An Overview: Reference Distribution and Synchronization Systems,

from Sub-picoseconds to Sub-femtoseconds Stability.

Marie Kristin Czwalinna, Sebastian Schulz, Holger Schlarb

On behalf of :

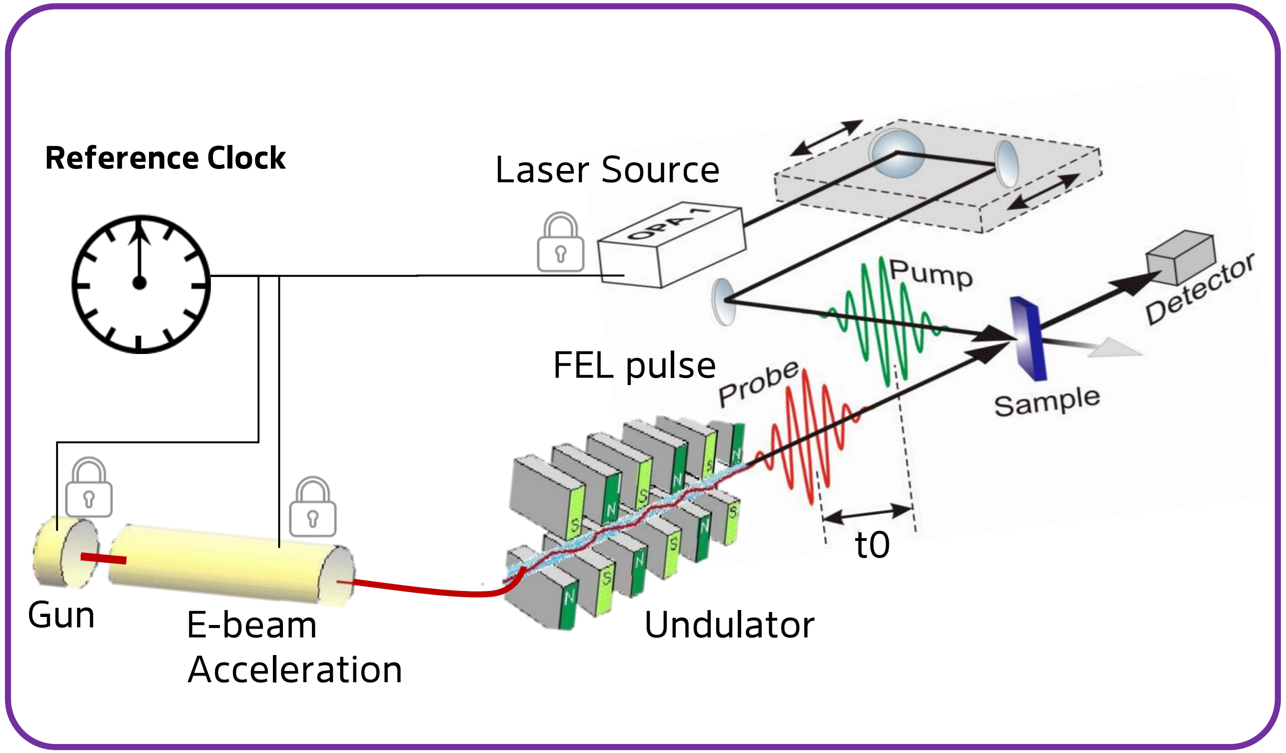
group for accelerator beam controls (DESY, MSK)

Agenda

Motivation

Motivation

X-ray/Optical Pump-Probe Experiments with Femtosecond Temporal Resolution



Pump-probe experiment,
With 2 or more disjunct sources

Limitations for achievable resolution:

$$\tau_{resolution} = \sqrt{(\tau_{XUV}^2 + \tau_{Laser}^2 + \sigma_{jitter}^2)}$$

Data post-sorting with timing information:

nature photonics — LETTERS

PUBLISHED ONLINE: 17 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.11

Achieving few-femtosecond time-sorting at hard X-ray free-electron lasers

M. Harmand[1†*], R. Coffee[2], M. R. Bionta[2,3], M. Chollet[2], D. French[2], D. Zhu[2], D. M. Fritz[2], H. T. Lemke[2], N. Medvedev[4], B. Ziaja[4,5], S. Toleikis[1] and M. Cammarata[6*]

Recently, few-femtosecond pulses have become available at hard X-ray free-electron lasers. Coupled with the available sub-10 fs optical pulses, investigations into few-femtosecond dynamics are not far off. However, achieving sufficient synchronization between optical lasers and X-ray pulses continues to be challenging. We report a 'measure-and-sort' approach, which achieves sub-10 fs root-mean-squared (r.m.s.) error measurement at hard X-ray FELs, far beyond the 100–200 fs r.m.s. jitter limitations. This timing diagnostic, now routinely available at the Linac Coherent Light Source (LCLS), is based on ultrafast free-carrier generation in optically transparent materials. Correlation between two independent measurements enables unambiguous demonstration of ~6 fs r.m.s. error in reporting the optical/X-ray delay, with single shot error suggesting the possibility of reaching few-femtosecond resolution.

The advent of femtosecond lasers has opened the way to study the dynamics of matter with high time resolution (tens of femtose-

hard X-ray FEL facilities (wavelength-specific[8] or impractical for long facilities[9,10]) or require specific installations for a terahertz beamline[11], which introduces significant complexity and cost.

Induced ultrafast optical switching of bulk refractive indices is a common cross-correlation technique[12–14] that has been recently extended to VUV or soft X-ray FEL pulse excitation[5,6,15–17]. Absorption of a fraction of the X-ray beam intensity can produce a rapid change in the free carrier density by photoionization and subsequent cascade ionization[18]. This technique, pioneered at the FEL in Hamburg (FLASH)[6,15] and further developed at the Linac Coherent Light Source (LCLS) at the National Accelerator Laboratory (SLAC)[5,16,17,19], has been demonstrated for soft X-rays where the short penetration depth (~100s of nanometres) ensures the creation of a high density of free carriers. For hard X-rays, this density will be one to two orders of magnitude lower.

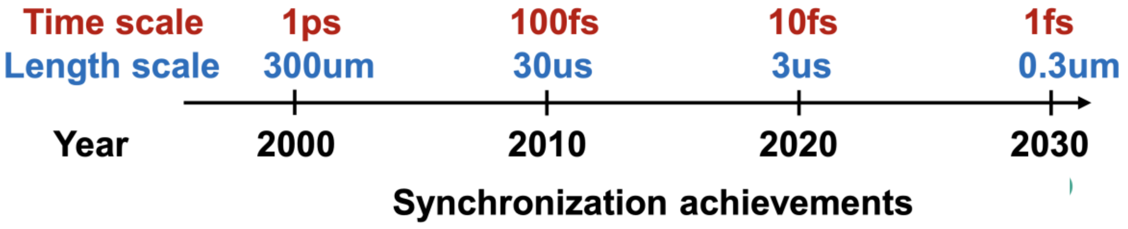
In this Letter, we demonstrate how optical switching correlators can be used for hard X-ray instruments. By using redundant and

But, if post-sorting of data no option:

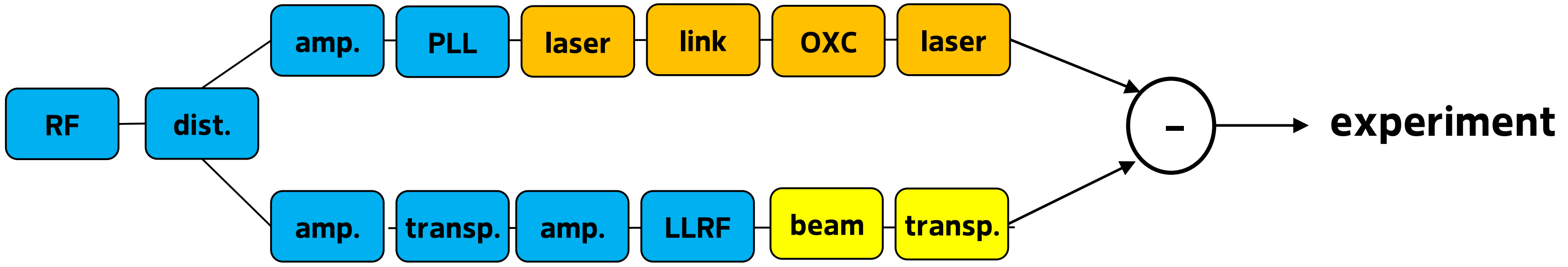
→ Level of synchronization limiting factor
(experiments with low interaction rates / small cross-sections / averaging detectors)

Timing Jitter and Drift Considerations

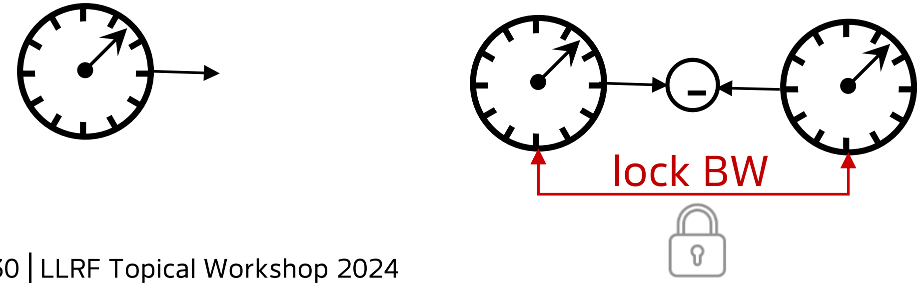
Overview.



- time and length scales
- duration
  - **short range** **10 µs … 1 ms** power supplies, EMI, electronics, materials properties
  - **mid range** **1 ms … 10 s** acoustics, seismic activities, air/water flow, fans, …
  - **long range** **10 s … days** thermal effects, humidity, air pressure, …
- long "chain" of devices
  - accelerator
  - laser(s)



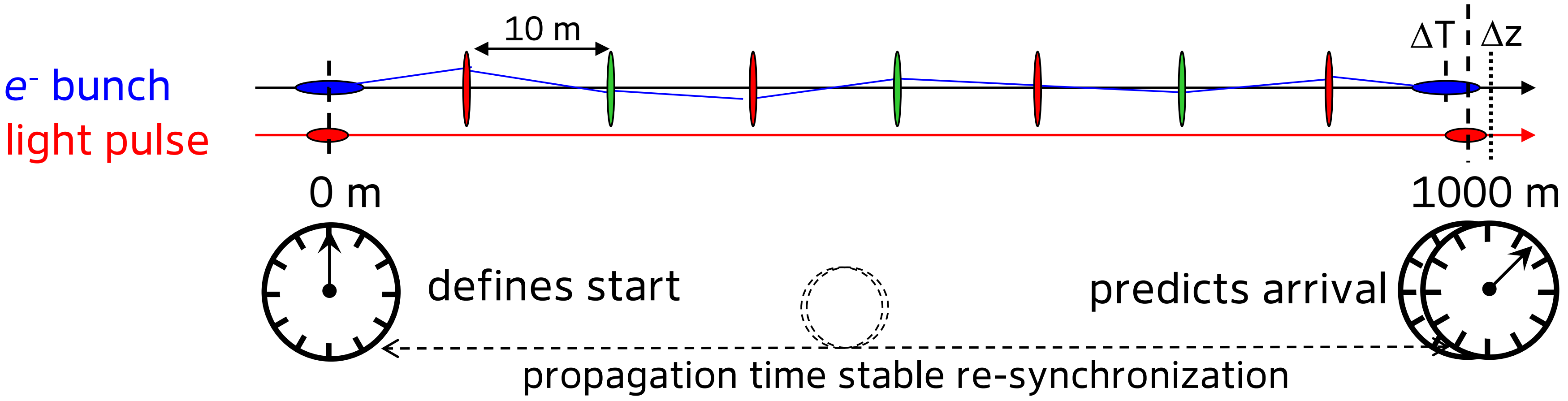
- **absolute & relative timing jitter**
  - large difference in link length and locking bandwidths



Introduction

Sources of Timing Jitter from Distribution system

In Straight Sections of the Accelerator:



Lorentz factor $\gamma = E/m_0c^2$

$E = 1$ GeV

$\beta \approx 1 - \frac{1}{2\gamma^2} = 0.999999869$

$\Delta T = 435$ fs

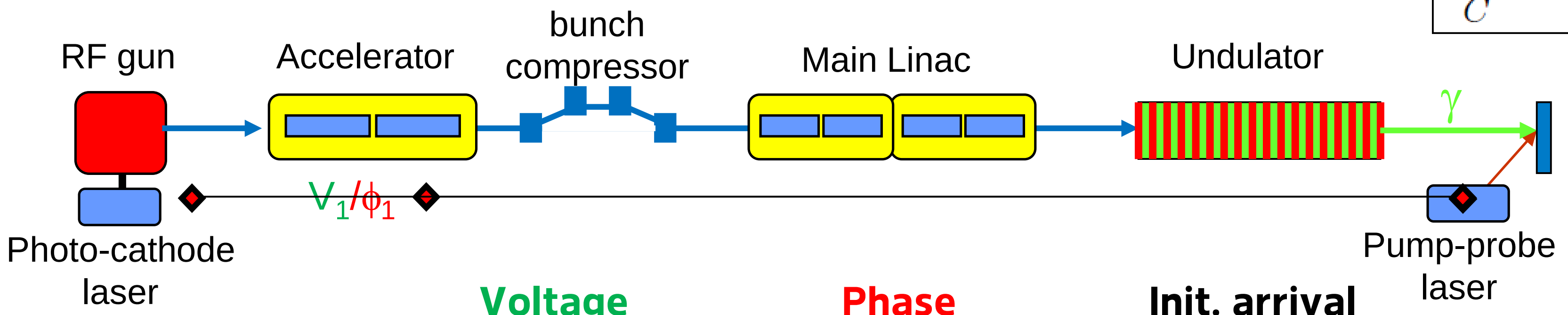
• **energy jitter**	$\Delta E/E < 0.1\%$	⇒	$\Delta t < 0.8$ fs	🙂
• **orbit deviation**	$\Delta x < 50\ \mu m$	⇒	$\Delta t < 0.04$ fs	😃
• **vibration**	$\Delta z \sim$ *few 100 nm*	⇒	$\Delta t \sim 1$ fs	🙁
• **ground motion/relocations**	$\Delta z \sim 10\ \mu m$	⇒	$\Delta t \sim 30$ fs	🥺

…but **slow, and somewhat predictable**
⇒ feedforward?!

Sources of Timing Jitter: Beam

Electron Bunch Acceleration and Compression

a) RF acc. fields defines arrival



Compression factor C:

$$\frac{1}{C} = \frac{\partial s_f}{\partial s_i} \Rightarrow C_1 = \frac{1}{1 - R_{56}\delta'(0)}$$

Timing jitter behind BC

Voltage — **Phase** — **Init. arrival**

$$\Sigma_{t,f}^2 = \left(\frac{R_{56}}{c_0}\right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left(\frac{C-1}{C}\right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2} + \left(\frac{1}{C}\right)^2 \cdot \Sigma_{t,i}^2$$

XFEL: 1.5ps/%
FLASH: 7.0ps/%

2 ps/deg
L-band

0.05 ps/ps
C=20

C ~5 … 20 typically

for $E_0 << E_1$ and $E_0' << E_1'$
(else more distributed across stations)

b) RF acc. fields large impact on longitudinal phase space

3 …, 6

$$\frac{\delta C}{C_1} = -(C_1 - 1)\left[\left(3\tan(\phi_1) + \frac{1}{\tan(\phi_1)}\right)(\delta\phi_1 - \omega_{RF}\delta t_{ini}) + 4\frac{\delta V_1}{V_1}\right]$$

Tolerance ∝ Compression

Phase & Init. arrival

Voltage

Conclusions

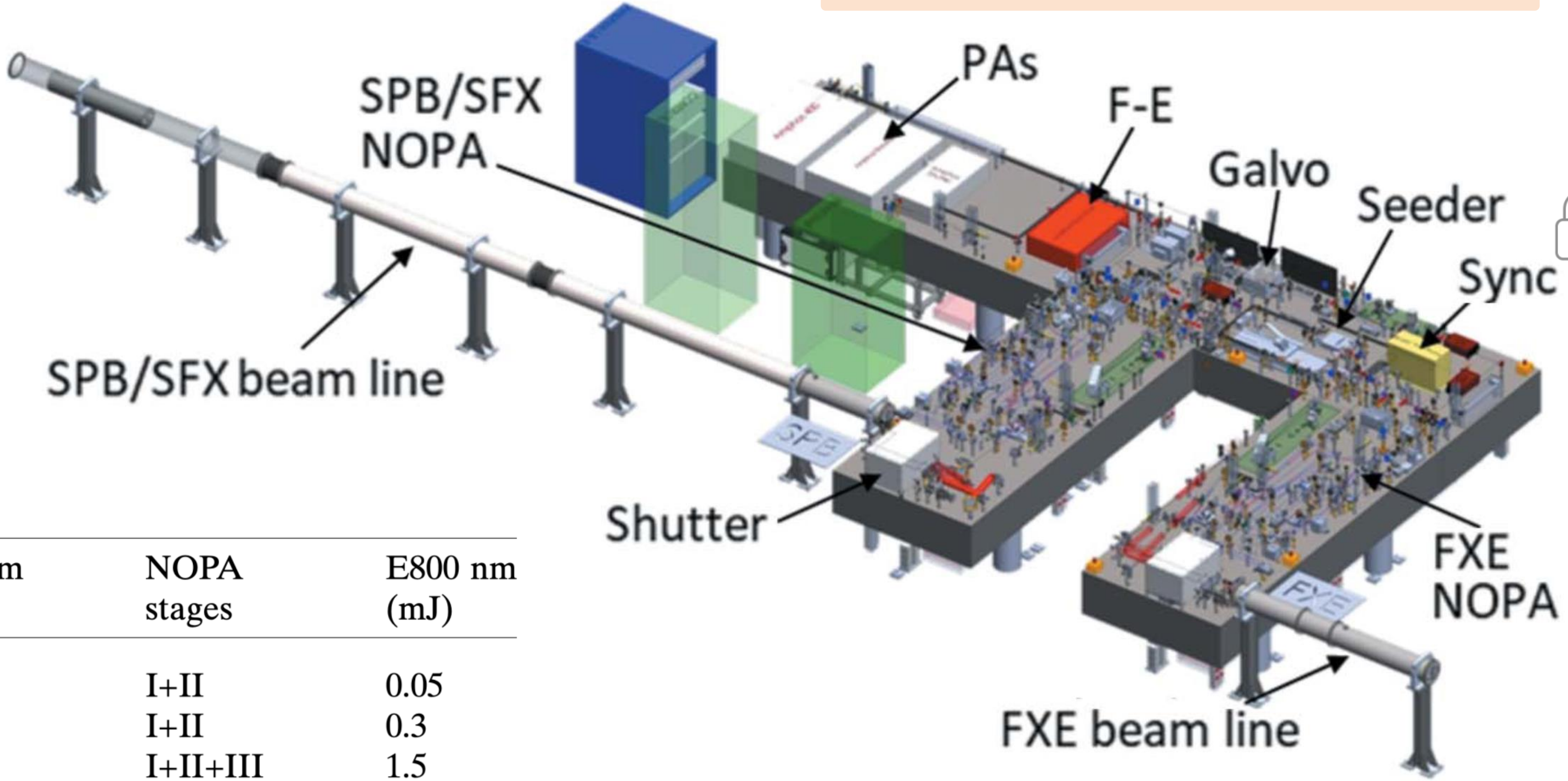
- Use multiple compressors
- **RF field control is critical**
- RF reference vs. PP-laser closely locked

Sources of Timing Jitter and Drift: Laser Systems and Beam Delivery

Example: Pump-Probe Laser System at SA1 Beamlines at EuXFEL

long path lengths
lab → ILH → experiment ~100 m

- common seeder & FE
- 20 Hz operation
- two **separate** NOPAs
  - **SPB/SFX** and **FXE**
- 800 nm / 15 fs
- 1030 nm / sub-ps
- different pulse patterns

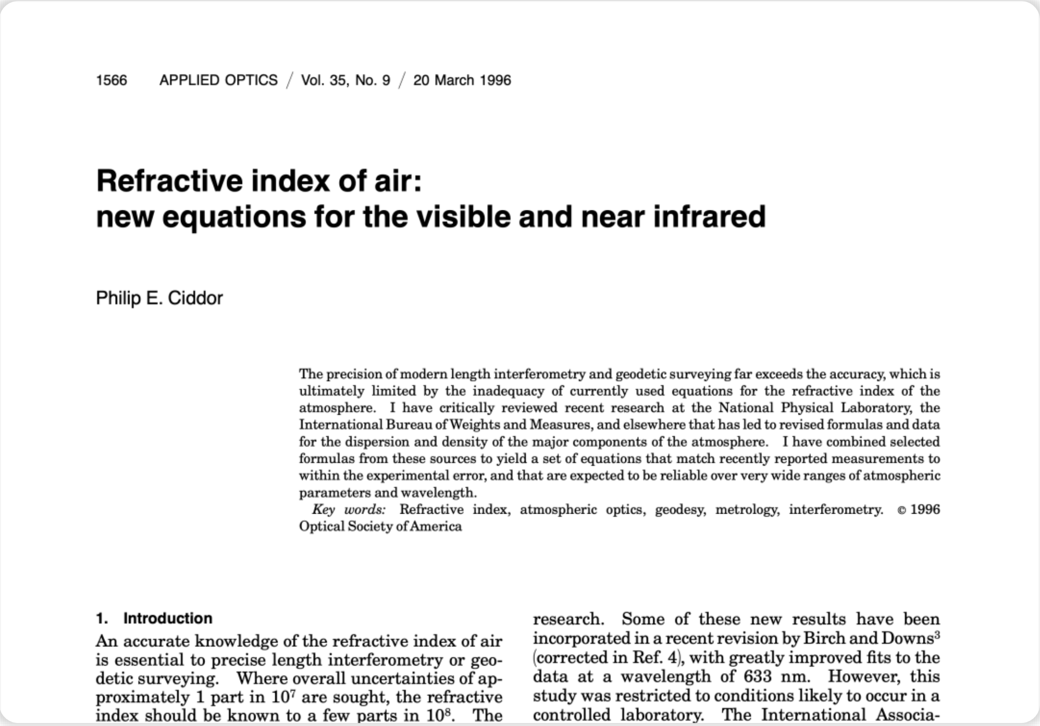


Set point	Repetition rate (MHz)	E1030 nm (mJ)	NOPA stages	E800 nm (mJ)
1	4.5	1	I+II	0.05
2	1.13	4	I+II	0.3
3	0.188	21	I+II+III	1.5
4	0.1	40	I+II+III	2.5

Influence of Air Condition on Laser Pulse Propagation Time

Ciddor's Equation - Around Nominal Parameters of 1550 nm, 45% RH, 101.325 kPa, 450 ppm

• temperature	**3.1 fs/m/K**
• relative humidity	**0.04 fs/%/m**
• air pressure	**−0.9 fs/mbar/m**
• CO_2 concentration	**−0.5 as/ppm/m**



1566 APPLIED OPTICS / Vol. 35, No. 9 / 20 March 1996

Refractive index of air: new equations for the visible and near infrared

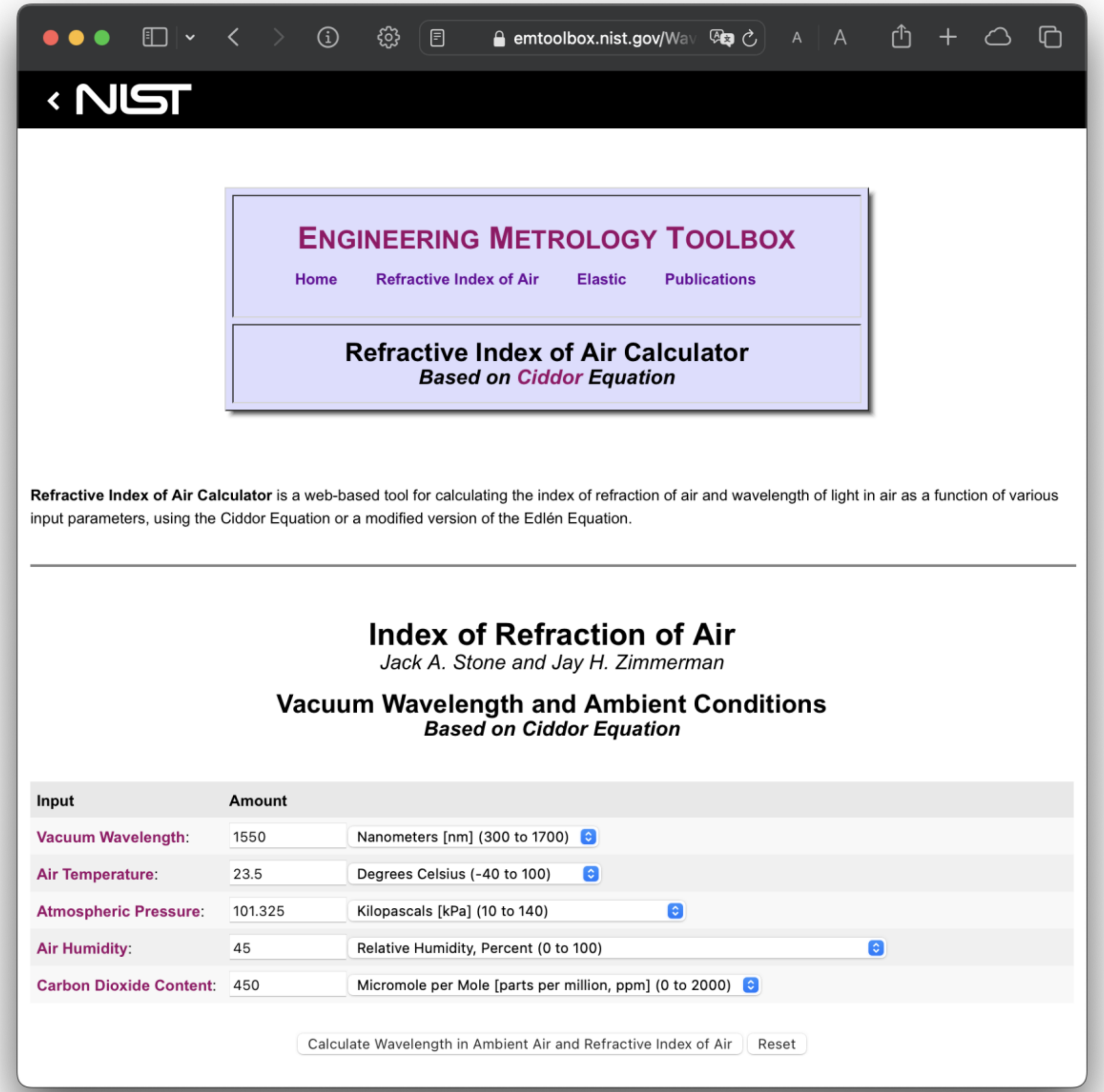
Philip E. Ciddor

The precision of modern length interferometry and geodetic surveying far exceeds the accuracy, which is ultimately limited by the inadequacy of currently used equations for the refractive index of the atmosphere. I have critically reviewed recent research at the National Physical Laboratory, the International Bureau of Weights and Measures, and elsewhere that has led to revised formulas and data for the dispersion and density of the major components of the atmosphere. I have combined selected formulas from these sources to yield a set of equations that match recently reported measurements to within the experimental error, and that are expected to be reliable over very wide ranges of atmospheric parameters and wavelength.

Key words: Refractive index, atmospheric optics, geodesy, metrology, interferometry. © 1996 Optical Society of America

1. Introduction

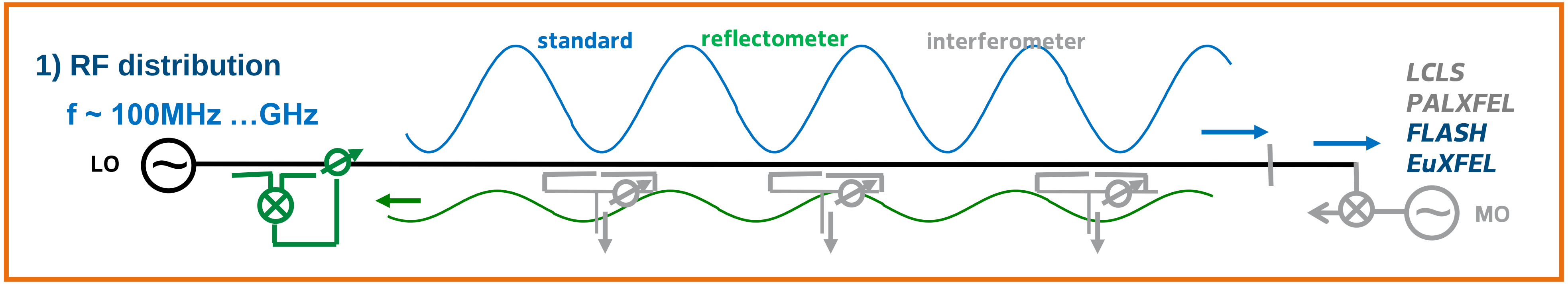
An accurate knowledge of the refractive index of air is essential to precise length interferometry or geodetic surveying. Where overall uncertainties of approximately 1 part in 10^7 are sought, the refractive index should be known to a few parts in 10^8. The research. Some of these new results have been incorporated in a recent revision by Birch and Downs[3] (corrected in Ref. 4), with greatly improved fits to the data at a wavelength of 633 nm. However, this study was restricted to conditions likely to occur in a controlled laboratory. The International Associa-



Synchronization Techniques

Different Synchronization Techniques

RF Distribution – active or passive



$$\frac{\Delta t}{t} \sim \frac{\Delta f}{f}$$

Jitter

Short range = 1us…1ms
PS, EMI, Material Properties, Electronic Noise…

Mid range = 1ms…10s
Acoustic, Seismic, Air flow, Water flow, ..

Drift

Long range = 10s … days
Temperature, Rel. Humidity, Air Pressure, …

→For Details

Basics of RF Reference Signal Generation and Synchronization Systems

30 Oct 2024, 17:00 — Krzysztof Czuba (Warsaw University of Technology)

Different Synchronization Techniques

Continuous Wave (CW) Optical Distribution / RF-over-Fiber

- Transmits Amplitude (AM) or frequency (FM) modulated signals
- Relatively low costs while still reaching ~10 fs sync. level
- Mitigation to <1 ps drift over days, requires more complex design
- Phase-detectors may suffer from AM-to-PM detection errors

$$\frac{\Delta t}{t} \sim \frac{\Delta f}{f}$$

Jitter

Short range = 1us…1ms
PS, EMI, Material Properties, Electronic Noise…

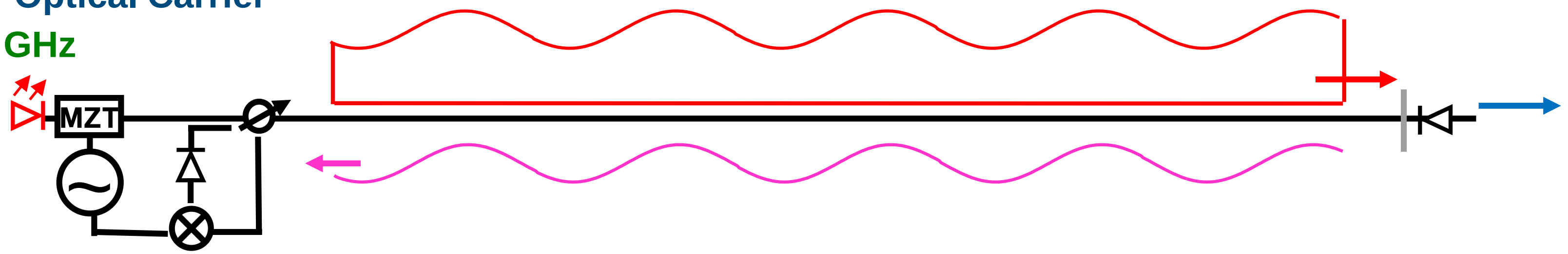
Mid range = 1ms…10s
Acoustic, Seismic, Air flow, Water flow, ..

Drift

Long range = 10s … days
Temperature, Rel. Humidity, Air Pressure, …

2) CW Optical Carrier

f ~ GHz



SwissFEL
(SACLA)
PALXFEL
LCLS

→For Details

LCLS II precision timing system

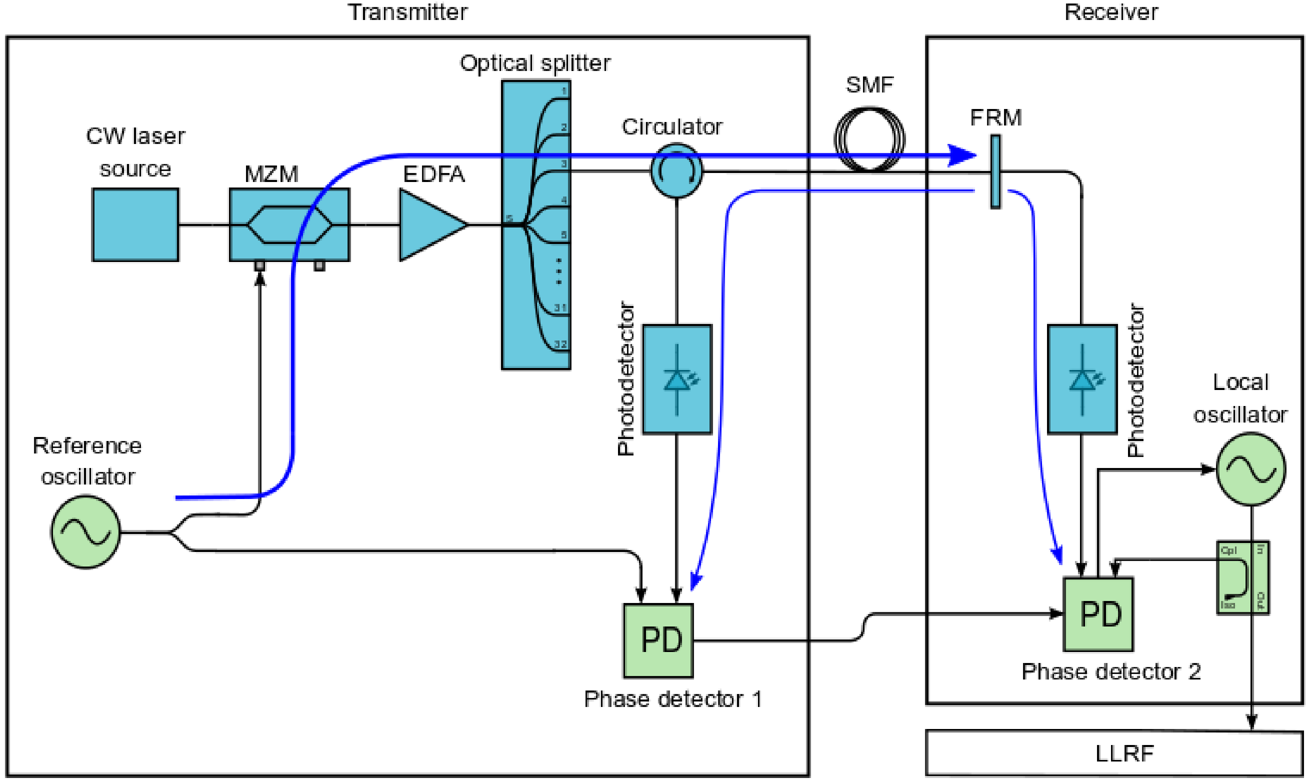
30 Oct 2024, 12:05

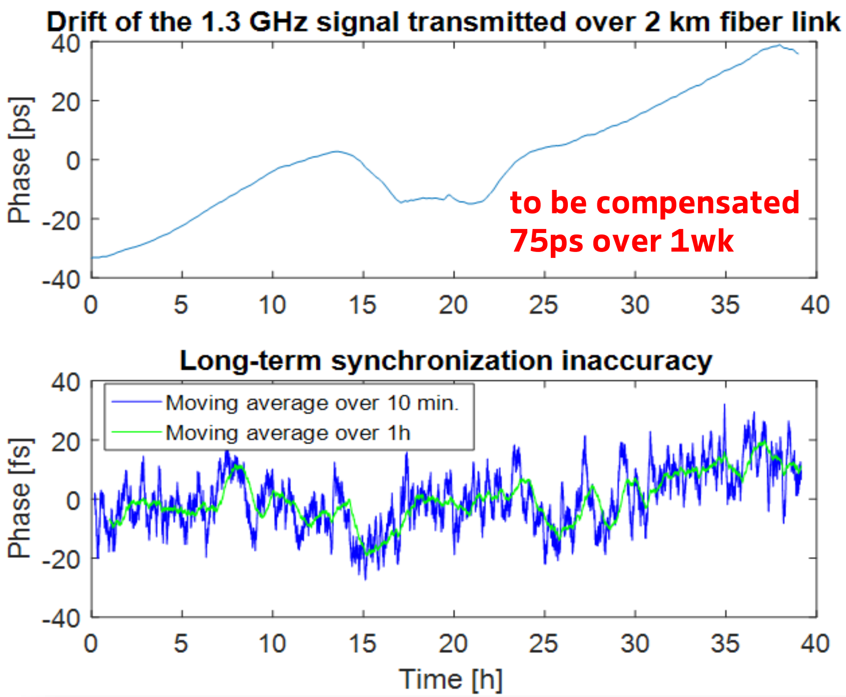
Chengcheng Xu (SLAC National Accelerator Lab)

RF-Distribution →CW optical Links

Phase drift correction by the reflectometry technique :

(Standard SMF)
Drift ~40fs/m/K, 2.5 fs/m/%RH





$$\varphi_{drift} = {\varphi_1}/_2 + \varphi_2$$

$$Drift\ reduction: \ {72\ ps}/_{53\ fs} = 1358$$

Long-term stability:
< 50 fs_pp for distances < 0.5 km
<100 fs_pp for distances < 2 km

Other good examples:
Libera Sync, Berkeley Sync-Head

Courtesy: S. Jablonski, F. Ludwig

Different Synchronization Techniques

Pulsed Optical System – Versatile Client Systems

- Uses Mode-locked laser oscillators, ultra-short pulses (~100 fs FWHM, ~pJ…nJ pulse energy)
- typically require highest investment costs (infrastructure, components)

→ **allows for all-optical non-linear mixing techniques:**
high resolution (10..100 as)
immune to AM-to-PM errors

→ Delivers precise time markers for arrival time monitors

→ Laser-to-RF direct conversion + selecting of harmonics suited for heterodyne mixing techniques

$$\frac{\Delta t}{t} \sim \frac{\Delta f}{f}$$

Jitter

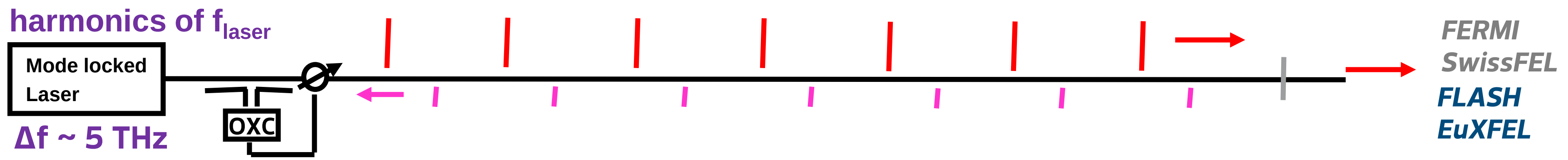
Short range = 1us…1ms
PS, EMI, Material Properties, Electronic Noise…

Mid range = 1ms…10s
Acoustic, Seismic, Air flow, Water flow, ..

Drift

Long range = 10s … days
Temperature, Rel. Humidity, Air Pressure, …

3) Pulsed optical source

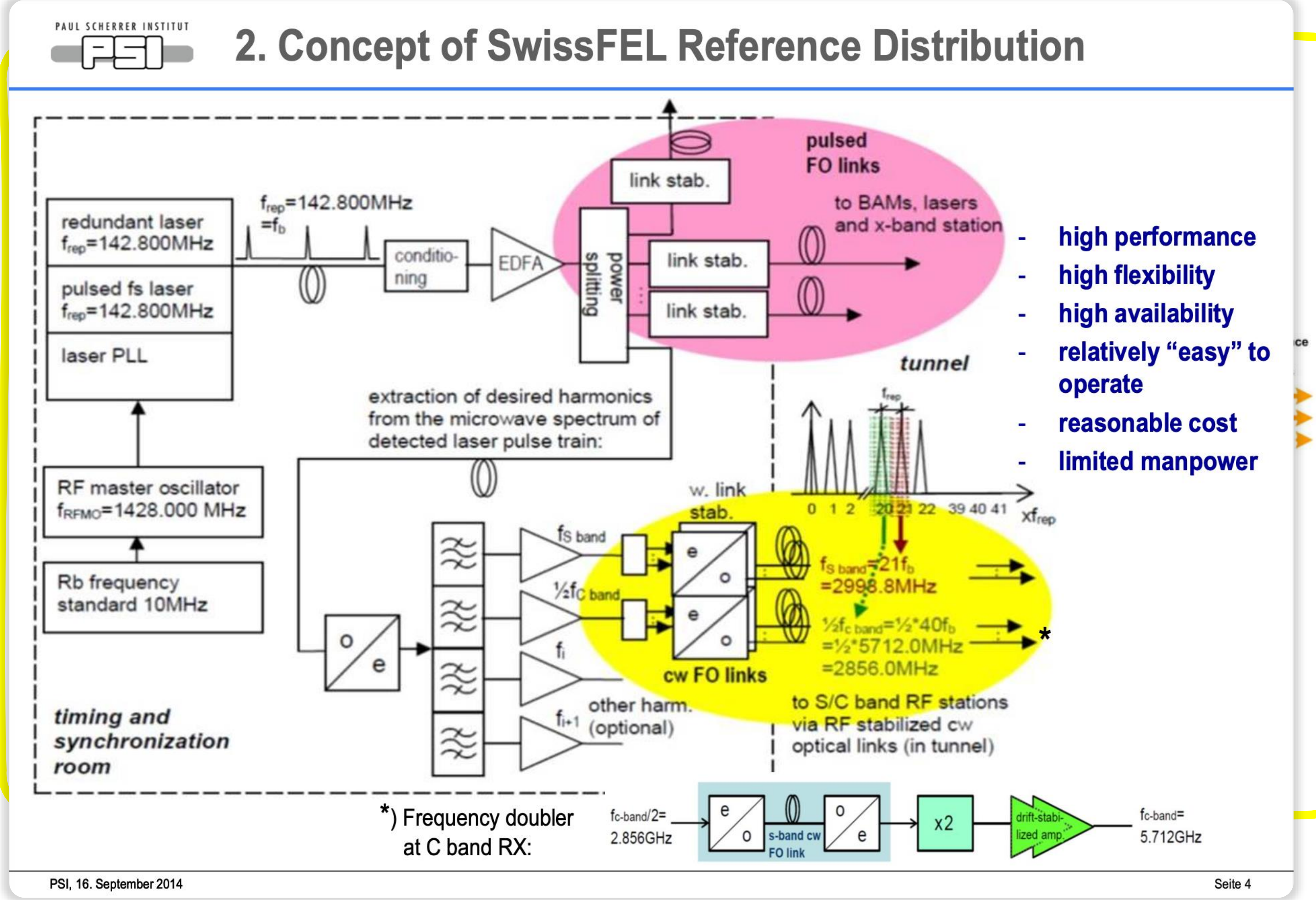


First proposed: J. Kim et al. Proc. of FEL 2004 conf., 339-342 (2004)
Overview: M. Xin et al. Light: Science & Applications (2017) 6, e16187;

Courtesy: H.Schlarb

Hybrid Approaches: SwissFEL

Pulsed Optical Synchronisation + RF-over-Fibre Links



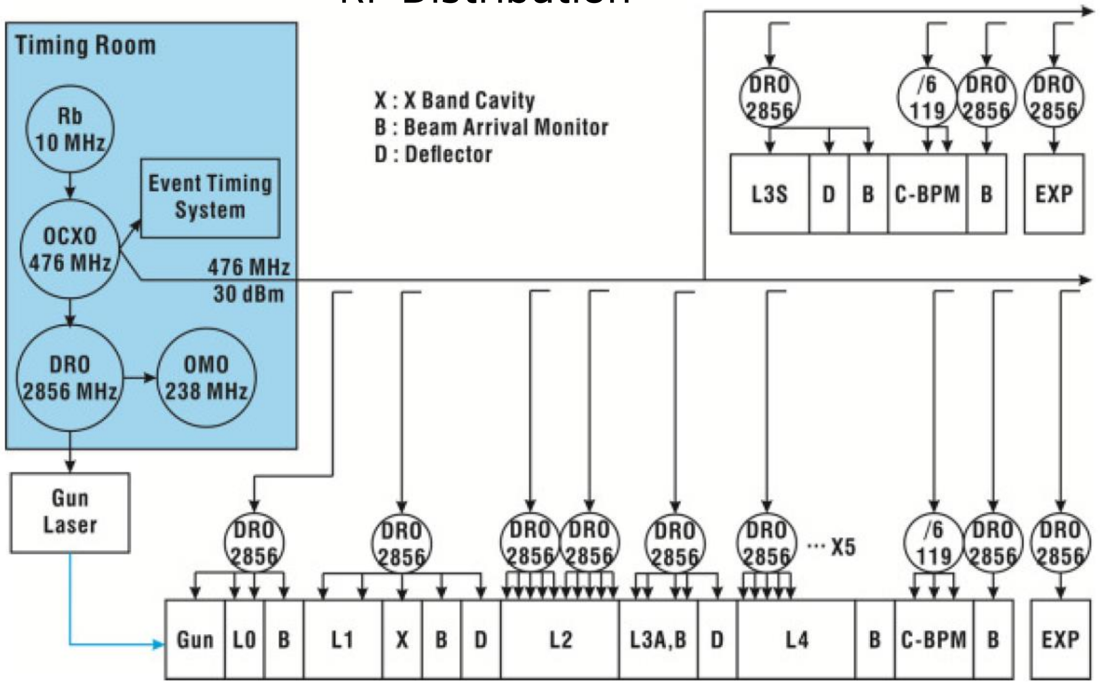
- **cw fibre links**
  - collaboration with I-Tech
  - transmitter/receiver units
  - amplitude modulation (AM)
  - two optical fibres per link
    - active drift stabilisation
    - "low jitter link"
  - at Rx side, both signals are demodulated to RF
  - **40 fs peak-to-peak (24 h)**
  - **sub-10 fs rms [10 Hz, 10 MHz]**

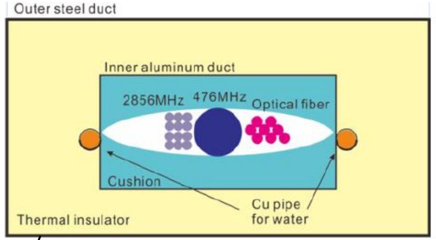
P. Orel et al., in Proc. NA-PAC2013, pp. 1358-1360
S. Hunziker et al., in Proc. IBIC2014, pp. 29-33

Hybrid Approaches: PAL-XFEL

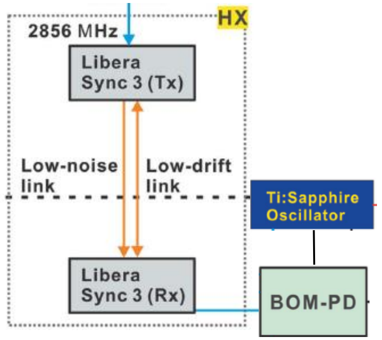
RF Distribution (Temperature Stabilised) + Beam-based FB (X-ray Photon Pulse Arrival-ime Monitor)

RF Distribution

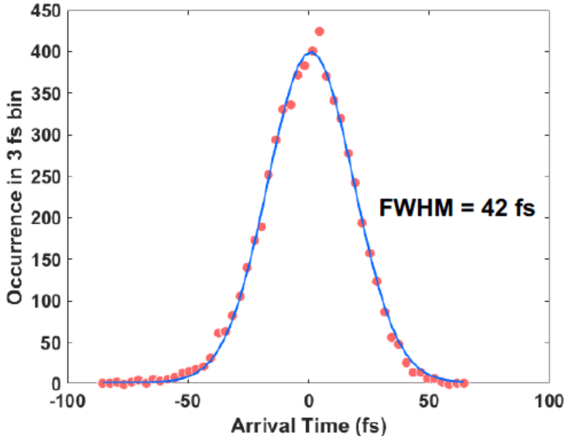


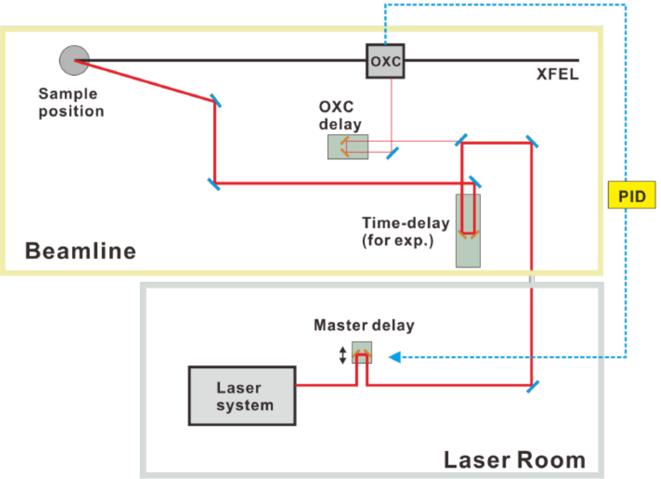


+ CW Optical Link

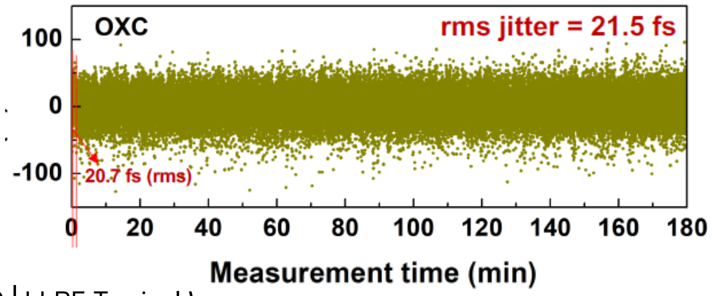


6000 XFEL shots@30Hz





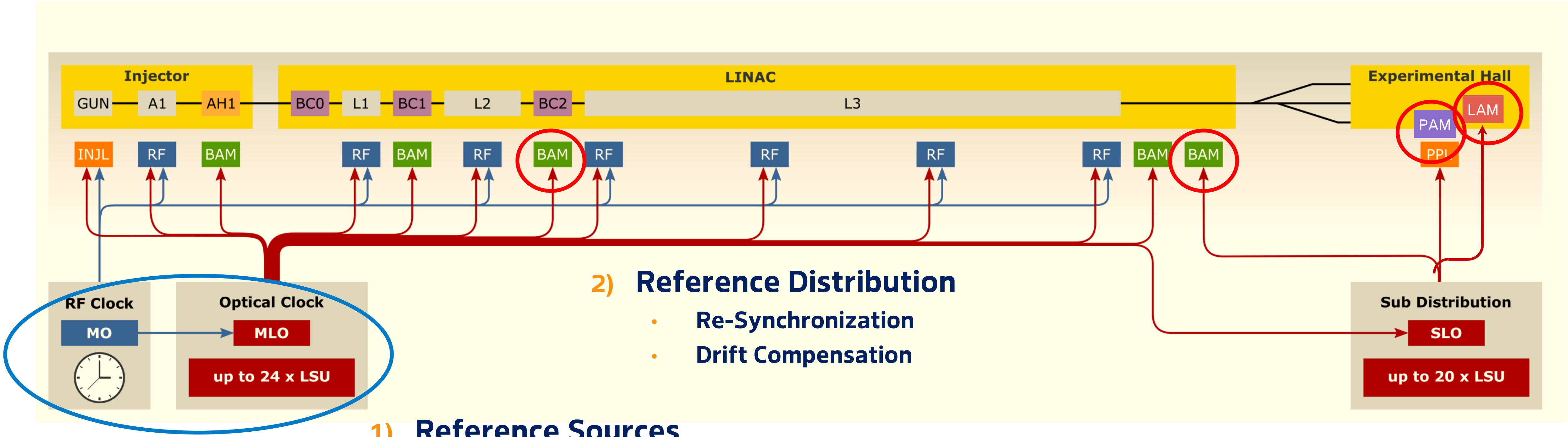
Stability for 3 hours



further reading:
C. K. Min *et al.*, Proc. IPAC2016, p. 4234
M. Kim *et al.*, J. Synchrotron Rad. 26 (2019)
I. Eom *et al.*, 5-Way Meeting 2019, SLAC

Hybrid Approach: EuXFEL

RF Backbone (Re-Sync'ed to Optical Source) + Pulsed Optical Links.



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**

State-of-the-Art Building Blocks

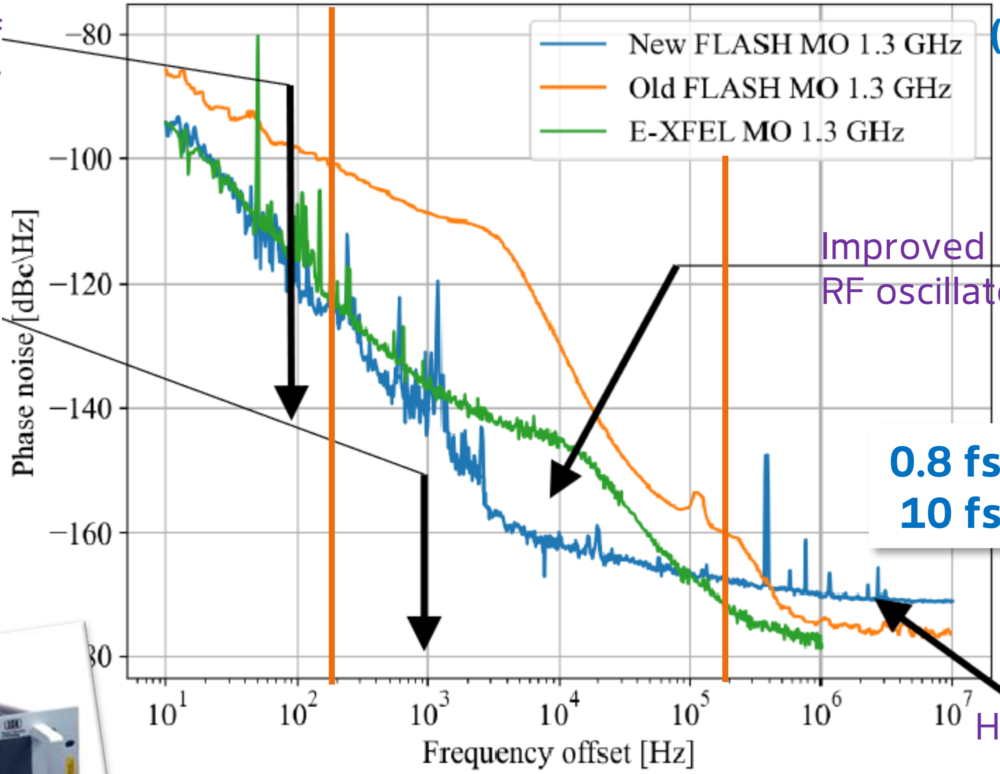
Reference Sources

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

See also Poster
by M. Urbanski et. al. ,

„Recent Experience in the Operation of FLASH2020+ RF Reference Generation System“, (LLRF24)

Commercially available at KVG
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

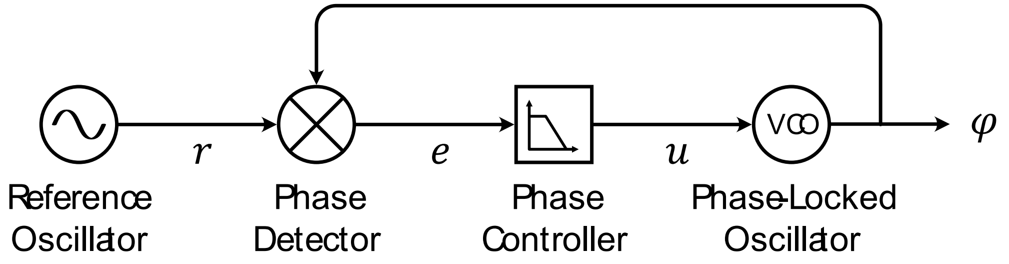
Courtesy: F.Ludwig, H. Pryschelski, T. Lamb

Phase Locking

Detection & Feedback

objective

- minimise phase error between controlled oscillator and reference oscillator (“synchronisation”)

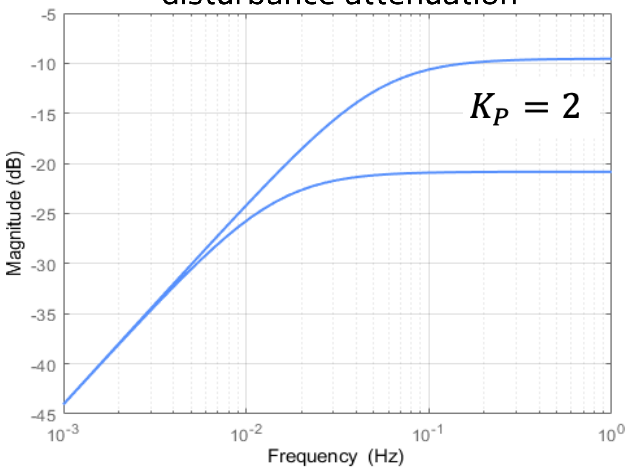


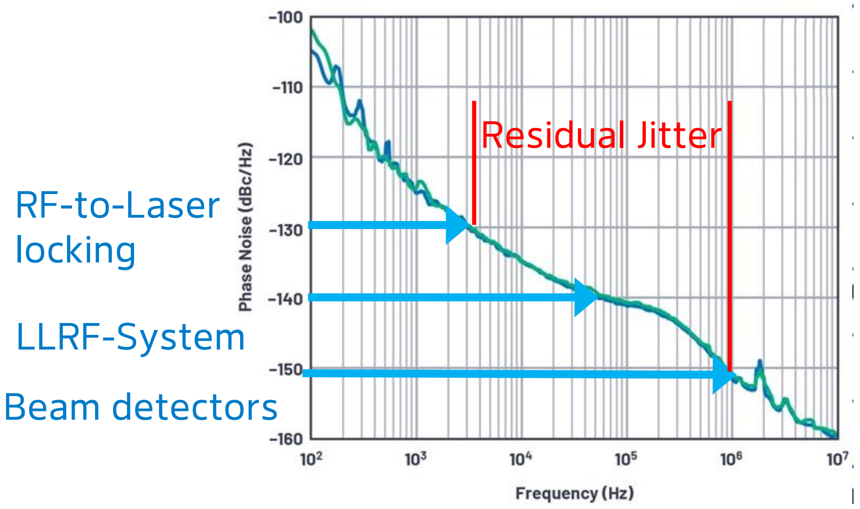
how

1. **Detection**
   RF←→RF
   or, RF ←→ optical
   or, optical ←→ optical
2. **Feedback**
   via phase control of tuneable oscillator, usually PI sufficient

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau \qquad C(s) = K_P + \frac{K_I}{s}$$

disturbance attenuation

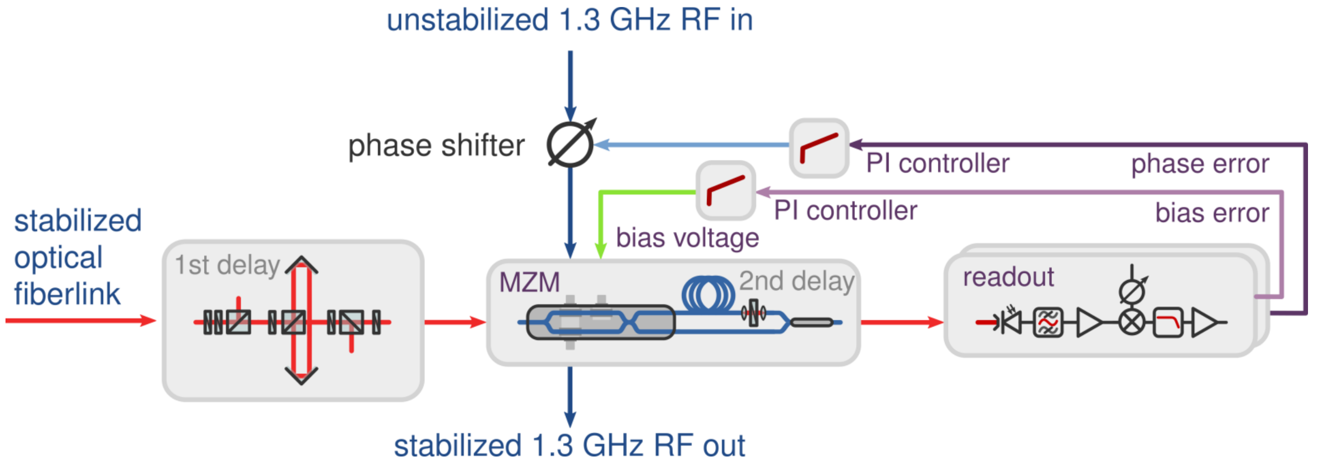




- Low 1/f-noise RF-Oscillator
- Low noise optical reference
- Noise modelling, optimal BWs

MZM-based, Balanced Laser to RF Phase Detector

Tightly Phase-locking RF and Optical Oscillators.



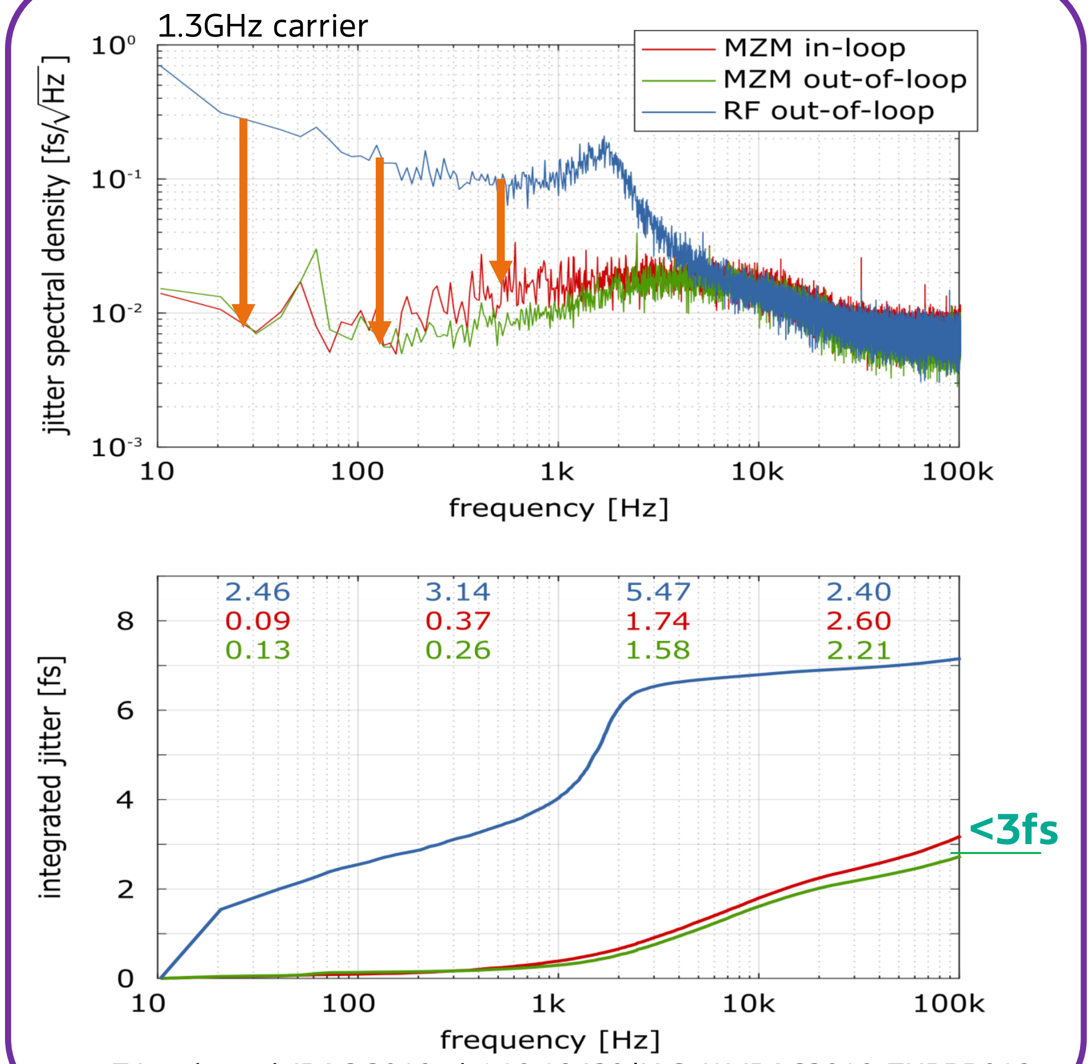
Typical performance of PLL:

Low-noise	: ~**3 fs rms**
Ultra-low-drift	: **< 2 fs pk-to-pk over 1 week**

REFM-OPT Design:

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

MLO –to – MO PLL



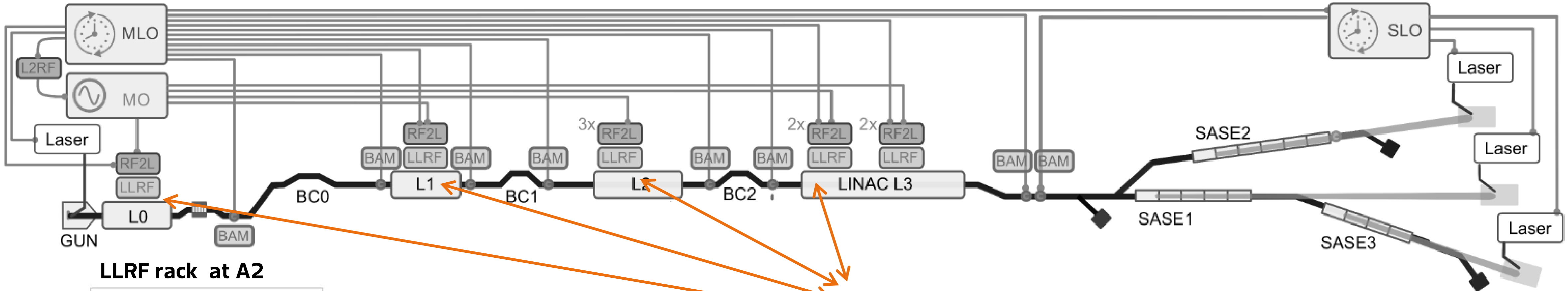
T.Lamb et al, IPAC 2019, doi:10.18429/JACoW-IPAC2019-THPRB018

[https://innovation.desy.de/: Laser-to-RF phase detector](https://innovation.desy.de/)

Courtesy: T. Lamb

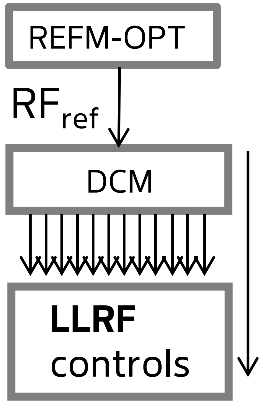
REFM-OPT → Re-Synchronize 1.3GHz RF to MLO

Local Drift Compensation of RF Input to LLRF Systems.



LLRF rack at A2

RF signal chain



phase drifts w/o compensation:

- After shutdowns >10ps drift observed
- During operation ~ 0.5ps

→ Local re-synchronization of RF reference to optical system

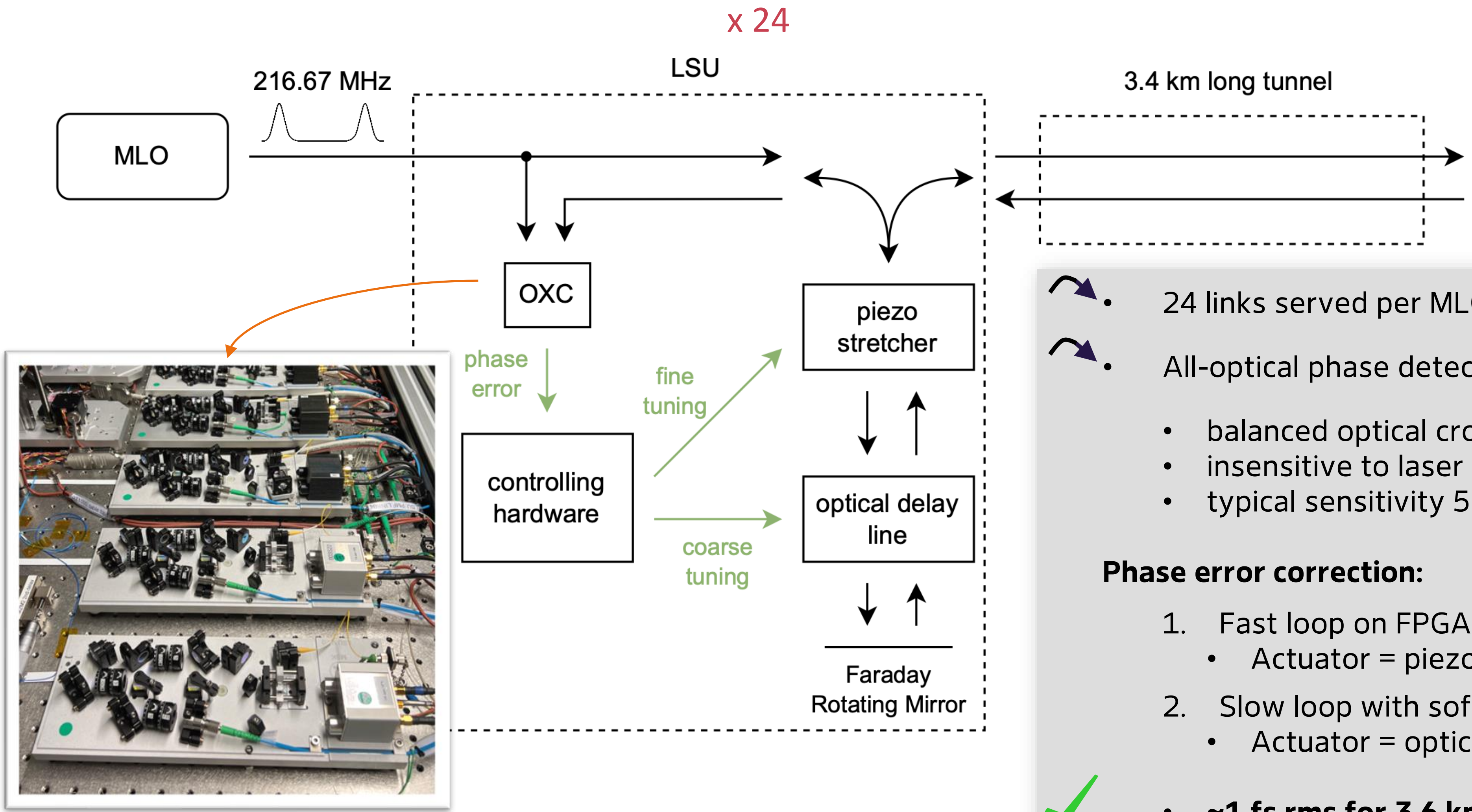
Reliable, Optically Augmented RF Reference Distribution with Femtosecond Stability

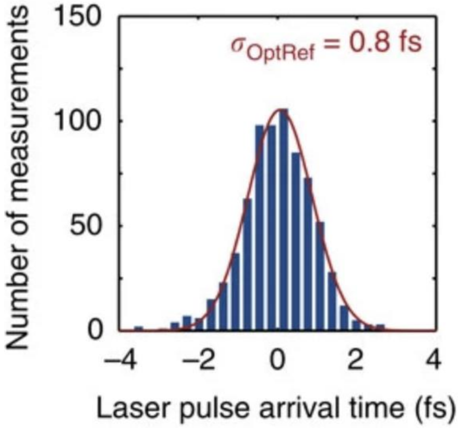
30 Oct 2024, 15:40 Maximilian Schütte (Deutsches Elektronen-Synchrotron (DESY))

Courtesy: 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:

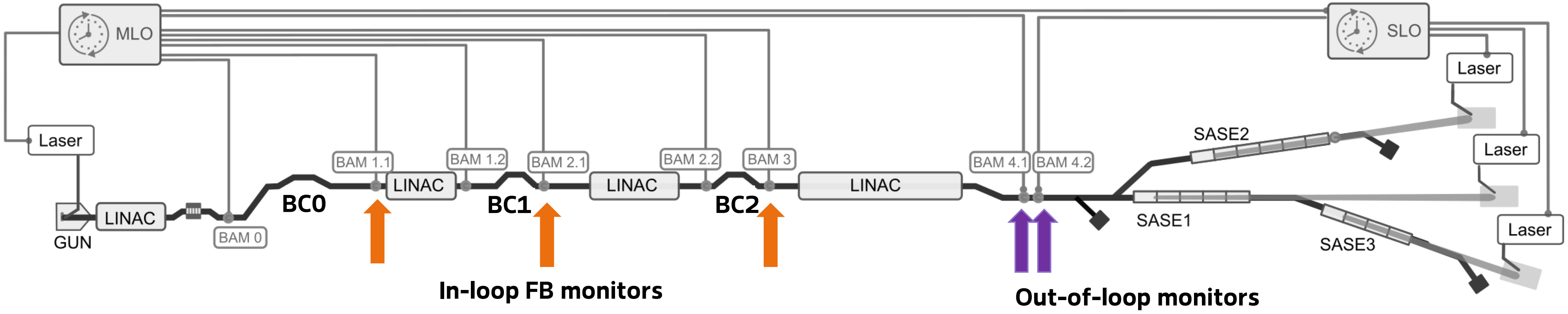
1. Fast loop on FPGA-based (PI controller)
   - Actuator = piezo-based fibre stretcher, **~kHz BW**
2. Slow loop with software
   - Actuator = optical delay line

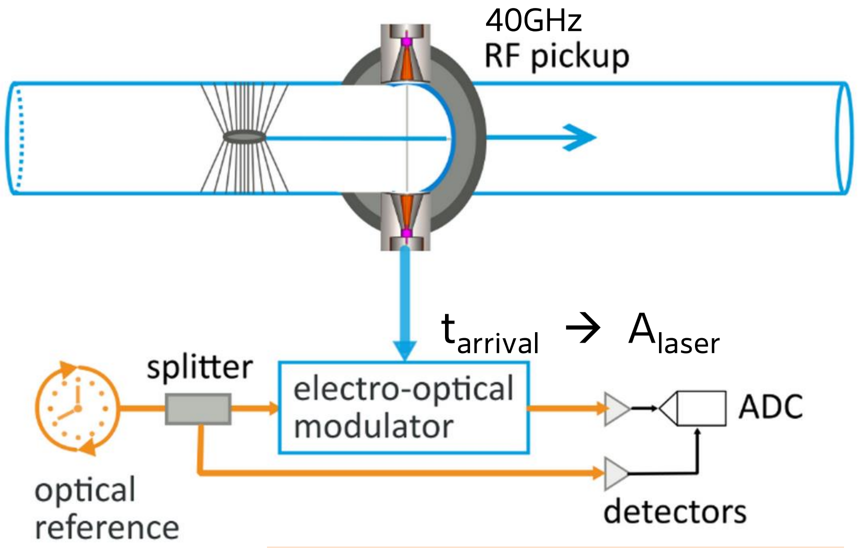
- **~1 fs rms for 3.6 km fibre link**

Arrival-time Monitoring & Active Feedbacks

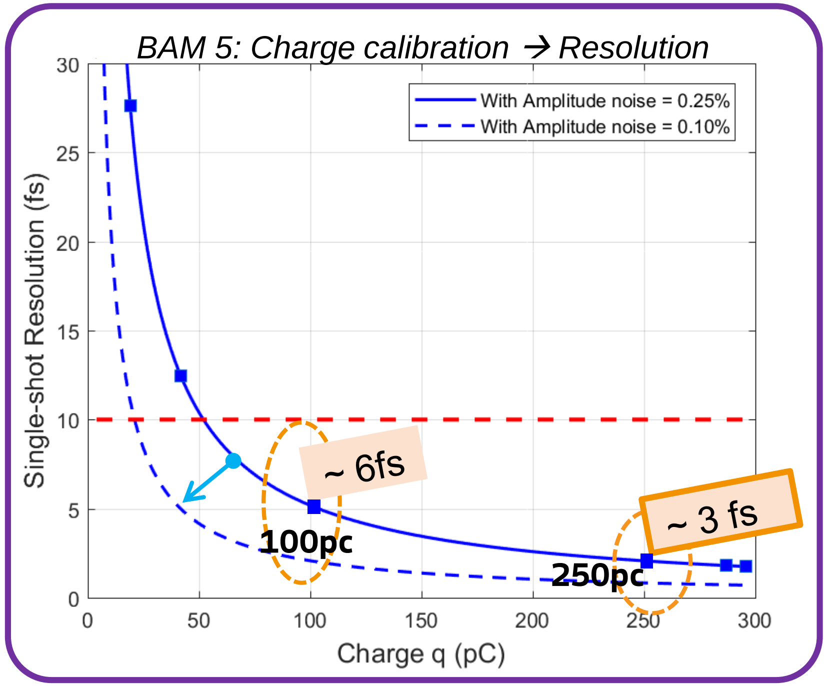
Electro-optical Bunch-Arrival-time Monitors

Few femtoseconds single-shot resolution.

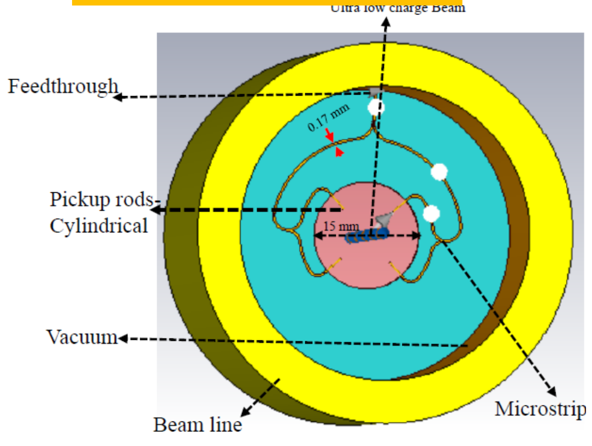




Typical resolution **3 fs** (250pc)



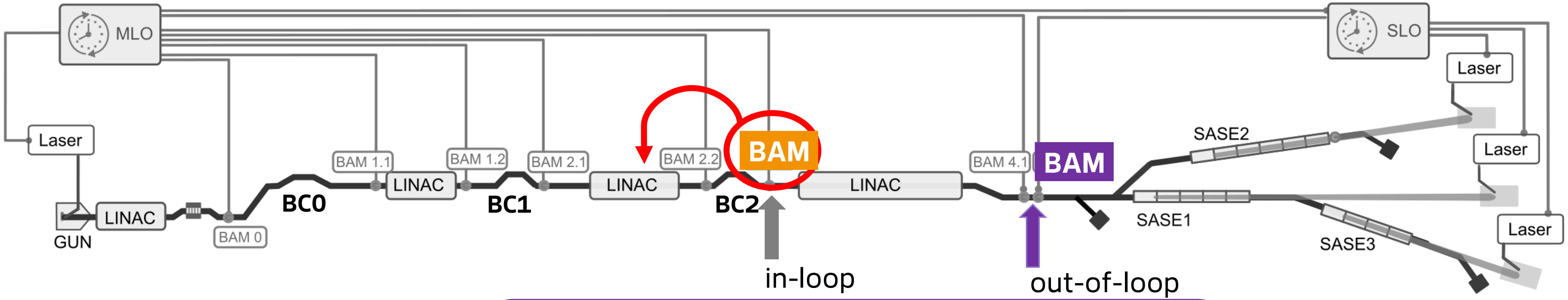
Goal: 1 fs @1pC

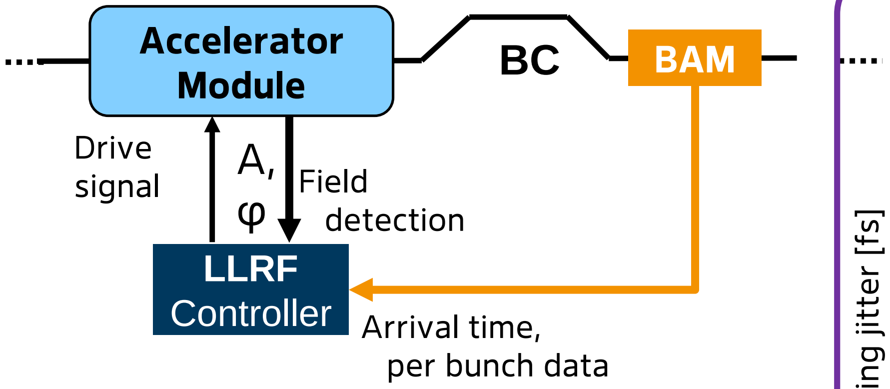


100GHz BAM

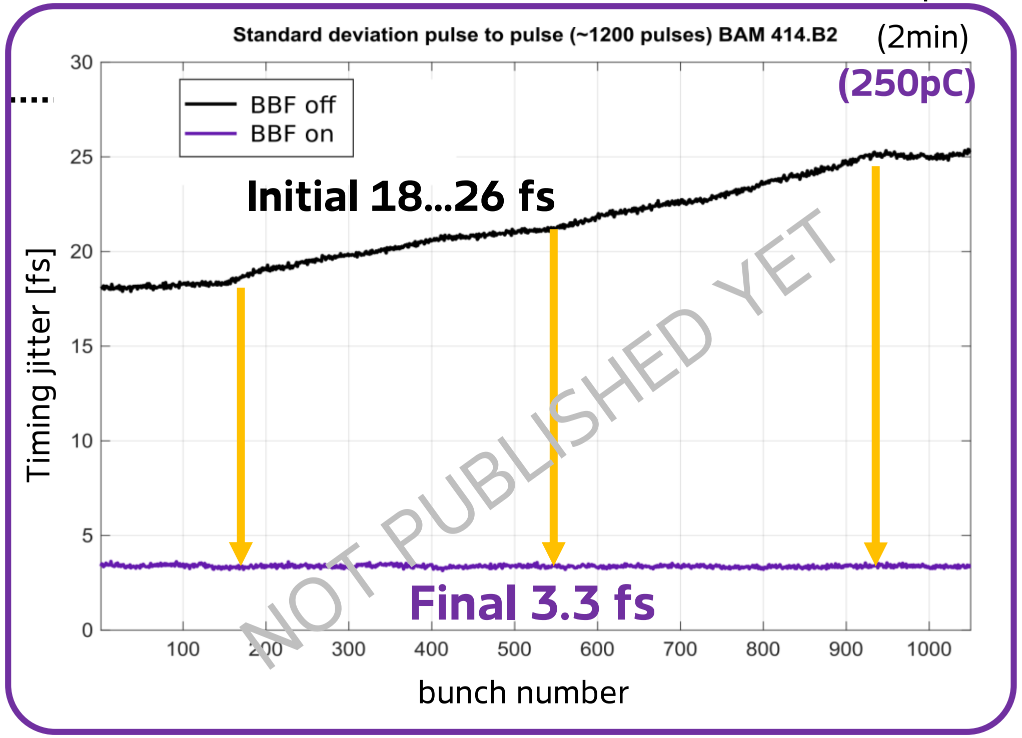
New record stability @European XFEL

Intra-train arrival-time feeback = L-IBFB with <4fs rms residual jitter.





Basic feedback loop:
Error signal combination in the LLRF controller.

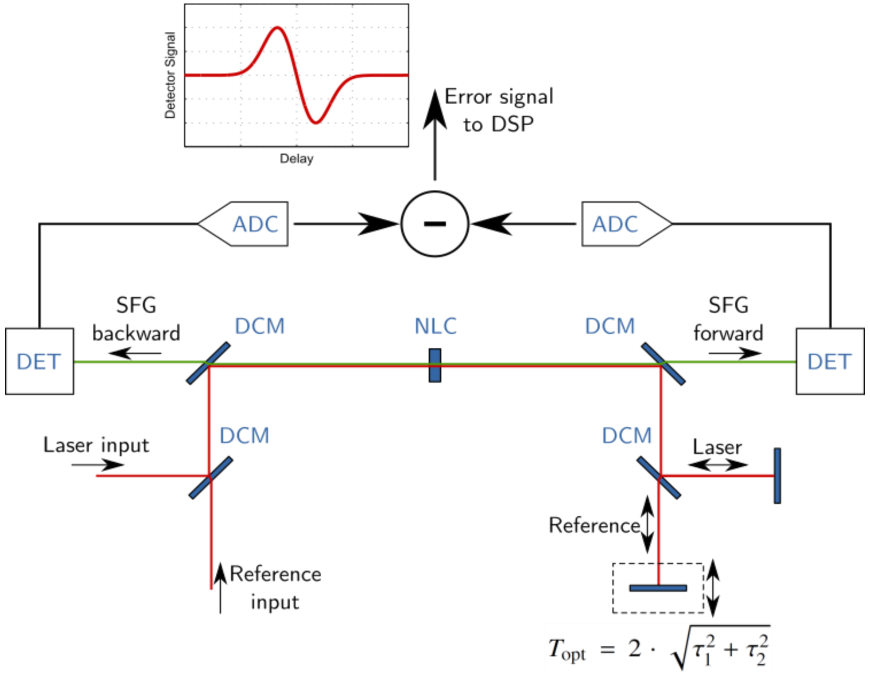


Facility	Best	Daily
EuXFEL	3.3 fs	~ 4…5 fs
FLASH	4.7 fs	~ 6 fs

Laser Pulse Arrival Time Monitor

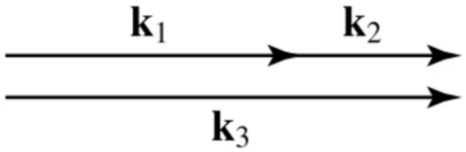
Two-Colour Balanced Optical Cross-Correlator

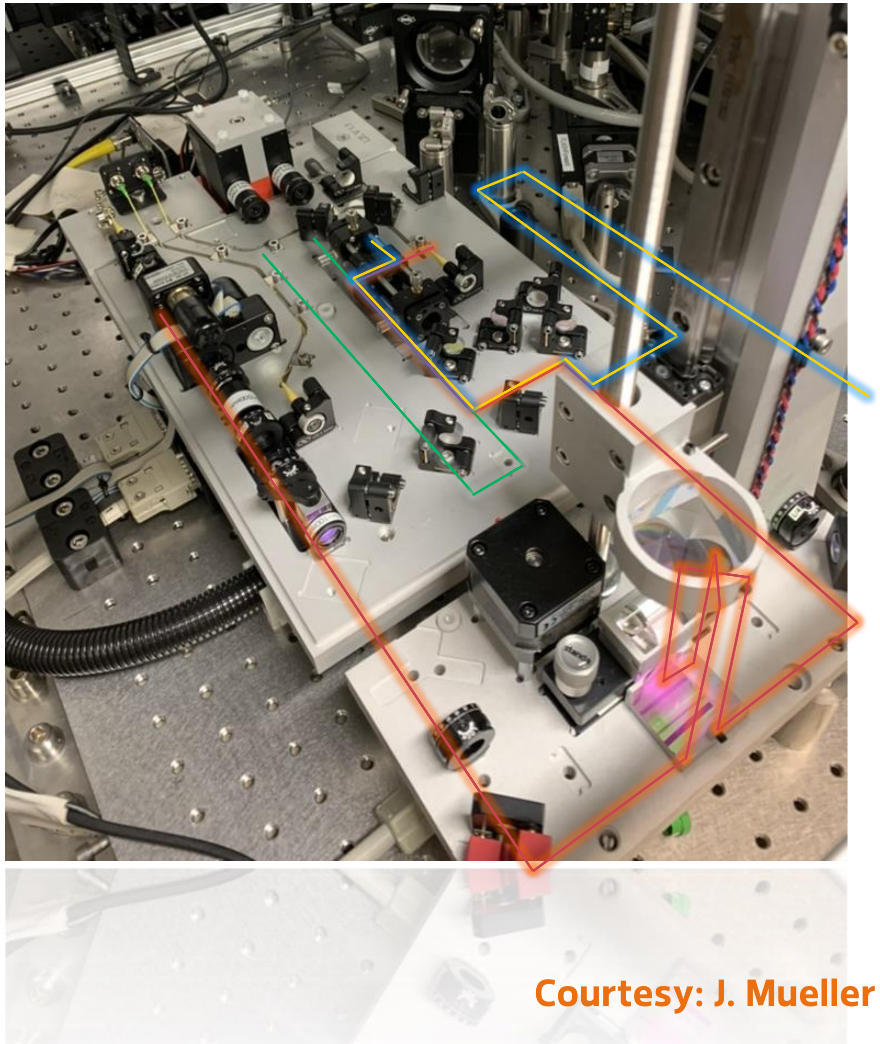
- foundation: established monolithic platform
  - all-optical scheme, very high sensitivity
  - **balanced collinear** nonlinear cross-correlation



  - can include 5 ns **user experiment delay control**
  - adaptable to different laser parameters … **real…**

Collinear design

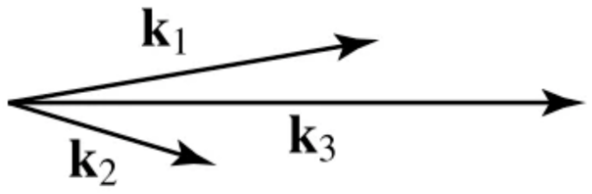




Courtesy: J. Mueller

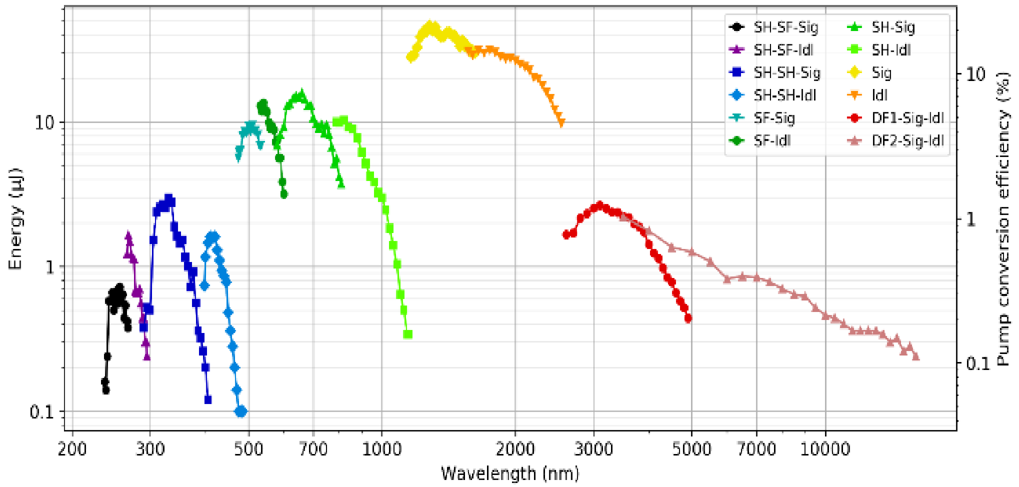
Advanced Laser Pulse Arrival Time Measurements

One Challenge: Covering a Huge Spectral Range for User Experiments



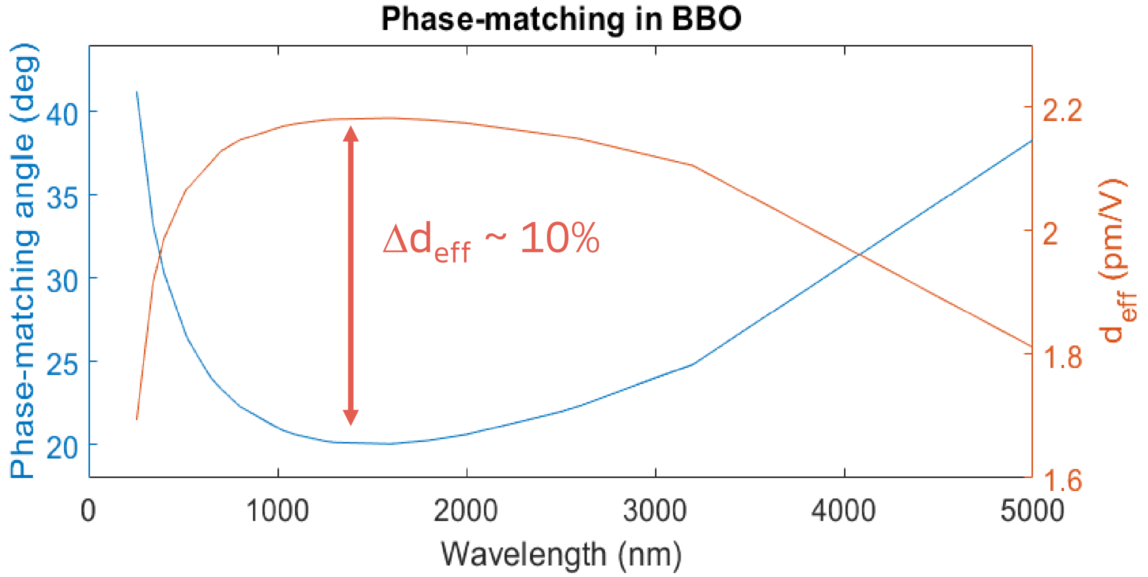
✅ fundamentals: **800 nm** and **1030 nm**

- SHG, THG, FHG: 400 nm, 266 nm, 515 nm, 343 nm, 258 nm
- NOPA, SFG, DFG, e.g. with Topas:



- signal separation (dichroic mirrors), GDD?

→ **non-collinear phase matching to the rescue?!**
would allow for automated crystal tilting WL tuning



$$U_{vec} = (A^2 + B^2 + 2AB\cos\gamma_{vec})/C^2$$

$$W_{vec} = (A^2 + B^2 + 2AB\cos\gamma_{vec})/F^2$$

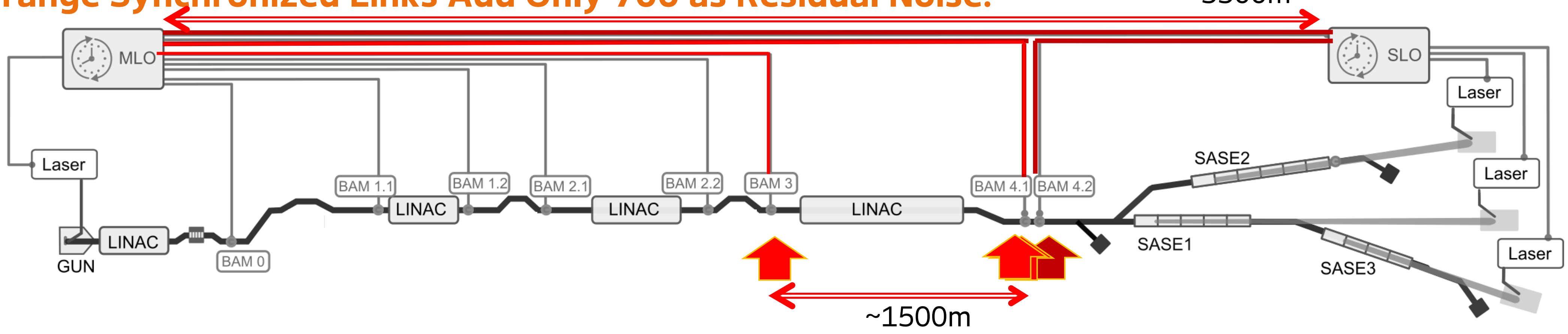
 Courtesy: A. Calendron, D. Schwickert, N. Kschuev, S. Hoseinkhani

Evaluation of the Synchronization Performance

- Residual noise of optical links
- Correlation FEL ←→ Electron Bunch
- Laser Pulse Drift Compensation

Short-term Stability → Jitter Performance

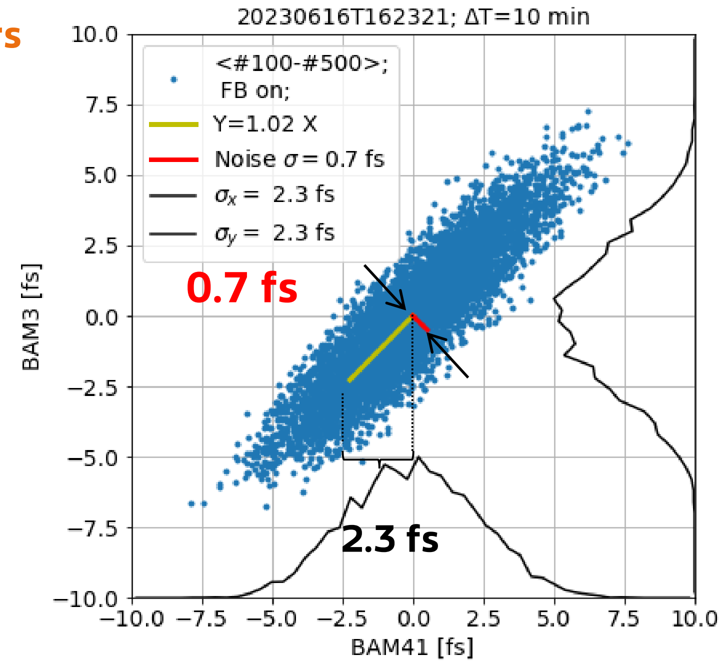
Long-range Synchronized Links Add Only 700 as Residual Noise.

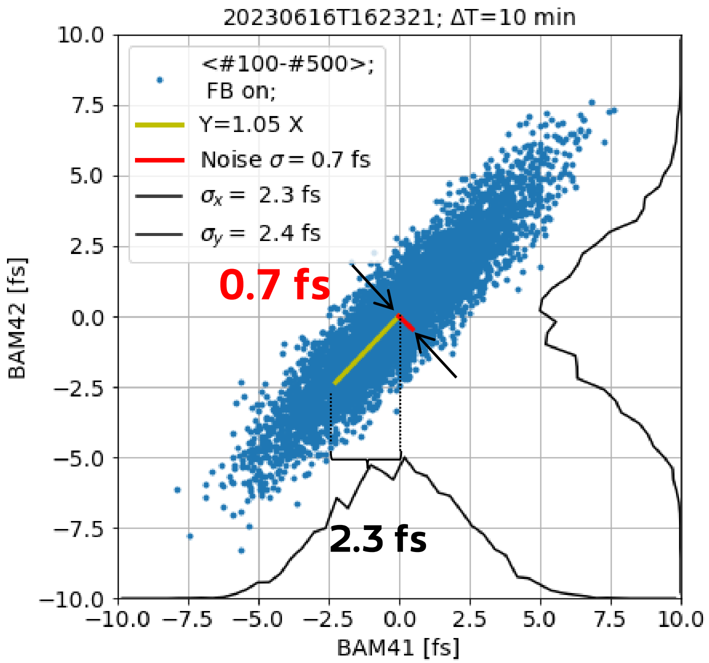


Correlation of redundant arrival time monitors

- 10 min. (6000 trains), intra-train mean (400 bunches)
- Removal of BAM high-freq. instr. Noise
- Correlated : jitter of bunch train mean arrival time

Uncorrelated noise
→ **sub-fs stability of optical reference**

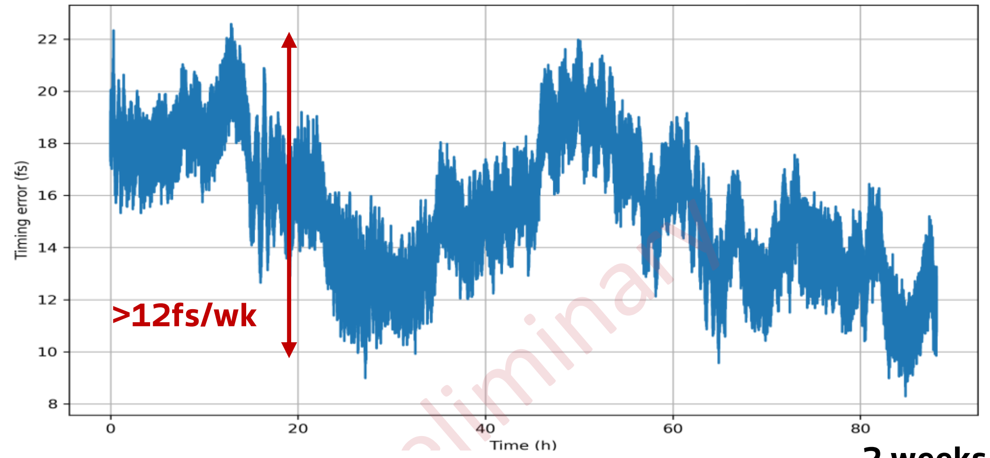


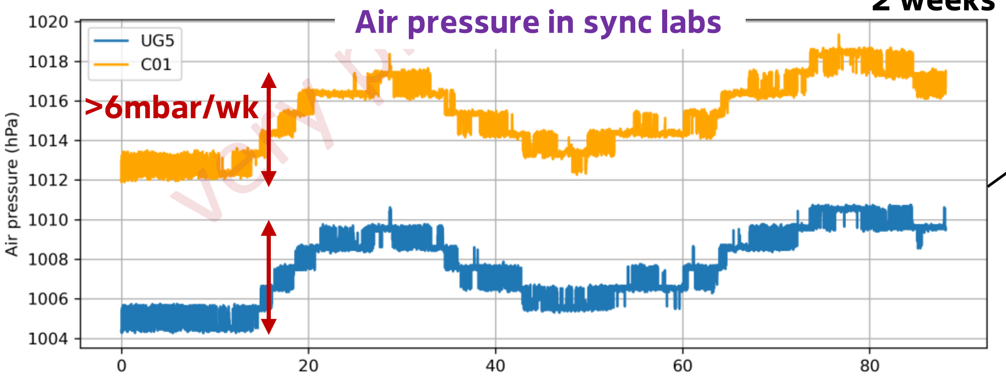


Long-Term Effects: Timing Drift vs. Environmental Parameters

Most Prominent –And Uncontrollable– Effect: Air Pressure

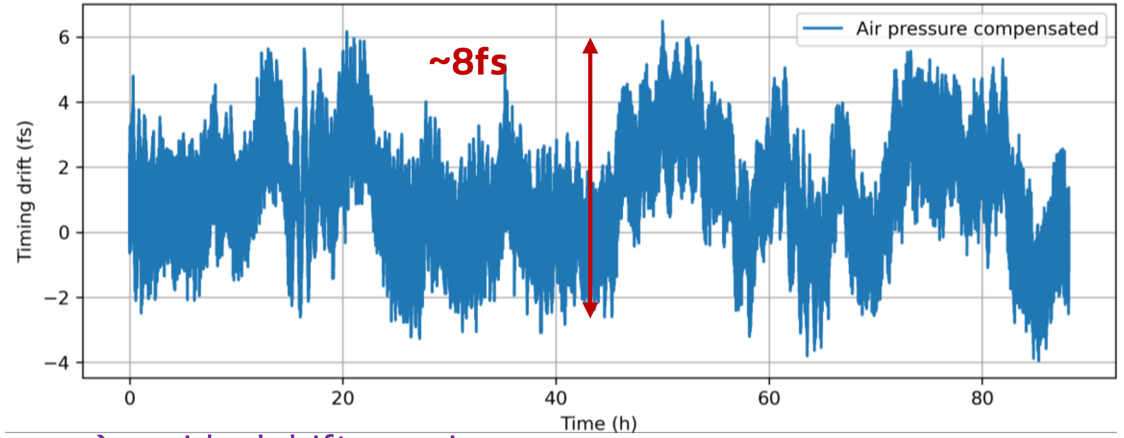
Round-trip timing error





- correlation factor **-1.11 fs/mbar/m**
  + other effects
- Remaining, uncompensated optical path

Correlation removed from data

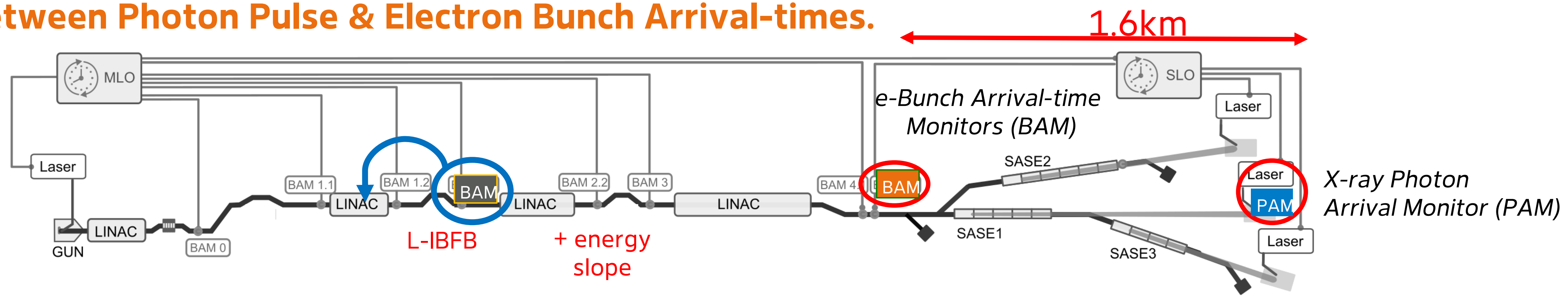


→ residual drift remains
~8fs peak-to-peak, ~3.5 fs rms

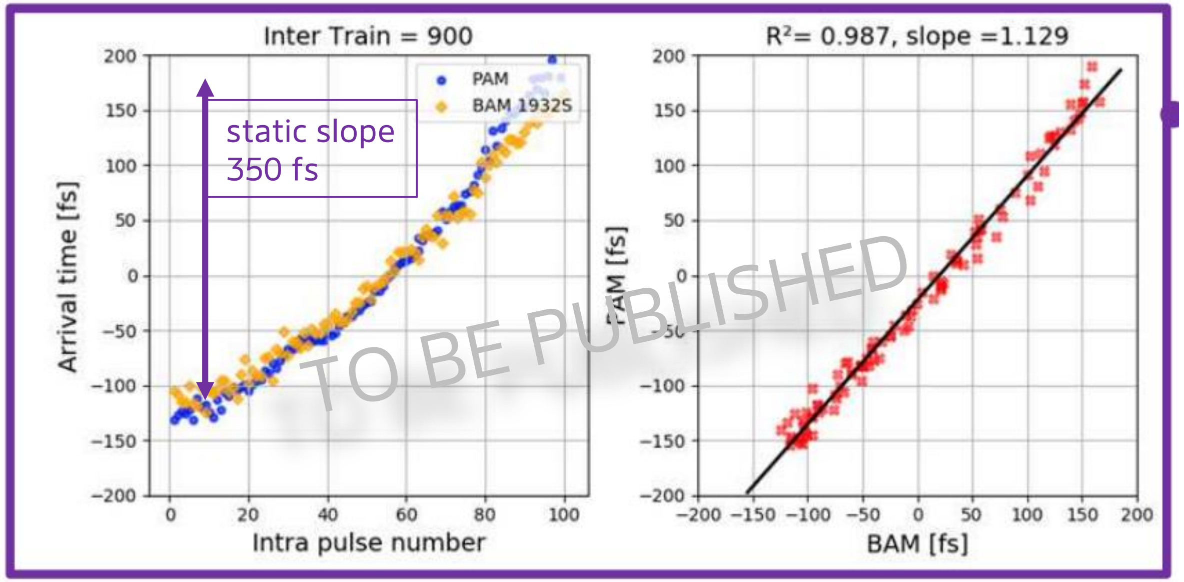
Courtesy: M. Schuette

Photon Arrival-times vs. Electron Bunch Arrival-times

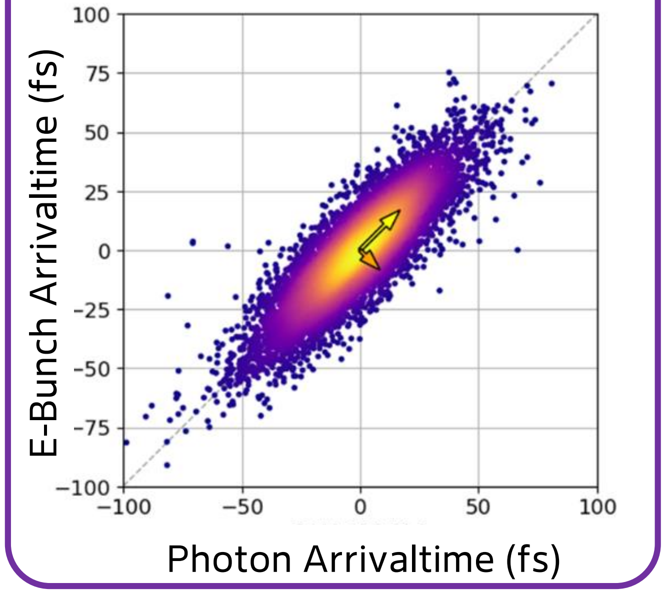
Correlation between Photon Pulse & Electron Bunch Arrival-times.



- ✓ L-IBFB → <6fs rms jitter (train to train)
- ✓ Applied static energy slope across train on purpose
  → **Enables single shot, pump-probe timing scans**



Short pulse mode **(100pC)** :
- 7fs rms (L-IBFB)
- 12fs rms un-correlated noise

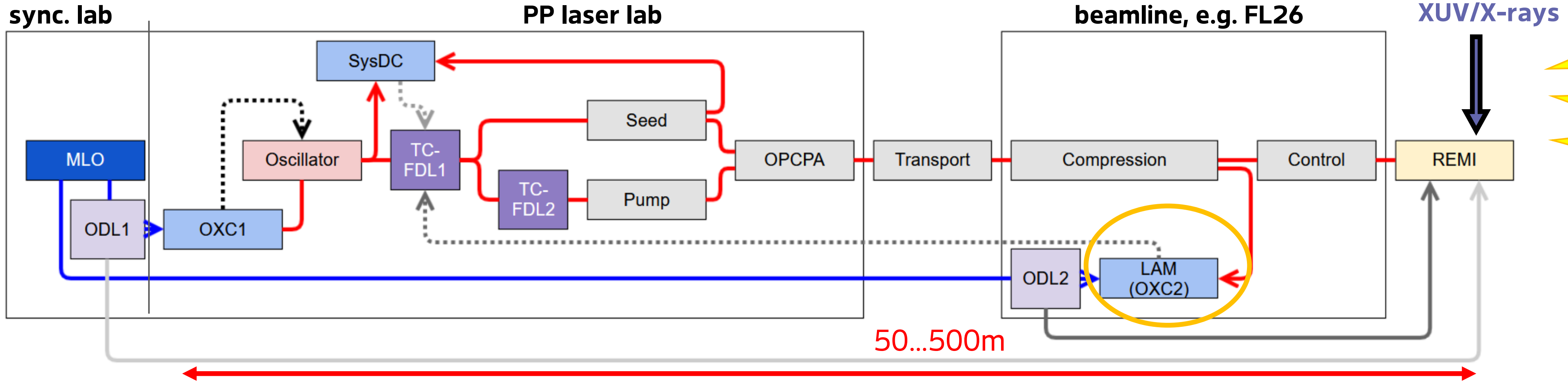


Courtesy : Jia Liu, XFEL (XPD)

Drift Correction in Laser Beam Delivery for Experiments

FLASH.
Free-Electron Laser FLASH

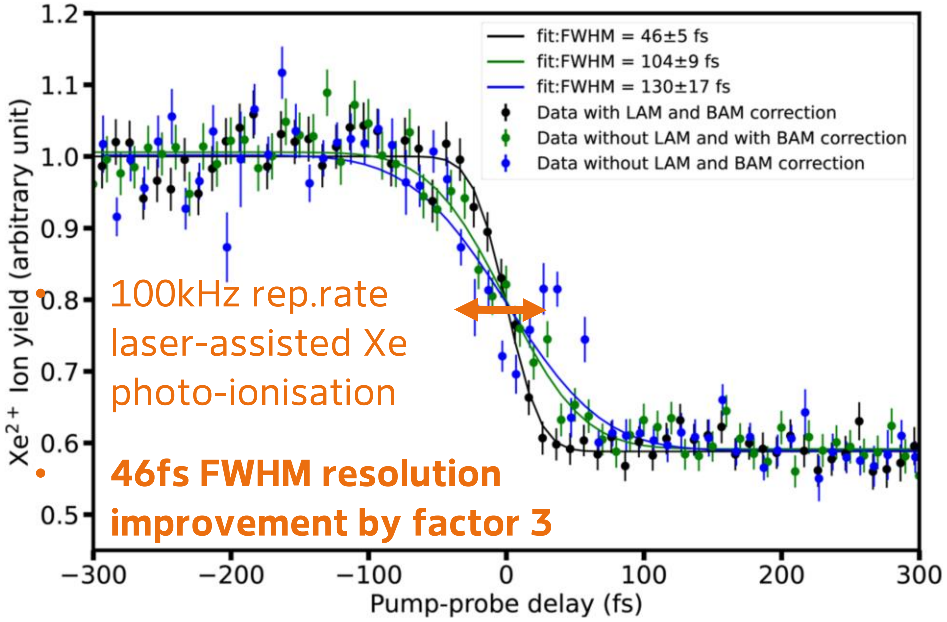
Laser Arrival-time Monitor Feedback

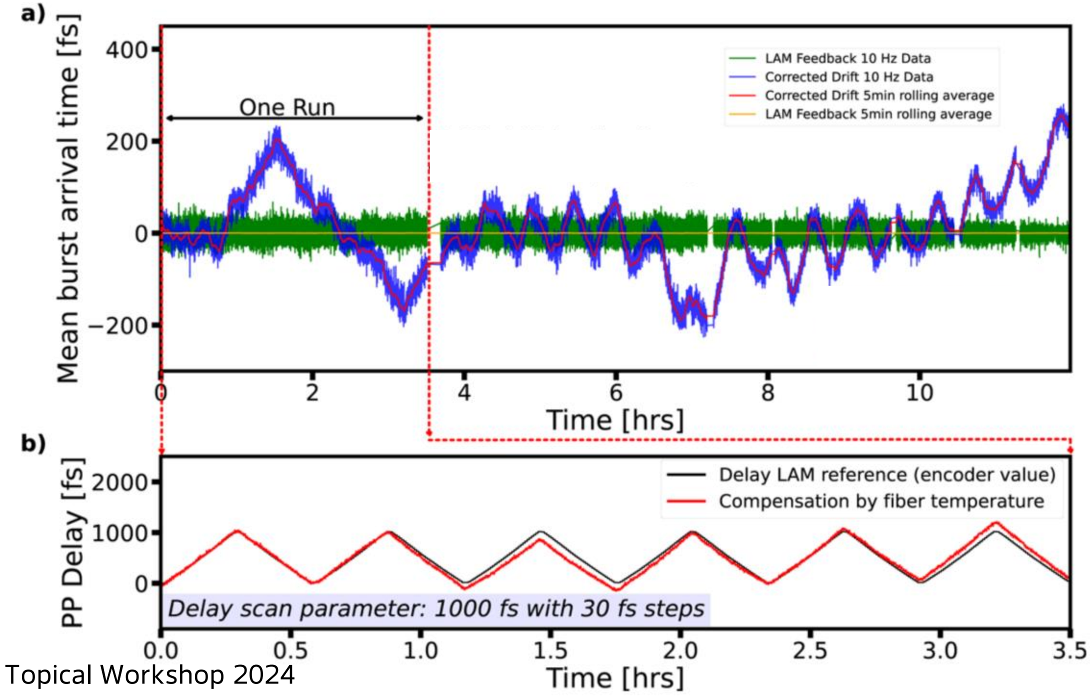


Air pressure
Rel. humidity
Temperature

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**

External Disturbances,
→ Seismic Influence

Long-haul Effects from P and S Waves

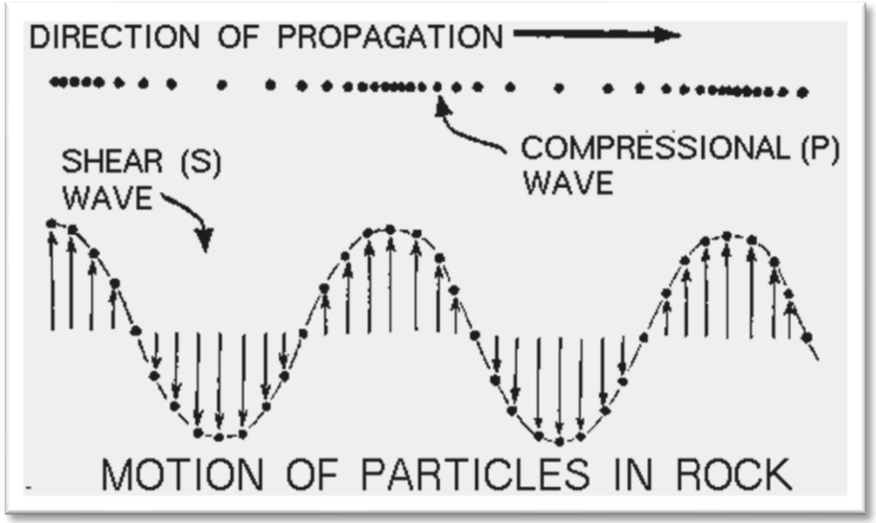
Body Waves Inside the Earth

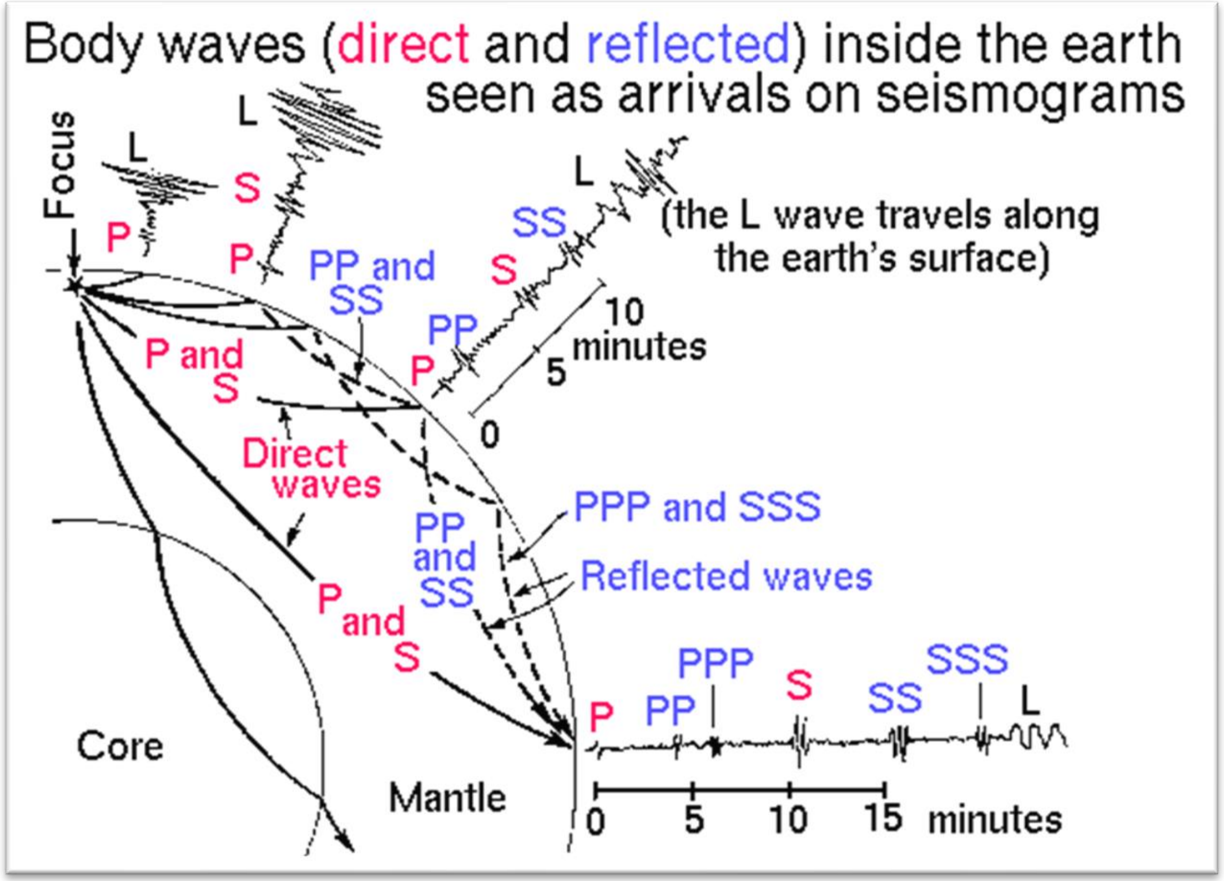
P or compressional wave

- velocity typically **6 km/s**

S or shear wave

- velocity **~3.4 km/s** close to surface
- no propagation through liquid material



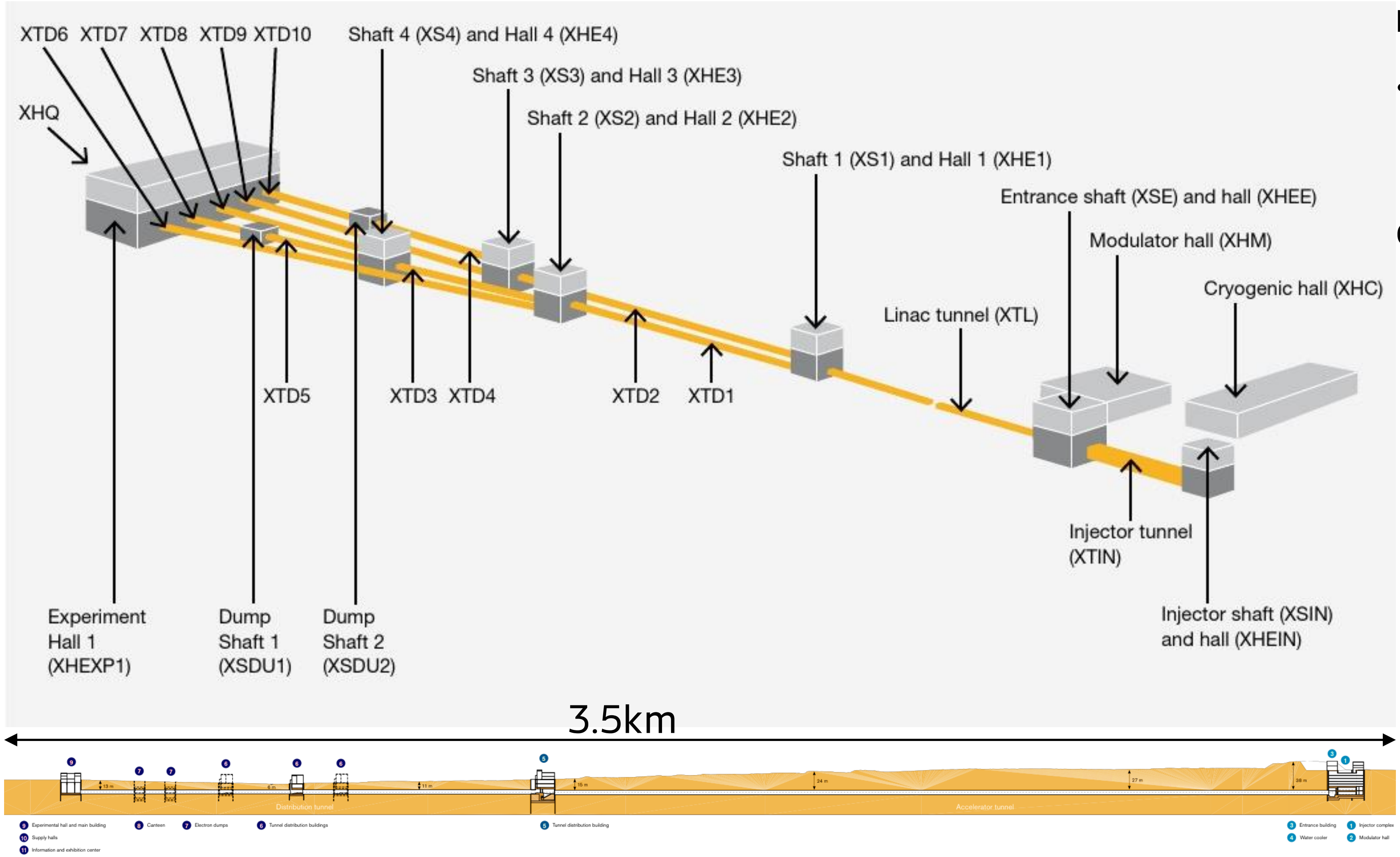


https://earthquake.usgs.gov/earthquakes/events/1906calif/18april/earthwaves.php

L or Love wave, **R** or Rayleigh wave

European XFEL Building Overview

Tunnels, Halls, Shaft Buildings



Building structure

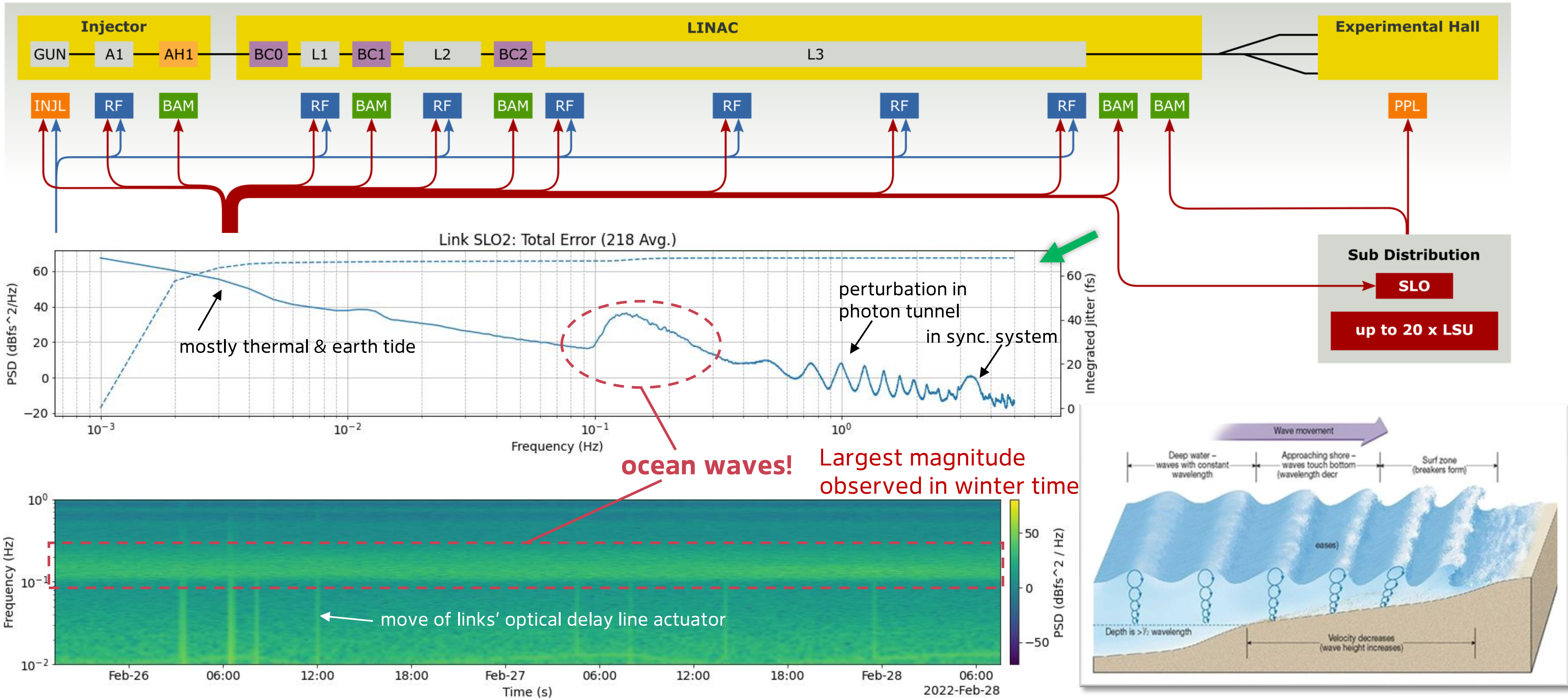
- Halls, shaft building connected with tunnels (buffer zones included)

Optical fiber installation

- horizontally in ducts (XTL) and on trays (XTDs)
- vertically on trays in shaft buildings
- within rigid protective tubing

Atlantic & North Sea Ocean Waves Detected on Long-haul Fiber Links

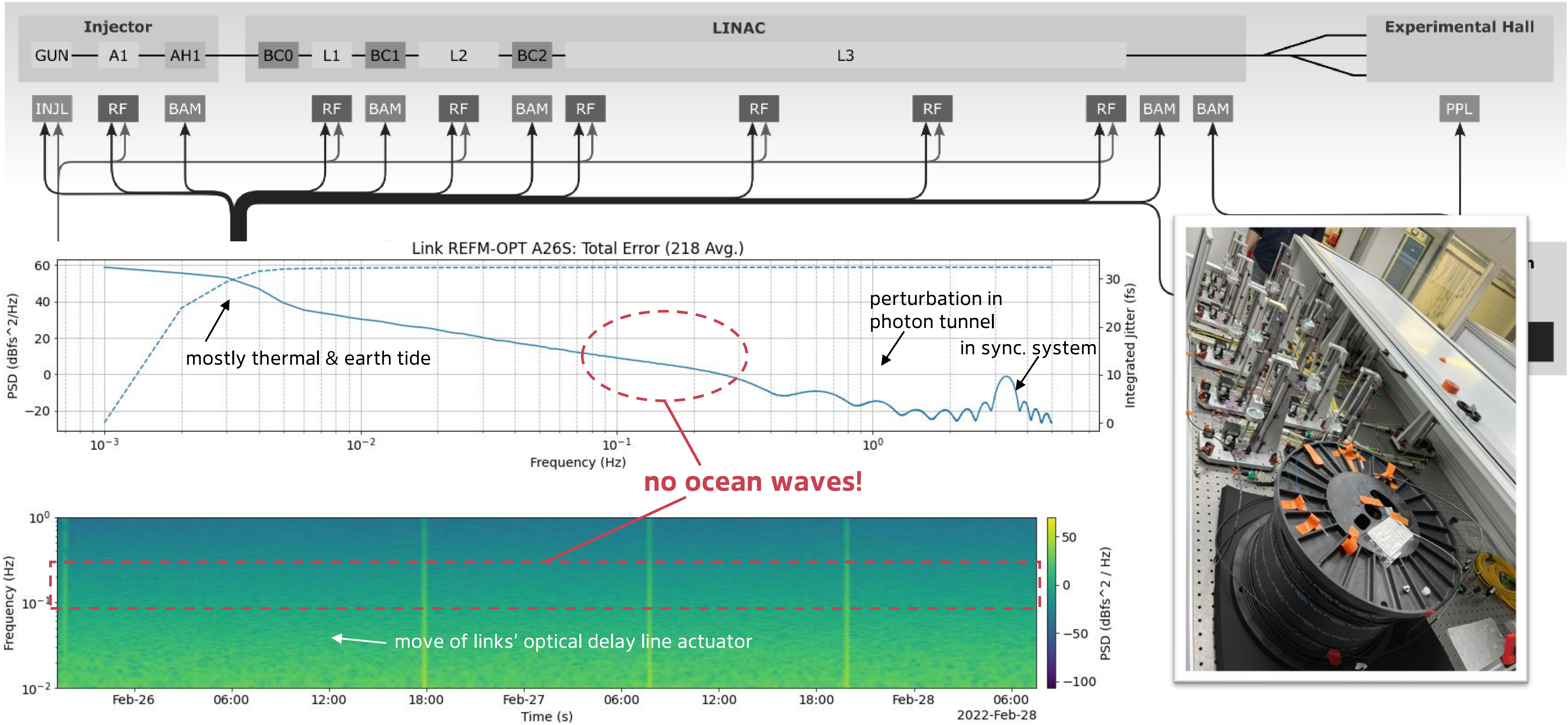
3.5 km-long with typical noise increase at 0.2Hz.



Courtesy: M. Schuette

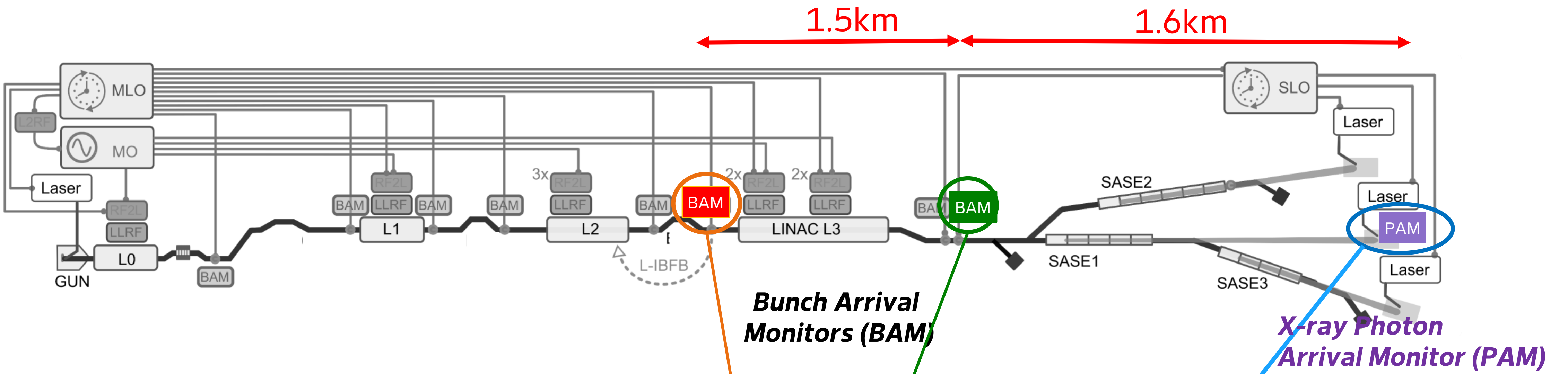
Cross-Check in Main Synchronisation Lab to Rule out Other Causes

2.0 km Mechanically Decoupled Fiber Spool Link Verifies : 0.2Hz noise is dependent on Elongation.



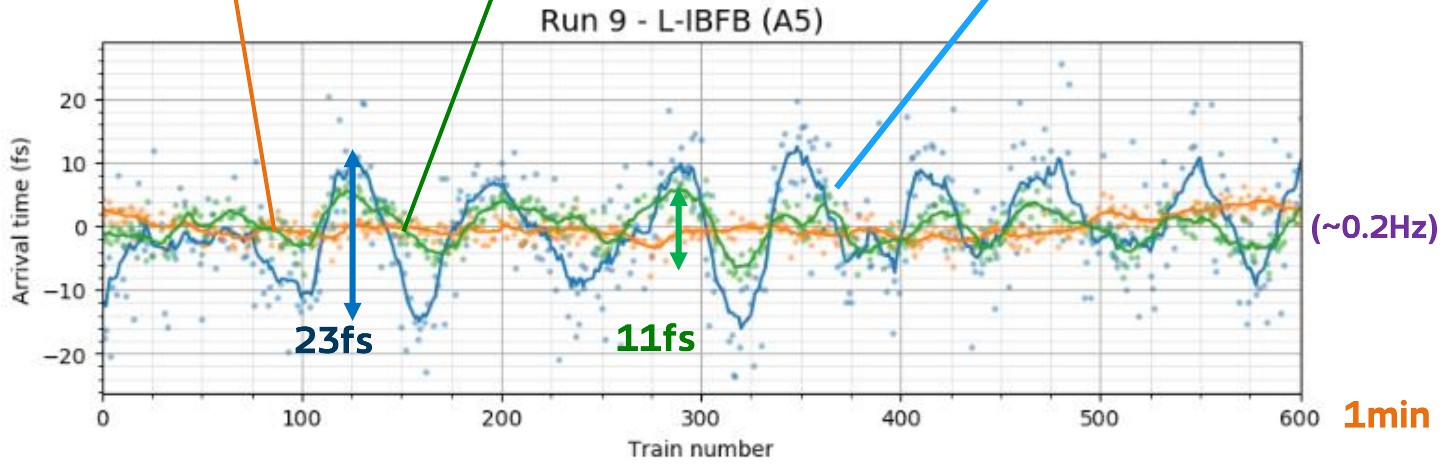
Ocean Waves Appearing in Beam-based Measurements

Relative Arrival-times Revealed Periodic Disturbance with ~ 0.2Hz.



Observed arrival-time fluctuation :

- ca. 5sec period, oscillation between distributed sensors
  - ❑ Ruled out Main RF frequency drift
  - ❑ Ruled out issues with optical synchronization
  - ❑ Visible also in compensated drift in optical links
  - ❑ **Origin of error ??**

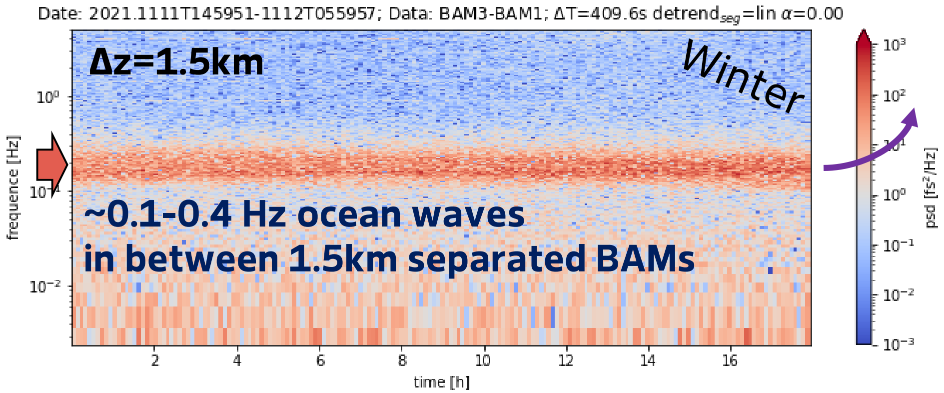


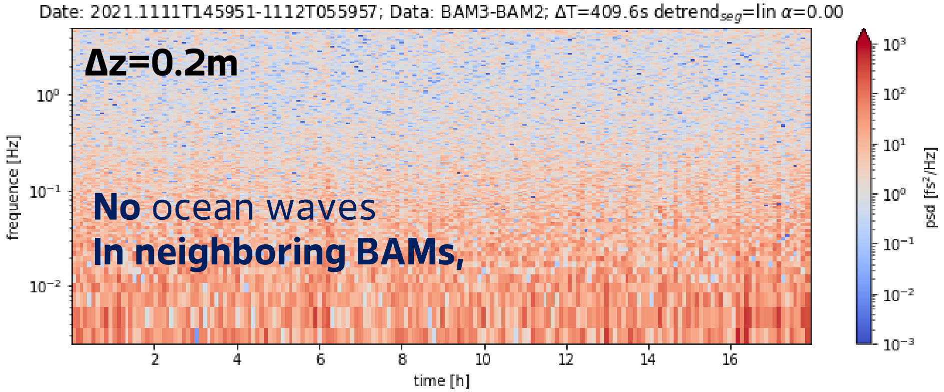
- autumn, Oct. 2020

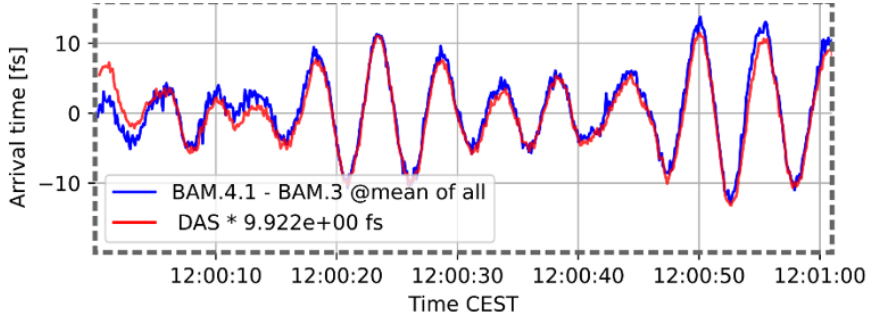
Romain Letrun, Tokushi Sato, Henry Kirkwood, Jayanath Koliyadu
SPB/SFX Instrument, European XFEL
Oct.2020 – Mar. 2021

Measurable Effect @EuXFEL from Micro-seismics 100..400mHz

Ocean Waves, Verified by Distributed Accousted Sensing (iDAS).





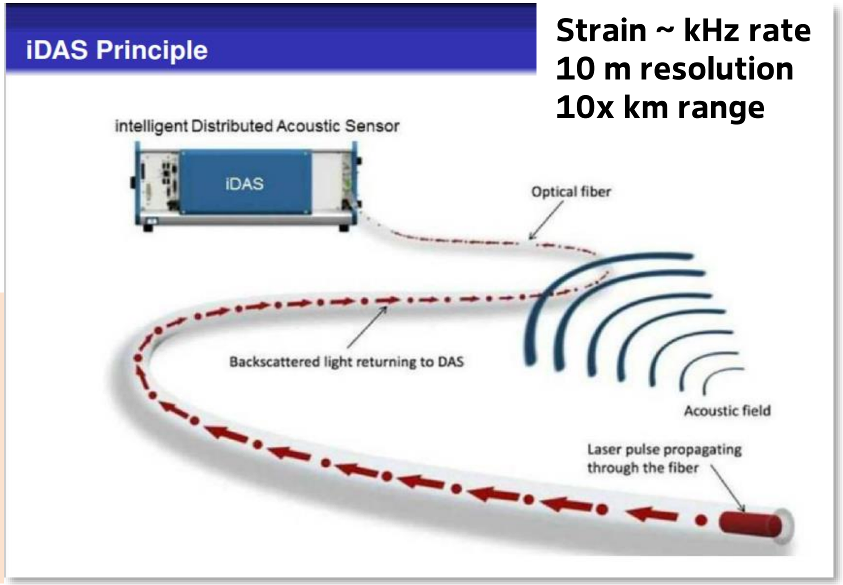


- **0.1…0.2Hz**
- **adds ~2.8 fs rms over minutes**

Issue for sub-fs stability,

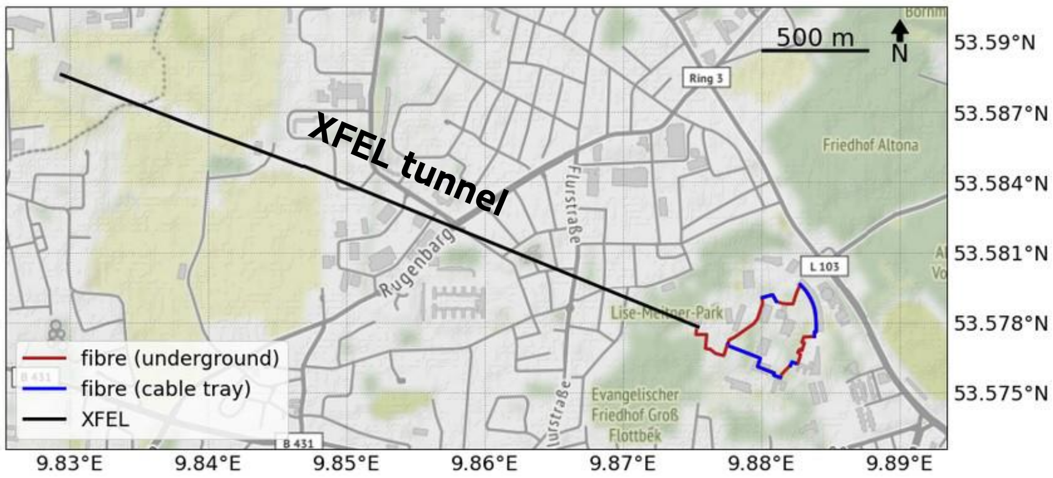
mitigation path:

- Modelling on iDAS data
- pattern recognition
- A posteriori data sorting
- Feed-foward delay control



Strain ~ kHz rate
10 m resolution
10x km range

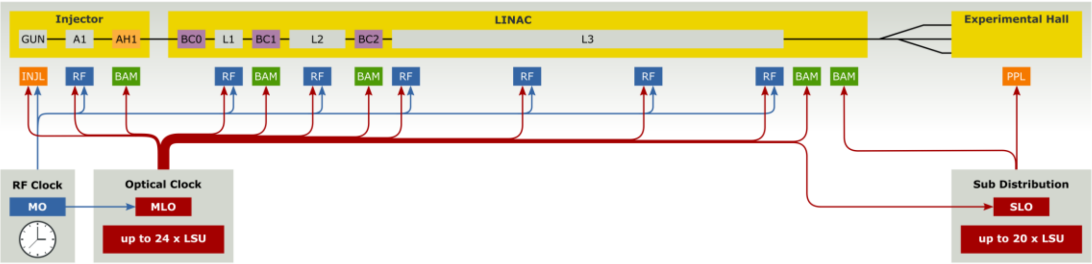
Measurement campaign 12.6 m length

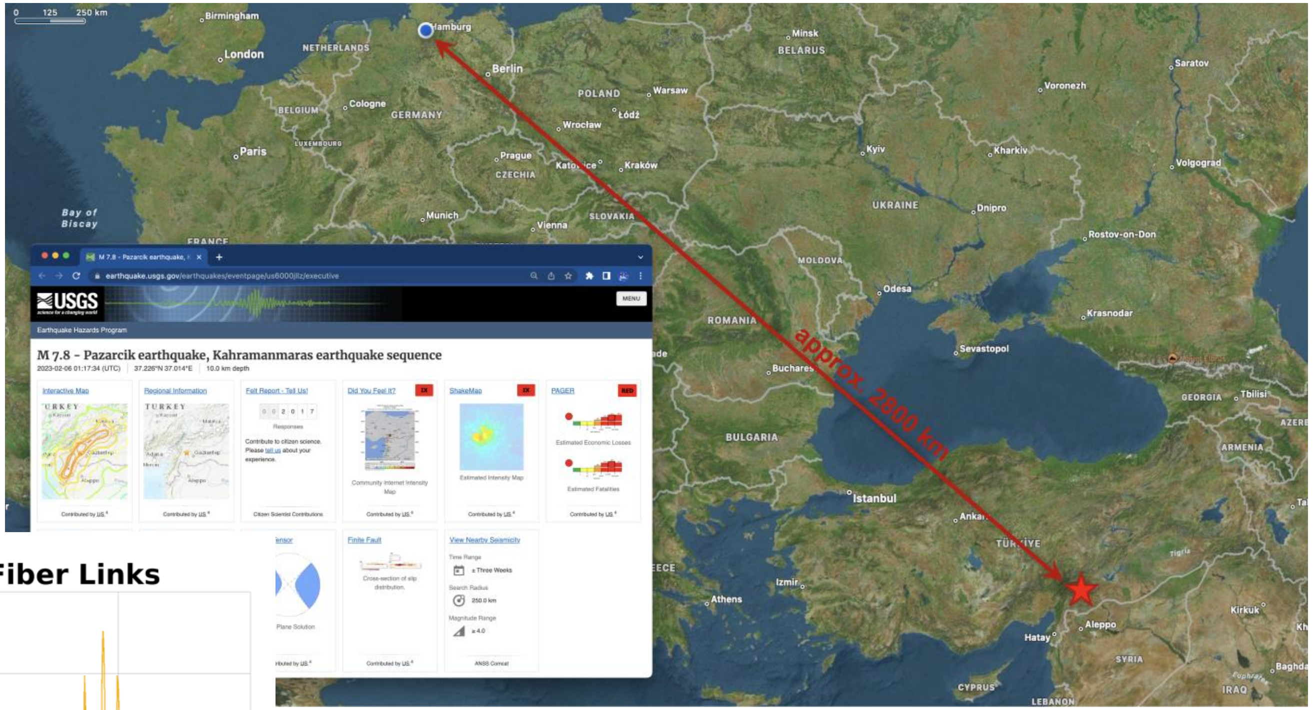


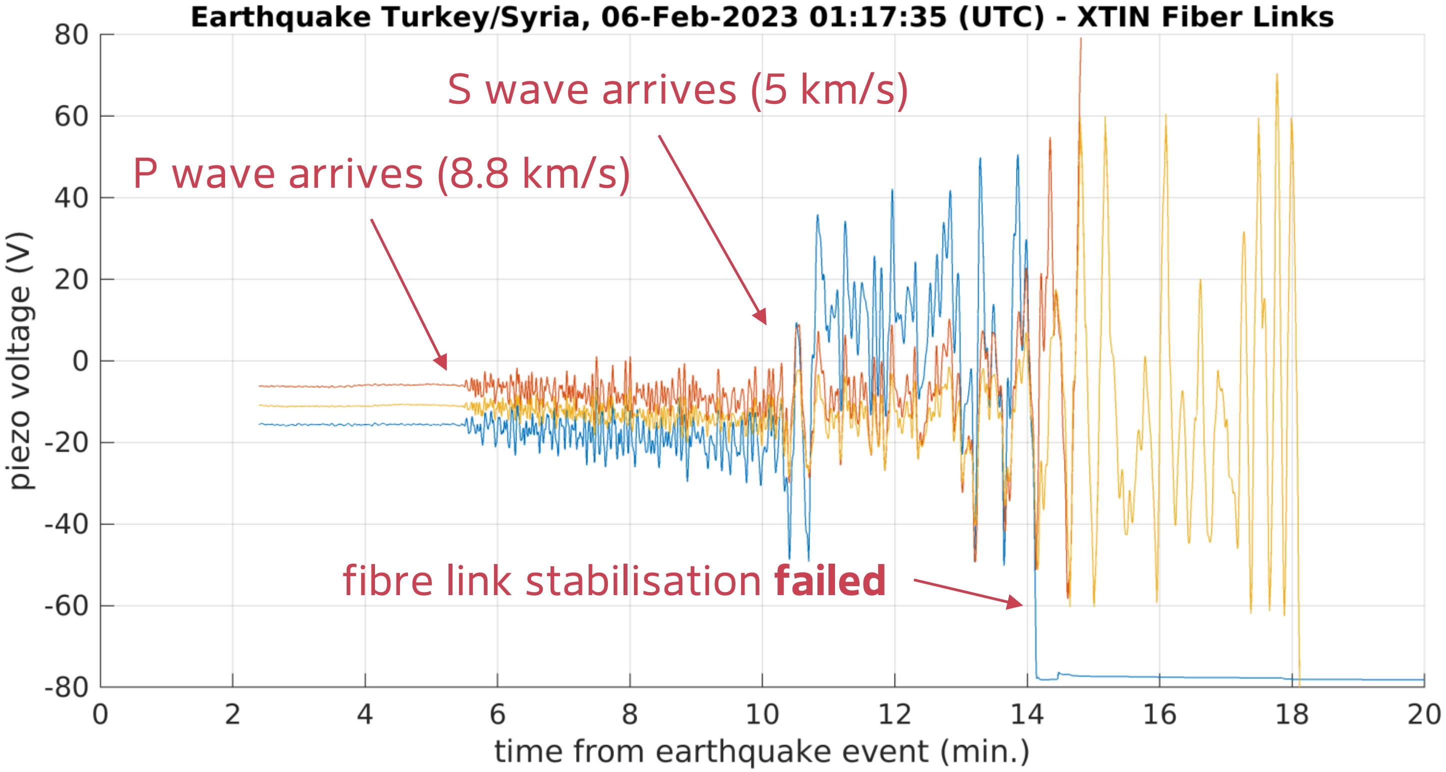
See http:\\wave-hamburg.eu

Exceptional Events: Earth Quakes

Fibre Link Stabilisation (Partly Failing)





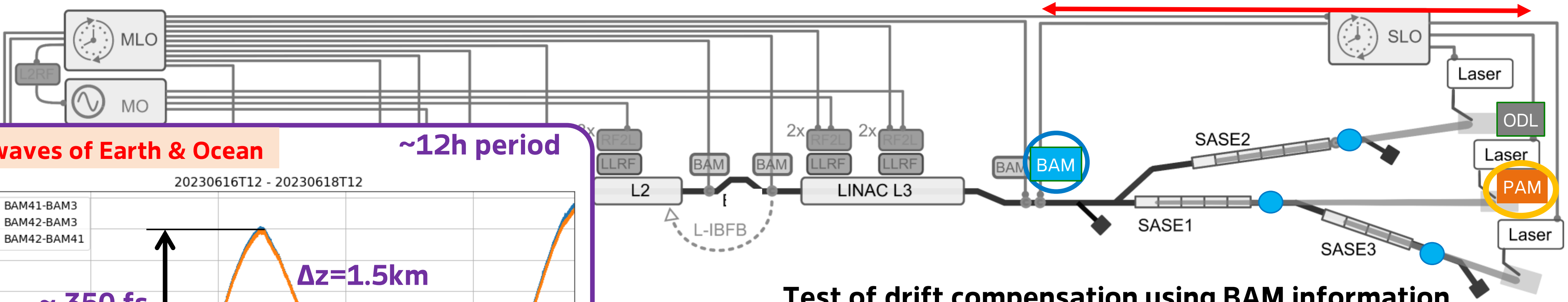


- **EuXFEL has been stretched > 3 mm**
- distortion visible > 1 h

→on-going project :
seismological modelling of EuXFEL building dynamics

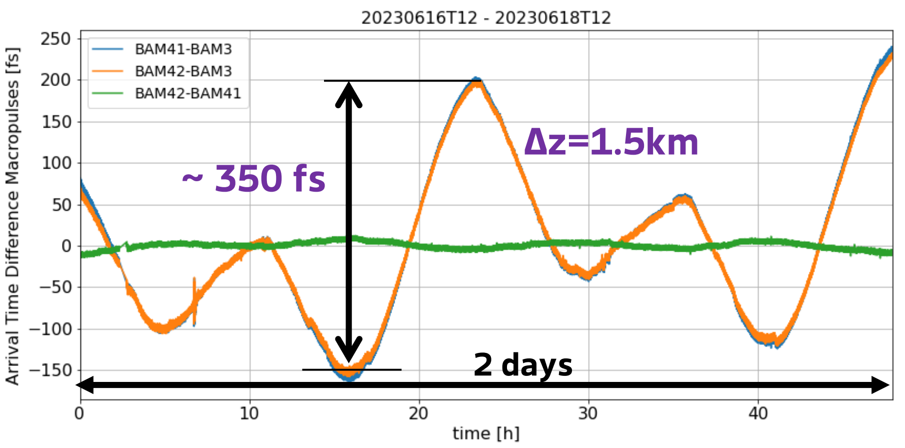
Micro-Seismics, Long-term Effects (~ mHz)

Earth & Ocean Tide → 100..300fs T0 Timing Drift → Possibility of Drift Suppression Demonstrated

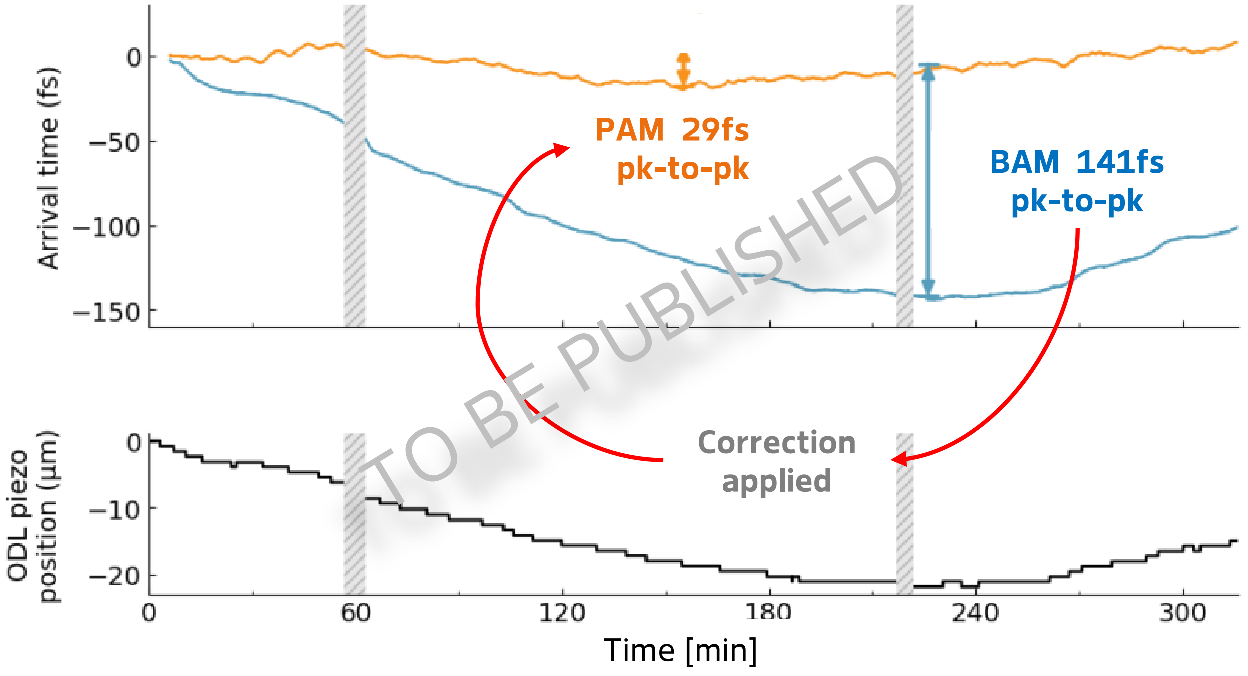


Tidal waves of Earth & Ocean

~12h period



Test of drift compensation using BAM information



Tidal wave drift compensation

→ Suppression by factor 4…5

→ **But** requires further investigation :

- Use BAMs closer to Experimental Hall
- Model-based understanding of geophysics
- Establish feedforward compensation

R. Letrun et al., manuscript submitted Sep.2023
Increasing the efficiency of time-resolved 2 experiments at X-ray free-electron lasers

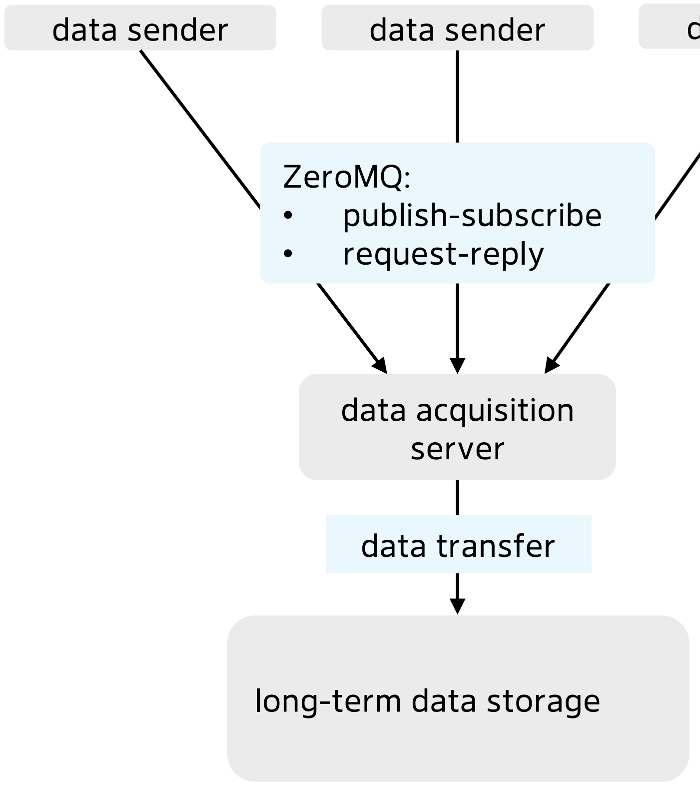
Data-driven Approach

→ Fault Detection, Controller Optimisation, …

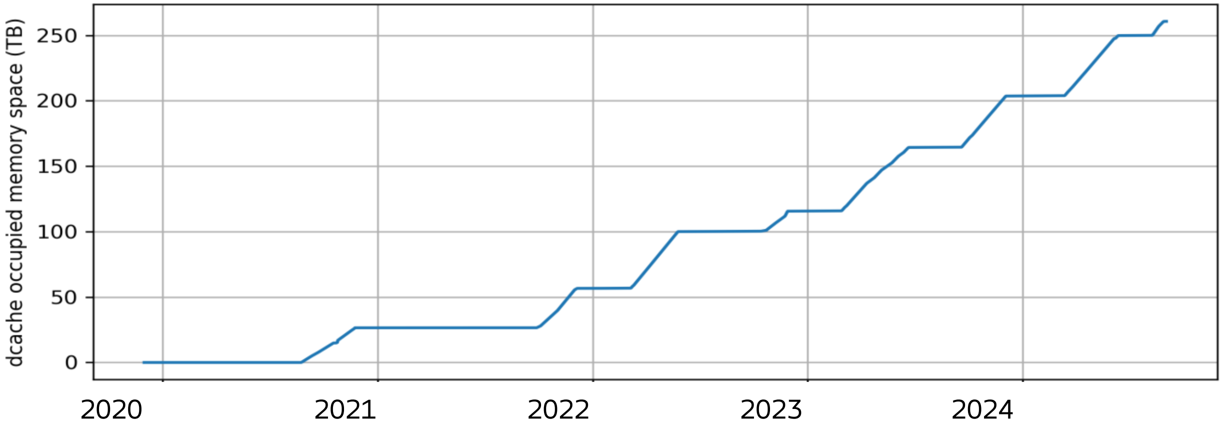
Data Acquisition and Storage

Dedicated DAQ System for the Laser-Based Synchronisation System

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

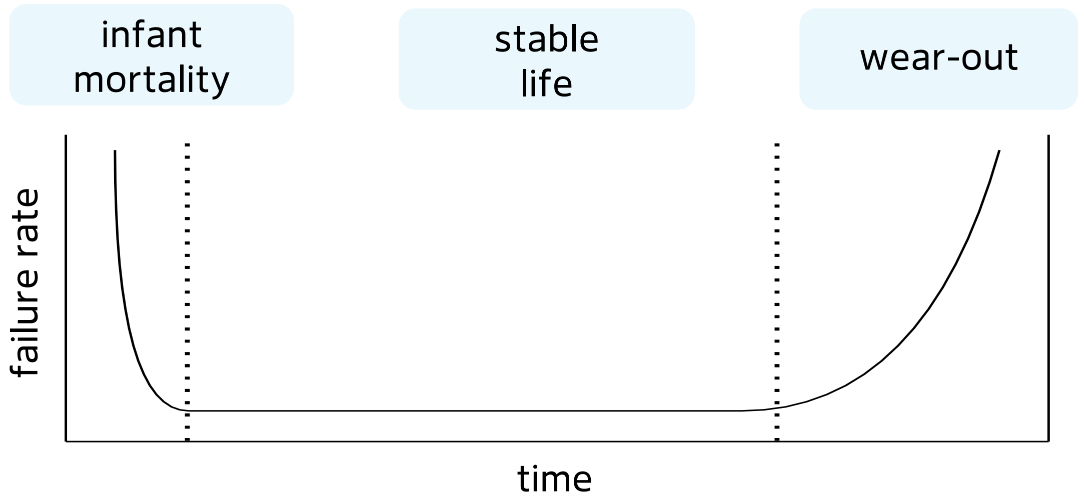


- data sources **~47k control system channels**
  - controller I/O of all feedback systems
  - configuration
  - environment (*T*, relative humidity, air pressure)
- dCache volume **~250 TB** since 2021
  - 10 Hz acquisition rate
  - daily 10-second long snapshots of "fast" data



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

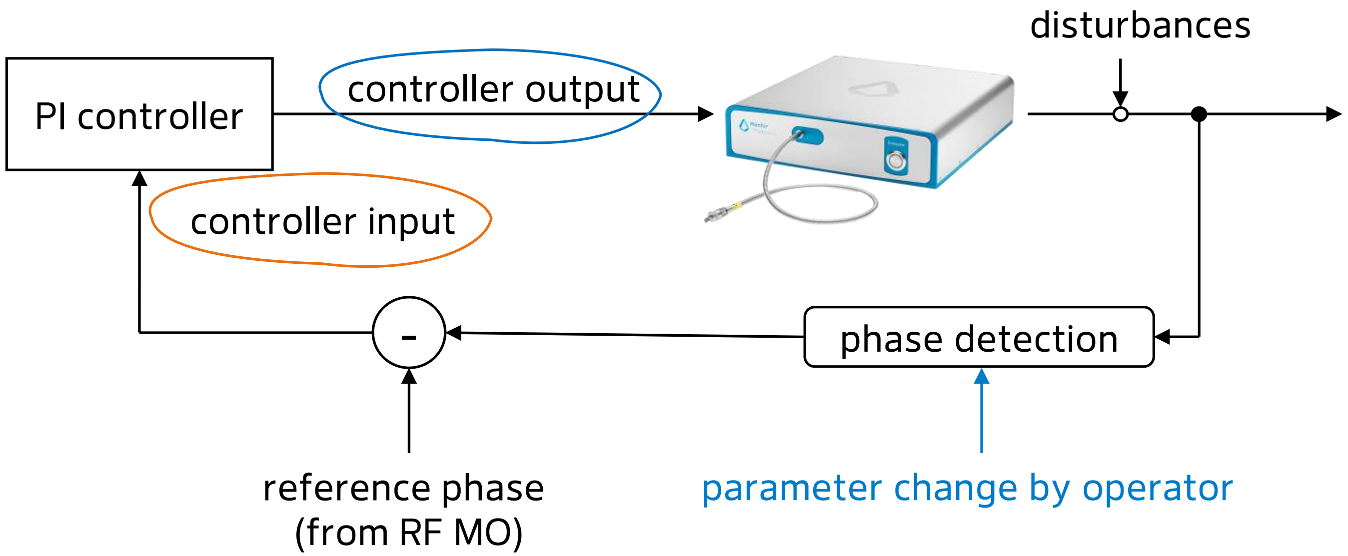
Ensure availability

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

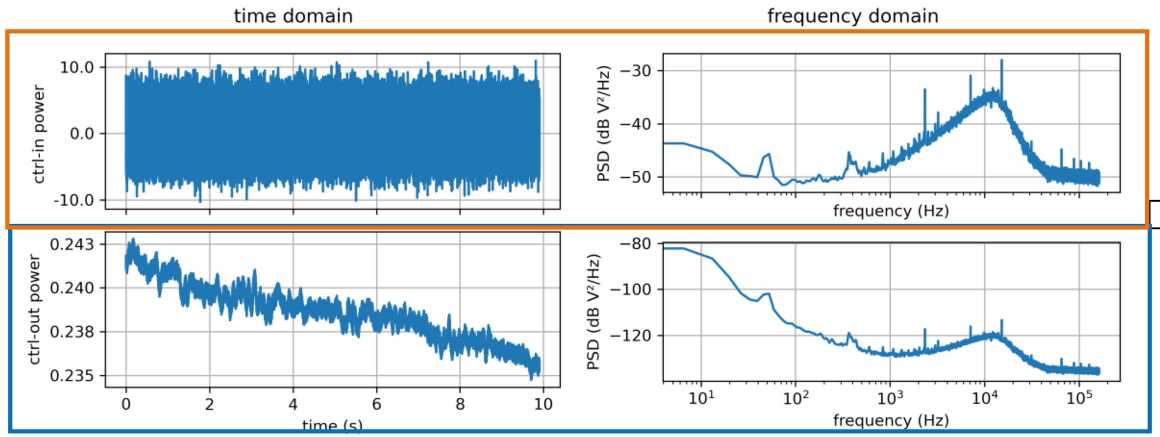
Courtesy: A.Grünhagen

Example: Main Laser Oscillator PLL Signal

Project : Fault Analysis & Classification of States



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



CNN autoencoder (trained)

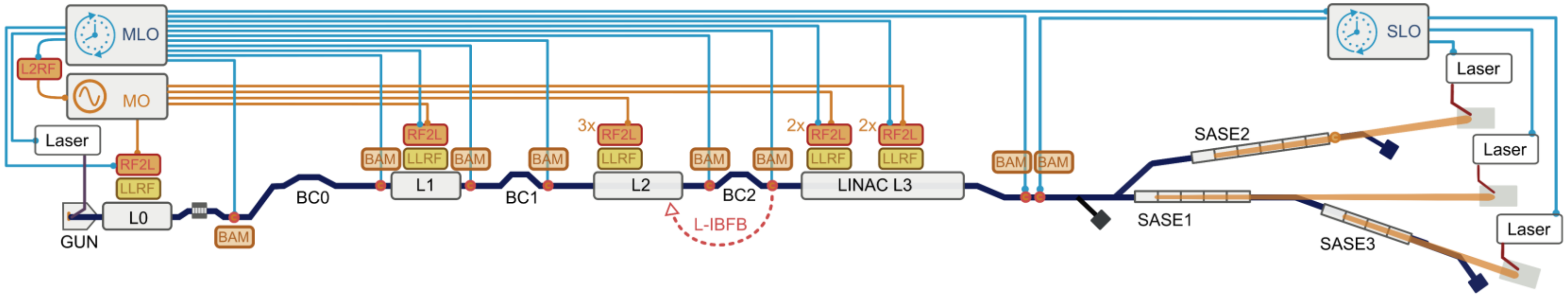
class	certainty
healthy	health score
fault class 1	class 1 score
fault class 2	class 2 score
fault class 3	class 3 score
…	…

Courtesy: A.Grünhagen

Summary & Outlook

Conclusion 1

Goal of ~1 fs stability [mHz…MHz] facility-wide is feasible, but controlling drifts is challenging !



European XFEL

	Achieved :
• Laser-based Phase detectors	< 100 as
• Stability of optical reference [kHz…MHz]	< 700 as
• **Electron beam stabilization [10Hz…MHz]**	< 4 fs
	Observed :
• **Impact of ocean waves (in winter) [~0.2Hz]**	~ 2 fs/km
• **Pump-laser system jitter**	~ 10-20 fs
• **Earth & Ocean tide effects, [mHz]**	~ 150 fs/km

Conclusion 2

Matured Synchronization & FeedbackTechniques → Continuous Effort to Further Improve

Criteria for choice of synchronization system :

- Has to match performance demands from users / applications
- Robustness & reliability of the critical subsystems is a vital
- Costs for installation, operation and maintenance

novel techniques & approaches :

- Data-driven applications & machine learning
  - optimisation of controller design
  - fault diagnosis & prediction

further developments identified,
→ approaching the few 100 attosecond accuracy regime :

- improvements of the MO,
- ultra-low noise RF field receivers,
- higher resolution of the bunch arrival time monitors,
- development of versatile laser pulse arrival time monitors

novel problems and issues :

- ocean waves and other seismic activity
  - → yet another field of expertise required (geophysics)

→ communication & knowledge exchange is key

Thank you .

Acknowledgements

- WAVE-Hamburg Seismic Network in the Science City Hamburg, Bahrenfeld
- FLASH
  - Operation team, photon instrumentation and laser groups
- European XFEL GmbH,
  - photon diagnostics (XPD), photon instruments (SPB/SFX, SQS/SCS), lasers (LAS)
  - MXL, DESY group for EuXFEL operation

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Czwalinna, Marie Kristin

marie.kristin.czwalinna@desy.de
+49 (0)40 8998 9 2912