RF-Based Detector for Measuring Fiber Length Changes with Sub-5 Femtosecond Long-Term Stability.

J. Zemella[1], V. Arsov[1], M. K. Bock[1], M. Felber[1], P. Gessler[1], K. Gürel[3], K. Hacker[1], F. Löhl[1], F. Ludwig[1], H. Schlarb[1], S. Schulz[2], A. Winter[1], L. Wissmann[2]

[1]Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

[2]Institute for Experimental Physics, Hamburg University, Germany

[3]Department of Physics, Bilkent University, Ankara, Turkey

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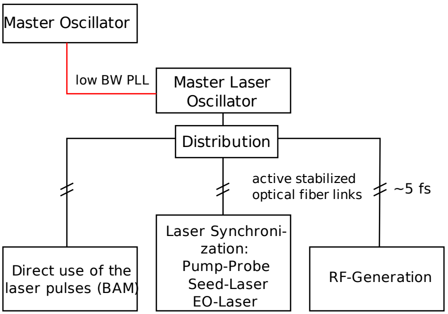
Laser-Based Synchronization System at FLASH.

Current State

- **Goal:** Synchronization system with a long-term stability of sub-10 fs



- Modelocked Erbium-doped Master Laser Oscillator with 216 MHz repetition rate
- Distribution of the laser pulses to 14 endstations using optical fiber links
- Link stabilization with optical cross correlator (OCC)
- Endstations like beam arrival-time monitor (BAM), two-color OCC or local RF generation (Sagnac loop)

Motivation for RF-Based Detector.

Optical Cross Correlator and Conventional RF-Phase Detector

Optical Cross Correlator:

- Necessary: Exact pulse overlap, dispersion compensation, feedback

⇒ Rather complex, cost intensive but allows fs or $<$ fs resolution.

Femtosecond timing not required for most endstations

Conventional RF-phase detector:

- Limitations: AM to PM, offset drifts of the mixer, thermal phase drifts of the photo detection process and the filter

⇒ Long-term drift $\sim 50 - 100$ fs

Alternative solution:

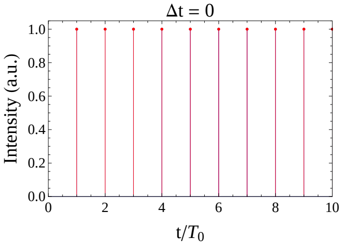
- Amplitude measurement of high harmonics of the interference pattern of two superimposed pulse trains.

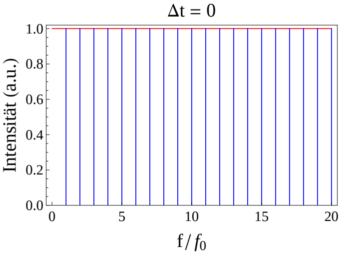
⇒ Less complex, less expensive system

Frequency Spectrum of the Photodiode Output.

Basics

- Laser pulse train leads to a frequency comb
- Frequency lines are spaced by $f_0 = 1/T_0$
- The superposition of two laser pulse trains $(I_1 = I_2)$ leads to:
  - $\Rightarrow$ Modulated frequency comb
  - $\Rightarrow$ Modulation of the n^{th}-harmonic: $I(nf_0) \propto \cos^2(\pi n f_0 \Delta t)$
  - $\Rightarrow$ Intensities of the harmonics depend on the temporal offset Δt





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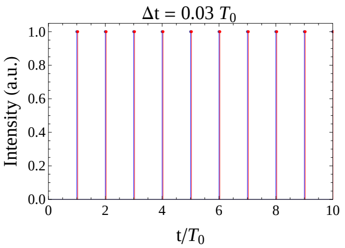

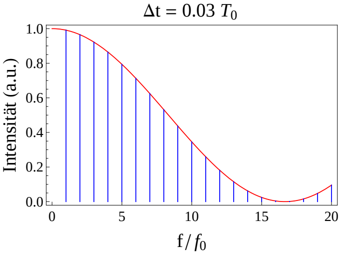

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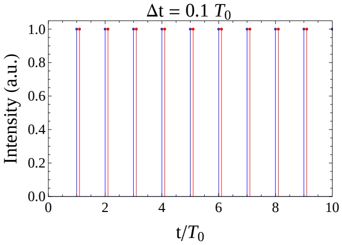

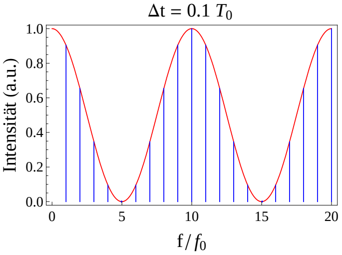

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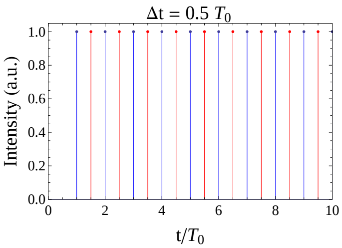
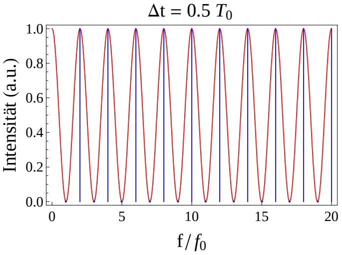
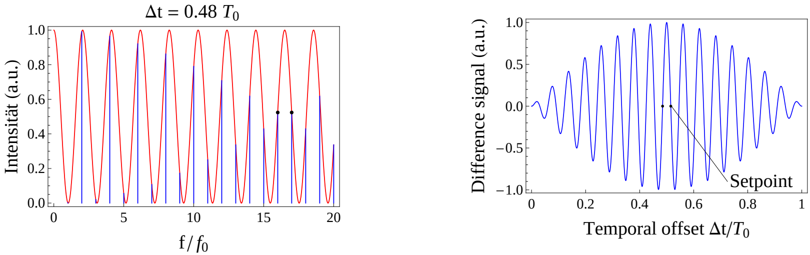




Frequency Spectrum of the Photodiode Output.

Basics

- With the observation of one harmonic a change of the temporal offset is possible
- Change of the observed harmonic n-times larger for the n^{th}-harmonic
- Observing two harmonics seperated by a minimum resp. maximum of the modulation eliminates amplitude dependence



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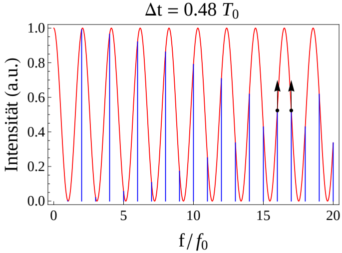

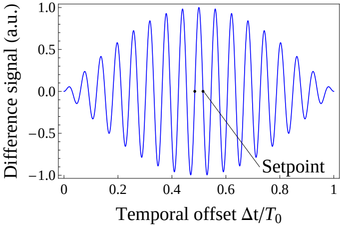

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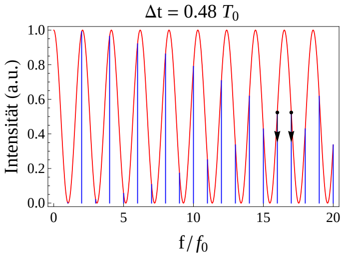

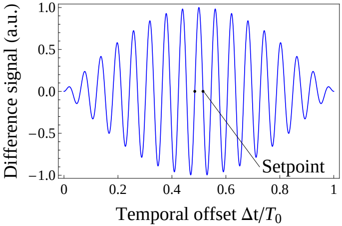

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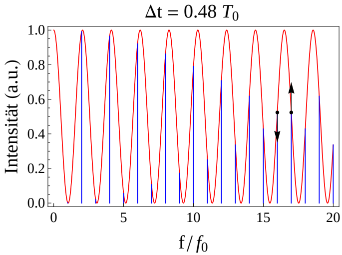

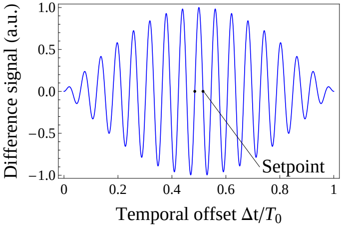

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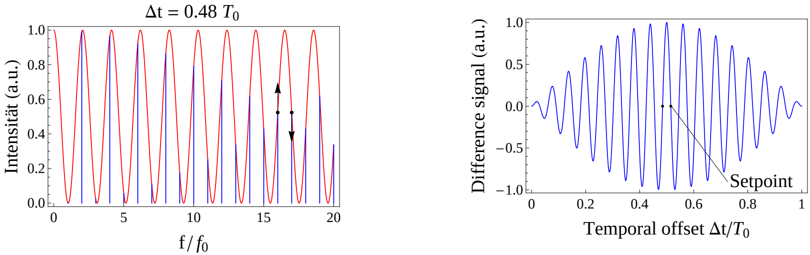

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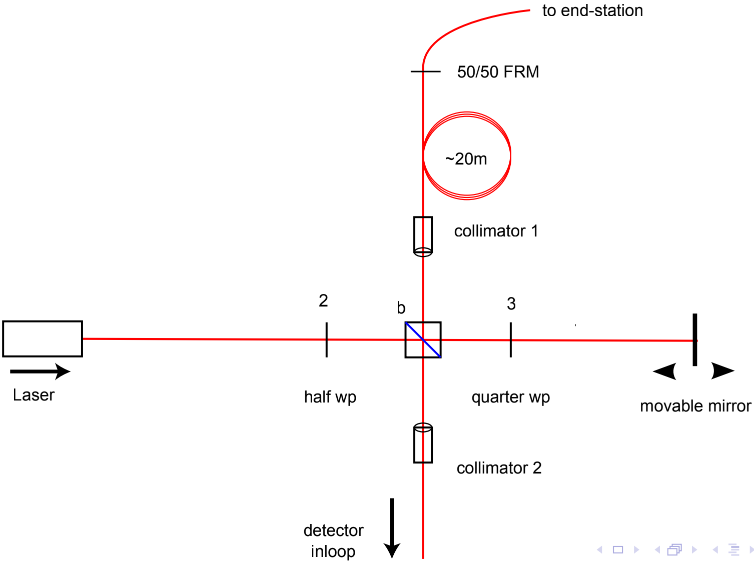
Optical Part.

Schematics of the Superpostion of the both Pulse Trains



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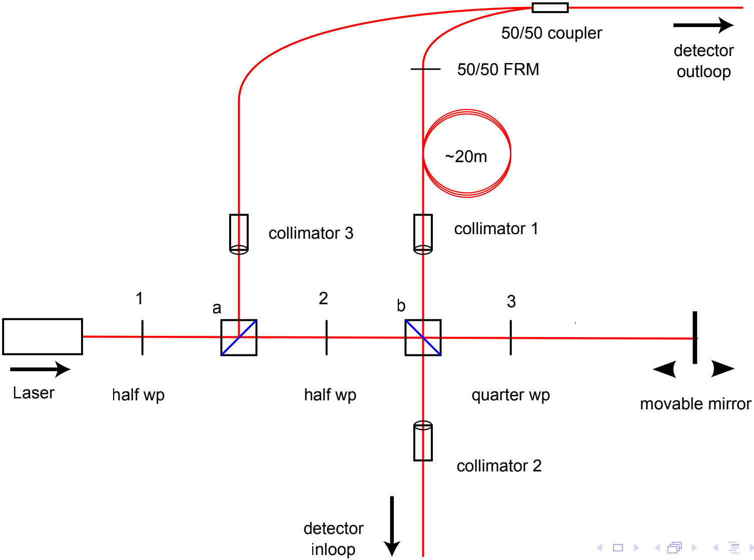
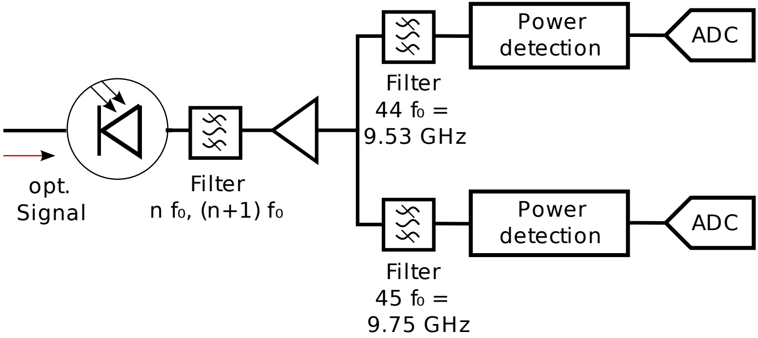


RF-Part.

Balanced Detection Scheme.

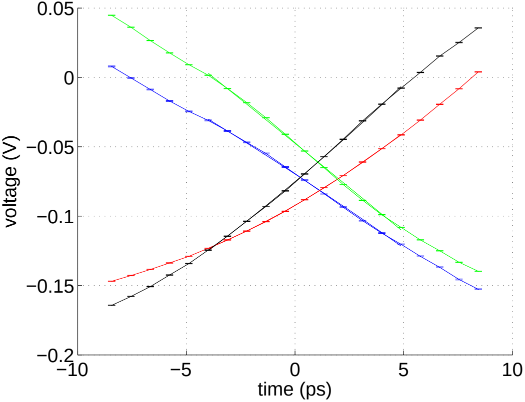


- Photodiode with 10 GHz bandwidth
- Power-detector: Zero Bias Schottky Detector
- ADC with 1 MHz sampling rate and a bandwidth of 40 MHz

Calibration.

The Voltage Change of the Detector Channels.

2^{nd}-order polynomial is fitted to the data to calculate the voltage into time



$$\frac{dV}{dt} \approx 10 - 15 \,\frac{mV}{ps}$$

Blue: Inloop detector $44\ f_0 = 9.53\,\text{GHz}$

Red: Inloop detector $45\ f_0 = 9.75\,\text{GHz}$

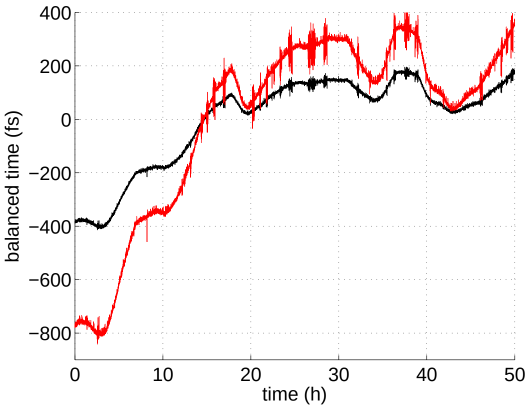
Green: Outloop detector $44\ f_0 = 9.53\,\text{GHz}$

Black: Outloop detector $45\ f_0 = 9.75\,\text{GHz}$

50 h Long-term Measurement.

Balanced Time Change of the Inloop and Outloop Detector

$$t_{1,2} = \frac{1}{2}\left(t_{9.53\,\text{GHz}} + t_{9.75\,\text{GHz}}\right)$$



Red: Inloop detector $t_{pp} = 1.24$ ps

Black: Outloop detector $t_{pp} = 0.61$ ps

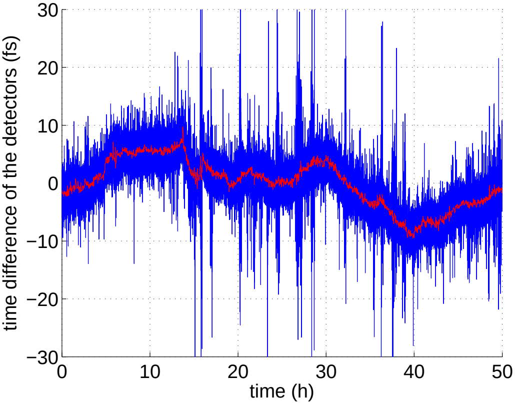
Inloop detector measures fiber length changes twice

Measurement bandwidth: 500 Hz

50 h Long-term Measurement.

Time Difference of the Inloop and Outloop Detector

$$\Delta t = \frac{1}{2} t_1 - t_2$$



Peak-to-peak of the time difference:

$t_{pp} = 20$ fs

Standard deviation of the time difference over 50 h:

$$\Delta t = 4.6 \text{ fs}$$

Resolution of one detector:

Blue: $t_{Res} = 3.2$ fs

Measurement bandwidth:

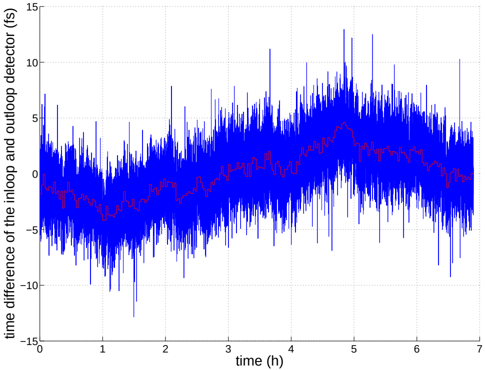
Blue 500 Hz

Red 10 mHz

Application of the Detector

Length Change Measurement of PSOF Link

Temperture change for the fiber $\Delta T = \pm 3^\circ$ C



$t_{pp} = 55$ fs @ $\pm 3^\circ C$, link length ~ 20 m

$T_k = 0.4$ fs/m K

$\Delta t = 3$ fs (RMS)
$t_{Res} = 2.1$ fs (RMS)

Conclusion and Outlook.

- New detection principle based on interference pattern of two superimposed pulse trains.
- Drift-free because of the use of only one photodiode and an amplitude measurement instead of a phase measurement.
- Long-term resolution over 50 h of 3.2 fs could be achieved.

- Try to use the scheme for longer fiber links.
- Comparison with the optical cross correlator.
- Install a stabilized link to connect the photo injector laser at FLASH to the synchronization system.

Acknowledgements.

On behalf of the FLASH-LbSyn-Team and involved DESY-Groups

Thank you for your attention!