Femtosecond Synchronization of Large Scale FELs
– Achievement, Limitations and Mitigation Paths –

FLS 2023

Holger Schlarb on behalf of the LbSync, Special Diag. and LLRF team at DESY
Lucerne, Switzerland, 30th of August 2023

- **Introduction**
- **Why precision synchronization & Sources of timing jitter**
- **Optical synchronization – achievements / mitigation**
- **Conclusion**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Introduction

Time & length scales:

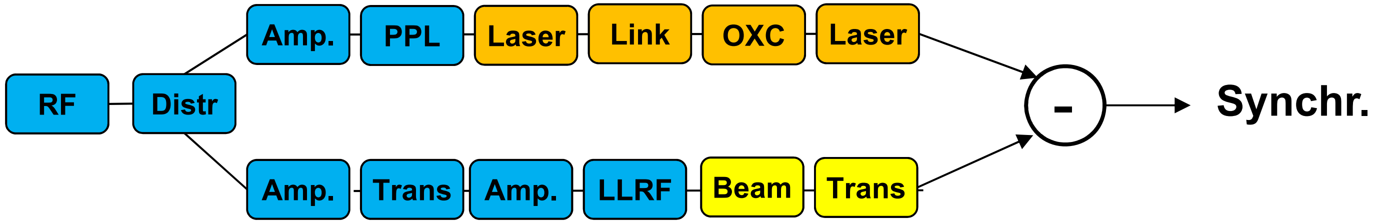
Time scale	1ps	100fs	10fs	1fs
Length scale	300um	30us	3us	0.3um
Year	2000	2010	2020	2030

Synchronization achievements ?

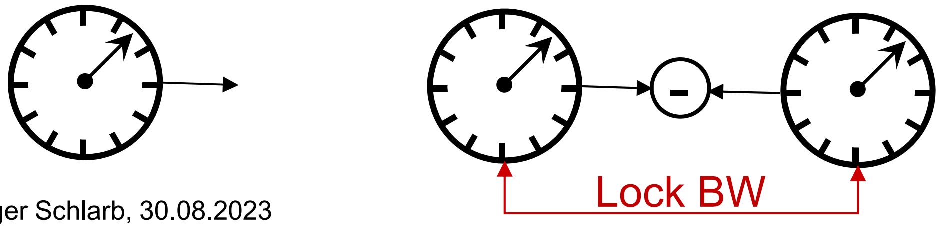
Duration matters!

Short range	1us … 1ms:	PS, EMI, Electronics, Material Prop., …
Mid range	1ms … 10s:	Acoustic, Seismic, Air/Water flow, Fans, …
Long range	10s … days:	Thermal, Humidity, Air Pressure,…

Long chains of devices:

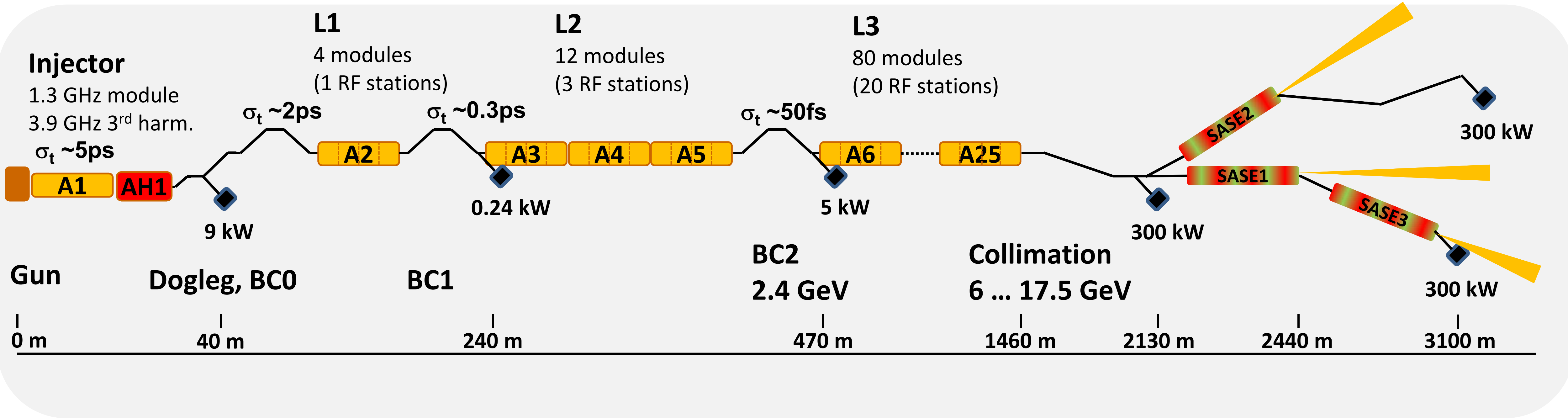


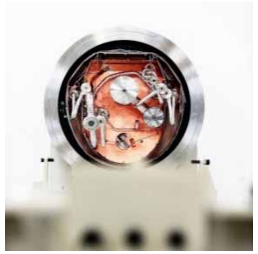
Absolute & relative timing jitter:



European XFEL
Schematic layout







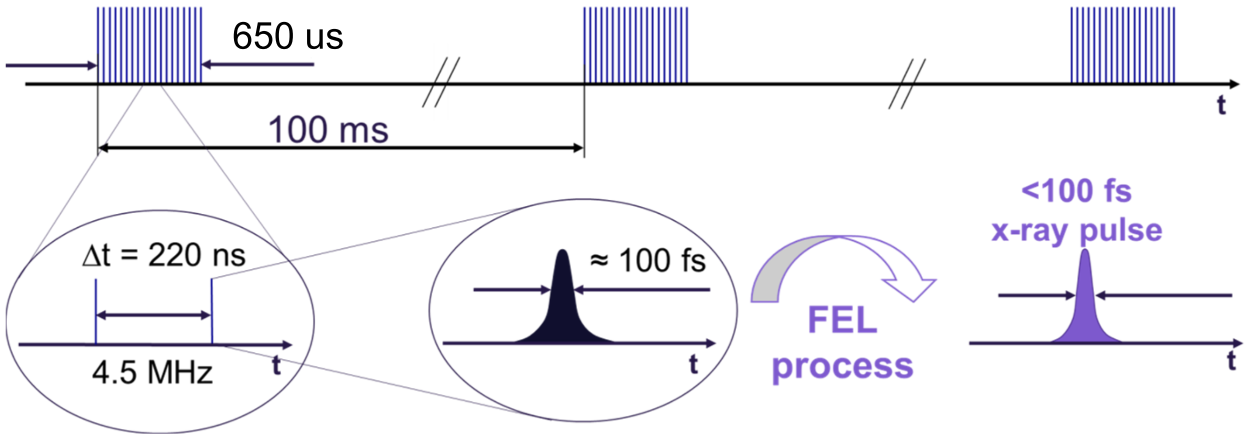


SASE 1/2 : 3.0 – 25 keV
SASE 3 : 0.3 – 3 keV

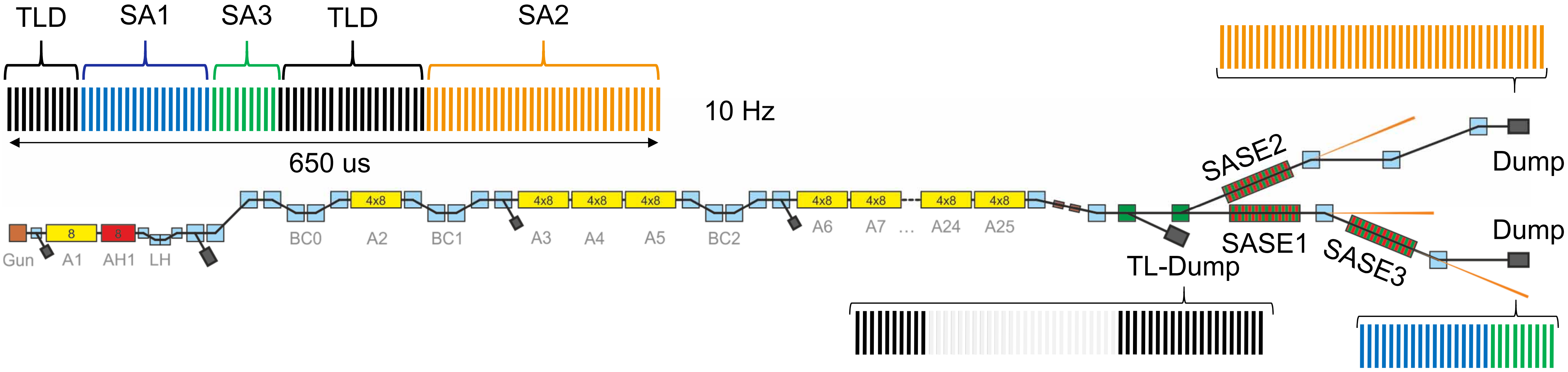
European XFEL

Time structure & multiple beamline (SA1/SA2/SA3)

- Pulsed operation (RF ~ 1.4ms, 10Hz)
  - ➔ 27000 / sec
  - ➔ e- bunches 220ns spaced
  - ➔ 100ms separation



- Switchyards
  - Fast Kicker System
  - Precise (Slow) Flat-Top Kicker

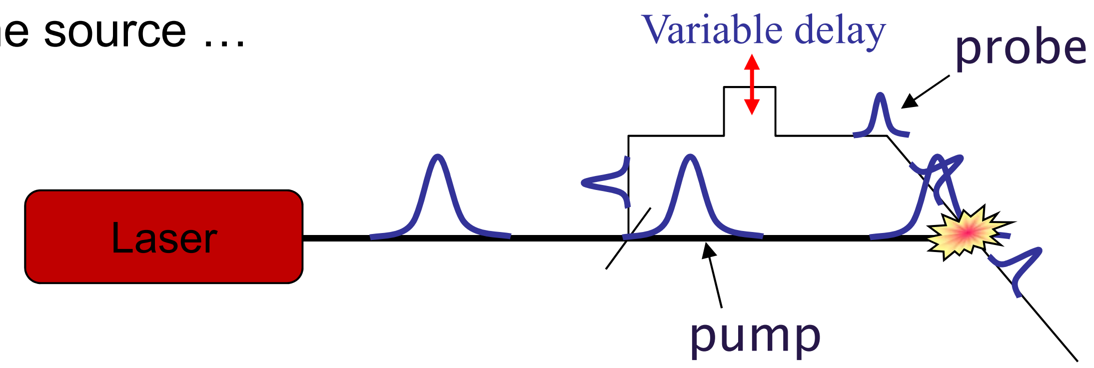


Why precision Synchronization?
&
Source of timing jitter

Source of timing jitter for FELs

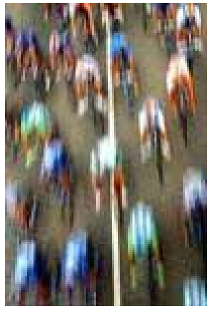
Pump-probe experiments

- Same source …



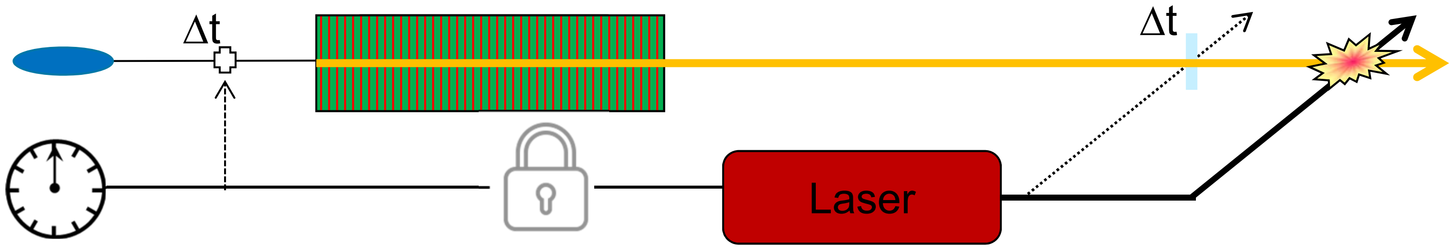
Pump

Probe = flash



Shot pulses fs ⟵ ps

- FELs: disjunction source



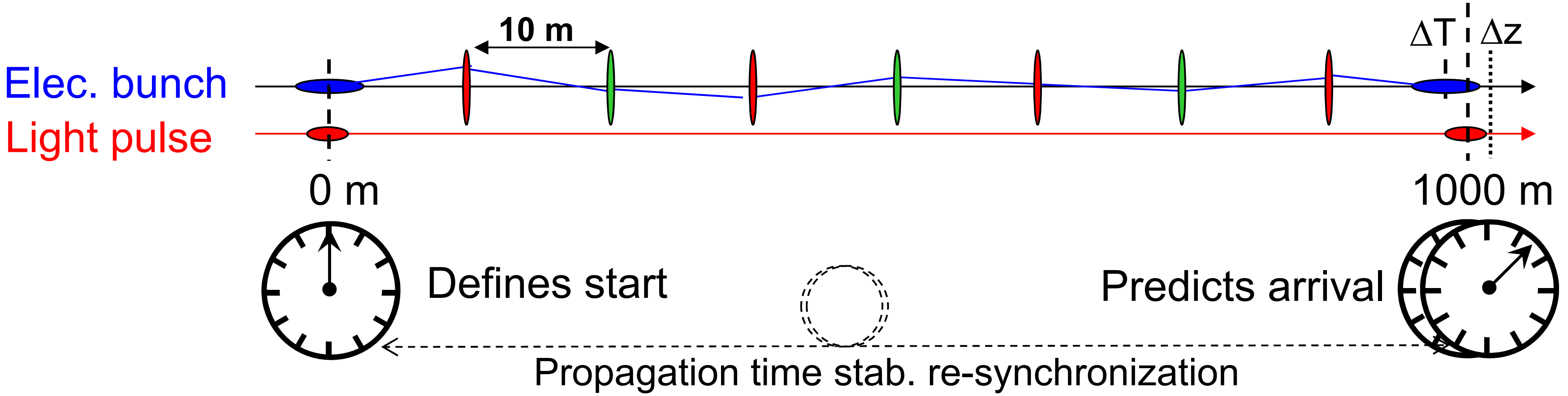
Precision: depends on experiment
Ideally: jitter < pulse durations

But: post-sorting often also possible!

- Post-sorting become problematic if:
  - ➢ Special timing requirements in experiment
  - ➢ 3rd independent source involved
    (laser→e$^-$ mani. / e$^-$ driven THz source / …)
  - ➢ Low interaction rates / cross-sections
    (HIBEF / dilute targets / aver. detectors)

Source of timing jitter for FELs

Straight sections … energy … ground motion



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

E = 1 GeV

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

ΔT = 435fs

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 100nm	➔	$\delta t < 1$ fs	(😐)
Ground motion/relocations:	$\delta z \sim \ldots 10\ \mu m$	➔	$\delta t \sim \ldots 30$ fs	(☹) (slow, may predictable…)

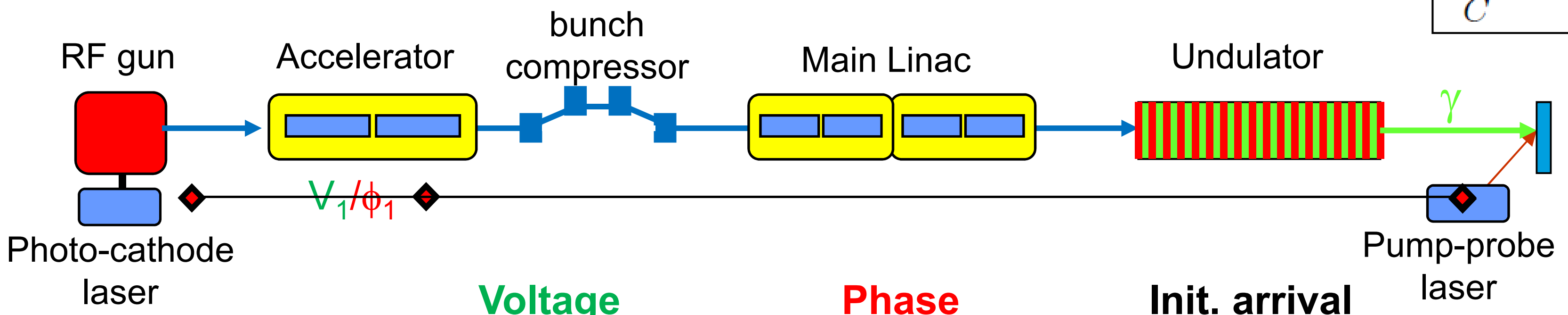
Source of timing jitter for accelerators / FELs

Magnetic e-bunch compression impacts:

Compression factor C:

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

a) RF acc. fields defines arrival



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 $E_0 \ll E_1$ and $E_0' \ll E_1'$
(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

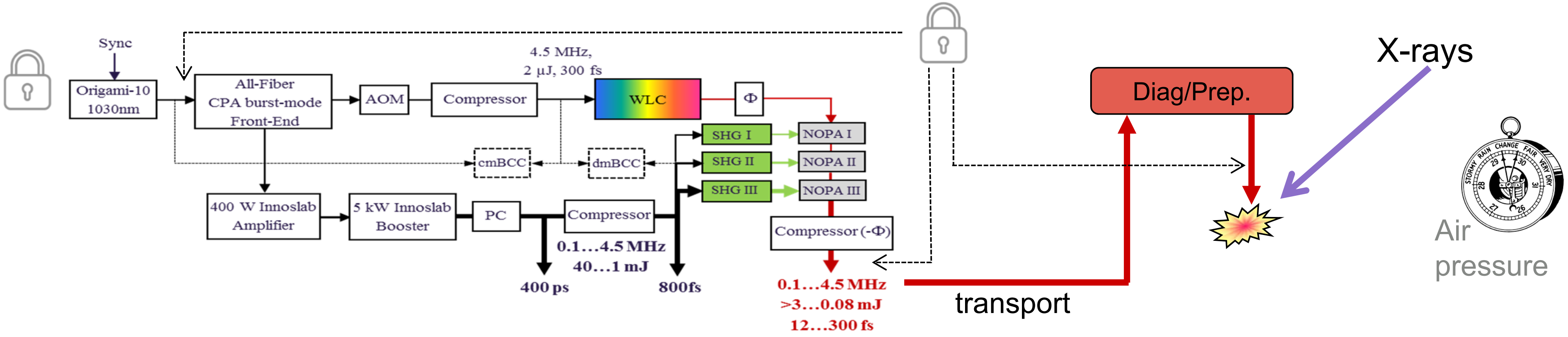
Phase & Init. arrival **Voltage**

Conclusions:
- Use multiple compressors
- RF field control is critical
- RF reference vs PP-laser closely locked

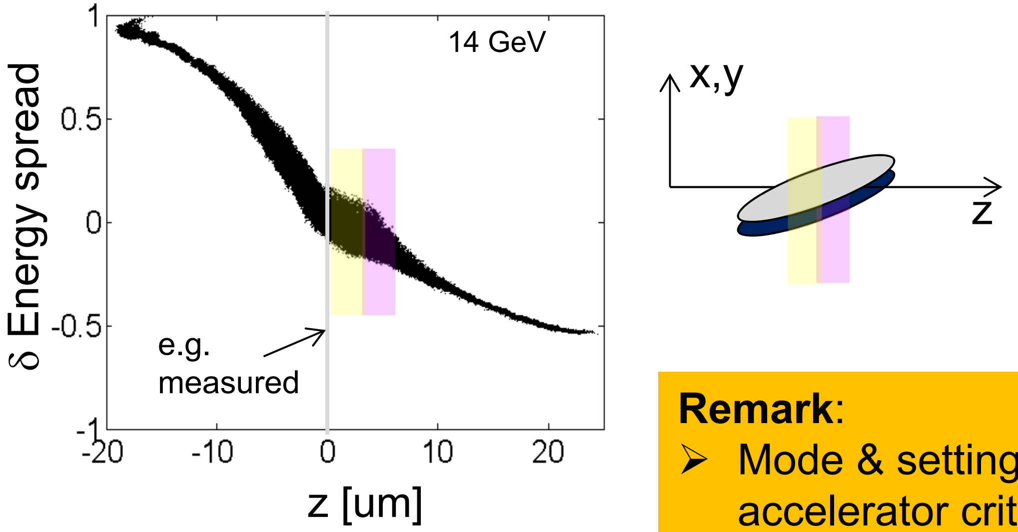
Source of timing jitter for FELs

Additional time jitter sources …

- **Laser systems**



- **Spatial - longitudinally distortion in electron beam**



Remark:
- ➢ Mode & setting of accelerator critically influences timing jitter

- **SASE fluctuations**

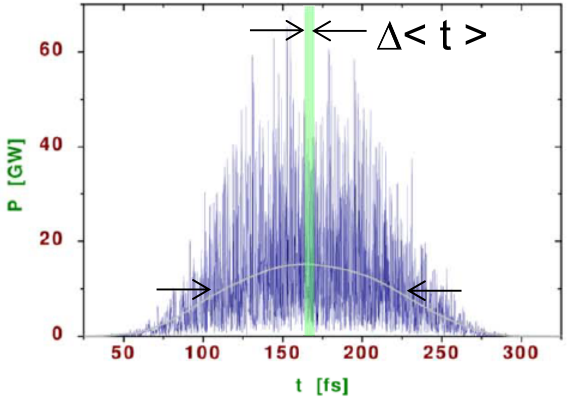


Image: Schneidmiller/Yurkov

$\Delta<t>$ ~ pulse width σ_t

$\Delta<t>$ ~ 1/M (or $1/\lambda_{ph}$)

will depend on saturation (tails start to lase…)

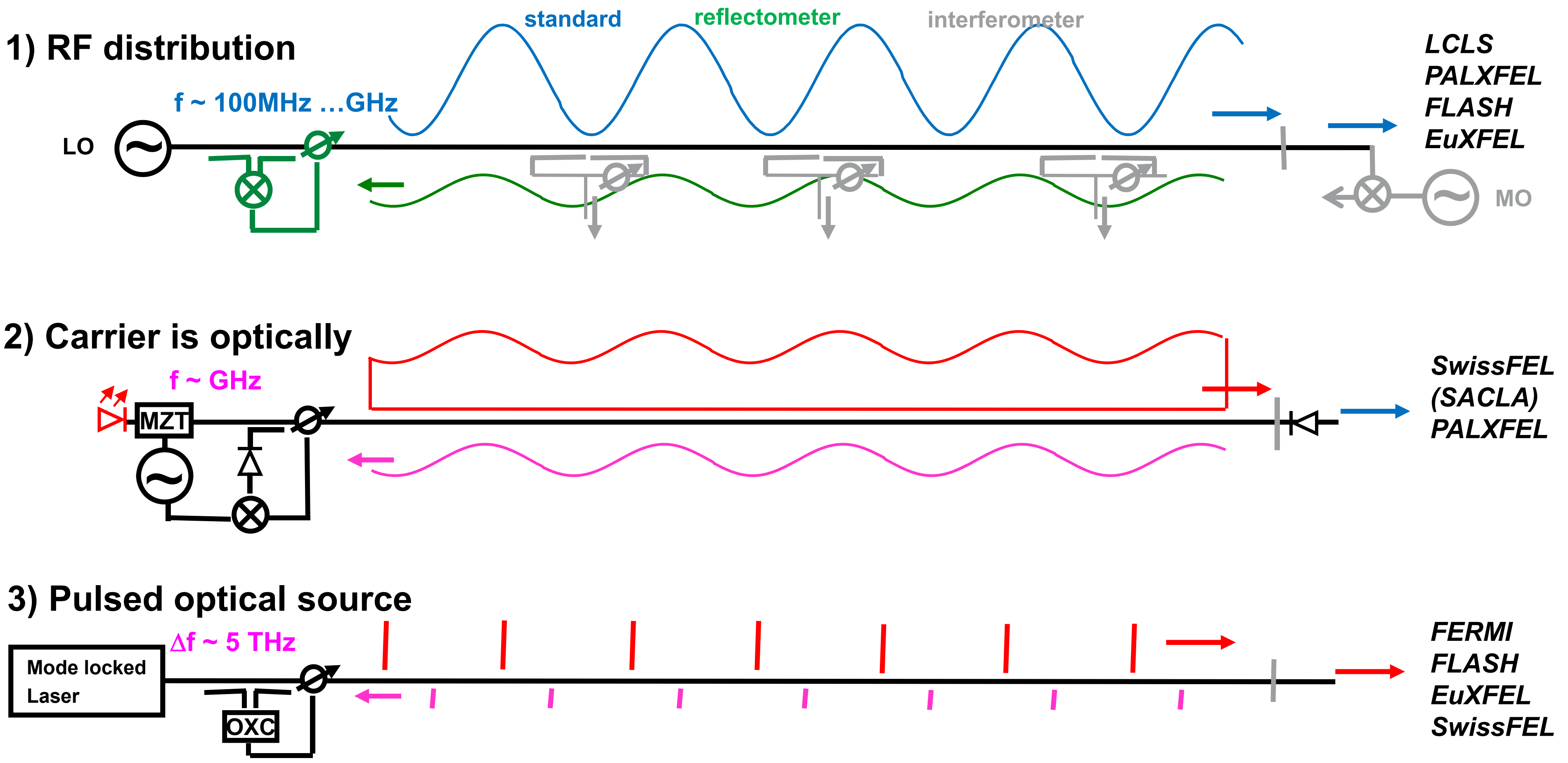
EuXFEL ~ 0.3 fs

Optical Synchronization System at European XFEL

Different synchronization approaches

Various approaches:

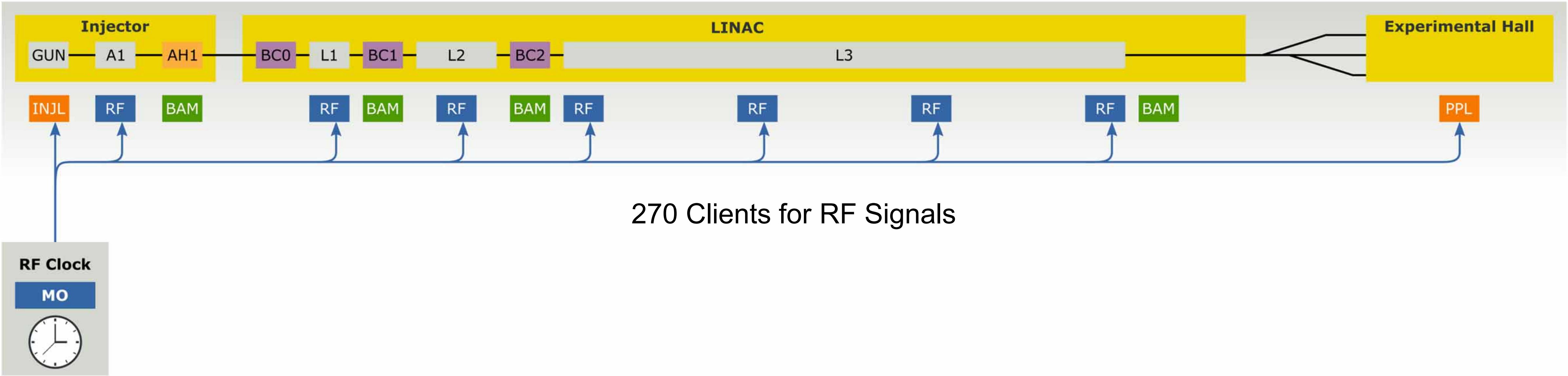
$$\frac{\Delta t}{t} = \frac{\Delta f}{f}$$



First proposed: J. Kim et al. Proc. of FEL2004 conf., 339-342 (2004)
Overview: M. Xin et al. Light: Science & Applications (2017) 6, e16187;

Optical Synchronization System at EuXFEL

World-wide Unique Large-Scale 24/7 Operation

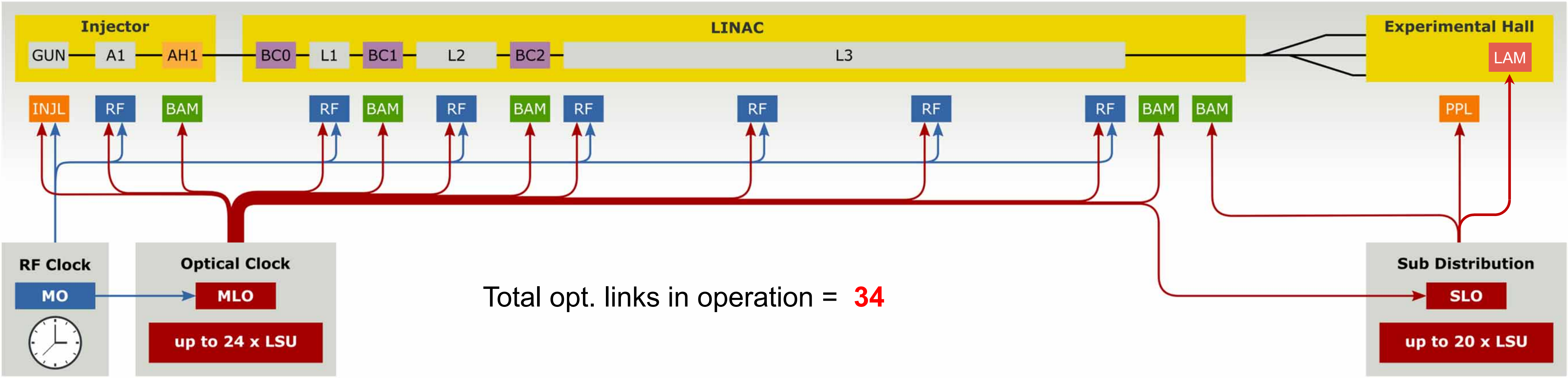


- **Availability:** RF mature technique, 24/7
- **But:**
  - **Cable drift**: ~10 fs/m/K → **35 ps/K** (3.5 km)
  - **Cable losses**: ~0.03 dB/m → **~100 dB** (3.5 km) → amplification adds drift/jitter
  - RF signals susceptible to **EMI**

➔ **Laser synchronization** – ultimate performance only with optical methods

Optical Synchronization System at EuXFEL

World-wide Unique Large-Scale 24/7 Operation

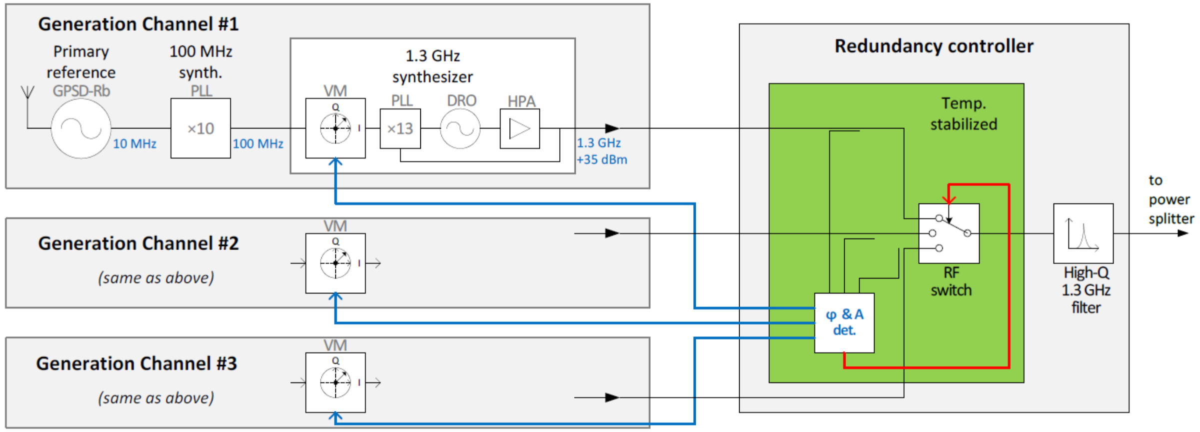


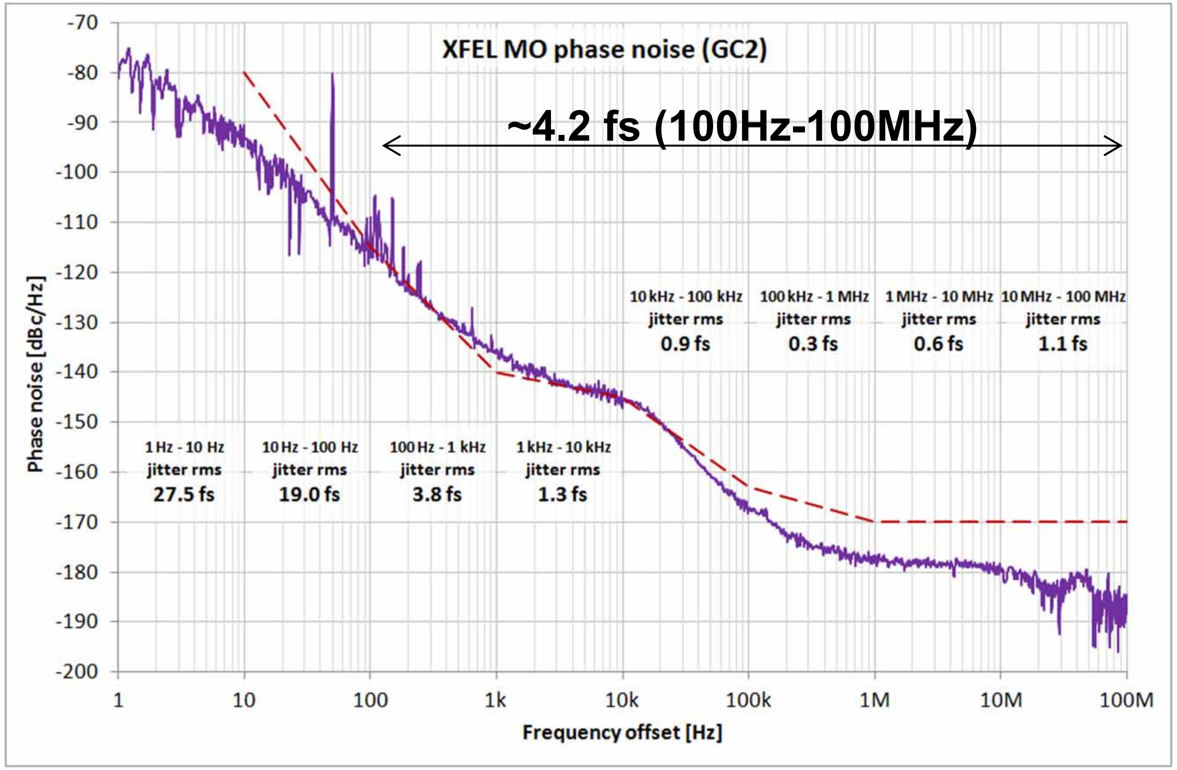
- **optical reference** (Main Laser Oscillator, MLO) tightly locked to RF Main Oscillator (MO), **distributed via length-stabilized optical fiber links** and used for
  - **Laser locking** (injector, pump-probe, …)
  - RF re-synchronization (**REFM-OPT**)
  - Bunch Arrival time Monitors (**BAM**)
  - Laser-pulse Arrival time Monitors (**LAM**)

RF Main Oscillator (MO)

Design

- phase stability of 10^{-11} by locking to GPS
- 100 MHz OCXO
- 1.3 GHz DRO
- 24/7 operation, 3 redundant setups





Courtesy: H. Pryschelski

Main Laser Oscillator (MLO)

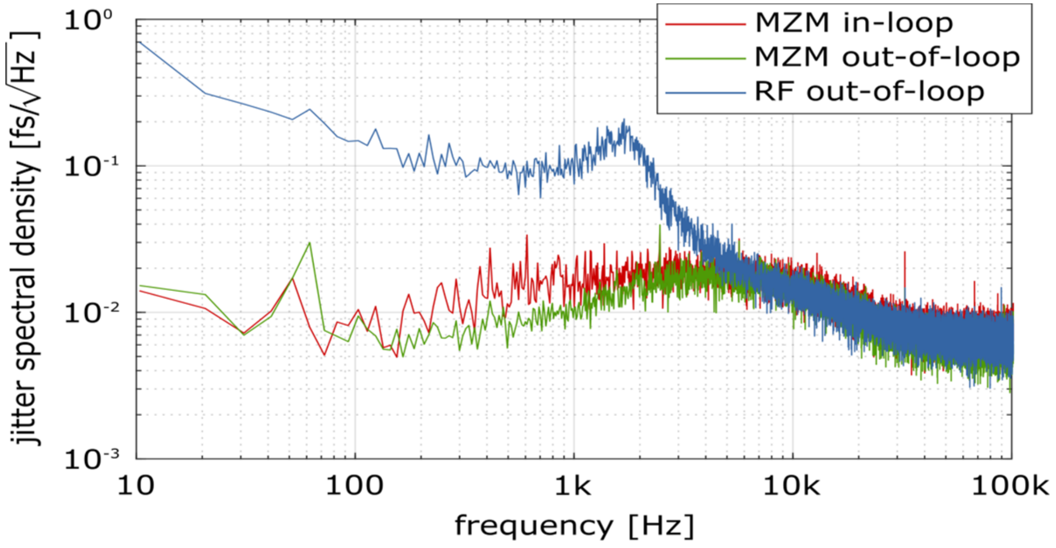
The Main Optical Reference

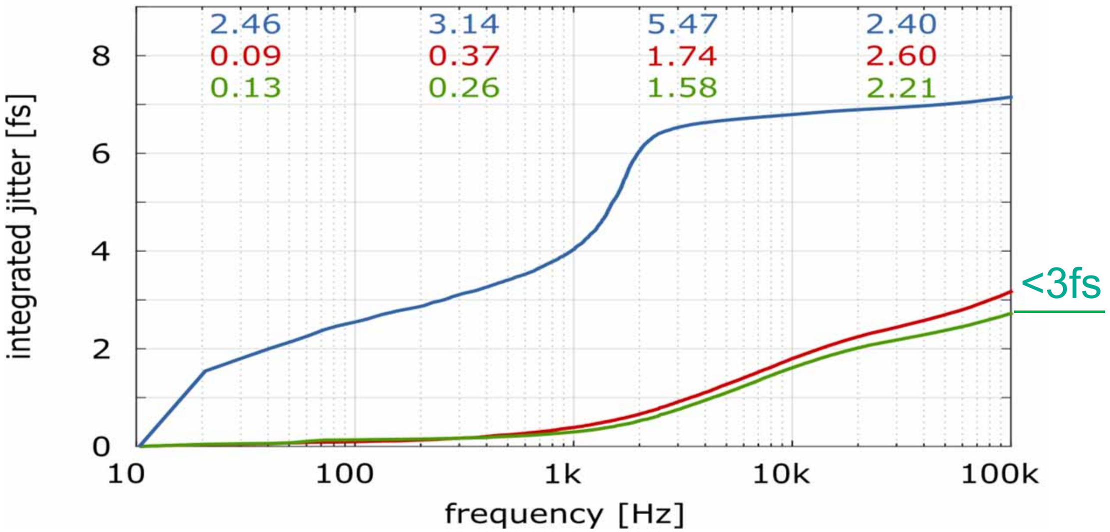
Oscillator

- commercial osc.
- **216 MHz** → 1.3 GHz / 6
- Ultra-low phase noise, 1550 nm
- **24/7 operation**
- 2 MLO installed for redundancy, fast switching

Laser-to-RF synchronization

- Locked to RF MO
  - amplitude insensitive locking scheme
- Low-noise (~**3 fs rms**)
- Low-drift **(< 2 fs pkpk, 1 week,** out-of-loop MZM)





Courtesy: T. Lamb

Free-Space Distribution

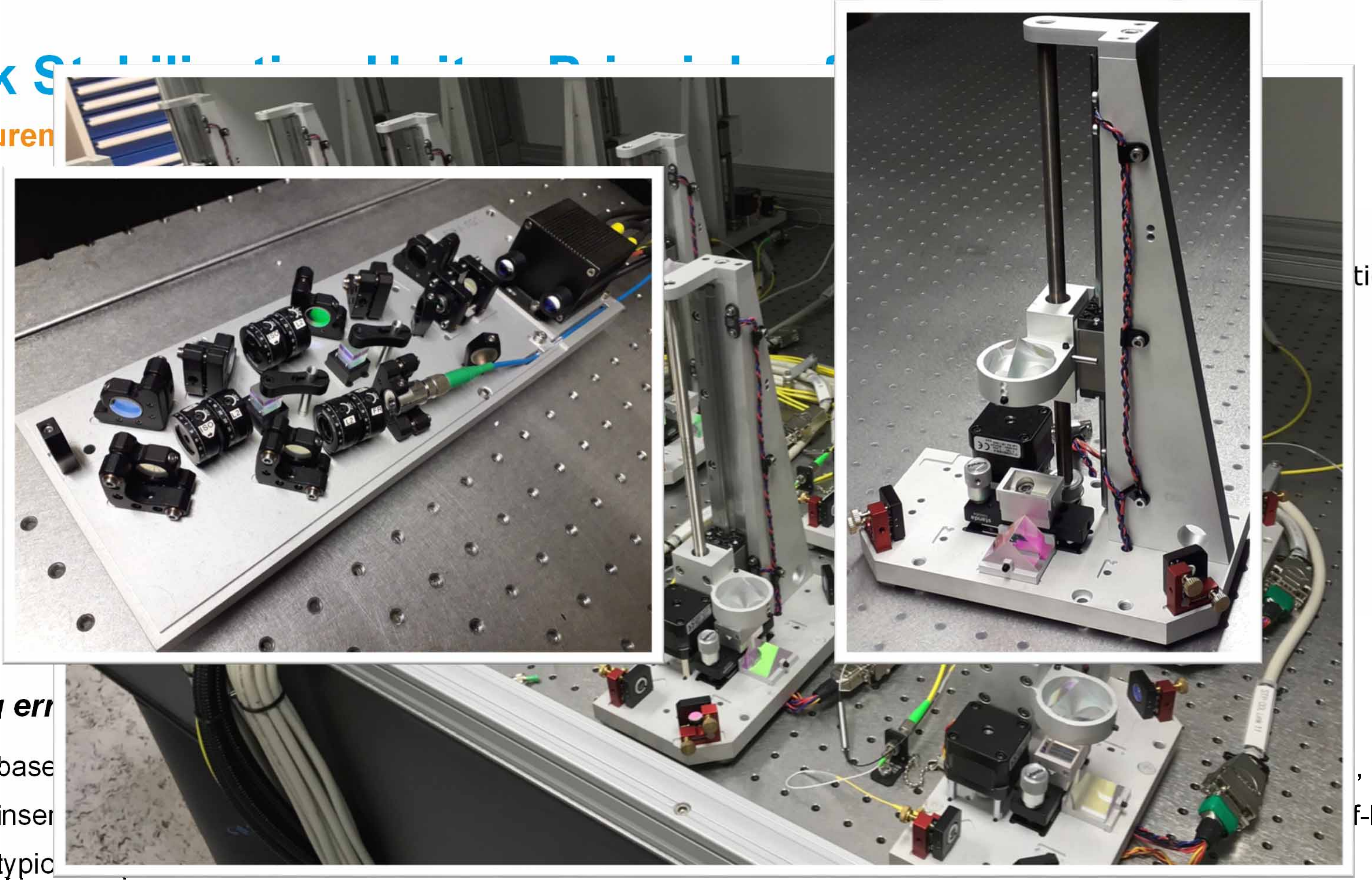
Laser Beam Distribution for 24 Fiber Link Stabilization Units

- **SuperInvar** optical table
  - thermal expansion coefficient ~1 fs/m/K
  - table covered and environmentally stable
  - ≪ 0.1 K temperature stability
  - < 1 % RH pkpk
- Space for **24 link stabilization units**
  - identical path lengths, symmetric setup
- 8 fiber links with **4 ns optical delay stage**
  - arbitrary timing possible for BAM operation

Courtesy: J. Mueller

Link S

Measuren



tion

timing err

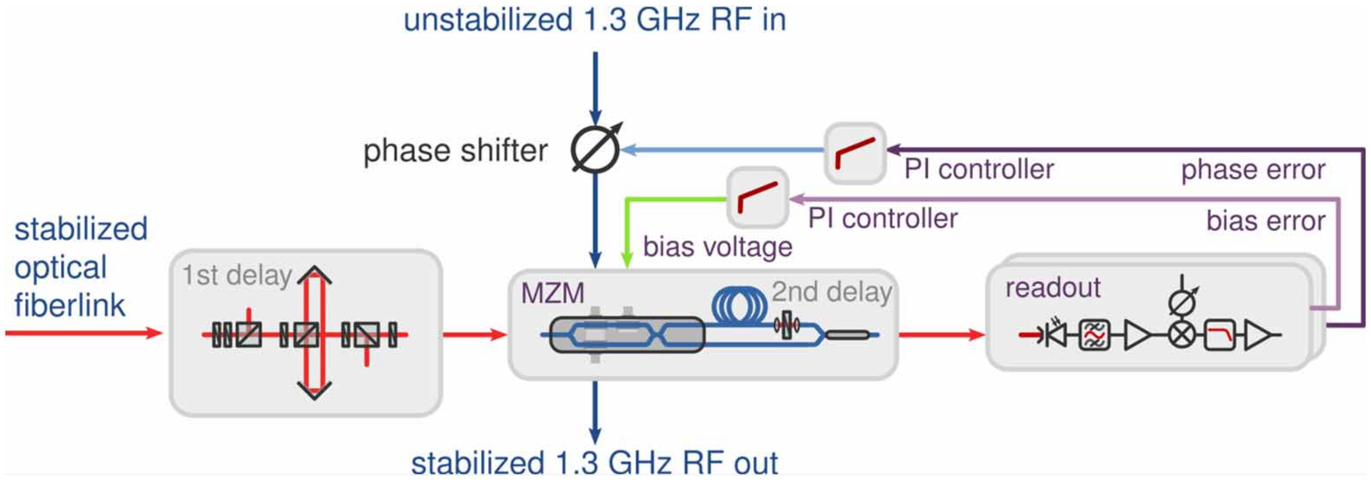
- base , fast)
- inser f-built
- typic

Courtesy: J. Mueller

The Optical Reference Module (REFM-OPT)

Femtosecond RF Reference Phase Stabilisation

- Employs a **drift-free laser-to-RF phase detector**
- Locally re-synchronizes the 1.3 GHz RF reference with **femtosecond precision** in a PLL
- 1^{st} delay line → RF sampled at 0° and 180°
- 2^{nd} delay line → increase SNR + phase/bias feedback
- Sophisticated **exception handling**



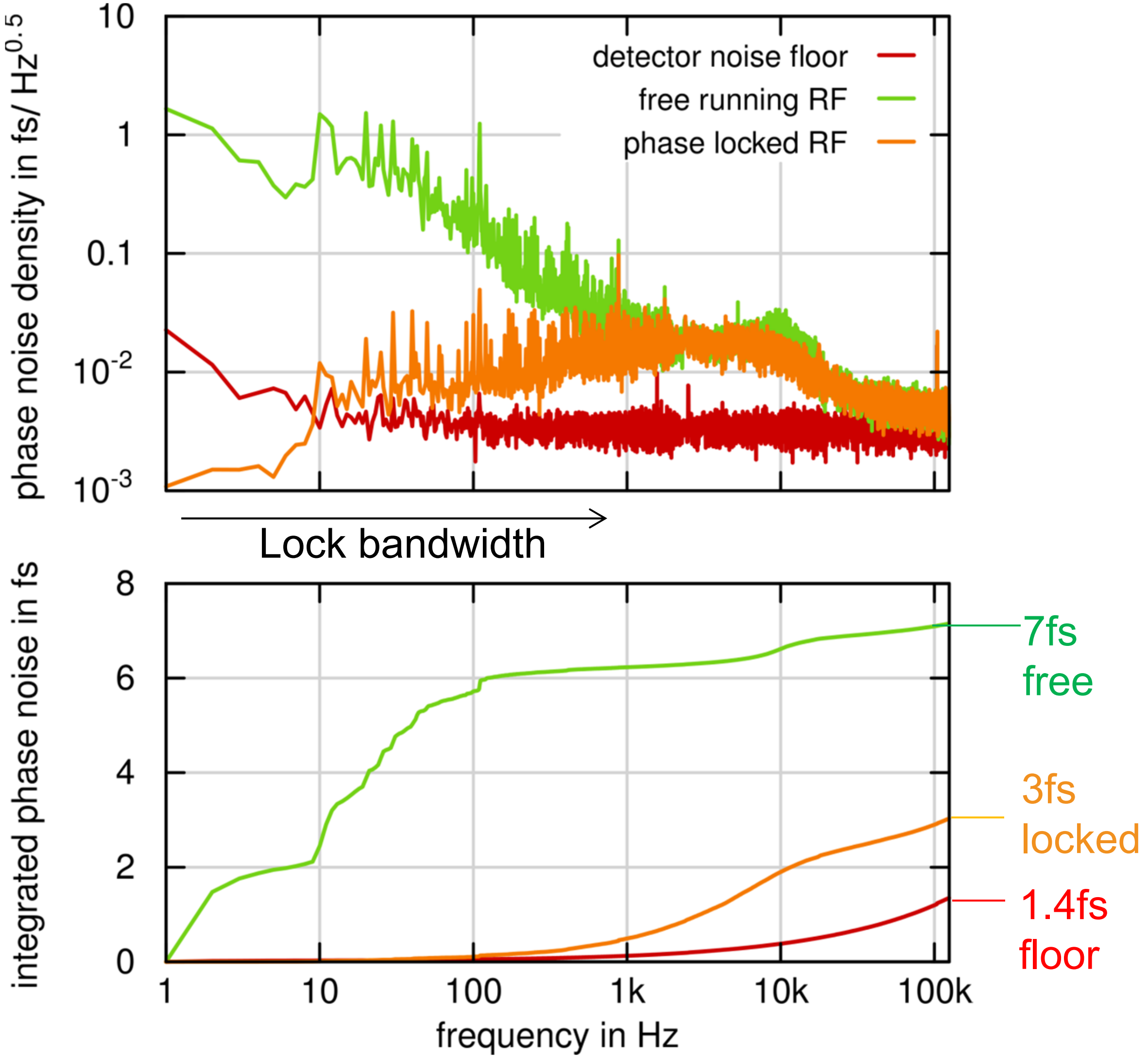
engineering

- **fully integrated** stand-alone 19“ module
- temperature and humidity stabilized optical compartment

Courtesy: T. Lamb

The Optical Reference Module (REFM-OPT)

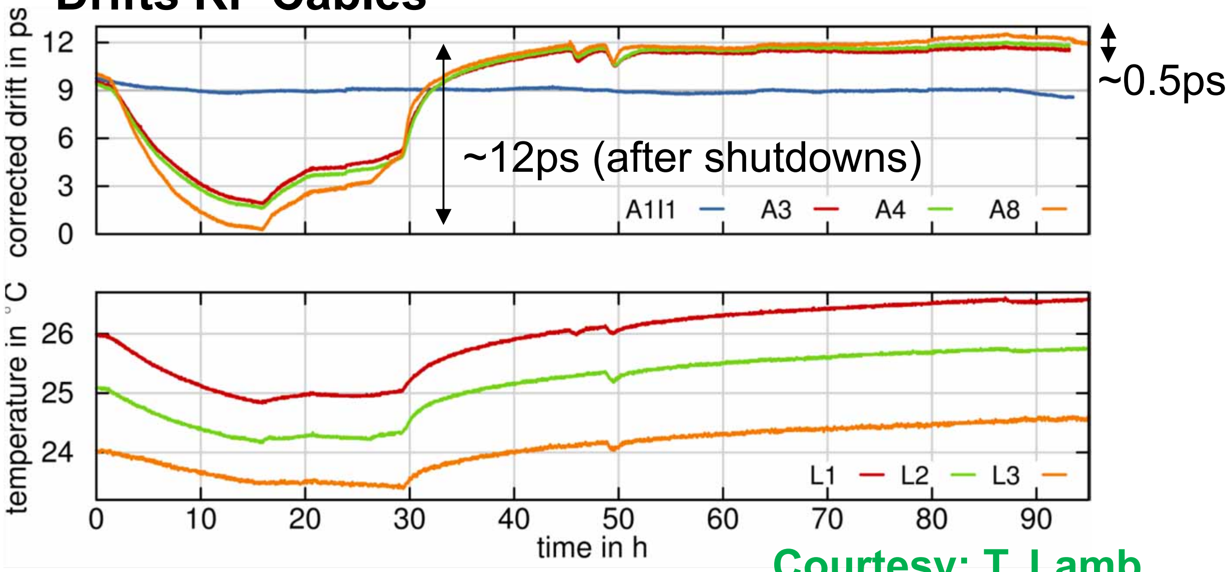
Femtosecond RF Reference Phase Stabilisation



Measurement Bandwidth 1 Hz to 125 kHz

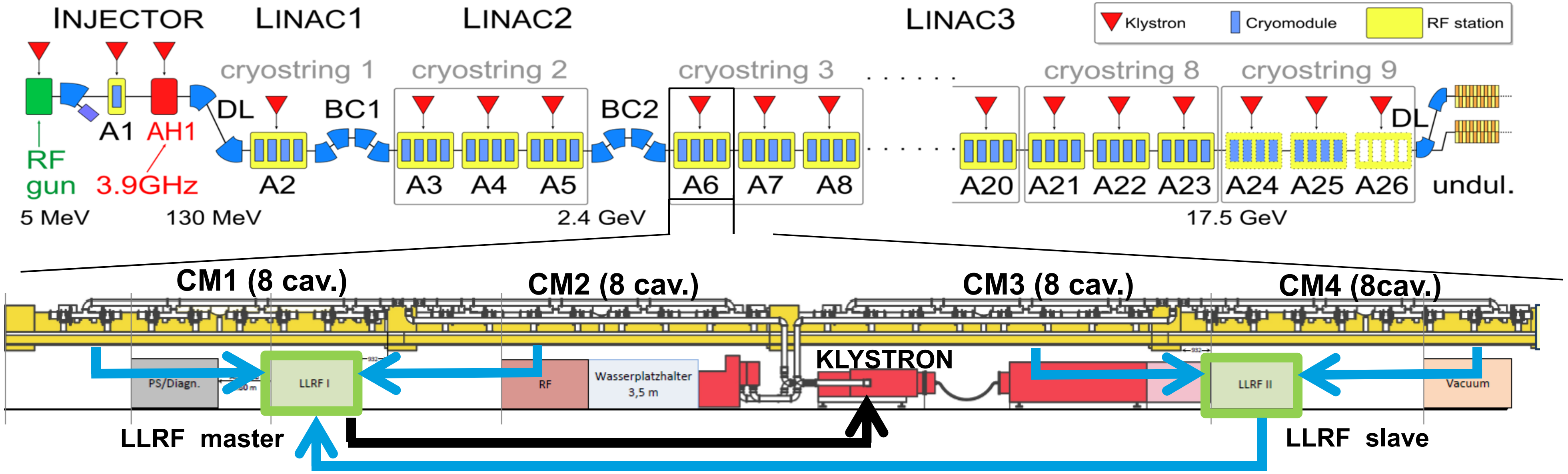
- K_φ of 3.1 V/ps
- integrated detector noise floor 1.4 fs (red)
- unlocked RF integrated jitter 7.2 fs (green)
- locked RF integrated jitter 3.0 fs (orange)

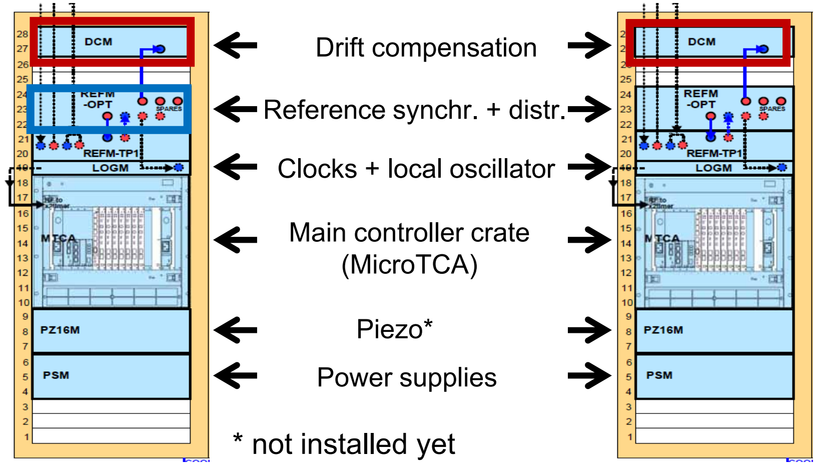
Drifts RF Cables

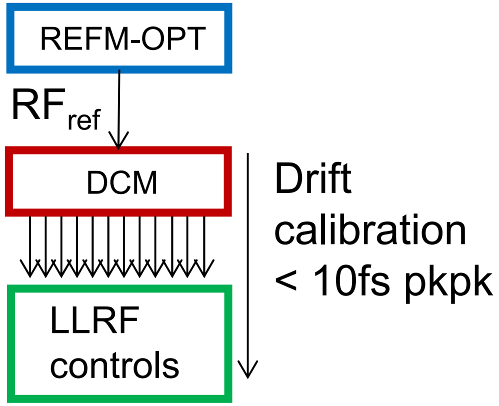


Courtesy: T. Lamb

Precision RF controls







More than 3000 RF channels
Requirements: <0.01deg and <0.01%

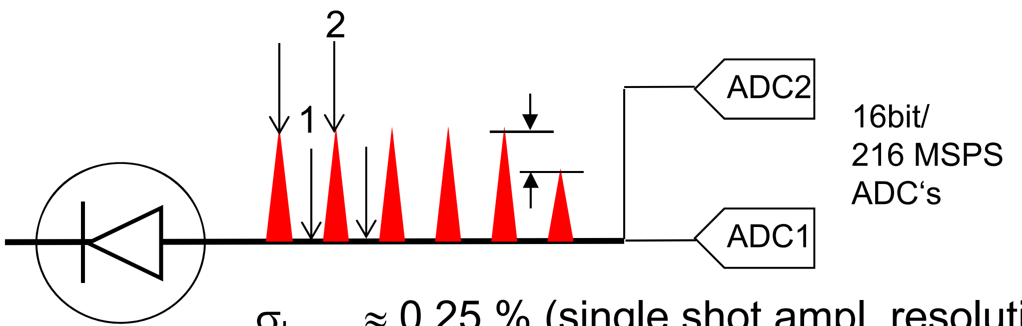
Courtesy J. Branlard

Bunch Arrival Monitor (BAM)

Schematic and functionality

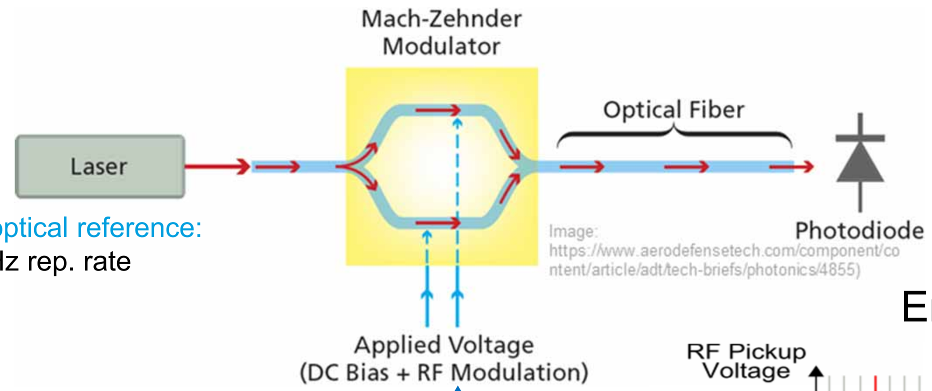
- **e- field pickup**: 40GHz, broad-band design
- **Time reference** from optical synchronization reference
- Used for **slow & fast feedbacks** (pending for XFEL)

Laser pulse train readout & procession in FPGA.



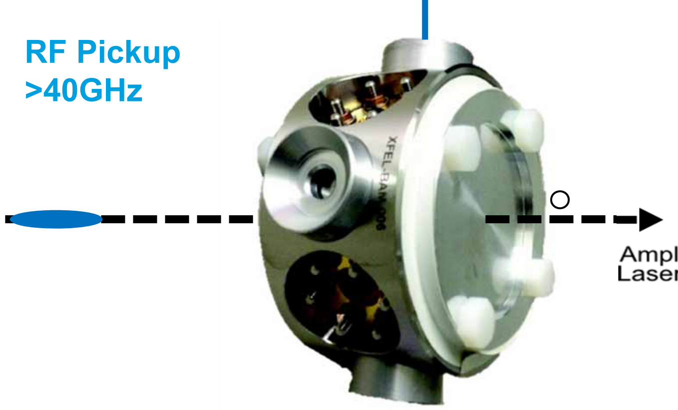
$\sigma_{Laser} \approx 0.25$ % (single shot ampl. resolution)

Resolution: σ_t = slope · $\sigma_{Laser} \approx 3$ fs

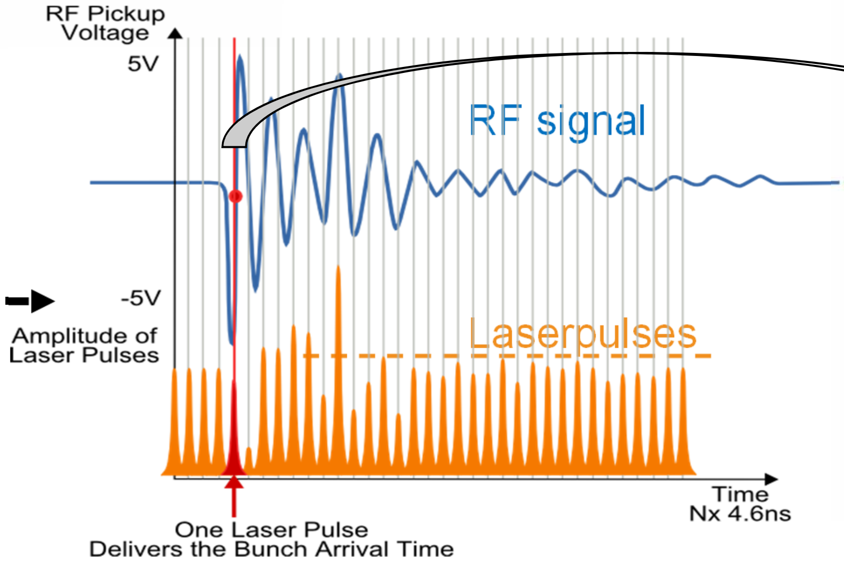


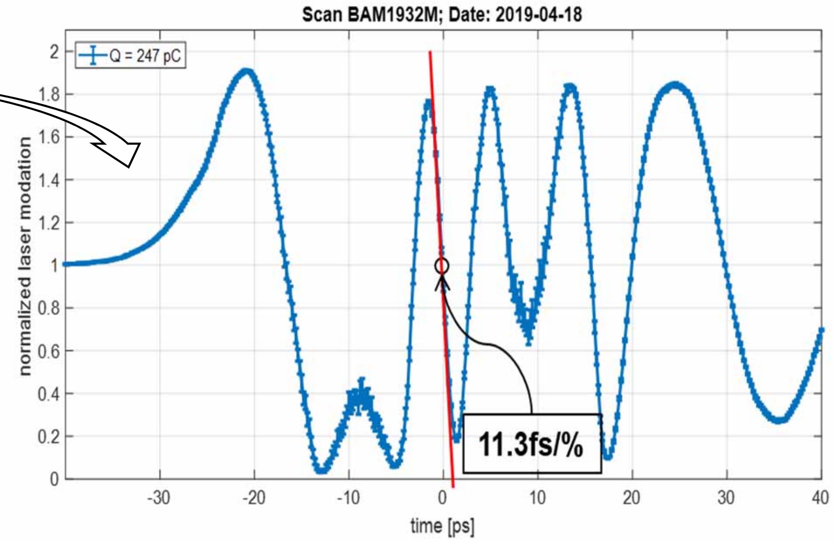
From optical reference:
216MHz rep. rate

RF Pickup
>40GHz



Encode $t_{arrival} \rightarrow A_{laser}$





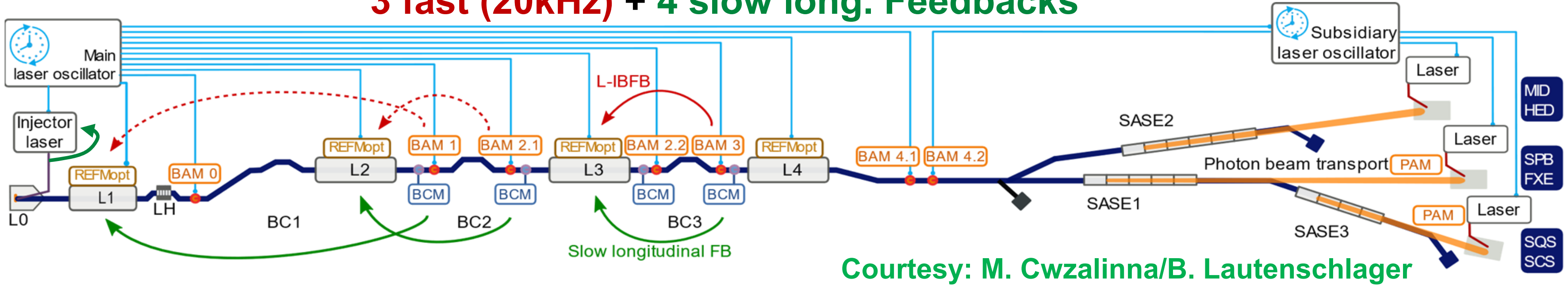
Ref.:
PHYSICAL REVIEW STAB, 18, 012801 (2015)

Courtesy: M. Czwalinna

Beam Arrival Time Feedbacks

Achievement and limitations

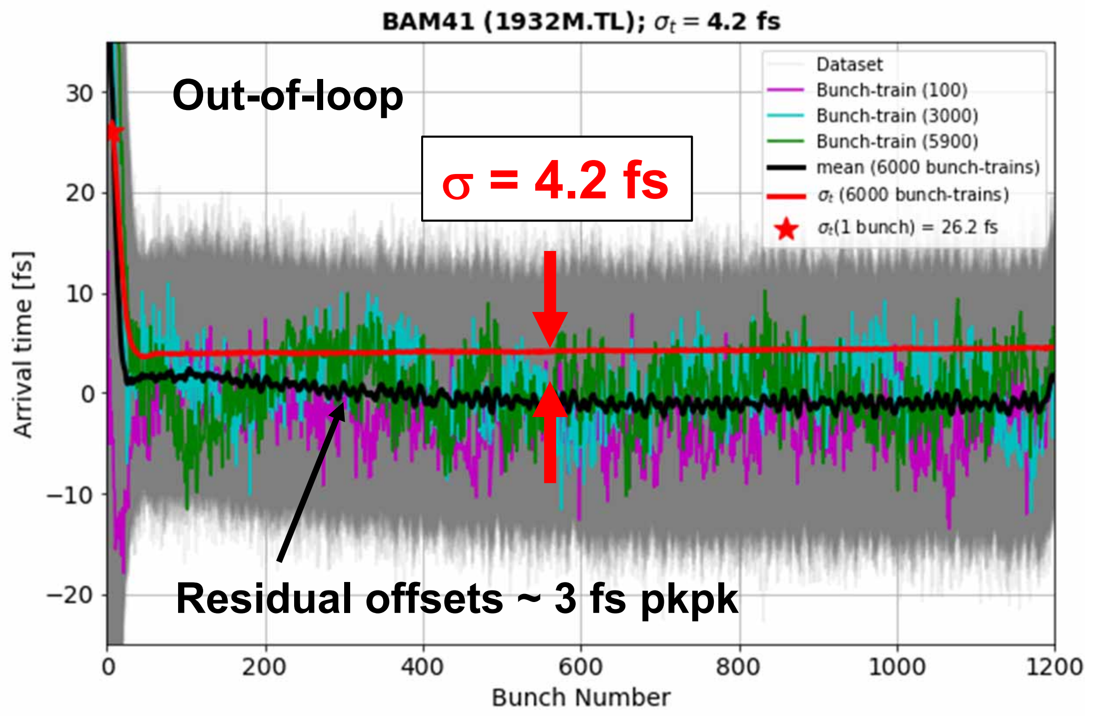
3 fast (20kHz) + 4 slow long. Feedbacks

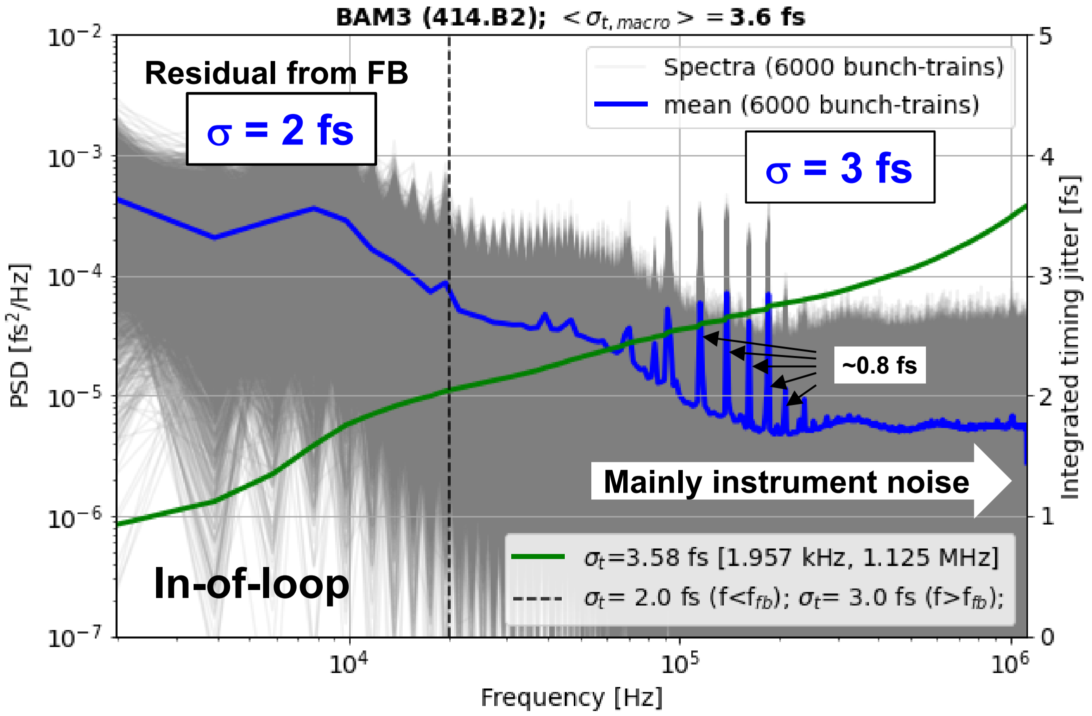


Courtesy: M. Cwzalinna/B. Lautenschlager

Mitigation path:

1) Improve electronics
2) Improve FBs
3) New 100 GHz BAM

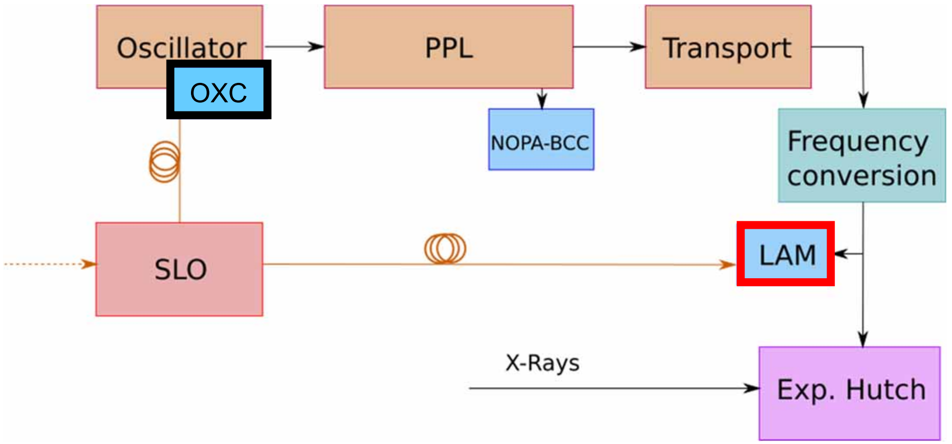




3.6 fs

Laser pulse Arrival Monitoring

Control jitter and drifts of pump-probe lasers..

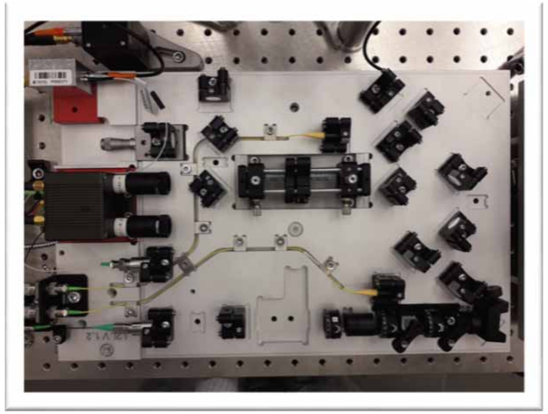


Mitigation path:

Laser pulse arrival monitor at the location of the experiment to reduce:

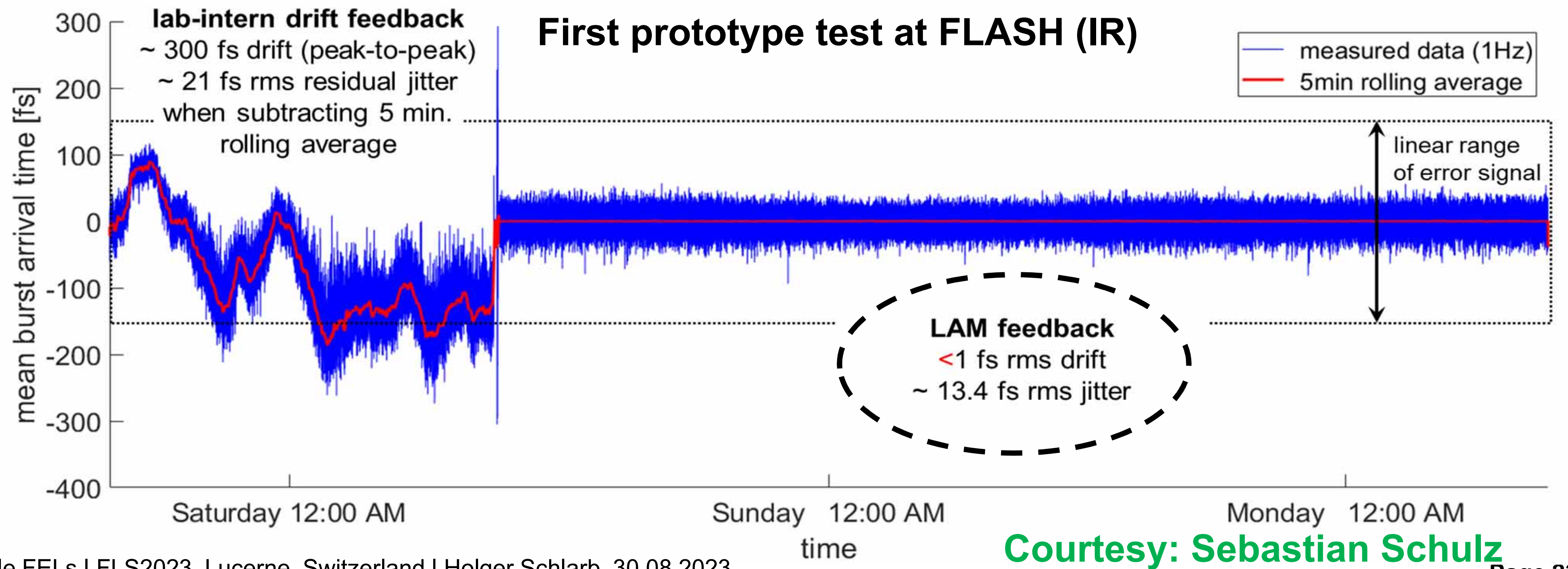
1) Slow drifts
2) "Fast" jitter (in future)

OXC - to lock Laser Osc.



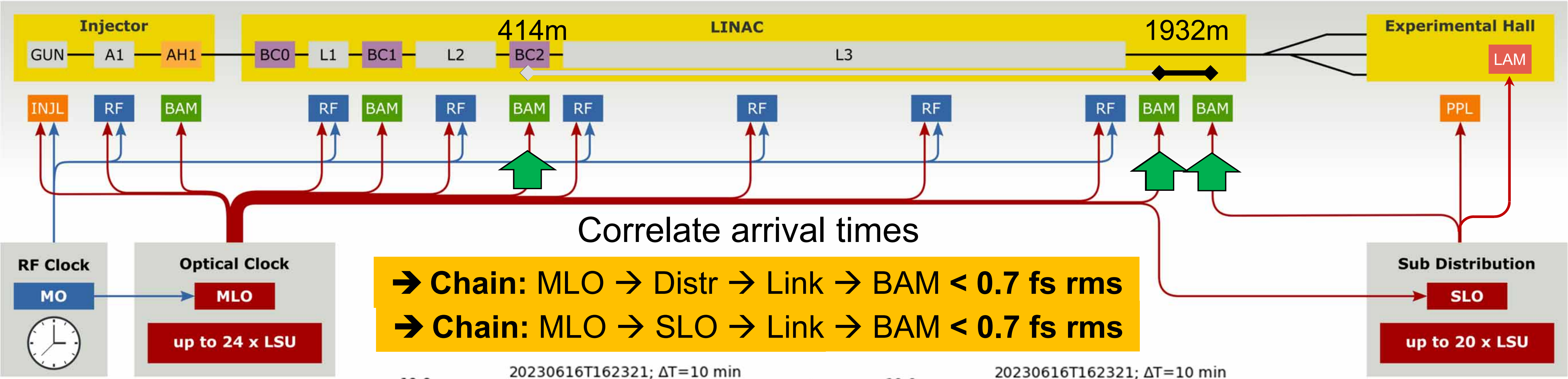
Wideband version for LAM

First prototype test at FLASH (IR)



Courtesy: Sebastian Schulz

Evaluation of optical synchronization system: - mid range -



Correlate arrival times

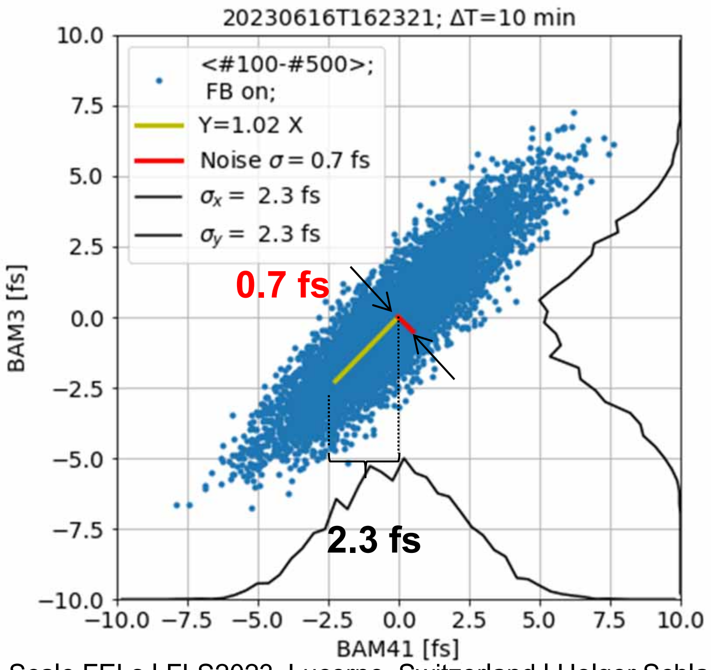
➔ **Chain:** MLO → Distr → Link → BAM **< 0.7 fs rms**

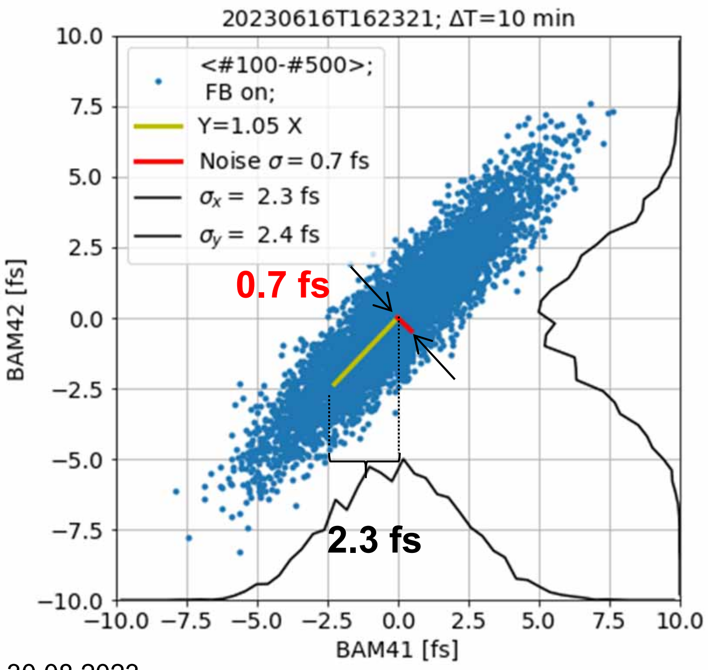
➔ **Chain:** MLO → SLO → Link → BAM **< 0.7 fs rms**

10 min. (6000 trains)
mean(400 bunches)

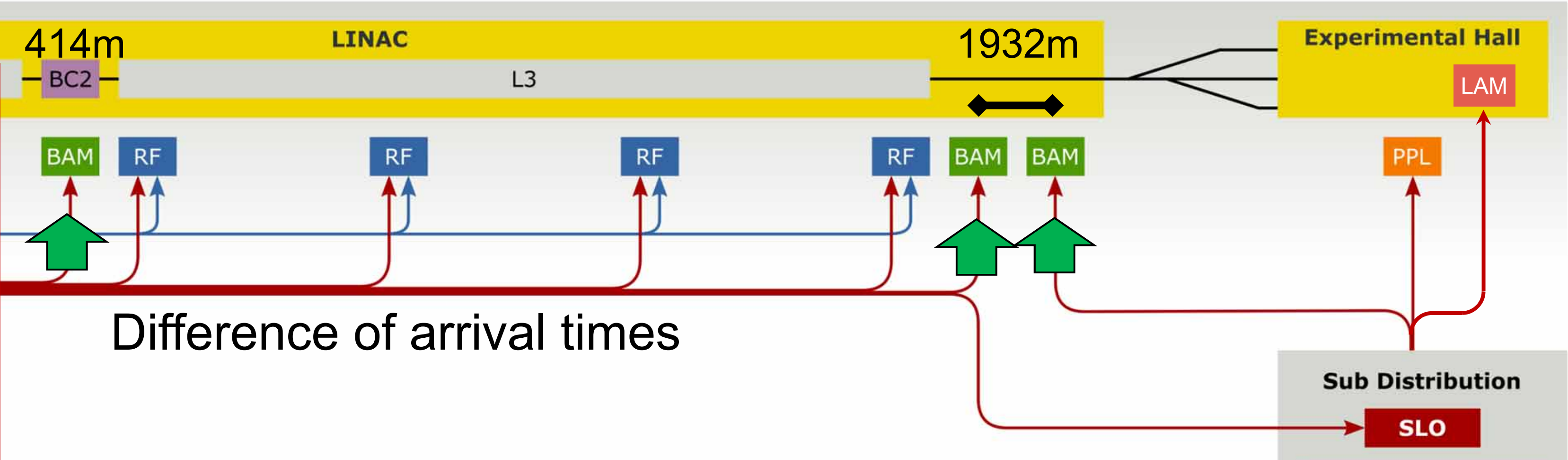
➔ Remove BAM high-freq. instr. noise

➔ Residual jitter of macro-pulses

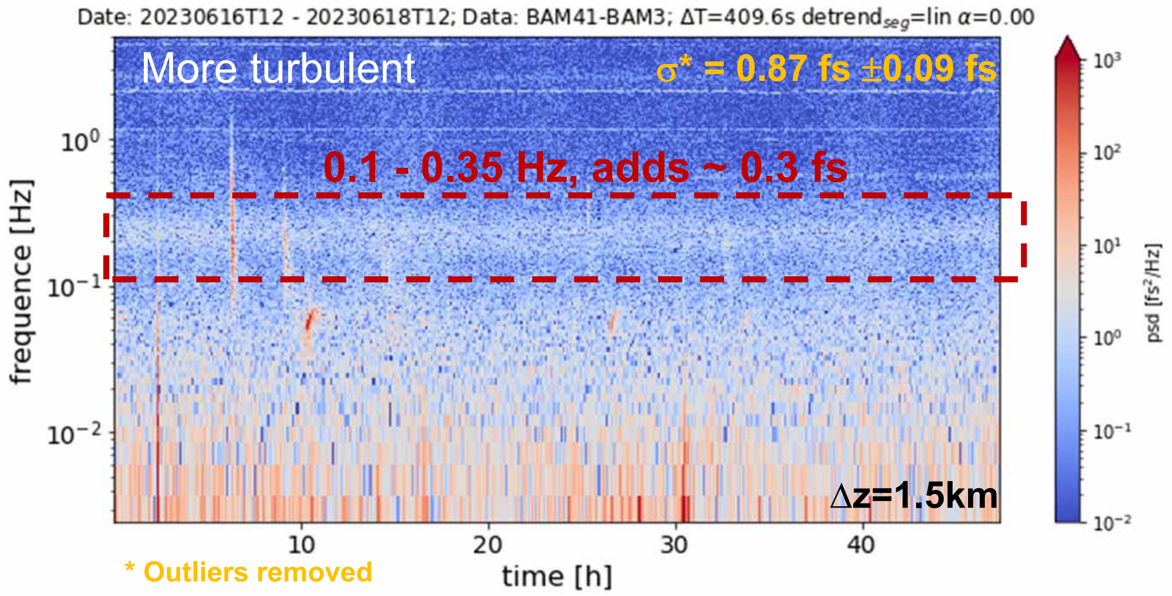




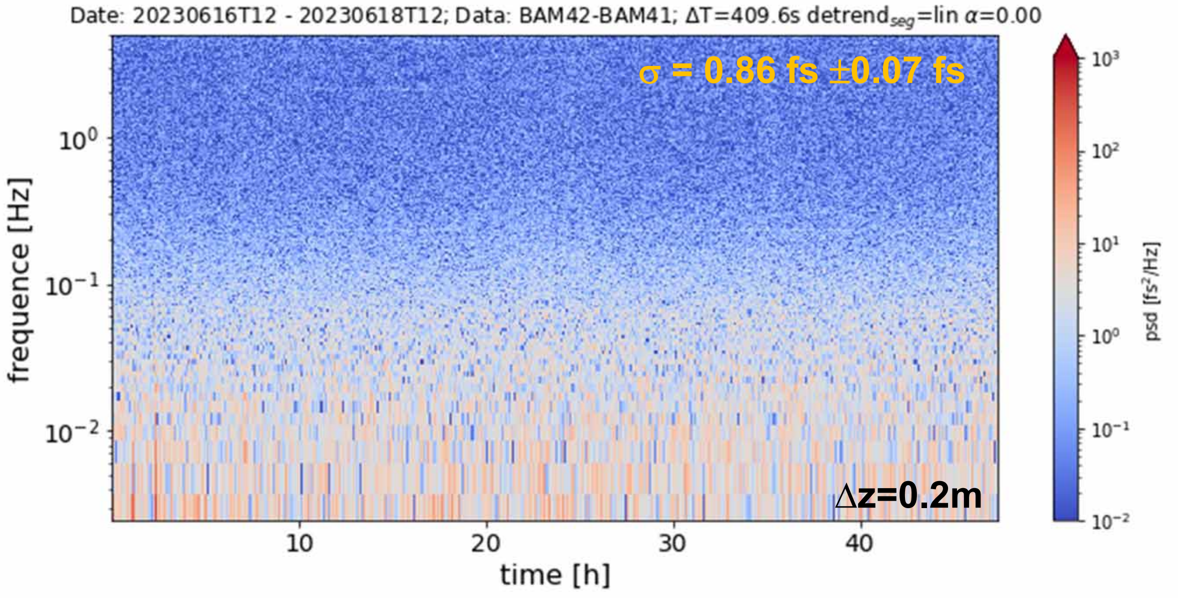
Evaluation of optical synchronization system: - mid range -



rogram 48h, freq. range= [2.4 mHz … 5 Hz]

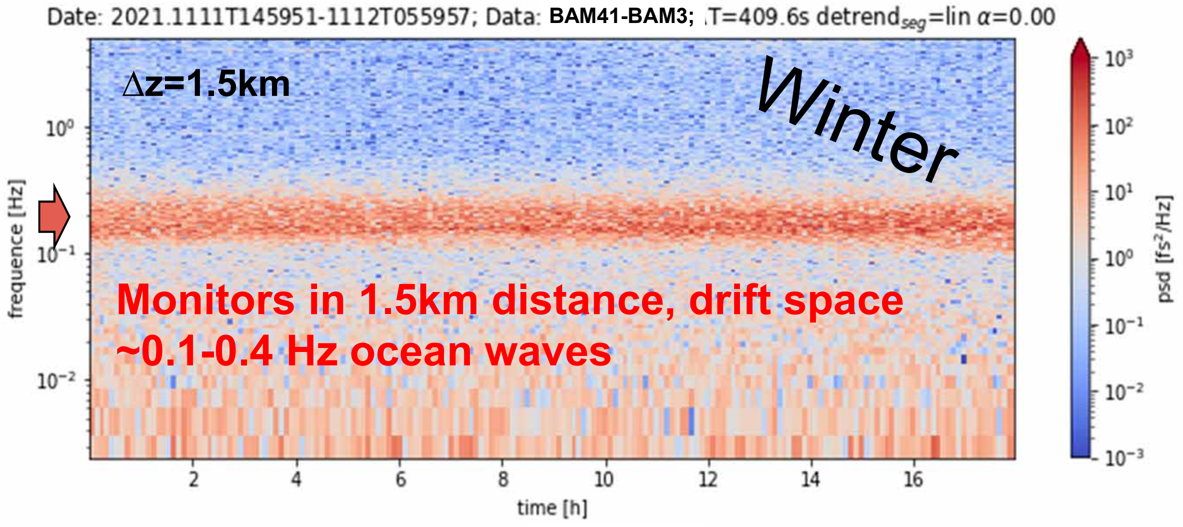


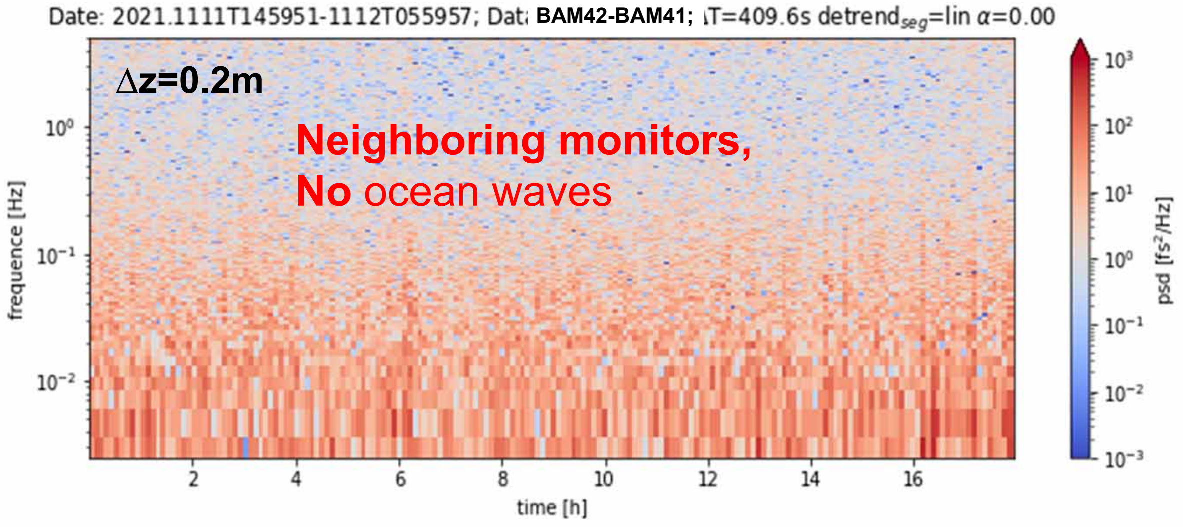
* Outliers removed

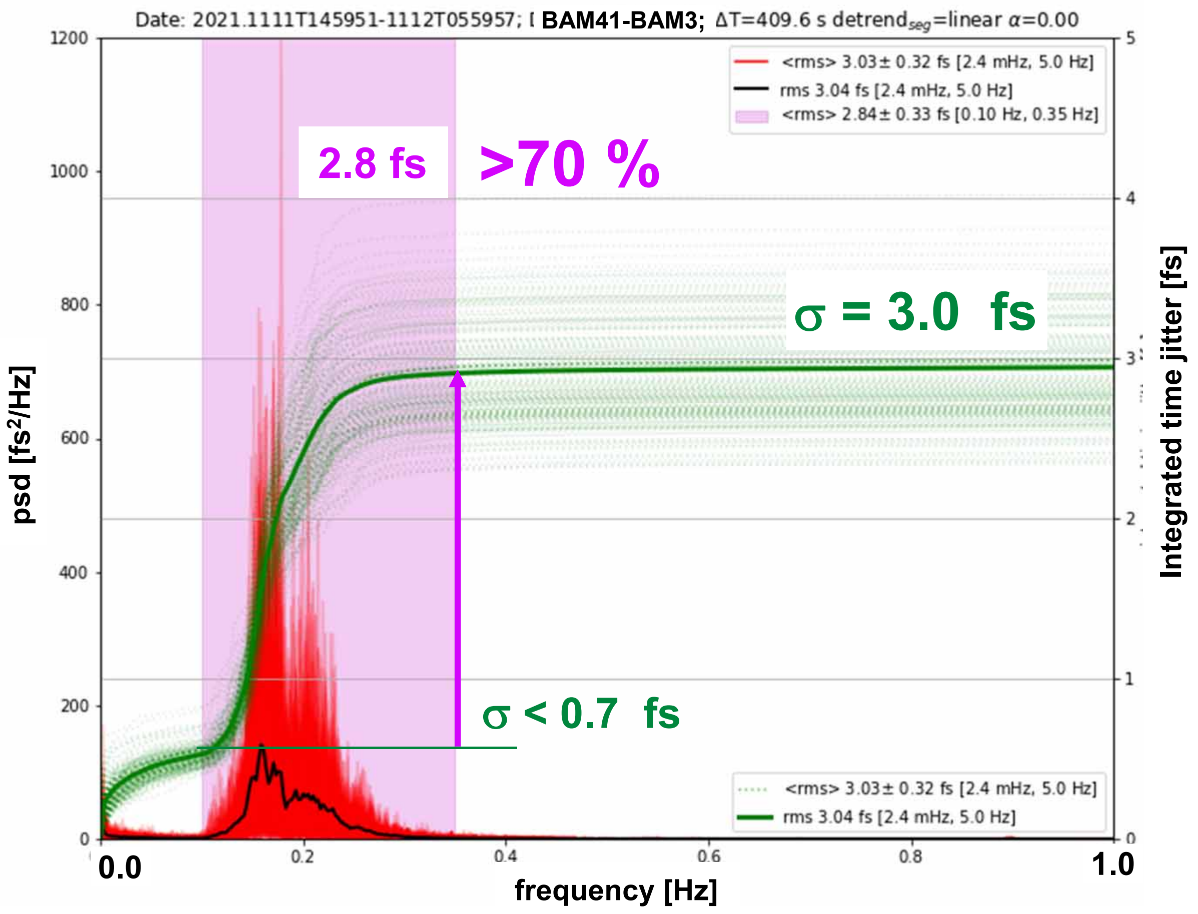


Ocean wave effecting beam arrival

Detection of ocean waves in electron bunch straight path

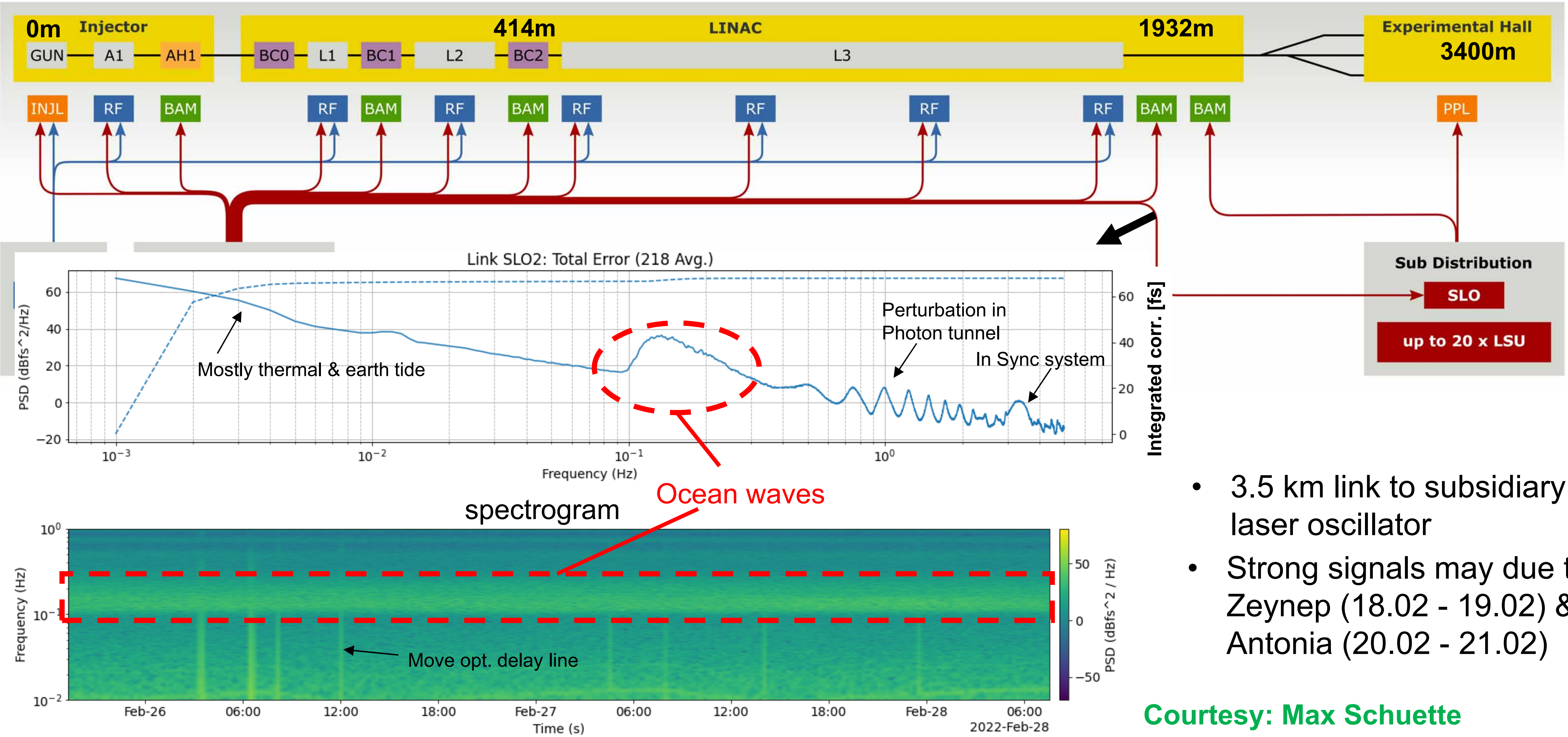






Ocean waves on optical links

➔ **Femtosecond stable optical synchronization detect ocean waves**

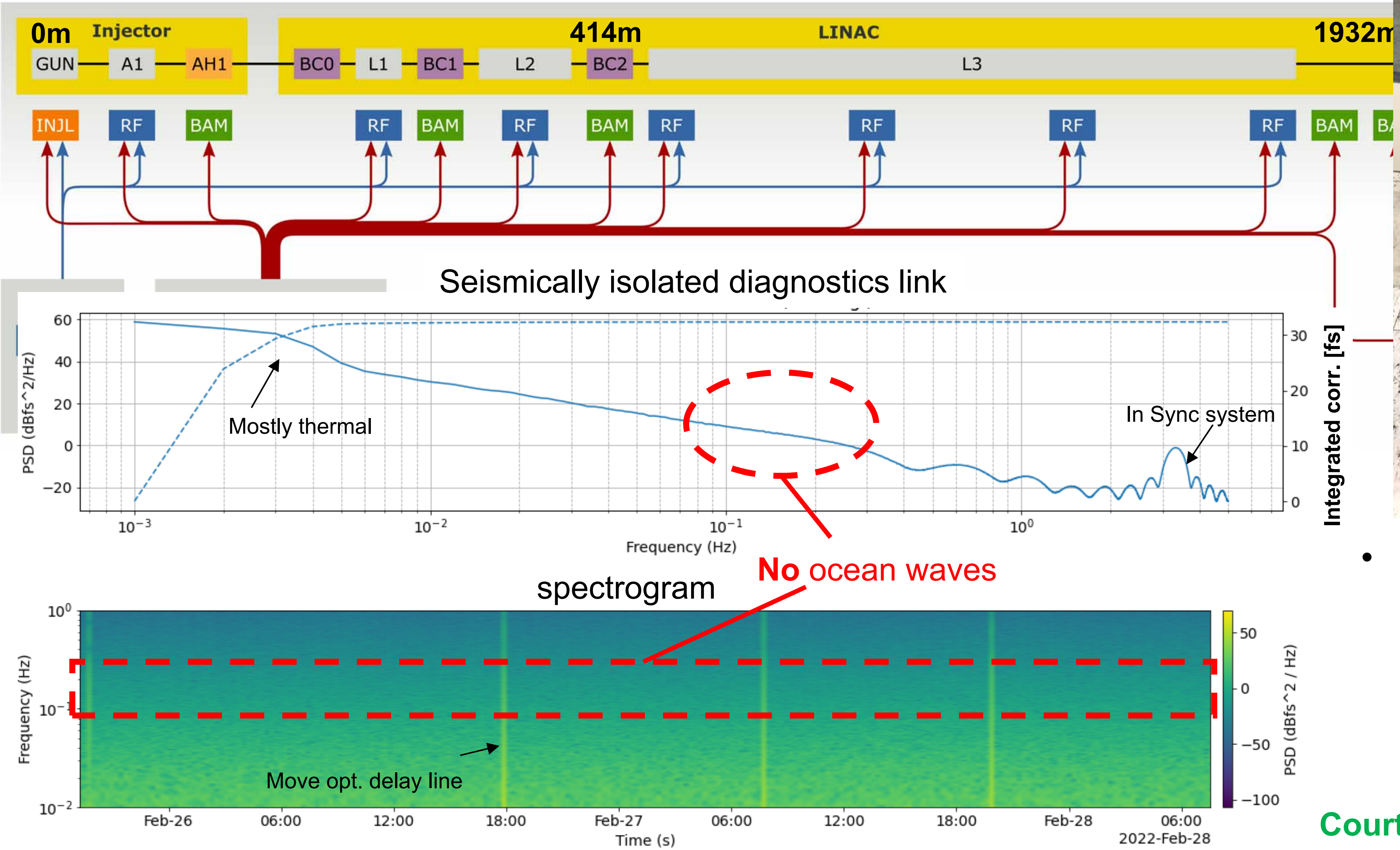


- 3.5 km link to subsidiary laser oscillator
- Strong signals may due to Zeynep (18.02 - 19.02) & Antonia (20.02 - 21.02)

Courtesy: Max Schuette

Ocean waves on optical links

➔ **Femtosecond stable optical synchronization detect ocean waves**

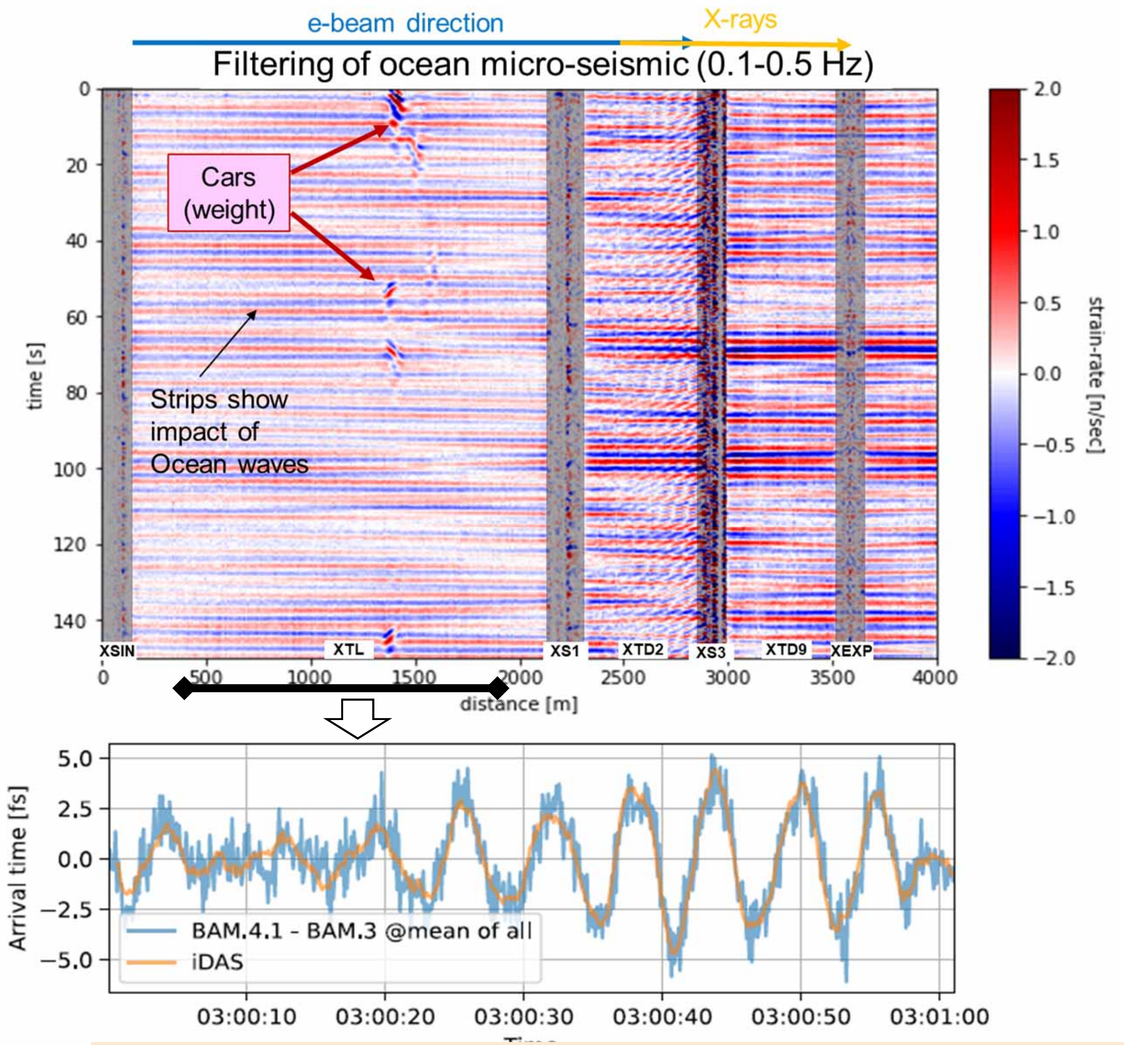


- 3.5 km link seismically isolated link connected to MLO

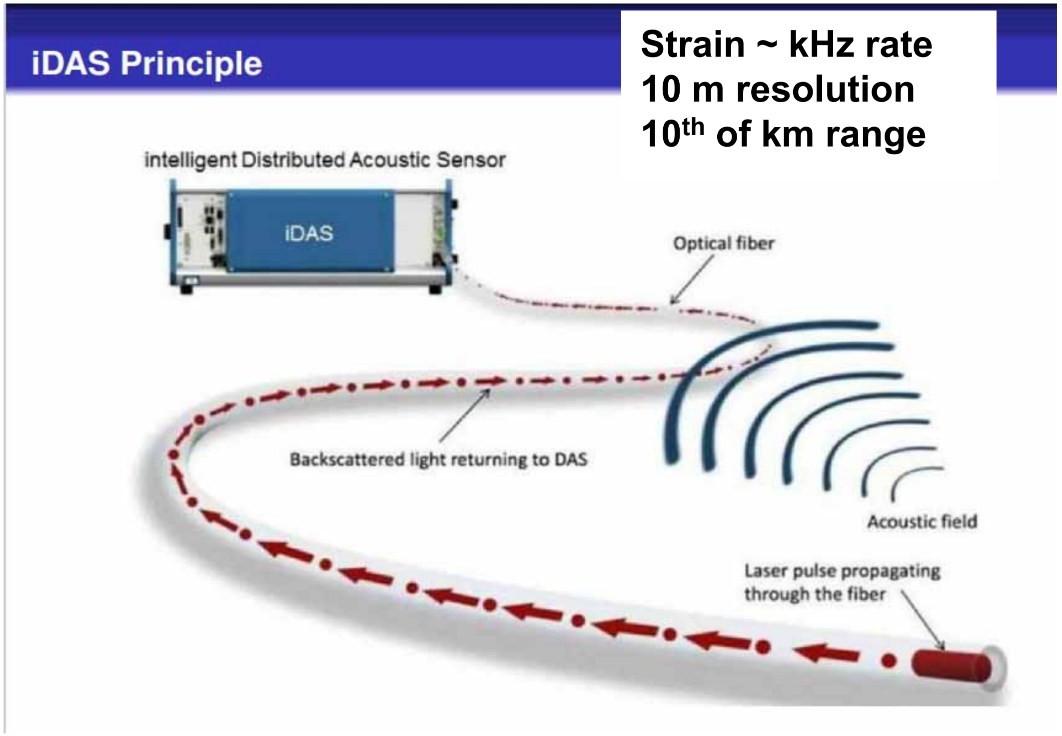
Courtesy: Max Schuette

Mitigation of micro-seismic

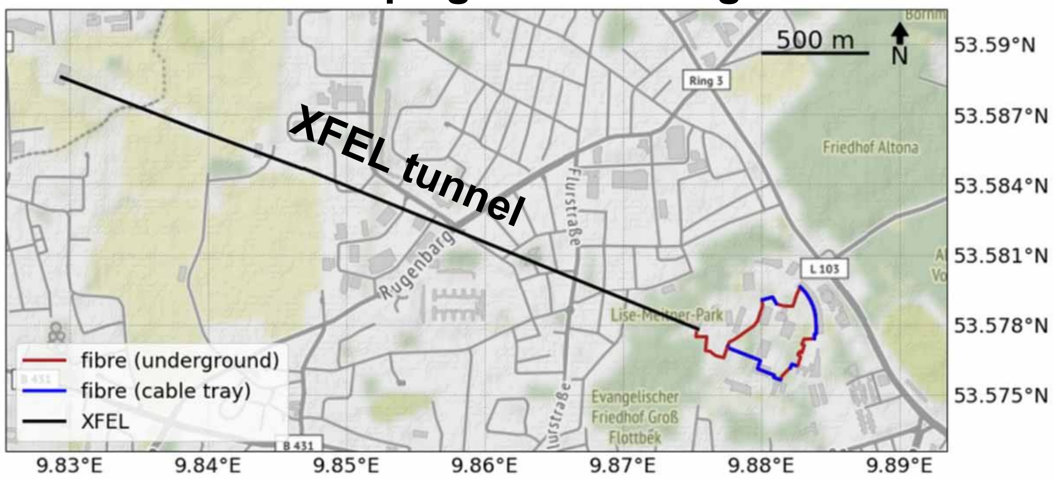
Using distributed optical fiber sensing (DOFS) …



Mitigation path: predict impact of ocean wave

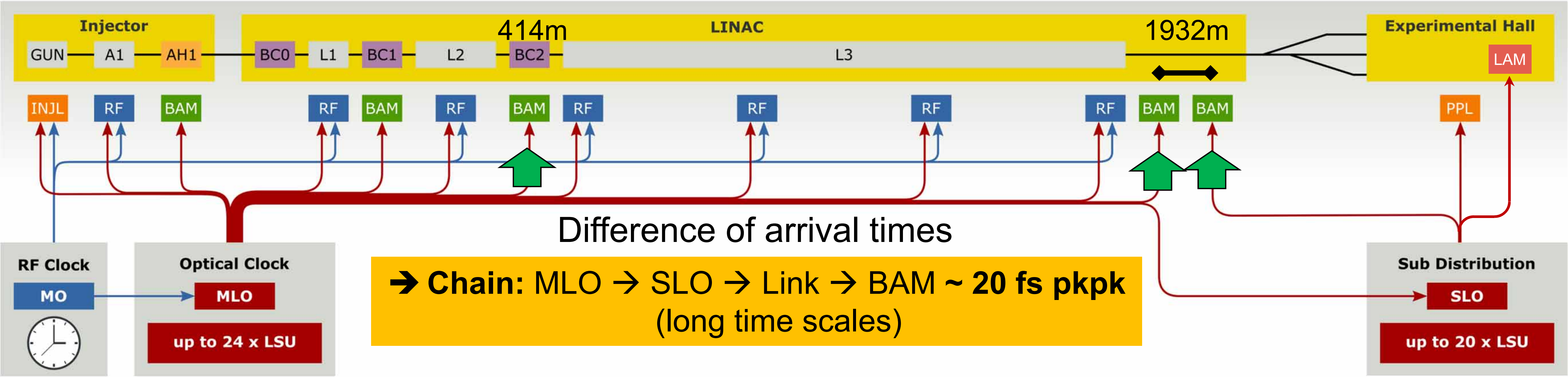


Measurement campaign 12.6 m length

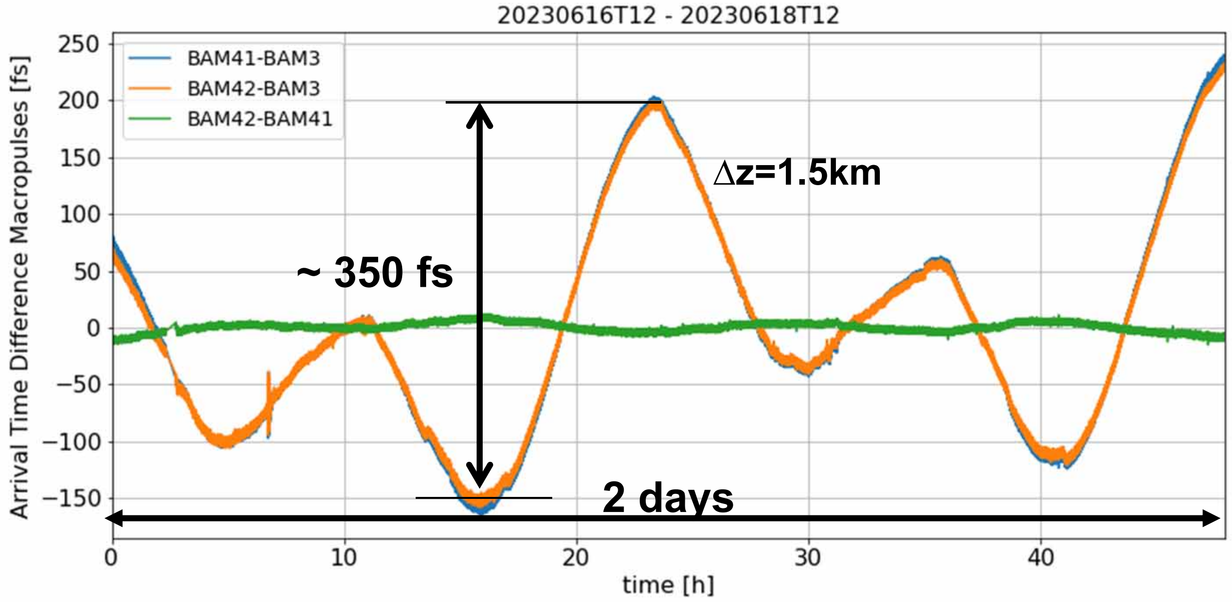


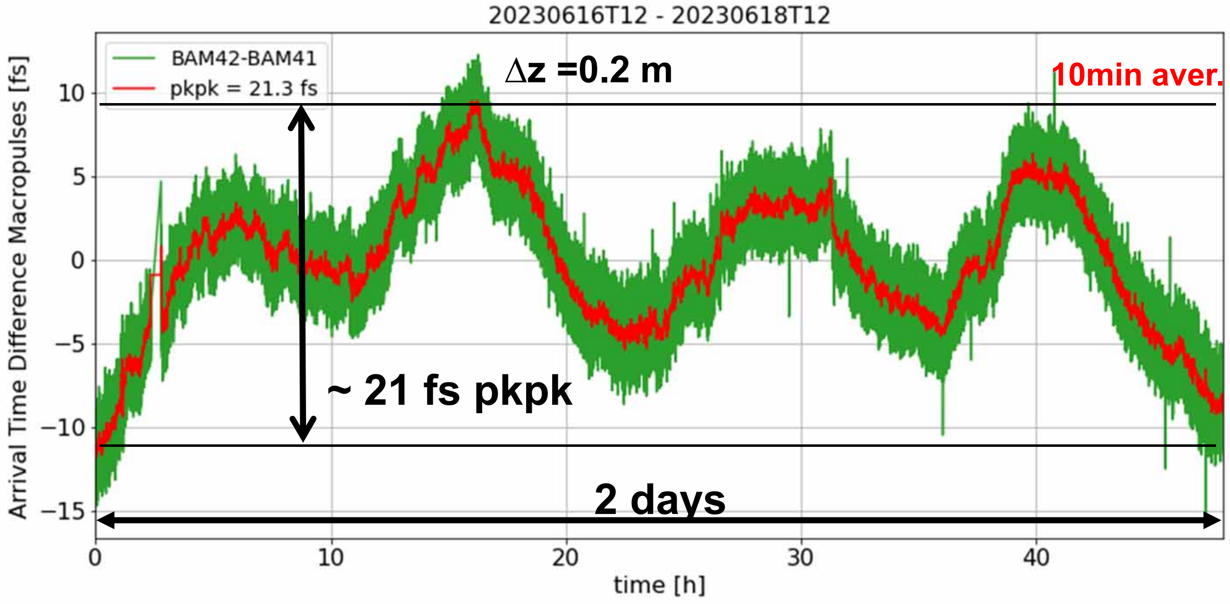
See http:\\wave-hamburg.eu

Evaluation of optical synchronization system: - long range -



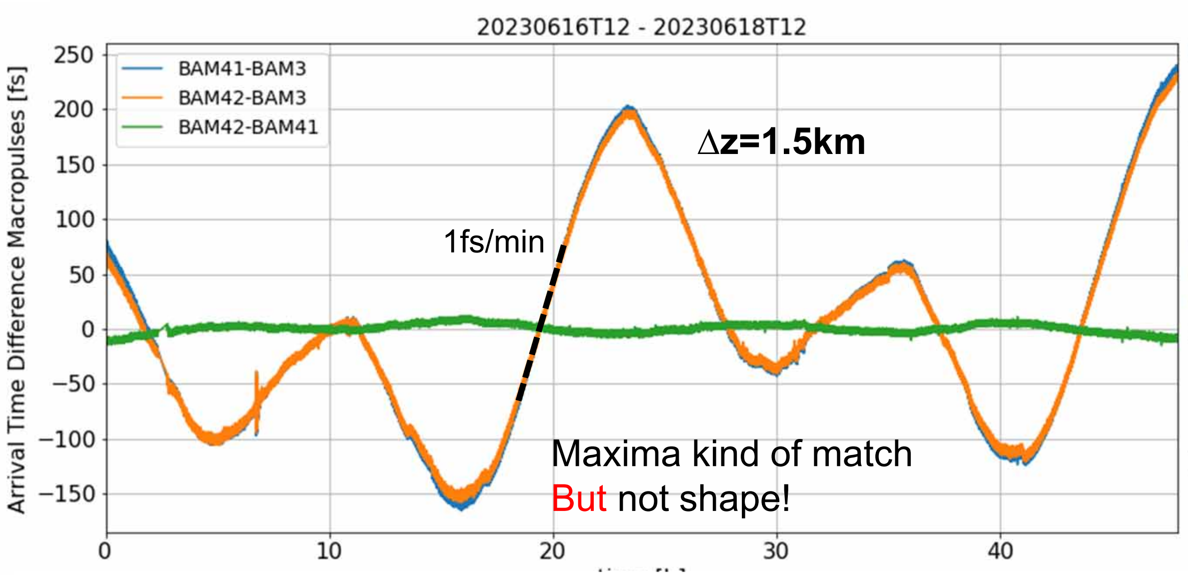
➔ Chain: MLO → SLO → Link → BAM **~ 20 fs pkpk**
(long time scales)

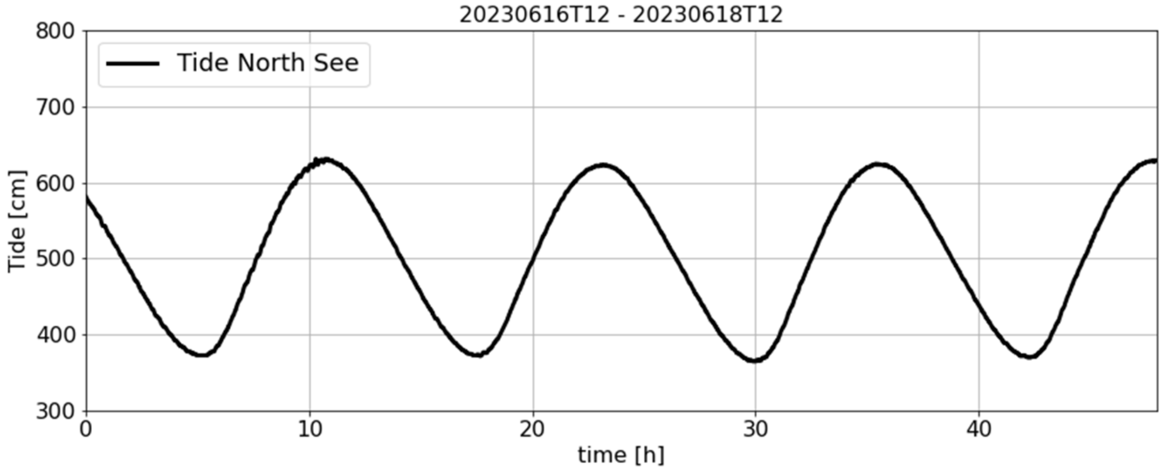




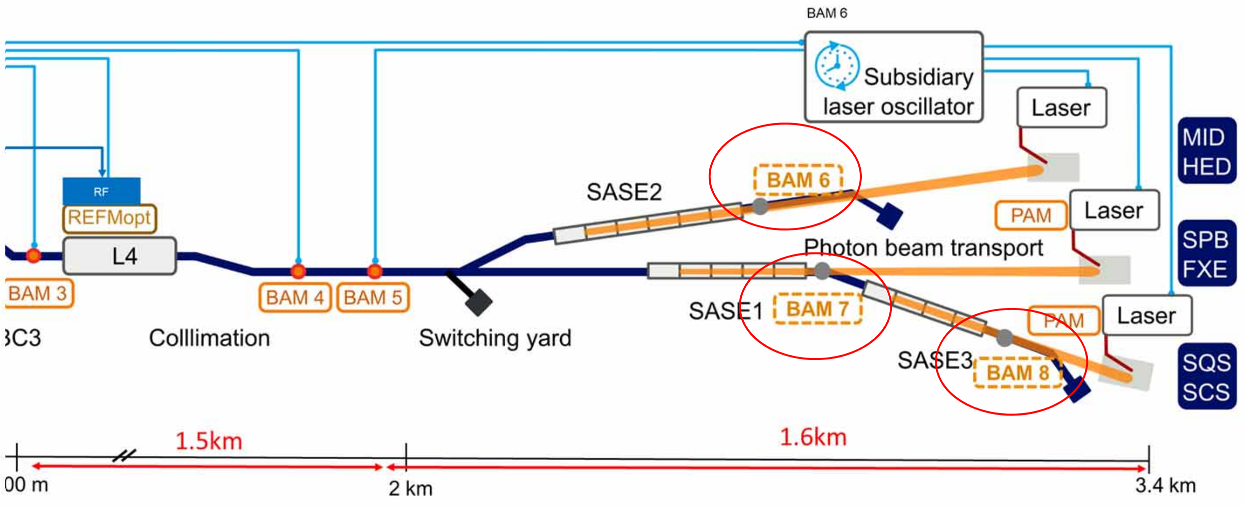
Impact of Earth & Ocean Tide

Combined effect earth & ocean tides





Tide data source: www.pegelonline.wsv.de



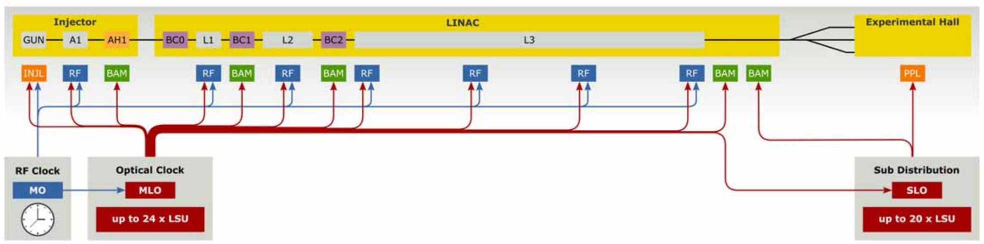
Mitigation path:

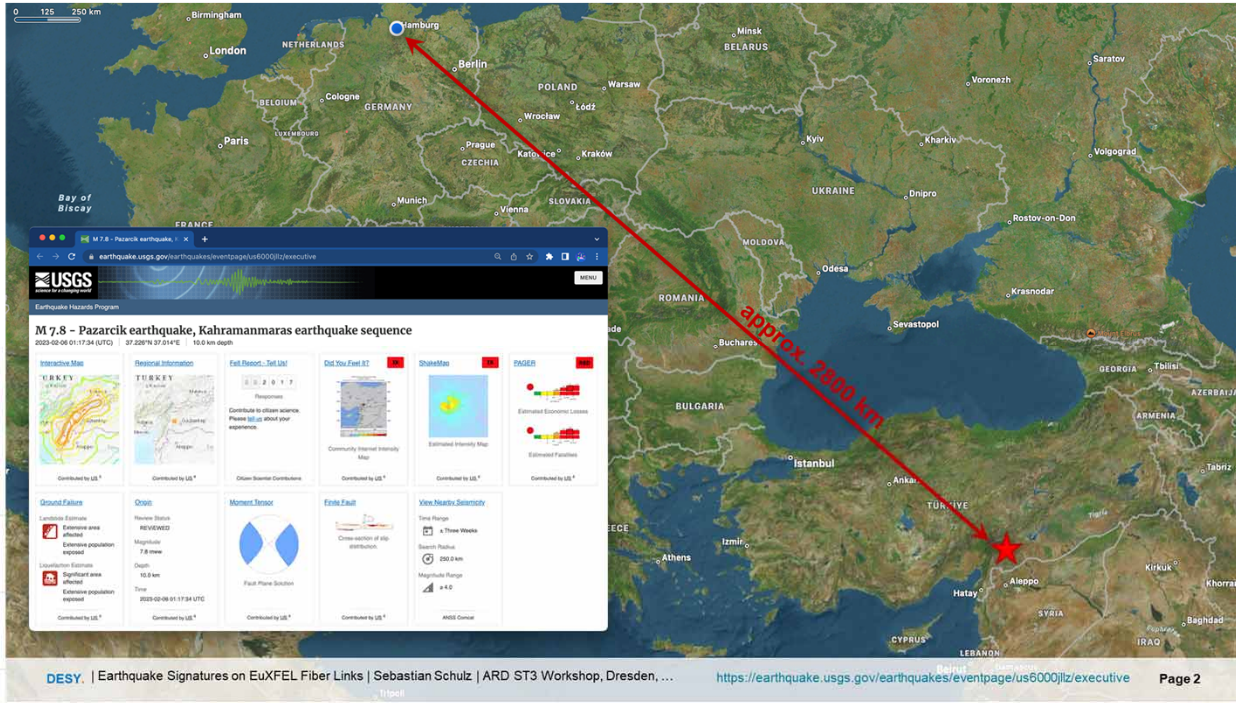
Slow but large variation ➔ precise prediction

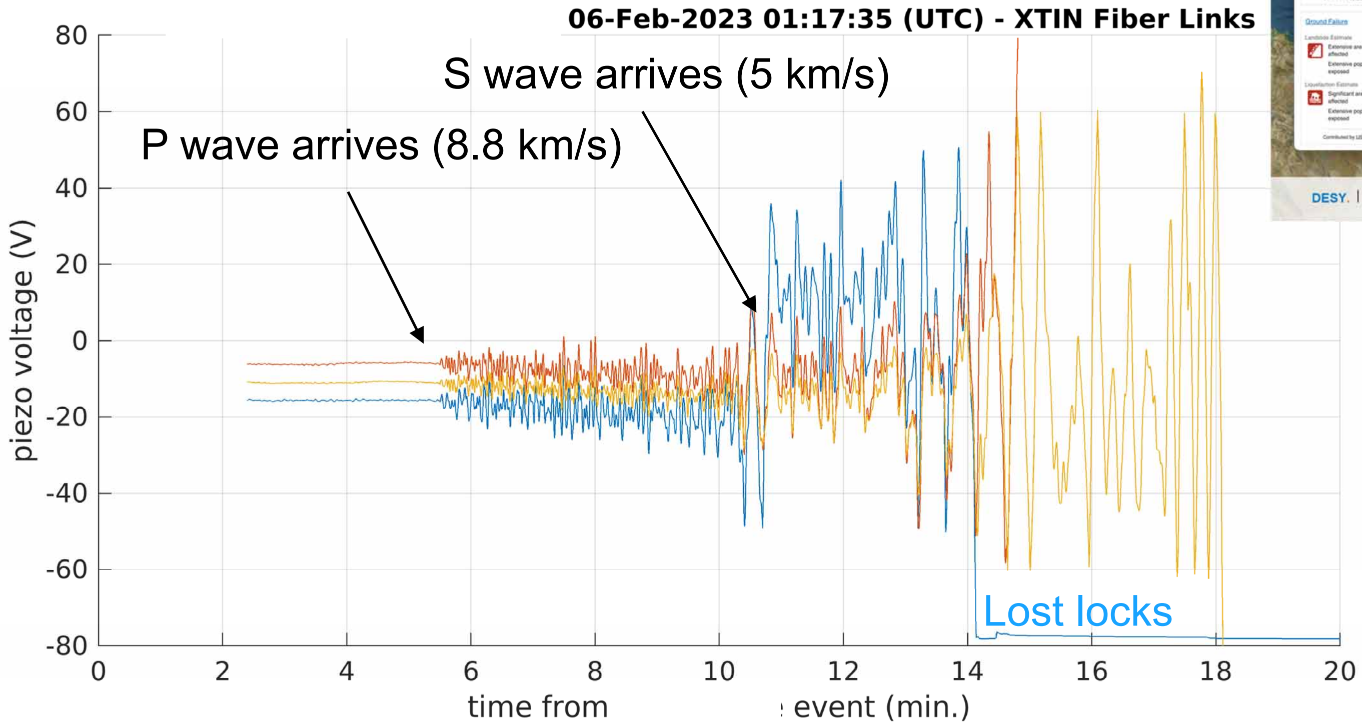
1) **Add new BAM's behind SASE Undu.**
2) Exp. monitor of tide effect@DESY side
3) Numerical modelling

Singularities!

Failed link length compensation ...







*From analysis ➔ EuXFEL > **3 mm** stretched!*
Event was visible > 1 h

Courtesy: Sebastian Schulz

Conclusion & Outlook

Control jitter and drifts of pump-probe lasers..

• Features can be resolved with resolutions of	< 100 as		
• Stability optical reference system [kHz…mHz]	< 700 as		
• Electron beam stabilization	~ 4 fs	→	next gen BAMs
• Impact of ocean waves (in winter)	~ 2 fs/km	→	DOFS
• Pump-laser system jitter	~ 10-20 fs	→	LAM / fast-FB
• Drifts of optical reference system	~ 20 fs pkpk	→	tbd.
• Tide effects	~ 150 fs/km	→	add. meas.

- ~1 fs stability MHz – mHz seems feasible, but controlling drifts will be tuff!
- microstructure for as pulse generation ➔ Photon Arrival Monitoring increased relevance

Thanks for attention

Acknowledgement:
J. Branlard, L. Butkowski, A.-L. Calendron, M. Czwalinna, M. Felber, J. Georg, B. Lautenschlager, T. Lamb, M. Killenberg, T. Kozak, F. Ludwig, U. Mavric, J. Müller, D. Rothe, S. Pfeiffer, Ch. Schmidt, S. Schulz, S. Sydlo, E. Schneidmiller, M. Yurkov, … SPM/SFX-team, FXE-team, Beam Dynamics team, and many more…