# Synchronisation and Beam Stabilisation – Midterm Plans –

## Mini Workshop – UKFEL/EuXFEL & DESY Collab.

Marie Kristin Czwalinna, Anne-Laure Calendron, Sebastian Schulz
on behalf of group for accelerator beam controls

5th of December 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# Optical Synchronisation &
# Beam-based Stabilisation

# @European XFEL

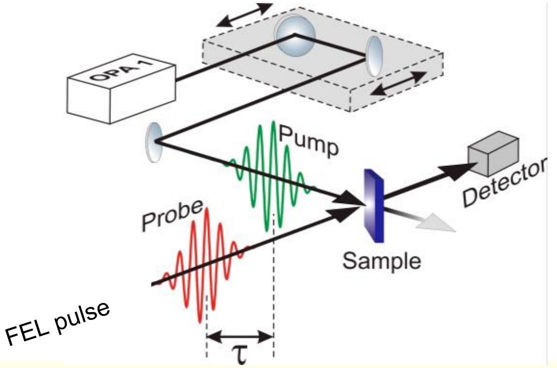
# Status

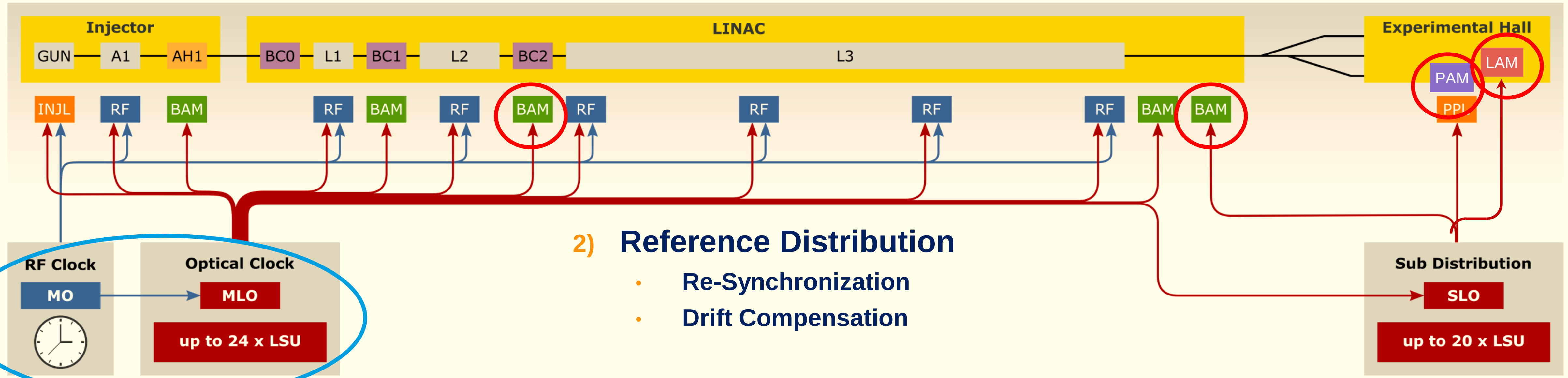
# Hybrid Synchronisation System

## RF Backbone + Optical Long-haul Links for Highest Performance.

- **Sources of timing jitter**
  - **Short range 1 us…1ms** PS, EMI, Material Properties, …
  - **Mid range 1ms…10s** Acoustic, Fans, Seismic, Air/Water flow,
  - **Long range 10s … days** Temperature, Rel. Humidity, Air Pressure, …

**Time-resolved, Pump-probe Experiments**




2) **Reference Distribution**
- Re-Synchronization
- Drift Compensation

1) **Reference Sources**
- Main RF Oscillator (MO)
- Main Laser Oscillator (MLO)

3) **Arrival-time Detection**

4) **Beam-based Feedbacks**

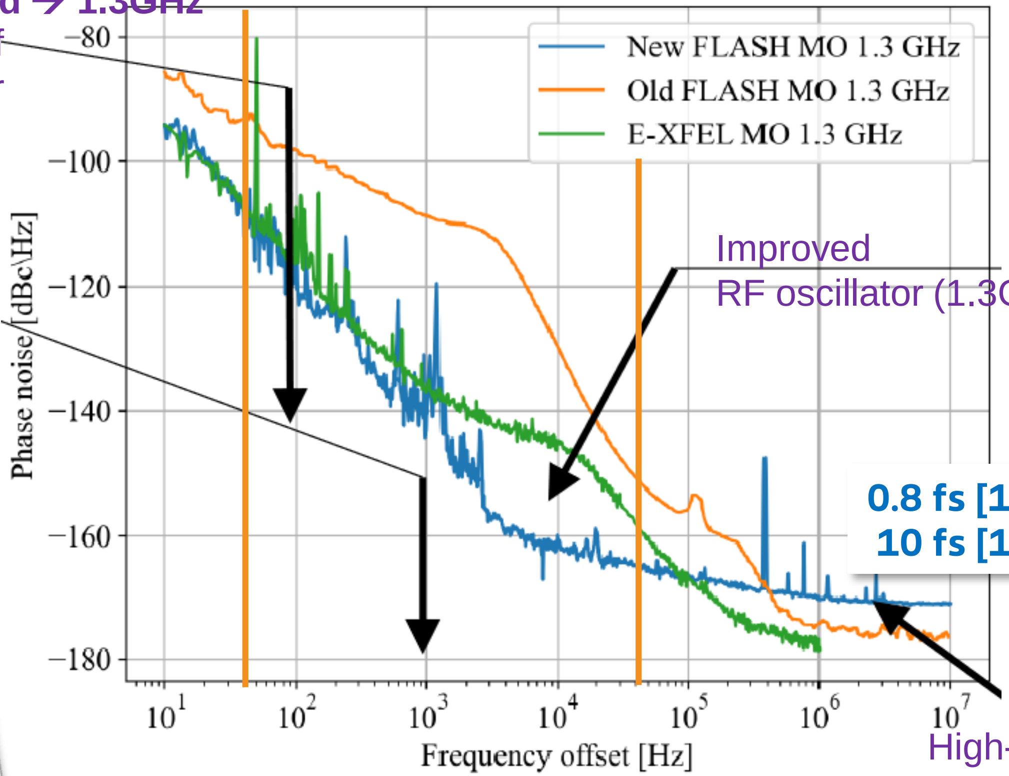
# Reference Sources

## Ultra-Low Absolute Phase Noise.

**MO** **RF Oscillator,**
**9MHz, GPS disciplined → 1.3GHz**

Choice of quartz clock oscillator

Vibration damping




(2022)
(2008)
(2018)

Improved RF oscillator (1.3GHz)

**0.8 fs [1kHz, 1MHz]**
**10 fs [10Hz, 1MHz]**

High-power amplifier (+46dBm), filtered by cavity

MLO is commercially available
https://kvg-gmbh.de

**Cooperation in between DESY and WUT**

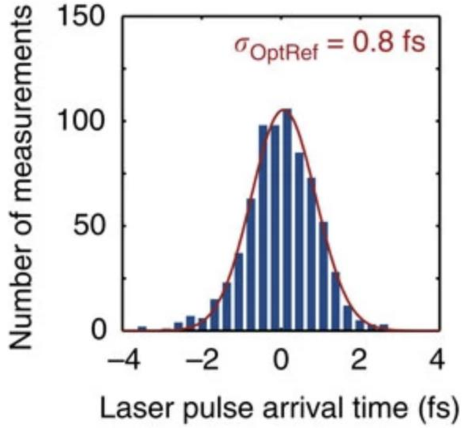
**MLO** **Laser Oscillator,**
**216 MHz** (= 1.3GHz/6)


- **Commercial laser** oscillator;
- 1550 nm , soliton-like pulses,
- Ultra-low phase noise,
- **24/7 operation,**
- 2x MLO for **redundancy** with fast switching

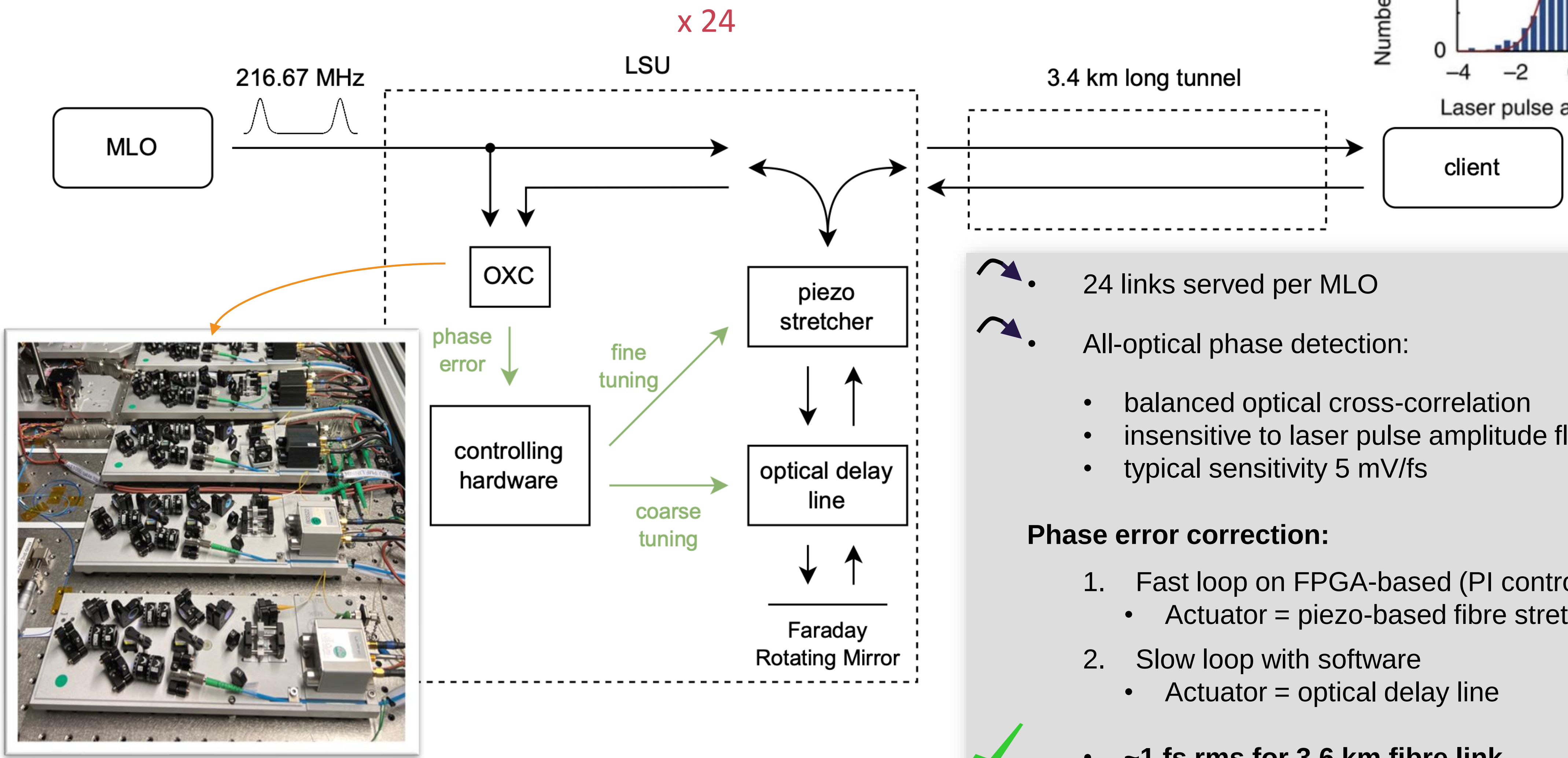
**Courtesy: F.Ludwig, H. Pryschelski, T. Lamb**

# Pulsed Optical Reference Distribution

## Round-Trip Time Stabilised Fiber Links.




Schulz *et al.* DOI:10.1038/ncomms6938




- 24 links served per MLO
- All-optical phase detection:
  - balanced optical cross-correlation
  - insensitive to laser pulse amplitude fluctuations
  - typical sensitivity 5 mV/fs

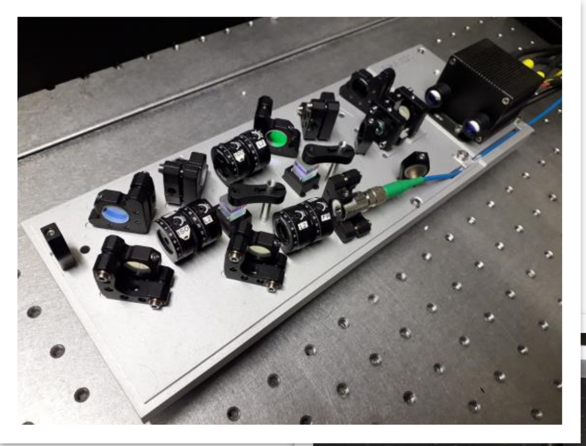
**Phase error correction:**

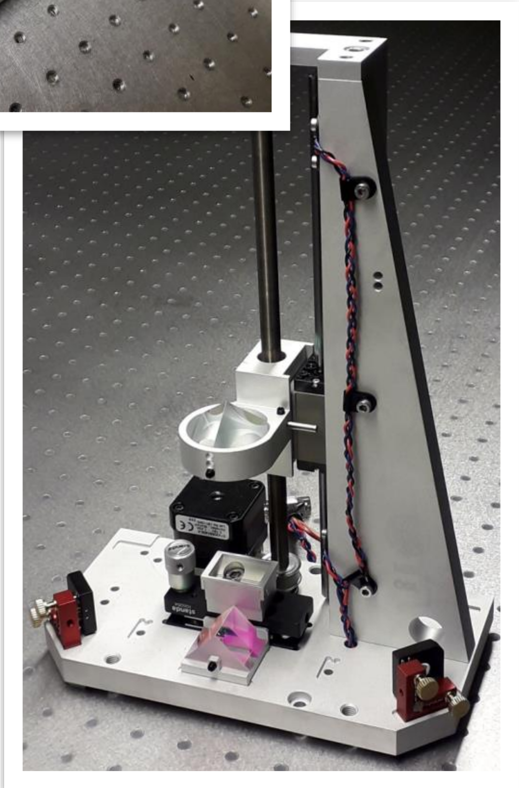
1. Fast loop on FPGA-based (PI controller)
   - Actuator = piezo-based fibre stretcher, **~kHz BW**
2. Slow loop with software
   - Actuator = optical delay line

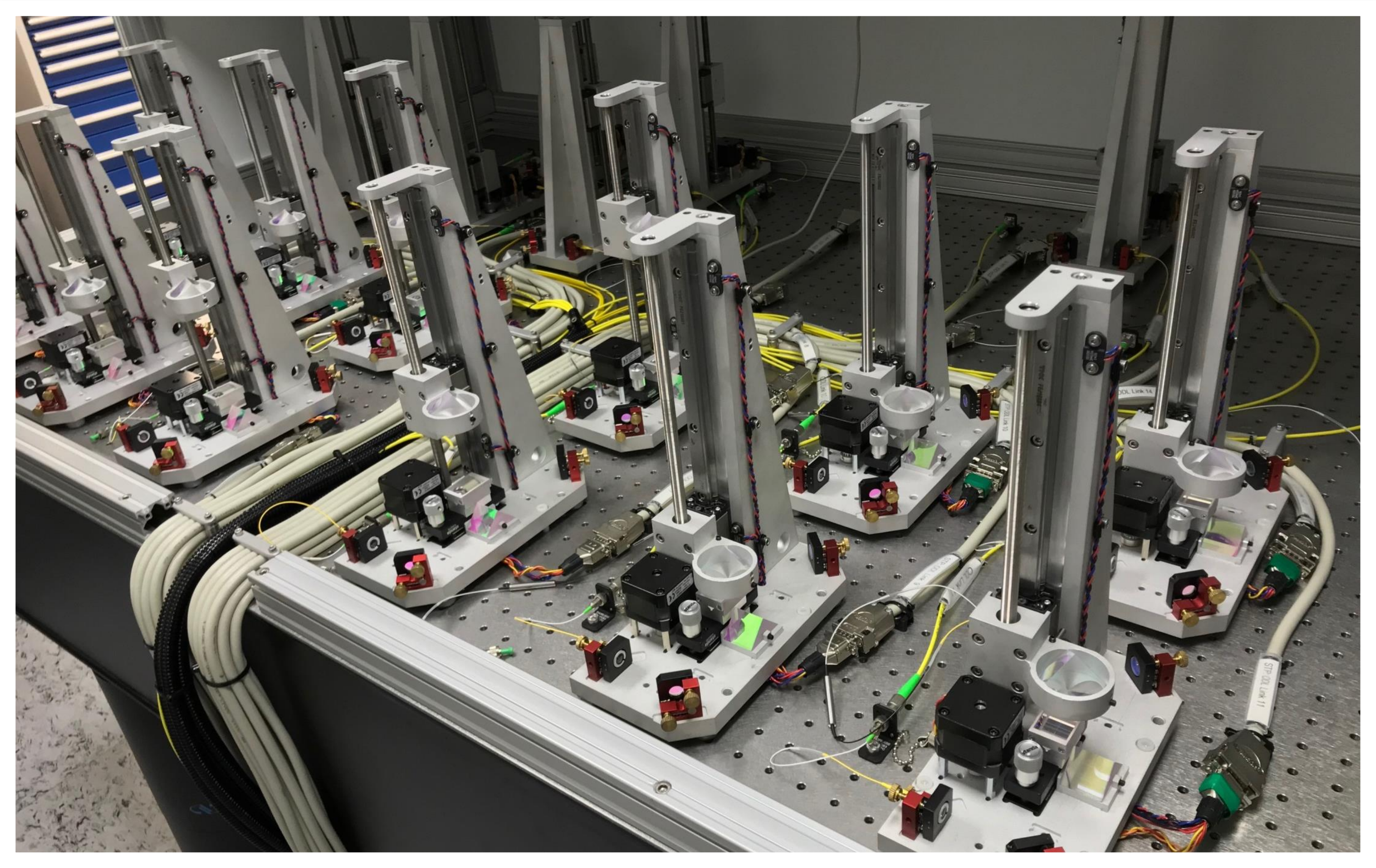
- **~1 fs rms for 3.6 km fibre link**

# Link Stabilization Units – Optical Building Blocks

## Measurement and Compensation of Fiber Link Transit Time Variations



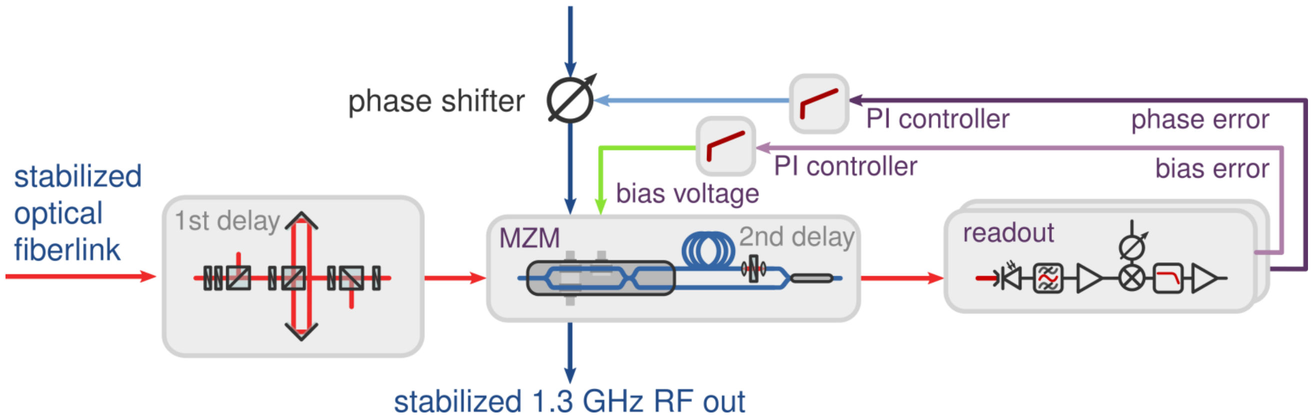




Courtesy: J. Mueller

# MZM-based, Balanced Laser to RF Phase Detector

## Tightly Phase-locking RF and Optical Oscillators.




**REFM-OPT Design:**

- MZM-based laser-to-RF phase detector,
- 19'' module,
- Fully engineered,
- Automated controls.

**Typical performance of PLL:**

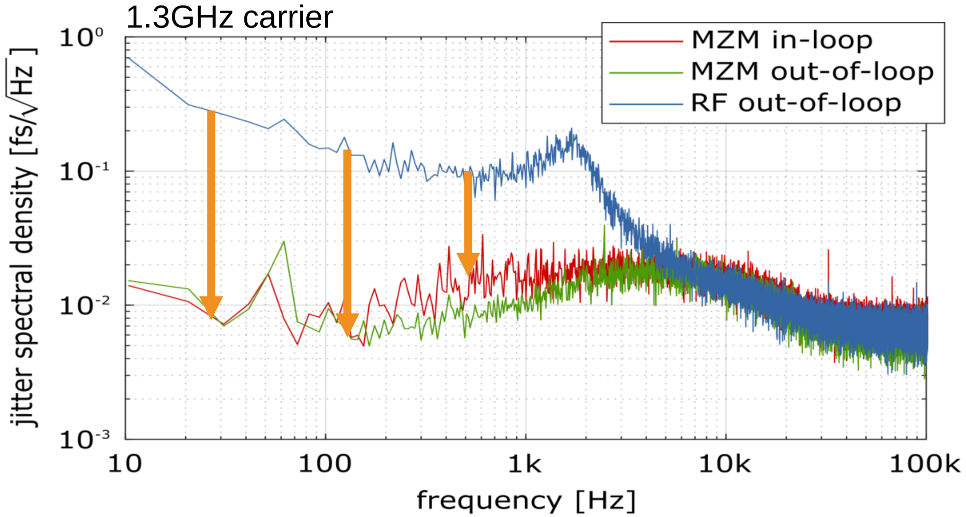
Low-noise : ~**3 fs rms**

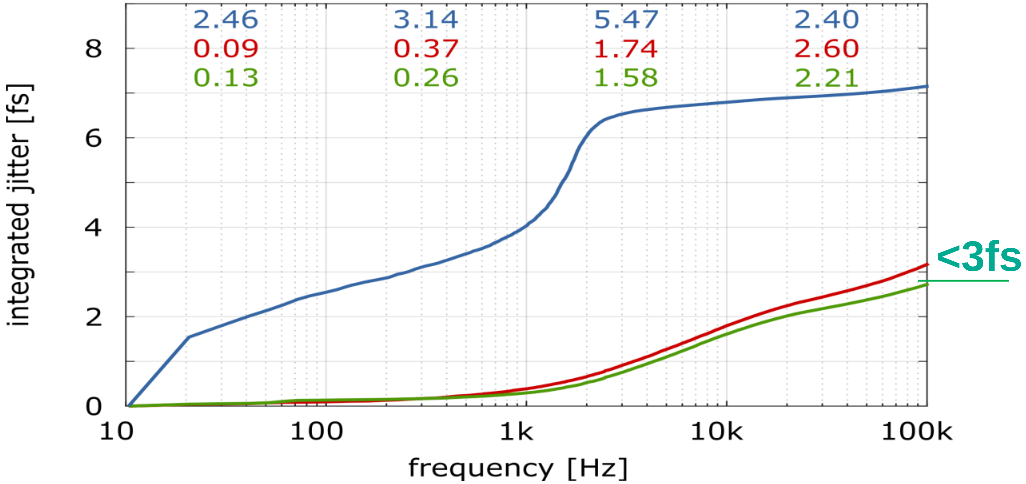
Ultra-low-drift : **< 2 fs pk-to-pk over 1 week**

**Applications**

- **MLO to MO locking**
- **RF resynchronization**
  - **at location of RF modules**
  - **locking bw <1kHz**
  - **Removal of phase drifts from RF distribution**

MLO –to – MO PLL



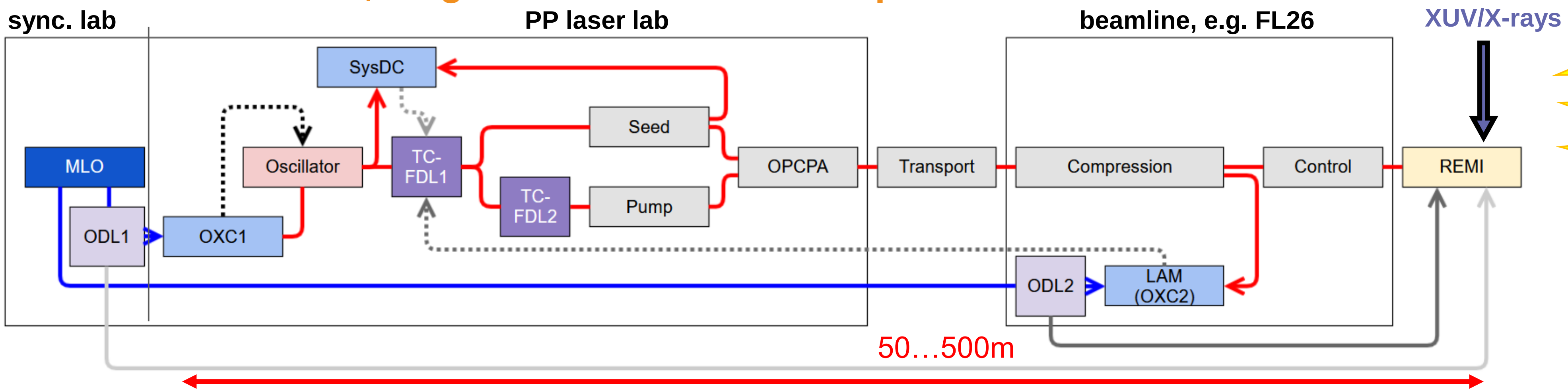




*T.Lamb et al, IPAC 2019, doi:10.18429/JACoW-IPAC2019-THPRB018*

Courtesy: T. Lamb

# Laser Pulse Arrival Time Monitors

## Drift correction with fs, single-shot Laser-to-Laser phase detector.



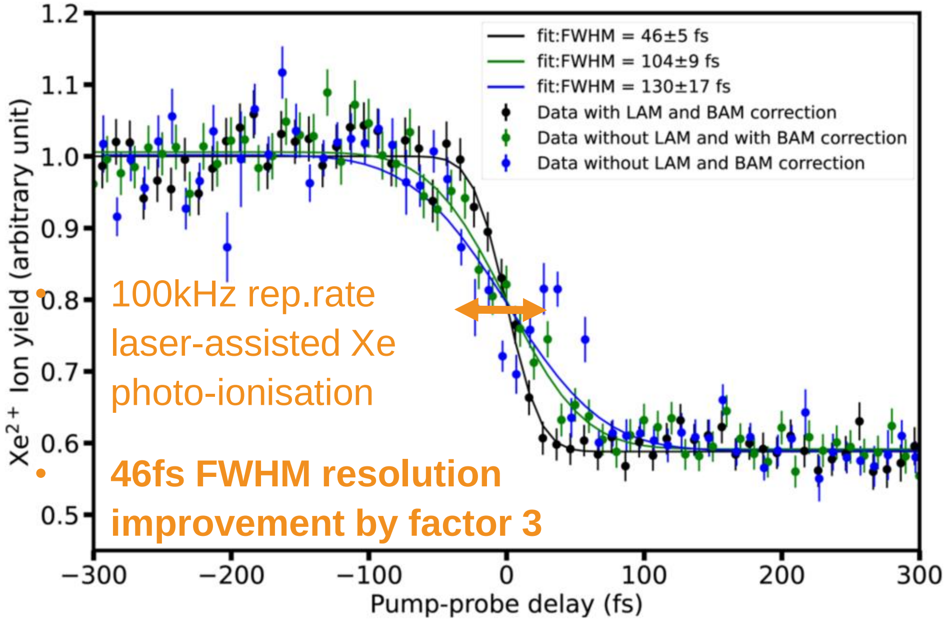

**Air pressure**

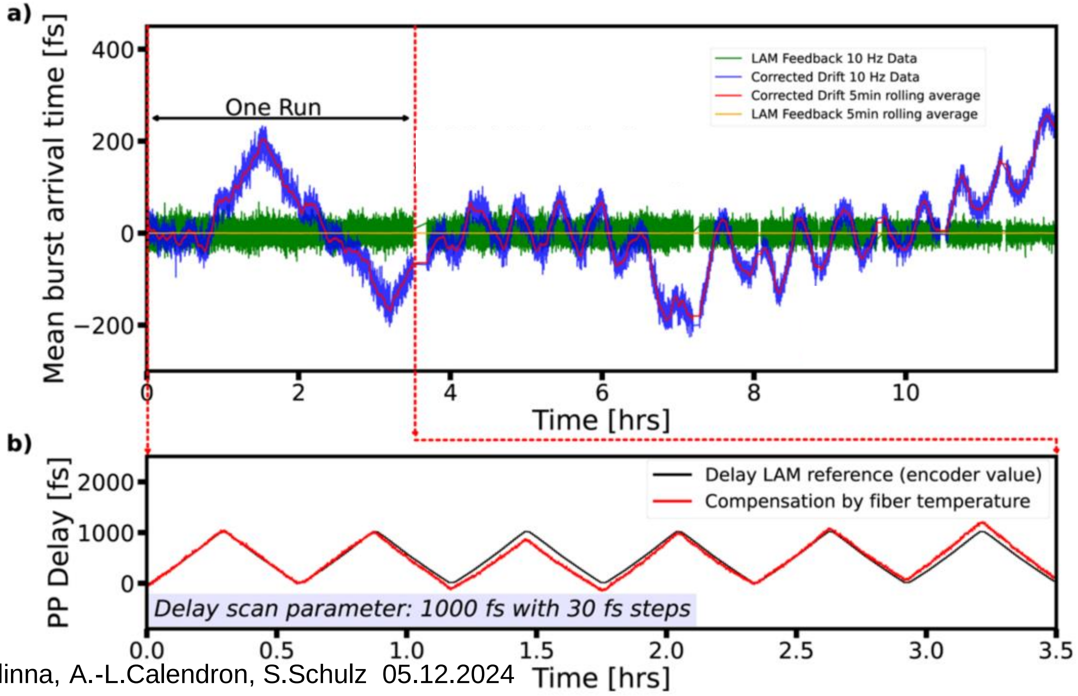
**Rel. humidity**

**Temperature**

**LAM:**
Nonlinear optical mixing for laser-to-laser phase detection.

**LAM FB,**
Removal of T0 drift.



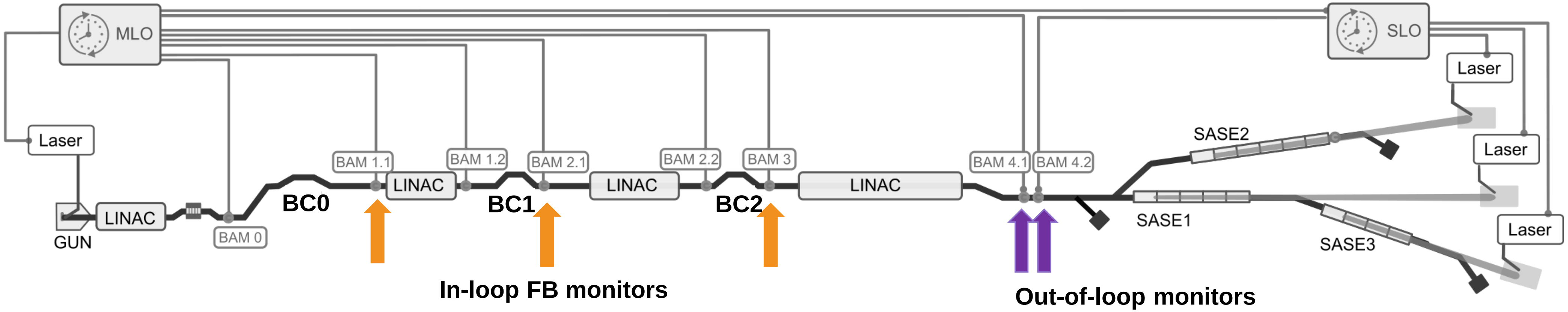



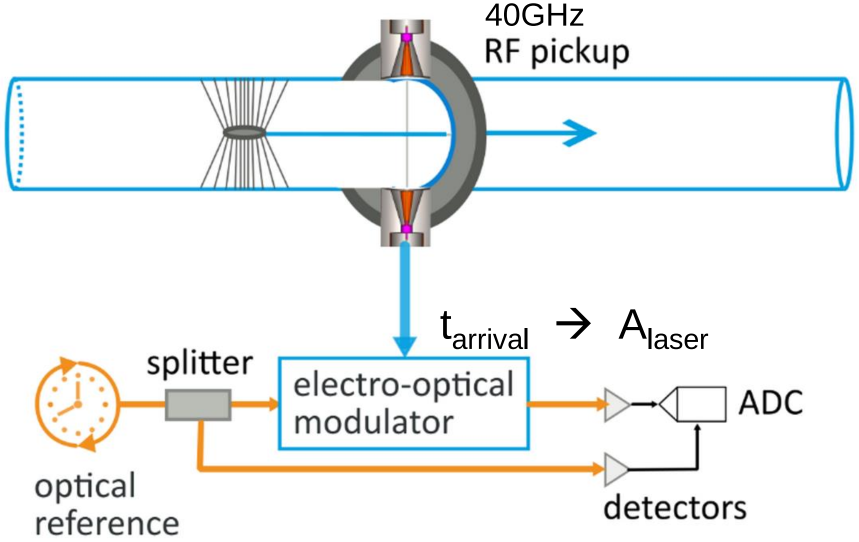

**Compensated drift: ~500 fs pk-pk**

**Remaining**
- ✓ **<1fs drift**
- ✓ **~10fs rms jitter**

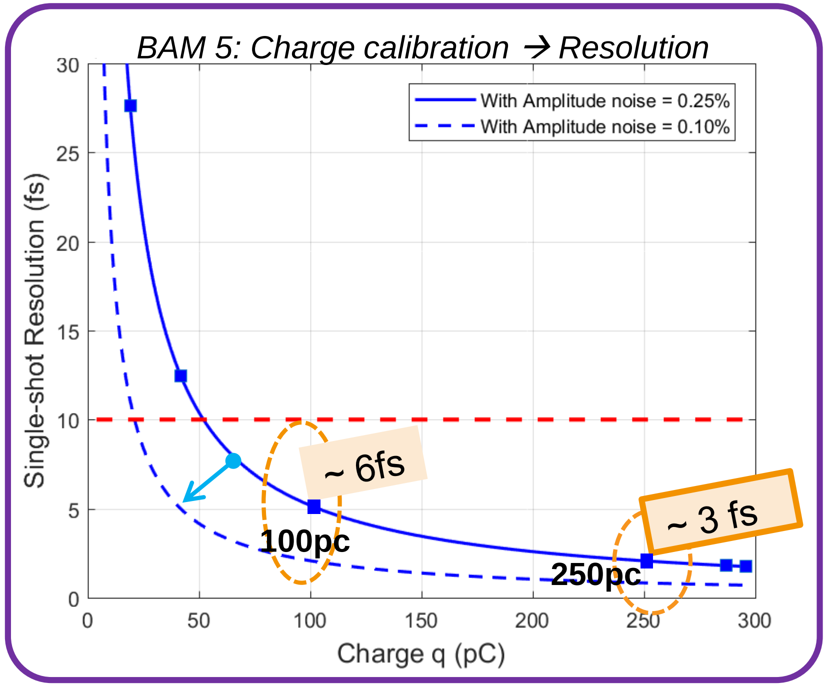
# Electro-optical Bunch-Arrival-time Monitors

## Few femtoseconds single-shot resolution.

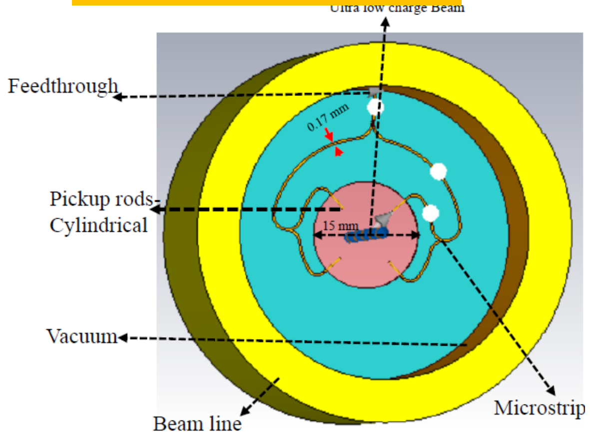



Typical resolution **3 fs** (250pc)



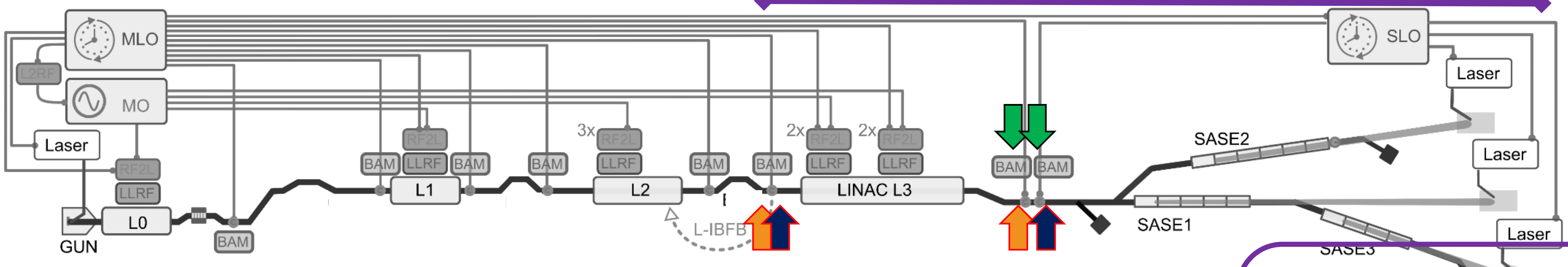

**Goal: 1 fs @1pC**




100GHz BAM

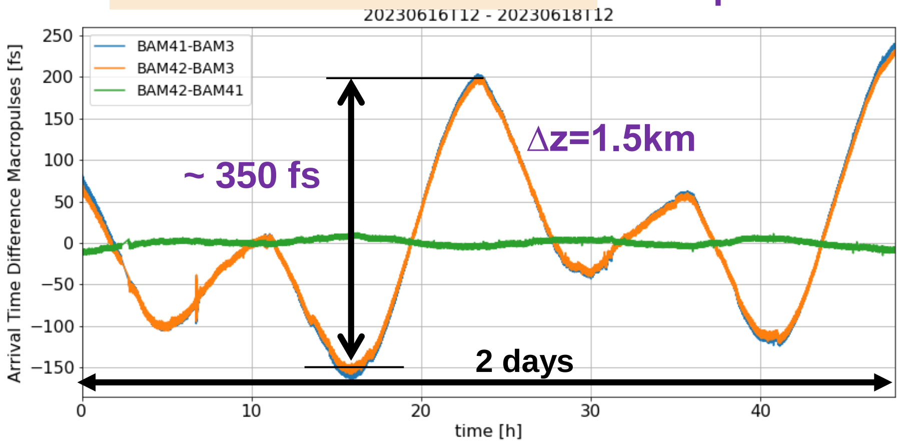
# Observation : Seismic and Micro-Seismic Effects (< 1Hz)

## EuXFEL Facility is Periodically Stretched and Compressed from Earth and Ocean Tides.




- 0.1…0.2Hz
- adds ~2.8 fs rms over min.

Tidal waves of Earth & Ocean ~12h period

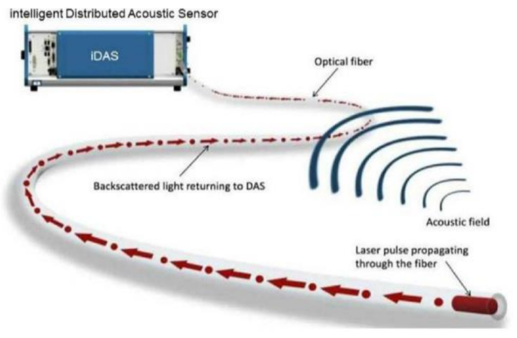


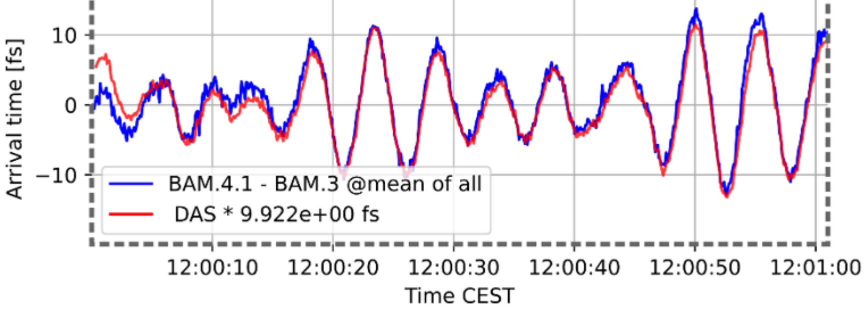

- Drift FEL vs. PP Laser
- Requires feed-forward

Differential Arrival-times

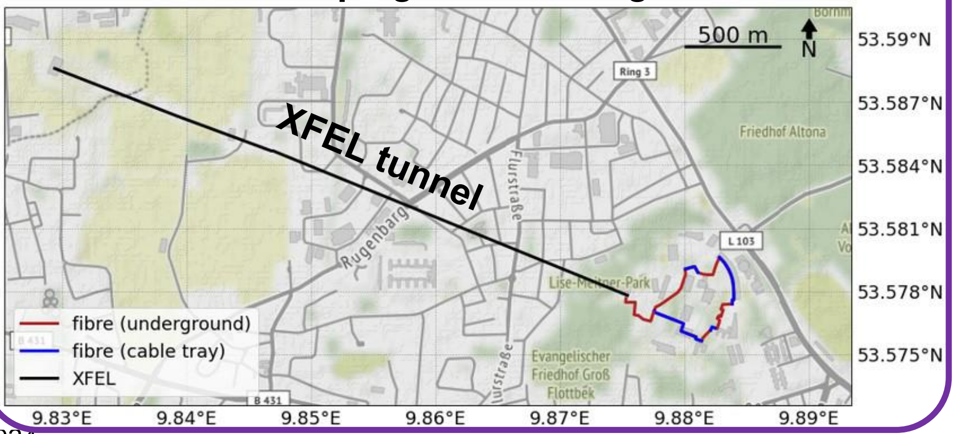
Strain ~ kHz rate
10 m resolution
10x km range

iDAS




Measurement campaign 12.6 m length




See http:\\wave-hamburg.eu

# Further Developments

## Midterm Plans

## & On-going Projects

# Developments

## Overview

1. **Beam Diagnostics**
   A. **Bunch arrival-time monitors with <1fs resolution**

   B. Bunch compression monitors,

2. **Beam-based Feedbacks**
   A. **New feedback concept for cw operation mode**
   + Modelling of noise sources and impact on beam

   B. Data-driven / model-predictive approach → compensation of sub-Hz disturbance

3. **Synchronization System**
   A. **Laser pulse arrival-time monitors & feedback**

   B. **Data-driven improvements of algorithms, configurations and fault diagnosis**

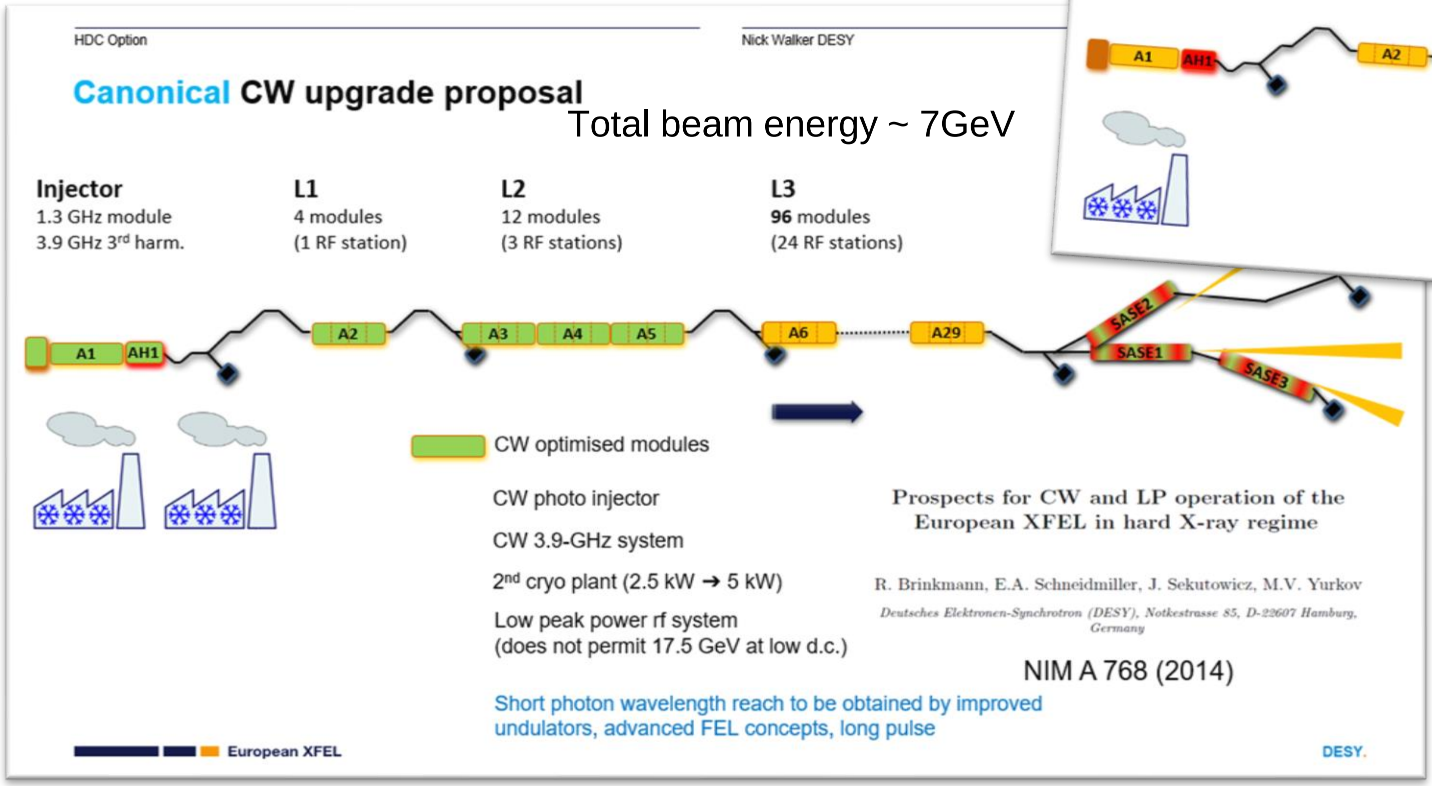
4. Proposed : Photon Arrival time Monitor @1550nm

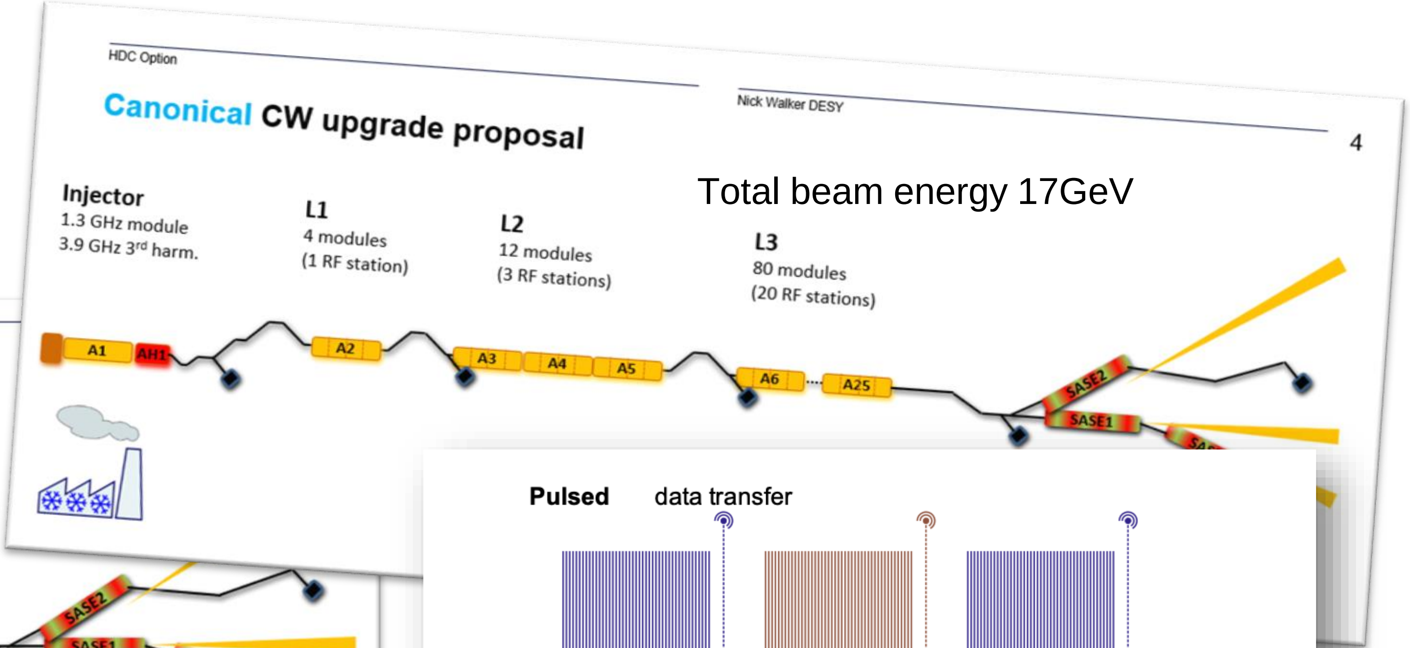
# Change of Operation Mode @EuXFEL

## Also means, change of bunch repetition rates.

**Macro-pulsed** : bursts @1..10Hz
high beam rep.rate >1MHz

**Pure cw:** slow beam rep.rate <<1MHz



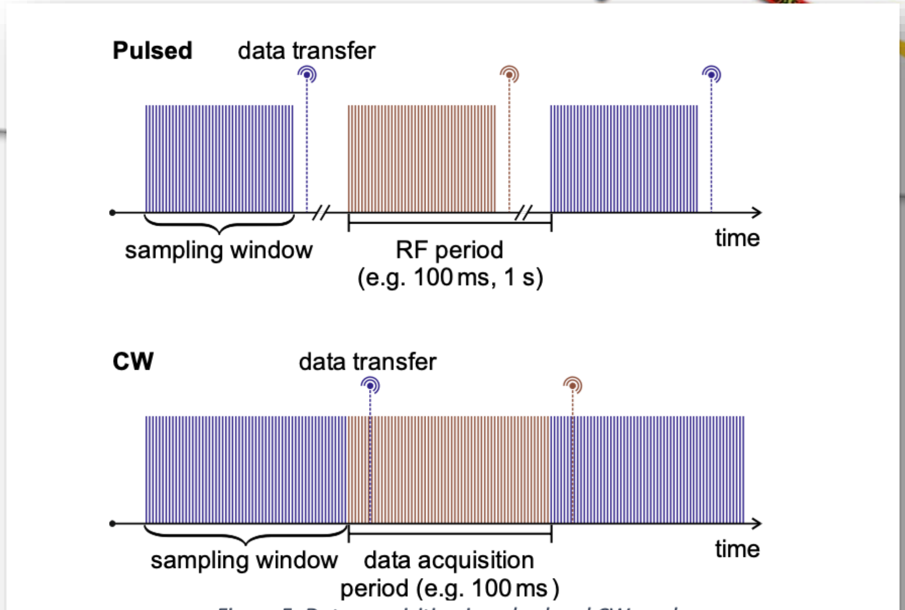



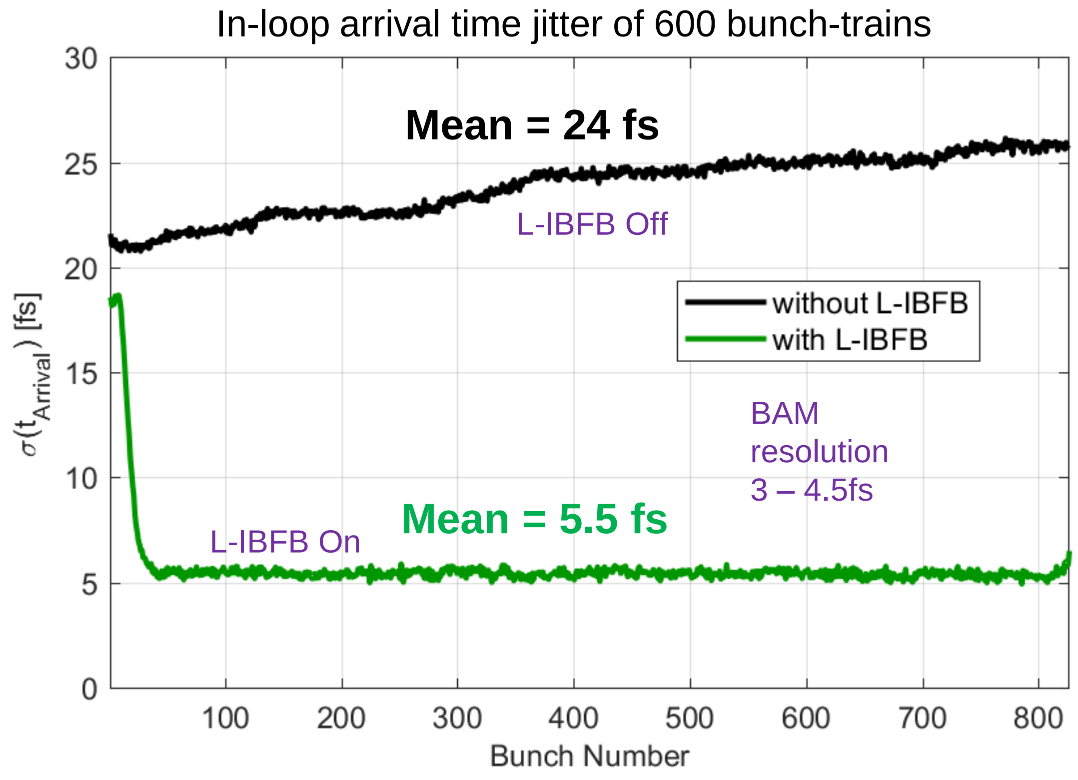

*Figure 5: Data acquisition in pulsed and CW mode.*

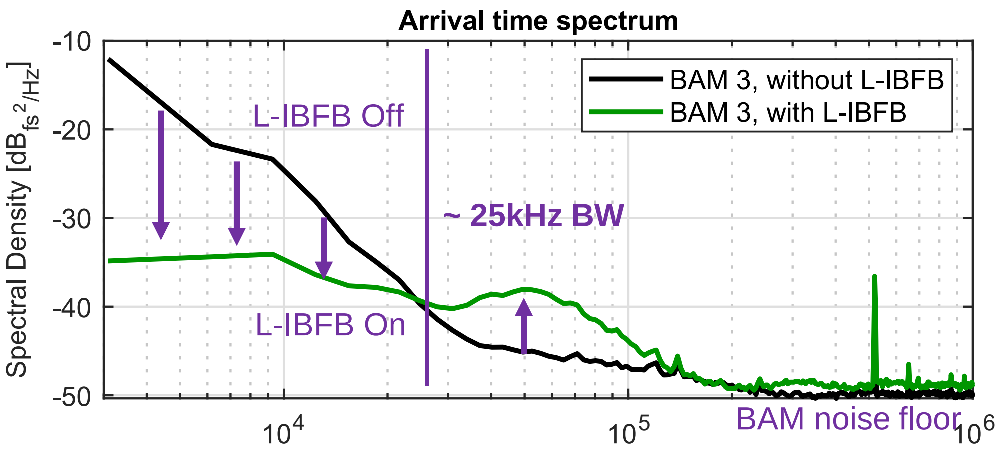
# Intra-Burst Arrival-time Stabilization

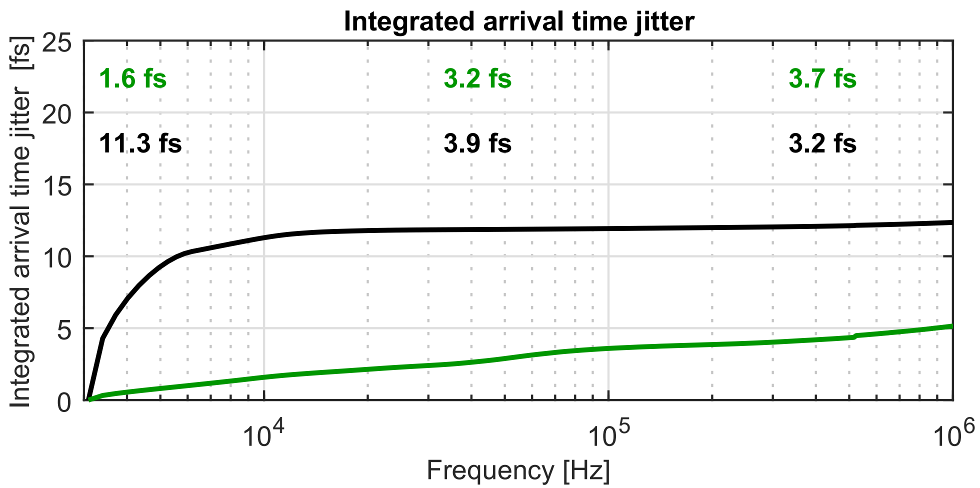
## State-of-the-art, Suppression of RF field fluctuations within 25kHz BW.

| Facility | Best | Daily |
|---|---|---|
| **EuXFEL** | 3.3 fs | **~ 4…5 fs** |
| **FLASH** | 4.7 fs | **~ 6 fs** |

- Energy corrections ~ $10^{-6}$ (e.g. **±5MeV @2.4GeV**),
- Adaptation time ~ 10-15 µs,
- Operation stable over days,
- Limited regulation range → offset correction by slow feedbacks.



# Implications from Change to CW Mode @EuXFEL

## Beam-based Feedback Control to be Optimized for cw Operation.

**Macro-pulsed** : bursts @1..10Hz
high beam rep.rate >1MHz

**Pure cw:** slow beam rep.rate <<1MHz

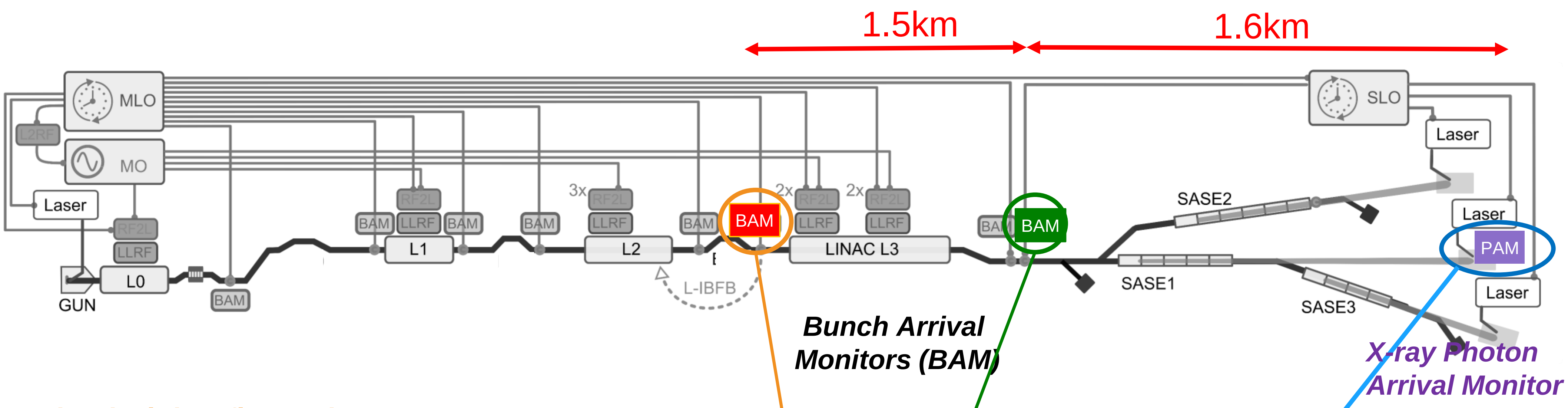
- Feedback implemented right now
  1. Slow drift compensation
  2. Adaptive to remove repetitive errors across burst
  3. Fast, intra-burst feedback
     - Acts in time domain. Measures bunch and corrects 2-5us later
     - Controller bandwidth up to 25kHz
     - Requires high sampling rate of bunches (>250kHz rep.rate)
     - → not applicable at <<250kHz bunch rep.rate.

- **Requires different concept.**
  **Steps:**
  1. estimate RF performance → expected noise spectra
  2. Model impact on beam stability; main contributions <100Hz?
  3. Global controller / FFT (take advantage of continuous measurement)

  Needs possibility for tests with beam

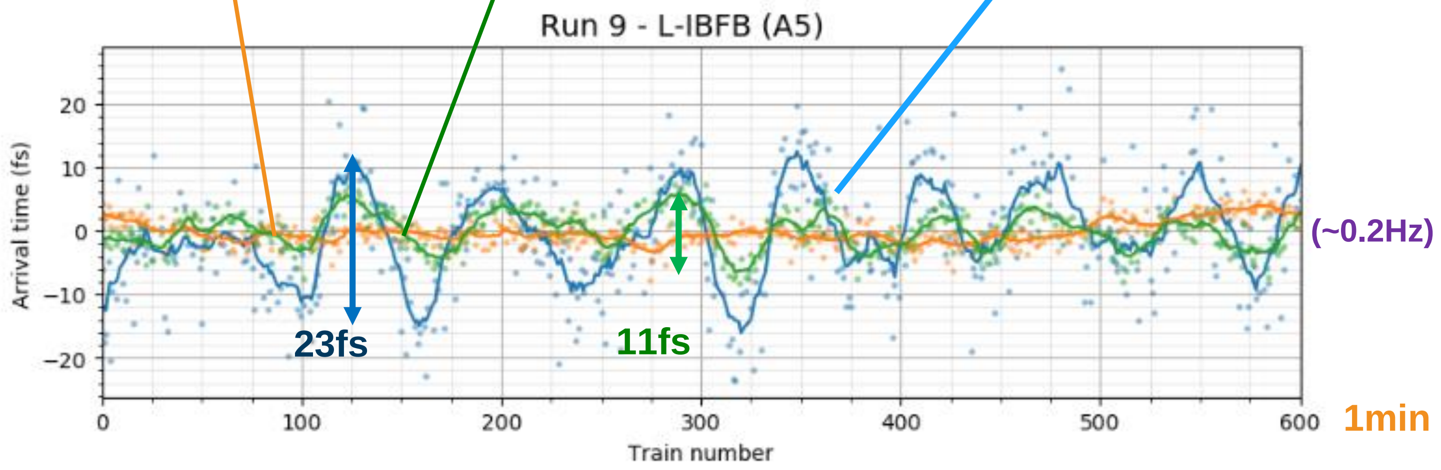
# Ocean Waves Appearing in Beam-based Measurements

## Relative Arrival-time change requires compensation for high-precision pump-probe experiments.




**Observed arrival-time fluctuation :**

- Include additional arrival time montors
- **Model + prediction**
- **Apply compensation**
- **Critical for <10fs FWHM overall stability**



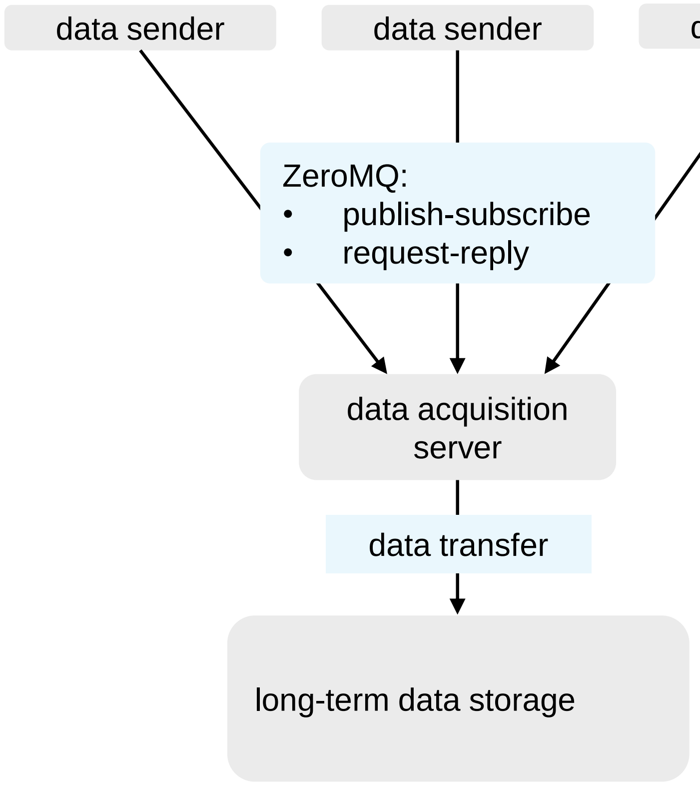

- autumn, Oct. 2020

Romain Letrun, Tokushi Sato, Henry Kirkwood, Jayanath Koliyadu
SPB/SFX Instrument, European XFEL
**Oct.2020 – Mar. 2021**

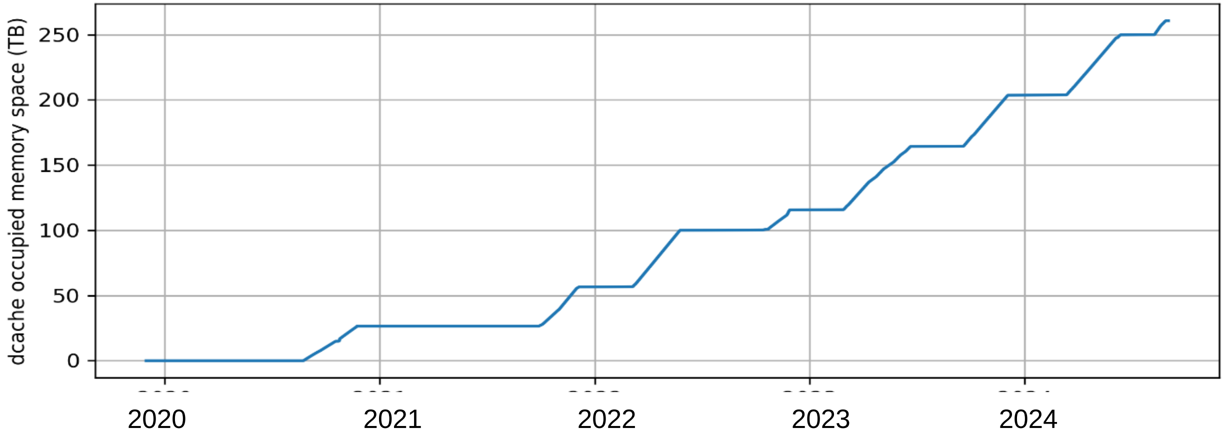
# Data Acquisition and Storage

## Dedicated DAQ System for the Laser-Based Synchronisation System

- deep integration into the control system
- foundation of ML applications

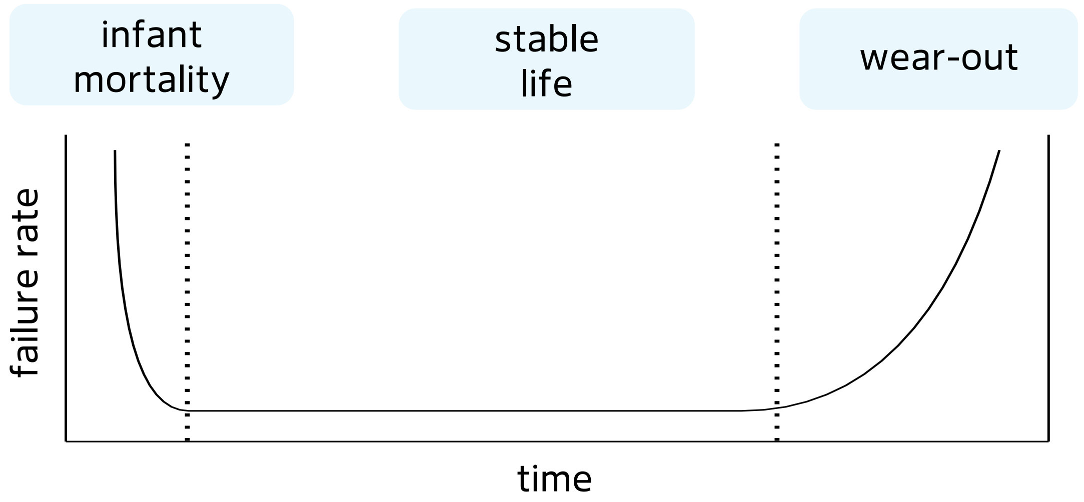



- data sources **~47k control system channels**
  - controller I/O of all feedback systems
  - configuration
  - environment (*T*, relative humidity, air pressure)
- dCache volume **~250 TB** since 2021
  - 10 Hz acquisition rate
  - daily 10-second long snapshots of “fast” data
  - → 5-day ring buffer of full fast data set of select subsystems, e.g. MLO



# Data-Driven Condition Monitoring

## The Bathtub Curve – Failure Rates Over the Lifetime of a System




**Typical Life-time of a System**

**a) infant mortality phase**

- manufacturing defects, installation issues

**b) stable life phase**

- low and stable failure rate, random/unexpected failures due to sudden, not age-related events

**c) wear-out phase**

- aging effects, components wearing out

### Goals

**Enhance reliability**

- early fault detection,
- consistent performance,
- extended lifespan

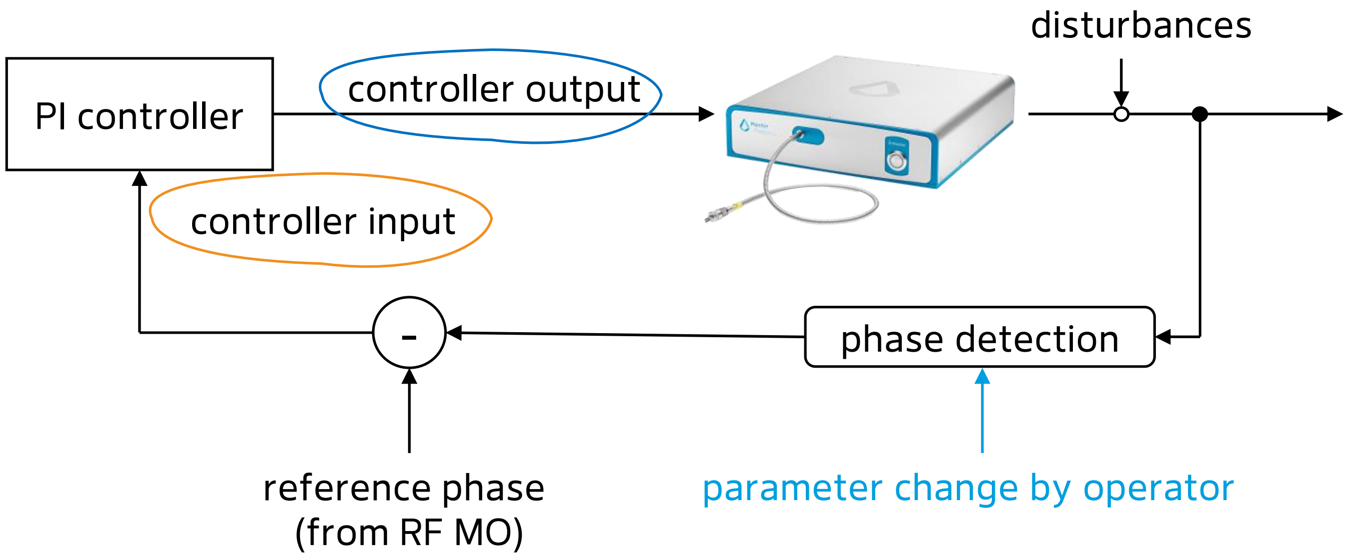
**Ensure availability**

- minimisation of unplanned downtime,
- avoidance of unnecessary maintenance activities

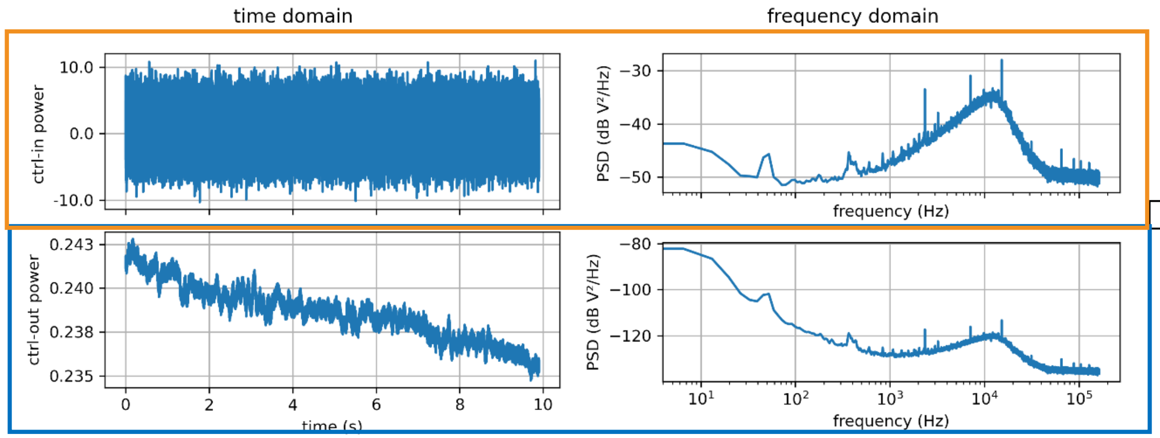
Courtesy: A.Grünhagen

# Project : Fault Analysis & Classification of States

## Example: Main Laser Oscillator PLL Signal




- difference w.r.t. *ground truth*
- ground truth / healthy state
  - ➢ defined by operator
- problem: external influence
  - ➢ metadata capturing
- **work in progress**




**CNN autoencoder** (trained)

| class | certainty |
|---|---|
| healthy | health score |
| fault class 1 | class 1 score |
| fault class 2 | class 2 score |
| fault class 3 | class 3 score |
| … | … |

**Courtesy: A.Grünhagen**

# Developments & Status

## Potential for Cooperation

On-going;1st demonstrator done.
Now technical realization & improvement.
→ Will benefit from more tests at different facilities

1. **Beam Diagnostics**
   A. **Bunch arrival-time monitors with <1fs resolution**

In preparation; detector development.
Funding proposals submitted.

   B. Bunch compression monitors,

2. **Beam-based Feedbacks**

On-going. Based on extensive previous work.
→ One of our focuses in next 2-3y

   A. **New feedback concept for cw operation mode**
   \+ Modelling of noise sources and impact on beam

Work in progress.
First demonstration done,
for a tidal-wave drift mitigation.

   B. Data-driven / model-predictive approach → compensation of sub-Hz disturbance

3. **Synchronization System**

Work in progress. → large overlap and benefit from cooperation.

   A. **Laser pulse arrival-time monitors & feedback**

Work in progress.

   B. **Data-driven improvements of algorithms, configurations and fault diagnosis**

Feasibility study needed.
Might be of mutual interest.

4. Proposed : Photon Arrival time Monitor @1550nm

# Thanks for your attention