

# Advanced LIGO High Power Oscillator

USER MANUAL  
- LIGO-T0900641-v5 -  
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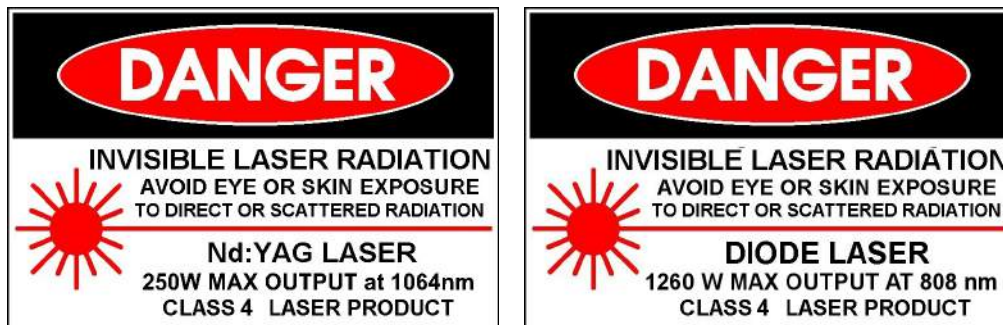
# 1 Introduction

This manual covers the operation and handling of the Advanced LIGO oscillator and the set up of the high power laser. It can be used for the initial installation of the system and should be consulted as a tool for troubleshooting and open questions in general. Reading this handbook carefully and following the instructions will help you to get a feeling about the handling of the system. We tried to highlight the critical procedures, whose nonobservance might influence the long time stable operation and lifetime of the Advanced LIGO laser. However, if you get into difficulties which are not covered by this manual, please contact the manufacturer.

This handbook does not include the complete operation and start-up procedure for the front end (eLIGO system), although some basics are described. Please catch up on how to run this system (LIGO document T0900646).

Furthermore, it does not include any information about stabilization, the pre-mode cleaner, diagnostic tools or a detailed description of the electronics. Knowledge of laser physics and experience in aligning optical beam paths is assumed. Never touch any optical surfaces with your hands or other tools! Furthermore, laser safety goggles are indispensable when working while laser radiation is emitted from pump diodes or one of the laser systems (see chapter 2).

## 2 Laser safety instruction



The High Power Oscillator and its 35 W MOPA Front-End emit invisible radiation at high power levels. The laser source components, e.g. diode lasers and MISER (NPRO), and the assembled laser systems are classified as CLASS 4 laser products. Diode lasers, used for optical pumping of the solid-state crystals inside the MOPA and HPOSC, emit at a wavelength of 808 nm. The radiation of these lasers is guided from the diode enclosure via fiber-bundles to the laser table. These fiber-bundles are protected by a metal tubing but do not feature a break detection. A max output power of 1260 W can be delivered by these diodes and brought through the fiber bundles into the laser enclosure.

The HPOSC and the MOPA emit at an invisible wavelength of 1064 nm. The maximum output power in front of the HPOSC is 35 W whereas the power after the oscillator is  $>200$  W. Be aware that reflected and transmitted beams can travel long distances without a significant change of beam diameter.

Avoid eye or skin exposure to direct, reflected or transmitted radiation. Materials exposed to the laser radiation may suffer thermal damage. Exposure of flammable materials, e.g. plastics, is a major fire hazard. The use of suitable eye protection

against emission of 808 nm and 1064 nm is required for all personnel working in the designated laser safety areas.

Be aware, that opening the lid of the HPOSC during operation will give you free access to the laser oscillator and its max pump-power of 1260 W at 808 nm. Only personnel trained and qualified by the LZH or AEI should open the housing during laser operation. Keep in mind that radiation of 1064 nm is transmitted deep into the human skin. Direct exposure of the 200 W beam onto one's hand or other extremity can cause severe injuries that just look like a normal blister from burns.

Always block any transmitted free running beams with appropriate beam blocks. Double check with your beam block vendor if the product can stand the power.

**Read this manual carefully before  
installing and operating all laser  
components!**

**Caution – use of controls or adjustments  
or performance of procedures other than  
those specified herein may result in  
hazardous radiation exposure.**

### 2.1 Safety labels and lid-override

You will find safety signs as shown in figure 2.1 at the laser box near the output aperture. In addition, a warning lamp above the output aperture will switch on, as

soon as one starts operating the oscillator.

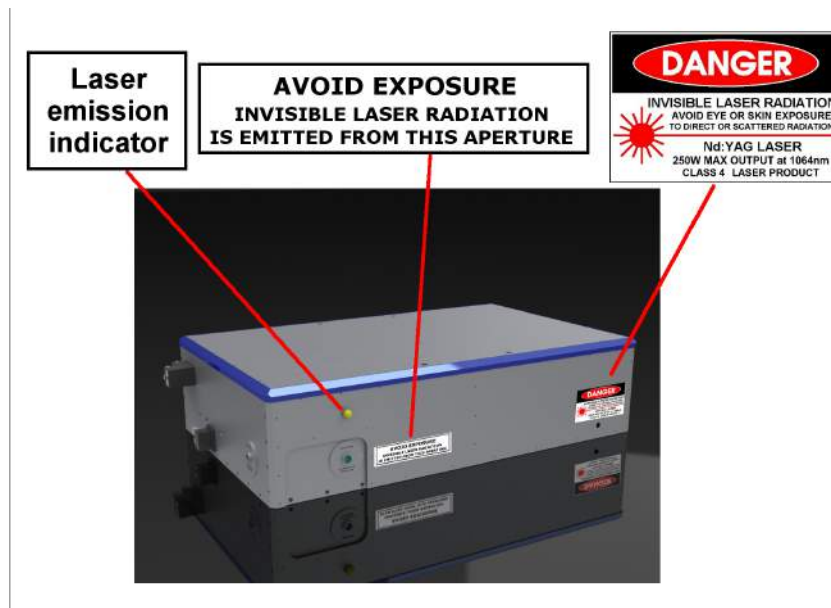


Figure 2.1: Placement of the laser warning signs

In normal user-mode, opening the lid of the oscillator box during operation will shut down the system immediately. However, in the password-protected "service mode" as described in section 8, the lid interlock can be defeated. An orange background of the lid-override button will indicate that the system is running in this mode and the lid can be removed without triggering the lid interlock. For safety reasons the lid-override will be deactivated after 10 seconds automatically, if activated without moving the lid. **Only trained personnel should operate the laser with the lid opened!** As an indicator of the danger of emission of laser radiation out of the top of the oscillator, a warning sign as shown in figure 2.2 is placed near the lid on the oscillator box.



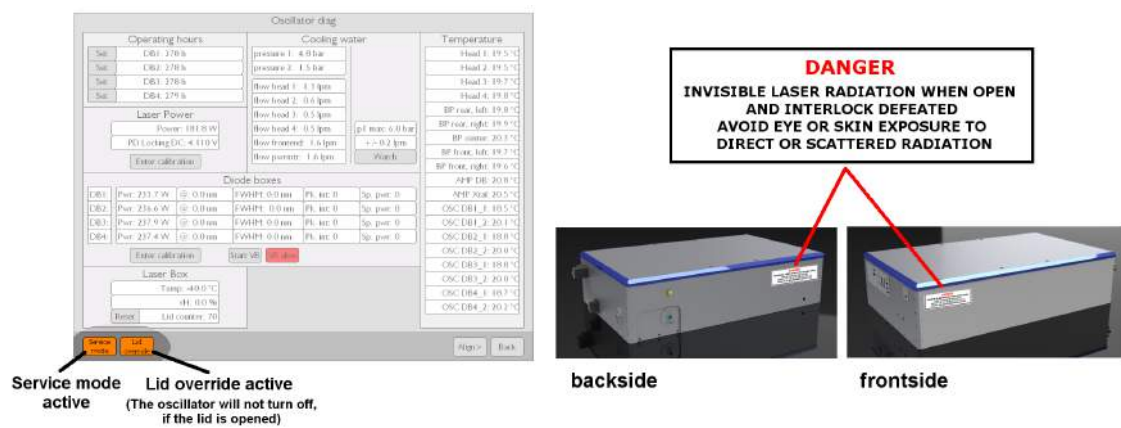


Figure 2.2: Left: The orange button indicates that opening the lid will not turn off the oscillator; right: placement of the laser warning sign for the defeatable lid interlock.

### 3 Optical layout and laser concept

This chapter gives a brief introduction about the high power oscillator and describes the principles of operation.

The high-power laser is based on a ring resonator design with four end-pumped laser heads. Thermally induced mechanical stress in the Nd:YAG laser rods results in birefringence and causes depolarization and bifocussing. The stress induced birefringence can be compensated by using pairs of identically pumped laser rods and a 90° quartz rotator in between. A relay optic, consisting of two identical lenses, images the principal planes of the rods onto each other while keeping the laser field unmodified. Therefore, an almost perfect birefringence compensation can be achieved. In the high power stage, two birefringence compensated pairs of laser heads are assembled to form a ring resonator cavity, see Fig. 3.1.

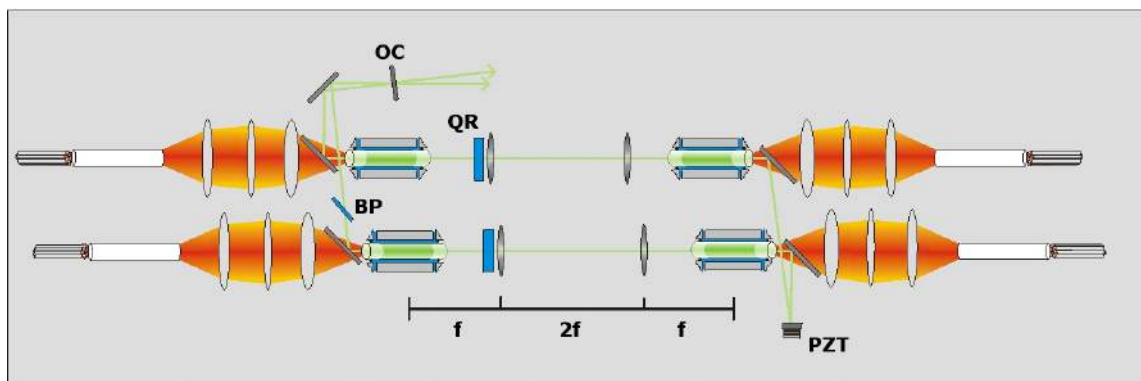


Figure 3.1: Schematic of the high power ring laser.

#### 3.1 End pumped laser heads

Each of the four laser crystals is pumped by 7 fiber-coupled laser diodes, each with a nominal power of 45 W and a wavelength around 807 nm. The laser diodes are

individually temperature stabilized which ensures a narrow overall emission spectrum of about 2-3 nm FWHM for each fiber bundle. Operating the laser diodes at a derated output power of about two thirds of their nominal power improves diode lifetime and reliability. The specified lifetime at full power is about 12,000 hours, during which less than a 20 % increase in driving current is needed to keep the output power constant.

The pump light is delivered by a bundle of 7 fibers with 400  $\mu\text{m}$  core diameter, NA 0.22 each. One end of the fiber bundle is attached with a bare fiber SMA905 connector to the laser diodes. On the other end the bare fibers are glued in an aluminum holder, which fits into a watercooled mount. This mount is part of the so-called pump head. If the light from the fiber bundle was directly imaged into the laser rod, hot spots due to the inhomogeneous pump light distribution would occur. For this reason, a fused silica rod homogenizes the transverse pump light distribution of the seven incoming fibers due to the spatial mixing of the light rays emerging from different fibers. By this homogenization, the formation of hot spots is prevented. In addition, this setup ensures a nearly unchanged pump light profile in case of failure or degradation of up to three individual pump diodes. A two lens optic images the end surface of the homogenizer into the laser crystal (see Fig. 3.2).

The laser crystal consists of a 3 mm diameter multi-segmented Nd:YAG rod with two 7 mm long undoped segments at both ends and a 40 mm long low-doped center segment. The undoped end caps reduce the thermally induced mechanical stress on the end surfaces of the rod and eliminate any mechanical deformation of the ends. Furthermore, the entire doped central region of the rod can be effectively cooled, which is essential for the end-pumped geometry in connection with direct water cooling.

The coupled pump light is mixed and guided by total internal reflection at the rod's surface during propagation. A coating for double passing the pump light is applied to the backplane of the crystal to reduce the longitudinal thermal gradient and the overall mechanical length.

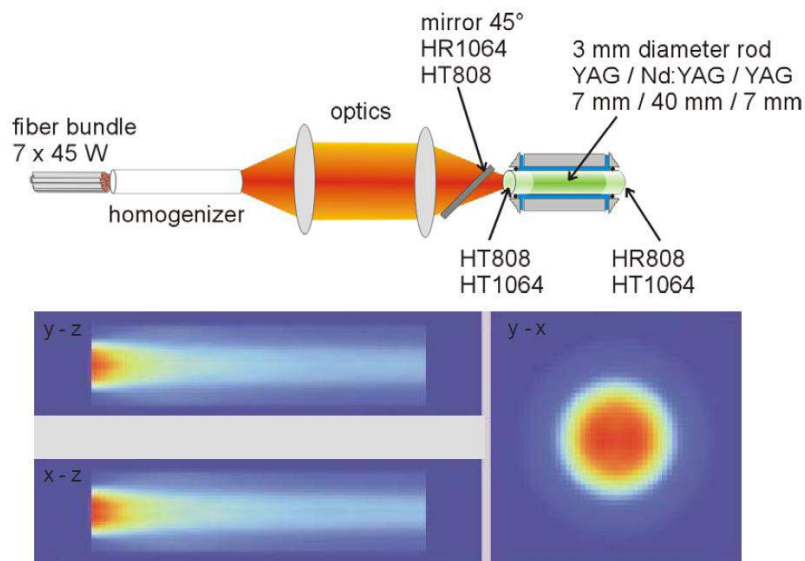


Figure 3.2: Schematic layout and pump light distribution in the end-pumped laser head.

### 3.2 Resonator design for fundamental mode operation

Scaling the laser power by increasing the pump power introduces thermally induced aberrations in the crystals due to the temperature dependence of the crystal material properties such as thermal conductivity and thermally induced refractive index changes. By keeping the average temperature in the rod below 60°C, thermally induced aberrations are drastically reduced. The second source of aberrations is the pump light distribution, which is concentrated near the rod-axis (see Fig. 3.2). This results in spherical aberrations responsible for a thermal lens depending on the incident laser beam radius and therefore on the mode size. The laser resonator was designed to use these spherical aberrations as a control mechanism for the fundamental mode operation of the laser system. An asymmetric resonator was designed to split the resonator stability range in two parts with respect to the applied pump power. Furthermore, due to the aspherical thermal lens inside the crystals, higher order modes experience a thermal lens with lower effective dioptric power than the

fundamental mode due to their larger mode field diameter. By choosing the right cavity parameters, a working point where only the  $TEM_{00}$  mode is stable can be found. For an output power of 200 W, approximately 240 W of pump power per head is needed. The position in respect to pump power of the second stability range can be changed by varying the short resonator length. The mode size inside the cavity can in principal be altered by changing the output coupler arm length of the resonator. The  $TEM_{00}$  laser mode size is chosen to have a good overlap with the pump light and uses the laser crystals as an additional aperture to suppress higher order modes.

### 3.3 Depolarization

The depolarization loss caused by thermally induced mechanical stress in the laser crystals is greatly reduced by a birefringence compensation involving a  $90^\circ$  quartz rotator and a relay optic for imaging one rod's principal plane onto the other. A reduction of total depolarization loss to less than 5% of the resonator internal power was achieved with this scheme.

### 3.4 Output power

An overall output power of the injection locked laser of 200 W can be achieved. Stable operation has been demonstrated in a long-term test. The measured power downstream a high power premode cleaner is 165 W, corresponding to 82% in  $TEM_{00}$ . The losses of 35 W are mainly caused by a corona, which surrounds the main beam. This corona is blocked by a water cooled aperture inside the laserbox.

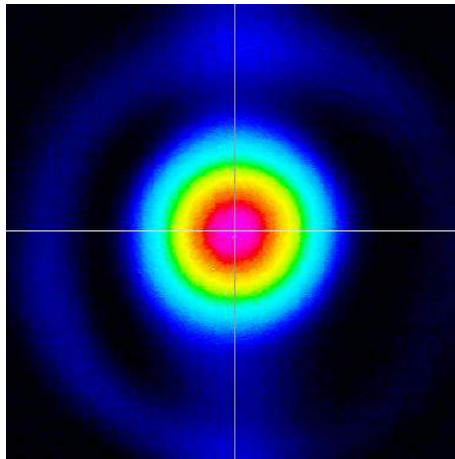


Figure 3.3: Unfiltered beam profile (data from engineering prototype.)

## 4 Delivery of the laser system

The high power laser, the electronics and all required subcomponents are shipped in one container. Inside this container all major components are packaged in boxes to prevent the parts from damage during transport, humidity and temperature.

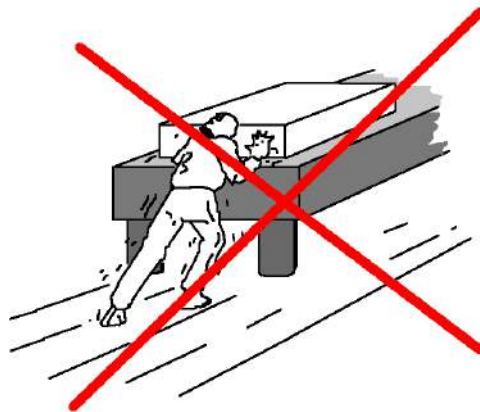


Figure 4.1: Do not try to slide the laser on top of the table !

All components other than the high power laser itself can be handled and lifted by one or two persons. The weight of the high power laser had been measured to be about 330 kg, such that a folding crane is required to lift it out of the package and onto the optical table. Moving the system manually on the laser table might be possible with strong effort, but can destroy either the steel plates underneath the ground plate, which are supposed to assure the flatness of the baseplate, or the surface of the table.

Optical components will have at least two layers of packaging. One outer layer (wooden box) and an inner layer (plastic wrap). These components should be taken out of the wooden box outside the clean room area, whereas the plastic wrap should only be removed inside.

# 5 Partlists

## 5.1 List of included parts

This list will give you an overview on all parts, which should be delivered with the oscillator. Please check, whether any part is missing.

Quantity	Name
1	Oscillator in a housing, including all optics
1	Supporting frame
2	Water distribution box (inlet and outlet)
	Hoses to amplifier, powermeters, crystals, laserheads
6	Fiber bundles
4	Diode boxes, including pump diodes, electronics
1	PC, including Beckhoff / TwinCat / Software
1	Control box, updated to run the amplifier as well
	Wires and cables
6	Power supplies to run the diodes and the peltier elements



## 5.2 List of not included parts

The following lists will give you an overview on all parts, which are helpful during laser operation. The components mentioned in these lists are not included. Please note that because of the nature of “unexpected things”, this lists can’t be complete.

### 5.2.1 Tools

To set up the laser, a number of tools will be necessary. Besides the common workshop equipment there are some special tools, which shall be ordered for this system. The following list also includes tools to set up and align opto-mechanical parts. Since working in immediate vicinity of optical components will become necessary, one should use clean room capable tools (i.e. made of appropriate materials, e.g. without powder-coating) with non-reflective surfaces.

Quantity	Tool	Special features
2	Set of ball drivers	long handles
1	Set of Hex keys	
2	Set of wrenches	
1	Set of Phillips screwdrivers	
1	Set of flat-headed screwdrivers	
1	Set of watchmaker screwdrivers	
1	Nipper	
1	Multi grip pliers	
1	Cable stripper	
2	Utility knife	
1	Sliding caliper	
2	Tweezers	metal, one with them angulated
1	Hemostat	to hold the cleaning tissues

### 5.2.2 Technical equipment

For alignment and operation of the laser, a minimum of technical equipment is required. The following list gives an overview of useful instruments.

<b>Instrument</b>	<b>Recommended specifications</b>
2 oscilloscopes	4 channel, 500 MHz
1 signal generator	50 MHz sine, 2 phase-lockable channels, 0-5 Vpp, ramp waveform
1 microscope	impinging light option, magnification: x40
1 power meter	watercooled, power up to 250 W
1 power meter	water- or aircooled, power up to 45 W (to monitor the power, which is reflected at the Brewster plate)
1 power meter	power up to 1 W (to check the power at positions, where Photodiodes are going to sit, for isolator alignment)
1 CCD camera	for example "data ray" beam analyzing system "WinCamD-UCD12": 1/2" CCD chip, 1360 x 1040 pixel, 4.65 x 4.65 $\mu\text{m}$ each, active area: 6.5 x 4.8 mm, wavelength range: 355 - 1150 nm (standard).
1 PC	1 GHz Pentium, Windows 2000/XP Pro/Vista, 512 MB RAM, 10 GB Drive Space, Monitor 1024 x 768 Pix. USB2.0 interface
1 soldering station	this should either be clean room classified or be located outside the laser room
2	Multimeters

<b>Instrument</b>	<b>Recommended specifications</b>
1	Movable lamp (if you are going to use a flashlight, assure that the batteries are charged)

### 5.2.3 Other stuff

<b>Quantity</b>	<b>Name</b>
1	Electric IR viewer
2	Viewer cards
6	Iris apertures
3	Beam block for low powers

## 6 Preparations prior to operating the system

### 6.1 Laboratory environment

The Advanced LIGO laser is a CLASS 4 laser system. Therefore, an adequate infrastructure needs to be available, which includes laser safety features and laser warning signs. Beside this a minimum of cleanliness is necessary. The advanced LIGO engineering prototype has been built and successfully tested in a class 1000 (ISO 6) cleanroom with laminar airflow from the top. Additionally, we worked with appropriate clean room clothes. **Especially if the laser box is open, we recommend to wear gloves, a clean room overall, and a clean room cap!**

A bottle of acetone, ethanol, and isopropanol should be in the laser laboratory, as well as a packet of optics cleaning tissues.

### 6.2 Water pipes and chillers

**For installation of the chillers see the chiller handbook!**

Connect all water hoses to the oscillator box, the amplifier and the diode rack as shown in figures 6.1–6.3. Connect the hoses to the chiller. Make sure that the flow limiters are in the water inlet. A scheme of the water distribution can be found in figure 6.4.

Fill the water tanks of both chillers with DI water. Each chiller includes a DI cartridge and a conductivity sensor to keep the water conductivity actively between 4 and 7  $\mu\text{S}$ .

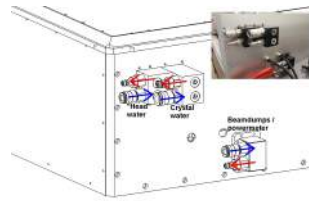
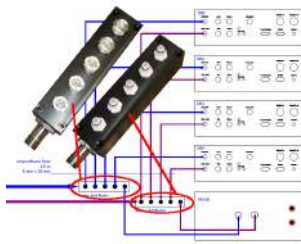


Figure 6.1: Water distribution at diode rack.

Figure 6.2: Water distribution at oscillator box.

Figure 6.3: Water distribution at amplifier.

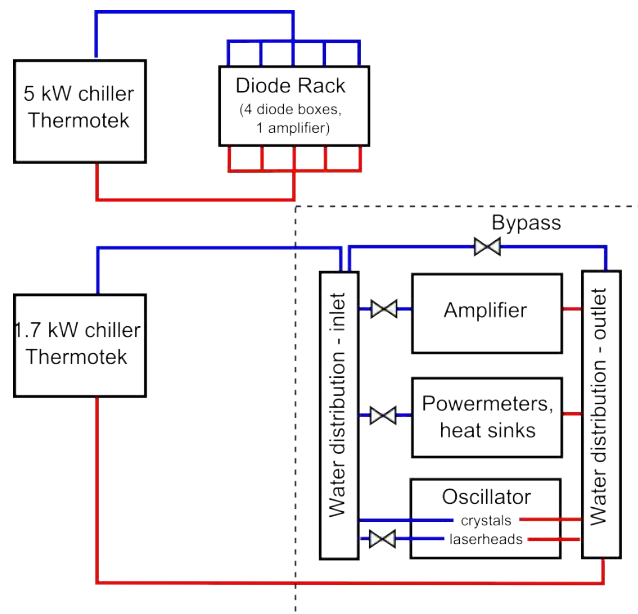


Figure 6.4: Scheme of the water distribution.

Since the volume of the tanks is rather small, we recommend to fill the water pipes with DI water before connecting them to the chiller. Otherwise one had to alternately refill and restart the chillers to fill the pipes.

The flow through the different components should be set with the pressure reducing valves at the water manifold next to the laser to values shown in table 6.1.

No.	Flow through	Flow rate	Chiller
1	Diode rack	>20 l/m	5 kW ThermoTek P605-AW-DI
2	Amplifier	>1.3 l/m	1.7 kW ThermoTek P325-AW-DI
3	Nd:YAG crystals	> 12 l/m	1.7 kW ThermoTek P325-AW-DI
4	Laser heads	>0.5 l/m per head	1.7 kW ThermoTek P325-AW-DI
5	Power meters and beam blocks	>1.5 l/m	1.7 kW ThermoTek P325-AW-DI
	total crystal chiller flow	>15 lpm	

Table 6.1: List of flow rates to the components.

Connect the RS232 connection to the control box.

Run the chillers in “remote control” modus (see chiller manual).

## 6.3 Fiber bundle installation

### 6.3.1 Installation at the diode box side

Work with a vertical flow box, clean room garb and gloves. Insert the SMA-connected fiber ends one by one into the diode box. Approximately 10 cm of the metal armored tube should stick inside the box as well. Fix the metal tube in the middle of the box with some tape. Ensure that the fibers are not tangled up. Arrange three of the fibers clockwise turns and bring the SMA ends close to the three pump diodes on one of the cooling banks. Arrange the four remaining fibers in counter-clockwise turns and bring their SMA ends close to the remaining four diodes. Make sure that the bending radius is as big as possible. The fibers must not be stressed on sharp edges (for example the end of the metal tube). Remove the protection caps on the diodes and on the fibers and connect the parts. The screws should be fastened just hand tight (do not use any tools !). The result should look as shown in figure 6.5.



Figure 6.5: Connected pump fibers inside the diode box.

### 6.3.2 Installation at the oscillator side

Insert the fiber bundle including its protection cap through the stress relief until the metal tube is inside the laser housing. Take the water cooled fiber bundle holder out of the be-ri mount. Feed the fiber bundle through the be-ri mount and remove the protective cap. Screw the thin M10 nut over the fiber-bundles thread and then screw it into the water cooled holder. Rotate the holder, *not* the fiber, otherwise the bundle will get twisted and may break. When the tip of the aluminum part points out of the holder for approximately 5 mm, rotate the fiber bundle holder such that one water connectors point upwards and the other one to the outside of the corresponding pump head. Tighten the nut to lock the position of the fiber and push the holder all back into the be-ri mount. The fiber bundle holder can then be bolted down at the pump head with the two upper screws. Connect the water piping to the homogenizer holder, which should be set to the right position and orientation already. Then attach the other end of the tube to the back of the laserhead.

Move the Bre-ri mount towards the homogenizer by pressing it down and to the arrester at the side until the fibers ends are just a few millimeters away from the homogenizer tip. Be careful with the fiber tips, they may break on the slightest contact. Secure the pedestal of the be-ri mount with one M4x6 screw and a washer

on the side. Loosen the screw a bit and shift the be-ri mount forward until there is just a tiny air gap between the tip of the fiber bundle and the homogenizer. Try not to tilt the be-ri mount during the movement. If you can't assess the width of the air gap, put a black painted piece (for example a Thorlabs clamp) directly under it to increase the contrast. Lock the screw on the side and insert an additional M4x6 screw into the ear of the pedestal. Use a ball driver to fix that screw, too.

## 6.4 Wiring

All data-cables should be labeled. Connect them to the corresponding plugs at the oscillator box, and the control box.



# 7 Description of the Oscillator

## 7.1 Shutters

The oscillator is equipped with two shutters:

1. An *external shutter* (outside the resonator), which is meant as a laser safety feature. It can be used to block the emission of laser radiation from the oscillator box (not necessarily inside the box).
2. An *internal shutter*, which blocks the beam path inside the resonator. If the Front-End is running, its radiation will be partly reflected at the outcoupling mirror and may exit the oscillator box if the high power shutter is not closed.

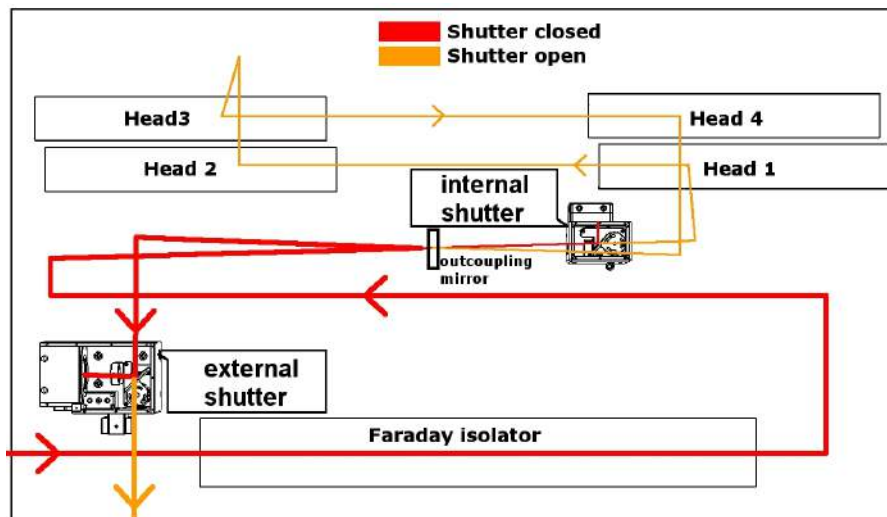


Figure 7.1: Schematic of the positions of external and internal shutters.

### 7.1.1 External shutter

This shutter can be closed, if no laser radiation is desired at the beam path outside the oscillator box. To block the beam for a short time (up to some hours, but not several days), this shutter should be used. Note that this will not turn off the laser. This may be beneficial, since it will not get out of thermal equilibrium and thus, no warm-up phase is needed, when the shutter is re-opened. The closed shutter deflects the beam to a power meter. The power which is measured here can be read out. Usually, it will be around 35 W higher compared to the power, which is emitted from the box, since an additional thin film polarizer and an aperture is mounted downstream this shutter to clean up the beam.

The external shutter will close automatically, if one of the interlocks trips. In this case the pump diodes will also be switched off and the system will need to be reset after elimination of the cause of the failure.

### 7.1.2 Internal shutter

The internal shutter can be used to block the beam path inside the oscillator. It is meant to be used, if less than the maximum output power of the laser is needed ("low power mode"). The power is decreased to approximately 50 % of the amplifier power and is it originates exclusively from the amplifier.

**Do not open this shutter while the Nd:YAG crystals inside the oscillator are pumped!** This might cause some damage on optical surfaces, since it might produce an unwanted Q-switch pulse inside the resonator. To make sure that the peak power does not become too high, proceed as follows:

1. Lower the pump power of at least one of the heads (see chapter 8)
2. Open the shutter. You will get a warning concerning the possible Q-switch. Confirm the warning, if the pump current of one of the heads has been decreased to zero. The shutter will open and the laser will not emit light at 1064 nm.
3. Re-set the pump current of the unpumped head(s) to the original value(s). Depending on the time, the whole procedure took, it might take some minutes

to get the diode temperature and current back to the set values.

## 7.2 DC stage and Piezo actuator

The oscillator box includes two actuators: The piezo actuator, which moves the 0° HR mirror on the “short” resonator arm in order to injection lock the system on the amplifier and a slowly moving DC-stage (the so-called long range actuator, LRA) to compensate for changes of the resonator length due to room temperature variations. This DC-motor driven linear stage moves the PZT-mirror mount to the middle of its actuator range if the piezo voltage exceeds a specified range. The stage should be activated, if the system is running constantly and no intentional changes of the environmental conditions are made (i.e. changes of the airflow, experiments on the laser itself, maintenance etc.).

### 7.2.1 Configuration of the DC stage

On the user interface one can reach the menu for configuring the DC-stage and the piezo actuator (locking) by pressing the “Lock”-button at the main screen. The screen, shown in figure 7.2, will appear.

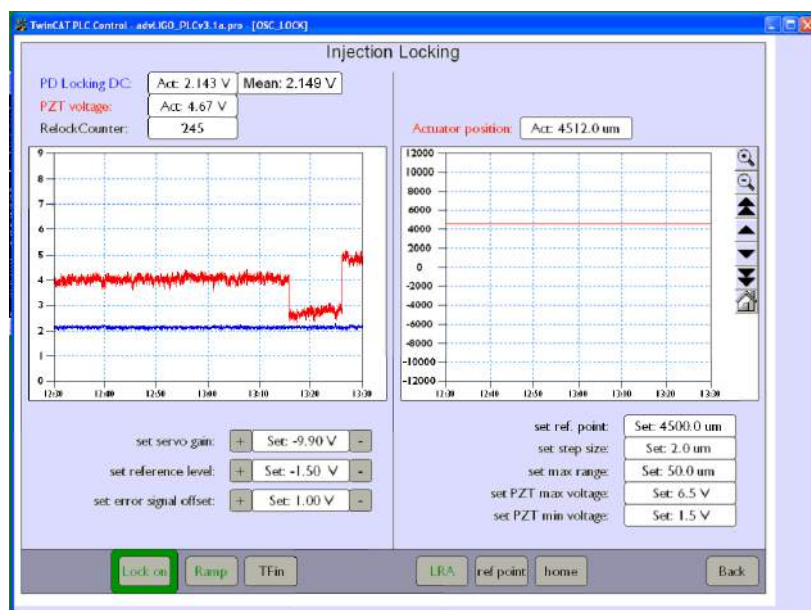


Figure 7.2: Screen to configure the DC-stage.

While the locking can be managed on the left hand side (see chapter 7.3), the LRA can be configured at the right hand side of this screen. Above the graph, which shows the absolute movement trend of the linear stage over time, the actual position is shown. Below the graph one can set four values:

- **set ref. point:** In this field the reference position is set. This is usually done, when the system is getting aligned. Therefore, this point should represent the optimal position of the system at the conditions, which had been found during assembly and alignment. This value should only be changed by personnel, which is familiar with the assembly and the optimization of the high power oscillator. Varying the reference point position might cause the laser to stop working.
- **set step size:** Here, the range of one movement step in  $\mu\text{m}$  can be set. This value should move the piezo to a position, where the driving voltage is in the middle of its range.
- **set PZT max voltage:** This is the upper boundary of the injection locking piezo actuator voltage. The DC stage will be moved (and thus shorten the resonator) by one step, if this value is reached. Of course this value should be well below the maximum PZT voltage.
- **set PZT min voltage:** The lower boundary of the injection locking piezo actuator voltage can be set in this field. Make sure that the PZT can work in a reasonable control range and the stage does not move all the time by setting the upper and lower boundary!

Three buttons are available in the same window: The “**LRA**”-button enables the long range actuator. The “**ref point**”-button forces the DC-stage to move to the reference point, which is set one field below. Press this button, if the laser is going to be switched on, and the long range actuator is *not* at its reference point (have a look at the “Actuator position”-field). The “**home**”-button brings the DC stage to the zero-position, which is set by the manufacturer of the stage. This will automatically

be done, when the control box of the system is started to initialize the system! Furthermore, this button must not be pressed during laser operation.

### 7.2.2 Behavior of the LRA

In figure 7.3 it is shown, how the LRA stabilizes the injection locking of the laser system: Here, the room temperature was increased via the air conditioning. The temperature inside the laser follows the trend, but the long range actuator can compensate for the elongation of the resonator due to thermal expansion. At the port in transmission of the locked high power premode cleaner no relock was detected during the test. Note that not only temperature induced changes of resonator length couple into the performance of the injection locking. A change in atmospheric room pressure will also change the index of refraction of the air inside the laser box and hence the optical cavity length. The maximum range of the stage is 24 mm, but moving the stage over the whole range will misalign the resonator.

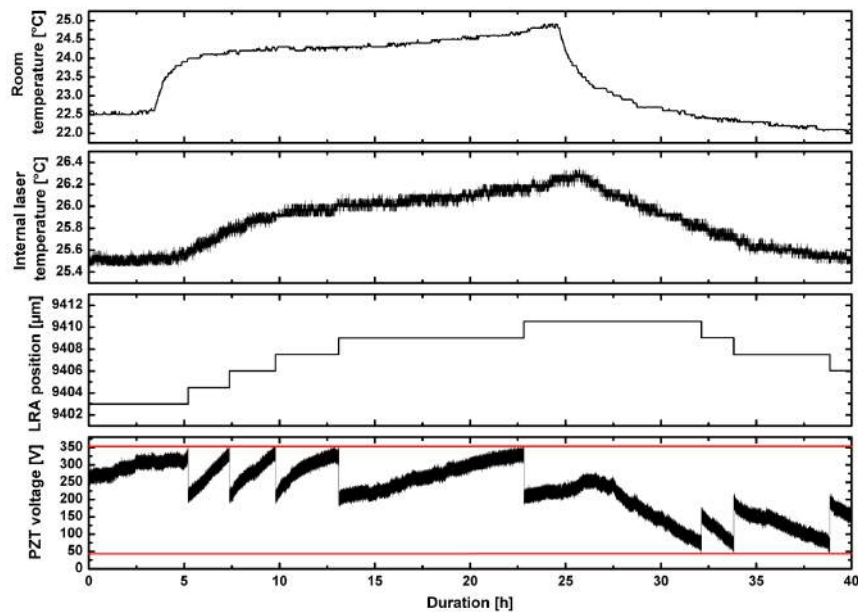


Figure 7.3: Long term test of the functionality of the temperature compensation scheme for the high power oscillator.

## 7.3 Injection locking

### 7.3.1 Principle

In order to achieve a stable single-frequency operation, injection locking can be applied to transfer the frequency properties of a master laser (the amplifier / frontend) to the high-power slave laser (oscillator). An active length control system based on the Pound-Drever-Hall scheme is used to keep the difference between master and slave laser cavity frequencies to a value within the injection locking range. For this, the amplifier is phase modulated by an EOM at a frequency of 35.5 MHz. The combined signal, which consists of the reflection at the outcoupling mirror and the part which is transmitted through the oscillator, is picked up with the locking photodiode. This signal is mixed down with the (phase shifted) modulation frequency, which creates an error signal, which can be used as a control signal for the PZT.

### 7.3.2 Preparation and preferences

First install the injection locking electronics and do the mode matching of the amplifier to the resonator:

- connect all signals to the power supply and the injection locking fieldbox, respectively. This is described in detail in the electronics manual. Connect
  - AC-signal of the locking photodiode to the mixer
  - local oscillator to the mixer
  - local oscillator to the EOM
  - piezo actuator to the power supply
  - fieldbox signals to the control box
- do the mode-matching between amplifier and oscillator (these steps might have been already done, when the laser is delivered)
  - use an attenuated amplifier beam to prealign it to the optical axes (use apertures to do so). Make sure that the beam propagates through the center of all mode-matching lens holders.

- the beam should travel through the unpumped oscillator and produce an interference pattern at the output of the oscillator box (usually the interference pattern are not concentric rings, since the size of the beam traveling through the resonator is too big).
  - install the mode matching lenses at the calculated positions
- start the oscillator and power up the amplifier
- Press the “Lock”-button at the main screen of the user interface. Then press the “Ramp”-button. You will now see the ramp of the PZT at the oscilloscope screen.
- optimize the mode matching by shifting the lenses if necessary. Compare the beam sizes of oscillator and amplifier at different positions (this step might have been done already, when the laser has been delivered)
- monitor the following signals at an oscilloscope while doing the modematching between amplifier and oscillator:
  - the DC-signal of the photodiode
  - the PZT monitor
  - the error signal
  - the lock acquisition signal
  - we recommend to use the ramp as trigger signal
- If you already see the resonance-signal at the DC-channel on the oscilloscope, set the reference level. The binary signal of the lock acquisition should shows it's upper value (5V) just at the DC-peak (this step can also be done or corrected later).
- if the prealignment has been done properly, you should already see error signals on the oscilloscope. If you do not see any signal, have a look at a CCD image of the output beam. You should see both spots (amplifier and

oscillator). Overlay them with the two steering mirrors, which bring the seed beam into the oscillator (M3 and M4 in figure 10.1).

Adjust the phase of the local oscillator to get the error signals symmetric. Align the steering mirror in front of the locking photodiode to get their amplitude as large as possible (this might have been done already!).

- Again, optimize the alignment of M3 and M4 to get the error signals' amplitude as large as possible. Install a CCD camera at the output beam and check the beam profile. You might see, if the amplifier beam does not match the oscillator's. **Handle the two mirrors M3 and M4 with care! You are moving several tens of watts in forward and backward direction!**
- The DC-signal should look clear and without noise on the oscilloscope's screen. Set the lock acquisition signal by tuning the reference level if not already done. The lock acquisition is detected by comparing the reference level with the DC-voltage of the injection locking photodiode (channel "Resonant" at the locking electronics).
- The signals on your oscilloscope should now look similar to figure 7.4

Now press the "Lock"-button at the user interface. Set the gain close below the value, where the PZT starts to oscillate.

**Gain too high:** The PZT makes some annoying noise, signals on the oscilloscope are oscillating

**Gain too low:** No injection locking

**Reference level too high:** system indicates that it is locked (green background at the "Lock"-button), but it is not. (There is still a lot of power propagating backwards and the system is not running in single frequency mode)

**Reference level too low:** system does not even try to lock



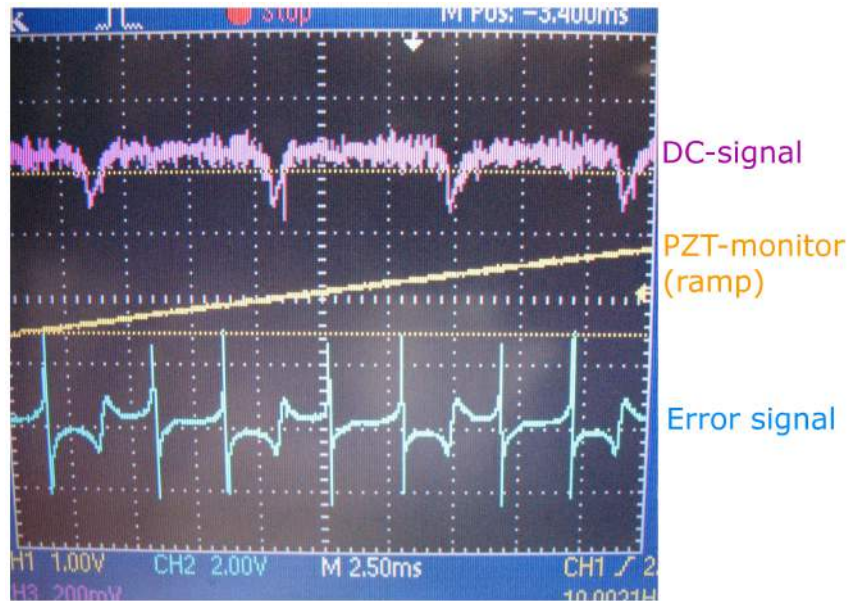


Figure 7.4: After finishing the described steps, the signals on the oscilloscope should look similar to this screenshot (lock acquisition not shown, depending on the amplitude of the ramp there might be less signals).

## 7.4 Faraday isolator and back-reflected light

The oscillator box contains a thermal lens compensated high power Faraday isolator, which protects the Front end from back reflected light, see Fig. 7.5. The isolation ratio of this isolator is specified as 36 dB. Therefore, it is possible to run the oscillator unseeded (without the amplifier). Since no optical diode is provided in the ring resonator, light will propagate in both (forward and backward) directions. While the forward propagating light will be emitted through the exit window, the backwards propagating light will be deflected at a thin film polarizer between the isolator and the amplifier and dumped by a built-in powermeter behind the Faraday isolator. If the amplifier is neither running nor pumped<sup>1</sup>, for- and back propagating light should have approximately the same power. The backwards propagating power is monitored at PD-ISO and the powermeter, respectively.

<sup>1</sup>If the amplifier crystals are pumped, but this system is not seeded, just the spontaneous emission from the pumped amplifier crystals will be sufficient to let the oscillator run in unidirectional mode.

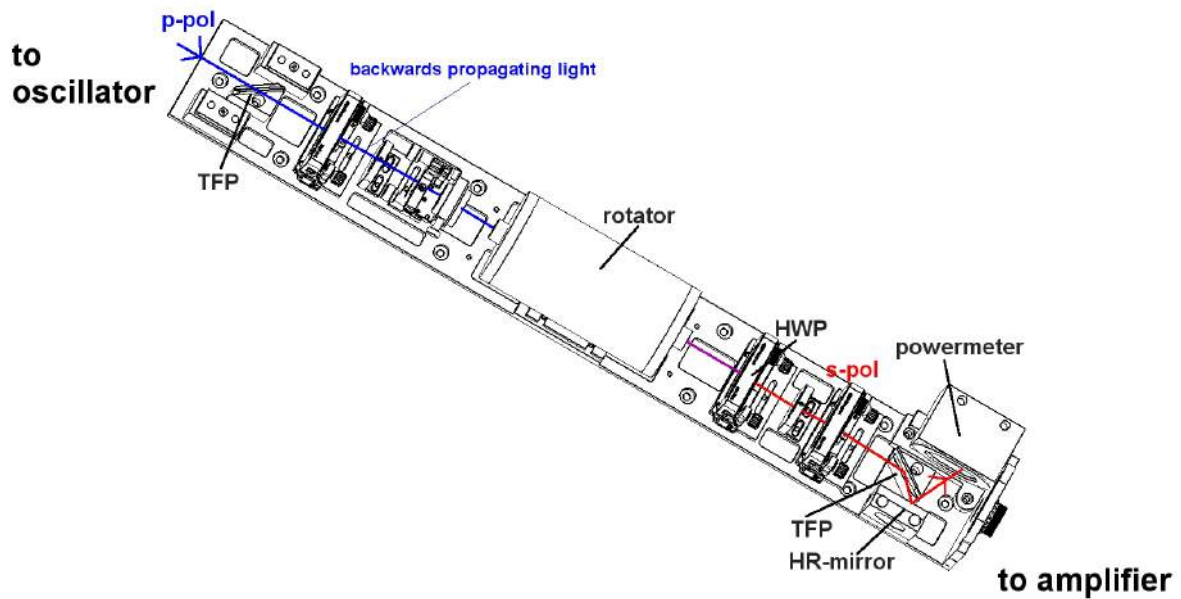


Figure 7.5: Beam path through the Faraday isolator.

## 7.5 Watchdog

The laser is equipped with an automatic emergency stop. It is meant to shut down the laser, if something inside the laser box is going really wrong. By pressing the “Watch”-Button at the main user interface screen, the laser power propagating to the output window is monitored by a photodiode. In case of failure of a pump diode, a chiller-problem<sup>2</sup>, the injection locking electronics or some other component, the power will decrease immediately. If the power changes by more than 10 % for more than five seconds, this will trigger the power watchdog and switch off the system. Due to this time lag, a shutdown due to a relock event is prevented.

## 7.6 Diagnostics

### 7.6.1 Pump light diagnostics

For proper functionality of the oscillator, the pump light power and pump light spectrum are highly important. These values are pre-set, when the oscillator is delivered. However, the emission spectrum depends on the pump power and the pump power

<sup>2</sup>A shutdown of the chiller will switch off the laser immediately via the interlock box, but if the chiller is running and no water is flowing through the pipes, this will influence the laser power

will change, if the diodes are getting older. Furthermore, it might be necessary to check the pump power and the spectrum in connection with troubleshooting. Therefore, a pump light monitor is included. It includes a spectrometer and a photodiode for each head.

The pump power can be set to a 100% value at the working point (this should correspond to about 250 W). Calibration of the diodes is just possible in service mode. To do so, follow the instructions as described in section 8.4.

The spectrum can be monitored by an internal spectrometer: Press on the schematic of the corresponding laserhead at the main screen and start the spectrometers software ("SpectraSuite"). At "SpectraSuite, zoom into the wavelength region of interest, i.e. 802nm to 812nm and adapt the integration time such that the spectrum is not clipped. In Beckhoff, pick an individual diode and change it's temperature by several degrees. Watch the change of the overall spectrum of all seven diodes in "SpectraSuite". From this change, estimate the optimal temperature for this diode to get a peak wavelength of 807.5nm. Repeat this for the remaining diodes. You are aiming for an overall spectrum, being as narrow as possible. Repeat this for the remaining three pump heads. The fine tuning of diode temperatures can be done by monitoring the output power of the injection locked laser.

### 7.6.2 Monitor photodiodes

Five photodiodes are installed inside the oscillator box to monitor the power at 1064nm at several positions. They can help to do the troubleshooting and might also help to realign the system, if it has to be reinstalled for some reason.

#### 7.6.2.1 Photodiode for Front-end power behind the high power Faraday isolator

This is a monitor photodiode (PD AMP, Fig. 7.6) for the power of the amplifier, which seeds the oscillator. It is located behind the Faraday isolator. If the system behavior changes, have a quick look at this port. If the monitored power at this photodiode has decreased, try to find the error either at the Faraday or at the amplifier - not inside the oscillator.

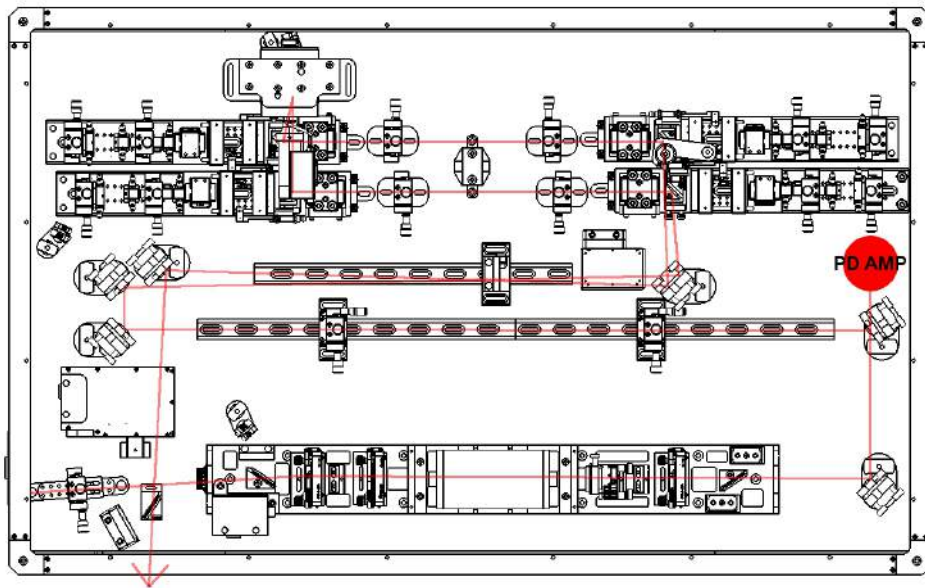


Figure 7.6: Position of the photodiode, which monitors the amplifiers power inside the oscillator box (PD AMP).

#### 7.6.2.2 Photodiode for backwards propagating light

The injection locking may not perfectly force the oscillator to run unidirectionally. A fraction of about 2 to 3 W will probably still propagate in backwards direction. This amount of power can be detected with a photodiode at the “entrance” of the Faraday rotator. The backwards propagating light is rotated in polarization inside the rotator, and is then reflected at a thin film polarizer and sent to a power meter and the photodiode PD ISO (Fig. 7.7), respectively. The measurements of this photodiode are only useful, if the system is locked. The measured value is a criterion on how good the injection locking works and therefore, how well the mode matching between amplifier and oscillator is done. It will be saturated, if the oscillator is running as an unseeded laser.

#### 7.6.2.3 Photodiode at the Brewster plate

The linearly polarized output of the system is assured by a Brewster window inside the oscillator. Light in the “wrong” polarization direction (which means other than p-polarized) will be reflected here. The reflected beam is then sent to the photodiode PD BP (Fig. 7.8). The measured power here shows therefore, how well the birefrin-

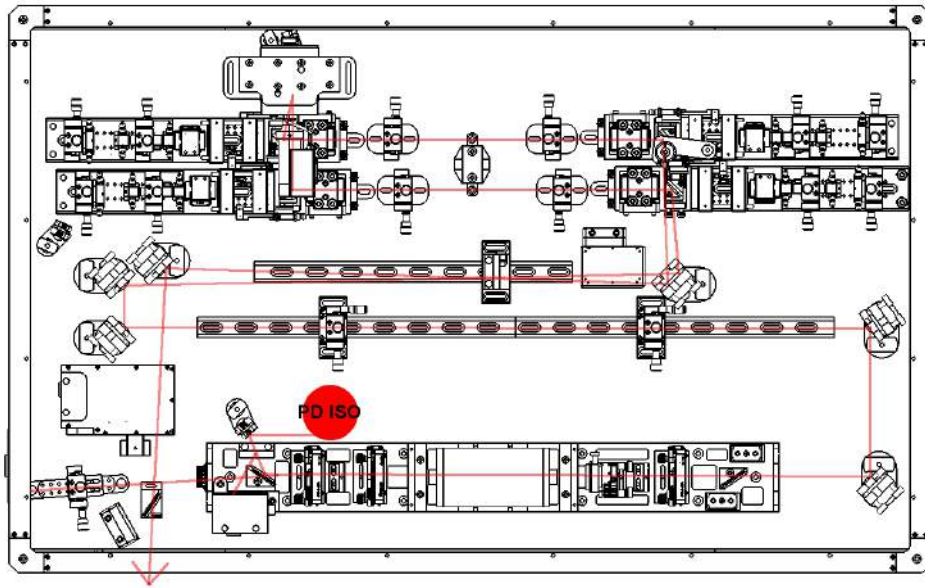


Figure 7.7: Position of the photodiode, which monitors the backwards propagating power (PD ISO).

gence compensation (a set of 4f-imaging optics and 90° quartz rotator between each pair of crystals) works. If this is not perfectly aligned, the measured power at PD BP will rise. In addition, it will also rise, if something else changes the polarization state of the laser, as e.g. the pump light distribution. Since the laser output is strongly depolarized, if the 4f and the quartz rotators are not installed (for example during pre-alignment / maintenance), the photodiode will saturate in this case. It can be used for resonator alignment.

#### 7.6.2.4 Resonator internal photodiode

This photodiode (Fig. 7.9) monitors the power of the resonator internal circulating power.

#### 7.6.2.5 Locking photodiode

This photodiode (Fig. 7.10) is not purely a monitoring photodiode, since it is part of the injection locking electronics (see section 7.3). However, it can be used to get a value for the output power of the system. The power which corresponds to the output of this photodiode is shown at the main screen of the user interface as “output

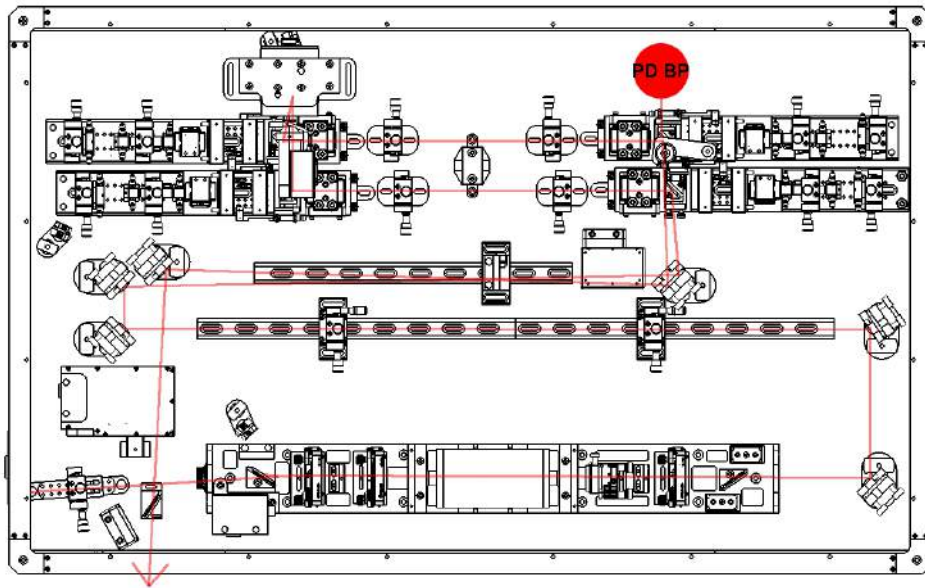


Figure 7.8: Position of the photodiode, which monitors the power which is reflected at the Brewster plate (PD BP).

power”.

In addition, a change of the mean DC-voltage of this photodiode will trigger the watch-dog (if activated).

To monitor the correct output power value, this photodiode needs to be calibrated. This can only be done in *service mode* (password protected). Proceed as follows:

1. Press the “DIAG”-button at the main window of the user interface to navigate to the diagnostics screen.
2. In service mode the buttons “Enter Calibration” in the Laser power field will be available. Press it and follow the shown instructions.
3. measure the output power with a calibrated power meter. We recommend not to use the powermeter inside the external shutter, since the power, which is emitted from the box might be a little lower than what is measured here.
4. Insert the measured power value to the corresponding field and press the “Calibrate”-button.



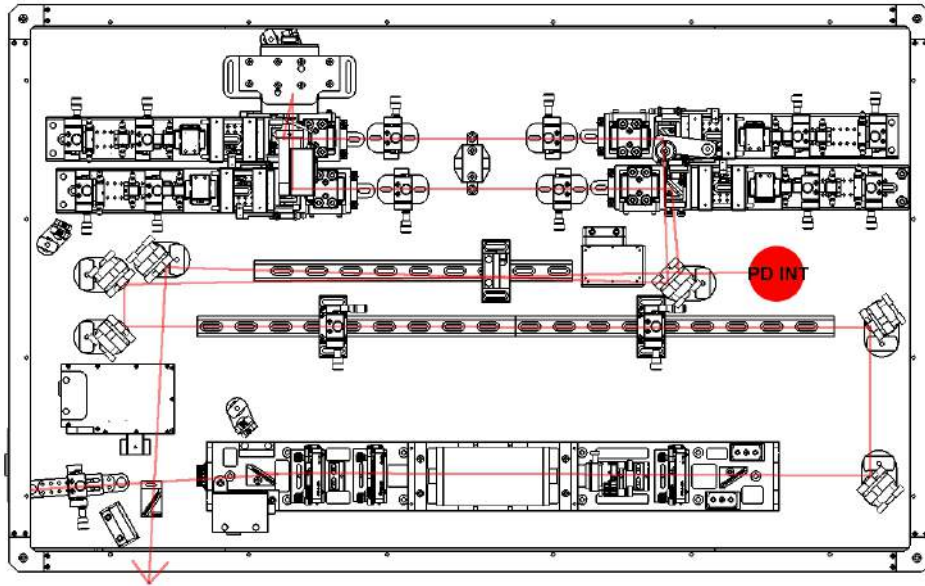


Figure 7.9: Position of the photodiode, which monitors the circulating power inside the resonator (PD INT).

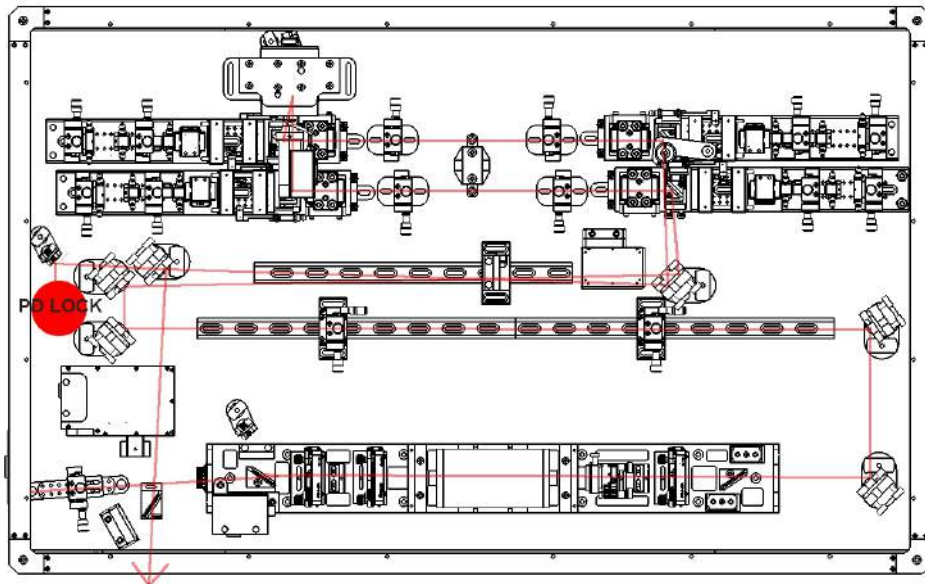


Figure 7.10: Position of the locking photodiode (PD LOCK).

## 8 User Interface

The laser system is controlled by a GUI connected to the TwinCAT SPS-environment. After starting the visualization one will see the screen, shown in figure 8.1, called “main screen” in the following sections.

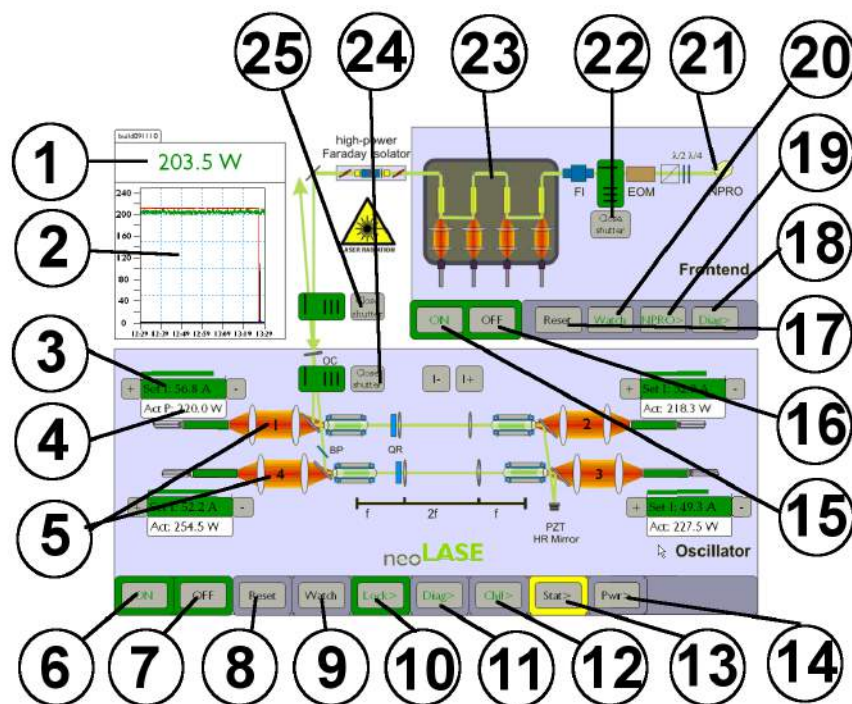


Figure 8.1: The main screen. Look into the following sections to get explanations for the labeled fields.

For explanations and references of the shown numbers see table 8.1.



Table 8.1: Explanation of the main screen.

Number	Function
①	Output power monitor. The shown value is measured at the DC-channel of the locking photodiode (section 7.6.2.5). It needs to be calibrated.
②	Power vs time plot of the last hour. Shown data: calibrated value of locking photodiode, powermeter at Faraday isolator, powermeter at external shutter, external powermeter (connected to the plug outside the laserbox)
③	The set value of the pump current for the corresponding head is shown in this field. The background of this field turns green, if the laser is running and the set-value is reached. In addition a small green bar above this field shows the progress of diode ramping. To set the pump current see section 8.1. To add or subtract pump current for a single head in 0.1 A-steps use the + and - sign beside the set value box. To add or subtract pump current in 0.1 A steps for <i>each head at the same time</i> use the + / - buttons in the middle of the oscillator schematic.
④	Inside the box below the "settings" field the relative value of the measured pump power is shown. This value can be calibrated in the "Diag"-menu if <i>service mode</i> is activated.
⑤	To view or change the pump light characteristics directly click on the pump optic of the corresponding laserhead inside the main scheme. The following steps are described in section 8.2.
⑥	Pressing this button will turn on the oscillator, which means that the laser diodes will ramp to their set-values. This is just possible, if the "reset"-button ⑧ has been pressed before and there are no current error flags active (see ⑬). You will get a confirmation box, before pump light is emitted.

Number	Function
⑦	Pressing this button will switch off the pump diodes of the oscillator. To prevent switching off the system by mistake, a confirmation box will appear, before the pump diodes are ramped downwards. This is <i>not</i> an emergency button, which switches the system off immediately. The pump currents will be ramped down. The amplifier will <i>not</i> be switched off by pressing this button.
⑧	Press the “Reset”-button before starting the system. This will reset the interlock box and all existing error flags.
⑨	Pressing this button will activate the watchdog of the oscillator. The oscillator (not the amplifier!) will be switched off, if the mean output power differs by more than 10 % from the value, which has been measured at the time, when the watchdog was activated. It is connected to the locking photodiode, therefore the watchdog will not be triggered by closing the external shutter ⑳. The power needs to be decreased or increased by more than 5 seconds to shut down the diodes.
⑩	This button guides you to the injection locking screen, where the long range actuator can be parameterized as well. See section 8.5 for more information.
⑪	This button will give you a screen, which shows the most important diagnostic channels for the oscillator. See section 8.4 for detailed information. In this window one can also enter the “service mode”, which for example allows to run the system with an open lid (see section 8.7).
⑫	The chiller can be remote controlled by pressing the “Chill”-button. The screen that is showing up is described in section 8.6.
⑬	This button guides you to the status and warnings - screen.

Number	Function
⑭	Here you can enter the powermeter displays (section 8.8).
⑮	This button will turn on the amplifier. The NPRO and the pump diodes will ramp to their set-values (see point ⑳). Switching the MOPA on is only possible if there are no error flags present and the “reset”-button ⑱ was pressed after an error occurred.
⑯	Pressing this button will switch off the pump diodes of the amplifier and the NPRO. To prevent switching off the system by mistake, a confirmation box will appear. Note that the oscillator will <i>not</i> be switched off.
⑰	Press the “Reset”-button before starting the system. This will reset the interlock box and delete potential existing error messages.
⑱	same function as pressing ㉓
⑲	same function as pressing ㉑
⑳	This button activates the watchdog of the amplifier, which works similar to the oscillator watchdog ⑨. Triggering this watchdog will also switch off the oscillator!
㉑	Here, the parameters and the status of the NPRO can be seen.
㉒	Here, the shutter between NPRO and amplifier can be opened/closed. This will interrupt the seed beam to the oscillator. There will be ASE coming out of the amplifier when the laser diodes are still operating. These few photons, which are only visible on a brown viewer card, are enough to force the oscillator to work in unidirectional operation. The effect is similar to a self injection lock of the high power ring cavity.
㉓	Clicking into this field will guide you to the amplifier menu, which is described in section 8.3.

Number	Function
②④	The internal shutter blocks the path inside the oscillator and can be used to bring the system in the “low power mode”. In this mode about 50 % of the MOPA’s power is reflected at the OC mirror. Low power operation is described in section 9.2. Read also section 7.1 on how to handle this shutter.
②⑤	This button opens/closes the external shutter (see section 7.1).

Each sub-menu can be left by pressing the “Back”-button.

## 8.1 Setting the pump currents for the oscillator

The pump currents can be directly set to those values, which belong to the oscillators working point by clicking into the box, which is shown at ③ in figure 8.1. A box will appear, which can be used to set or change the value. Press “OK” in this box to transfer the values to the power supply or “ESC” to go back to the main window. Proceed like this for all four laser heads of the oscillator.

## 8.2 Setting the pump light characteristics

To set up the pump light variables for each diode box press on the orange scheme of the pump light optics in the main window.

In this screen (see Fig. 8.3), one can see the actual diode temperatures, the set-temperatures and the actual values of the monitor photodiode, which is built into each laser diode. Below these values, a reference number (WPD) can be seen. At the working point this number can be calibrated to 100 % by pressing the “WPD cal.” button. To change the temperature for a certain diode press the “set”-box and change the value. Confirm the changes by pressing “OK”.

The optical spectrum can be monitored with an optical spectrum analyzer connected to the spectrum diagnostic port of the laser system. Consult the handbook of this analyzer for more details of its function.

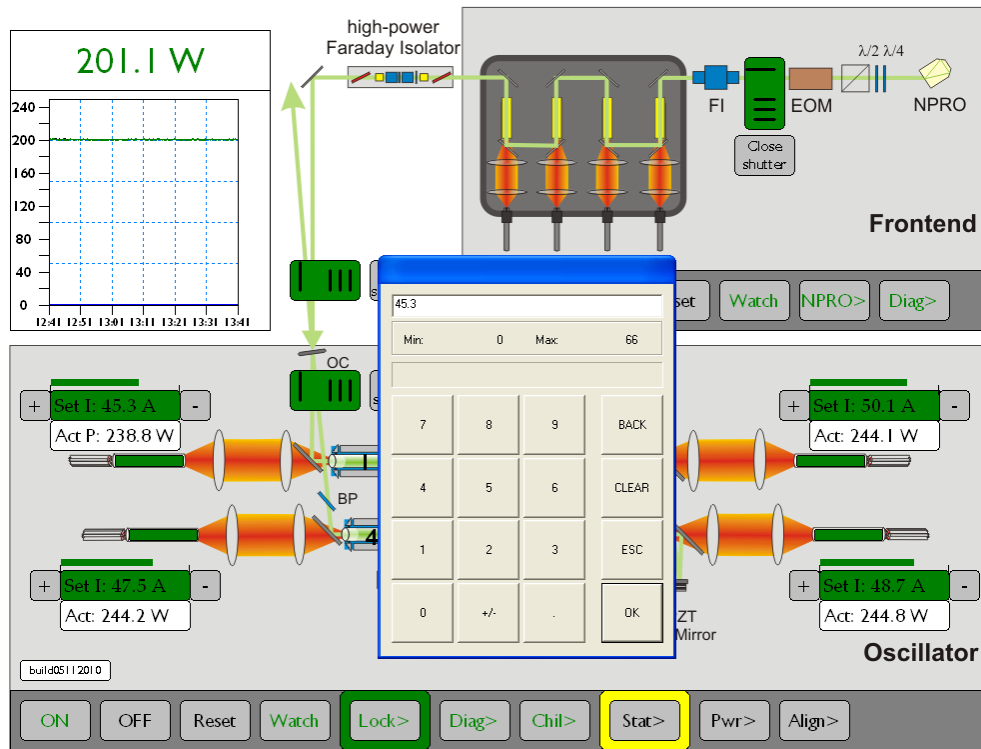


Figure 8.2: Setting the pump currents.

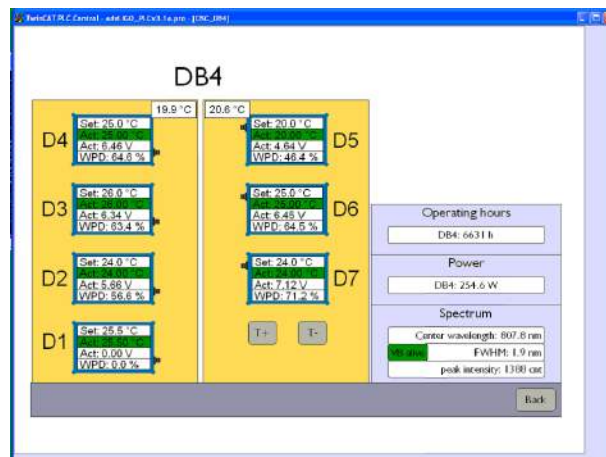
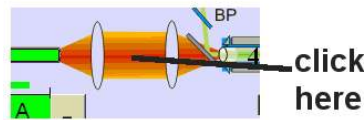


Figure 8.3: This screen shows the interface for controlling the optical output characteristics of a diode box.

### 8.3 Setting up the amplifier / manual mode of the amplifier

The amplifier menu is shown in figure 8.4.

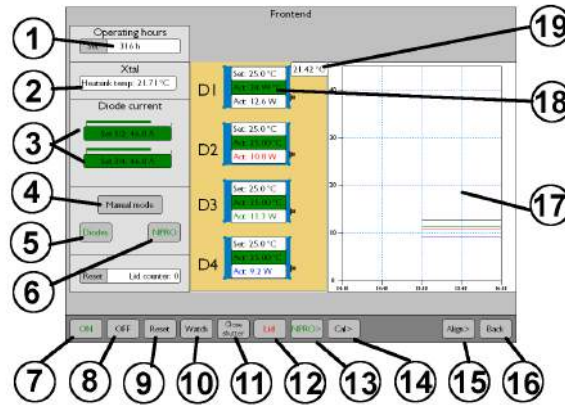


Figure 8.4: Control window to set up the amplifier.

Table 8.2 summarizes the functionalities of this screen:

Table 8.2: Explanation of the amplifier menu.

Number	Function
①	This field shows the operating hours
②	This field shows the temperatures of the copper heat sink, cooling the crystals. A value above 35 °C will switch off the amplifier. This normally occurs only, when the flow through the heat sink is too low.
③	These fields show the laser diode current of the two pairs of diodes. The diodes pumping crystal one and two are arranged in the first group whilst the second pair pumps crystal three and four. Clicking into these fields will enable you to change their values pairwise. The background of this field will become green, if the set-value is reached.
④	This button activates the manual mode which allows to switch components of the system (pump diodes and NPRO) on or off independently (only available in service mode).

Number	Function
⑤	The pump diodes can be switched on and off by pressing this button in manual mode. The diodes will be switched on automatically by starting the amplifier by pressing the "On"-button either at the main screen or at this screen (⑧).
⑥	Pressing this button switches the NPRO on and off in manual mode. The NPRO will also be turned on by pressing one of the "On"-buttons.
⑦	Turns the amplifier on. The letters will become green, if the amplifier is running.
⑧	Switches the amplifier off. A confirmation window will appear first and then the laser diodes will be ramped down (this is <i>not</i> an emergency shut down).
⑨	The reset button needs to be pressed before starting the amplifier. You will get a reminder in the status field ⑭.
⑩	Activates the amplifier watchdog.
⑪	Pressing this button will close the shutter between NPRO and amplifier. As a consequence, the amplifier beam will be blocked.
⑫	This button overrides the interlock, which is triggered by opening the housing of the amplifier. Keep in mind that laser radiation and scattering might leave the opened box, if the lid is removed and the amplifier is running (only available in service mode).
⑬	Switches on the NPRO (only in service mode).
⑭	The "Cal"-button guides you to the calibration menu.
⑮	This window brings you to the "alignment window" (service mode only).
⑯	Brings you back to the main window.
⑰	This window shows a power versus time plot for the pump diodes. The last two hours are plotted.

Number	Function
⑱	For each pump diode, the set-temperature, the actual temperature and the diode power are shown. The power is measured by a diode-internal photodiode, which needs to be calibrated (see ⑫). The set-temperature can be changed by clicking into the field. The box will become green, if the set-temperature is reached.
⑲	Readout of the temperature sensor at the pump diodes heat sink.

## 8.4 Oscillator diagnostic channels

Pressing the “Diag”-button in the main window will show you some of the most important diagnostic channels. On the next screen one can also calibrate the pump light pickoffs and the measurement of the laser power via the locking photodiode, if the service mode is active.

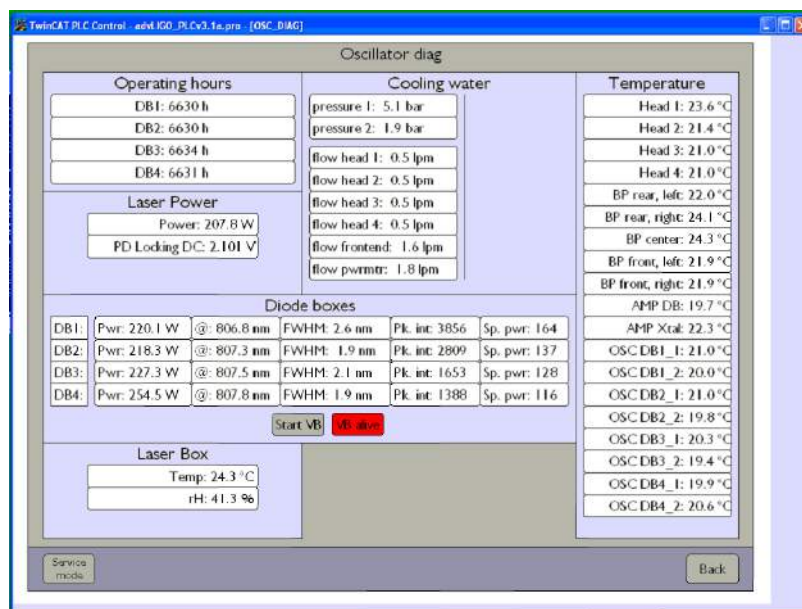


Figure 8.5: Diagnostics screen for the oscillator

The upper left corner shows the operating hours of the diode boxes and the locking PD voltage and the corresponding calibrated values of the laser power. In the upper



middle region the cooling water flow values for the subcomponents are available. Underneath these fields the pump pickoff values (spectral width, calibrated powers) are shown. The air temperature and relative humidity shown below are measured inside the oscillator box. On the right side the temperature values from the baseplate, the laserheads, and the diode boxes are summarized.

The mentioned photodiodes can be calibrated in “service mode” (password required). “Enter Calibration”-buttons will appear in the Diag-screens. Proceed as described in the windows to calibrate the diodes and press “BACK” to go back to the calibration window.

## 8.5 The Injection Locking interface

The “Lock”-button at the main screen will bring you to the injection locking interface. Figure 8.6 shows a screenshot of the user interface. An instruction how to use this tool is given in sections 7.2 and 7.3. However, a short description of the screen is given here:

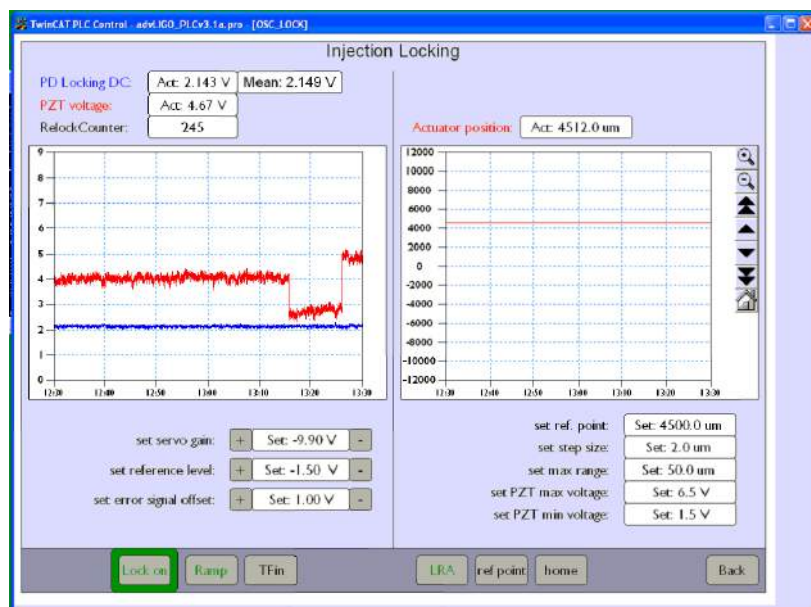


Figure 8.6: The Injection locking screen.

The left hand side of this screen gives access to the injection locking parameters, while on the right hand side, the parameters for the DC-stage can be set. In the

upper left corner, the monitored voltage at the DC-channel of the injection locking photodiode (chapter 7.6.2.5), the monitoring port of the piezo HV-driver (one has to multiply this value with 50 to get the real PZT voltage) and a counter for relock events are shown. This counter can be set to zero in service mode. A graph below shows a voltage vs time plot of the last hour. The function of the buttons below is described in section 7.3. Click into the set-fields to get a number pad, which allows to enter new values. If the system is injection locked, the border of the “Lock on”-button will light up green. The color will turn to red, if the system does not lock. For a description of the right hand side of the screen see section 7.2.

## 8.6 Chiller remote control

The chiller menu is shown in figure 8.7.

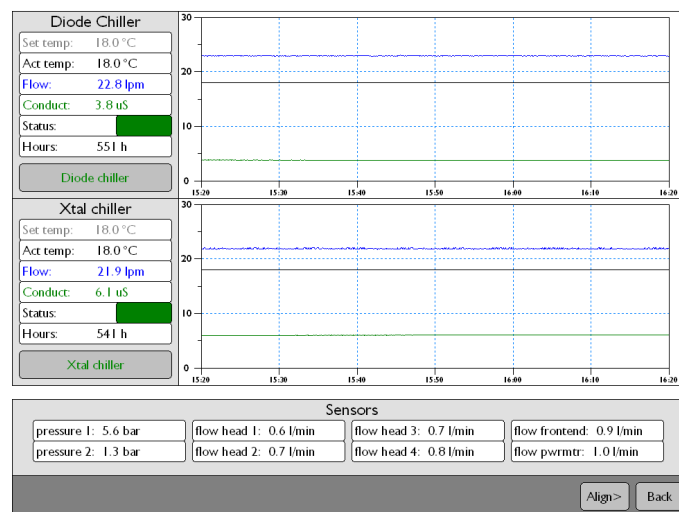


Figure 8.7: Chiller menu at the control screen.

The upper part of this screen shows the status of the diode chiller. This includes the set-temperature, the actual temperature, the flow, as it is measured by a flow sensor inside the chiller and the conductivity. The status box will become green, if conductivity<sup>1</sup>, flow and cooling temperature reach their set-values. The “Diode

<sup>1</sup>the set-value is reached by automatically pumping the water through a DI cartridge if the conduc-

Chiller”- button below will turn on the chiller. *One can only do so, if the remote control is activated at the chiller - see chiller manual!*. Beside this, all data from the last hour are plotted in the graph on the right.

The lower part of the screen looks similar and shows the status of the crystal chiller, which also cools the laserheads, the internal power meters, shutters, apertures and the amplifier. The minimum values for the required flow are set in *service mode*. If the measured value is lower than required, the flow watchdog will be triggered after 10 seconds. The background of the corresponding field will turn yellow. In addition, the values “Pressure 1” and “Pressure 2” are shown. These are the flow pressure and the return pressure as they are measured at the water distribution close to the optical table.

## 8.7 Status control

Pressing the “stat”-button at the main screen lets the system status screen appear (Fig. 8.8). Here, an overview of all errors and warnings is shown and therefore troubleshooting should always start with having a look at the system status. The interface is divided into parts for the Beckhoff control, the NPRO, the amplifier, and the oscillator. An additional field shows, which interlock triggered the watchdog and prevents the user from switching the system on, respectively. The red colored fields give hints on the parameters, which might cause trouble. The “Warnings”-area shows parameters, which do not cause a shutdown of the laser system, but need some attention.

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tivity is too high. The conductivity-value which triggers this can be set directly at the chiller. As a default value the conductivity is set between 4 and 7 mS.

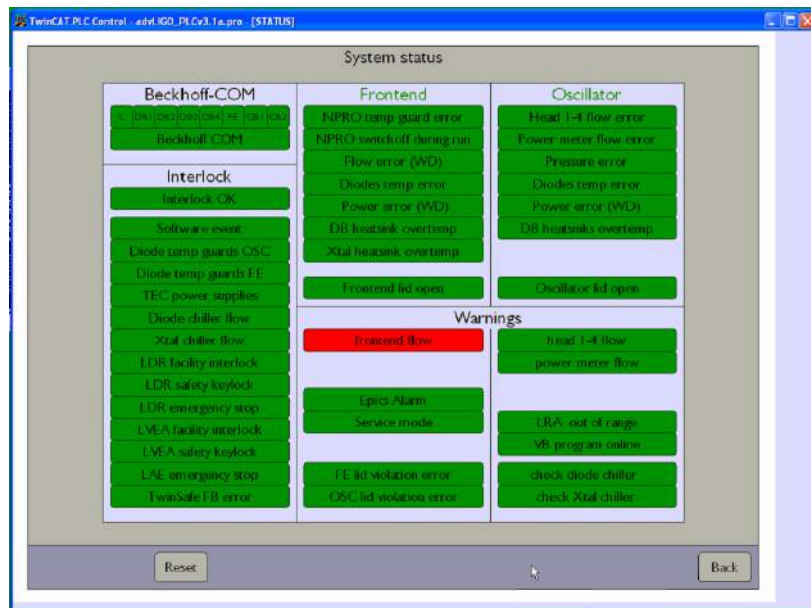


Figure 8.8: Status monitor.

## 8.8 Power screen

By pressing the “PWR”-button at the main screen, the readout of the three powermeters is accessible (Fig. 8.9). Namely these are

- Head 1: The powermeter in front of the Faraday-isolator (should be around zero, if the system is locked)
- Head 2: The powermeter inside the external shutter (should be zero, if the shutter is open)
- Head 3: An additional powermeter outside the laser box (it’s up to you, where you place it...)

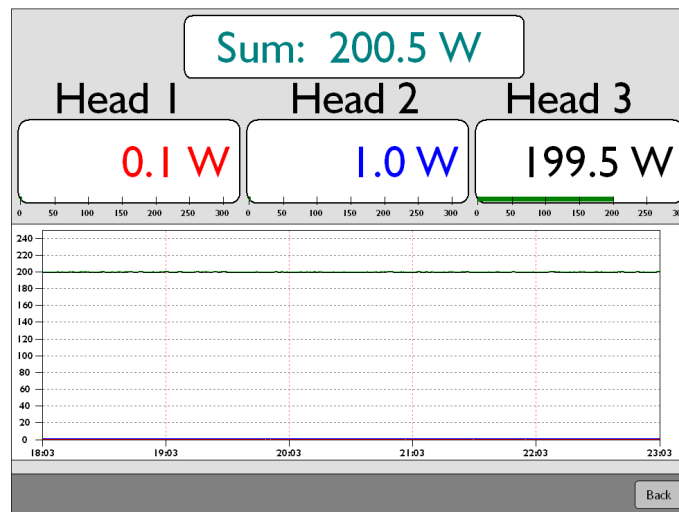


Figure 8.9: Readout of the installed powermeters.

## 9 First run

### 9.1 Quick start for starting the oscillator

- Connect the wiring as described in section 6.4
- Connect the water distribution as described in section 6.2
- Switch on the needed power supplies (for the diode boxes etc.) Make sure that they will not run into the voltage-limitation. Ensure that the laser diodes are not short plugged (check back of laser diode boxes)
- Start the user interface at the control PC
- Start the control box by turning the key; go to "Laser Hazard".
- Start both chillers: Press the "chil"-button at the user interface. Press both, the "Diode chiller"- and the "Xtal chiller"-button in the appearing menu. Wait until the "status"-fields become green. The flows monitored at the same screen should be as follows:

DCHIL > 22.5 lpm

XTALCHIL > 13 lpm

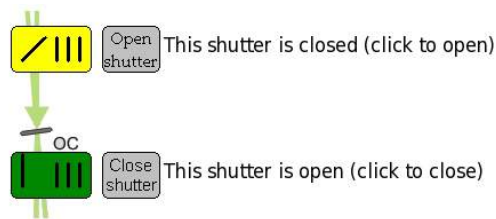
LASERHEADS all > 0.4 lpm

PWRMTR > 1.3 lpm

FRONTEND > 1.3 lpm

press BACK to return to the main screen. If one of the set values is out of specification, the water flow watchdog will be triggered after a delay of 10 seconds.

- Press the “stat” button at the main screen and then press the “reset” button. The fields remaining red need your attention. Warnings (e.g. “OSC lid violation error” when in *service mode*) will not prevent you from turning the system on.
- Set the pump currents for the oscillator diode boxes to a value, which complies with 250 W of pump power, if these values are not already set. The values should be around 52 A per box and can be changed by clicking into the corresponding set-field at the main screen.
- Set the oscillator’s diode temperatures to values, such that the pump light spectrum has its peak at 807.5 nm. The FWHM of the spectrum should be as small as possible (see section 8.2)
- Make sure that the internal shutter is open. The status can be seen at the shutter control. It should be green.



- **Prepare all laser safety arrangements, such as safety goggles, warning signs, etc.**
- Go back to the main interface screen. Press the “reset”-button near the oscillator scheme and the “reset”-button near the amplifier scheme.
- If the frontend was already running (“low power mode”):close the shutter between NPRO and amplifier.
- Press the “on”-button below the oscillator screen. The diode current will ramp now to the working point. Since the oscillator is not seeded, it will emit laser radiation in forward- and backward direction. The power should be approximately the same for both directions. The backwards propagating power can be read out with the power meter behind the high power Faraday isolator. The

forward propagating power can be measured with an external power meter or with the power meter inside the high power shutter (close this shutter to measure the power). In addition it can be measured at the DC-port of the locking photo diode, if this photo diode is calibrated (see chapter 8). The total output power should be around 170 W.

The beam profile (and also the output power) depend on the working point at the resonator's stability range, which depends on the pump power and the pump light spectrum, see Figure 9.1. At too low pump powers the output power is significantly less than 170 W and the beam profile looks smeared. At too high pump powers the output power will be quite high, but the beam looks (slightly) multi-mode.

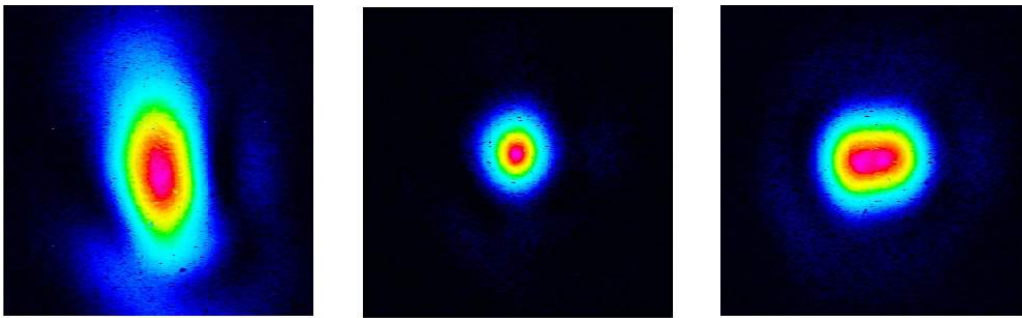


Figure 9.1: Beam profile at too less (left), too much (right), and optimal (middle) pump powers.

Both output power and beam profile can be influenced by the pump diode spectrum and therefore by the pump diode temperatures.

## 9.2 Starting the “low-power mode”

In the low power mode the output beam is generated by the amplifier (not by the oscillator) and it therefore depends on the output delivered by the MOPA. The MOPA beam runs through all the optics in front of the oscillator (high power Faraday isolator, mode matching optics). The part of the light, which is reflected by the outcoupling mirror will then be emitted at the output window of the oscillator box. Since the



outcoupling mirror has a reflectivity of about 50 %, the output power in the low power mode will be approx. 17 W, if the MOPA emits 34 W. The beam profile should be comparable with the MOPA beam profile. To run the system in low power mode

1. Prepare the wiring and the water distribution as described in the section above
2. Close the resonator internal shutter (low power shutter)
3. Start the amplifier as described in the amplifier's user manual.

### 9.3 Single-frequency mode (Injection locking)

- Do the wiring of the injection locking fieldbox as described in section 6.4
  - Prepare the wiring and the water distribution as described in the sections above
  - Make sure that both shutters stay open
  - Start the amplifier as described in the amplifier manual
  - Start the oscillator as described in the first section of this chapter. The power will no longer be equal for both directions. The main part of the power will be detected at the output of the system. It should be around 195 W.
  - Start the injection locking electronics:
    - apply power supplies / HV for the PZT
    - start modulation of EOM\*
    - start the local oscillator\*
    - start the PZT-ramp (section 7.3)
- \* set phase and output power of the corresponding frequency generators and local oscillators/delay lines, respectively.
- Check the error signals as described in section 7.3. They should look like shown in figure 9.2
  - Press the "Lock on"-button in the locking menu of the user interface.

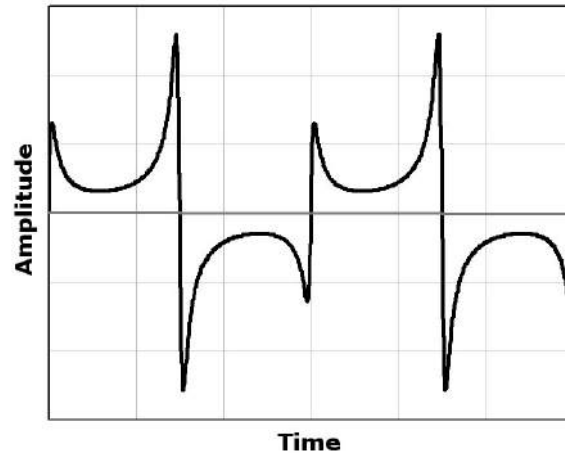


Figure 9.2: Calculated shape of an error signal

## 9.4 Expected output characteristics

The injection locked laser system will emit radiation with the following properties:

- Wavelength: 1064 nm
- Power behind the aperture:  $> 180$  W in  $TEM_{00}$
- Position of the beam waist: 750 mm behind the output coupler
- Size of the beam waist: approx.  $500 \mu\text{m}$
- Beam divergence: 0.6 mrad

# 10 Alignment procedures

In this chapter, we give a short alignment instruction. There are several situations which might cause the need for a realignment of the laser. The headline of the following sections describes these situations. Please refer to Fig. 10.1 for all labels of optical components inside the beam path.

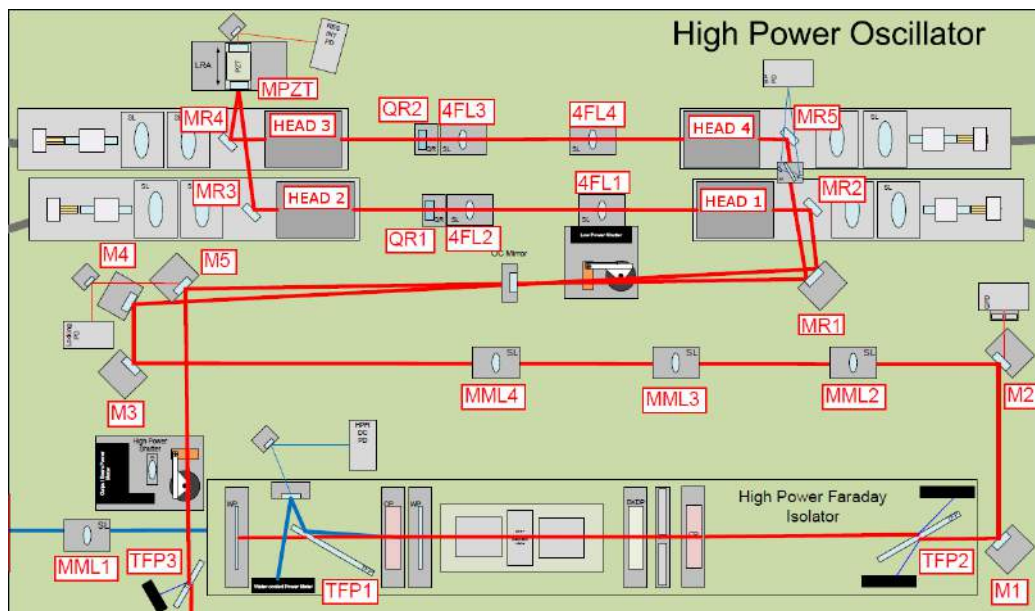


Figure 10.1: Definition of names for beam path components inside the high power oscillator housing.

## 10.1 The beam path between MOPA and oscillator box

Usually one has to do this once, when the oscillator has been delivered and has to be installed. If one of the steering mirrors between the two boxes is misaligned by mistake, this section might also be helpful.

The beam coming out of the amplifier then needs to be aligned to the oscillator box.

A mode matching lens between the two boxes is not needed, but a lens with a long focal length (i.e.  $f=400$  mm) is placed directly behind the entrance of the oscillator box. The distance between the two boxes is given in Fig. 10.2. Two HR steering mirrors guide the beam from the amplifier to the oscillator as shown in Figure 10.2. The mirror close to the entrance of the oscillator box should have a transmission of 0.2 % in s-polarization to give a pick-off beam for characterization of the MOPA with the DBB.

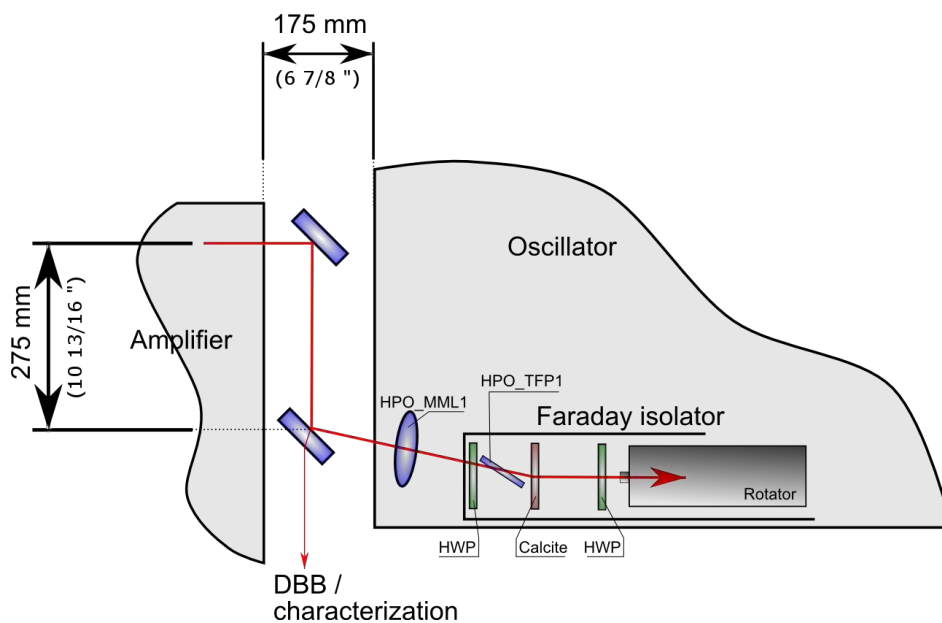


Figure 10.2: Distances and components between the MOPA stage and the high power stage of the adv. LIGO laser.

- Decrease the amplifier power to 2W by rotating the HWP in front of the isolator between NPRO and amplifier (inside the MOPA-box).
- Center the beam on both steering mirrors.
- For the second mirror (the one with  $T=0.2$  %) a right-handed mirror mount is required, which allows the beam to pass through as it needs to be detected behind the amplifier box.
- Align the beam parallel to the housings / threaded holes of the optical table.

- Optimize the orientation of the half wave plate at the entrance of the Faraday isolator's housing, such that the reflection at the first thin film polarizer is minimized. Use a brown viewer card to check for this.
- When aligning the beam through the housing of the oscillator box towards the Faraday isolator it *needs to be detuned* by a three degrees. The beam going through the Faraday will be deflected at the calcite wedges (cut in a wedge of approx  $3^\circ$ ) and then pass the Faraday on its optical axis. Ensure that all optical components on the Faraday baseplate (thin film polarizers, half wave plates, calcite wedges, apertures) are hit in the center. Lens MML1 should be removed to check for the position of the beam in respect to the calcite wedge.

## 10.2 How to get maximum suppression of backward propagating light / Faraday alignment

The Faraday isolator in between amplifier and oscillator prevents the NPRO from being destroyed by backward propagating light from the oscillator stage (which of course would be amplified in the Nd:YVO stages). But even in case of more or less good alignment a reasonable fraction of light propagates backwards through the amplifier. Therefore a second isolator is placed in between NPRO and amplifier. If the suppression by the isolators is insufficient, the NPRO will be disturbed. A stable operation and injection locking will become quite hard, because the NPRO starts q-switching when it sees back-propagating light during unlocked state of the oscillator.

The isolator should at least be pre-aligned after delivery, but nevertheless we describe the alignment procedure in the following steps:

The isolator can stand up to 500 W and an isolation of more than 40 dB has been demonstrated. To achieve these values the complete isolator has to be aligned in reverse. We recommend to align the isolator with the amplifier beam, which propagates reverse to the operational direction. Thus, setup the beam path as shown in figure 10.3. It might be necessary to use one or more lenses on the beam path to get a reasonably collimated beam. Also, p-polarization is required for this procedure, so

an additional half wave plate in this beam path is needed.

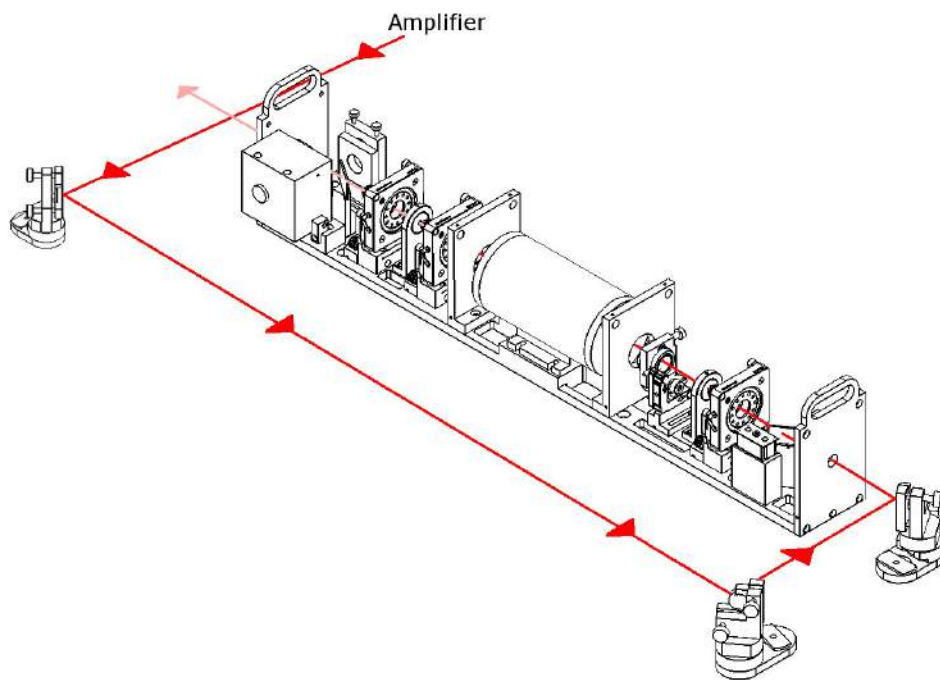


Figure 10.3: Beam path of the MOPA for alignment of the high power isolator

Measure the power of the amplifier beam after it has propagated through the Faraday isolator in backward direction (it should be close to zero, if the isolator is perfectly aligned.) For the following alignment steps the MOPA should be set to its full power level. Use the low power beam just for pre-alignment, as the Faraday isolator is designed for high power levels.

- Remove the Macor apertures from the Faraday-setup and ensure that the backwards propagating beam is centered on all Faraday-optics.
- Turn the half-waveplate in front of the rotator (not the one, which located at the isolators entrance frame) until the power behind the housing is minimized and the power, which is reflected at the TFP is maximized.
- Adjust the holder of the HWP *in all three directions*. Maximal suppression can just be reached by aligning the tip/tilt of the HWP *and* the mount.

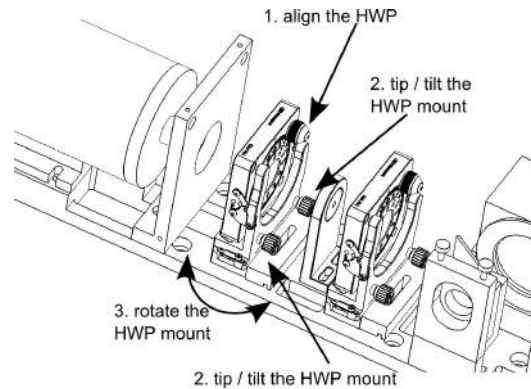


Figure 10.4: Adjust the mount of the half wave plate in front of the Faraday rotator in all three directions.

- Adjust the calcite wedge holder. This aligns the wedges with respect to the (non-adjustable) thin film polarizers.
- Rotate and tip/tilt the DKTP mount until maximum suppression is reached.
- Repeat the last three steps iteratively to reach maximal suppression.
- Put irises into the corresponding mounts on the Faraday baseplate and move these mounts (long hole), to center the beam here. In order to optimize the seed alignment, we recommend to use irises instead of the original Marcor apertures and replace them, once the Seed alignment is done.

**Warning:** For high power laser operation, you need to use the Marcor apertures. They can stand much higher laser powers than the metal irises.

### 10.3 The beam on the ground plate

- Decrease the amplifier power to 2W by rotating the HWP in front of the isolator between NPRO and amplifier (inside the MOPA-box).
- The beam needs to be on the optical axis of the mode-matching lens holders MML2 and MML3. Do the first alignment without any lenses (the beam will be quite big at the end of the path, but for perfect mode-matching it is important to encounter the lenses in the middle.) Mount an iris holder with an iris inside

on the mode-matching lens holders as shown in figure 10.5. (Do not put the irises into the adjustable part of the lens mount!)

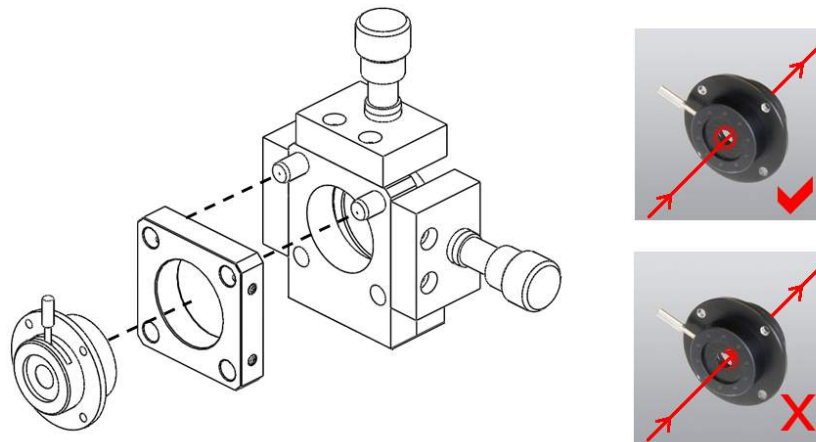
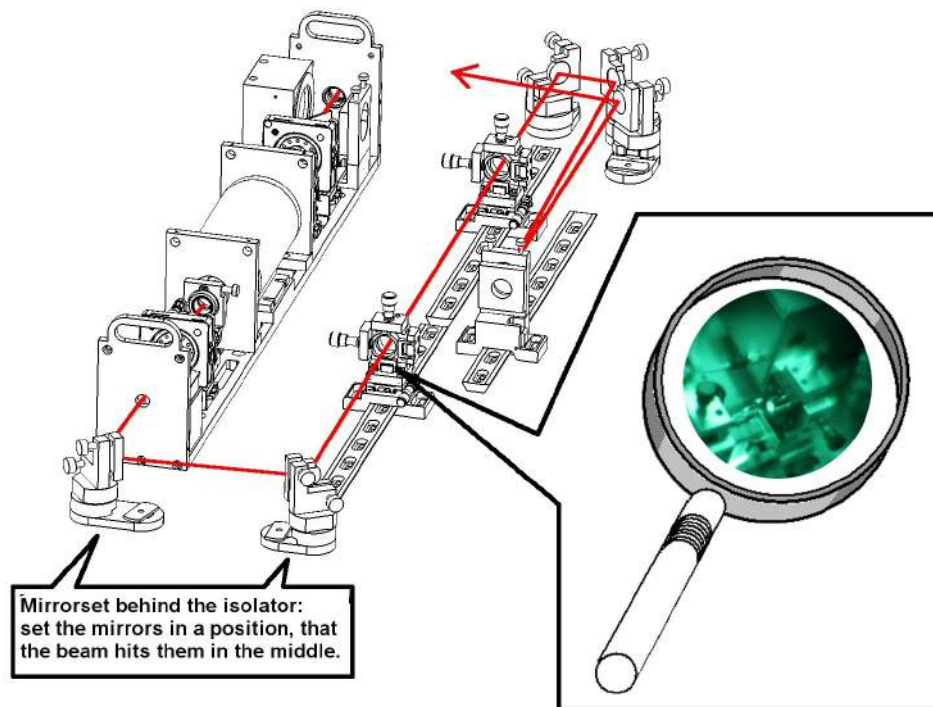


Figure 10.5: Put an iris inside the mode matching holders as shown in this Figure.

- Close the iris aperture and use the mirror set M1 and M2 behind the high power isolator to align the beam, such that the outer region of the beam is concentric with the pinhole itself (figure 10.3). It may be necessary to unscrew and move the mirror mounts M1 and M2, so that the beam is centered on both mirrors.
- Position M3 to have the incoming beam from the MML's to be in its center. Then steer the beam in a  $90^\circ$  angle to M4. Place M5 on the baseplate, such that it is on axis with the outcoupling mirror's rail. Putting mirror M5 onto the baseplate in forehand saves a lot of time, since one would immediately see, if the beam, coming from M4, is clipped at the edge of M5. Put a aperture in the OC mirror mount to hit the outcoupling mirror in its center. See section 10.4 for a detailed description of how to align the resonator.
- At this point both, the reflected part of the beam and the beam travelling through the aligned resonator, should be visible. Use the OC mirror to overlap both beams and check for the resonator alignment again. Use M5 to deflect the beam(s) through the high power shutter and out of the lasers housing. Check with a brown viewer card for the transmitted beam through the mirror with a transmission of 0.01 % (M5). Move the position of M5 to center the beam and





constantly check that the transmitted beam is not blocked at M4. If this is the case, move the mount of M5 slightly towards laserhead 2 and check for the transmitted beam not to be blocked again.

- Remove the irises and put the *second*<sup>1</sup> mode-matching lens in. Align it, so that the position of the output beam remains unchanged. Now put the first mode-matching lens into it's holder and align to keep the position of the output beam unchanged.

## 10.4 Resonator alignment

This has to be done, if one or more optical components (crystals, mirrors or lenses) have to be exchanged. If the component had just been cleaned without removing them, one could try to establish the old configuration by just aligning this component. However, realigning just one exchanged *crystal* rarely worked in the past (and it is also much faster to do the complete alignment procedure...)

<sup>1</sup>Usually it is easier to put the second lens in first, because otherwise the beam diameter becomes even bigger

1. Loosen the fixing screws of the HR 1064 nm  $45^\circ$  dichroic MR2 in front of the pump chamber. Do not unscrew and remove it completely from the pump head's base plate.
2. block the beam path between pump heads 3 and 4.
3. Pump light and steering mirror adjustment:
  - Start with pump head No.1. Take a white viewer card and place it in front of the first lens of the pump optics. Increase the pump current for laserhead No. 1 slowly until you can see the fluorescence on the viewer card. The typical current value is between 7 – 10 A. The position of the beam profile should be centered on the lens. If it's not, move the beam up and down adjusting the beam mount of the homogenizer. Do the same for the fiber bundle as well to move it to a concentric position in front of the homogenizer tip. Be sure not to move the homogenizer too far away from the fiber bundle before adjusting it, too.
  - Put the white viewer card in between the two pump lenses. Use the fiber bundle holder to align the fiber bundle, so that the shape of the pump light looks as a set of concentric rings, as shown in Fig. 10.6.
  - Remove the viewer card and place it in front of the Macor part of the  $45^\circ$  dichroic mirror. Move the unscrewed turning mirror in front of the pump chamber socket vertically to the optical axis so that the pump light at that position passes the substrate without clipping. Do check the position of the pump-light after the  $45^\circ$  mirror to be not too close to the mirror's edge.
  - Bolt the mirror mount down. The base plate of the mount should be pushed down to hold the mirror in place with one finger while doing so.
  - Switch off the laser diode box of laserhead No. 1 and start all over with head No. 2, 3 and 4.
4. Replace the 4f lens holders between pump head 1 and 2 with aperture mounts. These mounts are included for alignment purposes. These holders are equipped

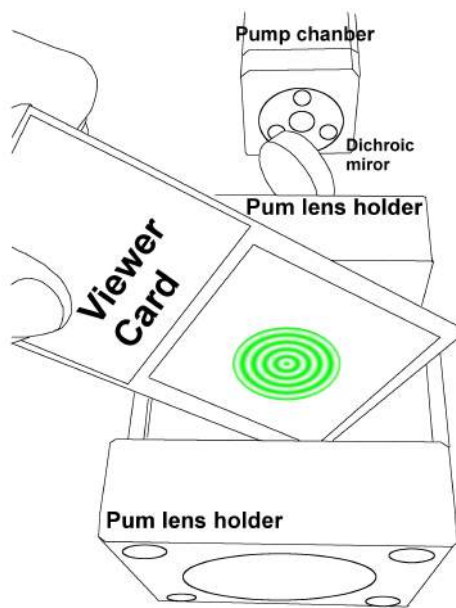


Figure 10.6: Pump light profile in between the two pump lenses

with an iris as a beam reference Fig. 10.7. The Holder should be moved to the farthest possible positions in direction of the laser heads.

5. Use the attenuated amplifier beam for the following alignment procedure. 2W of output power should be sufficient. **Make sure, that white/green viewer cards will not start to burn at this power level. Keep the viewer cards away from optical components!**
6. The position of pump head 1 from the electrical interface side wall should be approx. 45 mm.
7. Bolt the mount of mirror MR1 in front of pump head No. 1 down, such that the mirror's center is left of the center of MR2. Furthermore the mount should be moved by some mm towards the laserhead to have the center of the MR1 not coaxial with the one of the OC mirror.
8. Adjust the laser beam with M4 onto MR1. Then, use MR1 and the dichroic steering mirror of laserhead No. 1 (MR2) to align the beam through both iris. Mirror MR1 is used for the position on the first iris, whereas mirror MR2

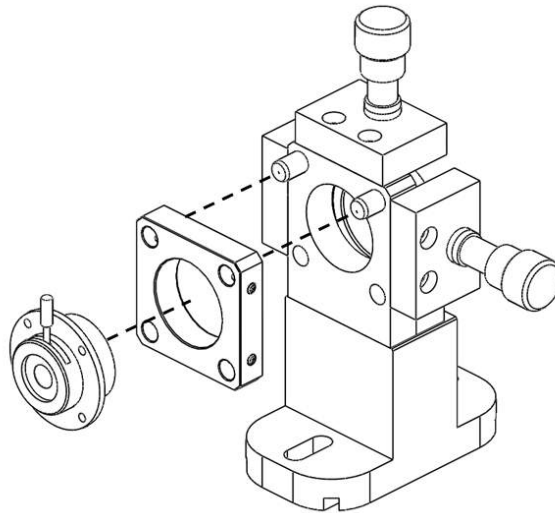
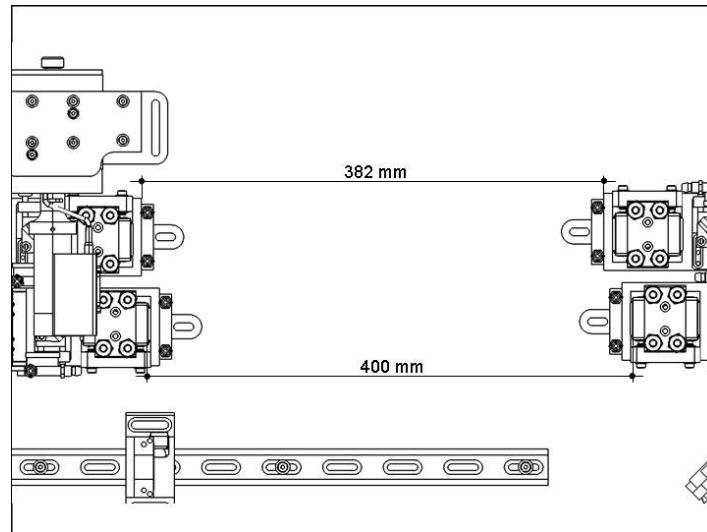


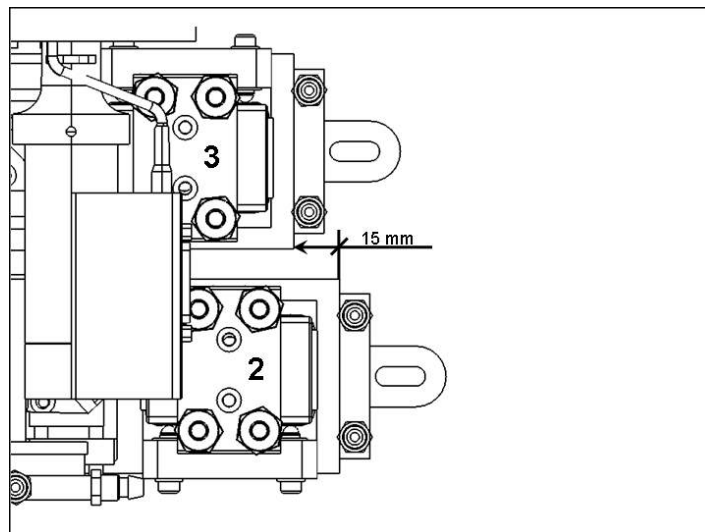
Figure 10.7: For alignment of the oscillator use iris apertures mounted to special made holders at the  $4f$  position.

adjusts the angle and therefore the alignment to the second iris.

9. When the beam is centered to the optical axis of laser head No. 1 and 2 loosen the screw inside the elongated holes of head No. 2. Move laser head No. 2 and align mirror MR3 such that the beam is deflected by  $90^\circ$  to the center of the PZT mirror. laser head No. 3 might have to be moved as well to get through the gap in between the dichroic steering mirror MR4 and pump chamber afterwards.
10. As soon as pump head No. 2 is aligned, bolt it down to the HPOSC ground-plate.
11. The distance in between two *laser crystals* is set to be 400 mm. This results in a distance of 382 mm between two opposing *pump heads*. This distance is measured from the upper front edge of one head to another (not from the ear in the middle of the optical bench). Pump head No. 2 is the reference in that case. After moving head No. 1 to its designated position you can bolt it down it with the M6 screws.
12. Align the beam using MR1 and MR2 through the iris aperture again following the steps above.



13. Pump head No. 3 should be pushed backwards (in direction of the water interface wall) by 15 mm in respect to the edge of pump head No. 2. This should allow the beam coming from MR3 to travel through the gap in between MR4 and the pump-chamber of pump head No. 3.



14. Then move pump head No. 4 so that the distance in between the crystals is set to 400 mm (procedure see steps above).
15. Replace the 4f lens mounts between pump heads 3 and 4 with the two remaining iris aperture mounts. Move them to the position closest to the pump heads. Align the beam through the pinholes using the PZT mirror (MPZT) and MR4. Check that the linear stage is moved to its reference point (see section 7.2).

Use MR4 for alignment of angle and MPZT for the position.

16. Be aware that the PZT mirror will move a lot during alignment. Double-check that the beam coming from pump head No. 2 is still centered on MPZT. If it's not go back to step 9.
17. After having the beam on the optical axis of pump heads No. 3 and 4, align the beam with MR5 through the gap between MR2 and the pump-chamber.
18. The beam coming from MR5 should strike the resonator internal steering mirror MR1 such that it exits the resonator on axis with the rail, holding the OC mirror. The beam should then be centered on M5. In most cases it is necessary to loosen the screw of the resonator mirror MR1 and move it. After slightly tightening the screw of the mirror socket again one has to realign the beam through the iris apertures in between laser head No. 1 and 2 again and check for the position of the beam coming from MR5.
19. Redo this procedure until you have found the right position for mirror MR1. Note that one has to move the resonator external mirror M4 as well, to guarantee that the angle on the outcoupling mirror is as low as possible. Just move one component after another and align it afterwards again to the reference aperture in between laser head No. 1 and 2.
20. Now put the semi-transparent outcoupling mirror into it's designated holder. Use M4 and MR2 to realign the incoming beam to compensate for the slight deviation caused by the mirrors substrate **Do not touch MR1 again from now on!**.
21. Use MR5 to overlap the beam, coming into the resonator with the outgoing beam on the output coupler (i.e. "close the ring"). The partly reflective side of the output coupler is facing towards the resonator. A weak reflection should be visible on the PR coating side of the mirror with an electric IR viewer. If the beam is not clearly visible, you can use a lens cleaning paper to detect the incoming and outgoing beam.

22. Place a white viewer card in front of mirror M5. There should be two beams visible on the viewer card. Do not block the incoming beam with the card, the distance in between both beams at that position is just about a few mm. Align the OC mirror mount, so that both beams overlap. You should see concentric fringes on the viewer card at that point. If there are no fringes to be seen, check the alignment of the beam coming from pump head No. 4 on the OC mirror again as described in 20.
23. See section 10.3 from here on to align the external components and use the HPS as a beam block.
24. Close the MOPA's internal shutter. Then install all four pump-chambers with the laser crystals already in place. Connect the water piping system to the pump-chambers.  
To reduce the depolarization effects inside the oscillator the crystals need to be aligned with the amplifier as a reference<sup>2</sup>. Using the prealigned beam of the MOPA as a reference, the crystals will perfectly face each other after the following steps.
25. Before starting the alignment process, a "diffuser" plate has to be prepared. Properly clean two glass microscope slides. Cut a piece of lens cleaning tissue to a strip that fits onto the glass slide. Adjust the size of the paper to leave a gap to the edge of the microscope slide around it. Fix the second glass slide with four drops of adhesive or transparent nail polish in the corners. Do not touch the lens tissue with the adhesive. Put some insulating tape around one long end of the diffuser plate to give it more grip for tweezers there.
26. Block the beam behind laser crystal No. 4 to suppress the interference pattern on the beam.
27. Remove the ASE apertures at head 1 and head 3.

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<sup>2</sup>see N. KUGLER ET. AL: "INVESTIGATION OF THE MISALIGNMENT SENSITIVITY OF A BIREFRINGENCE-COMPENSATED TWO-ROD Nd:YAG LASER SYSTEM", APPLIED OPTICS, VOL. 36, No. 36 (1997)

28. Place the diffuser plate directly in front of the first crystal. Some parts of the transmitted amplifier beam will be scattered at the tissue, while others still propagate in an unchanged direction. The diffused beam will be reflected at the inner barrel surface of the crystals. By holding a screen (for example a viewer card) in a distance of 4 to 7 cm behind the crystal one can use an electric IR viewer to find some rings. The task here is to create a concentric pattern by aligning the four-axis table underneath the crystal. The x- and y-axis close to the seed beam input aligns the inner part of the pattern. The screws towards beam outlet move the outer rings.

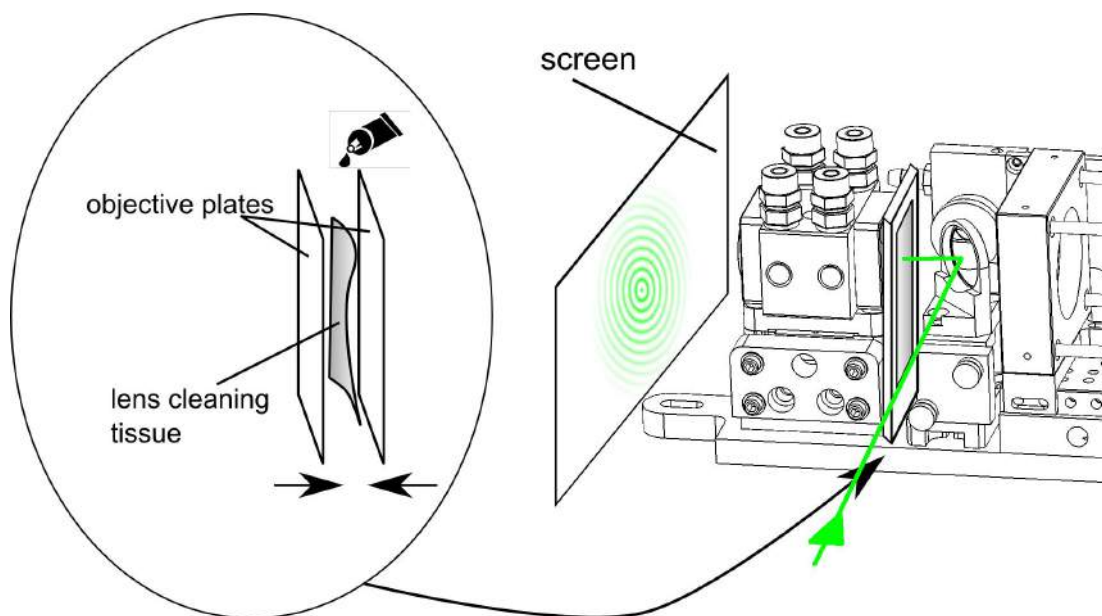


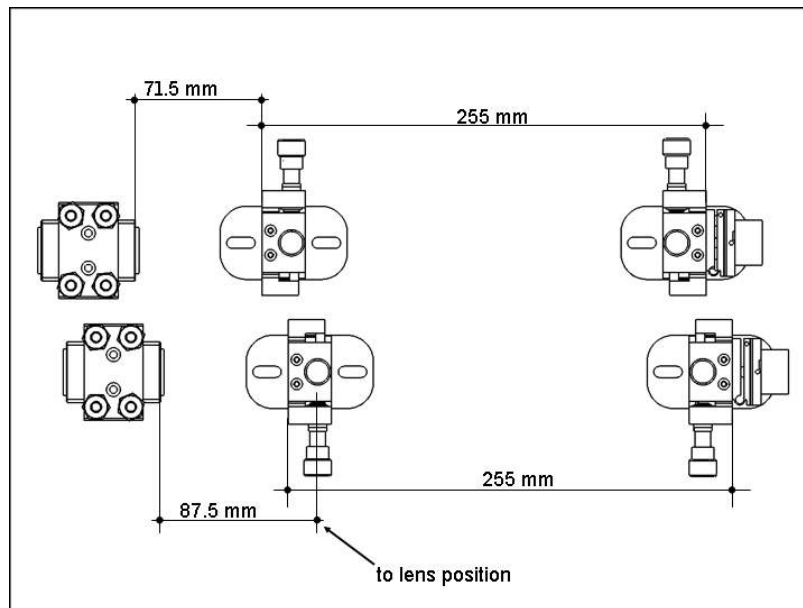
Figure 10.8: Use the self-made diffuser plate to bring the crystals to the optical axis of the resonator.

29. Align the second, third, and fourth laser crystal in the same way.
30. Turn the amplifier off (Do not only close the shutter after the NPRO, but turn also the pump diodes off!).
31. Set the pump current of diode box 1 to 8.5 A. Hold a **clean** white viewer card in front of the laser crystal and align the pump light with respect to the aperture of the pump chamber. Move the pump spot by moving the homogenizer, but do not misalign it too much with respect to the fiber bundle. Switch off the diode



box and repeat the procedure with all other laser heads.

32. Remove the iris diaphragm mounts. Insert the 4f be-ri lens mounts in between the laser heads. The distance of the lens on the left hand side is meant to be 87.5 mm from the crystal as shown in Fig. 32. This value is barely measurable at all, so move the mount with its flat side to a distance of 53.2 mm in respect to the ASE beam block. This length can be measured with caliper. The distance in between the opposing be-ri mounts should be 255 mm as seen in Fig. 32.



33. Insert the quartz rotator into the Siskyou IXF1.0ti mount and fix it with the setscrew. The mirror mount should be set to a neutral position.
34. **Now the resonator is assembled and prealigned.**

#### 10.4.1 Multi-mode resonator alignment

1. Take out the 4f lenses if they are still installed.
2. Start the oscillator with a pump power of  $\approx 150$  W per laser head.
3. The laser should start emitting light from scratch. If there is no light at the output of the laser (this can be checked either with a white or a orange viewer card) tip or tilt the OC mirror a little bit watching the card. If there is still no light coming out of the oscillator go back to 20.

4. Align the output coupler mirror and the dichroic bending mirror MR5 to maximize the output power. The achievable output power level is roughly about 60W without Brewster plate inside the resonator. If the Brewster plate is still in, the power level decreases to approx. 40 W. The beam profile should look substantially symmetric (not necessarily circular symmetric) monitored on a CCD camera at the end of the alignment.

#### 10.4.2 Operation point alignment

1. Close the resonator internal shutter and install the set of 4f lenses between pump heads 3 and 4. Turn the pump light off, open the shutter and turn the diodes on again. The pump power per head should be set to the nominal operation point (250 W). Align the lower 4f lenses to maximum output power. In case that the laser does not emit any light put one of the lenses approximately to a mid position. Shift the second lens to upper position and "scan" from one side to the other. Push the lens a little lower and scan back. Repeat, until the laser starts to emit light. Then start to align both lenses. Since the oscillator is not very stable in this configuration, just a few Watts (10W-40W) will be emitted. This is just a prealignment of the lower 4f-optics, do not spend too much time optimizing it.
2. Close the internal shutter again and put in the remaining pair of 4f lenses. Turn at least one diode off, open the shutter and turn it on again. Repeat the procedure as described for the first pair of lenses. Then align all four lenses. We recommend to align them by corresponding pairs. Optimize the oscillator alignment with respect to:
  - The sum of forward and backward emitted output power
  - The equal distribution of forward and backward power
  - The beam profile, monitored with a CCD camera. It should be symmetric. If you can see a doughnut-shaped beam profile the pump power is too high. If you see a longish profile and output powers below 50 W, either the resonator is not well aligned or the pump power is too low.

- Optional: The power, which is reflected at the Brewster plate. This can only be done, when the Brewster plate was already installed. See 4 for more details.
3. Align carefully the homogenizer holders and the fiber bundle holders to maximize the performance. Then alternately align the pump light and the 4f lenses.
  4. Close the low power shutter and mount the Brewster plate at it's designated position. Assure, that the angle of incidence is set to  $56^\circ$ . The mark on top of the mount points in direction of propagation. The height has to be adjusted so that the beam can pass centered through the plate. Open the shutter. Since the substrate changes the beam path, you need to realign the set of output coupler and the dichroic  $45^\circ$ -mirror next to laser head 4 (MR5). The Brewster plate mount has got two outputs for the reflected beam at the glass substrate. Rotate and move the mount up and down until you can see both beams coming out of the top holes. You can also use the included photo diodes for power optimization. After alignment, double check the position of the output coupler and the dichroic mirror MR5 (see section 2).

## 10.5 Mode-matching between amplifier and oscillator

This is needed to be realigned, if something at the general setup of one of the systems has been changed (for example change of the position of one of the systems, change of position or size of the beam waists, etc.)

- Put a CCD camera at a position outside the oscillator, and measure the beam profile. Measure the caustic of both, oscillator and amplifier and calculate position and type of the mode-matching lenses. Make sure that they can be placed on the provided rail.
- Let just the oscillator run in free-running mode. Memorize the position and size of the beam at the CCD camera (use crosshairs).
- Close the low power shutter and turn the amplifier on. Make sure that the

beam position and size matches the previously measured oscillator beam at the camera position. Shift the mode-matching lenses, if required.

- Close the NPRO shutter and open the internal shutter (proceed as described in chapter 7.1!) The high power oscillator should now run in one unidirectional, since the MOPA diodes are still on. Open the NPRO shutter. Error signals will be available from the locking electronics (chapter 7.3). Optimize the beam profile and the height and shape of the error signals by aligning the mirror set M3 and M4.

**Hints:**

- Do not try to get as much output power as possible in this step, since you will get the most output power, if the amplifier beam is slightly misaligned!
- Do not use too much pump power for the oscillator. A small peak in front of the sidebands in the error signals indicate that the Nd:YAG crystals are pumped little too hard.
- Keep a look on both, error signals and beam profile.

# 11 Never...

We tried to prevent the laser from being damaged due to technical or human failure, but there are still some points one should keep in mind when running the system. In the following sections we tried to describe some situations, in which laser damages might occur if one does not follow the described steps. Most likely the list is not complete since we have not considered all possibilities to destroy the laser system.

## 11.1 ...open the internal shutter, when all laserheads are pumped

Opening the internal shutter while the laserheads are optically pumped may produce a Q-switch pulse inside the resonator, which can cause spots on the optics (especially the crystals). Read section 7.1 on how to proceed, if you want to open the low power shutter.

## 11.2 ...start the oscillator, when the frontend is already running

Always start the oscillator first or close the shutter between NPRO and amplifier. If the oscillator does not turn on, this might indicate that the long range actuator is not set to it's decent position. If the shutter between NPRO and amplifier would stay open in this state, the PZT mirror and / or crystal 3 might become badly damaged.

### 11.3 ...put non-optical components into the 200 W beam

This includes viewer cards and viewer ceramics as well as any kind of paper, wood, fingers (or any other part of your body) and other materials. Due to the high power these materials will either start to burn or at least produce some dust, which settles down on external and internal optics. Metal parts which can stand the high power might cause reflections in unwanted directions or heat up. Always use an attenuated beam to pre-align the optics behind the laser (since the beam is linearly polarized, attenuation is pretty easy by using a polarization optic, for example).

### 11.4 ...inconsiderately move the LRA actuator

It is possible and sometimes necessary to move the DC stage during operation (see section 7.2) – but this is also a way of destroying components: If the amplifier beam is seeded to the oscillator, this works as an amplifier, even if the resonator is not well aligned. The seed beam reaches the mirror at the DC stage after passing through two Nd:YAG crystals. It can be amplified to a power of more than 70 W at this position. Movement of the long range actuator at this state will misalign the resonator, which means that it is possible to bring the amplified seed beam to really undesirable positions, which may cause damage at the pump chambers or the crystals.

### 11.5 ...interchange the water hoses for inlet and outlet

The water pressures and flows are well chosen and set in advance and flow regulators are put into the water circuits. Never remove these flow regulators or interchange inlet and outlet. The pressure would be too high for the hoses inside the oscillator and amplifier box, respectively. Also ensure that each hose is connected to the circuit where it belongs to. Too low water flows might cause trouble, too.

## 11.6 ...Let the cooling water stand inside the system, if the system is not used for a long period

Cooling of all components inside the laserhead is done via water in order to bring the heat out of the Laser Area Enclosure (LAE). Although almost all water cooled parts are coated with non-corroding materials, some corrosion might occur - probably at commercially available parts as powermeters etc. Therefore, small particles from electro-chemical processes and mechanical friction might be present inside the water circuit. If there is no water flowing through the system for time periods on a month scale, these particles will accumulate in the relatively narrow water channels and hoses. On a long term scale, this would lead to a complete blockage of the system. As an example, the effect of water standing inside the system for about two years on the fiber bundle mount is shown in figure 11.1.



Figure 11.1: Effect of standing water in the water cooled fiber bundle mount. Left: new part, right: effected part.

Therefore, drain the system, if not used for more than a month, unless the chillers are constantly running and therefore flush the system.

## 12 Troubleshooting

What happened ?	Please check	See chapter
Laser turned off	Watchdog	7.5
	Shutters	7.1
Injection locking does not work	Amplifier running ?	
	Oscillator running and low power shutter open ?	
	Error signals / DC signal at PD lock	7.3
	Reference level	7.3
	Phase of the Injection Locking EOM inside the Amplifier box	7.3
Single relocks occur in irregular time intervals	laser environment (temperature/humidity stability)	
	Long range actuator	7.2, 8
Long range actuator out of range / does not move	press LRA reset on the back of the control box, afterwards press "home" in the LRA menu, then press "ref point". Follow the start procedure again.	



What happened ?	Please check	See chapter
System tries to lock, but this works just for a very short moment although all signals look fine	Local oscillator: Try to turn the phase of the local oscillator by 180° to get a mirrored error signal.	7.3
System locks, but the piezo makes a strong creaky noise and the PZT signal at the oscilloscope oscillates	Reduce the gain	7.3, 8
System does not lock although the error signals are visible on the oscilloscope	Increase the gain; increase or decrease the offset; increase or decrease the reference level	7.3
Beam quality gets worse	Pump light	8, 7.6.1
	Spots on external optical components	
	Back reflections / interferences	
	Spots on internal optical components	<b>contact manufacturer</b>
Output power decreases over several days	Pump light	8, 7.6.1
	Properties of freerunning oscillator (without amplifier)	7.6
	Amplifier properties	
		<b>contact manufacturer</b>
System cannot be started	System status: eliminate the shown errors	8.7

What happened ?	Please check	See chapter
	key position at the control box: switch off the maintenance mode	