LAPIN AMK
Lapland University of Applied Sciences

The introduction of a CO_2 laser cutting and engraving device into engineering education

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Bachelor Thesis
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Mechanical Engineering
Bachelor of Engineering

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Abstract of Thesis

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The engineering education at Lapland University of Applied Sciences is apparently already very diverse. The practical part of the education is supported by a number of laboratories and practical work. This Bachelor's thesis deals with the integration of a new device into this environment. The device under investigation is a compact tabletop laser cutting and engraving device that expands the possibilities of the students in terms of their projects and knowledge growth. It is manufactured by Flux and the product name is BEAMO. The work is roughly divided into three major parts consisting of theoretical basics, the testing phase and the development of projects.

Work began with a comprehensive research on the topic of laser technology. This was important to understand the possibilities of the own device and the theory behind the obstacles, limitations and problems encountered. During an extensive test phase, 11 different materials were examined using a standardised test scheme and other limiting factors such as resolution and influence of the focal point were analysed. The results of the cutting operation were digitised for better clarity and all obtained test samples are available for inspection at the 3D printing laboratory of Lapland University of Applied Sciences in Kemi.

The results of the test phase were then used to draft recommendations for later users, which are recorded in the guidebook. Since all the materials used could be processed under the conditions recommended by the manufacturer, there were many possibilities for independent projects. Due to the ease of use of the device and the short processing times compared to additive manufacturing processes, this device will now be able to make a valuable contribution to the training of young engineers in the future.

Key words	engineering education, CO_2-laser, material testing
Other information	The thesis includes a separate Guidebook.

CONTENTS

FOREWORD

Finally.
After years of procrastination and meaningless actions I am very blessed to be upon the first double degree students of UAS Technikum Wien and Lapland UAS in Kemi. This would not have been possible without Mr. Peter Franz, who introduced me and my fellow colleagues to the program and his work and efforts to get us to this fascinating country. Johanna in Vienna and Sanna in Kemi did their best in supporting us with all the minor issues due to our guinea pig status.

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All the staff of Lapland UAS, the lunch ladies and the ravintola team have created the best working environment I ever studied in but watermelons and onions should not be mixed into a salad, just saying.

SYMBOLS AND ABBREVIATIONS

AM	Additive Manufacturing
Ar	Argon
CAD	Computer Aided Design
CNC	Computer Numerical Control
CO	Carbon monoxide
CO_2	Carbon dioxide
DF	Fluorodeuterium
DPI	Dots Per Inch
FEL	Free electron laser
HAZ	Heat affected zone
HBr	Bromine-hydrogen
HCl	Hydrogen-chlorine, Hydrochloric acid
He-Ne	Helium-Neon
HF	Flourine-hydrogen
Lapland UAS	Lapland University of Applied Sciences
LFS	Low Force Stereolithography
MPE	Maximum permissible exposure
N	Nitrogen
PC	Poly Carbonate
PLA	Polylactic Acid
PMMA	Polymethylmethacrylate
PVC	Polyvinylchloride
RF	Radio (wave) frequency
TEM	Transverse electromagnetic mode
UI	User Interface
YAG	Yttrium aluminium garnet

1 INTRODUCTION

This chapter deals with the introduction of the Bachelor thesis, the motivation and justification behind the thesis and the aims and non-goals. It should attract the reader's interest and provide a good transition to the theoretical foundations. The framework of the thesis is set out in the course of this chapter. Practice-oriented learning characterises the Mechanical Engineering degree programme at Lapland University of Applied Sciences (Lapland UAS). Through hands-on successes and setbacks, learned theoretical knowledge can be practically applied in the university's laboratories, thus consolidating the knowledge. In addition to a laboratory for 3D printing technology, the range of instruments has been expanded with the acquisition of a laser device. In the future, the device will be available to students for learning and creating.

1.1 Motivation

The continuous development and improvement of study programmes to meet the needs of the industry motivates to contribute to the appropriate implementation of a new technology at Lapland UAS. The acquired device promises a good insight into the topic of laser technology and should help to support the interest and understanding of the students. This thesis deals with the clever integration of this new device into the study programme of the future mechanical engineers. During this bachelor thesis, theoretical basics are collected, the device is put into operation and tests are carried out. Finally, projects with all necessary additional materials are developed, described and made available.

1.2 Objectives

One of the main objectives of this work is to set up the new laser device in the laboratory area and perform tests with different materials. Furthermore, one of the main goals is to prepare documents for the Finnish students to be able to carry out their own projects safely. In addition, the carbon dioxide (CO_2) technology used is to be compared with other commercially available technologies in order to be able to recommend possible further expenditures.

Advantages and disadvantages of different technologies are to be worked out and described.

1.3 Non-objectives

This paper aims to simplify the introduction of laser cutting and engraving into the student learning process and to anticipate most of the problems that happen in the first attempts. However, no claim is made for actual successful projects, as experience and skill in topics such as woodworking and finishing lie with each individual imitator. In general, the safety guide and the instructions for use are intended to facilitate smooth and safe operations for both the machine and the user. However, the documents provided can only be recommendations; injuries and damages are the responsibility of the user.

1.4 Scope

In the course of this Bachelor project, in addition to the thesis itself, a guidebook for Finnish mechanical engineering students will be created, which will contain all the necessary documents for operating the new laser device as well as some safety instructions. These instructions will be adapted to the actual use of the students and other operators and will be a simplification of the already existing operating instructions. In order to prepare the laboratory exercises properly, tests will be carried out after the machine has been set up and commissioned. Different materials are tested using a uniform method to describe the capabilities of the laser. The paper and all materials produced will be written in English and made available to Lapland UAS and provided in online databases.

1.5 Methodology

The general method used in this work is the scientific method of trial and error. Based on a literature research and the study of the documentation of the device, tests are carried out and as many settings and applications of the device as possible are worked out through the try and error principle. Figure 40 shows a schematic sequence of the work in semi-chronological order. Due to the necessary size of the figure, it has been moved to Appendix 1. In Figure 40 you can see a flow chart of the work steps, sorted by order and approximate integration. The red ellipses always mark the beginning or end of an important milestone. The yellow rhomboids represent inputs or outputs of the supervisor during the work. The bevelled rectangles symbolise stand-alone documents that have been created and will be part of the final submission. All rectangles between the arrows are process steps or rough chapter divisions and are meant to clarify the elements of the flow of the work. The five rough divisions of all events on the left side serve the purpose of classifiability and merge smoothly into each other.

2 THEORETICAL BACKGROUND

The word laser is defined as „...*a device that produces a powerful narrow beam of light that can be used as a tool, for example to cut metal, to perform medical operations, etc. The beam of light is also known as a laser*" (Cambridge University Press 2014). When the word laser is used in this work, it can refer either to the device that generates the laser beam or to the beam itself, since per definition both things can be meant. It will always be clear from the context which term is being used. This first content chapter deals with basic fundamental knowledge about laser technology. In a coherent sequence, this technology is explained and techniques are compared. Starting with the production of a laser beam by emitting photons through orbital jumps, through the bundling and handling of laser beams to the areas of application and some examples, this chapter will be structured like this.

2.1 Physical basics of laser beam generation

The word laser comes from the abbreviation Light Amplification by Stimulated Emission of Radiation. This abbreviation essentially describes the function of a laser. Namely, the artificially induced emission of photons by amplifying the absorption transition during the orbital jump of an excited medium. (Demtröder 2010, 271) Figure 1 shows three electron transmissions in an atom using the orbital model. It serves as a detailed explanation for the formation of light through orbital jumps.

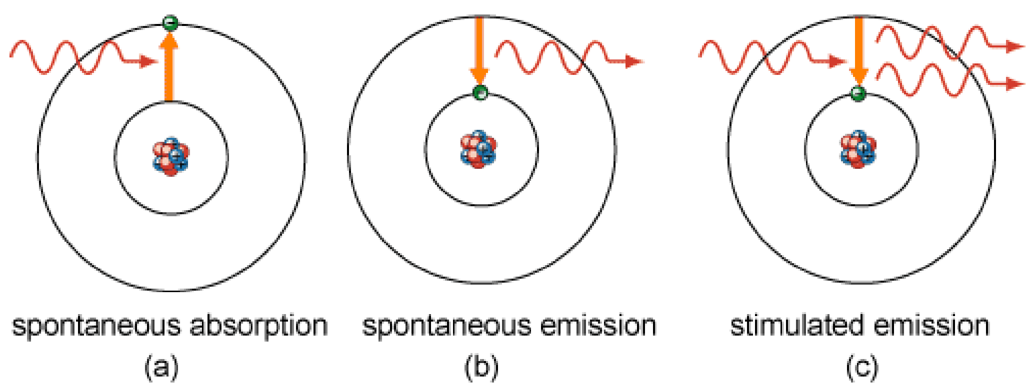

Figure 1. Electron transition in an atom (Kwok-san & Shiu-sing 2000)

As can be seen in Figure 1, a distinction is made between three possible changes of state with corresponding effects. Electrons can be lifted to higher energy levels by external influences such as radiation, which is called absorption (a). Absorption can happen spontaneous and is driven e.g. by the sun's radiation and can be felt as heat on a absorbing surface. However, since this new state does not happen without external forces, it is unstable but of higher energy. Therefore, energy is released in the form of photons when the electron returns to its original position on its own (b). The higher orbits are reached here, the more photons are also released. In the case of several spontaneous emissions, however, neither the alignment, phase nor polarisation of the photons match. It can therefore be practically ruled out that a directed light beam will form naturally. In the third case, the emission of photons is stimulated (c). The frequency and phase of the emitted photon match those of the added photon. This means that the polarisation and direction of the resulting light wave is also uniform. This process now enables the creation of a directional coherent laser beam. (Steen & Mazumder 2010, 14–16)

A simple laser is made up of three components. Firstly, an active medium is needed from which light is generated and amplified. This medium usually gives the process its name, for example CO_2 laser. The active medium can be solid, liquid, gaseous or in the state of a plasma. For example, rubies in solid lasers, dyes dissolved in alcohol or water, or gases such as helium-neon (He-Ne), CO_2, argon (Ar) and nitrogen (N) are used as active media. As a further component, a laser device needs a so-called pumping source or mechanism. Any form of energy can be used as a source. Common pumps consist of flash lamps, other lasers, electrons, chemical reactions, ion beams and X-rays. The third component of a simple laser are the resonators, which cause optical feedback. The two resonators reflect the generated light between the parallel surfaces and thus induce an oscillation. If the distance between the reflectors matches the gain, the light is amplified with each pass. One of the two reflectors is not 100 % reflective and allows a certain amount of light to escape from the reaction chamber with each pass, resulting in the shaping of a laser beam. The resonator is also responsible for the monochromaticity and unidirectionality of the beam. (Steen & Mazumder 2010, 12–13) Figure 2 shows the basic structure of a laser and the three components described above.

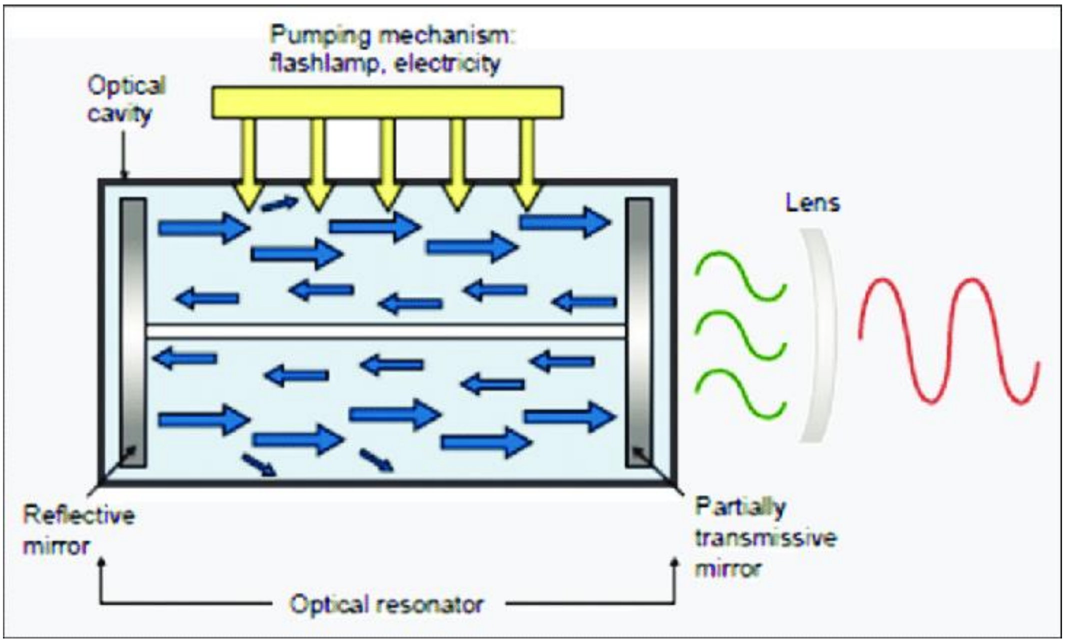

Figure 2. Basic working mechanism of a laser (Kale, Garde, Garde & Gupta 2017)

The basic structure of a laser with any active medium is shown in Figure 2. The area of the active medium and the indicated radiation directions of the excited photons can be seen in blue. Furthermore, the pump source can be seen in yellow. It serves to excite the active medium by introducing energy. The two different reflectors can be seen to the left and right of the active medium. As described above and visible in the illustration, they return part of the induced radiation to the active medium and thus form a light oscillator. The distance between the two optical resonators plays a decisive role in the amplification factor of the laser generator. (Demtröder 2010, 23–24; Steen & Mazumder 2010, 271–272)

2.2 Laser beam characteristics and handling

This chapter is intended to explain some of the most important terms related to laser light in order to understand the influence, the meaning and the effects of various changes in the later chapters. First, more fundamental terms such as wavelength and coherence are explained, followed by the significance and influence of the diameter of laser light. The chapter is concluded by the topics of polarisation and the role and effect of optics in manipulating light.

2.2.1 Wavelength

As is well known, light can be seen as a particle and as a wave. This assumption is changed depending on which view is better suited to an investigation. This is called wave-particle dualism. Photons can be absorbed by matter and their energy can also be emitted again in the form of light. However, the concept of quantisation can only be explained with the particle model. In this case, the light of a given wavelength can no longer be distinguished, since this energy contains that of a single photon. Each individual photon can therefore have its own wavelength. In the model, the electromagnetic wave describes the range of visible and invisible light. This light propagates in waves in a space. These waves are decisively characterised by their wavelength, whereby one also speaks of reciprocal frequency. For humans, the wavelength range from 380 nm to 780 nm is visible. At wavelengths shorter than 380 nm, the so-called ultraviolet range begins and above 780 nm the term infrared range is used. (Beyerer, León & Frese 2016, 27) Figure 3 below shows the electromagnetic spectrum. It is intended to help visualise the wavelengths of different laser beams and also to support safety and visibility assessments.

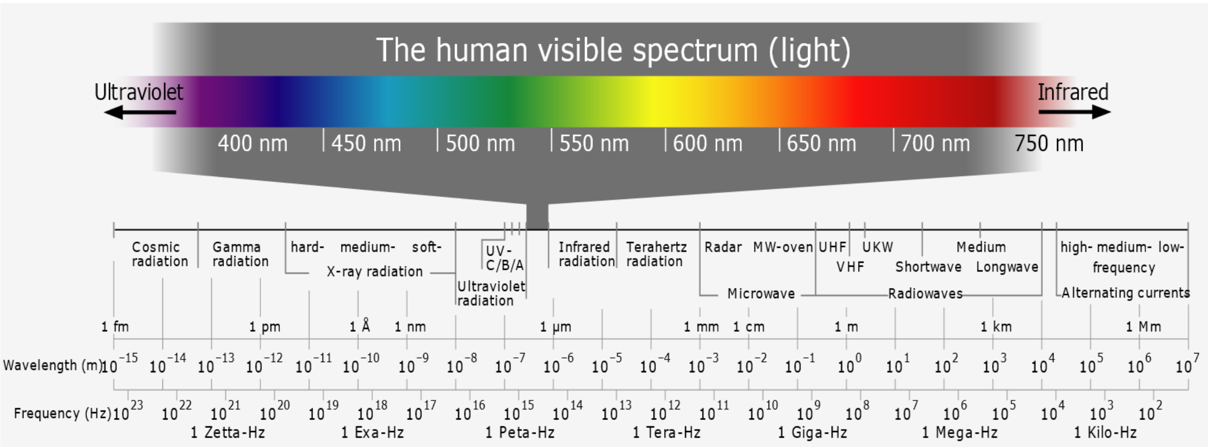

Figure 3. The electromagnetic spectrum (Frank 2006)

Figure 3 above shows a wide spectrum of the wavelength that electromagnetic waves can have. It is easy to see that the visible range of radiation is quite small relative to the spectrum shown here. One usually speaks of light only within this spectrum, although this name for electromagnetic waves is also used for laser light outside this range. Generally speaking, the light emitted by lasers is one of the purest spectra there is. This means that within a concentrated beam, a certain wavelength predominates, which makes lasers so effective. (Steen & Mazumder 2010, 98)

2.2.2 Coherence

Laser light is further exciting because of the coherence of the individual light waves. Unlike natural incoherent wave clusters, the uniform beams of artificially generated laser light can serve different purposes. This property can be used for distance measurement, Doppler velocity measurements and spectral interferometry. In materials processing, however, the measure of coherence has no practical applications yet, nor is it given any special attention. (Steen & Mazumder 2010, 98)

2.2.3 Mode and beam diameter

As discussed in chapter 2.1, laser light is generated in a specific cavity. The generated wave is standing, coherent and its shape depends directly on the shape of the cavity. However, not only are identical waves generated in a plane and on an axis, but these waves can also lie at a certain angle along the axis. How the light image looks when it is emitted from the cavity is described by the so-called mode. The shape of these wave images is called transverse electromagnetic mode (TEM). In addition, there is the specification TEM_{plq} where: *p* is the number of radial zero fields, *l* is the number of angular zero fields and *q* is the number of longitudinal zero fields. (Steen & Mazumder 2010, 100)The most common modes are shown in Figure 4. It is intended to show the different forms in which laser beams occur or are generated.

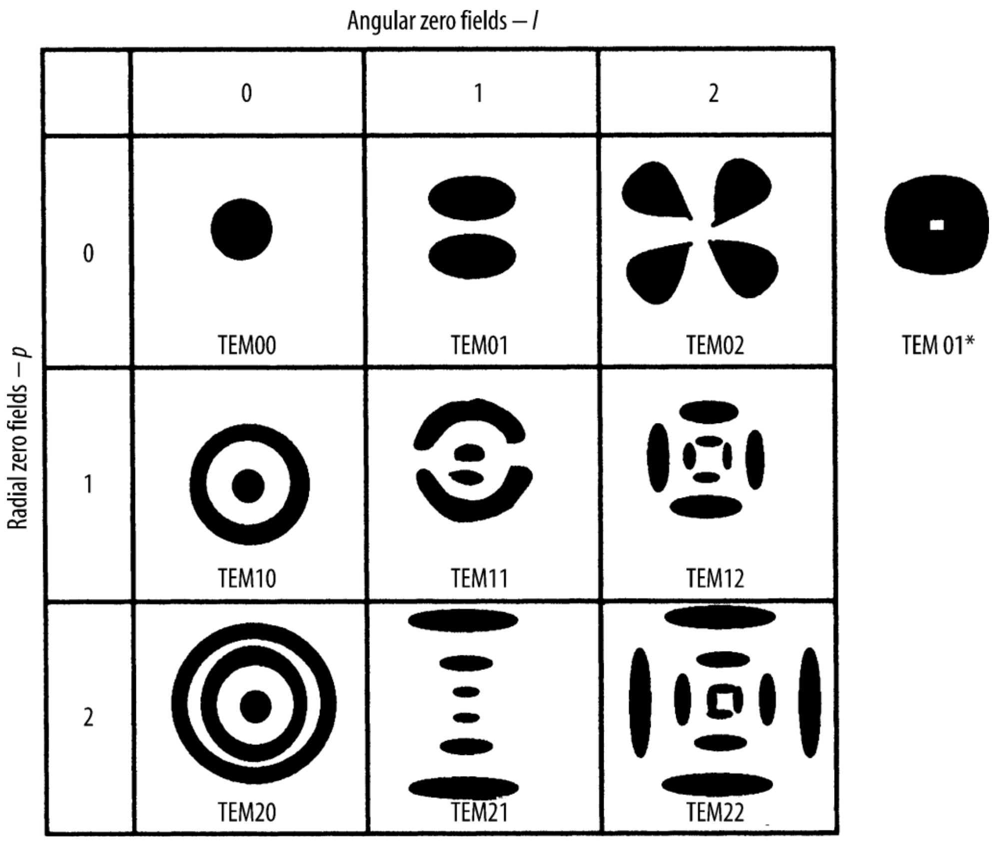

Figure 4. Various mode patterns (Steen & Mazumder 2010, 101)

Most slow-flow lasers have near-perfect TEM00 or TEM01* modes. Transverse lasers usually have a large number of different modes due to the temperature differences along the glass cylinder in gas lasers. As the mode height increases, so does the effort required to focus the beam, because the light no longer comes from a single source. Another point to consider when processing materials is the beam diameter. Depending on the application, a smaller spot size is desirable in order not to heat the surrounding material too much. (Steen & Mazumder 2010, 101)

2.2.4 Polarisation

The next term describes the polarisation of the emitted light bundles. The product of stimulated emissions is characterised not only by the resulting long chains of waves but also by the fact that their electric vectors are uniformly aligned. This is referred to as a polarised beam. However, this is only possible on its own in the two-dimensional theory. To generate a polarised beam with real laser devices, filtering is required. Non-polarised laser light can influence the quality of material processing, as the degree of reflection at the cutting edge significantly changes the cutting pattern. The polarised light can be aligned with the help of a circular polariser. (Steen & Mazumder 2010, 101–102)

2.2.5 Laser optics

A laser device without some kind of optical element is hardly possible. Almost every technology and application requires the manipulation and controllable modification of many properties of the laser beam. The most important type of optical element, apart from numerous filters, are the lenses. For the purpose of better representation of their effect, stigmatised representation is used. It transforms all possible object points into ordered image points. (Meschede 2008, 26) Figure 5 shows the functional principle of simple stigmatised lenses.

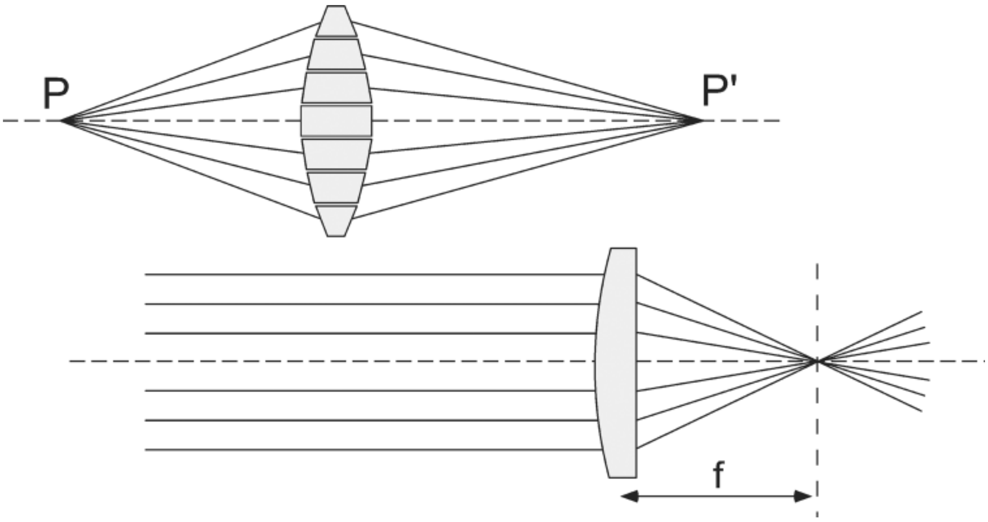

Figure 5. Stigmatic display of lenses (Meschede 2008, 27)

An optical element is one that reunites or focuses all rays from a point source back into one point. This basic operation is shown in Figure 5 above. Let the point source of light be labelled **P** and **P'** show the point of convergence equidistant from the optical element. In the case of very distant point sources, one can speak of quasi-parallel beams. This also applies to the parallel unbundled radiation of a laser tube. In this case, a lens can be used to bundle the beams. Since the energy density is highest at the bundling point, this is also referred to as the focal point. The distance from the lens to the focal point is called the focal length which is shown as **f** in Figure 5. (Meschede 2008, 26–27) Since most laser applications require very small spot sizes, there are also a variety of optics to focus the beams, some of which are several mm wide, to less than 0.01 mm in some cases. For CO_2 lasers, lenses with resulting focal point sizes as small as 0.03 mm are available. (Universal Laser Systems, Inc. 2021)

Lets look at the beam pattern in Figure 5 and consider that the cloud of beams around the focal point could be above or inside the material to be machined. You can already see the first problem with machining three-dimensional objects with tools that can only be relocated in two dimensions.

2.3 Applied laser technologies

The following subchapter deals with the brief introduction of some known laser technologies. Some of them differ significantly due to their active medium. After the short introductions, the application areas of selected technologies are presented and discussed. After that, another subsection will deal with the topic of safety and classification into safety classes. After a brief introduction to the history and development of laser technology over time, general advantages and disadvantages of the technologies in certain applications will be presented.
As already described in the introduction, lasers are not only used in material processing. In addition to medical applications, they are also used for surveying and entertainment purposes. However, since this paper deals with material processing, the other possible applications will not be considered further. Only in the comparisons will other areas of application be mentioned as examples. The laser technologies that are mainly used in material processing are CO_2 lasers, various forms of yttrium aluminium garnet lasers (YAG, Nd:YAG, Yb:YAG, Er:YAG) and diode lasers. (Steen & Mazumder 2010, 12)

2.3.1 Semiconductor laser

Semiconductor lasers or diode lasers are the most widely used lasers today. The first lasers were operated at low temperatures, but in the 1970s operation at room temperature was developed. In semiconductor lasers, electric current is converted directly into laser light and the small dimensions of the laser crystals make them particularly interesting. Normally, the dimensions of the crystals are around 300 µm x 100 µm x 100 µm. Furthermore, the differential laser efficiency reaches comparatively high values of up to 50 %. This means that up to 50 % of the pump current can be converted into coherent light output. Of the three ways in which a diode laser can generate a beam, the injection type is important because it is more widespread. With the help of specially doped semiconductor layers, light with a wavelength of 370 nm to 32 µm is generated. Gallium, indium, aluminium and arsenite are mainly used for doping. The output power can range from 1 mW to over 300 W and is in part strongly temperature-dependent. (Sigrist 2018, 307, 311, 345)

2.3.2 Dye laser

Another type of laser is the dye laser. As the name suggests, the laser light is generated with the help of dyes. For a long time, they were the most common technology in the visible light range, but in recent years they have been increasingly ousted from the market by the more advanced diode lasers. The dye used is usually dissolved in a liquid such as methanol or water, although experiments have also been carried out with solid-state matrices. Dye lasers are optically pumped lasers, as the dye molecules are irradiated with visible or ultraviolet light and show broadband fluorescence. Due to this broad tuning range, modern spectroscopy mainly uses dye lasers. In addition, there are broad areas of application in dermatology and for the therapy and destruction of tumours. Either flash lamps or pulsed respectively continuous lasers can be used as pumps. Nowadays, mainly excimer lasers are used as pumps. With different dyes, the tuning range of excimer laser pumped dye lasers ranges between 320 nm and 985 nm. These lasers have average powers of 0.1 to 10 W and have pulse repetition frequencies between 20 and 200 Hz. (Sigrist 2018, 283, 289, 299–301, 304)

2.3.3 Solid state laser

Another laser technology is the solid-state laser. They consist of glass-like crystals and, with dimensions of several centimetres, are much larger than semiconductor lasers. The crystalline structures are doped by optically active ions and thus transformed into the active medium of the solid-state laser. Ions of transition metals such as Cr^{3+}, or of rare earths such as Ho^{3+} and Nd^{3+} are mostly used for this. The density of the laser-active ions is in the order of 10^{19} cm^{-3}, which is much higher than, for example, in gas lasers. Therefore, despite the relatively low efficiency of around 0.1 %, high powered light outputs can still be achieved. Solid-state lasers are usually excited by pumps from flash lamps or diode lasers. The most important solid-state laser today is the neodymium laser. In the past, glass and today mainly host crystals of cubic yttrium-aluminium garnets are doped with neodynium. Nd:YAG lasers built in this way can have outputs between a few watts and several kilowatts when excited with diode lasers. (Sigrist 2018, 351, 356–357)

2.3.4 Chemical laser

With chemical lasers, the laser radiation is generated directly by chemical reactions. In this process, the chemical energy is converted into coherent radiation energy without any significant input of, for example, electrical energy. However, the laser systems used are usually not purely chemical lasers, because here the atoms are treated by photolysis, electrical discharges and electron beam excitation. Since chemical compounds and reactions contain large amounts of energy, large light outputs can be assumed. One of the most studied chemical lasers is the fluorine-hydrogen (HF) laser. Through the reaction of fluorine and hydrogen, the resulting molecules can be set into vibration and through further chain reactions, a beam with wavelengths between 2.7 µm and 3.3 µm can be generated. Some laser transitions are similar to those of carbon monoxid (CO) gas lasers and when electrical discharges are used, the pulsed HF lasers resemble CO_2 lasers with pre-ionisation. The continuous light output ranges up to 10 kW, with the most important applications being in the military sector. Other important representatives of chemical lasers include the fluorodeuterium (DF) laser, hydrogen-chlorine (HCl) laser, bromine-hydrogen (HBr) laser and finally the iodine laser. The latter technology achieves pulse peaks of several TW of power due to the atomic iodine produced during photodissociation of CH_3I, which is why it was of interest for laser fusion research. (Sigrist 2018, 399, 401–402)

2.3.5 Free-electron laser

The next laser technology discussed is the Free Electron Laser (FEL). Here, a relativistic electron beam is sent through a strong periodically alternating magnetic field. This field of force induces the electron beam to move in a wave-like motion. This motion causes the electrons to emit electromagnetic waves, which are called synchrotron radiation. Since this type of laser beam generation does not use an active medium in the classical sense, the question arises whether FELs should be called lasers or purely electronic radiation sources. The development of FELs was already promoted in the 1980s. FELs are interesting because of their wide tuning range and high peak and average powers. However, such facilities are very expensive and complicated, which is why they are used in the more unconventional areas of the THz range and the vacuum UV and X-ray range. The emitted radiation also has a high transversal coherence, which means that the radiation can always be focused to a diffraction-limited spot size and can thus be transported over very large distances. Another typical application is in molecular and atomic physics, where the lasers are used in material investigations, isotropic separations, lithography and biological studies on ultra-short time scales. The further development of this technology will simplify procedures in X-ray spectroscopy in the future. (Sigrist 2018, 403–404, 407, 409)

2.3.6 Gas laser

In this laser category, the active medium is present in a gaseous or vapour phase. Most gases, especially noble gases, are suitable as laser medium. Each of them provides several laser transitions. The output ranges span from the UV range to the submillimetre wave range. The gas lasers include neutral atom (e.g. He-Ne, metal vapour), ion (e.g. Ar+), molecular (e.g. CO_2) and excimer (e.g. KrF) lasers. Gas lasers have a number of properties that make them particularly suitable for applications in industry and research. The excitation of the active medium in a gas laser usually occurs through an electrical discharge. However, there are also gas lasers in which the excitation takes place by optical pumping with another laser, by a gas-dynamic expansion or by chemical pumping. In an electrical gas discharge, free electrons and ions are produced. These charge carriers gain kinetic energy through acceleration in the electric field of the gas discharge. In this process, the movement of the ions is generally unimportant, since only the free electrons contribute to the excitation of the gas atoms, ions or molecules. Continuous gas lasers are normally operated with a low-pressure discharge because a continuous discharge cannot be maintained at higher pressure.

Since the laser used in this work is a CO_2 gas laser, this type is discussed in detail here. The CO_2 laser belongs to the group of vibrating rotating lasers and is one of the most important molecular lasers. It was first realised by Patel in 1964 and is today one of the most powerful lasers in the world. In contrast to other gas lasers, it is still very strongly represented on the market today. Continuous outputs of around 80 kW are achieved and, together with the high efficiency of 15 - 20 %, there are a number of possible uses, especially in industrial applications.

The construction of CO_2 lasers can be roughly divided into eight categories. The gas laser used in the course of this work belongs to the designs with longitutinal slow gas flows. Therefore, only this design will be presented in more detail in the following. For the sake of completeness, however, the other types will be mentioned. In addition to the construction type already mentioned, there are also closed lasers, waveguide lasers and so-called slab lasers. Furthermore, there are CO_2 lasers with fast gas flow, transversely excited atmospheric pressure lasers, gas-dynamic lasers and continuously tunable high-pressure CO lasers. The first CO_2 laser ever built, in 1964, was of the same design as the laser used in this work. The characteristic slow longitutinal gas flow takes place in a glass tube with an internal diameter of about 1 to 3 cm, which is usually water-cooled from the outside. The active medium is formed by a CO_2-He-N_2 mixture which is excited by means of a direct current discharge in the axial direction. The reflector mirrors can be positioned either in contact with the gas mixture in the tube or outside. The composition of the gas mixture at the usual 20 mbar depends, among other things, on the gas flow, the tube diameter and the degree of decoupling. The discharge current is primarily used for light output control and the maximum output is directly influenced by the length of the discharge tube. With an ultimate efficiency of around 10 %, typical laser powers of between 50 and 80 W per metre of tube can be achieved. (Sigrist 2018, 223, 248–249, 256–257) Figure 6 below shows the typical structure of a slow-flow transverse gas laser. Since this configuration is similar to that of the laser tube used and presented later, a closer look at this technology is quite reasonable.

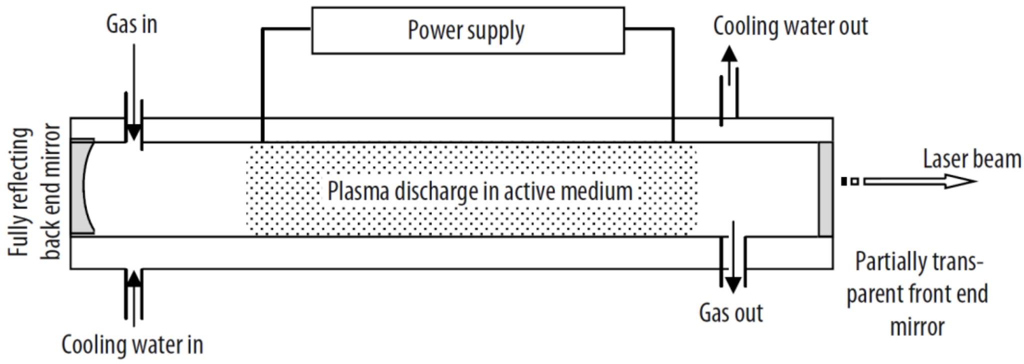

Figure 6. Basic construction of a slow flow gas laser (Steen & Mazumder 2010, 36)

Figure 6 above shows the schematic structure of a low-flow gas laser. Most of these laser tubes are cylindrical, but there are also square and triangular shapes.(Steen & Mazumder 2010, 36) The flow direction of both media can be clearly seen in the figure. The cooling water is cooled elsewhere in the system by heat exchangers in form of radiators and should be as bubble-free as possible to obtain good cooling performance. The energy supply can come either from a direct- or alternating current power source and can also be provided by means of a radio wave (RF) discharge. Such CO_2 gas lasers have a light output of between 3 and 100 W at an initial wavelength of 10.6 µm and are exclusively operated continuously. (Steen & Mazumder 2010, 33)

2.3.7 Applications

Lasers have been used for many different purposes since their development. In some fields, they can replace proven technologies and are now among the workhorses of material processing. In addition to this field of application, there are many others such as entertainment, medicine, research and surveying. Since this thesis revolves around a material-processing laser cutter, the following chapter will focus more on the different uses of lasers in this field as well as their properties, advantages and disadvantages.

Cutting material is one of the main tasks of industrial laser equipment. The advantage over conventional technologies such as oxy flame, NC milling and abbrasive fluid jetting lies in higher processing speeds and better edge qualities. Of course, this only applies to flat workpieces, which already brings the first disadvantage of laser technology. Furthermore, there is no need to clamp the workpiece before machining and the tool does not experience any wear except for the ageing of possible laser tubes and the cleaning of the focus lenses. When it comes to cutting material, cheaper and faster manufacturing processes such as cutting dies are only available for very large quantities of 10,000 or more. (Steen & Mazumder 2010, 131–133, 183)

Focused laser beams have the highest energy densities available to industry and are comparable to electron beams. These high power densities cause the material to vaporise when the energy is absorbed. The resulting slit is filled by the surrounding liquid material during welding and is called keyhole welding. Since these slots are very narrow and the processing speed is relatively high due to the high power, the zone around the weld seam that is affected by the heat (HAZ) is also relatively small. Another characteristic of lasers used for welding is, that compared to other conventional methods such as tungsten inert gas (TIG) welding, there is hardly any contamination in the surrounding area. Unlike electron beams, which are also very powerful, welding with lasers can also be carried out at atmospheric pressure. The areas of application in which lasers are used for cutting and welding work are constantly increasing. Today, for example, many steps in car production are already done by lasers. These include the precise cutting of airbag parts, welding of car body parts, welding of gear wheels in transmissions and marking work on all parts and materials. Lasers are also used to weld fibres, plastics, marine components and bimetal saw blades. (Steen & Mazumder 2010, 199–201, 241–242)

2.3.8 Safety classes, genreal issues

Any kind of energy can be dangerous or deadly. Lasers are no exception, although general reputation and caution have led to relatively safe handling. The main dangers posed by a laser beam include injury to the eyes and skin, the risk of electrocution and injuries due to fire and toxic fumes. The human organ most at risk from laser radiation is the eye. In order to correctly assess the danger of a laser to the eye, it is first necessary to understand what happens in the eye with radiation or what kind of radiation triggers what. A distinction is made between transmission into the eye and absorption of radiation from the retina. This is because not all radiation that enters the eye also has an effect on the retina. The wavelength of the laser light is decisive for this. (Sigrist 2018g, 411; Steen & Mazumder 2010, 519) Figure 7 shows two graphs that can be used to explain the hazard potential for the eye of different laser technologies.

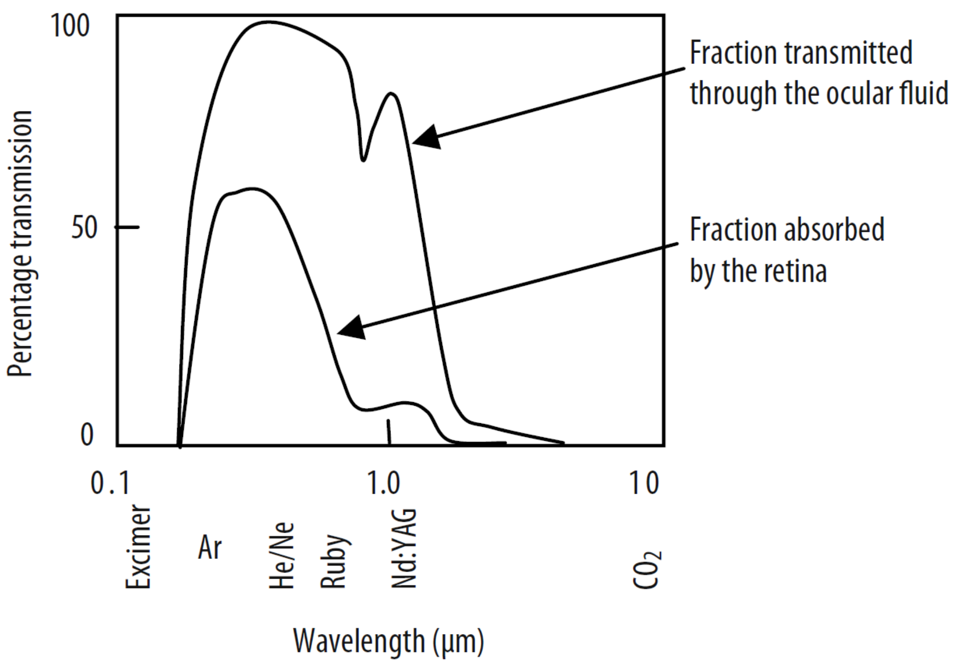

Figure 7. Spectral transmissivity of the ocular fluid and the absorptivity of the retina (Steen & Mazumder 2010, 521)

Figure 7 above shows the range of wavelengths absorbed or transmitted by the vitreous body in the eye and the retina. From this, one can directly conclude the possible damage caused by laser light in the eye. In addition to the wavelength, the x-axis also shows the ranges in which different laser technologies are found. For example, one can see that the emitted beam of gas lasers with a helium-neon mixture penetrates the vitreous body very well and is absorbed by the retina by more than 50 %. This is of course due to the fact that ruby lasers are in the visible range of light and can therefore easily cause damage to the eye. However, it should be mentioned here that the duration of exposure has a very large influence on the damage caused. Many dangers are reduced by the natural blink reflex; after all, you cannot look directly into the sun for very long either. This is not to say that lasers that are outside the wavelength ranges presented above cannot be harmful to the eyes. Another danger posed by lasers is damage to the skin and eyes caused by thermal effects, among other things. There are different permissible exposure times which are divided into so-called maximum permissible exposure (MPE) levels. Wounds caused by lasers on the skin that do not cut directly through the body are usually relatively harmless because the interfaces are clean and can grow over well. However, thermal damage to the eye usually leads to permanent loss of vision. So the rule of thumb is never to hold parts of the body within the range of laser beams or to cross them. (Steen & Mazumder 2010, 520–523)

According to EN 60825-1:2001, laser devices are divided into 7 safety classes depending on their relative hazard potential. For example, all lasers that can be used to process material are classified as class 4 lasers. Exceptions are made for laser devices that are completely enclosed and thus inaccessible to humans, or are equipped with certain safety and shutdown devices. The laser classes are as follows: 1, 1M, 2, 2M, 3R, 3B, 4. Class 1 lasers are either so harmless that you can look into them continuously or are designated as such if more powerful lasers are built into a fixed housing. These include industrial laser material processing equipment, CD players and laser printers, for example. From class 1M, protective goggles are mandatory and the rays are dangerous to the eyes. There is still no danger to the skin. Class 2 and above must be marked with a special warning symbol. From class 3R there is little danger to the skin and from class 3B the natural blink reflex is no longer sufficient to prevent serious eye damage. Class 4 lasers are capable of burning or vaporising material and are subject to further regulated safety precautions in addition to enclosures.

Since electrically excited gas lasers are sometimes operated at very high voltages, there is also a real risk of electric shock and death from electrification. CO_2 lasers, for example, are operated at up to 30,000 volts and smoothing capacitors can still have a lot of energy stored even after the device is switched off. Another source of danger comes from the fumes and smoke produced during material processing. Especially organic materials such as wood and leather can emit very toxic substances such as cyanides and other carcinogenic substances during irradiation. Benzene, toluene, nitrogen dioxide and acetylenes make up a small part of the large group of toxic substances, which is why good ventilation and exhaust air treatment are very important in material processing with lasers. (Steen & Mazumder 2010, 523–526)

2.4 Advantages / Disadvantages of lasers

This chapter is dedicated to some advantages and disadvantages various laser technologies have over the traditional technology of computer numerical controlled (CNC) milling machines and the relatively new additive manufacturing (AM) technology, which is sometimes reffered to as 3D printing technology. As all those technologies are constantly developed and very specific usecases always need special tools, some of those points may seem irrelevant in the near future.

One of the biggest advantage laser machines have compared to other technologies is speed of operation. When laser machines are set up, they can quickly perform desired work and produce multiple identical parts in a short time through precise repetition. Furthermore, there is no physical connection or contact points between the tool and the workpiece when using lasers. Unlike CNC machines or with AM processes, there are no wear parts due to abrasion on the material, etc. Of course, optics and lasers have to be maintained themselves, but in terms of wear, they still have great advantages over the aforementioned technologies.

One disadvantage of the current laser technologies is the two-dimensional working plane. While the focal point can sometimes be adjusted to work on uneven surfaces, most machines are limited to machining relatively flat workpieces. Nowadays, multi-axis CNC machines can work on a workpiece at many different angles and the workpieces themselves are sometimes mounted on multiple moving axes. Of course, it only makes limited sense to compare subtractive and additive manufacturing processes.

Another positive point of lasers is the variety of materials that can be processed. While classic CNC machines specialise in metal and plastic parts and AM processes can only process fusible plastics, a laser device can be used on a wide variety of materials. Organic or non-organic, in the end the active medium and the light output determine the limitations with regard to material. A disadvantage that goes hand in hand with increasing quality demands is the need for expertise. Setting up and operating large laser systems economically requires specialised personnel and training. Furthermore, high acquisition costs are a negative point. Compared to conventional plasma cutters and waterjets, laser machines with comparable capabilities can cost more than twice as much to purchase. On the other hand, the moderate operating costs are limited to the electricity bill and the possible need to replace the laser emitter. (Velling 2020)

3 FLUX BEAMO LASER DEVICE

This chapter deals with the introduction of the new laser cutting and engraving device into the laboratory environment at Lapland UAS. The setup process and the testing phase are described here and the chapter ends with a conclusion of the testing phase which leads into the next big part of this work, the design of projects for students and other users. The laser device will be named just BEAMO at some points, which is the product name and is to be seen as equivalent to its function. Which software to use and what file types are supported with the main user interface is described in the beginning of chapter 3.2.

3.1 Setup

As the BEAMO is a new device that has never been operated let alone been installed in the laboratory environment of Lapland UAS, this chapter deals with the setup and installation process of the device. First, a quick introduction to the topic is given by the showing of some product photos and looking at the equipment and tools that were shipped along with the main device. After this the BEAMO is set into position and the mandatory exhaust air hose is connected to the main ventilation system of the laboratory. This process and accompanying problems are described in Chapter 3.1.3. The final setup process leads directly into the initial testing phase. This phase has a dedicated chapter due to the large extent and it is described in detail.

3.1.1 The equipment

The device came shipped in a cardboard box and was securely held in place by foam parts. Its dimensions are 615 x 445 x 177 mm and it weights about 22 kg. In addition to the device itself the manufacturer has provided a number of important parts. Those include a basic maintenance set with a funnel and some lubrication oil as well as a plastic vent hose and a dedicated hose clamp. The vent hose proved itself to be of rather unpleasing quality and was too short for being hooked up to the main ventilation system so it has not been used at all. A power cord and a Wifi dongle could be found in the package as well as a small sample of thin plywood for initial testing and double sided tape for securing the work piece. Figure 8 shows a product shot of the device which gives first impressions and tells the arrangement of all the parts and features. The main chamber is accessed via a transparent lid and the power button is located to the right side, which is the only physical button on the machine. The laser device stands on four rubber feet to dampen the vibrations but the fast movement of the laser head causes the whole table to resonate and this issue is dealt with in Chapter 3.1.2.

Figure 8. Flux BEAMO product image (Flux Europe 2021b)

Figure 9 gives a view on the back side of the device where all the ports and the exhaust fan opening are positioned. The laser tube is also located in the backside of the device and can be accessed via an own lid which is held down with six hex key screws.

Figure 9. View of the back side

Figure 10 shows a top view of the device with the laser tube cover removed. The laser tube and the water hoses for cooling the gas chamber are visible under the back cover. In addition to that the BEAMO is equipped with an air pump. The generated pressured air is fed through the laser head onto the surface of the workpiece to help with the removal of burned material and to extinguishe embers. Problems with this function will be described in chapter 3.3

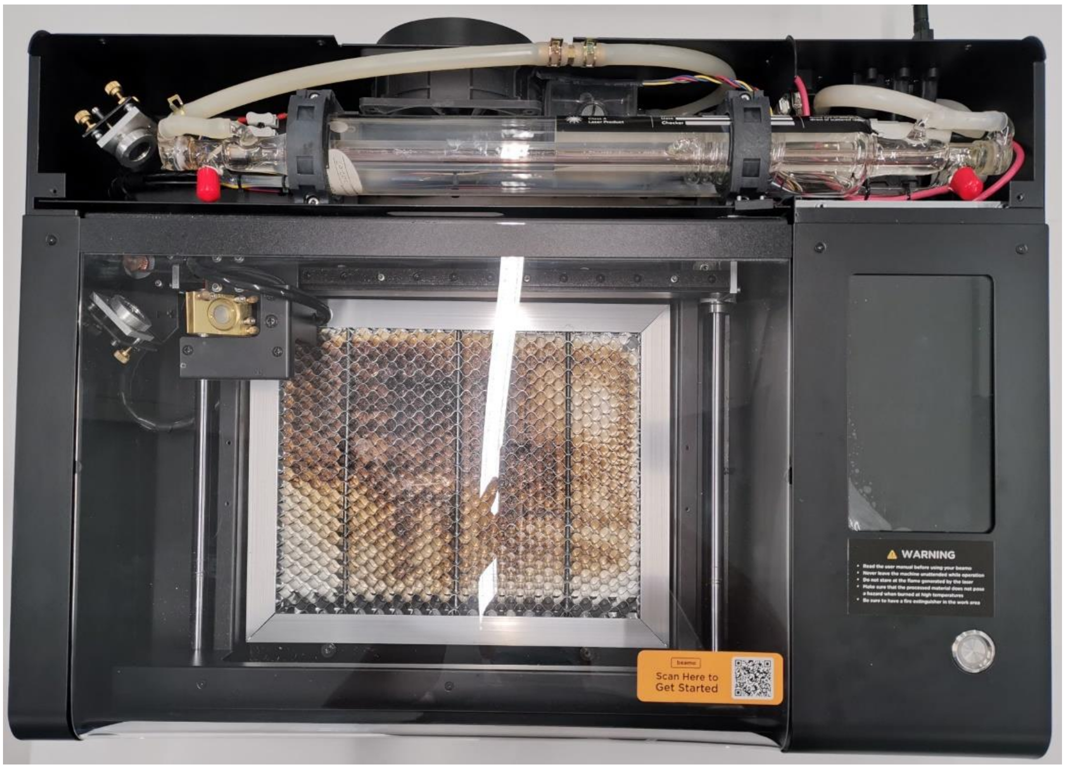

Figure 10. Top view of the device with laser tube cover removed

The laser tube is filled with the active medium CO_2 gas and the glas vile is surrounded with another tube for liquid cooling purposes. Because this gas laser is excited via a hich voltage DC pumping unit, anode and kathode of the pumping mechanism can be made out through the red insulation caps in Figure 10. The three mirrors which guide the unfocused laser beam to the focusing lens in the laser head can be seen on the upper left corner of the figure. Two of those mirrors are inside the operating chamber and are separately moved along the x- and y-axis with the help of stepper motors. The x-axis holds the third mirror together with the laser head and slides on a linear rail. The y-axis supports the x-axis and the second mirror together with the stepper motor for actuating the x-axis. It is guided via two metal rods and associated gliding parts.

3.1.2 Peripheral factors, workspace layout

This subchapter is dedicated to the setup process of the BEAMO itself and the surrounding precautions. The installation of Beam Studio, which is the main desktop User Interface (UI) is described in chapter 3.2.1. Figure 41 shows the laser device installed on one of the laboratory tables with the attached exhaust air hose leading to the overhead ventilation system. The figure was moved to Appendix 1 because of its size and to remain a good flow of reading. A fire blanket was installed directly next to the laser device for safety purposes. General safety issues are described in chapter 3.2.4. If the negative pressure of the main ventilation system is enough to suck out all of the fumes or if adjustments have to be made were examined next. Figure 11 shows the connection between two enclosures.

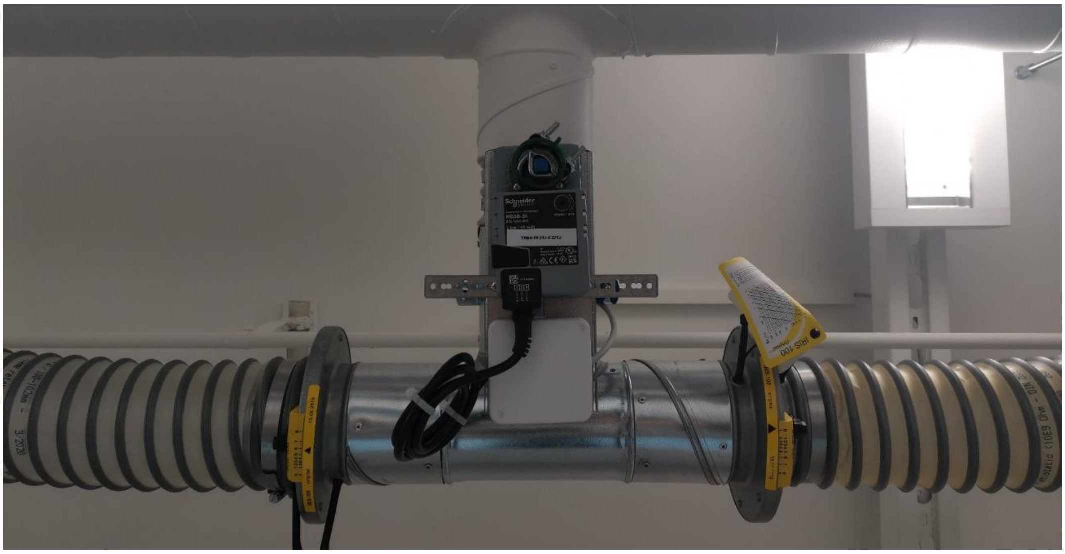

Figure 11. Connection of the air hoses to the main ventilation system

To increase the suction of the ventilation system all the unused air connections in the laboratory would be sealed off with the help of endcaps. Figure 11 shows how the two hoses are connected together and that the airflow can be cut off with the help of a electronically actuated flow regulator. To ensure a propper function of the vantilation system, this regulator has to stay in an open position.

3.1.3 Problems during installation and start up

The first problems came shortly after the first startup of the machine. The initial approach was to try out the designated phone application for controlling the decive and sending pictures for engraving purposes. The connection to the printer via the wireless network worked good but the phone app was very unreliable. The installed version was 1.0.5 which was last updated in the Google Play Store on the 28th of August 2020. After multiple crashes and only one successful engravement of a picture the attempt of using the laser device was adjourned. The next problems arose when the latest version of the desktop app *Beam Studio* was not able to connect to the BEAMO neighter via Lan nor a wireless connection. This problem was fixed by manually updating the firmware to the latest stable Version 3.2.6 with a thumbdrive. To have the latest firmware installed on the device out of the factory would have been pleasant.

One of the biggest issues during the startup phase after the installation of the air hose to the designated iris valve was that the smoke generated while cutting plywood sheets was pushed out into the Low Force Stereolithography (LFS) enclosure. The connection of the two air hoses and the irises can be seen in Figure 11. This caused an unwanted smell and would subsequently lead to harmful fumes entering the laboratory, which has to be prevented. The exhaust hose from the laser device is connected on the right side which is indicated by the change in color due to the fumes and particles from operation. As can be seen in Figure 9 the BEAMO has its own exhaust fan, which proved itself to be more powerful when it came to pushing the exhaust out into the air duct than the ventilation system being able to pull in the gases. This resulted in an unwanted positive pressure in the exhaust air system which led to the shortcut of the airstream into the LFS enclosure. This problem could be fixed by changing the fan speed of the BEAMO in increments of 10 % steps until, at 30 % fan speed, the main ventilation system generated enough suction to prevent a shortcut into the laboratory. In addition to the now fixed air flow, no fumes escaped the enclosure during the next tests even though the fan speed was seemingly low.

3.2 Testing

One objective of the practical work of this Bachelor thesis is the testing of different materials and how to get the wanted results with the BEAMO. Cutting and engraving different patterns and pictures on different materials is the main goal of this task. The following subchapters describe the process in detail and should help users to produce successful parts later right away. Although materials such as acrylic sheets are very homogen in their composition, wooden materials can lead to very differing results due to the natural grain and thus changes in hardness for example. Some of the figures and tables showing the results were moved to Appendix 1 and Appendix 2 respectively because of the large number and different expressions.

3.2.1 Beam Studio

Beam Studio is the main desktop UI when it comes to preparing files for cutting or engraving processes. The software is supplied by the manufacturer and the link can be found in Appendix 3. The used version was 1.4.6 and has proven to be quite stable. Figure 12 shows the layout of the user interface from which files can be imported, resized and prepared for operation. Further the connection with the laser device can be established from here and also debugging and live video of the current camera feed is supported from here.

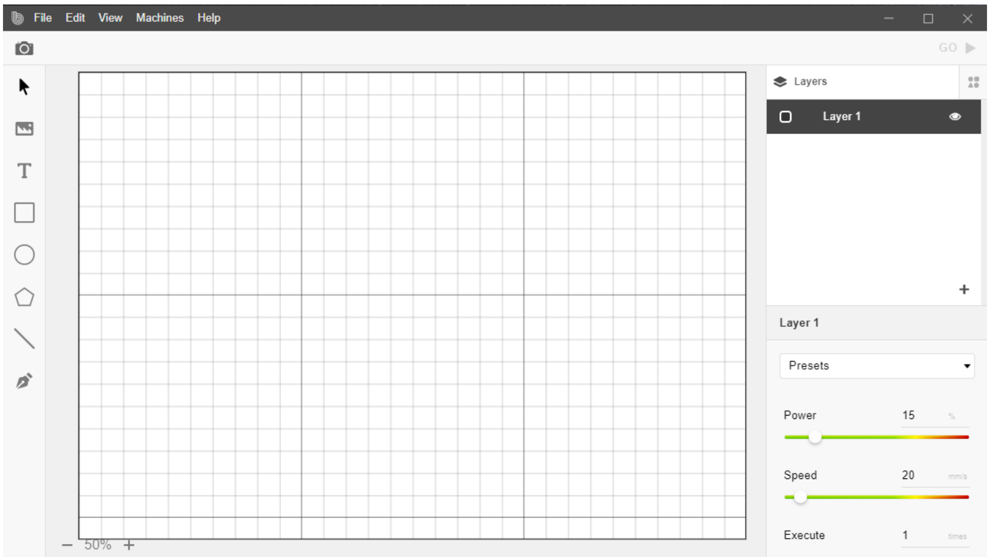

Figure 12. Main window of Beam Studio

A camera symbol can be seen in the upper left corner of the UI which when clicked opens the view finder function via the built-in camera. This camera sits under a cover directly on the laser head and has its own light. For the purpose of aligning the edges of the used material in the device to the digital project file, the camera stitches an overlay of the actual situation in the BEAMO together. This process can be seen in Figure 13.

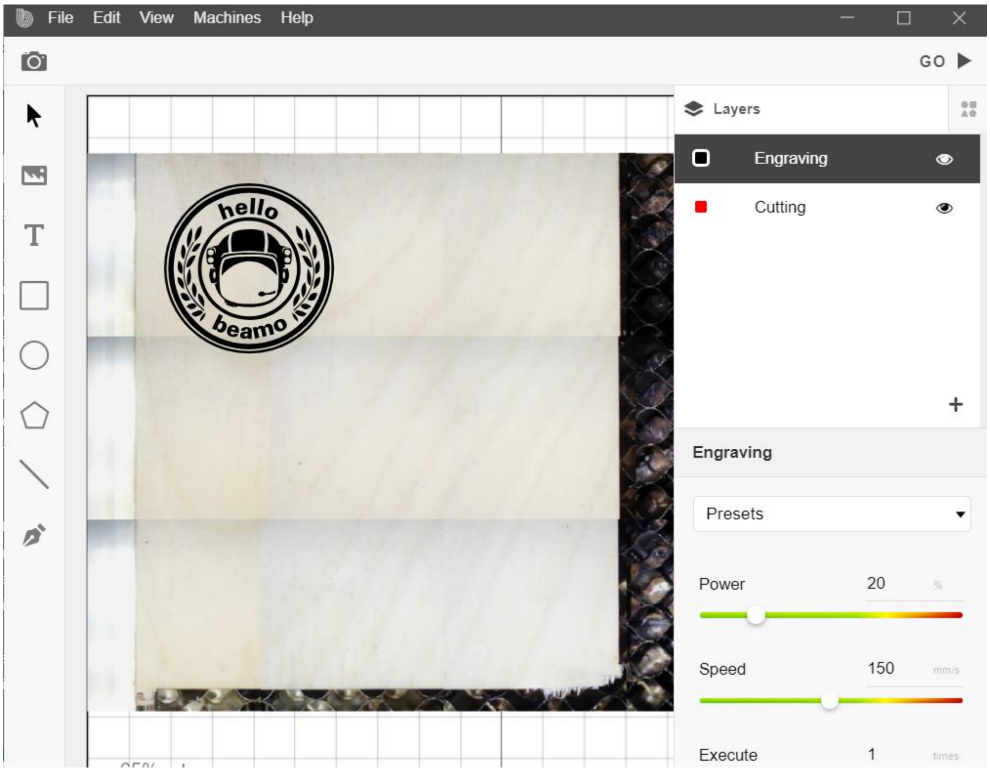

Figure 13. Camera overlay preview window of Beam Studio

Problems with the stitching functions are described in chapter 3.3. Figure 13 also shows the layer list which is used to implement multiple layers into the same operation. This function makes all the testing possible, as every tested square will have its own layer with dedicated settings. Multiple recommended premade setting configurations can be found within the *Presets* Drop-down menu. Below this menu, sliders for the power and speed increments can be seen and the number of executions can be set for every layer individually as well. The left menu bar allows to import pictures, write text and draw various kinds of shapes. All of those can be re-arranged and resized with the tools shown in Figure 42 which was moved to Appendix 1 due to its size.

3.2.2 Other Software

The Beam Studio software is able to handle a number of different file formats that can be imported through *File -> Open*. Supported filetypes are listed in Table 1. Every program which can export vector files with one of the supported filetypes can be used within Beam Studio. For engraving, pictures with mostly used filetypes can also be imported and prepared with the onboard tool set.

Table 1. Supported file types of Beam Studio

Filetype	**Description**
.svg	Vectorfile
.bvg	Savefile, Flux
.jpg	Bitmap, picture
.png	Bitmap, picture
.dxf	Vector, AutoCAD
.js	Text, Java Script
.beam	G-code, Flux
.ai	Logos, Adobe
.pdf	Documents

The real potential of the laser device in this specific laboratory environment lies in the production of parts created from computer aided design (CAD) drawings when it comes to cutting operations. There are multiple CAD programs which can export vector files in the *.dxf* format but only two examples are desceibed here as they were already used for other projects with the BEAMO. The first program is AutoDesk Inventor which is often used during the engineering education at Lapland UAS. Vectors can be exported from 2D drawings when the drawing borders are removed so that only the parts for the export are left. Vectors are exported as follows: *File -> Safe As -> Safe Copy As -> .dxf*. The created files can be imported into Beam Studio and further processed for operation. The dimensions of the parts are the same in Beam Studio although the user is asked to enter the unit of the file while importing. This demanded unit seems to be a multiplication factor and can be set to *1* if no changes in size are needed in this first step. The transfer from a simple sketch in Inventor into Beam Studio can take up to four steps, which needs some time to get used to.

Another versatile way to export vector files of drawings is by using AutoCAD from AutoDesk. The basic scale settings of AutoCAD can lead to the creation of vectors which do not fit within the work area boundaries. They are usually way too big and therefore not even visible in the UI of Beam Studio. Drawing templates are recommended to make the size of the vectors fit into the work area.

3.2.3 Testing strategy

This chapter describes how the testing of the chosen materials was planned and then executed. The two processes of cutting and engraving was investigated separately. Not every material was tested with both applications. For example with the polylactic acid (PLA) sheet only the engravement test was carried out. This is because it is not very useful to cut a premade sheet of AM filament with a laser as the shape could also have been created with the AM process. Further, the materials paper and fabric also only were tested with the engraving pattern. First the stragety for the cutting tests will be described here. In order to make this procedures more organized, a standardised test grid from the manufacturer was used. The basic idea is to test different laser head speeds over the gradients of light power output. Another variable of testing the capabilities of the device is the amount of passes over the same spot. Multiple passes usually result in deeper cuts but the limits of that will be described during the commenting of the individual samples. The resulting matrix of the cutting test can be seen in Figure 14.

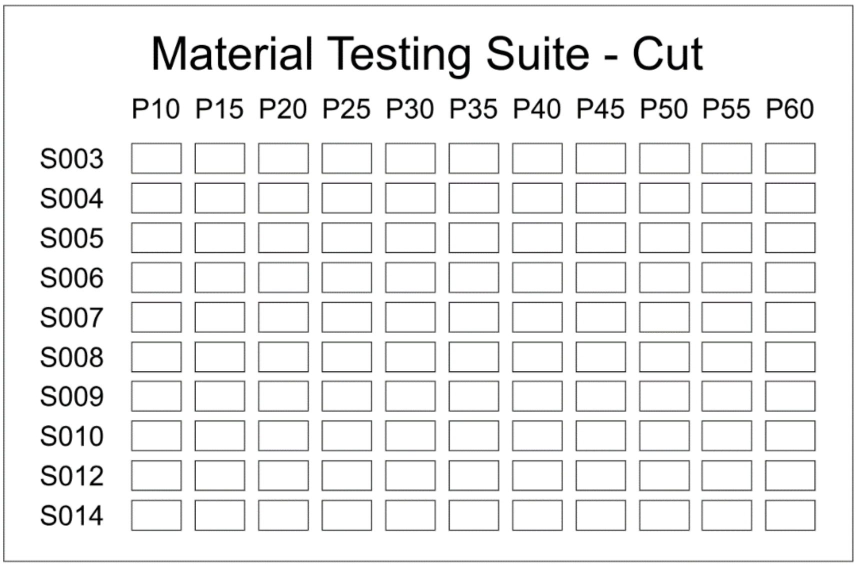

Figure 14. Test matrix for cutting

This matrix was aligned with the different materials and the focus point was set to the top surface with the help of the focus bar. The focus was lowered beneath the top surface with materials thicker than 5 mm. The focus test in Chapter 3.2.16 will give the explanation to this modification. The power during this test hits the upper limit of 60 %. The manufacturer recommends to stay below 70 % to prolong the lifespan of the laser tube. Later tests show the effects of 60 % power output and for most of the applications no higher power is needed and the laser tube should be preserved. The results of the cutting tests will be transferred into digital tables for commenting and a three color scheme will be applied to distinguish the different results in the separate areas. This method was chosen to keep the focus of the reader on the results and to maintain a standardised environment. Further the reader shall not be distracted by the real pictures and fot the sake of investigating the results, digital tables are well suited. The color scheme uses green, yellow and red to differentiate between clean holes, almost holes and no holes. Figure 15 shows how the color scheme was applied to the real test samples.

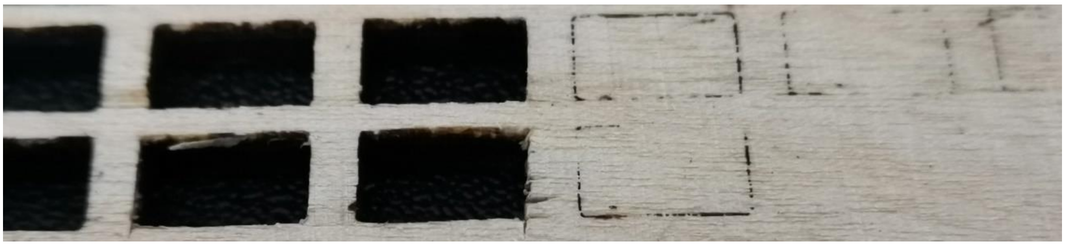

Figure 15. Test example for explaining color scheme

Figure 15 shows how the color scheme for the digitalisation of the real test samples was applied. It should be clear to see which settings resulted in holes ad which ones have not. The yellow color is used, when the outlines of the laser beam are visible on the bottom side of the sample but the cube is not entirely free yet. As some test samples consist of natural materials with changing densities, this color marks an edge case. Here it could simply be enough to swap out the sample and get a successful result. That is why those seemingly unsuccessful results were mentioned here as well. All test samples for cutting got a unique number engraved onto the top right corner of the part. Those numbers are found on the digital test sheets. As the real samples could potentially provide additional information to the user, they are stored near the device in the laboratory.

Next, the testing method for engraving the chosen materials is explained. The engraving patterns used are made by Flux and can be accessed the same way as the cutting pattern via the UI of Beam Studio. Engraving on even surfaces uses repeated head movement with constant laser feed over the area chosen. The engraving process works like a conventional plotter, where the picture or the pattern is sliced into fine lines on the x-axis. The laser head then moves from left to right in a set speed and steps down on the y-axis to form the two dimensional workpiece. The distance between the lines and the distance between the dots on the x-axis depends on the speed, power output and the set resolution of the BEAMO. Those values can be changed in the UI of Beam Studio. All the following tests have been carried out using the Medium resolution of 250 dots per inch (DPI). A later done DPI test shows the differences and effects of changing DPI values in chapter 3.2.15. The results of the engraving tests are not converted into digital tables as has been done with the cutting tests. This is because there are too many different results and the rating of the squares is very subjective. For this reason, real images are used to comment the results and point out the problems and challenges of the materials. Figure 16 shows the matrix for the engraving test.

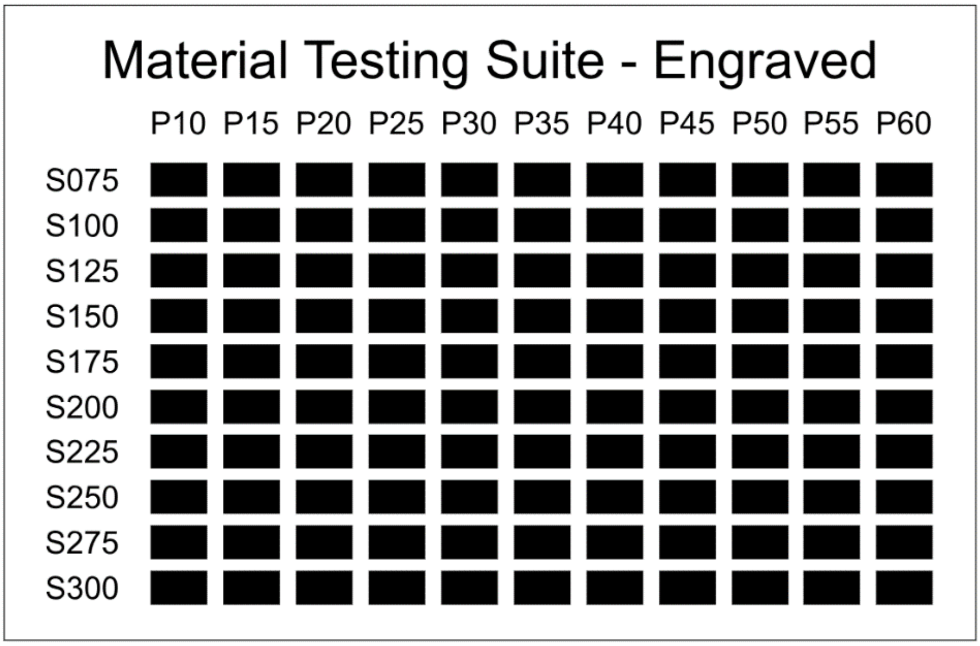

Figure 16. Test matrix for engraving

As the maximum speed of the laser head is limited to 300 mm/s and the maximum recommended power output is just under 70 %, this test grid covers almost the entire range of settings. Because the opinions on the results of the engraving tests are highly subjective, all samples are stored near the BEAMO in the laboratory like the cutting samples.

3.2.4 Safety issues

Most of the materials that are tested are known and their behaviour during the laser treatment is predictable. The same applies to the fumes and particles that are emitted caused by the laser impact. A possible source of danger comes from unknown or undefinable materials. Those materials are transparent and opaque plastics for example. While polymethylmethacrylate (PMMA) or acrylic glass is safe to use with the laser device, materials such as polycarbonate (PC) and polyvinylchloride (PVC) emit harmful gases such as dioxin or hydrochloric acid (HCl). Those gases will harm the lungs and can corrode machine parts. (Flux Europe 2021c, 47) That is why special attention has to be paid to those unknown materials. Especially with thicker wooden materials there exists a potential fire hazard. The embers produced could be further excited by the pressured air which is fed through the laser head. It is therefore really important to stay in close circumference of the machine during cutting operations.

3.2.5 Materials for testing

This chapter containes all the materials tested with and without the standardized test grids. Not all of the materials which should be workable with the BEAMO were tested during this phase of the work. Some additional materials such as cement slabs, stone and EVA foam will not be covered. The used materials are listed in Table 2.

Table 2. List of tested materials

Material	Thickness [mm]
Plywood	4, 6.5
Acrylic glas	3, 8
Leather	~2
Rubber	1.5
Corrugated cardboard	2, 4
Wood, natural	18
Paper, fabric	-
PLA	-
Glass	-
Anodized aluminium	-

Table 2 lists all the different materials that were tested. The thickness of the materials is provided when cutting operations have been done. The thickness of the paper and fabric tested is negligible and has therefore not been mentioned. A slab of natural wood got tested as well, to confirm potential limitations during cutting operations with plywood caused by the glue and changing densities.

3.2.6 Test 1: Plywood

The first material tested were sheets of birch plywood in two different thicknesses. The material was tested with the cutting and the engraving test grids and the results can be seen in the digitalized tables down below. As the plywood was precut out of large sheets and due to the natural deformation of those thin sheets, most of the resulting test sheets were warped slightly. This could be prevented by storing the sheets in a big pile with flat surfaces pressing them together and straighten them over time. During both tests, no problems were caused by this warping effects but some larger faces of parts during the project production experienced tight fits due to this issue. Table 3 marks the first test on the machine after the setup and its result are described below.

Table 3. Material test sheet; plywood, 4 mm, 1 pass, cut

Material Testing: Cut											
Material:		Plywood				*Thickness:*			4 mm		
Passes:		1				*DPI:*			250		
1.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

As the caption of Table 3 tells, the thinner plywood sheet was tested first. With 4 mm the sheet expierienced the most amount of warping but the effects on the test sheets are minor. As the digital version of the test implies only four settings led to successful holes being cut through the entire sheet. Slight burn marks can be seen on all of the top edges of the successful holes, due to the slow speed and high laser power output. As the table tells, this first test configuration was applied only once. The next test was repeated two times with the same material sheet and the results can be seen in Table 4.

Table 4. Material test sheet; plywood, 4 mm, 2 passes, cut

Material Testing: Cut											
Material:		Plywood				*Thickness:*			4 mm		
Passes:		2				*DPI:*			250		
1.2	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Table 4 shows the digitized results of the second test. Compared to the first operation, many more holes could be created by treating the sheet for a second pass. This implies that many of those now successful cuts were rather close on the first pass already. A slight anomalie can be made out near the bottom right corner of the test sheet. One could question why the areas with 40 % power and 12 mm/s speed resulted in the creation of a hole but not with higher power at the same speed. As wood is a natural material with varying densities, those test rigs cannot be taken serious obviously. It is furthermore possible that the glue bonding the layers of wood together plays an important role when it comes to cutting through those sheets. The next test configuration treated the same material three times and the digitized results can be seen in Table 5.

Table 5. Material test sheet; Plywood, 4 mm, 3 passes, cut

Material Testing: Cut											
Material:	Plywood				*Thickness:*			4 mm			
Passes:	3				*DPI:*			250			
1.3	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

In this next test, the seemingly logical arrangement of successful holes is visible. This test resulted in the most number of holes, although the increase of holes compared to the second test is not as significant as from the first to the second operation. The later described problem of a reflective carbon layer which forms within plywood sheet at multiple treatment passes could be the reason for this only slight increase the number of successfully cut holes. The next tests that were carried out treat the thicker plywood sheets. With those sheets being 6.5 mm thick they exceed the limits that the manufactorer gives the machine over 200 %. Flux claims the BEAMO is able to successfully cut through 3 mm of wood (Flux Europe 2021d).

The next table was moved into Appendix 2 as the number of tables require separation. Table 12 clearly shows the limits of the machine and contains the results of the third test with the 6.5 mm thick plywood sheets. The test grid got passed over the sheet three times, but other than some marks on a few of the areas on the backside, no holes were successful. The two prior digitized test sheets are not in this list because the results are not meaningful. The limits of the machine as far as the cutting of thick plywood sheets were reached during this test. The problems with the test sheets catching fire during the runs are described in chapter 3.3. Due to the unsuccessful treatment of the thicker 6.5 mm plywood sheets, this material is not suited for projects, as the holes that were successful had extensive burn marks on the cut edges. Another test revealed an interesting phenomenon of plywood. Some kind of charred carbon layer seems to build up during multiple passes wich hinderes further treatments. This will be discussedd in more detail in chapter 3.3.5.

The next text was carried out to see the capabilities of the BEAMO for engraving plywood sheets. As plywood sheets aim to have a rather uniform surface, the results presented here might not be useful for natural wooden surfaces which contain differing densities and grain structures. Changes in color and penetration depth might occur with natural wood. The results for engraving on plywood can be seen in Figure 17.

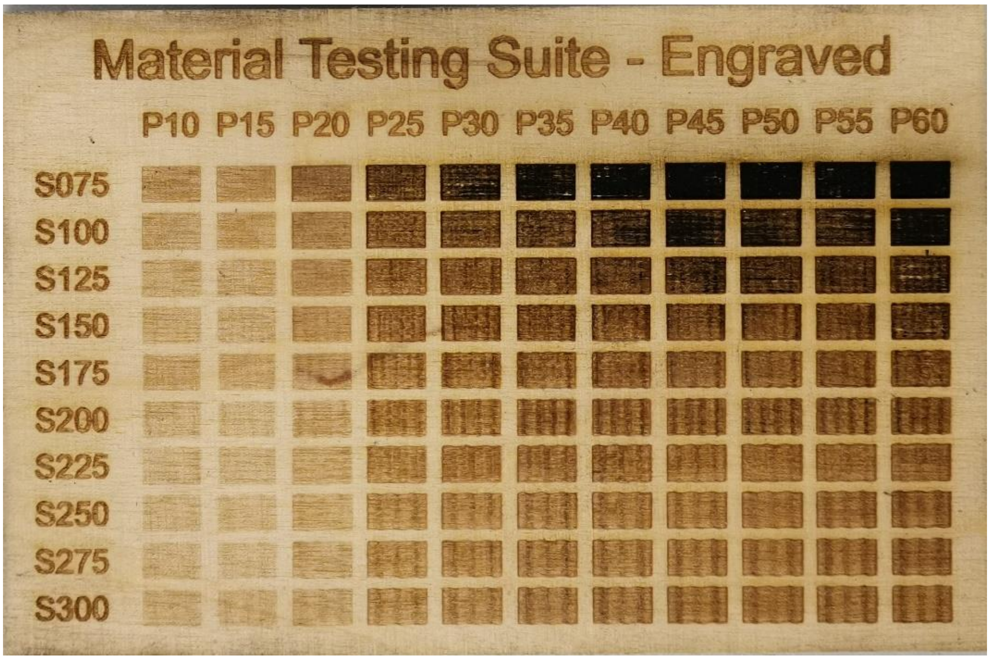

Figure 17. Material test sheet; plywood, engrave

In this first standardized engraving test, plywood was treated with the test grid provided by the manufacturer FLUX. The results in Figure 17 promise a wide variety of applications as every test square shows color changes varying from settle to rather dark charred surfaces. This is advantageous when picking the settings for engraving projects, as the color tone can be chosen out of a wide range of settings. As all standardized engraving tests are done with a resolution of 250 dpi and later separate testings (see chapter 3.2.15) show the significant changes in penetration depth when changing the resolution, the use cases for this machines seem plentiful. Upon closer inspection, faster speeds seem to lead to a wobbling motion on the x-axis. It is yet to be assessed if this issue is only present with plywood or other materials are also affected which would make this a material-independent and hence a machine problem. The interpretation of the resulting colors is quite subjective and is therefore not commented further. The real samples are stored near the machine in the laboratory at Lapland UAS and can be used as reference and in teaching in the future.

3.2.7 Test 2: Acrylic glass

The second material that was used to test the limits and capabilities of the BEAMO was polymethylmethacrylate (PMMA) also known as acrylic glass. PMMA is a polymer and synthetically produced so the density and inner structure can be assumed to be very homogenous. This would result in a good repeatability of the cuts with given settings. The material usually comes with two protective polymer films on each side. The upper film gets removed right before the tests, to ensure a clean test sample piece and not to disturb the result through a potentially resistive plastic film. As one of the layers has some kind of colouring, the bottom one is kept in place to make the alignment through the onboard camera easier, as the otherwise transparent material leads to visibility issues. The manufacturer only claims that the sheets with a thickness of 3 mm could be cut successfully but the later tests almost expands this range three times. Additionally, two different thicknesses were tested and Table 6 shows the digitalized results of the first PMMA test at 3 mm thickness.

Table 6. Material test sheet; acrylic glass, 3 mm, 1 pass, cut

Material Testing: Cut											
Material:	Acrylic glass				*Thickness:*			3 mm			
Passes:	1				*DPI: 250*			250			
3.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

The first test with the thin PMMA sheet resulted in 31 clean holes and is shown in Table 6. This already makes the material quite workable and promises good results. The holes follow the same step pattern as with cutting plywood, where the increase in power and derease of laser head speed similarly result in successful cuts. The last increasing steps of the power increments do not seem to have any further influence, which leads to multiple interpretations. Either, the reduction of the laser power does not really follow the said increments of 5 % or the material develops a kind or resistance to the higher output powers. Changes in density could also be possible in theory but the PMMA sheets seem to have quite a uniform density distribution. The test grid was applied a second time and the result can be seen in Table 7.

Table 7. Material test sheet; acrylic glass, 3 mm, 2 passes, cut

Material Testing: Cut											
Material:	Acrylic glass				*Thickness:*			3 mm			
Passes:	2				*DPI: 250*			250			
3.2	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

79 holes and one test square almost successfully cut is the result of the second iteration with the thin PMMA sheet which is visualized in Table 7. As the first test was already very successful, this is only a bonus but it shows the capabilities of the machine quite well. Edge quality seems to be linked to the speed setting. At slower speeds, the surface stays melted for longer and therefore has time to even out, which leaves an almost polished finish. This test shows that the operation time of projects which do not require a perfect surface quality of the cutting edges can be done much quicker than with the recommended settings.

The next two tests deal with the thicker PMMA sheets with a thickness of 8 mm. The two digitised tables of results have been moved to Appendix 2, as the overall result is not the best and due to the space some selected results are only presented here in written form. As can be seen after the first process in Table 13, there were no continuous holes. As this material is more than twice as thick as specified by the manufacturer, this result was not expected, but was not particularly surprising either. What was noticeable, however, were the non-vertical cut edges, visible from the side. These seem to be more pronounced at higher cutting speeds than in the lower speed range. This will be discussed again later. The second test resulted in at least 14 successful holes, although one spot was almost successful and due to the crooked edges most of the cubes had to be pushed out with force. This already indicates a limited range of application if straight edges are required in this rigid material. The resulting pattern can be found in its digitised form in Table 14. The material was tested a third time due to the moderately successful number of holes, applying the same pattern three times. The result can be seen in Table 8.

Table 8. Material test sheet; acrylic glass, 8 mm, 3 passes, cut

Material Testing: Cut											
Material:	Acrylic glass				*Thickness:*			8 mm			
Passes:	3				*DPI:*			250			
4.3	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Compared to previous tests, the number of successful holes has not increased significantly by 11. 25 successful holes have the same tilted vertical edge as in the two tests before. It can be assumed that either the light output of the laser is simply not sufficient, or that some kind of hardening of the material is taking place, which makes further processing more difficult. Since it is still possible to cut through the material and the crooked edges do not allow any interlocking applications anyways, it is left with the three tests.

The next test was conducted to show the BEAMOs capability of engraving PMMA material. The upper layer of protective film was removed to ensure propper results and to eliminate disturbances by the films own properties. Figure 18 shows the resulting pattern on the material.

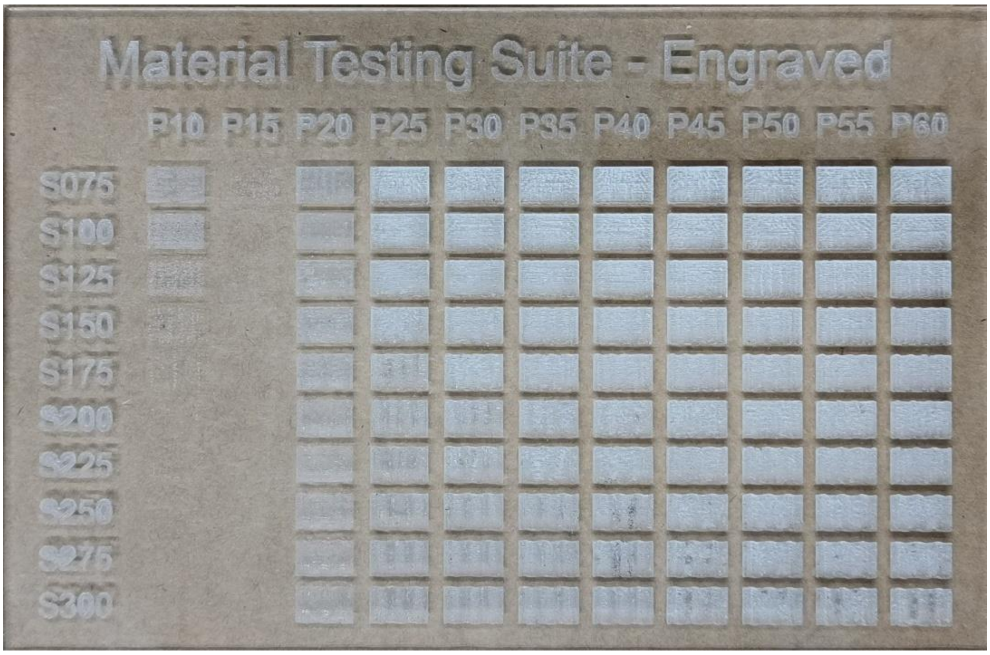

Figure 18. Material test sheet; acrylic glass, engrave

As it is visible in Figure 18 the sheet was engraved successfully and various applications seem to be possible with this. The gradients show an interesting pattern because the step from 15 % power to 20 % gave an interesting result. The two columns suddenly change and the usual steady course does not occur. This leads to the assumption that the gradation of the light output does not correspond to the indicated 5 % steps. If this phenomenon repeats with other materials, is yet to be found out. The texture is not commented further, as varying expectations make an objective assessment tricky.

3.2.8 Test 3: Leather

The next material to be assessed is leather. A roughly 2 mm thick piece of leather was prepared for the test by using some painters tape for fixing the rough and warped material to the workarea. This material was tested with both premade test grids and it has to be noted here that the leather used is a genuine natural material. This means that according to the manufacturer, harmful fumes can be emitted during the operation containing nitrogen oxides and aromatic compounds. (Flux Europe 2021c, 44) The aromatic part of the fumes is characterised by a very strong odour similar to burned hair. The results of the cutting test can be seen in Table 9.

Table 9. Material test sheet; leather, ~2 mm, 1 pass, cut

Material Testing: Cut											
Material:	Leather				*Thickness:*			2 mm			
Passes:	1				*DPI:*			250			
5.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

This table shows the rather successful cutting operations after the test. The test piece was kept inside of the ventilated chamber for two minutes to get rid of the smell. And again this material shows a deviation from the usual pattern after the cutting process in that there is no gradual arrangement of the holes but an abrupt difference between 30 and 35 % power. This may be due to poor power control or a change in density within the material. A black layer of burned material got stuck around the right part of the test grid and around the parts of text. Due to the airflow inside of the chamber, most of the sheet was covered in this residue which got removed with a pressured air hose. The odour remains after the cleaning, further washing can help to minimise this issue. Due to this material being made out of natural fibres, some strands of fibres have not been cut through all the way which is attributable to a change in density. The next test was done to examine the capability of the machine for engraving this rather rough material. The result of the engraving test grid can be seen in Figure 19.

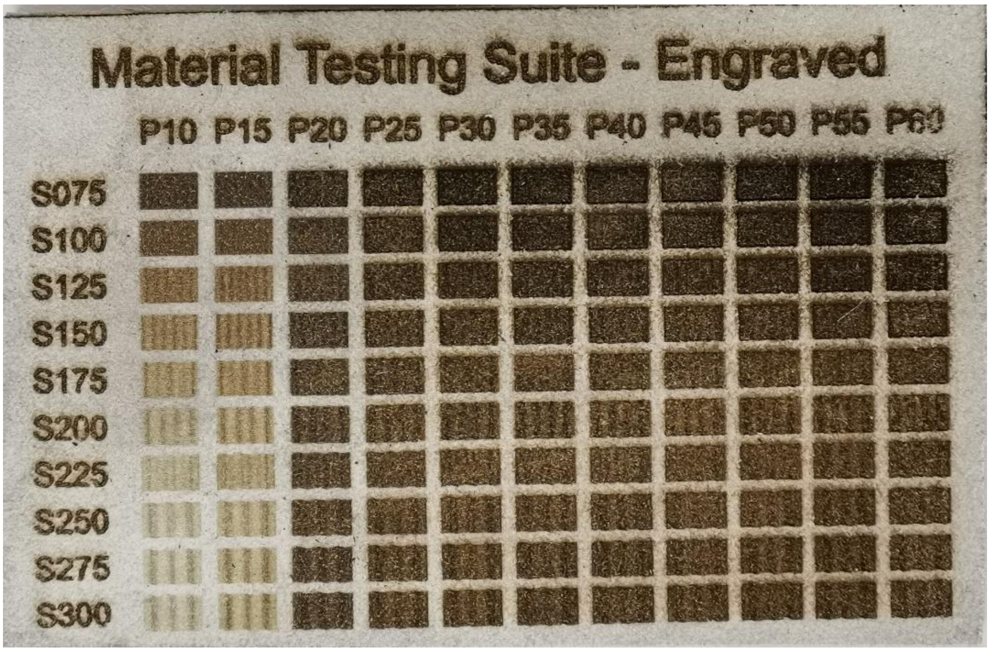

Figure 19. Material test sheet; leather, engrave

Compared to other materials tested, leather showed less color change overall in the higher affected areas near the top right corner as for example wood. Figure 19 shows, that with the test in leather, the step from 15 to 20 % in power increase also seems to mark a barrier for the laser beam regarding the color change of the material. The assumption, that there is a faulty power controlling present gets increasingly settle with this additional material behaving in a similar way. Further, a wave pattern can be located near the bottom left corner of the test grid, which also indicates problems with beam regulation or a problem with the axis movements leading to changes in operation speeds and therefore changes in the exposure time. Those wave patterns are also visible within the test squares of the engraved plywood shown in Figure 17.

3.2.9 Test 4: Rubber

Rubber was one of the materials that only got tested with the standardized engraving test grid. Initial testing without the cutting grid revealed the build-up of some sort of protective oxide layer during the cutting process and the clearly noticeable scent. As the manufacturer also does not provide premade settings for the cutting of rubber, this test was set aside. The results of the engraving test on rubber can be seen in Figure 20.

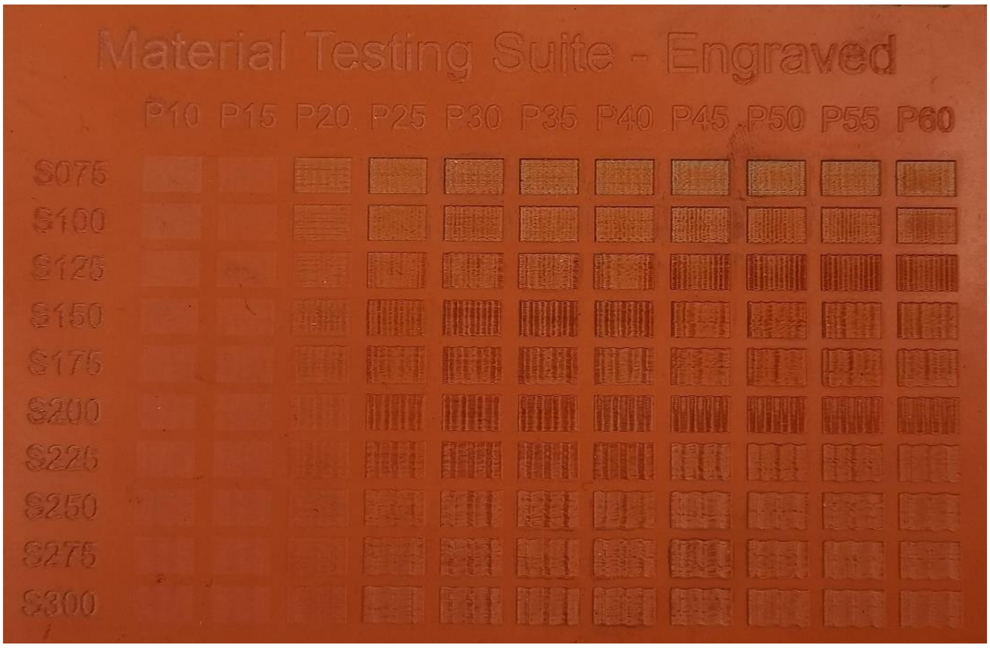

Figure 20. Material test sheet; rubber, engrave

Figure 20 shows that even the weakest settings leave markings on the surface, which indicates a good workability. As there are verious kinds of rubbers, the safety factor when it comes to hazardous fumes shall not be neglected. A slight odor could be sensed after the operation but the built-in housing fan removed most of the exhaust gases. Due to the resolution set to 250 dpi in all of the engraving tests and the fire retardant properties of the type of rubber used, single lines which were not exposed to the laser beam remained standing and left a rough surface on some of the embossed faces. Figure 21 shows a detailed section of the bottom right corner on the test sheet where the uneven surface and some distortions along the x-axis are visible.

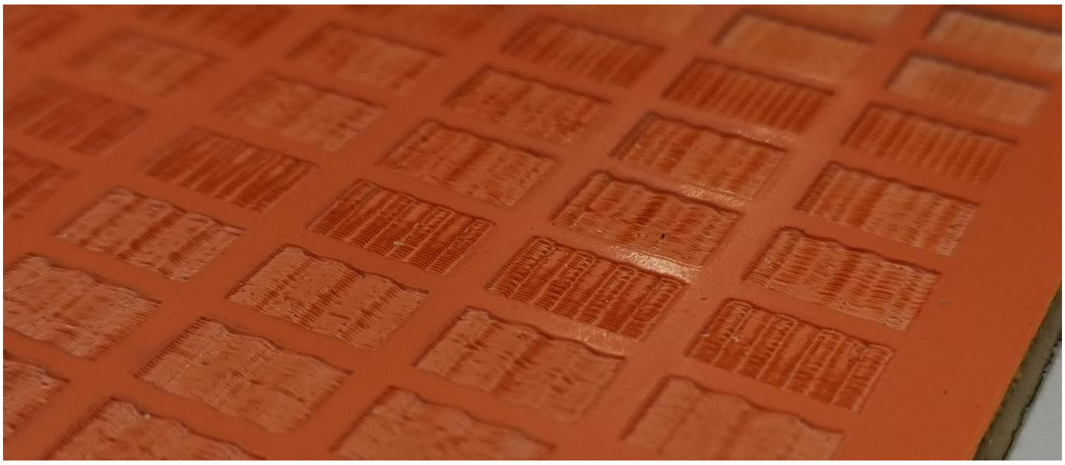

Figure 21. Detail of engraved rubber test sheet

The uneven surfaces at the bottom of the embossed faces and the curvy appearance of the edges on the x-axis are cearly visible in Figure 21. As those lines appear to be formed in other materials during engraving as well, the topic will be discussed in chapter 3.3.3 in more detail. What is noticeable is, that the rubber does not change color through the treatment. This means fast processing times for basically the same results on the one hand but no clear visible markings compared to plywood when the surfaces are kept clean. Staining the engraved surfaces might work well due to the remaining fine lines holding colorings.

3.2.10 Test 5: Corrugated cardboard

Corrugated cardboard sheets were tested next with both test grids. Two different sheets were chosen but they only differ in overall thickness to one another measuring in at four mm and two mm. They both consist of three layers, one top and bottom, and one corrugated layer in between This is type of cardboard is called single wall board. The sheet between the surfaces which also have the names liners or linerboard, is called flute. There are different types of cardboard with differing numbers of walls/liners and flutes with varying shapes as well. (Hanchett Paper Company 2021) Giving this basic layouts of the two used sheets, it can be estimated that the results from the cutting test will be quite similar as basically the same amount of material has to be passed, only with different gap sizes. The first test results can be seen within Table 10.

Table 10. Material test sheet; cardboard, 4 mm, 1 pass, cut

Material Testing: Cut											
Material:		Cardboard				*Thickness:*			4 mm		
Passes:		1				*DPI:*			250		
6.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

The first result of the cardboard cutting operation again shows the rapid change between the 15 % and 20 % column. As those two test sheets basically only consist of three layers of glued paper and therefore do not pose a very great obstacle to the laser beam, the assumption of some sort of power regulation problem solidifies gradually. All the holes are clean when inspected from the top but the ones in the upper right corner got the bottom edge completely burned away due to the high power settings and the slow cutting speed. The airstream which should help the laser beam with cutting could have excited the removal of the paper layer as well. The second result table has been moved to Appendix 2 as it shows quite similar results apart from two spots, where no holes were successful. The results can be found in Table 15.

Next the thin sheet was used to apply the engraving test grid. As the material is so thin and fragile, the results were awaited with great interest. The resulting patterns are provided in Figure 22.

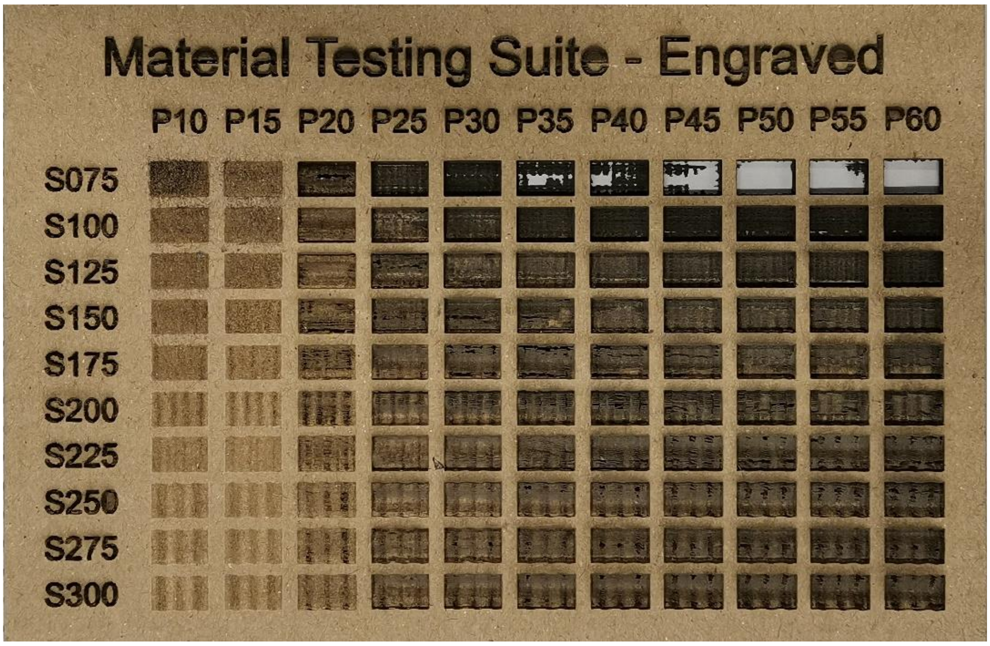

Figure 22. Material test sheet; cardboard, engrave

The results of the cardboard engraving test provide some interesting insights into what the BEAMO is capable of. Figure 22 shows the very differing results caused by the test grid settings. As with some materials prior, the two most left columns have different results than the rest of the squares and distinguish themselfs greatly from the third column. All squares in those two columns are the only ones that did not penetrate through the first layer of paper at all. Only the different gradings in color are what separate them from each other. From the third column on, every square penetrates through the first layer of paper at least with the top right ones cutting all the way through the third layer as well. Here again the wavy course in the squares with faster speeds can be seen. Another finding of this test is, that it takes only very little power to successfully engrave paper, which can also be achieved with the highest speed settings. This could be used when creating custom paper or cardboard shapes with the addditional engraving of text or symbols on top. Apart from the burned bottom edges, this test is considered a success and provides important details regarding the capabilities of the BEAMO.

3.2.11 Test 6: Wood, natural

This next test will be carried out to show how natural wood reacts to the laser treatment and how the results can differ compared to those from plywood and why. For this purpose, a 18 mm thick piece of natural fur wood slab was cut to size with a jigsaw. As this test is meant to compare the cutting behaviour of the two materials only the cutting test grid were applied to it. The grid was repeated three times right away as the thickness is way beyond the recommended dimensions and capability of the machine according to the manufacturer. For this, the slab got layed onto the metal mesh and the focus mechanism had to be pushed as high as it got. After the second pass, the focus point got lowered due to the thickness of the part. The focus point could only be lowered by approx. 4 mm due to the height limitations on the laser head. Figure 35 shows how this step hit one dimensional barrier of the laser device. Table 11 shows the results of the cutting test.

Table 11. Material test sheet; natural wood, 18 mm, 3 passes, cut

Material Testing: Cut											
Material:		Wood, natural				*Thickness:*			18 mm		
Passes:		3				*DPI:*			250		
8.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Although no holes were successful, multiple things can be assumed based on the results visualised in Table 11. Firstly, the exact same test resulted in an almost identical pattern on the back side with the 6.5 mm thick plywood sheet. Both tests with three repetitions each revealed no successful holes but the natural wood slab has almost three times the thickness. Differences in density between birch wood (510-770 kg/m³) and fir wood (530 kg/m³) can be neglected (Engineering ToolBox 2004). It can therefore be assumed, that either the layer configuration of the plywood and/or the additional laser resistance from the glue itself between the plywood layers increase the overall laser resistance in such a way that the natural wood is much easier to work with. This additional resistance could arise because the reflectivity or the density of the glue is higher and/or the insulating carbon layer is more prominent which would also lead to a decreased workability.

3.2.12 Test 7: Fabric

This test was created to show the low end capabilities of the BEAMO. The low end describes the minimal power settings of the machine, which turned out to be not very sensitive based on prior tests. The significant jump between the 15 % and the 20 % power rating is of particular interest here. The material that was chosen to examine those goals is a thin industrial fabric. It can be found in the form of cleaning cloths in various laboratories throughout the campus. Here, only the engraving test grid was applied due to the weak material which is assumed not to withstand any of the cutting settings and therefore give no useful information about this very property. The result of the engraving test was moved to Appendix 1 as it does not contribute as much useful information as other test results in this testing phase. Figure 43 shows the results and the clear border between the two critical power settings can be seen again. All of the test squares with 25 % power or higher got removed completely and the bottom section starting at a speed of 150 mm/s shows uneven edges in the horizontal direction due to the x-axis wobble again. The overall results of the remaining 20 test squares in the 10 % and 15 % power columns show a good range of color. This material is therefore usable for engraving text and symbols with very light settings and with the highest speeds the BEAMO can achieve.

3.2.13 Test 8: PLA

Another material that was tested is PLA which is widely used in AM processes. It seems not very useful to cut parts from the AM process as the designs are often not limited to two dimensions and can be designed and produced in the desired way through the AM process in the first place. It can be useful, however, to engrave details onto flat surfaces, as the implementation of text or symbols into printed parts can be difficult to achieve, especially with small sizes. For this reason a flat sheet of PLA was printed and then tested with the engraving test grid. The result of this test can be seen in Figure 23.

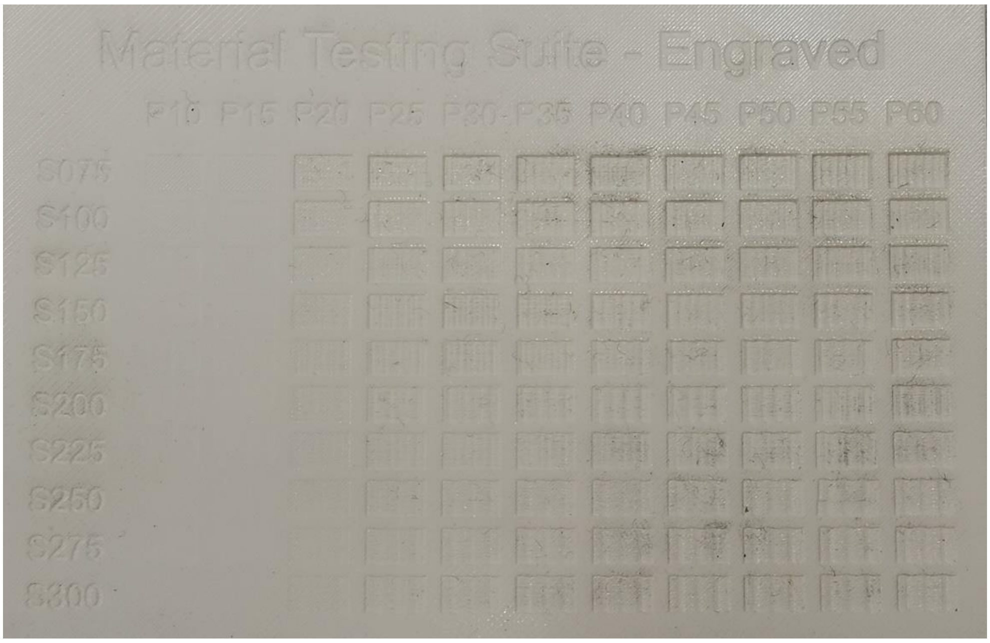

Figure 23. Material test sheet; PLA, engrave

The engraving test on PLA was successful and is provided in Figure 23. Every square got affected by the treatment and the individual results reach from some slight visual appearances near the bottom left corner to major indentations around the top right corner. The quality of the results are not commented for the reason of the quality being too subjective to be rated here. It is however important to mention that the white material has not changed color caused by the laser treatment and is therefore comparable to the engraving results of PMMA which are provided in Figure 18. The wobble on the x-axis is visible in the lower section of squares again. Further, the jump in texture from the 15 % to the 20 % power increment column is noticable with this material as well.

3.2.14 Additional Materials

More materials got tested, all of which got engraved. Those materials get mentoined separately because the standardized cutting and engraving grid has not been applied due to either the lack of space on the piece or the inconvenient way the operation was carried out. The first material than got engraved with a custom pattern was a glass mirror. Text was engraved onto the surface with the settings premade by the manufactorer. The result of the operation can be seen in Figure 24.

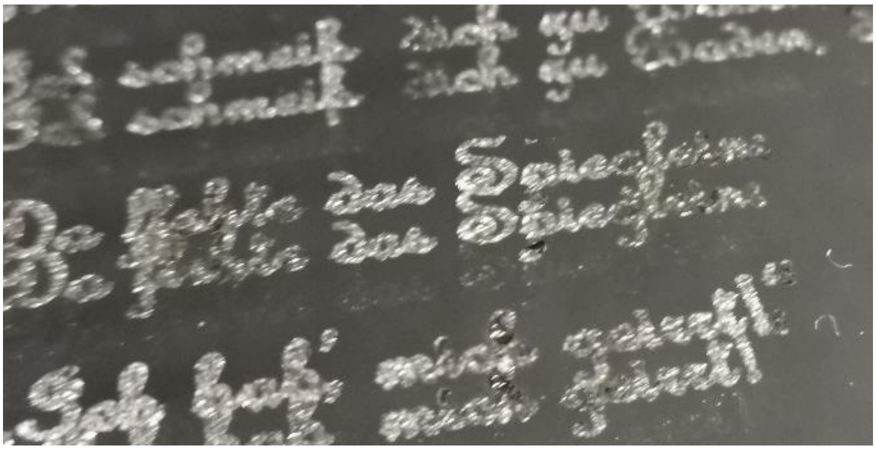

Figure 24. Material test; glass, engrave

Figure 24 shows the engraved text on the mirror. Due to the mirroring effect, the text appears twice and is rather hard to read. This would not happen with a ordinary piece of glass of course, but the size and the font of the text add up to the inconvinient reading experience. As the tested mirror was small enough to fit into the operation chamber of BEAMO, the testing procedure was straight forward. However, due to the limited space in the chamber it is not possible to engrave larger pieces and the number of useable products seems rather limited. Some of the letters were not immediately visible, but could be made to appear by pressing firmly on them. This probably has to do with the fact that the glass shatters into very small pieces in the treated area, which does not seem to work reliably due to changing densities and strengths. This problem could be improved by adjusting the operating settings.

The next material that was tested without the test grids and with no particular testing strategy was anodized aluminum. The housing of an ANKER PowerCore battery pack was chosen, as it acts as a sacrificial test piece for the next planned aluminum test, where the backside of a laptop case will be engraved. The operation was conducted with the suggested power rating but with double the speed as the resolution was cranked all the way up to 1000 dpi. The differences that occur when changing the resolution are examined and discussed in chapter 3.2.15. One of the two results can be seen in Figure 25.

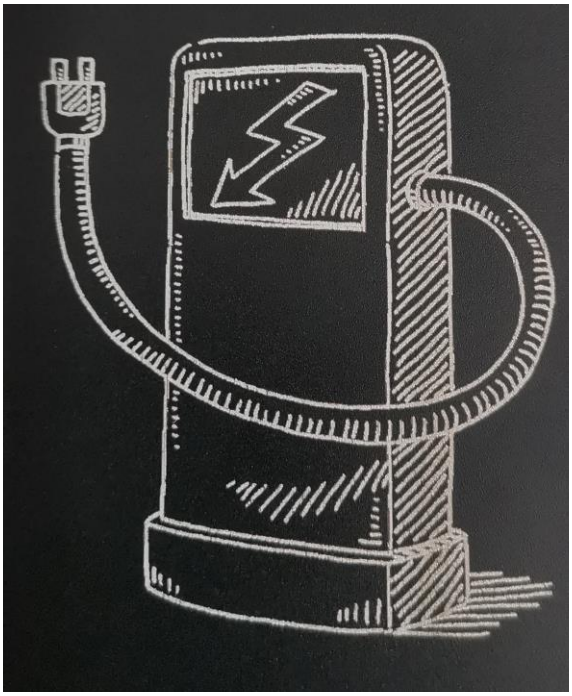

Figure 25. Material test; anodized aluminum, engrave

Figure 25 shows the resulting picture which was engraved onto the aluminium surface of a ANKER powerbank. Since there are no particularly small details, the resolution was set to 250 dpi. The lines are the result of the paint being removed by the laser which reveales the bare metal underneath. Due to the lasers inability to penetrate aluminuim and the high reflection of the beam, the insides of the case were safe and the surface stayed cool to the touch. The second *.png*-picture that was engraved on the backside of the same powerbank is provided in Appendix 1 due to its size. Figure 44 shows a complex wiring diagram of an unknown circuit and convinces with a very high level of detail. For this operation, the resolution was switched to 1000 dpi and the speed of the provided settings was increased to reduce overtreatment due to the very small step width with this high resolution setting. Due to the large area covered, the operation took about 50 minutes to finish and the powerbank stayed cool to the touch the entire time. Figure 45 is also provided in Appendix 1 and shows a detailed view of the engraved circuit. It can be seen that some lines appear stronger than others. This could be the result of the grading and sharpening process during the preparation of the source picture in Beam Studio. The smallest sized text samples are not readable anymore, which shows the limit of the BEAMO, at least on this not 100 % smooth surface.

3.2.15 DPI test

This next test does not focus on the capabilities of the BEAMO regarding to one specific material but rather examines the effects of one of the more basic settings which affect engraving operations. As the title of this chapter indicates, the next tests deal with the influence of the resolution setting. There are four different dpi settings available with the BEAMO which can be set via Beam Studio. The setting can be found under *Edit -> Document Settings* in the main window, which leads to a small settings window. In addition to the resolution, the work area of all the available machines can be set here. Under those two options, several add-ons to the machine such as the rotary tool, autofocus mechanism and the additional diode laser can be activated. As the used machine has none of those features at the time of testing they will not be discussed further. The four dpi settings range from *Low* (100 dpi) and *Medium* (250 dpi) to *High* (500 dpi) and *Ultra High* (1000 dpi). The testing was carried out using the slightly smaller classic engraving test grid provided by the manufactorer and was applied to PMMA sheets. This material was chosen, because the effects and depth of penetration can be observed from the side due to the transparent matter. The scope of the next tests is to examine the resulting engravment patterns caused by the decreasing step distances on the y-axis in order to reach higher resolutions. The same pattern will be applied to four different PMMA sheets to make the results comparable. Figure 26 shows the classic engraving test sheet from above at 100 dpi.

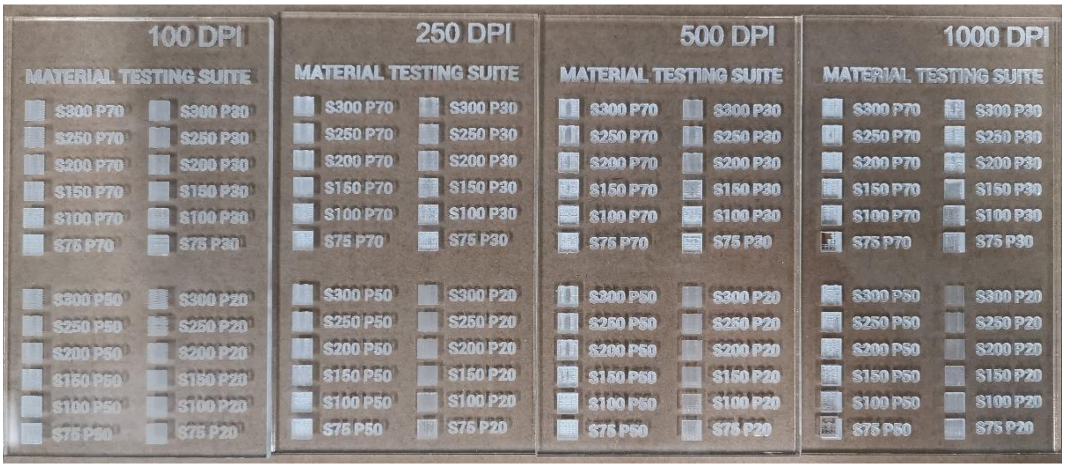

Figure 26. DPI testing; example view on test grids

The basic arrangement and settings for each test square is visible here and the the following detailed visualisations will focus on the bottom left corner of all four sheets. Figure 27 shows the first DPI test with the minimum resolution of 100 DPI.

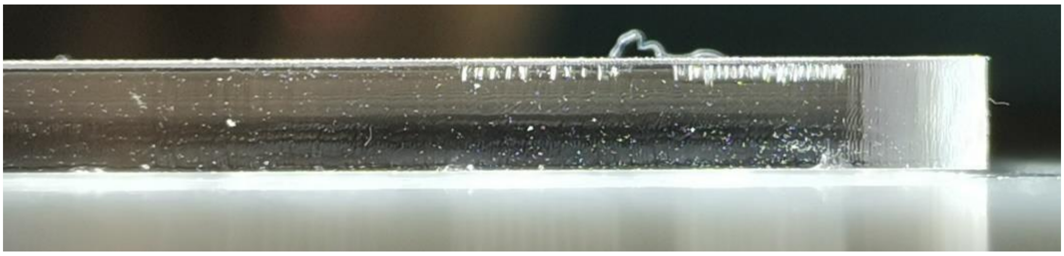

Figure 27. DPI test, 100 DPI

The result of the first test took 3 minutes and 4 seconds to complete and is visualized in Figure 27. The operation time is important in this test as it gradually increases with higher resolution settings. It can be seen here, that the laser beam hardly penetrates the surface, as the sheet is 3 mm thick for comparison. Further, the rather rough y-axis steps are clearly visible. This also affects the look of text as is shown in a collage of all four test sheets which concentrates on the heading text in Figure 47 provided in Appendix 1. Here, the line width of the different resolutions is really visible. In addition, the BEAMO seems to have a problem with straight lines at the middle two resolutions. This issue is most visible in the bottom right letter ”E”. Interestingly, at the highest setting with 1000 DPI, this issue seems to be no longer the case and straight lines are engraved correctly. The next test was carried out using a resolution of 250 DPI. The resulting cross section can be seen in Figure 28.

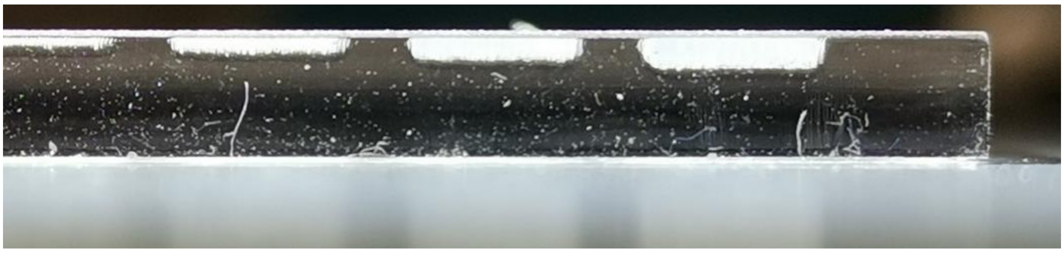

Figure 28. DPI test, 250 DPI

The detailed result of the classic engravement test grid with a resolution of 250 DPI can be seen in Figure 28. No single lines can be made out in comparison to the last test anymore. While only two squares are visible from the side with the lowest resolution, here four squares got engraved deep enough to see them. Due to the laser beams being closer together but with the same speed and power settings, the resulting faces are embossed down into the PMMA deeper. Although the resolution is more than double the value, the operation time only increased by about one minute and 35 seconds to 4 minutes and 41 seconds. Depending on the desired result, this setting can therefore be convincing compared to the previous one, as the processing time does not increase proportionally. How much deeper the embossment of the face becomes, cannot be commented on yet. This connection can be better interpreted with the help of the next result, shown in Figure 29.

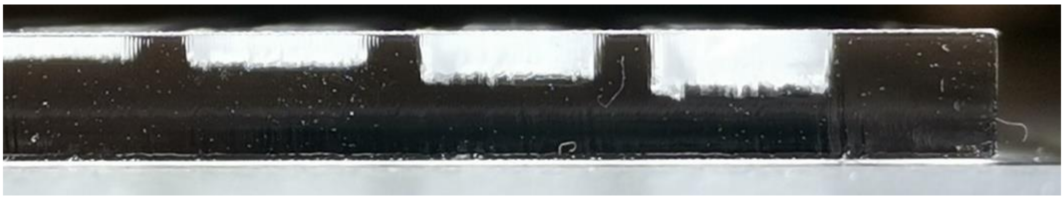

Figure 29. DPI test, 500 DPI

The test grid was applied on a third sheet of 3 mm thick PMMA and the results can be seen in Figure 29. This operation, with double the resolution took about 1.8 times longer than the previous one. After eight minutes and 15 seconds, the faces were embossed about twice as deep into the material when compared with the previous side view. The bottom of the created impressions starts to become a little rougher here, which is noticable in the right most ditch. Based on the image material above, it can be said that it was possible to penetrate approximately 1.5 mm deep into the material. The edges of the indentations are still comparatively vertical, which seems to change drastically in the last test with the highest resolution. The results of this last application are visible in Figure 30.

Figure 30. DPI test, 1000 DPI

The final interpretations based on the effects of resolution are developed in this test and are visualized in Figure 30. This test took more than twice as long as the last one at double resolution. While the most left impression looks almost similar as the most right in the previous test, the other edges expierienced quite a bit of distortion. As every spot of all of the test faces got treated only once, the interpretation of those crooked edges seems a little difficult and exceptional. A possible explaination could be some sort of optical effect which bends the laser beam alongside the y-axis. As this effect is only visible in the bottom half of the edges, the previous resolutions can not be taken to confirm this assumption. The problem of warped edges was already described during the interpretation of the results of the thicker PMMA sheet during cutting.

3.2.16 Focus test

As discussed in section 2.2.5, laser devices work with optics to focus the light beam into powerful tools. Due to the nature of those optics, only focus points can be created which limits a fixed lens installation like the BEAMO has, in its standard configuration in theory. Figure 5 was used to describe the shape of the generated laser beams and how the angle of attack could affect the cutting capabilities. To link this theoretical aknowledgements to real world findings, this next test is designed to make the beam visible as it gradually gets unfocussed and therefore should lose cutting power and lead to non vertical cutting edges. A simpe test rig was built for this purpose. To max out the range of treatment, the metal grid mesh got removed out of the operation chamber. The material of choice is plywood as it easily changes color and is handy to work with. The result on the test rig is shown in Figure 31.

Figure 31. Focus test

For the test, a simple text was projected in a 45° angle to the edges and four different lines for cutting were placed on the test sheet. This test specimen can be observed in the laboratory near the BEAMO. Due to the limits of the machine being approached, the focus point laid slightly below the top edge of the test piece. As expected the beams patterns gradually widened towards the bottom edge and the power being used range from 70 % and 60 % to 30 % while keeping a constant speed of 3 mm/s. A fourth vertical line was cut using 70 % of power and a speed of 10 mm/s to examine the effect of quicker cuts. The resulting cone is slightly less wide compared to the most left one, which is caused by the shorter exposure time. Although the focus point was more than 4 cm above the bottom of the chamber, the cardboard piece which holds the plywood in place was removed by the laser beam which shows the power of the machine and/or the workability of cardboard in that sense. The results of this test show that the focuspoint is quite stretched out in reality, giving the operator the ability to cut materials with several milimeters in thickness with only minor changes of the cutting edge angle. Further, the beam seems to bend outwards after the first centimeter cutted. It then expands in a very narrow cone and gets about 4 mm wide by the time it hits the bottom of the operation chamber.

3.3 Problems during testing

This chapter is dedicated to minor and major flaws and difficulties which occured during the testing phase. Some of them could easily be fixed through software patches, others may require further investigation and proper training before using the machine. Of course, some of the problems were created while using the machine outside of the recommended boundries which was one of the goals for this initial testing phase. The first issue came up on one of the first cutting tests for plywood. The first test pieces were aligned with the help of the onboard camera. Some of the resulting images turned out to be very misaligned and unusable. Figure 32 shows a case of a heavily distorted picture, the result of poor digital stitching.

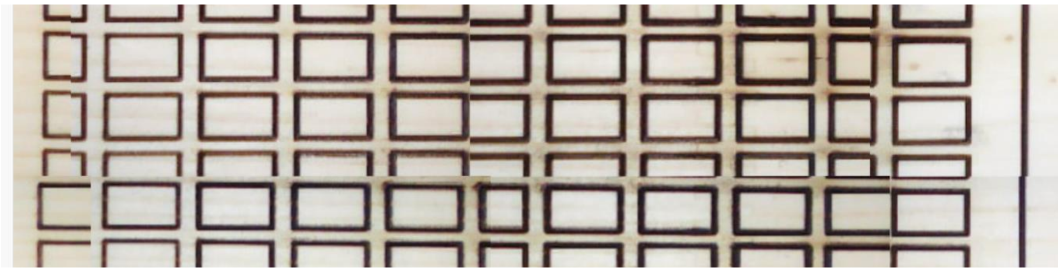

Figure 32. Distorted camera stitching

This issue was not a big problem during the test phase as the raw material was usually big enough and the test sheets were either treated only once or have not been moved during multiple passes. It could, however, become more severe when there is only a limited amount of space available and precise engraving is mandatory. This is one of the problems that could easily be fixed by software enhancements. Figure 32 represents the worst result of the stitching process and it is not visible everytime. User errors could be causing this artefacts too, for example through bumping into the table during the stitching process or dirty axial rails and therefore imprecise movements.

3.3.1 Failed attempts

With extensive initial testing operations, failed parts and issues due to user error or limitations of the BEAMO or the material are always present. During the very first tests with the thick plywood sheets, the material started to burn on the inside. This problem is provided for visual inspection in Figure 33.

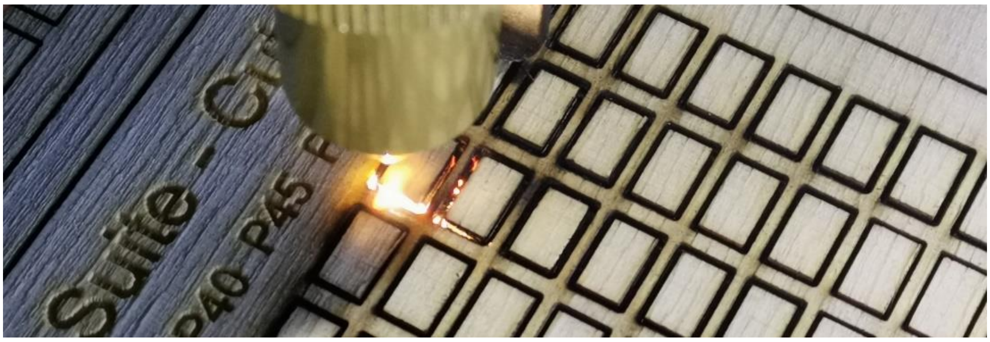

Figure 33. Glowing embers inside of test sample

The incident occured in the top right corner of the test grid which contains the most powerful settings combined with the slowest movement steps possible. This, together with the pressured assistant airflow resulted in embers being pushed past the cutting edges into the untouched material. Due to the relatively high laser settings being applied on such a small surface, the squares burned away almost completely and did this with a clearly visible smoke development. The test was paused multiple times because the embers grew to an uncomfortable size and were extinguished with a moistened cloth. The damaged test sheet can be seen in Figure 34.

Figure 34. Failed Material test

The failed test sheet is stored near the BEAMO in the laboratory for closer inspection. This test proved that the machine must no be unattended for longer periods of time whilst cutting operations. All of this happened in under two minutes and without the immediate actions, greater damage could have been caused to the test sample and the machine. As during the time of this particular test the ventilator speed was just being adjusted down, the laboratory environment was filled with fragrant scents. Multiple steps got developed to prevent this from happening in the future. First, some of the thicker plywood sheets were damped in water just before treatment to extinguish embers right away. This turned out to be quite successful, the cutting edge quality was increased at the same time. In a second step, whenever multiple passes of the same path had to be done, the whole pattern was finished first and then repeated so the intividual squares had no chance of developing embers that got excited due to multiple powerful passes within a short amount of time. Lastly, as the thicker plywood sheets turned out to be quite hard to work with and no projects will be developed in the course of this thesis with it, not using it in the first place prevents any cases of damages.

Another incident happened during the preparation of the projects for the students. Two-layer cardboard was chosen because of its higher stability compared to single-layer cardboard for cutting shapes. Since the single-layer cardboard proved to be easy to work with and safe in the previous tests (see chapter 3.2.10), this material was also chosen because of its very good availability. Since the chosen material consists of five paper layers instead of three, slightly higher operating settings were selected to ensure a successful cut. A strong smoke development obstructed the view of the workpiece during the process, which meant that the formation of severe glowing spots within the structure was overlooked. Additional air came through the two fluted channels, eventually forming an open flame. This flame was quickly extinguished with a wet cloth and the process stopped immediately, but parts of the laser head and cover were still affected by the fire for a few seconds. The burned piece of cardboard is provided in Appendix 1 as Figure 50 for inspection. While the laser head and the control panel showed no visible damage, the transparent cover of the operating room was slightly bent by the heat. Although the operation of the laser device could be continued without any problems, this incident clearly shows that even a seemingly harmless material can lead to severe damage and danger if it is not under supervision.

3.3.2 Physical limitations of the device

This chapter describes the limited operating space in the machine. Since the workpieces affected by these limitations are usually not cut, they tend to limit the engraving of thick or bulky objects. The machine is shipped with an approximately 20 mm thick cutting pad as shown in Figure 10. From the top of this base on, there is a working volume with a maximum height of 16 mm. This height is achieved by moving the laser head upwards as far as it will go. For larger objects, the cutting base can be removed, which opens up to roughly 36 mm of vertical space. Even though cutting operations are hardly practical without this work surface and at these thicknesses, they should not be carried out because the gases produced have to escape downwards and can thus cause discolouration around the exit points. Such cutting operations are also not really practical because of the non-variable focal point. The focus issue was described in chapter 3.2.16, where almost all the available space was also used for testing. The extreme case was also investigated during the tests and the very close distance created from laser head to workpiece can be seen in Figure 35.

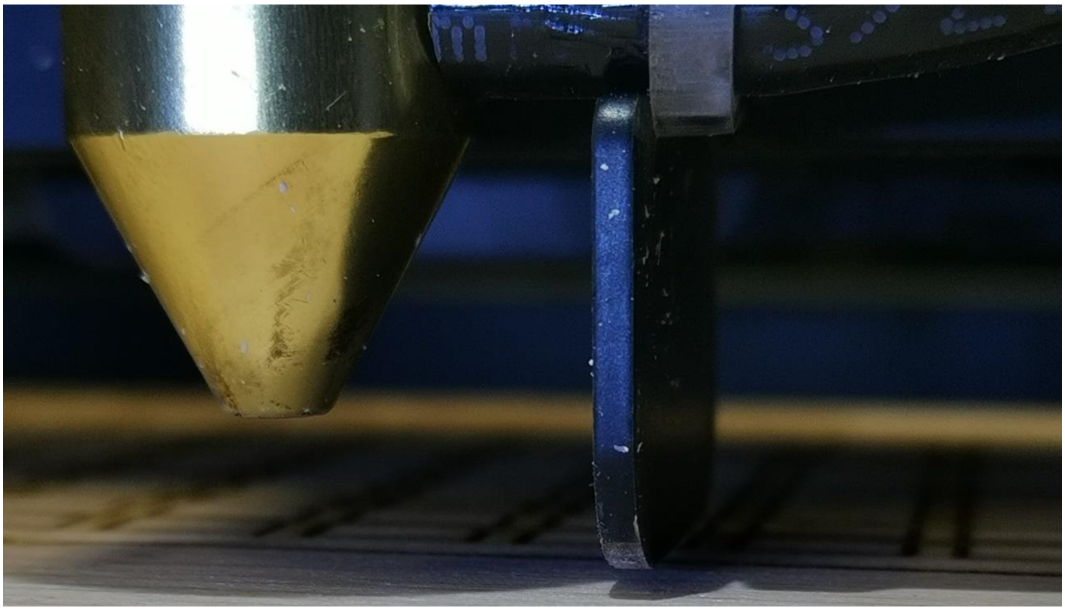

Figure 35. Height limitation of the laser head

The work piece visble in Figure 35 is the thick piece of natural wood that was treated in chapter 3.2.11. With such close distances, care must be taken that no contact points are possible and that the workpiece lies flat and stable on the base. In the case of the test with the thick piece of natural wood, the focal point lay well below the top surface, which was a known constraint from the beginning.

3.3.3 X-axis wobble

Another issue that came up during the testing phase was the problem with straight lines on the x-axis on several occasions and settings. This problem has already been discussed in chapter 3.2.15 with the help of Figure 47. This phenomenon seems to occur the strongest at high laser head speeds and with medium resolution settings. A possible explaination could be an issue with the gear belt that moves the laser head and is driven by the x-axis stepper motor. Vibrations in the belt and its own flexibility could result in a hopping motion along the x-axis. This problem is also known with AM processes. Here, artefacts near sharp corners where the print head has to slow down or accelerate can cause distortions and uneven surfaces. (Simplify3D 2021) An example picture is provided in Appendix 1 as Figure 49 to make this analogy clearer. The issue is again clearly visible in Figure 22. For further tests and projects, slower speeds and resolution settings while engraving would prevent this problem with a simultaneous increase of operation time. This problem seems to appear regardless of the material used, as shown in Figure 17, Figure 18, Figure 19, Figure 20 and Figure 22. When looking at printed parts, it can be assumed that this wobbling or ringing effect usually only occures near sharp corners. Those corners would convert to the y-axis limits of the test squares within the engraving tests. It is yet to be examined if this effect is still visible when the laser head moves over a longer distance along the x-axis. This would then lead to the assumption, that the quick changes in movement is causing this artefacts. The origin of this problem could lie in a mechanical problem such as a loose belt or a software problem when it comes to deceleration.

3.3.4 Unknown materials and dangers

This chapter focuses on unknown materials and associated hazards. As already announced in chapter 3.2.4, there are many different categories, ingredients and potentially hazardous emitted substances, especially in the case of plastics. The danger when it comes to direct use in the machine is that a harmless piece of PMMA can hardly be distinguished visually from a dangerous piece of PC. Therefore, it is important to use known material sources and not to laser process certain leftovers from old projects, for example. While many materials can be used in the workshop without any problems, they can develop carcinogenic substances when processed with the laser. It so happened that among the transparent plastics selected for testing was also a piece of alleged PC and the result can be seen in Figure 36.

Figure 36. Dangers with unknown materials

The difference to the harmless PMMA becomes visible at the latest when working with it. The material is not only very hard and cannot be cut with the usual settings, but it also develops a yellowish-brown smoke which even settles on the workpiece. Since these fumes are not only very harmful to health but can also damage machine parts, no further tests were carried out with this material.

In addition to the dangers linked to unknown materials, potential damages and contaminations of the machine are unwanted too. As seen in Figure 48, provided in Appendix 1, the equipment can also get covered with debris and could suffer in terms of accuracy and performance. Here the dangerous fumes that were emitted from the PC sheet shown in Figure 36 led to a deposit of charred debris around the nozzle center. This was a clear visualisation of the dangers, as nobody should inhale those black particles. Those debris could be cleaned off with ease but other unknown materials may cause greater permanent damage.

3.3.5 Carbon build-up with plywood cutting

To create a hole in the thicker plywood sheet with operation time ignored, multiple passes of the same settings got applied. Those revealed an upper limit of how often a piece of plywood is even workable. After 15 passes with settings that should be able to cut through a 30 mm sheet with ease in theory, the attempt was aborted. Upon closer inspection the maximum penetration depth was about 5 mm, with no visible stains on the other side. The 6.5 mm thick plywood sheet was basically uncuttable. The settings that were applied to the board were P40/S006 with 15 passes. The lower power was chosen to get a cleaner cut edge and to preserve the lifetime of the lasertube. A possible explaination for this failure is the creation of a heat resistant and insulating charred carbon layer, generated by the laser beam. This accumulation probably occurred during the first repetitions, which made the later repetitions useless. It can be assumed that the lower power had a sgnificant share in the creation of this phenomenon. The problem of burning wood when using higher power settings and lower speeds has already been described in chapter 3.3.1. On the basis of those findings, the limits of the machine had been found in terms of the ability of cutting plywood. In addition to that it can be stated that using more power and slower speeds with fewer repetitions is more effective than using less power with significantly more passes although edge quality has to be sacrificed here.

3.4 Conclusion of the testing phase

This chapter serves as a summary and general evaluation of the entire test phase. Furthermore, some indications for a successful cutting or engraving process are presented here. Apart from a few incidents and unexpected results, this test phase can be considered a success. The failed workpieces and incidents contribute as much valuable insight into the machine's capabilities as the many successful tests. While there were predictably good results with some materials, such as PMMA, the thicker versions of the test pieces gave far-reaching insights into the function, malfunction and capabilities of the machine under investigation. The machine environment proved to be well set up and tests could be carried out efficiently and neatly. By building a register, the resulting pieces could also be stored neatly. They are an important source of information for future projects that do not have the time and material to test the limits first. As described, natural materials such as wood and leather can vary due to changing density, so testing with the same material before production is advisable for larger projects. Requirements for safety and attention of the operator were made clear and justified by the failed tests, which sometimes included the development of fire. Especially with PMMA, a recommendation for achieving smooth surfaces can be given after this test phase based on the normal material tests and the resolution tests. Figure 37 shows the result of fast laser head movements.

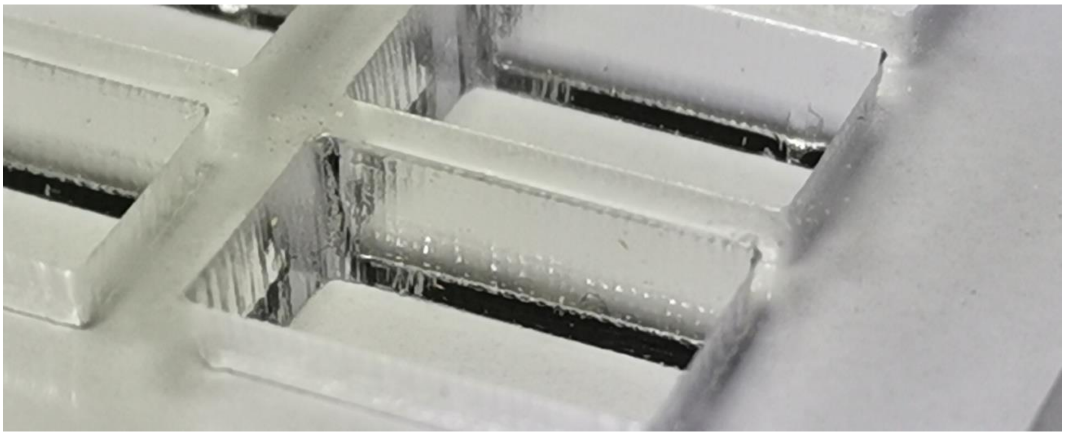

Figure 37. Effects on edge face quality with high cutting speeds

Here you can see how the fast movements can significantly reduce the working time but only with a reduced surface quality. With faster movements you notice that the material has less time to melt smoothly, resulting in a rougher surface. With round shapes, this can also lead to cut edges not being square and parts getting caught in each other. There are several solutions that lead to beautiful surfaces and do not require any finishing. Firstly, the surface quality of cut PMMA is influenced by the number of repetitions. Even though lasers are very precise tools, minimal deviations from the previous path can lead to clouding and contamination of the previously smooth surface. Further, Figure 38 shows how much more appealing surfaces become when the processing speed is reduced.

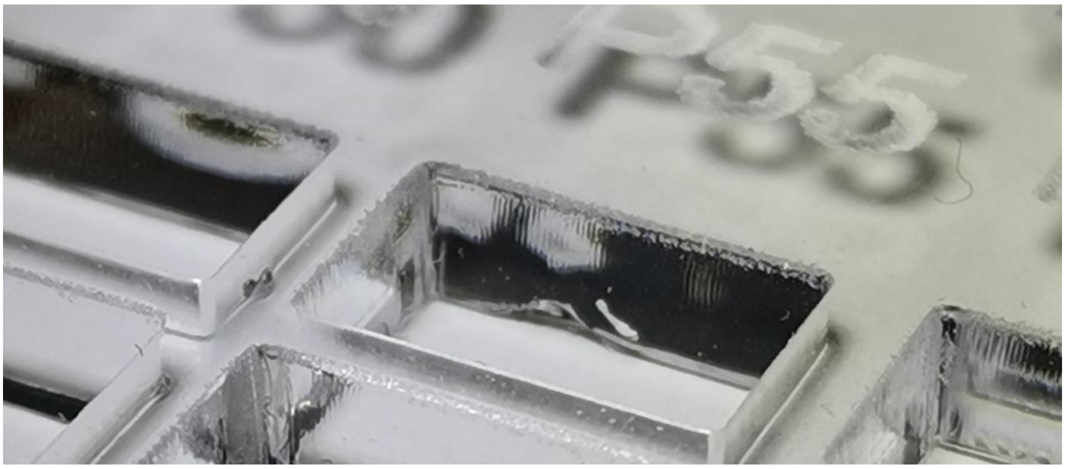

Figure 38. Effects on edge face quality with low cutting speeds

With slower speeds, of course, the working time also increases, but if the surface quality is in the foreground, this compromise should be made. Even if the setting with faster movements and less power and more repetitions is equal to a single slow powerful repetition in terms of a successful cut, the slower one is advisable. The tolerances created by the necessary removal of material are also worsened by repeating more often at best.

3.5 Maintenance

As the manufacturer suggests, the laser device needs frequent maintenance which includes cleaning and checking the water level in the reservoir. All the moving parts should be wiped and lubricated at weekly or two-weeks intervals and the water should be changed every three month. For the purpose of taking care of the machine, a maintenance schedule was created. In the course of this work, several lubrications and one water change were done which provided material for the guidelines and showed how it is done and what to look out for. The UI of the BEAMO includes a counter which shows the operating hours of the laser tube. A replacement tube was purchased together with a replacement grid bed during the ordering of the main device. The new and unused laser tube can be seen in Figure 39.

Figure 39. Replacement gas laser tube

The laser tube has a limited lifespan of about six months to a year. The manufactorer limits the general warranty of the device to 12 months excluding the laser tube which gets only three months of a claim period. As the mirrors and lenses also have a limited lifespan of about one year and are consumables, maintenance is required here to ensure a long lasting service. (Flux Europe 2021a)

4 DESIGN OF MATCHING PROJECTS FOR LAPLAND UAS STUDENTS

This chapter now combines the theoretical knowledge from the elaborated basis and the acquired knowledge from the practical tests with the machine. It is roughly divided into the general description, the scope of the projects, safety notes and the description of own projects. Throughout this chapter there are frequent references to the extra Guide, which will be included in the appendix of the final version of the thesis. It will contain detailed instructions and provide suggestions in case of e.g. failures.

4.1 Description, Scope

The aim of this part of the thesis is to develop a system to familiarise the Lapland UAS students with laser processing. This includes practical examples and explanations of how to complete successful projects of one's own. In the course of this development, an online platform for sharing the results and a guidebook will be developed to provide detailed knowledge about working with the BEAMO to save the students problems, material and time. The manual will contain safety instructions as well as precise settings for processing the most common materials. Furthermore, there will be tips and tricks in case there is a problem with the process. The guidebook is intended as a supplement to the existing manual provided by the manufacturer. Besides the basics, it already contains very good instructions on maintenance and cleaning. Therefore, the self-created guide will refer to these instructions at most, but will not give any instructions of its own regarding maintenance and repair. The guide is provided in printed and bound form in DIN A5 format in the laboratory. Schematics and plans for some projects are provided in electronic form. As detailed instructions for each project cannot be provided due to time constraints, links to two websites that allow the creation of simple yet interesting projects are provided in the guide and in Appendix 3.

4.2 Safety sheet and handling instructions

As this manual and the machine are used by students, rules for use must be defined. This is not only to protect the projects from the next user from damage due to heavy contamination of the last user etc. but has simple safety reasons. As already experienced during the testing, some materials pose a very real fire hazard. Therefore, the machine must never be left unattended during processes that involve cutting, for example. These rules will be integrated into the guide in simple language and without ambiguity. A Finnish translation could clarify the importance of this matter. These rules are also important because at the time of writing only one unit of the BEAMO is available in the laboratory.

4.3 Theoretical basics of CO_2 laser technology

In order to give the students a general overview of the laser technology and also to support them with regard to their own learning curve, the guide will additionally include basic general knowledge about lasers and compare different lasers with the BEAMO and other process technologies such as AM or CNC by means of a simple pro and con list. This should ensure that the students can also work on reasonable projects with the laser device and evaluate firstly what the limits are and secondly when it might be better to use a different technology. All possible upgrades of the machine would have to be elaborated in a further work, so that the creative horizon of the students can be adequately adapted and even more diverse projects can be created in the future. The diode laser module deserves special mention here, as it would immediately expand the BEAMO's range of applications and, for example, make metal a new material that can be processed.

4.4 Description of purposed student projects

The proposed projects for the students are described in this chapter. The detailed elaboration will be found in the final Guidebook. The projects are designed in such a way that mainly the laser device can be used for production. Some of these projects are also possible without this technology, which gives the opportunity to describe advantages and disadvantages of this process. The projects are chosen so that they can be completed either alone in a few days or in pairs in one day. They are also meant to serve as inspiration for own project work, which may lead to variations of the proposed projects and completely own projects in the future. Since the aim of these projects is to be integrated into engineering education and to transfer knowledge, the projects try to come up with different materials and levels of difficulty. In addition, the online platform offers the possibility to share projects and get inspiration. Details can be found in the guidebook. In the following, the individual projects are briefly presented to give an overview. The projects can be roughly divided into cutting and engraving projects, whereby the other method can also be integrated in each case.

4.4.1 Cutting projects

This type of project describes those whose main part falls on cutting operations. Decorations and inscriptions can also be made with engravings. This type of project requires much shorter production times on average than projects with a lot of engraving. This is due to the fast processing speeds, which are sufficient for a successful result with most materials. Plywood boxes with a simple plug-in system are presented as the first project. For this, 4 mm thick plywood sheets are used to cut out the designed shapes. The shapes for the complicated geometries are defined with the help of an online tool, whereby a very high degree of individual ideas can be achieved. The only limitation here is the size of the operating space and the availability of the material. This project deals with wood as a material and the associated details in terms of tolerances. The laser beam always burns a little more material than specified, which requires fine adjustments in terms of fit.

The next project is leading to self-designed and produced puzzles. The required shapes are again made with an online tool and the materials range from paper and cardboard to wood and acrylic. Examples can be found in the guide and the entire process is also described there. It is possible to engrave the image of the puzzle on the material with the laser device. Jigsaw puzzles are a relatively simple project, but aligning and designing a meaningful jigsaw puzzle takes time and creativity.

4.4.2 Engraving projects

This type of project consists mainly of engravings. Since each engraving is unique and not only virgin material can be processed for engravings, the projects will be differentiated by material. While shapes, writing and ornaments can be engraved on the surface when producing wooden boxes from new material, own objects can also be decorated. This includes objects made of wood, metal and plastics. For this purpose, all objects and materials that appear interesting are tested, presented and documented in the guidebook. Plastics engravings are embedded on mobile phone covers, charging adapters and in acrylic glass, among other things. With a little creativity, thick paper can be made into business cards, for example, and monochrome paper engravings generally make for vivid projects. Apart from the boxes, wooden engravings are also incorporated into barbecue forks, for example. With anodised aluminium, battery packs and a laptop cover form the final stage of engravings for own objects. The purpose of these engravings is to show what is possible through the examples given and to promote one's own creativity. Of course, the concept of the ethnic engineering also comes into play here. Defacing and destroying other people's property or depicting reprehensible images does not belong in this environment and should not be made possible through this project. A link to the Code of Ethics in Engineering can be found in Appendix 3.

4.4.3 Production and documentation

The handbook will include the fundamental operating mode of the laser machine and some general tips and tricks in case of problems. Detailed instructions with important checkpoints and hints for the production of the student projects will also be provided. These will be explained step by step and each project will be assessed on the basis of feasibility and risks and prerequisites. Whether prior knowledge of topics such as soldering, woodwork or steady hands might be required is also assessed. The approximate time each project will take may also be of interest in planning the work. Therefore, in addition to the pure active machine time, the approximate finishing and/or pre-processing time is also estimated.

5 CONCLUSION AND DISCUSSION

This chapter deals with the summary of the whole thesis by explaining the links from the practical part to the theoretical part. The work is evaluated here according to whether the set goals were achieved and how this happened. Finally, an outlook on possible future work is given.

5.1 Summary

In the course of this Bachelor thesis, the new laser device from Flux called BEAMO was set up in the 3D printing laboratory at Lapland UAS in Kemi. Based on theoretical knowledge, the capabilities and limits of the machine were tested with the help of prefabricated test grids. Part of the method consisted of a long and extensive testing phase to try out most of the scenarios on the most common materials to enable reasonable and feasible projects. This testing phase got described in chapter 3.2.3. In addition to the materials, basic physical and other limits of the machine were also investigated. This included the influence of a changing focus point, the effects of different resolution settings and the spatial limits of the operating chamber.The problems with glow nests due to too much light output and with non-straight edges were recorded and evaluated. The test grid proved to be very practical as it covered the main part of the application range and was applicable to most materials due to its relatively compact size. 11 different materials were tested in this way and with the suggested project ideas and detailed descriptions, students can work with them in the future.

It can be said that all the goals were achieved and that the timetable was realistic. Some points were more complex than expected but this was compensated by less complex points. During this work, the machine was also used for some other tasks and small projects, but the author reserved the right not to release the machine to the rest of the community yet. Of course, with the completion of this work, this is a given.

5.2 Practical work

The practical work can be divided into two parts. The test phase and the project description phase. In the test phase it was found that under the recommended conditions all materials can be successfully processed as indicated. In addition, the maximum possible thickness of some materials such as wood and acrylic glass was exceeded by more than double in some cases. The dangers posed by artificial materials such as PC were clearly experienced and described as is describd in chapter 3.3.4. Furthermore, it was found out that an acceptable focus line with a length of about 10 mm is available, taking into account slightly slanted cutting edges. The effects on texture and penetration depth of different resolution settings were also investigated. It was found that acceptable textures can be achieved at 250 dpi with a relatively low process time as is described in chapter 3.2.15. Depending on personal taste in engraved textures, a comprehensive collection of engraving samples is now available in digital form in this thesis and in real in the laboratory. All patterns are also available in the lab and can be assigned thanks to the individual numbering.

The second part of the practical work consisted of working out useful and interesting projects for the Finnish students. It is described as Development phase in chapter 1.5 and the rough process can be seen in Figure 40 in Appendix 1. It included production and documentation of the individual parts as well as the eventual finalisation of the workpieces. In addition, a guidebook with all the descriptions, instructions and safety informations was produced in the course of this section. The most important points before working with the device and the start-up process are described here. QR codes make it easy to download software and lead to the mould generators, among other things. A set of rules has been developed to ensure safe and efficient operation for all involved. Additionally, detailed suggestions for settings to process certain materials are given. The project descriptions conclude the guidebook and it is now available in printed form in the laboratory.

5.3 Outlook

Only time will tell whether the online tool for sharing one's own projects will prove its worth. Meanwhile, future work can take care of expanding the knowledge base around laser technologies in the laboratory setting. Expanding the machine with the add-ons or expanding the test results can help to give students even more opportunities to make their education at Lapland UAS more diverse. For example, all engraving tests could be carried out again with the three remaining resolution settings in order to actually exhaust all available settings with regard to engraving with this device. In addition, the machine could be supplemented with the three extensions currently available to increase the range of applications. The diode laser module could allow metal as an additional material and further work can be done to evaluate the usefulness of this acquisition first. Furthermore, the rotary add-on could also enable round materials to be processed and the autofocus module could make the BEAMO fit for uneven surfaces and automatic focus direction for changing materials.

BIBLIOGRAPHY

Beyerer, J., León, F.P. & Frese, C. 2016. Licht. Automatische Sichtprüfung, 23–120.

Cambridge University Press 2014. Definition of Laser. Accessed 20 February 2021 https://dictionary.cambridge.org/de/worterbuch/englisch/laser.

Demtröder, W. 2010. Laser. Experimentalphysik 3, 271–296.

Engineering ToolBox 2004. Density of Various Wood Species. Density of Various Wood Species Accessed 26 April 2021 https://www.engineeringtoolbox.com/wood-density-d_40.html.

Flux Europe 2021a. beamo. FLUX | Craft Your Imagination Accessed 21 March 2021 https://flux3dp.com/beamo/.

Flux Europe 2021b. Beamo - Flux Europe. Accessed 19 March 2021 https://www.fluxlasers.com/beamo.html.

Flux Europe 2021c. beamo-user-manual-20191203.pdf. Accessed 19 March 2021 https://cdn.webshopapp.com/shops/290919/files/316242658/beamo-user-manual-20191203.pdf.

Flux Europe 2021d. FLUX Beamo. Flux Europe Accessed 30 March 2021 https://www.fluxlasers.com/products/beamo/?source=facebook.

Frank, H. 2006. Electromagnetic Spectrum. Accessed 25 February 2021 https://www.e-education.psu.edu/geog160/sites/www.e-education.psu.edu.geog160/files/file/spectrum.html.

Hanchett Paper Company 2021. The Ultimate Guide to Corrugated Boxes | Shorr Packaging Corporation. Accessed 23 April 2021 https://www.shorr.com/packaging-news/2019-07/ultimate-guide-corrugated-boxes.

Kale, L.N., Garde, J.B., Garde, S.S. & Gupta, P. 2017. Figure 1: Basic mechanism of the working of a laser (Reproduced from... ResearchGate Accessed 20 February 2021 https://www.researchgate.net/figure/Basic-mechanism-of-the-working-of-a-laser-Reproduced-from-Robert-A-Convissar_fig1_316625757.

Kwok-san, L. & Shiu-sing, T. 2000. Further physics - What is laser? Accessed 20 February 2021 http://www.hk-phy.org/articles/laser/laser_e.html.

Meschede, D. 2008. Optik, Licht und Laser. Wiesbaden: Vieweg+Teubner.

Prusa Research a.s. 2021. Ghosting. Prusa Knowledgebase Accessed 27 April 2021 https://help.prusa3d.com/en/article/ghosting_1801#_ga=2.90850393.296515191.1590136653-718336605.1583915167.

Sigrist, M.W. 2018. Laser: Theorie, Typen und Anwendungen. Berlin, Heidelberg: Springer Berlin Heidelberg.

Simplify3D 2021. Vibrations and Ringing. Accessed 27 April 2021 /support/print-quality-troubleshooting/vibrations-and-ringing/.

Steen, W.M. & Mazumder, J. 2010. Laser Material Processing. London: Springer London.

Universal Laser Systems, Inc. 2021. Erhältliche Linsen. Accessed 26 February 2021 https://www.ulsinc.com/de/available-lenses.

Velling, A. 2020. What Are the Advantages & Disadvantages of Laser Cutting? Fractory Accessed 30 March 2021 https://fractory.com/laser-cutting-advantages-disadvantages/.

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Appendices present information that you feel is important but does not fit entirely in the text, such as manuscripts, photos, paintings, interview questions, drawings, programme lists, multipage tables and figures and odd-sized graphical presentations. Appendices must always be commented on in the text. Do not use any appendices that are not referred to in the text. The appendices themselves must contain all the information needed to interpret them: a heading and an explanation of the photo or table. It is not necessary to use the thesis layout in the appendices.

If an appendix consists of more than one page, mark the page of the appendix and the total number of pages as follows: Appendix 1 1(3); mark the next page: Appendix 1 2(3); etc.

Appendix 1

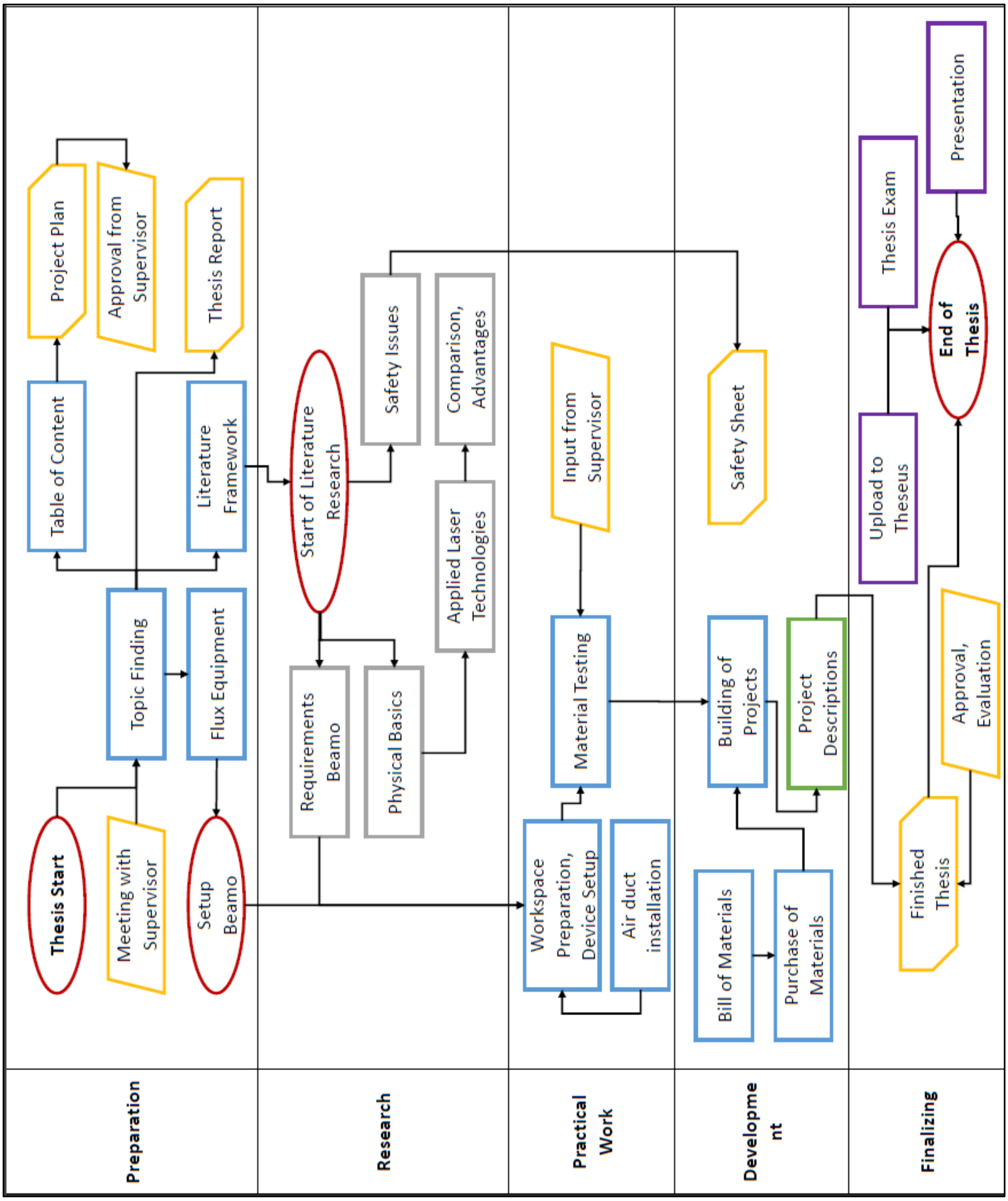
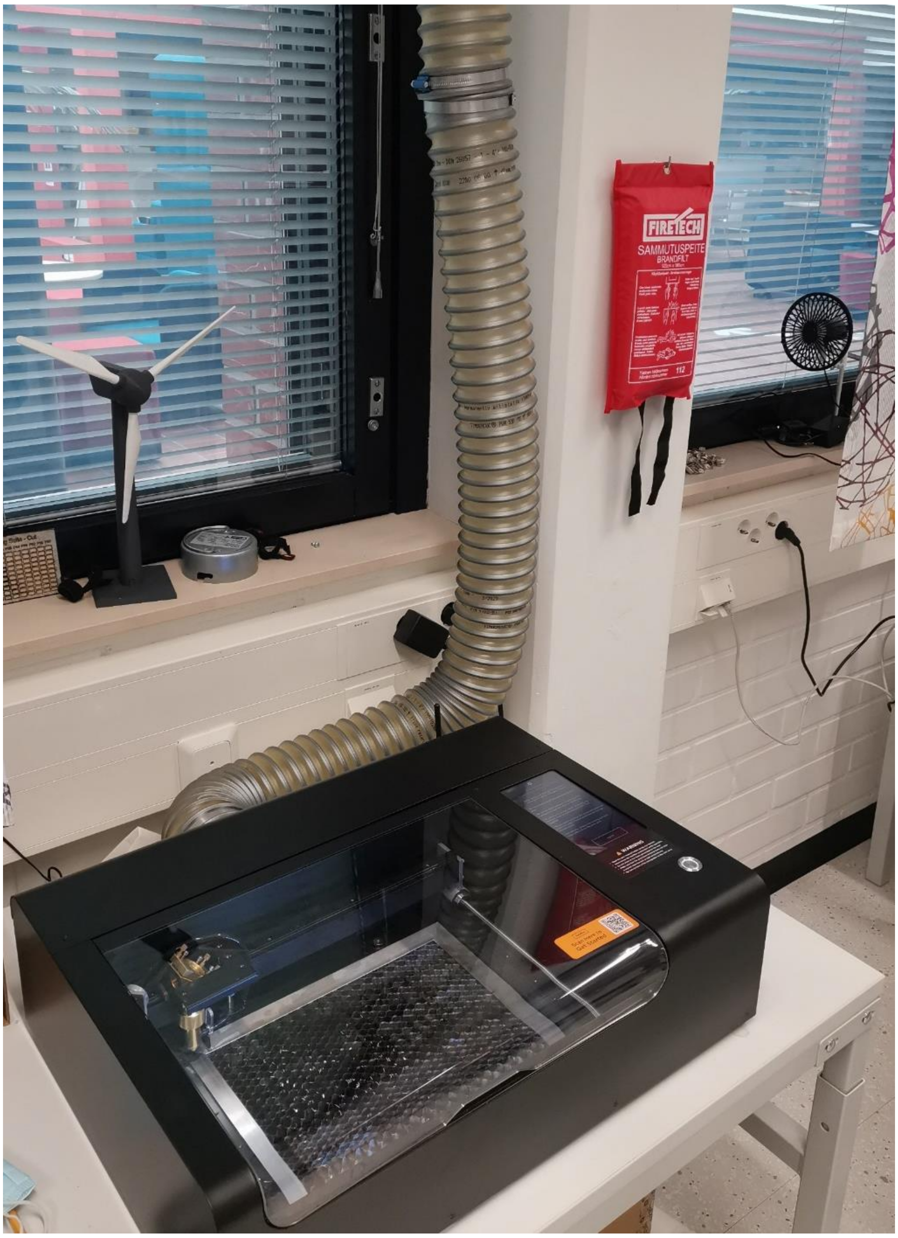


Figure 40. Methodolical flow chart of the thesis process



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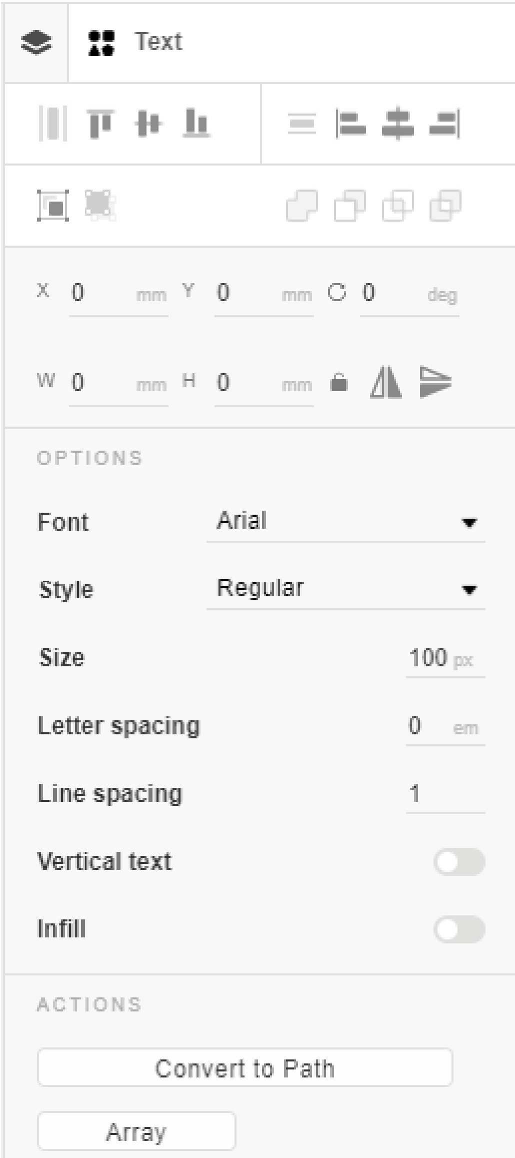


Figure 42. Menu for editing selected elements

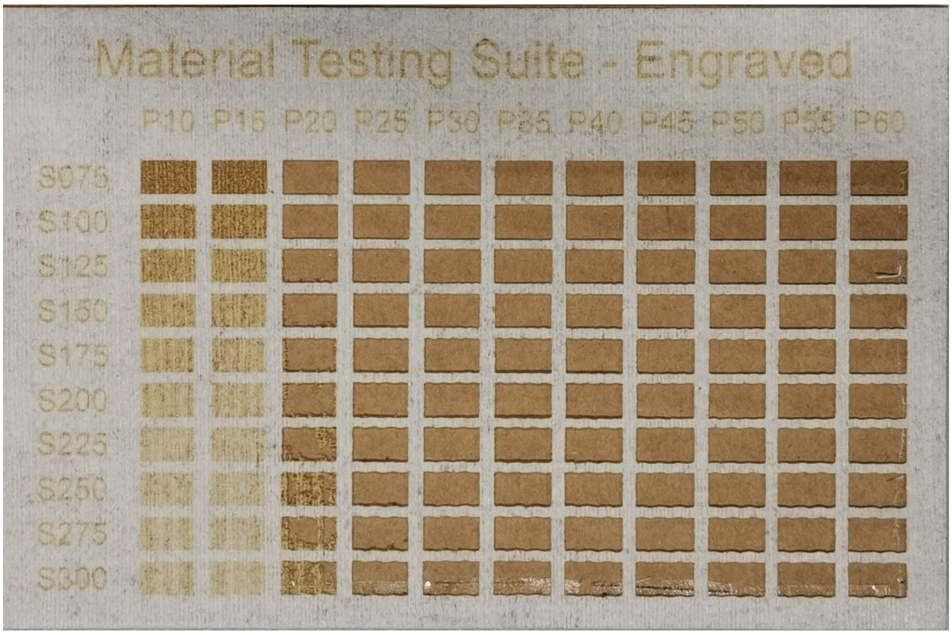


Figure 43. Material test sheet; fabric, engrave

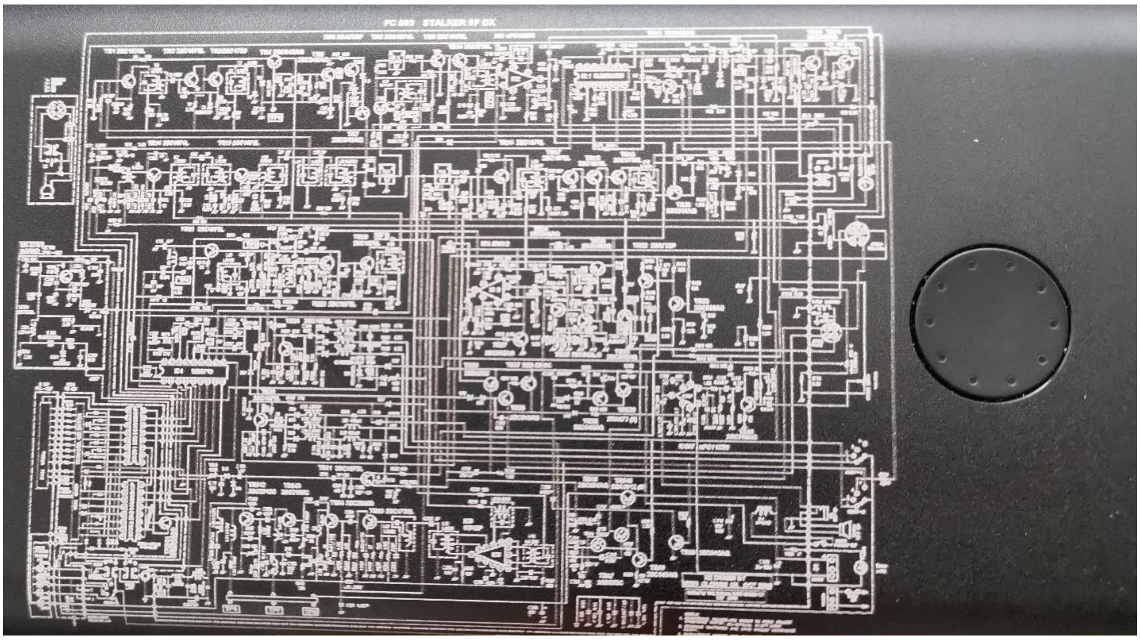


Figure 44. Engraved Circuit on anodized aluminum

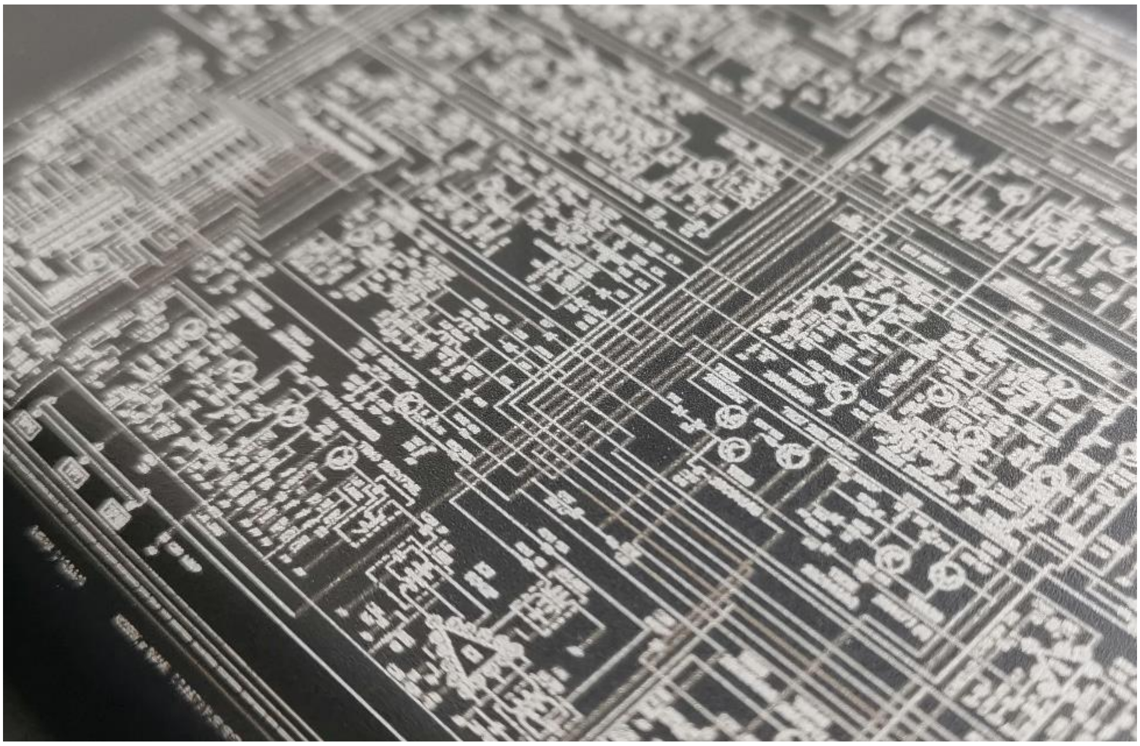
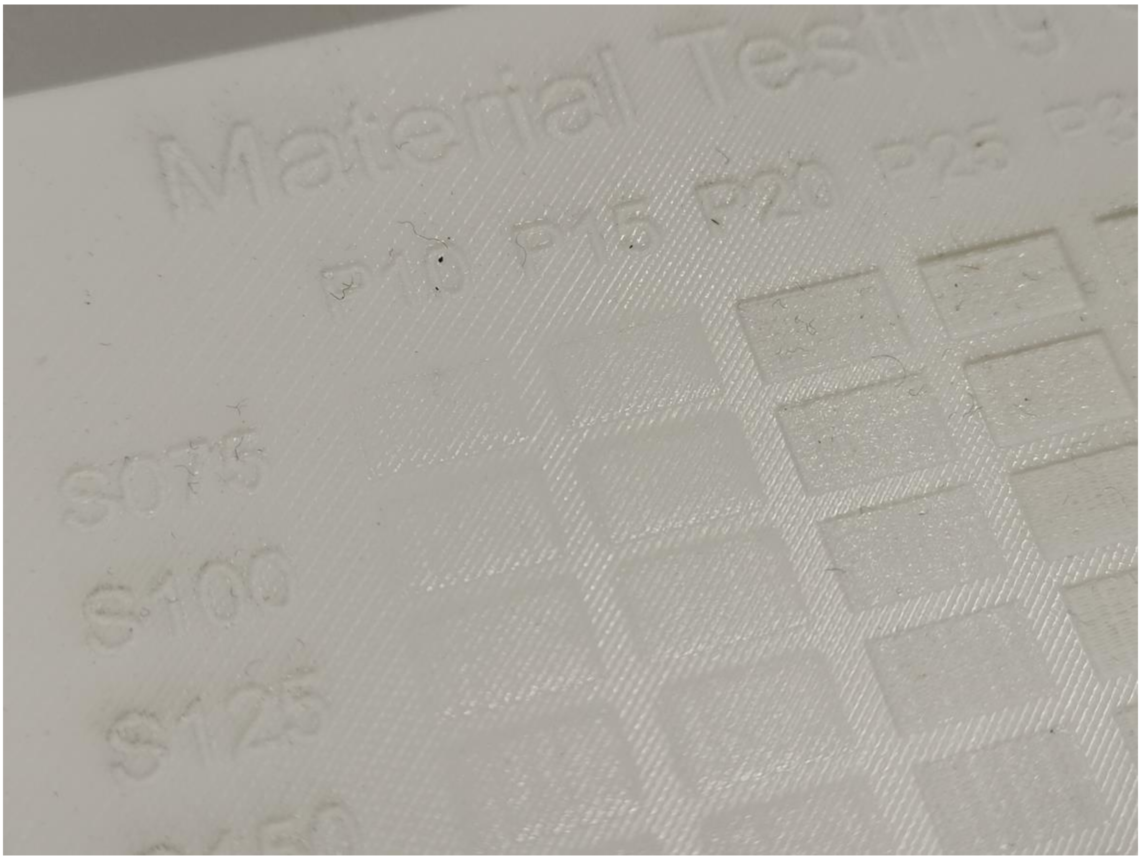


Figure 45. Detailed view of the engraved circuit



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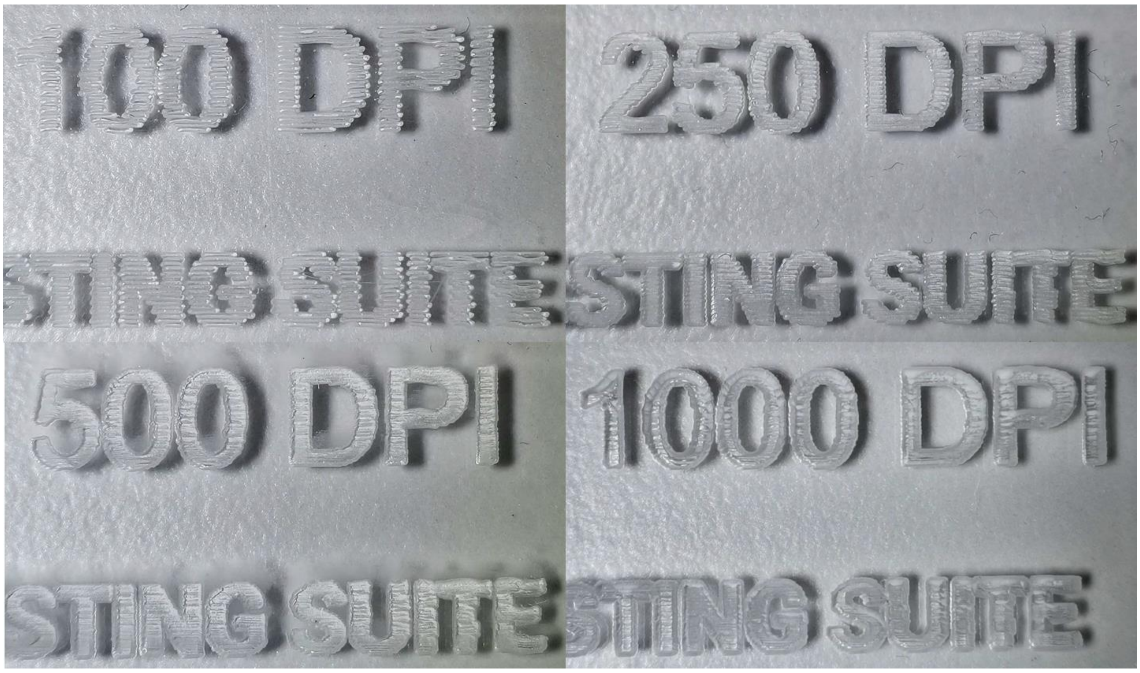


Figure 47. DPI test; detail of texts

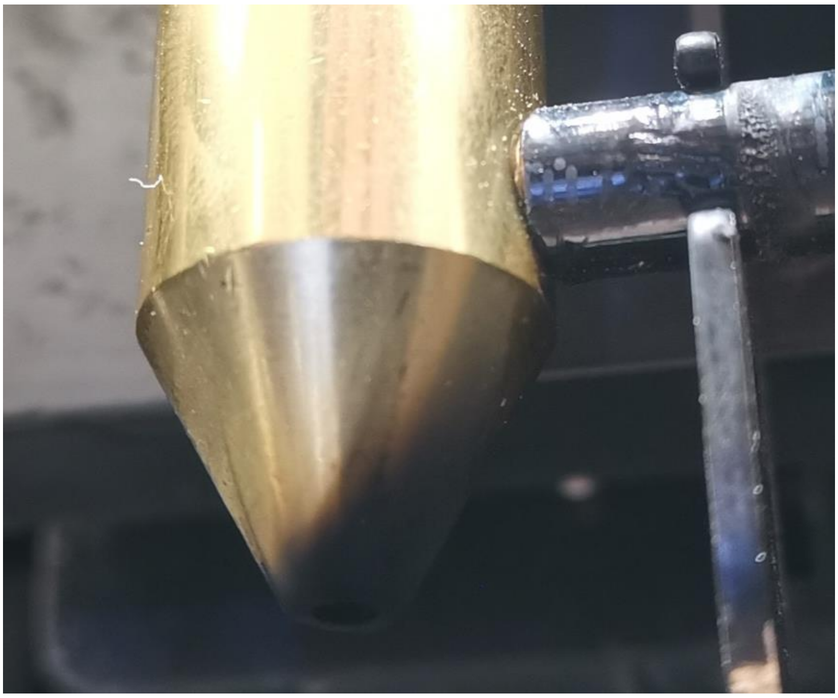


Figure 48. Filthy nozzle after PC cutting

Figure 49. Analogy of ringing in AM parts (Prusa Research a.s. 2021)

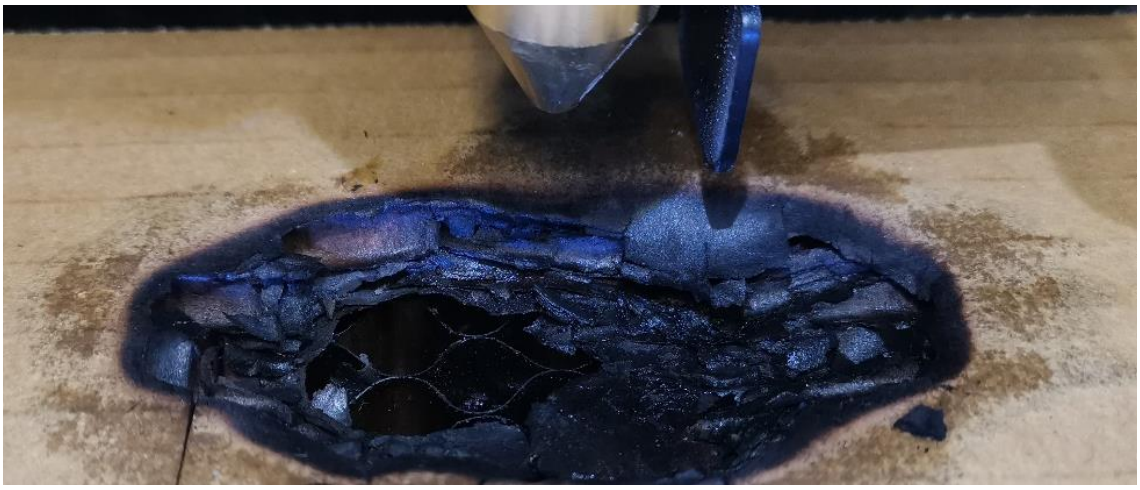


Figure 50. Burned two-layer cardboard after failed cutting operation

Appendix 2

Table 12. Material test sheet; plywood, 6.5 mm, 3 passes, cut

Material Testing: Cut											
Material:	Plywood					*Thickness:*			6.5 mm		
Passes:	3					*DPI:*			250		
2.3	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Table 13. Material test sheet; acrylic glass, 8 mm, 1 pass, cut

Material Testing: Cut											
Material:	Acrylic glass					*Thickness:*			8 mm		
Passes:	1					*DPI: 250*			250		
4.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Table 14. Material test sheet; acrylic glass, 8 mm, 2 passes, cut

Material Testing: Cut										
Material:	Acrylic glass				*Thickness:*			8 mm		
Passes:	2				*DPI:*			250		
4.2	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Table 15. Material test sheet; cardboard, 2 mm, 1 pass, cut

Material Testing: Cut										
Material:	Cardboard				*Thickness:*			2 mm		
Passes:	1				*DPI:*			250		
7.1	P10	P15	P20	P25	P30	P35	P40	P45	P50	P55	P60
S003											
S004											
S005											
S006											
S007											
S008											
S009											
S010											
S012											
S014											

Appendix 3

- Beam Studio and firmware download:
  https://www.fluxlasers.com/downloads/
- Add-Ons:
  https://www.fluxlasers.com/beamo-rotary-extend.html
  https://www.fluxlasers.com/hybrid-diode-laser.html
  https://www.fluxlasers.com/autofocus-module-beamo.html
- DWG to SVG file conversion:
  https://cloudconvert.com/dwg-to-svg
  https://anyconv.com/de/dwg-in-svg-konverter/
  https://www.microsoft.com/en-us/p/dwg-to-svg-converter/9pffgw6mtpcb?activetab=pivot:overviewtab
- Plywood box generation:
  https://festi.info/boxes.py/?language=en
- Puzzle shape generation:
  https://cdn.rawgit.com/Draradech/35d36347312ca6d0887aa7d55f366e30/raw/b04cf9cd63a59571910cb226226ce2b3ed46af46/jigsaw.html
- Code of Ethics:
  https://www.ieee.org/about/corporate/governance/p7-8.html

Appendix 4

<u>This section will be added later and will contain the whole guidebook.</u>

GUIDELINES

beamo

Flux BEAMO laser cutting and engraving device

Author: Markus Mayer

UASTW_GOES_LAPLANDUAS

FLUX
EUROPE

Contents

Introduction

This document shall help first users and students with starting and completing products and projects with the Flux BEAMO laser device successfully. It is intented to be used exclusively in the working environment of the 3D printing laboratory at the Lapland University of Applied Sciences in the Kosmos Campus in Kemi. In the course of my Bachelor's thesis I set up the new laser cutting and engraving device from Flux named BEAMO. It is a 30 W CO_2 laser plotter in a compact desktop design. Part of my work was to test the abilities of BEAMO with different materials of different thicknesses. I applied a premade test grid to look for the best resulting settings and developed a number of small projects for recreational use. This guide is structured in a way that the startup process and the selection of the material and possible problems with quality etc. are described in a cronological order. If a work piece hasn't worked out the way it should have, don't touch the part yet and look for the 'Tips and Tricks' to maybe turn the tide and end up with one piece less for the trash can.

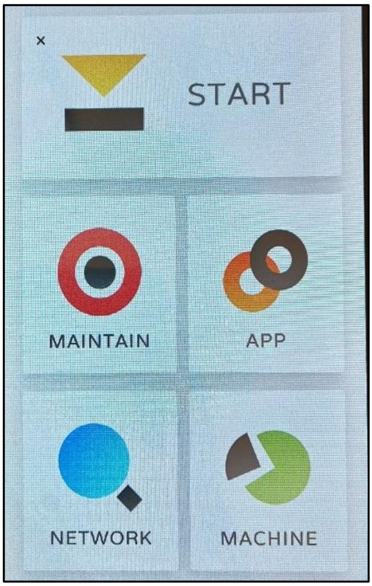
If you like your part and want to share your project with the BEAMO family of Lapland UAS, use the hashtag *#beamedatlapin* to share and see other previous parts and projects, click here to get to the collection.

Disclaimer:
Any harm or damage that is caused by the laser device during operation is the absolute fault of the operator. This guide is full of recommendations on the basis of personal experiences. Careful handling, logical thinking and acting with common sense are expected. The author is not responsible if the rules of the game are not observed or careless work is done.

Startup of the device / User Interface

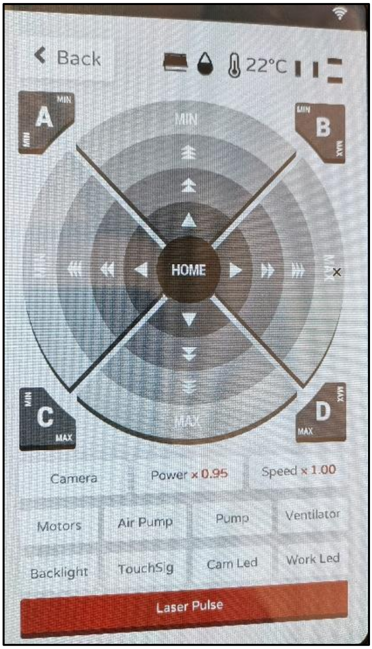
Operating the BEAMO needs two things: The properly set-up and running device and the Beam Studio software. The set-up of the machine is described here and the software part gets introduced in the next chapter. There are some things that have to be checked before starting up the BEAMO. Always check the following things:

- **Power cable is plugged in**
- **Exhaust air duct is connected propperly**
- **Shut off valve of central ventilation system is open**
- **No visible damage to the machine, e.g. the laser head or the belts**
- **W-Lan dongle is plugged in when wireless connection is wanted**
- **No objects are blocking the path of the laser head or the belt system**

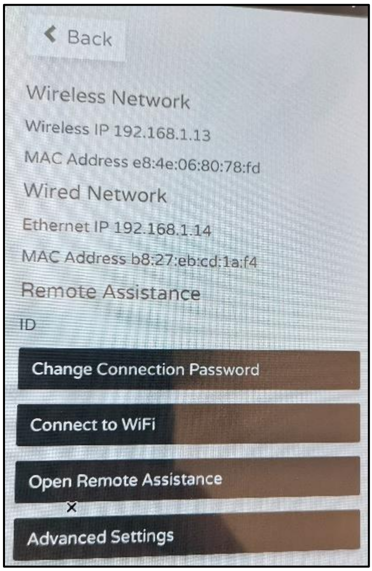


To power up the machine, simply push the silver **power buttom** on the bottom right corner of the BEAMO. After some seconds, the boot-up should be done and the following ‚safety screen‘ should appear. This warns you of the dangers that are linked to the operation and you have to **accept** it in order to get access to the ‚home screen‘. This central menu is shown in the figure on the right hand side. From here on, the basic functions of the machine can be accessed.

This is the **MAINTAIN** menu. Here, the laser head can be controlled and moved with the help of the arrows. The home position moves the laser head to the top left corner of the chamber. The movements come in handy during cleaning operations, because the four corners (marked **A-D**) can quickly be reached and thus the rails and rods of the axis cleaned and lubricated. This menu is further of interest to quickly test new materials through very short laser pulses, activated via the big red button in the bottom of the screen.



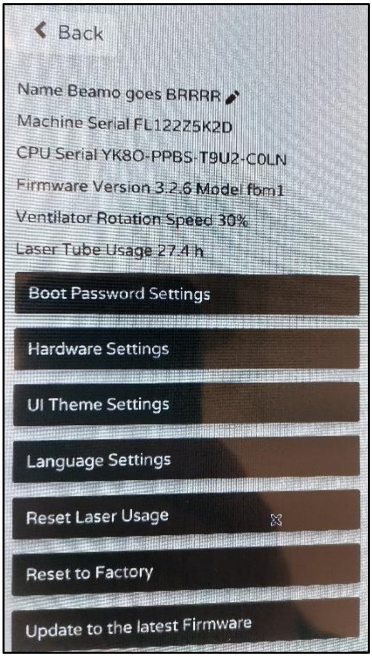
This is one of the more important menus, the **network** settings. The BEAMO comes with a W-Lan Dongle which allows it to connect to wireless networks. The set-up process and the connection can be established either through an own **hotspot** from an own device or the machine can be accessed through the wireless ‚3D Lab' network.



Note: <u>It is important that the BEAMO is in the same network as your laptop or computer!</u>

Note: Sometimes the BEAMO does not immeadiatly react to the touchscreen inputs. This is normal and just needs some times and multiple tries. The brain of the machine is a Raspberry Mini Computer, so it has limited processing capabilities!

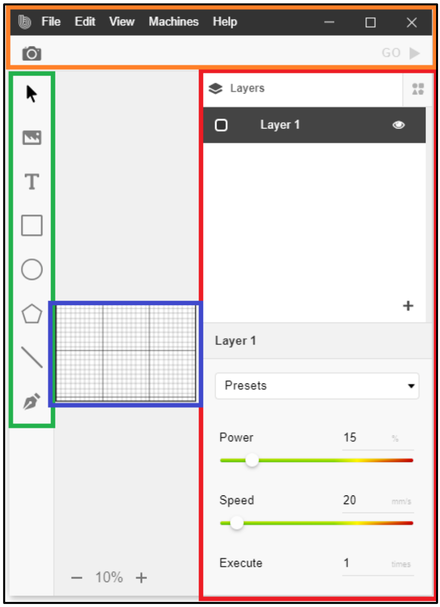
This is the **MACHINE** menu that contains general information and settings options. The only things that might be interesting here are the firmware version, the ventilator rotation speed and the laser tube usage. The ventilator speed was set to this low setting based on the suction capabilities of the central ventilation system where the BEAMO is connected to. It shall not be changed, the suction of the fan is enough for not letting fumes escape. If you have to update the firmware, you can find the latest version following this link.

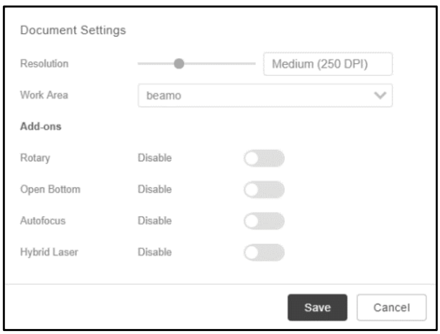


For more detailed information regarding the set-up process look in the manual provided by the manufacturer. You will find the digital version by following this link.

Software

The second vital part of the operation is the Beam Studio software. It can be downloaded using this link and is available for Windows, MacOC 10.13+ and Ubuntu. The used stable version is the latest Version **1.4.6** and was used on a Windows laptop. The mobile phone application was not very stable at the point of testing (April 2021) and is therefore not mentioned and described further. After the installation of the software, open it to get started.

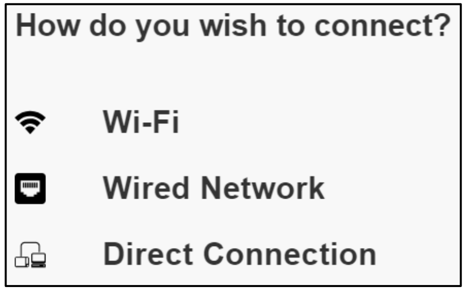


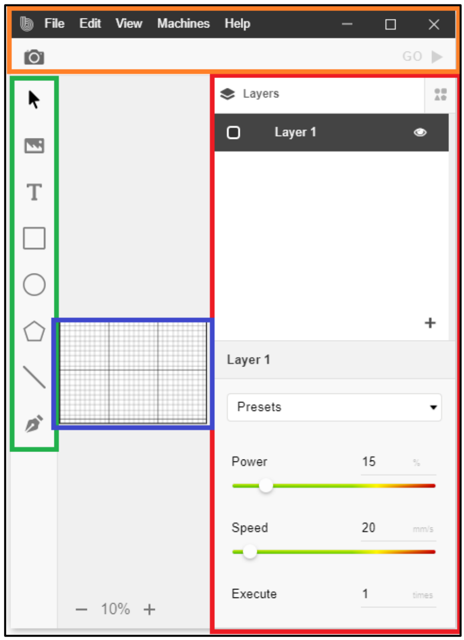


On the right side, the main window of Beam Studio is shown. The main elements are visible and are grouped together in colored squares. Within the orange square you find the ‚File' header. It is used to import files, open projects, export g-code and set preferences. The standard preferences should not be changes, although the language can be set there for example. There are some initial settings, that have to be changed in order to ensure a proper function. The ‚Edit' header is used to undo, copy/paste objects and change the **Document Settings**.

The blue square contains the ‚work area' of the BEAMO and its size has to be changed using the Document Settings. On the right the Work Area can be changed to **‚beamo'** and also the resolution of the engraving process can be altered. This setting does **not** affect the cutting performance of the machine.

All future add-ons to the machine can also be enabled in the Document Settings. To apply the settings just press **‚Save'**. The next important thing is the setup of the connection to the BEAMO. For this click **‚Machines'**, found in the orange square. A drop-down menu appears. When no machine is connected, only two options are available, **‚Machine Setup'** and **‚Test Network Settings'**. When you want to connect the Machine click the first one and this window should appear. The wireless connection can be set by entering the IP-adress of the BEAMO which can be found in the Network menu after a successful connection to a wireless network. The BEAMO also recieves a IP-adress from the accesspoint when connected via an Ethernet cable. The BEAMO can be connected wireless





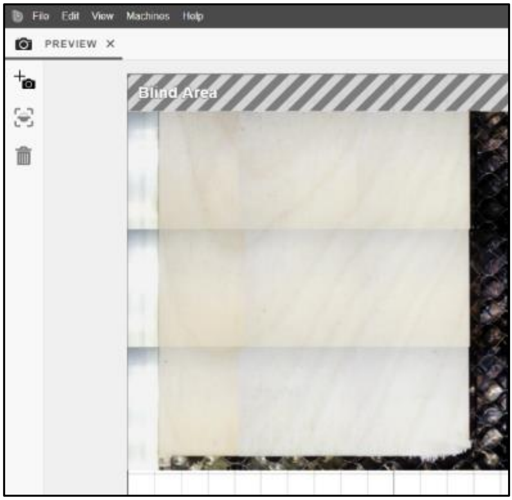
and via wire at the same time. The connection wizard guides you through a problem and when you want to test the networks speed and connectivity.

The green square includes all the tools you need for basic operations like the drawing of simple shapes and the importing of picture files. The supported file formats for pictures can be found on the last page of this guidebook. **Vectors** can also be imported by clicking on the **Image symbol** under the arrow in the green square. The red square contains all the settingsss for layer management and the power and speed settings for the operation. Multiple layers can be created to combine different settings within the same operation. The order of layers from top to bottom is also the order of execution.

Note: Keep the order of the layers in mind before you start the operation! If you cut out small pieces that you also want to engrave, it is always better to engrave them first, so move the layers with the mouse.

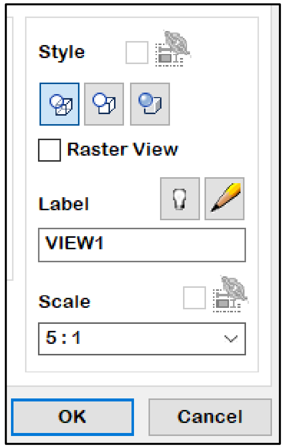
There are already a lot of presets provided by the manufacturer. They can be accessed through clicking on the ‚**Presets**‘ drop-down menu found in the red marked square on the previous page. Those contain most of the materials that can be processed but some additional ones like thick paper have been tested during this project. Most of the times, the provided settings are enough to get successful parts. But for some materials, **more efficient** settings can be applied to cut the production time. The engraving settings provided here work best at **250** dpi, an adaptation for higher resolution settings has to be made to prevent ‚**over-treatment**‘. It is possible to add own presets with the option near the bottom vsible in the screenshot on the right.

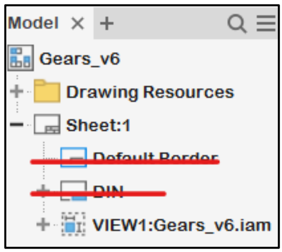
For setting up the workpiece in the operation chamber and aligning the drawings, vectors and images with the workpiece, there is a built-in **CMOS camera** on the laser head with a **stitching** feature. To get to this preview function, click on the **‚camera‘** symbol found in the top left corner of the Beam Studio homescreen. This function is only available if the BEAMO is **connected**, of course. To start scanning the work area, simply **draw a square** with yout computer mouse and the laser head will move along a path to gain all the necessary picture parts. As you can see in the screenshot on the right, a **blind spot** is left on the top edge of the work area. This is the result of the camera being located beneath the laser nozzle and it cannot ‚see‘ the upper part, otherwise the laser head would smash into the wall of the operation chamber. It is of course possible to place the workpiece there.



Note: <u>The stitching can sometimes be distorted and missaligned. Always scan your whole workpiece if spacing is important! If you see any unwanted glitches, do the whole process again. You can delete the stitched image with the ‚bin‘ symbol found in the left toolbar.</u>

Inventor

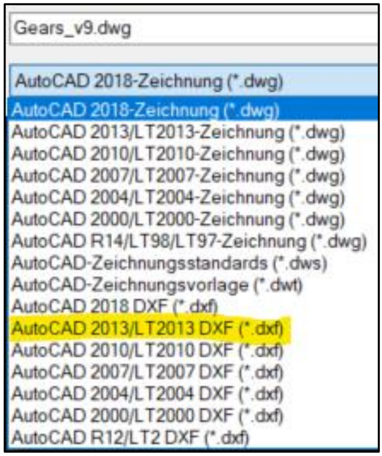




One of the most versatile ways to use the BEAMO is by laser-cutting forms and shapes from **CAD** drawings. Wether this may be parts for your project like gears or folding shapes, Inventor can export the right files and here is a short description. To export vector files from Inventor, a drawing has to be created with ‚**File**' > ‚**New**' > ‚**Drawing.idw**'. The template of the drawing does not matter, any will work. **Import** your drawing into the plan layout by clicking on 'Base' in the top left corner and select the right scale. After that you have to **remove everything** except the drawing itself, so all borders and plan heads etc. have to go as shown in the right screenshot. **Next**, to export the vectors of your work, go to '**File**' > '**Safe as**' > '**Safe Copy as**' and then select the **.dxf** format. This is the vector format which can be processed by Beam Studio.

AutoCAD

Another CAD program which easily can export **vector** files is AutoCAD from AutoDesk. Here the process is almost the same as with Inventor, although the scale of the drawings can deviate strongly depending on the version of the program and the template. To export your drawing from AutoCAD, simply click on the AutoCAD Icon in the top left corner as shown in the screenshot on the right. Then navigate to **'Safe as'** > **'other Formats'** and choose the **.dxf** format in the **AutoCAD 2013 version** as shown on the right. The newer version of 2018 works too but Beam Studio likes the 2013 one for some reason. AutoCAD is a very good tool to create shapes that are a little more complex than just rectangles, which of course can also be drawn with the built-in feature in Beam Studio.



Note: <u>It can happen, that the .dxf file does not show up after importing it into Beam Studio! It is most likely that the scale is way off and you either can not see the file because it is too small or because it is so big, that it does not fit onto the work area at all. Keep that in mind before exporting and measure your parts. Beam studio works in Milimeters.</u>

Safety precautions and rules of use

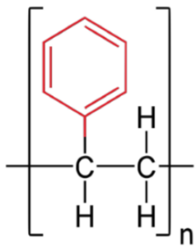
Lasers are dangerous even if they are properly enclosed. A certain risk always remains, espacially when the machine is used by many people at once and some are just learning how to use it. As this document shall help users to get their projects done safe and with ease certain rules and guidelines have to be made up. Those rules aim to procets the user as well as the machine to ensure a long lasting lifetime. The following safety rules have to be understood and applied:

- **Never leave the machine alone during cutting operations!**
- **When pricessing flamable maerials, always have a wet cloth besides the machine!**
- **Do not use the machine if you see any visible damage to the laser head or the belts!**
- **Do not open the lid during operation!** (There is a safety switch but it is not super fast)
- **Make sure the material you have is safe to use!** (see dangerous materials on page 15 for info)

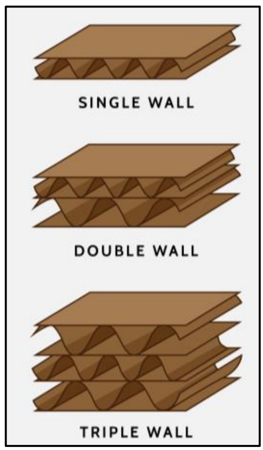
Note: There is a fire extinguisher in the hallway just out of the lab door. Just saying!

Dangerous Materials

There are a number of hazardous materials which are divided into two different categories. The first category includes all materials that release **toxic substances** and particles when exposed to the laser. Despite the use of an exhaust system, these particles can stick to the workpiece and some substances can even damage parts of the machine through corrosion. These substances include the materials **PVC**, **PC** and **ABS**. They release **carcinogenic** substances when processed by laser light and certain acids can attack machine parts. In general, materials with aromatic **benzene rings** in their chemical structure are not suitable for processing. The problem with polycarbonate, for example, is that it is very difficult to distinguish visually from the safe **PMMA**, which is another name for acrylic glass.



The second category includes substances that do not emit any hazardous substances in principle, but which pose a safety risk in terms of fire hazard due to their composition. This includes wood that is thicker than 5 mm and multi-fluted cardboard. An example of multi-fluted cardboard is shown on the right. These materials can catch fire especially when high light power is combined with slow laser head movements. Processing the

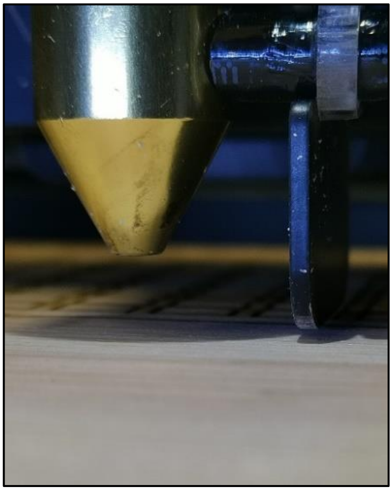


same areas several times in short intervals can also promote pockets of embers. Sufficient time must therefore be allowed when planning the operation to avoid igniting possible small pockets of embers by repeating the operation too quickly. Since the laser head and the electronics attached to it are very close to the workpiece, even a small open flame can cause serious damage. The lens in the laser head can soot and possibly even break under the heat. On the right you can see an example of an incident with double-walled cardboard. This result was very surprising and educational. Only by following the safety rules could the open flame be extinguished quickly and damage to the machine prevented.

Limitations

Of course the machine has some limits due to its compact size and the maximum laser light output of 30 W. This results in a set of restrictions which are listed and described below. A distinction is made between physical limits and limitations ragarding some materials. The specifications of the BEAMO can be found by following this link.

Physical Limits

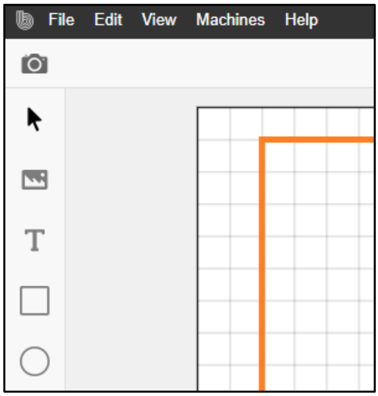


The area which can be processed with the laser is approximately **300 mm wide and 210 mm tall** and is therefore a little more than on a standardised DIN A4 sheet. The maximum thickness of parts that fit beneath the laser nozzle is approx. **16 mm** with the cutting pad installed and roughly **36 mm** without it. Keep in mind that the focus point lies slightly below the metal guard which can be seen on the right. Such **short distances** should be **avoided** for safety reasons. If the laser head gets caught in the workpiece, the belt system and the laser head may be damaged. The larger the workpieces, the greater the risk that an unevenness in the material will lead to contact with the laser head. Especially with materials that **warp** or are already **bent** under the influence of the laser, it must be checked whether there is enough clearance at all points.

Secure those materials with painters tape to avoid collisions and misalignment.

Note: If it is possible, it is always better to cut the raw material into smaller pieces already to avoid collision. With stiff materials this is less important.

Another limitation exists in regards of the work area. The work area in Beam Studio and the real world work area **do not overlap** exactly, which can lead to parts being cut outside of the material. Two things have to be kept in mind before starting to align the part. Firstly, it seems that the real work area is shifted a little bit down and about double the amount to the right. On the right you can see the approximate **top left corner** of the real work area in orange, which is also the home position of the laser head. The second thing to keep in mind is, that the first rule is only applicable if the meshed real work area is pushed all the way to the **bottom** end stops! If you remove the mesh for cleaning, make sure to **slide it down** all the way to not have another person misalign their work.



Note: Use the camera preview feature to make sure, your drawing fits onto the material well. But also do not place your parts in the middle of a big sheet to safe some of it. Common sense!

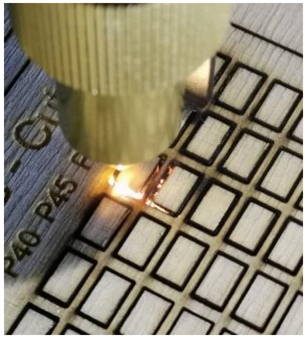
Material Limits

Of course, there are certain materials that simply cannot be processed with the normal gas laser. These include all types of metal and generally very thick materials. The respective maximum tested thicknesses are listed in the Cutting chapter from page 20. Stainless steel can be processed with the help of the diode laser module, which is available separately. On the right you can see a piece of plywood with a thickness of **6.5 mm**, which can no longer be cut with the BEAMO. Since wood can ignite with slow movements and high light output, this poor result even poses a fire hazard.

You can find all the minimum capabilities regarding the workability of materials on the website of FLUX by following this link.

Note: During the testing period of this thesis, not all the available materials got tested with all the possible combinations of power settings. It is very likely that there are settings, which can ultimately result in successful parts even though they are here presented as not workable.

Cutting



In order to enable the user to carry out successful projects and to save the lengthy test phase, this chapter contains recommendations for the cutting operation with the laser device. These recommendations may not be effective with organic, natural materials, as even slight differences in density can influence the result. This is especially noticeable with plywood. The following table contains several recommendations for several materials:

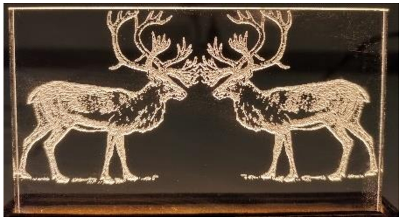
Material	Thickness	Power	Speed	Executions
Plywood	4 mm	P50-P70	S003-S006*	3x
PMMA	3-4 mm	P40-P55	S003-S006**	1x
PMMA	8 mm	P50-P60	S003-S005	3x
Leather	~2 mm	P40-P60	S003-S014	1x
Cardboard	1 flute	P20-P60	S003-S014	1x
Paper	1 mm	P20-P35	S014-S025	1x
Paper	2.5 mm	P45-P55	S012-S015	2x

*Keep in mind, that too fast repetitions can excite embers. See the picture in the top rigt corner!

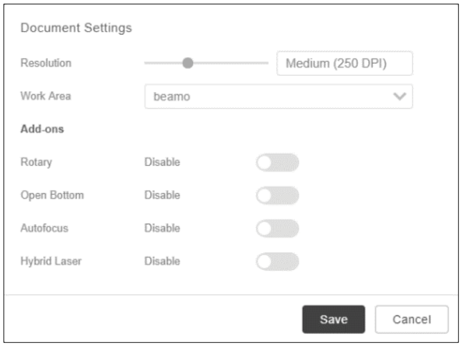
**The surface finish gets better when using slower speeds.

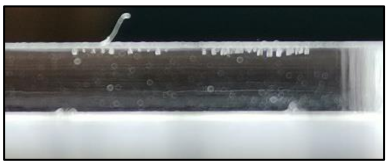
To achieve the best desired result, some experience is always necessary. The test pieces from the test phase are always available for viewing near the machine. It is advisable to take a look at the test pieces before the operation. If surface quality is not of great importance, acrylic glass, for example, can also be cut much faster, which can greatly reduce the operation time.

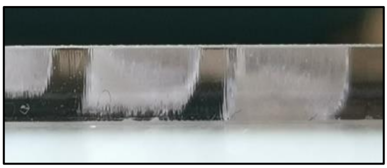
Engraving



Getting good engravings can be difficult. Especially with real photos, the results can be unattractive. Especially on acrylic glass, it is not recommended to engrave faces, for example. Other objects such as landscapes can look good on acrylic glass with a little practice. The results of the tests are available in the laboratory and are very subjective. One important setting can have a decisive influence on the quality of the engraving. The resolution can be set in four steps and controls the spacing of the lines on the x-axis. This setting is **comparable to** the layer height in **3D printing**. Finer lines or higher resolutions multiply the operation time. To change the resolution, go to ‚**Edit**' in the main window of Beam Studio and then to ‚**Document Settings**'. For most engraving operations, **250** dpi are well suitable but for really fine details choosing **1000** dpi will result in the best quality. As already said, the quality changes with higher resolutions and the engraving depth does the same. Here you can see he same power settings with **100** dpi and **1000** dpi. Note, how the upper sample barely got scratched and the bottom one is cut all the way through.

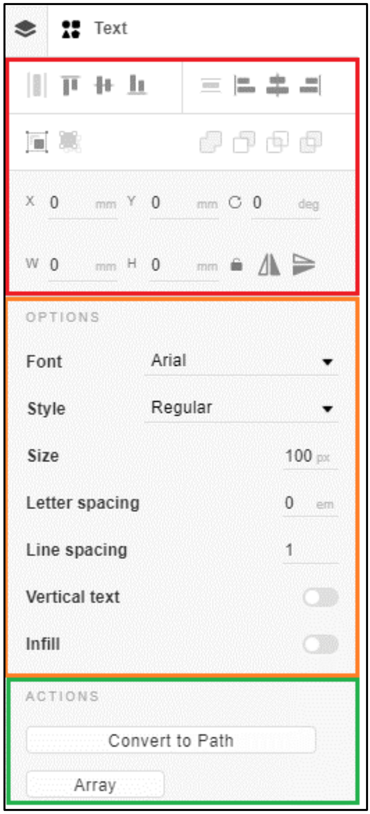




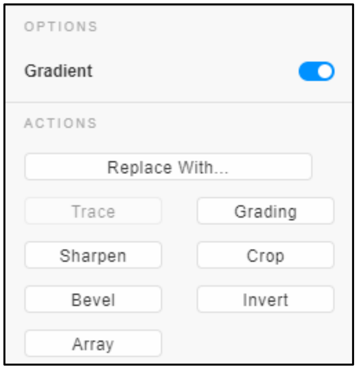


To import pictures and vectors for engraving simply either click on ‚**File**‘ > ‚**Open**‘ or choose the **picture** symbol in the toolbar on the left edge of Beam Studio.

Text: Found in the toolbar, text can easily be placed within Beam Studio. There are many options to edit the written text within the settings menu on the right side. You can align the textbox in reference to the work area and change its position with the tools found in the red square. Within the orange square you will find menus to change the font, size and style of the text. Further, spacings and vertical text can be set. The ‚Infill‘ setting is important. When **disabled,** the text is converted into paths and get **cut** out. It is important to check this setting if you don't want to cut right through your phone case or laptop back! When **enabled,** the text gets sliced for the **engraving** operation. The options in the green square allow you to make automated arrays of the textbox or to convert the letters into paths for disassembly.



Pictures: Every picture that is imported into Beam Studio is automatically recolored using a greyscale. Because the laser can only produce one* **„color“** this is mandatory and using colored pictures requires some editing to get a good result. When the chosen image is selected, this editing menu appears on the right side of Beam Studio. Some **tips** for choosing pictures before the editing steps are described:



- Best case: Take monochrome pictures if possible
- High contrast is important for the grey scaling
- All surfaces that should be visible have to be lit approx. The same amount
- No big shaddows are possible, only with loss in details
- Eye sections have to be properly lit to avoid a racoon effect.

The gradient can be edited by clicking on the ‚**Gradient**‘-button. You can disable the gradient and then choose a threshhold gradient uppon which the pixel gets added to a **pure black/white** picture. All the white spots are removed and are seen as **transparent.** Keep that in mind, it can look awkward if you engrave a face and just the cheeks and the forehead have blank spots! With the gradient disabled, you can ‚Trace‘ the outlines of your picture to get vectors for cutting if you disable the ‚Infill‘ in addition.

***other laser technologies can produce different colors on metals for example by varying their frequency and intensity.

Odd shapes

It is possible to cut and engrave materials and faces that are not perfectly flat. This is due to the focus point acting more as a focus line with an approx. 8 mm length. Further, due to the always bigger gaps appearing resulting from the burning away of surrounding material, slight changes in focus do not matter that much anyways. This enables a whole new set of objects that can be treated with precious laser light.

Round objects

Grill forks for example! Due to their round face and relatively small diameter, the edges get rather steep quickly when viewed from the top. For this very reason, when engraving round objects, always leave some free space to the sides, the resulting engravements or cutting edges would only look good exactly from the top. More on the topic of engraving grill forks on page 36.

Uneven faces

Due to the same reason of the focus point acting more as a line, even quite rough surfaces can be engraved. This is shown with the leather engravings found from page 37 on. The limits of the maximum roughness lies within the ~8 mm focus line.

Tips and Tricks

This chapter can help you if something did not go as planned.

-) The piece caught fire during the run!

Be careful when processing **multiflute cardboard** or thicker **plywood!** Always have something **next** to the BEAMO to extinguish the flames!

The excitement of embers or even flames can happen uppon multiple reasons. It is firstly possible that the chosen material was soaked in a **flamable liquid** like IPA or Acetone, either from cleaning beforehand or oily remains. Secondly, treating multiflute cardboard and plywood with high power settings at low movement speeds can result in the excitement of embers. Especially with the thicker cardboard, air that reaches through the flutes from the side can perfectly support the generation of this unwanted incident. It was found that making flammable surfaces wet before treating them with an intense laser beam can help to delay the heating up and ignition a bit.

Remember tho: It should be common sense that the operation chamber should **not be flooded** with water!

-) The result is not satisfying!

If the work piece is not what it should be after the process is finished and it is still laying exactly as it was before, there are a number of things that can be done now.

With plywood there seems to be a **limited amount of passes** that can still remove material. Some kind of work hardening or another form of resistance to laser light develops during multiple lower power passes. With plywood it is always advisable to crank the power all the way up (the machine limits the maximum increment to **70 %** to preserve the lifetime of the laser tube) and find a slow enough speed, where the parts just does not catch on fire immediately.

Thicker acrylic glass tends to distort the laser beam when the speed is too high, so slow speeds result in straighter and cleaner edges. Multiple passes are also possible with acrylic glass but the surface finish will **degrade** with more executions.

-) No connection between Beam Studio and BEAMO!

There is the autmatic Connection Wizard for troubleshooting in Beam Studio. Check if your computer and the BEAMO are actually in the same network! If so then check if the BEAMO has got a valid IP-address from the router. You can also ‚**Test the Network Settings**', the User Interface where to find this option is shown on page 8.

-) It smells bad or like barbeque in the lab!

Multiple reasons could lead to a smoky lab situation.

Check if the shut off valve is in an open position. There is a switch on the wall near the workplace of the BEAMO. It should light up when the valve is open. Next, check if the built-in ventilator is set to **30 % speed**. If it is set to a **lower speed**, fumes can not get sucked out properly and could escape through the gaps of the device.

If the speed is set **higher**, initial testing showed that the fumes then got pushed out of the SLA printer enclosure and entered the lab room in that way. Either way is bad and depending on the material, harmful fumes could lead to longterm **respiratory damage**.

Note: For more tips and tricks, look in the BEAMO manual provided by the manufacturer. The printed version should be near this guidebook and the digital version can be accessed through this link.

Projects

Here, five projects are described for recreational use. The settings with which most of them got done are supplied, although for the first one having plywood as material changes in density etc. could lead to unsuccessful attempts of recreation. More treated objects and little projects are present on display in the lab near the BEAMO. There are also more pictures of additional projects from page 37 on.

Skill in craftmanship and creativity are required with the post-processing of some parts of the projects, but I am no artist myself either so everything is doable of course.

Again, if you like your project and want to share it and see other previous works, use the hashtag #beamedatlapin to contribute to the collection. You can reach the official collection via this link.

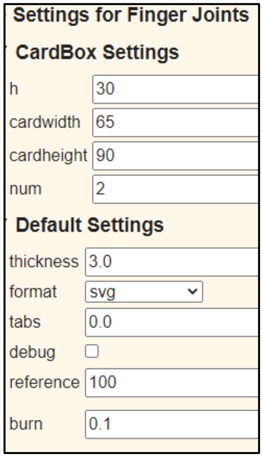
Plywood boxes

The first projects are the plywood boxes. They can either be designed as poker card boxes or act as storage bins with multiple compartments inside. All the shapes for the various boxes are created using the boxes.py web-tool.

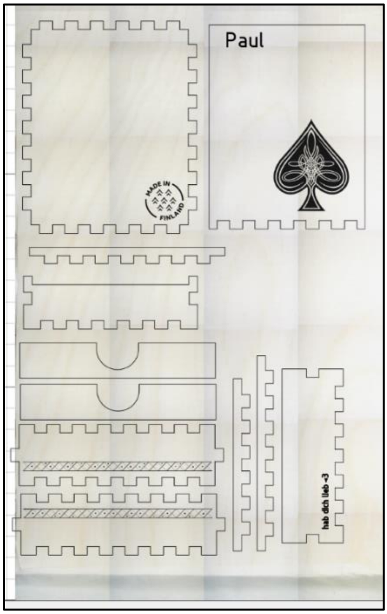
It can be accessed by following this link and is free of use. Down below you can see the main page.

The boxes are usually made out of plywood, but cardboard and thick paper like watercoloring sheets could also work.

After typing in all the required specifications into the web-tool simply generate all the shapes of the parts by pressing ‚**Enter**‘ on the keyboard or click the ‚**Generate**‘ button. On the right you can see the most important text boxes which have to get filled. All the text boxes have descriptions besides them but don't forget to set the thickness of the material and you can set the ‚**reference**‘ box to ‚**0**‘ to not generate one piece of trash more. The burn factor can be set to **0.2** to tighten the fit a little bit but this changes from material to material of course.



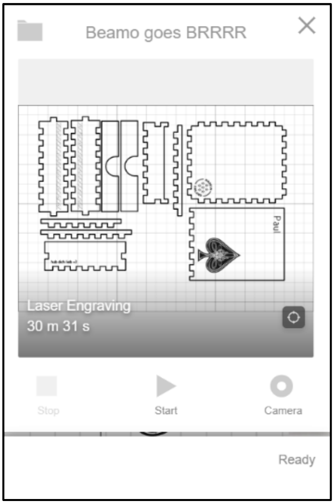
When the shapes are generates and saved, import them into Beam Studio. Choose ‚**Layers**‘ when importing to get one layer per shape. This is important to be able to move them around and fit them onto the work area afterwards. As shown on the left, additional symbols and text can be added to the work area but keep in mind to **add a separate engraving layer!** After you are done with arranging the shapes with the help of the camera preview function you can group all the shapes together by selecting them all and choosing ‚**group**‘ with the right mouse button clicked.



After you are finished you can slice your operation and start the process. Due to the plywood being a little harder to cut and the very real chance of it to start a fire, **stay next to the machine** and have a wet cloth ready!

After the successful cut, remove the parts and clean them off with the help of pressured air. You can also wipe the edges off to remove the charred ash.

After that, you can start with the assembly using **woodglue**. You can then sand the faces and edges to get a clean look and sharp edges. Look at page 29 for an example of clean edges. For additional **reinforcement**, try using little **nails** that can be found in the workshop. Be careful not to split the thin sheets.



Used Settings:
E: 500 dpi, **P25 S175**
C: **P65 S007 3x**

Business cards

The next project was created using PowerPoint. Business cards can give the opportunity to get creative using the tools in the workshop. For this piece, the standard pocket card size of **85 mm x 54 mm**. You will find different common dimensions for other cards online. The different parts of the card are achieved by **exporting** the vetors for cutting **separately** to the ones for engraving. Export your shapes out of PowerPoint by going to **‚File‘** > **‚Safe as‘** and select the **.svg** filetype. It is again advisable to engrave first and then cut out the shapes and outline.

Thick paper with **300 g/m²** was used for this project for higher rigidity which can be found in the arts and crafts aisle in **Tex** (of course).

Note: As engraving anything can take a long time, try by printing your business card or any other card with a regular toner printer and just cut out the shapes precisely later. This will speed up yout production time significantly, especially if you want to produce more than two cards.

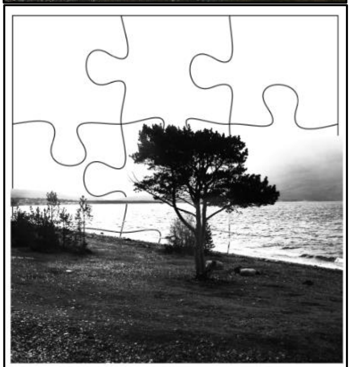
Phone case engraving

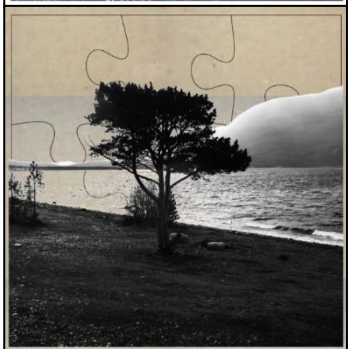
Engraving phone cases is a good way to decore personal objects permanently. For this reason, think in advance what exactly you want to engrave onto the surface. There are cases with a leathery look, they require a little stonger settings but this material is easily burned through, so be gentle in ramping them up. If you do not like the result of the texture, just apply it again. On the right you can see multiple images and shapes engraved onto a phone case. Fine lines are as well possible as bigger faces. Some cases will end up with a glossy look and the material should not curl up during the process, that means a too deep cut.

As cheap cases are often made out of nasty plastics, don't exaggerate it with the engraving.

Settings used:
E: 250 dpi, **P13-P15 S140**

Puzzles





Another possible project is the creation of self designed and produced puzzles. Two different kinds of puzzles can be made. The first one is the easiest one and only requires the raw material on which the picture or pattern is engraved and the puzzle shape is cut at the same time. You can see the manufacturing process of a simple nine piece puzzle on the right hand side.

The raw image got edited to get the best result possible. Then the generated puzzle shape is overlayed in a separate layer for cutting! To make the transparent spots more visible, the camera preview feature is used to get the real color of the cardboard in contrast to the black engraving spots. The last picture shows the finished puzzle. Due to the weak properties of the cardboard, the fit of the pieces is quite loose because alot of material got removed. With other and thicker materials, this effect is not as strong.

Settings used:
E: 250 dpi, **P15 S095**
C: **P25 S006**

The puzzle shapes for cutting get generated using a free **web-tool**, which can be accessed using this link. Here you can set the sliders and export the neccessary **.svg** files via the ‚**Download SVG**' button.

Note: You can also just glue normal pictures to a piece of cardboard or thick paper to get a nice colorful puzzle.

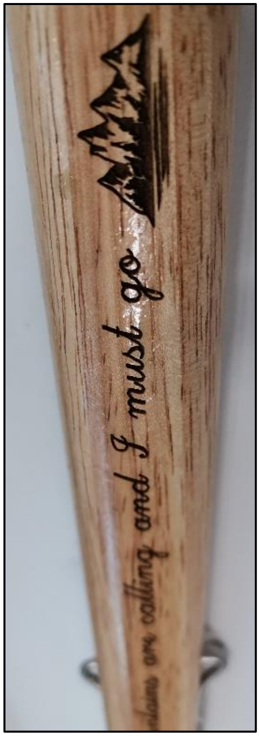
For this you have to adjust the settings a bit because you have to cut through the image paper in addition, also if you are using thick watercoloring sheets.

Settings used: for cutting thick paper + picture paper: **P45 S015 2x**

Here, a picture was engraved directly on **~2 mm** thick watercoloring paper and cut with the settings mentioned above. The watercoloring sheet is perfect for this, as it is rigit, white for better contrast and burns cleanly and leaves just a very thin edge on the back side.

Grill Forks

As already mentioned, grill forks are another project possible. Here the meshed work platform has to be removed to get more clearance and using the previewing camera feature is vital to the success. Due to the steep angles on the sides, **leave gaps** of about **3 – 4 mm** to either side to prevent visible distortions.



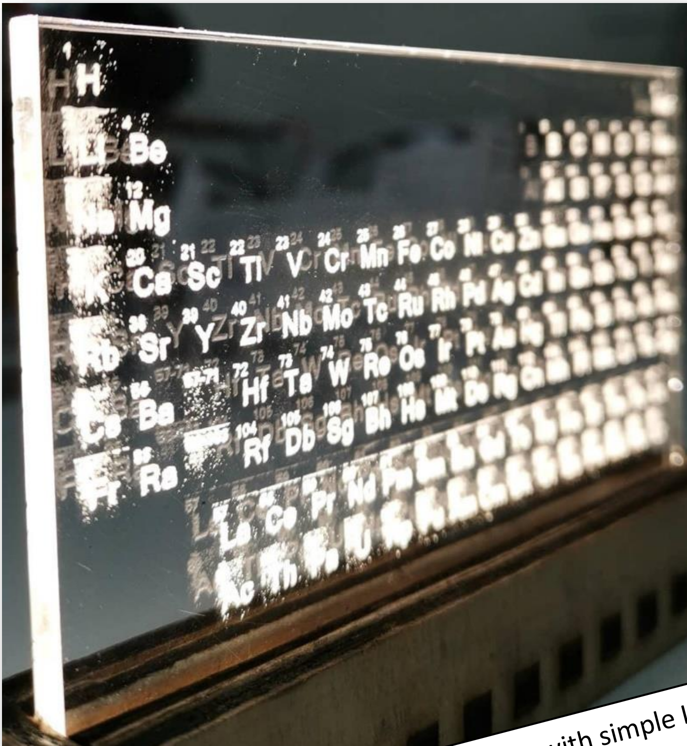
The premade settings for engraving wood are applied here and the focus is set to the top edge closest to the laser nozzle. As those forks are round, they **have to be fixed** in place using painters tape to prevent them from rolling away during the operaton.

On the right, you can see the preview of two forks with some **stitching distortion** in the top part. Here, the premade settings were applied but with **500 dpi**, which resulted in very deep embossments. They are approx. **1 mm deep** and help to keep the texture on the surface for a long time.

Note: <u>You can rotate your object between engraving sessions to get more surfaces covered. The rotating add-on for the BEAMO would speed up this process!</u>

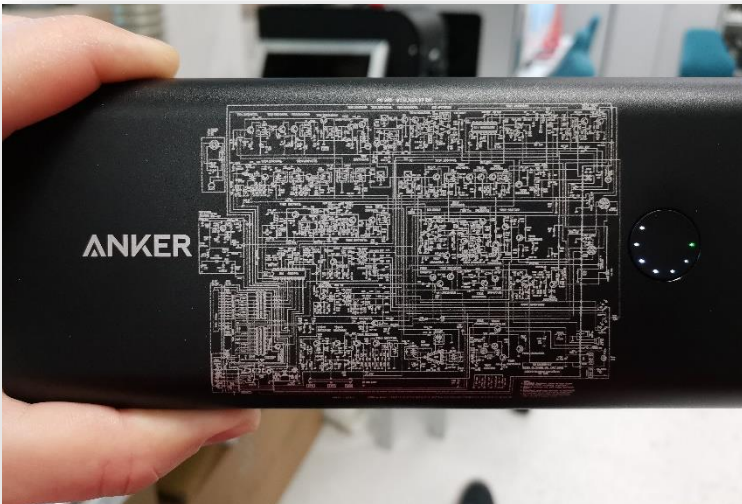
Additional Inspirations

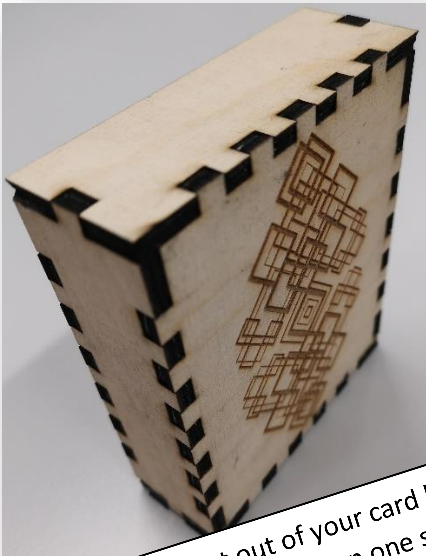
This last chapter is dedicated to all the other projects and materials I worked on during the testing phase. Some of the same images and projects can also be found under the already mentioned hashtag *#beamedatlapin* and on the official BEAMO Instagram project page by following this link.



Enlighten your engraved PMMA sheets with simple LED strips for nice looking displays in high quality!

Anodized aluminum of a power bank? No problem!





Get the most out of your card boxes by engraving more than one side!

Leather tends to curl up during laser engraving.
Use some painters tape to hold it down securely!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Useful Web-Links

Here, useful links are provided in clear text. Enjoy!

Flux Europe Download (for Firmware, Beam Studio, BEAMO user manual):
https://www.fluxlasers.com/downloads/

Flux Europe BEAMO specs:
https://www.fluxlasers.com/products/beamo/

Box vectors for projects:
https://festi.info/boxes.py/?language=en

Puzzle shape vector generator:
https://cdn.rawgit.com/Draradech/35d36347312ca6d0887aa7d55f366e30/raw/b04cf9cd63a59571910cb226226ce2b3ed46af46/jigsaw.html

Instagram page of Lapin UAS projects:
https://www.instagram.com/uastw_goes_laplanduas/

Free Vectors for Laser Cutting:
https://3axis.co/

DXF Projects page:
https://dxfprojects.com/

Icons and Photos:
https://thenounproject.com/

Quick Start Guide

This quick start guide contains only the most important steps without any descriptions. Simply follow this steps to get started right away.

1. **Power on the machine**
2. **During boot-up, clean out the work area, lies it flat?**
3. **Put the raw material into the operation chamber**
4. **Set the focus with the help of the little transparent guide piece**
5. **Connect the BEAMO with your laptop/ Beam Studio**
6. **Align your image/vector with the help of the camera feature**
7. **(Correct the image in regards of gradients and sharpness)**
8. **Set the power and speed settings and bring the layers in order**
9. **Slice the operation**
10. **Get started!**

Important Notes:

Do not forget about setting the **focus!**

Never leave the machine alone during **cutting** operations!

Always have something to extinguish fire **next** to the machine!