Temperature controlled fiber segment for delay-variation compensation of a long link

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Abstract

This report summarizes my work during DESY's Summer Student Program 2015 at the CFEL in the Ultrafast Optics and X-rays Division supervised by Aram Kalaydzhyan and Johann Derksen.

Contents

1 Introduction

X-ray Free Electron Lasers (FEL) as bright sources of next generation of X-ray facilities represent a useful tool for probing ultrafast processes, which require a precisely timed signal distribution for various components [1].
In X-ray FELs electron bunches are emitted from an electron gun using a photo-cathode laser, compressed by magnets and accelerated to energies in the GeV range via radio frequency cavities. Entering the undulators simultaneously with pulses from a seeding or slicing laser cause an emittance of coherent X-ray photons. Finally, exciting the probe to be observed using an intense laser pulse makes imaging of complex processes within the probe possible.
Figure 1 shows the general layout of an X-ray FEL scheme and its signal distribution. These devices can range from about 300 m length (FLASH in Hamburg, Germany) up to 3 km (SLAC in Stanford, US as well as the actual constructed European XFEL in Schenefeld, Germany). The synchronization of the sub-devices such as the photo-cathode

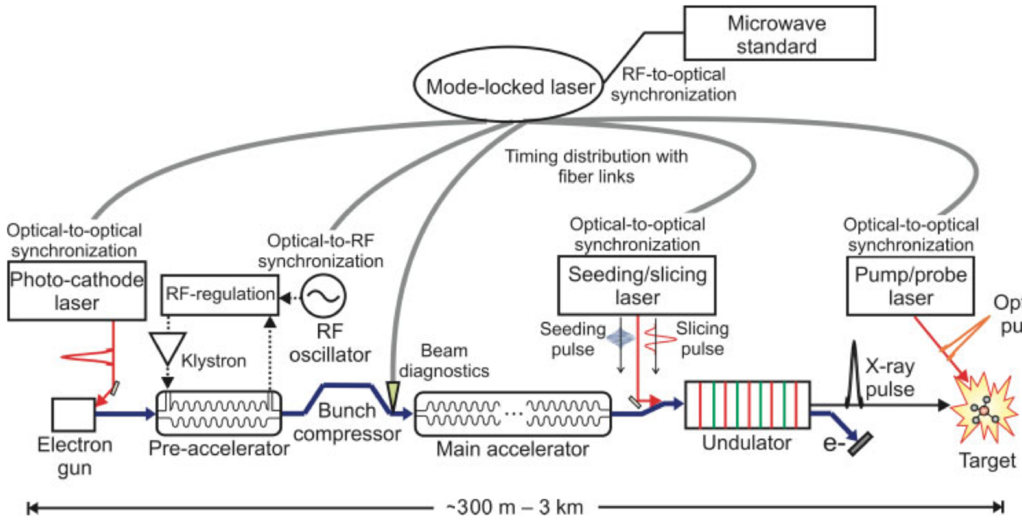

Figure 1: Scheme of an X-ray FEL. Figure adapted from [2].

laser, seeding or slicing laser, and pump or probe laser as well as the RF-regulation is done by optical-to-optical synchronization and optical-to-RF synchronization, respectively. For precisely timed synchronization signals from a mode-locked laser driven by a microwave standard are distributed via fiber to each component.
Any disturbances, e.g. change in temperature, moisture or acoustical noise affect the different fibers and may cause synchronization errors having a negative influence on the running system and on the X-ray experiment.

1.1 Fiber length control

Optical fiber links guide light based on the phenomena of total reflection. Therefore it consist of a cladding having a low refractive index and a core having a high refractive index. The cladding also has the function of stabilizing the fragile inner core commonly composed of silica. The advantage of signal transmission using optical fiber links instead of coaxial cables is a faster transmission velocity and a lower affectivity of disturbances, such as electromagnetic interferences. However, they are sensitive to thermal drifts in the environment so that even during 12 hours operation already timing errors in the range of pico seconds may occur [2]. Therefore, the idea of compensating the thermally induced expansion or contraction of the whole fiber by controlling the length of a certain fiber segment will be followed. The aim is to warm up or cool down a thermal isolated fiber segment, to reduce the delay in signal transmission of the whole signal path due to environmental influences.
For the fiber segment 100 meter of single mode SMF-28 fiber from Corning will be used. It has a cladding diameter of 245 µm and a core diameter of 8.2 µm. The refractive index of the core material is n = 1.4682 for a wavelength of $\lambda = 1550\,\mathrm{nm}$ [3]. The thermal expansion coefficient of the core material is $\alpha = 0.55\frac{\mu\mathrm{m}}{\mathrm{m\,K}}$ [4].
A direct relation between temperature change ΔT and timing delay Δt of the transmitted light pulse can be expressed by equation 1,

$$\Delta t = \frac{\Delta T \cdot \alpha \cdot \mathrm{L} \cdot \mathrm{n}}{\mathrm{c}} \tag{1}$$

where L is the length of fiber, and c represents the speed of light in vacuum. Hence, a change in temperature of e.g. 1 °C causes a fiber expansion of 55 µm what corresponds to a timing delay of about 270 fs. Obviously, the more precise the temperature control can be achieved, the final resolution of compressing the timing error improves.

1.2 Sagnac interferometer

Sagnac interferometers based on temperature controlled fiber links are an effective instrument for detecting small changes in temperature. Due to the fiber's birefringence, the difference in indices of refraction of the fast and the slow axis, any changes in the fiber length cause a phase change and result in a shift of the light spectrum.

In figure 2 the scheme of such an interferometer is depicted. White light is sent into a 50/50 coupler and separated to two outputs where it propagates clockwise and counter clockwise through the thermal isolated fiber segment back into the coupler. Finally, the wavelength dependent intensity is recorded by a spectrometer.

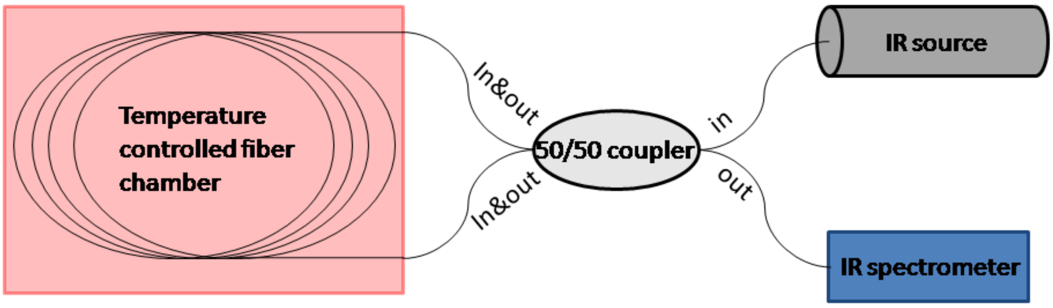

Figure 2: Scheme of the Sagnac interferometer.

Expected results can be seen in figure 3 where (a) shows the spectrum which indicates that a rising temperature causes a shift to smaller wavelengths and (b) illustrates the linear relation between temperature and wavelength focussing on a specific point (the dip) of the spectrum.

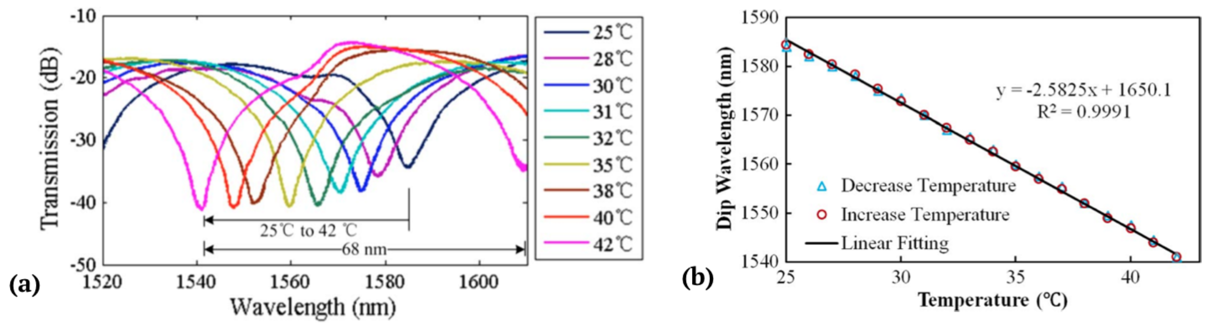

Figure 3: Results of a Sagnac interferometer taken from [5].

Finding a characteristic peak or dip in the spectrum allows to follow the temperature dependent shift of the spectrum. Each change in wavelength gives a direct correlation to the actual temperature drift, what in turn gives a certain length variation followed by a time delay of the transmitted light through the optical fiber link.

2 Experimental setup

In this section the components and their implementation are described. Figure 4 depicts the setup of the prototype with its general components. Basically, white light is fed via fiber into a 50/50 coupler. The two resulting counter-rotating beams propagate each through the 100 m thermal isolated and temperature controlled fiber segment back into the coupler (in&out). From the output of the coupler the light finally terminates in the spectrum analyzer.

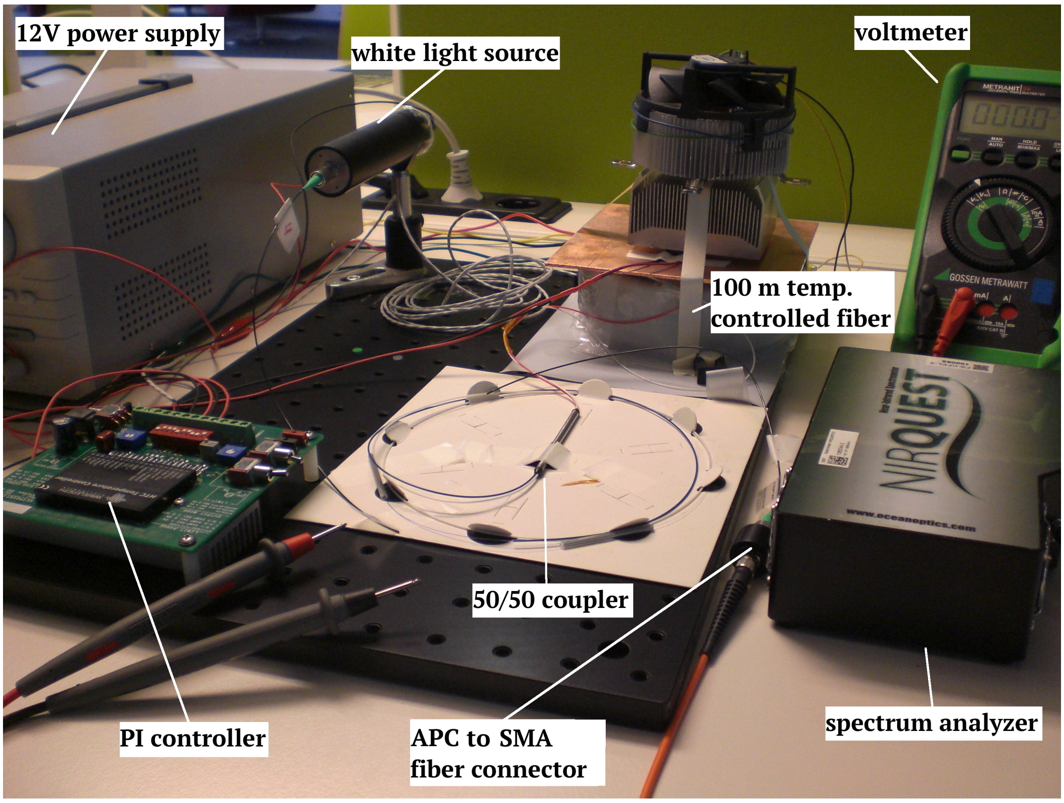

Figure 4: Photograph of the setup.

The white light source consists of a 2 watt bulb attached to two 5 cm long lens tubes (SM1, Thorlabs) with a 250 N-BK7 A coated plano convex lens in-between focussing the light onto the APC fiber adapter (SM1FCA, Thorlabs) into the single-mode fiber (SMF28, Corning).
For recording the spectrum of the light a NIRQuest512 spectrometer is used providing a female SMA input. That restricts the simplicity of the setup due to the APC connection of the SMF-28 single-mode fiber from the coupler's output. Thus it is linked to an APC to SMA fiber adapter connected to a multimode fiber with a male SMA link.

2.1 Temperature controller

For regulating the temperature the HTC4000 temperature controller from Wavelength Electronics is used. It is a PI controlled loop offering various setting of controlling parameters. In principle it provides a sensor input and a thermoelectric cooling (TEC) output. The desired temperature can be either set externally or by means of a potentiometer (grey colored). For monitoring the temperature the printed circuit board provides measuring points by setting a switch to actual or set temperature. Another two potentiometer (blue colored) can be used for adjusting the proportional gain and for limiting the TEC output current. The latter can be chosen to range either from 0 to 1.5 A or from 0 to 3 A. Without any limitation the maximal output is 4 A.

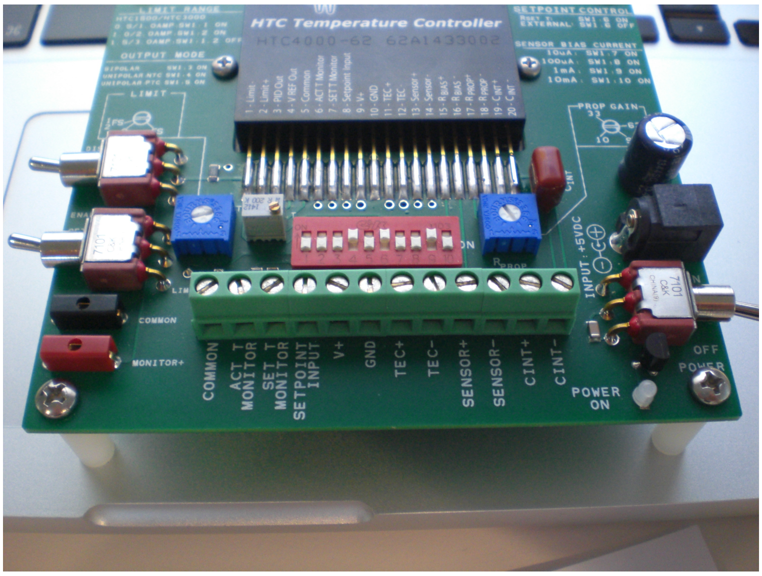

Figure 5: PI Controller.

The red block provides 10 switches offering the user to connect different devices to the evaluation board. In this set up the TEC output current is limited to 0 to 3 A (switch 1 off, 2 on), a bipolar TEC is used (switch 3 on, 4 and 5 off), the desired temperature is set on board (switch 6 on), and a PT100 resistance sensor [6] is connected (switch 7, 8, 9 off and 10 on). The latter application causes a constant bias current for the PT100 of 10 mA. By means of the equation R = U/I any measured voltage representing a certain temperature can be calculated to the corresponding resistance. Based on that, the correlation of voltage and temperature for this set up is determined by equation 2.

$$T(U) = 265.88 \frac{°\mathrm{C}}{\mathrm{V}} \cdot U - 262.39\,°\mathrm{C} \qquad (2)$$

The digital voltmeter used offers a resolution of 1 mV which corresponds to a temperature resolution of about 0.25 °C.

2.2 Temperature controlled optical fiber segment

The fibers's thermal isolated environment consists of a stainless steel bellow mounted on a bread board and surrounded by teflon foil. 100 meter fiber is winded in an outer channel of the bellow. A fan on the inside ensures a constant temperature within the chamber. In an inner channel near the fiber the PT100 sensor is positioned and embedded in thermal paste.
For good thermal conductivity a copper plate is put on the bellow with a layer thermal paste in-between. The peltier element which serves for heating as well as for cooling is located upon the copper plate with a layer thermal paste in-between as well. In case of common polarity the hot side of the peltier element is in contact with the copper plate. The cold side of it is provided with heat sink to ensure a proper heat transfer.

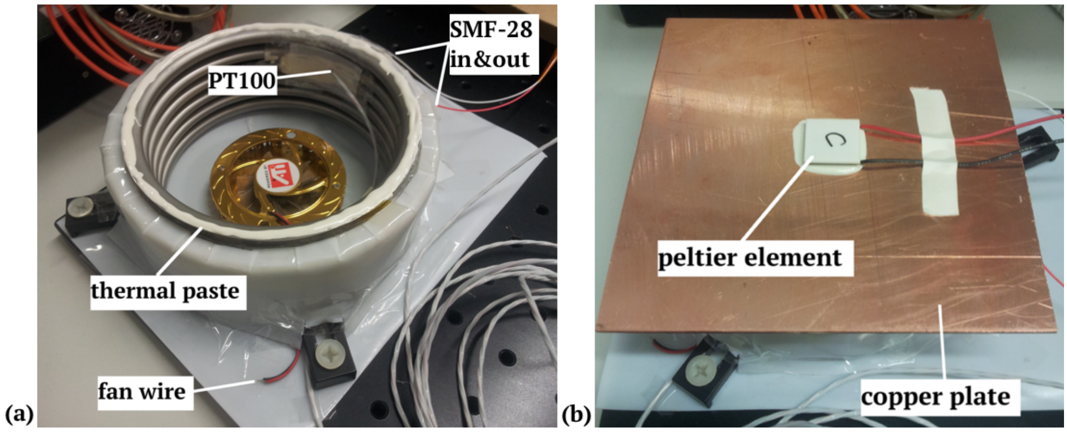

Figure 6: Thermal isolated coil containing 100 m optical fiber. (a) depicts the stainless steel bellow, a PT100 sensor embedded in thermal paste, the fan in the inside and teflon foil. (b) shows the copper plate upon the bellow and the peltier element.

2.3 ZedBoard

For automatic data collection the ZedBoard micro controller is used. An electronic circuit board provided with three NTC resistors is connected to the input. Running a program written on the micro controller sends measurement data depending on automatically adjusted currents and voltages over the resistance sensors to the output where an RS232 connection to a PC is connected as shown in figure 7. Next to the automatic data collection, another great advantage is a much more sensitive temperature resolution due to a much larger change in resistance of the NTC sensors (about 130 Ω/K) in comparison with the PT100 sensor (about 0.4 Ω/K) as shown in figure 8.
Data collection is done using linux with the following console commands:

```
sudo chmod 777 /dev/ttyUSB0
```

```
cat /dev/ttyUSB0 > ~/filename.txt
```

stop recording data by pushing "control" and "c"

```
grep . filename.txt > newfilename.txt
```

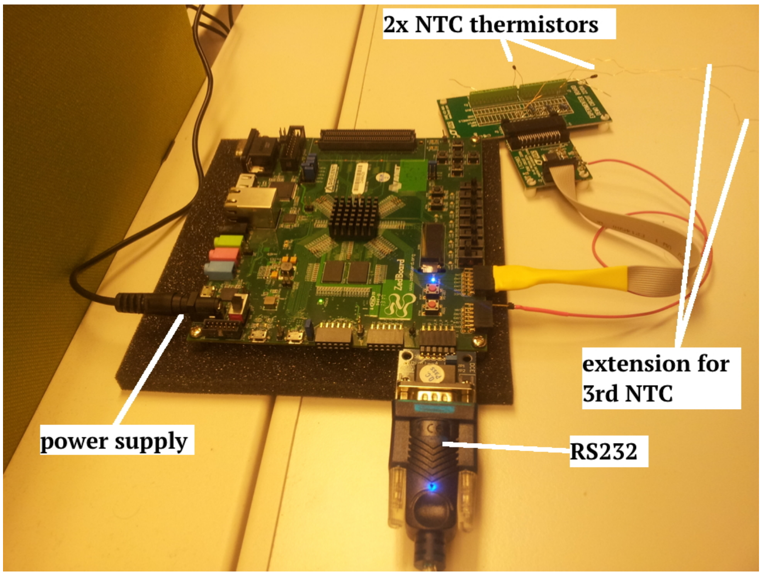

Figure 7: ZedBoard.

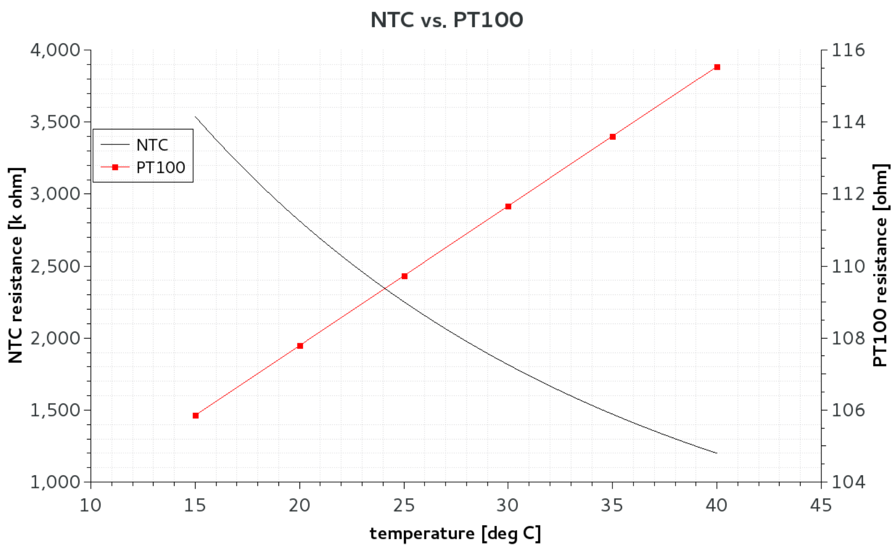

Figure 8: Resolution of the NTC and PT100, data taken from [7] and [6].

3 Results and outlook

3.1 Results

Here an overview of the measurements carried out for testing the setup:

- recording the spectrum of the white light source directly without the fiber delay segment (figure 9)
- recording the spectrum of the white light source with the delay segment and its dark current (noise) (figure 9 and figure 10)
- CFEL's room temperature from 19:20 to 10:20 using the ZedBoard and the NTC thermistors (figure 11)
- Heating up fiber segment using peltier and measuring with NTC thermistors and PT100 for 60 minutes (figure 12)
- 64 hours measurement of the CFEL room temperature and controlled fiber segment from friday 19:41 until monday 10:41 (figure 13 and figure 14)

3.1.1 Specturm measurements

Figure 9 shows the spectrum of the white light source. The measurement of the green curve is carried out without the fiber segment, so the spectrometer's fiber was directly connected to the output of the white light source.

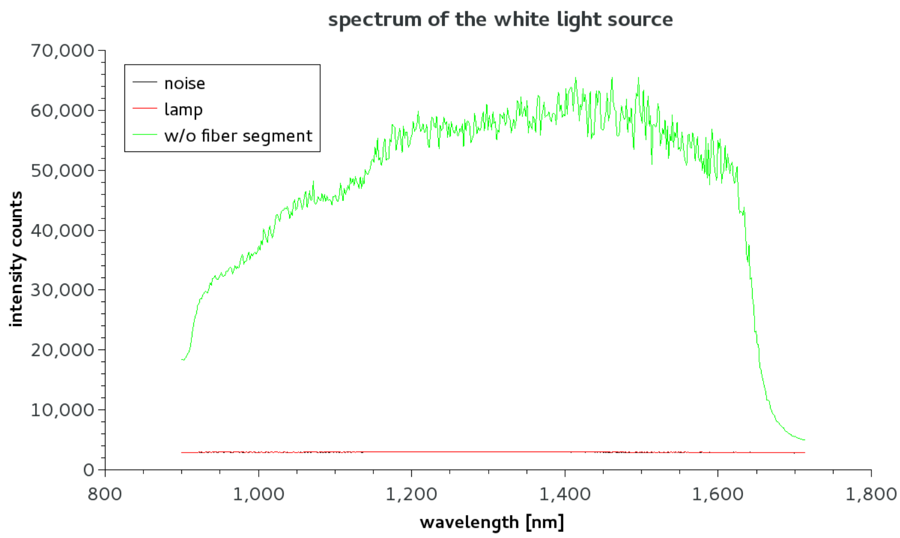

Figure 9: Spectrum of the white light source.

The black and red curve in figure 9 show the intensity spectrum including the fiber

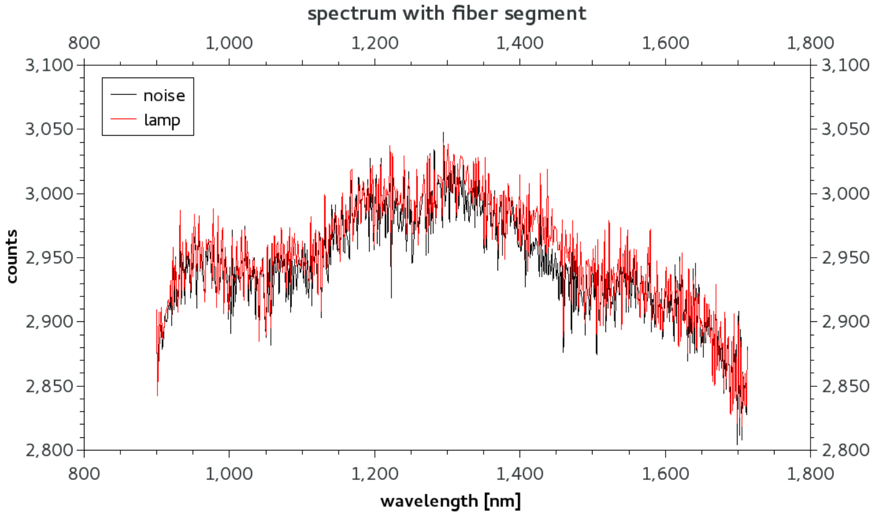

Figure 10: Dark current (black) and spectrum of the light (red) traveling through the fiber segment.

segment with the bulb switched off and on, respectively.

For a more precise view of these two curves figure 10 shows the spectrum with a larger intensity axis scale. The red and the black curve lay almost upon each other. Only in the range from 1,400 nm up to 1450 nm one may observe a noticeable difference in the spectrum. In conclusion it can be found that we are operating almost at noise level so the spectrometer is not capable of such low intensities delivered through the fiber segment. Hence, no remarkable peaks occur here, which are the bases for proper Sagnac interferometry measurements.

3.1.2 Temperature measurements

Unfortunately, the HTC4000 PI temperature controller did work properly only once with this set up. Afterwards, it seemed to be destroyed because neither current limiting worked nor the general controlling of the temperature appearing by simply ignoring the set temperature and heating or cooling the system permanently.
After contacting the producing companies technical service it was found out that on one hand the switch configuration on the evaluation board was set incorrect. Apparently, switch 3, 4 and 5 determine the type of sensor used and not the type of heating device. Thus, for using the PT100 as a sensor, only switch 5 should have been activated. On the other hand, it was found out, that the device was used above the recommended safety operating area (SOA), what in fact unfortunately destroyed it. The SOA can be checked here: http://www.teamwavelength.com/support/calculator/soa/soatc.php.

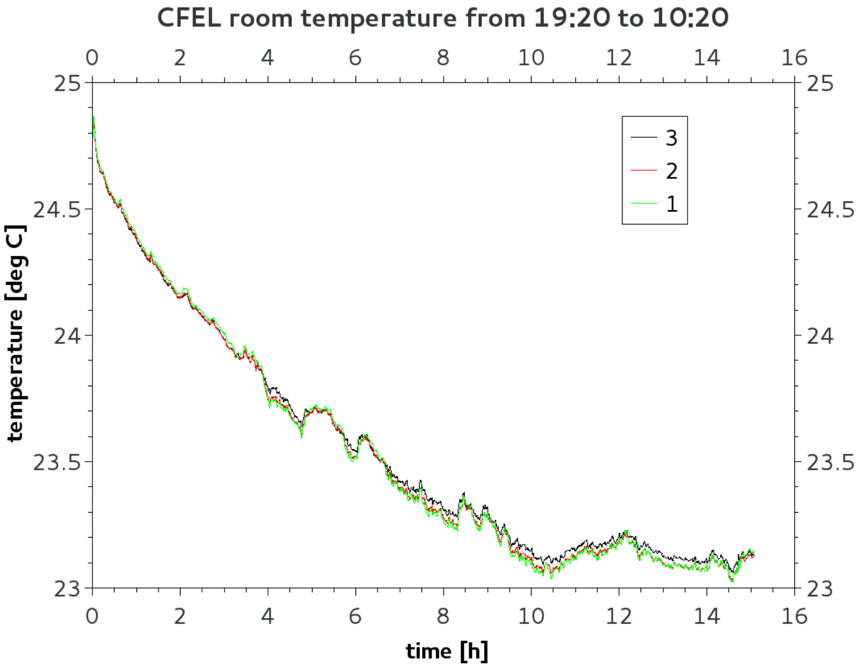

Figure 11: CFEL building temperature from evening to morning.

To determine the ZedBoards performance and accuracy the room temperature of the CFEL building was measured over night. It was found, that the ZedBoard delivers 2.133 measured values per second. To determine the effective temperature each value needs to be divided by 1024. But still, it should be noticed that neither PT100 nor NTC are proven to be well calibrated. Figure 11 shows the cooling down process of the CFEL building during night from about 25 down to about 23 degree celsius. It's noticeable that the calibration of the third sensor seems to vary from the other two slightly.

Figure 12 shows the next measurement carried out by connecting the peltier element and the fan inside of the temperature controlled chamber to a 5 power supply delivering 3 and 0.5 A to the peltier element and to the fan, respectively. Observing the temperature was down by extending and positioning one of the NTC sensors to the bottom of the chamber and measuring the rise in temperature for 60 minutes. Besides the PT100 sensor was connected to idestaQE temperature controller replacing the crashed HTC4000 (explained further in the next measurement) and manually collecting the actual temperature from the display. The temperature delivered by the PT100 is about 2 degrees lower than measured by the NTC while temperature is rising but in saturation (about 32.5 °C) it differs only about 0.2 degrees.

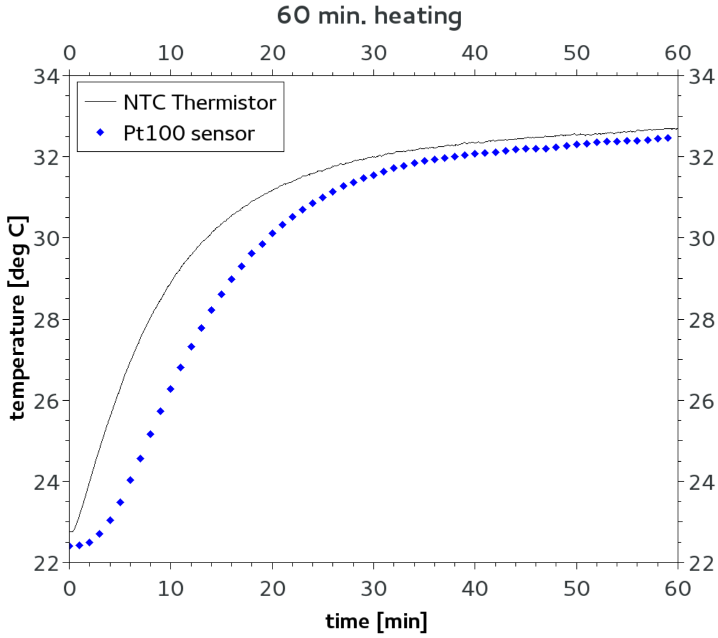

Figure 12: Heating curve measured by PT100 (blue) and NTC (black).

The idestaQE consists of a temperature controller from Watlow (PM3C1FC-1AAAAAA), an amplifying heating controller from Thorlabs and an RS232 connection as in and output. Internally, the sensor inputs R1, S1 and T1 of the Watlow temperature controller are directly connected to the pins 2, 1 and 6 of the RS232 connection. The Watlow heating connections F1 and G1 are linked to the Thorlabs heating controller and from there to two outputs on the RS232 connection (pin 3 & 4 and 9 & 5). The device is controlled by two buttons on the front panel of the Watlow controller. If the set temperature is below the actual temperature a voltage of 10 V (50 mA) is transferred to 20 V (1.6 A) by the Thorlabs heating controller. If the set temperature is above the actual temperature there is still about 500 mV on the RS232 corresponding to 600 mA.
Figure 13 and figure 14 show the temperature control using peltier element connected to one of the RS232 outputs with a set temperature of 26 °C.
In contrast to the HTC4000 temperature controller, which was reducing the TEC current as soon as the set temperature was almost reached, the idestaQE (not calibrated to PT100 sensor used) simply switches to low or high voltage supply if the actual temperature is above or below the set temperature, respectively. That causes 25 heating up and cooling down cycles within 10 hours (every 24 minutes) with a peak-to-peak temperature change of about 0.8 °C corresponding to 215 fs fiber timing delay.
Another unlikely disadvantage of the idestaQE temperature controller is that it is influenced by longterm temperature changes (peak-to-peak from 6 p.m. to 6 a.m.). Normally, the device should compensate these fluctuations completely to avoid any deformation of the fiber induced by the environment and achieve the desired temperature accurately.

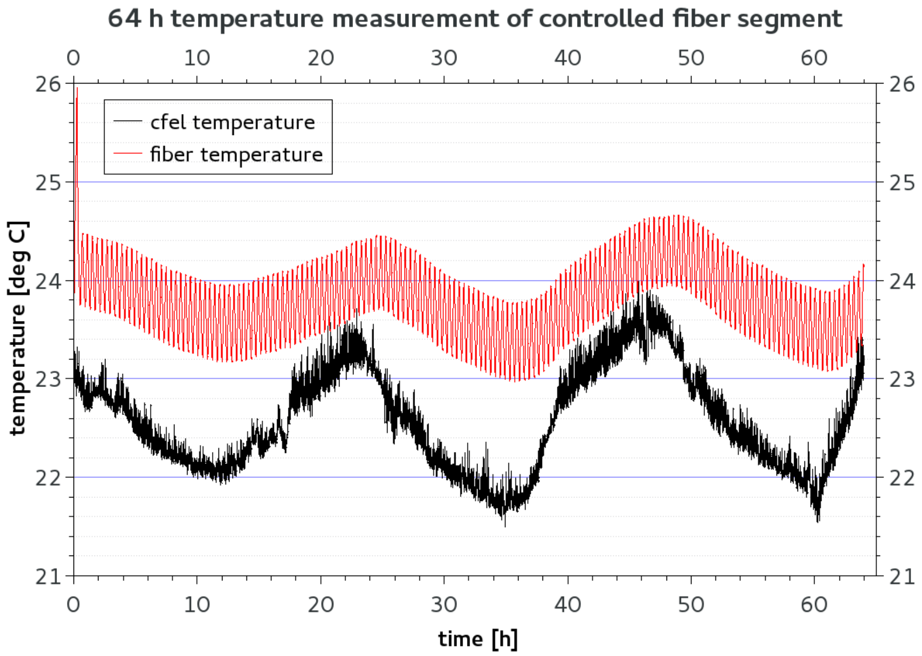

Figure 13: Measurement of the CFEL temperature (black) and temperature controlled fiber chamber (red) from friday 6:40 p.m. until monday 10:40 a.m.

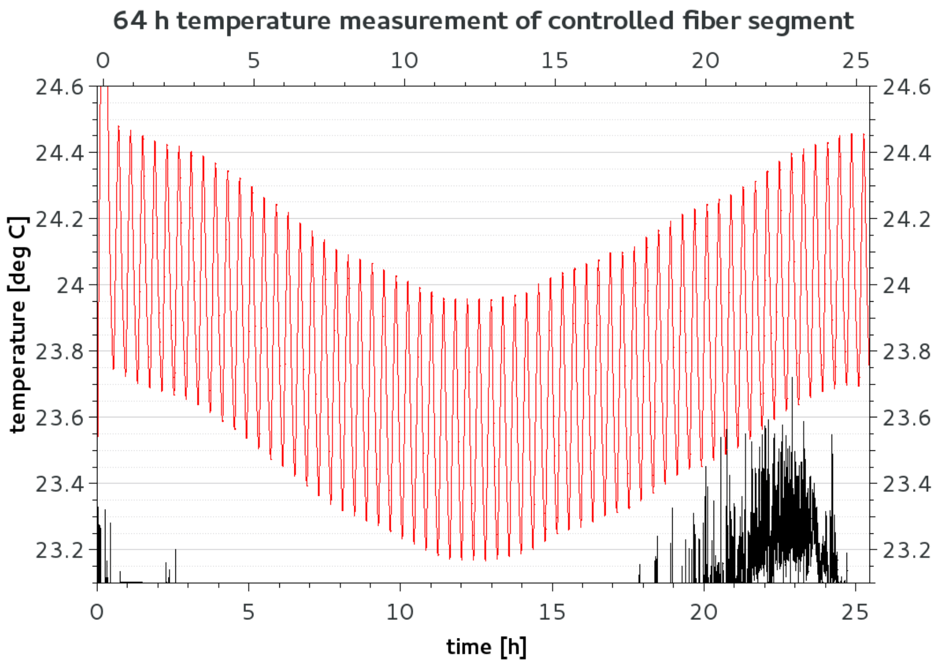

Figure 14: large-scale of the fiber temperature within the first 25 hours.

3.2 Outlook

- Renew the PI temperature controller or replace it by a more robust one, e.g. the WTC3243 from wavelength electronics.
- Increase thermal conductivity of the system using same material (replace stainless steel bellow and aluminum heat sink).
- Measure wavelength shift due to temperature change of the fiber with appropriate spectrometer above noise level.
- Replace temperature sensor by sagnac interferometer delivering actual temperature due to calibrated wavelength shift.

Acknowledgements

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