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Masterarbeit

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Development of a Hand-Held Piece for application with the Picosecond Infrared Laser

Fakultät Life Sciences
Department Medizintechnik

Faculty of Life Sciences
Department of Biomedical Engineering

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Masterarbeit eingereicht im Rahmen der Masterprüfung

im Studiengang Biomedical Engineering
am Department Medizintechnik
der Fakultät Life Sciences
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in Zusammenarbeit mit:

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D. List of Abbreviations

Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
PDT	Photodynamic Therapy
PIRL	Picosecond Infrared Laser
Laser	Light Amplification by Stimulated Emission of Radiation
MEMS	Micro-Electro-Mechanical-System
ER:YAG	Erbium-doped Yttrium Aluminium Garnet
TEM	Transverse Electromagnetic Mode
NA	Numerical Aperture
HHP	Hand-Held Piece
CaF_2	Calcium Fluoride
AR	Anti-Reflective
Au	Gold
Ag	Silver
Al:	Aluminium
UV	Ultraviolet
AMA	Articulated-Mirrored-Arm

E. List of Symbols

ω_0:	Gaussian beam waist radius at z_0 $[m]$
I_0:	Laser peak power intensity $[\frac{J}{cm^2}]$
r:	Radius $[m]$
z:	Location along the laser beam’s propagation axis (z-axis) $[m]$
z_R:	Rayleigh length $[m]$
z_0:	Location of the Gaussian beam waist radius ω_0 $[m]$
λ:	Wavelength of the laser $[m]$
$R(z)$:	Radius of curvature at z $[m]$
θ:	Far-Field divergence $[rad]$
M^2:	M-square-factor [/]
$d(z)$:	Laser beam diameter at z $[m]$
d_0:	Laser beam diameter at z_0 $[m]$
n:	Refractive index [/]
n_{core}:	Refractive index of the optical fiber’s core [/]
$n_{cladding}$:	Refractive index of the optical fiber’s cladding [/]
θ_{ac}:	Optical fiber’s acceptance angle [°]
θ_{sp}:	Light cone divergence angle at the optical fiber’s exit [°]
f:	Focal length $[m]$
d_1:	Distance from the lens to the new beam waist of the Gaussian beam in the image plane $[m]$
ω_1:	New beam waist radius of the Gaussian beam in the image plane $[m]$
D_{LC} :	Light cone diameter at position z $[m]$
Δ_{FA} :	Distance between optical fiber’s exit and lens A $[m]$
Δ_{AB}:	Distance between lens A and lens B $[m]$

Δ_{BS}: Distance between optical fiber’s exit and focal point $[m]$

Δ_{BS1}: Distance between lens B and fixed mirror $[m]$

Δ_{BS2}: Distance between lens B and MEMS $[m]$

Δ_{BS3}: Distance between MEMS and focal point (working distance) $[m]$

f_{mems}: Scanning frequency MEMS $[Hz]$

f_{laser}: PIRL’s repetition rate $[Hz]$

1. Introduction

The application of lasers in medical disciplines became an important field of research since the first working laser system was developed in 1960. The primary medical application of lasers in 1961 was to perform reattachment of retinas [1].

However, in the last decades, laser surgery in ophthalmology dominated the variety of medical laser use [2]. This particular development refers to the ability of cutting quicker, more precise and more efficient with lasers than with regular surgical equipment (e.g. surgical blades) [3].

While there are different kinds of lasers, three Systems are mainly used in medical areas: The CO_2 laser is used in surgical applications, due to its bleeding control properties. This control mechanism is achieved by transforming the light energy into heat, which vaporizes the targeted tissue. Additionally, lasers are used, which lead to quicker blood coagulation. The radiation of the Nd:YAG laser leads to quick blood coagulation and can be transported through optical fibers. The Argon laser is commonly used in dermatological treatments, due to its penetration characteristic [4].

As a result of changing health standards [5], new cutting systems became necessary which provide better results referring to healing time and tissue preservation. For this reason, new research projects in the field of medical laser systems were initialized in order to fulfill new requirements. A new laser system, which is improving tissue preservation and shortening healing time, is the **P**icosecond **I**nfra**r**ed **L**aser (PIRL) [6]. With this laser, water molecules in the tissue are energized. This form of selective energizing does not lead to plasma formation or ionization during the cutting process. Since the pulse length is at picosecond range, the ablation is driven faster than thermal exchange of energy and shock wave propagation in the tissue. Additionally, no photochemical or photo thermal effects are generated with the PIRL, which is a main advantage over other surgical lasers.

Laser systems improve the efficiency of surgical treatments, since there are less sterilization issues, due to less surgical elements, which are in direct contact to the tissue [7]. Furthermore, scanning systems are able to achieve faster surgical procedures which can also lead to less physical impact to the body [8].

It is possible to propagate the laser light with fiber optics into the body (e.g. the human gastrointestinal tract). This is used to bypass invasive interventions. [9]

Considering the advantages of lasers for medical applications, it is worthwhile to invest further effort in research and development.

2. Motivation and Goals

During the development of the PIRL, a two-dimensional scanning system was integrated in order to provide precise cutting results [10]. Testing this type of scanners on vocal cords, in the laboratory, delivered surgically clean results. By avoiding coagulation and carbonization, the treated tissue was minimally damaged [11].

The surgical challenges became more complex and the targeted zones became more sensitive, as well (e.g. invasive eye treatment). Due to higher complexity, a system with more degrees of freedom has to be developed in order to provide more efficient results.

Another critical aspect is the accessibility of hard reachable areas of the human body. With a static set-up it is not possible to reach all parts of the body. A Hand-Held Piece would enhance approachability. Due to the Hand-Held Piece's flexibility, the laser light could be principally carried to any targeted zone.

To achieve optimal laser treatment, it is beneficial to develop a device in which fast laser handling and more dimensional laser scanning could be combined. A solution is required which minimally affect the energy during beam propagation. Furthermore, it is necessary to develop a system, which is ergonomically habituated in surgical applications (e.g. surgical blades) in order to provide an accepted device used by surgeons. For this, a Hand-Held Piece coupled with the PIRL for laser handling improvement, would be advantageous.

To realize faster and more dimensional scanning at the same time, a solution is required, which fits into a Hand-Held Piece and could be individually actuated by the operator. Based on this, a micro-electro-mechanical-mirror-system (MEMS) is used which has a high point to point frequency and is able to deflect the laser beam in two dimensions.

By using an articulated arm or a fiber especially designed to transmit light employed by the PIRL into the Hand-Held Piece, it is possible to provide all degrees of freedom during its use.

The goal of this thesis is to develop a Hand-Held Piece, which supports two-dimensional scanning combined with ergonomic aspects without losing much of the PIRL’s advantages.

3. Technical background

This chapter provides technical information about the PIRL and and its physical properties. Linked to this, the behavior of a Gaussian beam is termed as well.

3.1. The Picosecond Infrared Laser (PIRL)

The PIRL is a mid-IR laser scalpel meant to be used in minimal invasive surgery. Its pulse duration and wavelength are the key elements of its benefit. Due to the picosecond pulse duration, there is a significantly reduced shockwave excitation and thermic interaction in the surrounding tissue during the cutting process. This leads to less damage in the surrounding tissue [6]. The heat produced by the PIRL during the cutting process is much smaller than an Erbium:YAG Laser. An investigation was performed by Jowett et Al. where ex vivo porcine skin was ablated in a 5-mm line pattern with an ER:YAG laser and the PIRL. The results show, that the maximum peak rise temperature in skin surface was 2.05°C for the PIRL and 18.85°C for the Erbium:YAG Laser [12]. The PIRL's temperature rise leads to the prevention of unnecessary tissue coagulation or carbonization. Additionally, fig. 1 shows that the PIRL's hot spot is smaller than the one produced by the Erbium:YAG laser, due to reduced photothermal excitation, which leads to less area damage.

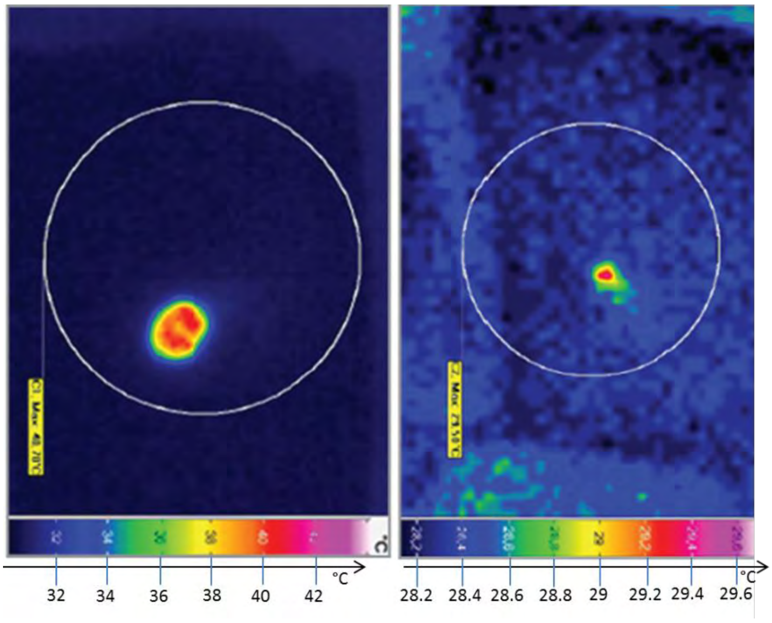


fig. 1 Thermal imagesof the porcine skin ablation. The circle represents a circular zone of ≈1 mm (diameter).
Left, Thermal image of the Erbium:YAG laser ablation.
Right, Thermal image of the PIRL ablation. [12]

Optical Specifications:	Electrical Specifications:
Central Wavelength:	Supply Voltage:
3000nm ± 100 nm	210-240V, 50/60 Hz
Pulse duration:	Maximum Current:
400±200 ps	16A
Pulse energy:	
>750µJ @ 1kHz	
Repetition rate:	
1000 Hz	

Table 1 PIRL's Specifications

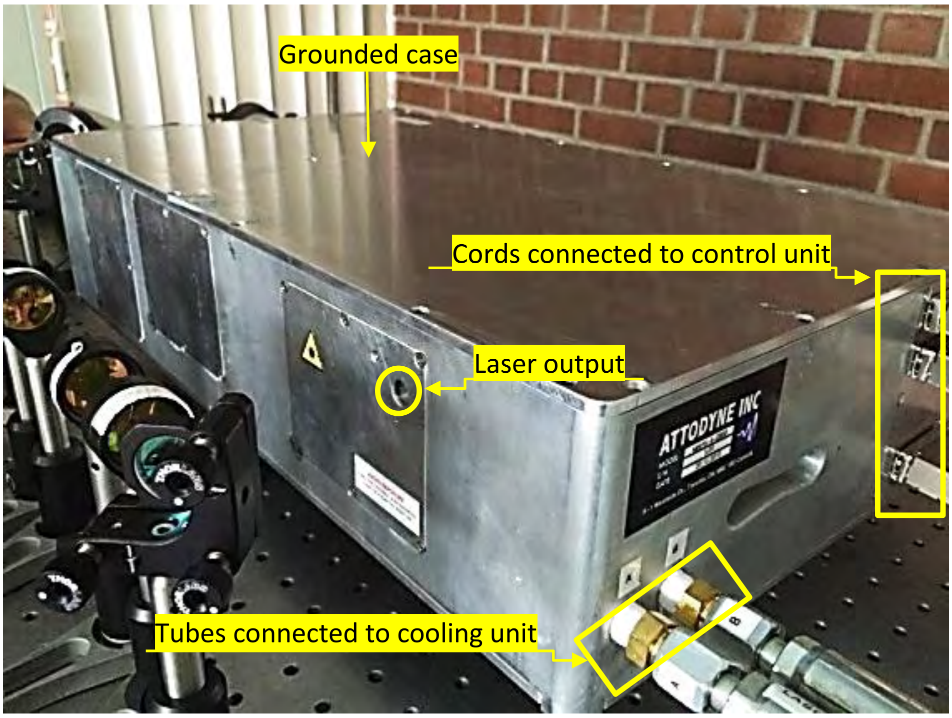


fig. 2 Output unit of the PIRL

3.2. Gaussian optics

Gaussian beam optics are a convenient model in laser optics. The benefit of a laser operating on the fundamental transverse mode (TEM_{00}), is that the laser beam is transformed into another Gaussian beam after being refracted by a lens. This leads to calculable results given a set of parameters [13].

3.2.1. Gaussian beam

The Gaussian beam is a satisfying solution of the paraxial Helmholtz equation [14]. Where the paraxial Helmholtz equation is represented by the Maxwell's equations for time harmonic wave of frequency in free space [15]. Paraxiality is given for waves with wavefront normals making small angles with respect to the propagation direction. Additionally, the intensity distribution is ideally a symmetric Gaussian function, centered about the beam axis. This behavior is observed in all transverse planes along its path. [16]

3.2.2. Transversal beam profile

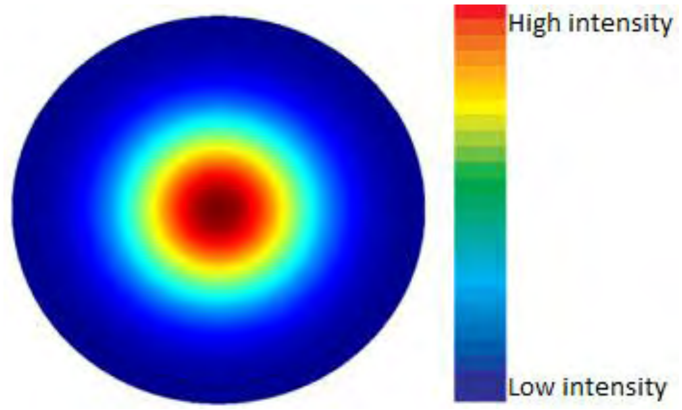


fig. 3 The ideal transverse intensity profile of a Gaussian beam spot.
Dark red (high intensity), dark blue (low intensity) on a Gauss distributed scale. [17]

The limitations of a Gaussian beam spot are not clearly bordered unlike the diameter of a circular aperture. Due to this, the definition of a Gaussian beam waist radius (ω_0) is set as the distance from the spots peak power intensity to which the power intensity decreases to $1/e^2$ (≈ 13.5 %) of its peak value [18].

The intensity distribution of a Gaussian beam $I(r)$ is concentrated within the distance of $2\omega_0$. The intensity distribution at the outer boundary of $2\omega_0$ is 0.0003 of the beams peak power intensity (I_0). Since it is a Gaussian beam spot, the half maximum of the lasers peak power intensity lies at the point of $0.59\omega_0$. [19]

To calculate the power distribution at any radius (r) for a given Gaussian beam spot it is necessary to know the peak power intensity (I_0) and ω_0 [16]:

$$I(r) = I_0\, \mathrm{e}^{-\frac{2r^2}{{\omega_0}^2}} \quad [\frac{J}{cm^2}]$$

Equation 1: Intensity distribution of the Gaussian beam

The calculation of the spot's power distribution is essential. It indicates whether the tissue ablation threshold is reached or not.

On the one hand, the peak power intensity decreases during the propagation of the laser beam along the z-axis. On the other hand, the beam diameter expands in the transverse direction (r-axis) while propagating along the z-axis fig. 4 (energy conservation). The profile shape remains Gaussian [20].

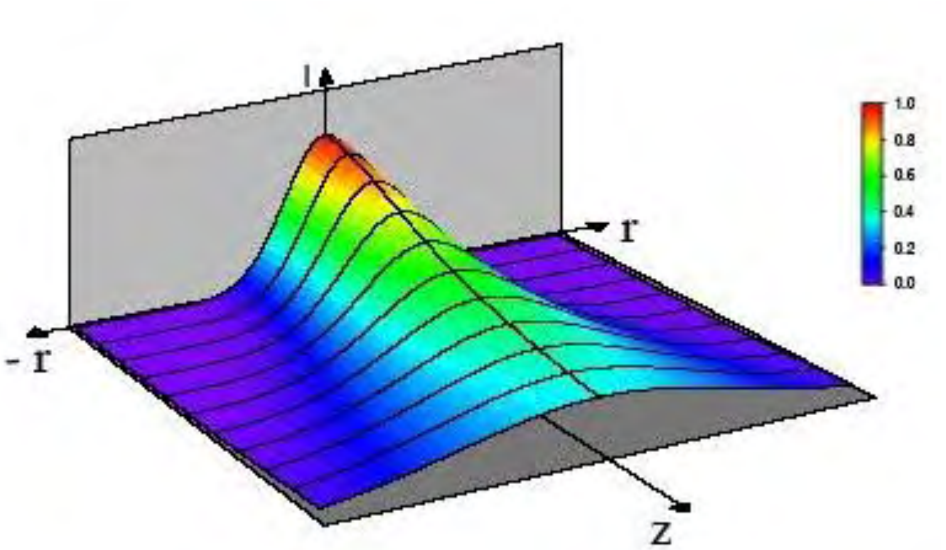


fig. 4 Peak power intensity amplitude of the laser beam decreases while propagating along z (0-low intensity, 1-high intensity) [21]

3.2.3. Axial beam profile

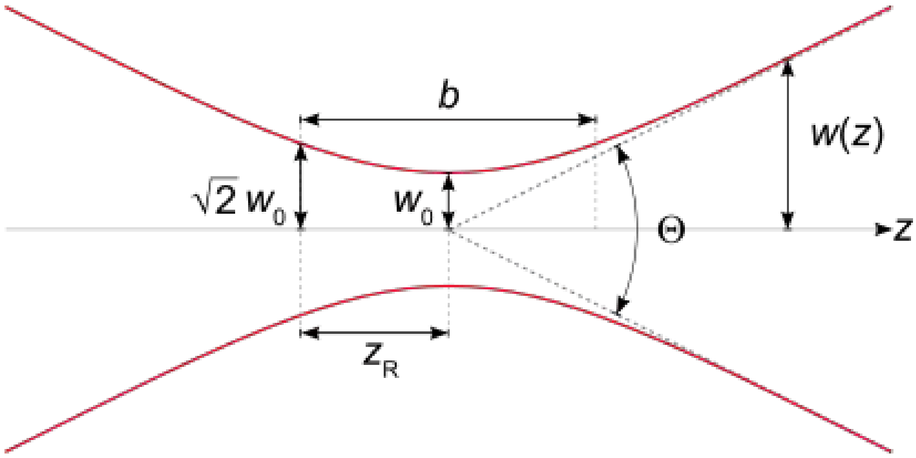


fig. 5 Axial beam profile Gaussian beam width *w*(*z*) as a function of the distance *z* along the beam propagation direction. *w*$_0$: beam waist radius; *b*: depth of focus; *z*$_R$: Rayleigh range;Θ: total angular spread (divergence) [22]

The Rayleigh length (z_R) is the distance along the propagation direction (z-axis) of a laser beam from the waist (z_0) to the point where the radius of the beam has increased to $\sqrt{2}\omega_0$ [23].

The Rayleigh length for an ideal Gaussian beam is given by the following relation [24]:

$$z_R = \frac{\pi {\omega_0}^2}{\lambda}$$

Equation 2: Ideal Rayleigh length

ω_0 is the radius of the beam waist at z_0 and λ the laser's wavelength in vacuum divided by the refractive index n of the material.

Past the Rayleigh length, the beam expands at a constant rate or angle (far field beam divergence). A Gaussian beam in TEM$_{00}$ Mode has the smallest far field divergence and the largest Rayleigh length compared to other modes [25] [26].

For beams with poor beam quality and a certain beam waist radius, the Rayleigh length is practically decreased by the M^2 factor. This leads to the situation that such beams have a larger beam divergence given a certain beam waist radius. This influences the possibility of focusing a Gaussian beam properly. [27]

3.2.4. Radius of curvature

As the beam propagates along the z-axis, the radius of curvature according the wave front of the beam, changes. It is infinite at the beam waist and decreases rapidly to a minimum at the Rayleigh length after the beam waist. It is also beneficial to know that R(z) → ∞ with z → ∞. The radius of curvature R(z) increases with larger distances from the beam waist (z_0) [26].

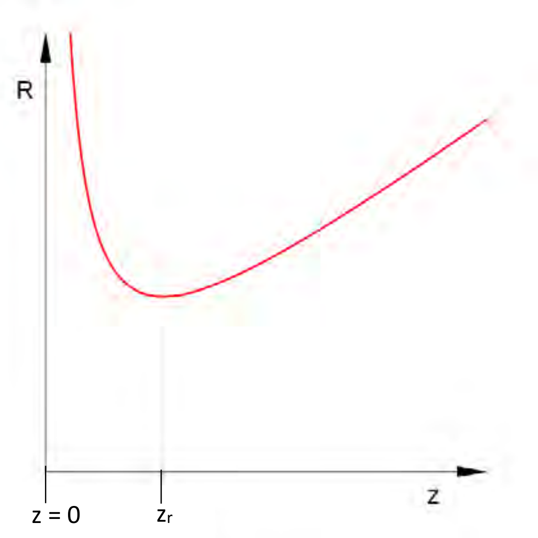


fig. 6 Radius of curvature R vs. the position along the propagation direction z.

R minimal at z_r [22]

The radius of curvature R(z) is defined through the following function:

$$R = z\left[1 + \left(\frac{\pi {\omega_0}^2}{\lambda z}\right)^2\right]$$

Equation 3: Radius of curvature

$R(z)$ depends on the position z of the beam along its propagation direction, the beam's wavelength λ in vacuum divided by the refractive index n of the material and ω_0 which is the radius of the beam waist at z_0 [26].

3.2.5. Far-field divergence

The divergence of a Gaussian beam is inversely proportional to its waist size. On the one hand, a laser beam focused to small waist size leads to higher divergence in the far field. While on the other hand, larger waist sizes leads to better collimation of the laser beam [28]. As mentioned in chapter 3.2.3, the divergence θ constantly expands the beam waist diameter after passing the Rayleigh-Length (far-field divergence).

The divergence in radians of an ideal Gaussian beam is given by [29]:

$$\theta = \frac{\lambda}{\pi\omega_0}$$

Equation 4: Ideal far-field divergence

This relationship clarifies that the divergence angle is increased with smaller beam waist.

3.2.6. M²-factor (M-square-factor)

The M²-factor is a parameter for measuring the laser beam's quality. It determines how small the laser's beam waist can be focused. For an ideal Gaussian beam in TEM_{00} mode, the M²-factor equals one. For a non-perfect Gaussian beam, M² is bigger than one [30].

M² is defined as "The ratio of a beam's actual divergence to the divergence of an ideal, diffraction limited, Gaussian, TEM_{00} beam having the same waist size and location" [31].

M² describes "how far" to an ideal Gaussian the laser beam is. Following equation (in radians) clarifies the relationship between far-field divergence θ and M²-factor [32]:

$$\theta = M^2\frac{\lambda}{\pi\omega_0}$$

Equation 5: Real far-field divergence

The given equation shows, that the laser beam's divergence proportionally increases, the bigger M² or the smaller ω_0 becomes.

Additionally, the M²-factor affects the Rayleigh length (chapter 3.2.3):

$$z_R = \frac{\omega_0}{\theta} = \frac{\omega_0}{\frac{M^2\lambda}{\pi\,\omega_0}} = \frac{\pi\,{\omega_0}^2}{M^2\lambda}$$

Equation 6: Real Rayleigh length

3.2.7. Beam far-field divergence vs. beam diameter

The following equation displays the relationship between beam far-field divergence θ and beam diameter $d(z)$ [33]:

$$d(z) = \sqrt{d_0^2 + \theta^2\,(z - z_0)^2}$$

Equation 7: Beam far-field diameter

Where d_0 denotes the beam waist diameter at z = 0, z the location along the optical axis (propagation axis) and z_0 the beam waist location.

3.2.8. Numerical aperture (NA)

The NA is a dimensionless figure which characterizes the light collecting capability of an optical fiber, since it delivers information about the fiber's acceptance angle at the entrance and the light spreading angle at the exit [34].

To calculate the NA, it is necessary to know the refractive indices of the optical fiber's core and cladding [34]:

$$NA = \sqrt{{n^2}_{core} - {n^2}_{cladding}}$$

Equation 8: Numerical aperture

Where n_{core} is the refractive index of the core and $n_{cladding}$ the refractive index of the cladding.

The following function delivers information about an association between the numerical aperture and the optical fiber's acceptance angle [35]:

$$NA = n \sin(\theta_{ac})$$

Equation 9: Numerical aperture and acceptance angle

Where n is the light refractive index of the medium before entering the optical fiber and θ_{ac} the acceptance angle.

Since in all cases discussed in this work, the laser beam is propagating through air, the light refractive index n equals 1.000293 ≈ 1 [36]. This leads to following equation for the acceptance angle (in degrees):

$$\theta_{ac} = \sin^{-1}(NA)$$

Equation 10: Optical fiber's acceptance angle

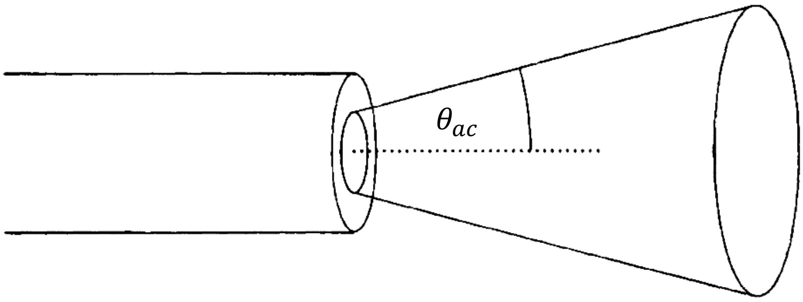


fig. 7 Acceptance angle θ_{ac}.[35] **The acceptance angle defines a conical zone, where its possible for light to enter an optical fiber**

The acceptance angle θ_{ac} at the optical fiber's entrance, equals the light cone divergence angle θ_{sp} at it's exit [35].

3.2.9. Ray transfer matrix analysis and focusing

The ray transfer matrix analysis is used to calculate the laser's new beam waist radius and its respective distance along the z-axis, within an optical system with multiple optical elements [37].

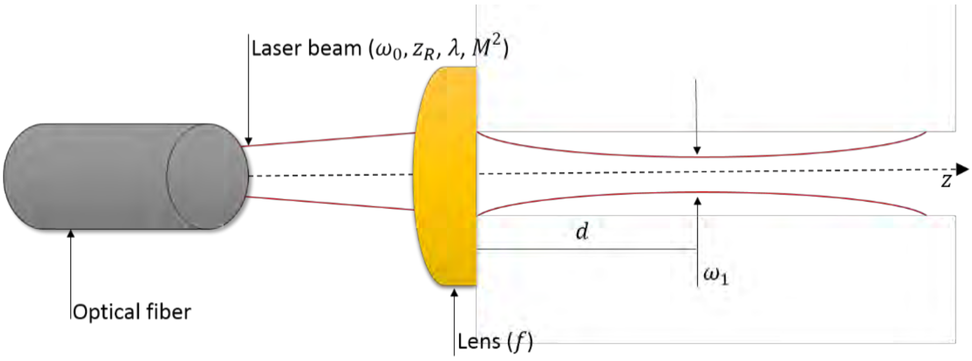


fig. 8 The new beam waist of the laser beam and its position.After the laser beam propagates through the lens, the new beam waist (ω_1) and its respective distance from the lens (d) can be calculated with the ray transfer matrix analysis.

To calculate the position of the beam waist and its diameter after a lens with given focal length, it is helpful to apply the ABCD law of a Gaussian beam. This calculation is called ray transfer matrix analysis [37].

$$ABCD = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{d}{f} & d \\ -\frac{1}{f} & 1 \end{pmatrix}$$

$$A = 1 - \frac{d}{f} \qquad B = d \qquad C = -\frac{1}{f} \qquad D = 1$$

Where f is the focal length of the lens and $d = d_1$ the distance from the lens to the new beam waist of the Gaussian beam in the image plane.

$$d_1 = \frac{f}{1 + \frac{f^2 \lambda^2}{{\omega_0}^4 \pi^2 n^2}}$$

Equation 11: New beam waist distance

The position of the new beam waist in the image plain depends on the lens's focal length f, the beams wavelength λ, the refractive index n and the beam waist in the object plane ω_0 [37].

It needs the following equation to calculate the beam waist radius in the image plane ω_1 [37]:

$$\omega_1 = M^2 \frac{f\lambda}{\omega_0 \pi n} \frac{1}{\sqrt{1 + \frac{f^2}{z_R^2}}}$$

Equation 12: New beam waist radius

With using the ray transfer matrix analysis and focusing method, it is possible to rapidly calculate and simulate beam waists and spots on the PC. This is a cardinal advantage, since the simulation combines a range of different lenses with different properties to figure out the optimal combination (Attachment-I Simulation program).

4. Hand-Held Piece (HHP)

The following chapter addresses the development of the HHP and states why it is valuable to invest into its research. A requirement analysis according the HHP is also made. Additionally, all mechanical components are described. Furthermore, a technical drawing containing the design of the HHP is included.

The HHP is a device which is held by the surgeon throughout the cutting process, during an invasive operation. The purpose of this module is to enhance the handling of the laser beam in order to reach inner areas easily. As the surgeon operates usually with the scalpel as a cutting instrument, it is beneficial to develop something familiar.

4.1. Requirements

As mentioned, it is necessary to consider ergonomic criteria. Due to this, the development is concentrated on a Hand-Held Piece which could be carried by the surgeon during an operation. The crucial aspects are the HHP's dimensions and weight. They need to be within convenient bounds.

Furthermore, it is essential to integrate optical and electro-mechanical components that fit the laser's characteristics. This is needed to be done to achieve minimal reduction of the laser's beam quality and power during beam propagation through the assembled components.

Additionally, the assembled material has to be resistant to high temperature change, which could be developed by the laser beam during propagation.

A solution to protect the HHP's optical components during a cutting process would be helpful, as well.

Moreover, controls attached on the HHP's surface or a foot pedal to switch the laser into "On" and "Off" state would be a helpful feature in order to have control of the cutting laser beam.

4.2. Optical and Mechanical elements

4.2.1. Lenses

Based on the PIRL's characteristics (3.1), CaF_2 lenses with an Anti-Reflective (AR) coating where chosen. In fig. 9, it is perceptible that the lens has a transmission rate of over 98% at λ = 3 µm. Additionally, this kind of lenses are commercially available in different dimensions, which fit into the HHP.

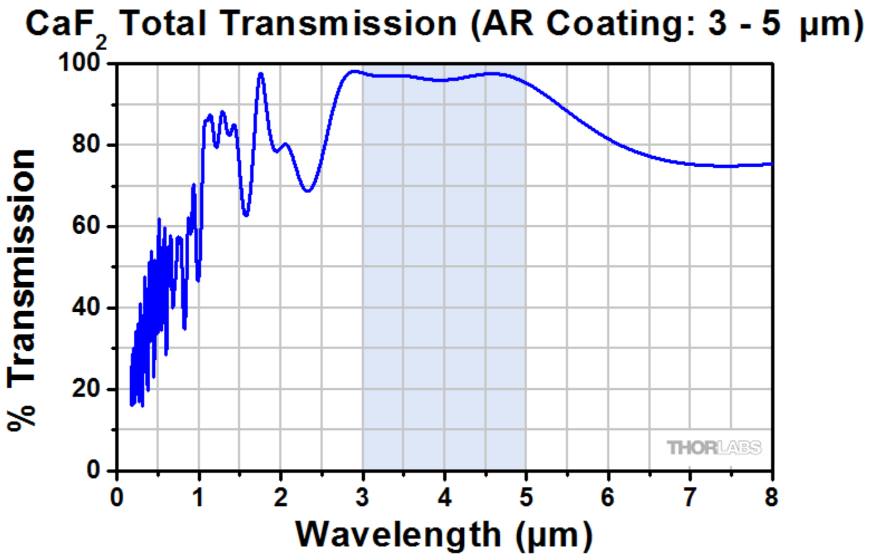


fig. 9 Lens transmission (%) vs. Wavelength (µm) [38]. For wavelengths between 3µm and 5µm.

4.2.2. Mirrors

Considering the PIRL's properties, a protected silver coated mirror delivers satisfying results.

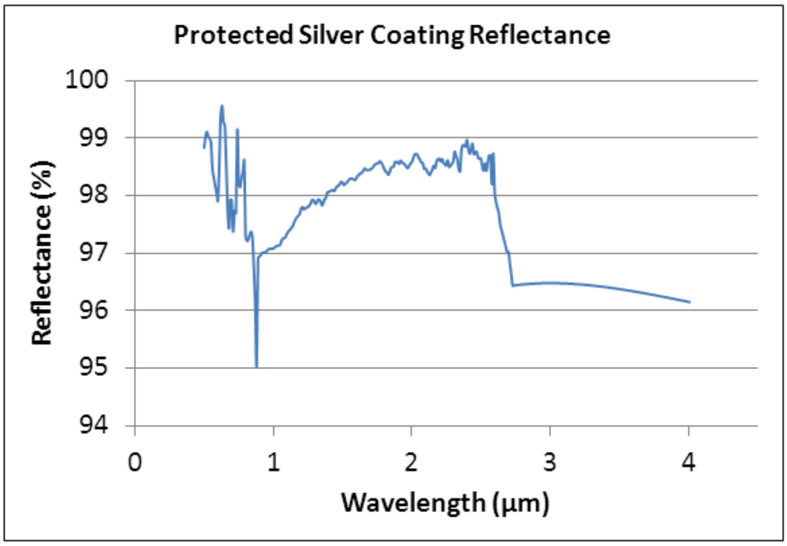


fig. 10 Laser beam reflectance (%) vs. wavelength (µm) [39]**. Total reflectance of ≈96 % for 3µm wavelength.**

As shown in fig. 10, the amount of reflectance is ≈96% at a wavelength of 3µm.

Due to the specific damage threshold (3 J/cm^2) [40], it is possible to combine this kind of mirrors with the PIRL. The energy density of the PIRL's laser beam is 1 J/cm^2 with a pulse length of 500 ps [41] and lies therefore in the scope of the mirror's damage threshold [40]. Round protected silver coated flat mirrors are assembled in the HHP (chapter 4.4).

4.2.3. Micro-Electro-Mechanical-System (MEMS)

Generally, a scanning module supports the surgeon during cutting processes. It enables more precise cutting by periodically deflecting the laser beam while keeping the scanning accuracy [42]. Additionally, it is beneficial to have scanning systems which could be programmed "Ad-Hoc" in order to directly change deflection, velocity and resolution.

Since the HHP’s dimensions have to be within certain limits, it is advantageous to integrate compact and programmable MEMS, which occupy less space, compared to other scanning modules [43].

MEMS mirrors are able to deflect the laser beam with high resolution and velocity in a 2D plane. Furthermore, they are programmable “Ad-Hoc”, which enables to periodically redefine deflection, velocity and resolution e.g. to change from point-to-point line scanning to shape scan [44].

To figure out if the MEMS mirror is appropriate to apply with the PIRL, it is necessary to know which damage threshold the mirror’s surface has. The pulse duration and energy density of the laser are therefore crucial. To achieve satisfying results, it is beneficial to know the MEMS reflectance of 3µm wavelength, as well. Furthermore, the maximal deflection angle of the MEMS mirror and its step resolution are essential to know.

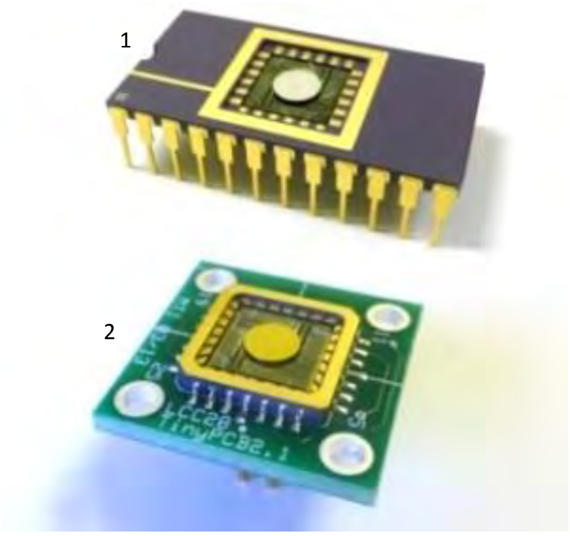


fig. 11 MEMS mirrors [45]**. 1-Bonded mirror device, 2-Integrated mirror device.**

To achieve maximum flexibility and accurate repeatability, it is necessary to use a MEMS mirror, which is constructed without actuators that could change characteristics if exposed to heat. Therefore, it is beneficial to integrate single-crystal silicon mono-Si mirrors with electrostatic actuators [46].

The available Mirrorcle S4342 MEMS mirror has a gold (Au) coating [47] and therefore a high reflectance at λ = 3 µm (fig. 12).

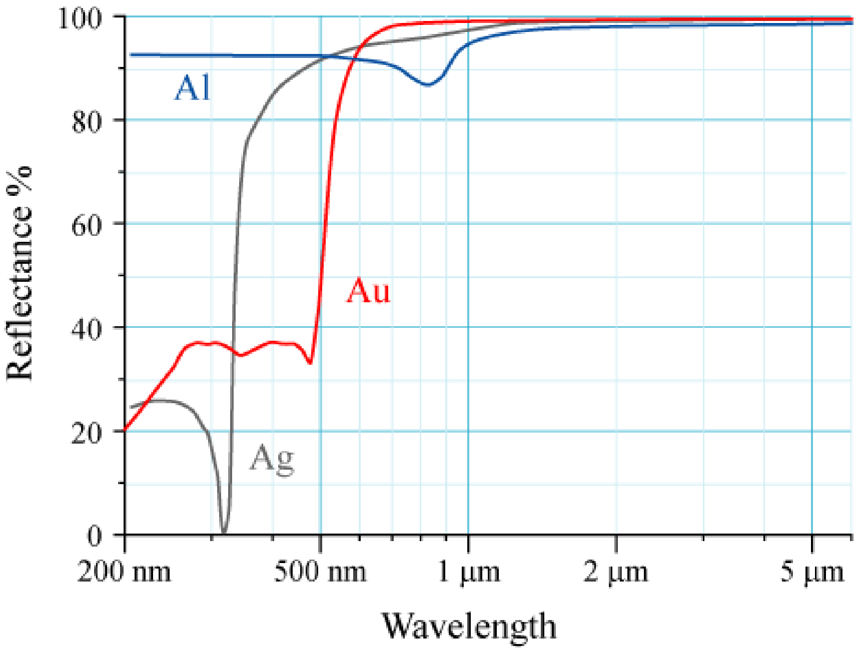


fig. 12 Reflectance of materials (%) of Al, Au and Ag vs. Wavelength (µm) [48].

Furthermore, the amount of energy the MEMS mirror can resist is about 4J/cm² at a pulse-rate of 1200 Hz [49].

The S4342 MEMS mirror with a mirror size of 2.0 mm, operates with a scanning frequency up to 1.2 kHz in both axes with a positional repeatability of 500 micro-degrees [50]. Additionally, the step resolution of the MEMS mirror is at 0.6 milli-degrees (10 micro-radians) within a maximum tilt range of ± 5° on each axis [50].

This velocity and accuracy fits the PIRL’s laser requirements, since the achievable scanning frequency is faster than the PIRL’s repetition rate of 1 kHz. This ensures laser scanning without spot overlap (4.4.6). The MEMS achieves a velocity of 1000 rad/s [50] and can be programmed with the delivered software (Attachment - IV MEMS programming).

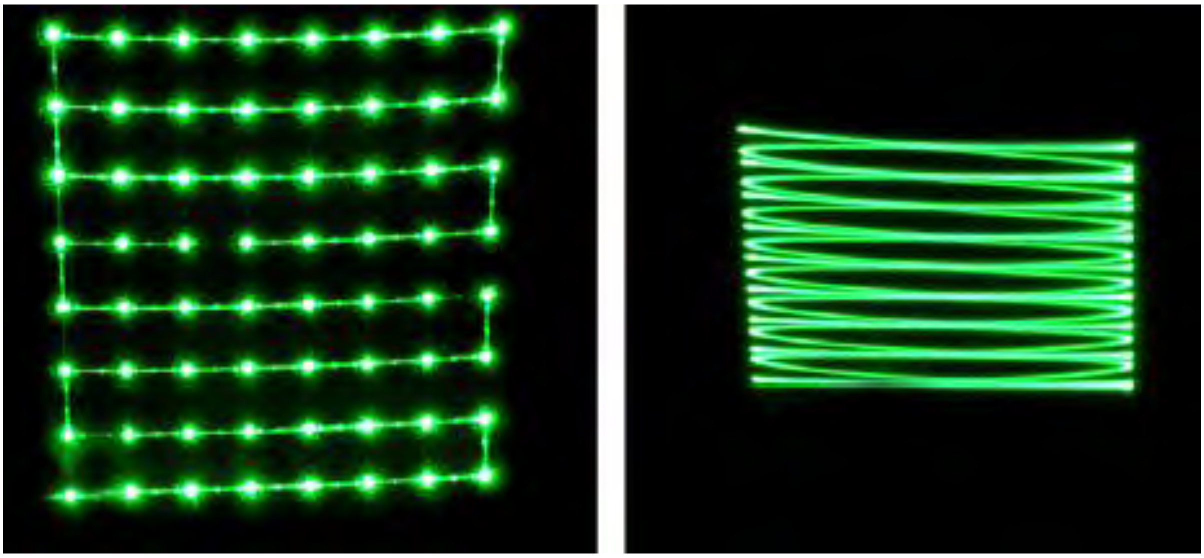


fig. 13 MEMS scanning modes. Point-to-point scanning mode for high step resolution (left) and resonant scanning mode for fast scanning procedures (right) [50]

There are two main methods to scan with the MEMS mirror. On the one hand, point to point scanning where the laser beam is stepwise deflected from one angle to another. This method is done with quasi-static motion, which leads to precise actuation. On the other hand, resonant scanning mode where the laser beam is deflected at high speed velocities with less precision then in quasi-static motion.

MEMS mirrors could be programmed and integrated in an embedded system as well. This leads to less maintenance, since they do not need to be set-up repeatedly.

4.2.4. Optical fiber

Since the HHP is developed to be held by the surgeon during a surgical operation, it is necessary to consider the freedom of movement according its steering possibility. Due to this requirement, the existence of flexible elements, which ensure all degrees of freedom without restrictions, is crucial.

Optical fibers are commonly used to carry light from one point to another without losing much information during transmission. After coupling the laser beam into the fiber, it is possible with fiber optics to steer the laser beam to any needed point at the end. [51]

It is important to integrate an optical fiber, which withstands the energy density of the PIRL and transmit the necessary power with minimal losses.

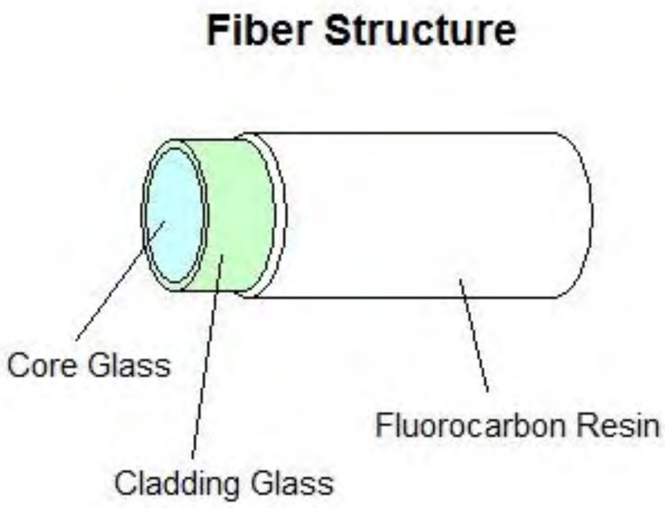


fig. 14 Optical fiber structure of AIF$_3$ (AMF-200/240), which is composed of: Core Glass, Cladding Glass and Fluorocarbon Resin. [52]

The AMF-200/240 is a multimode fiber type with three layers consisting of coating, cladding and core. Each layer has its specific characteristics in order to efficiently transmit the 3µm laser beam. The coating is made of heat resistant fluorocarbon resin established from UV-curable acrylate. The cladding and core material is composed of AlF_3-based fluoride glass, which transmit light with wavelengths between 0.3 µm and 3.5 µm with a loss of <0.1 db/m at a wavelength of 2.94 µm. The glass resists temperatures up to 367°C. [53]

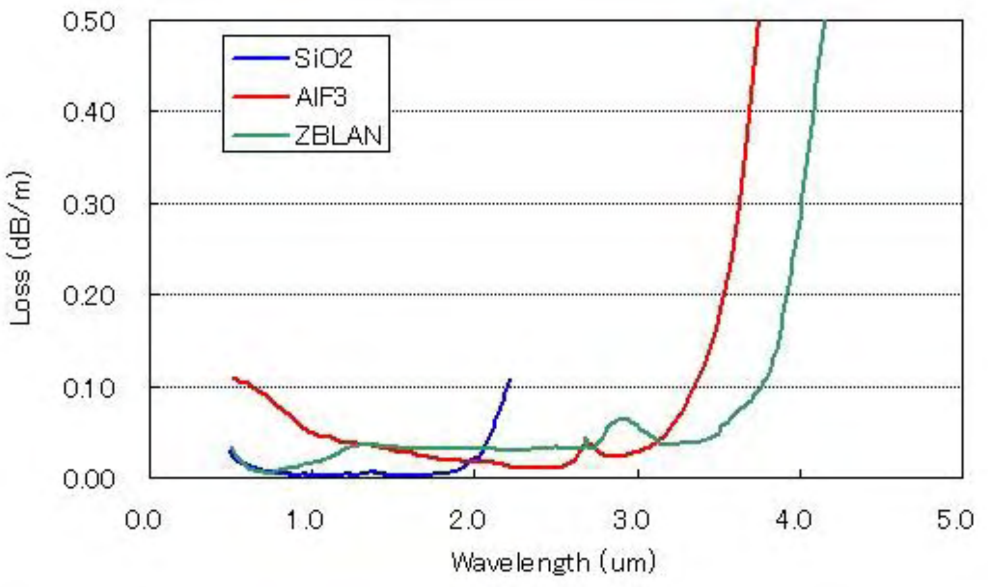


fig. 15 Energy loss (db/m) of three kinds of fiber vs. wavelength (µm) [54]

As shown in fig. 15, there is a power loss of <0.05 db/m at a wavelength of 3 µm (red). These glass transmission properties exist due to its composition. The glass fabricated in the AMF-200/240 ensures minimal power loss and higher transmission of light, compared to ZBLAN or SiO_2 [55]. Other fiber materials are able to transmit wavelengths of 3µm, but with a higher power loss e.g. sapphire (0.25 db/m) [56]. The requirements for an application with the PIRL are satisfied with the AMF-200/240 fiber, due to its properties.

4.2.5. Articulated-Mirrored-Arm (AMA)

An alternative method to couple the PIRL's laser beam into the HHP including maximal preservation of the beam's properties, is an Articulated-Mirrored-Arm [57].

The AMA is a mechanical instrument developed to transport the laser beam from one point to another with less movement restriction during actuation.

To handle the laser beam in an appropriate way and to have maximum flexibility at the same time, it is necessary that the AMA has at least five degrees of freedom. Two for angular directions and three for spatial positioning. A sixth degree of freedom is commonly not integrated in an articulated arm for surgical application, since the laser beam does not need to be mirrored back into its original shape, due to rotational symmetry of the laser light [58].

Furthermore, it is essential to operate with AMA mirrors which resist the pulse duration and energy density produced by the PIRL. However, the bending tolerance of the straight tubes between each joint and the stiffness of the joints themselves are crucial as well. Since the alignment of the AMA could be lost by a large bending tolerance of the straight tubes and the AMA's movement flexibility could be negatively influenced if the joints were too stiff.

fig. 16 Articulated-Mirrored-Arm (AMA) using a telescope [59]

An additional advantage of many AMAs, is the ability to collimate the incoming laser beam in order to ease its further manipulation at the AMA's output [60]. Taking the flexibility, beam manipulation characteristics and wavelength support into account, makes the AMA a considerable solution for laser coupling although it is not as swift as optical fibers [61].

A major drawback are the cost of a module including such device. Due to the aspect that the AMA has to be always in optimal alignment and swiftness, it makes the obstructed material expensive and hardly affordable, if they need to be replaced [62].

Integrating an AMA, results in less swiftness and higher maintenance cost, compared to an optical fiber. Additionally, the HHP design has to be different, according to the point of intersection between the AMA and the HHP. An AMA needs a more complex mechanism in order to be coupled with the HHP. Due to this, an optical fiber is used in further experiments.

4.3. Scanning concepts for the Hand-Held Piece

To figure out which scanning constellation fits best into the Hand-Held Piece, it is necessary to consider several scanning options. The concepts which are discussed in the following are concentrated on the positioning of the second lens (Lens B). The second lens is important for focus controlling.

The following constellations are composed of an optical fiber (4.2.4), which transmit the laser beam for further manipulation, a fixed mirror (4.2.2) for deflecting the laser beam in the MEMS direction and the MEMS (4.2.3) itself for laser scanning. Additionally, two lenses (Lens A and B) are installed for beam manipulation (4.2.1).

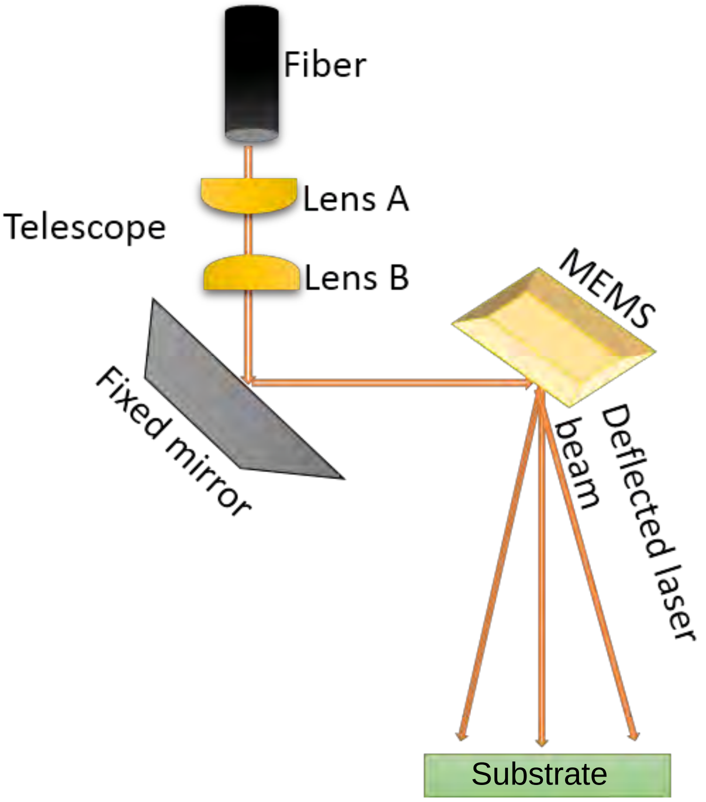


fig. 17 First scanning concept, Lens A and B are positioned before the fixed mirror.

Since the AMF-200/240 optical fiber with a core diameter of 200 µm and a numerical aperture of 0.22 is used, we have to position Lens A very close to the fiber's exit. This is needed to be done, since the divergence of the laser beam depends on the optical fiber's NA. For that reason, lens A has to be very close to the fiber's exit in all following scanning concepts, in order to capture the whole laser beam [63].

In fig. 17 we see lens A and B positioned before the fixed mirror. The advantage of this assembly is that both lenses build together a telescope which collimates and focuses the laser beam. Additionally, the focus can be manipulated by moving Lens B up and down along the laser beam's transmission axis to avoid going out of focus during the cutting process (autofocus) [63].

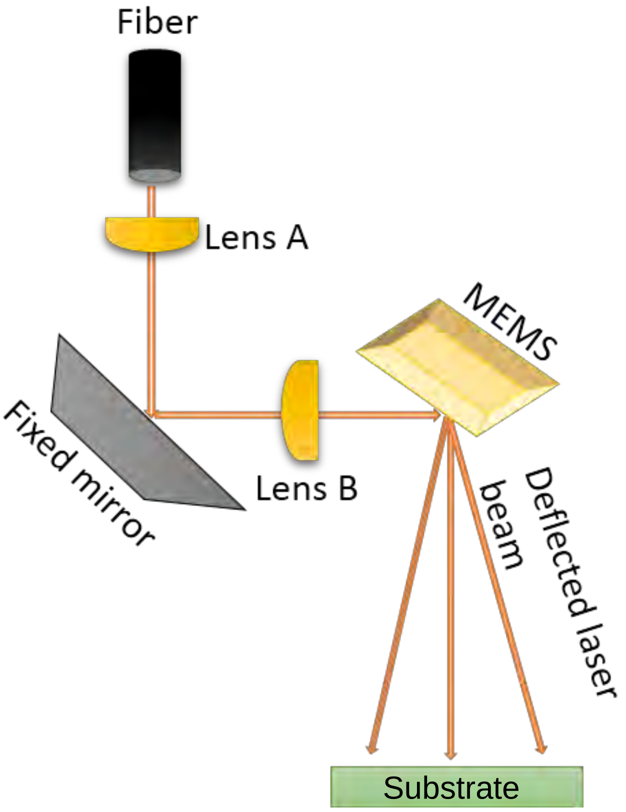


fig. 18 Second scanning concept

(Lens A is positioned before the fixed mirror. Lens B is positioned between the fixed mirror and the MEMS)

In fig. 18 Lens B is positioned between the fixed mirror and the MEMS. This setting reduces the distance to the substrate and increases the possibility of getting a smaller focus, which leads to a higher energy density (3.2.1).

The system's drawback is that the distance between Lens A and B is very large (far-field). The laser beam could reach Lens B with larger diameter than in fig. 17 and could exceed the lens's B diameter.

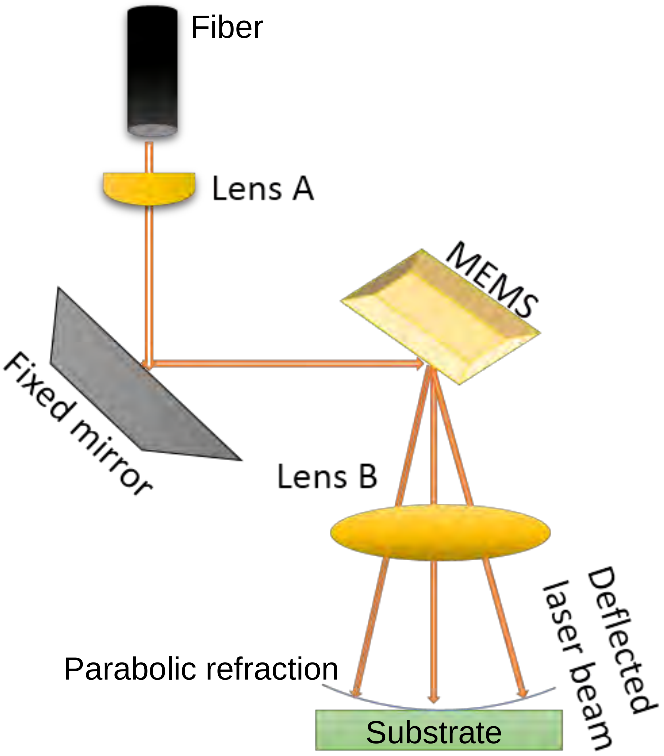


fig. 19 Third scanning concept

Lens A is positioned before the fixed mirror. Lens B is positioned between the MEMS and the Substrate

In fig. 19 Lens B is a spherical lens which is positioned between the MEMS and the substrate. The advantage lies in the shortest distance between Lens B and the substrate, compared to the scanning concepts in fig. 17 and fig. 18. Therefore, the focus's diameter would theoretically be the smallest, when the substrate is reached.

Since the distance between Lens A and Lens B lies in the advanced far field, the beam diameter is large as well. The laser beam could probably exceed Lens B's diameter, if Lens B is not large enough. An additional drawback is the parabolic refraction of the laser beam when transmitted through Lens B. This kind of refraction could result in focus distortion on the substrate and lead to an inhomogeneous energy distribution, as well [64].

Since the laser beam's far field divergence is large when focused strong [63], we need to position lens A and B close to each other. Another critical aspect is the M^2-factor, which additionally magnifies the laser beam's divergence. So, aligning the optical components as in fig. 18 may avoid laser beam diameters exceeding a needed laser beam spot size. Therefore, it is beneficial to apply the scanning concept displayed in fig. 18. Additionally, with applying this concept, it is possible to implement an autofocus system in further development by moving Lens B along the laser's propagation axis. This would ensure an optimal laser beam spot on the substrate.

4.4. Element selection and positioning

A spot size diameter of 300 µm is essential to reach the ablation threshold of 0.8 J/cm² [12]. To find the right position for each element along the beam's propagation axis and to select lenses with suitable focal lengths, it is important to gather the elements characteristics for further calculation.

A simulation program was developed using Python as higher level programming language (Attachment-I Simulation program) [65], to allow fast optimization for different elements with respect to their characteristics and positions [66].

Element	Characteristic
PIRL	Targeted ablation threshold: 100 µm Pulse duration: 400 ps [12] M²-factor : 2.88 (Attachment-VI Measurements)
Optical fiber (AMF-200/240)	Numerical Aperture (NA): 0.22 ± 0.02 Core Diameter [µm]: 200 ± 10 Coating Diameter [µm]: 450 ± 30
Calcium fluoride plano convex lens	Reflectance [%]: 0.72 at 3 µm Total transmission [%]: 99.27 at 3 µm Diameter [µm]: 12700 / 25400 Thickness [µm]: 4300 / 6100
Micro-Electro-Mechanical-System (Mirrorcle S4342 MEMS)	Reflectance [%]: > 99 Step resolution [micro-rad]: 10 Mechanical tilt range [°]: ± 5
Protected silver coated deflection mirror	Reflectance [%]: 96.48 at 3 µm

Table 2 Elements characteristic

4.4.1. The (effective) divergence at the optical fiber’s exit

According to chapter 3.2.8 the light cone divergence angle θ_{sp} at the fiber’s exit, with a numerical aperture of 0.22 and n = 1, is calculated as followed:

$$\theta_{sp} = \sin^{-1}(0.22) = 12.7\,°$$

The optical fiber’s outgoing light cone diameter (fig. 20) increases proportionally with distance and exceeds the lens’s diameter, if the lens is positioned too far from the fiber’s exit. This could result in critical energy loss. Therefore, the distance (d) between the optical fiber’s exit and lens A is limited by the lens’s diameter (D).

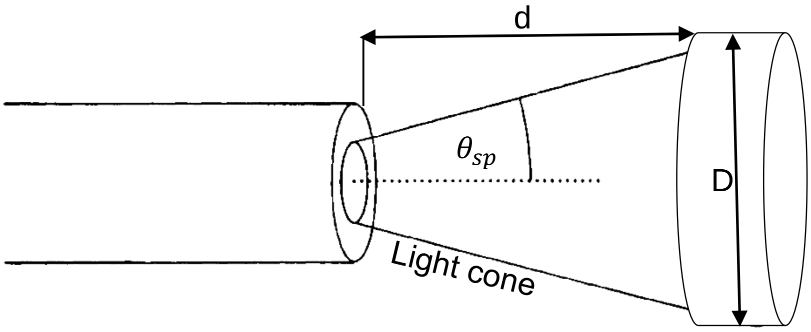


fig. 20 light cone divergence θ_{sp} and respective light cone ,

where D is the lens diameter and d the distance between the fiber’s exit and lens [35]

4.4.2. Determination of lens A's focal length and the distance between the optical fiber's exit and lens A

The distance (Δ_{FA}) between the optical fiber's exit and collimation lens A (fig. 18) equals lens A's focal length (f_A). Lenses with a focal length between 20 mm and 100 mm (in 10 mm steps) with a diameter of 12.7 mm or 25.4 mm are commercially available.

To determine if the light cone, which is propagating from the optical fiber's exit, exceeds the diameter of lens A after a certain distance, it is necessary to calculate the light cone diameter (fig. 20).

Since the light cone diverges linear with increased distance [35], the light cone diameter ($D_{LC}(d)$) is calculated as followed:

$$D_{LC}(\Delta_{FA} = f_A) = 2\ \tan(\theta_{sp})\ f_A + 2\omega_0$$

Where $\theta_{sp} = 12.7\,°$ represents the light cone divergence, Δ_{FA} the distance from the optical fiber's exit to collimation lens A, f_A the focal length of lens A and $\omega_0 = 100\ \mu m$, the beam waist radius at the optical fiber's exit.

A lens with a small focal length is required to achieve a small beam spot after collimation, since D_{LC} expands rapidly. Therefore, it is beneficial to integrate the lens with the smallest commercially available focal length of 20 mm and a diameter of 12.7 mm.

The simulation delivered the result that D_{LC} expands to a value of 9.2 mm after 20 mm distance from the optical fiber's exit and does not exceed the diameter of 12.7 mm.

4.4.3. Determination of lens B’s focal length, the distance between Lens A and lens B and spot size diameter

To define the exact position of lens B (fig. 18), it is necessary to know at what position the new beam waist (z_0') appears after lens A (referring to the laser beam’s propagation axis).

According to chapter 3.2.9 / Equation 11, the distance from lens A to the new beam waist in the image plane ($d_1 = z_0'$) with $f_A = 20\ \mathrm{mm}$, $\lambda = 3\ \mu\mathrm{m}$, $\omega_0 = 100\ \mu\mathrm{m}$ and $n = 1$ delivers the result of $z_0' = 14.61\ \mathrm{mm}$.

To determine the new beam waist radius ω_0' at position z_0' after lens A, the Rayleigh length and the M²-factor of 2.88 are required in addition to the parameters used to calculate z_0'.

Calculating the Rayleigh length (z_R) in reference to chapter 3.2.6 / Equation 6, provides the outcome of $z_R = 157\ \mu\mathrm{m}$.

By knowing z_R and the parameters used to calculate z_0', it is possible to calculate ω_0' after focusing the laser beam with lens A (chapter 3.2.9 / Equation 12). The result is $\omega_0' = 150\ \mu\mathrm{m}$

For further calculations, the divergence angle θ' after collimating the laser beam with lens A is necessary as well (chapter 3.2.6 / Equation 5). The provided value is $\theta' = 0.015\ \mathrm{rad} = 0.786\ °$

With the parameters z_0', ω_0', θ' and lens B’s focal length (f_B) it is possible to calculate the laser beam diameter $d(z)$ when the laser beam reaches lens B, after travelling a certain distance (chapter 3.2.7 / Equation 7):

$$d(z) = \sqrt{d_0^2 + \theta^2\,(z - z_0)^2}$$

$$d_0 = 2\omega_0'; \qquad \theta = \theta'; \qquad z_0 = z_0'; \qquad z = f_B$$

To simulate a range of focal lengths, f_B adopts several values during calculations. The equation $d(z)$ is therefore:

$$d(z = f_B\,) = \sqrt{2\omega_0^2 + \theta'^2\,(f_B - z_0')^2}$$

$$= \sqrt{(150{,}36\ \mu\mathrm{m})^{\,2} + (0.786\,°)^2\,(f_B - 14605{,}69\ \mu\mathrm{m}\,)^2}$$

$d(z = f_B)$ must not exceed a diameter of 25.4 10^3 µm or should preferably not exceed a diameter of 12.7 10^3 µm in the object plane. Simultaneously, the distance from lens B to the beam waist in the image plane must be large enough to integrate the MEMS (fig. 18).

Applying a range of values for f_B, delivers the best result at $f_B = 50\ \mathrm{mm}$. The beam diameter at lens B's object plane is $d(50\ \mathrm{mm}) = 20.6\ \mathrm{mm}$. This value is < 25.4 mm and does not exceed the lens's diameter.

On the one hand, smaller values for f_B would deliver smaller diameter in the object plane, on the other hand a too small distance to the beam waist in the image plane.

A value of $f_B = 50\ \mathrm{mm}$ delivers a 34.45 mm distance from lens B to the beam waist in the image plane ($z_0'' = 34.45\ \mathrm{mm}$)

Larger values for f_B deliver larger distances to the beam waist in the image plane, but a too large beam diameter in lens B's object plane, as well. Since, the larger f_B, the larger the distance between lens A and lens B, which leads to larger beam diameter when the laser beam reaches lens B.

For beam spot determination, the Rayleigh length at lens B's image plane is essential ($z_R' = \ 157\ \mu\mathrm{m}$)

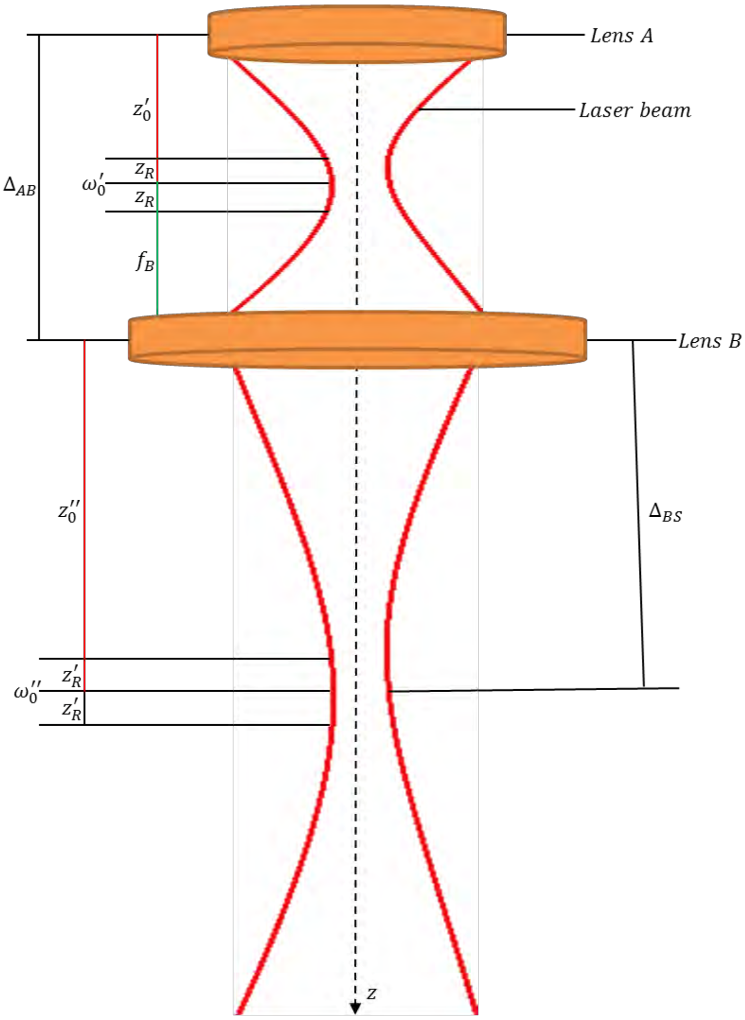
The beam waist radius at z_0'' satisfies the 300 µm condition:

$$\omega_0'' = 150.37 \text{ µm}$$

$$=> \; d_0'' = 2\omega_0'' = 300.73 \text{ µm}$$

Due to the calculations in chapter 4.4.2 and 4.4.3, the distance between the optical fiber's exit and lens A (Δ_{FA}) must be 20 mm, which equals the focal length of lens A. Furthermore, the distance between lens A and B (fig. 21) is defined as followed:

$$\Delta_{AB} = z_0' + f_B = 14.61 \text{ mm} + 50 \text{ mm} = 64.61 \text{ mm}$$



Positioning the lenses at this coordinates along the laser beam's propagation axis, delivers a spot size diameter of 300.73 µm after a distance (Δ_{BS}) of 34.45 mm between lens B and the substrate (fig. 22).

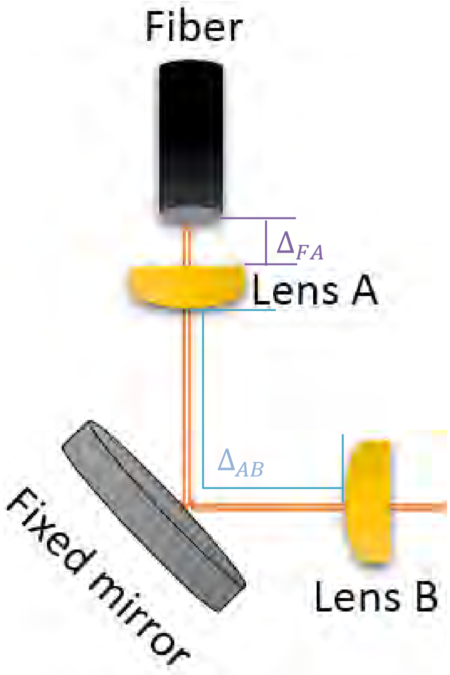


fig. 21 Definition of the distancesbetween optical fiber's exit and Lens A (Δ_{FA})
Definition of the distance between Lens A and Lens B (Δ_{AB})

4.4.4. Determination of the distance from the fixed mirror to Lens B (Δ_{FB})

The distance between the fixed mirror and Lens B (Δ_{FB}) depends on the fixed mirror's diameter of 7 mm (MD) and its 45° positioning angle (MPA):

$$\cos(MPA) = \frac{\Delta_{FB}}{\frac{\mathrm{MD}}{2}} = \frac{2\,\Delta_{FB}}{\mathrm{MD}}$$

$$=> \ \Delta_{FB} = \frac{MD}{2}\cos(MPA) = \ 2.48\,mm$$

4.4.5. Determination of Δ_{BS2} (Working distance)

The value of $\Delta_{BS} = 34.45\ \mathrm{mm}$ (chapter 4.4.3), determines the space for MEMS integration and remaining working distance before the laser beam hits the substrate (e.g. tissue). It is crucial to know the distance between the MEMS and the substrate (Δ_{BS2}). Since the maximal scanning area depends on Δ_{BS2} and the maximal tilt angle of the MEMS.

In order to calculate properly the positioning distance for each element, it is essential to know the dimensions of the MEMS.

Element	Dimension
MEMS (Mirrorcle S4342 MEMS)	Housing width [mm]: 8.89 [67] Housing length [mm]: 8.89 [67] Mirror diameter [mm]: 2.4

Table 3 Elements dimension

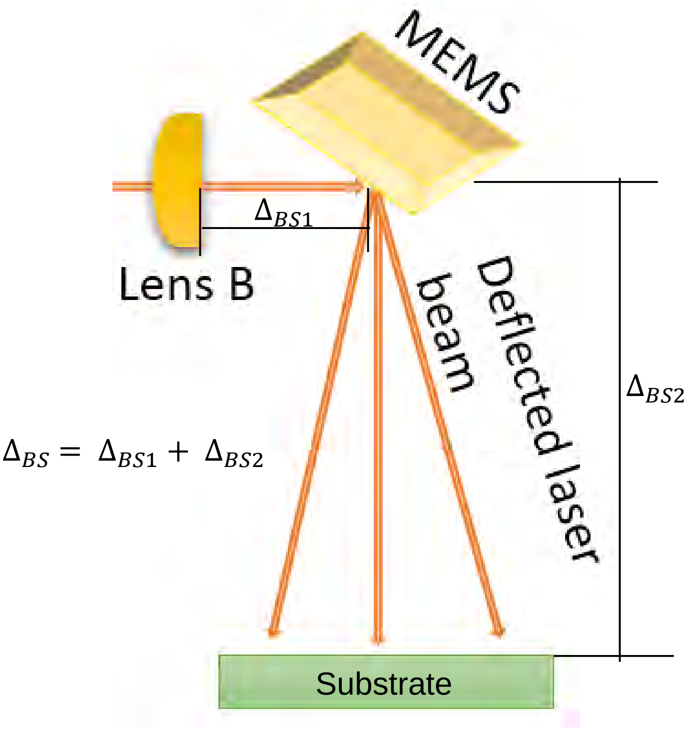


fig. 22 Definition of the distance between Lens B and the Substrate (Δ_{BS}), including Δ_{BS1} and Δ_{BS2}

To calculate Δ_{BS1}, the MEMS housing length of 8.89 mm (MHL) and its 45° positioning angle (MSPA) are required:

$$\cos(MSPA) = \frac{\Delta_{BS1}}{\frac{\mathrm{MHL}}{2}} = \frac{2\,\Delta_{BS1}}{\mathrm{MHL}}$$

$$\Delta_{BS1} = \frac{MHL}{2}\cos(MSPA) = 3.14\ \mathrm{mm}$$

To calculate Δ_{BS2}, the value of $\Delta_{BS} = 34.45\ \mathrm{mm}$ is essential (chapter 4.4.3):

$$\Delta_{BS2} = \Delta_{BS} - \Delta_{BS1} \approx 31\ \mathrm{mm}$$

4.4.6. Determination of the MEMS's scanning area and speed

According to chapter 4.4, the maximal tilt angle of the S4342 MEMS is ± 5°. Since the MEMS is positioned at a 45° angle to the substrate, the maximal tilt angle in x and y direction is reduced to ± 2.5°.

The scanning area depends on the maximal tilt angle of ± 2.5° and Δ_{BS2} of 31 mm:

$$\mathrm{x-direction} = \tan(\pm 2.5°)\ 31\ \mathrm{mm} = \pm 1.35\ \mathrm{mm}$$

$$\mathrm{y-direction} = \tan(\pm 2.5°)\ 31\ \mathrm{mm} = \pm 1.35\ \mathrm{mm}$$

Moreover, scanning frequencies up to 1 kHz in point-to-point mode can be achieved by the MEMS (f_{mems}). Since f_{mems} is equally to the PIRL's frequency (repetition rate) of 1 kHz (f_{laser}), it is possible to scan a certain area without critical spot overlap (fig. 23).

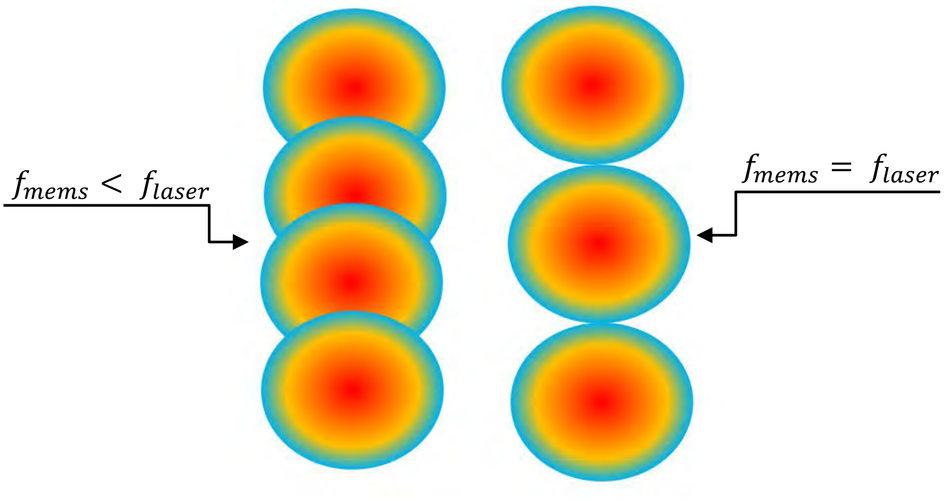


fig. 23 Spot overlap. If the scanning frequency of the MEMS (f_{mems}) is smaller than the PIRL's repetition rate (f_{laser}), spot overlap occurs and could lead to thermal damage and cell death

By avoiding overlapped spots, residual thermal damage and cell death decrease, compared to areas with overlap of laser impacts [68].

Additionally, the MEMS is programmed to scan from point to point and to scan a square shaped figure (Attachment-IV MEMS programming)

4.5. Three dimensional model of the Hand-Held Piece

A 3D-Model of the HHP is shown in the following images. Fig. 24 and fig. 25 are showing the cylindrical shaped mantle of the HHP with its components. The purpose of the Feedback- / Power-Button attached to the surface is to put the laser beam in an ON/OFF transmission state, in order to control the cutting procedure. The attached Button would trigger an external shutter, which blocks further beam propagation. For better distance control to the tissue, while operating with the laser, a distance holder with a support ring is mounted at the HHP’s front side. Attached to the support ring, is a panel, which shows the MEMS’s maximal scanning area.

The lenses, described in chapter 4.2.1 and 4.4, are responsible for collimation and focusing and are positioned in the Lens holding units. Furthermore, the fixed mirror, which is mentioned in chapter 4.2.2 and 4.4, is mounted on the mirror holding unit in order to deflect the beam in the MEMS direction. The scanning and steering action of the beam is performed by the MEMS, which are programed to deflect the beam from point to point or in a certain shape (chapter 4.2.3). The Infrared transmissive material is attached to the HHP’s front side, to protect the optical elements from the plume, while cutting with the laser.

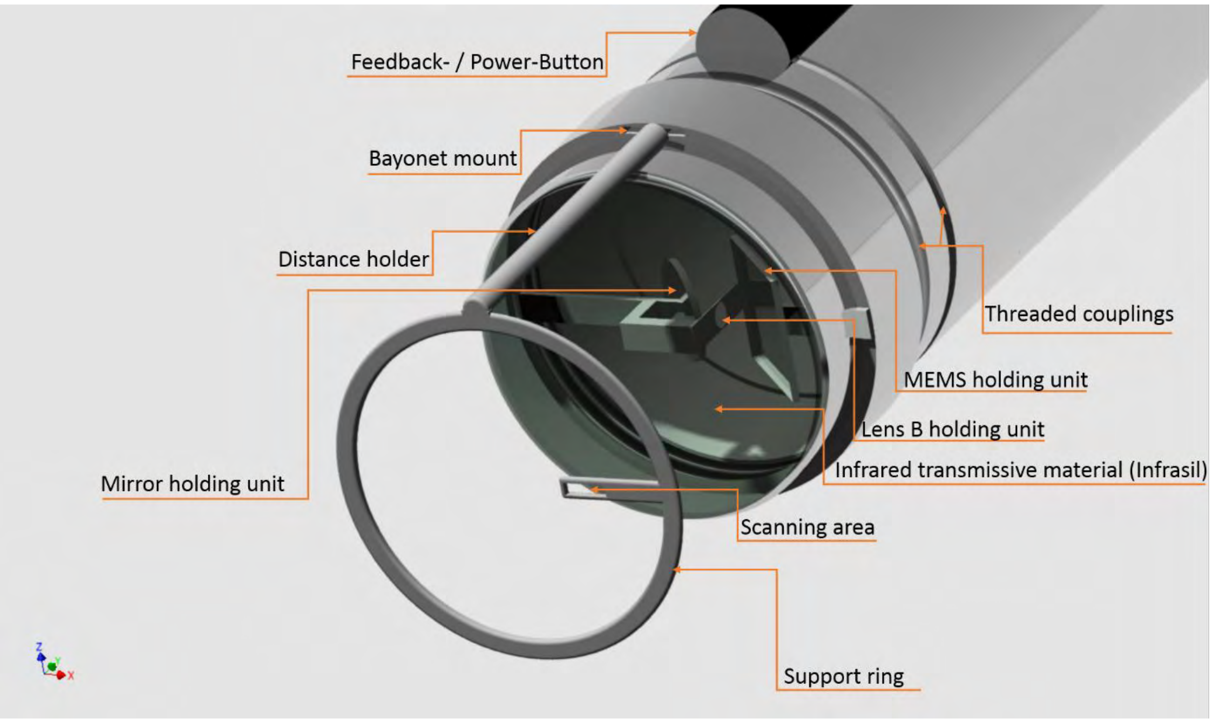


fig. 24 3D-Model of the Hand-Held Piece (front view).

The optical fiber's fixation unit is essential to couple the laser beam into the HHP. With the fixation block adjustment screw, it is possible to fix the optical fiber between the static fixation block and the movable fixation block. The holding unit of the Lens is positioned between the threaded couplings.

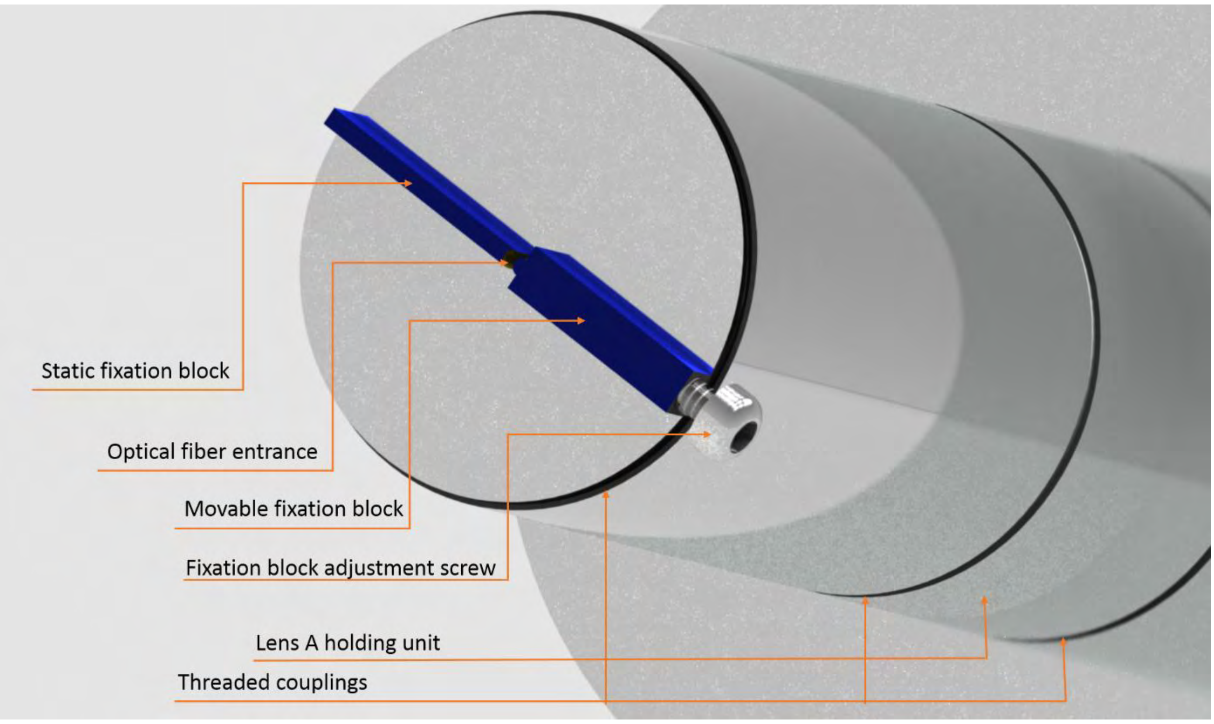


fig. 25 3D-Model of the Hand-Held Piece (rear view).

4.6. Technical drawing

To guarantee appropriate assembly of the HHP, it is necessary to deliver information about the construction. fig. 26 (see also Attachment-V Technical drawing) is a technical drawing of the HHP, which contains all required information about dimensions, positions and distances. Due to this information, it is possible to print the HHP with a 3D-Printer using a STL-File.

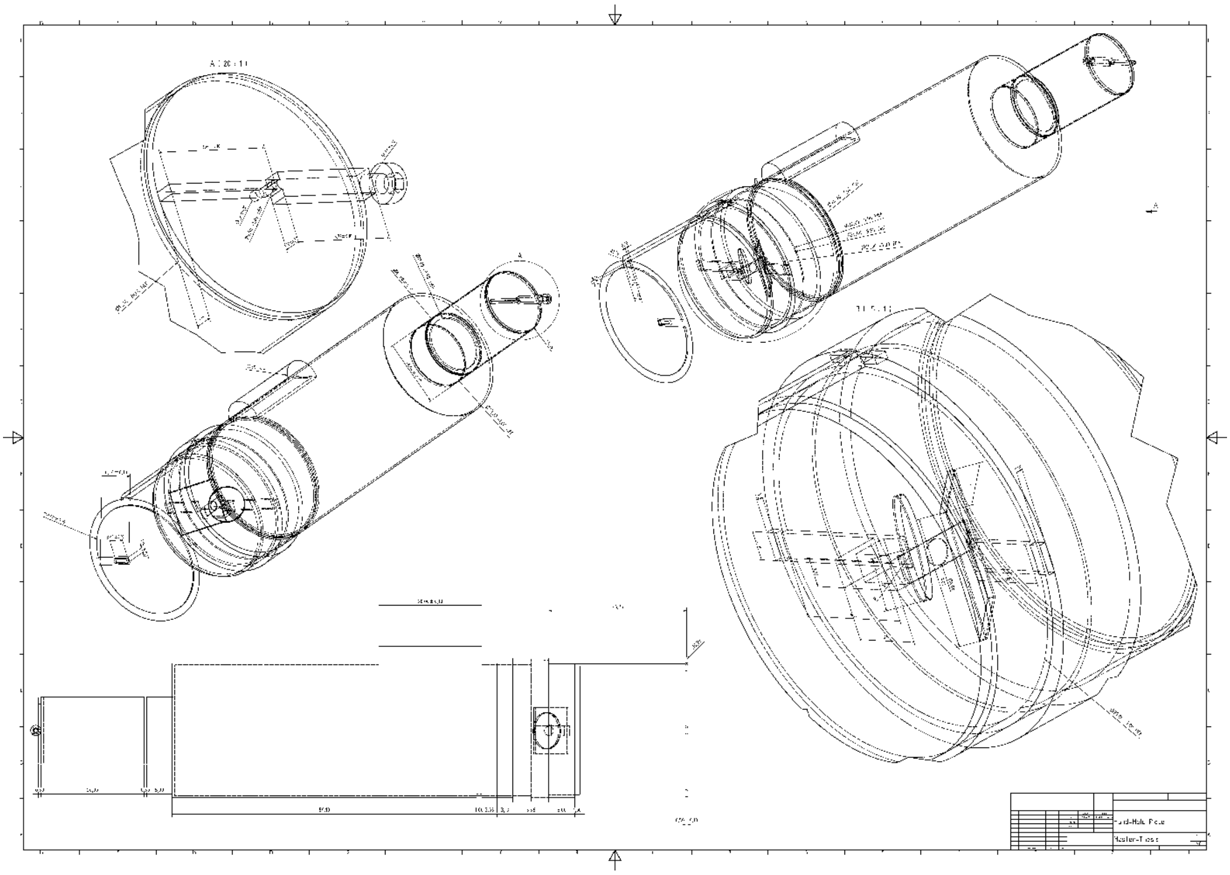
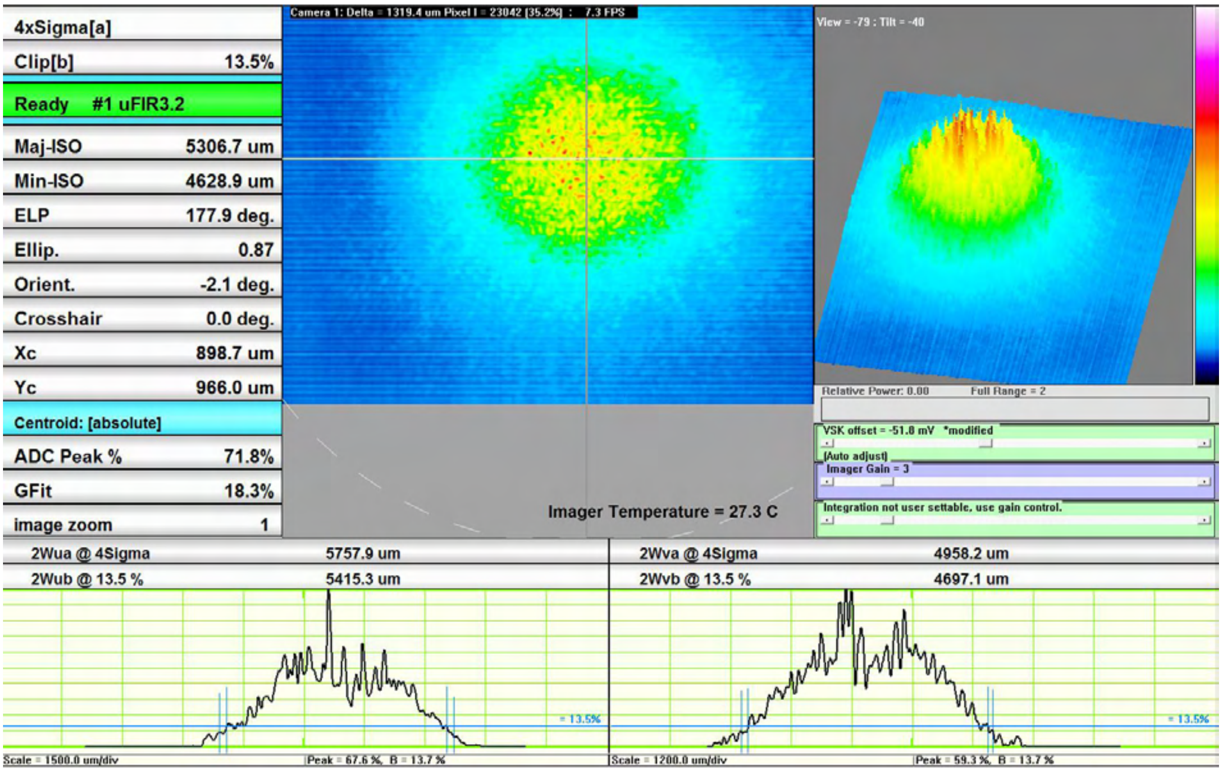


fig. 26 Technical drawing of the Hand-Held Piece (ISO-Norm).Overall length: 126.16 mm, Overall width: 30.25 mm

5. Measurement

To measure the resulting beam spot after the set up described in chapter 4.4, a compact, portable, port-powered, USB 2.0 FIR Beam Profiling camera is used . It is possible to measure beam spot sizes of laser systems. Featuring an emission wavelength of 2 – 16 µm.

Moreover, the included software package “DataRay v.7.1H25Ah” [69] delivers a wide range of information e.g. laser beam intensity profile, spot size in x and y direction and an overview of the spot’s intensity distribution (fig. 27).



4xSigma[a]	
Clip[b]	13.5%
Ready #1 uFIR3.2	
Maj-ISO	5306.7 um
Min-ISO	4628.9 um
ELP	177.9 deg.
Ellip.	0.87
Orient.	-2.1 deg.
Crosshair	0.0 deg.
Xc	898.7 um
Yc	966.0 um
Centroid: [absolute]	
ADC Peak %	71.8%
GFit	18.3%
image zoom	1

Camera 1: Delta = 1319.4 um Pixel I = 23042 [35.2%] : 7.3 FPS

View = -79 : Tilt = -40

Relative Power: 0.00 Full Range = 2

VSK offset = -51.8 mV *modified

(Auto adjust)

Imager Gain = 3

Integration not user settable, use gain control.

Imager Temperature = 27.3 C

2Wua @ 4Sigma	5757.9 um	2Wva @ 4Sigma	4958.2 um
2Wub @ 13.5 %	5415.3 um	2Wvb @ 13.5 %	4697.1 um

Scale = 1500.0 um/div Peak = 67.6 %, B = 13.7 %

Scale = 1200.0 um/div Peak = 59.3 %, B = 13.7 %

fig. 27 Screenshot of the DataRay software’s GUI

After numerous set up calibrations (example fig. 28) and measuring procedures (see Attachment-VI Measurements), it was possible to quantify the resulting laser beam spot (fig. 29).

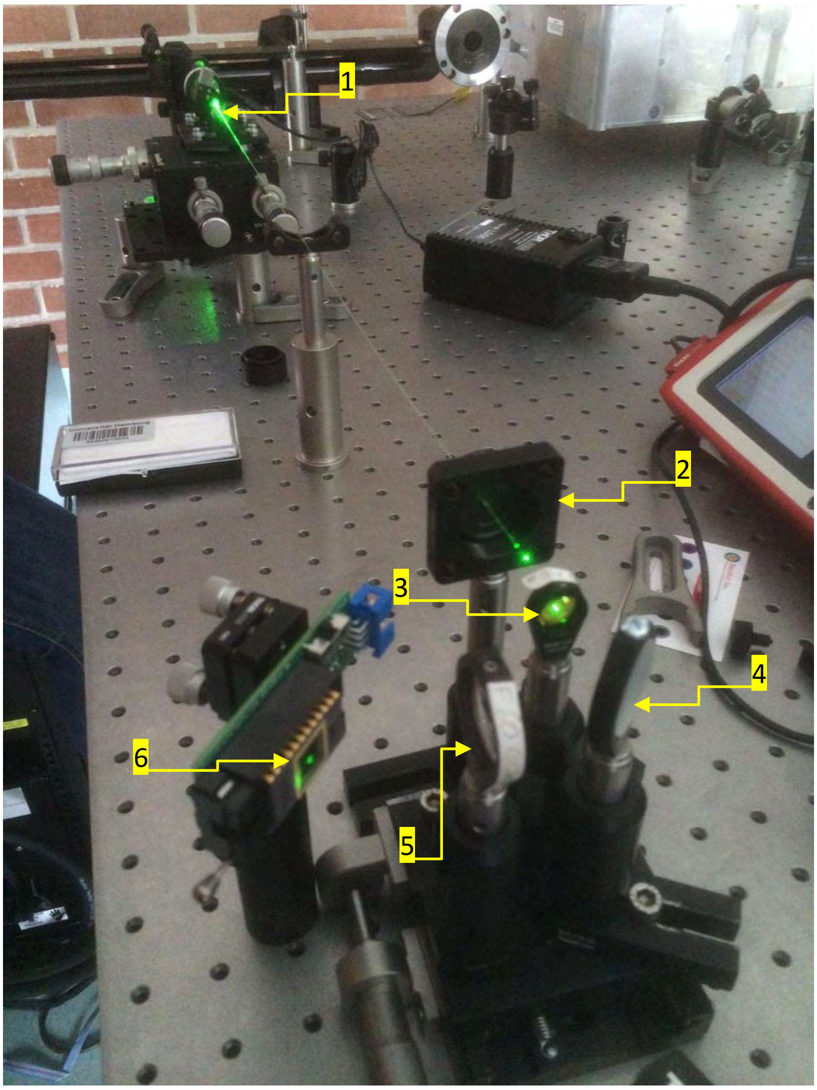
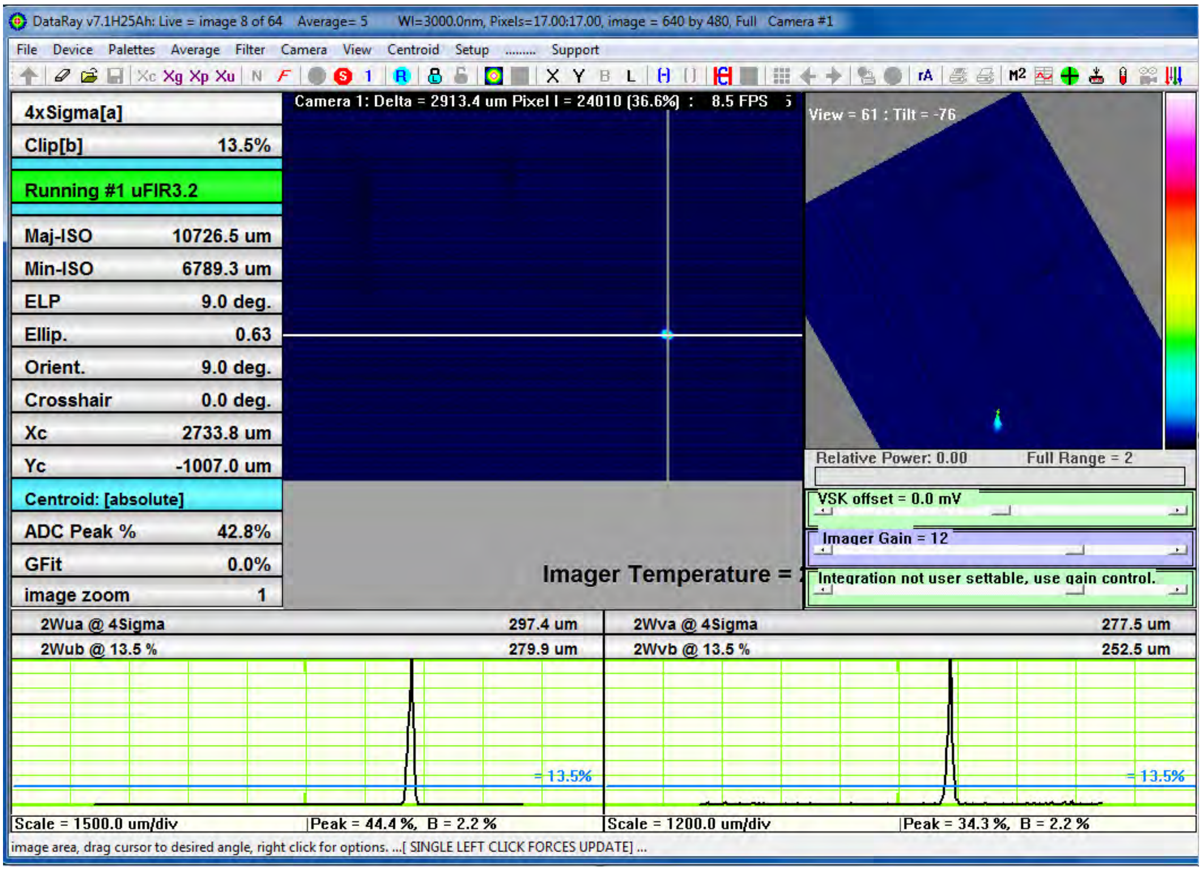


fig. 28 Set up of the Hand-Held Piecewith a green pilot laser for alignment and illustration.

Number	Description
1	Optical fiber
2	Optical fiber fixation
3	20 mm lens
4	Fixed deflection mirror
5	60 mm lens
6	MEMS

Table 4 Set up example



DataRay v7.1H25Ah: Live = image 8 of 64 Average= 5 Wl=3000.0nm, Pixels=17.00:17.00, image = 640 by 480, Full Camera #1

Camera 1: Delta = 2913.4 um Pixel I = 24010 (36.6%) : 8.5 FPS

View = 61 : Tilt = -76

4xSigma[a]	
Clip[b]	13.5%
Running #1 uFIR3.2	
Maj-ISO	10726.5 um
Min-ISO	6789.3 um
ELP	9.0 deg.
Ellip.	0.63
Orient.	9.0 deg.
Crosshair	0.0 deg.
Xc	2733.8 um
Yc	-1007.0 um
Centroid: [absolute]	
ADC Peak %	42.8%
GFit	0.0%
image zoom	1

Imager Temperature =

Relative Power: 0.00 Full Range = 2

VSK offset = 0.0 mV

Imager Gain = 12

Integration not user settable, use gain control.

2Wua @ 4Sigma	297.4 um	2Wva @ 4Sigma	277.5 um
2Wub @ 13.5 %	279.9 um	2Wvb @ 13.5 %	252.5 um

= 13.5%

= 13.5%

Scale = 1500.0 um/div |Peak = 44.4 %, B = 2.2 %

Scale = 1200.0 um/div |Peak = 34.3 %, B = 2.2 %

image area, drag cursor to desired angle, right click for options. ...[SINGLE LEFT CLICK FORCES UPDATE] ...

fig. 29 Measured laser beam spot

fig. 29 shows the laser beam spot diameter’s size. The value of 2Wua @ 4Sigma is essential and accounts 297.4 µm.

Comparing the actual spot size of 297.4 µm with the calculated one in chapter 4.4.3, results in a difference of -3.33 µm. Due to this, the measured beam spot diameter is smaller than the calculated one.

6. Discussion

This chapter discusses mainly the requirements in chapter 4.1, the calculated values in chapter 4.4, the dimensions of the HHP in chapter 4.6, the simulations in Attachment-II Simulation results and the measurements mentioned in chapter 5.

The HHP's overall dimension amounts a value of 126.16 mm in length and 30.25 mm in width. With this, ergonomic aspects were taken into account regarding haptic challenges mentioned in chapter 4.1, as well . Since the state of the art for HHP's in maxillary surgery for distal area exploration amount roughly the same values [70].

To keep the optimal distance permanently, a distance holder with the length of Δ_{BS2} ≈ 31 mm is integrated at the HHP's tip (chapter 4.6). This ensures a fixed beam waist diameter, which is essential to reach the required energy density for ablation (chapter 4.4). Due to the distance keeper and the consequential distance to the tissue, the surgeon is also provided with a clear field of view.

While mainly the standard for a laser triggering mechanism is a foot pedal [71], a button is attached in fig. 24 to the HHP's surface to switch between “OFF” and “ON”. The switch could be considered in further development as potential alternative. A possible benefit of this alternative is the foot pedal's non-existents, which could reduce the HHP's overall costs. The drawback could be the non-habituated handling with an attached switch, since surgeons usually use foot pedals while cutting with lasers [72].

Threaded couplings are integrated in the HHP (fig. 24), since it is necessary to disassemble the parts in order to replace defective components. Additionally, part purification and sterilization gets easier for medical experts, as well, if the parts could be disassembled [73].

The simulation software written in the third level programming language python (Attachment-I Simulation program), includes a Graphical User Interface (Attachment-III Graphical User Interface (GUI)). It is a straightforward designed software with integrated documentation, which supports individual inputs in order to deliver results as accurately as possible. Each simulation outcome can be saved into an individual excel sheet for documentation purposes. The outcomes in Attachment-II Simulation results provide theoretic suitable results compared to actual measurements from the experimental set-up (fig. 29).

7. Conclusion and Outlook

A prototype of the Hand-Held Piece is the result of the thesis. Each component is chosen by means of physical properties with respect to the PIRL's characteristics. The prototype is designed with the CAD-Software "Autodesk Inventor Professional 2013" and printed with a 3D printer. The purpose of the prototype's development is to push further research in this field of technology.

The technical design of the HHP mainly satisfies ergonomic aspects and exhibits minimal power loss. Moreover, the laser scanning procedure is performed by the MEMS and is able to be programmed Ad-Hoc.

Additionally, the integrated distance holder ensures optimal distance to the tissue, makes sure of the needed beam diameter size in order to reach the tissue's ablation threshold and guarantees clear vision at the treated area.

Furthermore, the programed software is designed to perform simulations for Gaussian beams in order to rapidly calculate the best component and measurement combination for a HHP prototype. The graphical user interface facilitates the Software's handling.

Furthermore, the MEMS is programmed with a console application written in C++ (Attachment-IV MEMS programming) which can be embedded on the MEMS itself. The MEMS is therefore able to operate without being permanently connected to a computational unit.

To ensure further HHP development, it is essential to cooperate with surgeons. Since professional feedback and evaluation in order to subtilize technical and ergonomic aspects are vital.

The integration of an Autofocus system would be advantageous in case the distance, to the tissue, changes. This would assure a fixed beam diameter in exceptional circumstances by readjusting the lenses. A possible solution would be the integration of an ultrasonic range measurement system, which supports adjustable repetition rates up to 1000 Hz with a resolution of about 0.1 mm.

The developed HHP prototype has to be considered as potential solution among other possible alternatives. Its mechanical design and the assembled optical components are one solution, as well. Additionally, further research regarding the optical fiber has to be done, in order to investigate into more efficient light propagation with less divergence at the fiber's exit. Light propagation through an optical fiber with a much lower numerical aperture than the AMF-200/240, could possibly make additional lenses in the HHP unnecessary. The consequence would be a completely different mechanical design of the developed HHP prototype and its software.

Moreover, one of the PIRL's further development aspects shall be in the direction of lowering the M^2-factor in order to reach more efficient laser beam manipulation and lower far-field divergence. This would be essential to reach a laser beam spot diameter of 100 µm at the tissue's surface.

Another possibility is to operate the PIRL in combination with a commercially available robotic surgical system (e.g. "The Da Vinci Surgical System") in order to enhance precision. The surgeon would control the robotic system from a console. As a result, the HHP could be considered as alternative, if the medical facility is not equipped with a robotic surgical system.

Overall, the thesis's topic "Development of a Hand-Held Piece for application with the Picosecond Infrared Laser" is predominantly satisfied. Nevertheless, additional investigations, statistical evaluations and "real-world" experimentations are necessary to enhance the HHP's ergonomic and technical properties.

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9. Attachments

(A Master-Thesis version with attachments, is available on included CD, which is attached to the book’s spine)

I Simulation program

This program simulates a range of lenses to calculate the best fit for the Hand-Held Piece and exports all results into individual excel sheets.

```
# -*- coding: utf-8 -*-
#==============================================================================
# START of File: Simulation.py
#==============================================================================
"""
This program simulates a range of lenses to calculate the best fit for the
Hand Held Piece and exports all results into individual excel sheets.
"""
# Written by Bilal El Banna (c) 2014
# Coded @ DESY, HAW-Hamburg, UKE, Philips AG

#==============================================================================
# module imports
#==============================================================================

import os
import math
from xlwt import Workbook

#==============================================================================
# Clear Console
#==============================================================================

clear = lambda: os.system('cls')
clear()

#==============================================================================
#GUI
#==============================================================================




#==============================================================================
#Function defs
#==============================================================================

def rayleigh_length (beam_waist_radius, wavelength, M_sq):
    """
    Function to calculate the rayleigh length.

    input:
    beam_waist_radius: laser beam waist radius at z(0)
    wavelength: laser wavelength
    M_sq: M_square-factor >= 1
    """
    rayleigh_len = (math.pi * (beam_waist_radius**2))/(M_sq * wavelength)
    return rayleigh_len


def numerical_aperture_angle_exit(NA):
    """
    Function to calculate the fiber's exit angle.
```

```
    input:
    NA: Numerical aperture
    M_sq: M_square-factor >= 1

    output:
    effective_angle: effective spread angle in degrees
    """
    angle_rad = math.asin(NA)
    angle_deg = angle_rad * 180 / math.pi
    effective_angle = angle_deg
    return effective_angle

def far_field_divergence(wavelength,M_sq = 1, beam_waist_radius = 0):
    """
    Function to calculate the far-field divergence.

    input:
    wavelength: laser wavelength
    M_sq: M_square-factor >= 1
    beam_waist_radius: laser beam waist radius at z(0)

    output:
    divergence_deg: far-field divergence in degrees
    """
    divergence_rad = (M_sq * wavelength) / (math.pi * float(beam_waist_radius))
    divergence_deg = divergence_rad * 180.0 / math.pi
    return divergence_deg

def beam_far_field_diameter (beam_waist_diameter, far_field_divergence,z,z_0):
    """
    Function to calculate the beam diameter at any location z along
    the propagation axis after the rayleigh length.

    input:
    beam_waist_diameter: laser beam waist diameter at z(0)
    far_field_divergence: far-field divergence in
    z: beam location along propagation axis
    z_0: beam waist location of beam waist diameter

    output:
    d: beam diameter at location z
    """
    d=math.sqrt(beam_waist_diameter**2 + (far_field_divergence**2)*(z-z_0)**2)
    return d

def ray_transfer_analysis(focal_length, wavelength,waist_radius,n, diverg,M,
                          rz):
    """
    function to determin position and size of the beam waist at the image plane
    after lens focussing

    input:
    focal_length: Lens's focal length
    wavelength: laser's wavelength
```

```
    waist_radius: radius of beam waist in object plane
    n: refractive index
    diverg: far field divergence of the laser beam
    M: M_square factor
    rz: rayleigh length

    output:
    distance: Distance from lens to beam waist in the image plane
    beam_waist: new size of the beam waist radius
    """
    distance = focal_length/(1.0 + ((focal_length**2) * (wavelength**2)/
                                ((waist_radius**4) * (math.pi**4) * n**2)))

    beam_waist = (float(focal_length) * diverg *
    (1./(math.sqrt(1+((focal_length**2)/(rz**2))))))

    return (distance, beam_waist)


#==============================================================================
# Main function
#==============================================================================
#Begin of for loop
def __main():

    for i in range (10000,110000,10000):    #range(min_focal, max_focal, steps)
        for k in range(10000,110000,10000): #range(min_focal, max_focal, steps)


            print ("----------------begin----------------")

            wavelength_micm = float(2.999)
            print("\nwavelength_micm:",wavelength_micm)

            M_square = 1.62
            print("\nM_square:", M_square)

            beam_waist_radius_micm = 100 #equals core radius of the fiber
            print("\nbeam_waist_radius_micm:", beam_waist_radius_micm)

            numerical_aperture = 0.22
            print("\nnumerical_aperture:", numerical_aperture)

            lens1_after_fiber_micm = i
            print("\nlens1_after_fiber_micm:", lens1_after_fiber_micm)

            lens2_after_fiber_micm = k
            print("\nlens2_after_fiber_micm:", lens2_after_fiber_micm)

            refractive_index = 1

#==============================================================================

            ##Calculation after optical fiber
```

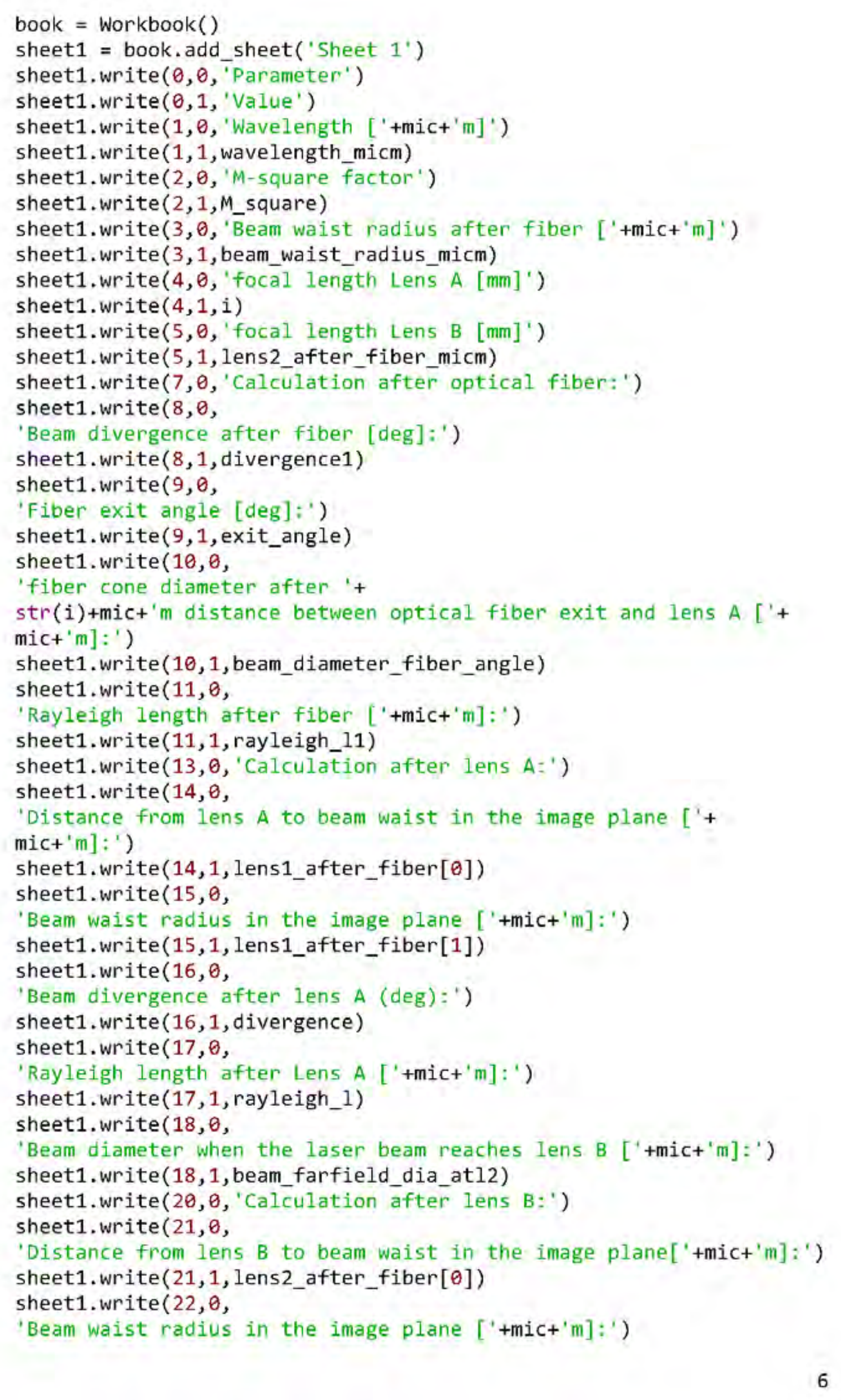
3

```
print("\nCalculation after optical fiber:")

divergence1 = far_field_divergence(wavelength_micm,M_square,
                                  beam_waist_radius_micm)

#debugging divergence
print("Beam divergence after fiber (deg):", divergence1)

distance_fiber_lens1_micm = i
#calculation of the spreading angle and cone

exit_angle = numerical_aperture_angle_exit(numerical_aperture)
exit_angle_rad = exit_angle * math.pi /180.
beam_diameter_fiber_angle = 2*((math.tan(exit_angle_rad) *
                            distance_fiber_lens1_micm)+
                            2*beam_waist_radius_micm)
#debugging exit_angle
print("Fiber exit angle (deg):", exit_angle)
print ("fiber cone diameter after",distance_fiber_lens1_micm,
      "micm distance between fiber exit and lens1 (micm):",
        beam_diameter_fiber_angle)

#calculation of beam diamter after distance between fiber and len1
beam_far_field_dia = beam_far_field_diameter (
                                        2*beam_waist_radius_micm,
                                        divergence1,
                                        distance_fiber_lens1_micm,
                                        0)
#debugging beam diamter after distance fiber and lens1
print ("beam diameter after",distance_fiber_lens1_micm,
      "micm distance between fiber exit and lens1 (micm):"
      ,beam_far_field_dia)

#calculation rayleigh length after fiber
rayleigh_l1 = rayleigh_length (beam_waist_radius_micm,
                              wavelength_micm,
                              M_square)

#debugging rayleigh length after fiber
print("Rayleigh length after fiber (micm): ",rayleigh_l1)

##Calculation after Lebeam_diameter_fiber_anglens 1
print("\nCalculation after lens 1:")
lens1_after_fiber = ray_transfer_analysis(lens1_after_fiber_micm,
                                         wavelength_micm,
                                         beam_waist_radius_micm,
                                         refractive_index,
                                         divergence1,
                                         M_square,
                                         rayleigh_l1)
#debugging lens_after_fiber
print(
"Distance from lens to beam waist in the image plane (micm):",
      lens1_after_fiber[0])
```

4

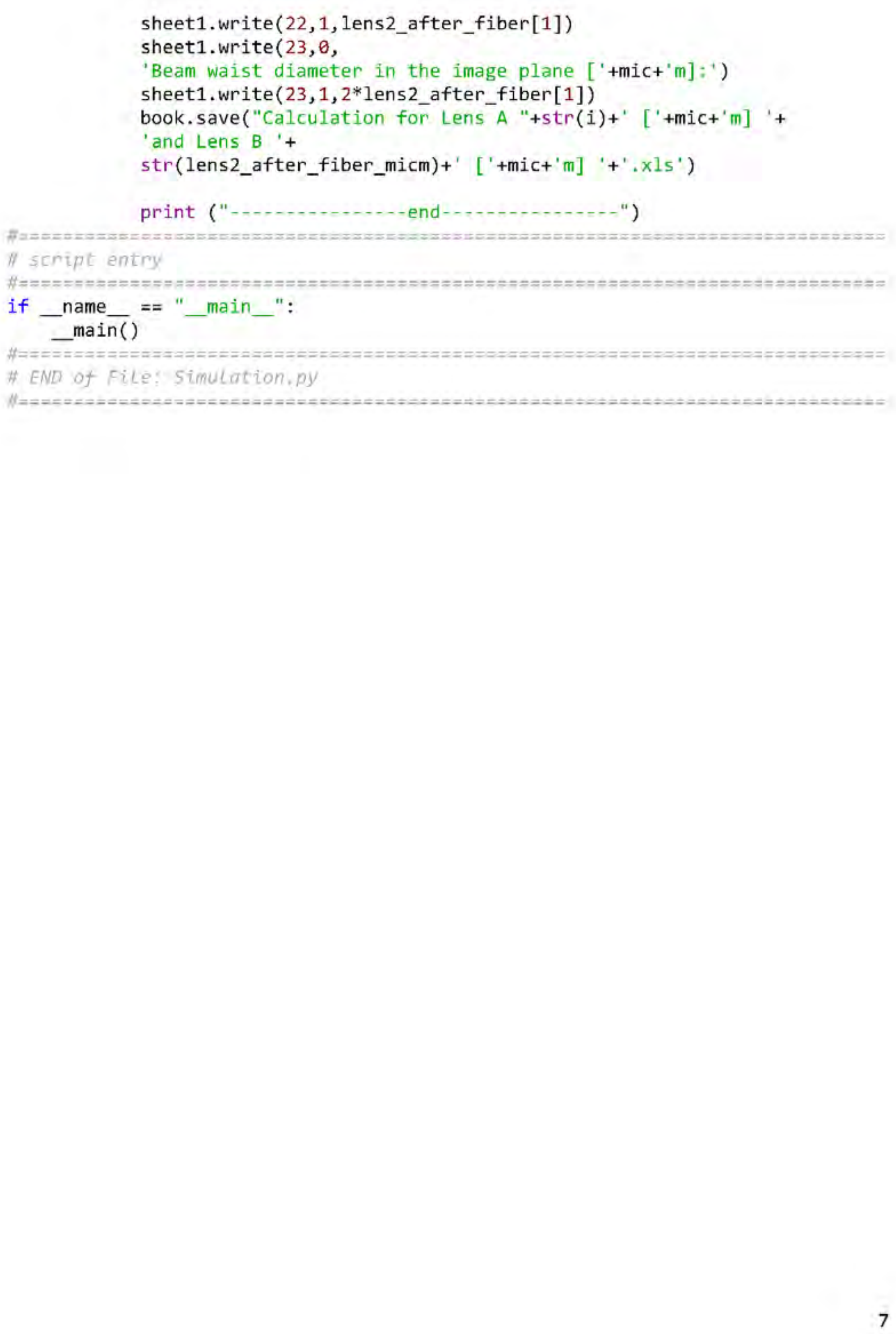
```
            print("Beam waist radius in the image plane (micm):",
                  lens1_after_fiber[1])

            divergence = far_field_divergence(wavelength_micm,M_square,
                                              lens1_after_fiber[1])
            #debugging divergence
            print("Beam divergence after len1 (deg):", divergence)

            #calculation rayleigh length after lens1
            rayleigh_l = rayleigh_length (lens1_after_fiber[1],
                                          wavelength_micm,
                                          M_square)
            #debugging rayleigh length after lens 1
            print("Rayleigh length after lens1 (micm): ",rayleigh_l)

            #calculation beam diameter when the laser beam reaches lens 2
            beam_farfield_dia_atl2 = beam_far_field_diameter (
                                                        2*lens1_after_fiber[1],
                                                        divergence,
                                                        lens2_after_fiber_micm,
                                                        lens1_after_fiber[0])

            #debugging beam diameter when the laser beam reaches lens 2
            print("Beam diameter when the laser reaches lens 2 (micm): ",
                  beam_farfield_dia_atl2)

#==============================================================================

            ##Calculation after lens 2
            print("\nCalculation after lens 2:")

            lens2_after_fiber = ray_transfer_analysis(lens2_after_fiber_micm,
                                                     wavelength_micm,
                                                     lens1_after_fiber[1],
                                                     refractive_index,
                                                     divergence,
                                                     M_square,
                                                     rayleigh_l)

            print(
            "Distance from lens to beam waist in the image plane (micm):",
                  lens2_after_fiber[0])
            print("Beam waist radius in the image plane (micm):",
                  lens2_after_fiber[1])

            print("Beam waist diameter in the image plane (micm):",
                  2*lens2_after_fiber[1])

#==============================================================================

            #writing results into Excel sheets

            mic =  unicode("µ")
            mic = mic[1]
```

5



```
book = Workbook()
sheet1 = book.add_sheet('Sheet 1')
sheet1.write(0,0,'Parameter')
sheet1.write(0,1,'Value')
sheet1.write(1,0,'Wavelength ['+mic+'m]')
sheet1.write(1,1,wavelength_micm)
sheet1.write(2,0,'M-square factor')
sheet1.write(2,1,M_square)
sheet1.write(3,0,'Beam waist radius after fiber ['+mic+'m]')
sheet1.write(3,1,beam_waist_radius_micm)
sheet1.write(4,0,'focal length Lens A [mm]')
sheet1.write(4,1,i)
sheet1.write(5,0,'focal length Lens B [mm]')
sheet1.write(5,1,lens2_after_fiber_micm)
sheet1.write(7,0,'Calculation after optical fiber:')
sheet1.write(8,0,
'Beam divergence after fiber [deg]:')
sheet1.write(8,1,divergence1)
sheet1.write(9,0,
'Fiber exit angle [deg]:')
sheet1.write(9,1,exit_angle)
sheet1.write(10,0,
'fiber cone diameter after '+
str(i)+mic+'m distance between optical fiber exit and lens A ['+
mic+'m]:')
sheet1.write(10,1,beam_diameter_fiber_angle)
sheet1.write(11,0,
'Rayleigh length after fiber ['+mic+'m]:')
sheet1.write(11,1,rayleigh_l1)
sheet1.write(13,0,'Calculation after lens A:')
sheet1.write(14,0,
'Distance from lens A to beam waist in the image plane ['+
mic+'m]:')
sheet1.write(14,1,lens1_after_fiber[0])
sheet1.write(15,0,
'Beam waist radius in the image plane ['+mic+'m]:')
sheet1.write(15,1,lens1_after_fiber[1])
sheet1.write(16,0,
'Beam divergence after lens A (deg):')
sheet1.write(16,1,divergence)
sheet1.write(17,0,
'Rayleigh length after Lens A ['+mic+'m]:')
sheet1.write(17,1,rayleigh_l)
sheet1.write(18,0,
'Beam diameter when the laser beam reaches lens B ['+mic+'m]:')
sheet1.write(18,1,beam_farfield_dia_atl2)
sheet1.write(20,0,'Calculation after lens B:')
sheet1.write(21,0,
'Distance from lens B to beam waist in the image plane['+mic+'m]:')
sheet1.write(21,1,lens2_after_fiber[0])
sheet1.write(22,0,
'Beam waist radius in the image plane ['+mic+'m]:')
```

6



```
            sheet1.write(22,1,lens2_after_fiber[1])
            sheet1.write(23,0,
            'Beam waist diameter in the image plane ['+mic+'m]:')
            sheet1.write(23,1,2*lens2_after_fiber[1])
            book.save("Calculation for Lens A "+str(i)+' ['+mic+'m] '+
            'and Lens B '+
            str(lens2_after_fiber_micm)+' ['+mic+'m] '+'.xls')

            print ("----------------end----------------")
#===============================================================================
# script entry
#===============================================================================
if __name__ == "__main__":
    __main()
#===============================================================================
# END of File: Simulation.py
#===============================================================================
```

7

II Simulation results

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	581,854559
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,55548
Beam waist radius in the image plane [µm]:	150,348395
Beam waist diameter in the image plane [µm]:	300,69679

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	6398,17693
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,1922
Beam waist radius in the image plane [µm]:	150,362381
Beam waist diameter in the image plane [µm]:	300,724762

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	12287,7723
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25804,5637
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729943

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	18179,5653
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31030,8424
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	24071,9424
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34444,154
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	29964,5589
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36356,1402
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	35857,2969
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37131,6287
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	41750,1048
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37102,9916
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	47642,9568
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36536,8659
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	10000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 10000µm distance between optical fiber exit and lens A [µm]:	4910,50802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9154,72372
Beam waist radius in the image plane [µm]:	150,358794
Beam divergence after lens A (deg):	0,5892986
Rayleigh length after Lens A [µm]:	157,507864
Beam diameter when the laser beam reaches lens B [µm]:	53535,8383
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35631,5623
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	2730,6276
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,58416
Beam waist radius in the image plane [µm]:	150,348394
Beam waist diameter in the image plane [µm]:	300,696787

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	3192,92032
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,399
Beam waist radius in the image plane [µm]:	150,362381
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	9076,4533
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,1576
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	14967,2349
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31031,9876
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	20859,1248
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34445,9177
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	26751,3907
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36358,4982
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	32643,8291
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37134,4984
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	38536,3607
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37106,2662
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	44428,9485
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36540,4383
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	20000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	50321,5728
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35635,3373
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	3774,2386
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,58948
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696787

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	2151,58099
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4373
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	8028,79302
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,2676
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	13919,1065
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,1997
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	19810,8387
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,2443
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	25703,0139
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36358,9349
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	31595,3844
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,0298
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	37487,8579
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37106,8726
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	43380,3927
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,0999
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	30000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 30000µm distance between optical fiber exit and lens A [µm]:	13931,5241
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16384,5762
Beam waist radius in the image plane [µm]:	150,366127
Beam divergence after lens A (deg):	0,58926986
Rayleigh length after Lens A [µm]:	157,515545
Beam diameter when the laser beam reaches lens B [µm]:	49272,9666
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,0365
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	3634,40495
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59134
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	2290,56925
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4508
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	8168,96187
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3061
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	14059,324
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,2739
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	19951,0568
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,3587
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	25843,2228
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,0878
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	31735,5807
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,2158
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	37628,0404
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,0849
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	43520,5606
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,3314
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	40000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 40000µm distance between optical fiber exit and lens A [µm]:	18442,0321
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	16146,5065
Beam waist radius in the image plane [µm]:	150,366528
Beam divergence after lens A (deg):	0,58926829
Rayleigh length after Lens A [µm]:	157,515965
Beam diameter when the laser beam reaches lens B [µm]:	49413,1195
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,2812
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	3028,17413
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,5922
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	2895,13342
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,457
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	8777,3007
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3239
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	14667,9061
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3083
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	20559,698
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4116
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	26451,8835
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,1585
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	32344,2477
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,3019
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	38236,7078
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,1831
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	44129,2254
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,4386
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	50000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 50000µm distance between optical fiber exit and lens A [µm]:	22952,5401
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	15113,4733
Beam waist radius in the image plane [µm]:	150,366714
Beam divergence after lens A (deg):	0,58926756
Rayleigh length after Lens A [µm]:	157,51616
Beam diameter when the laser beam reaches lens B [µm]:	50021,7803
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,3944
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	2303,80979
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59266
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	3621,08437
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4603
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	9506,00454
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3336
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	15396,8552
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3269
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	21288,7138
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4403
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	27180,9249
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,1969
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	33073,3001
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,3487
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	38965,765
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,2365
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	44858,2842
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,4968
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	60000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 60000µm distance between optical fiber exit and lens A [µm]:	27463,0481
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	13876,1653
Beam waist radius in the image plane [µm]:	150,366815
Beam divergence after lens A (deg):	0,58926716
Rayleigh length after Lens A [µm]:	157,516265
Beam diameter when the laser beam reaches lens B [µm]:	50750,8387
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,456
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	1602,59825
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59294
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	4328,99936
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4624
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	10215,6376
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3394
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	16106,6871
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3382
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	21998,6042
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4577
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	27890,8392
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,2201
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	33783,2256
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,3769
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	39675,696
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,2686
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	45568,2179
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,5319
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	70000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 70000µm distance between optical fiber exit and lens A [µm]:	31973,5562
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	12671,3334
Beam waist radius in the image plane [µm]:	150,366875
Beam divergence after lens A (deg):	0,58926692
Rayleigh length after Lens A [µm]:	157,516329
Beam diameter when the laser beam reaches lens B [µm]:	51460,7735
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,4931
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	977,65325
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59313
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	4971,52194
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4637
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	10859,2504
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3432
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	16750,453
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3455
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	22642,418
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4689
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	28534,6733
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,2351
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	34427,0697
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,3952
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	40319,5455
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,2895
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	46212,0701
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,5547
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	80000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 80000µm distance between optical fiber exit and lens A [µm]:	36484,0642
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	11578,6568
Beam waist radius in the image plane [µm]:	150,366915
Beam divergence after lens A (deg):	0,58926677
Rayleigh length after Lens A [µm]:	157,51637
Beam diameter when the laser beam reaches lens B [µm]:	52104,6272
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,5171
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	470,733183
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59325
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	5538,69232
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4646
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	11427,1464
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3458
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	17318,4664
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3505
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	23210,4701
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4766
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	29102,7422
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,2454
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	34995,1472
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,4077
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	40887,6276
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,3039
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	46780,155
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,5703
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	90000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 90000µm distance between optical fiber exit and lens A [µm]:	40994,5722
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	10614,5686
Beam waist radius in the image plane [µm]:	150,366942
Beam divergence after lens A (deg):	0,58926666
Rayleigh length after Lens A [µm]:	157,516399
Beam diameter when the laser beam reaches lens B [µm]:	52672,7135
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,5337
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	10000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	329,358951
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	9822,59334
Beam waist radius in the image plane [µm]:	150,348393
Beam waist diameter in the image plane [µm]:	300,696786

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	20000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	6034,464
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	18652,4652
Beam waist radius in the image plane [µm]:	150,36238
Beam waist diameter in the image plane [µm]:	300,724761

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	30000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	11923,4247
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	25805,3477
Beam waist radius in the image plane [µm]:	150,364971
Beam waist diameter in the image plane [µm]:	300,729942

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	40000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	17814,8359
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	31032,3541
Beam waist radius in the image plane [µm]:	150,365878
Beam waist diameter in the image plane [µm]:	300,731756

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	23706,8708
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34446,4821
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	60000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	29599,157
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36359,2528
Beam waist radius in the image plane [µm]:	150,366526
Beam waist diameter in the image plane [µm]:	300,733051

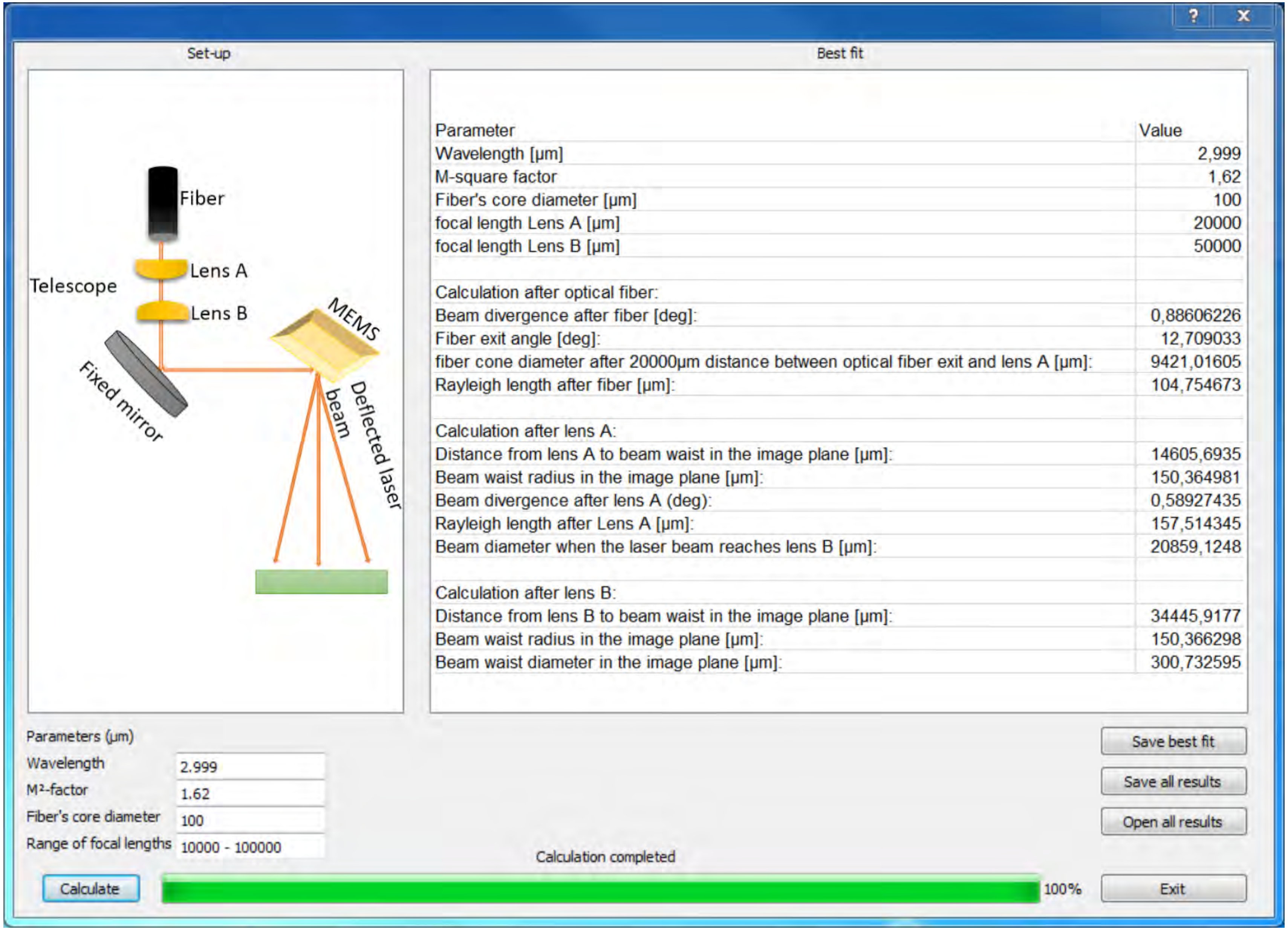
Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	70000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	35491,5692
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37135,4167
Beam waist radius in the image plane [µm]:	150,366663
Beam waist diameter in the image plane [µm]:	300,733326

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	80000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	41384,0536
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	37107,3141
Beam waist radius in the image plane [µm]:	150,366752
Beam waist diameter in the image plane [µm]:	300,733505

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	90000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	47276,5833
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	36541,5815
Beam waist radius in the image plane [µm]:	150,366813
Beam waist diameter in the image plane [µm]:	300,733627

Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Beam waist radius after fiber [µm]	100
focal length Lens A [mm]	100000
focal length Lens B [mm]	100000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 100000µm distance between optical fiber exit and lens A [µm]:	45505,0802
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	9772,08998
Beam waist radius in the image plane [µm]:	150,366961
Beam divergence after lens A (deg):	0,58926659
Rayleigh length after Lens A [µm]:	157,516419
Beam diameter when the laser beam reaches lens B [µm]:	53169,1432
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	35636,5455
Beam waist radius in the image plane [µm]:	150,366857
Beam waist diameter in the image plane [µm]:	300,733714

III Graphical User Interface (GUI)



Parameter	Value
Wavelength [µm]	2,999
M-square factor	1,62
Fiber's core diameter [µm]	100
focal length Lens A [µm]	20000
focal length Lens B [µm]	50000
Calculation after optical fiber:	
Beam divergence after fiber [deg]:	0,88606226
Fiber exit angle [deg]:	12,709033
fiber cone diameter after 20000µm distance between optical fiber exit and lens A [µm]:	9421,01605
Rayleigh length after fiber [µm]:	104,754673
Calculation after lens A:	
Distance from lens A to beam waist in the image plane [µm]:	14605,6935
Beam waist radius in the image plane [µm]:	150,364981
Beam divergence after lens A (deg):	0,58927435
Rayleigh length after Lens A [µm]:	157,514345
Beam diameter when the laser beam reaches lens B [µm]:	20859,1248
Calculation after lens B:	
Distance from lens B to beam waist in the image plane [µm]:	34445,9177
Beam waist radius in the image plane [µm]:	150,366298
Beam waist diameter in the image plane [µm]:	300,732595

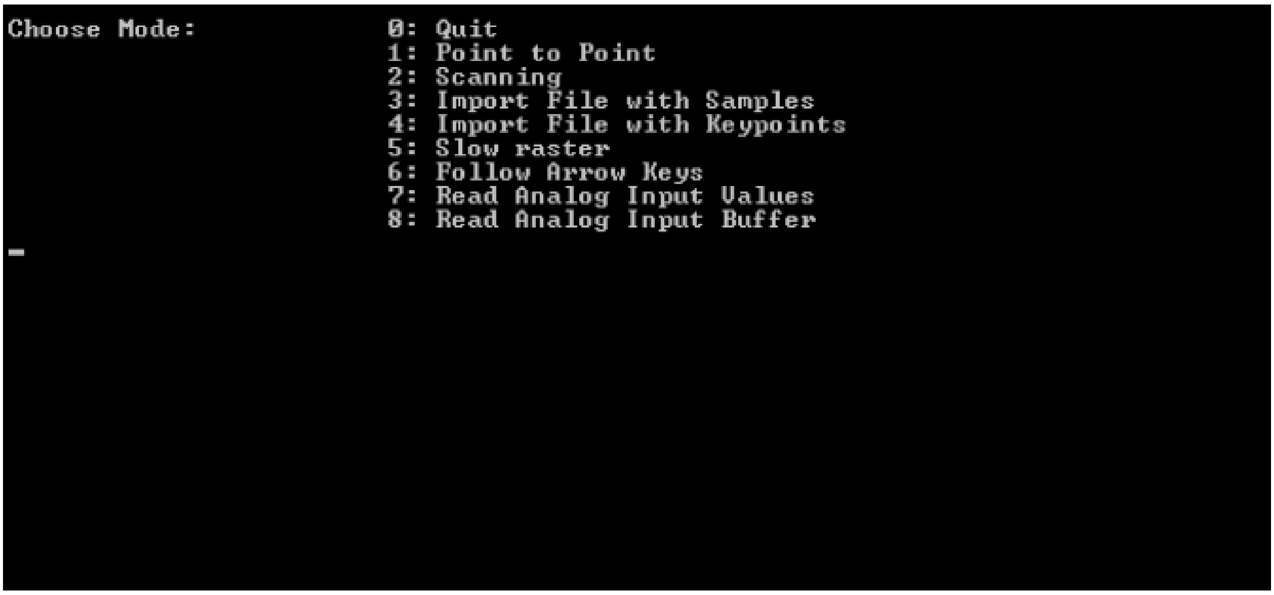
Parameters (µm)

Wavelength	2.999
M²-factor	1.62
Fiber's core diameter	100
Range of focal lengths	10000 - 100000

Calculation completed

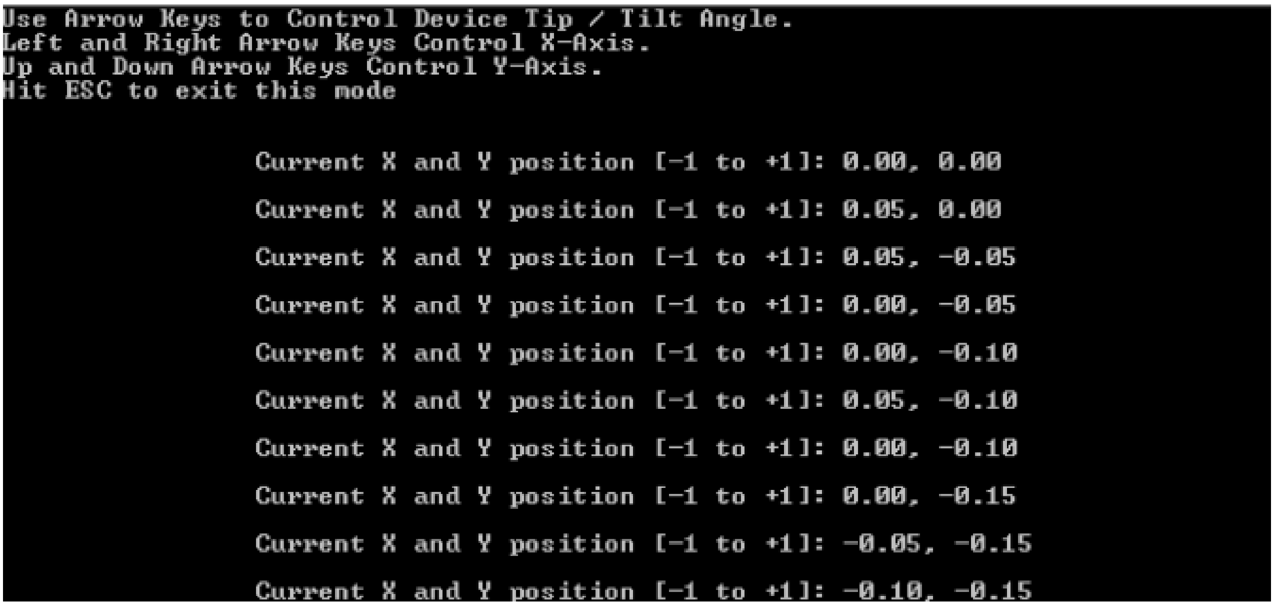
IV MEMS programming

With “Import File with Keypoints”, it is possible to import individual .txt-files with scanning information.



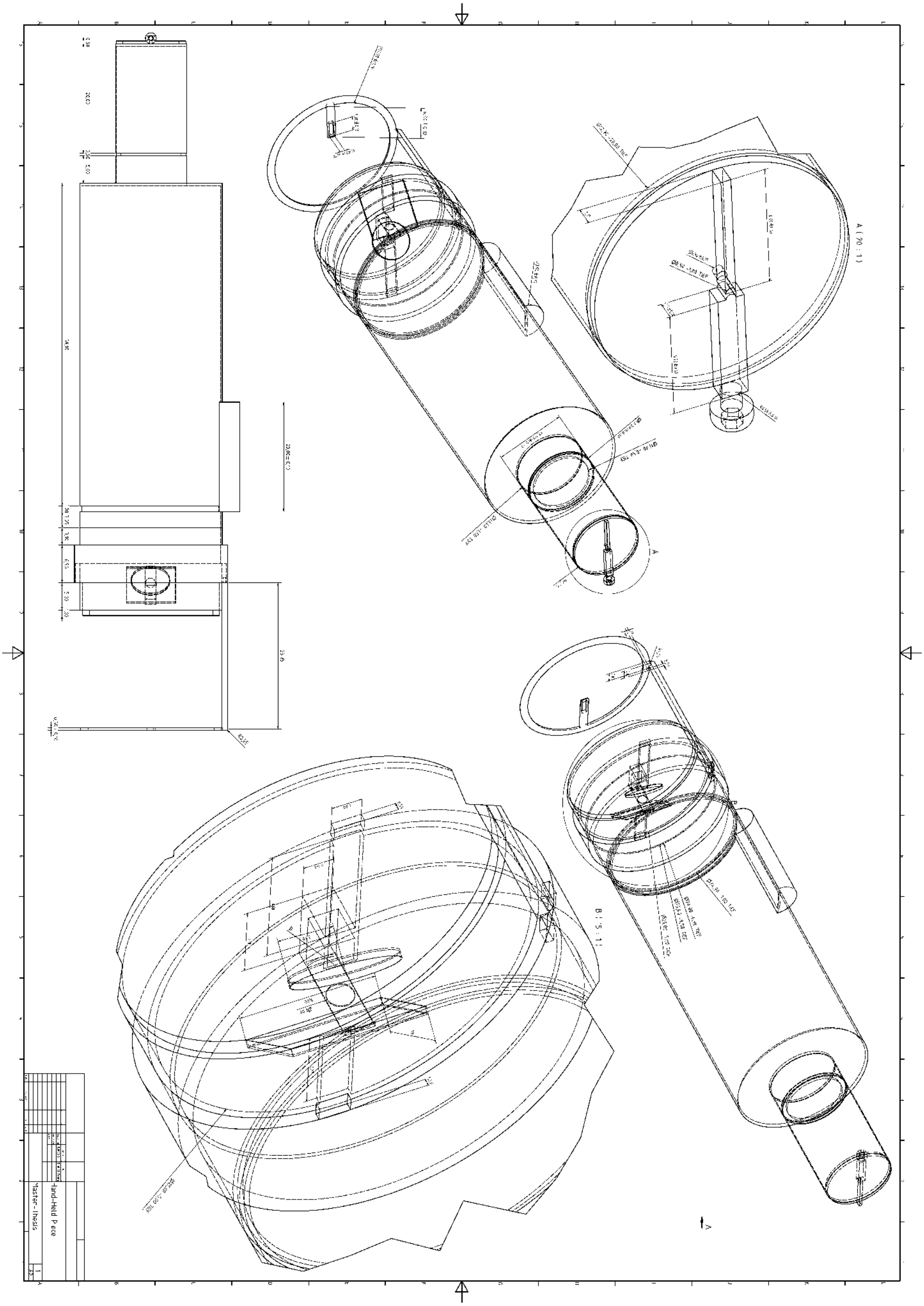
```
Choose Mode:                0: Quit
                            1: Point to Point
                            2: Scanning
                            3: Import File with Samples
                            4: Import File with Keypoints
                            5: Slow raster
                            6: Follow Arrow Keys
                            7: Read Analog Input Values
                            8: Read Analog Input Buffer
_
```

With “Follow Arrow Keys”, it is possible to control the MEMS directly with the computer’s arrow Keys, if the MEMS is connected to a computer.



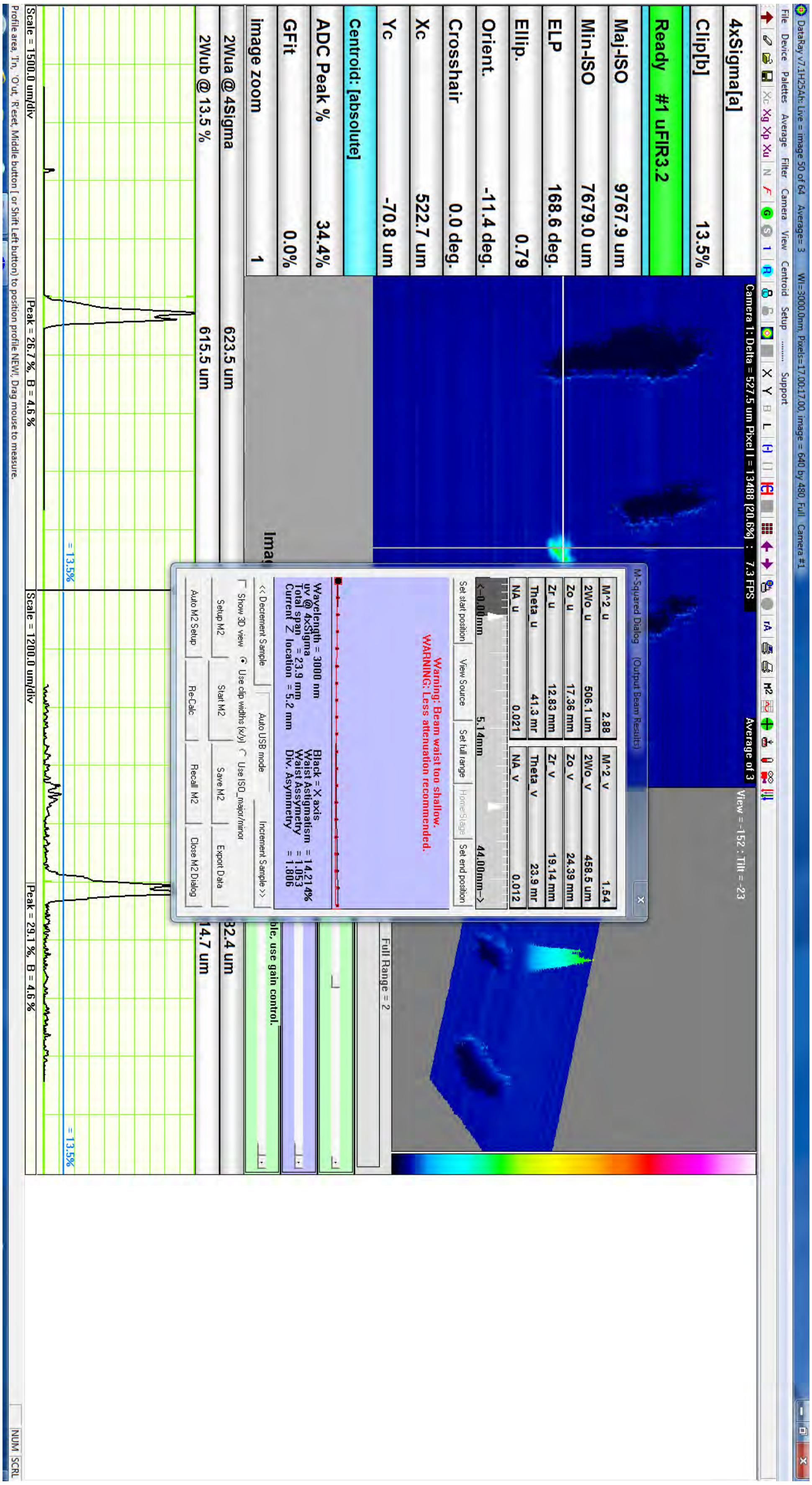
```
Use Arrow Keys to Control Device Tip / Tilt Angle.
Left and Right Arrow Keys Control X-Axis.
Up and Down Arrow Keys Control Y-Axis.
Hit ESC to exit this mode

                  Current X and Y position [-1 to +1]: 0.00, 0.00

                  Current X and Y position [-1 to +1]: 0.05, 0.00

                  Current X and Y position [-1 to +1]: 0.05, -0.05

                  Current X and Y position [-1 to +1]: 0.00, -0.05

                  Current X and Y position [-1 to +1]: 0.00, -0.10

                  Current X and Y position [-1 to +1]: 0.05, -0.10

                  Current X and Y position [-1 to +1]: 0.00, -0.10

                  Current X and Y position [-1 to +1]: 0.00, -0.15

                  Current X and Y position [-1 to +1]: -0.05, -0.15

                  Current X and Y position [-1 to +1]: -0.10, -0.15
```

V Technical drawing



VI Measurements

M²-Factor measurement



DataRay v7.1H25Ah: Live = image 50 of 64 Average= 3 Wl=3000.0nm, Pixels=17.00:17.00, image = 640 by 480, Full Camera #1

Camera 1: Delta = 527.5 um Pixel I = 13488 [20.6%] : 7.3 FPS Average of 3 View = 152 : Tilt = -23

4xSigma[a]	
Clip[b]	13.5%
Ready #1 uFIR3.2	
Maj-ISO	9767.9 um
Min-ISO	7679.0 um
ELP	168.6 deg.
Ellip.	0.79
Orient.	-11.4 deg.
Crosshair	0.0 deg.
Xc	522.7 um
Yc	-70.8 um
Centroid: [absolute]	
ADC Peak %	34.4%
GFit	0.0%
image zoom	1
2Wua @ 4Sigma	623.5 um
2Wub @ 13.5 %	615.5 um

M-Squared Dialog (Output Beam Results)

M^2_u	2.88	M^2_v	1.54
2Wo_u	506.1 um	2Wo_v	458.5 um
Zo_u	17.36 mm	Zo_v	24.39 mm
Zr_u	12.83 mm	Zr_v	19.14 mm
Theta_u	41.3 mr	Theta_v	23.9 mr
NA_u	0.021	NA_v	0.012

<-0.00mm 5.14mm 44.00mm->

Warning: Beam waist too shallow.
WARNING: Less attenuation recommended.

Wavelength = 3000 nm
uv @ 4xSigma
Total span = 23.9 mm
Current Z location = 5.2 mm

Black = X axis
Waist Astigmatism = 14.214%
Waist Assymetry = 1.053
Div. Asymmetry = 1.806

☐ Show 3D view ● Use clip widths (x/y) ○ Use ISO_major/minor

Full Range = 2

...ble, use gain control.

2Wua @ 4Sigma 82.4 um

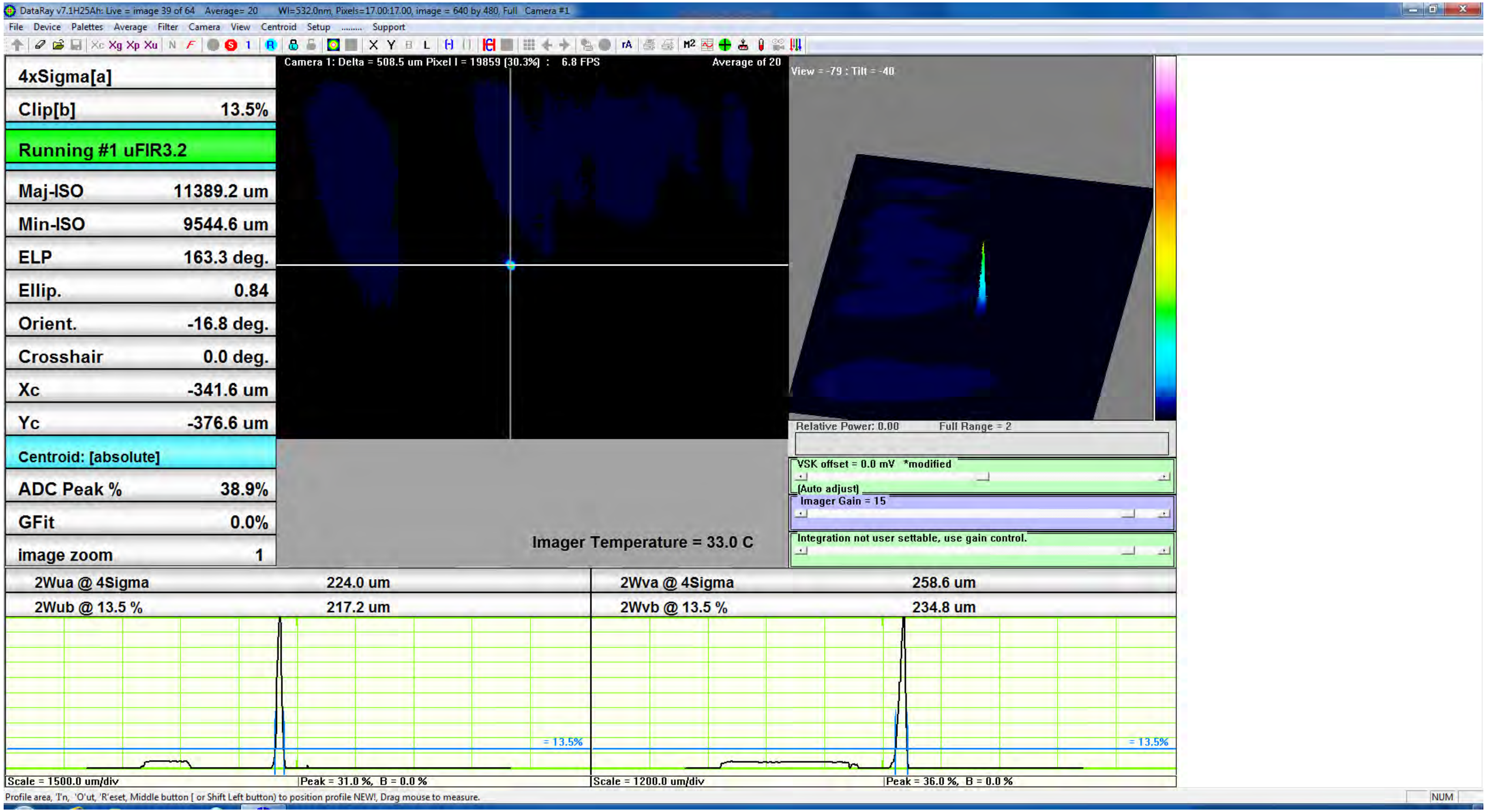
2Wub @ 13.5 % 14.7 um

Scale = 1500.0 um/div Peak = 26.7 %, B = 4.6 %

Scale = 1200.0 um/div Peak = 29.1 %, B = 4.6 %

Profile area, 'In,' 'Out,' Reset, Middle button [or Shift Left button] to position profile NEW!, Drag mouse to measure.

Beam waist after fiber and f-20 lens.



4xSigma[a]	
Clip[b]	13.5%
Running #1 uFIR3.2	
Maj-ISO	11389.2 um
Min-ISO	9544.6 um
ELP	163.3 deg.
Ellip.	0.84
Orient.	-16.8 deg.
Crosshair	0.0 deg.
Xc	-341.6 um
Yc	-376.6 um
Centroid: [absolute]	
ADC Peak %	38.9%
GFit	0.0%
image zoom	1

Imager Temperature = 33.0 C

VSK offset = 0.0 mV *modified

(Auto adjust)

Imager Gain = 15

Integration not user settable, use gain control.

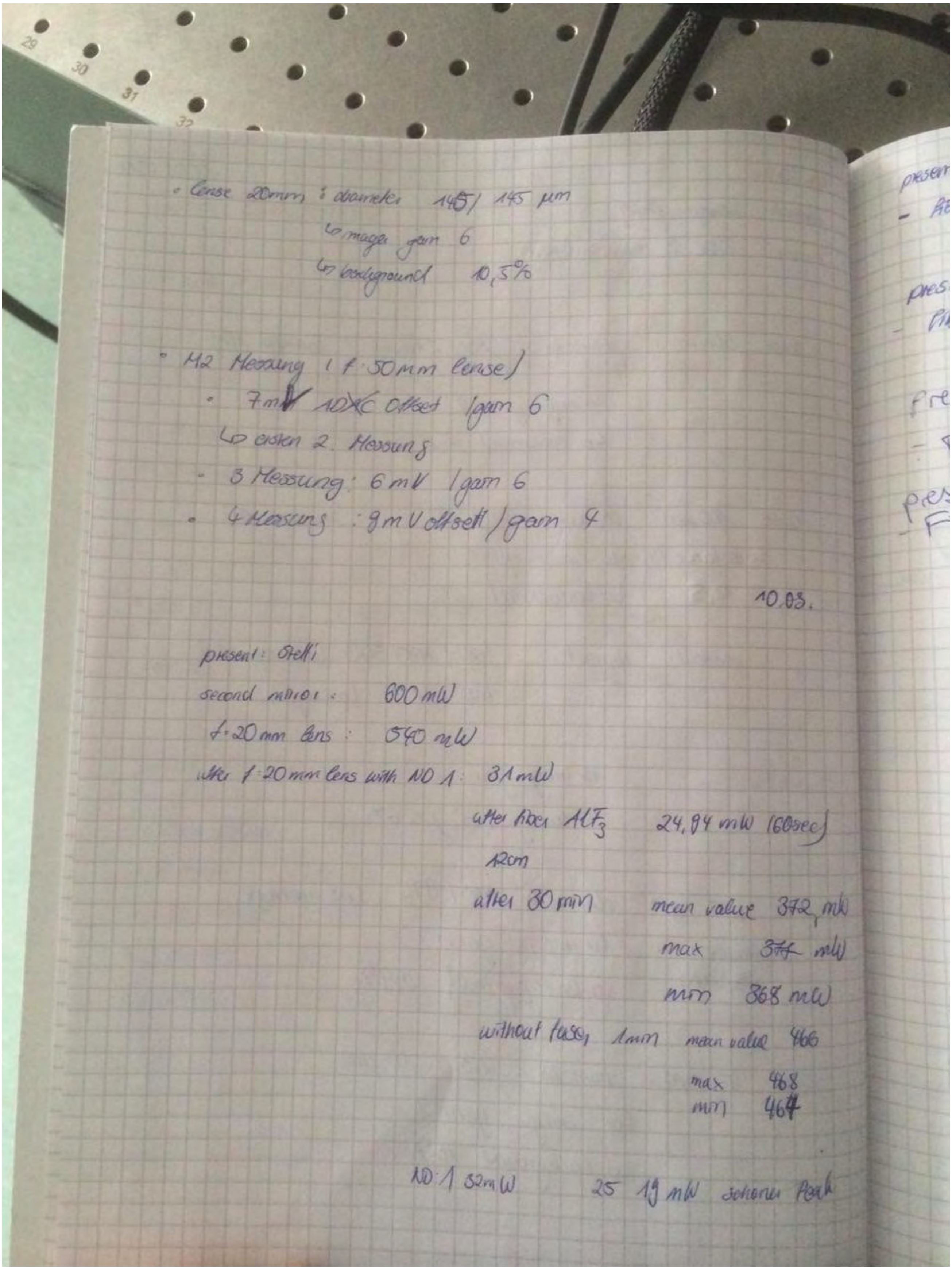
2Wua @ 4Sigma	224.0 um	2Wva @ 4Sigma	258.6 um
2Wub @ 13.5 %	217.2 um	2Wvb @ 13.5 %	234.8 um

Scale = 1500.0 um/div Peak = 31.0 %, B = 0.0 %

Scale = 1200.0 um/div Peak = 36.0 %, B = 0.0 %

Profile area, 'I'n, 'O'ut, 'R'eset, Middle button [or Shift Left button) to position profile NEW!, Drag mouse to measure.

Laboratory Data



- Lense 20mm : diameter 145/ 145 µm
  - ↳ mager gain 6
  - ↳ background 10,5%

- M2 Messung (f: 50mm lense)
  - 7mV 10XC Offset /gain 6
  - ↳ ersten 2. Messung
  - 3 Messung: 6mV /gain 6
  - 4 Messung : 9mV offset /gain 4

10.03.

present: Stelli

second mirror: 600 mW

f=20 mm lens: 540 mW

after f=20mm lens with ND 1: 31mW

after fiber AlF$_3$ 24,94 mW (60sec)

12cm

after 30 min mean value 372, mW

max 377 mW

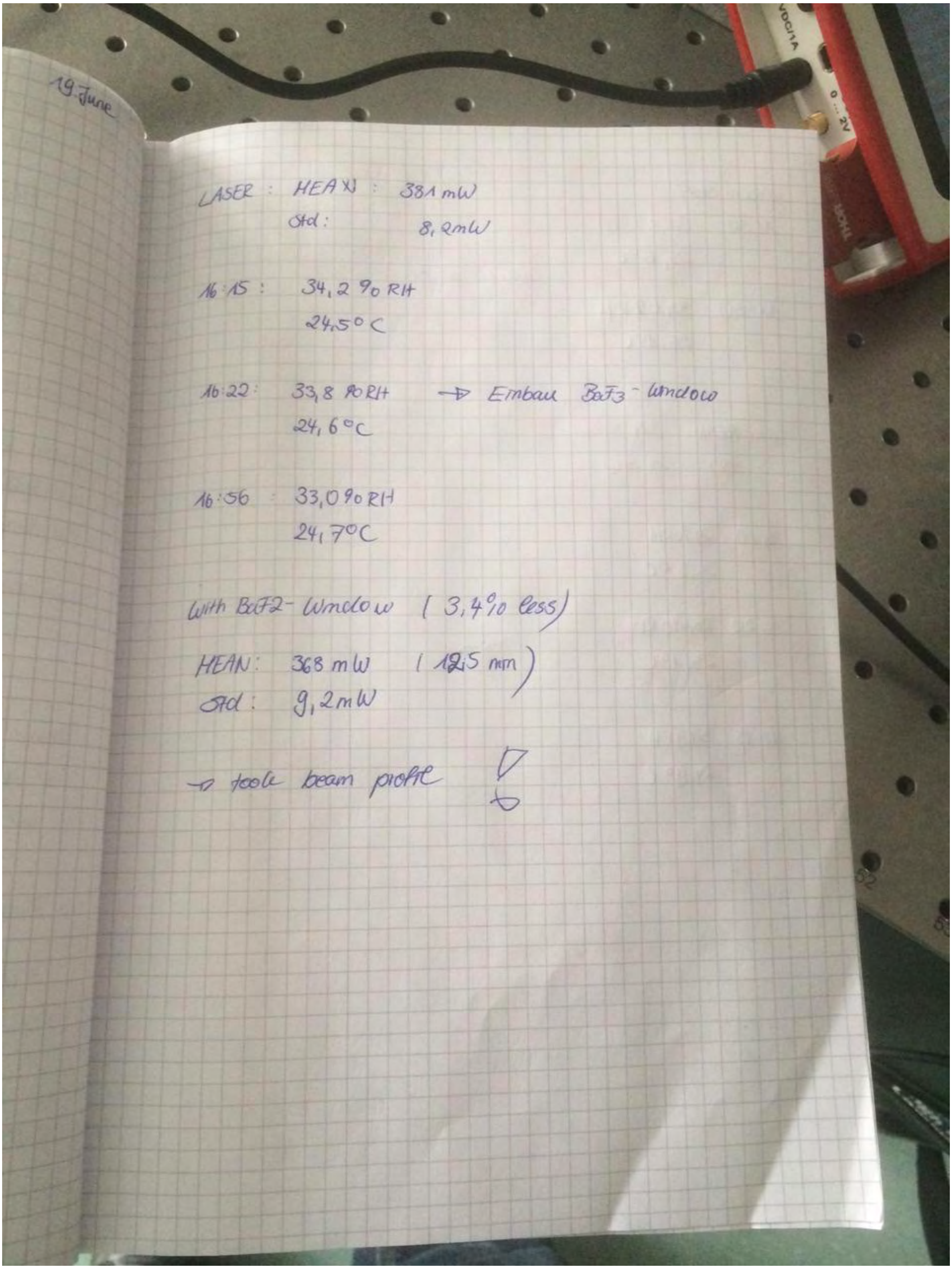
min 368 mW

without laser, 1mm mean value 466

max 468

min 467

ND:1 32mW 25 19 mW schönen Peak



19 June

LASER : MEAN : 381 mW
Std : 8,2 mW

16:15 : 34,2 % RH
24,5 °C

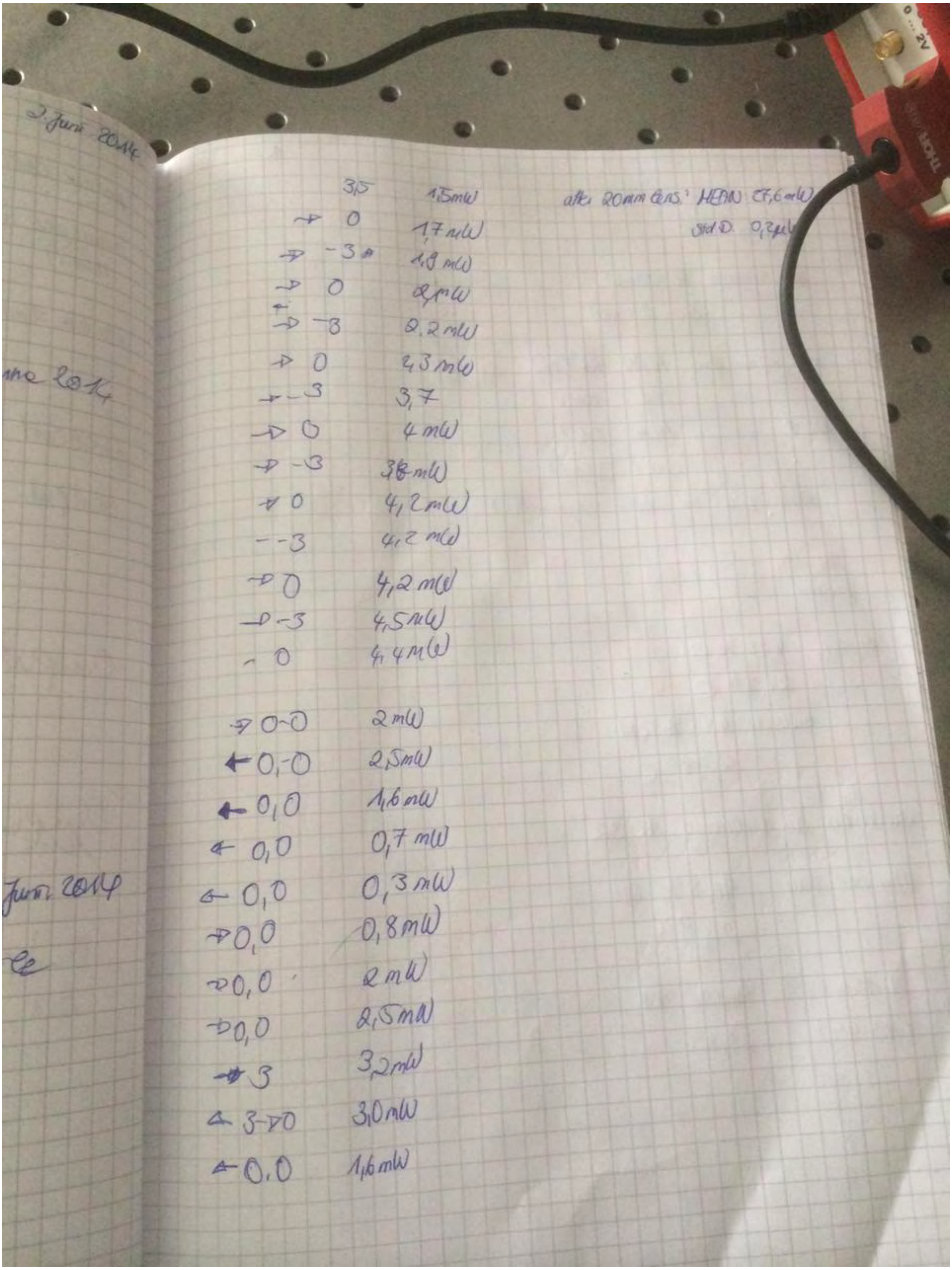
16:22 : 33,8 % RH → Einbau BaF3 - Window
24,6 °C

16:56 : 33,0 % RH
24,7 °C

With BaF2 - Window (3,4 % less)

MEAN : 368 mW (12,5 mm)
Std : 9,2 mW

→ took beam profile !



2. Juni 2014

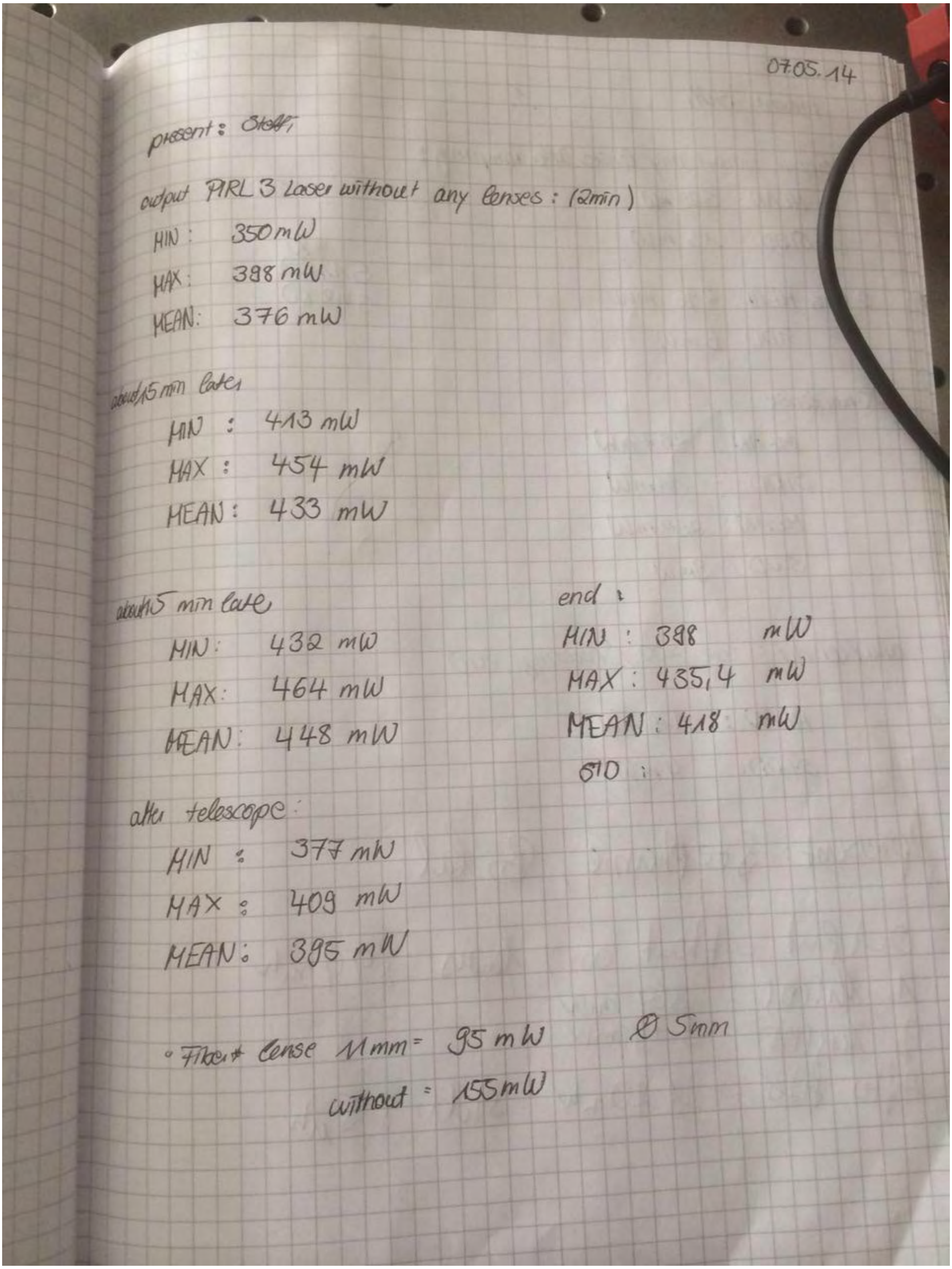
ne 2014

Juni 2014

3,5	1,5 mW
→ 0	1,7 mW
→ -3	1,9 mW
→ 0	2,1 mW
→ -3	2,2 mW
→ 0	2,3 mW
→ -3	3,7
→ 0	4 mW
→ -3	3,8 mW
→ 0	4,2 mW
- -3	4,2 mW
→ 0	4,2 mW
→ -3	4,5 mW
- 0	4,4 mW
→ 0-0	2 mW
← 0,-0	2,5 mW
← 0,0	1,6 mW
← 0,0	0,7 mW
← 0,0	0,3 mW
→ 0,0	0,8 mW
→ 0,0	2 mW
→ 0,0	2,5 mW
→ 3	3,2 mW
← 3→0	3,0 mW
← 0.0	1,6 mW

after 20mm lens: MEAN: 27,6 mW

std D. 0,2μ



07.05.14

present: Steffi

output PIRL 3 Laser without any lenses: (2min)

MIN: 350 mW
MAX: 398 mW
MEAN: 376 mW

about 15 min later

MIN: 413 mW
MAX: 454 mW
MEAN: 433 mW

about 15 min late

MIN: 432 mW
MAX: 464 mW
MEAN: 448 mW

after telescope:

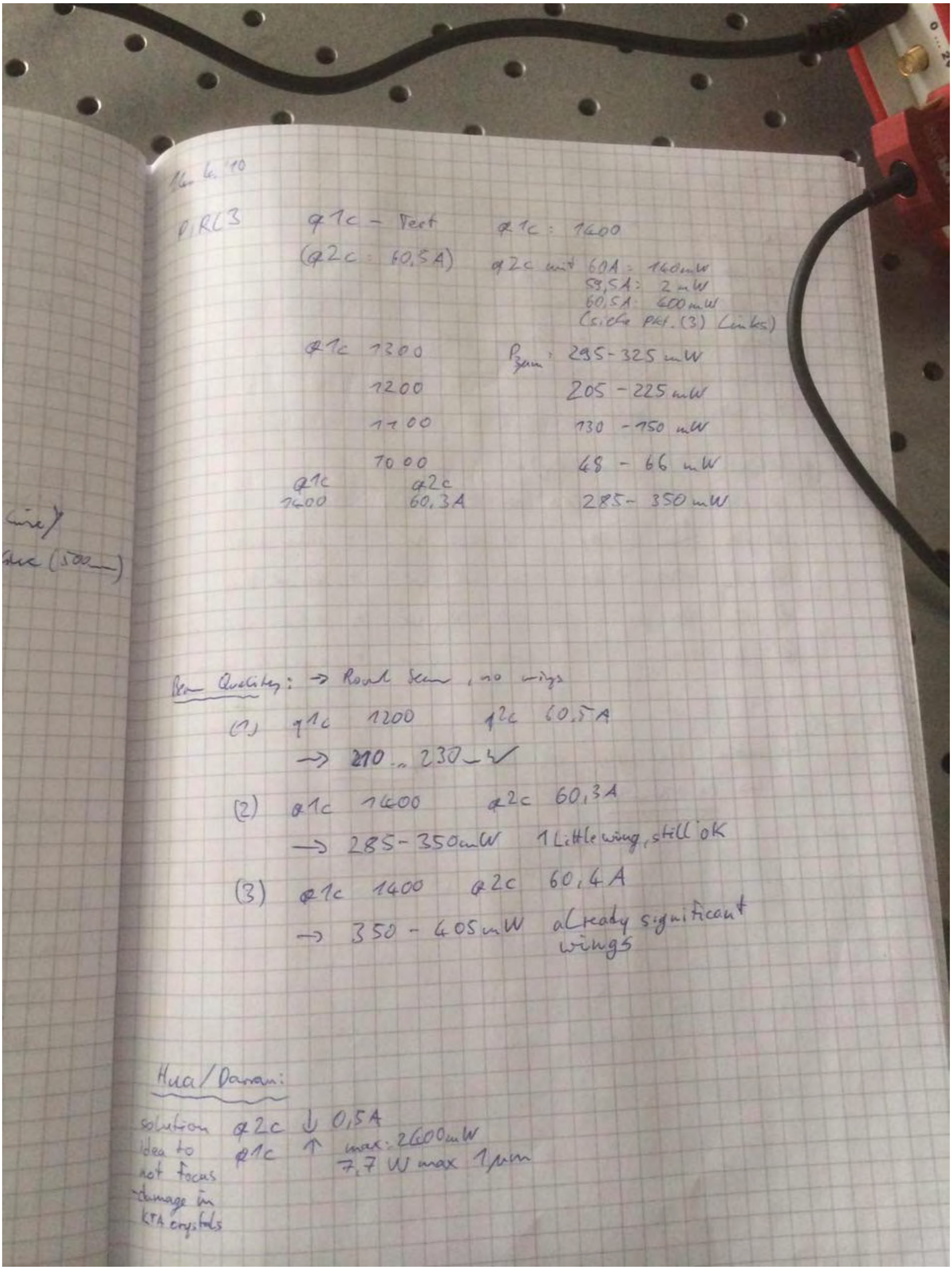
MIN: 377 mW
MAX: 409 mW
MEAN: 395 mW

end:

MIN: 398 mW
MAX: 435,4 mW
MEAN: 418 mW
σ10 :

• Fiber + lense 11 mm = 95 mW
without = 155 mW

Ø 5mm



16.6.'10

P. RL3

ø1c – Test

(ø2c: 60,5A)

ø1c: 1600

ø2c mit 60A: 140mW
59,5A: 2 mW
60,5A: 600 mW
(siehe Pkt. (3) Links)

ø1c 1300	$P_{3\mu m}$:	295-325 mW
1200		205 - 225 mW
1100		130 - 150 mW
1000		48 - 66 mW
ø1c 1600	ø2c 60,3A	285- 350 mW

Beam Quality: → Round Beam, no wings

(1) ø1c 1200 ø2c 60,5A
→ 210 .. 230 mW ✓

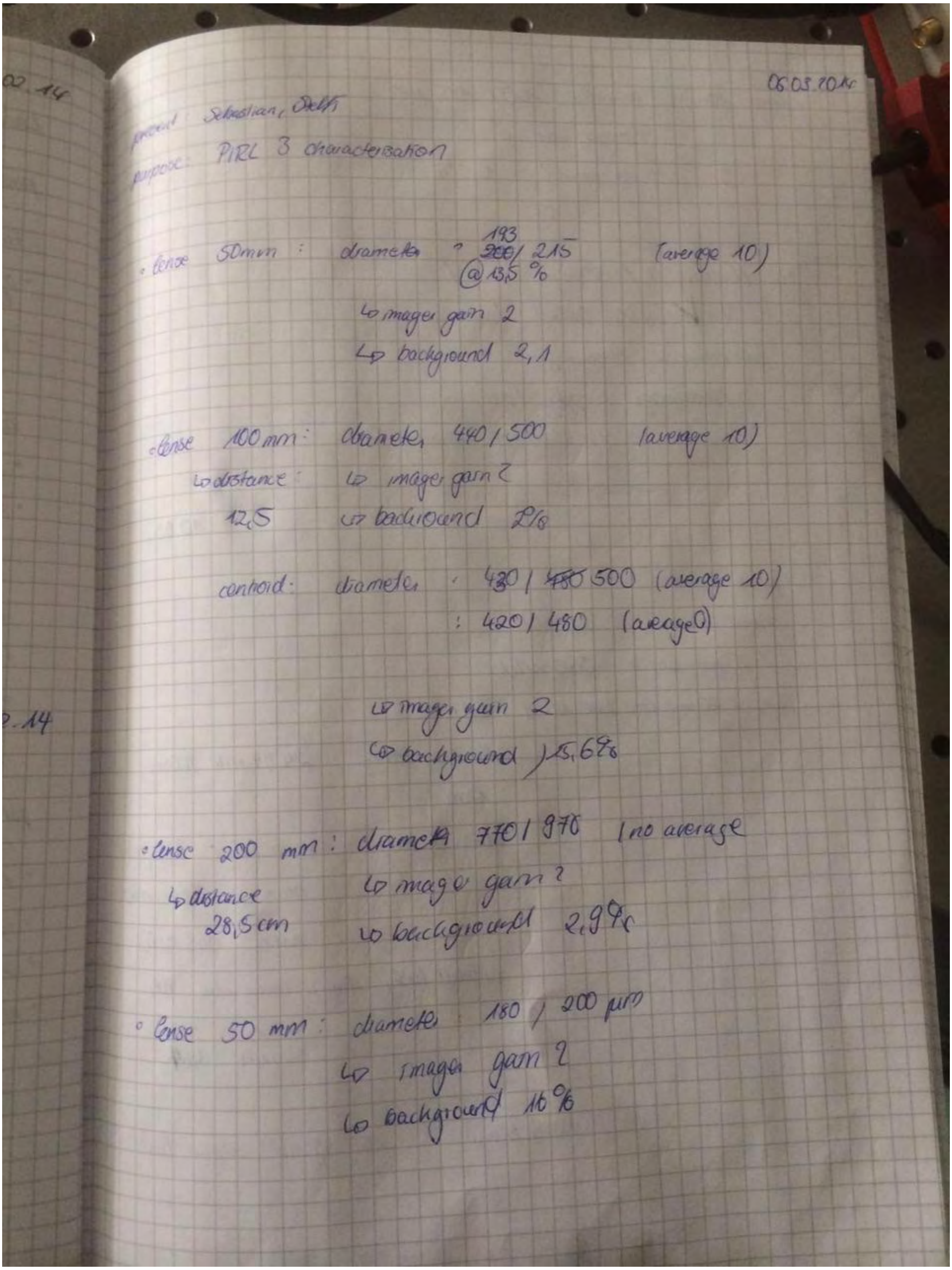
(2) ø1c 1600 ø2c 60,3A
→ 285-350mW 1 Little wing, still ok

(3) ø1c 1400 ø2c 60,4A
→ 350 - 405mW already significant wings

Hua/Daran:

solution idea to not focus damage in KTA crystals

ø2c ↓ 0,5A
ø1c ↑ max: 2600mW
7,7 W max 1μm



02.14

06.03.2014

present: Sebastian, Stefi

purpose: PIRL 3 characterisation

- lense 50mm : diameter : ~~200~~ 193 / 215 (average 10)
  @ 13,5 %
  ↳ imager gain 2
  ↳ background 2,1

- lense 100 mm : diameter 440 / 500 (average 10)
  ↳ distance : ↳ imager gain 2
  12,5 ↳ background 2%

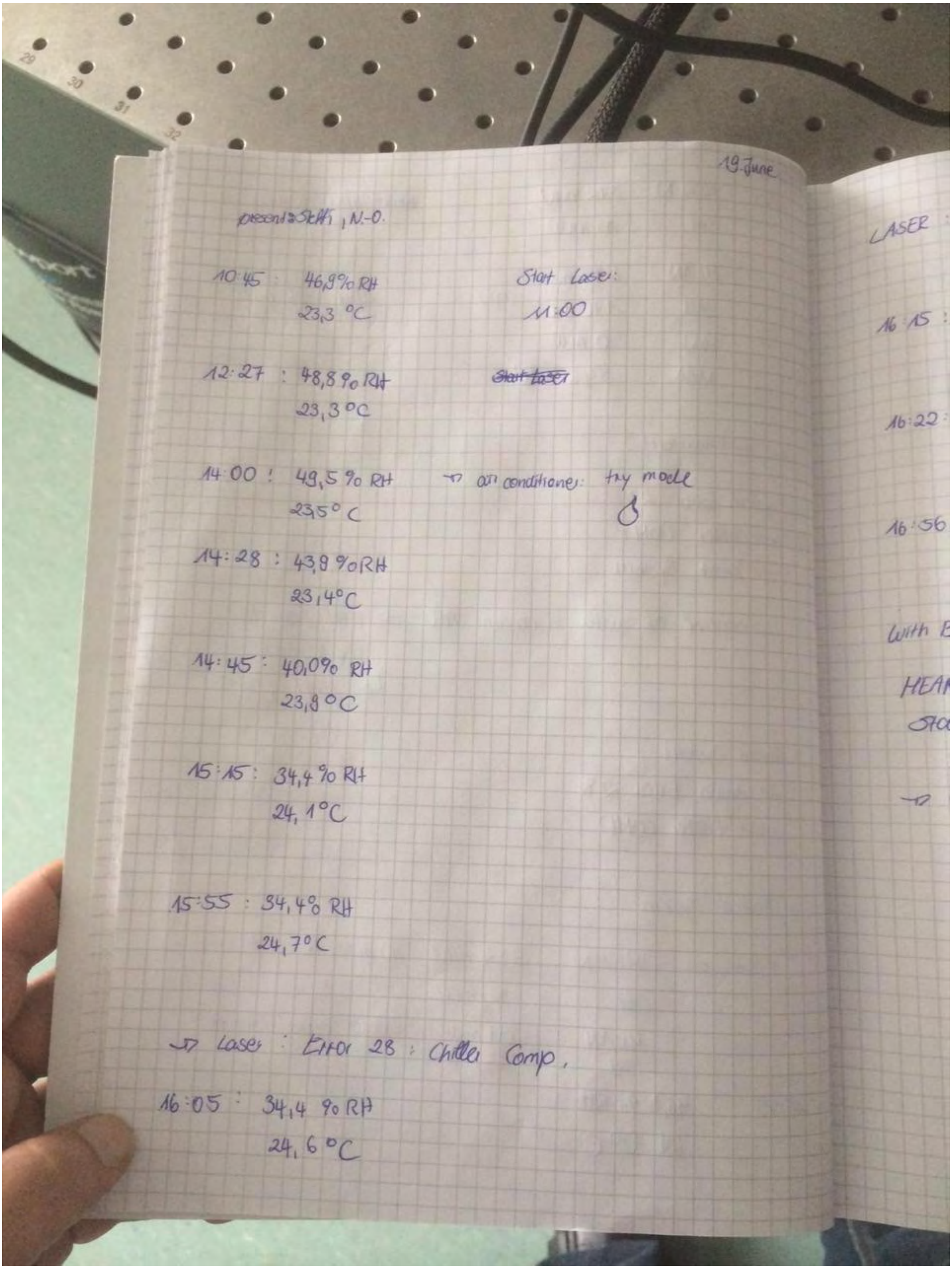
  centroid : diameter : 430 / ~~480~~ 500 (average 10)
  : 420 / 480 (average 0)

.14

↳ imager gain 2
↳ background 15,6%

- lense 200 mm : diameter 770 / 970 (no average
  ↳ distance ↳ imager gain ?
  28,5 cm ↳ background 2,9%

- lense 50 mm : diameter 180 / 200 µm
  ↳ imager gain 2
  ↳ background 16%



19.June

present: Stefi, N.-O.

10:45 : 46,9% RH
23,3 °C

Start Laser:
11:00

12:27 : 48,8 % RH
23,3 °C

~~Start Laser~~

14:00 : 49,5 % RH
23,5 °C

→ air conditioner: dry mode

14:28 : 43,9 % RH
23,4 °C

14:45 : 40,0% RH
23,8 °C

15:15 : 34,4 % RH
24,1 °C

15:55 : 34,4% RH
24,7 °C

→ Laser : Error 28 : Chiller Comp.

16:05 : 34,4 % RH
24,6 °C

LASER :

16:15 :

16:22 :

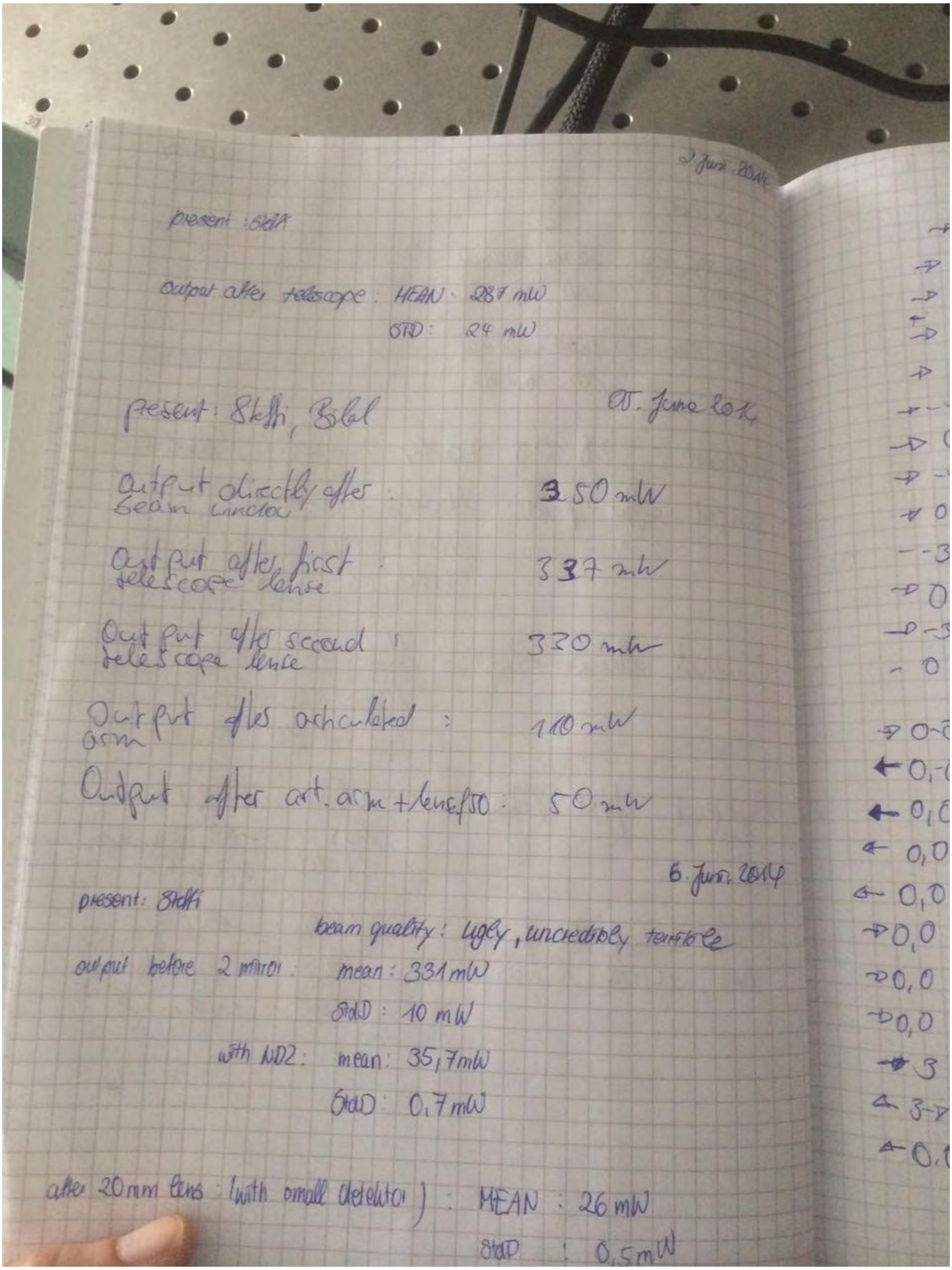
16:56

With

HEA

Sta

→



2. Juni 2014

present : Steffi

output after telescope : MEAN : 287 mW
STD : 24 mW

present : Steffi, Bilal

05. June 2014

Output directly after beam window : 350 mW

Output after first telescope lense : 337 mW

Output after second telescope lence : 330 mW

Output after articulated arm : 110 mW

Output after art. arm + lens f50 : 50 mW

6. Juni 2014

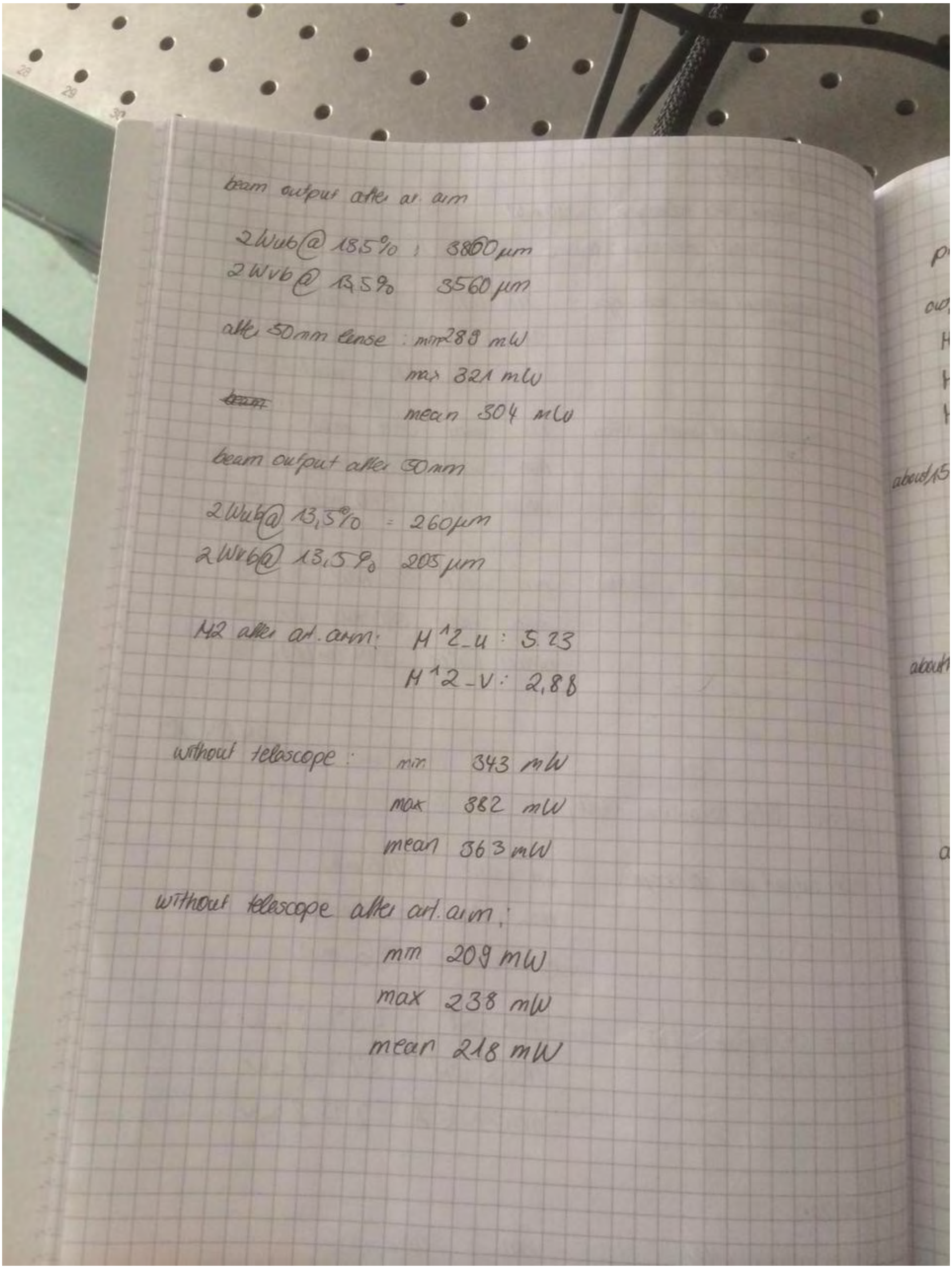
present : Steffi

beam quality : ugly, uncredibly terrible

output before 2 mirror : mean : 331 mW
StdD : 10 mW

with ND2 : mean : 35,7 mW
StdD : 0,7 mW

after 20 mm lens : (with small detektor) : MEAN : 26 mW
StdD : 0,5 mW



beam output after ar. arm

2Wub@ 18,5% : 3860 μm
2Wvb@ 13,5% 3560 μm

after 50mm lense : min 288 mW
max 321 mW
~~beam~~ mean 304 mW

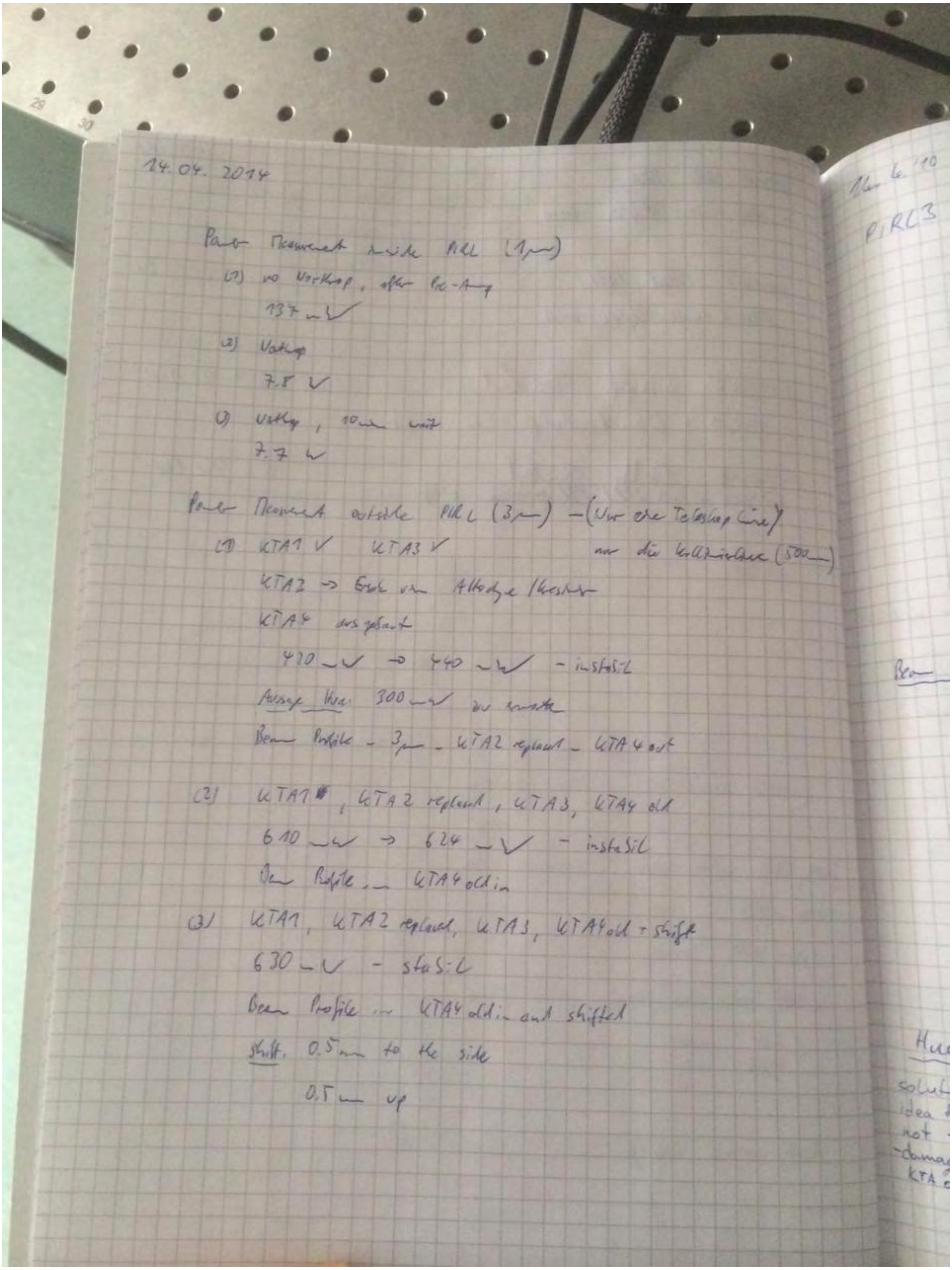
beam output after 50mm

2Wub@ 13,5% = 260μm
2Wvb@ 13,5% 205 μm

M2 after art. arm: M^2_u : 5.23
M^2_v : 2,88

without telescope : min 343 mW
max 382 mW
mean 363 mW

without telescope after art. arm :
min 209 mW
max 238 mW
mean 218 mW



14.04.2014

Power Measurement inside PIRL (1µm)

(1) no Vorkopf, after Pre-Amp

137 mW ✓

(2) Vorkopf

7.5 W ✓

(3) Vorkopf, 10 min wait

7.7 W

Power Measurement outside PIRL (3µm) – (vor der Teleskop Linse)

(1) KTA1 ✓ KTA3 ✓ nur die Kollimierlinse (500 mm)

KTA2 → Ersatz von Altechna Kristall

KTA4 ausgebaut

410 mW → 440 mW – instabil

Average Wert: 300 mW zu erwarten

Beam Profile – 3µm – KTA2 replaced – KTA4 out

(2) KTA1, KTA2 replaced, KTA3, KTA4 old

610 mW → 624 mW – instabil

Beam Profile – KTA4 old in

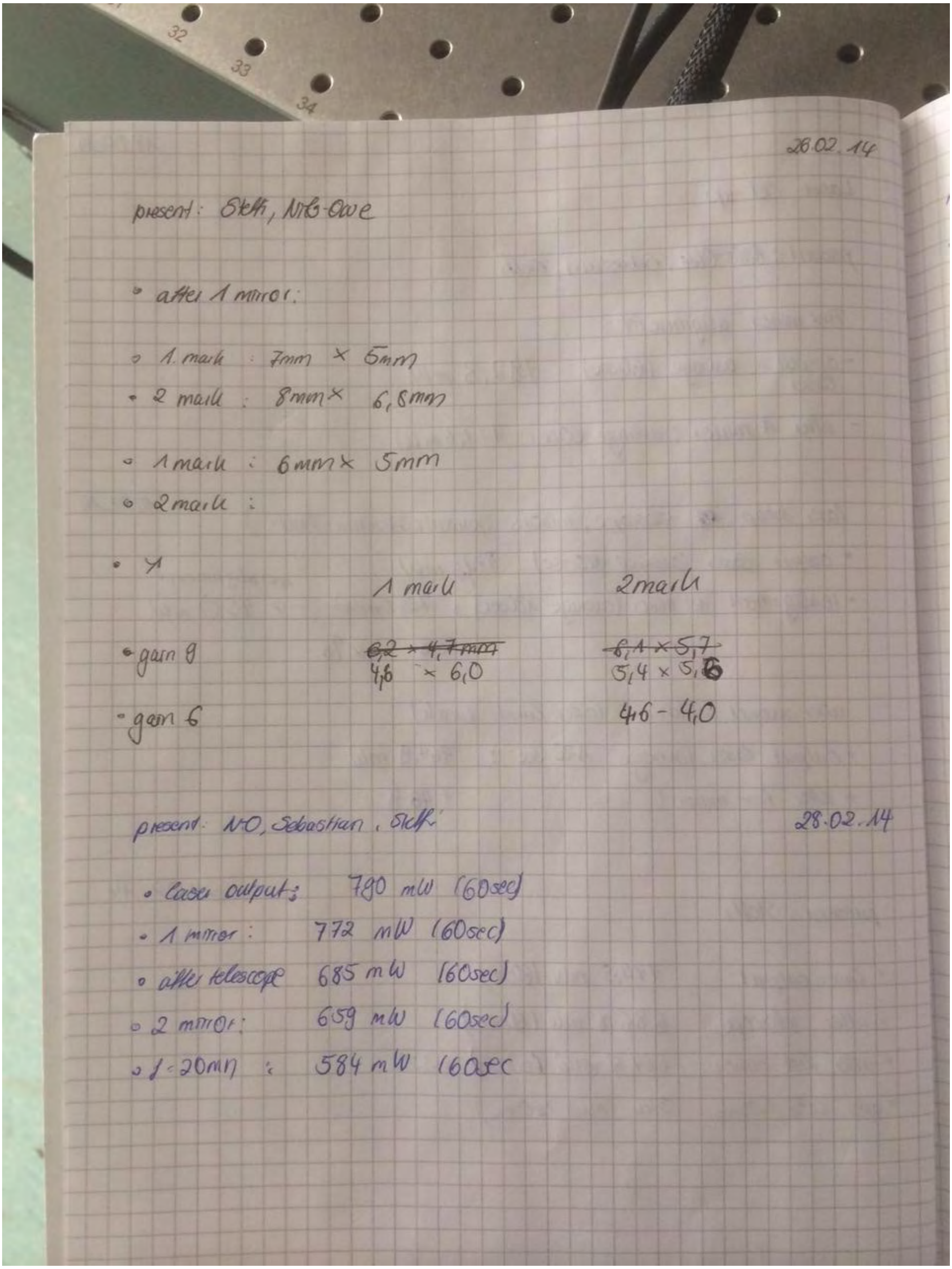
(3) KTA1, KTA2 replaced, KTA3, KTA4 old + shift

630 mW – stabil

Beam Profile – KTA4 old in and shifted

Shift: 0.5 mm to the side

0.5 mm up



26.02.14

present: Steffi, Nils-Owe

- after 1 mirror:

- 1. mark : 7mm × 5mm
- 2 mark : 8mm × 6,8mm

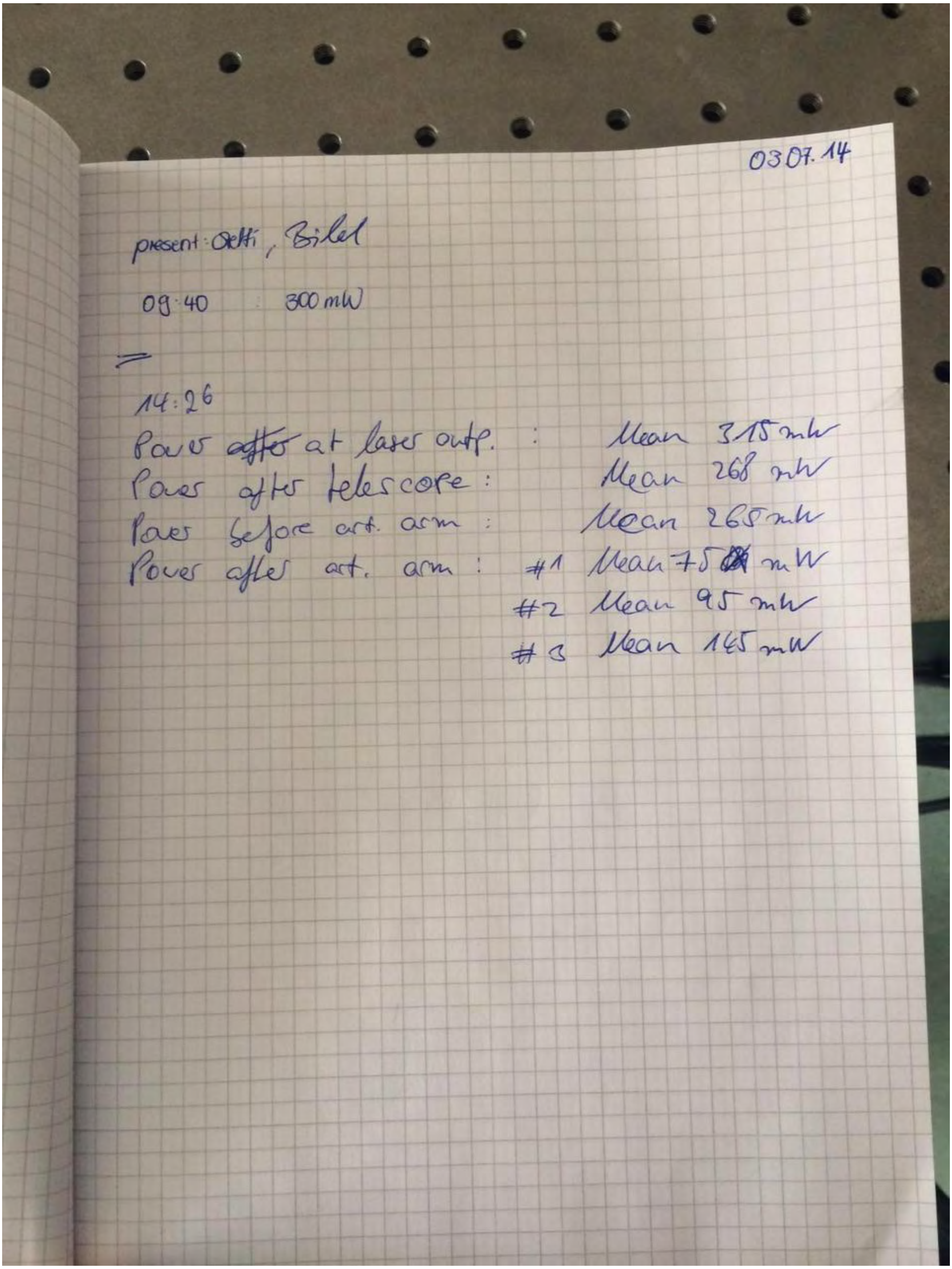
- 1 mark : 6mm × 5mm
- 2 mark :

- 1

	1 mark	2 mark
gain 8	~~6,2 × 4,7 mm~~ 4,8 × 6,0	~~6,1 × 5,7~~ 5,4 × 5,6
gain 6		4,6 - 4,0

present: N-O, Sebastian, Steffi 28.02.14

- laser output: 790 mW (60sec)
- 1 mirror: 772 mW (60sec)
- after telescope 685 mW (60sec)
- 2 mirror: 659 mW (60sec)
- f=20mm : 584 mW (60sec



03.07.14

present: Oetti, Bilal

09:40 : 300 mW

=

14:26

Power ~~after~~ at laser outp. : Mean 315 mW

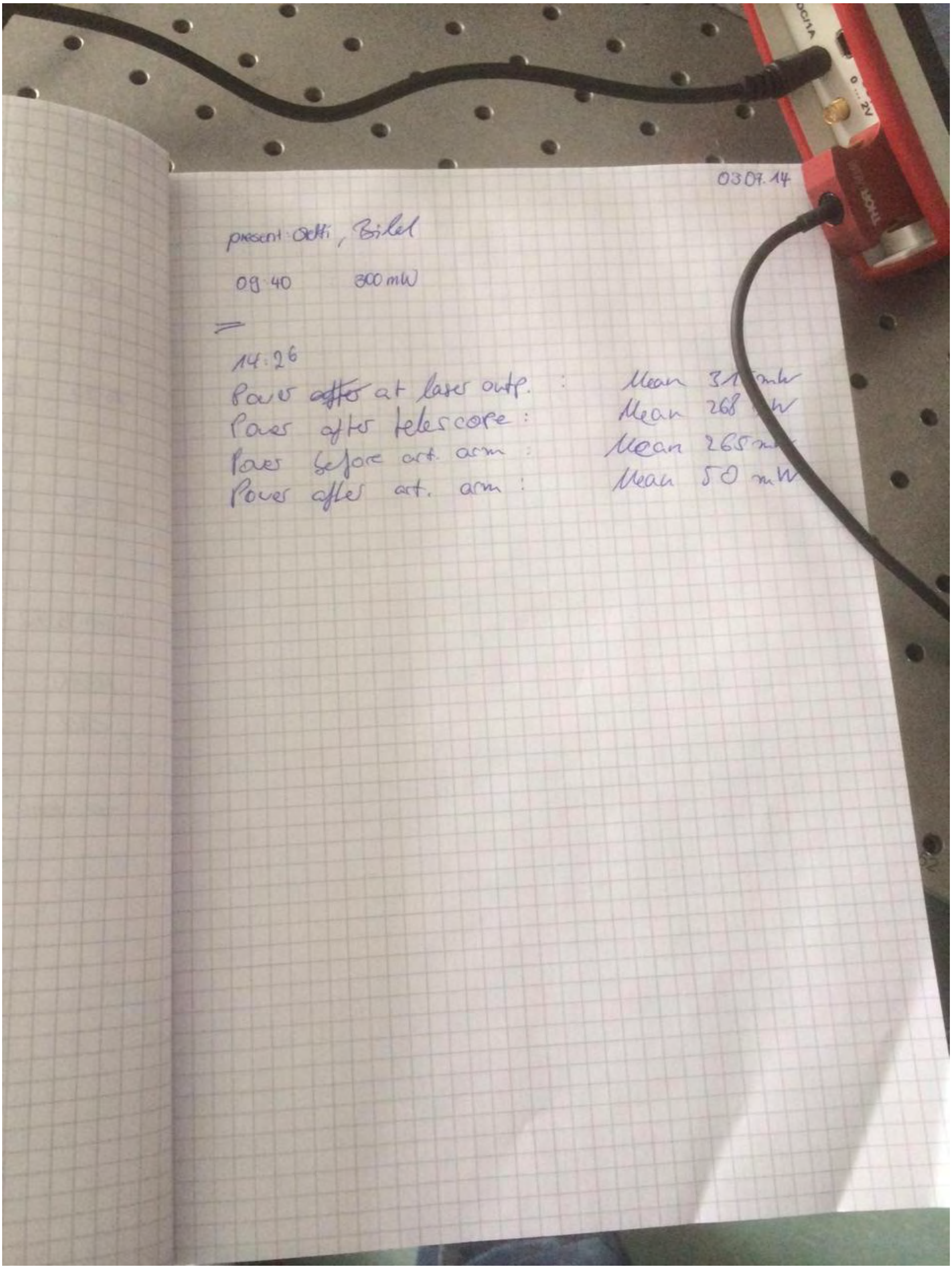
Power after telescope : Mean 268 mW

Power before art. arm : Mean 265 mW

Power after art. arm : #1 Mean 75 mW

#2 Mean 95 mW

#3 Mean 145 mW



03.07.14

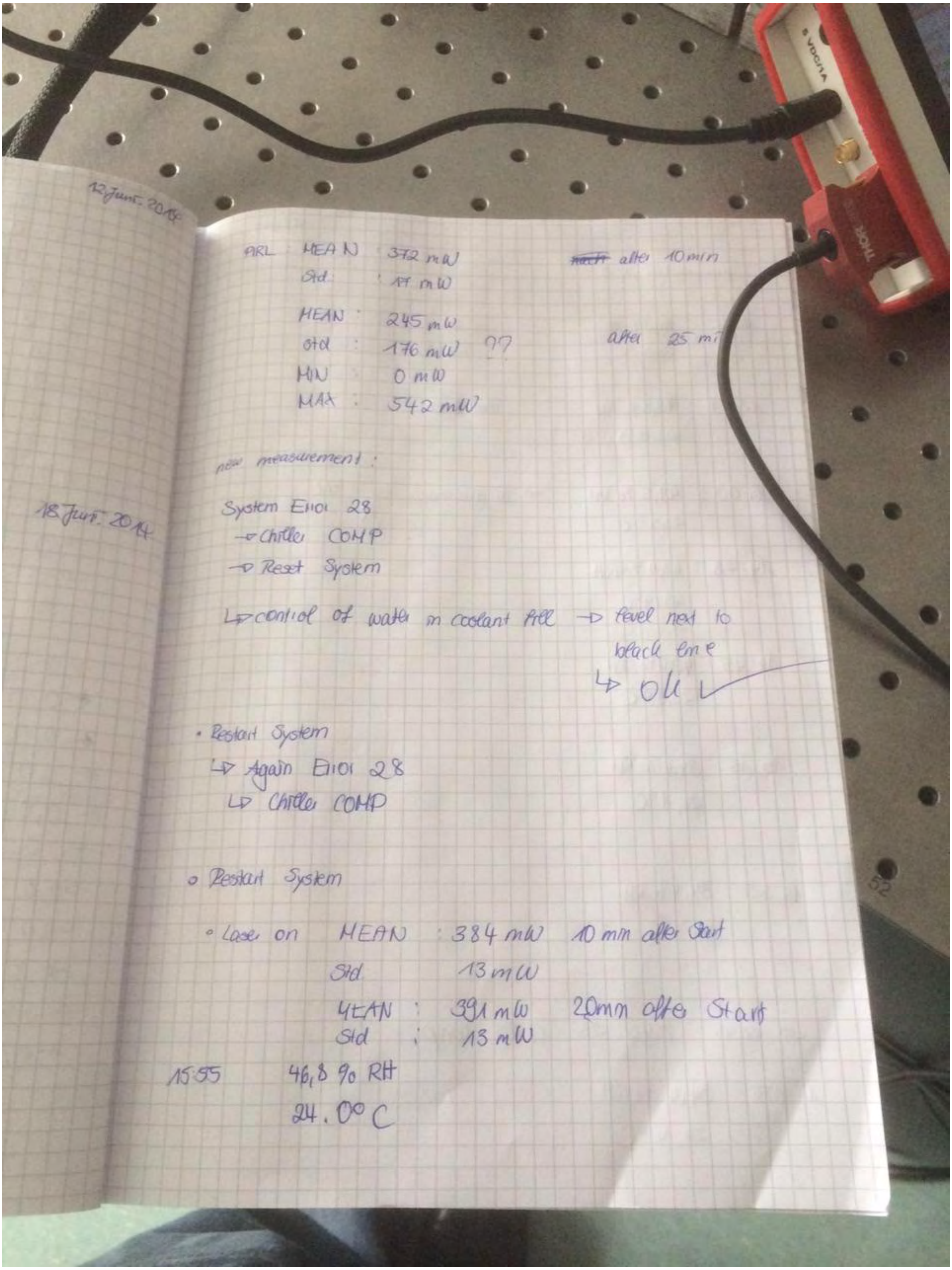
present: Oetti, Bilal

09:40 300 mW

=

14:26

Power ~~after~~ at laser outp. : Mean 31[illegible]mW
Power after telescope : Mean 268 [illegible]W
Power before art. arm : Mean 265 m[illegible]
Power after art. arm : Mean 50 mW



12 Juni 2014

ARL MEAN : 372 mW ~~nach~~ after 10 min
Std : 17 mW

MEAN : 245 mW
std : 176 mW ?? after 25 mi
MIN : 0 mW
MAX : 542 mW

new measurement :

18 Juni 2014

System Error 28
→ Chiller COMP
→ Reset System

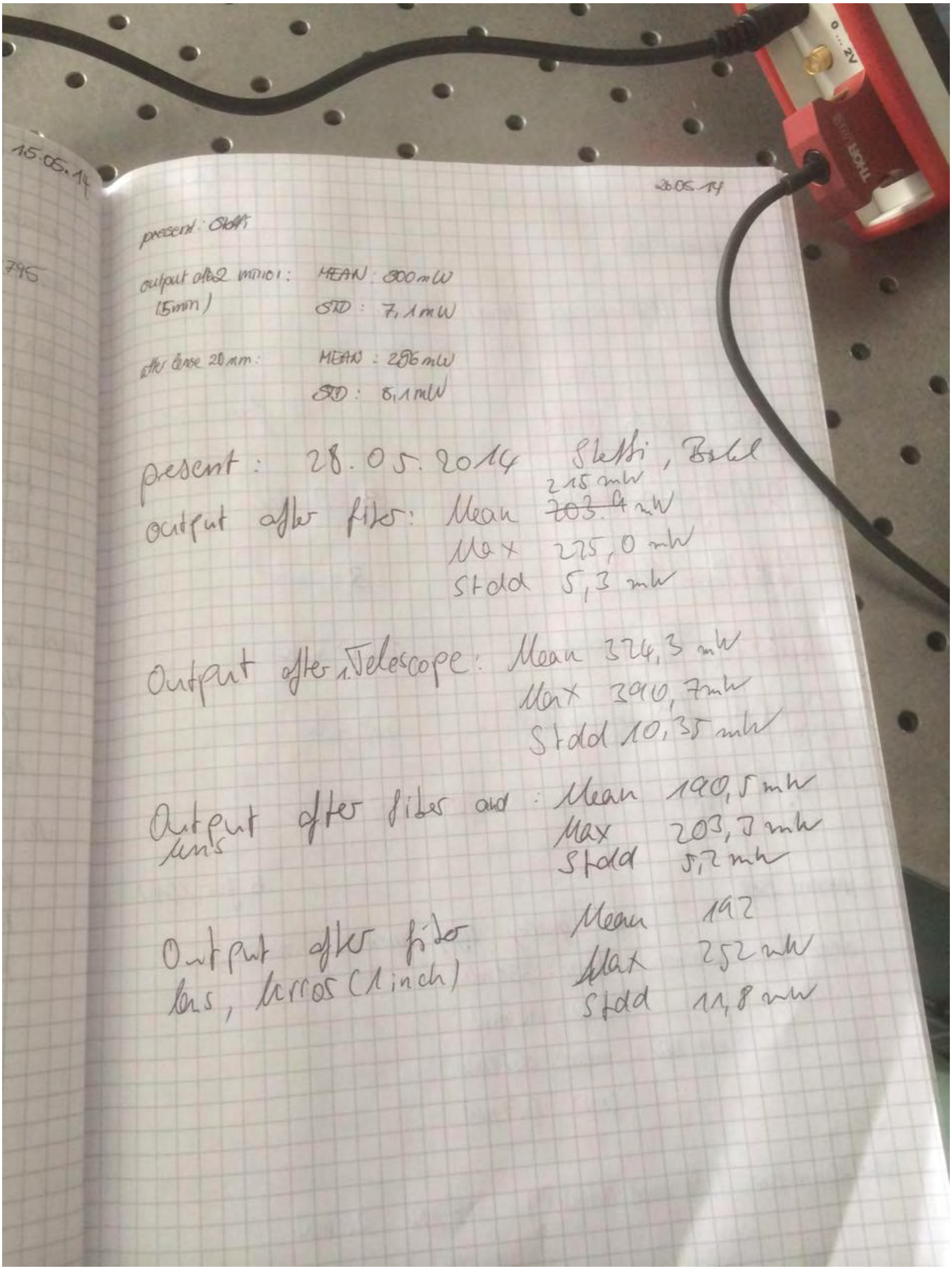
↳ control of water in coolant fill → level next to black line
↳ ok ✓

- Restart System
  ↳ Again Error 28
  ↳ Chiller COMP

○ Restart System

- Laser on MEAN : 384 mW 10 min after Start
  Std 13 mW
  MEAN : 391 mW 20 min after Start
  Std : 13 mW

15:55 46,8 % RH
24.0° C



15.05.14

795

26.05.14

present: Steffi

output after 2 mirror: (5min) MEAN: 300 mW

STD: 7,1 mW

after lense 20 mm: MEAN: 286 mW

STD: 8,1 mW

present: 28.05.2014 Steffi, Bahl

output after fiber: Mean ~~203.4~~ 215 mW

Max 225,0 mW

Stdd 5,3 mW

Output after 1. Telescope: Mean 324,3 mW

Max 390,7 mW

Stdd 10,35 mW

Output after fiber and lens: Mean 190,5 mW

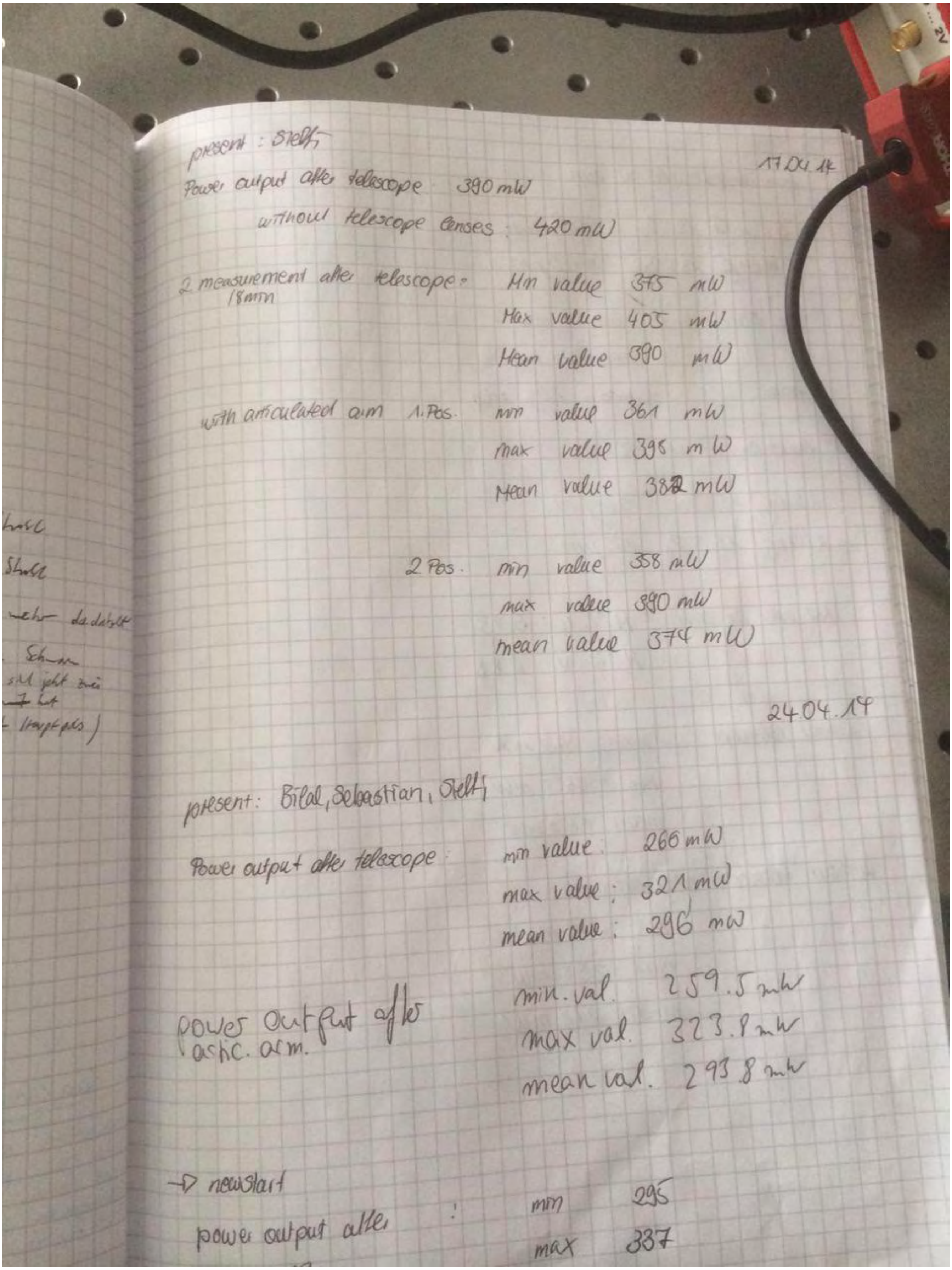
Max 203,3 mW

Stdd 5,2 mW

Output after fiber lens, mirros (1 inch) Mean 192

Max 252 mW

Stdd 11,8 mW



present : Steffi

17.04.14

Power output after telescope 390 mW

without telescope lenses : 420 mW

2 measurement after telescope : Min value 375 mW
18 mm
Max value 405 mW
Mean value 390 mW

with articulated arm 1. Pos. min value 361 mW
max value 398 mW
Mean value 382 mW

2 Pos. min value 358 mW
max value 390 mW
mean value 374 mW

24.04.14

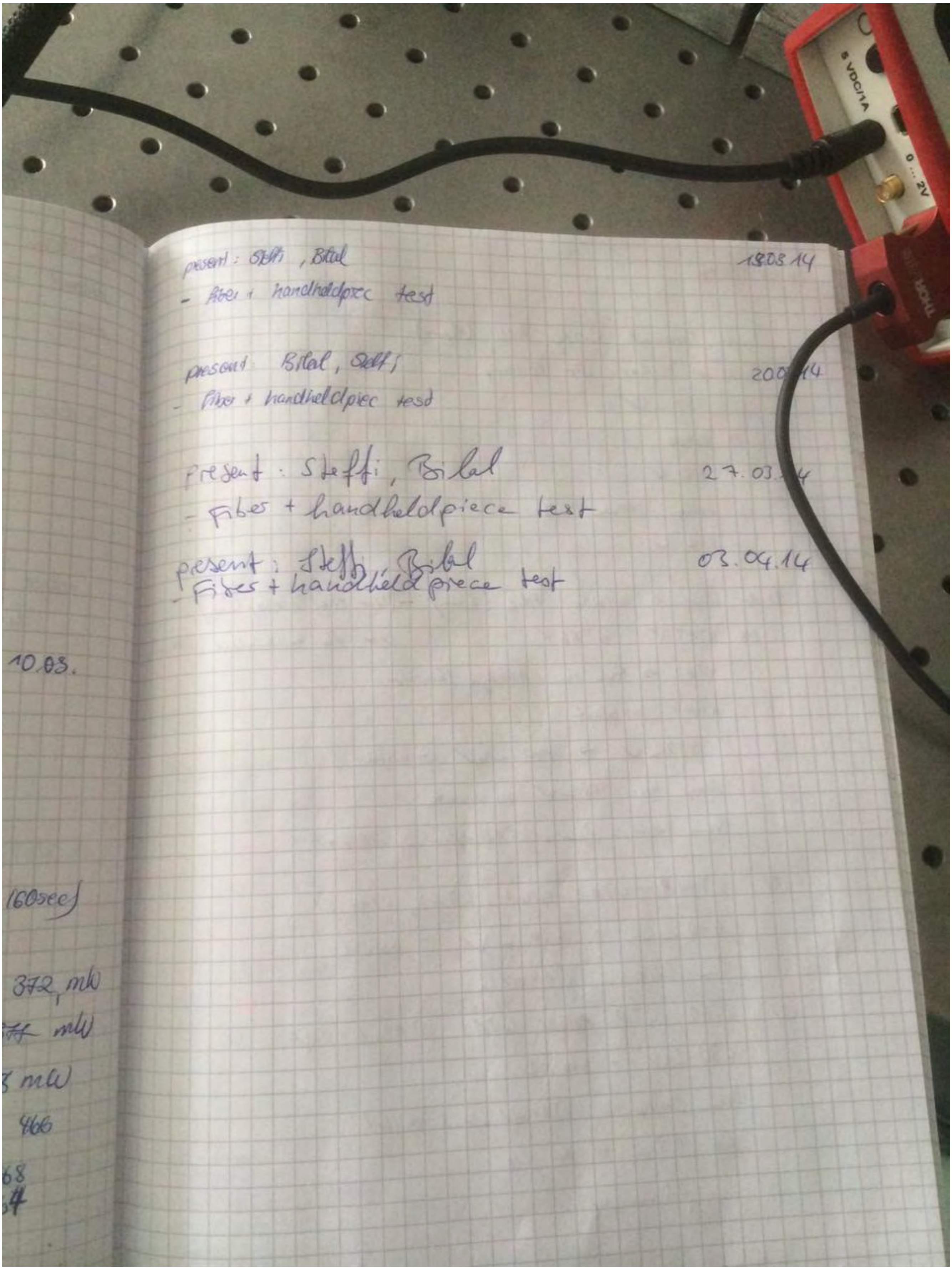
present: Bilal, Sebastian, Steffi

Power output after telescope : min value : 266 mW
max value : 321 mW
mean value : 296 mW

power output after artic. arm. min. val. 259.5 mW
max val. 323.8 mW
mean val. 293.8 mW

→ newstart

power output after : min 295
max 337



present: Steffi, Bilal 18.03.14
- fiber + handheldpiec test

present: Bilal, Steffi 20.0 14
- fiber + handheldpiec tesd

present: Steffi, Bilal 27.03. 4
- Fiber + handheldpiece test

present: Steffi, Bilal 03.04.14
- Fiber + handheldpiece test

10.03.

(60sec)

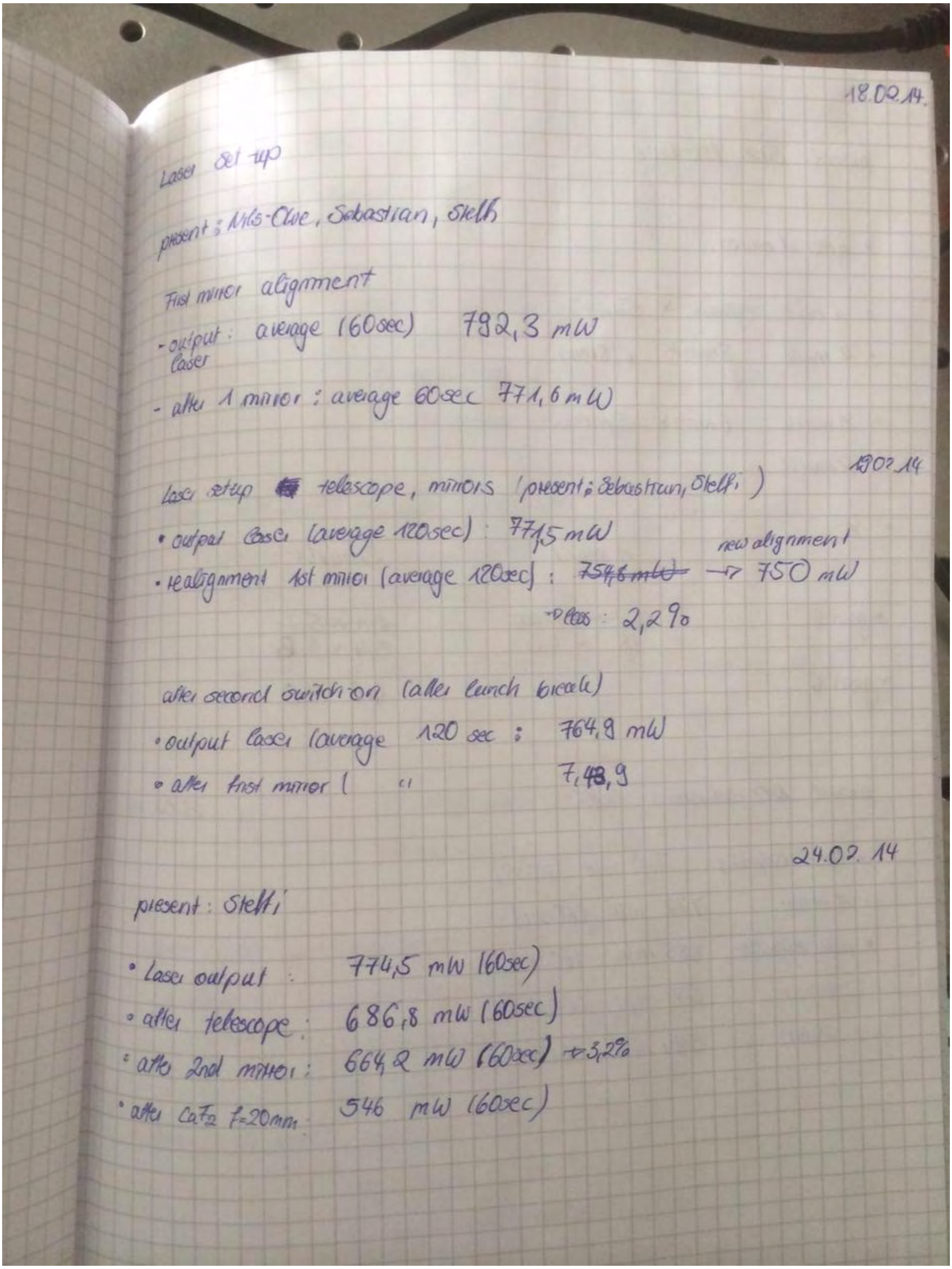
372, mW

mW

mW

466

68



18.02.14.

Laser set up

present: Nils-Ove, Sebastian, Steffi

First mirror alignment

- output laser: average (60sec) 792,3 mW
- after 1 mirror: average 60sec 771,6 mW

19.02.14

Laser setup [illegible] telescope, mirrors (present: Sebastian, Steffi)

- output laser (average 120sec): 771,5 mW
- realignment 1st mirror (average 120sec): ~~754,6 mW~~ → new alignment 750 mW

→ loss: 2,2%

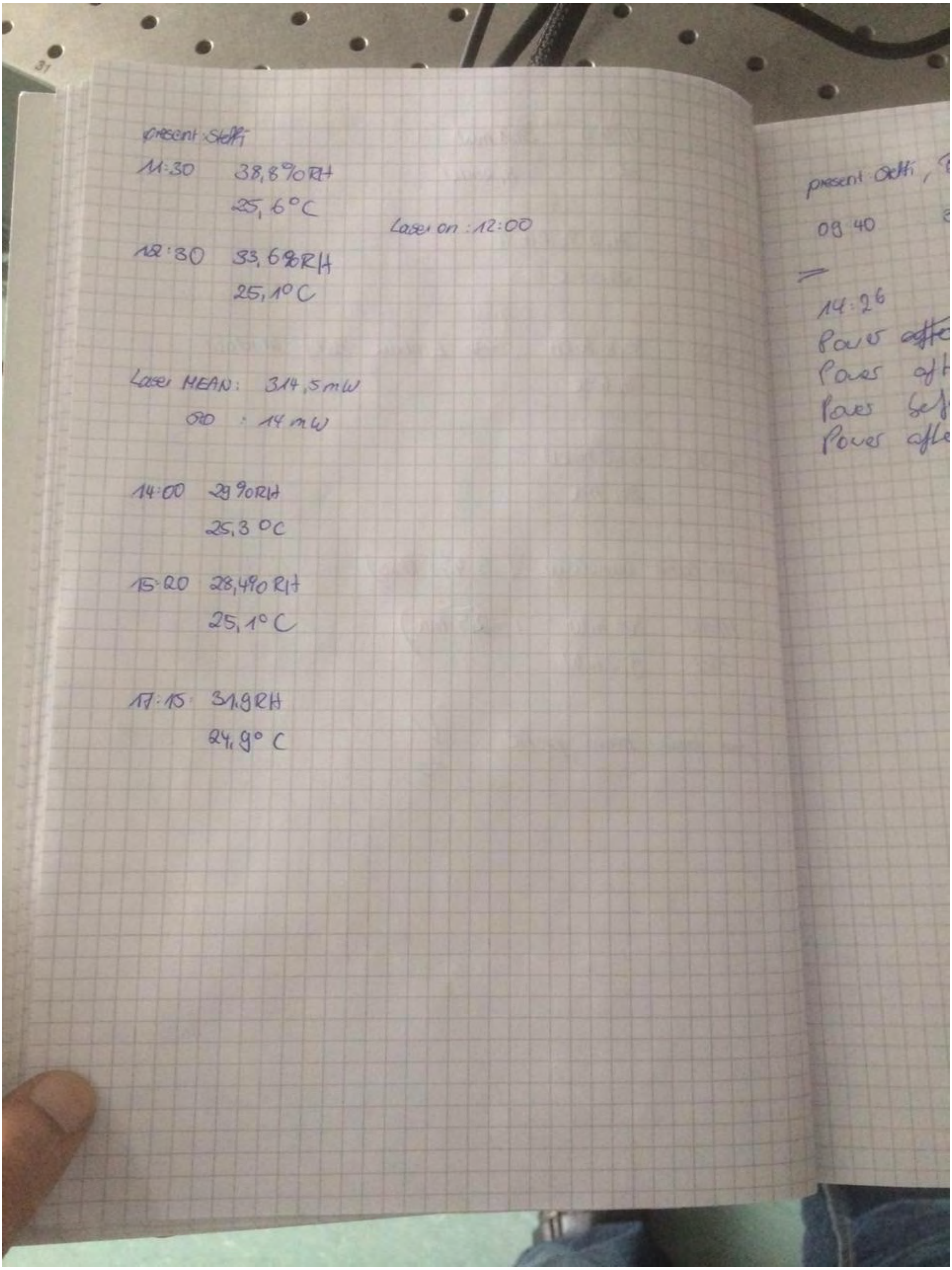
after second switch on (after lunch break)

- output laser (average 120 sec: 764,9 mW
- after first mirror (" 7,48,9

24.02.14

present: Steffi

- Laser output: 774,5 mW (60sec)
- after telescope: 686,8 mW (60sec)
- after 2nd mirror: 664,2 mW (60sec) → 3,2%
- after CaF_2 f=20mm: 546 mW (60sec)



present: Steffi

11:30 38,8%RH
25,6°C

Laser on: 12:00

12:30 33,6%RH
25,1°C

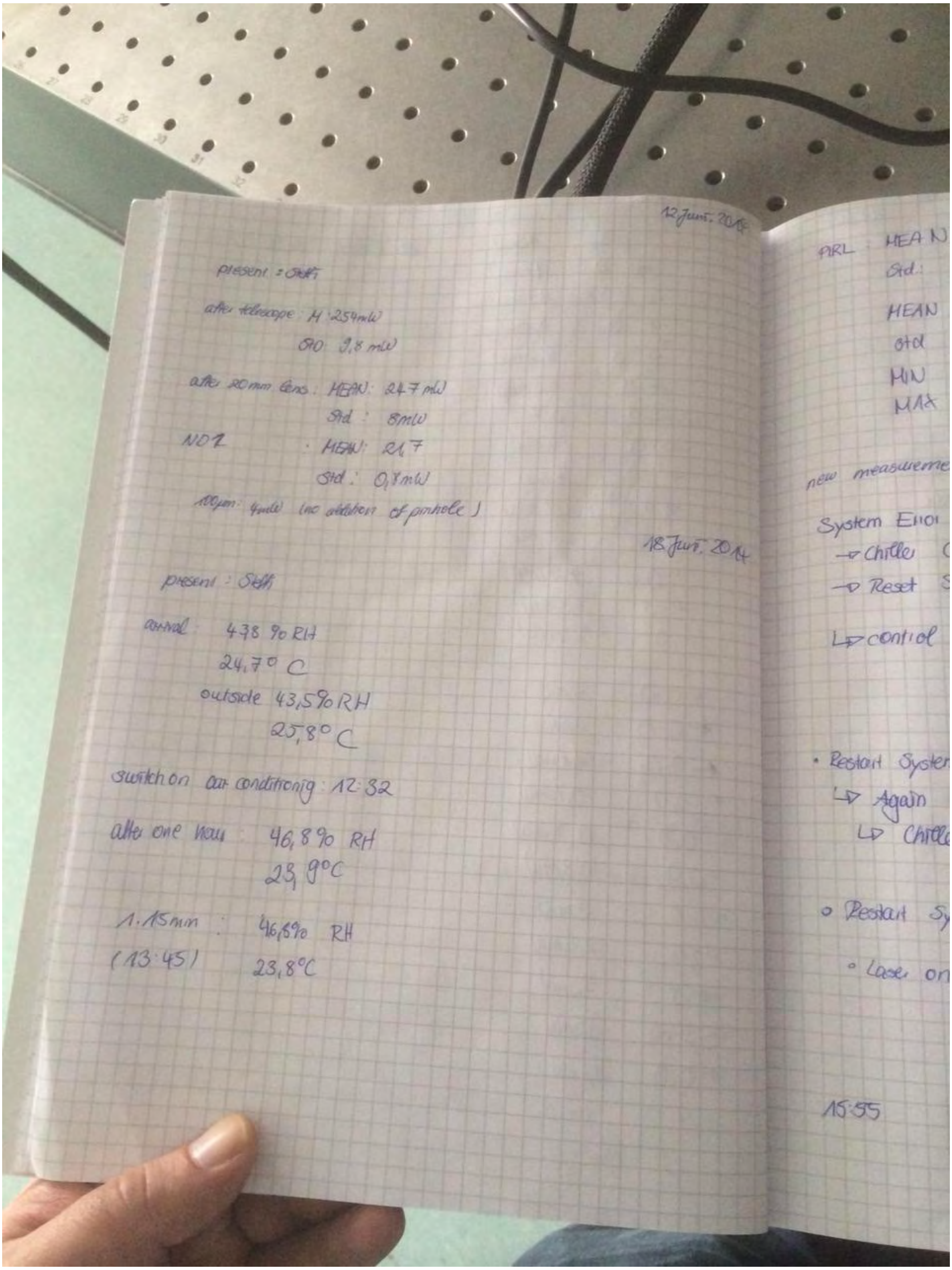
Laser MEAN: 314,5mW
SD : 14 mW

14:00 29%RH
25,3°C

15:20 28,4% RH
25,1°C

17:15 31,9RH
24,9°C

present: Steffi,
09:40
=
14:26
Power ~~afte~~
Power aft
Power bef
Power afte



12 Juni. 2014

present : Steffi

after telescope : M : 254mW
STD 9,8 mW

after 20mm lens : MEAN : 247 mW
Std : 8mW
ND1 : MEAN : 21,7
Std : 0,8mW
100µm : 4mW (no addition of pinhole)

18 Juni. 2014

present : Steffi

arrival : 43,8 % RH
24,7° C
outside 43,5%RH
25,8° C

switch on air conditioning : 12:32

after one hour : 46,8 % RH
23,9°C

1.15min : 46,6% RH
(13:45) 23,8°C

PIRL : MEAN
Std :
MEAN
std
MIN
MAX

new measureme

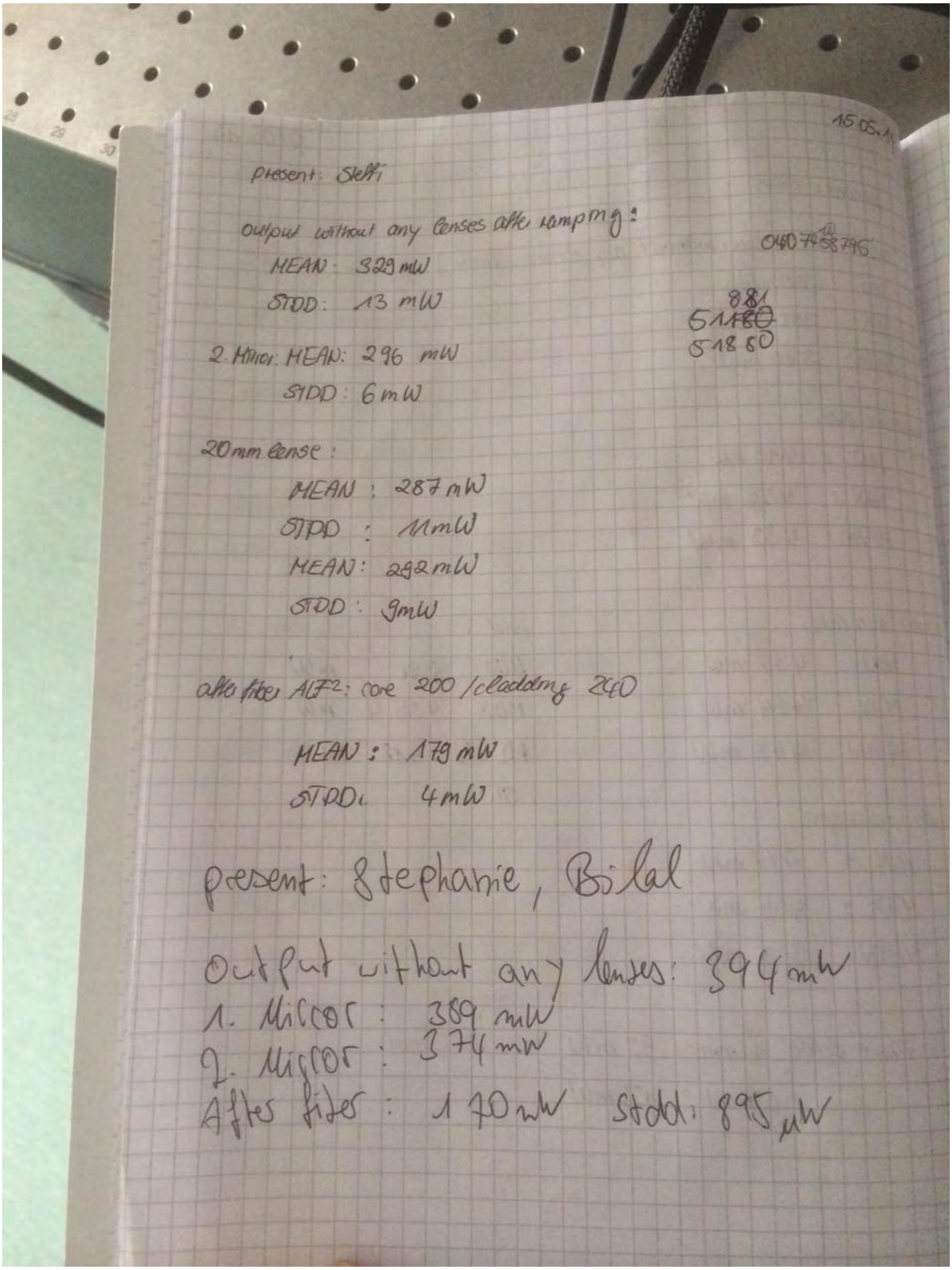
System Erro
→ Chiller C
→ Reset S
↳ control

• Restart Syster
↳ Again
↳ Chille

○ Restart Sy

○ Laser on

15:55



15.05.1

present: Steffi

output without any lenses after ramping:

MEAN: 329 mW

STDD: 13 mW

0160 7458795

881
51~~180~~
51860

2. Mirror: MEAN: 296 mW

STDD: 6 mW

20 mm lense:

MEAN: 287 mW

STDD: 11 mW

MEAN: 292 mW

STDD: 9 mW

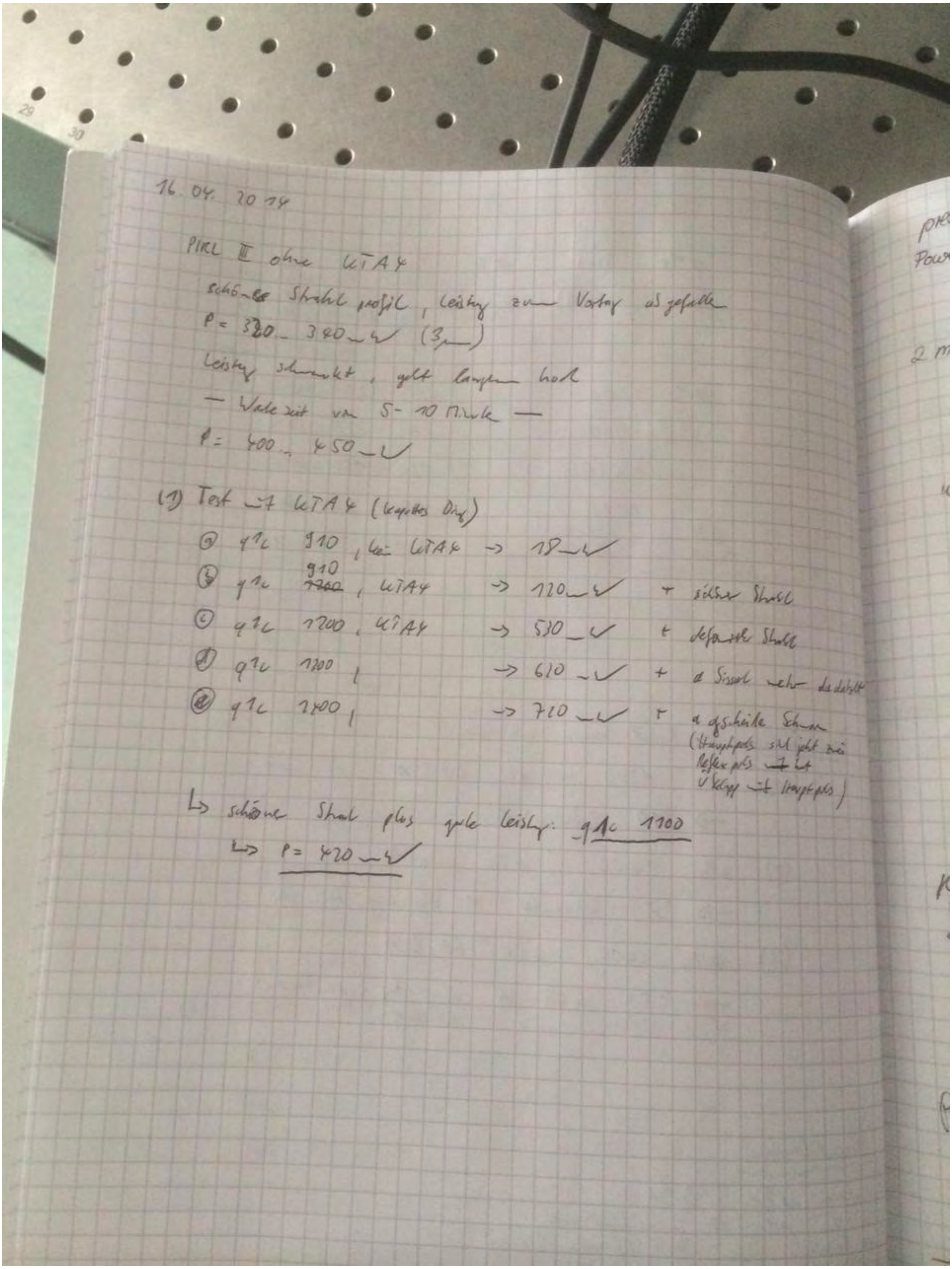
after fiber ALF2: core 200 / cladding 240

MEAN: 179 mW

STDD: 4 mW

present: Stephanie, Bilal

Output without any lenses: 394 mW
1. Mirror: 389 mW
2. Mirror: 374 mW
After fiber: 170 mW stdd: 895 µW



16.04.2014

PIRL III ohne kTA4

schöner Strahlprofil, Leistung zum Vortag ab gefallen

P = 320 – 340 mW (3 min)

Leistung schwankt, geht langsam hoch

— Wartezeit von 5 – 10 Minuten —

P = 400 – 450 mW

(1) Test mit kTA4 (kaputtes Ding)

ⓐ q1c 910, kein kTA4 → 18 mW

ⓑ q1c ~~1200~~ 910, kTA4 → 120 mW + schöner Strahl

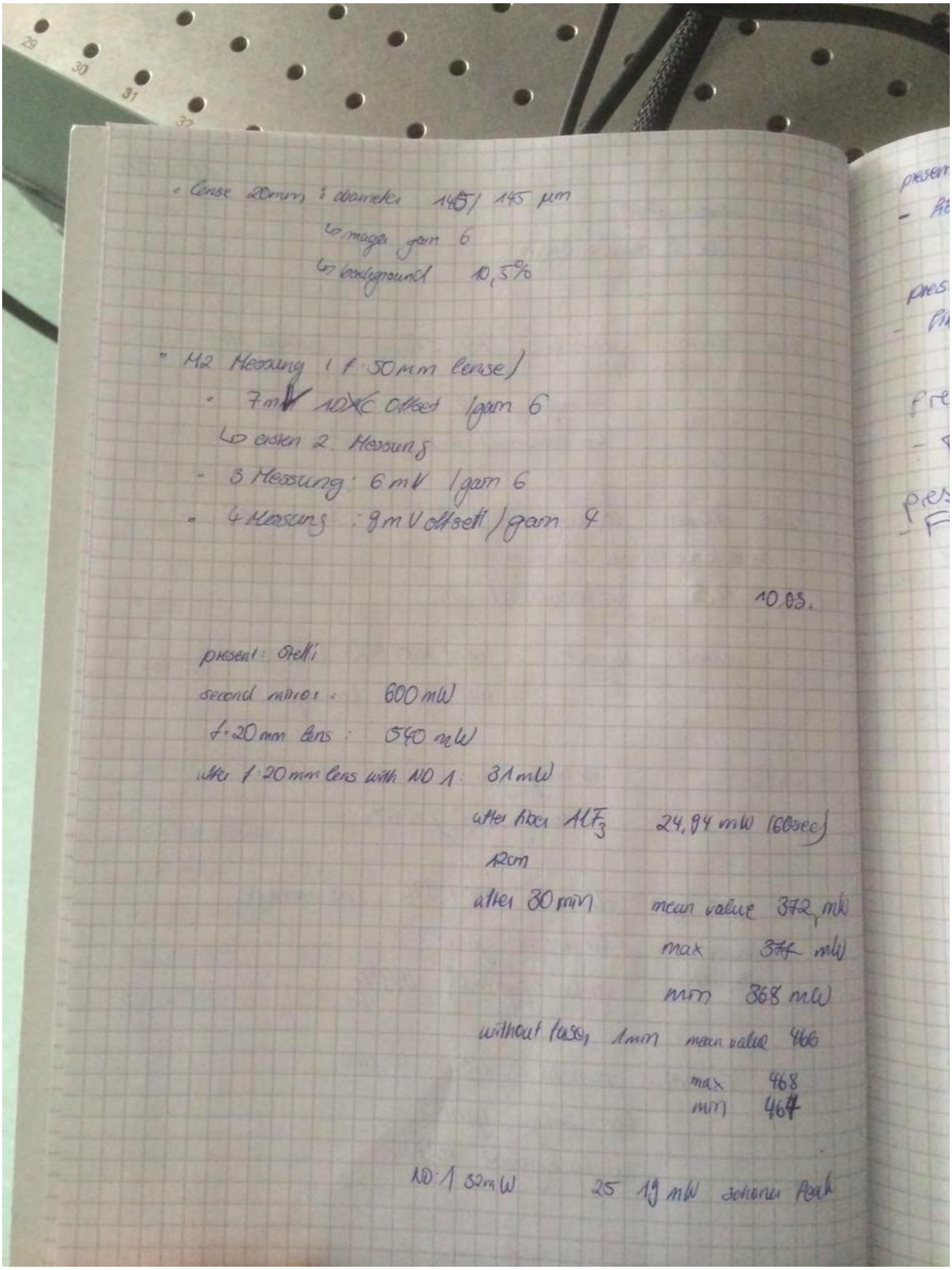
ⓒ q1c 1200, kTA4 → 530 mW + deformierter Strahl

ⓓ q1c 1200, → 610 mW + a Signal mehr deutlich

ⓔ q1c 1400, → 710 mW + a gscheiter Schmarrn (Hauptpuls sieht jetzt zwei Reflexpuls mit [illegible] Überlapp mit Hauptpuls)

↳ schöner Strahl plus gute Leistung: q1c 1100

↳ P = 420 mW



- lense 20mm : diameter 145/ 145 µm
  - ↳ mager gain 6
  - ↳ background 10,5%

- M2 Messung (f: 50mm lense)
  - 7mV 10XC offset / gain 6
  - ↳ ersten 2. Messung
  - 3 Messung: 6 mV / gain 6
  - 4 Messung : 9 mV offsett / gain 4

10.03.

present: Stelli

second mirror : 600 mW

f: 20 mm lens : 540 mW

after f: 20 mm lens with ND 1: 31 mW

after fiber AlF_3 24,94 mW (60sec)

12cm

after 30 min mean value 372 mW

max 377 mW

min 368 mW

without laser 1mm mean value 466

max 468

min 464

ND: 1 32 mW 25 19 mW schöner Peak