Latest Achievements in Femtosecond Synchronisation of Large Facilities

Tutorial and Overview with New Results, Technical Details and Select Future Challenges

Sebastian Schulz on behalf of everybody involved!

IBIC2024, Beijing, China | 9-13 September 2024

HEPS CEPC CSNS BEPC
IBIC2024
Sept. 9-13, 2024 · Beijing, China

European XFEL

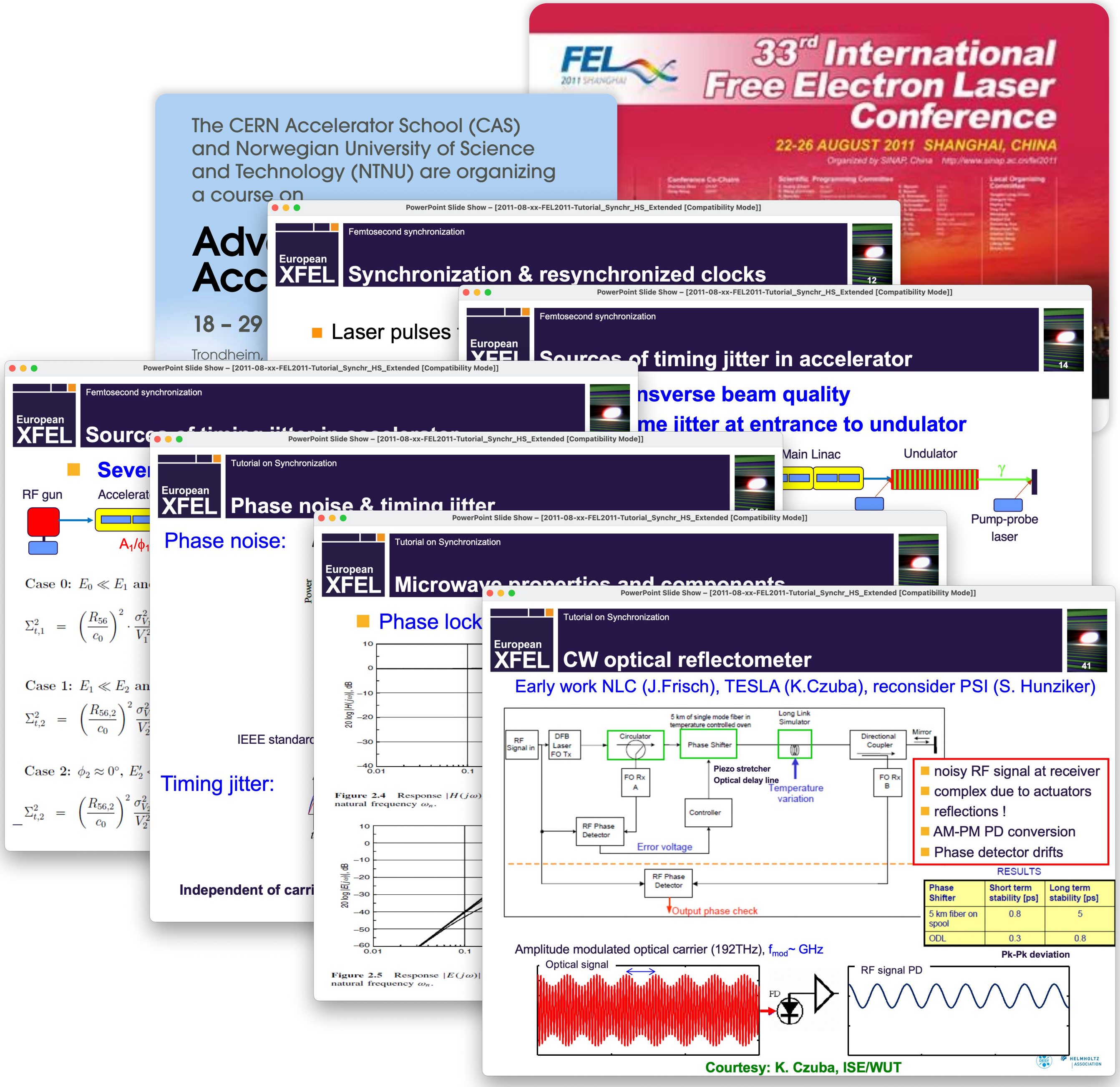
DESY.

HELMHOLTZ

Agenda

Latest Achievements …

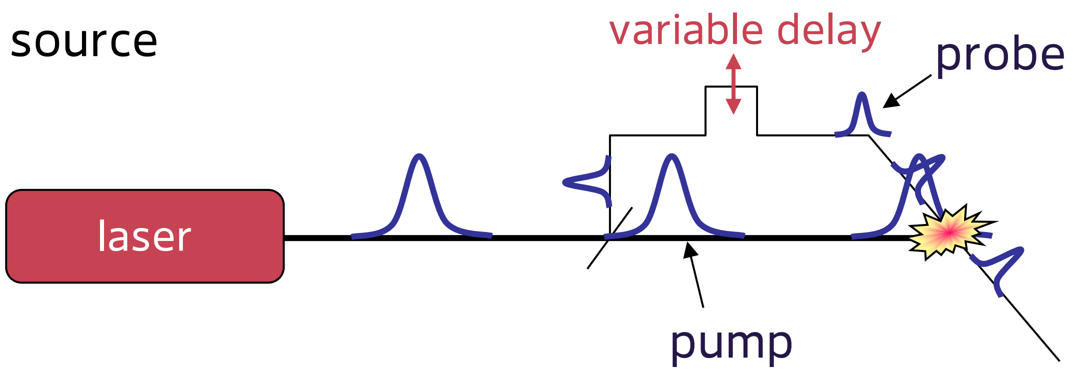
- Introduction and Basics
  - sources of timing jitter and drift
  - signal types and timescales
- Synchronisation Techniques
- Pulsed Optical Synchronisation
- System Performance Validation
  - self-contained
  - linac-based
  - user experiment
- Seismic Activity Influence
- Data-Driven Approaches
- Conclusion

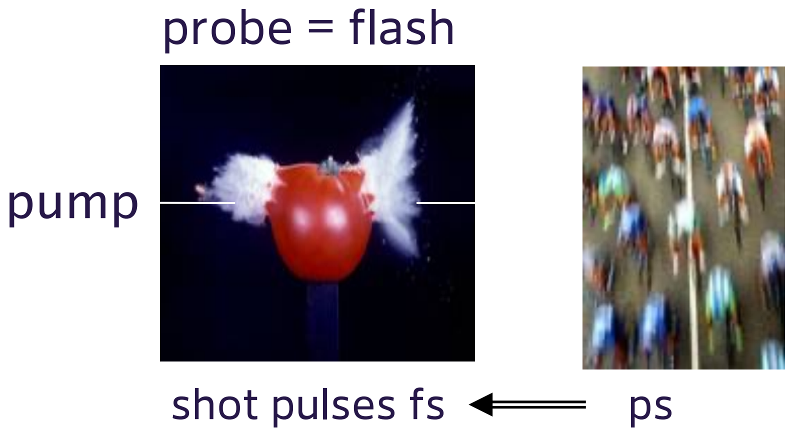


Motivation

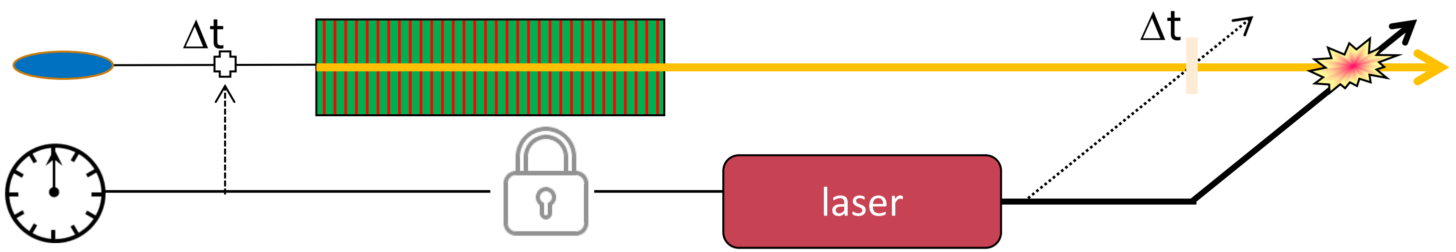
X-ray/Optical Pump-Probe Experiments with Femtosecond Temporal Resolution

- same source





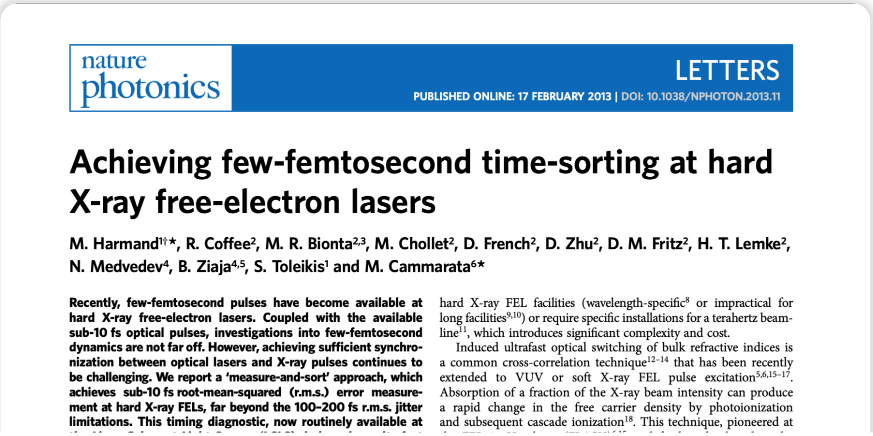
- at FELs: disjunct sources



precision: depends on experiment
ideally: jitter < pulse durations

but: *a posteriori* data sorting**!?**

- **however:** data sorting can be difficult
  - special timing requirements
  - 3rd independent source involved
  - low interaction rates / small cross sections / averaging detectors



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*]

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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

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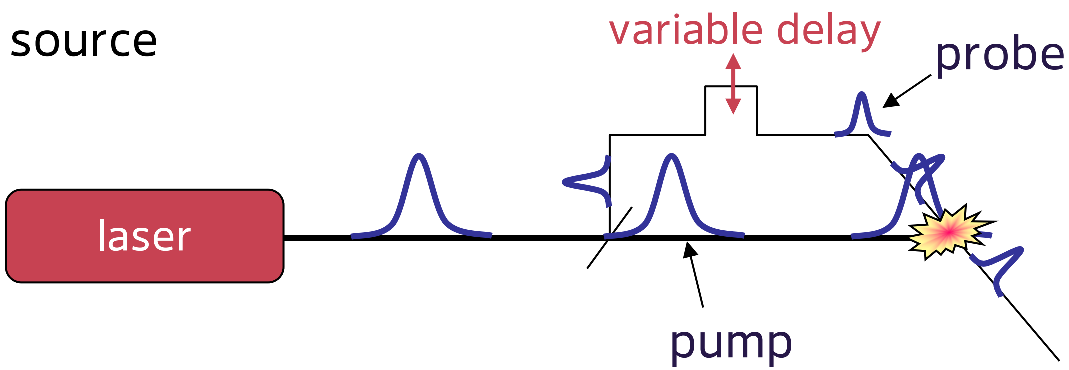
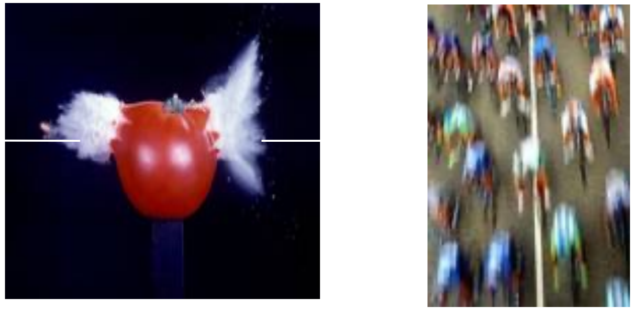


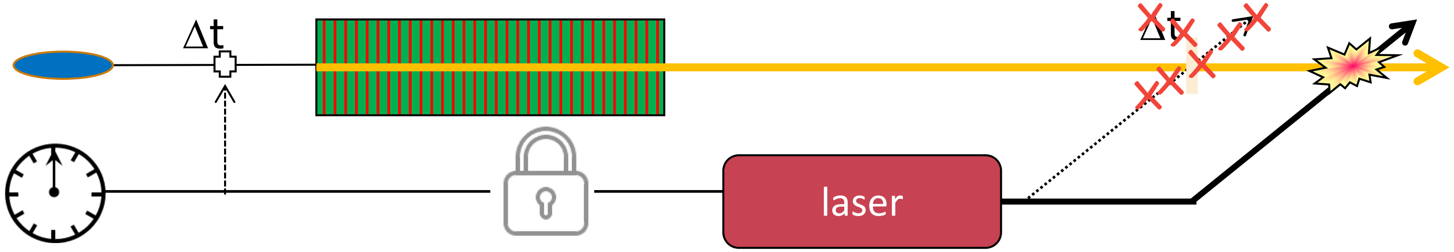
probe = flash

pump



shot pulses fs ⟵ ps

- at FELs: disjunct sources



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- **however:** data sorting can be difficult **/ impossible: no PAM!**
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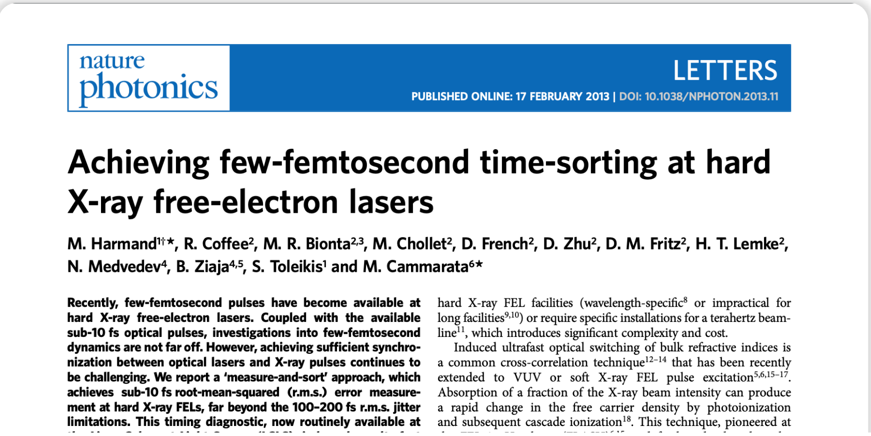

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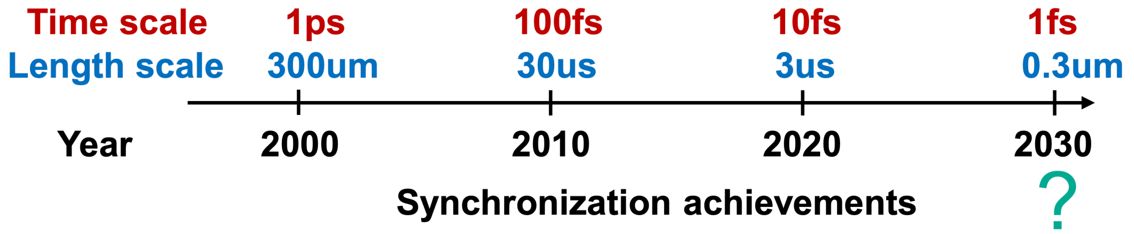
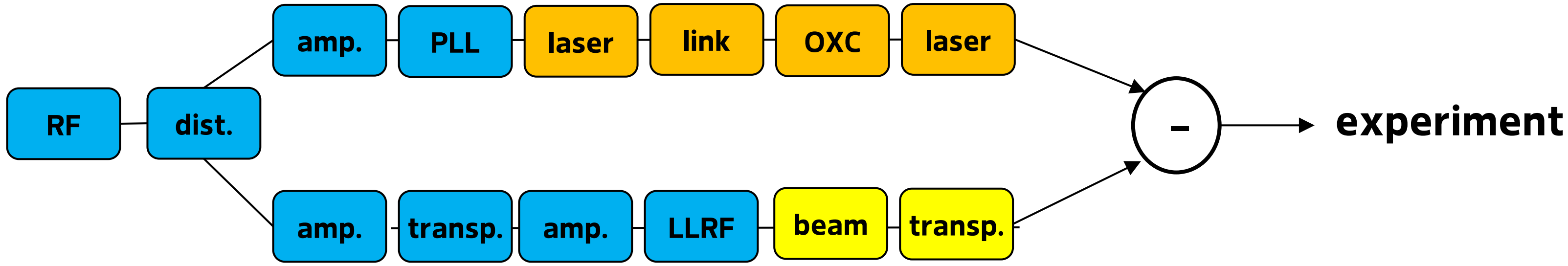
Timing Jitter and Drift Considerations

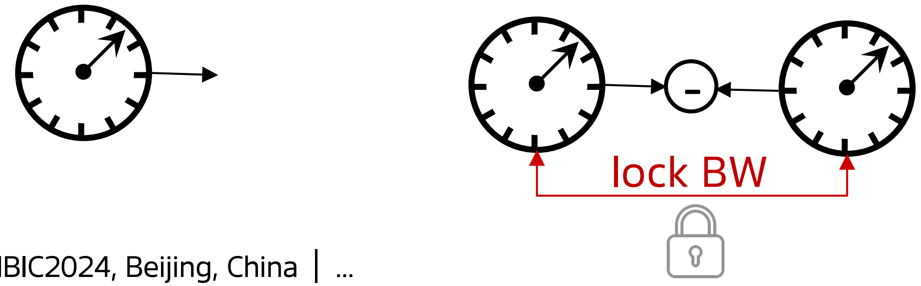
Overview



- 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 and **relative timing jitter**



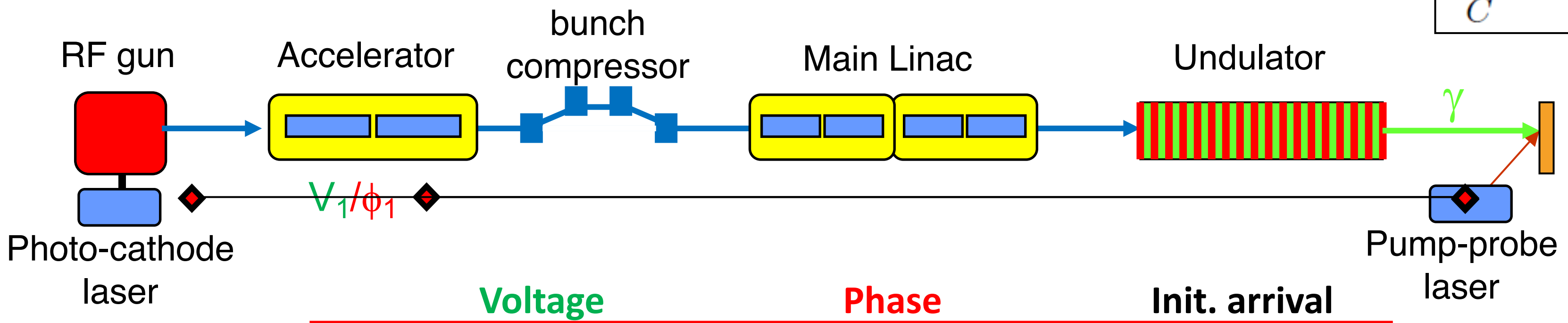
courtesy of H. Schlarb

Introduction and Basics

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

$$\frac{\delta C}{C_1} = -(C_1 - 1)\left[\overbrace{\left(3\tan(\phi_1) + \frac{1}{\tan(\phi_1)}\right)}^{3\,\ldots\,6}(\delta\phi_1 - \omega_{RF}\delta t_{ini}) + 4\frac{\delta V_1}{V_1}\right]$$

Tolerance ∝ Compression

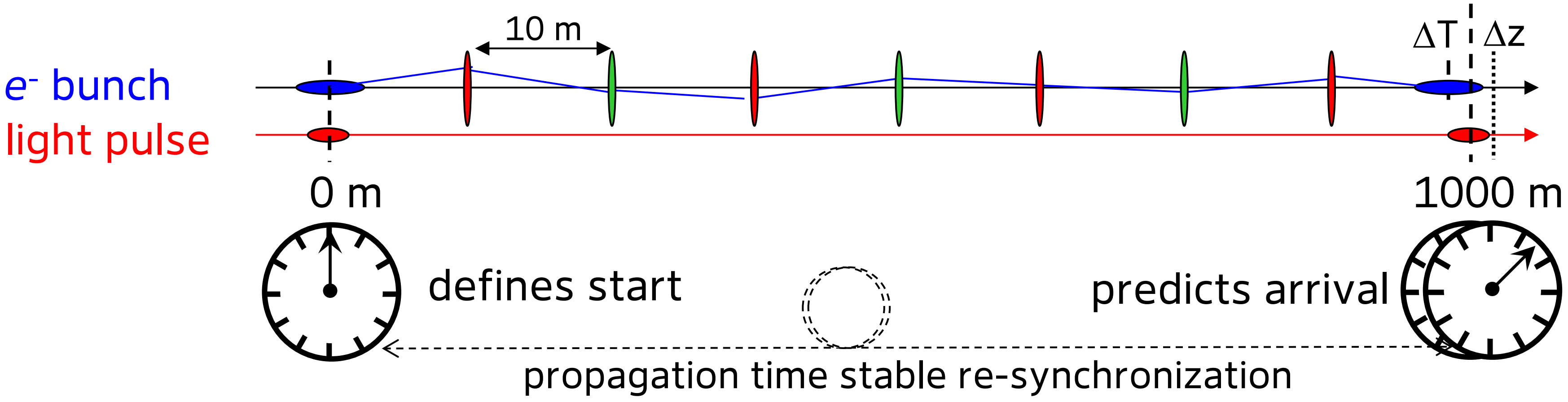
Phase & Init. arrival **Voltage**

Conclusions

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

Sources of Timing Jitter: Distribution

Accelerator Straight Sections, Energy Stability, Ground Motion, …



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

E = 1 GeV

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

ΔT = 435 fs

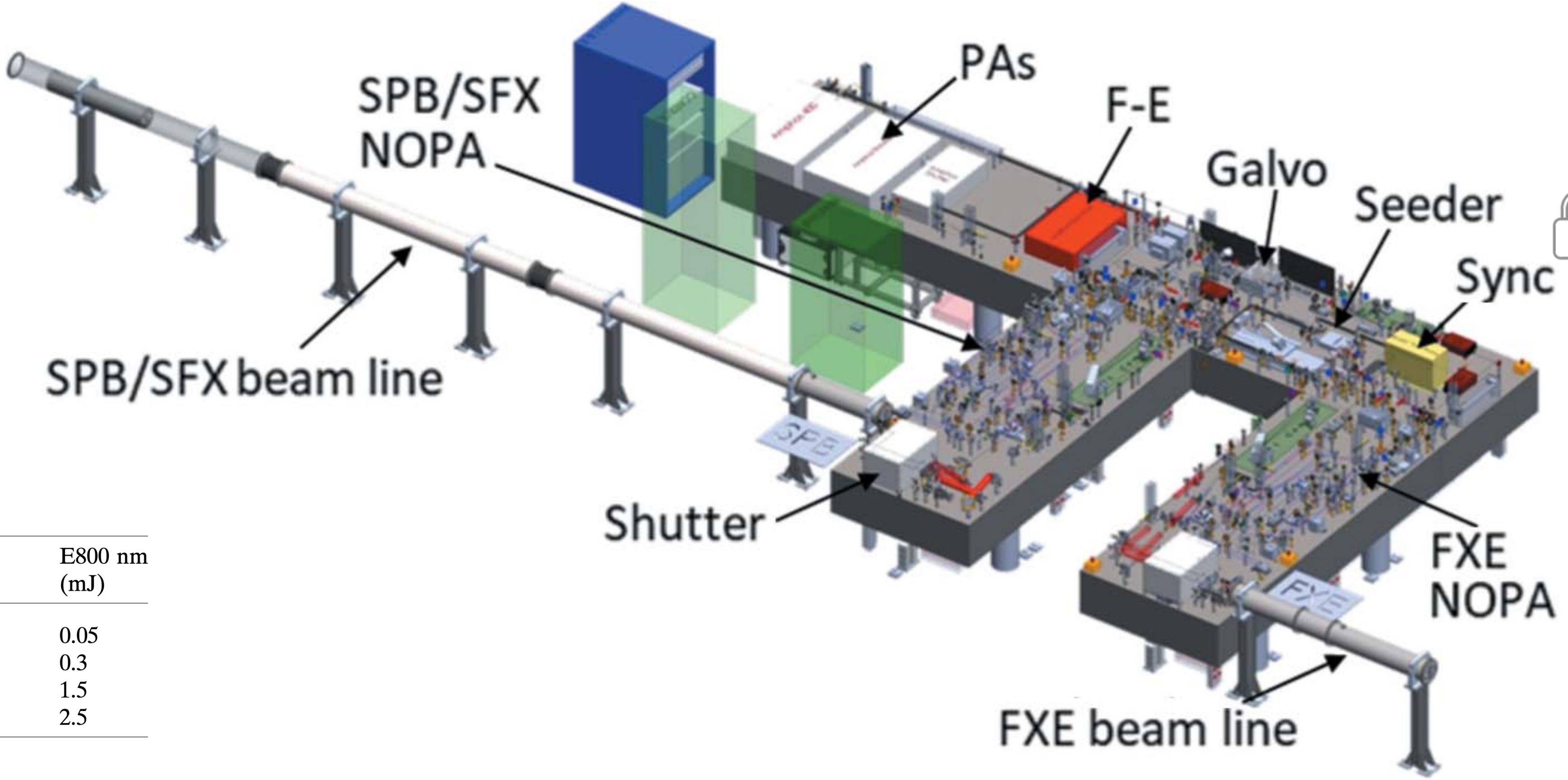
- energy jitter $\Delta E/E < 0.1\%$ ⇒ $\Delta t < 0.8$ fs 🙂
- orbit deviation $\Delta x < 50$ µm ⇒ $\Delta t < 0.04$ fs 😃
- vibration $\Delta z \sim$ *few 100 nm* ⇒ $\Delta t \sim 1$ fs 🙁
- ground motion/relocations $\Delta z \sim$ *10 µm* ⇒ $\Delta t \sim 30$ fs 🥺 but slow, and somewhat predictable ⇒ feedforward?!

Sources of Timing Jitter and Drift: Laser System and Delivery

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

- 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



G. Palmer et al., J. Synchrotron Rad. 26, 328–332 (2019)

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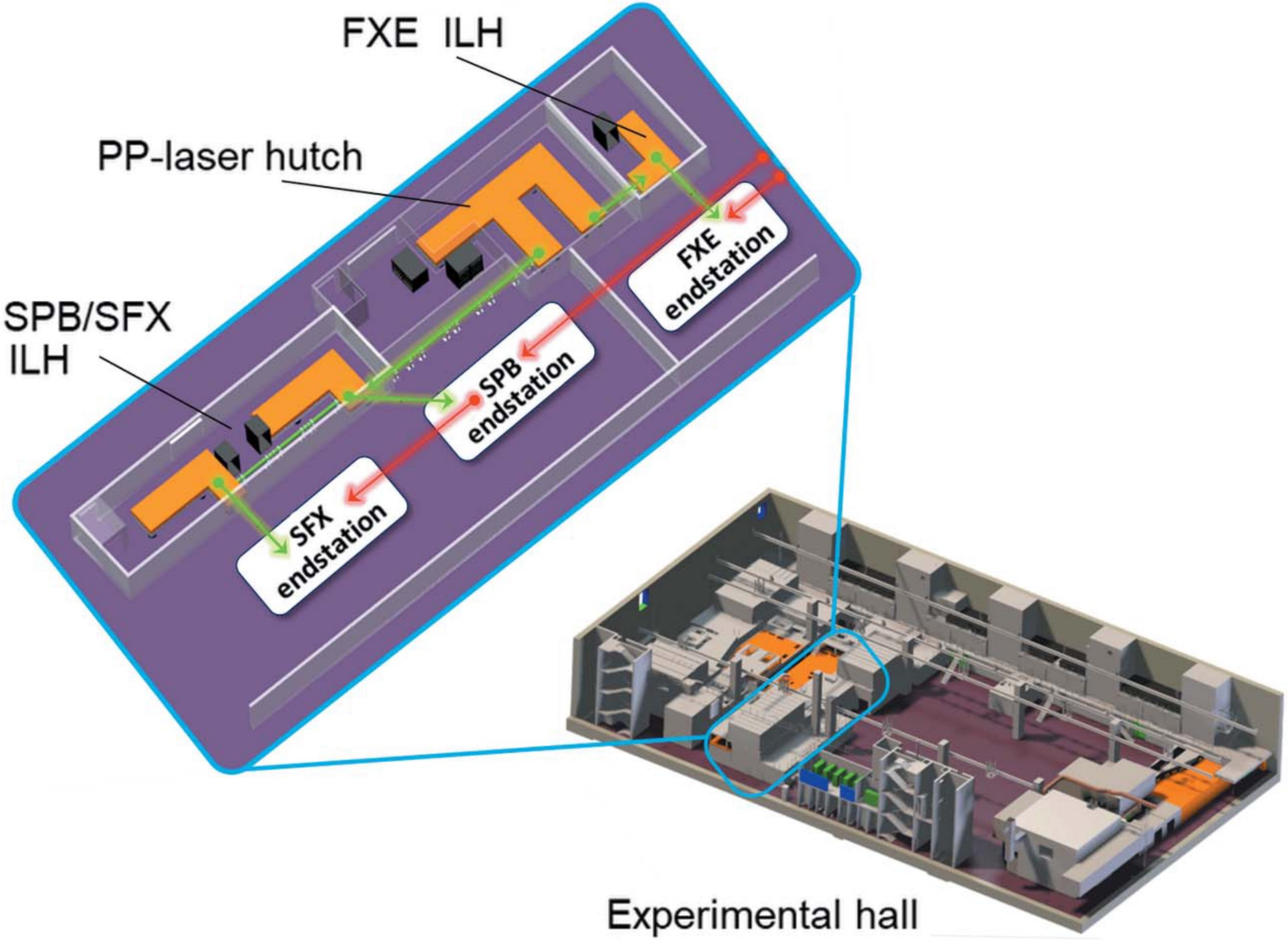
- **long path lengths**
  - lab → ILH → experiment ~100 m



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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

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emtoolbox.nist.gov/Wav

NIST

ENGINEERING METROLOGY TOOLBOX

Home Refractive Index of Air Elastic Publications

Refractive Index of Air Calculator
Based on Ciddor Equation

Refractive Index of Air Calculator is a web-based tool for calculating the index of refraction of air and wavelength of light in air as a function of various input parameters, using the Ciddor Equation or a modified version of the Edlén Equation.

Index of Refraction of Air
Jack A. Stone and Jay H. Zimmerman

Vacuum Wavelength and Ambient Conditions
Based on Ciddor Equation

Input	Amount	
Vacuum Wavelength:	1550	Nanometers [nm] (300 to 1700)
Air Temperature:	23.5	Degrees Celsius (-40 to 100)
Atmospheric Pressure:	101.325	Kilopascals [kPa] (10 to 140)
Air Humidity:	45	Relative Humidity, Percent (0 to 100)
Carbon Dioxide Content:	450	Micromole per Mole [parts per million, ppm] (0 to 2000)

Calculate Wavelength in Ambient Air and Refractive Index of Air Reset

Metrology Toolbox: https://emtoolbox.nist.gov/Wavelength/Ciddor.asp

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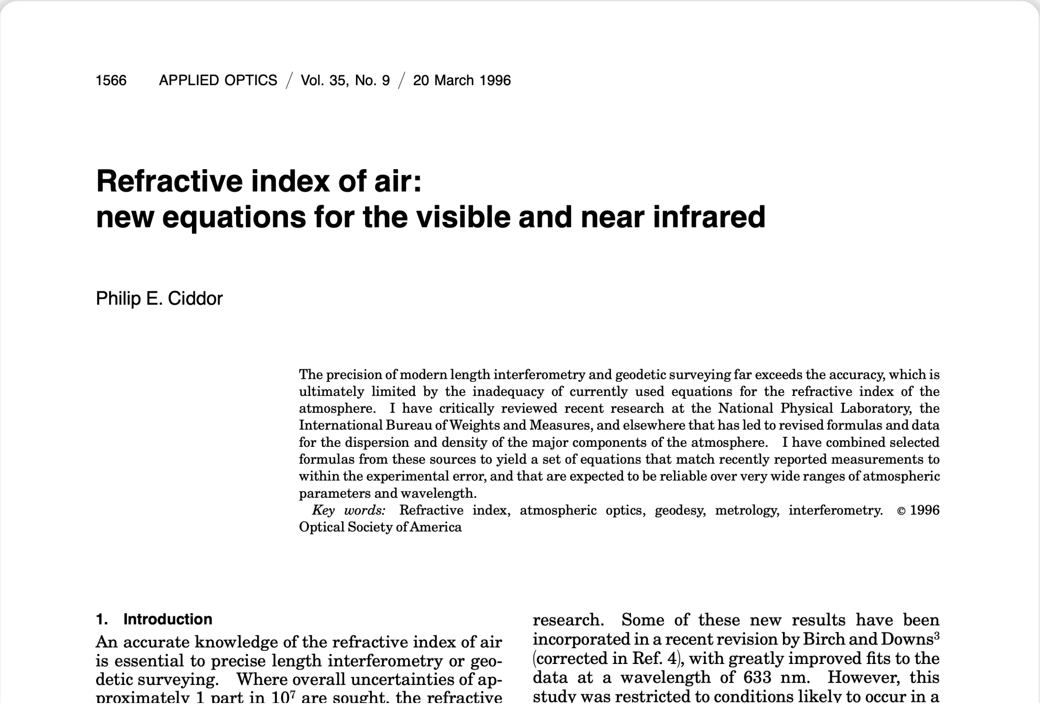

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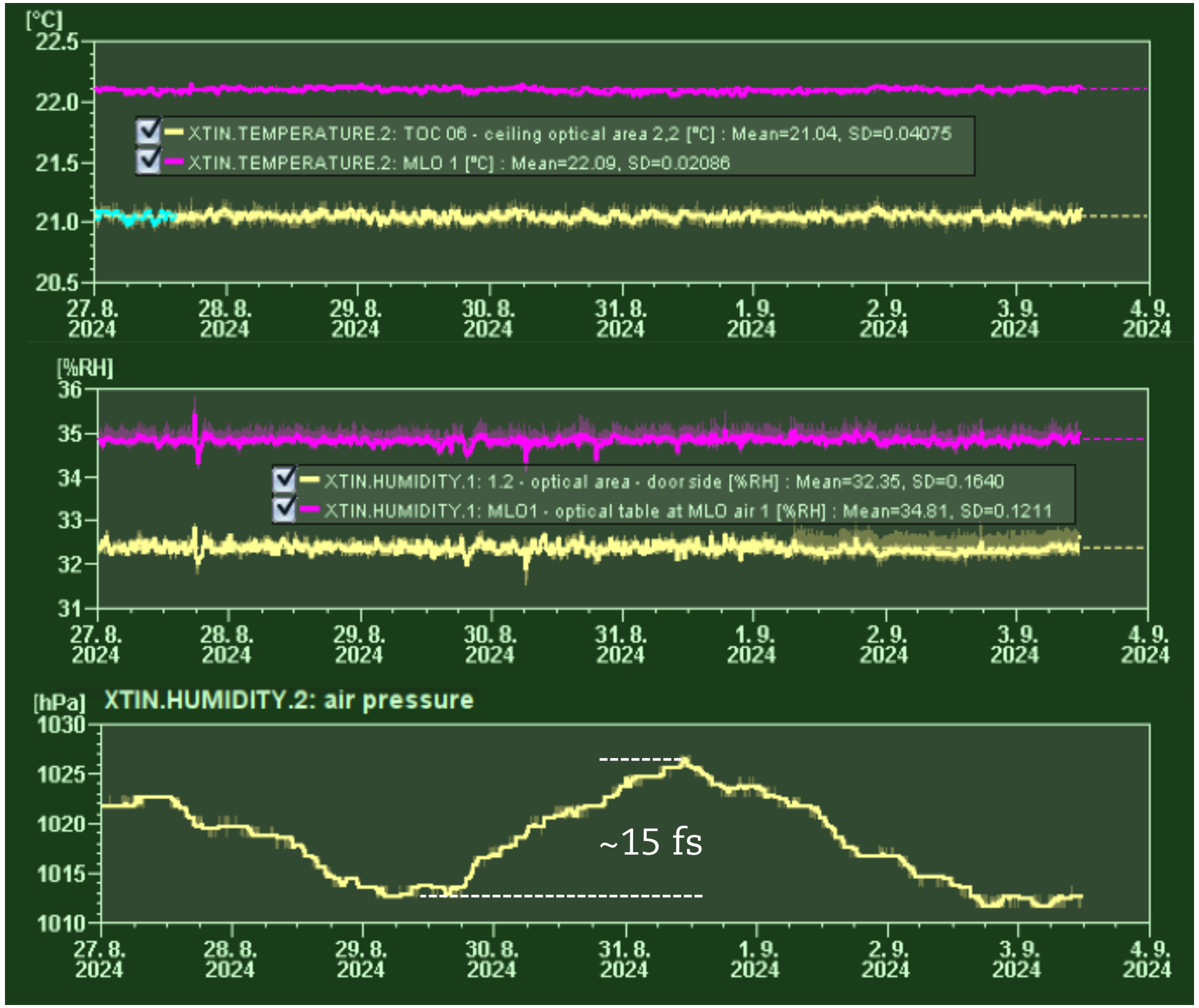


Metrology Toolbox: https://emtoolbox.nist.gov/Wavelength/Ciddor.asp

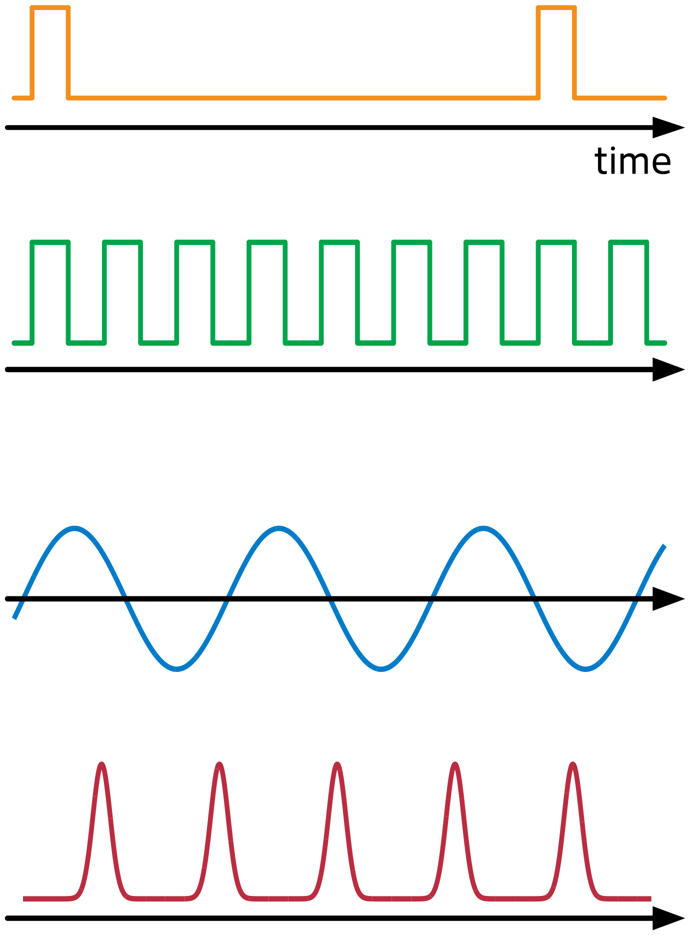
Signal Types

Triggers, Clocks, RF, Pulse Trains

DESY: "Hey, look at our (femtosecond) synchronisation system, based on an MLO, locking lasers with OXCs!

SLAC: "Cool, that's like our Pulsed Fiber Timing System, it has an OMO and TC-BOCs!"

- trigger signals
  - digital timing subsystems
  - laser pulse selection
- clocks
  - digital (timing) subsystems
  - ADCs, DACs, CPUs
- RF analogue
  - RF phase reference
  - diagnostics and instrumentation
- optical
  - laser pulse trains
  - diagnostics
  - experiment



- 10 Hz … 1 kHz (few MHz)
- 100 ps … ns

- 1 MHz … 200 MHz
- 5 ps … 20 ps

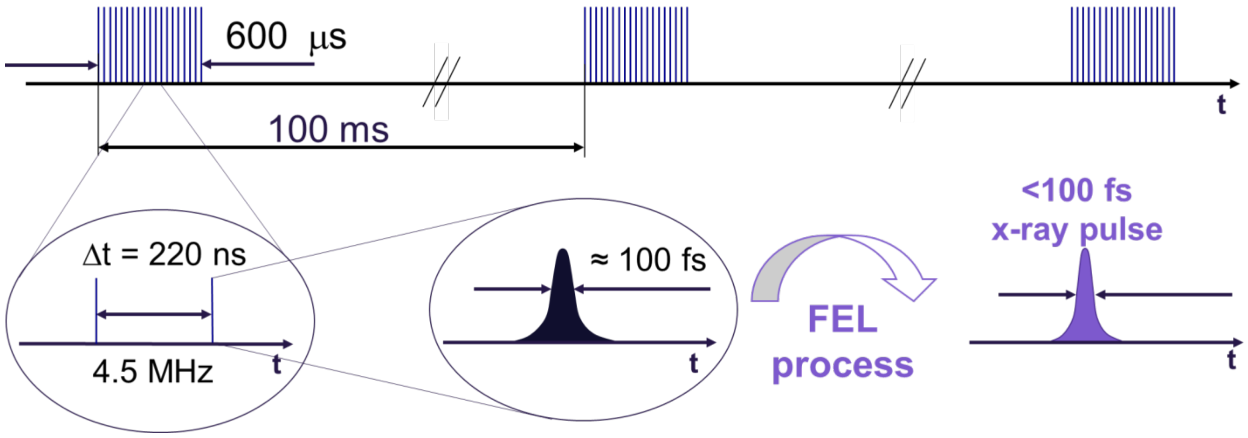
- 0.1 GHz … 10 GHz
- 50 fs … 1 ps

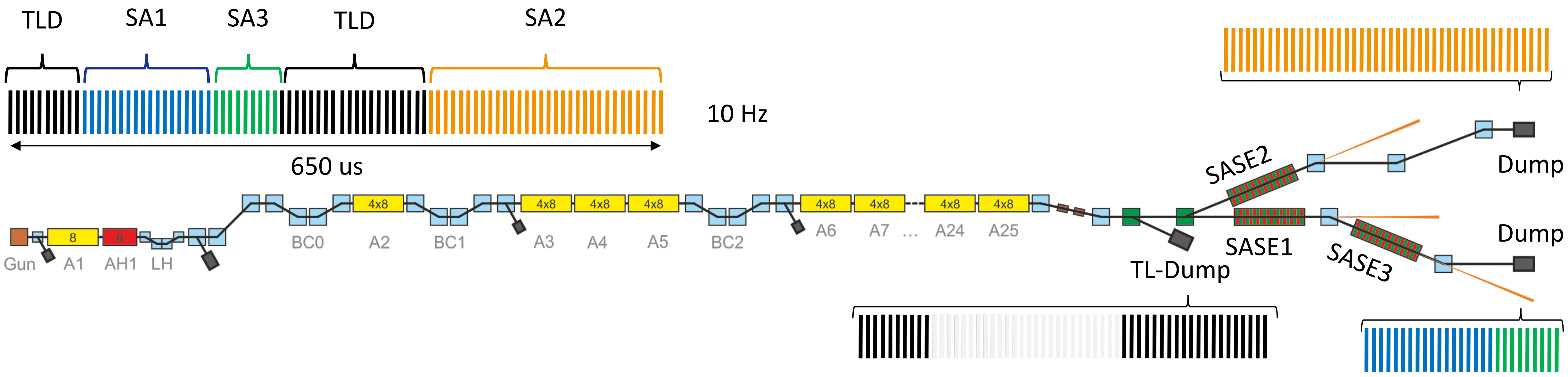
- 100s THz (carrier)
- MHz …100s MHz (rep'rate)
- 10 fs … 500 fs (duration)

Temporal Structure of Hamburg's Superconducting Linacs

Low Duty-cycle and Multiple Beamlines

- pulsed operation (RF ~1.4 ms, **10 Hz**)
  - **2700/macropulse at 4.5 MHz EuXFEL**
  - 800/macropulse at 1 MHz FLASH
  - **min. 222 ns intra-burst → single-pulse detection**
- switchyards + distribution
  - fast kicker system, precise slow flat-top kicker



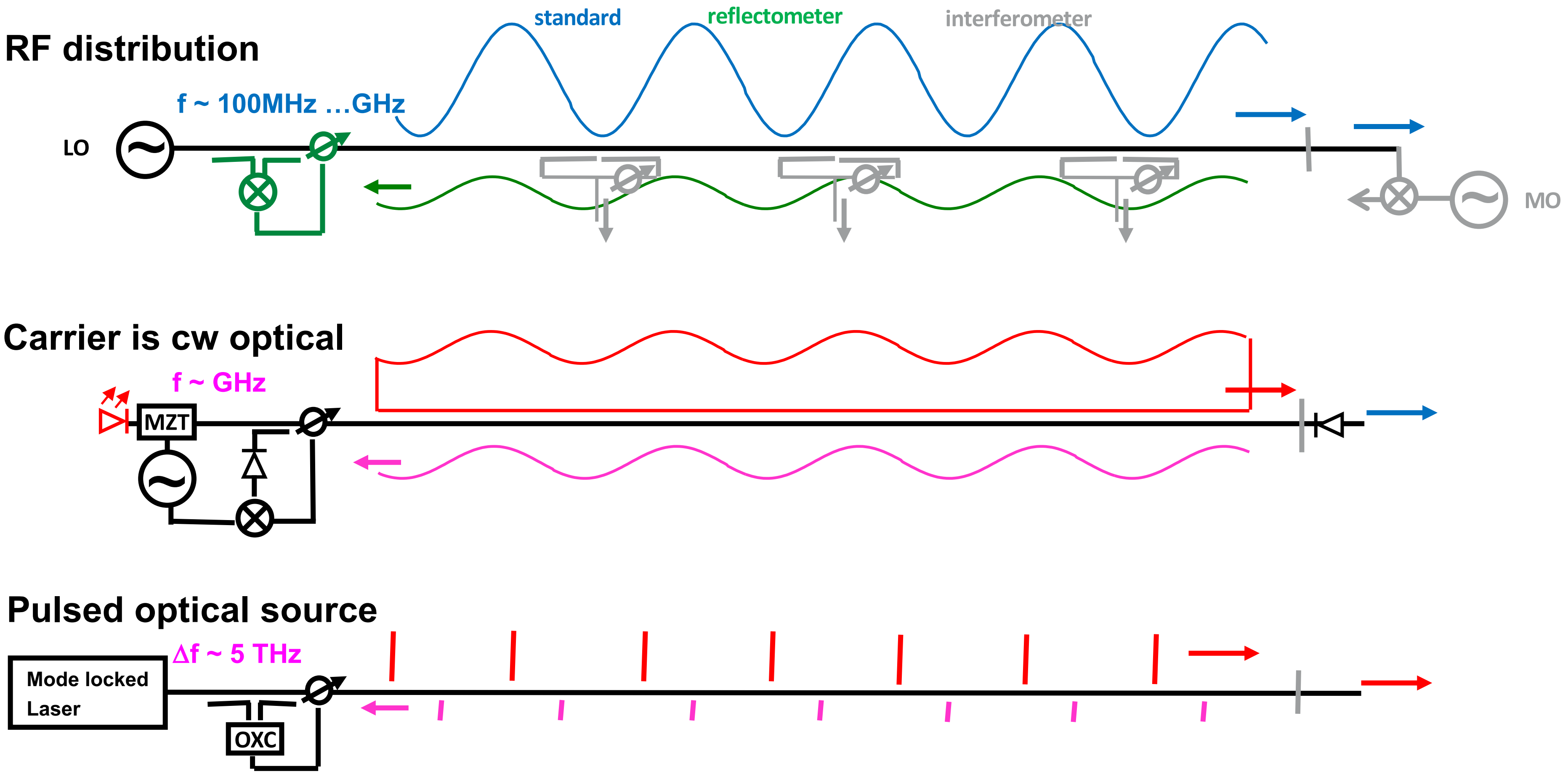


Synchronisation Techniques

Different Synchronisation Approaches

Difference in Carrier Frequency

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



- LCLS
- PAL-XFEL
- FLASH, EuXFEL

- SwissFEL
- PAL-XFEL
- SACLA

- FERMI
- FLASH, EuXFEL
- SwissFEL
- SXFEL, SHINE
- LCLS-II
- CLARA-FEBE
- TELBE

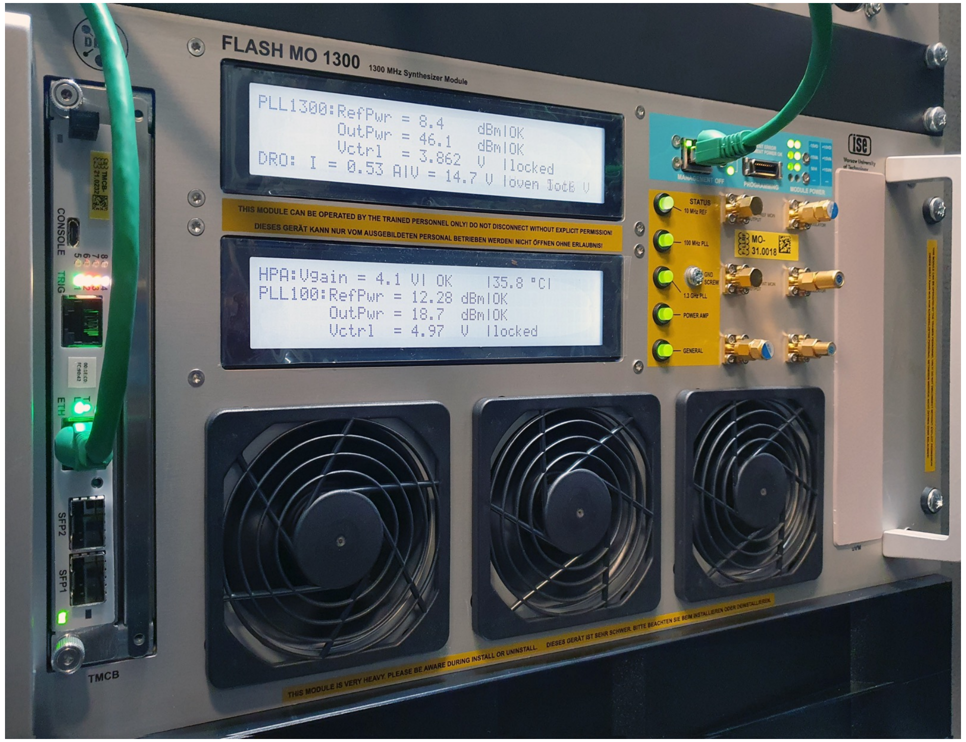
first proposed: J. Kim *et al.* Proc. FEL2004 Conf., 339-342 (2004)
overview: M. Xin *et al.* Light: Science & Applications 6, e16187 (2017)

courtesy of H. Schlarb

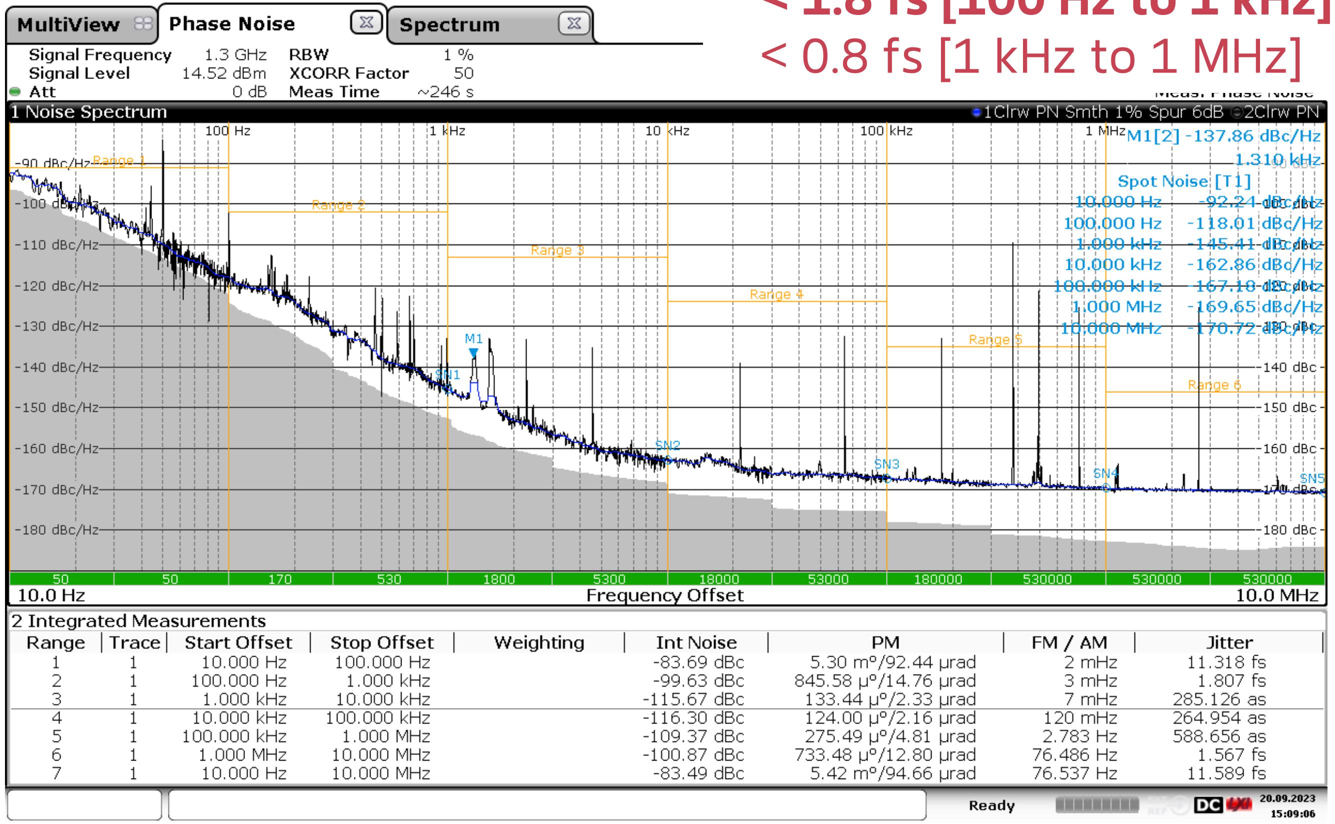
Common Feature: RF Main Oscillator (MO)

FLASH's Ultra-low Phase Noise High Power 1.3 GHz Source

integrated jitter:
< 12 fs [10 Hz to 100 Hz]
< 1.8 fs [100 Hz to 1 kHz]
< 0.8 fs [1 kHz to 1 MHz]



KVG Quartz Crystal Technology GmbH
info@kvg-gmbh.de



Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	1	10.000 Hz	100.000 Hz		-83.69 dBc	5.30 m°/92.44 µrad	2 mHz	11.318 fs
2	1	100.000 Hz	1.000 kHz		-99.63 dBc	845.58 µ°/14.76 µrad	3 mHz	1.807 fs
3	1	1.000 kHz	10.000 kHz		-115.67 dBc	133.44 µ°/2.33 µrad	7 mHz	285.126 as
4	1	10.000 kHz	100.000 kHz		-116.30 dBc	124.00 µ°/2.16 µrad	120 mHz	264.954 as
5	1	100.000 kHz	1.000 MHz		-109.37 dBc	275.49 µ°/4.81 µrad	2.783 Hz	588.656 as
6	1	1.000 MHz	10.000 MHz		-100.87 dBc	733.48 µ°/12.80 µrad	76.486 Hz	1.567 fs
7	1	10.000 Hz	10.000 MHz		-83.49 dBc	5.42 m°/94.66 µrad	76.537 Hz	11.589 fs

15:09:06 20.09.2023

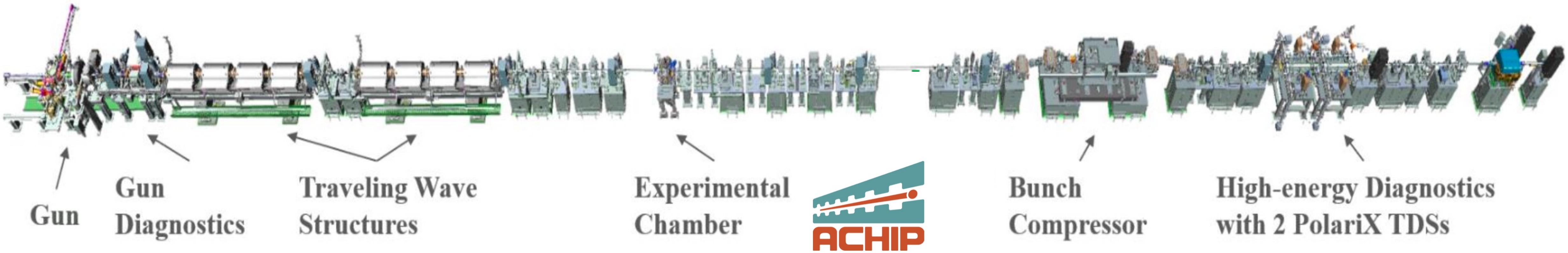
- Improvement of integrated jitter from 38 fs to 2 fs [100 Hz, 1 MHz]
- fs laser systems locked to the reference show significant improvement

courtesy of F. Ludwig, H. Pryschelski

RF-only Reference Distribution Concept I

Example: SINBAD ARES

- NC S-band linac for ultra-short bunches
  - low charge beams ~10 pC or less
  - **sub-10 fs arrival time stability**
- novel acceleration techniques/testbed, e.g.
  Accelerator on a Chip • DLA
- accelerator components R&D
- ML approaches “autonomous accelerator”



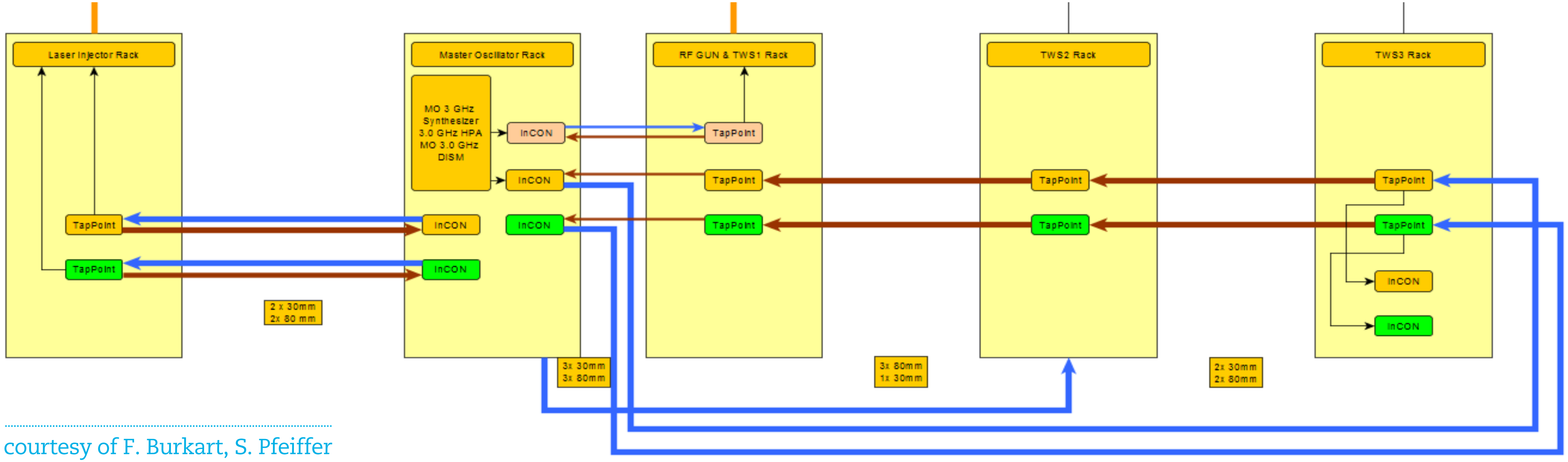
courtesy of F. Burkart, S. Pfeiffer

RF-only Reference Distribution Concept II

Example: SINBAD ARES

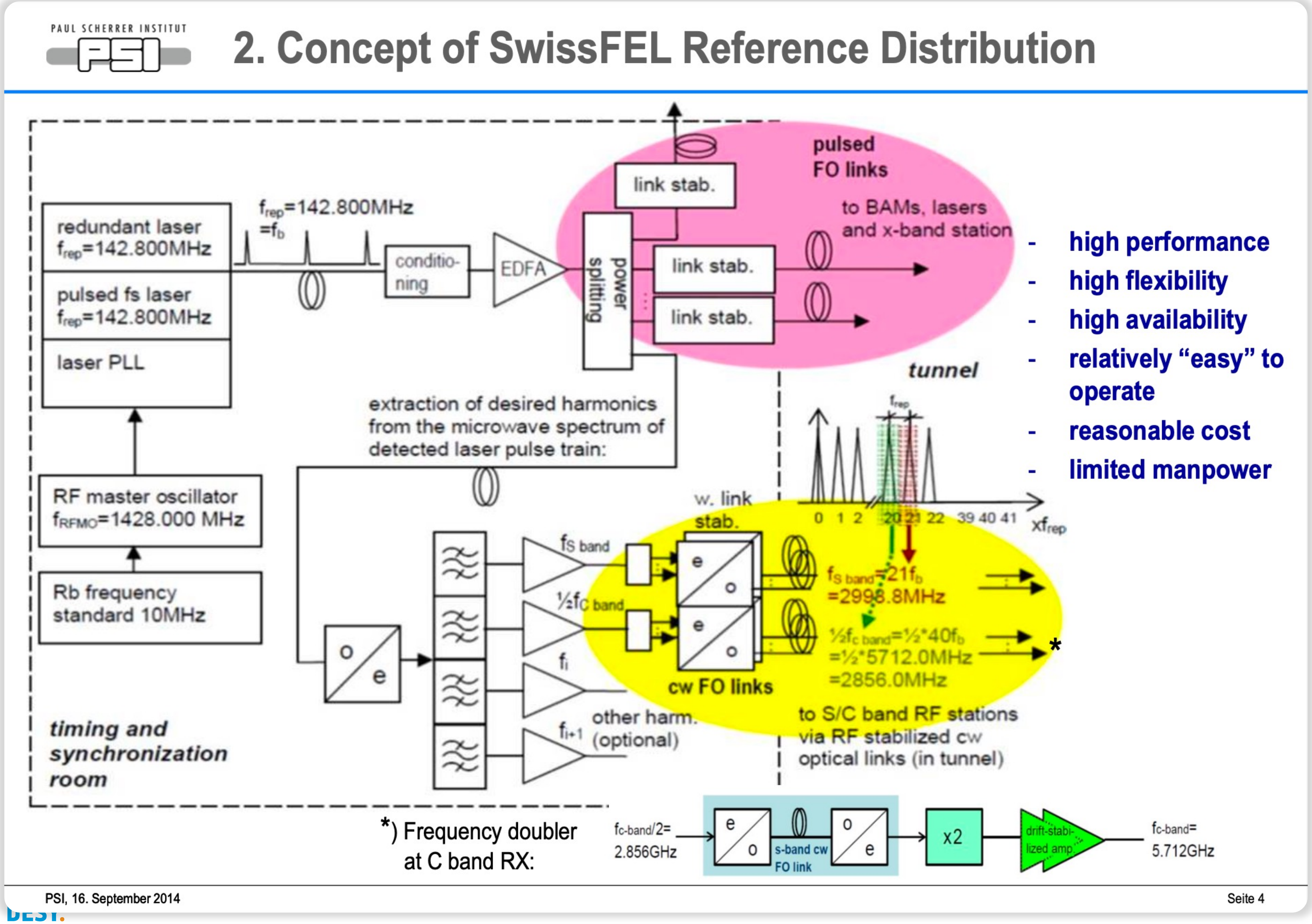
- installation in basement below acc. hall
- commercial / **custom-built MO** (2.998 GHz)
- RF distribution **on cables**
  - no additional stabilization presently
  - passive temperature stabilization → planned
  - active stabilization → planned

- **photocathode laser** synchronisation
  - direct RF lock ("heterodyne detection")
  - MZM-based laser-to-RF phase detector → planned
- ACHIP laser synchronisation (λ_0 = 2 μm)
  - **all-optical** balanced optical cross-correlation



Hybrid Approaches: SwissFEL

Pulsed Optical Synchronisation and "Radio-over-Fibre"



- US and slightly detuned European RF frequencies
- based on OMO, 142.8 MHz
- cw fibre links

Hybrid Approaches: SwissFEL

booth B07 -> INSTRUMENTATION TECHNOLOGIES

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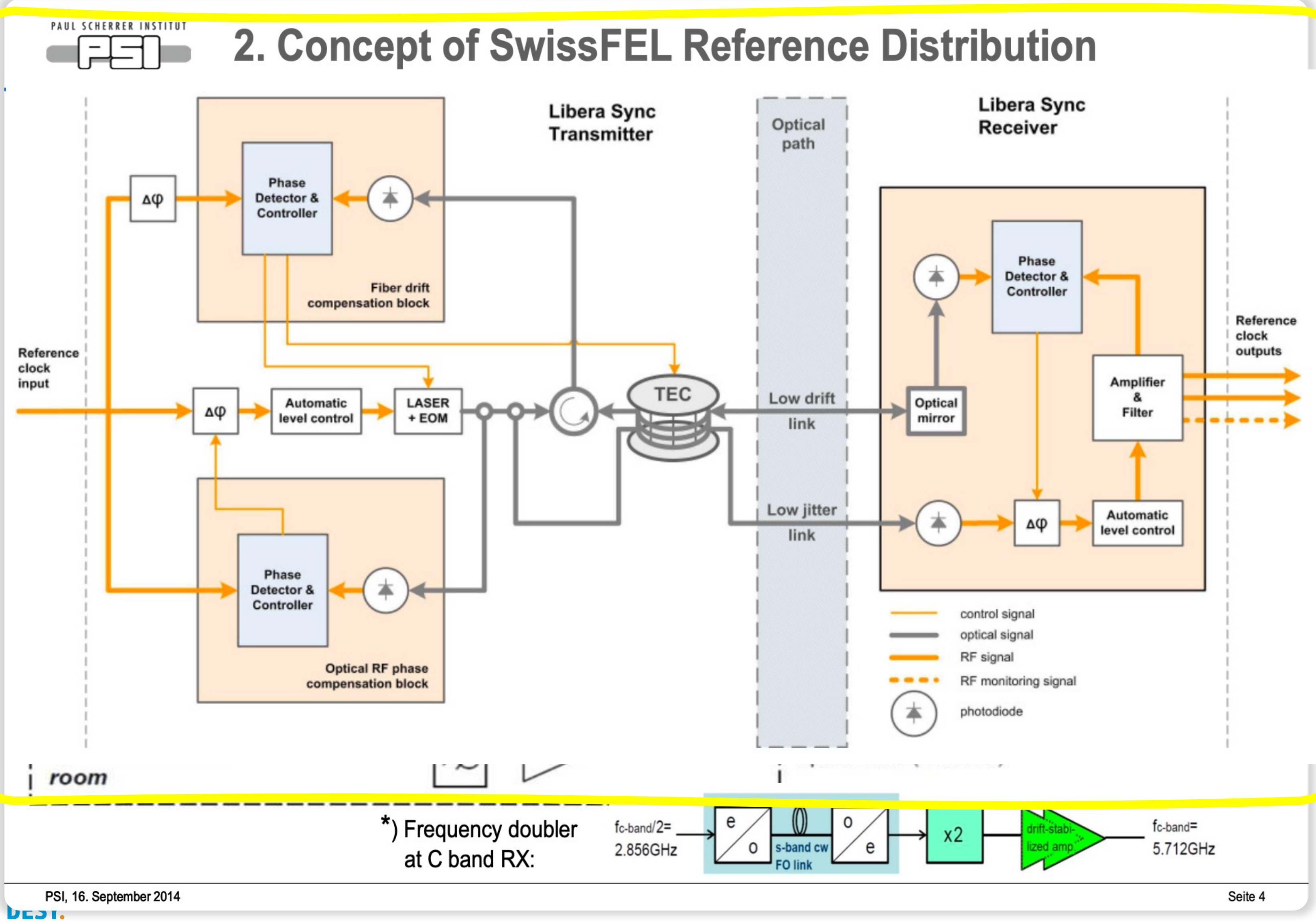

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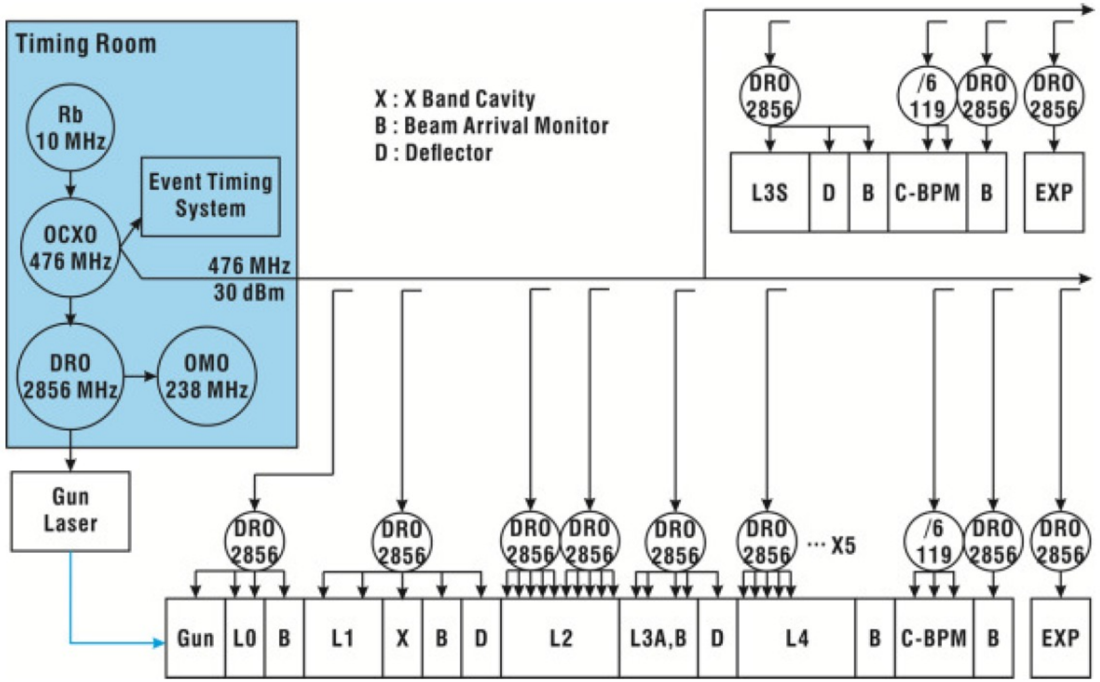
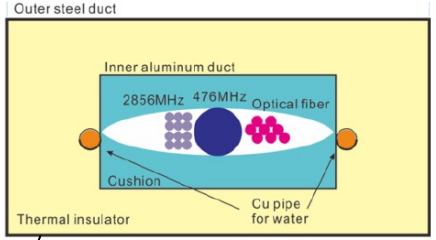
- based on OMO, 142.8 MHz
- cw fibre links
  - collaboration with I-Tech
  - transmitter/receiver units
  - amplitude modulation (AM)
  - two optical fibres per link
    - active drift stabilisation
    - "low jitter link"
  - at Rx side, both signals are demodulated to RF
  - 40 fs peak-to-peak (24 h)
  - sub-10 fs rms [10 Hz, 10 MHz]

S. Hunziker *et al.*, in Proc. IBIC2014, pp. 29-33

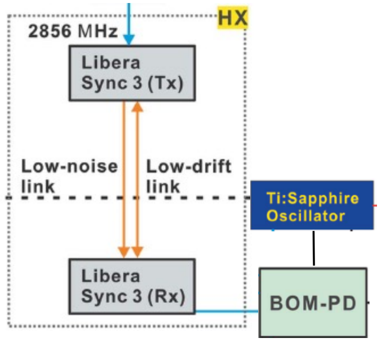
Hybrid Approaches: PAL-XFEL

Classic RF Distribution + Temperature Stabilised Cable Duct

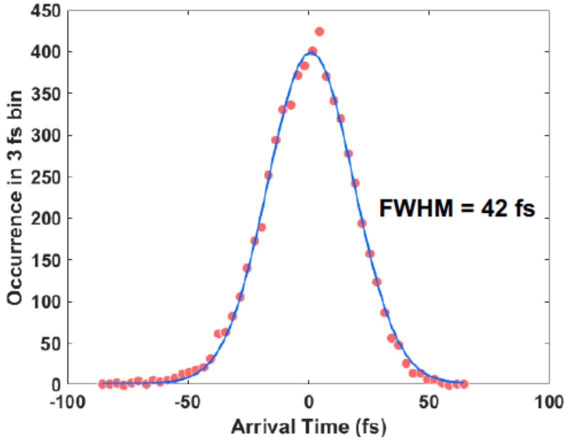


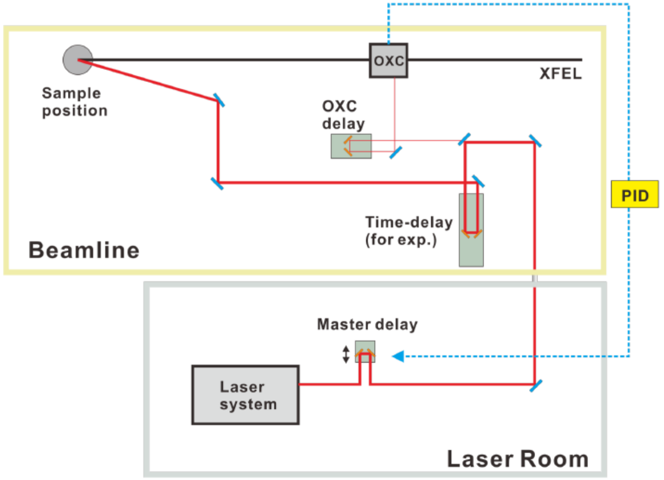


+ CW optical link

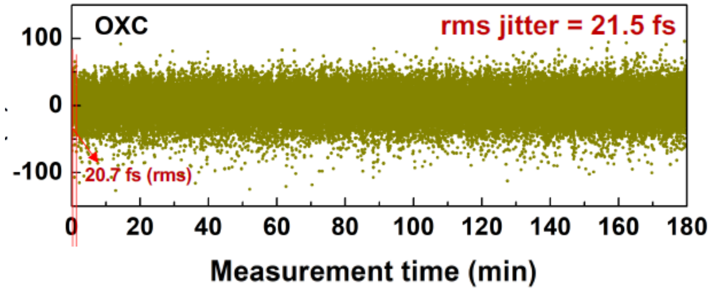


6000 XFEL shots@30Hz





Stability for 3 hours



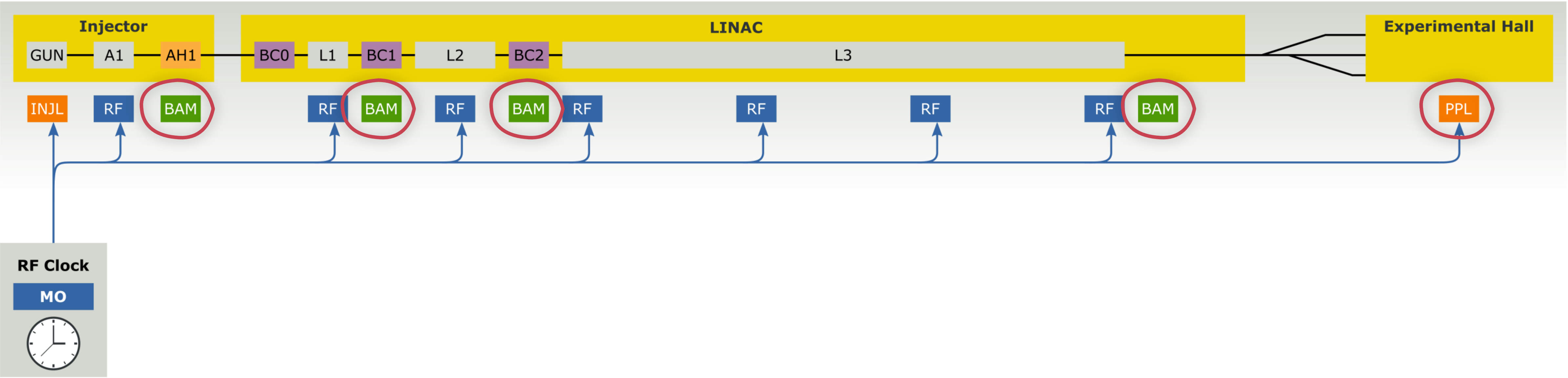
further reading:
C. K. Min *et al.*, Proc. IPAC2016, p. 4234
M. Kim *et al.*, J. Synchrotron Rad. 26 (2019)
I. Eom *et al.*, 5-Way Meeting 2019, SLAC

courtesy of H. Schlarb

Pulsed Optical Synchronisation

RF Reference Distribution

Integral Part of Particle Accelerator Operation



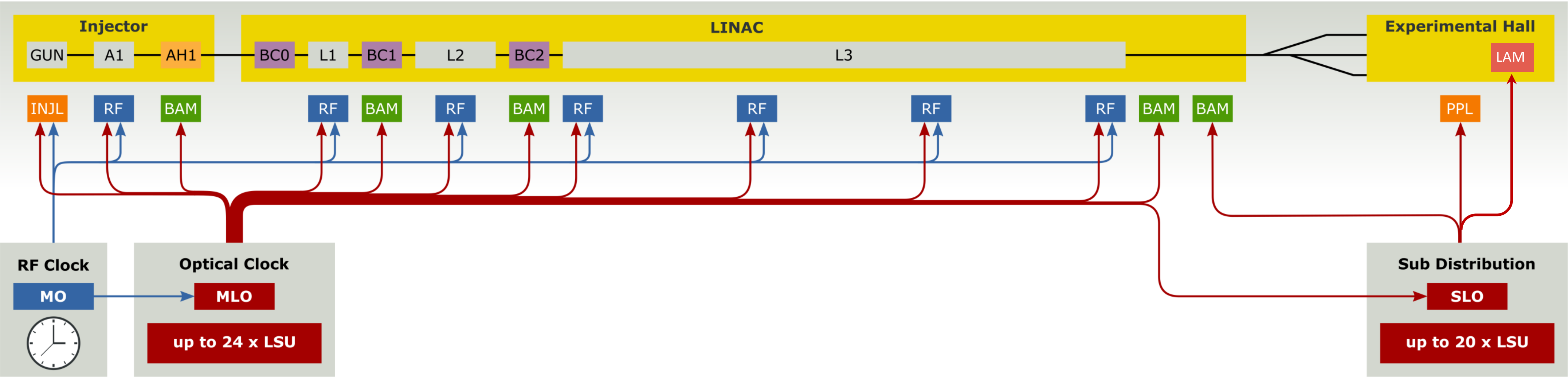
- availability 24/7, **mature and established** technology
- limitations
  - **cable drift**: ~10 fs/m/K ⇒ **35 ps/K** at EuXFEL
  - **cable attenuation**: ~0.03 dB/m ⇒ **~100 dB** at EuXFEL ⇒ amplification adds drift and jitter
  - RF signals susceptible to EMI

? but **best laser systems synchronisation performance, temporal beam diagnostics**

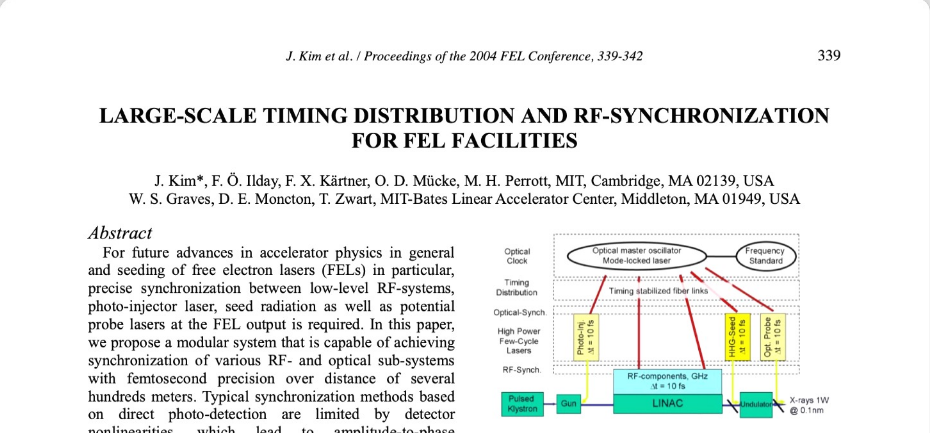
https://www.nanjingvolley.com/showroom/rg6-coaxial-cable-rg-6-ccs-communication-cable-rg-6.html

Laser-based Synchronisation System Topology

World-wide Unique Large-Scale 24/7 Operation of 30+ Fibre Links and Subsystems



- **optical reference** (main laser oscillator, MLO) tightly locked to RF main oscillator (MO) **distributed via actively length stabilized optical fibre links**
- laser lock (photocathode, **pump-probe**, …)
- RF re-synchronisation (**REFM-OPT**)
- bunch arrival time monitors (**BAM**)
- laser pulse arrival time monitors (**LAM**)



J. Kim et al. / Proceedings of the 2004 FEL Conference, 339-342 339

LARGE-SCALE TIMING DISTRIBUTION AND RF-SYNCHRONIZATION FOR FEL FACILITIES

J. Kim*, F. Ö. Ilday, F. X. Kärtner, O. D. Mücke, M. H. Perrott, MIT, Cambridge, MA 02139, USA
W. S. Graves, D. E. Moncton, T. Zwart, MIT-Bates Linear Accelerator Center, Middleton, MA 01949, USA

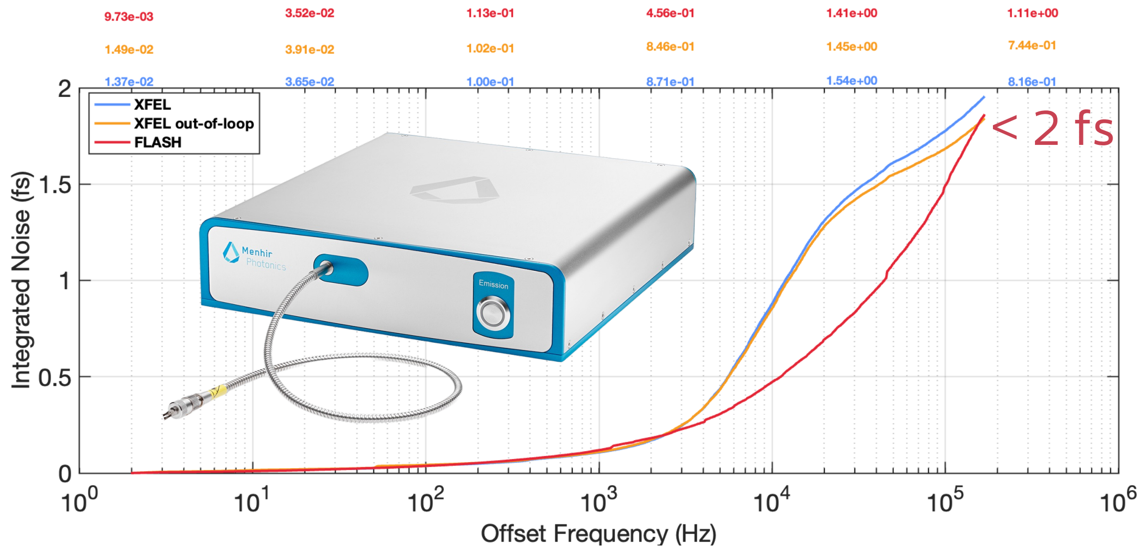
Abstract

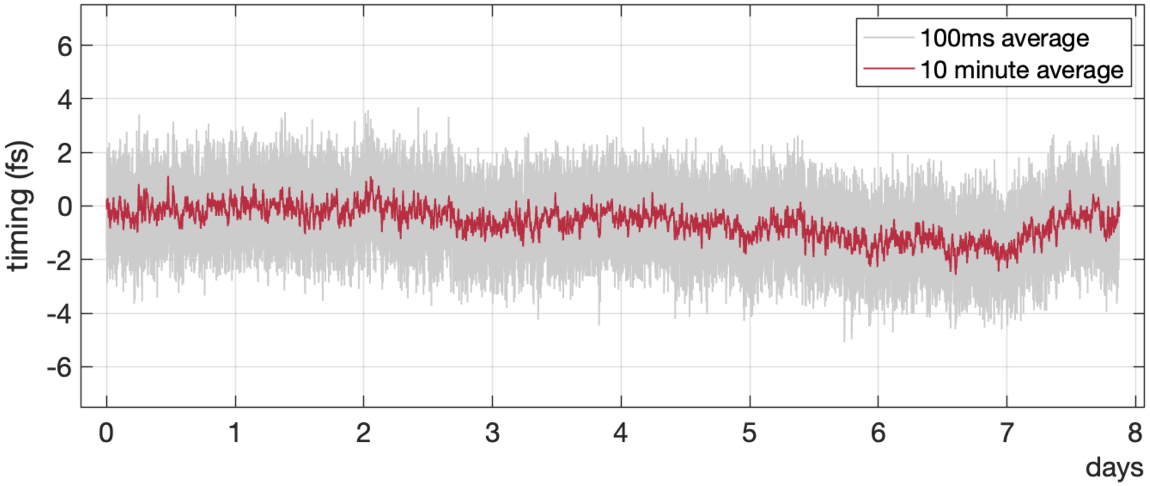
For future advances in accelerator physics in general and seeding of free electron lasers (FELs) in particular, precise synchronization between low-level RF-systems, photo-injector laser, seed radiation as well as potential probe lasers at the FEL output is required. In this paper, we propose a modular system that is capable of achieving synchronization of various RF- and optical sub-systems with femtosecond precision over distance of several hundreds meters. Typical synchronization methods based on direct photo-detection are limited by detector

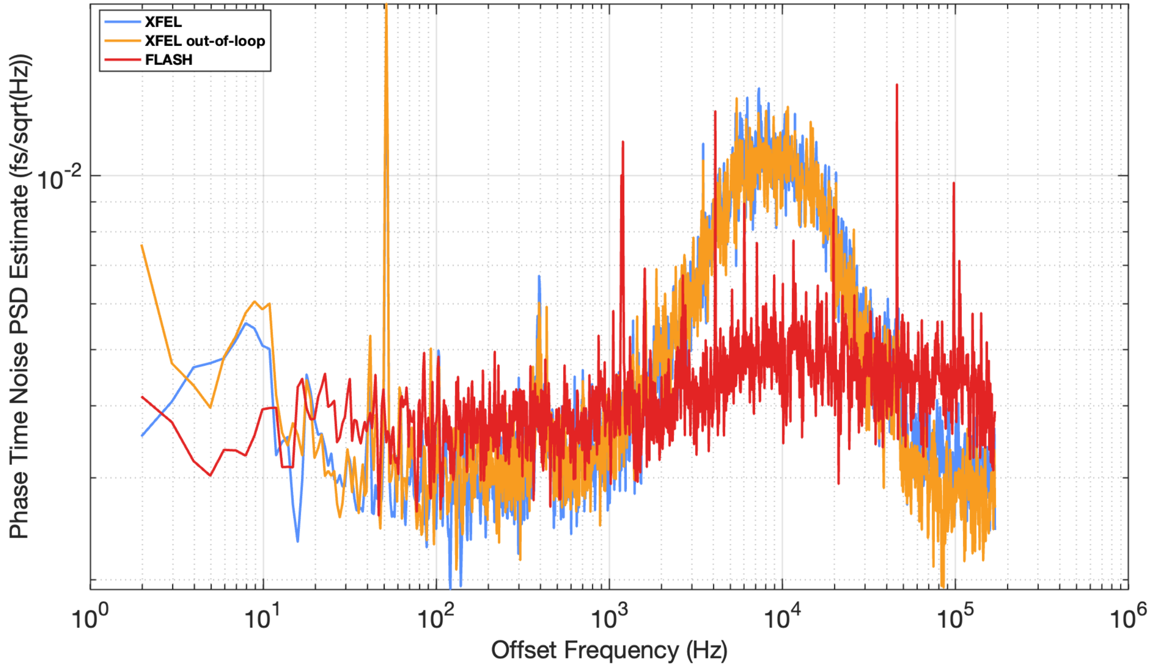
Main Laser Oscillator (MLO, OMO)

Low-noise Femtosecond Passively Mode-locked Laser System

- 216 MHz, 200 fs, 1550 nm, 125 mW
- 24/7 operation, 2 redundant systems
- tight lock to main RF oscillator (MO)
  - balanced MZM-based laser-to-RF phase detector
  - **sub-2 fs rms timing jitter**
  - **2 fs peak-to-peak drift**





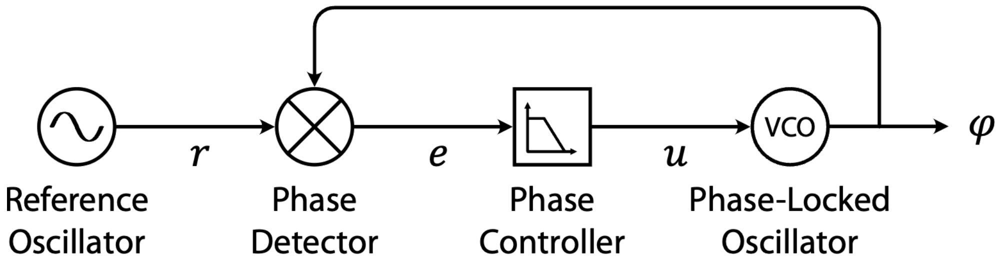


courtesy of T. Lamb, M. Schütte

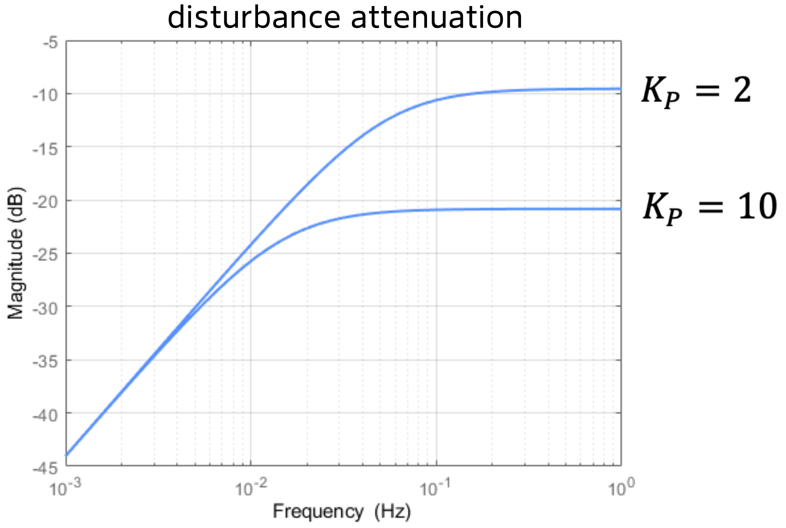
Phase Locking

Classic Phase-Locked Loop Scheme

- objective
  - minimise phase error between controlled oscillator and reference oscillator (“synchronisation”)
- how
  - detect phase error
    - RF-RF, RF-optical, optical-optical
  - feedback via phase controller to tuneable oscillator
  - PI controller usually sufficient
- considerations
  - faster/more aggressive controller response
    - higher loop bandwidth = less relative error / jitter
  - controller gains limited by loop stability
    - minimise loop latency and low-pass dynamics
  - high gains might add measurement noise via loop



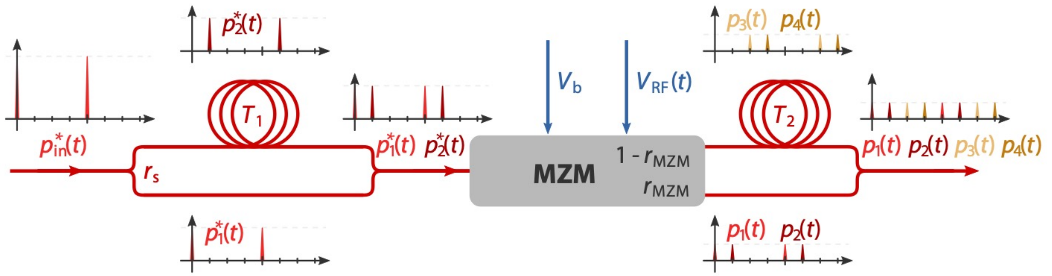
$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau \qquad C(s) = K_P + \frac{K_I}{s}$$



courtesy of M. Schütte

MZM-Based Laser-to-RF Phase Detector

Dual-Output MZM / Dual-Delay For Simultaneous Error Generation



- idea: laser pulse samples RF signal on both slopes
- amplitude modulation of laser pulses ∝ $\Delta\varphi_{RF}$
  - all four pulses involved
- simultaneously retrieve bias error, plus Δr_s
- delays $T_1 = T_{rep}/4$ and $T_2 = T_{rep}/2$

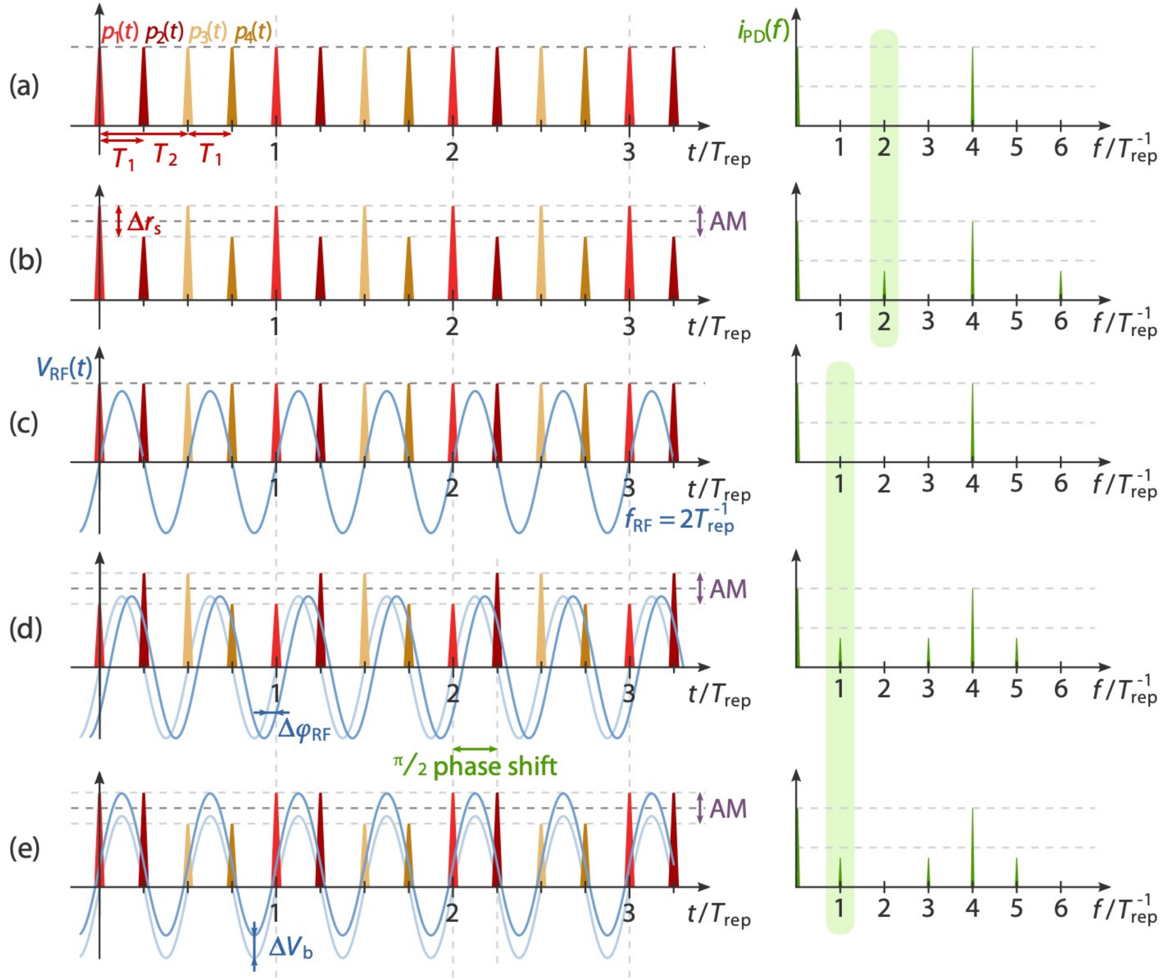
a) no RF, perfect delay arrangement $\Delta r_s = 0$

b) splitting ratio error Δr_s

c) RF applied, perfectly aligned to slopes

d) error $\Delta\varphi_{RF}$ on RF signal → modulation at f_{rep}

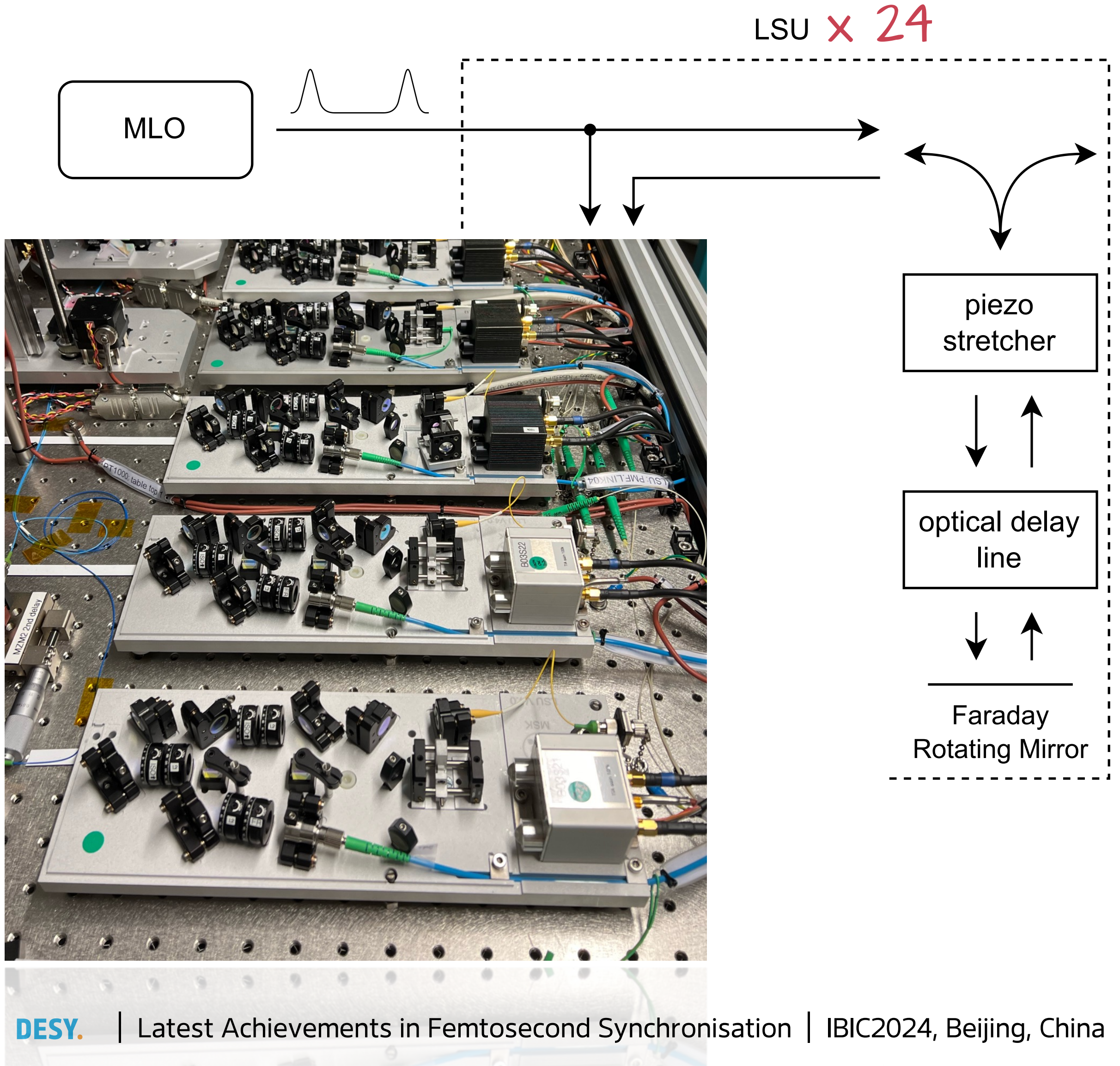
e) error ΔV_b on V_{bias} → modulation at f_{rep}, but phase shifted by π/2 → phase-sensitive detection

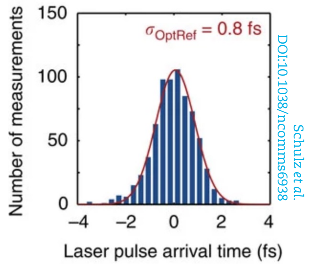


courtesy of T. Lamb

Reference Timing Distribution

Actively Stabilised Fibre-optic Links to All Timing-critical Subsystems

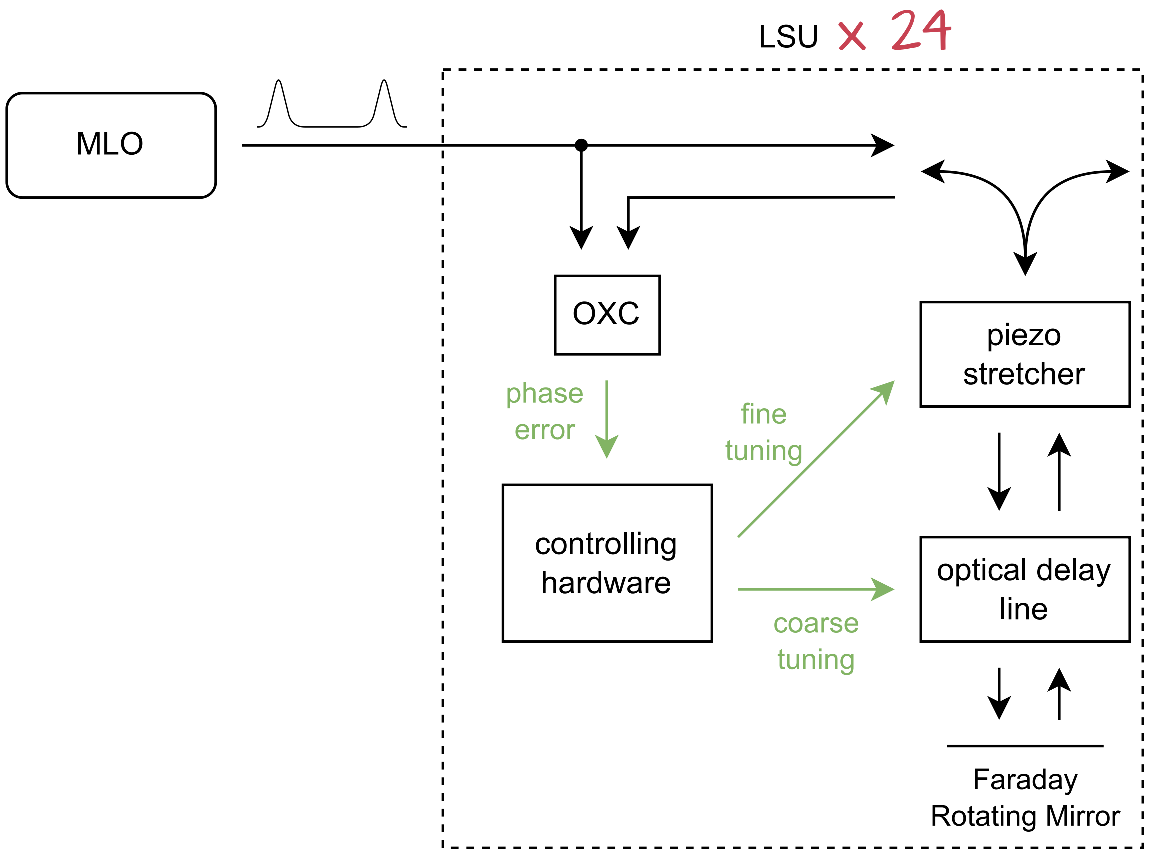


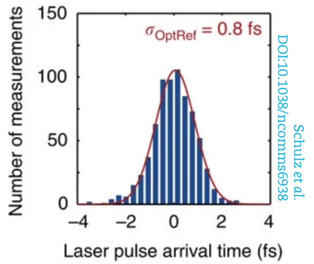


- fully engineered optical setups – 24/MLO
- timing error detection
  - balanced optical cross-correlation
  - insensitive to laser pulse amplitude fluctuations
  - typical sensitivity 5 mV/fs

Reference Timing Distribution

Actively Stabilised Fibre-optic Links to All Timing-critical Subsystems





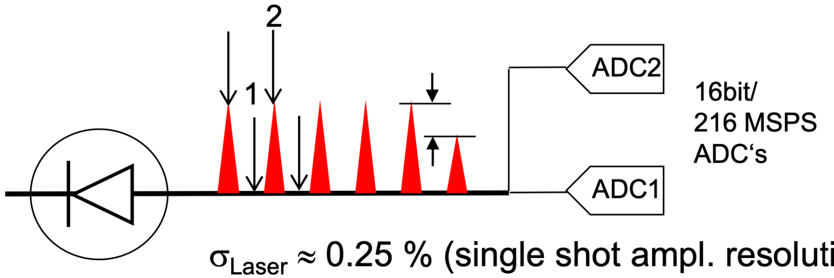
- fully engineered optical setups – 24/MLO
- timing error detection
  - balanced optical cross-correlation
  - insensitive to laser pulse amplitude fluctuations
  - typical sensitivity 5 mV/fs
- error correction
  - FPGA-based, high-resolution PI controller
  - piezo-based fibre stretcher (~3.5 ps range, kHz)
  - optical delay line (4 ns, slow)
  - **~1 fs rms for 3.6 km fibre link?**

courtesy of A. Grünhagen

Electron Bunch Arrival Time Measurement

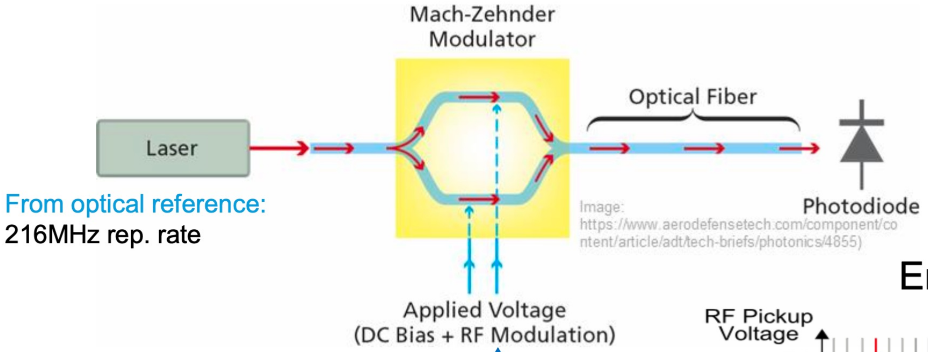
Schematics and Principle of Operation

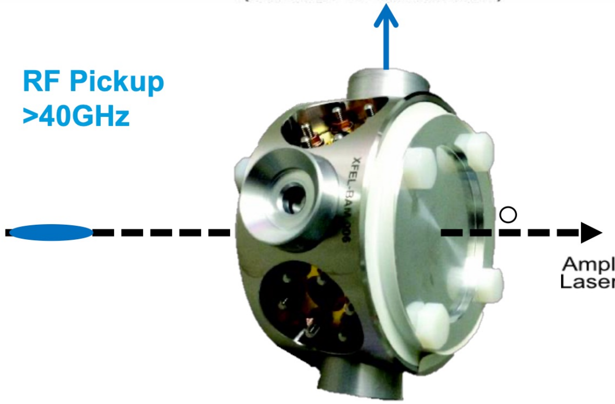
- pickup for transient E-field from e^- bunch: **40 GHz+**
- time reference from optical synchronisation system
- used for slow and fast longitudinal feedbacks



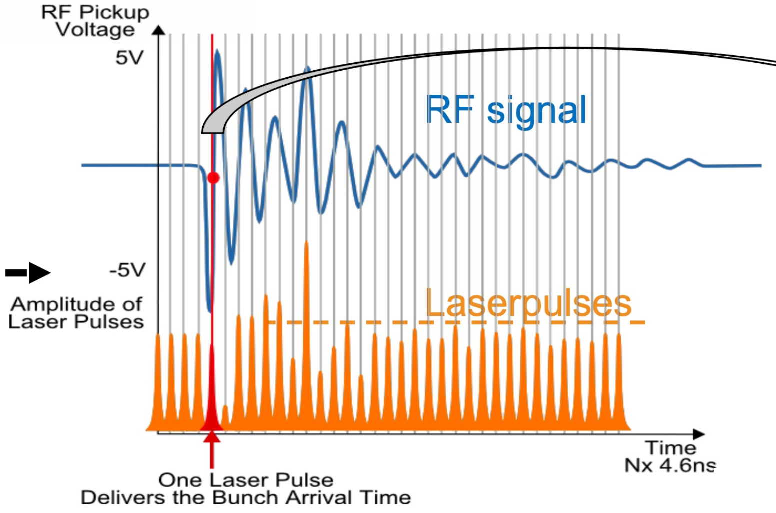
$\sigma_{Laser} \approx 0.25$ % (single shot ampl. resolution)

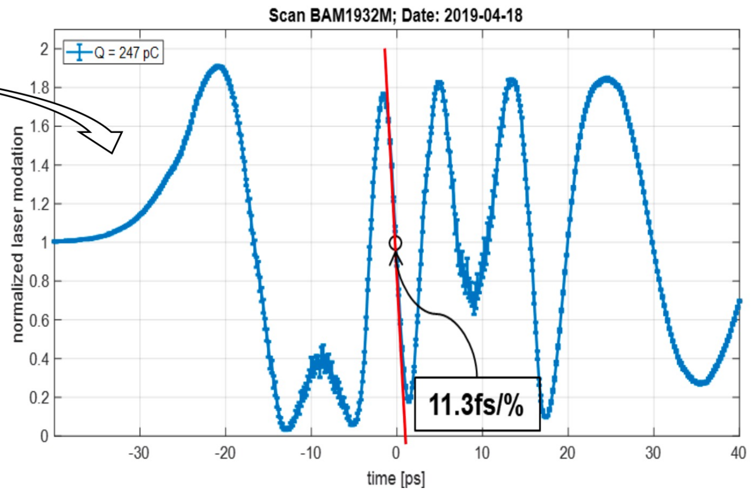
- FPGA-based readout & processing
- **resolution** σ_t = slope × σ_{laser} **≈ 3 fs**





Encode $t_{arrival}$ → A_{laser}



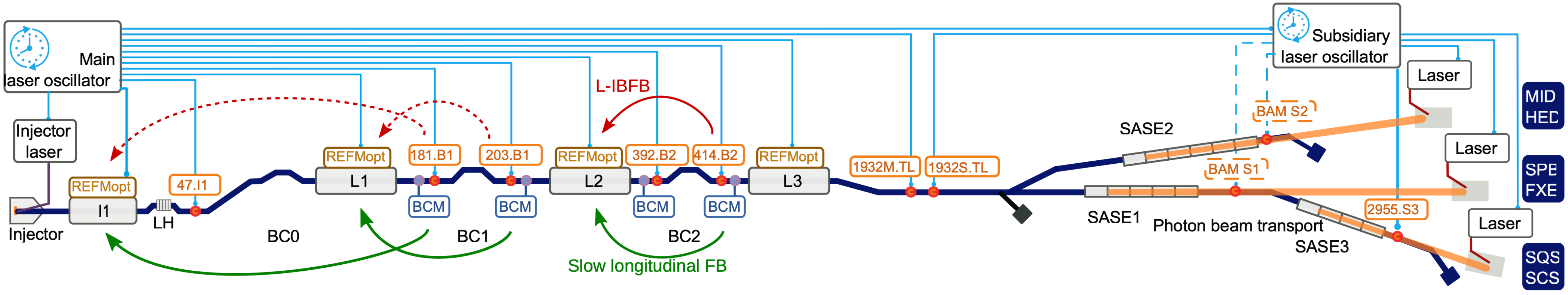


Ref.:
PHYSICAL REVIEW STAB, 18, 012801 (2015)

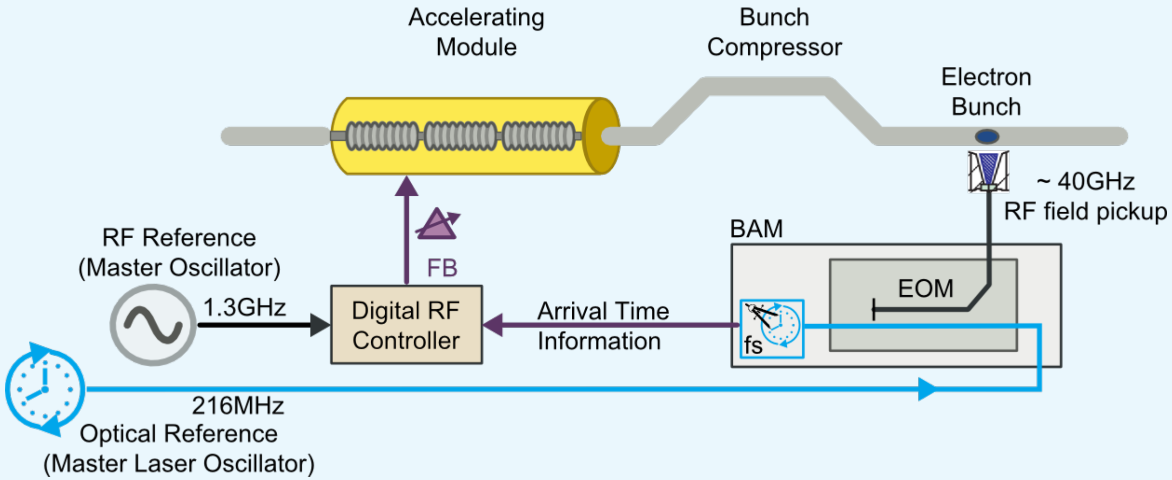
courtesy of M. K. Czwalinna

Electron Bunch Arrival Time Stabilisation

Multi-Stage, Multi-Bandwidth Feedbacks Along the Accelerator



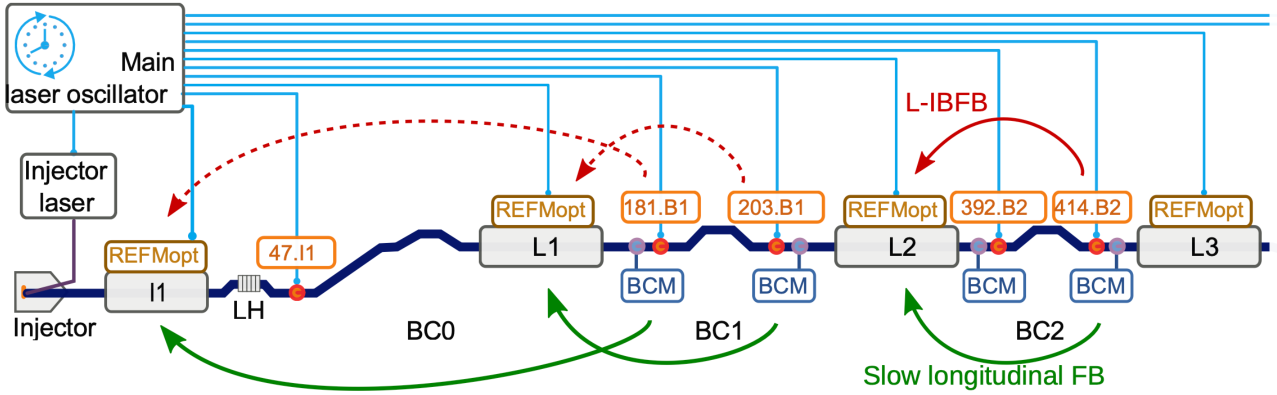
Beam based feedback (L-IBFB)

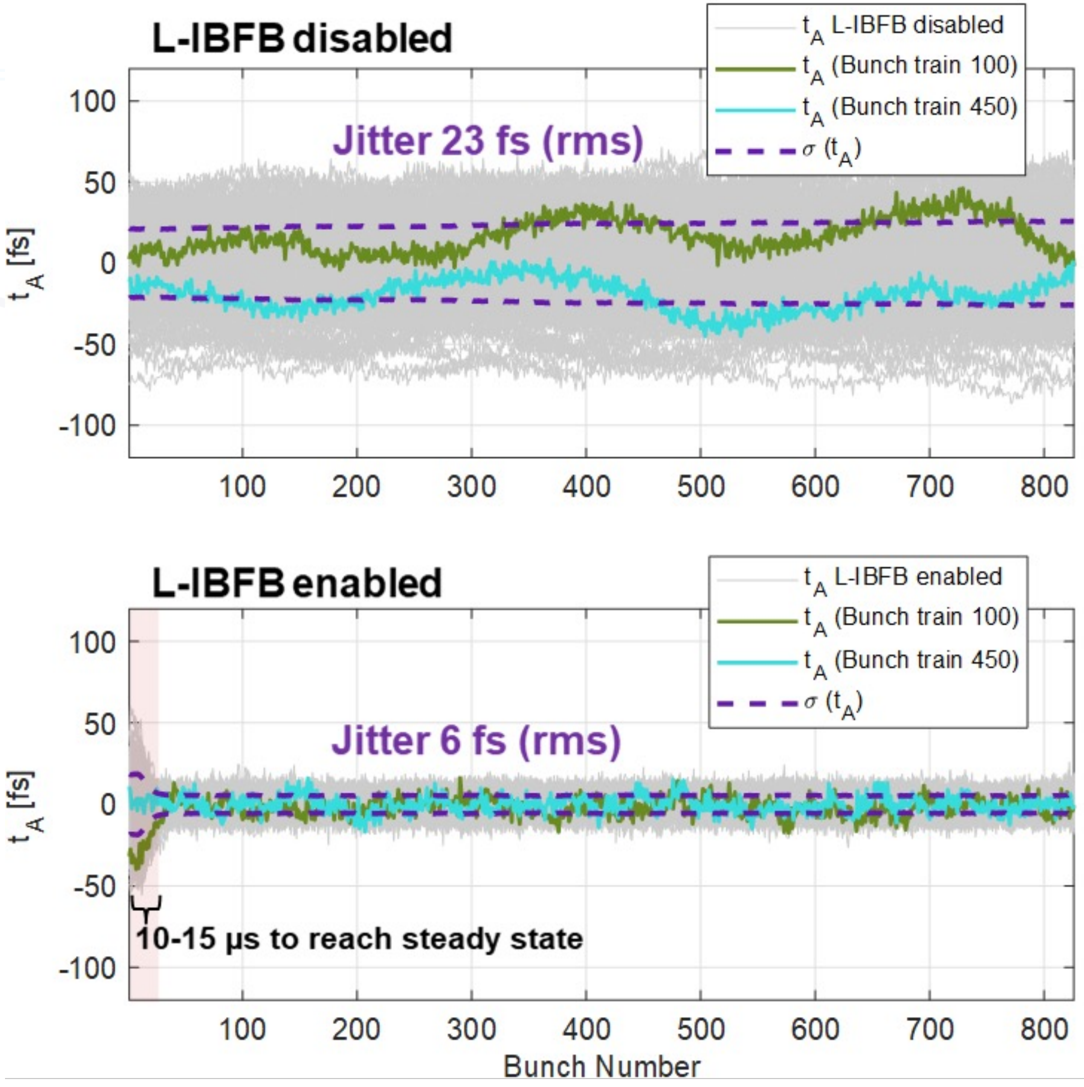


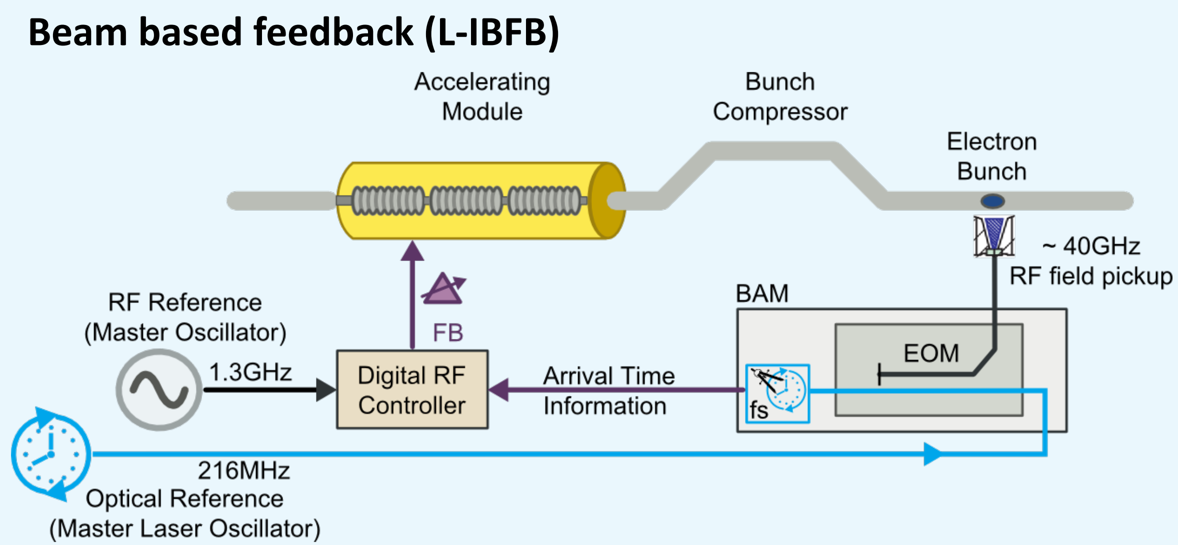
courtesy of M. K. Czwalinna, B. Lautenschlager

Electron Bunch Arrival Time Stabilisation

Multi-Stage, Multi-Bandwidth Feedbacks Along the Accelerator





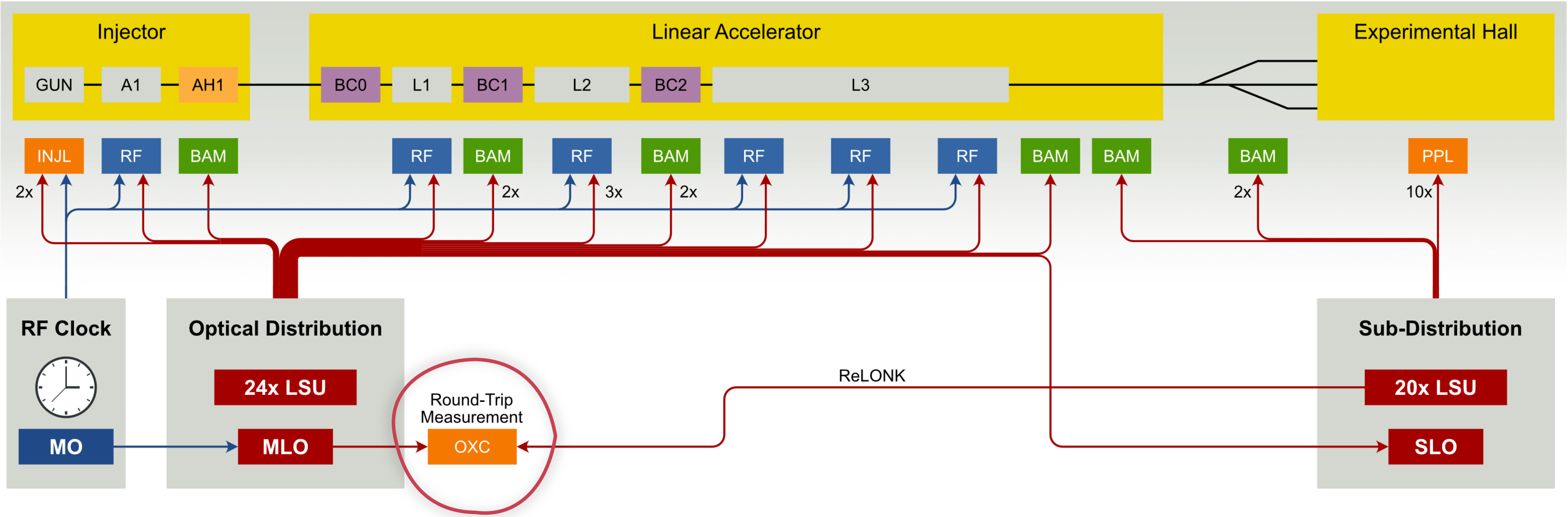


courtesy of M. K. Czwalinna, B. Lautenschlager

System Performance Validation

Self-Contained Validation and Benchmark

Timing Jitter and Drift Measurement After ~8 km of Fibre with Intermediate, Synchronised Reference Laser Oscillator

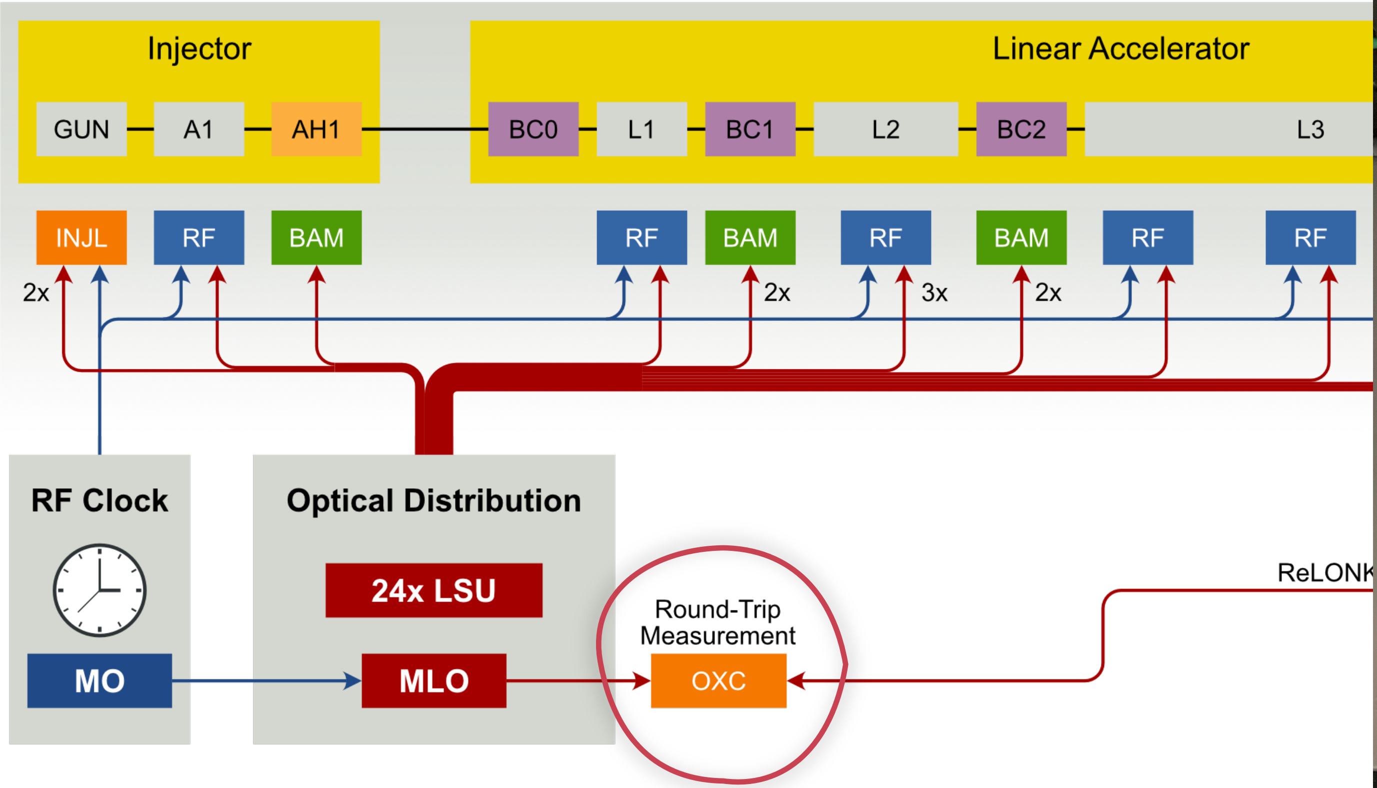


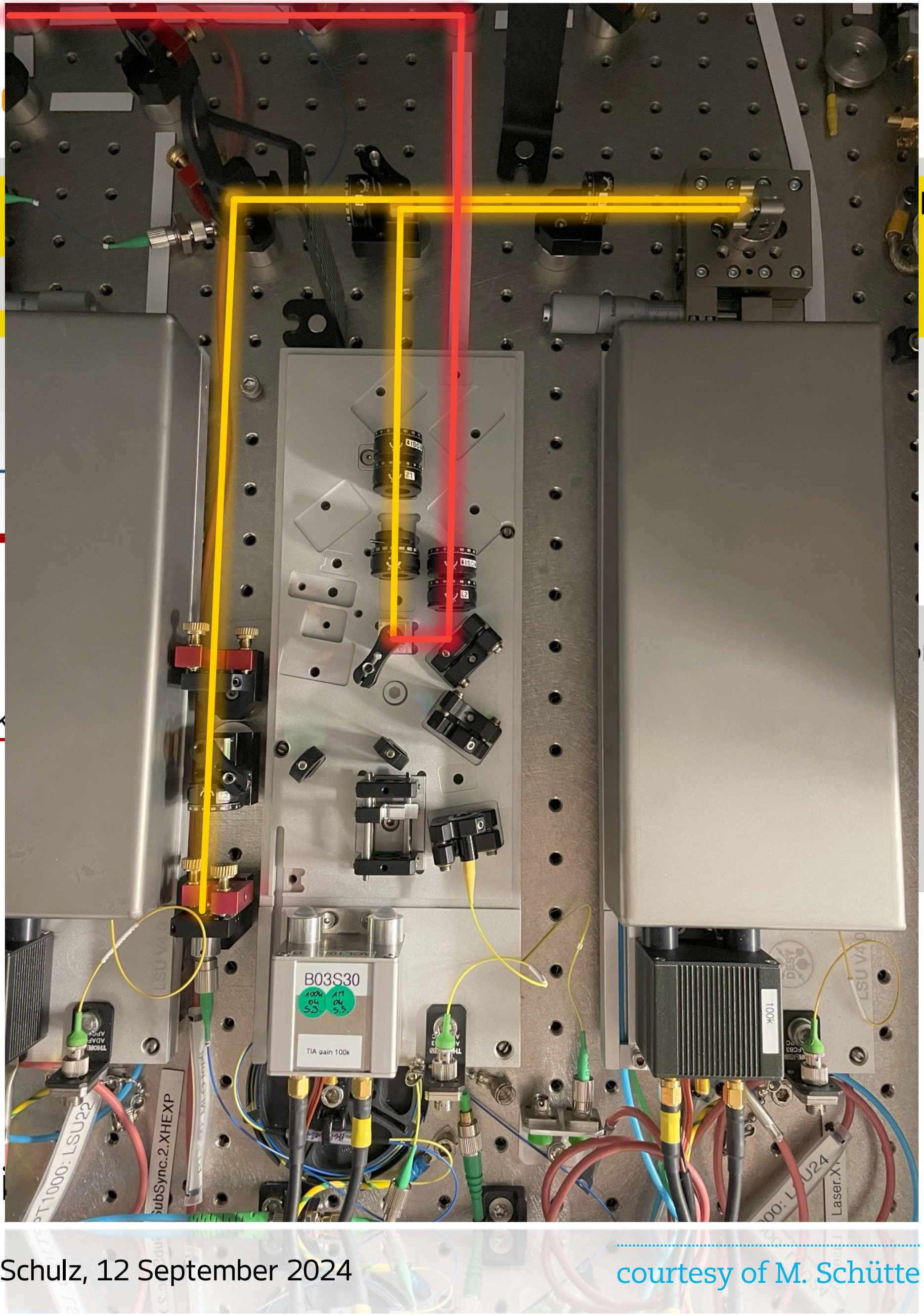
- establish a "loop" from main to sub-synchronisation lab and back
  - using spare fibre laid out in the tunnel
- all-optical measurement → caveat: temporal overlap in optical cross-correlator

courtesy of M. Schütte

Self-Contained Validation and Benchmark

Timing Jitter and Drift Measurement After ~8 km of Fibre with Interme





courtesy of M. Schütte

- establish a "loop" from main to sub-synchronisation lab an
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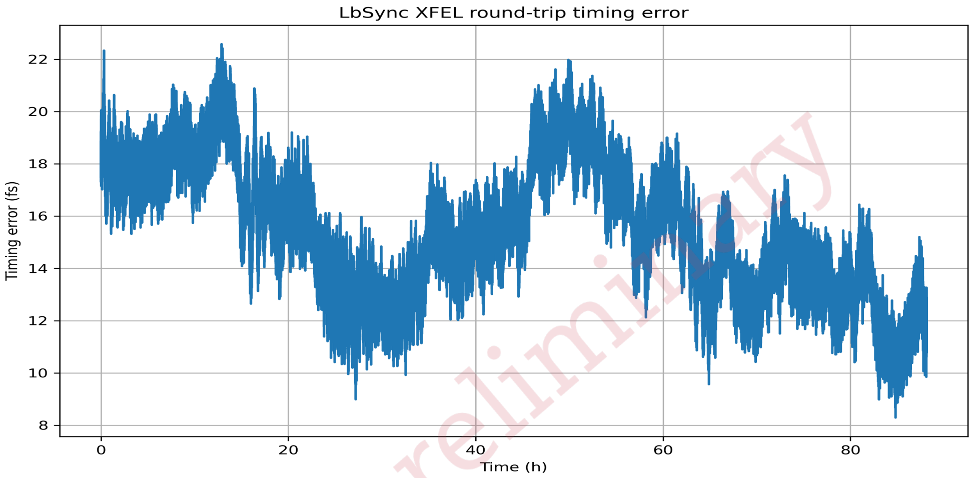
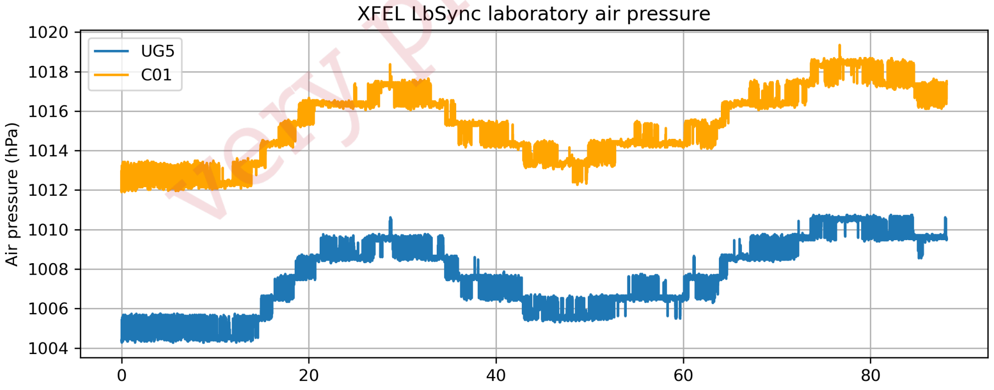
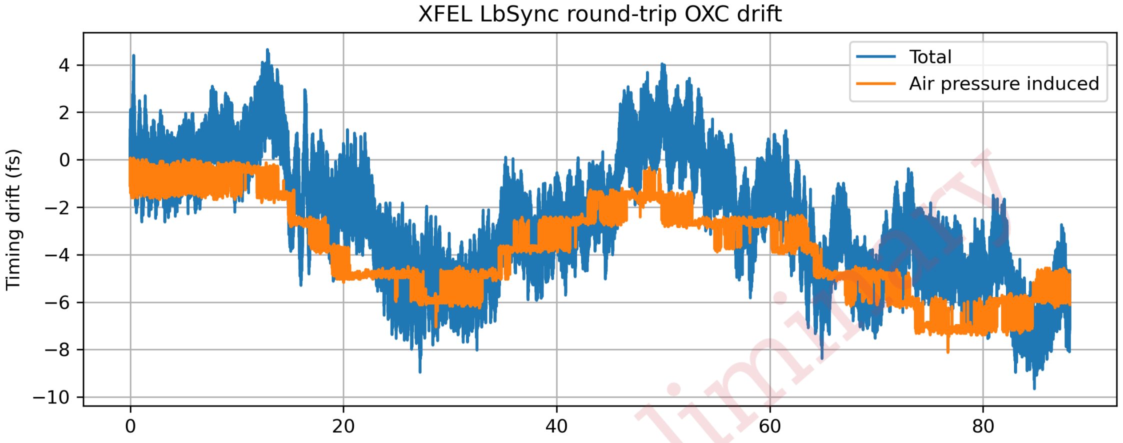
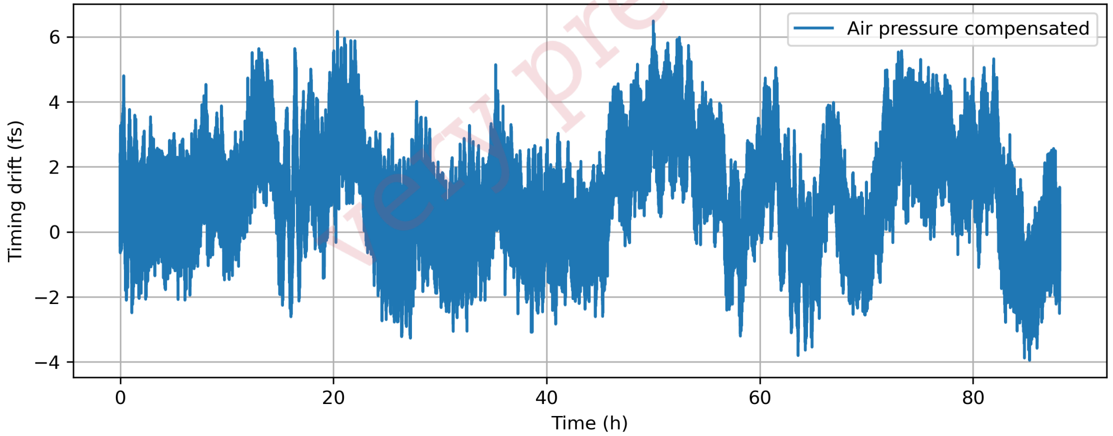
Round-Trip Timing Drift vs. Environmental Parameters

Most Prominent –And Uncontrollable– Effect: Air Pressure









- correlation factor **-1.11 fs/mbar/m**
  - remaining path difference, and other contribution
- residual drift ~10 fs peak-to-peak, ~3.5 fs rms
  - under investigation – delay line effect?

courtesy of M. Schütte

Round-Trip Timing Drift vs. Environmental Parameters

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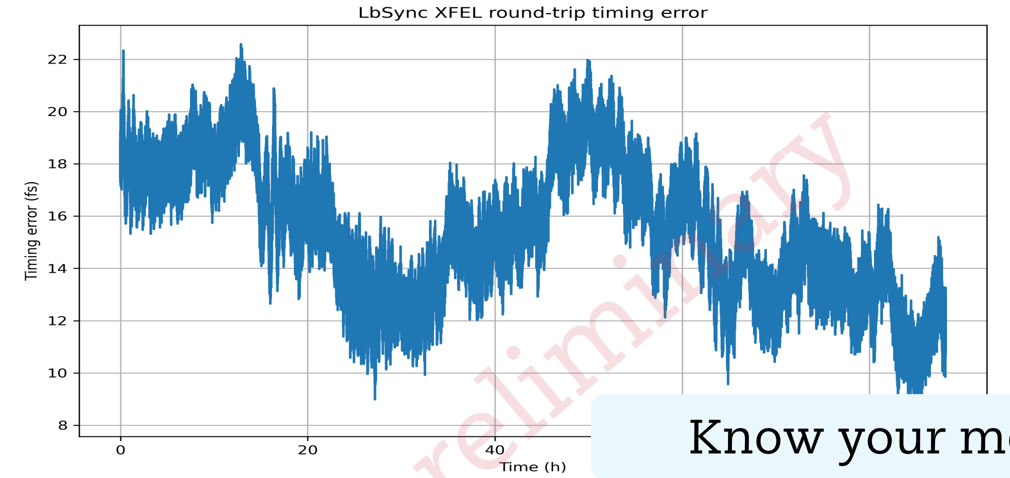
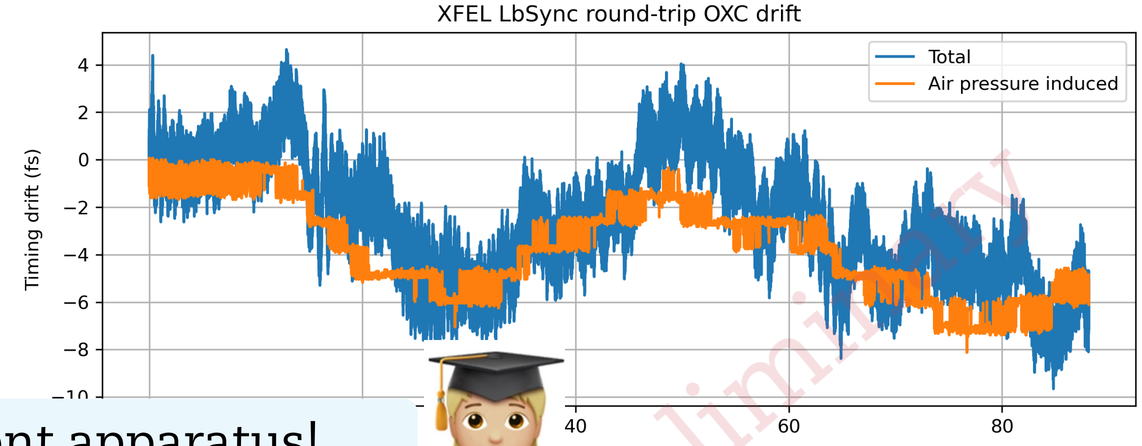
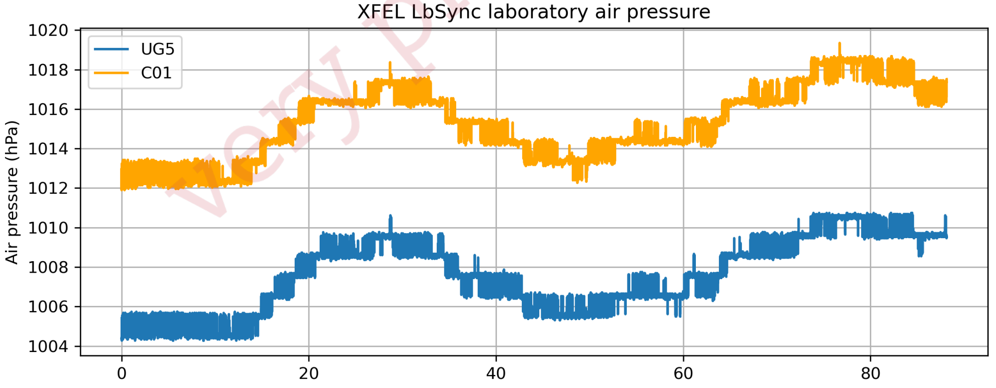
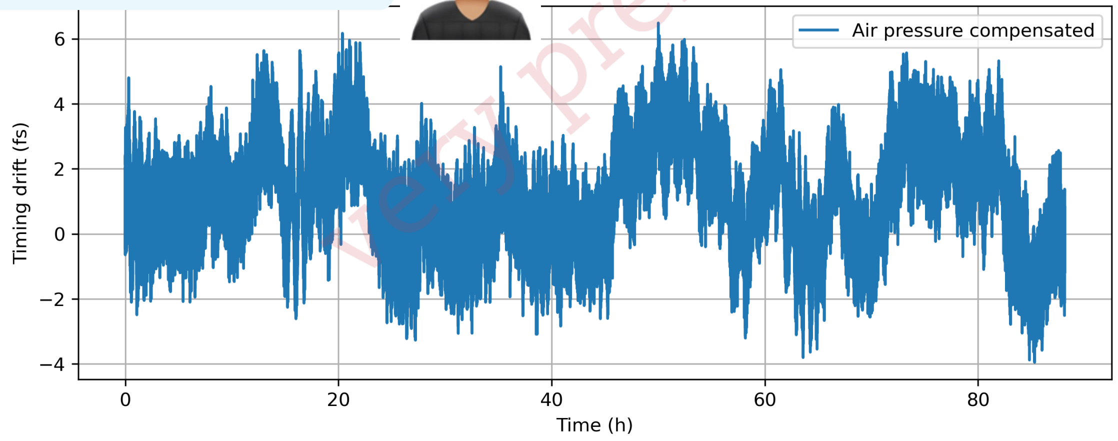




Know your measurement apparatus!





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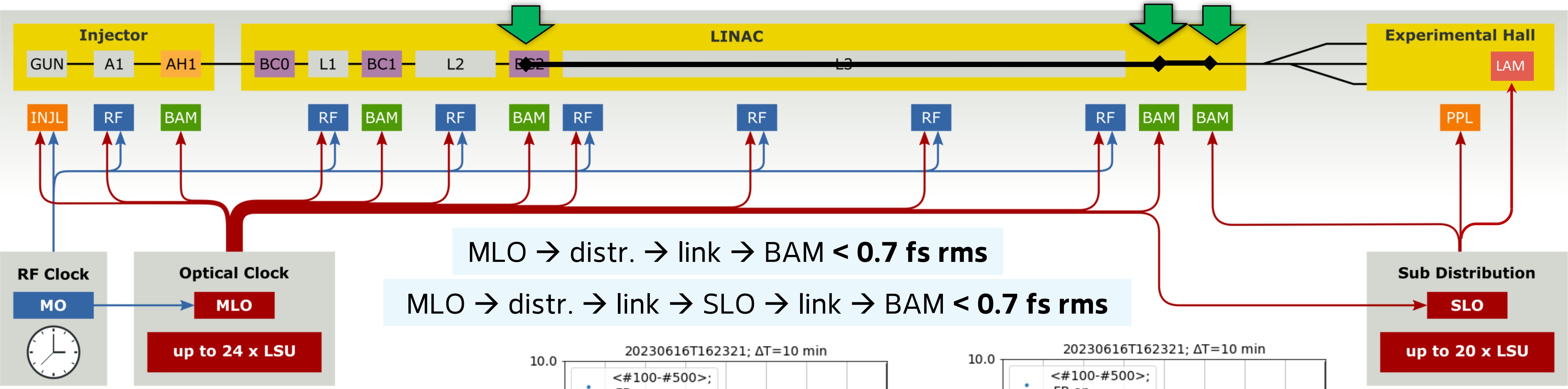
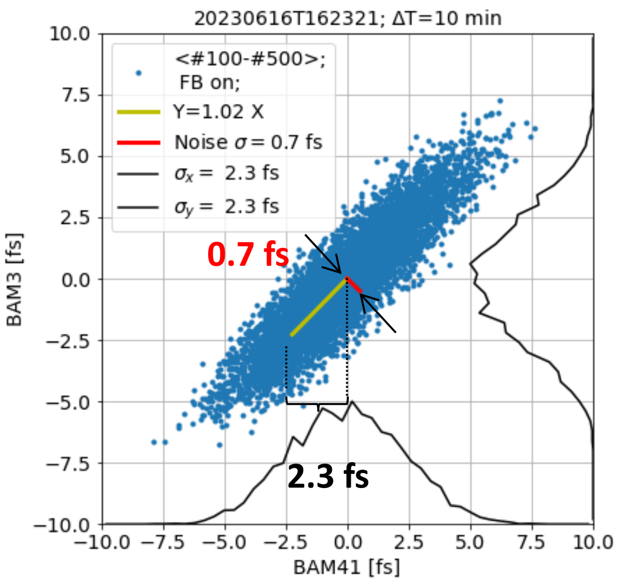
courtesy of M. Schütte

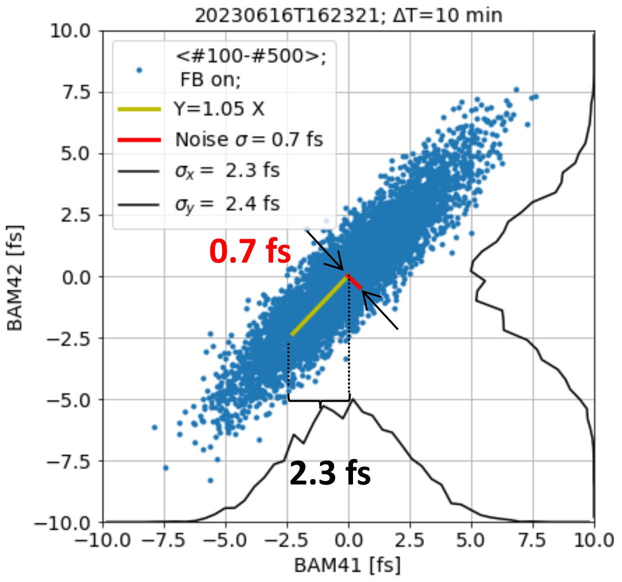
Synchronisation System Benchmark with Electrons: Time Domain

Beam-based Evaluation of the Performance by Arrival Time Correlation



- **10 minutes** (6000 trains), mean(400 bunches)
- remove BAM high-frequency instrument noise
- residual jitter of macropulses

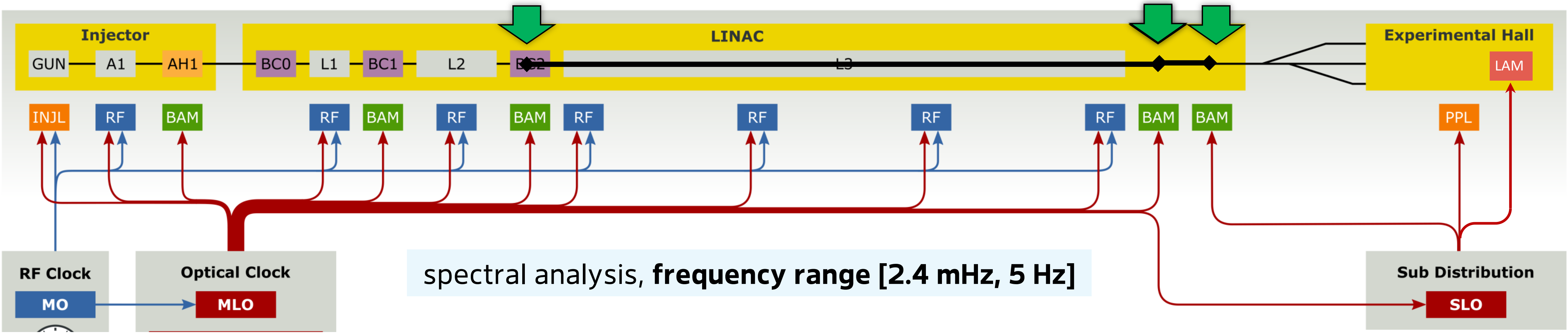




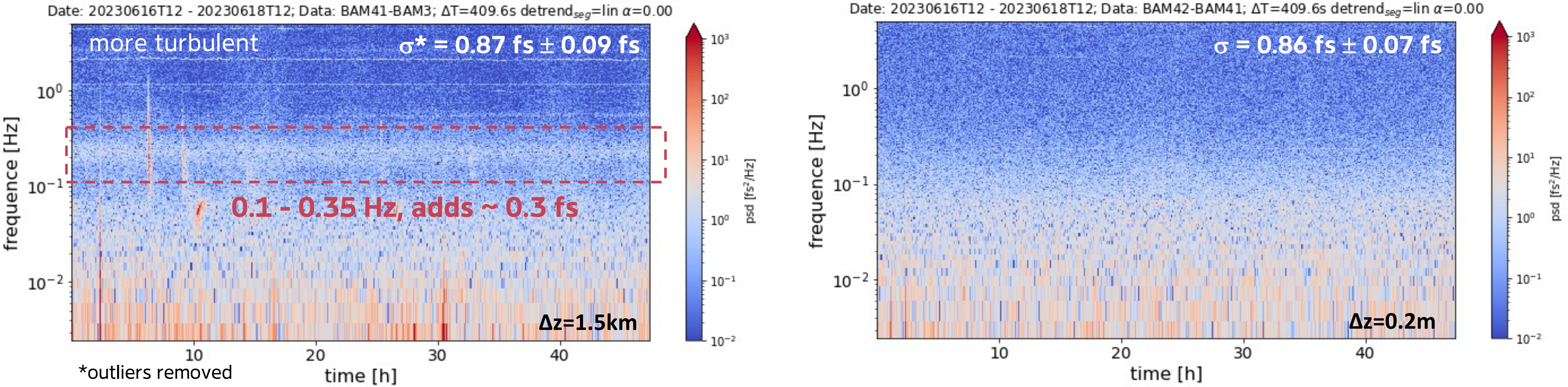
courtesy of H. Schlarb, M. K. Czwalinna *et al.*

Synchronisation System Benchmark with Electrons: Frequency Domain

Beam-based Evaluation of the Performance by Arrival Time Correlation



spectral analysis, **frequency range [2.4 mHz, 5 Hz]**

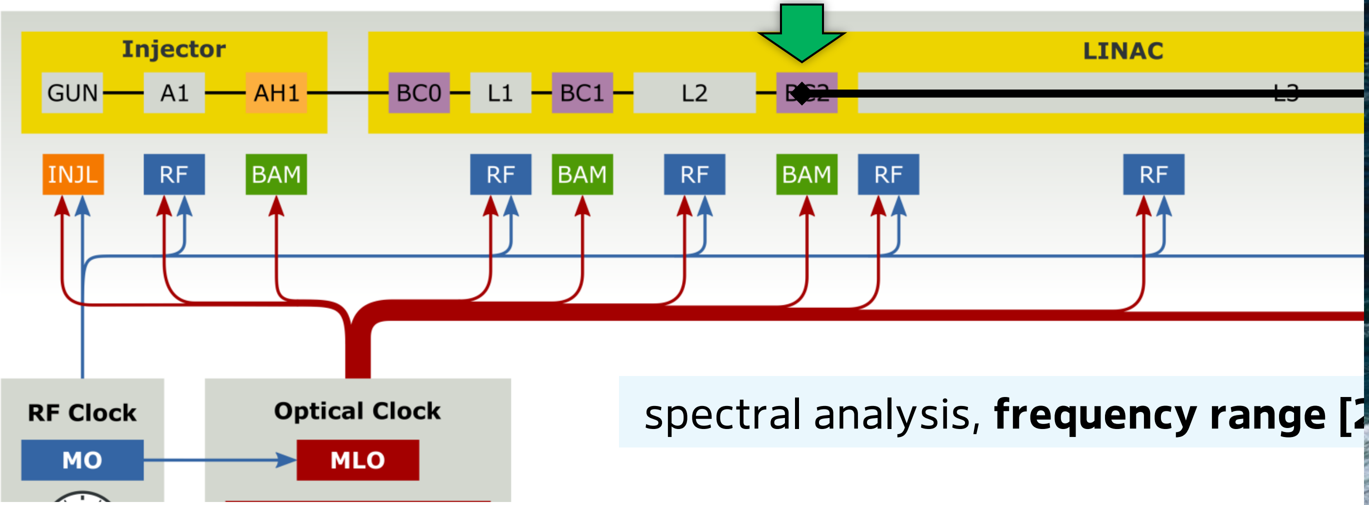


*outliers removed

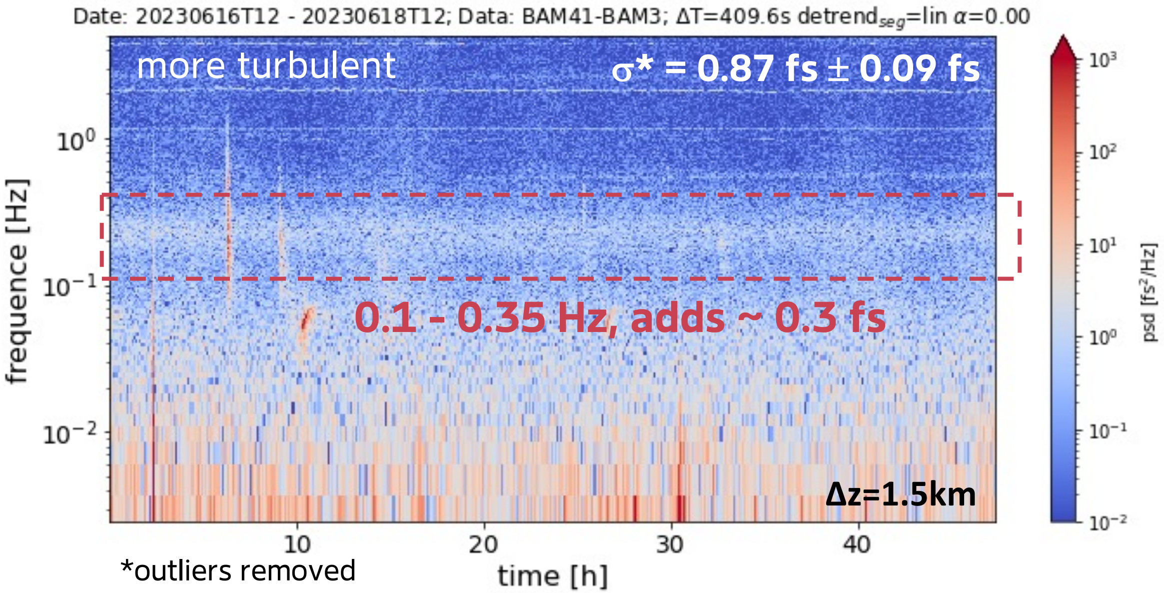
photo: Jean Guichard, “Phare de la Jument” courtesy of H. Schlarb

Synchronisation System Benchmark with E

Beam-based Evaluation of the Performance by Arrival Time Correlatio



spectral analysis, **frequency range [2**



*outliers removed

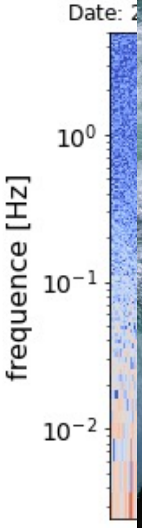
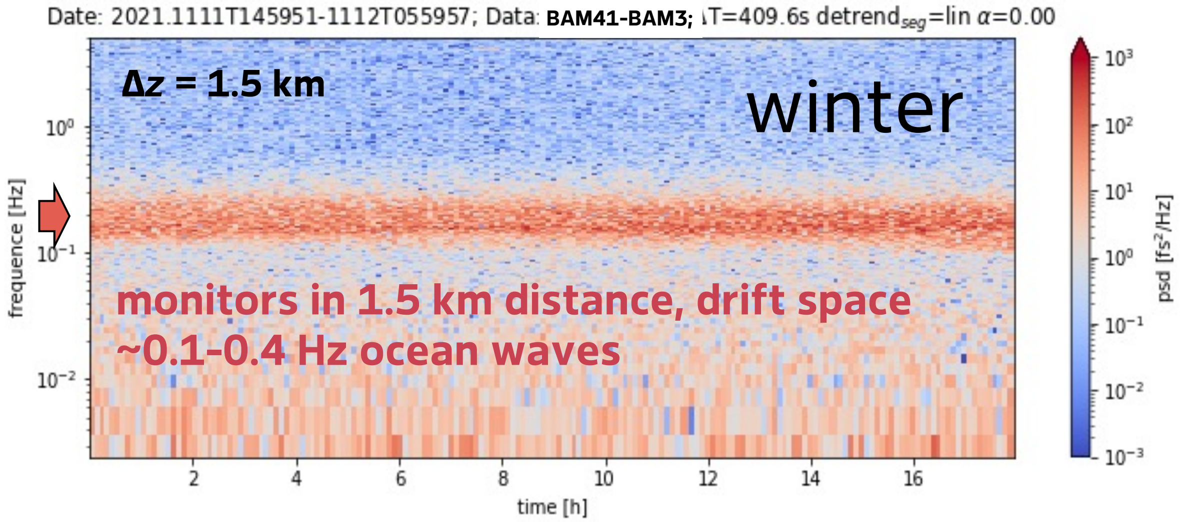
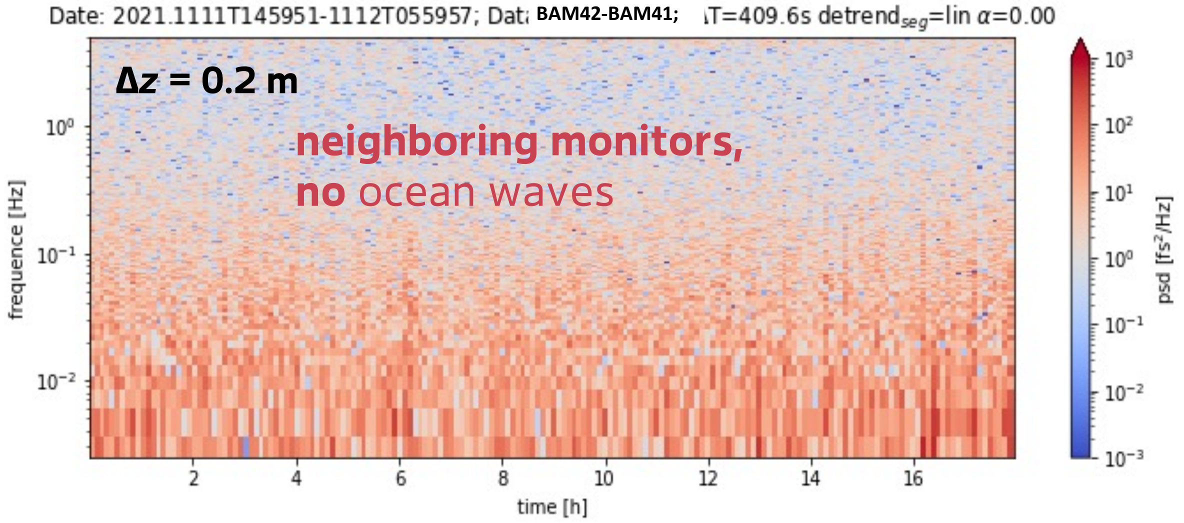


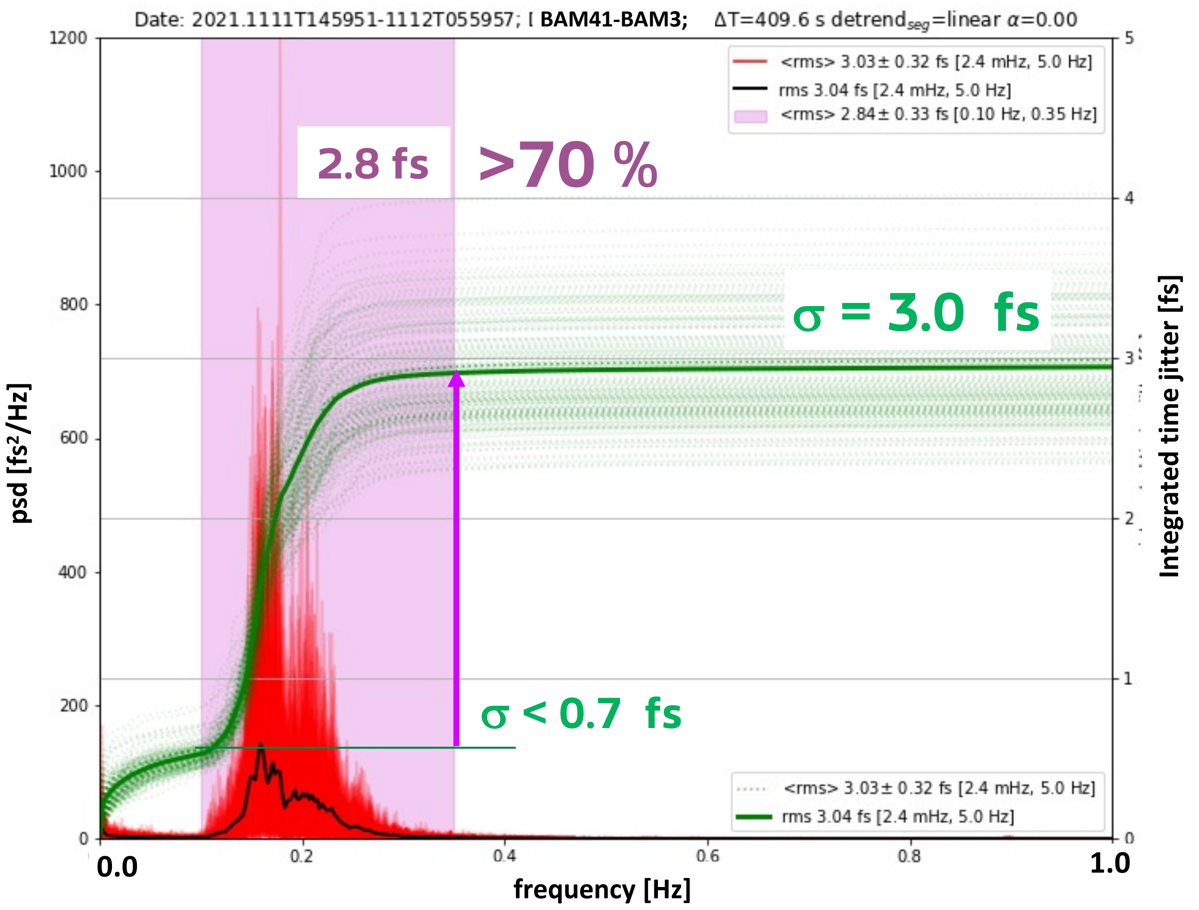
photo: Jean Guichard, “Phare de la Jument” courtesy of H. Schlarb

Ocean Wave Effect on Electron Bunch Arrival Time

Detection of Ocean Waves in Electron Bunch Straight Path



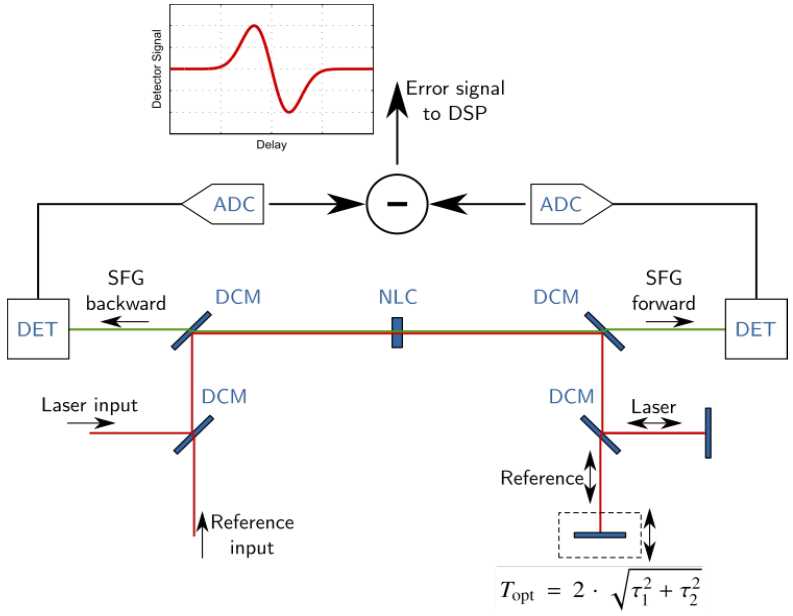




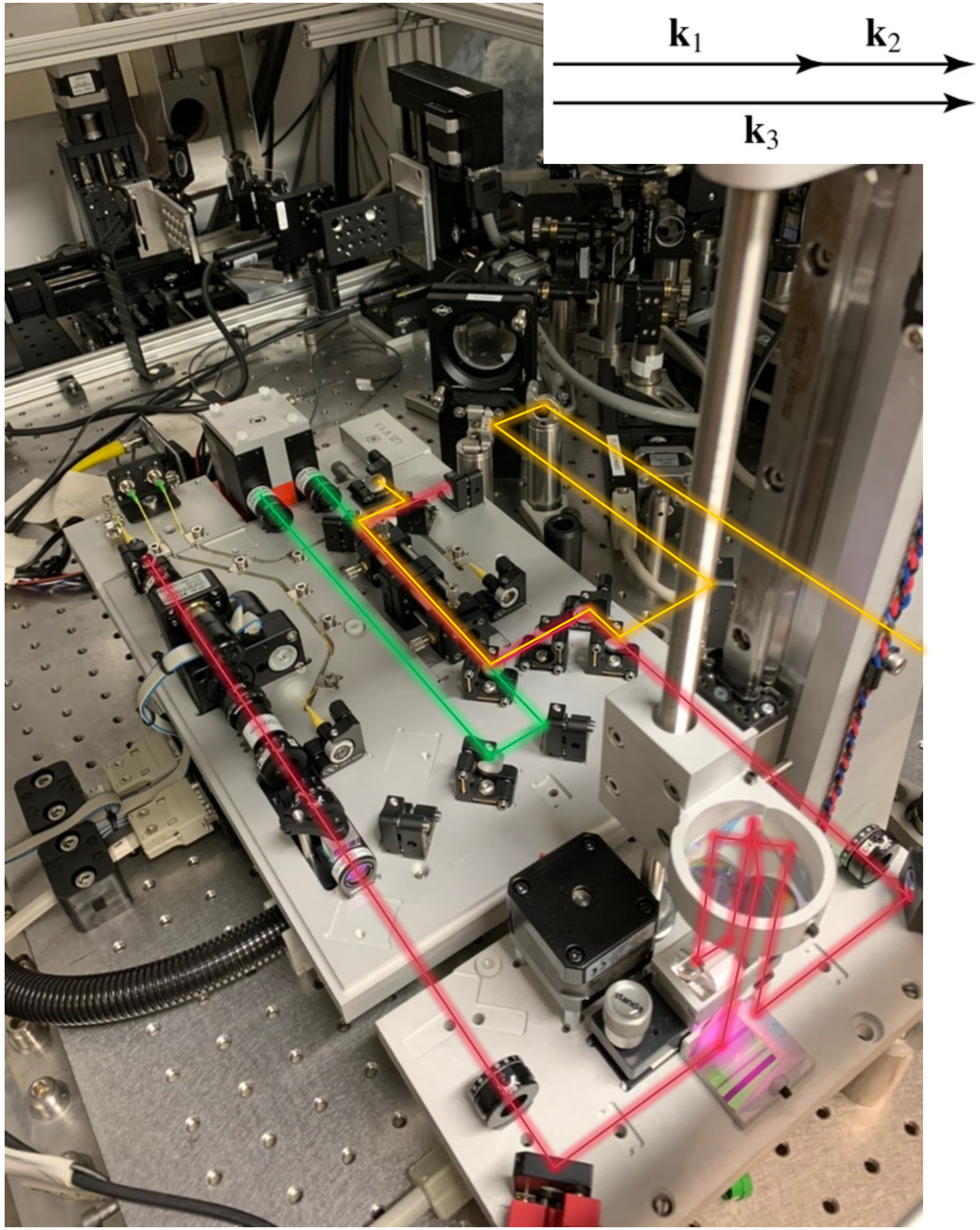
Laser Pulse Arrival Time Monitor

Two-Colour Balanced Optical Cross-Correlator

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

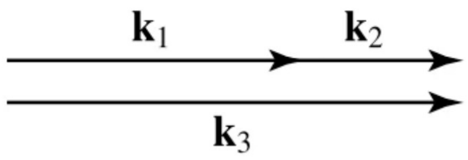


  - can include 5 ns **user experiment delay control**
  - adaptable to different laser parameters … **really?**



in parts courtesy of J. Müller

Laser Pulse Arrival Time Monitor Foundation



Sellmeier Equation, Phase Matching and Conversion Efficiency

$$\boldsymbol{k}_{3,3'} = \boldsymbol{k}_1 \pm \boldsymbol{k}_2 \quad \text{with} \quad |\boldsymbol{k}_i| = k_i = \frac{\omega_i\, n(\omega_i)}{c_0} = \frac{2\pi\, n_i}{\lambda_i}$$

$$n^2(\lambda) = 1 + \sum_j \frac{B_j \lambda^2}{\lambda^2 - C_j},$$

$$n^{\mathrm{e}}(\Theta) = \left(\frac{1 + \tan^2\Theta}{1 + (n_o/n_e)^2 \tan^2\Theta} \right)^{1/2}$$

negative uniaxial crystals	positive uniaxial crystals
$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{ooe})} = (1-U)/(W-1)$	$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{eeo})} \simeq (1-U)/(U-S)$
$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{eoe})} \simeq (1-U)/(W-R)$	$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{oeo})} = (1-V)/(V-Y)$
$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{oee})} \simeq (1-U)/(W-Q)$	$\tan^2\Theta_{\mathrm{pm}}^{(\mathrm{eoo})} = (1-T)/(T-Z)$

notation:

$U = (A+B)^2/C^2;\quad W = (A+B)^2/F^2;\quad R = (A+B)^2/(D+B)^2$

$Q = (A+B)^2/(A+E)^2;\quad S = (A+B)^2/(D+E)^2;\quad V = B^2/(C-A)^2$

$Y = B^2/E^2;\quad T = A^2/(C-B)^2;\quad Z = A^2/D^2$

$A = n_{o,1}/\lambda_1;\quad B = n_{o,2}/\lambda_2;\quad C = n_{o,3}/\lambda_3$

$D = n_{e,1}/\lambda_1;\quad E = n_{e,2}/\lambda_2;\quad F = n_{e,3}/\lambda_3$

conversion efficiency

$$\frac{P_3}{P_1} = \frac{8\pi\, d_{\mathrm{eff}}^2\, L^2\, P_2}{\varepsilon_0\, c_0\, n_1\, n_2\, n_3\, \lambda_3^2\, w_0^2}\, \mathrm{sinc}^2\left(\frac{|\Delta k|\, L}{2}\right)$$

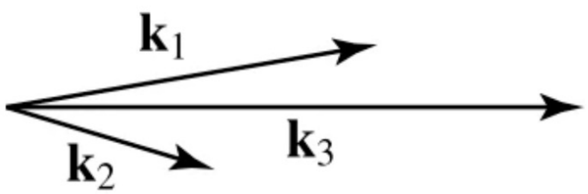
with $\Delta k = k_1 + k_2 - k_3$

and $d_{\mathrm{eff}} = d_{31} \sin\Theta - d_{22} \cos\Theta \sin\varphi$

Θ_{pm} = 22.2 deg for BBO, collinear type-I$^-$ mixing 800 nm and 1550 nm ⇒ 527 nm SFG, **efficiency ~1%**

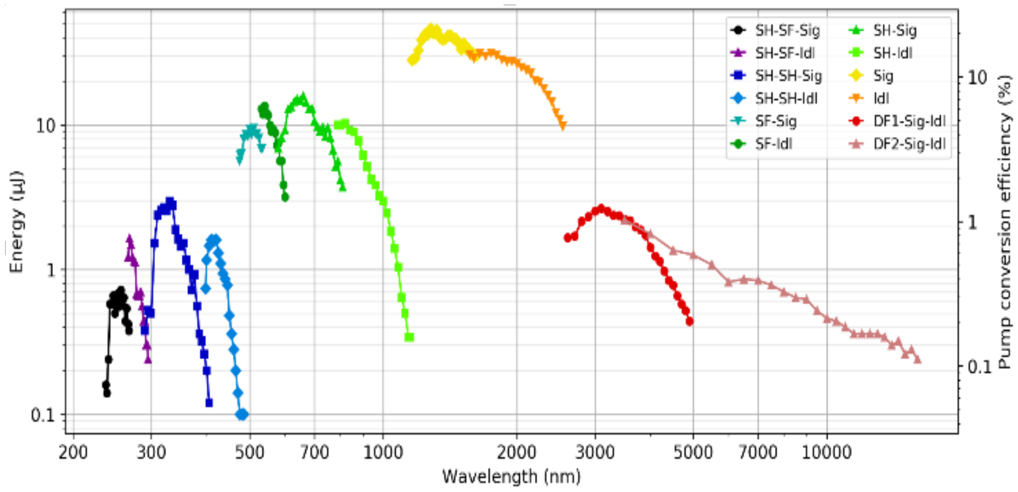
Advanced Laser Pulse Arrival Time Measurements

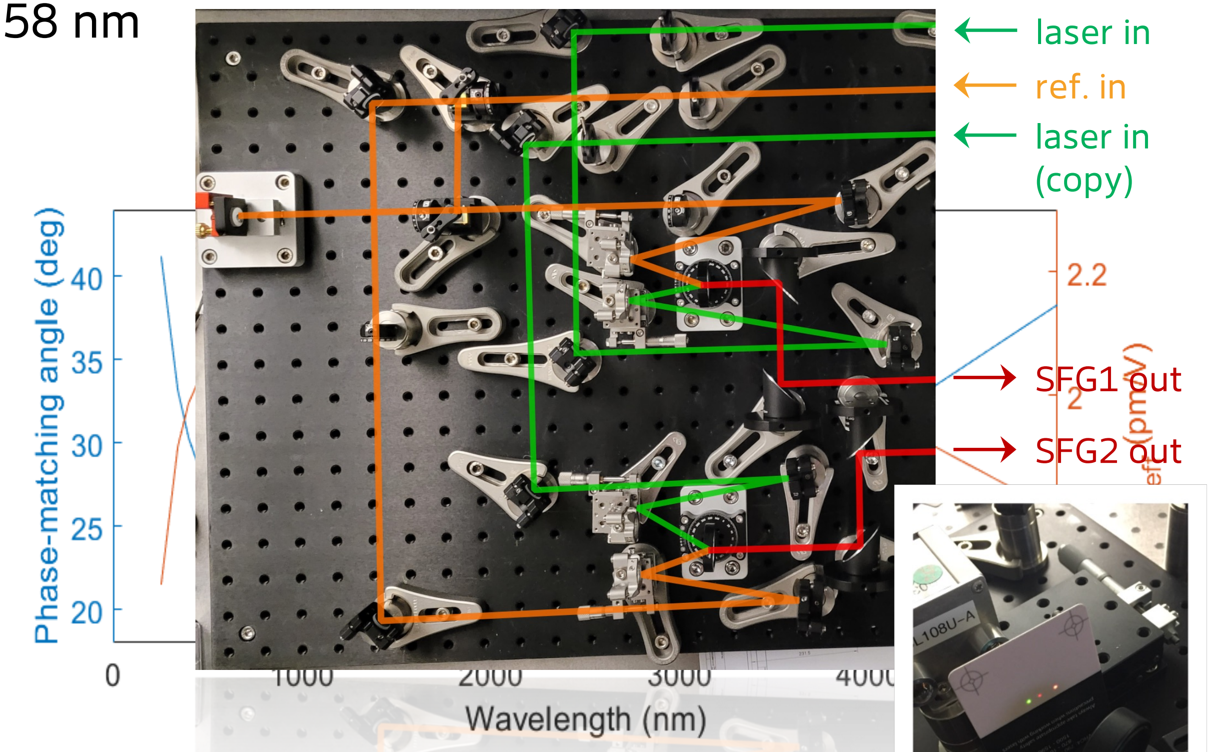
One Challenge: Covering a Huge Spectral Range for User Experiments



✅ 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

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

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

courtesy of A.-L. Calendron, D. Schwickert, N. Kschuev, S. Hoseinkhani

Advanced Laser Pulse Arrival Time Measurements

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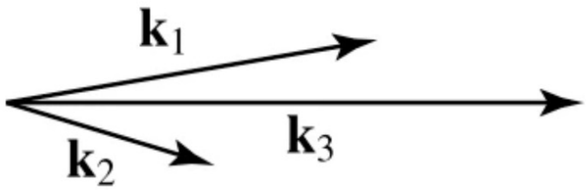

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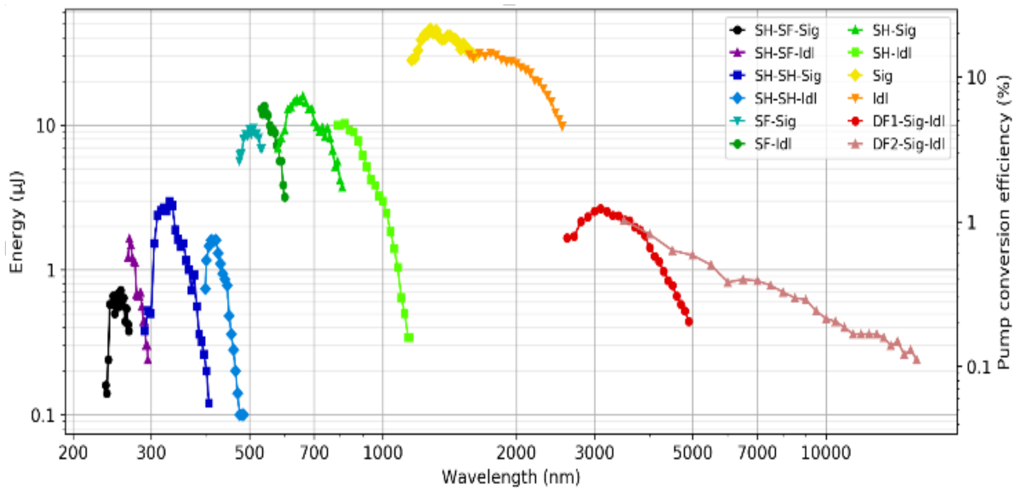

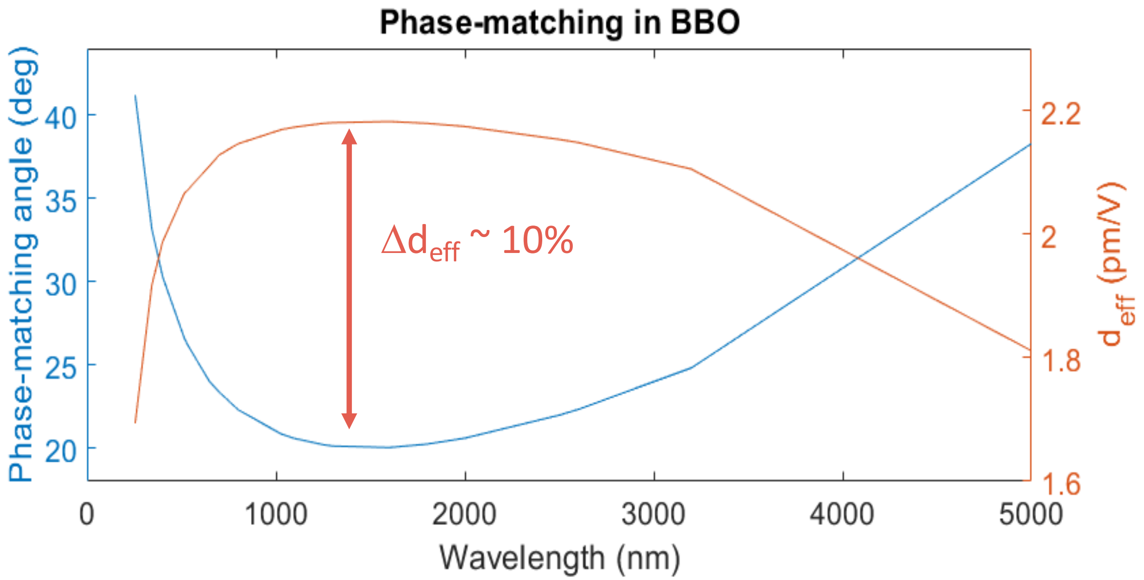

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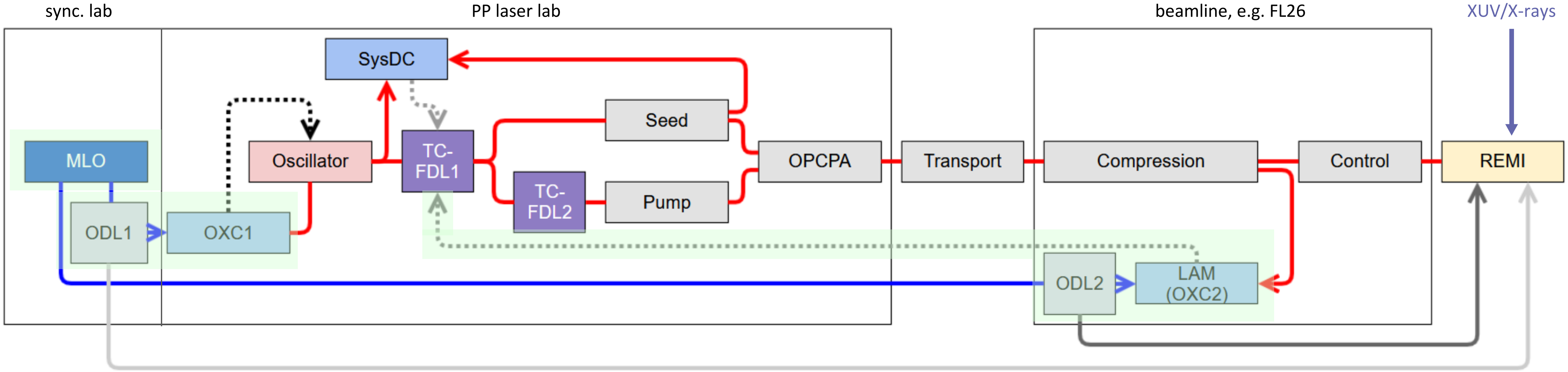
courtesy of A.-L. Calendron, D. Schwickert, N. Kschuev, S. Hoseinkhani

Laser Pulse Arrival Time Monitor at Experiment's Interaction Points

Complementary to PAM at Experimental Stations



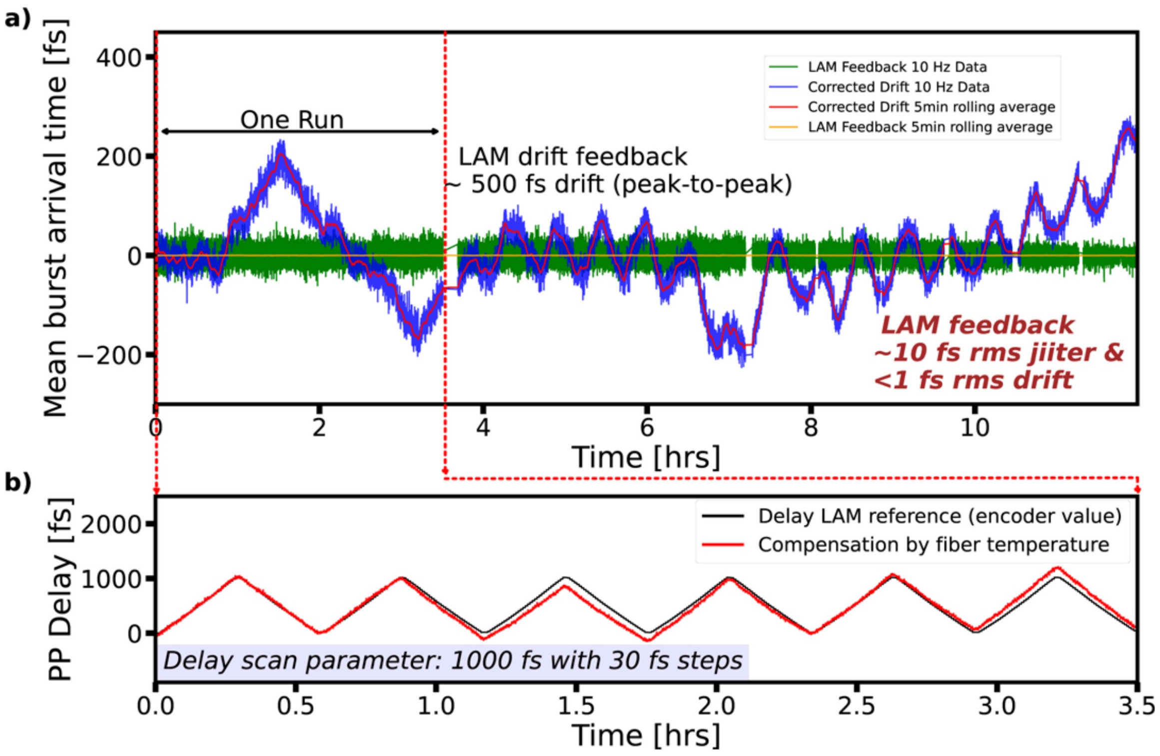
- based on common, fibre-based optical reference (MLO, 2 fibre links, 2 ODLs…)
- test and implementation at the FELs in stages
  - **single-pulse measurements** (up to 4.5 MHz at EuXFEL, **100 kHz** and 1 MHz **at FLASH**)
  - **feedback to compensate drifts** (up to 10 Hz rep'rate)
  - fast feedbacks over the burst or for HDC (requires additional LLL from LAM to lock/controller)
- **successful, active slow (~ 1 Hz) drift stabilisation in several user experiments**

courtesy of N. Schirmel

Temporal Resolution In FLASH User Experiments

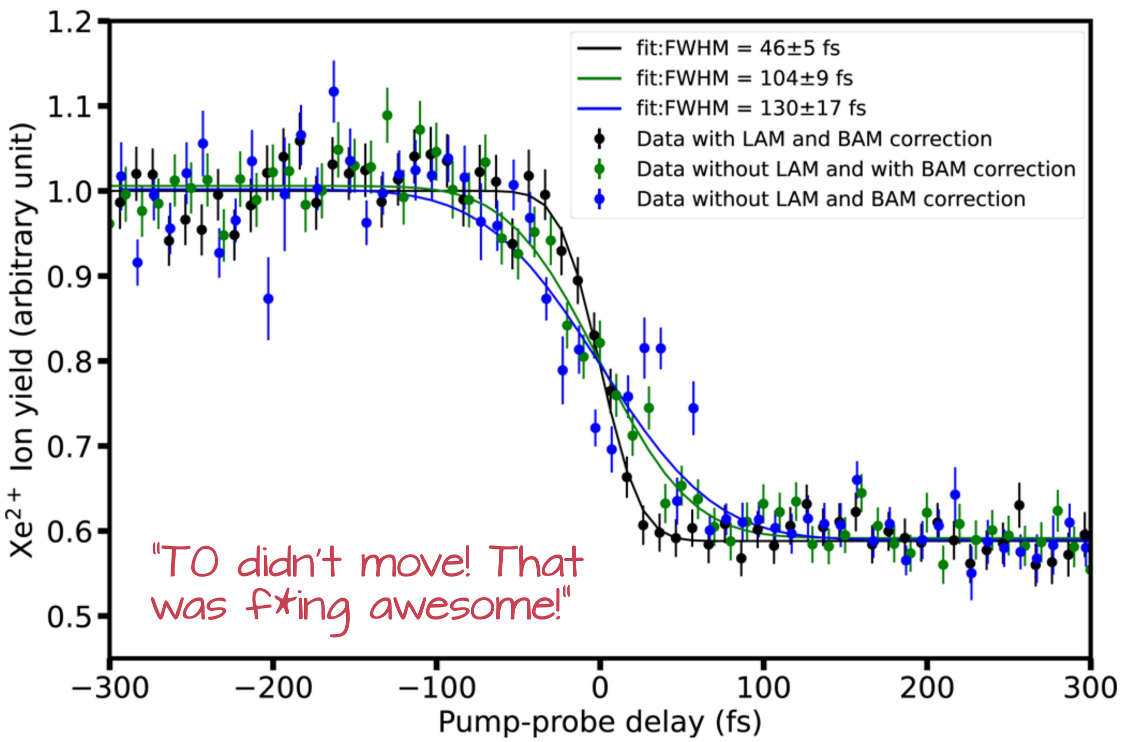
Benchmark at FL26 – Laser-assisted Xe Photoionisation Using 800 nm

- active arrival time feedback



- **~500 fs peak-to-peak drift compensated**

- **19.6 fs rms** relative timing jitter ⇐ LAM & BAM

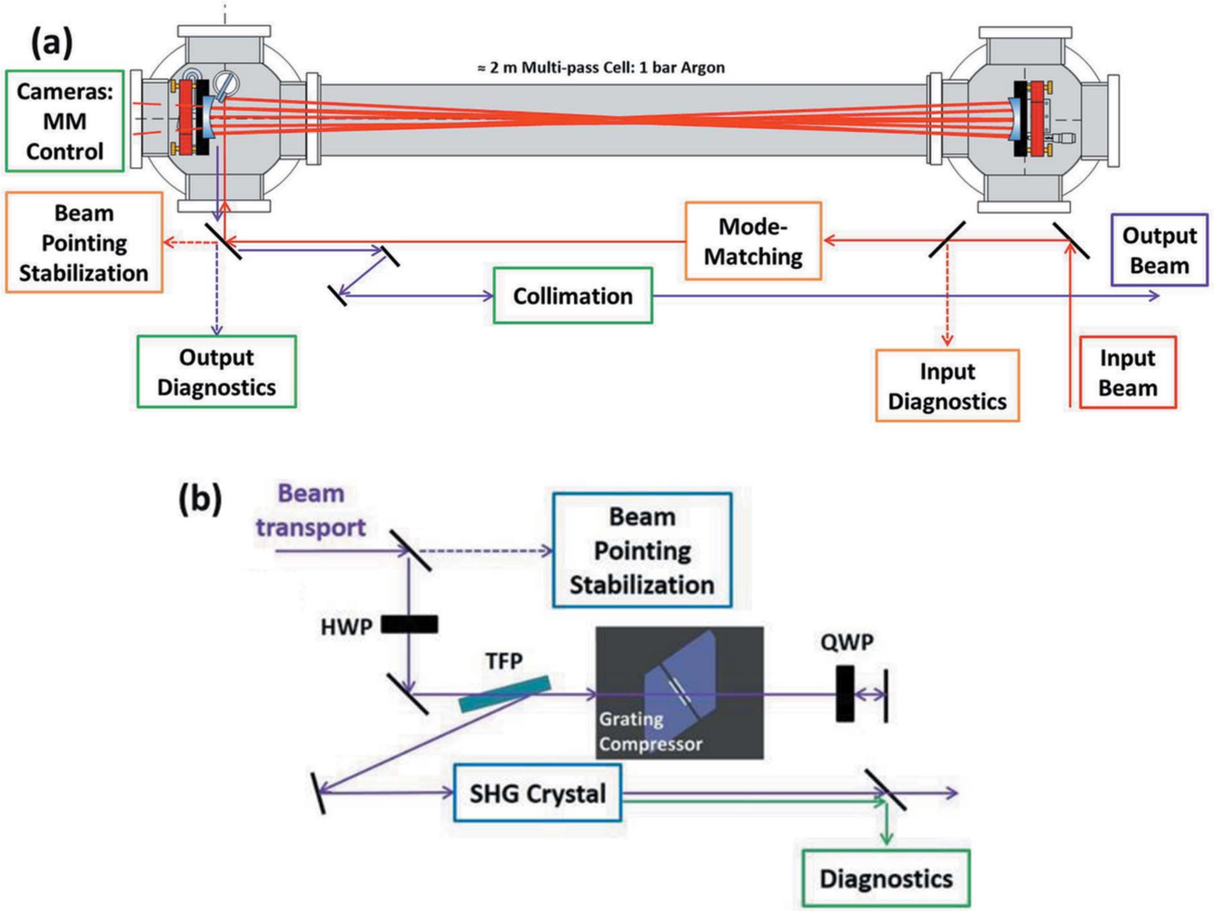


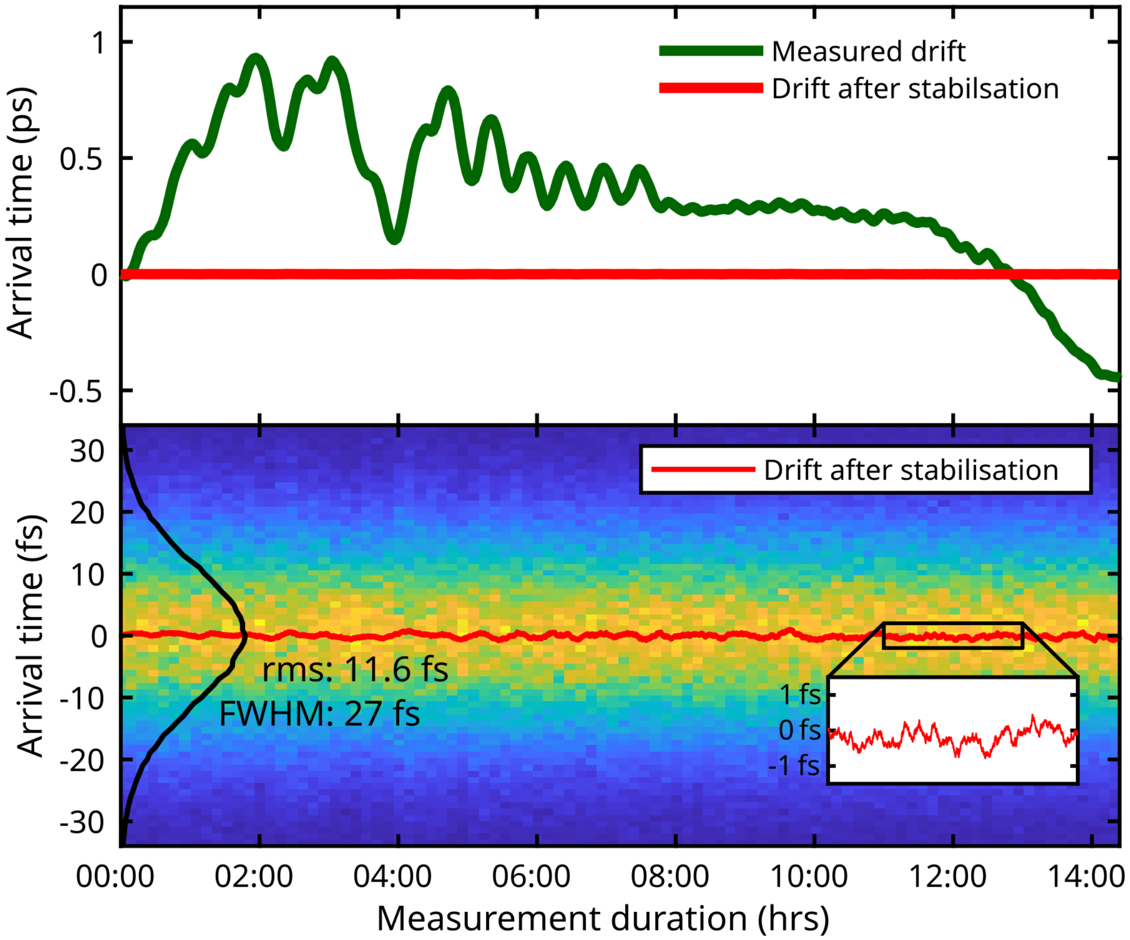
- final jitter contribution under investigation…

Atia-tul-noor *et al.*, Opt. Expr. 32, 657-6608 (2024)

Multi-Pass Cell Laser Delivery at FLASH FL23

Laser-only Arrival Time Benchmark Experiment at 1030 nm





- sketch of 2021 implementation
- 2024 measurement campaign

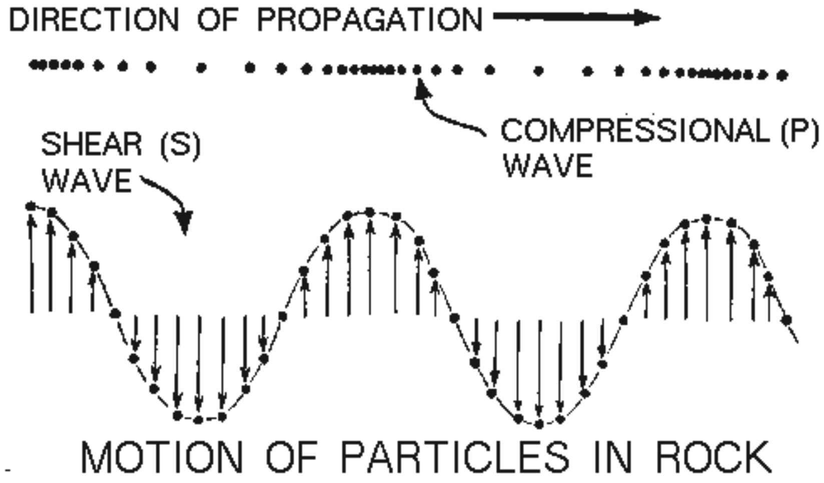
A.-L. Viotti *et al.*, J. Synchrotron Rad. 28, 36-43 (2021) | D. Schwickert *et al.*

Seismic Activity Influence

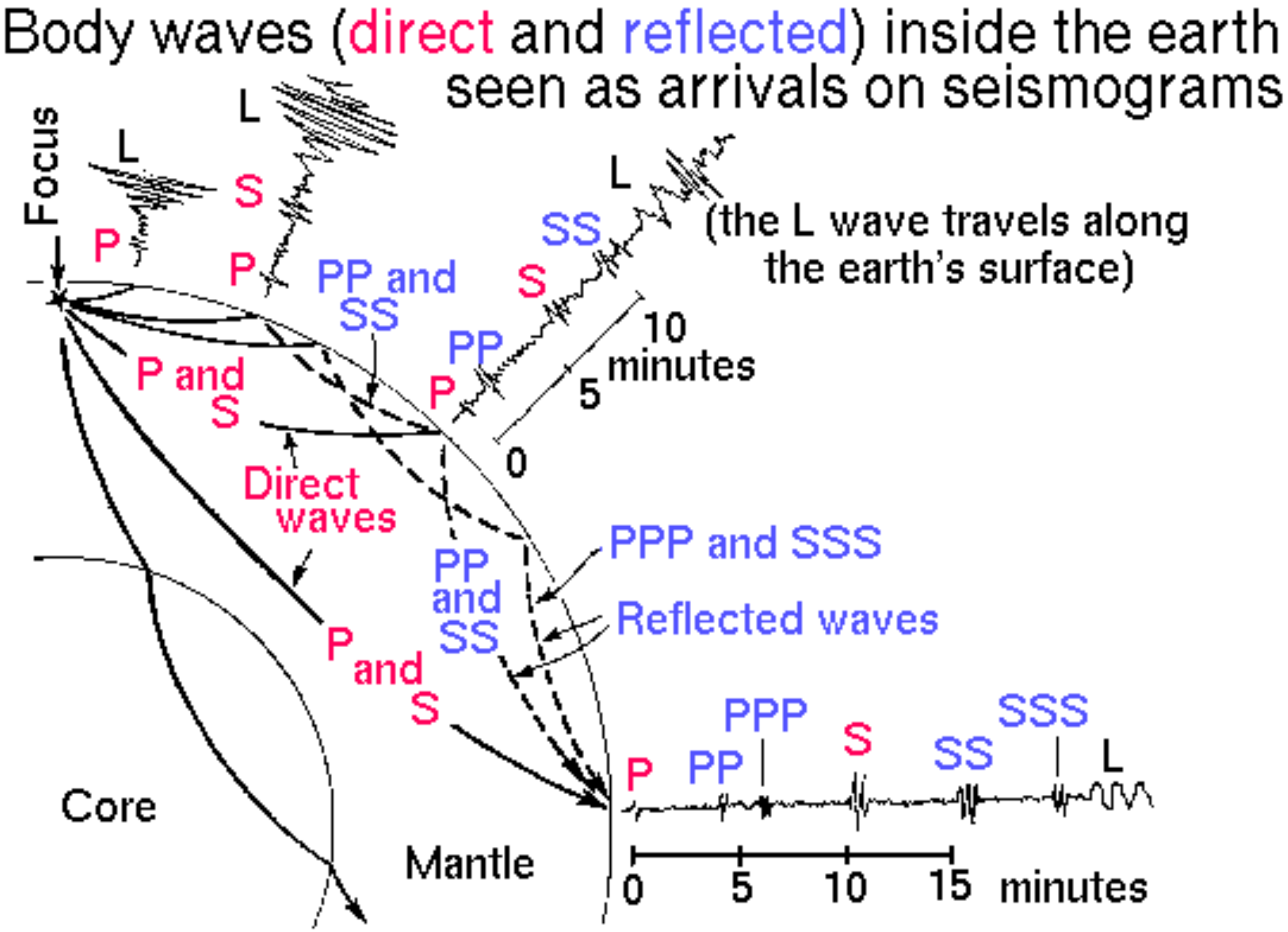
P and S Waves

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



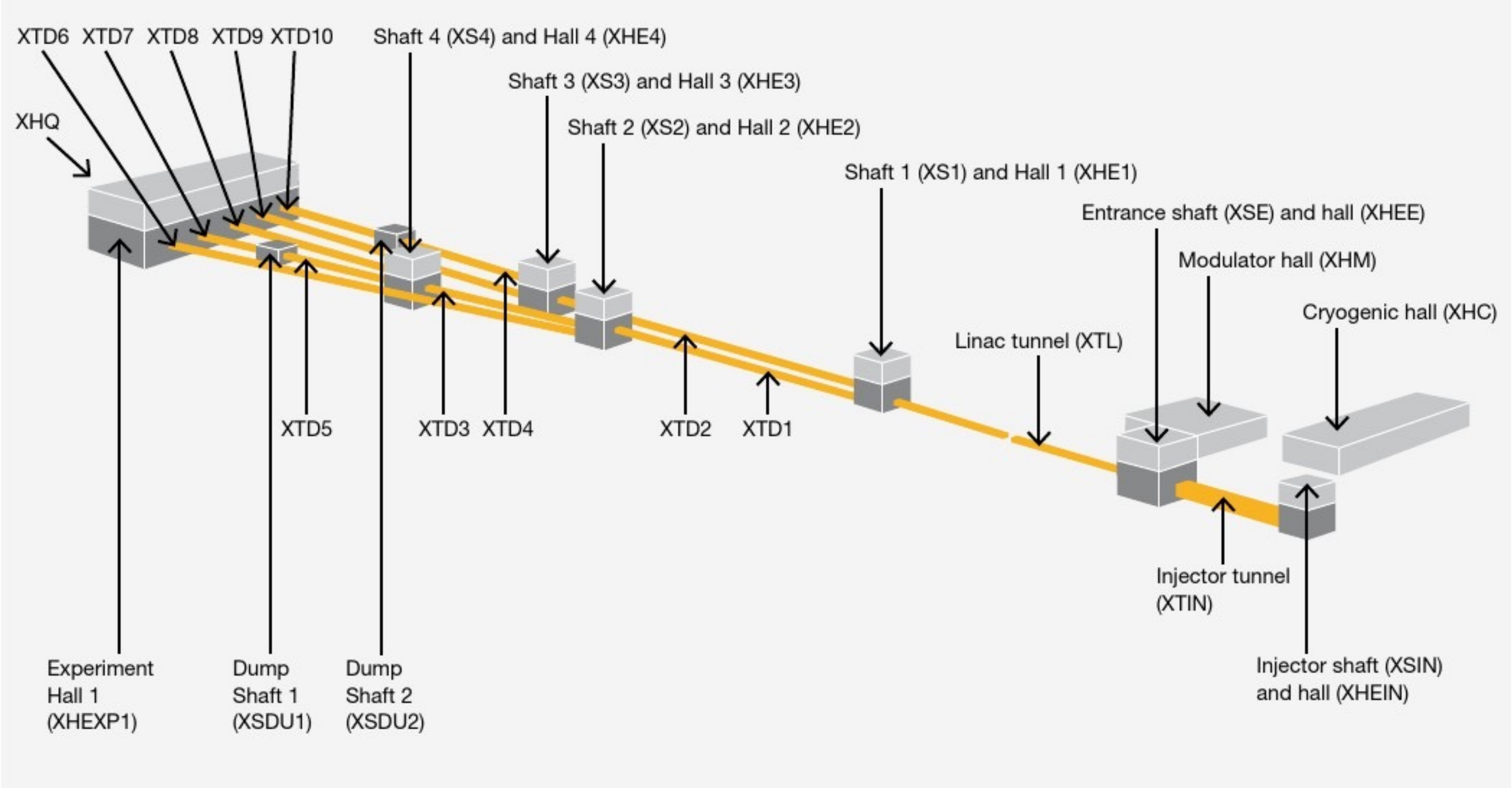
- **L** or Love wave, **R** or Rayleigh wave

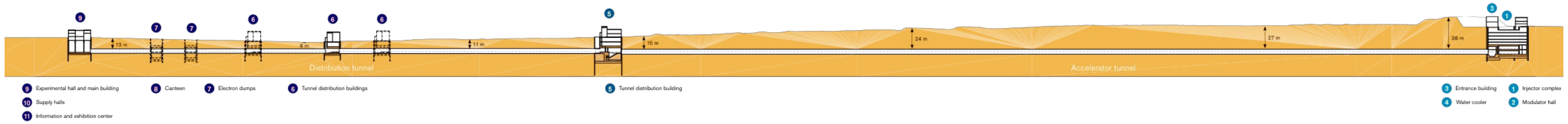


https://earthquake.usgs.gov/earthquakes/events/1906calif/18april/earthwaves.php

European XFEL Building Overview

Tunnels, Halls, Shaft Buildings

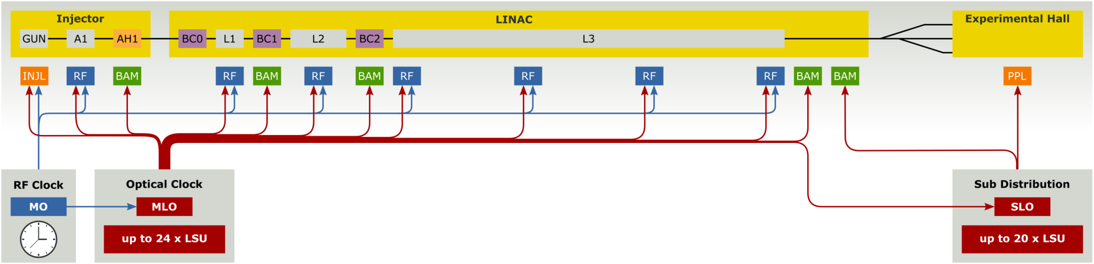


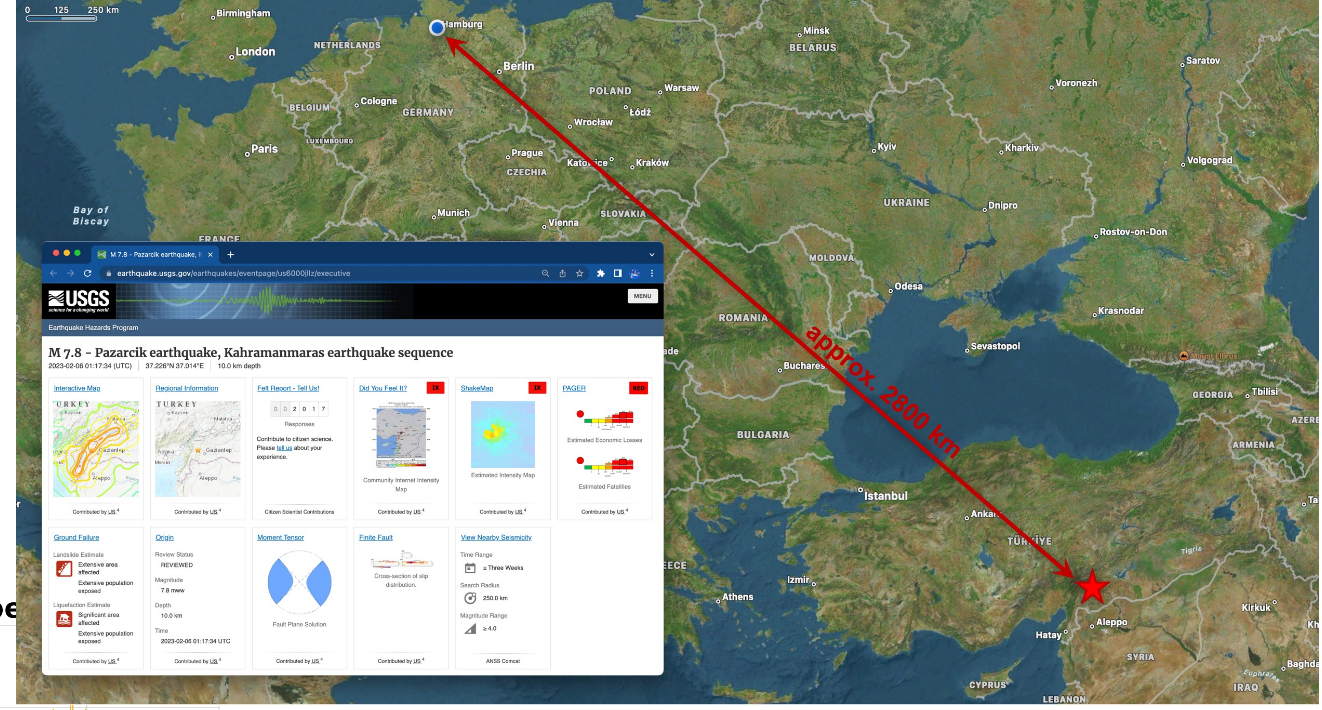


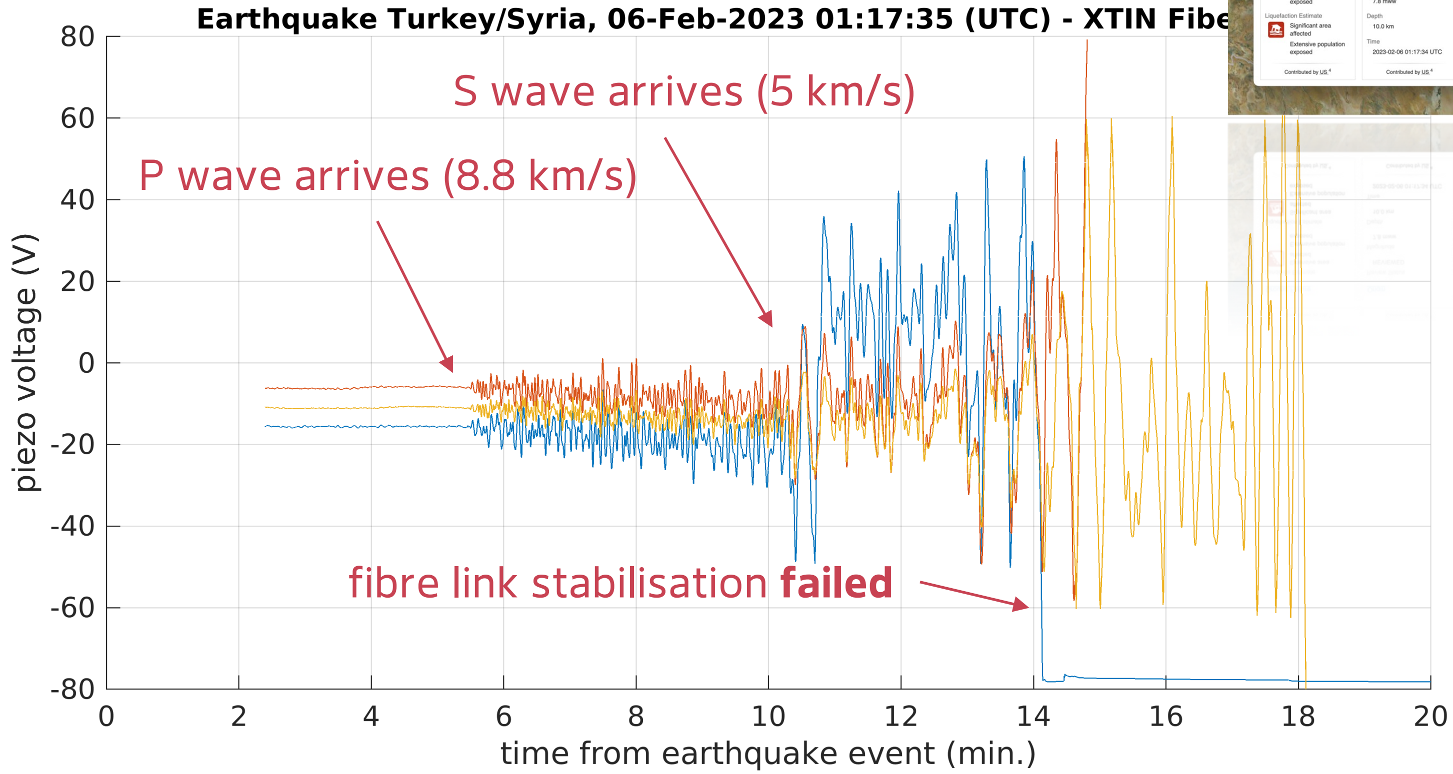
- experiment hall and shafts connected by e^- and photon tunnels
- ***synchronization labs and fibre installation***
  - horizontally in ducts (XTL), on trays (XTDs)
  - vertically on trays in shaft buildings
  - blown into quite rigid protective tubing
  - lubricant hardened over the years
- ***different routes in XTDs***

Singular Events

Fibre Link Stabilisation (Partly Failing) After an Earthquake



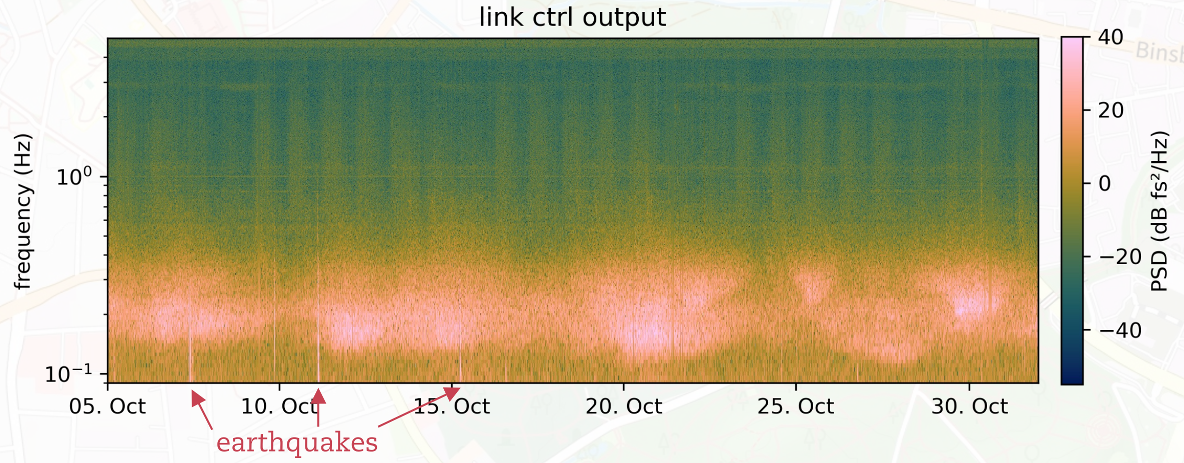




- EuXFEL has been stretched > 3 mm
- distortion visible > 1 h
- farther and weaker earthquakes detectable
- complementary DAS measurements
- started **seismological modelling of EuXFEL building dynamics**

Singular Events

Fibre Link Stabilisation Disturbance Analysis



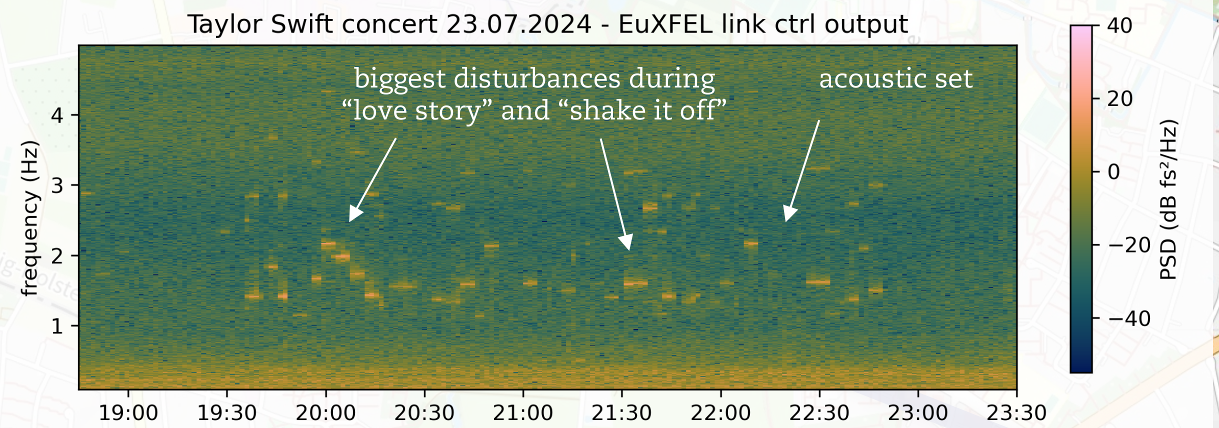
- seismic activities change the tunnel length
  - affects synchronisation **fibre length**
- sources of disturbance
  - ocean-generated microseism
  - earthquakes
  - human-made → traffic, civil constructions, concerts

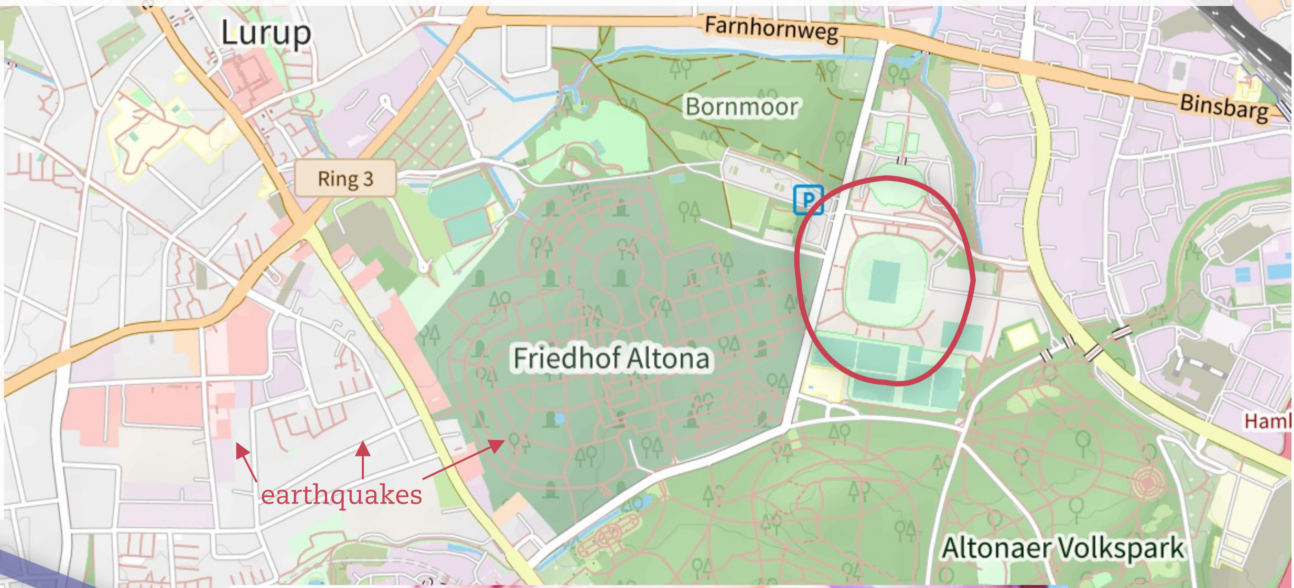
photo: Sebastian Madej, MOPO

courtesy of A. Grünhagen

Singular Events

Fibre Link Stabilisation Disturbance Analysis





- seismic activities change the tunnel length
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- sources of disturbance
  - ocean-generated microseism
  - earthquakes
  - human-made → traffic, civil constructions, concerts

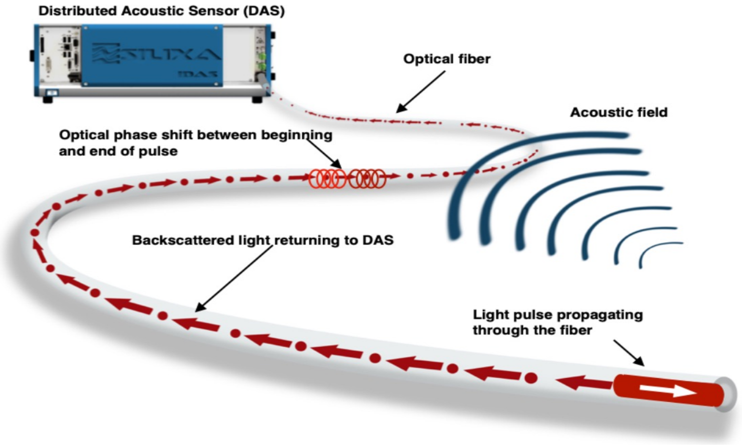
photo: Sebastian Madej, MOPO

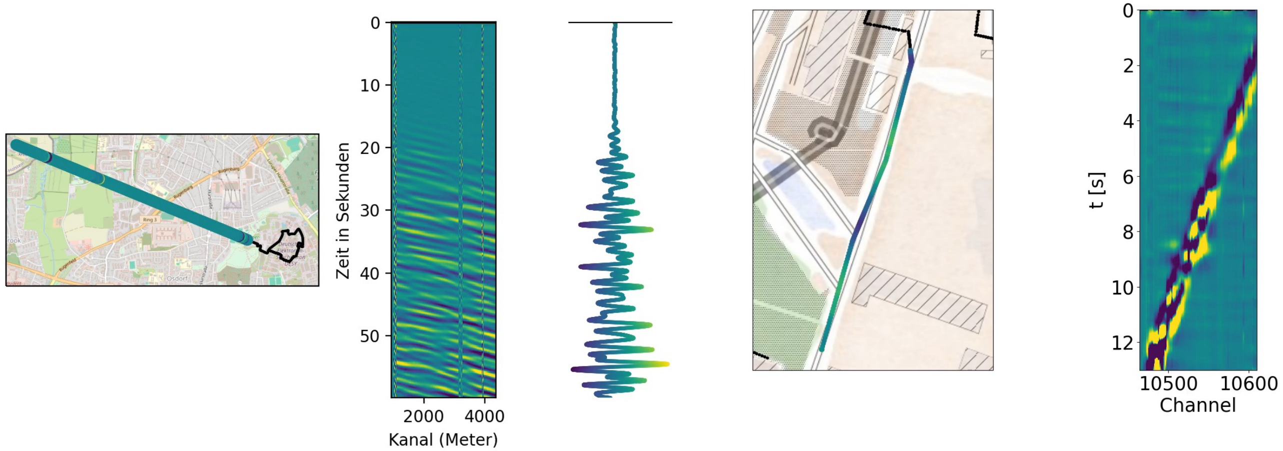
courtesy of A. Grünhagen

Distributed Acoustic Sensing

WAVE Hamburg

- **optical fibre as a sensor**
  - detect vibrations and acoustic signals along its entire length
- **light scattering and location**
  - analysis of back-scattered light to detect and locate disturbances along the fibre





- **real-time monitoring**
  - continuous detection of seismic activity over long distances (fibre length at DESY ~12 km)

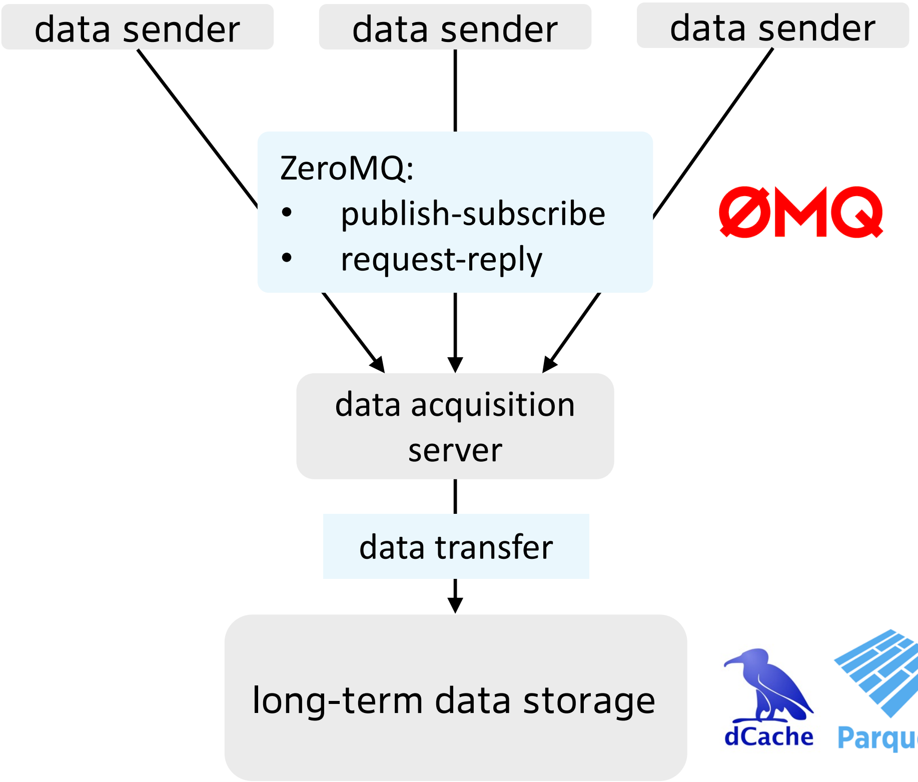
courtesy of A. Grünhagen | https://wave-hamburg.eu

Data-Driven Approaches

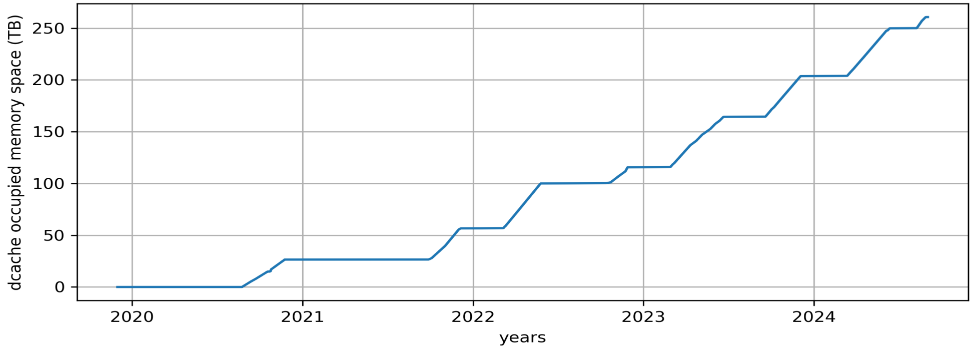
Data Acquisition and Storage

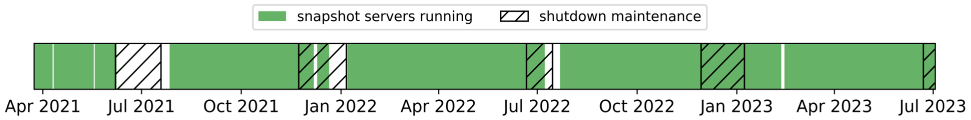
Dedicated DAQ System for the Laser-Based Synchronisation System

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



- data sources **~47000 control system channels**
  - controller I/O of all feedback systems
  - configuration
  - environment (*T*, relative humidity, air pressure)
- volume **~250 TB** since 2021
  - 10 Hz acquisition rate
  - daily 10-second long snapshots of “fast” data

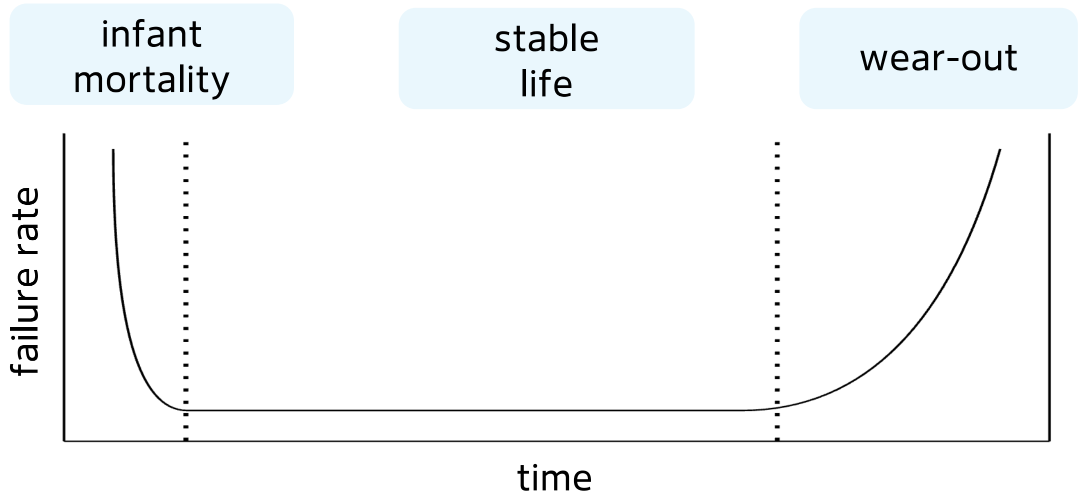




courtesy of A. Grünhagen

Data-Driven Condition Monitoring

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



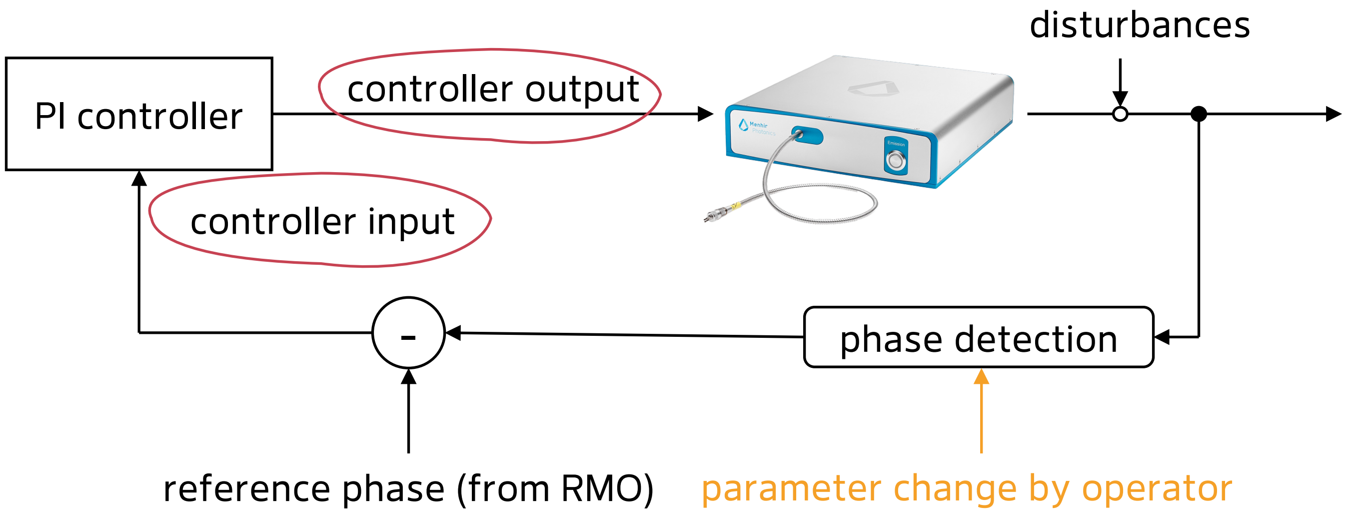
- infant mortality phase
  - manufacturing defects, installation issues
- stable life phase
  - low and stable failure rate, random/unexpected failures due to sudden, not age-related events
- wear-out phase
  - aging effects, components wearing out

- **reliability**
  - early fault detection, consistent performance, extended lifespan
- **availability**
  - minimisation of unplanned downtime, avoidance of unnecessary maintenance activities
- **data sources**
  - analysis of both fast and slow data

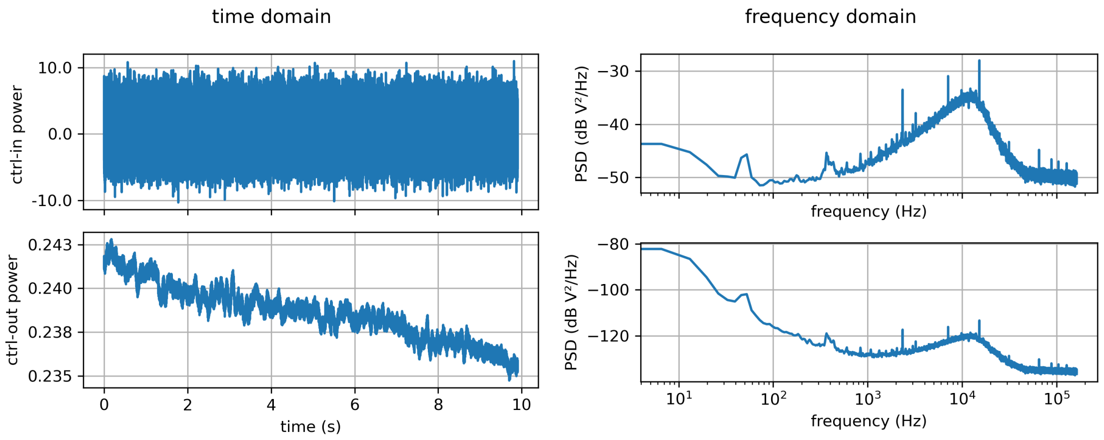
courtesy of A. Grünhagen

Main Laser Oscillator PLL Signal

Fault Analysis



- 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
…	…

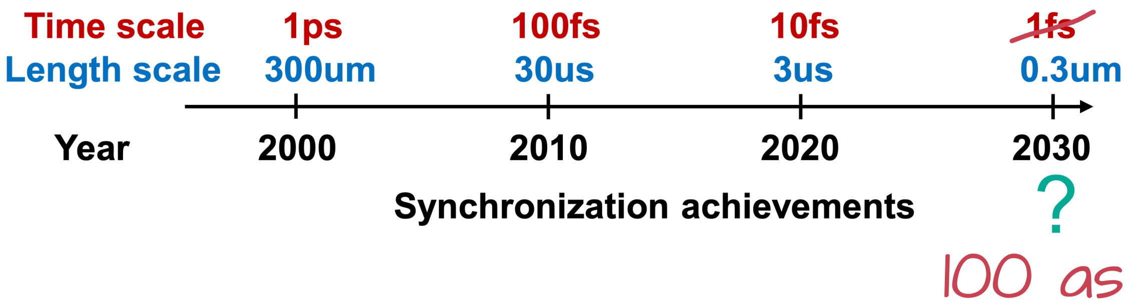
courtesy of A. Grünhagen

Conclusion

Latest Achievements … Based on a Solid Foundation

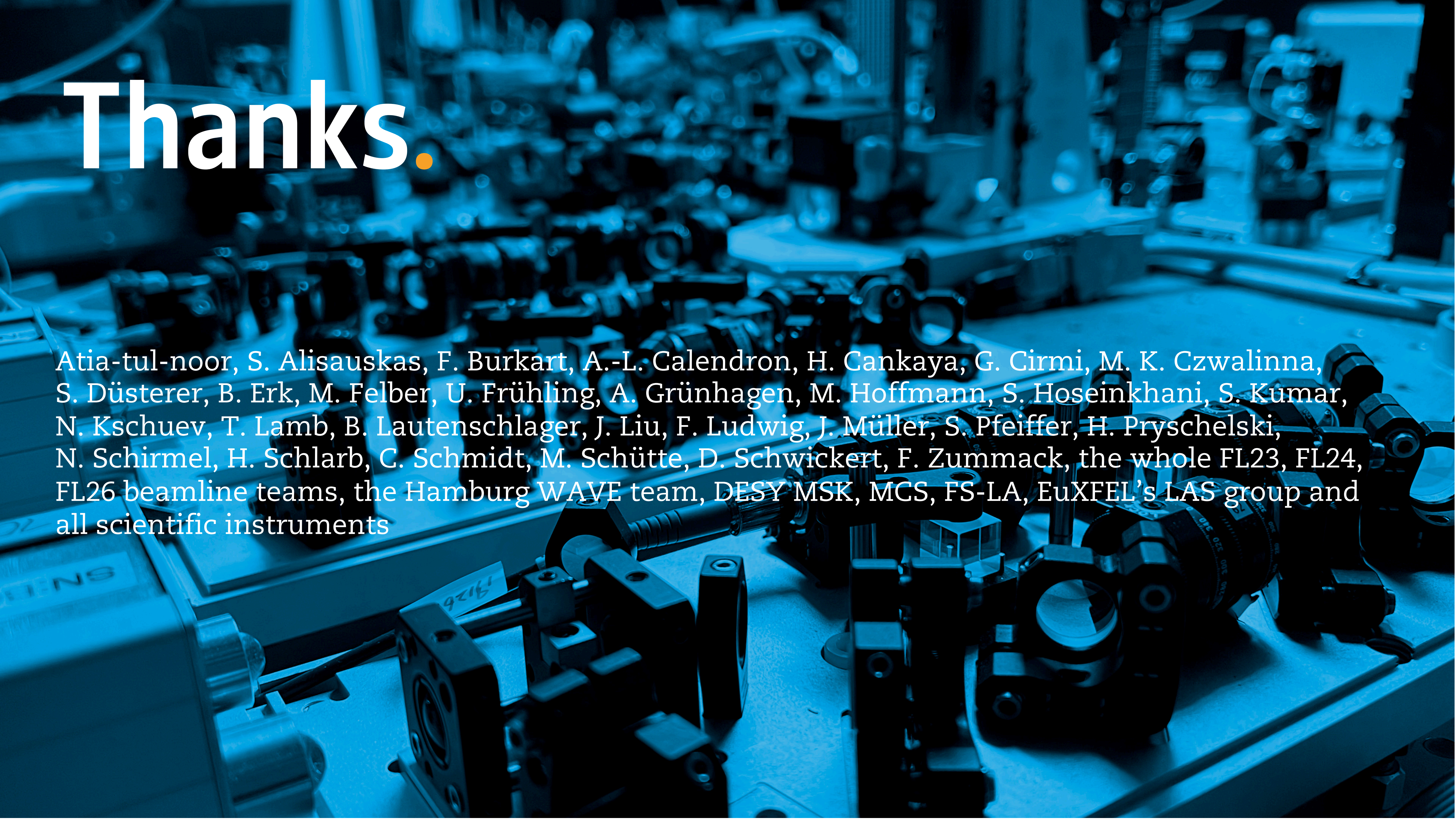
- foundations laid out 10-ish years ago
- improved performance
  - laser-to-RF synchronisation
  - electron bunch arrival time **FB**
- novel techniques and approaches rising
  - laser-pulse arrival time monitoring → FB, sorting
  - electron bunch arrival time **FF** → PP within a burst
  - machine learning, e.g. fault prediction
- novel problems and issues
  - ocean waves and other seismic activity
- learning curve: **communication with photon science people and users, as well as laser guys**

- LAM and user-delay control
- attosecond optical laser / e^- / X-ray timing jitter
- further data-driven and AI approaches
- another tutorial in 10 years?



- **learning from and teaching other facilities all around the globe!**

Thanks.



Atia-tul-noor, S. Alisauskas, F. Burkart, A.-L. Calendron, H. Cankaya, G. Cirmi, M. K. Czwalinna, S. Düsterer, B. Erk, M. Felber, U. Frühling, A. Grünhagen, M. Hoffmann, S. Hoseinkhani, S. Kumar, N. Kschuev, T. Lamb, B. Lautenschlager, J. Liu, F. Ludwig, J. Müller, S. Pfeiffer, H. Pryschelski, N. Schirmel, H. Schlarb, C. Schmidt, M. Schütte, D. Schwickert, F. Zummack, the whole FL23, FL24, FL26 beamline teams, the Hamburg WAVE team, DESY MSK, MCS, FS-LA, EuXFEL's LAS group and all scientific instruments

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Supplementary Material

Terminology / Glossary I

Wording Across the Globe…

- **BAM** (Electron Bunch Arrival Time Monitor): apparatus to measure the arrival time of the electron bunch with respect to an optical pulse train based on electro-optic sampling of the transient electric field induced in a high-frequency pickup antenna installed in the beam pipe.
- **BCC** (Balanced Cross-Correlator), **BOC** (Balanced Optical Cross-Correlator), **OXC** (Optical Cross-Correlator): normally refers to the optical implementation of a scheme based on nonlinear optical cross-correlation and usually realized in a balanced, i.e. amplitude fluctuation insensitive way. Depending on the specific implementation, application or related feedback systems, the acronym is extended, as in **TC-BOC** (Two-Color BOC), **cmBCC** (Common Mode BCC), **dmBCC** (Differential Mode BCC), **SysDC** (System Drift Correlator). The foundation of the **LAM** is also the balanced cross-correlation scheme. The acronym OXC is not to be confused with OCXO (Oven-Controlled Crystal Oscillator), which refers to a term in the RF domain.
- **FSD** (Free-Space Distribution): refers to the optical setup to split and distribute the laser beam of the MLO to the individual LSUs, either realized in a TSP or inside a actively and passively designed environmentally very stable lab. Alternatively, splitting can be realized using optical fibre couplers.
- **LAM** (Laser Pulse Arrival Time Monitor): opto- electronic implementation of an apparatus to measure the relative arrival time between two optical pulse trains, being usually the one of the pump-probe laser with respect to an optical reference and based on an OXC, with the goal to measure or provide feedback to stabilize the laser pulse arrival time. Depending on the context, either the whole implementation or only the optical part is referred to.
- **LSU** (Link Stabilization Unit), **FLS** (Fiber Link Stabi- lizer): opto-electronic device to measure and compensate for changes of an optical fiber. Depending on the context, only the optical (i.e. mainly the optical cross-correlator), only the actuator part or the whole implementation is referred to.
- **MLO** (Main Laser Oscillator), or **OMO** (Optical Main Oscillator): in pulsed optical synchronization systems, this oscillator provides the train of laser pulses with approx. 200 fs duration, where its repetition rate provides the timing reference for all connected subsystems.
- **MO** (Main Oscillator), or **RMO** (RF Main Oscillator): The main radio frequency oscillator of the accelerator facility.

Terminology / Glossary II

Wording Across the Globe...

- **ODL** (Optical Delay Line): device to precisely control and delay the arrival time of an optical laser pulse train. Depending on the implementation, an **FDL** (Fiber Delay Line) might be employed, where e.g. an optical fibre is altered in length by varying its temperature (**TC-FDL**, Temperature-Controlled FDL).
- **PAM** (Photon Pulse Arrival Time Monitor), or **ATM** (Arrival Time Monitor): apparatus to measure the relative arrival time of a XUV or X-ray pulse with respect to an optical reference pulse. Numerous implementations of PAMs are deployed across the different accelerator facilities, where normally the pump-probe laser serves as reference. However, also the reference pulse train of the optical synchronization system is used in specific applications.
- **PFTS** (Pulsed Fiber Timing System): mainly at LCLS, this term is used for the synchronization system based on a pulse optical laser oscillator as MLO. Note that other facilities use the term ”timing system” also for the less precise, i.e. not with femtosecond resolution and stability, distribution of clock and trigger signals.
- **TSP** (Temperature Stabilized Platform): In some implementations, the core components of the synchronization system (MLO, splitting, LSUs, ODLs) are installed in this well temperature and humidity controlled enclosure.

DESY: "Hey, look at our (femtosecond) synchronisation system, based on an MLO, locking lasers with OXCs!

SLAC: "Cool, that's like our Pulsed Fiber Timing System, it has an OMO and TC-BOCs!"