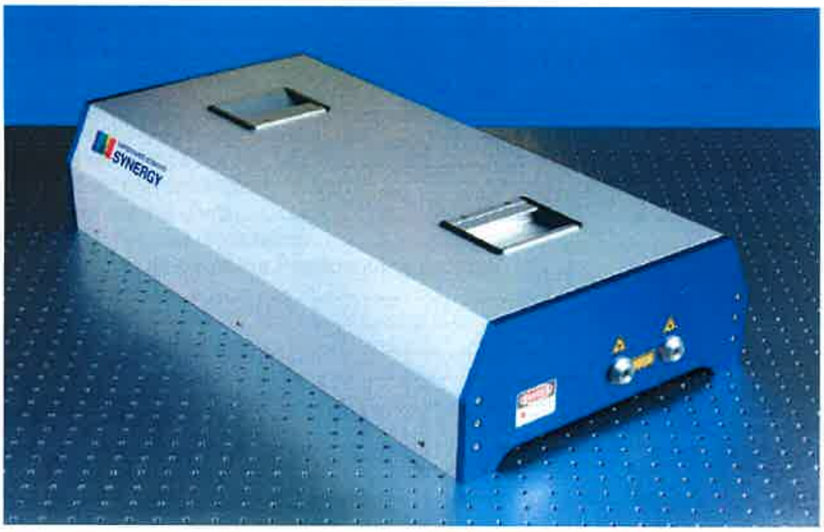
User's manual for

Mirror-dispersion-controlled Ti:Sapphire Oscillator

FEMTOSOURCE

Synergy



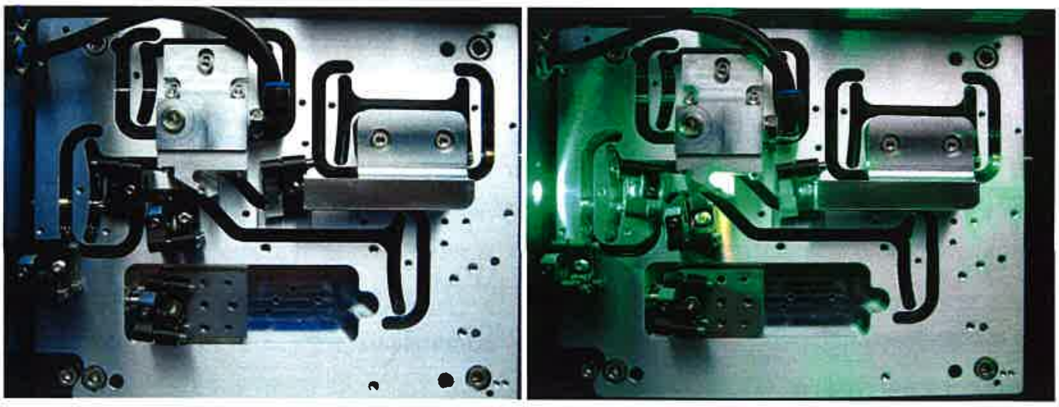
FEMTO LASERS
FEMTOLASERS Produktions GmbH

Fernkorngasse 10 • 1100 Vienna • Austria • Europe
phone: +43 1 503 70 02 0, fax: +43 1 503 70 02 99
email: office@femtolasers.com
web: www.femtolasers.com

1. Table of Contents

1. Table of Contents 2
2. Preface 3
3. Unpacking and Inspection 4
   3.1. Unpacking Your Oscillator 4
   3.2. System components 4
4. Laser Safety 5
   4.1. Precautions for the safe operation 5
5. Installation of CLH-4 7
   5.1. Preparations 7
   5.2. Water cooling 7
   5.3. Pump source 7
      Mode of the pump beam 7
      Polarization of the pump-beam 7
   5.4. Setting up the MDC oscillator 8
      Alignment of the pump-beam into the oscillator 8
      Fig.Schematic Layout of Synergy Oscillator 9
      Alignment of the resonator beam 10
6. Maintenance 12
   6.1. The CLH4 12
   6.2. The optical components 12
      Cleaning of the mirrors 12
      Cleaning of the crystal 12
6. System specifications and requirements 13
   6.1. Important notice: 13
7. Ultrashort pulses from the synergy - laboratory tests 14
   7.1. Self mode locking 14
      Initiating mode locking 14
      Steady-state performance 14
   7.2. Extracavity chirp compensation: 15
      Compensation of spatial chirp 15
      Compensation of material dispersion 15
8. Quick reference for the setup of the Femtosource synergy 16
9. Daily Operation 18
10. Appendix 20
   10.1. List of qualified pump lasers 20
   10.2. Synergy Oscillator 20
11. References 21

2. Preface



Chirped multi-layer dielectric mirrors® [1] have revolutionized ultra-short pulse generation at the cutting edge of optical time resolution. The mirror-dispersion-control (MDC) set comprises specifically designed chirped mirrors for broadband intra-cavity group-delay-dispersion (GDD)-control in a Ti:Sapphire oscillator and low-dispersion quarter-wave mirrors for coupling the pump beam into and the mode-locked pulse out of the resonator. The MDC-set in combination with a thin highly-doped Ti:Sapphire crystal, which is mounted in the CLH laser head, offers the potential for the generation of optical pulses with unprecedented quality, stability and reproducibility. This potential can be exploited with a number of mode locking mechanisms, such as saturable absorber mode locking, additive-pulse mode locking or self mode locking. Using the MDC technology, 8-fs optical pulses have recently been generated from a self-mode-locked Ti:Sapphire oscillator [2]. This manual provides guidelines for the installation of a mirror-dispersion-controlled Ti-sapphire oscillator using the MDC-set and the CLH laser-head.
Laboratory tests prior to delivery yielded highly stable sub-20fs / sub-12-fs pulse generation by self mode locking the MDC oscillator (see enclosed test results).

® US patent # 5,734,503, other patents pending

3. Unpacking and Inspection

3.1. Unpacking Your Oscillator

Your FEMTOSOURCE oscillator was packed with great care, and its container was inspected prior to shipment. It left FEMTOLASERS in good conditions. Upon receiving the system, immediately inspect the outside of the shipping container. If there is any major damage, insist that a representative of the carrier be present when you unpack the contents. If any damage is evident, such as dents or scratches on the covers or broken knobs, immediately notify the carrier and your FEMTOLASERS representative.
Keep the shipping container. If you file a damage claim, you may need it to demonstrate that damage occurs as a result of shipping. If you need to return the system for service, the container assures adequate protection.

3.2. System components

Set of carefully selected ultra-broad-band dispersive coupling optics and a specifically optimized CLH (compact laser head) for the generation of nearly bandwidth limited optical pulses of sub-20 / sub-10 fs in duration, directly from the MDC oscillator. The system comprises the following items already mounted in a thermally stabilized housing:

- A central mechanical unit - the Compact Laser Head (CLH) - which contains the most delicate components such as the highly doped Ti:S crystal, the dichroic dispersive focusing mirrors for the resonator beam, the focusing lens for the pump beam and the short arm with the end mirror on a. The CLH laser head will be assembled and aligned prior to delivery which allows you to set up the oscillator within a short time.
- Optics and opto-mechanical components for setting up the complete femtosecond oscillator.
- A periscope arrangement including steering optics and precision mirror mounts for coupling the pump beam into the oscillator.
- Extra-cavity dispersion control (optionally).

4. Laser Safety

Note: ***The FEMTOSOURCE synergy oscillators are Class IV - High Power Lasers. The dangers associated with the light they generate must be taken very seriously. Take precautions to prevent accidental exposure to both direct and reflected beams. A split second exposure to even a small portion of a reflected laser beam is sufficient to cause permanent loss of vision. The safe use of the lasers requires that all laser users, and everyone near the laser system, are aware of the dangers involved.***

4.1. Precautions for the safe operation

The following is a partial list of precautions to follow when operating or using the FEMTOSOURCE synergy. This list is not intended to and can by no means replace a comprehensive laser training course.

The oscillators and amplifiers from FEMTOLASERS and their pump lasers are Class IV - High Power Lasers. The dangers associated with the light they generate must be taken very seriously. Take precautions to prevent accidental exposure to both direct and reflected beams. A split second exposure to even a small portion of a reflected laser beam is sufficient to cause permanent loss of vision. The safe use of the lasers requires that all laser users, and everyone near the laser system, are aware of the dangers involved.

- Safety goggles: protective goggles must be worn every time. The selection depends on the wavelength (650-950nm) and the intensity of radiation, the conditions of use, and the visual function required.
- Output beam: never look directly into the laser light source or at scattered laser light from any reflective surface. Avoid direct exposure to the laser light in any case. The intensity of the beam can easily cause flesh burns or ignite clothing.
- Warning signs: post prominent warning signs and lamps in the area of the laser beam.
- Safety area: operate the laser in a room with controlled and restricted access. Limit the access to those trained in the principles of laser safety.
- Maintain a high ambient light level in the laser operating area.
- Be careful setting up your experiments:
- Use protective enclosures for all portions of the beam where access is not necessary.
- Set up beam dump(s) to capture the laser beam(s).
- Set up shields to prevent unnecessary specular reflections.
- Avoid direct exposure to the laser light. The laser beam is powerful enough to burn skin or clothing.

- Shutter: close the shutter when leaving the laser area. Also block the beam when placing new components in the beam path.
- Accidental reflections: watches must be taken off before any alignment. The same holds for other clothing or jewelry that could deflect a beam to eye level.
- Exercise extreme caution when using reflecting tools (such as screwdrivers, rulers, a.s.o.) in vicinity of the beam.
- Beam height: use a set up where the laser beam is either above or below the eye level.
- Enclosures: provide enclosures for the beam paths whenever possible.
- Shields: set up shields to prevent any unnecessary reflections.
- Information: advise all those using the oscillator of these precautions.
- Use of controls or adjustments or performance of procedures other than those specified in the manual may result in hazardous radiation exposure.
- Use of the system in a manner other than that described herein may impair the protection provided by the system.

Follow the instructions contained in this manual to ensure proper installation and safe operation of your laser.

5. Installation of CLH-4

5.1. Preparations

1. Put the whole housing on the optical table to the desired place and fix it with 4 screws.
2. Remove 2 stoppers from the water connectors.
3. Plug in a cooling tube (FESTO PUN tube with an inner diameter of 4mm/outer diameter 6mm) and connect it to a water cycling.

Note: The chiller pressure must not exceed 20 psi / 1.35 bar to avoid leakage of the base plate, otherwise warranty will be void.

4. Put the pumplaser in place (fixed by two pins) and fasten the holding forks.

5.2. Water cooling

The *water-cooling* removes the heat from the Ti:S crystal. It stabilizes the temperature. Water-temperature should be set between 18 – 20 °C (> ambient dew point and < 25°C) Flow should be kept constant to guarantee a high long term stability of the system. The heat removing assembly is equipped with connections for water cooling which fit to the chiller of the pump source.

5.3. Pump source

Mode of the pump beam

The mode has to be fundamental mode (TEM00) from a DPSS green (532 nm) pump laser. Please refer to the list of qualified pump lasers in the appendix. For optimum mode locked operation the pump power should be in the specified range, and should ***never exceed 10 W***.

Polarization of the pump-beam

Usually the output beam of a DPSS laser is vertically polarized (σ-polarization, SP). The CLH requires a horizontally polarized pump-beam (π-polarization, PP). Using the periscope for polarization rotation the polarization can be rotated and also the beam-height can be adjusted.

5.4. Setting up the MDC oscillator

Note: the pump power should never exceed 200mW during the first alignment!

Alignment of the pump-beam into the oscillator

The pump laser position is set at the factory to deliver an output beam parallel to the optical table (input of the polarization rotating periscope PER).The output beam of the periscope PER has to be aligned parallel to the optical by rotating the periscope around the vertical axis. After passing the steering mirrors the pump beam again has to be aligned parallel to the optical and pass through the center of the lens holder at the CLH (see Fig. 1).

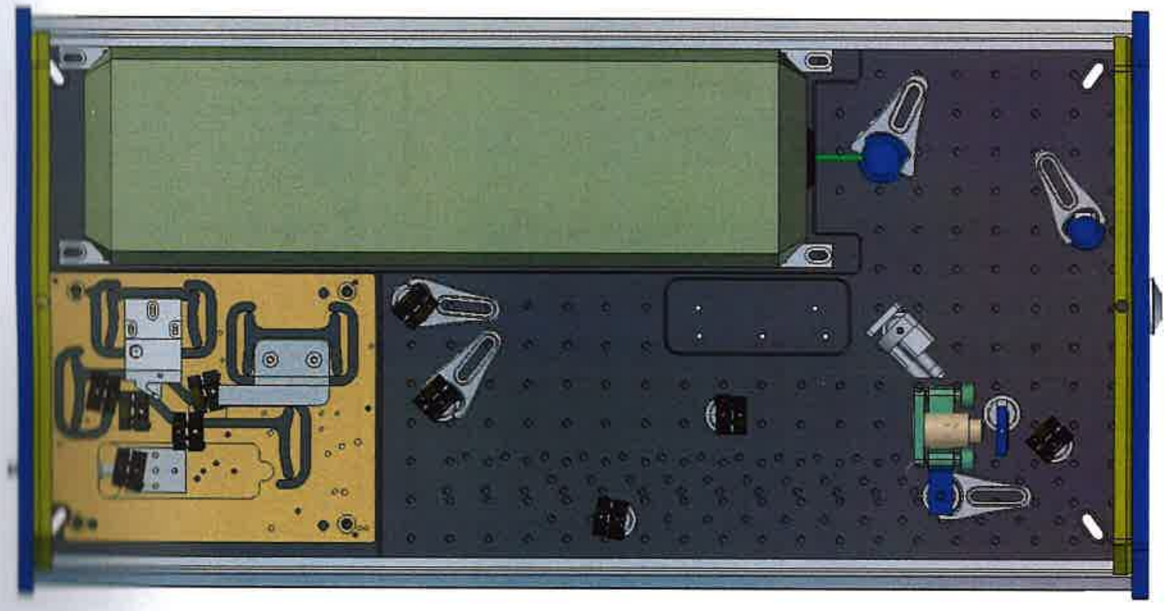


Fig. 1 Mechanical Layout of Synergy Oscillator.

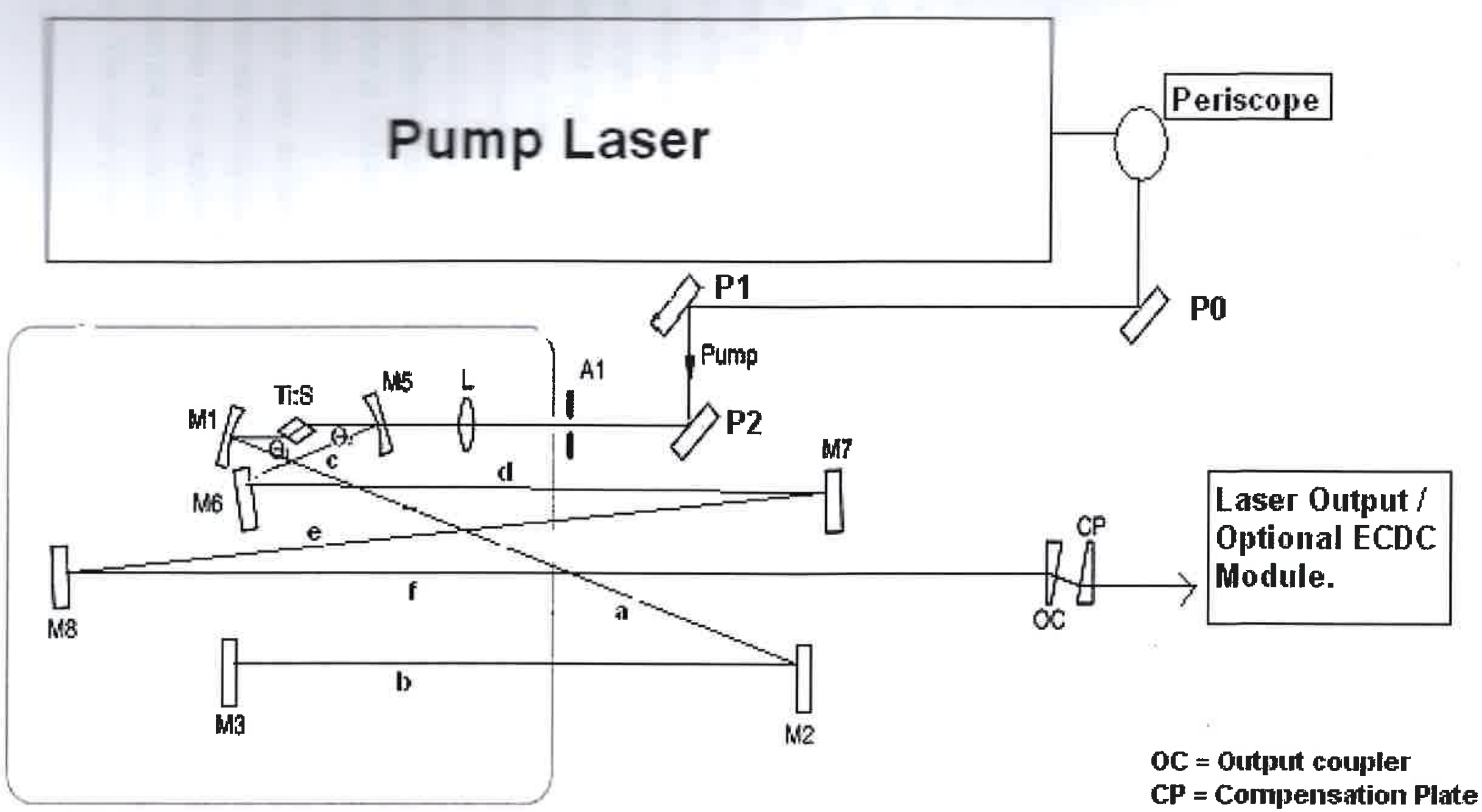


Fig:Schematic Layout of Synergy Oscillator.

The alignment can be done by the pump beam steering mirrors. The transmitted pump-beam on the backside of the housing must not show rings, it should be a clear circle (Fig. 2)

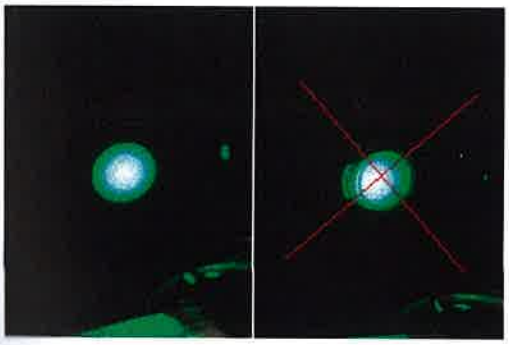


Fig. 2 Transmitted pump beam at the backside of the housing

Alignment of the resonator beam

Once the output beam from the pump-laser is coupled through the lens into the CLH, it can be used to define the resonator axis for a rough alignment of the cavity. This crystal transmits some 30% of the incident pump laser radiation. The transmitted pump beam must not show rings, but it should show a clear circle. Both cavity arms are pre-aligned, and the long cavity arm can be aligned using amplified spontaneous emission (ASE) from the Ti:S crystal or the transmitted green light from the pump laser. The output coupler (OC) can be aligned by reflecting back the ASE beam collinearly into the gain medium. Make sure that the mirrors M6 and M7 are hit once reflections on each mirror. This is only possible with a small angle. Next, the ASE signal transmitted through the OC should be detected with a large area Si-photodetector. The detector signal should then be maximized by fine alignment of the end mirror OC and if necessary the end mirror of the short cavity arm (open the access arrows at the back side of the laser head), of the stability range, as well as the crystal and the focusing lens, in an iterative way. This procedure should rapidly give rise to laser oscillation if the optics are clean and the pump power is of the order of 4-5 W. Once cw oscillation is realized, the output power can be maximized by following the same iterative approach.

With the laser oscillation one can trace out the *stability range,* the range of distances between the two curved focussing mirrors, for which the cavity is stable, i.e. laser oscillation is possible. It is expedient to introduce the parameters δ=d-2f, where d is the optical distance between the two curved focussing mirrors and f stands for the focal length of the focusing mirror. The range of values of δ for which laser oscillation is achievable is illustrated in Fig. 3.

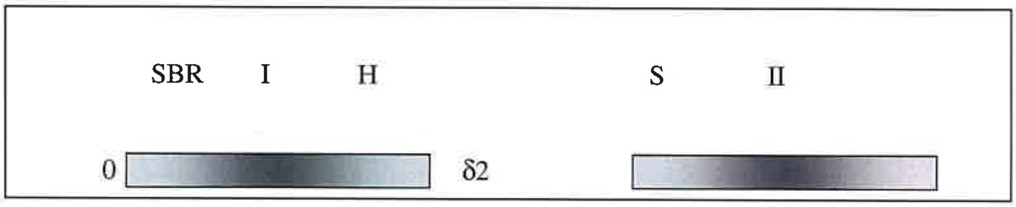


Fig. 3 Stability range of the x-cavity

Fig. 3 reveals that the stability range of our cavity consists of two discrete regions with a gap in between. For more details on tightly-focused 4-mirror cavities one should refer to Ref. 3.

Note: Make sure that the reflections on the mirrors M6, M7 (long cavity arm) are well placed on the mirror´s surface. Each visible reflection must be clearly apart from the edge of the mirror! No beam passing by may touch their edges!

6. Maintenance

6.1. The CLH4

There are three micrometer screws which are reachable from outside. They can be used to optimize lasing operation and to get mode-locking, i.e. they adjust

- the position of the crystal position,
- the lens position, and
- the stability range.

For fine alignment it is possible to adjust the end mirror inside the CLH4 for achieving better overlap between pump-beam and intracavity-beam as well as the OC. But if everything is aligned properly it will be only necessary to make very gentle adjustments.
The lens must not be adjusted.

6.2. The optical components

Cleaning of the mirrors

The output coupler can be cleaned like standard dielectric mirrors using acetone or methanol. Only if it is necessary the dispersive mirrors should be cleaned very gently because the upper layer of these mirrors is unusually thin. Dipping the mirrors into acetone bath should be avoided.

Cleaning of the crystal

The crystal is accessible from both sides. It can be cleaned in the same way like the chirped mirrors using q-tips and acetone or methanol.

6. System specifications and requirements

FEMTOSOURCE synergy	synPRO	syn20
Pulse duration	< 10 fs	< 20 fs
Spectral width	> 100 nm	> 40 nm
Output power (average)	> 400 mW	> 400 mW
Output energy @ 75 MHz	> 4 nJ	> 4 nJ
Pump beam diameter	2 mm ($1/e^2$), TEM_{00}	2 mm ($1/e^2$), TEM_{00}
Pump power @ 532nm	5 W	5 W
Cooling water	18-22°C, 10 W	18-22°C, 10 W
Size	728 x 378 mm	728 x 378 mm

6.1. Important notice:

It should be stressed that pulses in the 10 fs region are extremely "fragile" and can be significantly distorted (broadened) by even small amounts of dispersion in standard optical components. Hence, extreme care has to be taken, when steering the pulse external to the cavity and measuring it in an autocorrelator. Our autocorrelator and steering optics have been designed to meet the high requirements for high-fidelity pulse width measurements in the 10-fs range. Precise compliance with our guidelines for setting up and optimizing the sub-20 / sub-10-fs MDC system guarantees a reproduction of the results demonstrated previously in our laboratory *only* if our state-of-the-art steering and autocorrelator optics is used for pulse-width measurements (FEMTOMETER).

7. Ultrashort pulses from the synergy - laboratory tests

The quality of intra-cavity dispersion control is crucial for the generation of high-quality optical pulses in the sub-20-fs / sub-10-fs range, regardless of the mode-locking technique used. The chirped mirrors employed in the MDC Ti:S oscillator provide nearly constant GDD over bandwidths as broad as 80 THz, which is substantially higher than demonstrated with any other low-loss dispersion compensating technique previously.
In order to test the capability of the MDC Ti:S oscillator to generate high-quality optical pulses in the sub-20-fs / sub-12-fs range, the oscillator was mode locked via self mode locking prior to delivery.

7.1. Self mode locking

For optimum self-mode-locked operation, the length of the tightly-focused cavity arm was adjusted close to the shorter end of the II. stability region in Fig. 4 of the MDC-manual, at position „S".

Initiating mode locking

A small perturbation of the cavity length was introduced by shifting mirror M4 mounted on a translation stage towards OC and releasing it afterwards. If the oscillator was optimized the moving mirror M4 introduced enough cavity perturbation for starting mode locking.
If the oscillator was optimized, mode locking is started in the center of the stability range. Moving the adjustment screw for the stability range clockwise increases the spectral width.

***Note:** mode locking has started when the spectrum becomes brighter and the speckles disappear!*

Steady-state performance

After getting mode locking started, we optimized the position of the curved mirror M1 and the position of the gain medium along the resonator beam, until a stable pulse train was observed on the oscilloscope. The output of the laser was monitored with a fast (1 ns-response time) photodiode. The spectrum and the pulse duration of the self-mode-locked MDC Ti:S oscillator were measured with a standard spectrometer and a specifically-designed broad-band low-dispersion collinear autocorrelator. The results are shown in the appendix. The broad > 30 nm spectrum is nearly symmetric, indicating the absence of significant high-order dispersion in the cavity. Such a broad *symmetric* mode-locked spectrum centered at the peak of the Ti:S gain curve could not be achieved from any prism-controlled Ti:S lasers to date. The well-behave spectrum implies a pulse quality that can not be realized with any other laser in this domain. The clear visibility of the fringes in the wings of the interferometric autocorrelation provide clear evidence for the nearly transform-limited nature of the generated pulse.

7.2. Extracavity chirp compensation:

Compensation of spatial chirp

The output-coupler is wedged (10°) to prevent unwanted reflections from the rear side of the substrate. Additionally the rear side is also AR-coated. The *spatial chirp* (angular dispersion) introduced by the wedged plate has to be compensated by a compensating plate (CP) which is mounted as close as possible to the OC.

Compensation of material dispersion

Material dispersion is introduced by the OC, the CP and the beam splitter of the autocorrelator. To compensate for this positive dispersion the extracavity mirror pair M9 and M10 is introduced. For compensating the substrate of the OC, the CP and 1 mm fused silica at 45° (BS of the autocorrelator) 4 - 6 reflections of the extracavity mirror pair are required.

8. Quick reference for the setup of the Femtosource synergy Oscillator.

<u>Aligning Pump laser</u>

1. Set pump power to 200 mW.
2. Set output beam horizontally to height of the pump lens.
3. Set output beam parallel to the hole line, lock the pump laser.

<u>Aligning Periscope PER</u>

1. Set pump power to 200 mW.
2. Center Periscope horizontally.
3. Rotate periscope to achieve correct beam height at the steering mirror.

Test: Set pump power to 1 W and measure before and after the periscope. Power should be equal.

<u>Aligning Steering Mirror P0, P1</u>

1. Set pump power to 200 mW.
2. Direct beam horizontally.
3. Direct beam parallel to the hole line.

Test: Check in a distance of > 1m (3").

<u>Aligning Steering Mirror P2</u>

1. Set pump power to 200 mW.
2. Center beam on lens holder.
3. Walk beam with P1, P2, until a clear circle of the transmitted beam is seen.

Test: Check if beam still passes the center of the lens holder.

<u>Aligning Short Arm (Ti:S - M1 - M2 - M3)</u>

DONOT DISTURB THE ALIGNMENT OF MIRROR M1

<u>Alligning Cavity Mirror M2</u>

1. Set pump power to 5 W.
2. Align M2. Reflected fluorescence beam from M2 has to hit M3.

<u>Alligning Cavity Mirror M3</u>

1. Retro-reflect the beam from M3 back onto M2 and M1.

Aligning Long Arm(Ti:S – M5 – M6 – M7 – M8 – OC)

DONOT DISTURB THE ALIGNMENT OF MIRROR M5

Alligning Cavity Mirror M6

1. Set pump power to 5 W.
2. Reflected fluorescence beam from M6 has to hit M7.
3. Align M6, thus fluorescence pattern is located at the right mirror edge on mirror M7.

Alligning Cavity Mirror M7

1. Reflected fluorescence beam from M7 has to hit M8.
2. Set M7 thus that the center of the fluorescence beam is located at the right edge of the mirror on M8.

Alligning Cavity Mirror M7

1. Reflected fluorescence beam from M8 has to hit Output Coupler (OC).

Aligning Output Coupler OC

1. Reflect the beam from the OC back onto M7 and M6.

Install a large area Si-photo-diode and optimize the fluorescence signal.
By iteratively adjusting OC and end-mirror of the short cavity arm M3, to maximize the fluorescence signal, lasing is achieved. Install a power meter and maximize the CW power by aligning OC and M3. Also, adjust stability range and crystal position to optimize cw-power. Once the CW power is approximately same as the value specified in the test sheet, rotate the stability micrometer clockwise, while continuously pushing and releasing the Modelocking starter button. The procedure should result in modelocking.
Check the spectrum of the oscillator. If there is a CW spike on the modelocked spectrum, rotate the stability mirror CW direction to completely remove the CW spike.

9. Daily Operation

This Chapter describes how to *turn on* and *turn off* the Synergy oscillator, and how to optimize the daily laser performance.

Turn ON Procedure

It is assumed that the Synergy Oscillator is installed by Femto Lasers Personnel, and the alignment is undisturbed.

1. Make sure that the water is flowing through the Ti:sa crystal and the base plate of the Synergy Oscillator.
2. Turn on the pump laser in accordance with the pump laser manual.
3. Allow the system to warm-up. (warm-up time depends on the lab conditions. If the temperature inside the lab is well controlled, 15min warm-up is good enough)
4. Push the mode locking starter button to Modelock.
5. If the laser doesnot modelock, perform the procedure "*Optimizing the Synergy Oscillator*" described in next section.
6. Measure the laser power and record it in the log book.

Turn OFF Procedure

1. Turn off the pump laser in accordance with the pump laser manual.
2. Turn off all the electronic controllers of the Synergy Oscillator.

Optimizing the Synergy Oscillator

Make sure that the pump laser is running at the power level specified in the test sheet.

1. Install a power meter at the output of the oscillator.
2. Turn the stability range micrometer Counter Clockwise direction to go to CW position.
3. Check the max CW power and compare it with the test sheet value.
4. Align the two pico-motors of the pump steering mirror, PR using the pico-controller, to maximize the CW power.
5. If the power is still too low, then open the top cover of the Synergy oscillator and observe if the optics are dirty. If required clean the optics.

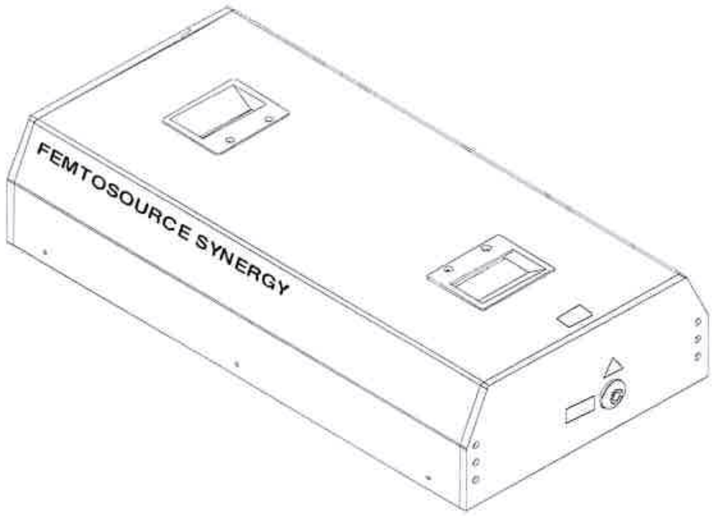
6. Optimize the OC mirror and end mirror, M3 iteratively to increase the CW power.
7. Once the CW power is approximately same as the value specified in the test sheet, rotate the stability micrometer clockwise, while continuously pushing and releasing the Modelocking starter button. The procedure should result in modelocking.
8. Check the spectrum of the oscillator.
9. If there is a CW spike on the modelocked spectrum, rotate the stability mirror CW direction to completely remove the CW spike.
10. Close the top cover of the Synergy Oscillator.

10. Appendix

10.1. List of qualified pump lasers

Spectra Physics Millennia (small type incl. chiller)
Coherent Verdi (all types incl. chiller, no chill plate required)

10.2. Synergy Oscillator



11. References

[1] R. Szipöcs, K. Ferencz, Ch. Spielmann and F. Krausz, "Chirped multilayer coatings for broadband dispersion control in femtosecond lasers" **OL-19**, p.201, (1994)

[2] A. Stingl, M. Lenzner, Ch. Spielmann, R. Szipöcs and F. Krausz, "Sub-10-fs mirror-dispersion-controlled laser", **OL-20**, p.602, (1995)

[3] C. Spielmann, P.F. Curley, T. Brabec and F. Krausz "Ultrabroadband femtosecond lasers" **QE-30**, p.1100, (1994)

[4] H.W. Kogelnik, E.P. Ippen, A. Dienes, C.V. Shank "Astigmatically compensated cavities for CW dye Lasers", **QE-8**, p.373, (1972)