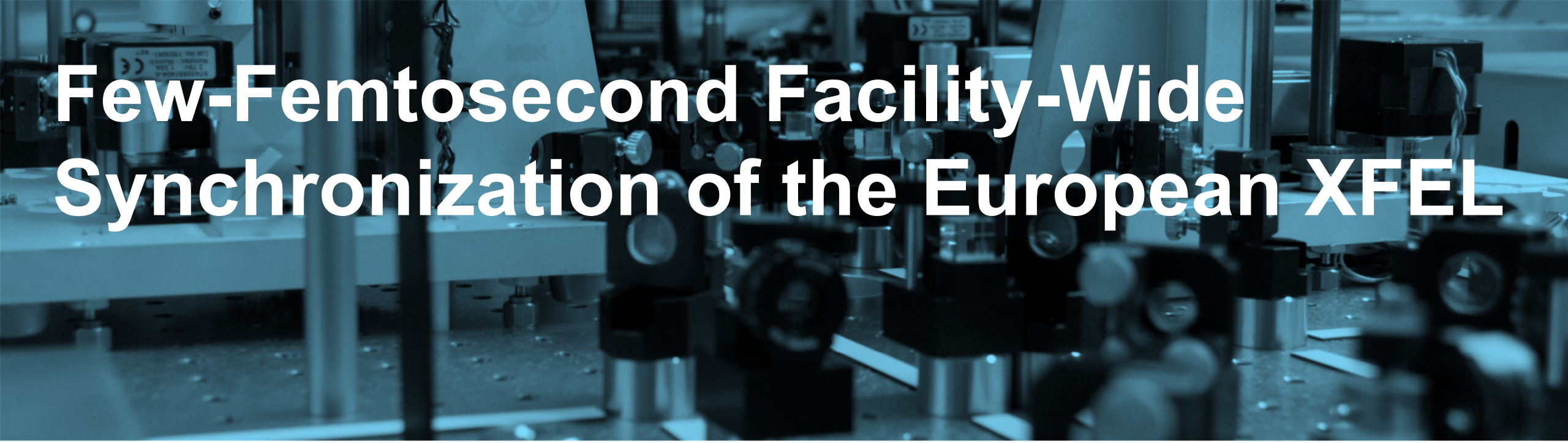


Few-Femtosecond Facility-Wide Synchronization of the European XFEL

Sebastian Schulz on behalf of DESY MSK and Supporting Groups

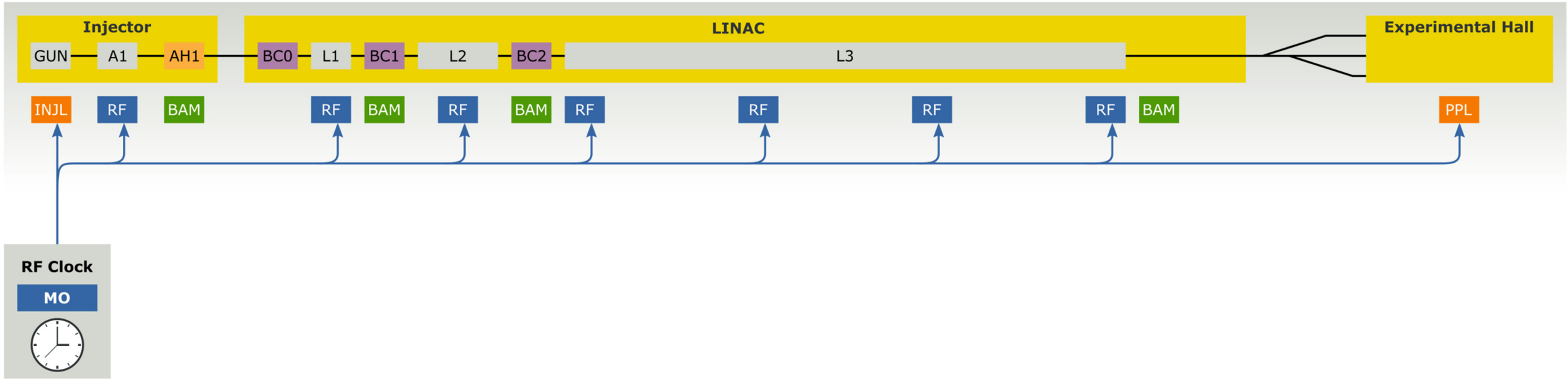
39th International Free-Electron Laser Conference
Hamburg, Germany — August 26 - 30, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Motivation

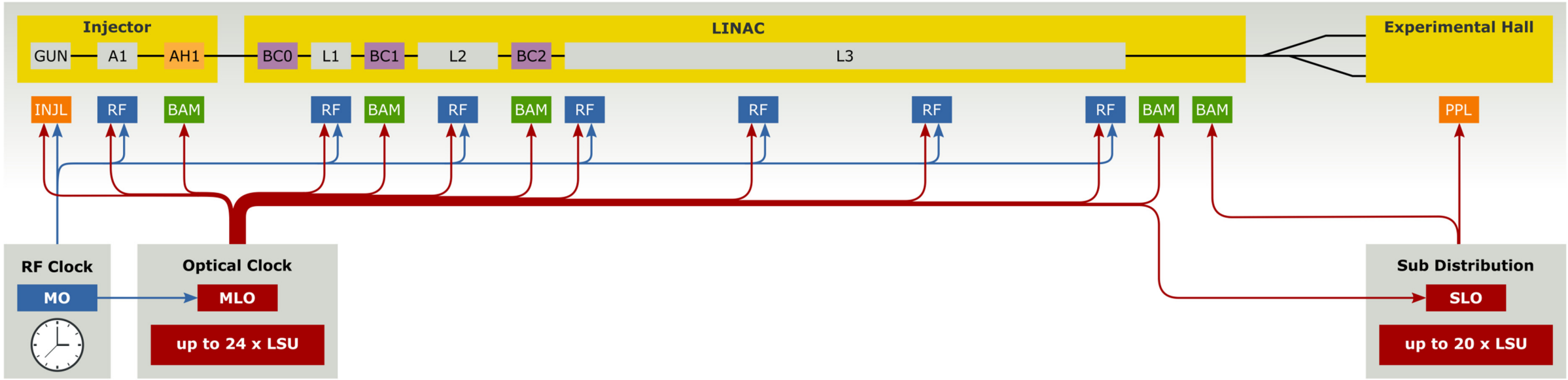
Why Is Implementing a Pulsed Optical Synchronization System Crucial at the European XFEL?



- **RF system: mature technology, 24/7 availability** for ~270 clients, but:
  - **cable drift**: ~10 fs/m/K → **35 ps/K** (3.5 km)
  - **cable losses**: ~0.03 dB/m → **~100 dB** (3.5 km) → amplification might add drift and jitter
  - RF signals susceptible to **EMI**
- **laser synchronization** – ultimate **performance for user experiments** only with optical methods
- **femtosecond bunch arrival time measurement (BAM)** requires pulsed optical reference

Overview

The Optical Synchronization Infrastructure at the European XFEL

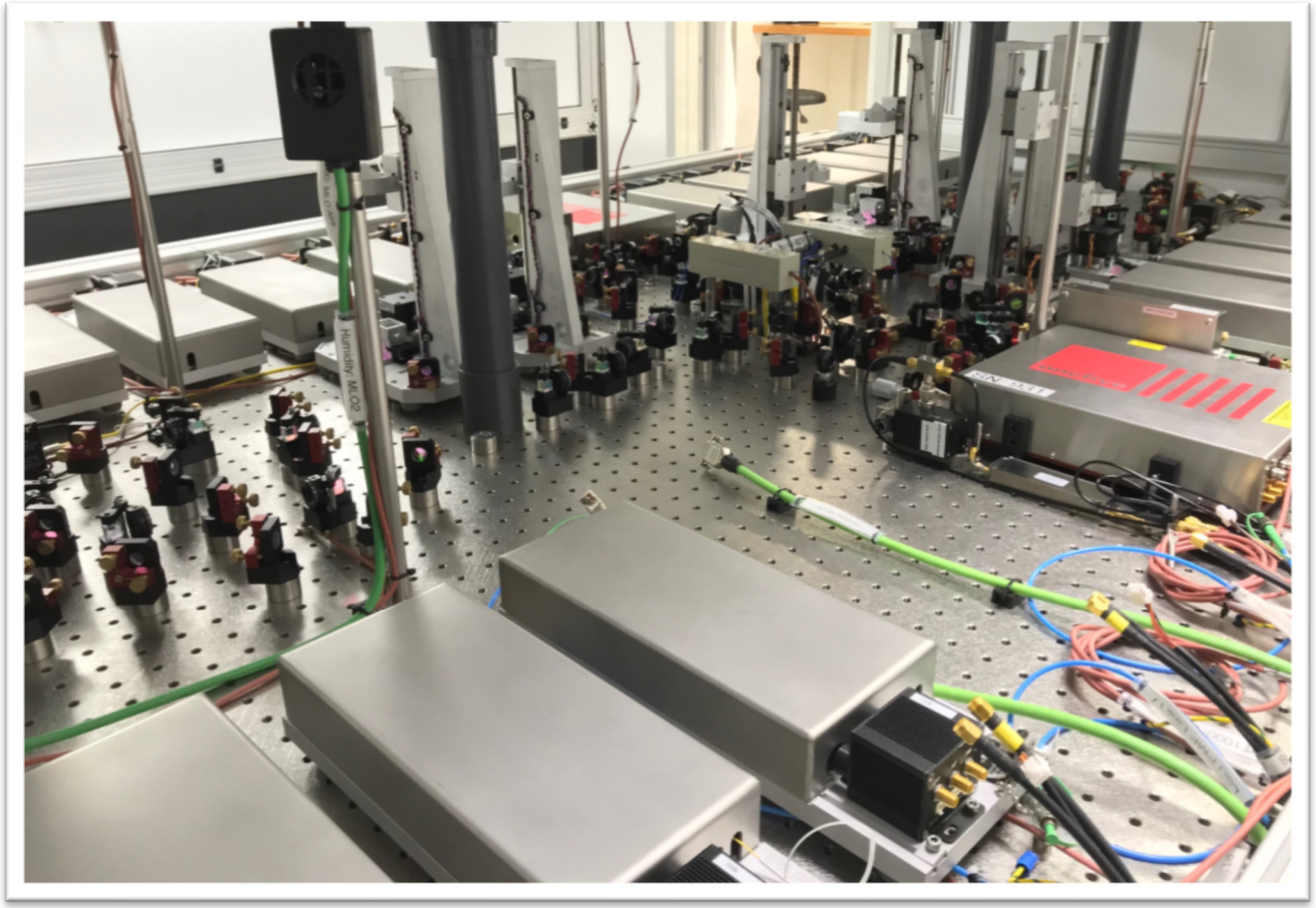


- **optical clock** (master laser oscillator, MLO) provides stable **pulsed optical reference**
  - phase-locked to radio frequency oscillator (MO)
- optical reference **distributed via length-stabilized optical fiber links** for
  - **laser locking** (injector, pump-probe, …)
  - RF re-synchronization (**REFM-OPT**)
  - bunch arrival time measurement (**BAM**)

Synchronization System Reference

Master Laser Oscillator (MLO, SLO)

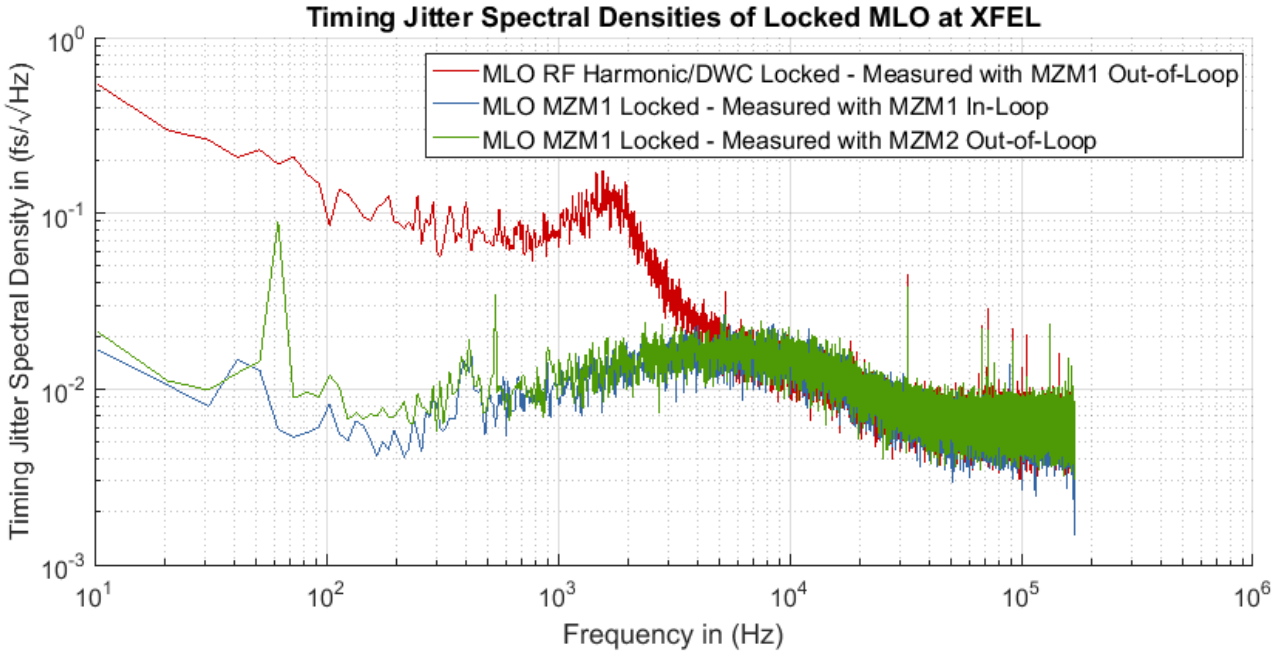
- commercial passively mode-locked fs laser
  - **repetition rate 216.7 MHz** = 1300/6 MHz
  - telecom wavelength 1550 nm
  - ultra-low phase noise
  - **24/7 operation**, redundant system
- 24-port free-space distribution (FSD)
  - SuperInvar optical table
  - **4 ns** optical delay line (8 stations)

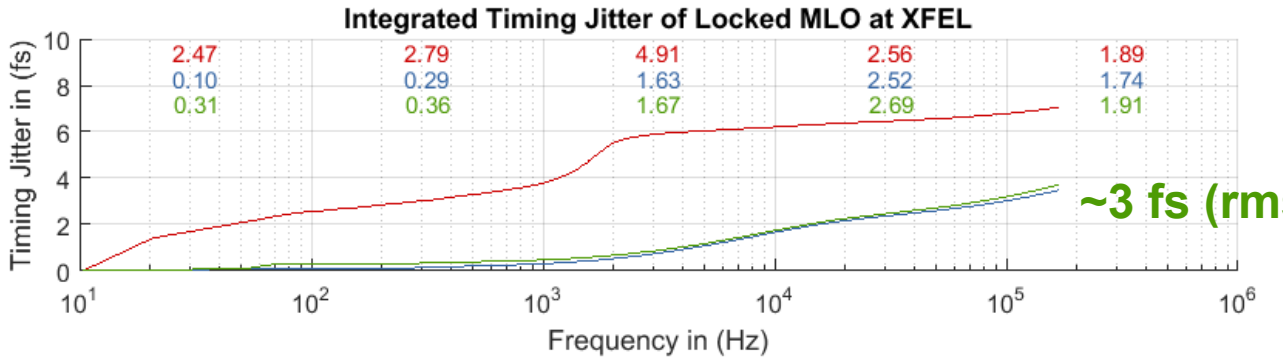


Synchronization System Reference

Master Laser Oscillator (MLO, SLO)

- commercial passively mode-locked fs laser
  - **repetition rate 216.7 MHz** = 1300/6 MHz
  - telecom wavelength 1550 nm
  - ultra-low phase noise
  - **24/7 operation**, redundant system
- 24-port free-space distribution (FSD)
  - SuperInvar optical table
  - **4 ns** optical delay line (8 stations)
- **~ 3 fs** (rms) timing jitter of lock to RF MO
  - novel scheme based on MZM
  - low-drift ~10 fs/24 h





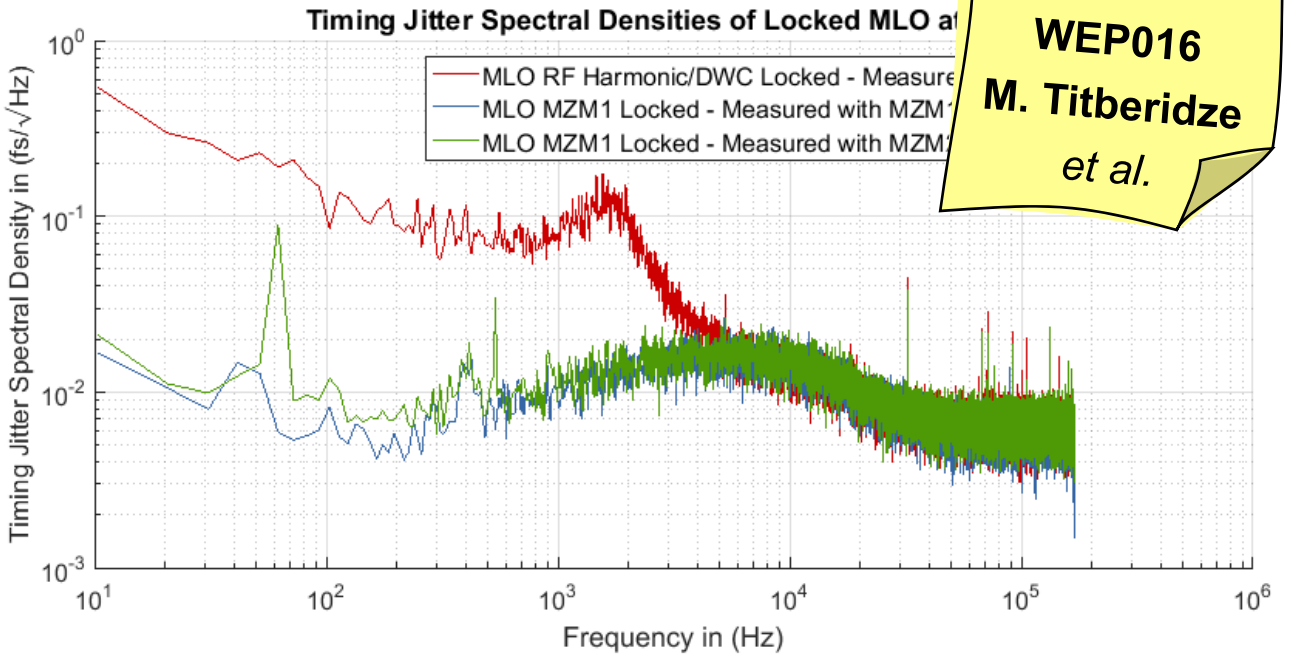
plot courtesy of M. Titberidze

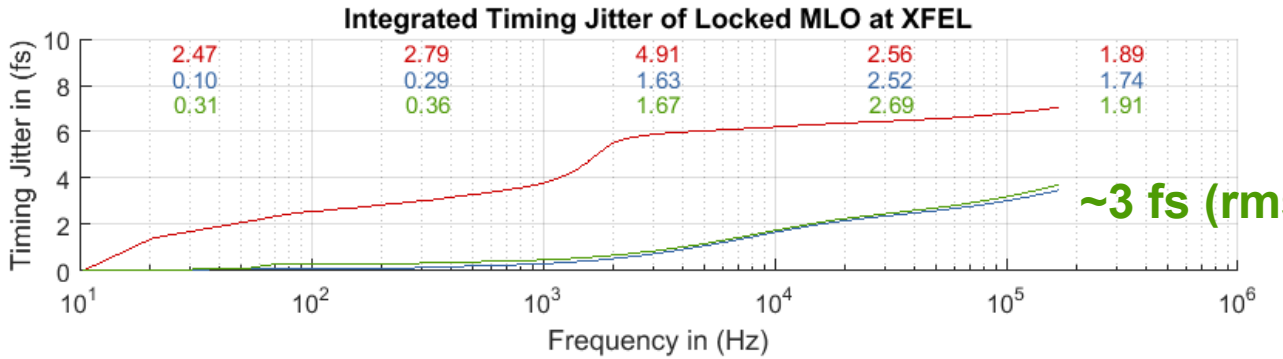
Synchronization System Reference

Master Laser Oscillator (MLO, SLO)

- commercial passively mode-locked fs laser
  - **repetition rate 216.7 MHz** = 1300/6 MHz
  - telecom wavelength 1550 nm
  - ultra-low phase noise
  - **24/7 operation**, redundant system
- 24-port free-space distribution (FSD)
  - SuperInvar optical table
  - **4 ns** optical delay line (8 stations)
- **~ 3 fs** (rms) timing jitter of lock to RF MO
  - novel scheme based on MZM
  - low-drift ~10 fs/24 h

laser lock poster **WEP016** **M. Titberidze** *et al.*



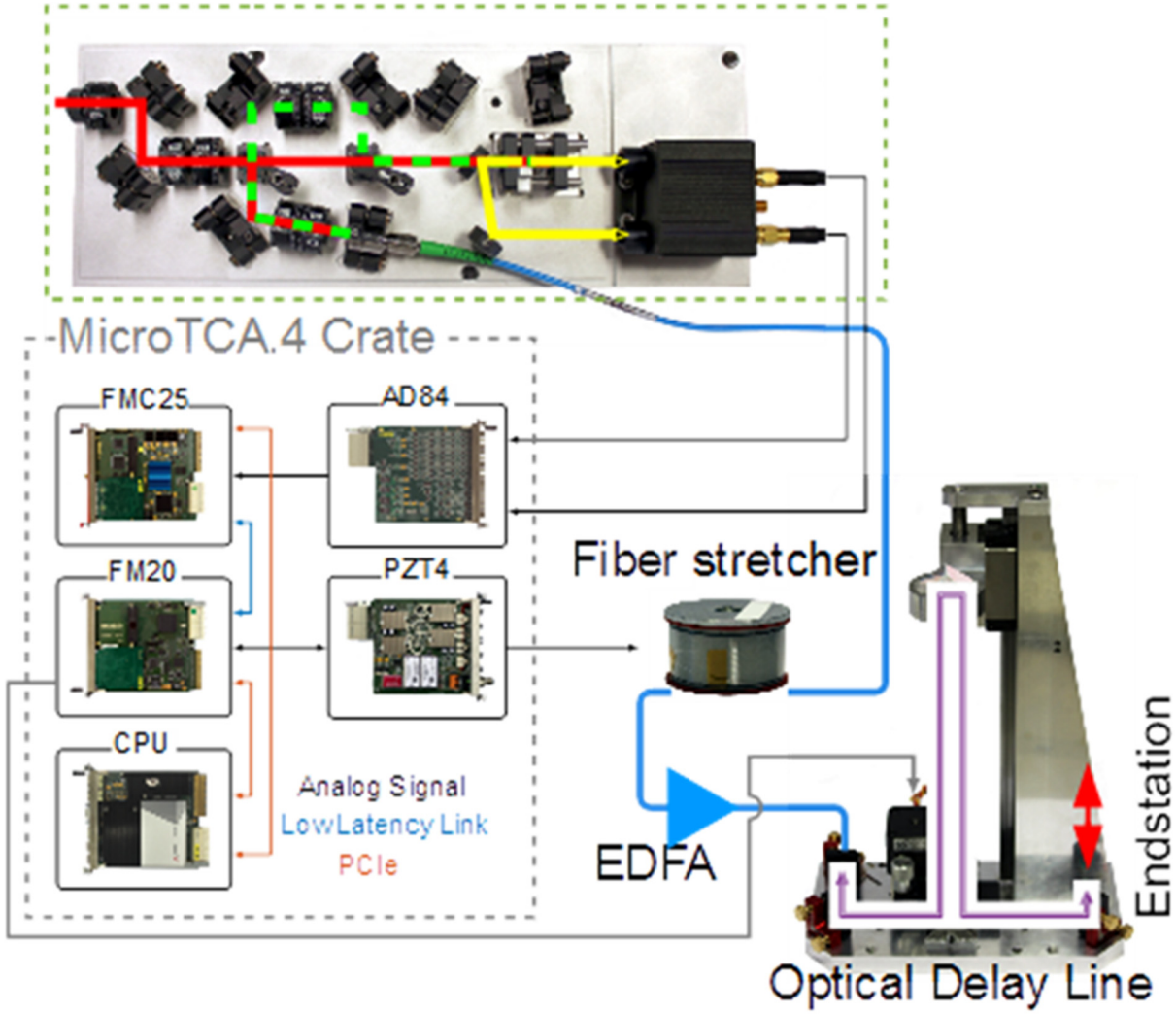


plot courtesy of M. Titberidze

Fiber Link Stabilization

Measurement and Compensation of Fiber Link Transit Time Variations

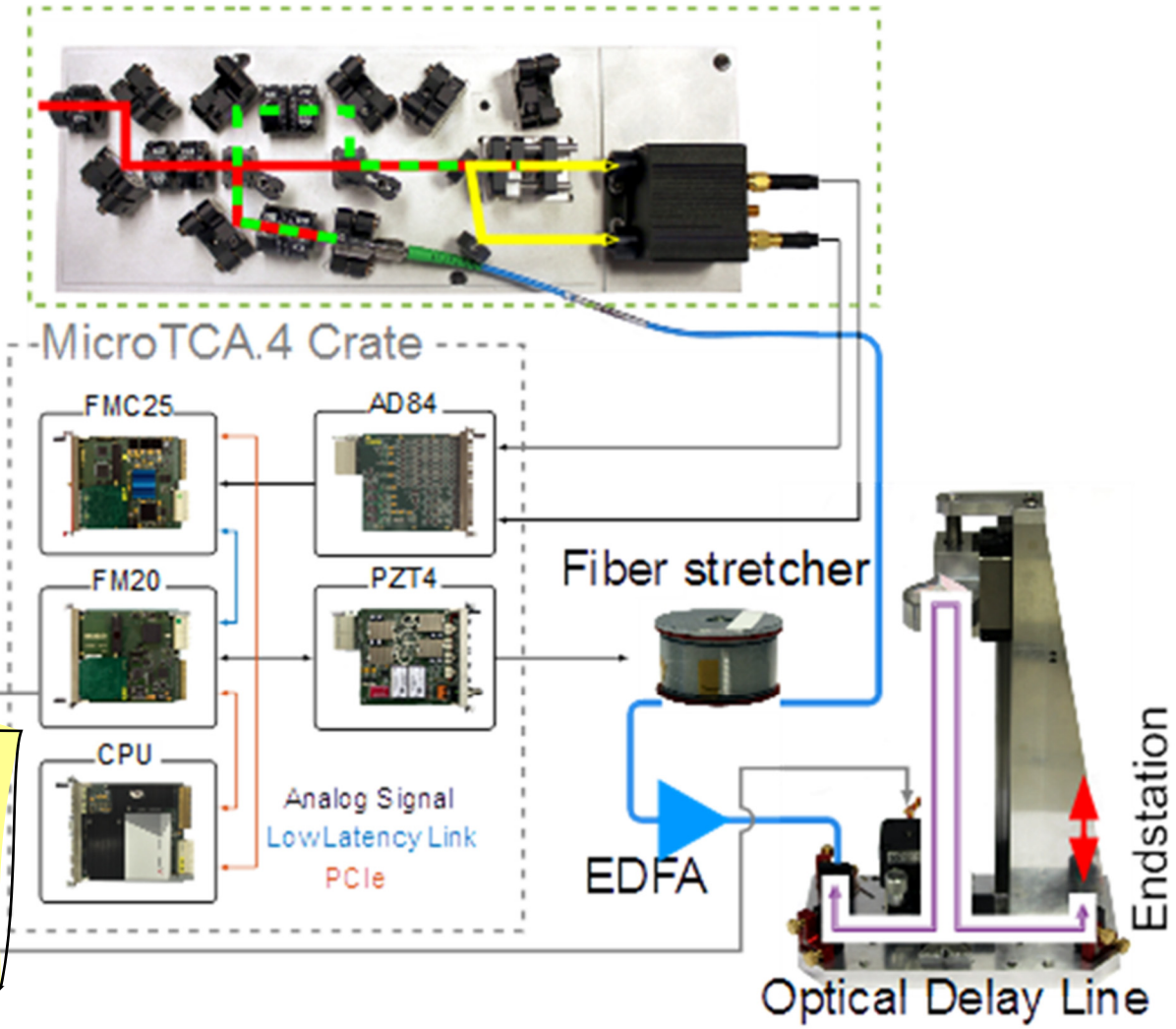
- balanced **optical cross-correlation**
  - insensitive to laser pulse amplitude fluctuations
  - typical slope 5 mV/fs
- **polarization-maintaining fibers** to mitigate timing errors caused by PMD
- self-built, low noise balanced photodetector (0.1 mV rms in 1 MHz bandwidth)
- **MTCA.4**: digitizer, FPGA-based controller, piezo- and motor drivers
  - piezo-based **fiber stretcher** (~ 3.5 ps range, fast)
  - **optical delay line** (4 ns, slow), self-built



Fiber Link Stabilization

Measurement and Compensation of Fiber Link Transit Time Variations

- balanced **optical cross-correlation**
  - insensitive to laser pulse amplitude fluctuations
  - typical slope 5 mV/fs
- **polarization-maintaining fibers** to mitigate timing errors caused by PMD
- self-built, low noise balanced photodetector (0.1 mV rms in 1 MHz bandwidth)
- **MTCA.4**: digitizer, FPGA-based contr… piezo- and motor drivers
  - piezo-based **fiber stretcher** (~ 3… range, fast)
  - **optical delay line** (4 ns, slow), s…



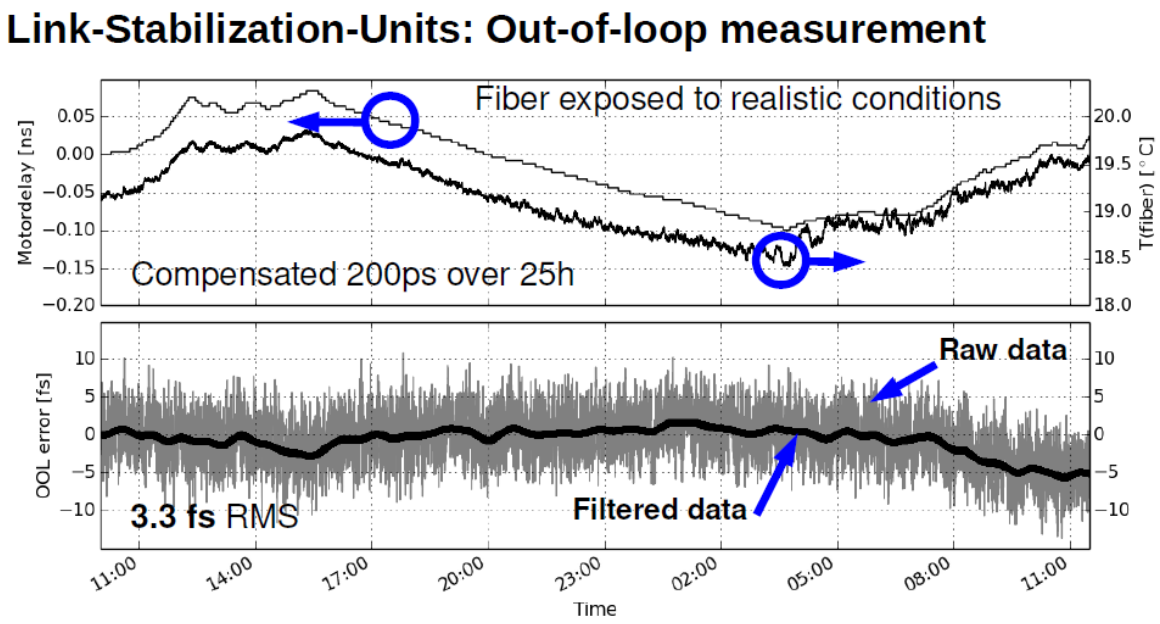
MTCA poster **WEP007** **M. Felber** *et al.*

Fiber Link Stabilization Results

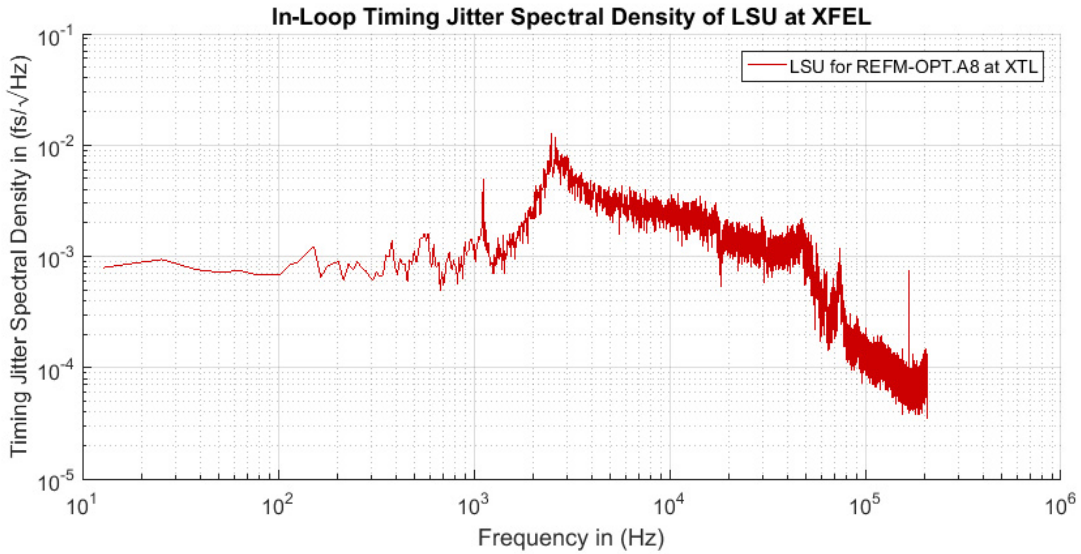
Performance Evaluation

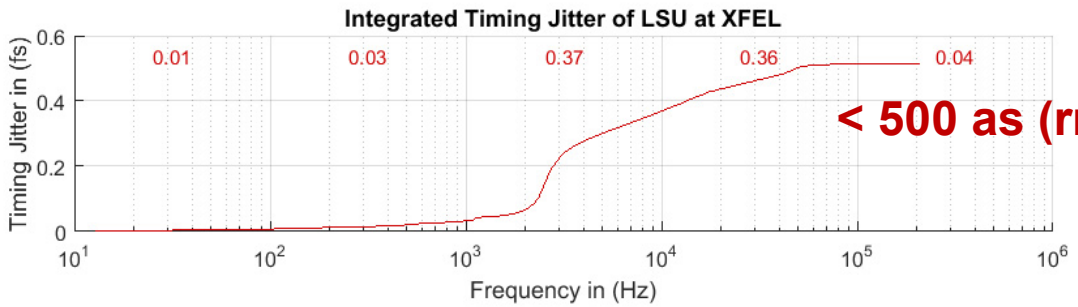
long-term (lab measurement)

- 3.3 fs timing error (rms, out-of-loop)
- observed and compensated drift at European XFEL **up to 200 ps/km**



short-term





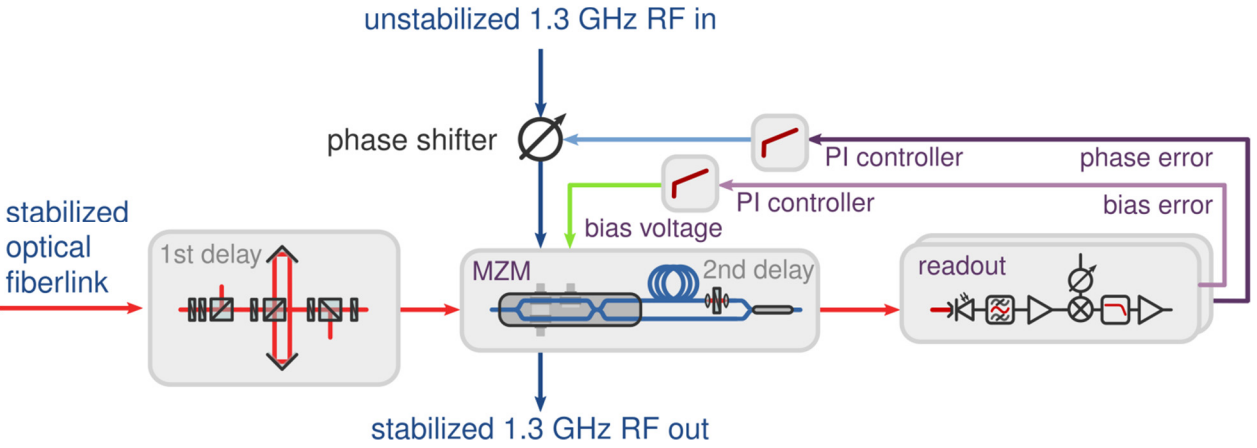
< 500 as (rms)

plots courtesy of C. Sydlo, T. Lamb

Accelerator RF Re-Synchronization

The REFM-OPT Module

- **drift-free, femtosecond accuracy** laser-to-RF phase detector based on MZM
  - optical pulse train “samples” the RF wave
  - **phase changes are translated into amplitude changes**
  - insensitive to source’s amplitude fluctuations
- **local re-synchronization of the 1.3 GHz RF** signal for accelerating cavities



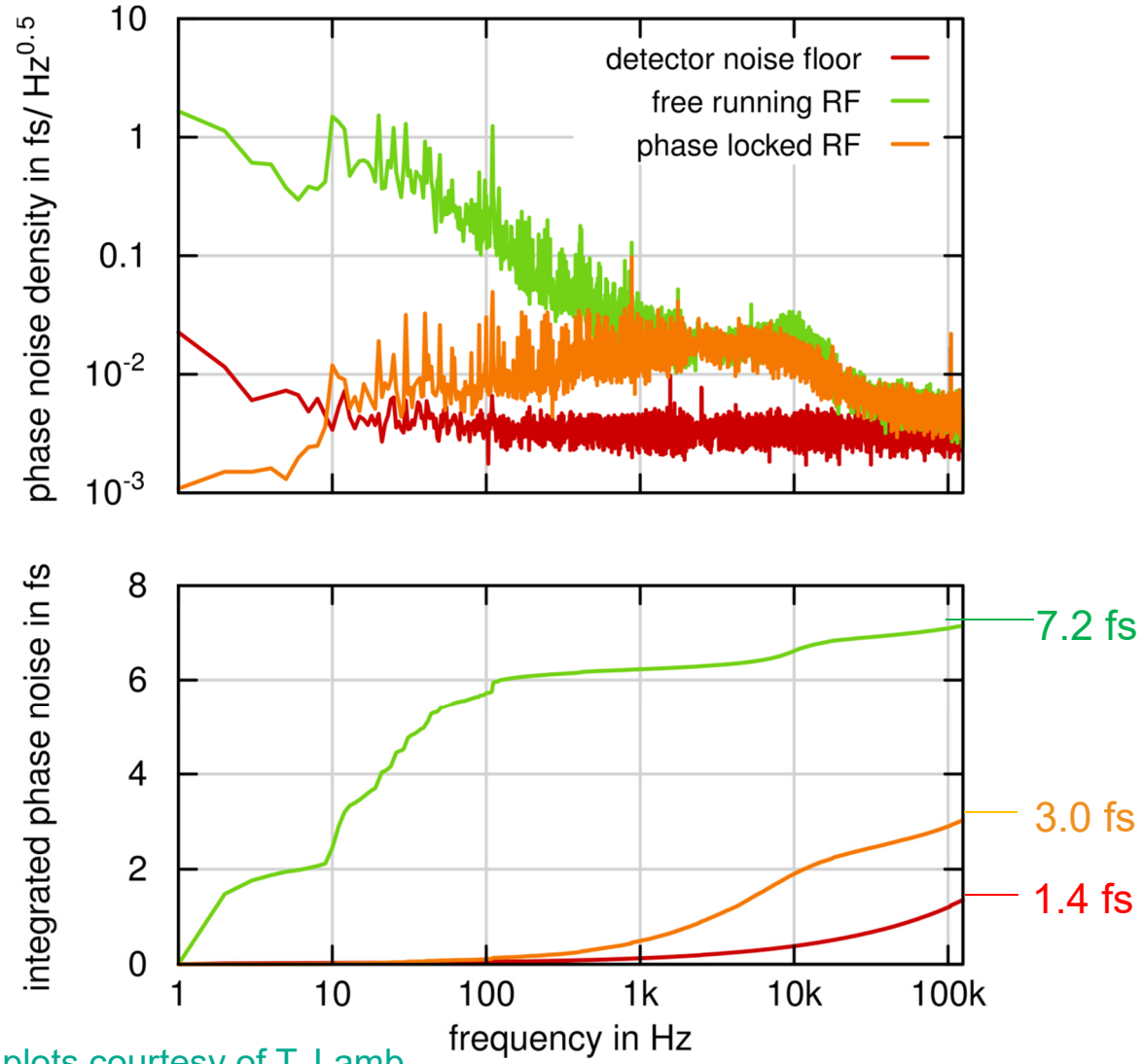
engineering

- fully integrated 19-inch module
- temperature and humidity stabilized optics part

illustrations courtesy of T. Lamb

Accelerator RF Re-Synchronization Results

The REFM-OPT Module



plots courtesy of T. Lamb

measurement bandwidth 1 Hz to 125 kHz

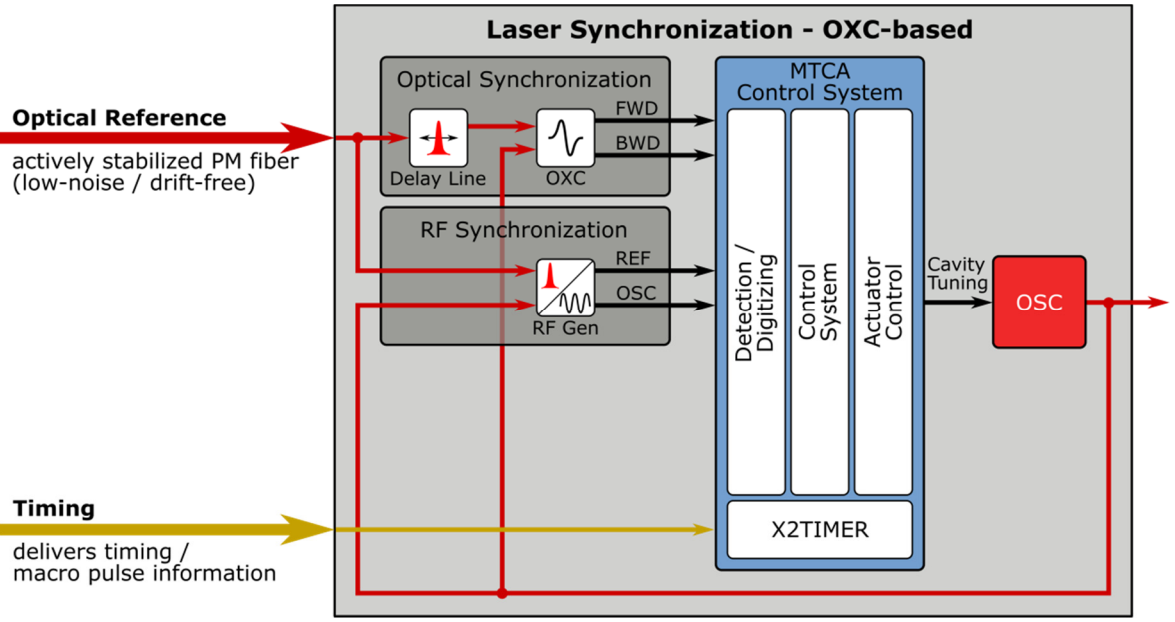
- in-loop
- K_φ of 3.1 V/ps
- integrated detector noise floor 1.4 fs (red)
- unlocked RF integrated jitter 7.2 fs (green)
- locked RF integrated jitter 3.0 fs (orange)

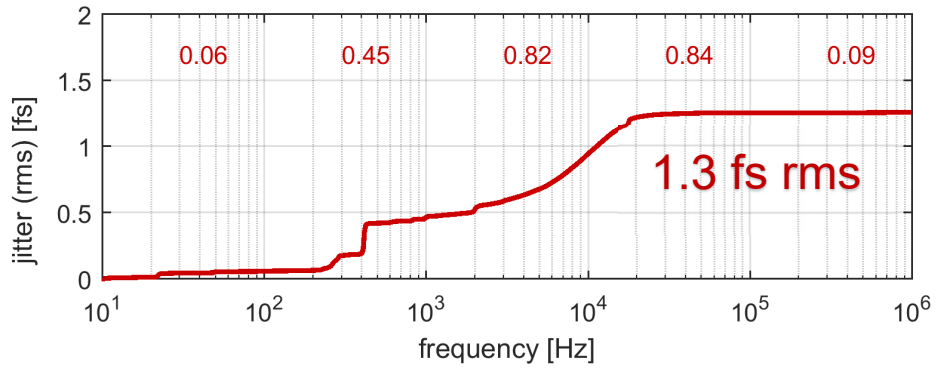
out-of-loop: poster WEP010 (this afternoon)

REFM-OPT
poster
WEP010
T. Lamb
et al.

Synchronization of External Lasers to Optical Reference

RF-Based or "All-Optical" Scheme





- **RF mixing** to an intermediate frequency (IF)
  - reference **1.3 GHz ⊗ (1.3GHz + f_{rep})** (from oscillator)
  - **IF** at **f_{rep} is digitized ⟶ phase** and magnitude
  - **allows for arbitrary phase set-point** in controller
  - EMI- and DC drift influence mitigated (no baseband)
- balanced **optical cross-correlation**
  - twofold **sum-frequency generation** in nonlinear crystal (BBO, KTP, PPLN, …)
  - **balanced, drift-free detection with high sensitivity**
- MTCA-based controller
- **adaptation to numerous different laser systems**
  - wavelength, repetition rate, pulse duration, actuators, lab conditions, burst mode, …

illustration courtesy of J. Müller

Synchronization of External Lasers to Optical Reference

RF-Based or “All-Optical” Scheme

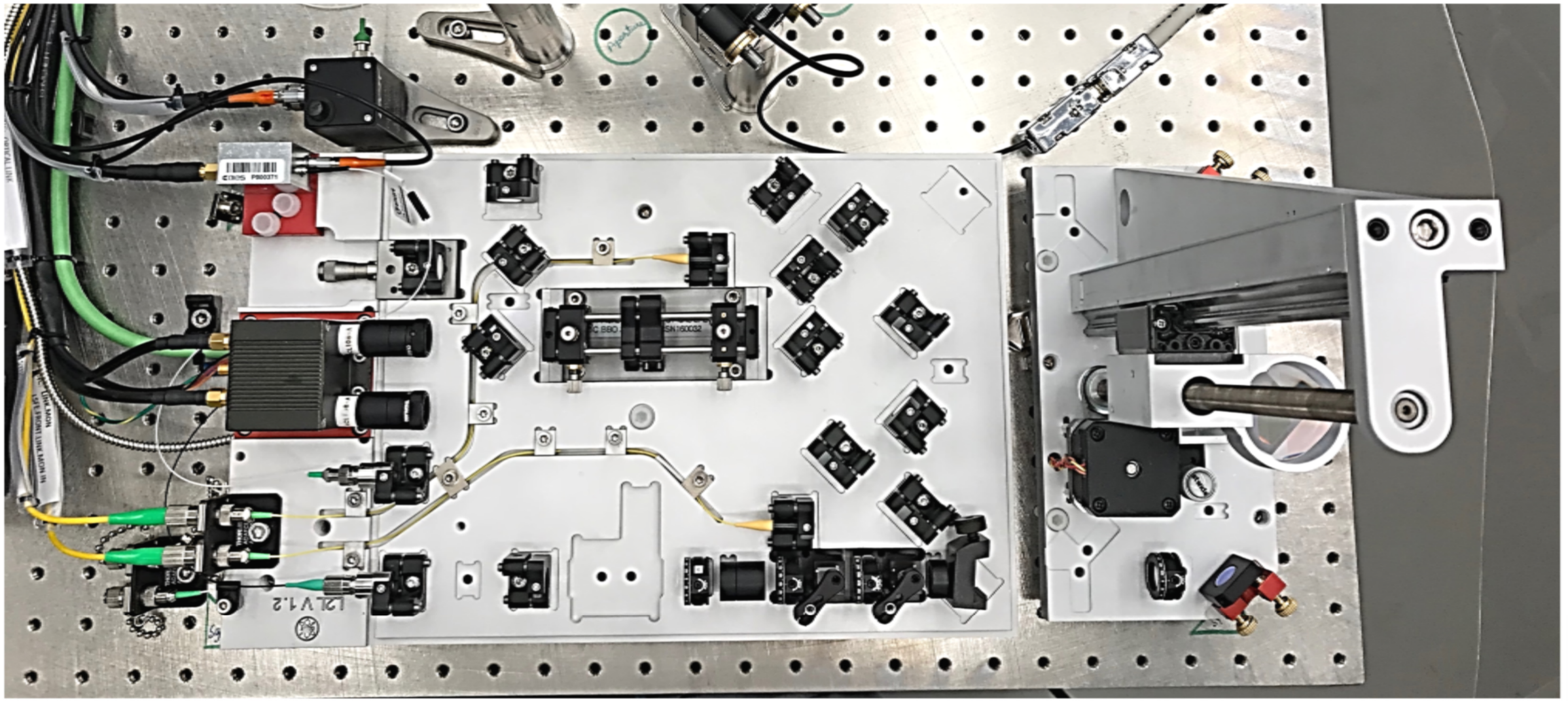
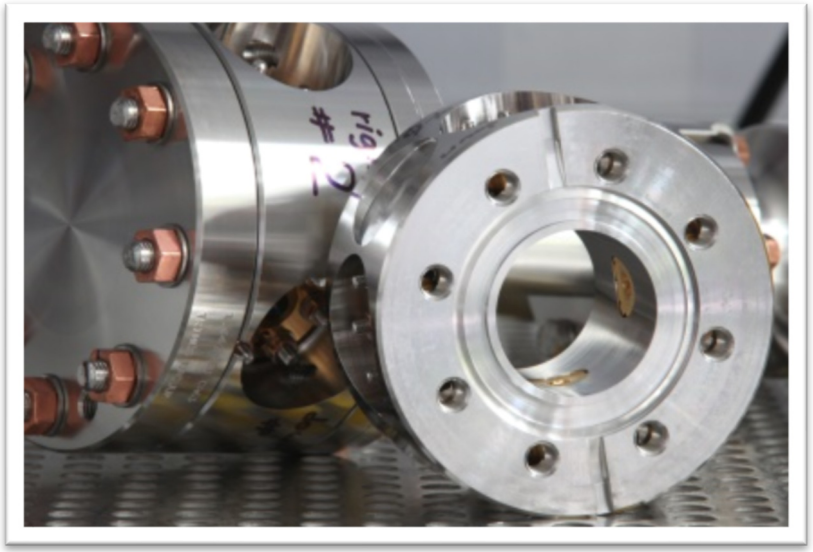


illustration courtesy of J. Müller

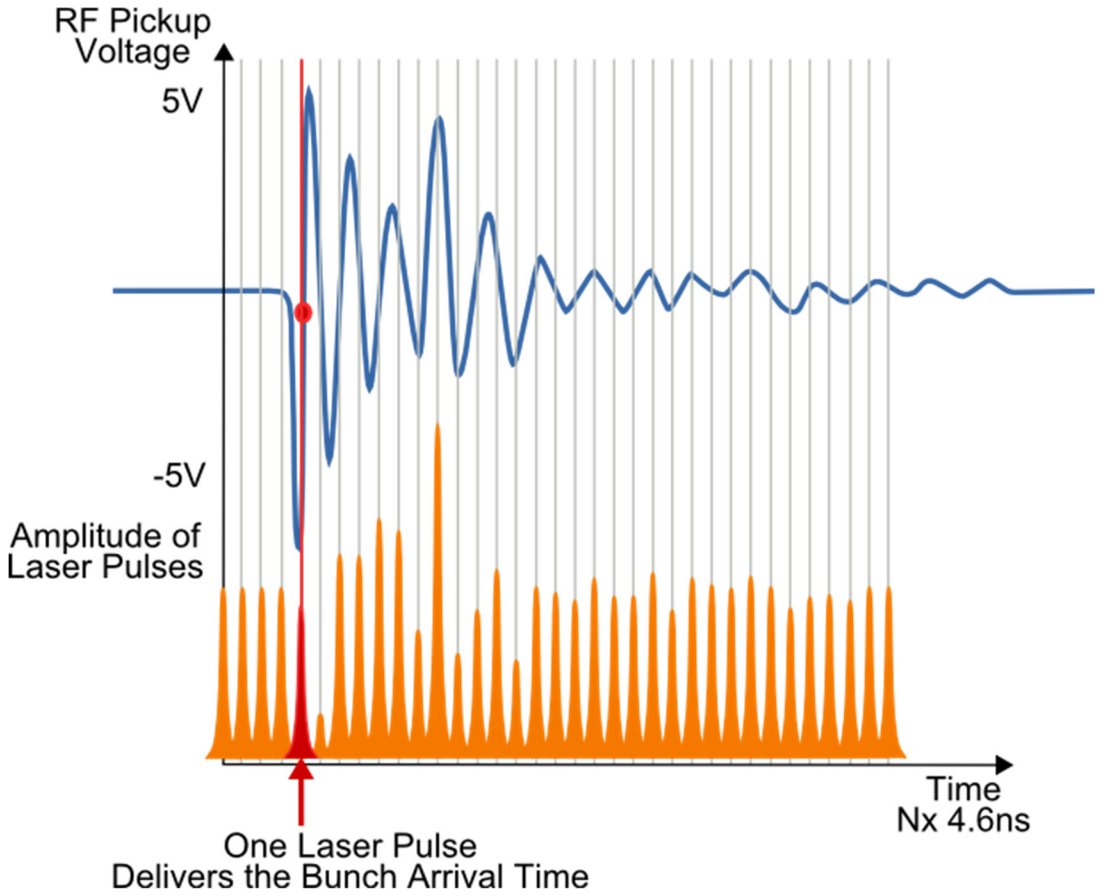
Electron Bunch Arrival Time Measurement

The "BAM" Principle

- **transient electric field** of e^- bunch is encoded into an **amplitude modulation of the laser pulse** train
- non-invasive, bunch-resolved
- broadband **40 GHz** pick-up (4 x per BAM)
- BAM signals applied in **slow- and fast feedbacks**



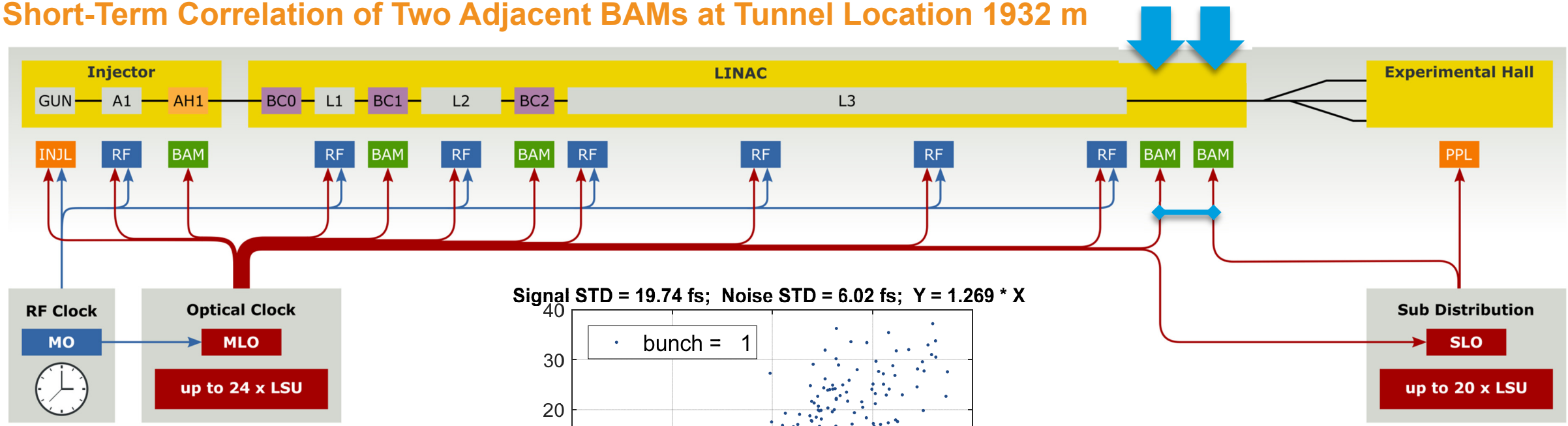
A. Angelovski *et al.* Phys. Rev. STAB **18**, 012801 (2015), illustration courtesy of M. K. Czwalinna

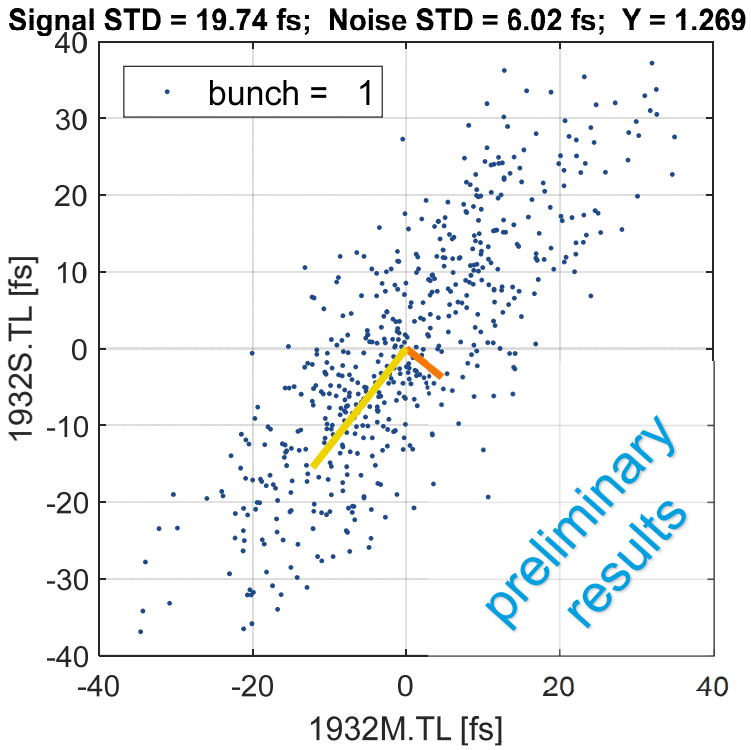


- sampling of amplitude modulation with fast ADCs
  - **single-shot processing** on MTCA/FMC boards

Facility-Wide Synchronization System Performance

Short-Term Correlation of Two Adjacent BAMs at Tunnel Location 1932 m



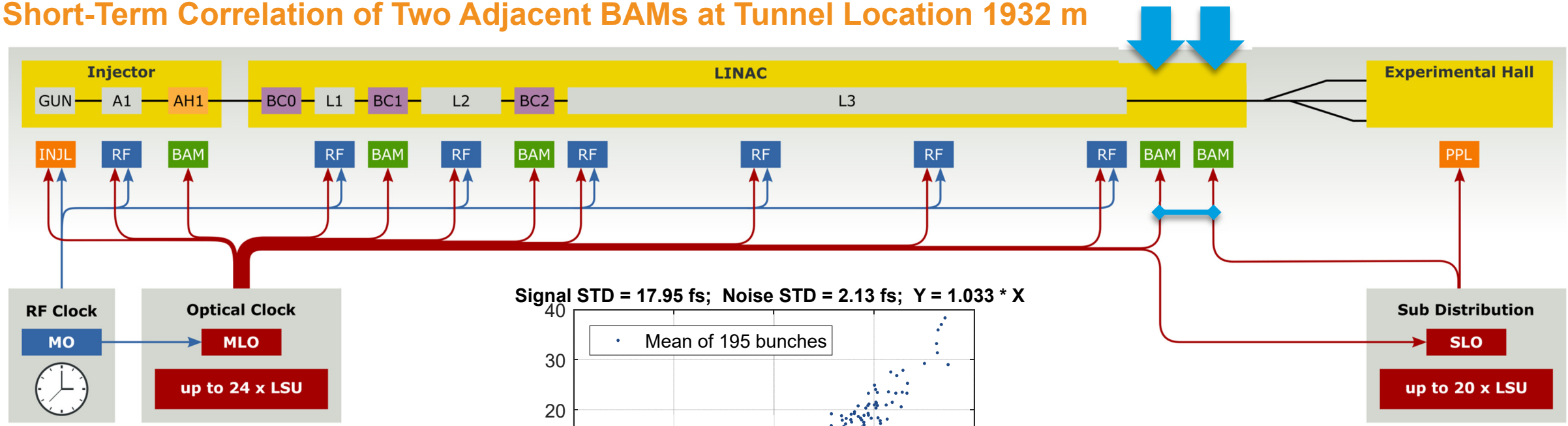


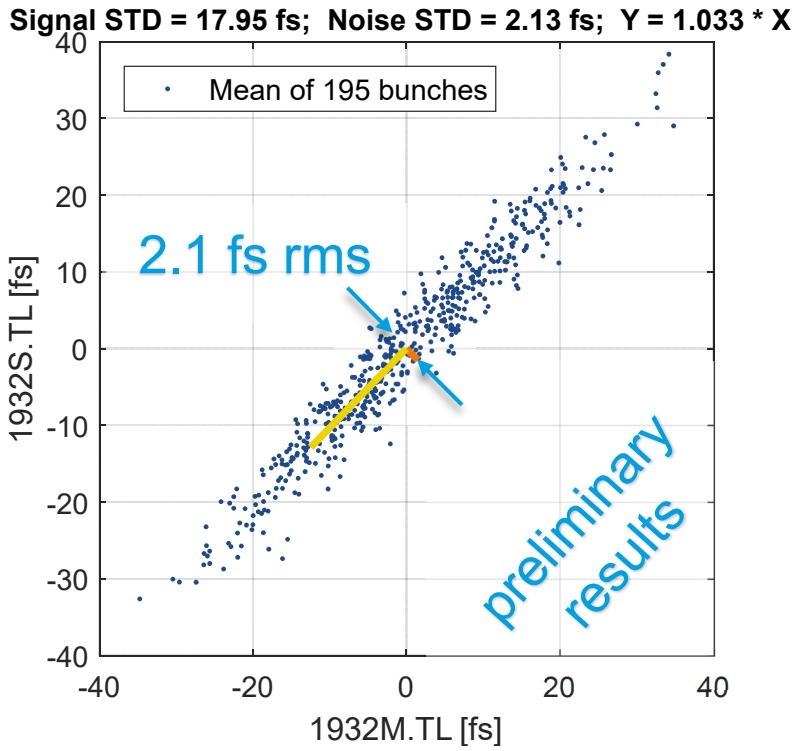
- 12 fs (rms) e^- arrival time jitter
  - macro-pulse to macro-pulse
- **6 fs (rms) correlation width**
  - **MLO, SLO, links, BAM**

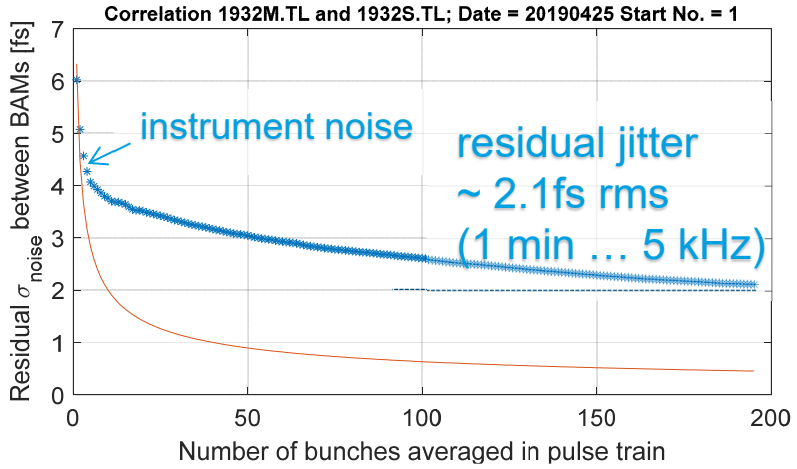
plots courtesy of H. Schlarb

Facility-Wide Synchronization System Performance

Short-Term Correlation of Two Adjacent BAMs at Tunnel Location 1932 m





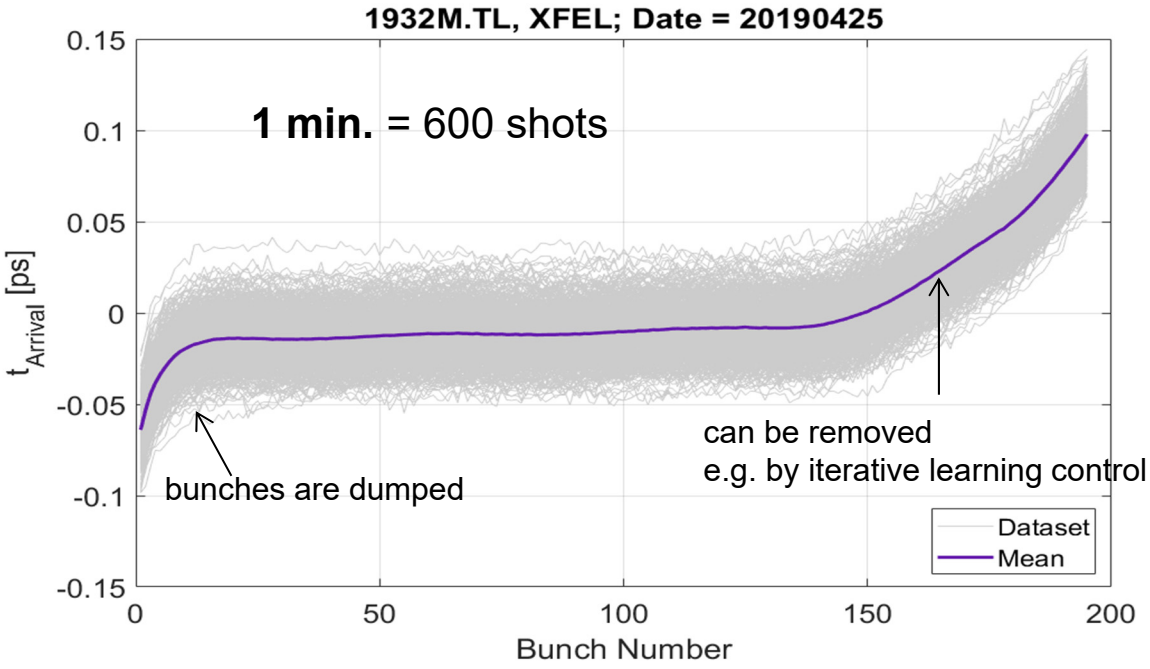


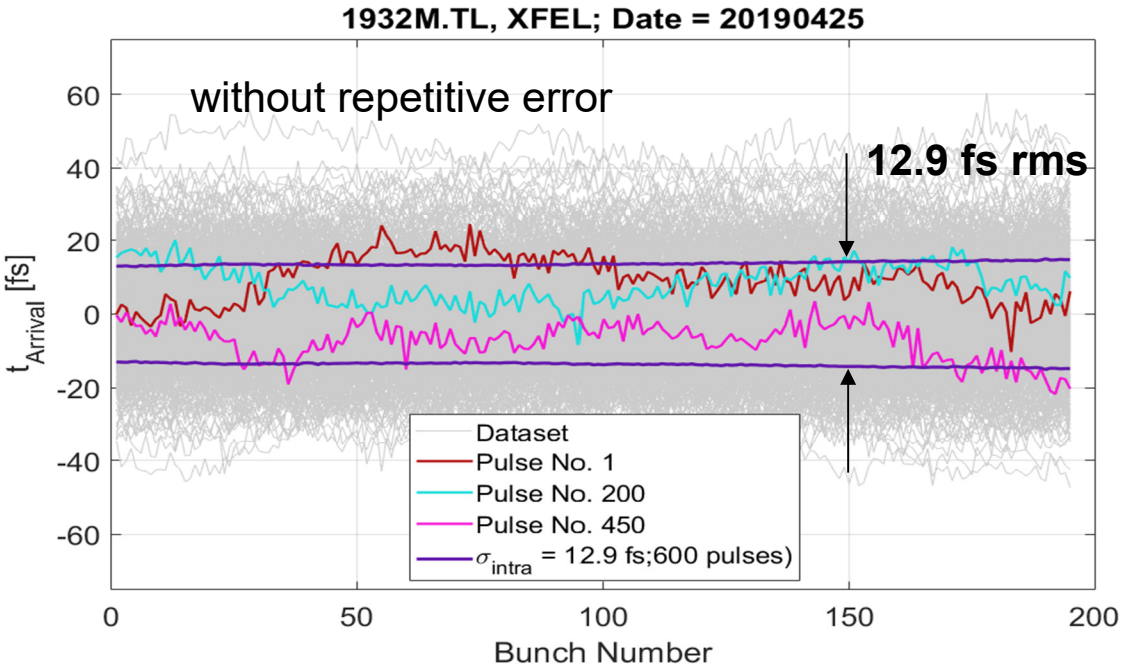
- 12 fs (rms) e^- arrival time jitter
  - macro-pulse to macro-pulse
- **6 fs (rms) correlation width**
  - **MLO, SLO, links, BAM**

plots courtesy of H. Schlarb

Short-Term Electron Bunch Arrival Time Jitter

Residual Arrival Time Fluctuations at End of Linac Without Any Longitudinal Feedback



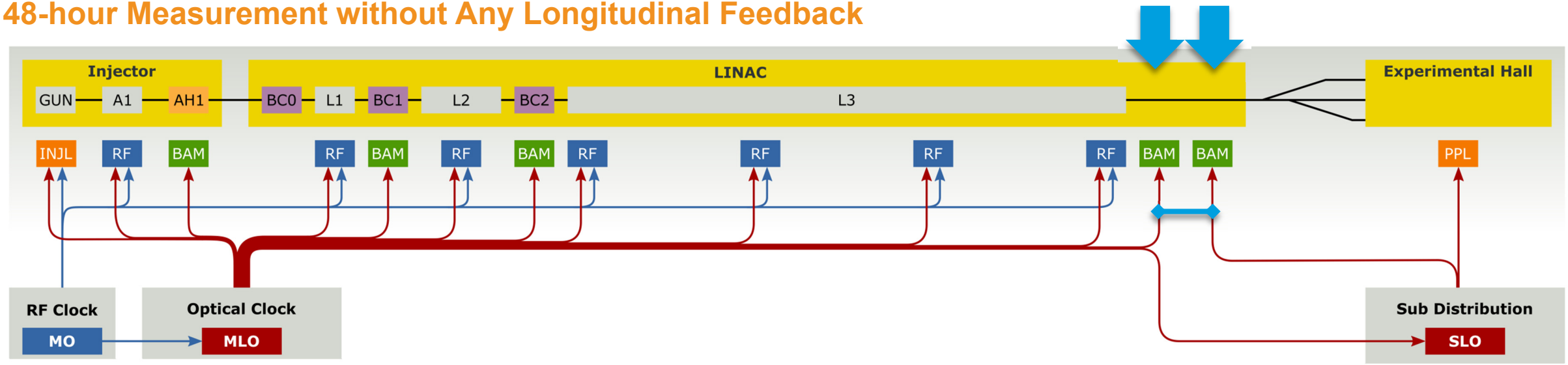


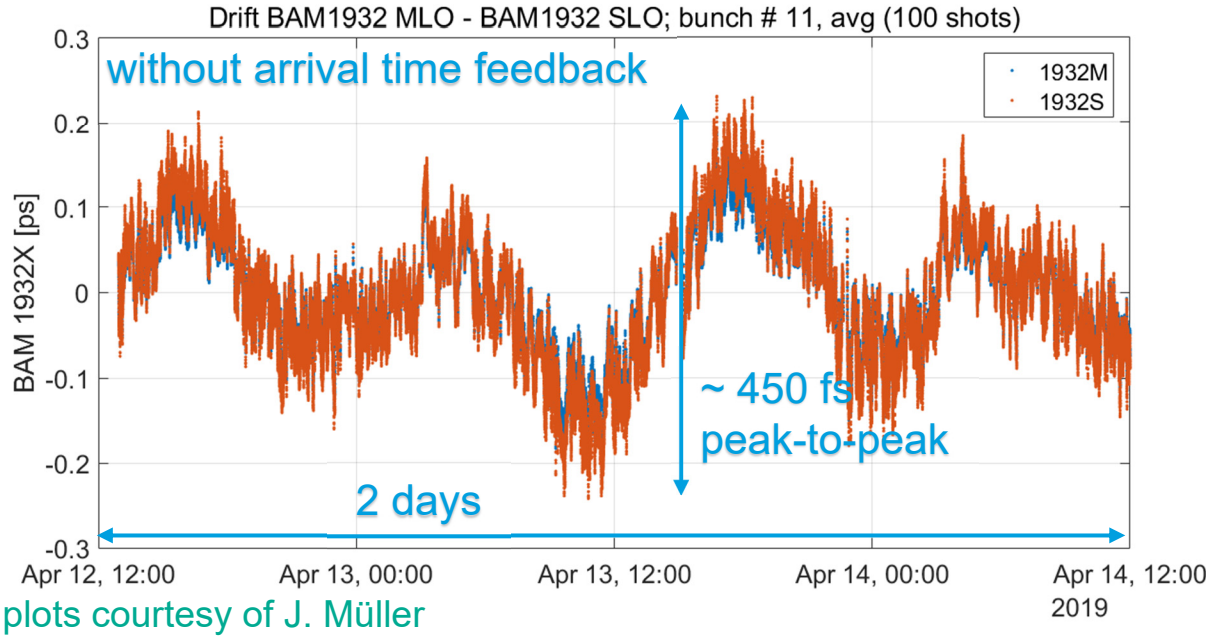
- arrival time of more than 110,000 bunches
  - 600 macro-pulses at 10 Hz, 195 bunches each
  - measured at 1932 m, link to MLO
- **12.9 fs rms arrival time jitter** across macro-pulse
  - no longitudinal feedback active
- **5 fs rms feasible** with feedbacks

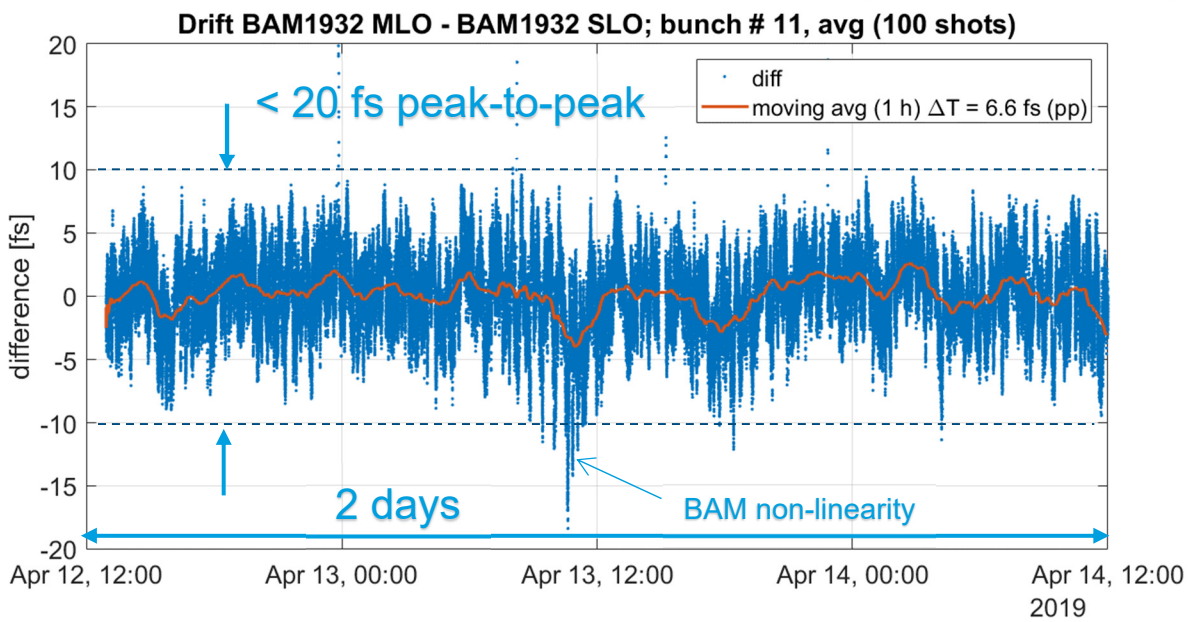
plots courtesy of H. Schlarb

Long-Term Electron Bunch Arrival Time

48-hour Measurement without Any Longitudinal Feedback







plots courtesy of J. Müller

Summary and Outlook

… and one more result

- **world's largest femtosecond-precision synchronization system** in operation
  - specifically designed and built with European XFEL in focus
  - almost every component is self-developed and optimized
  - based on pioneering works at FLASH
  - BAM-based **fast feedback** commissioning on-going
- **photo injector stabilization** & implementation to **slow feedback**
- investigations on remaining sources of drift, **final optimization of subsystems**
- **final installations in experiment hall** (laser synchronization)
  - future upgrade: 1550 nm at instruments → timing tool, drift stability
- timing tool campaigns → **~25 fs rms X-ray/optical timing jitter at SPB/SFX**, similar at **FXE**, **SQS**
  - T. Sato *et al.* **"Femtosecond timing synchronization at MHz repetition rates for an XFEL"**, *to be submitted "this week"*

photoinjector poster **WEP046** **A. Choudhuri** *et al.*

feedback poster **WEP009** **R. Kammering**

Thanks

Contact

DESY. Deutsches Elektronen-Synchrotron

Laser-based Synchronization Team
MSK

www.desy.de

lbsync-expert@desy.de