Infill: 100% Build Plate Adhesion: Skirt Supports: Yes Resolution: 0.2 mm The Mirror Mount has to be printed with supports. Glue the back of the piezo speaker onto the Piezo Mirror Mount. Once dried, glue the plastic spacer onto the piezo speaker and the back of the mirror onto the other side of the spacer. The rationale is that the mirror should move with the piezo speaker while keeping the speaker itself sufficiently flexible.
Light Dependent Resistor (LDR) Mount 	Filament material: PLA, ABS Infill: 100% Build Plate Adhesion: Skirt Supports: No Resolution: 0.2 mm Insert the LDR module into the LDR Mount; it should fit tightly. Close the mount with the lid. The screw is optional to further secure the assembly. Connections with the jumper wires can be made once the mount is fully assembled.

Polarizer Mount

Filament material: PLA, ABS
Infill: 100%
Build Plate Adhesion: Skirt
Supports: No
Resolution: 0.2 mm

To assemble the polarizer, first cut a piece of 12 x 12 mm linear polarizing film and insert it in the recess of the appropriate part. Close it using the lid and insert the assembly in the top part of the mount. Insert the nut into the opening of the lower part of the mount and place the preassembled parts onto the lower part of the holder. Place the scale onto the mount and fasten all the parts with the knurled screw.

Bibliography

[1] https://en.wikipedia.org/wiki/Michelson%E2%80%93Morley_experiment

[2] https://www.ligo.caltech.edu/page/what-is-ligo

[3] https://en.wikipedia.org/wiki/Michelson_interferometer

[4] Lloyd, S.; Paetkau, M. (2010): Characterization of a Piezoelectric Buzzer Using a Michelson Interferometer. In: *The Physics Teacher* 48 (9), S. 610–611. DOI: 10.1119/1.3517032.

[5] Cooper, S. J.; Green, A. C.; Middleton, H. R.; Berry, C. P. L.; Buscicchio, R.; Butler, E. et al. (2020): An Interactive Gravitational-Wave Detector Model for Museums and Fairs. Online available at http://arxiv.org/pdf/2004.03052v1.

[6] Hillmer, Rachel; Kwiat, Paul (2007): A do-it-yourself quantum eraser. In: *Scientific American* 296 (5), S. 90–95. DOI: 10.1038/scientificamerican0507-90.

[7] Ellerman, David (2015): Why delayed choice experiments do not imply retrocausality. In: *Quantum Stud.: Math. Found.* 2 (2), S. 183–199. DOI: 10.1007/s40509-014-0026-2.