

CO₂ ablation setup for machining micro-cavities

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Abstract

We report on the improvement of a existing setup to perform CO₂ laser ablation of optical fibers and substrates. The technique will allow the creation of spherical mirrors with ultra-low roughness, which is achieved by evaporating a part of the surface material and using the smoothing effect of the surface tension of the molten material. To achieve that, we alter the existing setup such that a reproducible movement between ablation and imaging is possible, which in turn enables us to properly characterize and optimize the ablation process for our purposes.

Contents

1	Introduction	2
2	Existing Setup	3
3	Built Setup	3
3.1	CO ₂ laser	4
3.2	Sample Translation	5
3.3	Imaging setup	7
4	Measurements	8
4.1	Hitting the fiber	8
4.2	Characterizing the fiber tip	9
5	Analysis	10
6	Conclusion	12
A	Technical Drawings	14
B	Code	16

1 Introduction

A promising approach to enable a conversion from stationary to flying qubits in ion traps is to use an optical cavity, which enables an efficient collection of photons emitted by the ions. The coupling strength between ions and photons is given by $g = \frac{\lambda}{\pi\omega_0} \sqrt{\frac{3c\gamma_c}{L}}$, with the wavelength of the photon λ , the light speed c , the cavity mode waist ω_0 , the cavity length L and the spontaneous emission rate between the states coupled via the cavity γ_c . To maximize the coupling strength, a small cavity mode waist ω_0 and cavity length L , combined with low losses are required. Fibre Fabry-Pérot cavities (FFPC) with concave mirrors produced by CO₂ laser ablation, were found to be a promising candidate to fulfill these requirements [1–5]. Due to the melting properties of silica, a smooth, concave surface can be produced [3], which enables an operation with low scattering losses. Additionally, FFPCs are by default mode matched to an optical fiber for efficient light collection

[2]. The technique of CO₂ ablation is used, because besides evaporating a small part of the material, it also provides the smoothing effect induced by the surface tension of the partially molten surface layer [3]. The first approaches to CO₂ ablation have been made with single laser pulses, which led to non-spherical profiles and a limited effective mirror diameter. These downsides can be overcome with the usage of several pulses, as shown in [5]. To implement such multishot ablation is the final goal of this setup. The first steps towards an automatic multishot CO₂ ablation setup are described in this report. It should enable the production of spherically shaped surfaces of optical fibers, which are required in a vast variety of fields [1, 6].

2 Existing Setup

Before the start of the project, a first iteration of the setup to perform and measure CO₂ ablation was already available. It was similar to the one shown in Figure 1, consisting of a pulsed CO₂ laser and an imaging system, but instead of the stage in the middle of the image, a sample holder had to be moved by hand between the laser and the imaging system. This movement required a displacement and a 90° turn. To eliminate the manual placement of components, the imaging setup had to be rearranged during the process of the project. Furthermore, the existing setup did not contain a Mirau-objective, but a simple laser interferometer. Both imaging systems will be described in section 3.3. The setup's purpose was to test the components, find the best polarizer settings and show that creating a depression in glass is possible. However, it did not provide the necessary accuracy and did not allow for reproducible switching between the imaging setup and the CO₂ laser.

3 Built Setup

The setup is based on the one implemented in [5]

The built setup was designed to enable CO₂ ablation, together with a direct analysis. As shown in Figure 1, it consisted of a pulsed CO₂ laser, an imaging system and a movable stage to switch between ablation and imaging region. The pulse length of the CO₂ laser could be externally controlled and a Brewster polarizer allowed an adjustment of the beam intensity. Changing these parameters allowed us to change the depression depth and the diameter of a single shot depression.

The imaging system was kept separated from the ablation beam and con-

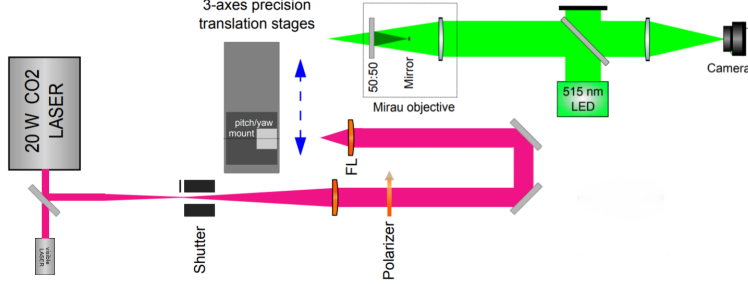


Figure 1: A schematic image of the built setup. Its main components are a CO₂ laser (red), an optical profilometer (green) and a translation stage (grey) to switch between the two beams. Figure modified and taken from [5].

sisted (in the final iteration) of a Mirau-objective to determine the exact shape of the created depression. The fiber was mounted on a translation stage which enabled reproducible switching between the imaging system and the ablation laser. To allow movements in the other two directions, a second stage was put on top of it. The translation stage was fixed on the optical table via a connection plate. The height of this plate, together with the two stages and the fiber mounting system exceeded the height of the CO₂ beam which, as a consequence, required us to raise the whole ablation system. Technical drawings of the connection plate and blocks to elevate the ablation laser can be found in appendix A.

3.1 CO₂ laser

The laser used for this setup was an air cooled Synrad firestar V30. It was controlled via an Adurino, allowing for pulse durations of 1 – 100 ms and provides a continuous power output of 30 W. Its wavelength of 10.57 – 10.63 μm is strongly absorbed by fused silica, making it ideal for this application [3]. To mark the beam path, it was confined by several apertures - one directly behind the polarizer and two between the polarizer and the focusing lens. Finding the exact path of the CO₂ laser was crucial for overlaying it with a visible laser, so that mirrors, the lens and the fiber could be properly aligned. The positions of the apertures was optimized in an iterative process. This process consisted of firing several CO₂ pulses, each with different aperture settings. In order to make the CO₂ laser visible after the apertures, thermal paper was used. Depending on the degree to which it was burnt, an estimation of the beam intensity was possible. After various shots, a comparison of the degree of burn provided the best aperture setting. An



Figure 2: An example of the measurements taken to align one of the apertures. The top line shows different shots of the CO₂ laser on thermal paper for different aperture heights, ascending from right to left. The second and the third line show shots for a vertical displacement of the aperture.

example of the burning pattern used for aperture centering can be found in Figure 2. The second and third line of burning spots show the horizontal- and the first line the vertical displacement of the aperture. This qualitative centering was only possible for one aperture which could be positioned using translation stages. The second one did not offer that option which led to an approximate centering, because it had to be centered manually by an iteration consisting of shooting, changing the aperture setting, shooting again and comparing the degree of burn. If the burning spot of the first shot was darker, the position of the aperture could not be exactly reproduced. All measurements have been performed with the maximum laser power, for which a suitable polarizer setting had to be found. To do so, we used again the "thermal paper"-method. After trying out all combinations and comparing the burning intensities, we found the maximum intensity in a range of 74 – 95 for the left filter and 85 for the right filter. The numbers are written on the polarizer tube as visible in Figure 3.

3.2 Sample Translation

To enable reproducible movement between ablation and investigation position, the stage "L-509.4ASD00" together with the controller "C-663.12" from "Physik Instrumente" was purchased. The controller is programmable with Python, and the stage offers a range of 102 mm with a bidirectional repeatability of 0.2 μm , measured by an incremental linear encoder. We communicated directly with the controller using the ASCII commands defined

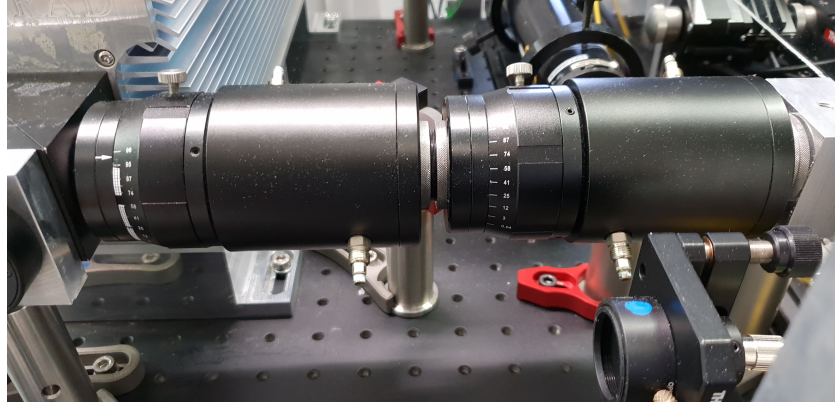


Figure 3: An image of the polarizer used in the setup. It is located between the mirror deflecting the CO₂ laser (left) and apertures for localizing the beam (right, not visible). The numbers on the tubes represent different alignments of the two filters.

in the P.I. general command set, rather than using the provided Python interface. Furthermore, we built a graphical interface for an easy operation. To operate the controller, we translated every command from the interface to a three character instruction that could be understood by the stage. A list of available commands can be found in the manual of the "C-863"-controller [7]. The commands were sent by a Python program using the command `ser.write()`. The interface window contains the option to drive to a specific target position together with a simple "+1 mm" and "-1 mm" button. To initialize the serial-port we use the command `self.ser = serial.Serial('COM5', 115200, timeout=0)`, followed by a closure and reopening of the port, identification, velocity initialization and a reference movement to the positive limit. Closing and opening the port was necessary, because in some cases the port is needed by an other program, which then caused conflicts. Every following step can be written in functions, of which the following provides an example for:

```
def moveto(target):
    d=target
    t=b"MOV 1 %d \n\r"%d
    ser.write(t)
```

It moves the stage to the value "target". The full code is written as a class and can be found in appendix B.

3.3 Imaging setup

The setup to characterize the shape of the depression on the fiber changed during the project towards the goal of an interferometric imaging system. During all evaluations the camera stayed the same. We used the Canon EOS 1000D to take the images after the lenses.

First Iteration Its general principle consisted of a beam splitter, a laser and a camera as shown in green in Figure 1. Light from the laser was split in two separate beams, of which one got reflected at the sample and one at a mirror at fixed distance. The reflected beams met again at the beam splitter and a part of the recombined beam reached the camera, where an interference pattern was visible. To focus the imaging laser on the sample, a microscopy lens was used. It was placed on a stage that enabled easy focusing by changing the distance to the fiber. The images of this iteration contained many unwanted interference patterns caused by the lens. They were a result of reflections on the air-lens interface. Although this procedure allows an exact surface characterization as it was done in [5], we focused on confirming that the fiber was hit, instead of its exact characterization, due to limited time.

Second Iteration To provide a quick qualitative confirmation if the fiber was hit we used illumination from an external white light source instead of a laser coupled in the camera path. The image was then not an interferometric one, but a direct image of the fiber. This was possible, because the coherence time of the light source was short enough to suppress any interference such that the image only contained the reflected light of the fiber.

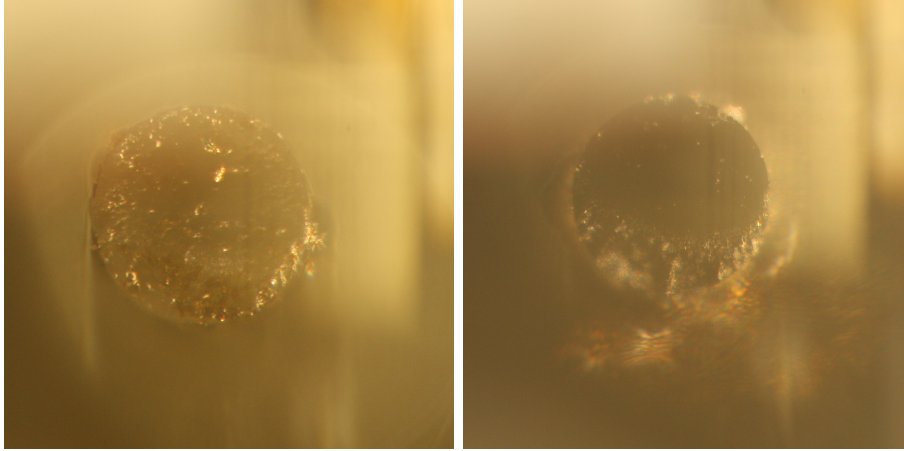
Third Iteration To remove the interference patterns that occurred in the first iteration, a Mirau objective was used. A setup similar to the first iteration was build, which allows a quantitative analysis of the depression shape. This is necessary for a precise surface characterization. After the finalization of the project, a green LED was used instead of a laser, because its coherence time matches the sizes we want to resolve in a way, that only the depression creates an interference pattern. Following [8], several images with different phase offsets could be used to reconstruct the height information. At the time of this report that analysis was not yet implemented.

4 Measurements

The aim of the project was to hit the fiber and take an image of it to characterize the created shape. This requires two steps to work properly: aligning the stage such that the fiber could be hit controllably and setting up the imaging system to visualize a possible depression.

4.1 Hitting the fiber

As a first step in this process, the beam of the CO₂ laser had to be overlaid with a visible beam, which got coupled in the polarizer via a semi-transparent mirror as shown schematically on the lower left of Figure 1. To do so, we aligned several apertures to the CO₂ beam as described in section 3.1. The visible laser was then aligned to these apertures. These constraints did not allow a beam path, such that the visible beam passed all apertures and matched with the burning spot on the thermal paper. Its closest approach to the spot was of the order of millimeters. This may be caused by a bad alignment of the apertures to the CO₂ beam. A further analysis is provided in section 5. Nevertheless, several approaches to hit the fiber without knowing the exact path of the beam were taken. The simplest one included the thermal paper placed directly in front of the fiber tip. The fiber was then moved until weak light coupled in the fiber from the back and the burning spot from the CO₂ laser were visually matched on the paper. Although this method gave a good estimate of the position of the fiber with respect to the laser, there was no bright flash visible on the surface of the fiber, which would indicate a hit. A second approach, relying on the reproducibility of the translation stage, was to fix a glass plate next to the fiber. The glass plate could then be hit with the ablation laser, without knowing the exact position of the hit. Afterwards it could be moved to the imaging position, while recording the distance it took to get from the initial position, where the glass was hit, to the imaging system, where the created depression could be centered in the image. Then the fiber was moved exactly to the same position in the image, where the depression was previously. Moving the fiber from that point on the recorded distance back, leads to the fiber being in the same spot where the glass got hit. The first tries of that method did not show any indications that the fiber got positioned properly, because no clear alteration of the surface was visible. Several shots at slightly different positions, with pulse lengths ranging from 6 ms to 12 ms, did not hit the target. To be able to detect any depression we wrote a program that rasters a rectangular pattern around the chosen



(a) The tip of the fiber before the shot (b) The tip of the fiber after the shot
pattern. pattern.

Figure 4: Two images of the fiber surface, illuminated with external lighting. In the right image an alteration is visible

fiber position. As the images, shown in Figure 4 suggest, the fiber surface was altered during that process. A discussion whether the fiber got hit, can be found in section 5.

4.2 Characterizing the fiber tip

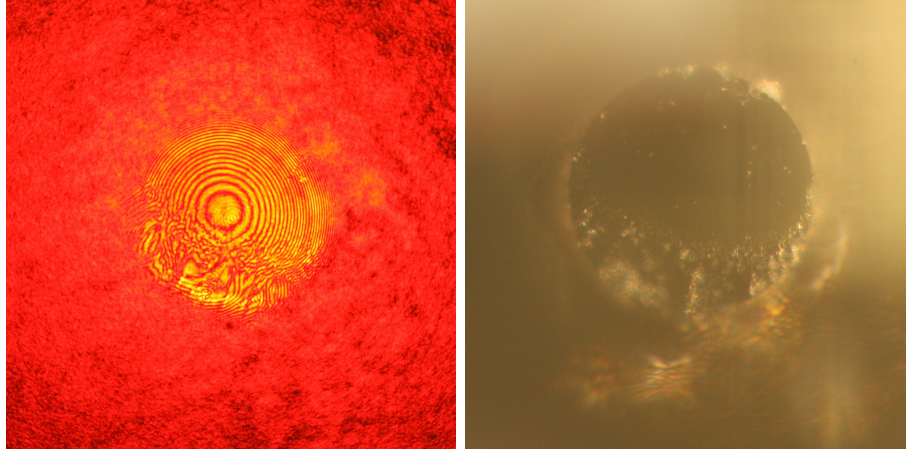
As stated previously, the imaging system changed during the evolution of the project. However, all three setups required a mechanism to focus the camera on the fiber. To do so, weak light was coupled in the fiber from the back, which enabled a quick localization of the fiber center, even when the camera was not in focus. After the switching off the illumination, the lens could be focused on the tip of the fiber. As visible in Figure 5a, the first iteration consisting of a microscopy lens and laser interferometry, produced many unwanted interference patterns caused by the lens. To remove these patterns, a second image without the fiber, but with a flat surface was taken. This was then subtracted from the fiber image, but the created image still showed many unwanted patterns. They originated from distance differences due to slight angular shifts between the fiber and the flat surface. If the fiber and the flat surface were not exactly orthogonal to the incident beam and had the same distance from the beam splitter, interference patterns occurred on positions, where no depression existed, decreasing the image quality of

the subtracted image. To get a better and quicker estimate of the surface structure of the fiber, the second iteration relied only on external illumination which led to images shown in Figure 4 and 5b. This implementation did not allow an exact profilometry, but the direct imaging of the fiber surface enabled a distinction whether a fiber got hit by the CO₂ laser or not. After the finalization of the project, the Mirau-objective, together with a green LED provided a quantitative analysis of the created depression. This imaging method could prove that the method of hitting a glass plate and matching its position with the fiber works, as Figure 5c and 5d show.

5 Analysis

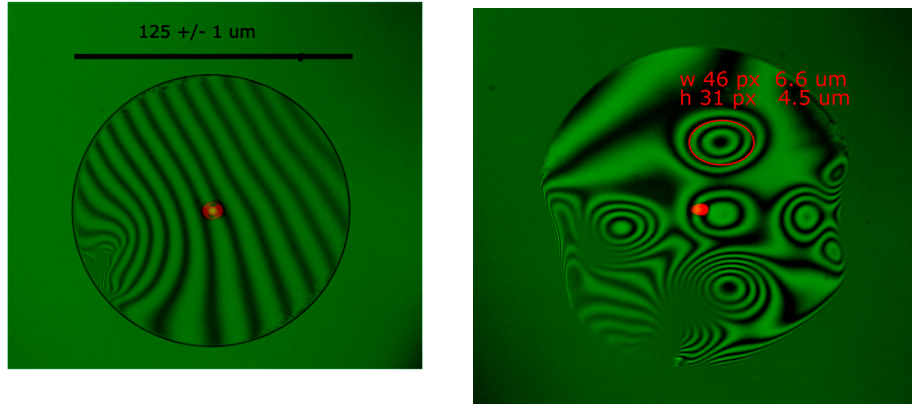
Comparing the two images in Figure 4, it is clearly visible that the surface structure has changed significantly. A possible explanation for the change could be that the fiber got hit several times in such a way, that no single depressions are visible. The smoothing is then a result of a melting of the silica, a theory that is supported by the fact that spacial distance between adjacent points in the pattern was only $1\mu\text{m}$ and the pulse length was 12ms, which is more than necessary to cause melting on the fiber surface. Later profilometry showed, however, that no depression originating from CO₂ ablation was visible on that fiber. Although this does not entirely eliminate the explanation above, it is much more likely that different imaging conditions give the impression of a change in the surface. The approach, consisting of a shooting pattern and the imaging method do not allow any assumptions on where the single pulses hit or how deep the depression got. These parameters have to be determined with further deterministic shots and images.

This inaccurate attempt is the result of the difficulty to overlay the invisible CO₂ beam with a visible red laser beam. If it would have worked properly, the light coupled in the fiber and the visible laser could have been matched on the surface of a paper with an accuracy sufficient to hit the fiber reproducibly. Possible reasons why the overlay did not work as planned, may either be a different index of refraction for different wavelengths at the beam splitter, a reflection of the CO₂ beam at positions that the visible beam can not reach, or a bad alignment of apertures with the CO₂ laser. The first explanation is unlikely, because the refraction properties of the beam splitter were checked previously, while the second is supported by the fact, that the CO₂ laser did not leave the polarizer in the center. This strongly suggests that the angle and the position of the beam on the mirror have to be adjusted, or that the apertures have to be realigned.



(a) The fiber surface structure measured by interference. The circularly shaped patterns are the result of reflections on the lens surface. In the lower left of the bright circle interference patterns caused by the actual surface profile of the fiber are visible.

(b) The fiber illuminated with external lighting.



(c) The fiber tip imaged with a Mirau-objective. The straight lines in the interference pattern indicate that the fiber contains no depression and that it is not exactly perpendicular to the imaging beam. The red dot marks the middle of the fiber and originates from light injected at the other end of the fiber.

(d) The fiber tip after five shots, measured with a Mirau-objective. The depressions they created are indicated by the circular interference pattern. The red circle marks the area used to measure the size of the depression and the red dot represents the middle of the fiber.

Figure 5: Four images of the fiber surface, taken with different imaging methods.

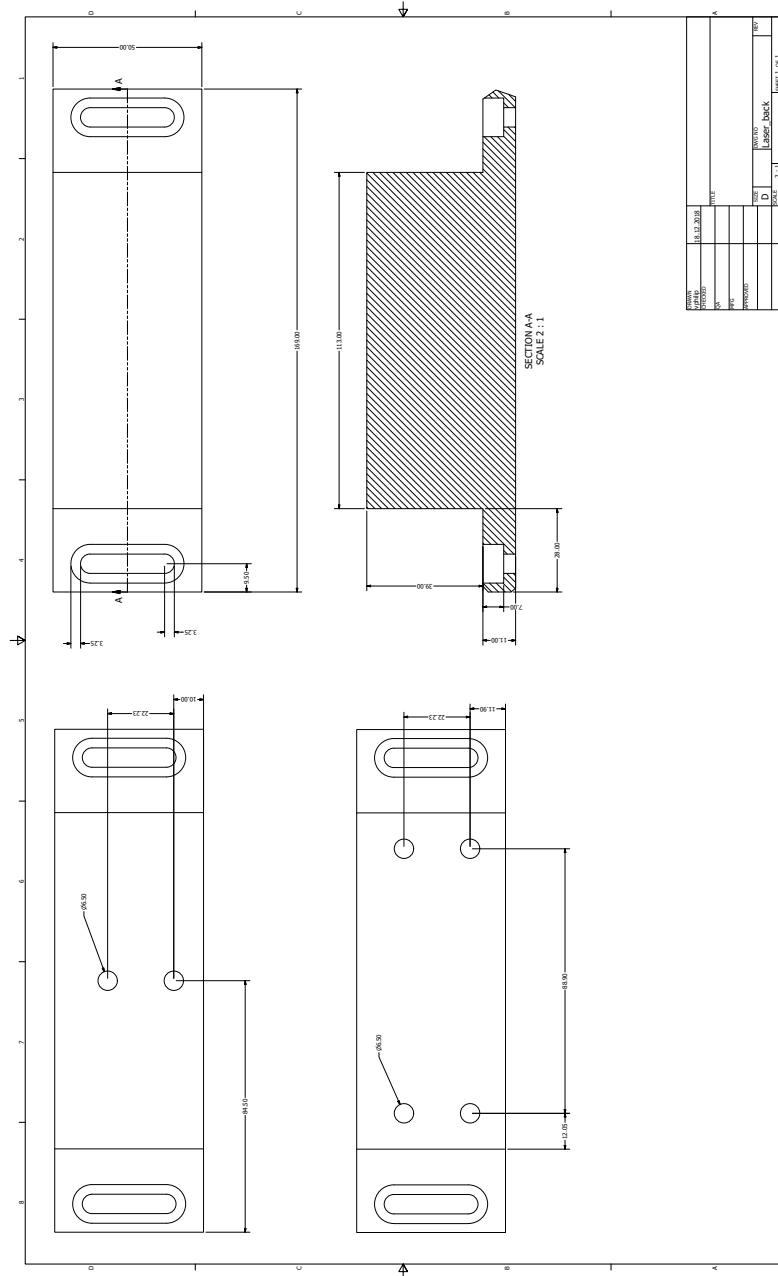
6 Conclusion

We reported on the improvement of a CO₂ ablation setup. The setup was changed in such a way, that a high precision translation stage could be included, a user interface to control the stage was built and several imaging methods were used. However, it remains to completely match the path of the CO₂ laser with a visible laser to enable a centering of the CO₂ laser on the fiber, as described in section 4.1. The current approach, consisting of a shooting pattern and an approximate centering, does not allow a controlled and reproducible ablation. This is crucial for the production of concave surface structures as they are required for the usage in fiber Fabry-Pérot cavities.

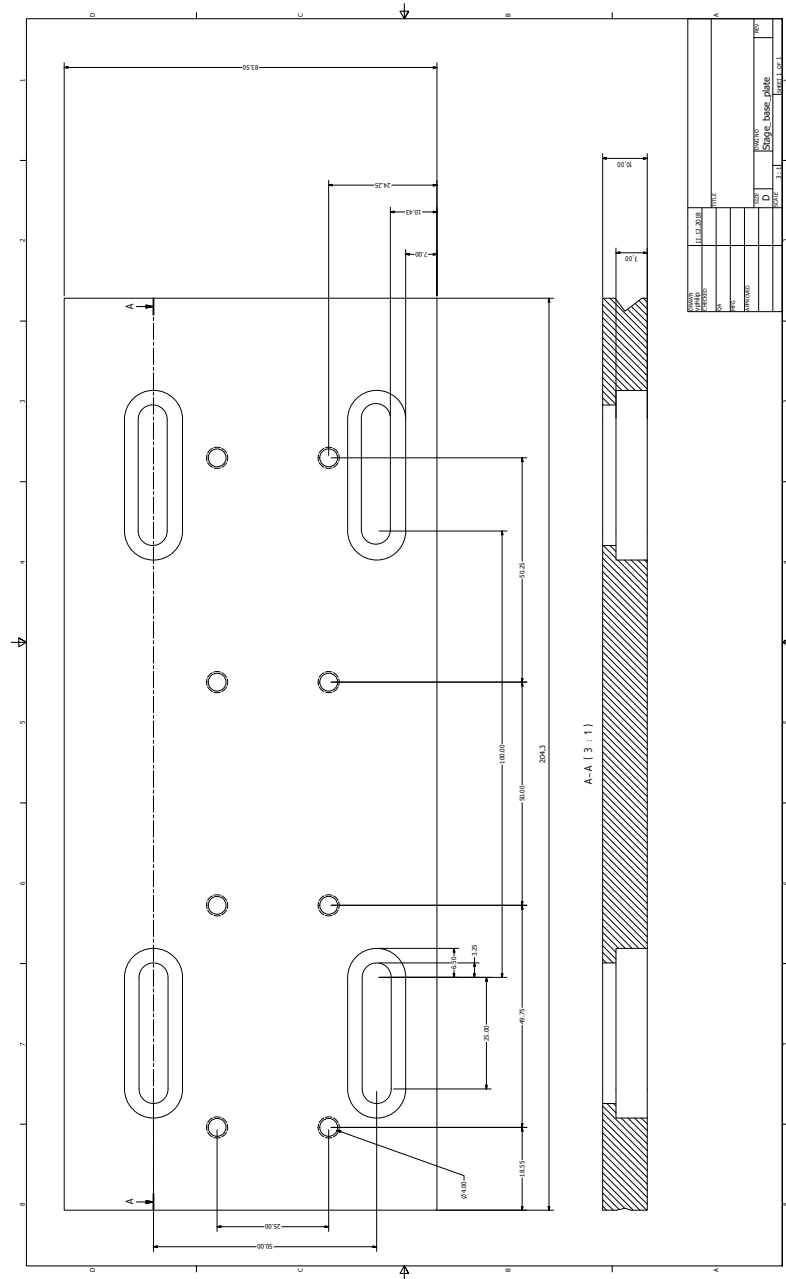
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A Technical Drawings



Technical drawings of three platforms to set the CO₂ laser on a higher level.



Technical drawing of the connection plate between the stage and the optical table.

B Code

The following is an excerpt of the program PIWidget.py. It contains the functions which address the stage directly. The remaining program consists of the definition of the class, the initialization of the stage and the creation of the control window.

```
def ontarget(self):
    #Returns 1 if stage is on target
    self.ser.write(b"ONT?\n\r")
    time.sleep(0.1)
    b=int(str(self.ser.readline()))[-4]
    return(b)

def waitforfinish(self):
    #wait until movement is finished
    b=0
    while b==0:
        b=self.ontarget()

def moveto(self, target):
    #Set new absolute target position
    d=target
    t=b"MOV 1 %d \n\r"%d
    self.ser.write(t)
    self.waitforfinish()

def position(self):
    #Returns the current position
    self.ser.write(b"POS?\n\r")
    time.sleep(0.03)
    b=float(str(self.ser.readline()))[4:13]
    return(b)

#What happens to the stage on click:
def on_click_minus(self):
    a=self.position()
    if a>=7:
        self.moveto(a-1.0)
```



```
        else:
            print('Min. limit reached')
def on_click_plus(self):
    g=self.position()
    if g<=102:
        self.moveto(g+1.0)
    else:
        print('Max. limit reached')
def on_click_comand(self):
    cmd = self.serialTargetInput.value()
    cmd = float(cmd)
    self.moveto(cmd)
```



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