LCLS II Precision Timing System

2024 LLRF Topical Workshop

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

Overview

Reference Distribution

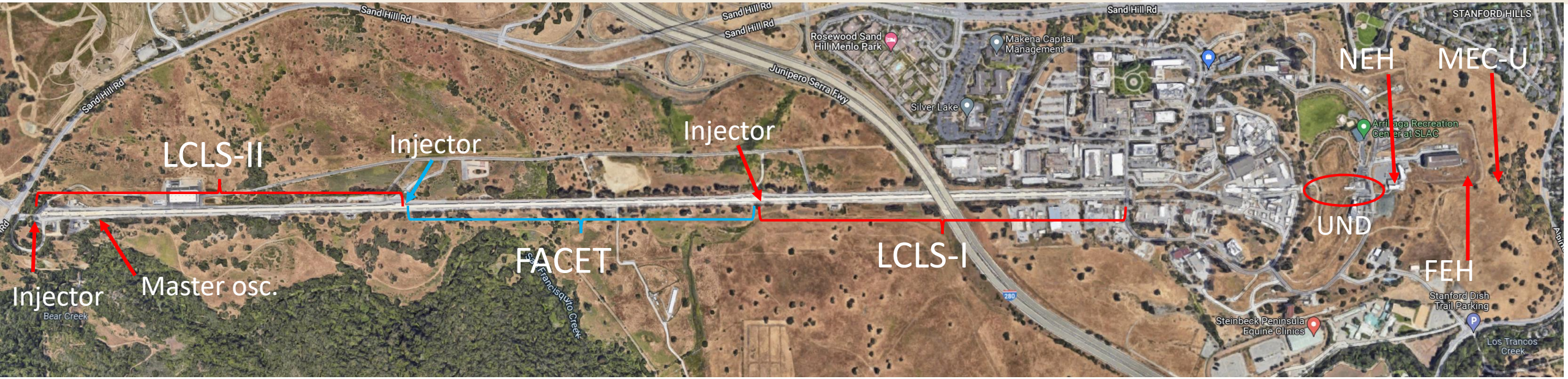
Phase Reference Line

RF Over Fiber

Pulsed Fiber Timing System

LCLS-II-HE Considerations

System Overview



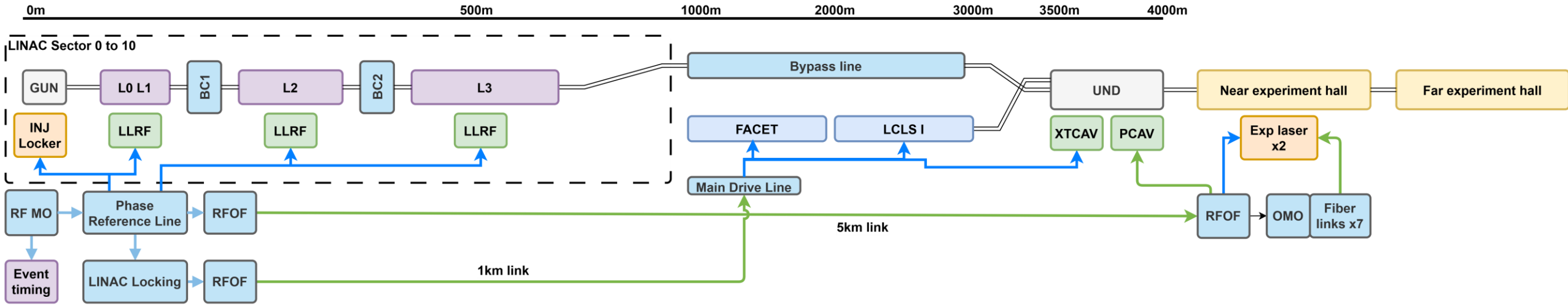
Event and Experiment Timing is Distributed to multiple facilities

- LCLS-II LIANC S0 through S10 (approx. 100m/sector)
- FACET S10 through S20
- LCLS-I LIANC S20 through S30
- LCLS-I & II user facilities (NEH & FEH)
- MEC-U (Petawatt laser facility)

Requirements

- 30fs **relative** jitter between pump laser and x-ray FEL with a goal of 10fs jitter
- <5fs time scan of the laser
- <30fs drift over 12hour shift
- Everyone has a **different** definition of jitter
  - RF jitter
  - Beam jitter/X-ray jitter
  - Laser jitter
  - Long term jitter = drift?
  - Temporal overlap accuracy/stability
- All devices are synchronized to the RF MO, but the differential jitter between each synchronization loop all contributes to the final performance
- Loopback test is ideal, but not always possible

Reference layout

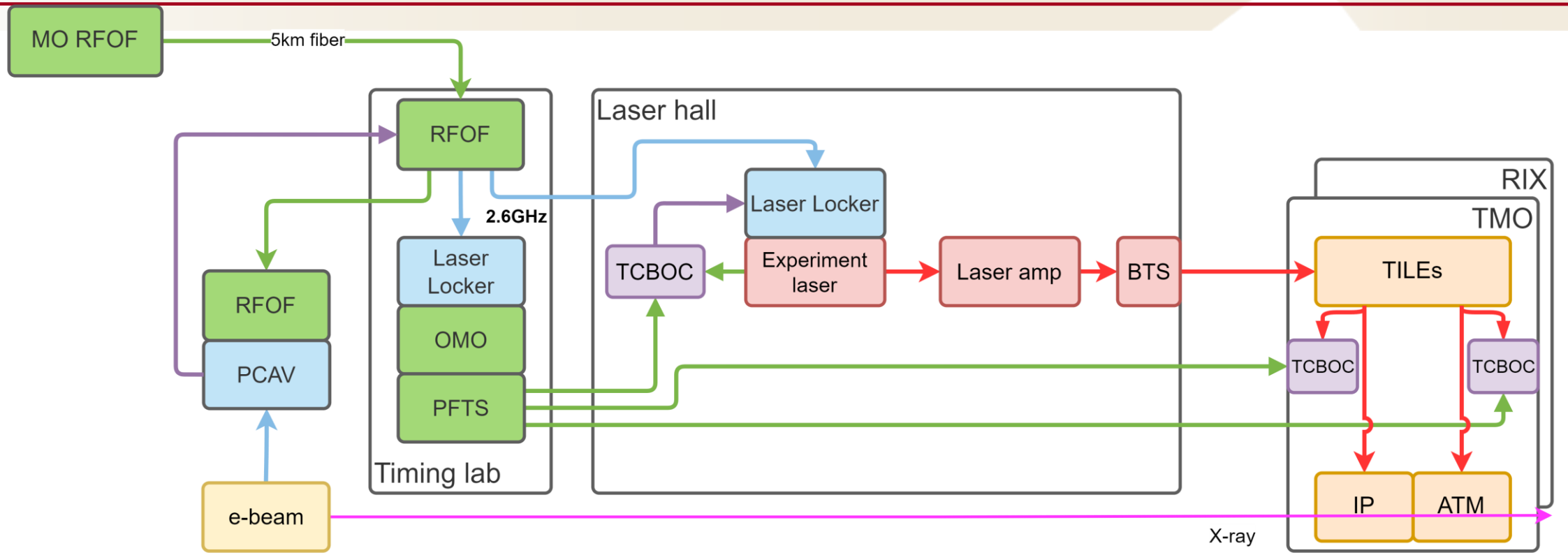


- One RF master oscillator for both LCLS-I and LCLS-II
- LINAC Locking system generates a phase locked Reference for LCLS-I and FACET*
- Phase reference line used to distribute 1.3GHz to SC LINAC
- Main drive line distributes 476MHz reference for FACET, LCLS-I LIANC and experience stations
- Two stabilized RF over fiber links used to transport reference signal to LCLS II experiment area and MDL
- LINAC and photon reference correlation against the beam measurement is missing

SLAC

* B. Hong - LINAC Locking Commissioning and Operation for the Phase Reference Line Synchronization between LCLS-I and LCLS-II at SLAC

LCLS-II Experiment timing distribution



- 1.3GHz RF over fiber link is converted to 2.6GHz RF
- 2nd RF over fiber link used to transport reference to phase cavity (PCAV) for beam calibration
- RF locking the optical master oscillator and the experiment laser oscillators
- High precision optical phase detectors (TCBOC) used at various locations for phase or drift feedback
- Arrival time monitor (ATM) used for monitoring shot to shot x-ray to experiment laser timing

It takes a few teams to realize this


C. Xu


D. Xiang

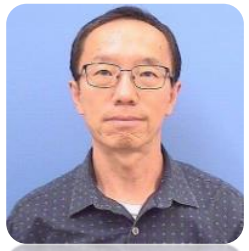

H. Ma


Q. Zheng


D. Magana


B. Hong


M. Weaver

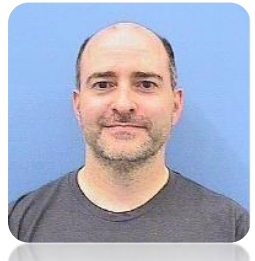

J. Yuan


S. Fung


R. Lodico


D. Valverde


Z. Mason

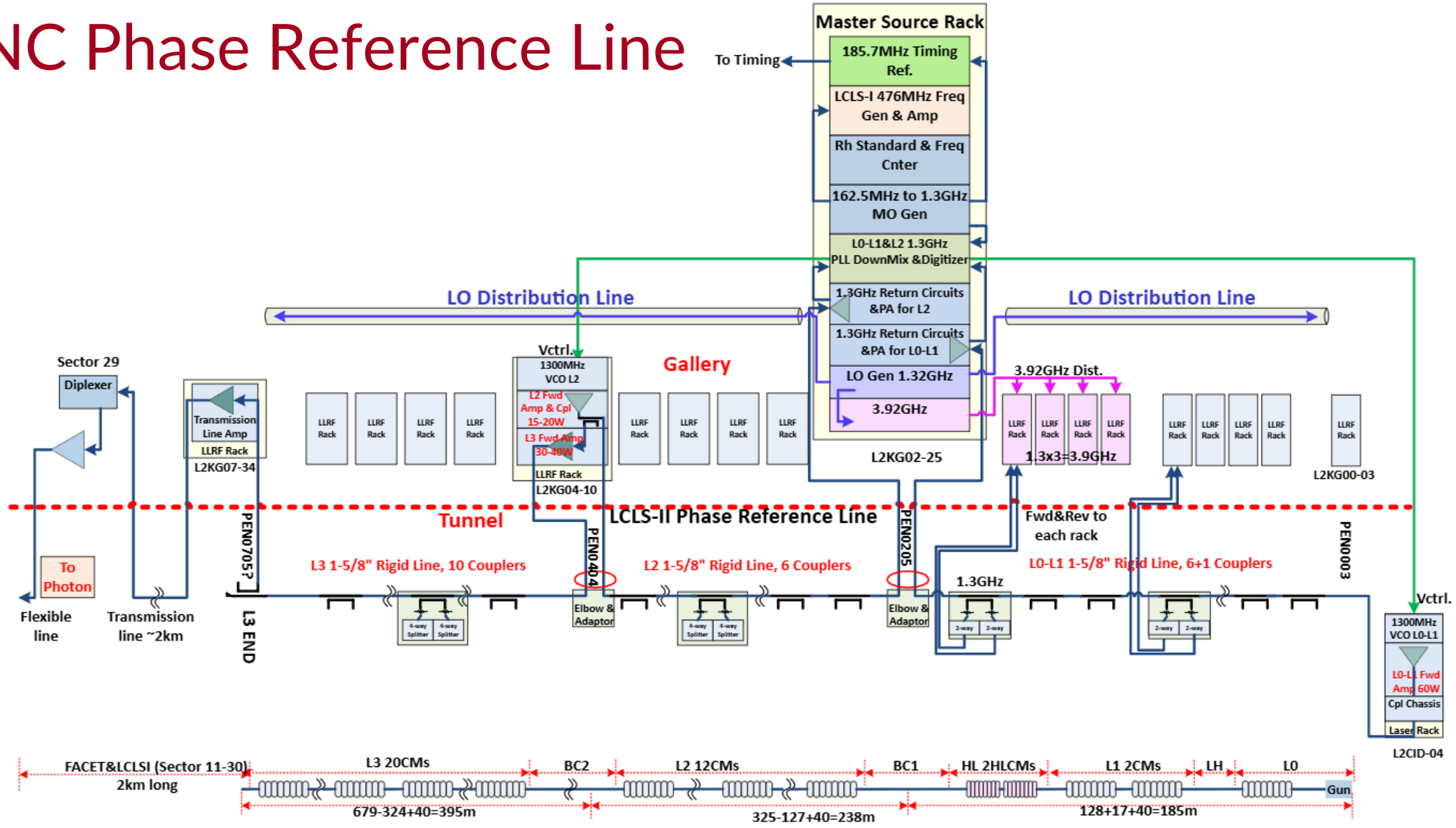

J. May


T. Johnson

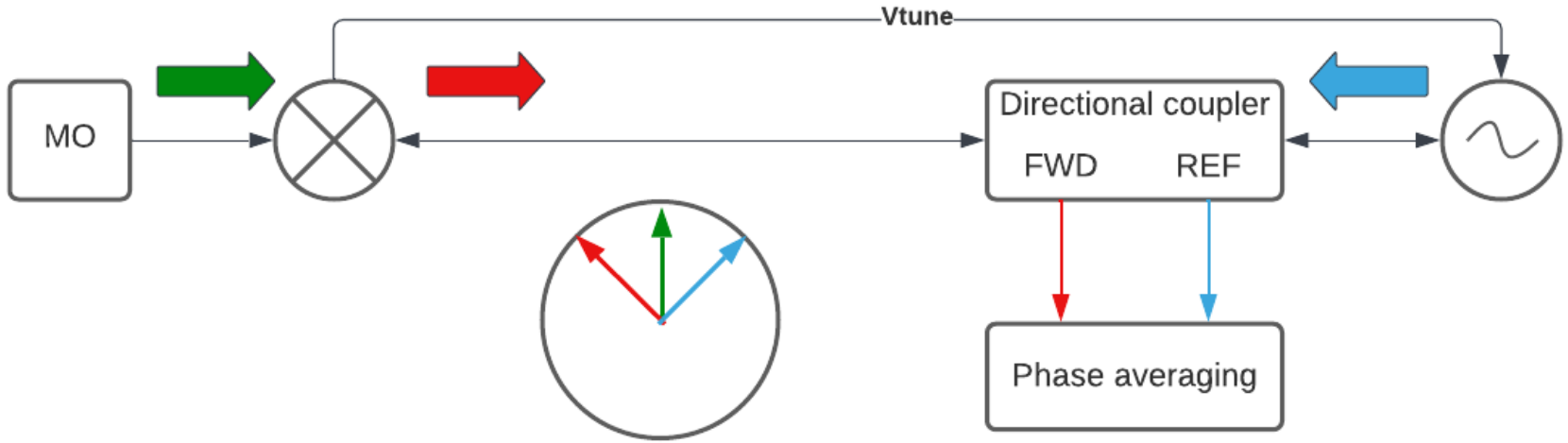
- Operation support:
  - 10 experiment lasers, 6 photo injector lasers
  - 4 phase cavities
  - 3 CW RF over fiber links and 7 pulsed fiber timing system
- Development: Optical timing setups, control systems, analog and digital electronics, system design

LINAC Phase Reference Line

LIANC Phase Reference Line



Phase Averaging

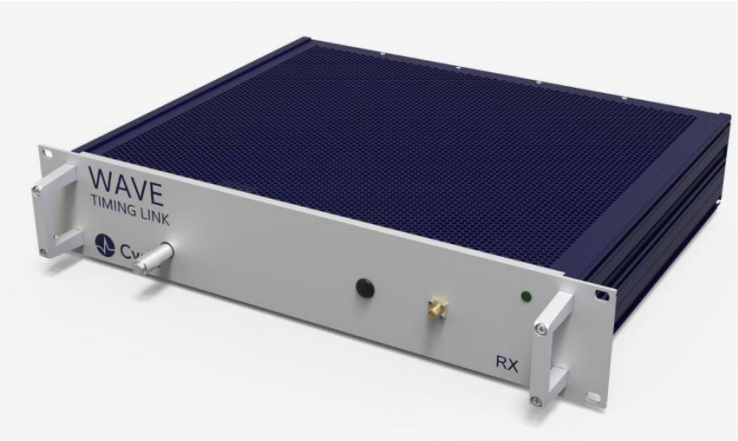


- Phase detector locks the VCO to the MO
- VCO generates a “forward” reference leading by phase delay of the cable, phase detector returns a “reflected” reference lagging by the cable
- Directional coupler extracts both references along the PRL
- Phase averaging for a stable reference
- Thermal drift of the cable is cancelled
- “Drift observations and mitigation in LCLS-II RF” – Larry Doolittle LLRF 2023

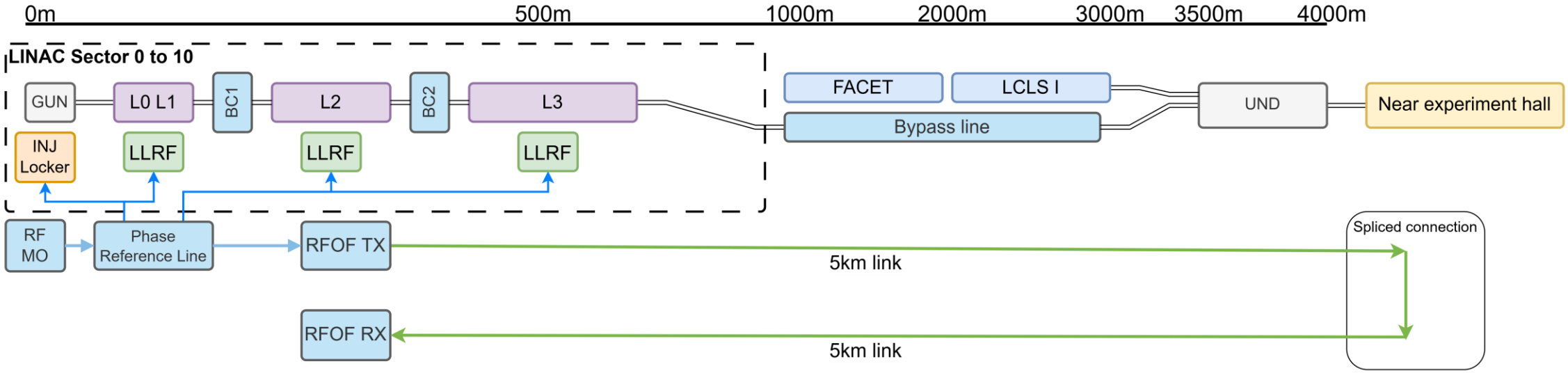
RF Over Fiber

RF Over Fiber

- 5km long link inside uncontrolled KLY gallery between the MO and experiment hall
- 200m long link in the photon tunnel
- >20degC daily temperature swing
- Typical single mode fiber drift coefficient is 40fs/m/K
- $40\frac{fs}{m\times K} \times 5000m \times 20\ K = 4{,}000{,}000fs = 4ns$
- In contrast to <100ps annual drift at EuXFEL
- Using stabilized RFOF from Cycle Wavelink and Libera Sync
- Validate performance by performing a loopback test



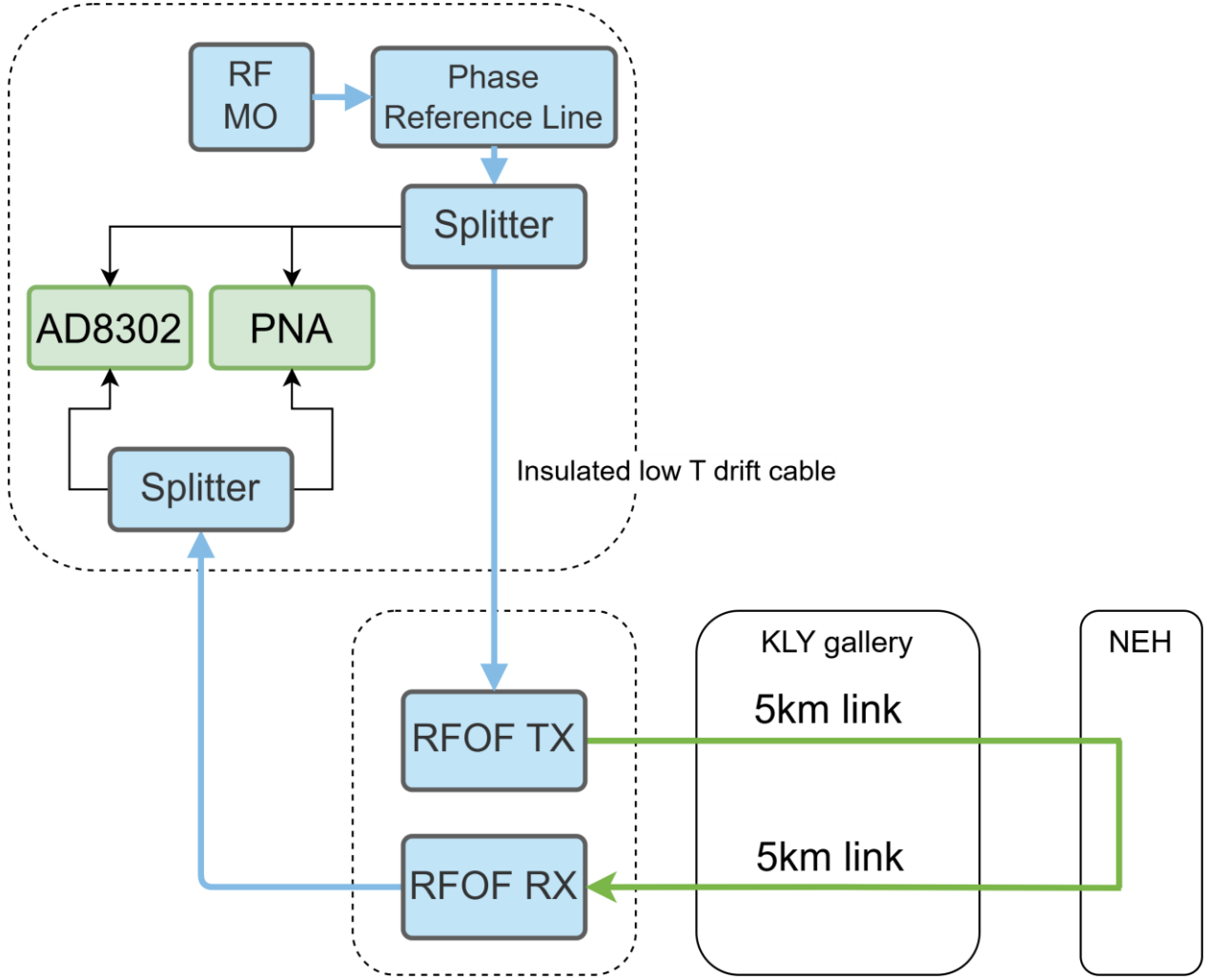
RF Over Fiber Loopback test



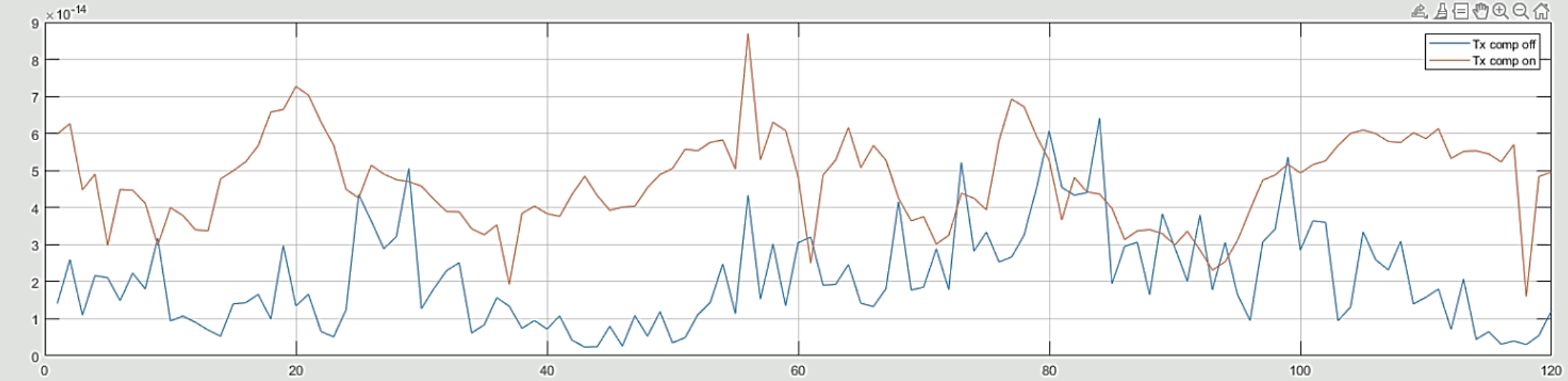
- 4 fiber cables were run between the LINAC and experimental area
- Two fibers were fusion spliced together to minimize signal loss at the experiment side
- Receiver unit was moved back to MO for loopback test
- Cycle's drift compensation isn't length dependent (you can ask them for the secret)

RF Over Fiber Loopback Test

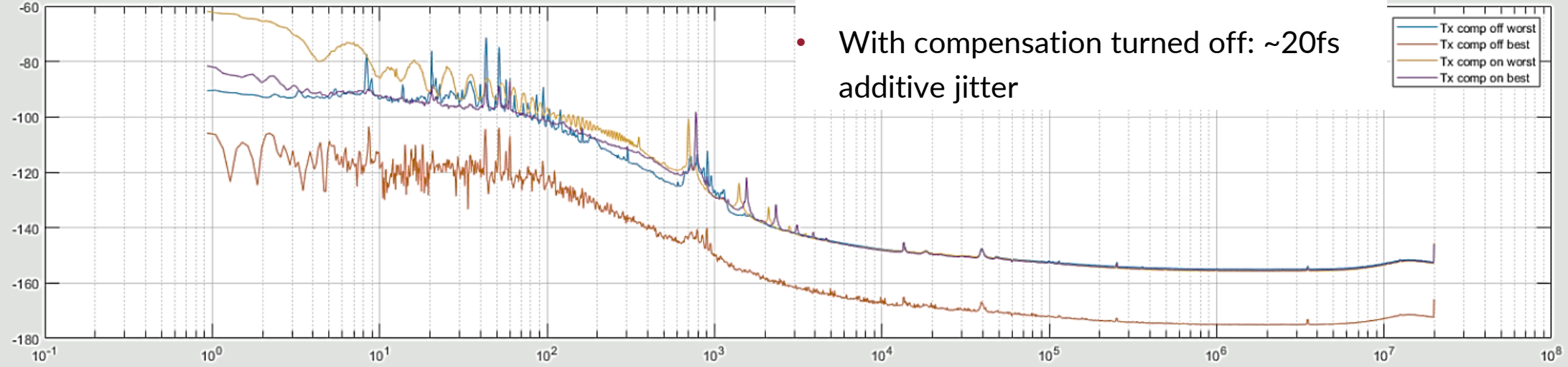
- RFOF and MO in different rack
  - Low temperature drift cable
  - Thermal insulated
  - Still some residual out of loop drift
- Long term loopback measurements:
  - Additive jitter of the system
  - Residual drift (in loop & out of loop)



RF Over Fiber Loopback Test (additive jitter)



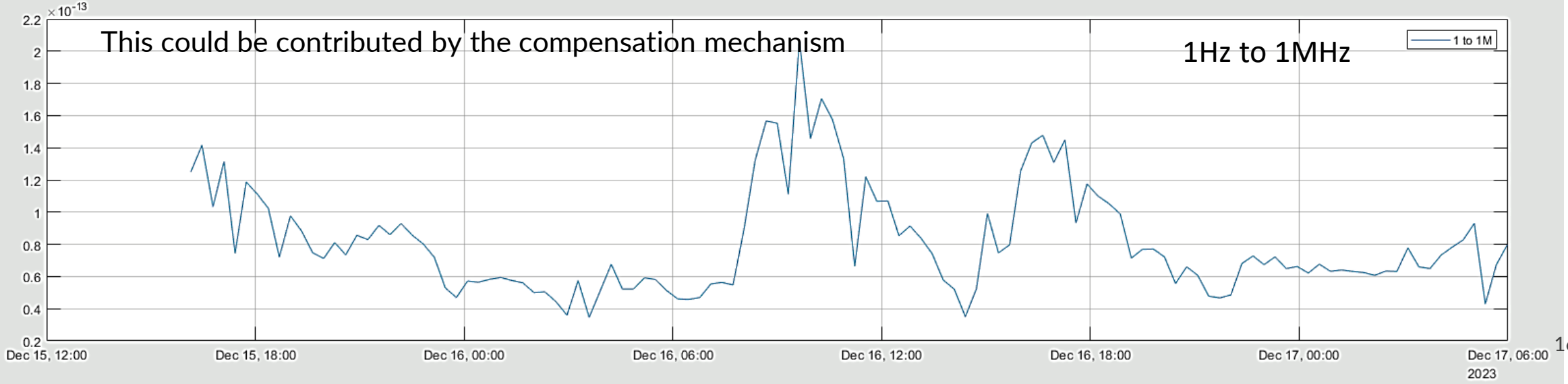
- With compensation on ~100fs additive jitter worst case
- With compensation turned off: ~20fs additive jitter



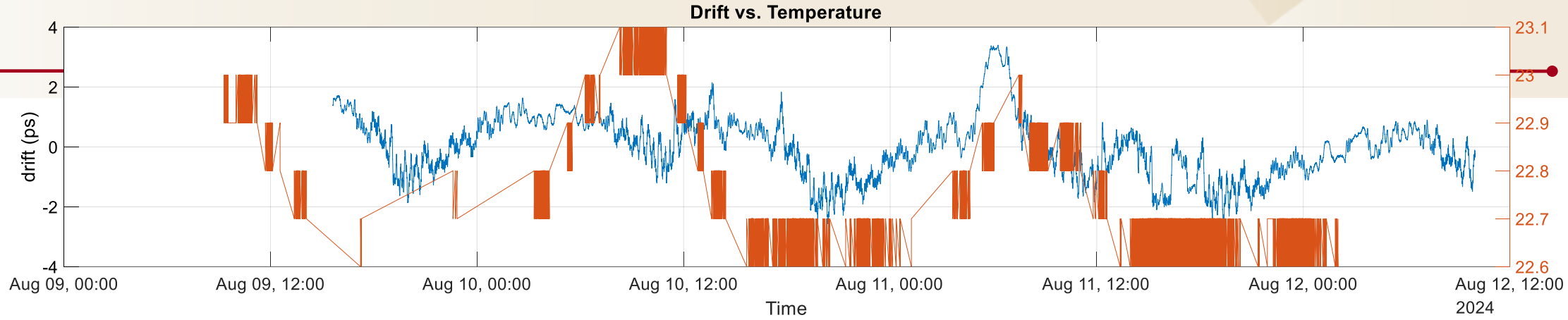
RF Over Fiber Loopback Test (1Hz vs 10Hz integration)

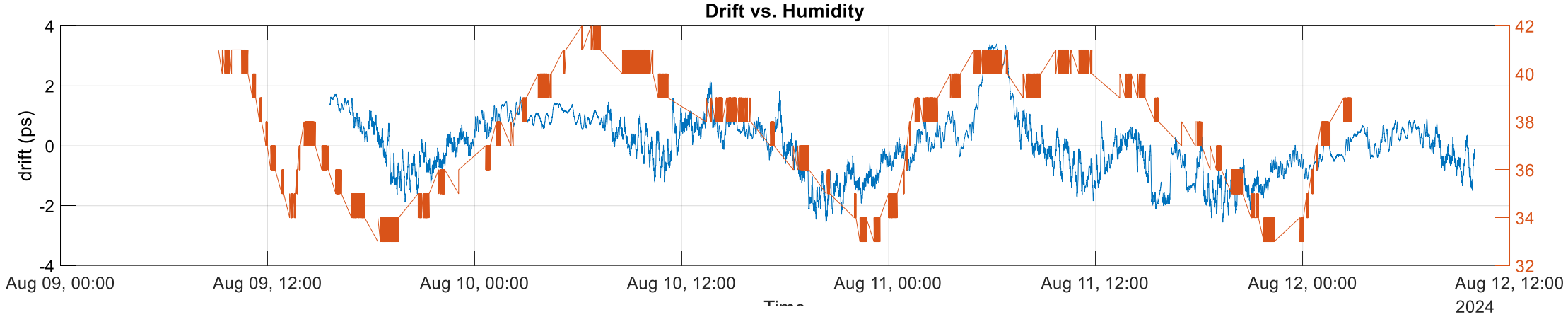
Compensation on, integrated jitter from 1Hz vs 10Hz to 1MHz is significantly different

This could be contributed by the compensation mechanism

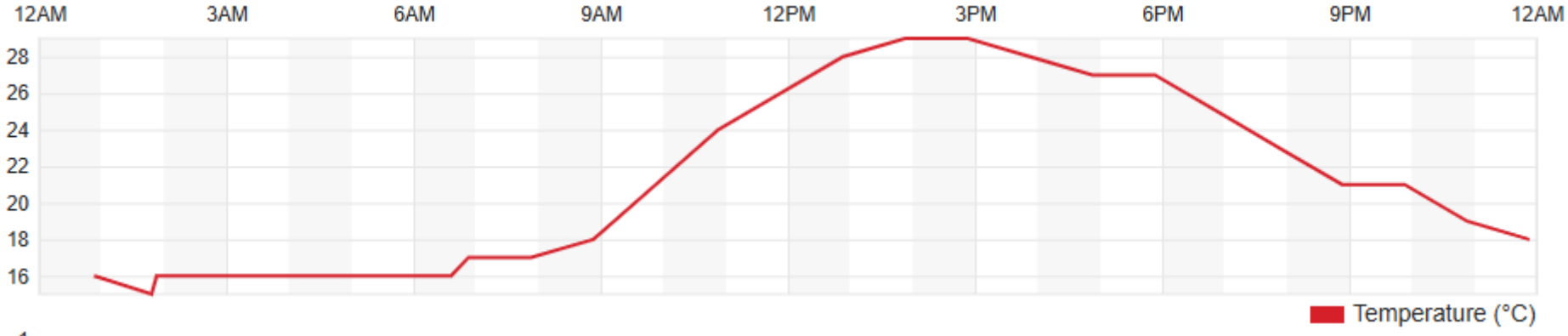


RF Over Fiber Loopback Test (residual drift)



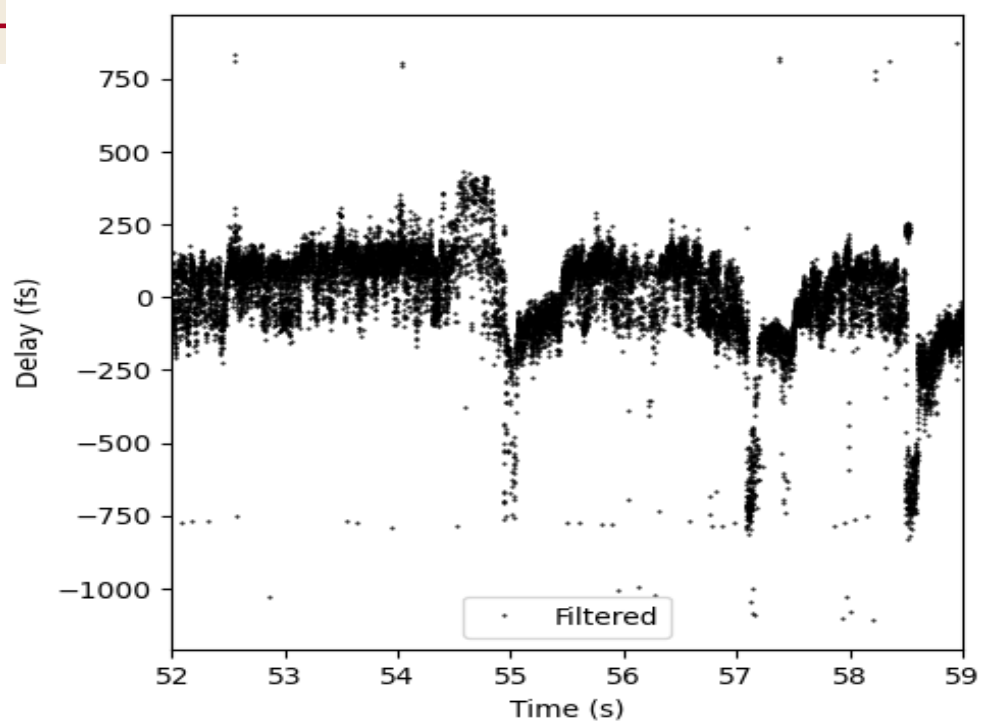


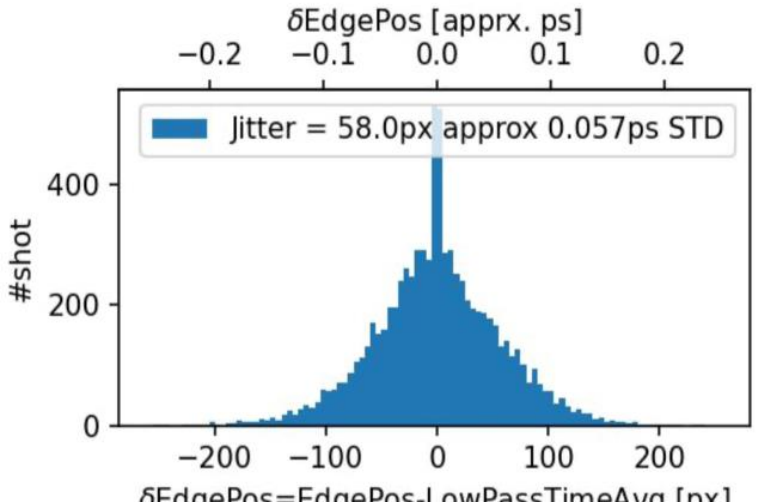
Temperature
At SLAC
On Aug 10th



RF Over Fiber LCLS-II Commission Result

- Installed and commissioned at LCLS II
- Compensation mechanism causes ~500fs jumps on the reference
- Jump frequency is correlated to the rate of temperature change outside
- 500fs >> 10fs, still ok for experiments that gets shot to shot timing data from the arrival time monitor
- ~60fs x-ray to laser jitter with post experiment process to take out the mean
- Problematic for experiments that integrates over a period of time

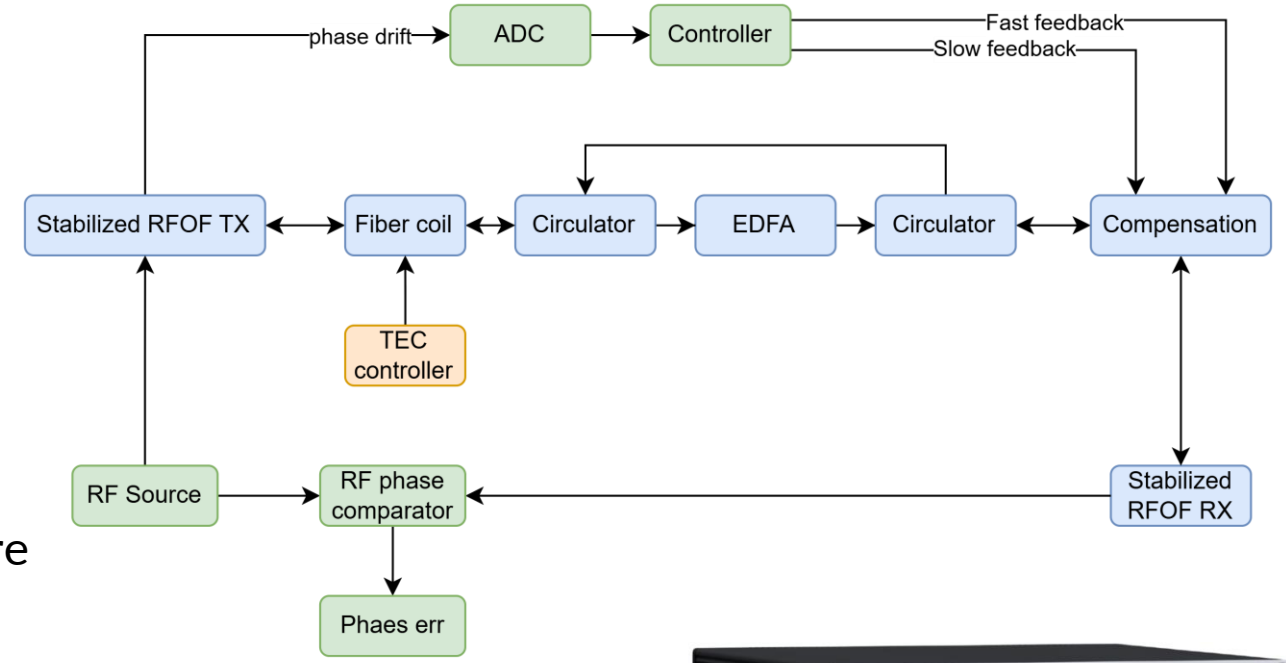


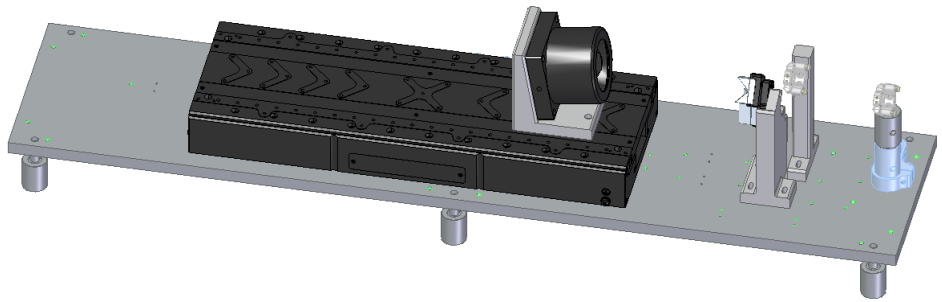


SLAC

RF Over Fiber Path Forward

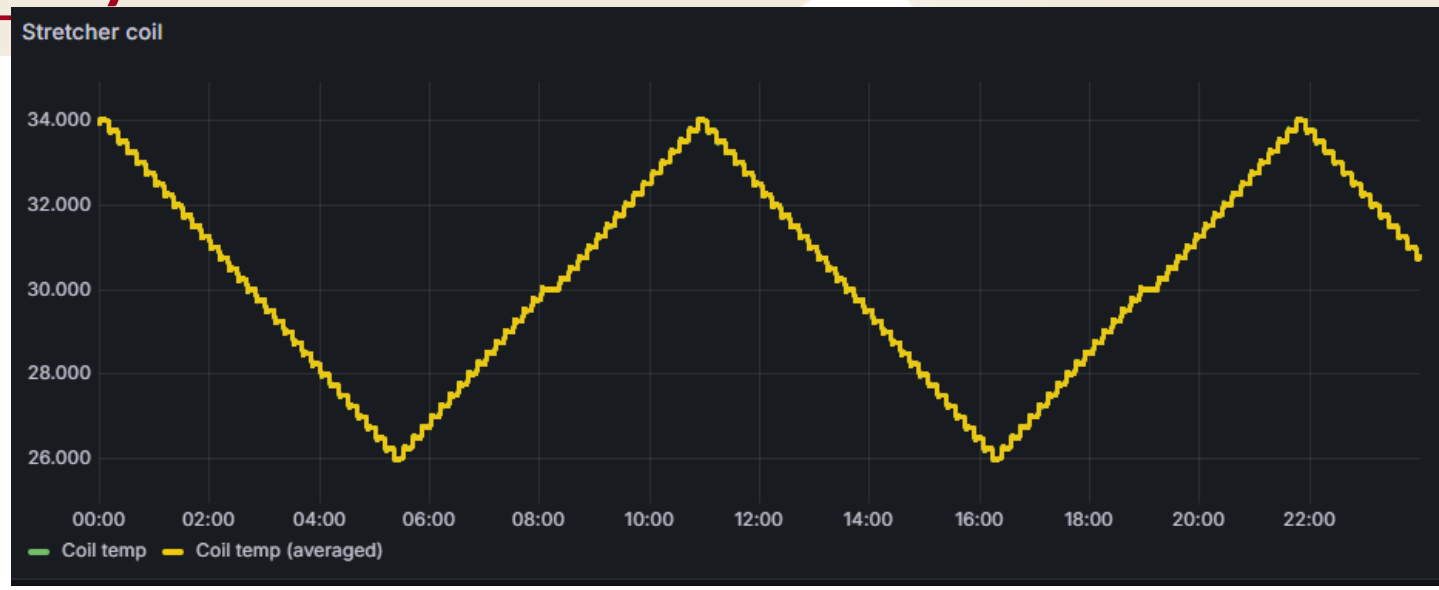
- Discrete large steps in the compensation mechanism can cause time jumps
- Working with Cycle to develop a SLAC made compensation mechanism
- 4ns for speed of light is 1.2m
- Tight requirement for mechanical and optical stability
- 10fs for speed of light is only 3um
- When using mirrors, more reflections you have, the more error you accumulate
- Current solution combination of stage with 6 path beam and piezo based stretchers

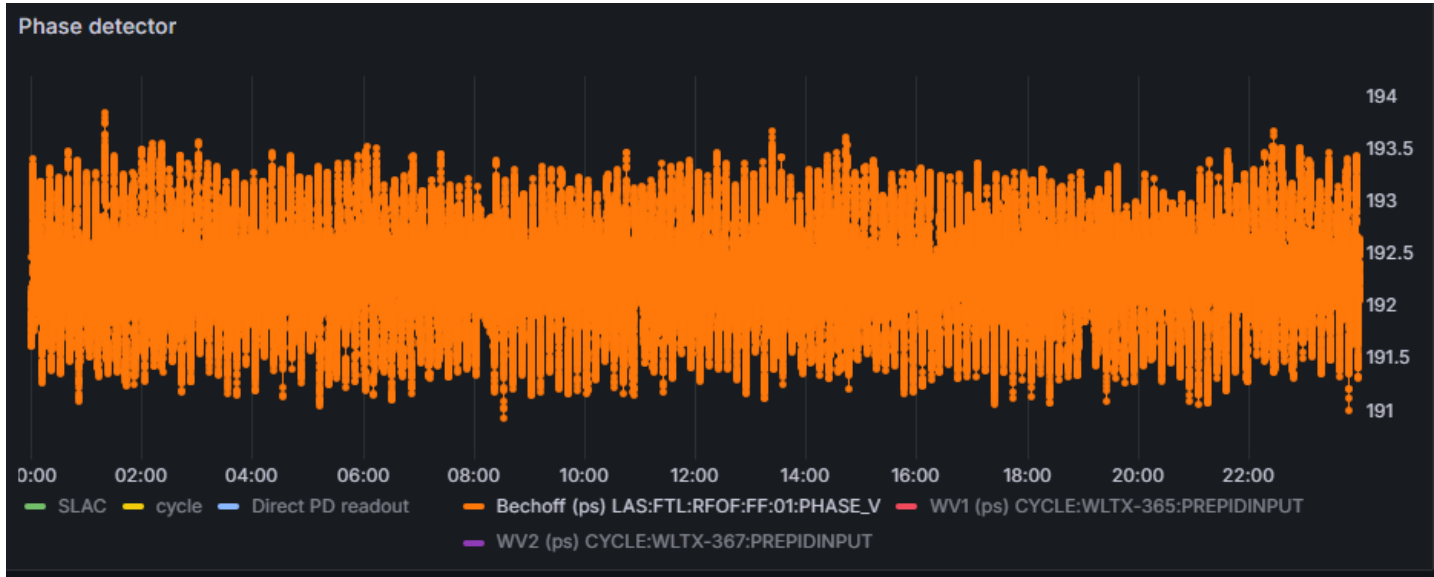




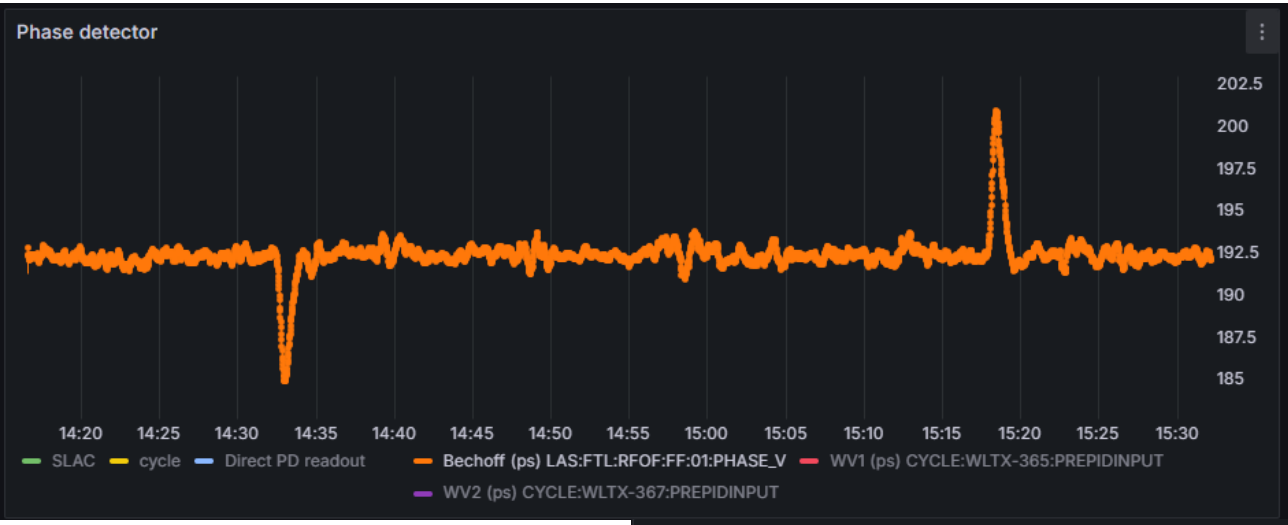
RF Over Fiber Preliminary Results

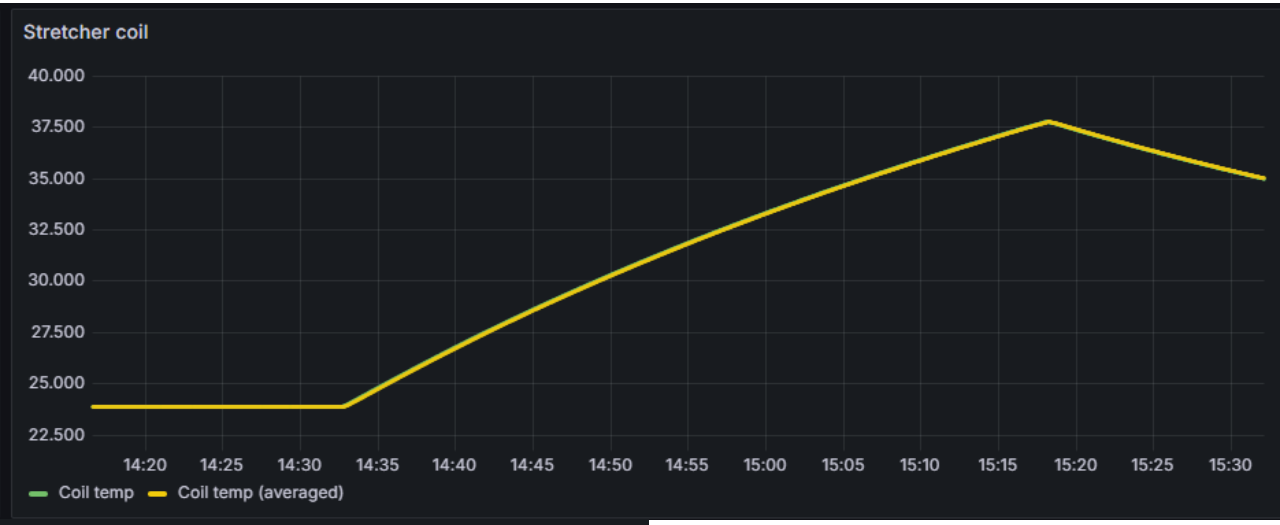
- Initial lab test result is optimistic
- ~2ps residual drift
- Stage has <nm steps, moving in almost analog fashion, no more phase jumps
- Using Bechoff low precision ADC for quick proto-typing
- ~1ps ADC noise with no feedback enabled
- New 4ns delay line not well environmental controlled

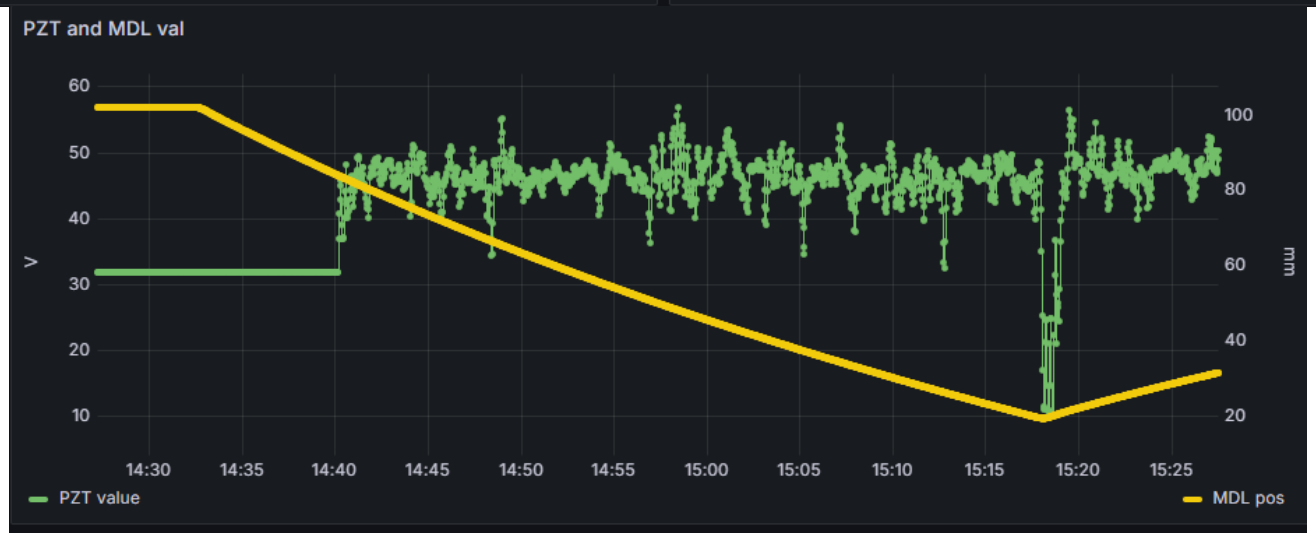




RF Over Fiber Preliminary Results





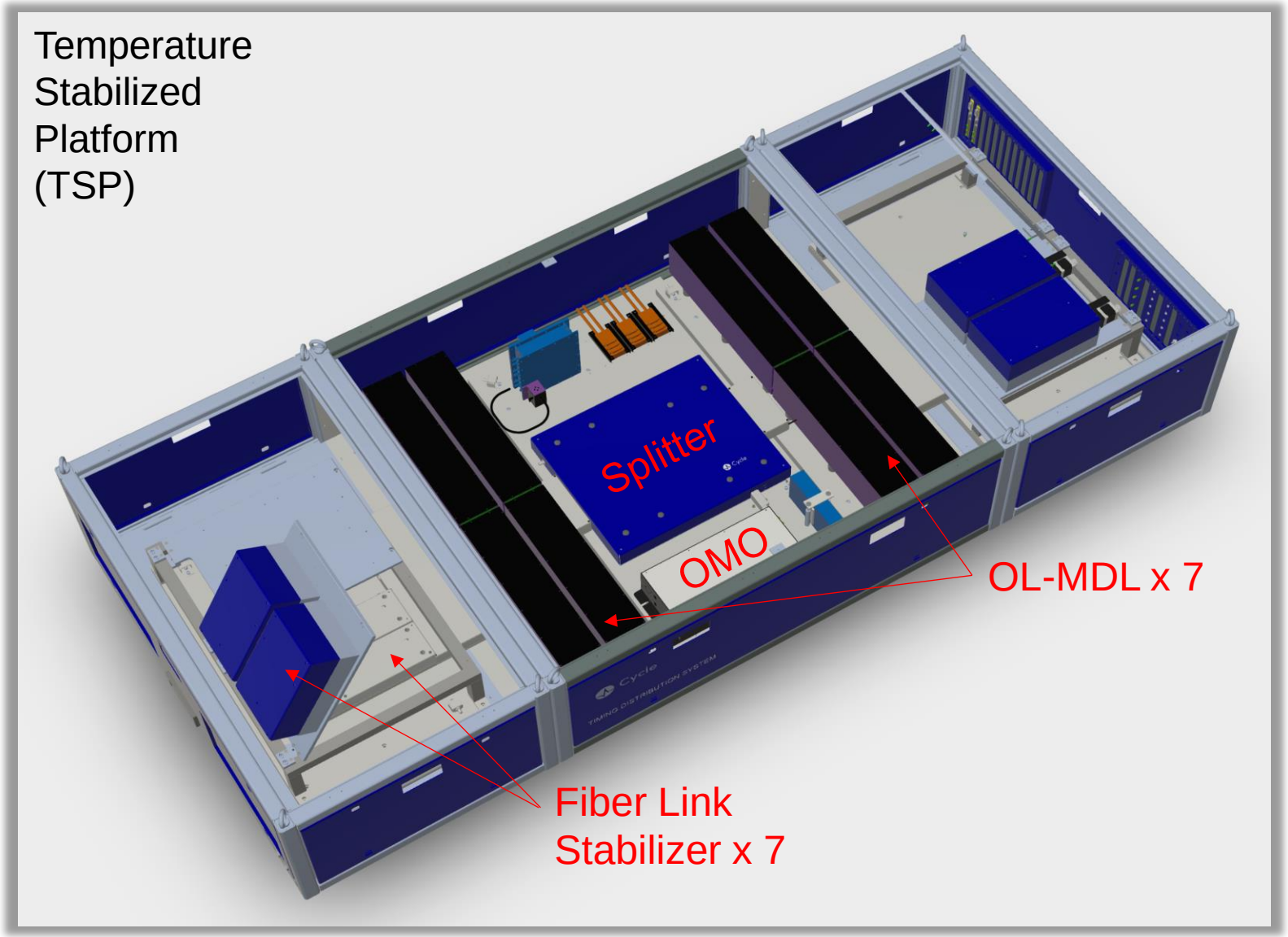


Pulsed Fiber Timing System

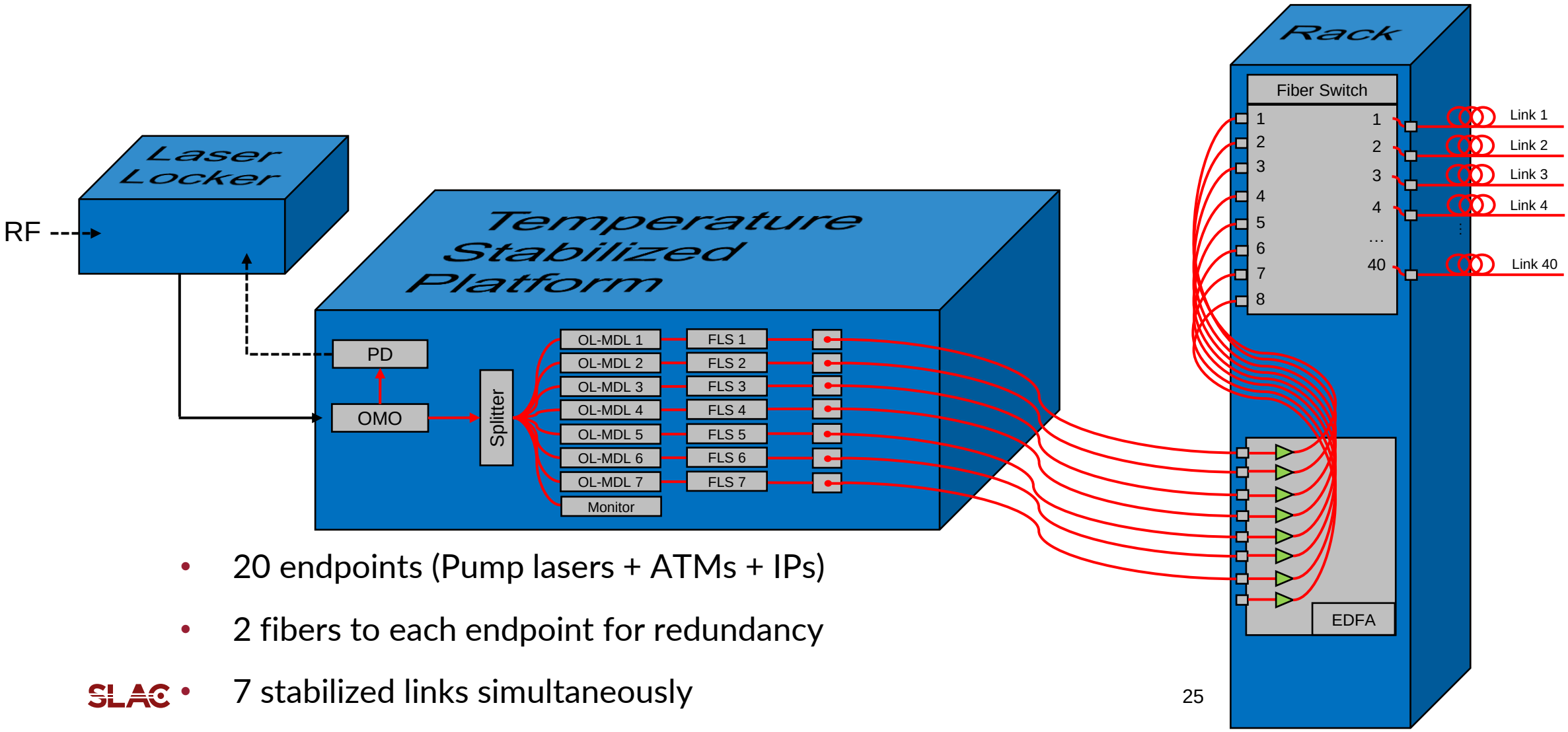
Pulsed Fiber Timing System

- Commercial system from Cycle
- Houses optical master oscillator from Mehnir (OMO)
- Mehnir runs at 325MHz, x2 of the MO frequency
- Split to serve 20 endpoints within Near Experimental Hall
- Timing links actively stabilized
- Performance: <1fs RMS [1Hz…1MHz]; (typical ~0.2fs **relative** jitter measured between 2 links)

Pulsed Fiber Timing System

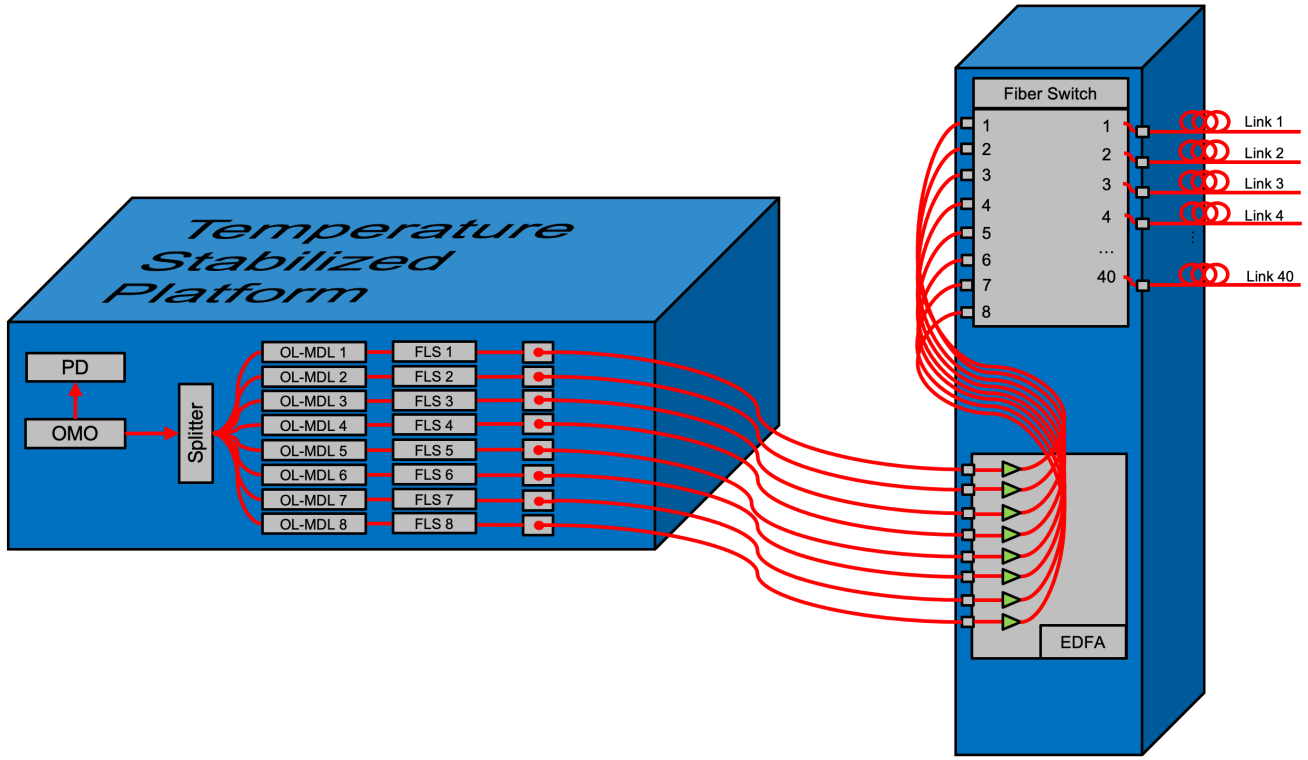


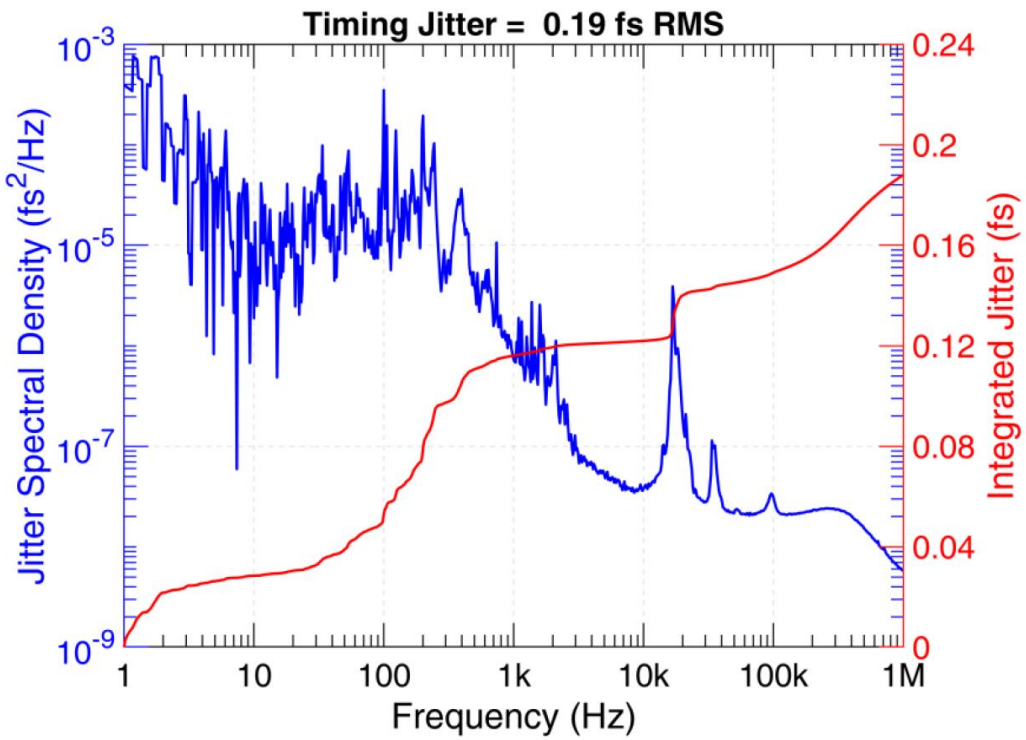
Pulsed Fiber Timing System



- 20 endpoints (Pump lasers + ATMs + IPs)
- 2 fibers to each endpoint for redundancy
- 7 stabilized links simultaneously

Differential Jitter Between 2 Links (92m)

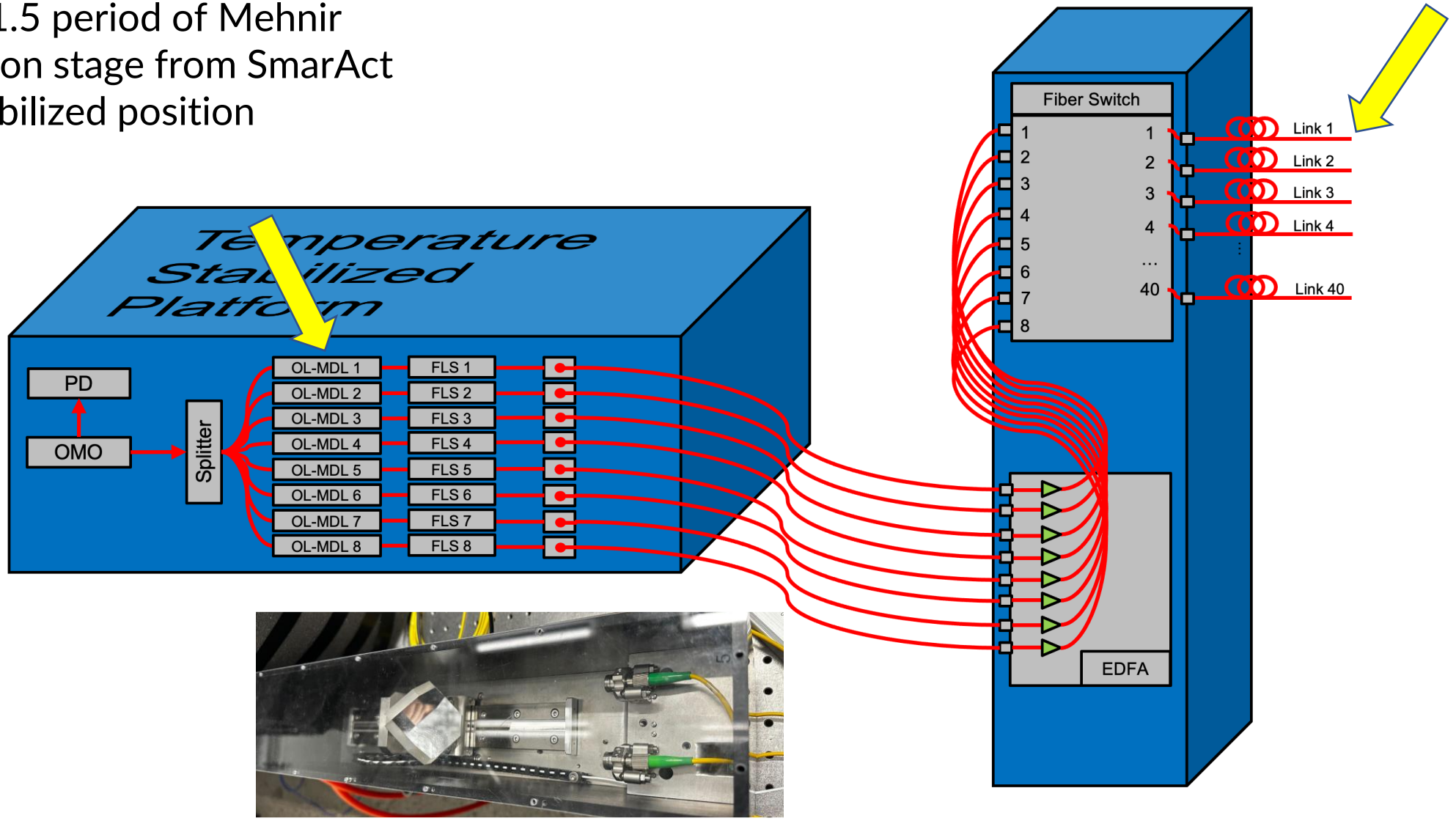




Differential jitter = 190as

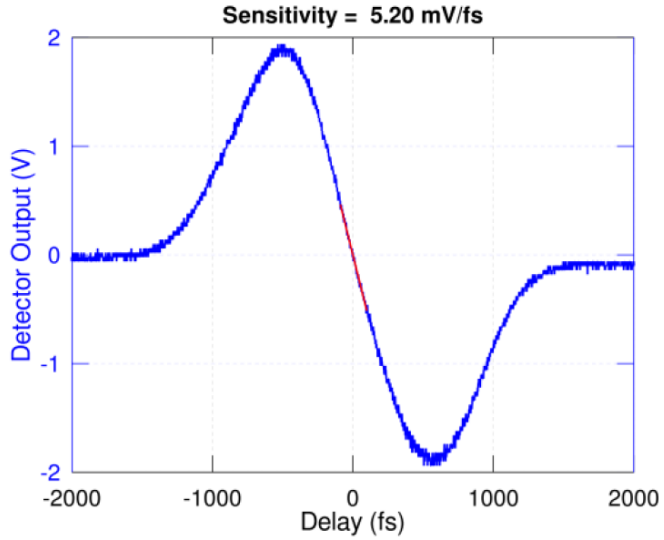
Experiment time scans via motorized delay line

- ~4ns delay range, 1.5 period of Mehnir
- Pico meter resolution stage from SmarAct
- Interferometric stabilized position



Two Color Balanced Optical Correlators

- High temporal resolution of BOC compared to RF technology
- Allows to detect smaller timing deviations between lasers
- Reduce timing error between pump laser and reference
- Still requires ADC with high ENOB and careful design of analog frontend
- Limited range ~500fs linear region ->

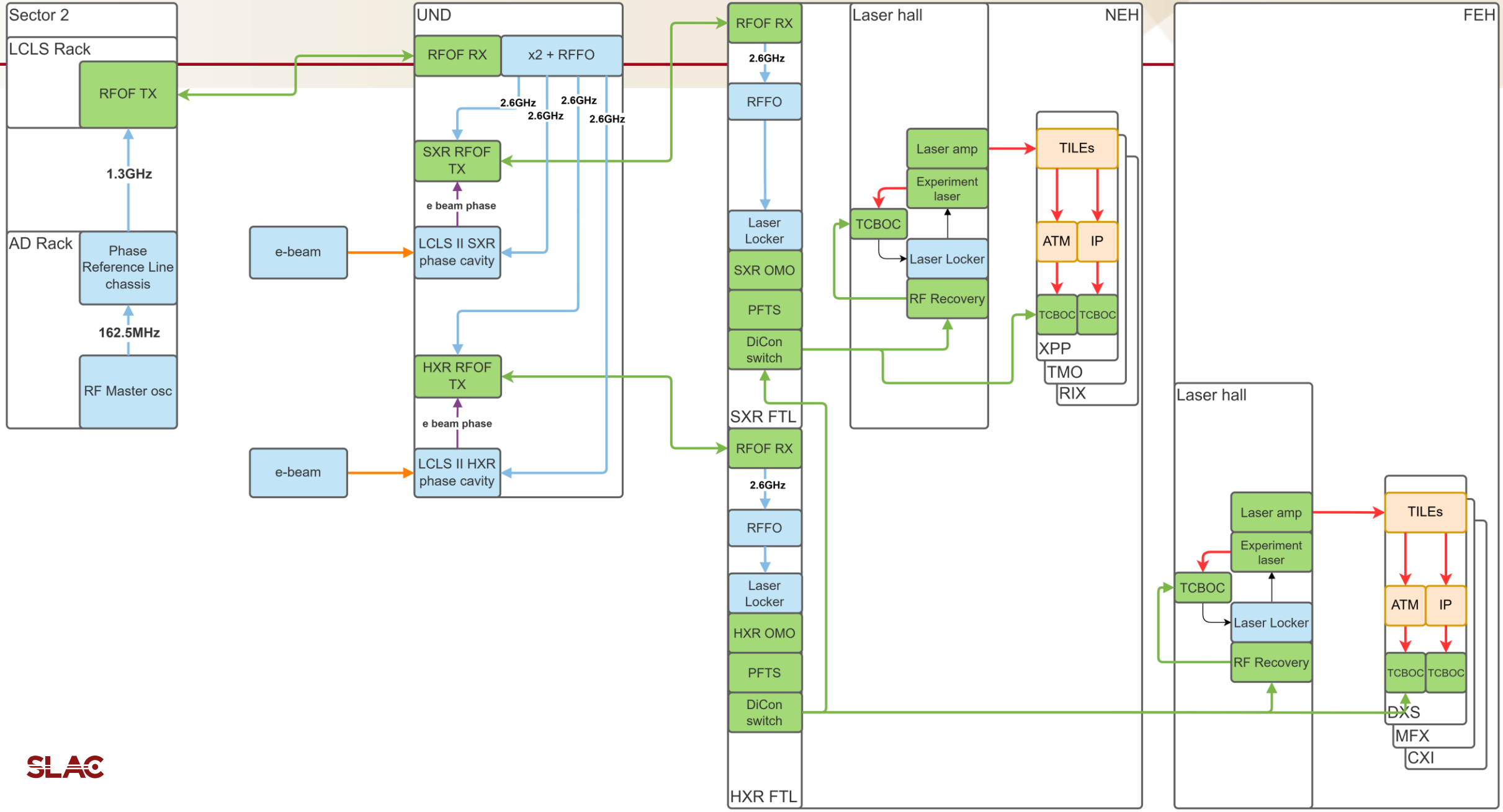


LCLS-II-HE Planning

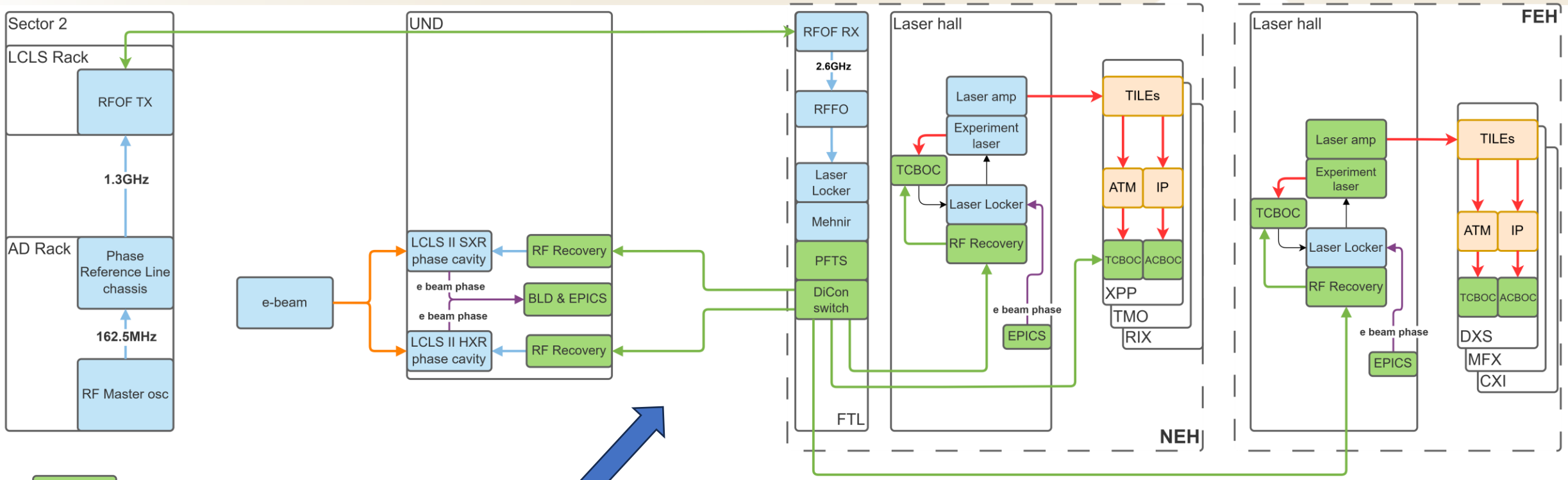
LCLS-II-HE

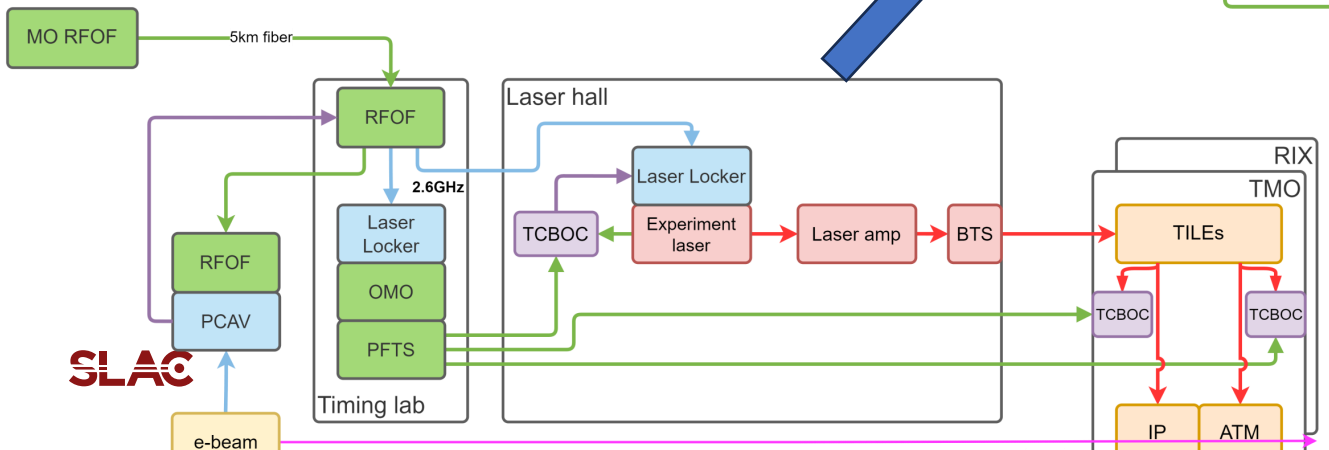
- Timeline
  - Enable SC HXR for LCLS-II, upgrade our existing 4 HXR instruments
  - XPP HXR instrument goes dark November 2024
  - Shutdown of the SC-LINAC November 2025
  - 2026 – 2027 upgrade of the SC-LINAC and XPP instrument
  - 2026 onward, rolling upgrade of HXR instruments
  - 2027 first HXR light
- Timing Task
  - Extension of the PRL to cover the new LIANC section
  - Timing and synchronization of the HXR instrument lasers (three experiment lasers)
  - Commission HXR phase cavity
  - Future expansion for projects like MEC-U or LCLS-X

Timing architecture



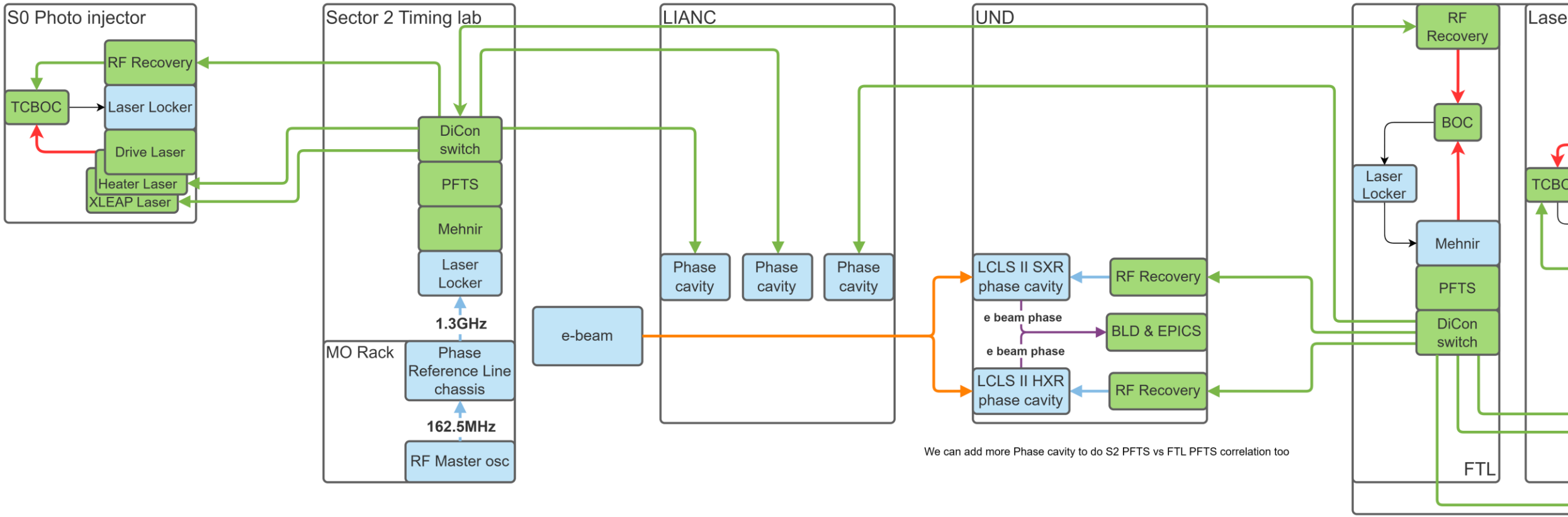
Proposed Architecture Phase 0





- Expand PFTS links to ~20 links
- Leverage delay line to set time delay for HXR and SXR
- But… differential jitter between OMO and RF MO is still missing

Proposed Architecture Phase 1



Final Thoughts

- Harsh environment of the KLY gallery is our biggest challenge, <fs scale at ns range
- If digging a trench is not possible, can we route the fiber through the tunnel? Fiber darkening from radiation? (need data)
- Validation of our synchronization performance requires careful planning of validation experiment
- Still need to perform system analysis and model of the machine for estimated pump probe jitter
- Identify upgrade areas for biggest impact
- Using OMO as experiment laser

Thank you