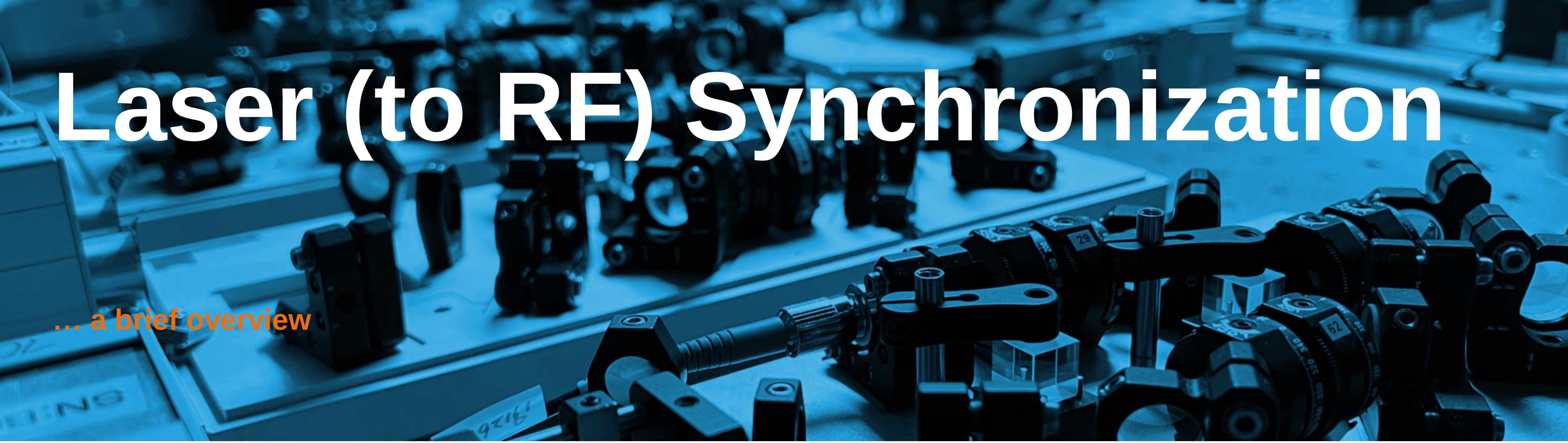
Laser (to RF) Synchronization

… a brief overview



Thorsten Lamb for the DESY LbSync Team

EuPRAXIA WP9, Discussion on RF Components, online, April 18, 2024

HELMHOLTZ

DESY.

Reference Distribution in Small and Large Scale Facilities

an Expert Domain of its Own

- clock reference (commercial or custom built RF oscillator)
  - determines common mode timing jitter for the entire facility
- reference distribution
  - RF distribution (passive - see below, active solutions are complex/expensive and not commercially available)
  - optical distribution (actively stabilized)
    - pulsed syncronization system (very expensive, complex, suited for large scale facilites)
    - cw synchronization system (very expensive, commercially available, focused on large distances)

- Sources of timing jitter short-term, long-term:

Short range 1 us…1ms:
PS, EMI, Electronics, Material Prop, …

Mid range 1ms…10s:
Acoustic, Fans, Seismic, Air/Water flow, …

Long range 10s … days:
Temperature, Humidity, Air Pressure,…

- Properties of a passive RF-cable distribution:

(+) Minor short-term jitter contribution

(+) Relatively low cost for small facilities

(--) Drift ~20fs/m/K **(T, RH, air pressure)** in the >10ps range

(--) Power loss **~3dB/100m** -> lower freq, ULN ampl. (>10dBm)

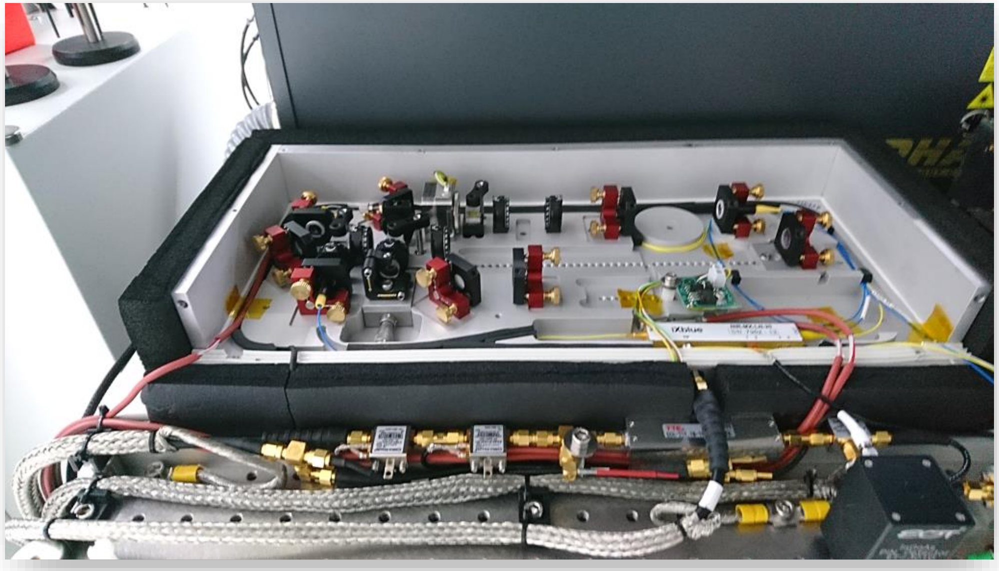
(--) EMC sensitive

courtesy of Frank Ludwig

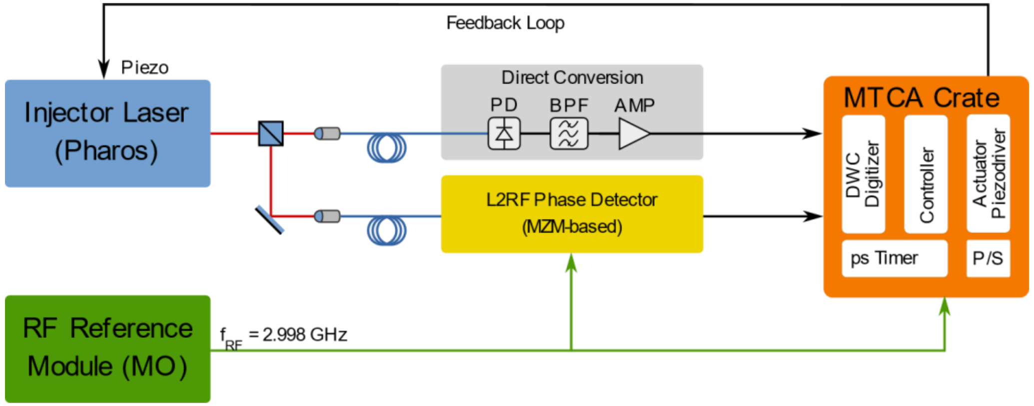
Laser to RF Synchronization Techniques

SINBAD Injector Laser (commercial Pharos Oscillator) as one example

- two types of phase detectors implemented
  - **direct conversion based synchronization (RF lock)**
    - robust scheme for day-to-day operation
    - short term performance: ~11 fs in-loop jitter
    - susceptible to long-term drifts
    - RF timing shifter available
  - **MZM-based Laser-to-RF synchronization**
    - amplitude modulation of the laser pulse train proportional to the phase error
    - laser pulses sample positive and negative slopes of the RF reference
    - excellent short term performance:
      - <7 fs (single output MZM) <2 fs in-loop jitter (dual output MZM)
    - temperature stabilized and humidity sealed setup
    - intrinsically low long-term drift
    - only fixed working point (no timing shifter available, ODL req.)
    - frequency and rep. rate dependent setup
- Sagnac-loop based phase detectors can be considered
  - similar properties to the MZM-based Laser-to-RF synchronization
  - implementation more challenging



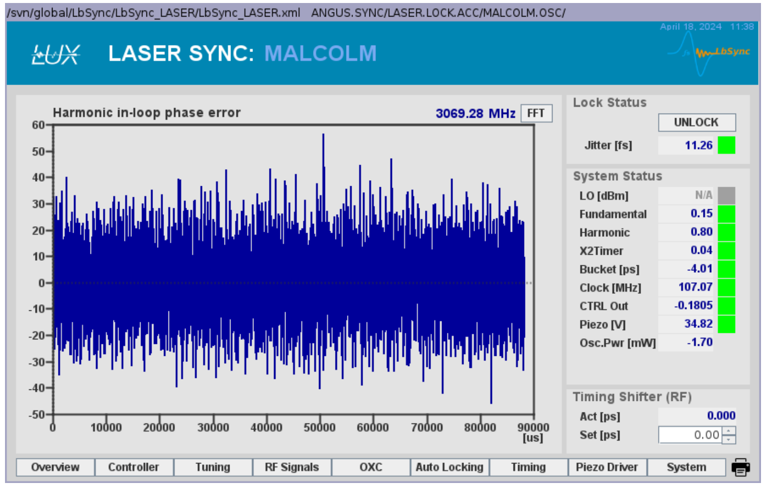
MZM-based Laser-to_RF Syncronization Setup



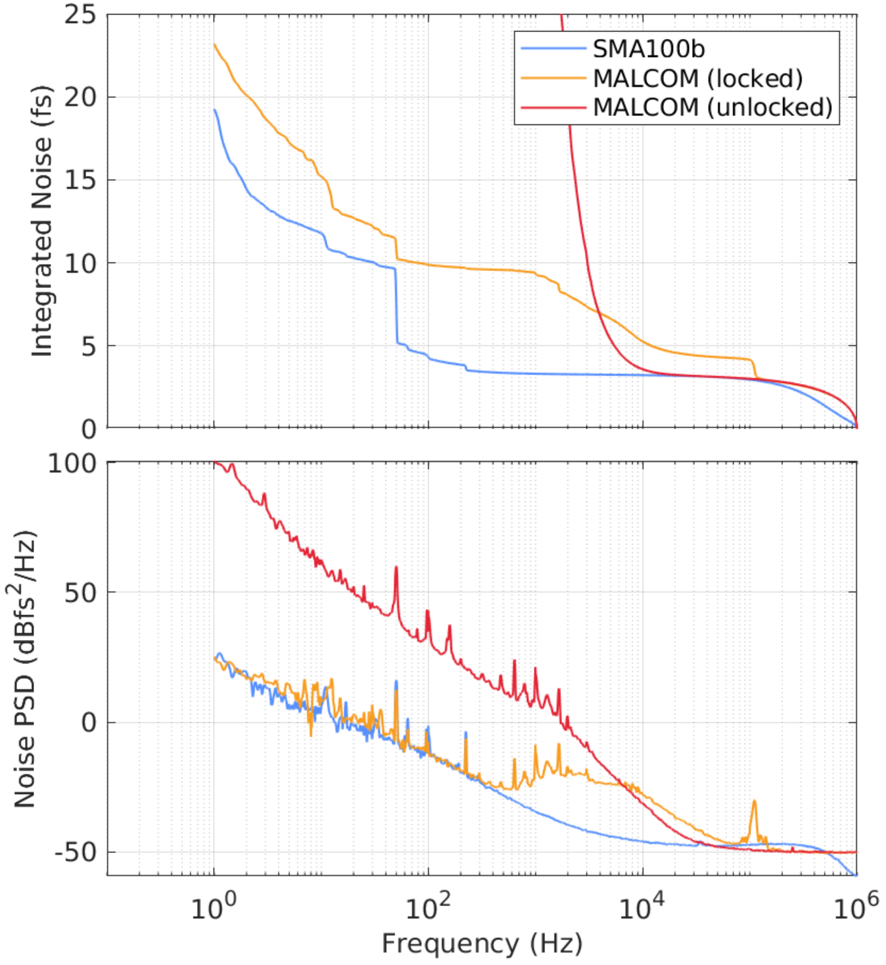
Direct Conversion Based Synchronization (RF Lock)

recently commissioned RF sync for ANGUS (laser system) and LUX (laser-plasma accelerator)

- **commercial MO** (main oscillator) as RF reference
  - Rohde&Schwarz SMA100B operated at 2.997 GHz
- **passive distribution** (RF cables)
- **direct conversion based laser synchronization**
- 11 fs in-loop jitter (10 Hz .. 186 kHz bandwidth)
- 23 fs absolute jitter (1 Hz .. 1 MHz bandwidth)



Absolute Phase Noise Measurement
MALCOLM (laser front end)

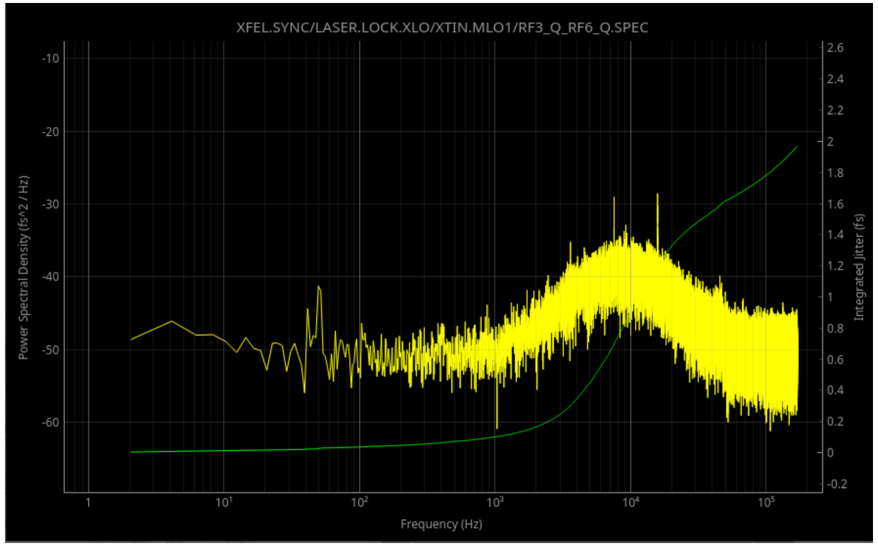


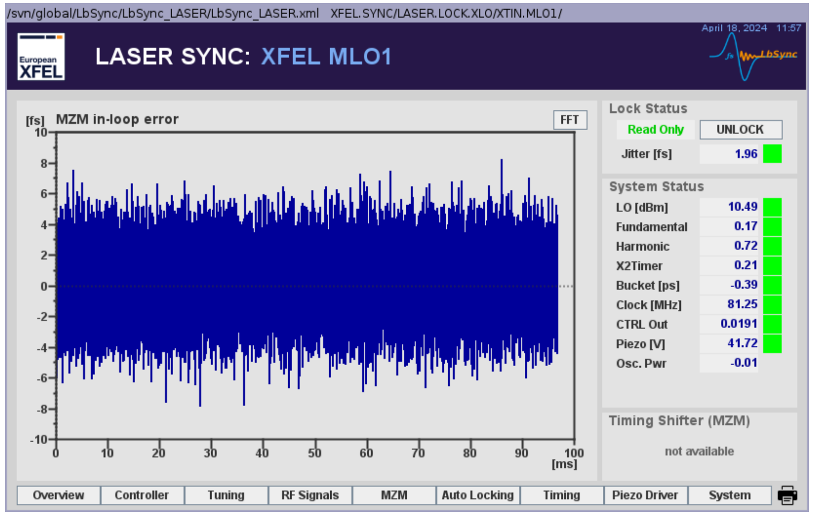
plots courtesy of Maximilian Schütte

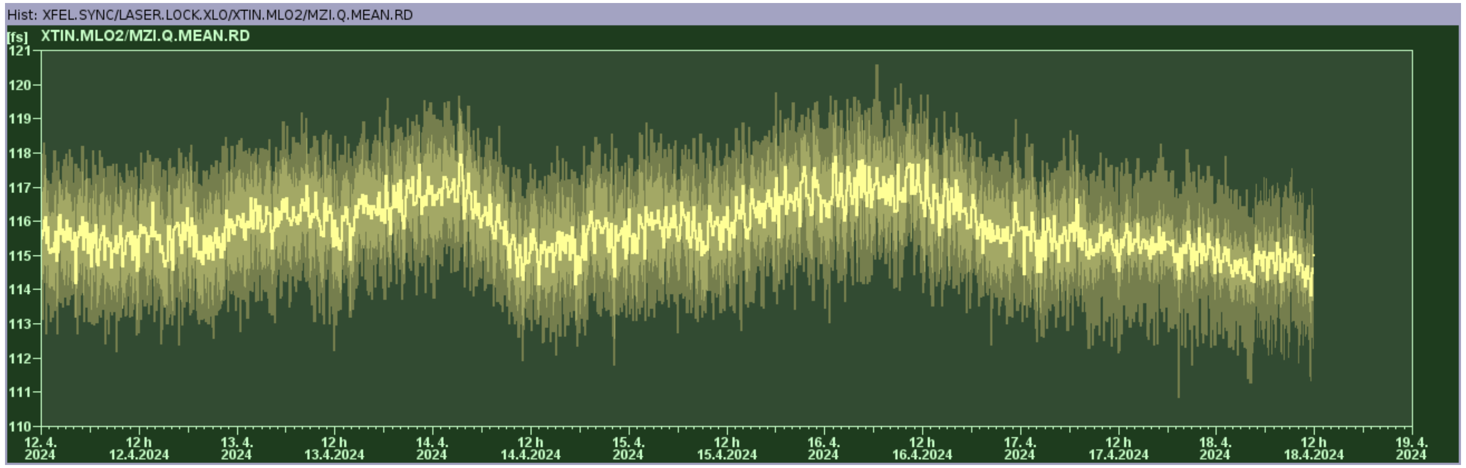
MZM-based Laser-to-RF Synchronization

Short Term Performance (dual output MZM), XFEL Main Laser Oscillator

- timing jitter (out-of-loop): **1.9 fs**
  - measurement bandwidth: 10 Hz - 186 kHz
- long term stability: 10 fs peak to peak (1 week, out-of-loop)
- currently only available for 1550 nm



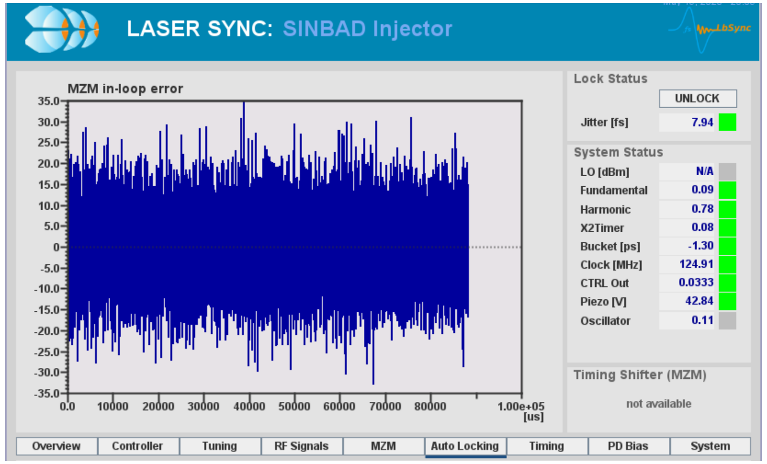




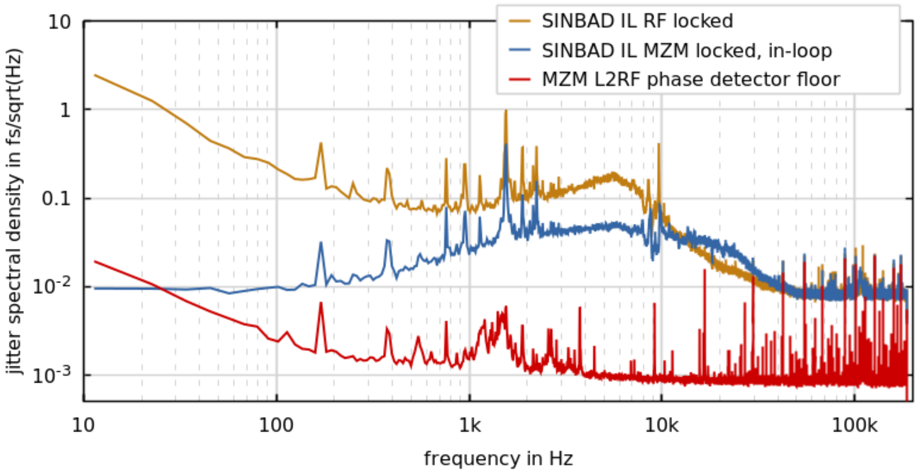
MZM-based Laser-to-RF Synchronization

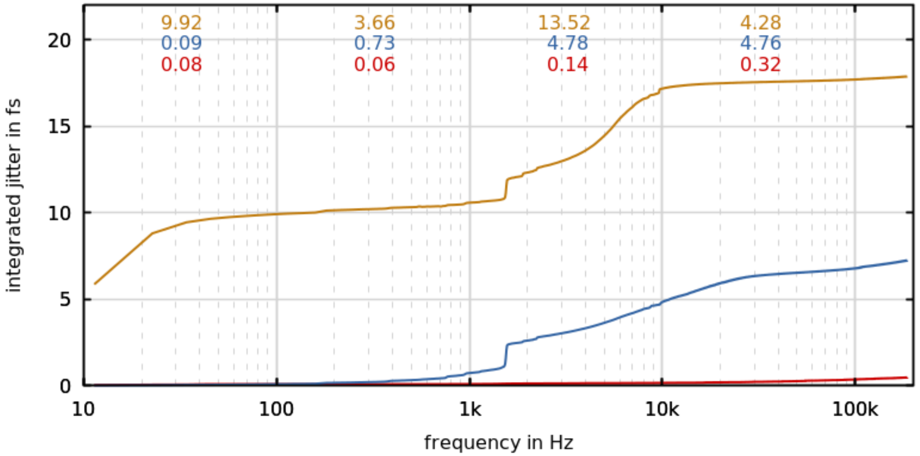
Short Term Performance (single output MZM), SINBAD Injector Laser

- MO and distribution similar to ANGUS
- integrated jitter:
  - detector noise floor (RF disconnected): **0.5 fs**
  - timing jitter (RF locked, measured with MZM): **17.9 fs**
  - timing jitter (MZM locked, in-loop): **7.2 fs**
  - measurement bandwidth: 10 Hz - 186 kHz
- measurements performed with the L2RF phase det.
- meanwhile improved (1.5 kHz oscillation removed)



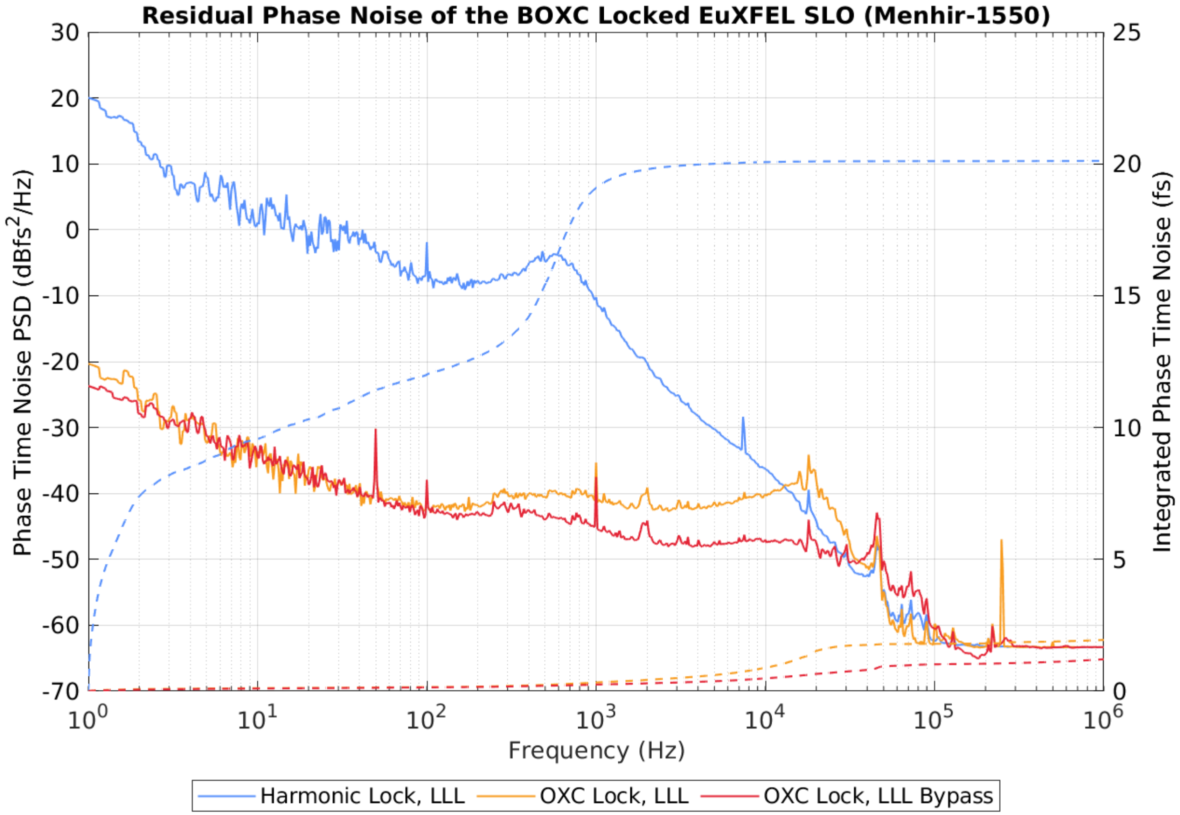
Relative Phase Noise Measurement

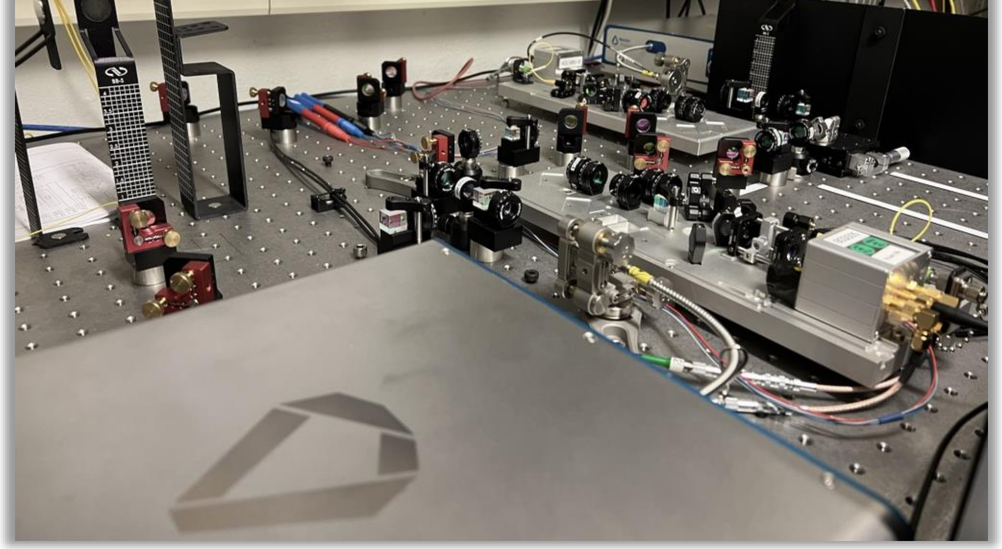


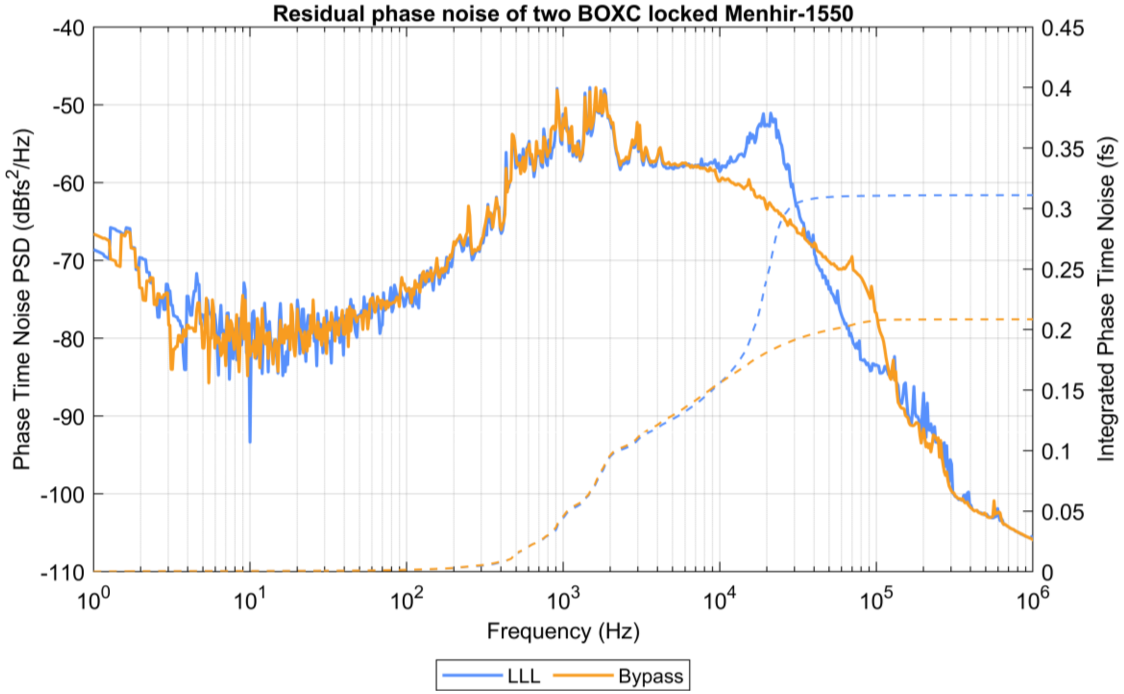


Laser-to-Laser Synchronization

Subsidiary onto Main Laser Oscillator





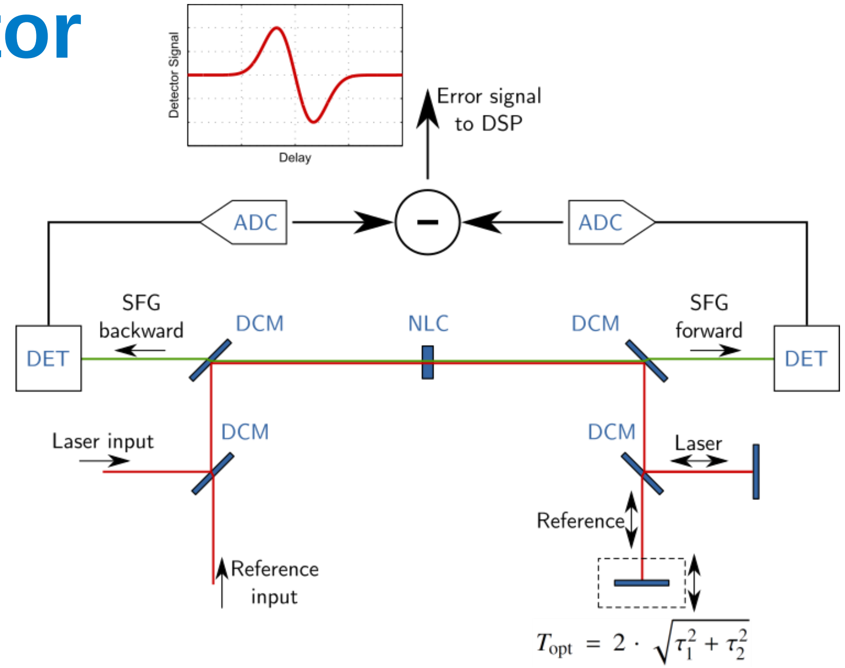


- laser-to-link (over 4 km of stabilized fiber): **1.1 fs** rms
- lab environment (over 1 m free-space): **0.2 fs** rms

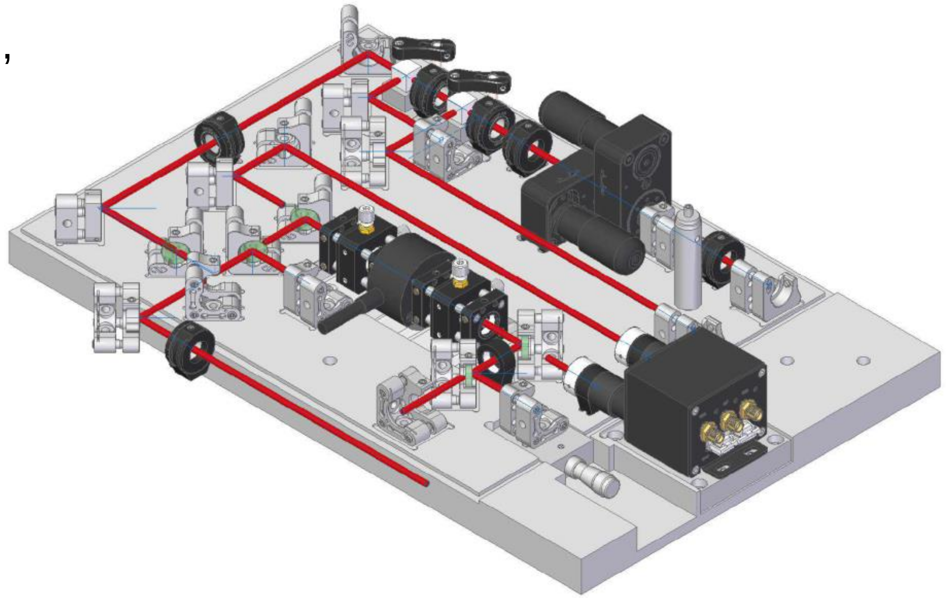
plots courtesy of Maximilian Schütte

Collinear Balanced Optical Cross-Correlator

An Established Platform …



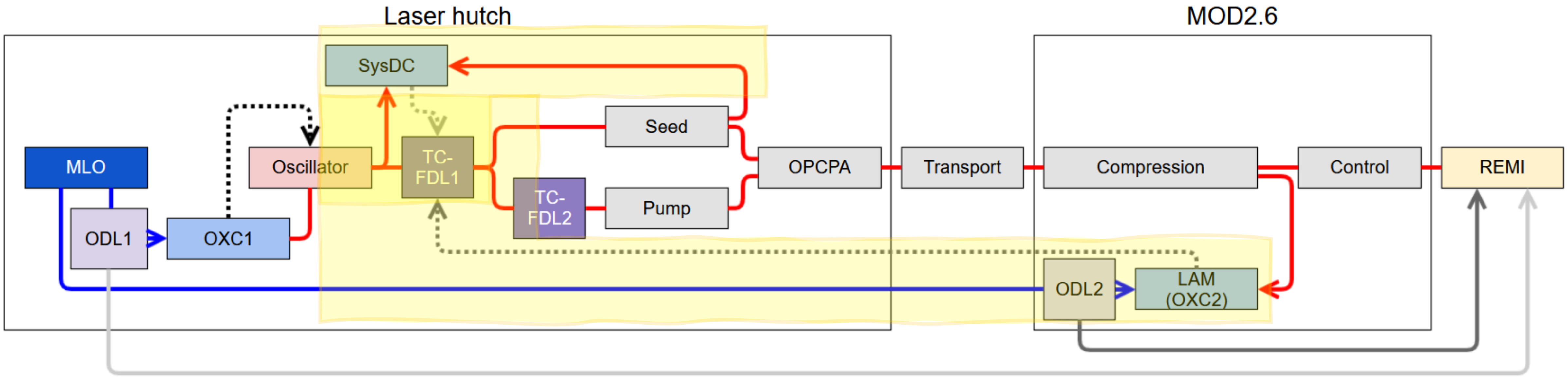
- **all-optical scheme** for precise timing detection of two pulsed laser sources
  - high sensitivity: sub-100 as/mV
  - purely phase-sensitive measurement, differential scheme eliminates AM-related influence
  - no drifts due to RF cables etc.
- based on two-color **collinear balanced optical cross-correlation**
  - twofold sum-frequency generation in a **single** nonlinear crystal, e.g. BBO, PPKTP, PPLN, …
- common, **monolithic optomechanical design** covering requirements of different laser systems
  - rep'rate, wavelength, pulse duration, …
  - simple change of crystal, DCMs, lenses and delay required
- self-built low-noise balanced photodetector for LbSync core system



images courtesy of Jost Müller

Laser Amplifier and Frequency Conversion Stabilization

FLASH2 Pump-Probe Laser and Stabilization as an Example



- even for well synchronized oscillators drift and jitter is added during amplification, conversion and transport
- laser internal stabilization required (here: SysDC / optical cross-correlator)
- beware: LAM only feasible for large scale facilities with a pulsed optical synchronization system

image courtesy of Nora Schirmel

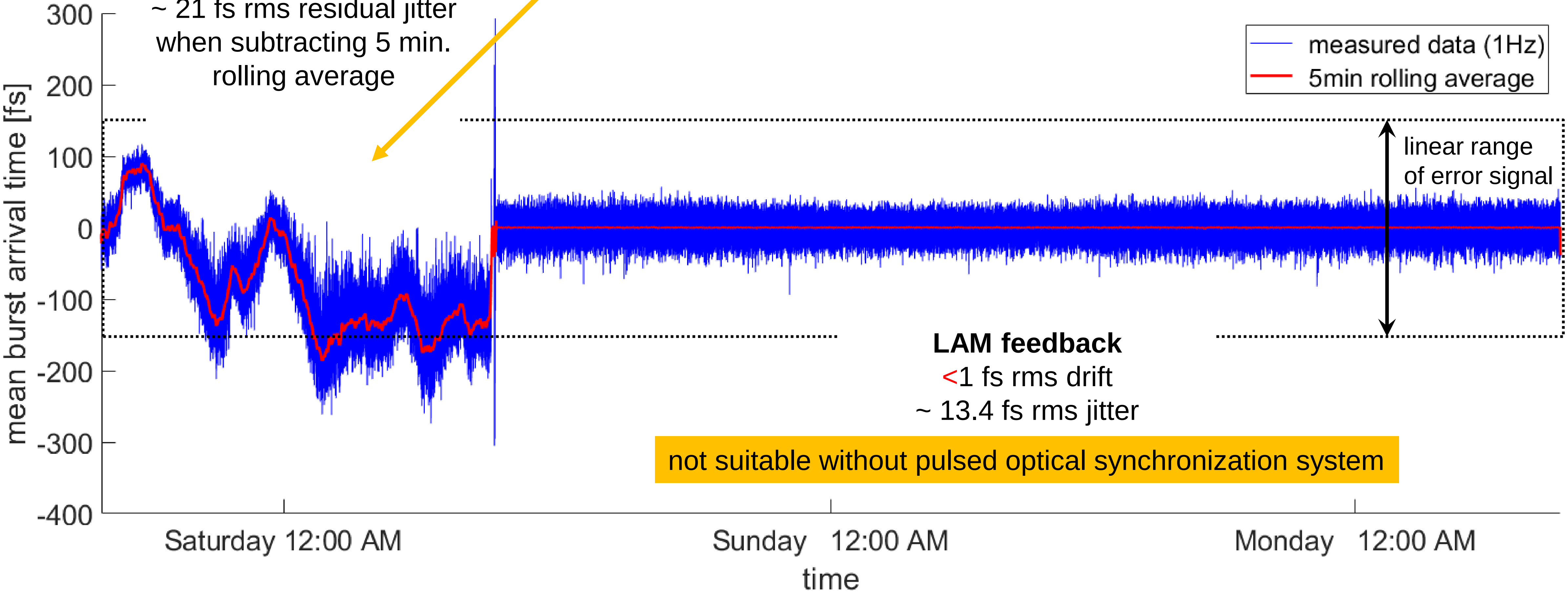
LAM Feedback

Data Taken During User Experiment

< 15 fs optical pulse duration
compressed by DCM compressor
wavelength fluctuation: 7.3 nm rms
~ 20 fs rms oscillator jitter

lab-intern drift feedback
~ 300 fs drift (peak-to-peak)
~ 21 fs rms residual jitter
when subtracting 5 min.
rolling average

typical drift and jitter after beam transport to experiment



LAM feedback
<1 fs rms drift
~ 13.4 fs rms jitter

not suitable without pulsed optical synchronization system

Thank you

Contact

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