# Femtosecond Synchronization of Large Scale FELs

## – Achievement, Limitations and Mitigation Paths –

**FLS 2023 talk extended version**

Holger Schlarb on behalf of the LbSync, Special Diag. and LLRF team at DESY
Darmstadt, BRD, 28th of June 2024

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

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# Introduction

# Introduction

## Time & length scales:

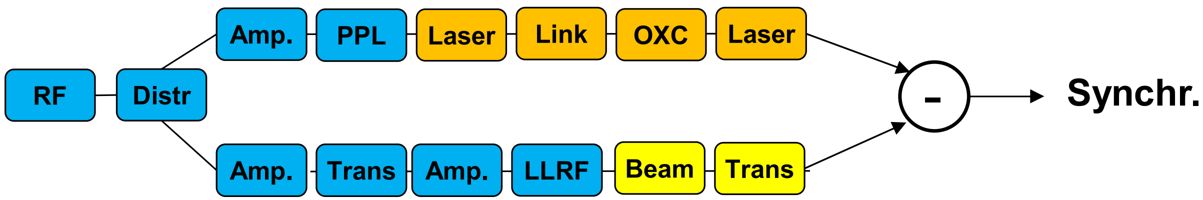
| | | | | |
|---|---|---|---|---|
| Time scale | 1ps | 100fs | 10fs | 1fs |
| Length scale | 300um | 30us | 3us | 0.3um |
| Year | 2000 | 2010 | 2020 | 2030 |

Synchronization achievements ?

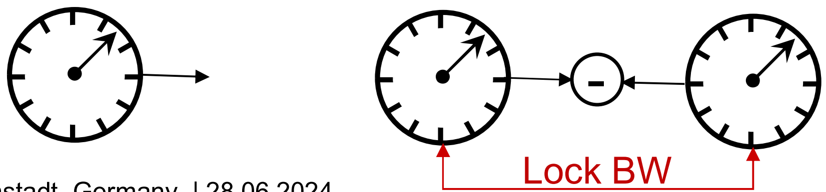
## Duration matters!

| | | |
|---|---|---|
| **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:



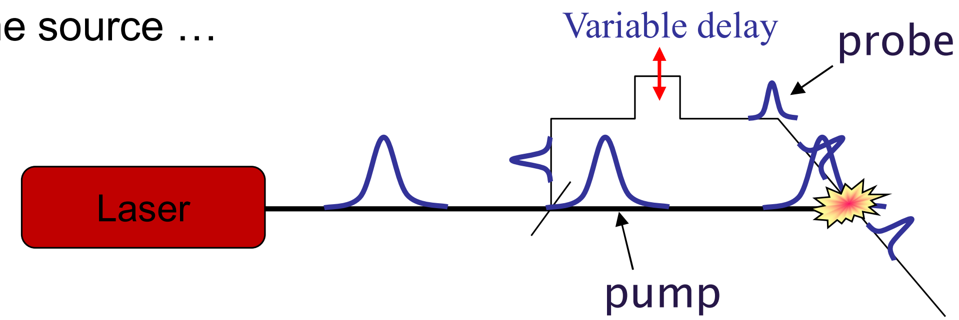
# Why precision Synchronization?
# &
# Source of timing jitter

# Source of timing jitter for FELs

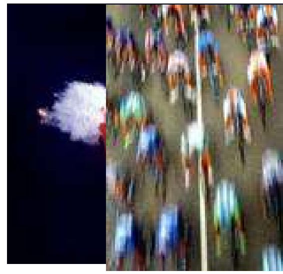
## Pump-probe experiments

Probe = flash

- Same source …

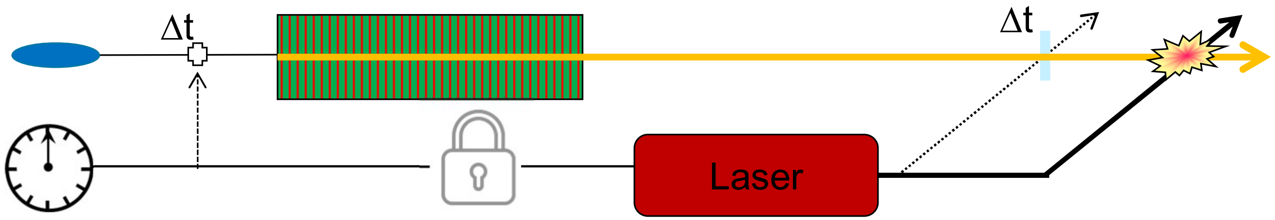



Pump



Shot pulses fs ⟵ ps

- FELs: disjunction source



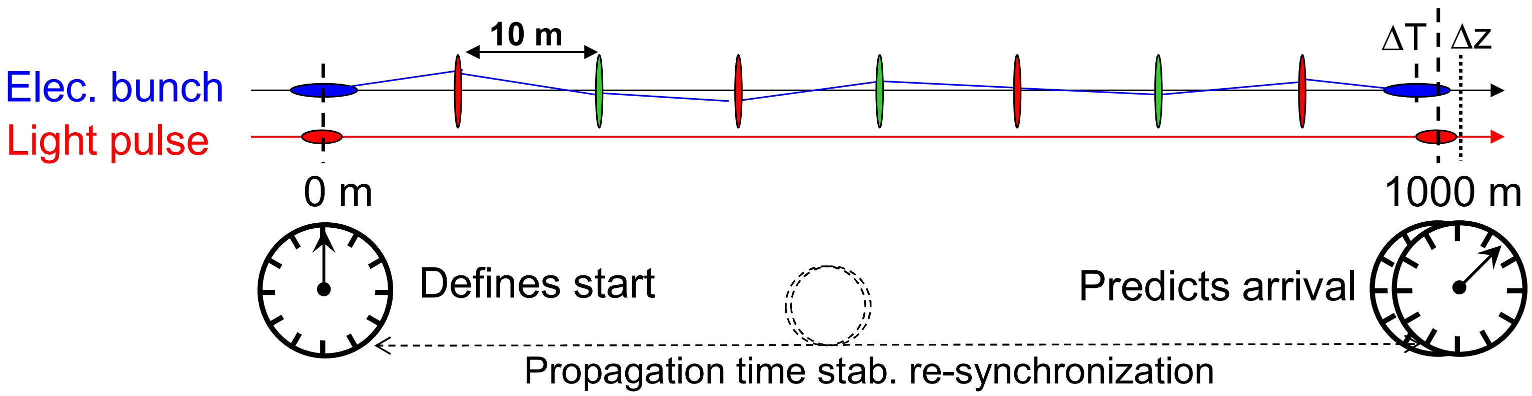

Precision: depends on experiment
Ideally: jitter < pulse durations

**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

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

$\Delta T = 435$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 100nm ➔ $\delta t < 1$ fs (😐)

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

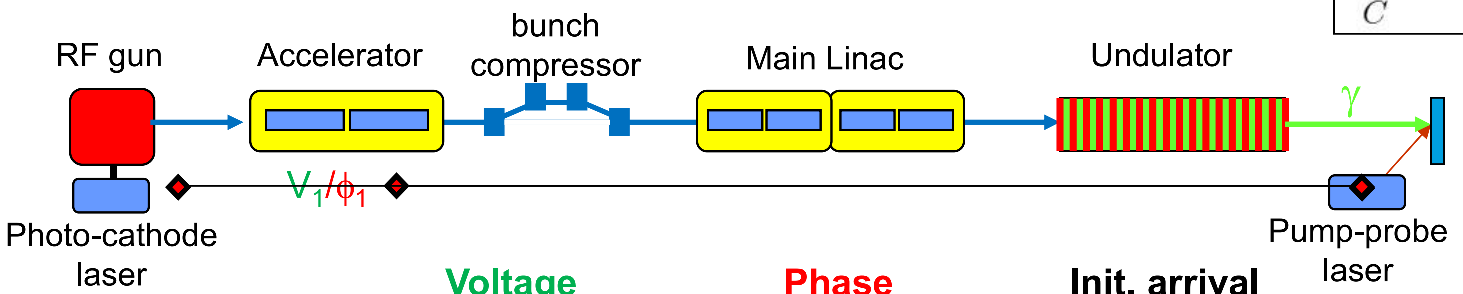
# Source of timing jitter for accelerators / FELs

## 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

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

| Voltage | Phase | Init. arrival |
|---|---|---|
| XFEL: 1.5ps/% <br> FLASH: 7.0ps/% | 2 ps/deg <br> L-band | 0.05 ps/ps <br> 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

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

**Tolerance ∝ Compression** — **Phase & Init. arrival** — **Voltage**

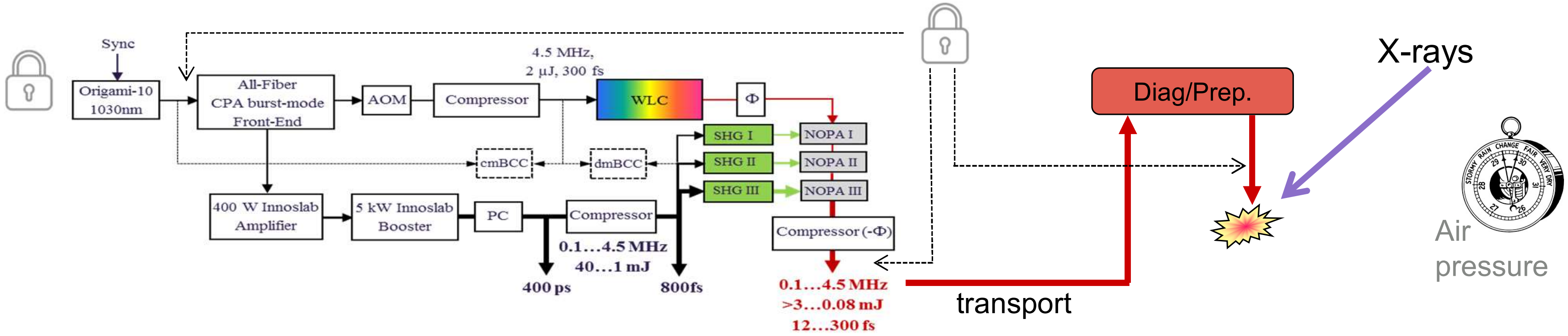
**Conclusions:**

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

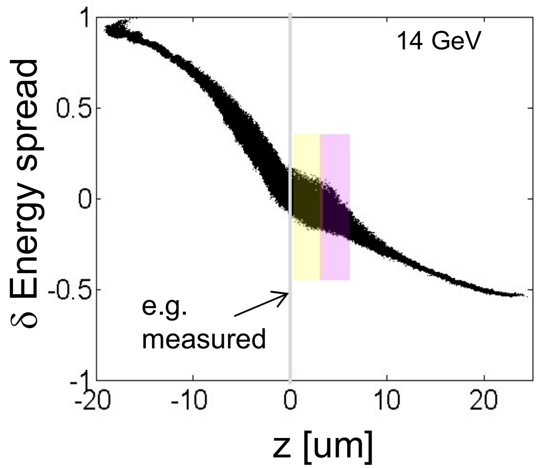
# Source of timing jitter for FELs

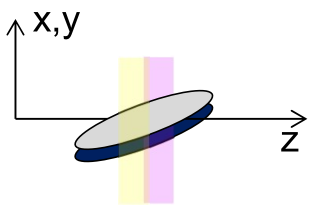
## Additional time jitter sources …

- **Laser systems**




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




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

- **SASE fluctuations**

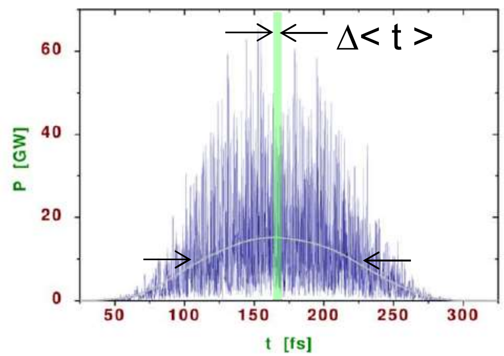



Image: Schneidmiller/Yurkov

$\Delta\langle t \rangle$ ~ pulse width $\sigma_t$

$\Delta\langle t \rangle$ ~ 1/M (or $1/\lambda_{ph}$)

will depend on saturation (tails start to lase…)

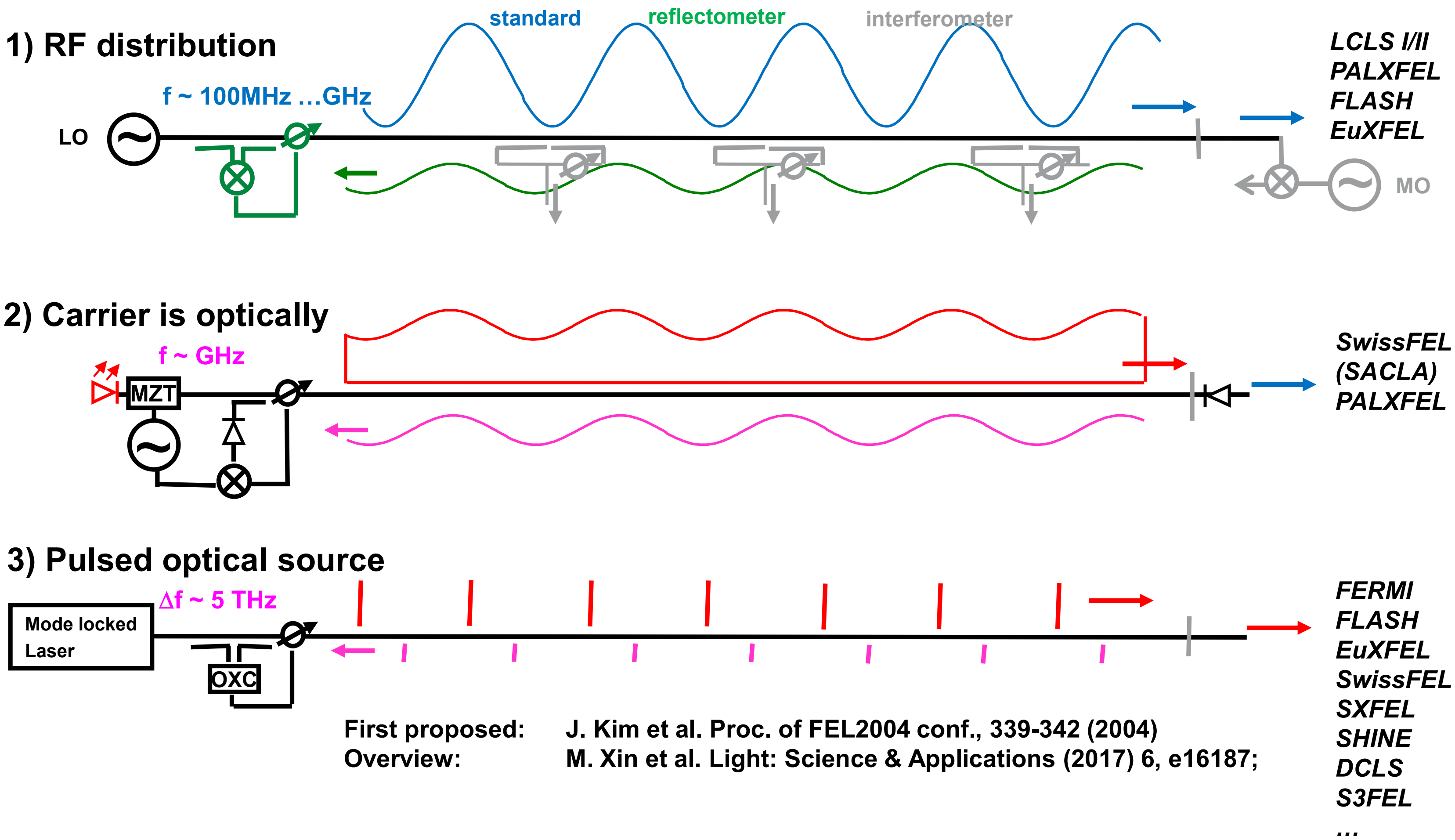
EuXFEL ~ 0.3 fs

# Optical Synchronization System at European XFEL

# Different synchronization approaches

## Various approaches:

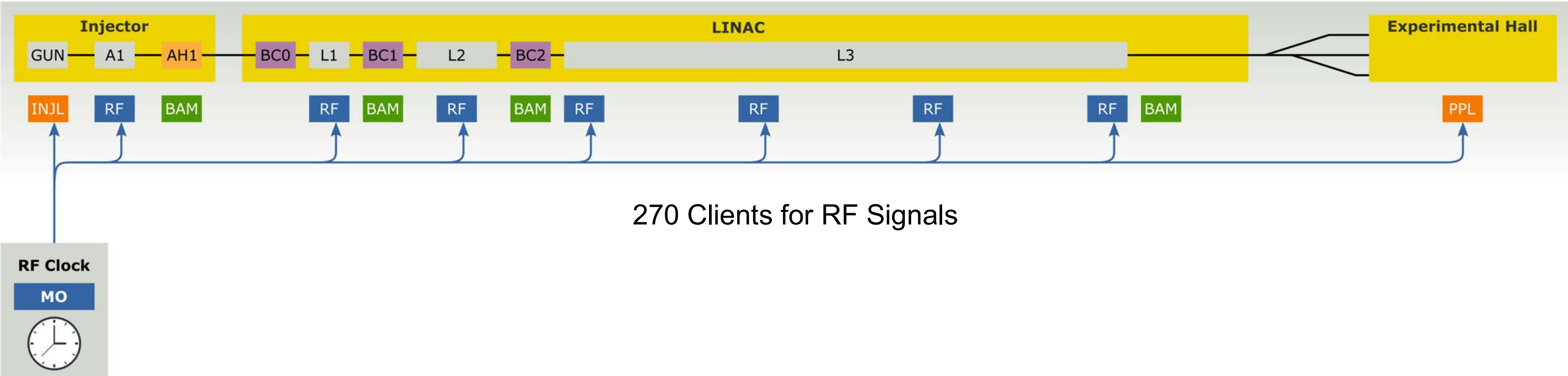
$$\frac{\Delta t}{t} = \frac{\Delta f}{f}$$




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

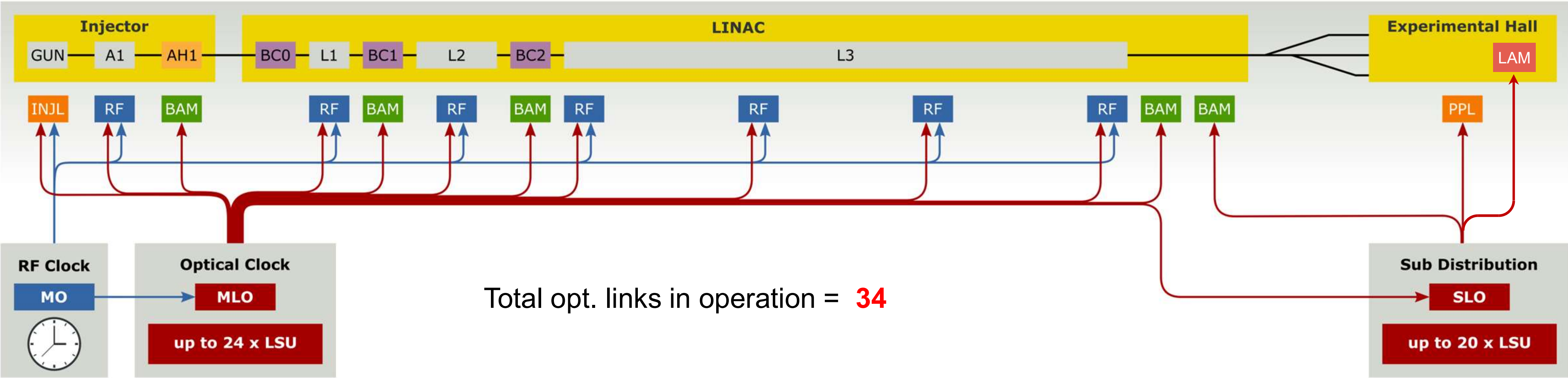



- **Availability:** RF mature technique, 24/7, low phase-noise!
- **But:**
  - **Cable drift**: ~10 fs/m/K → **35 ps/K** (3.5 km)
  - **Cable losses**: ~0.03 dB/m → **~100 dB** (3.5 km) → amplification adds drift/jitter
  - RF signals susceptible to **EMI**

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

# Optical Synchronization System at EuXFEL

## World-wide Unique Large-Scale 24/7 Operation

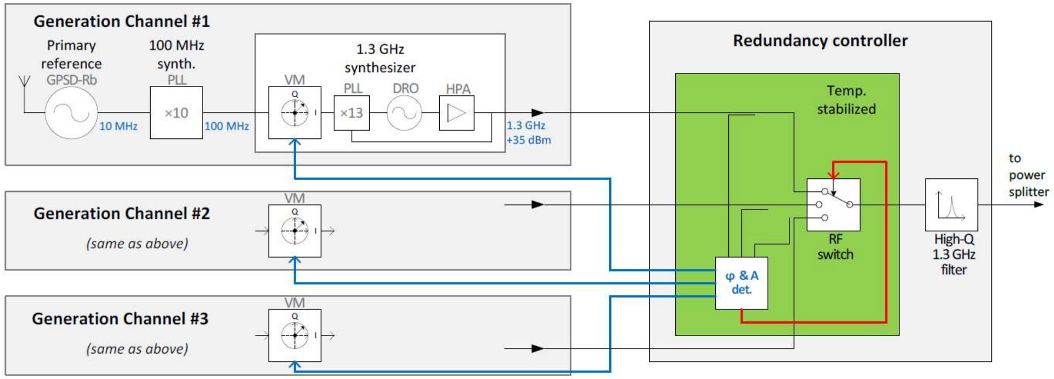


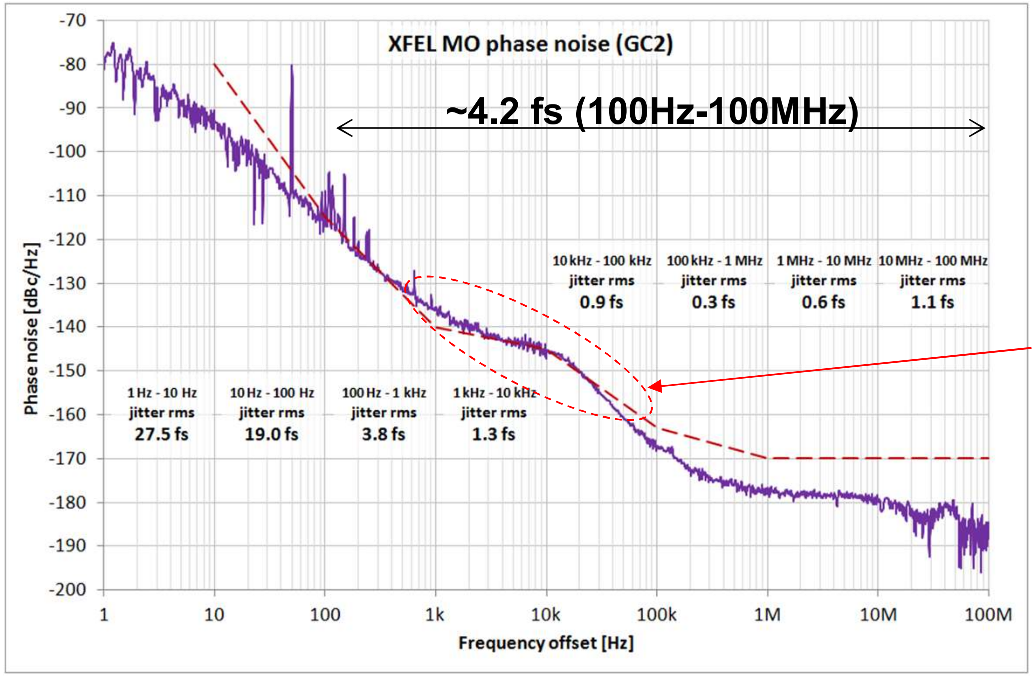

- **optical reference** (Main Laser Oscillator, MLO) tightly locked to RF Main Oscillator (MO), **distributed via length-stabilized optical fiber links** and used for
  - **Laser locking** (injector, pump-probe, …)
  - RF re-synchronization (**REFM-OPT**)
  - Bunch Arrival time Monitors (**BAM**)
  -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




Phase noise (&bump) caused residual error in MO - MLO Lock (~2-3 fs)

Courtesy: H. Pryschelski

# Main Laser Oscillator (MLO)

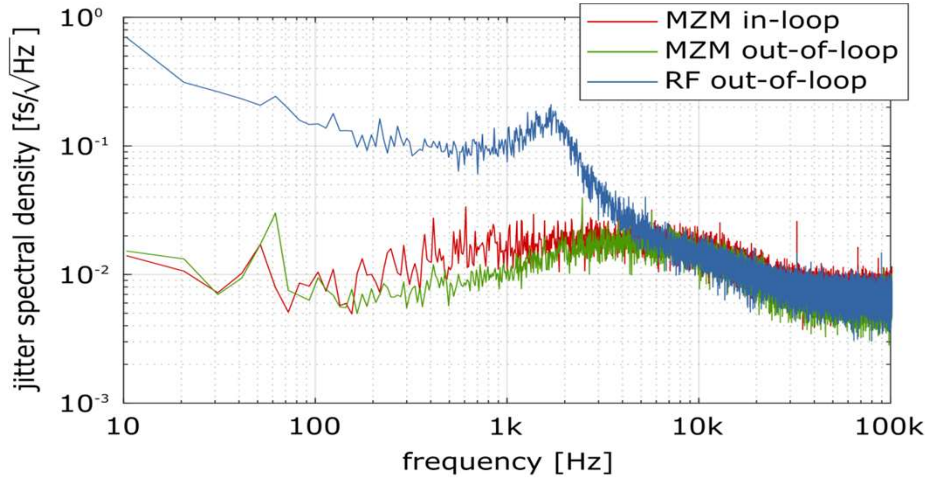
## The Main Optical Reference

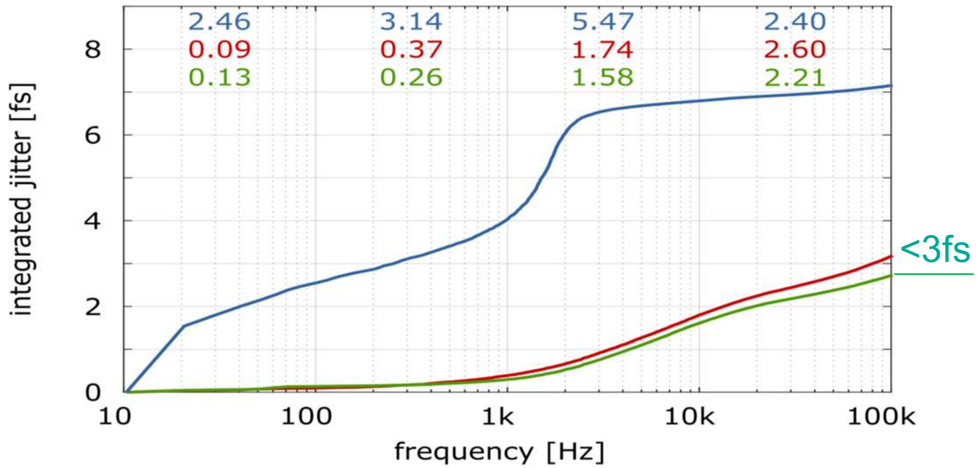
### *Oscillator*


- 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)



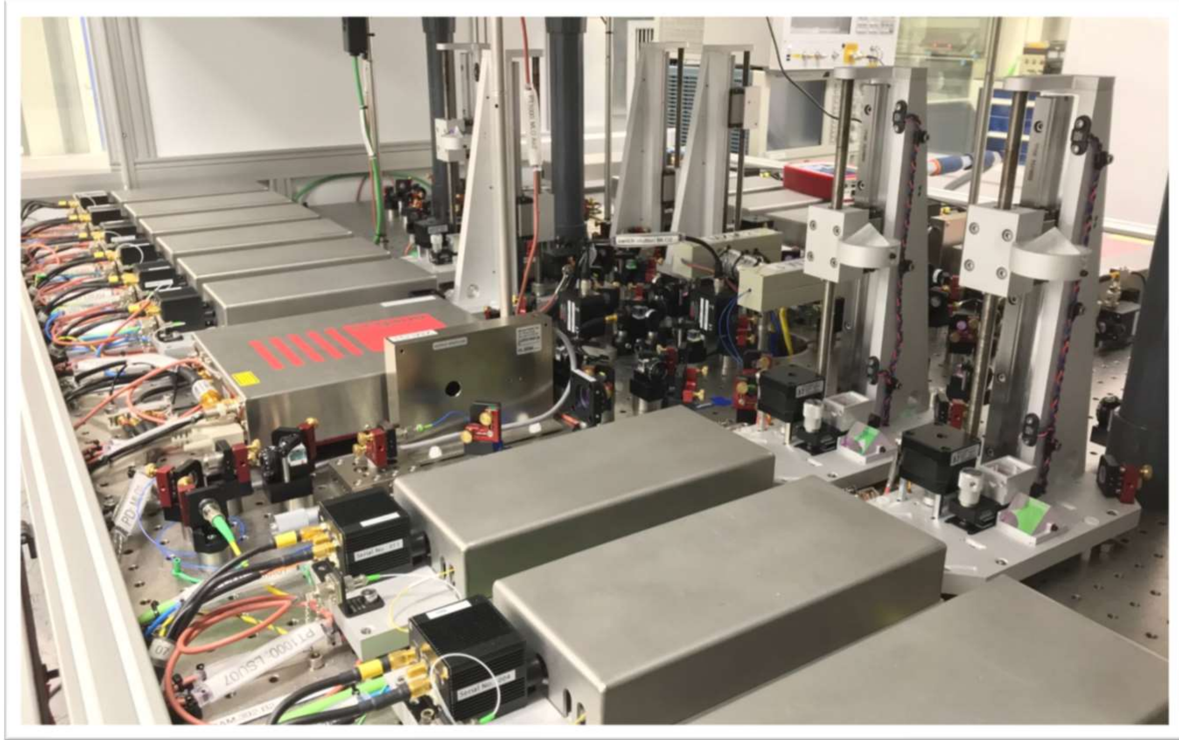




Courtesy: T. Lamb

# Free-Space Distribution

## Laser Beam Distribution for 24 Fiber Link Stabilization Units

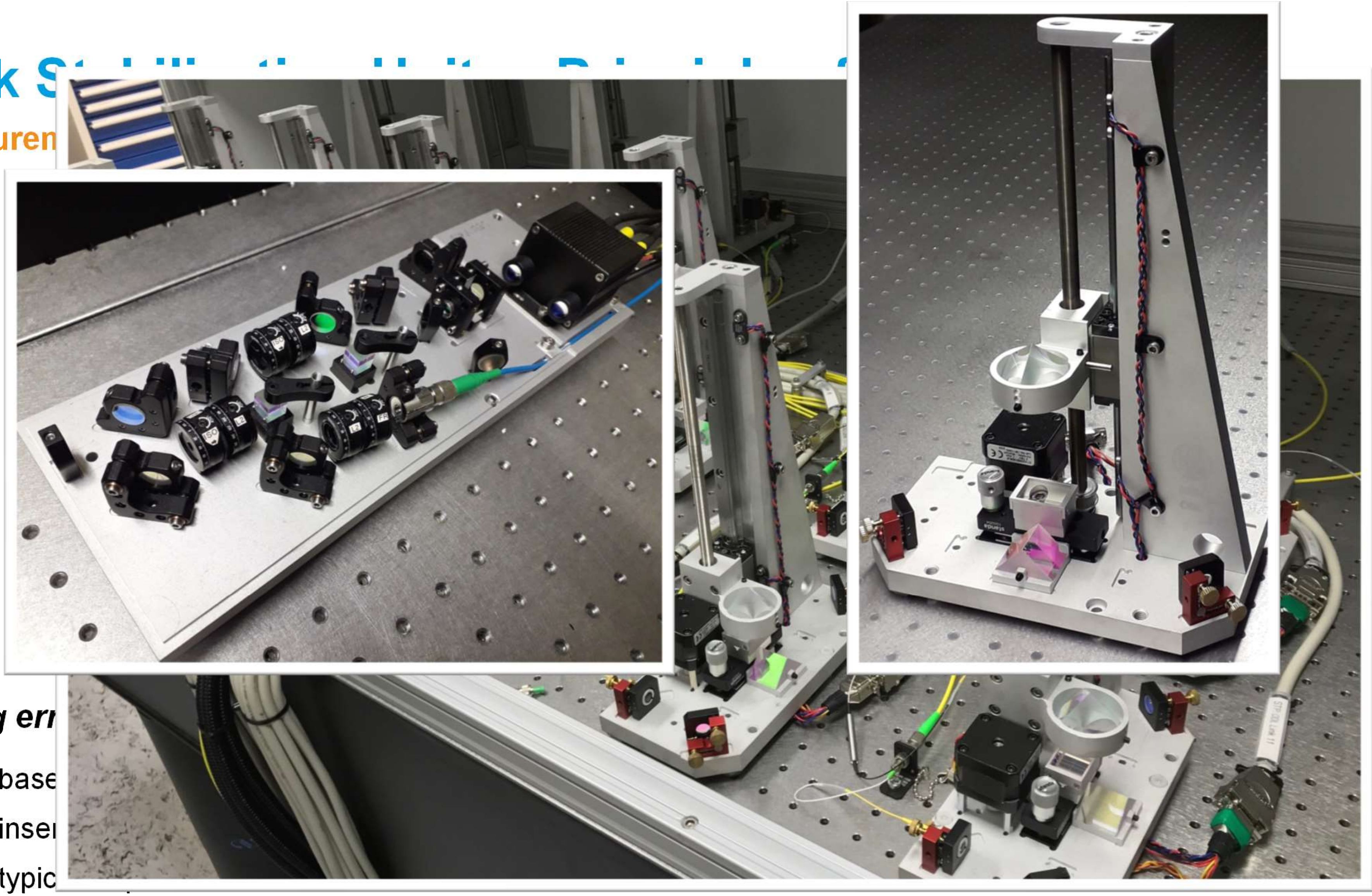
- **SuperInvar** optical table
  - thermal expansion coefficient ~1 fs/m/K
  - table covered and environmentally stable
  - $\ll$ 0.1 K temperature stability
  - < 1 % RH pkpk
- Space for **24 link stabilization units**
  - identical path lengths, symmetric setup
- 8 fiber links with **4 ns optical delay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



Courtesy: J. Mueller

# Link S

## Measuren



tion

***timing err***

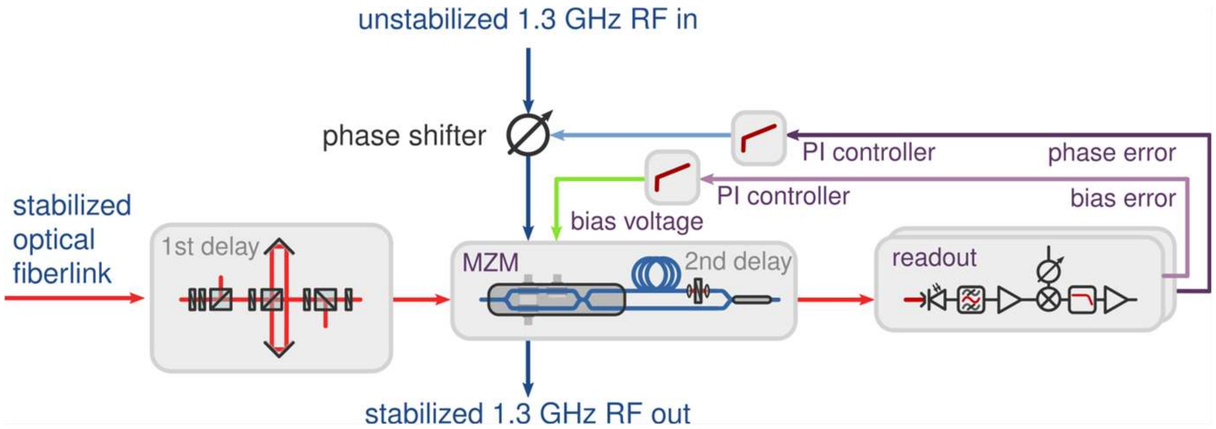
- base , fast)
- inser f-built
- typic

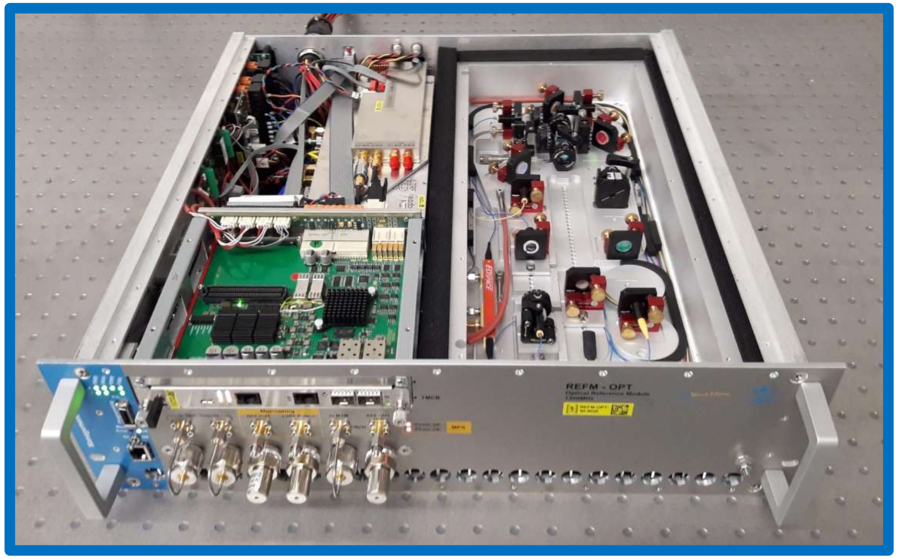
**Courtesy: J. Mueller**

# 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
- 1st delay line → RF sampled at 0° and 180°
- 2nd delay line → increase SNR + phase/bias feedback
- Sophisticated **exception handling**



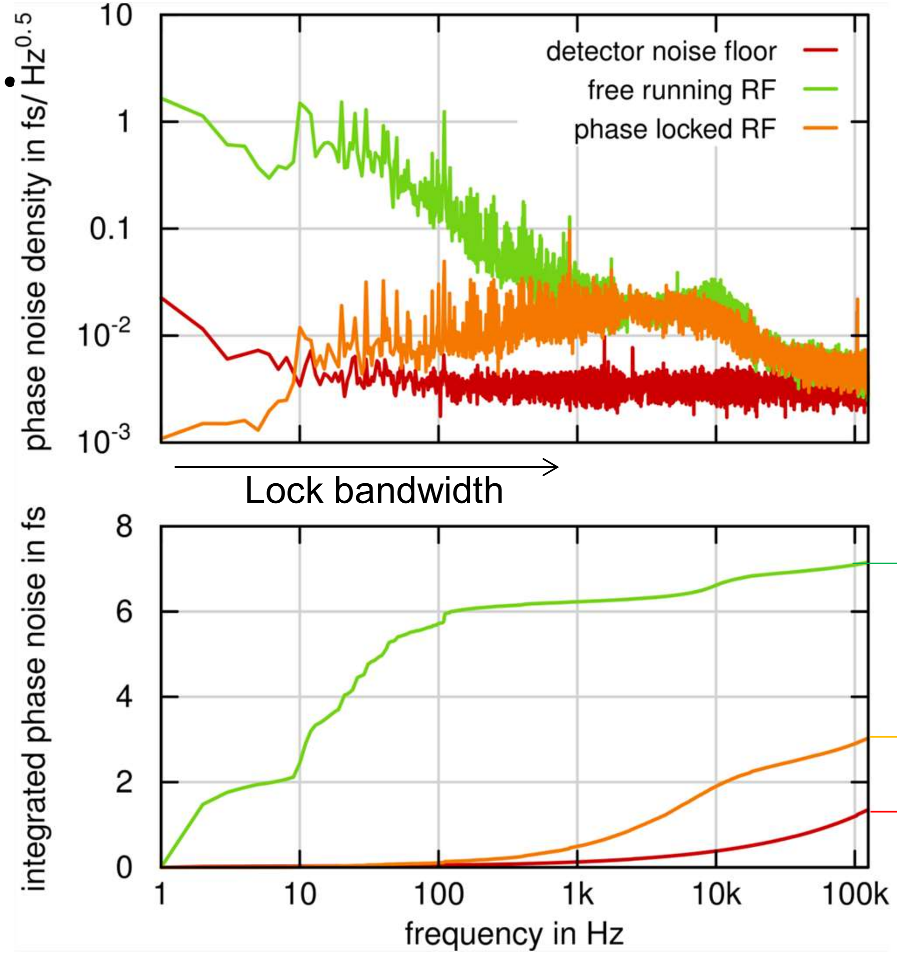

***engineering***

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

Courtesy: T. Lamb

# The Optical Reference Module (REFM-OPT)

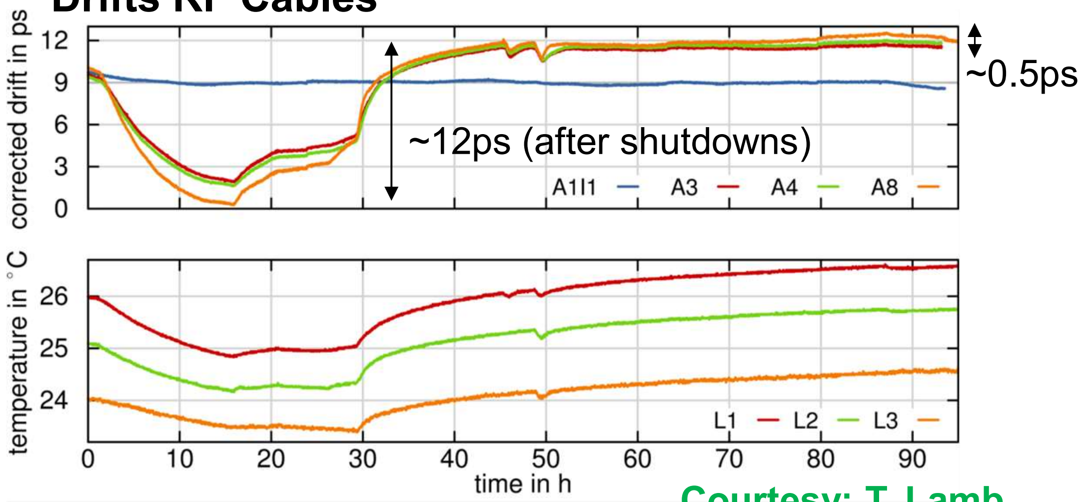
## Femtosecond RF Reference Phase Stabilisation




**Measurement Bandwidth 1 Hz to 125 kHz**

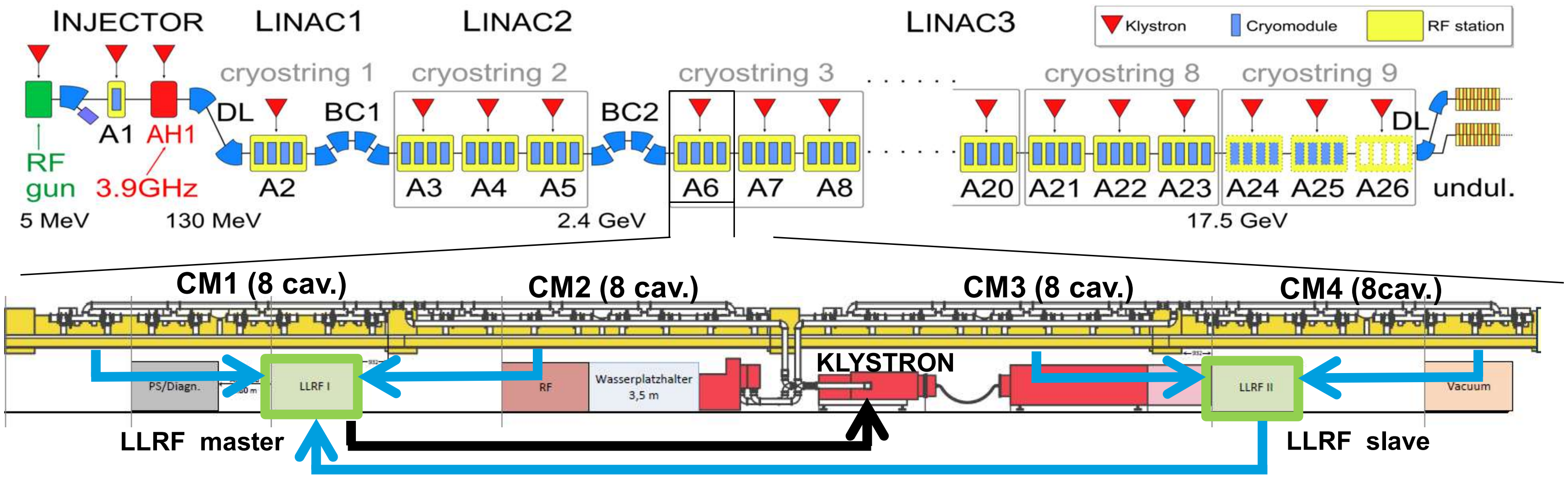
- $K_\varphi$ of 3.1 V/ps
- integrated detector noise floor 1.4 fs (red)
- unlocked RF integrated jitter 7.2 fs (green)
- locked RF integrated jitter 3.0 fs (orange)

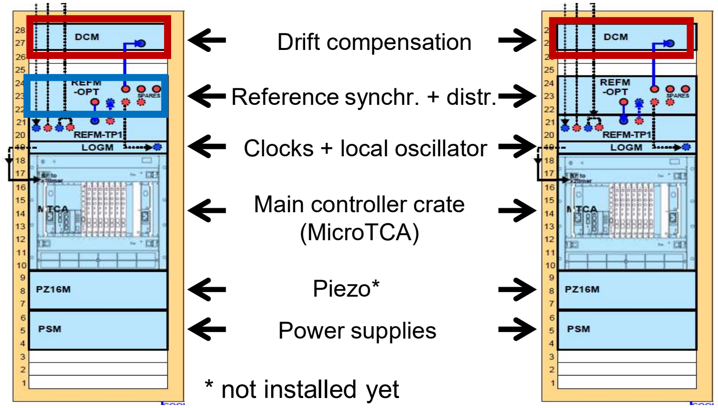
**Drifts RF Cables**

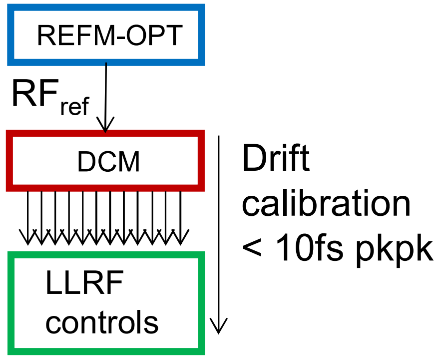



**Courtesy: T. Lamb**

# Precision RF controls



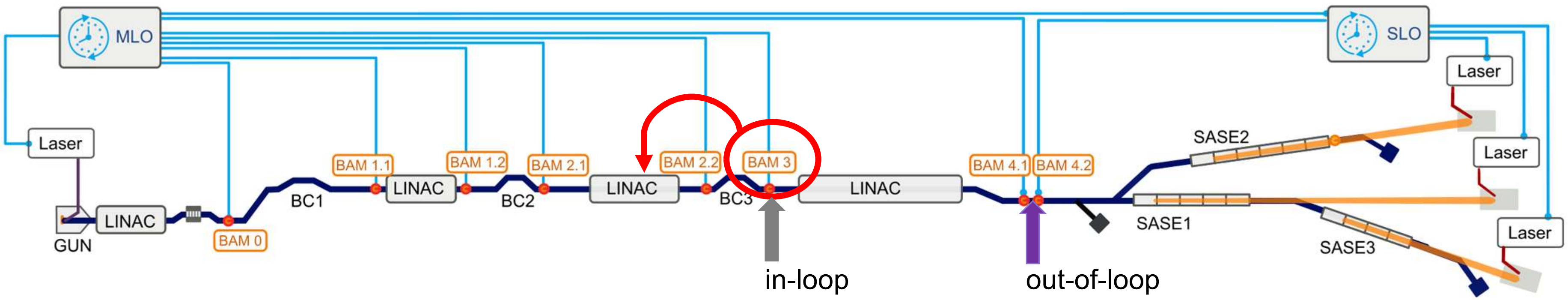



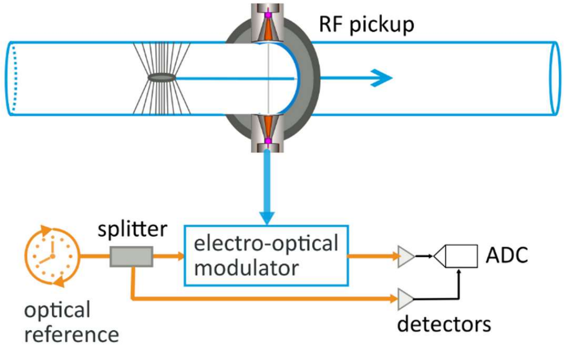

More than 3000 RF channels
Requirements: <0.01deg and <0.01%

**Courtesy J. Branlard**

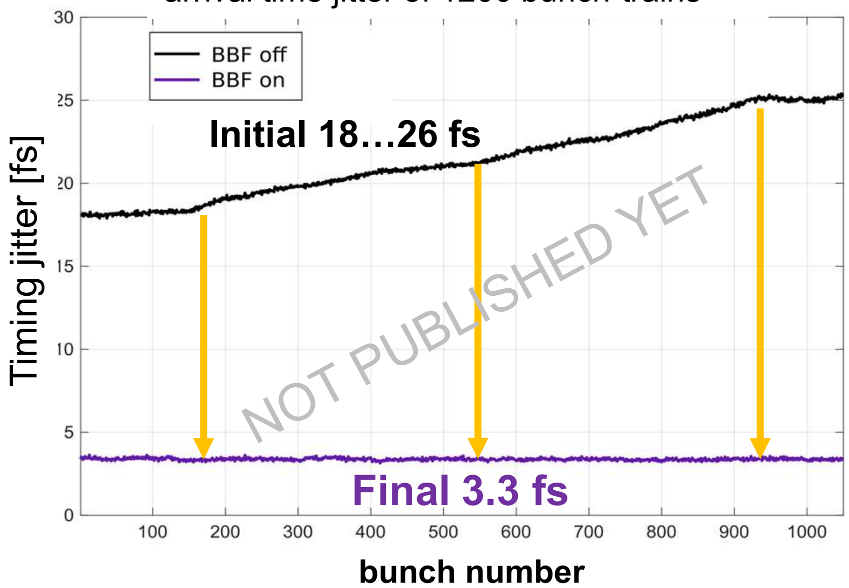
# New world record arrival stability

## Intra-burst arrival-time stability better than 4fs rms

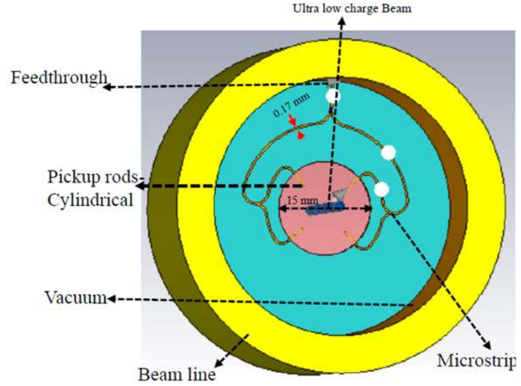



| Facility | Best | Daily |
|---|---|---|
| **EuXFEL** | 3.3 fs | ~ 4…5 fs |
| **FLASH** | 4.7 fs | ~ 6 fs |




**Goal: 1 fs next years**



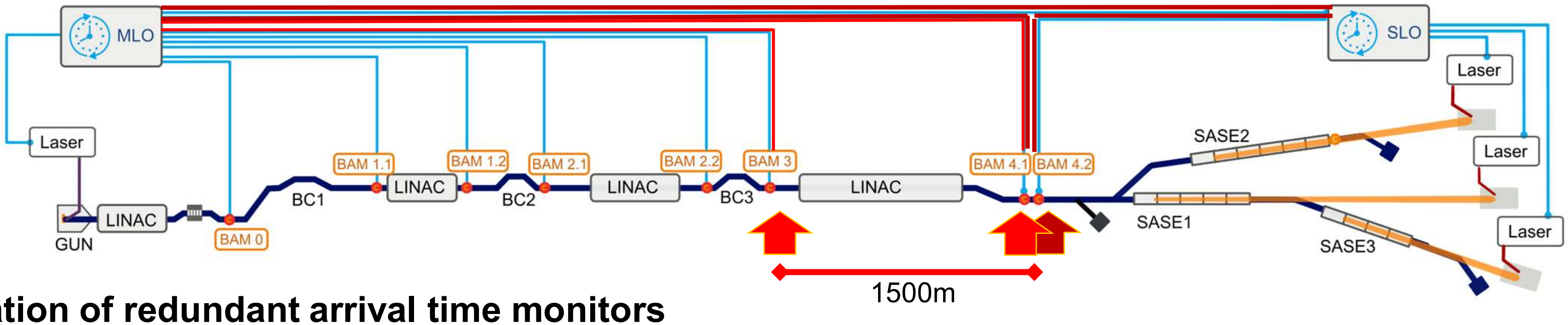

100GHz BAM



Courtesy: Marie Czwallina

# Evaluation of synchronization system performance

## Long-range synchronized links add only 700as residual noise



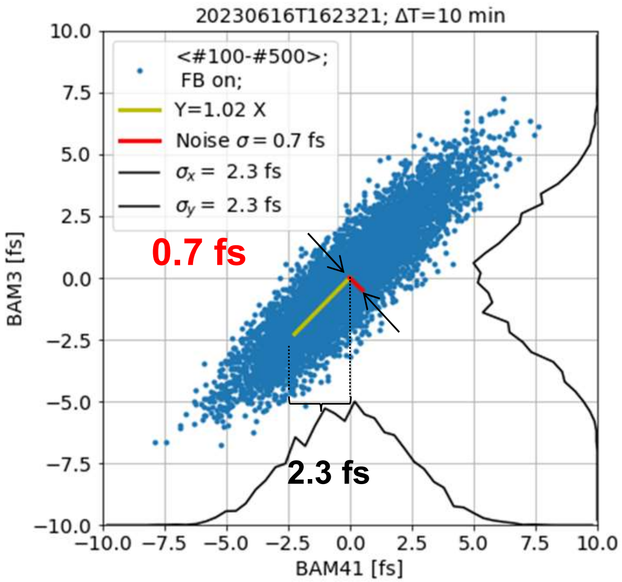

### Correlation of redundant arrival time monitors

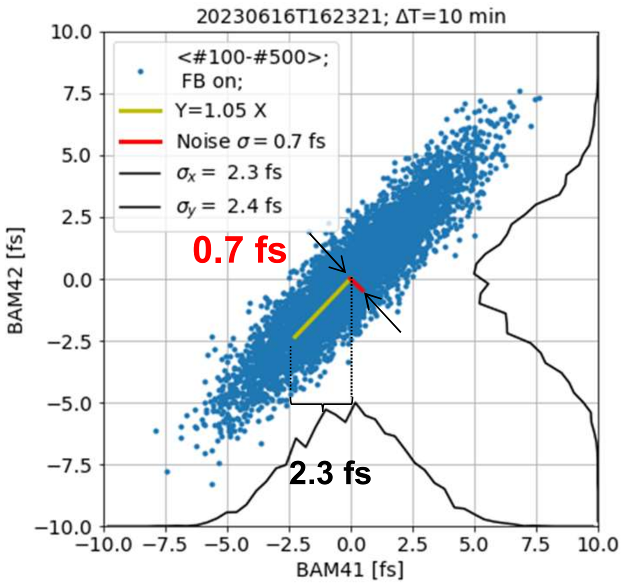
**10 min**. (6000 trains)
mean(400 bunches)

➔ Remove BAM high-freq. instr. noise

➔ Residual jitter of macro-pulses

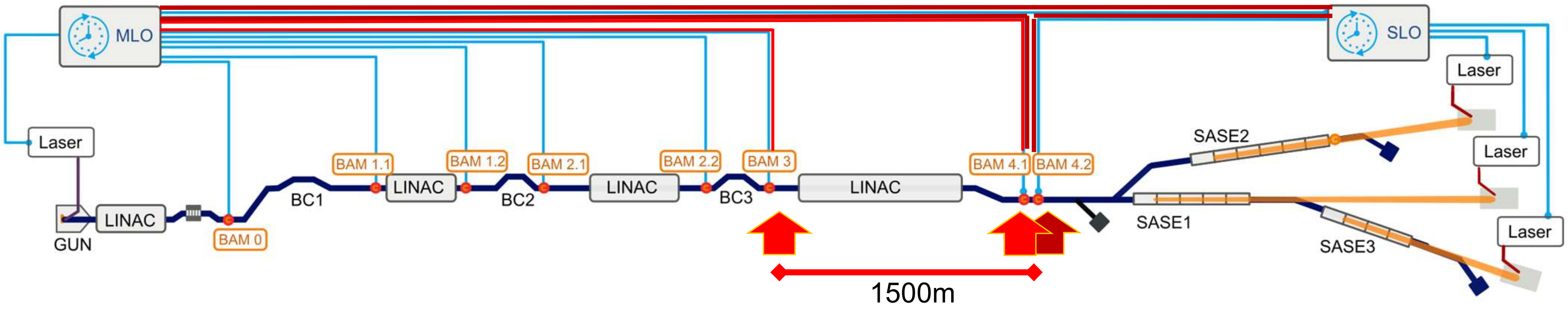
➔ Uncorrelated noise
= stability of optical reference

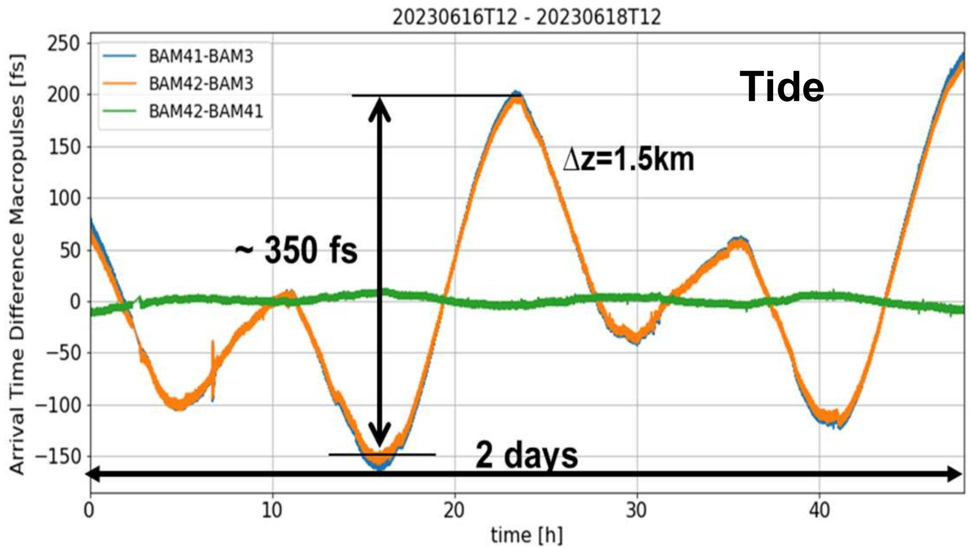


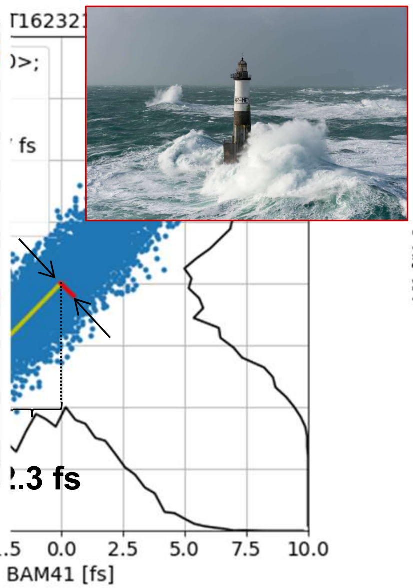



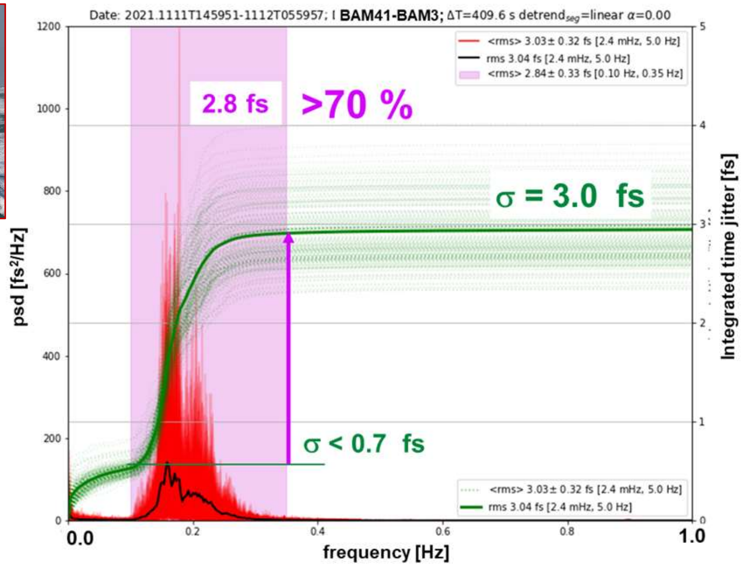
# Tide & micro-seismic

## Synchronisation



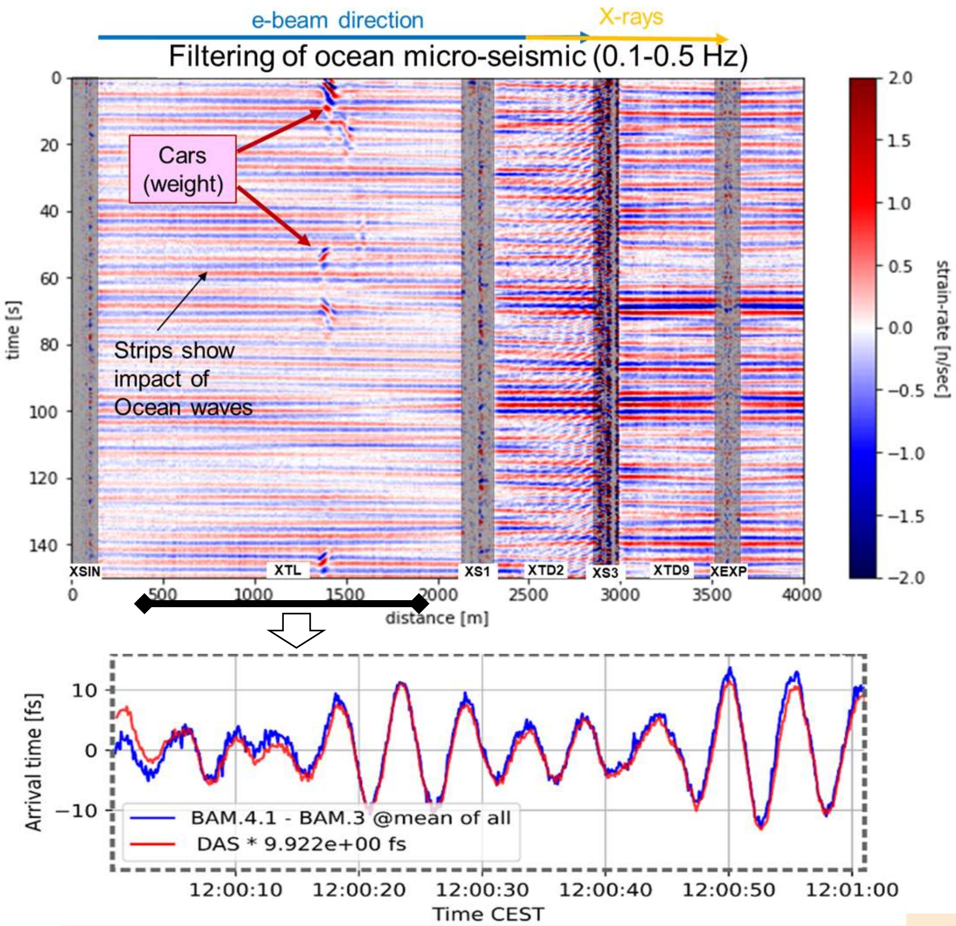



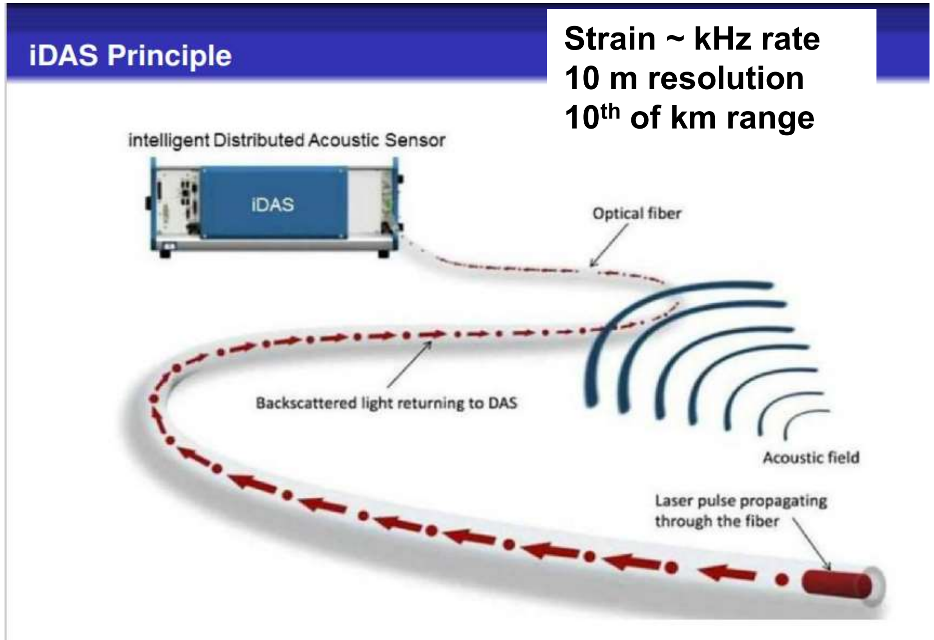



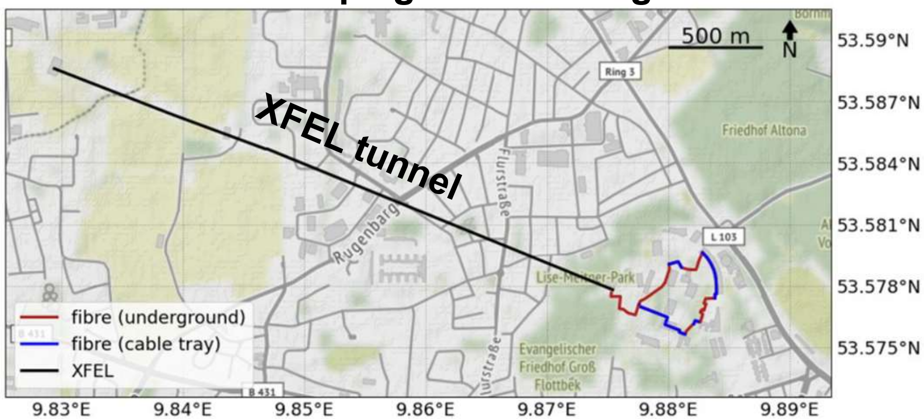
# Mitigation of micro-seismic

## Using distributed fiber optical sensing (DOFS) …



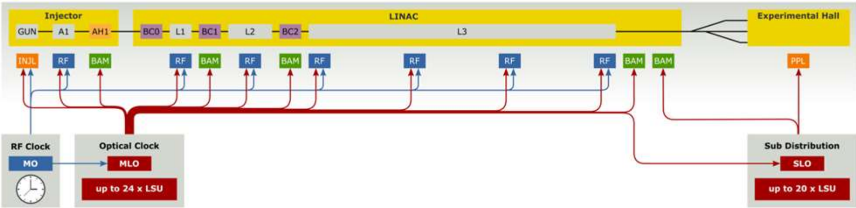

**Measurement campaign 12.6 m length**

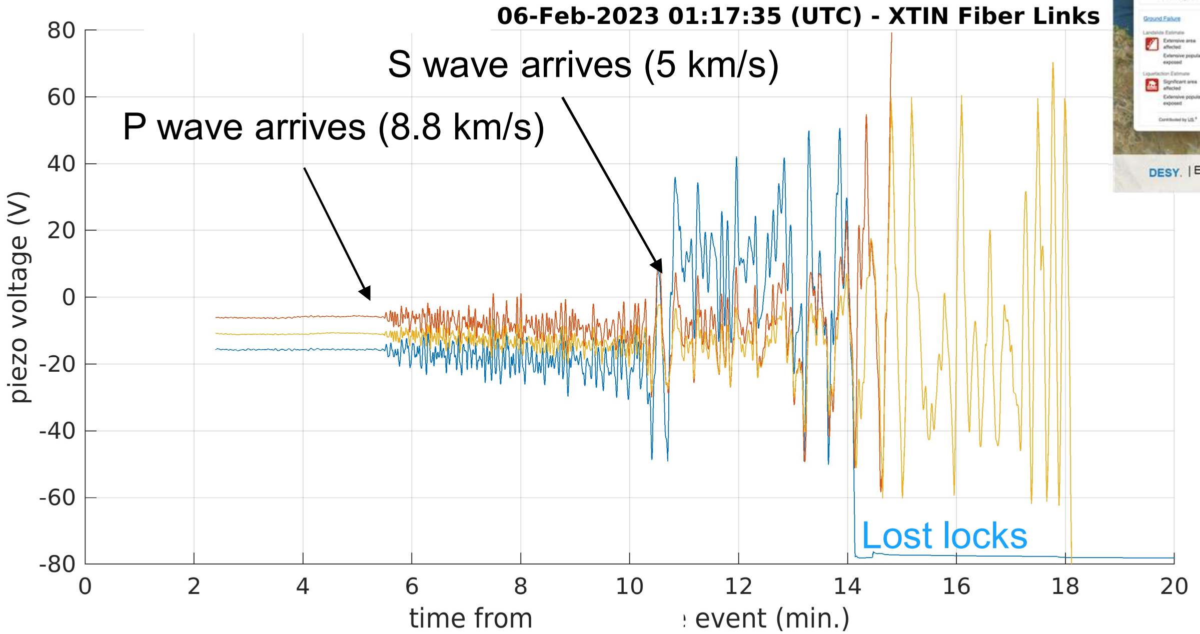


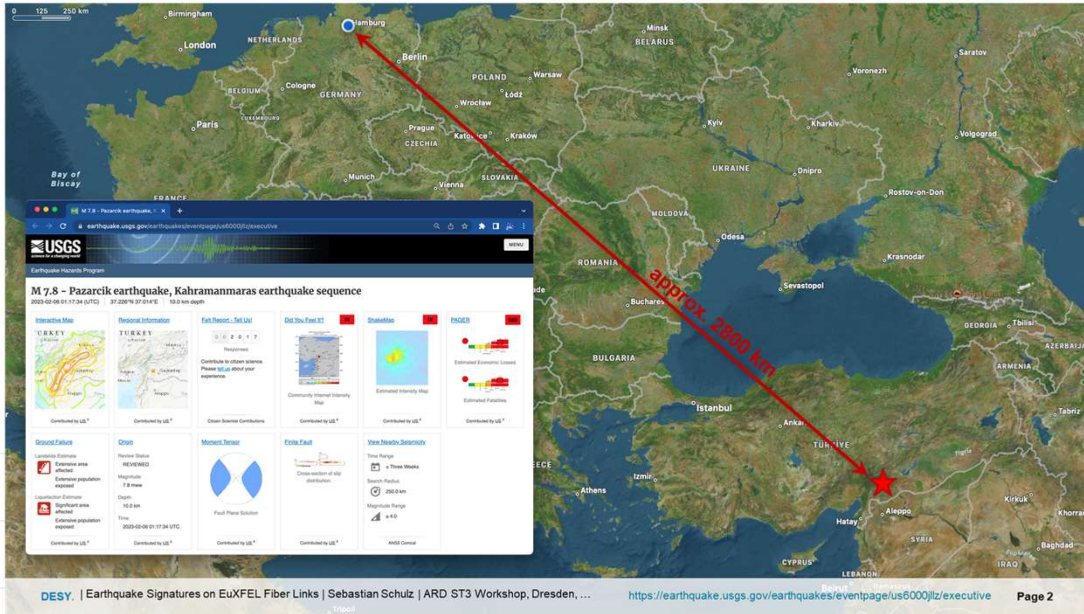

**Mitigation path:** predict impact of ocean wave

# 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 [mHz…kHz] | < 700 as | | |
| • Electron beam stabilization | ~ 4 fs | → | next gen BAMs ~ 1 fs |
| • 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 tough!
- 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, H. Pryschelski, Ch. Schmidt, S. Schulz, S. Sydlo, E. Schneidmiller, M. Yurkov, …
SPM/SFX-team, FXE-team, Beam Dynamics team,
and many more…

# What gives me headache ….

## Potential limitations e.g. in LLRF Systems

Short recab:

- ➢ R56 ~ 30mm @ 1fs stab. ➔ dA/A ~ 1e-5 (or better)
- ➢ Frequently observe beam stability worse than predicted by field measurements
- ➢ But also that lowering the beam rep. rate stability degrades (e.g. 1 MHz → 200kHz)

- Transient effect in cavities (filling/field variation)
- Long. Range Wakefields (pulsed but also in CW e.g. due to varying charge)
- Do we measure voltage that contributed to beam acceleration correctly?
  E.g. 7/9pi mode already contributes, imperfection of probe pickup, geometry
- Are chicane dipole PS stable enough (+ EMI may contribute)
- …