Reliable, Optically Augmented RF Reference Distribution with Femtosecond Stability

Maximilian Schütte on behalf of Thorsten Lamb and the LbSync & LLRF Teams
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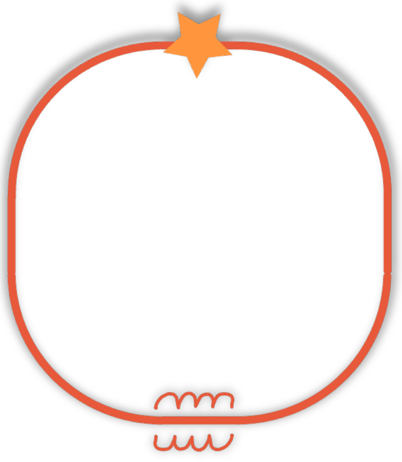
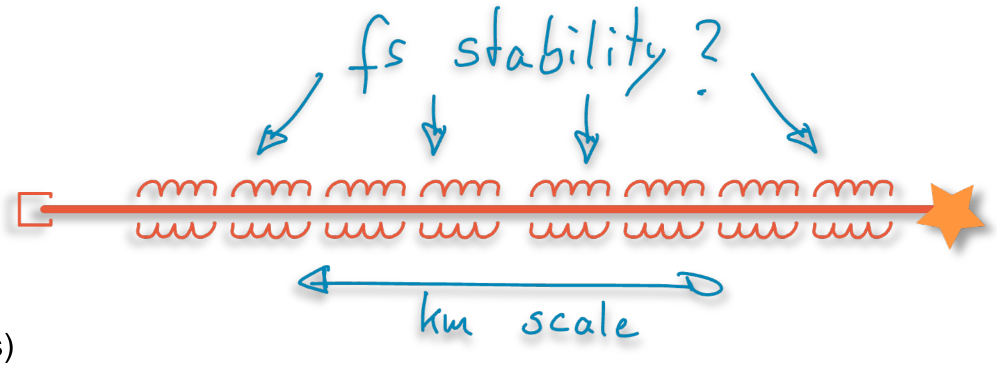
HELMHOLTZ

RF Reference Distribution for Accelerators

- Storage rings have **localized** LLRF systems
  - small number of cavities, close together, approx. picosecond requirements
- Linear accelerators (LINACs) have **distributed** LLRF systems
  - large number of cavities, **distributed** along the LINAC, the system scales with facility size
  - FELs have the highest stability requirements (femtosecond and attosecond science)



- Finding a suitable solution: Gather your requirements:
  - Frequency ➔ affects insertion loss
  - Distance, cable type ➔ insertion loss, drift stability
  - Number of clients, output power ➔ power budget, amplifiers
  - Phase stability (time scale / bandwidth) ➔ **stabilization (active or passive) required?**



- Not in this talk
  - In rack distribution aka „the last mile“ (this is a common problem of all presented solutions)
  - Accelerator based drift compensation (beam based feedbacks)

Centralized Coaxial Distribution

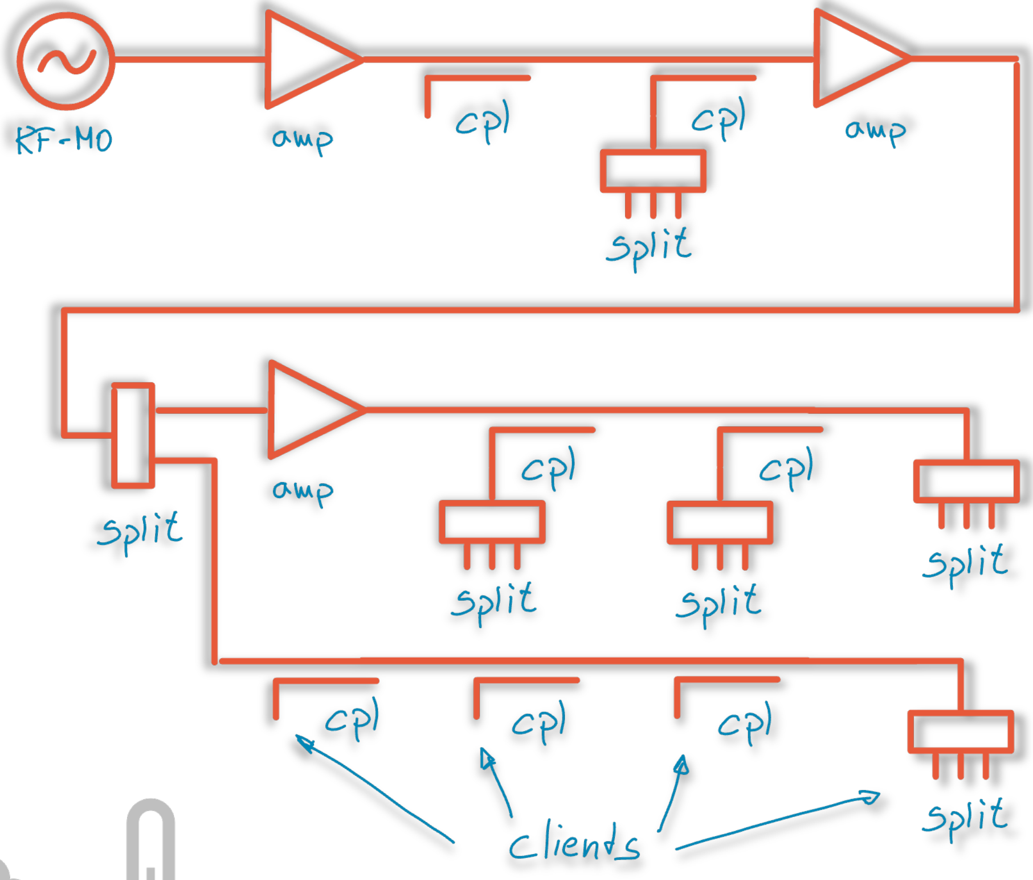
Unstabilized RF Distribution

- Central RF Main Oscillator (RF-MO)
  - **Redundant construction possible ➔ high reliability**
  - Low phase noise RF oscillators are expensive ➔ only invest once
- RF amplifiers (as required)
  - Mature technology -> high reliability
  - Negligible timing jitter increase (if carefully selected / designed)
- Cables, splitters, couplers

➔ Scalable, affordable

- Can be extended with high flexibility

➔ Low complexity, reliable components, self-sufficient



➔ Drawback: Long term drift due to environmental changes

- Temperature, Humidity (cable properties: **20fs/m/K or worse**, 100fs/m/%RH but with large τ)

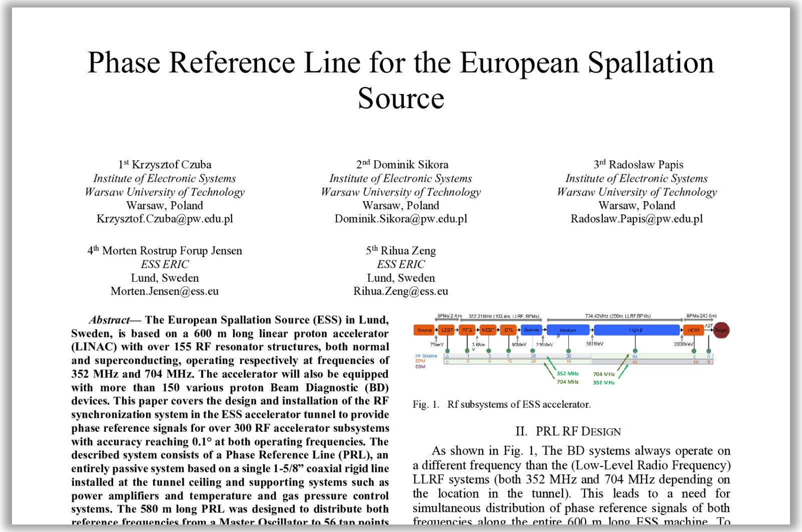
ESS Phase Reference Line

Temperature and Pressure Stabilization

- 1-5/8“ coaxial rigid transfer line
  - Two segments, driven from the center, ~600m combined length
  - 56 tap points
- 2 frequencies transmitted (352 MHz and 704 MHz)
- No intermediate (drifting) amplifiers
- Temperature stabilized (0.01°C pp)
- Transfer line flushed with dry nitrogen
  - Pressure stabilized to 1100mbar +/- 2 mbar
- Independent Stability measurement at 704MHz
  - **Distance 123m, duration 60h**
  - **0.58° (= 2.3ps) peak to peak drift -> well below spec**

➔ Limited length and number of clients due to power budget

➔ Residual drift



Phase Reference Line for the European Spallation Source

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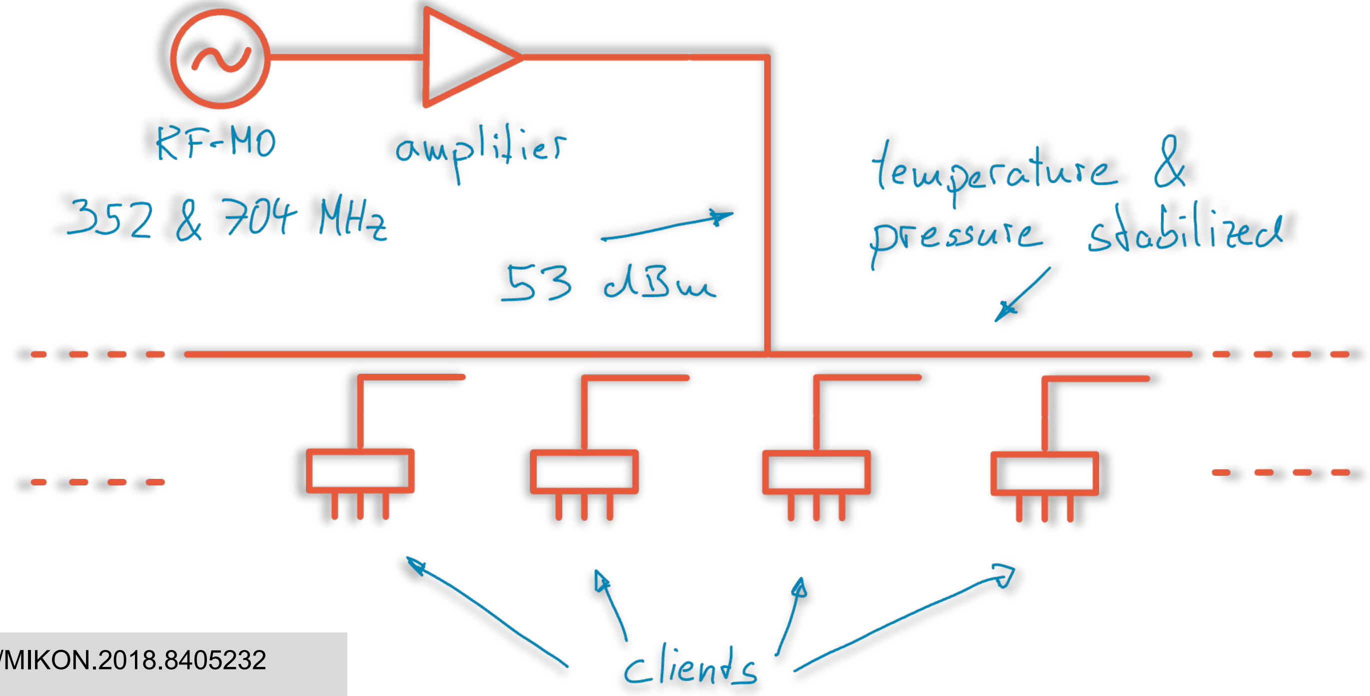
Abstract— The European Spallation Source (ESS) in Lund, Sweden, is based on a 600 m long linear proton accelerator (LINAC) with over 155 RF resonator structures, both normal and superconducting, operating respectively at frequencies of 352 MHz and 704 MHz. The accelerator will also be equipped with more than 150 various proton Beam Diagnostic (BD) devices. This paper covers the design and installation of the RF synchronization system in the ESS accelerator tunnel to provide phase reference signals for over 300 RF accelerator subsystems with accuracy reaching 0.1° at both operating frequencies. The described system consists of a Phase Reference Line (PRL), an entirely passive system based on a single 1-5/8" coaxial rigid line installed at the tunnel ceiling and supporting systems such as power amplifiers and temperature and gas pressure control systems. The 580 m long PRL was designed to distribute both reference frequencies from a Master Oscillator to 56 tap points

Fig. 1. Rf subsystems of ESS accelerator.

II. PRL RF DESIGN

As shown in Fig. 1, The BD systems always operate on a different frequency than the (Low-Level Radio Frequency) LLRF systems (both 352 MHz and 704 MHz depending on the location in the tunnel). This leads to a need for simultaneous distribution of phase reference signals of both frequencies along the entire 600 m long ESS machine. To



Czuba (2018) https://doi.org/10.23919/MIKON.2018.8405232
Czuba (2023) Talk: LLRF ‘23

PAL-XFEL Reference Line

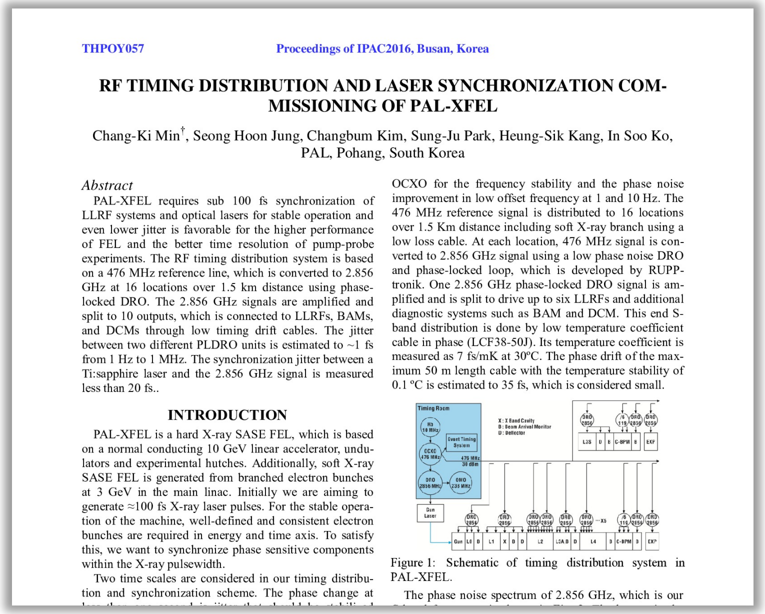
Temperature Stabilization and Local Resynchronization

- Coaxial transfer line (Cellflex cable)
  - 1.5km length, ~18 tap points
- 476 MHz transmitted
- distributed DROs (2856 MHz) locally resynchronized
- No intermediate (drifting) amplifiers
- Temperature stabilized (0.01°C per day)
- Independent stability measurement at 2856 MHz
  - **distance 750m, 3 days ➔1ps peak to peak drift**

➔ Residual drift (is removed via beam based feedback)

➔ Low phase noise DRO required

➔ Challenging installation (vibration sensitivity of DROs)


THPOY057 Proceedings of IPAC2016, Busan, Korea

RF TIMING DISTRIBUTION AND LASER SYNCHRONIZATION COM-MISSIONING OF PAL-XFEL

Chang-Ki Min†, Seong Hoon Jung, Changbum Kim, Sung-Ju Park, Heung-Sik Kang, In Soo Ko, PAL, Pohang, South Korea

Abstract

PAL-XFEL requires sub 100 fs synchronization of LLRF systems and optical lasers for stable operation and even lower jitter is favorable for the higher performance of FEL and the better time resolution of pump-probe experiments. The RF timing distribution system is based on a 476 MHz reference line, which is converted to 2.856 GHz at 16 locations over 1.5 km distance using phase-locked DRO. The 2.856 GHz signals are amplified and split to 10 outputs, which is connected to LLRFs, BAMs, and DCMs through low timing drift cables. The jitter between two different PLDRO units is estimated to ~1 fs from 1 Hz to 1 MHz. The synchronization jitter between a Ti:sapphire laser and the 2.856 GHz signal is measured less than 20 fs..

INTRODUCTION

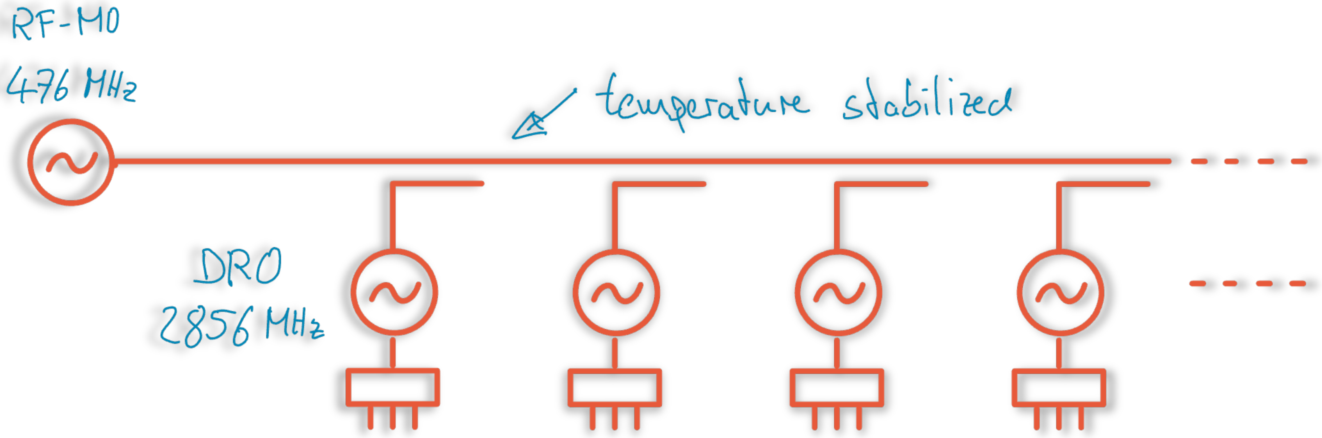
PAL-XFEL is a hard X-ray SASE FEL, which is based on a normal conducting 10 GeV linear accelerator, undulators and experimental hutches. Additionally, soft X-ray SASE FEL is generated from branched electron bunches at 3 GeV in the main linac. Initially we are aiming to generate ≈100 fs X-ray laser pulses. For the stable operation of the machine, well-defined and consistent electron bunches are required in energy and time axis. To satisfy this, we want to synchronize phase sensitive components within the X-ray pulsewidth.

Two time scales are considered in our timing distribution and synchronization scheme. The phase change at

OCXO for the frequency stability and the phase noise improvement in low offset frequency at 1 and 10 Hz. The 476 MHz reference signal is distributed to 16 locations over 1.5 Km distance including soft X-ray branch using a low loss cable. At each location, 476 MHz signal is converted to 2.856 GHz signal using a low phase noise DRO and phase-locked loop, which is developed by RUPP-tronik. One 2.856 GHz phase-locked DRO signal is amplified and is split to drive up to six LLRFs and additional diagnostic systems such as BAM and DCM. This end S-band distribution is done by low temperature coefficient cable in phase (LCF38-50J). Its temperature coefficient is measured as 7 fs/mK at 30°C. The phase drift of the maximum 50 m length cable with the temperature stability of 0.1 °C is estimated to 35 fs, which is considered small.

Figure 1: Schematic of timing distribution system in PAL-XFEL.

The phase noise spectrum of 2.856 GHz, which is our

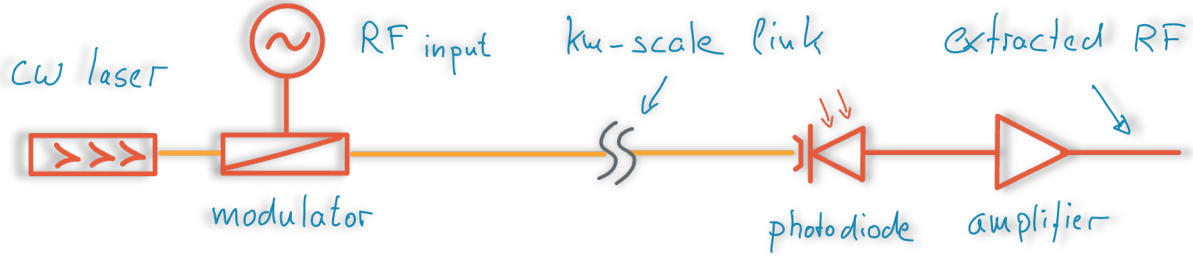


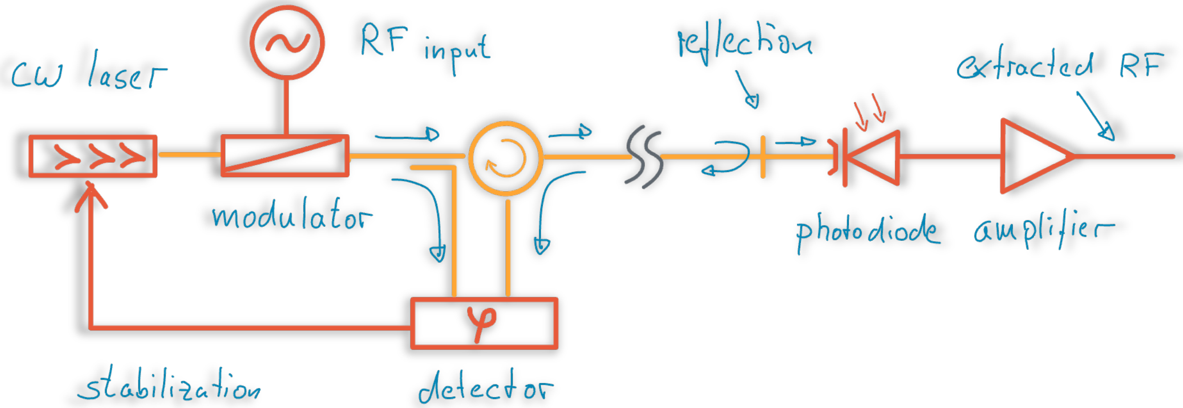
Min (2016) https://doi.org/10.18429/JACoW-IPAC2016-THPOY057
Min (2023) Talk: LLRF '23

RF over Fiber (RFoF)

CW Optical Transmission

- **Why use lasers if the client needs RF?**
- Optical fibers have much lower insertion loss than RF cables
  - Example: 7/8" CELLFLEX **4dB/100m** at 1GHz
  - Compare: SMF-28e+ **0.02dB/100m** at 1550nm wavelength
  - ➔ suited for long distance signal transmission
- Optical fibers are insensitive to EMI
- But: **optical fibers are (like RF cables) not length stable**
  - sensitive to temperature, humidity and mechanical stress
- Also: **(phase stable) signal recovery is non-trivial**
  - AM/PM in photodiodes, SNR
  - Low RF power from photodiodes, might need amplification (stability issue)
- Different topology: point to point connections, no intermediate taps (if stabilized)





Examples:
- Berkeley Sync Head (accelerator community development, pioneering work)
- i-tech Libera Sync 3 (commercial system, developed with PSI)
  - ➔ 40fs peak to peak drift (24h, 3GHz, Hunziker (2014) https://epaper.kek.jp/IBIC2014/papers/moczb2.pdf)

Intermediate Summary

Unstabilized Centralized Coaxial Distribution

- Periodically amplify the signal, tap/split as needed
- Low complexity ➔ high robustness

➔ **Cost efficient and scalable**
(number of clients, transmission distance)

➔ Phase drifts of cables, amplifiers, … (many picoseconds)

RF over Fiber

- Suited **for long distance transmission**
- Only point to point connections, no intermediate taps
- Careful additive jitter characterization (due to photodiodes)

➔ Stabilized but with residual drift (> 40 femtoseconds)

Stabilized Coaxial Distribution

- Temperature stabilization, pressure stabilization
- Interferometric stabilization (not presented)

➔ Successfully implemented in actual accelerators

➔ No intermediate amplifiers
(limited number of clients, limited distance)

➔ Stabilized but with residual drift (picosecond range)

Can we **combine all advantages** in one system?

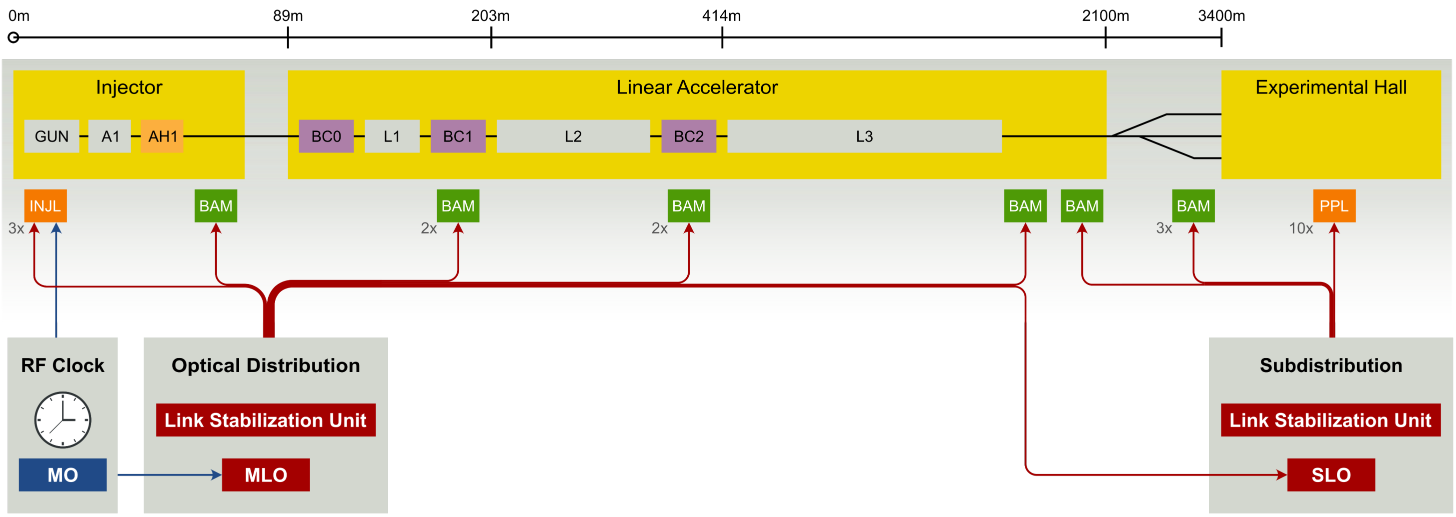
- **Cost efficient and scalable**
- **Long Distance Transmission**
- **Robust**
- **Low additive jitter (femtosecond range)**
- **Low drift (below 10fs) over long distances (~km)**

Pulsed Optical Synchronization Systems

Use the Existing Infrastructure

- **Many FELs already have pulsed optical synchronization systems**
  - SwissFEL, LCLS-II, FERMI, EuXFEL, FLASH, SHINE, SXFEL, TELBE, CLARA
- Active **fiberlink stabilization with femtosecond stability** (using optical cross-correlation)
  - Suited for **long distances due to low fiber insertion loss** (point to point connections)
- A pulsed optical synchronization system is typically used to
  - **synchronize lasers** on a femtosecond scale (using optical cross-correlation)
  - **measure the bunch arrival time with femtosecond precision** (BAM)

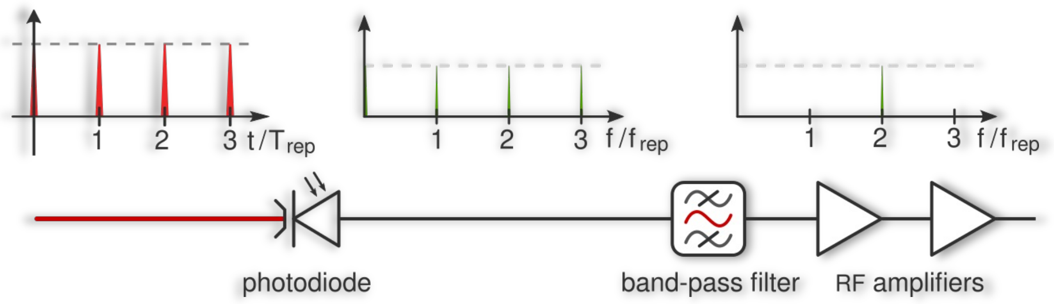
How to make use of the pulsed optical synchronization system to stabilize your RF distribution?



Opto-Electrical Phase Detection

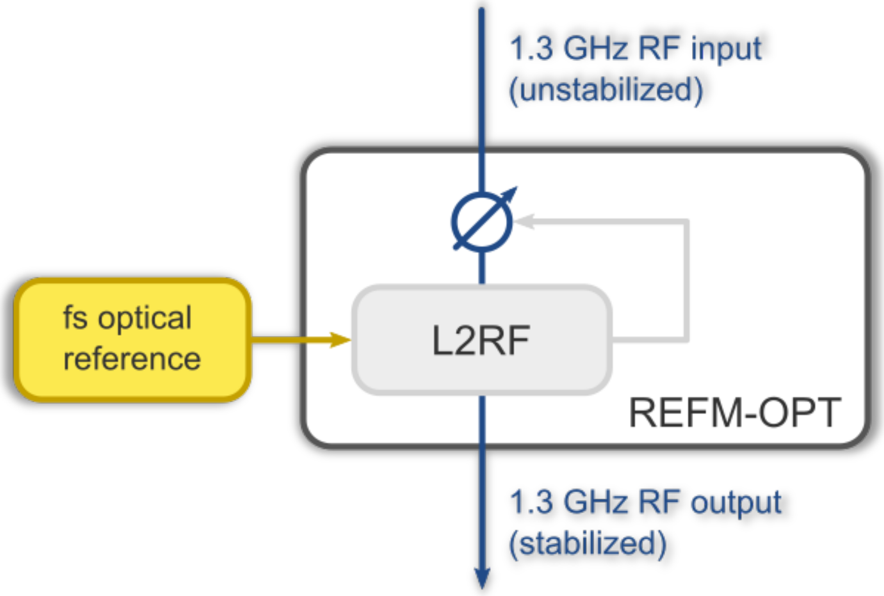
For Cross-Domain PLLs

- Low drift and low noise signal recovery using photodiodes is tricky and **not recommended if you aim for fs stability**
  - AM/PM in photodiodes, SNR
  - Temperature and humidity sensitivity of components



➔ Use an **opto-electric phase detector** to measure and correct the drifts of your RF signals

- **fs stability and sensitivity required**



- Established techniques for opto-electrical phase detectors
  - **Sagnac Loop** based phase detectors (known as BOM-PD, FLOM-PD, …)

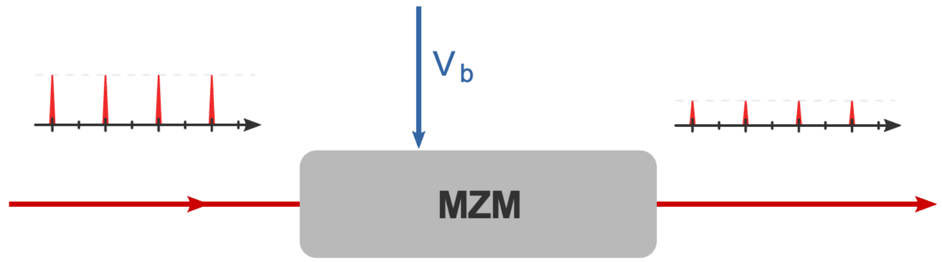
    Kim (2004) https://doi.org/10.1364/OL.29.002076
    Kim (2006) https://doi.org/10.1364/OL.31.003659
    Jung (2012) https://doi.org/10.1364/OL.37.002958
    Jeon (2018) https://doi.org/10.1364/OL.43.003997

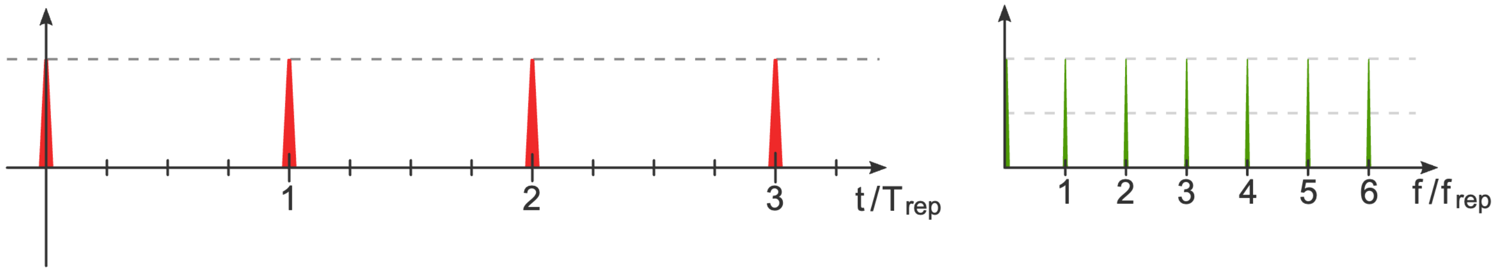
  - MZM based phase detectors (known as **L2RF phase detector**)

    Lamb (2017) https://doi.org/10.3204/PUBDB-2017-02117

L2RF Phase Detector Scheme

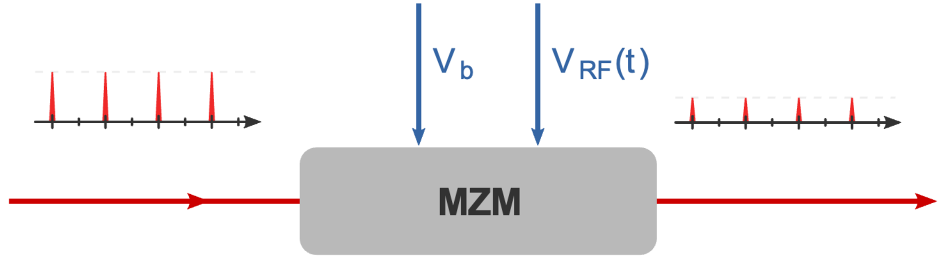
Sampling the RF Signal with Laser Pulses (Simplified)

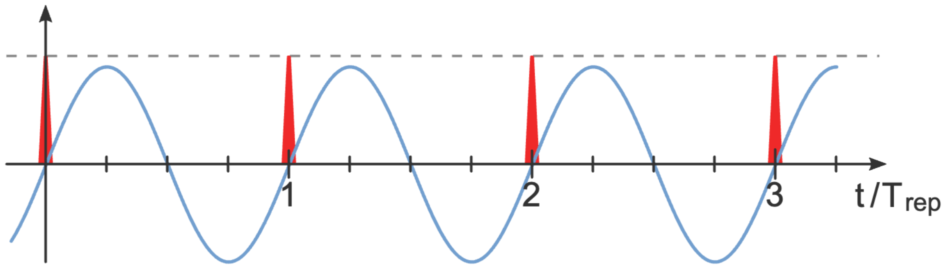


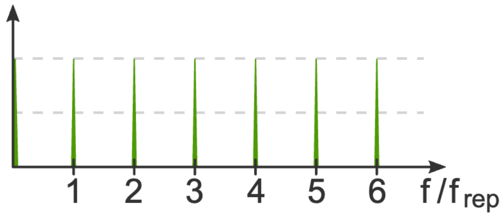


L2RF Phase Detector Scheme

Sampling the RF Signal with Laser Pulses (Simplified)

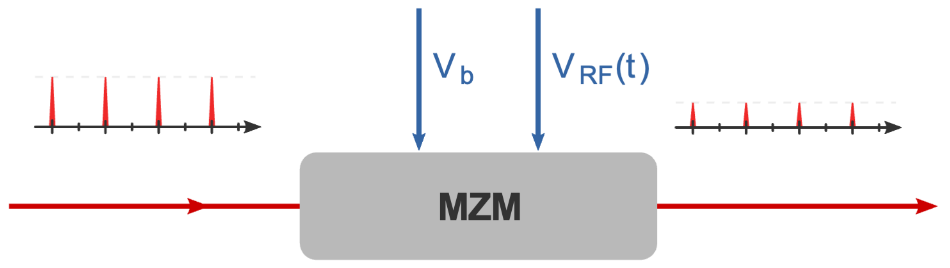


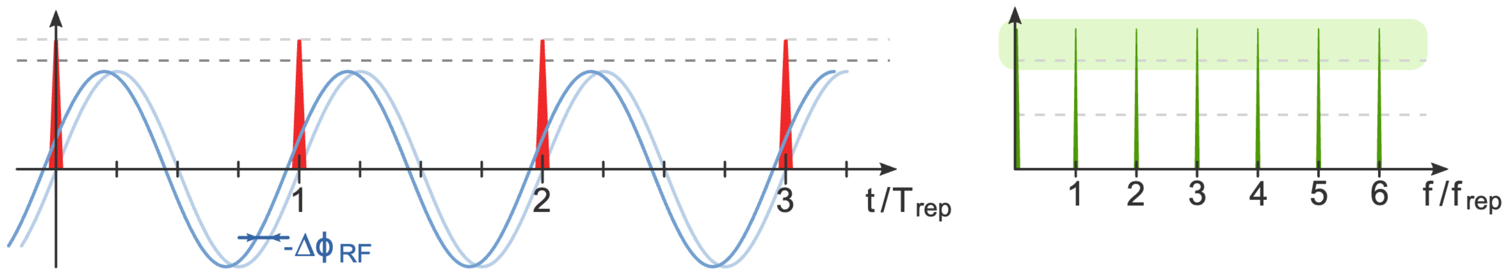




L2RF Phase Detector Scheme

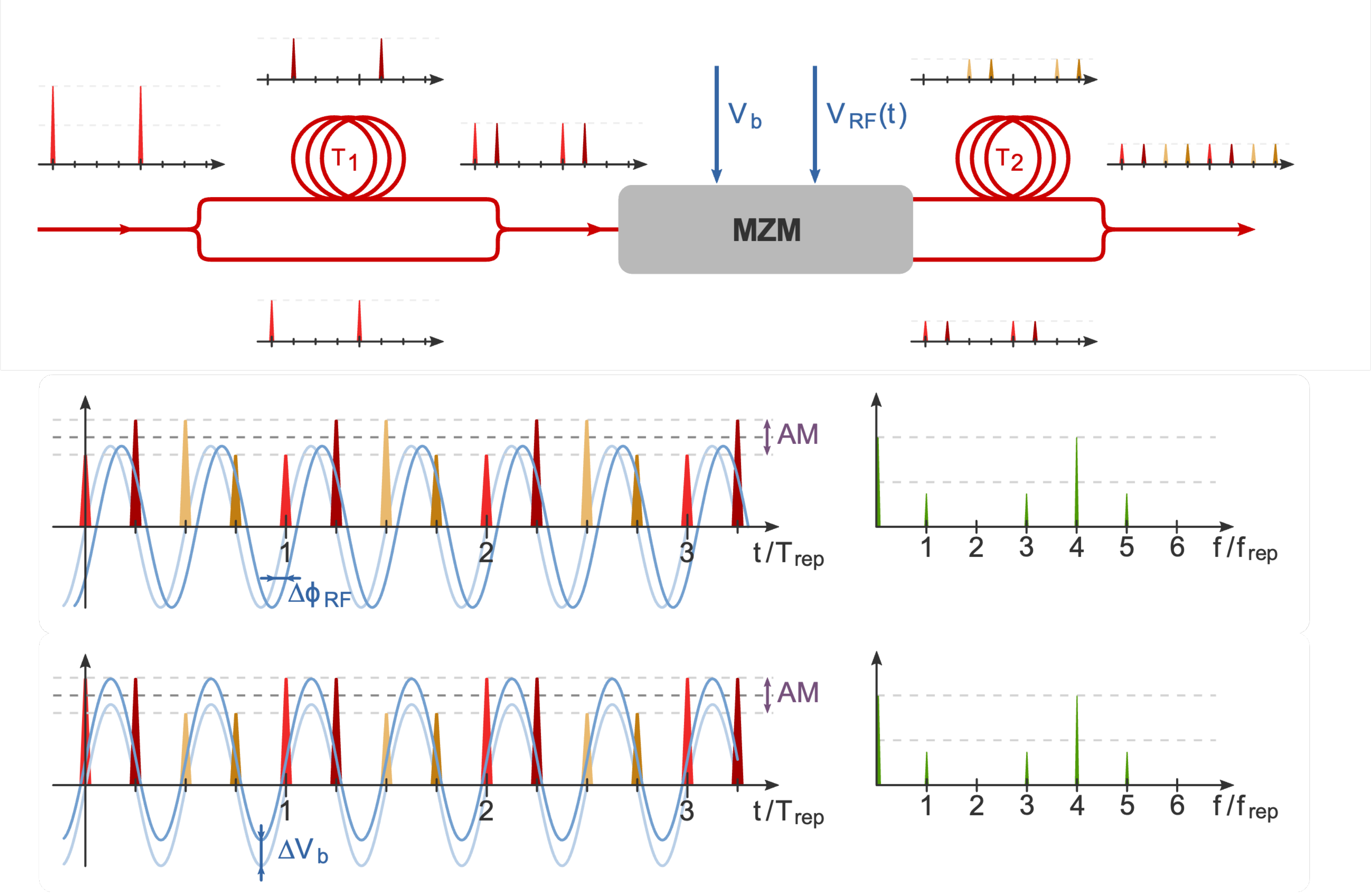
Sampling the RF Signal with Laser Pulses (Simplified)





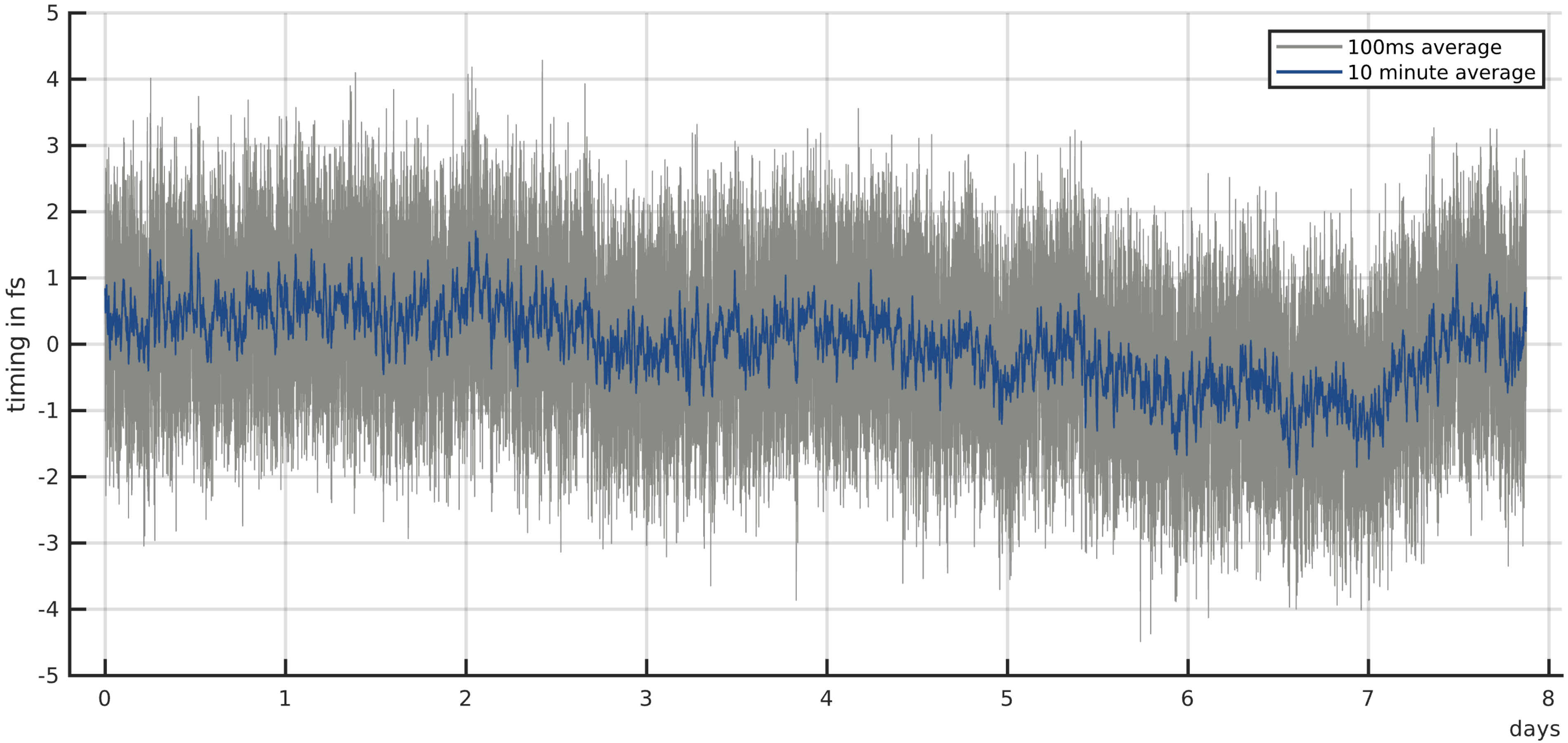
L2RF Phase Detector Scheme

Sampling the RF Signal with Laser Pulses



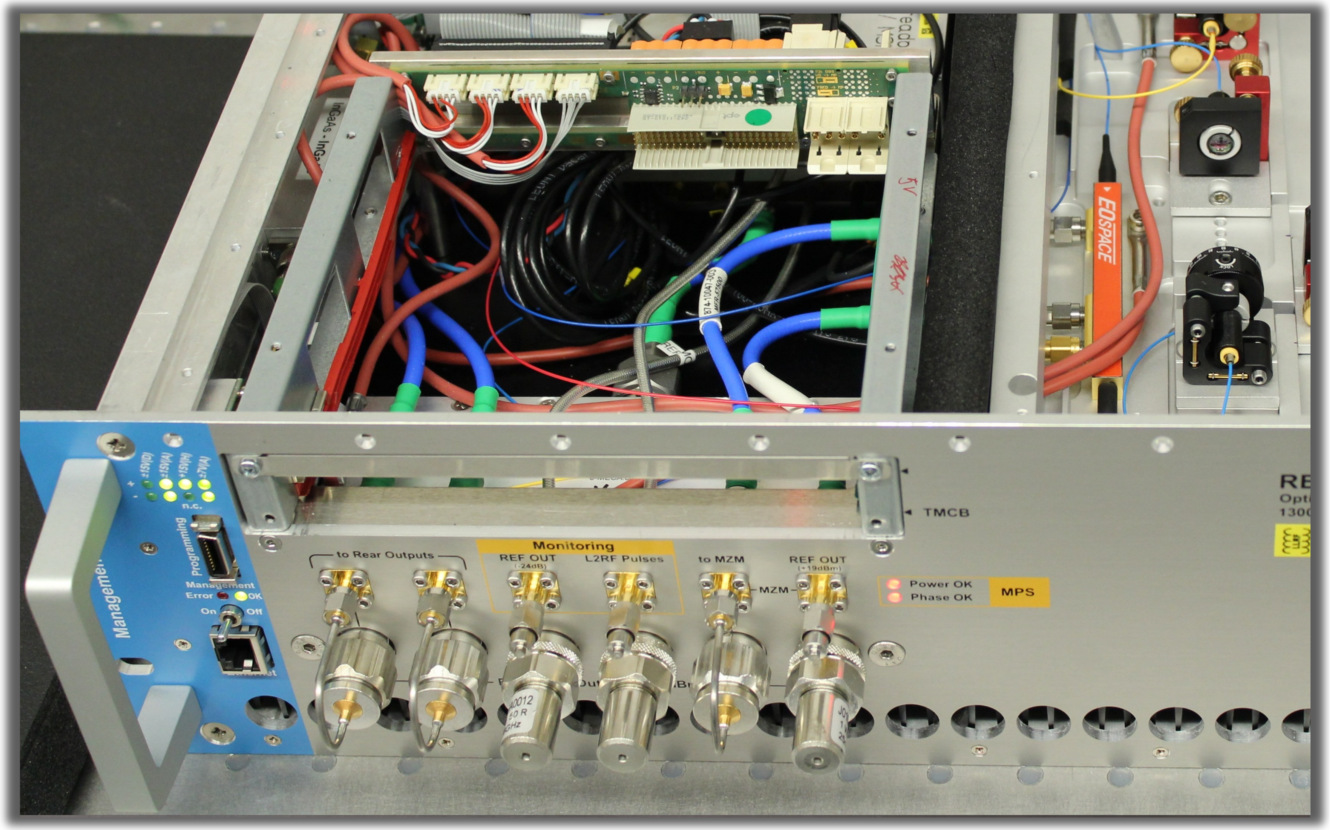
L2RF Phase Detector Stability

Out-Of-Loop Measurement of Two L2RF Phase Detectors

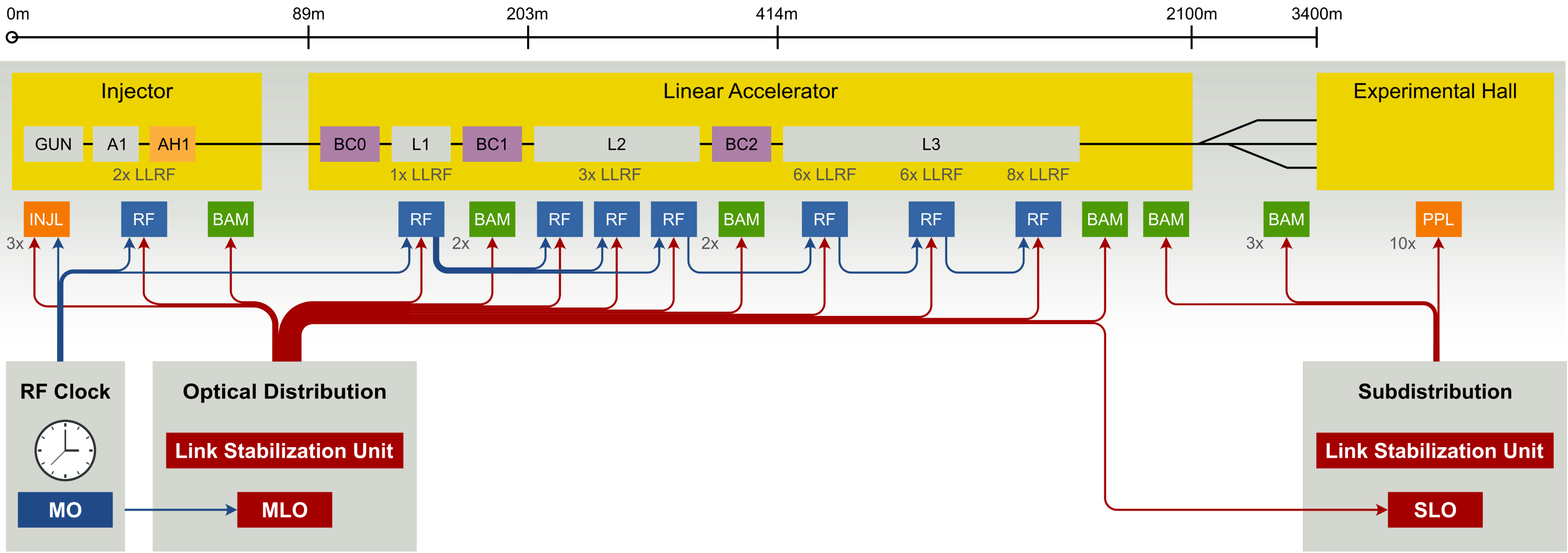


REFM-OPT Engineering

- **Redundant amplifiers**
- Controllable (electrical) phase shifter and attenuator
- **Phase stable cables**: Teledyne Phasemaster 190E 874
- **Weatherproof RF splitter**
  - stabilized, low differential drift: <40 fs/K
- **Environmentally stabilized L2RF phase detector**
  - Temperature controlled,
  - humidity sealed and buffered (silica gel) enclosure
  - **Stabilizes all internal RF components**
- Diagnostics (optical power, 2x RF power, temperatures, humidity, controller data, …)
- Remote management (supply voltage, current, soft fuses)
- Remote operation (control parameters)
- 3x control loops (RF power, RF phase, L2RF bias)

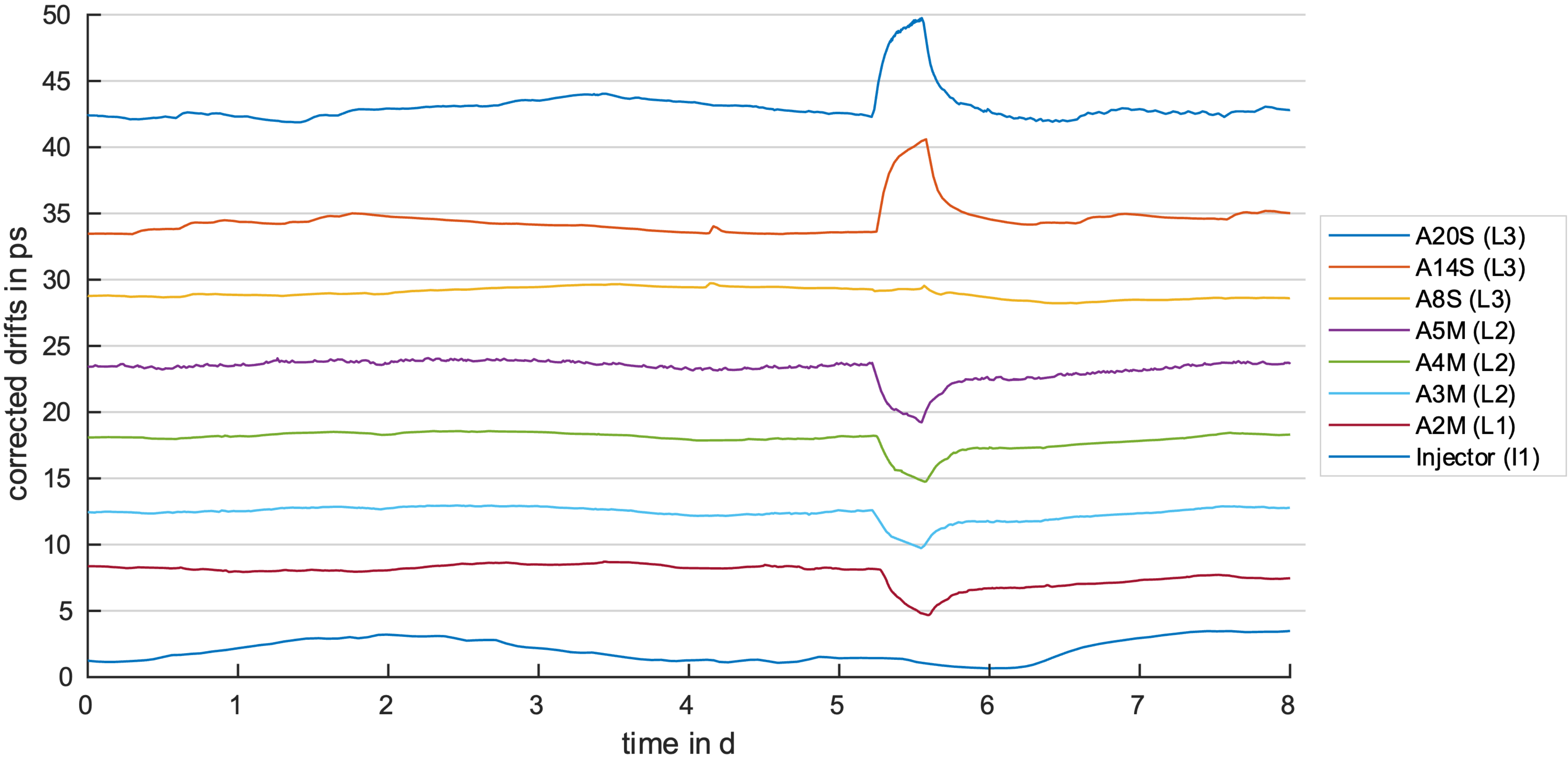


RF Distribution With Optical Augmentation



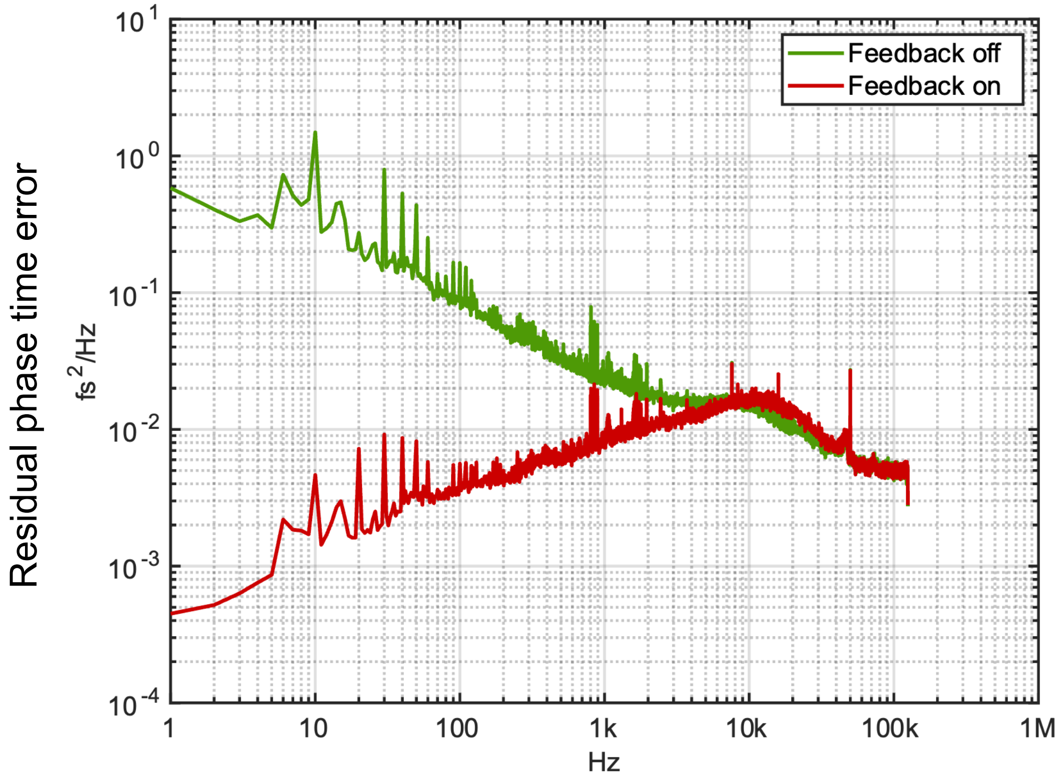
Corrected Drifts of the Coax Distribution

Corrections Applied by REFM-OPTs at the European XFEL During User Operation / Maintenance

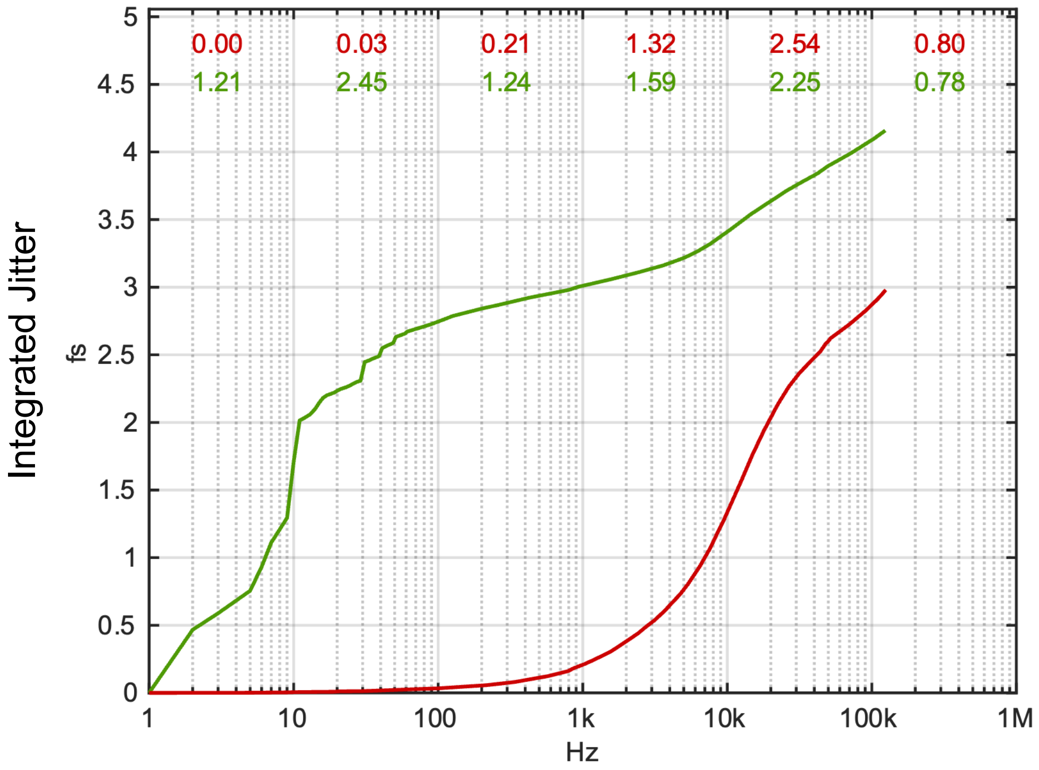


L2RF Short Term Performance

REFM-OPT A3M In-Loop Performance



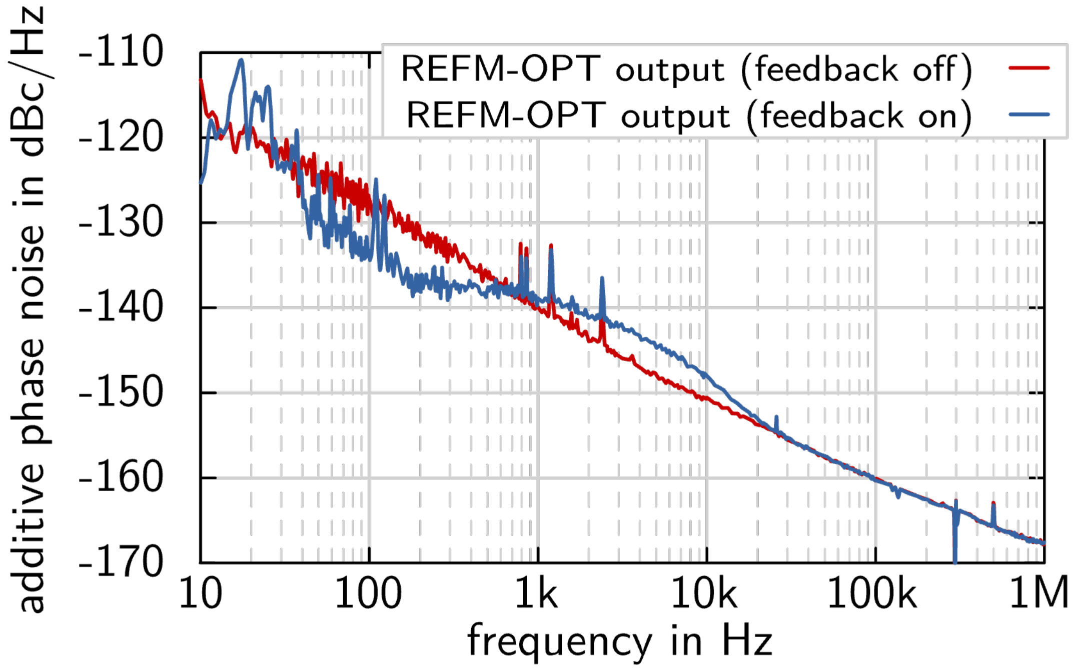
Fourier Frequency

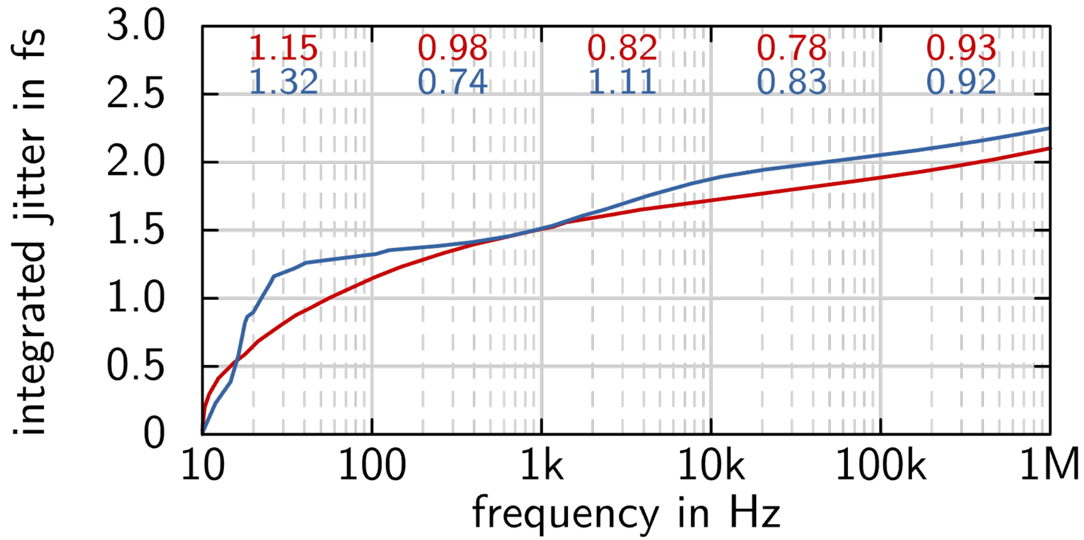


Fourier Frequency

L2RF Short Term Performance

Additive Jitter Measured of the REFM-OPT A2M





Advantages of the Augmented Reference Distribution System

Scalability

- Add **more unstabilized clients** with minimal effort
- Add **more resynchronization points** (REFM-OPT)

Efficiency

- Use **existing infrastructure** (pulsed optical synchronization system)

Reliability:

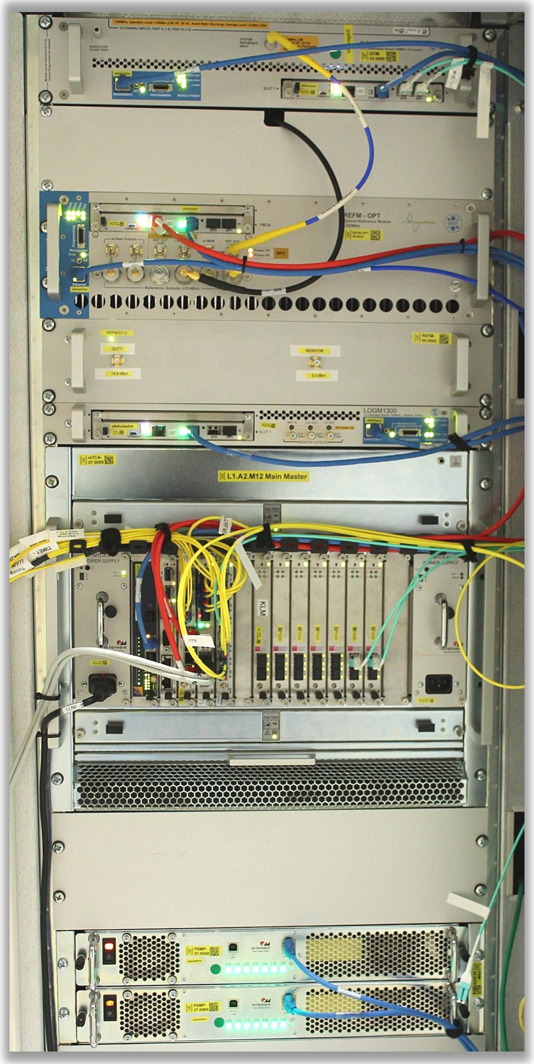
- Feedback and reference **failures affect the signal stabilization but not the delivery**
- Fiberlink failures cause **local drifts, can be stabilized downstream due to daisy chaining**

Costs

- Every REFM-OPT requires a dedicated pulsed reference (point to point, expensive)
- Passive distribution where requirements are relaxed

Performance (where needed)

- Sub 10 Femtosecond (short and long term) stabilization and
  phase noise measurements at arbitrary positions in the accelerator tunnel



Thank you!

Questions?

Contact

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www.desy.de

Thank you to my colleagues from the MSK LbSync, LLRF, and Analog Hardware teams:
Frank Ludwig, Heinrich “Heinz” Pryschelski,