

# Femtosecond Synchronization of Laser Systems for the LCLS

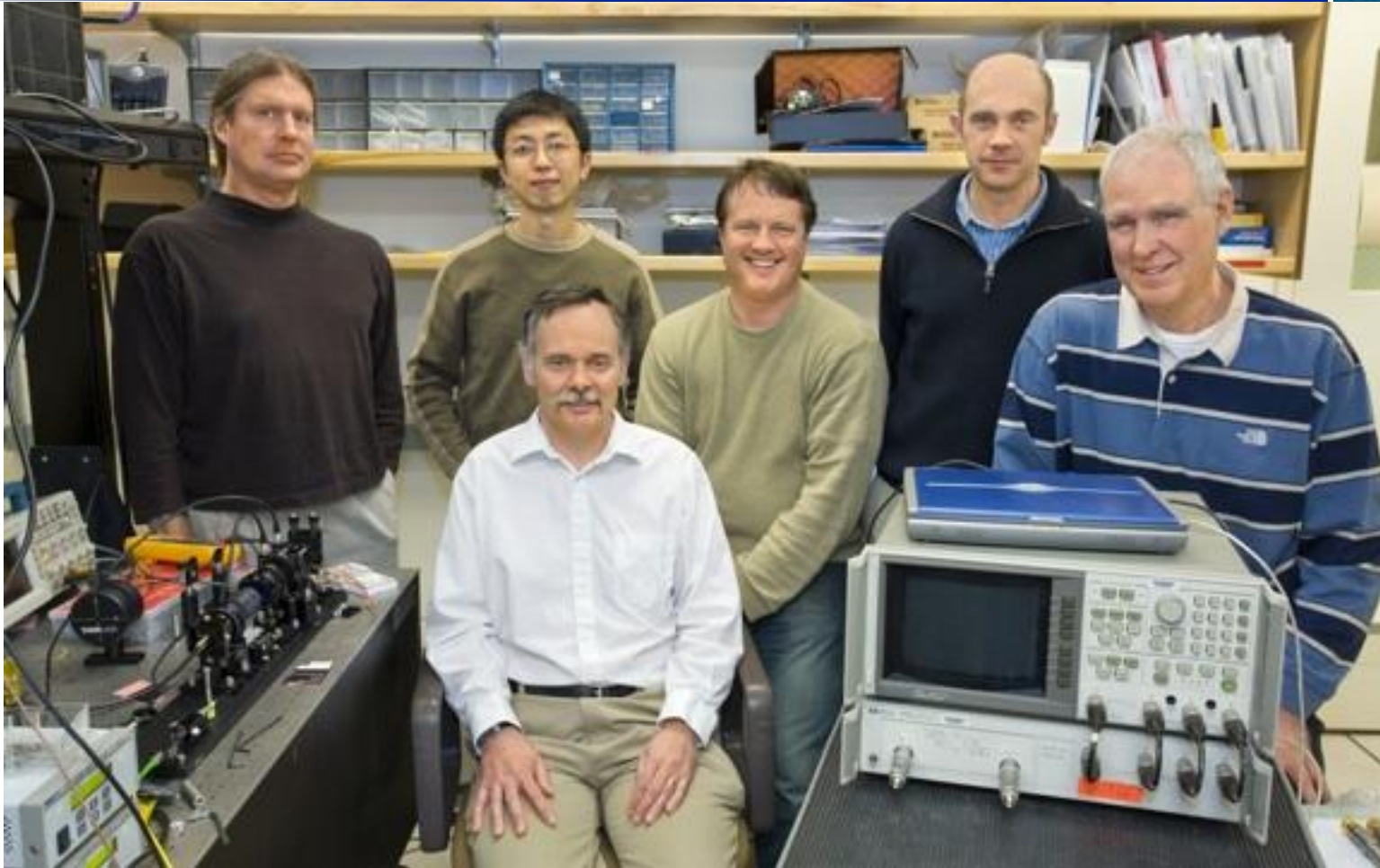
*John Byrd, Lawrence Doolittle, Gang  
Huang, John W. Staples, Russell  
Wilcox (LBNL)*

*John Arthur, Josef Frisch, William White  
(SLAC)*

# Berkeley Timing Group



John Byrd



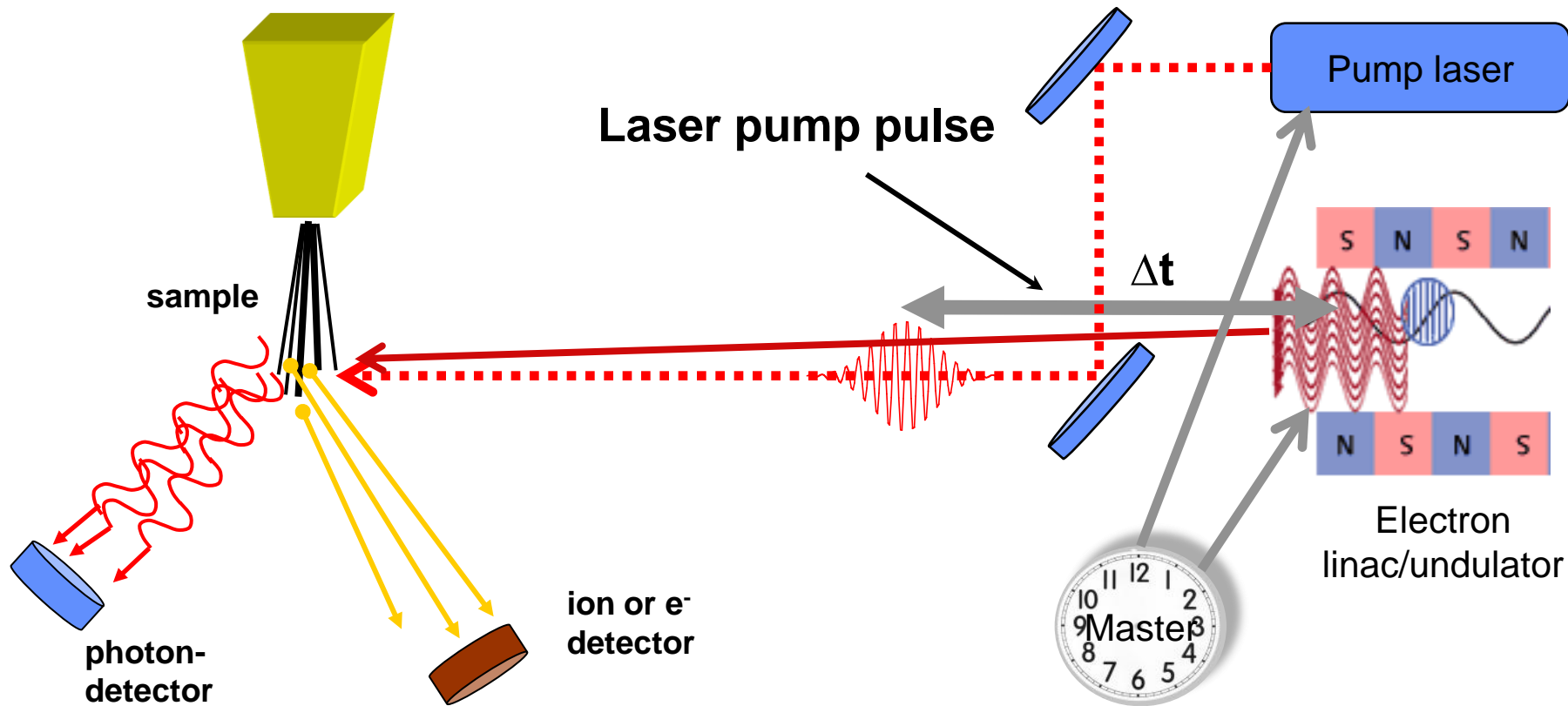
*Russell Wilcox, Gang Huang, Larry Doolittle, John Byrd, Alex Ratti, John Staples*

“The resulting new capabilities are unbelievably rich in terms of the tools and capabilities that have been created, and these in turn are reinforcing progress in these related contributing fields...Generation II comb applications now include: **low-jitter time synchronization between ultra-fast laser sources...** **Attractive topics of research for Generation III applications include precise remote synchronization of accelerator cavity fields**”

Nobel Lecture, December 8, 2005 by John L. Hall

# X-ray/optical Pump-probe

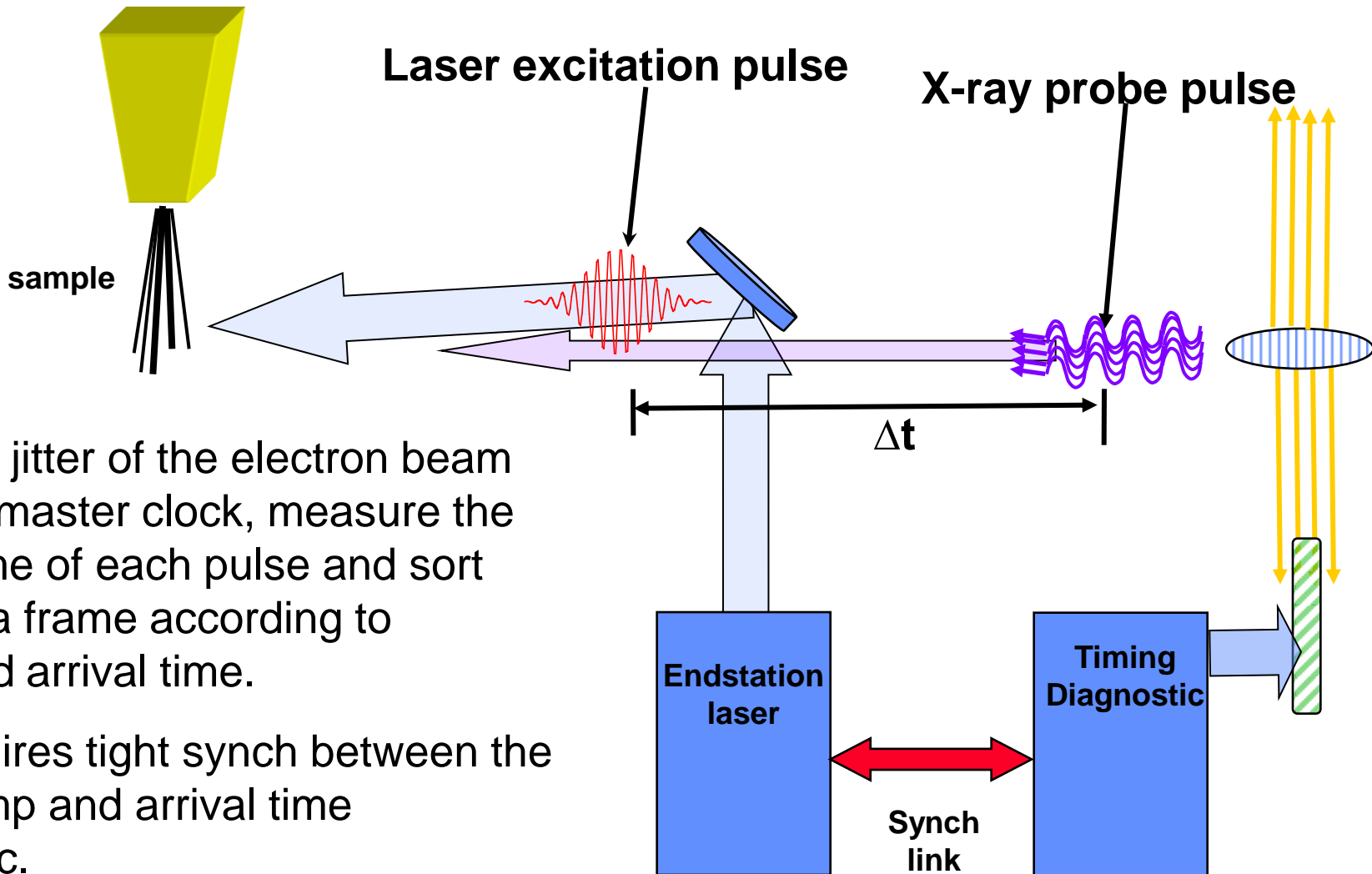
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- Ultrafast laser pulse “pumps” a process in the sample
- Ultrafast x-ray pulse “probes” the sample after time  $\Delta t$
- By varying the time  $\Delta t$ , one can make a “movie” of the dynamics in a sample.
- Synchronism is achieved by locking the x-rays and laser to a common clock.

# With respect to what?

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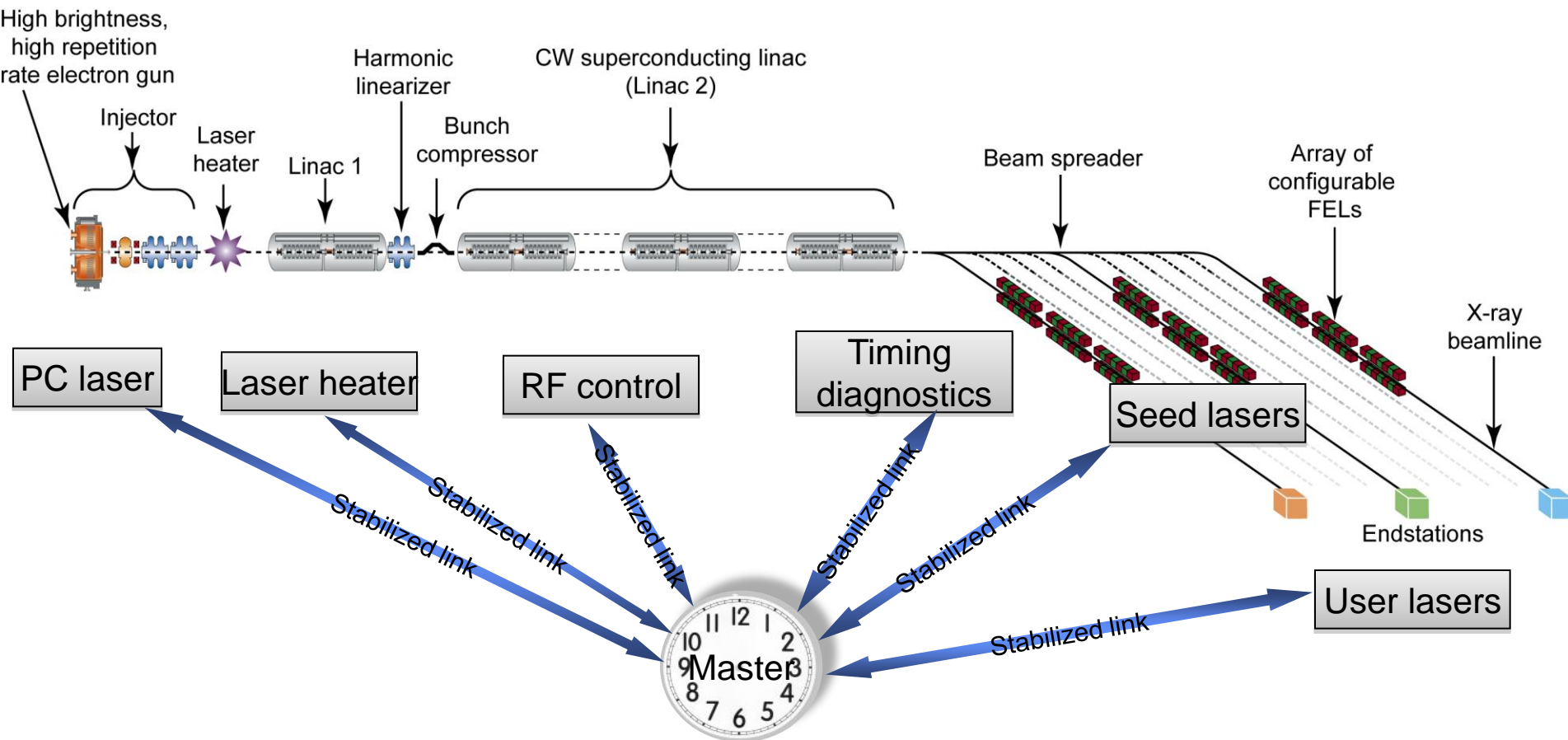


If there is jitter of the electron beam w.r.t. the master clock, measure the arrival time of each pulse and sort each data frame according to measured arrival time.

This requires tight synch between the laser pump and arrival time diagnostic.

# The Big Picture

- The eventual goal is to provide *remote* synchronization between all FEL driver systems: x-rays, lasers, and RF accelerators. Our current focus is to synch user laser systems with timing diagnostics.



# Three Challenges



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- Provide long-term stable clock over entire accelerator complex: injector, linac, diagnostics, and lasers
  - Use stabilized links to maintain stable relative phase
  - Laser-laser stability should be  $<10$  fsec (maybe better).
  - RF cavity stability should be  $<50$ -100 fsec.
- Lock remote clients to stable clock
  - Advanced digital controllers (RF and mode-locked laser oscillators)
  - Direct seeding of remote lasers
- Measure resulting electron and photon timing stability
  - Femtosecond electron arrival time and bunch length and energy spread monitors
  - Femtosecond x-ray arrival time, pulse length, spectrometer



# Why optical fiber links?



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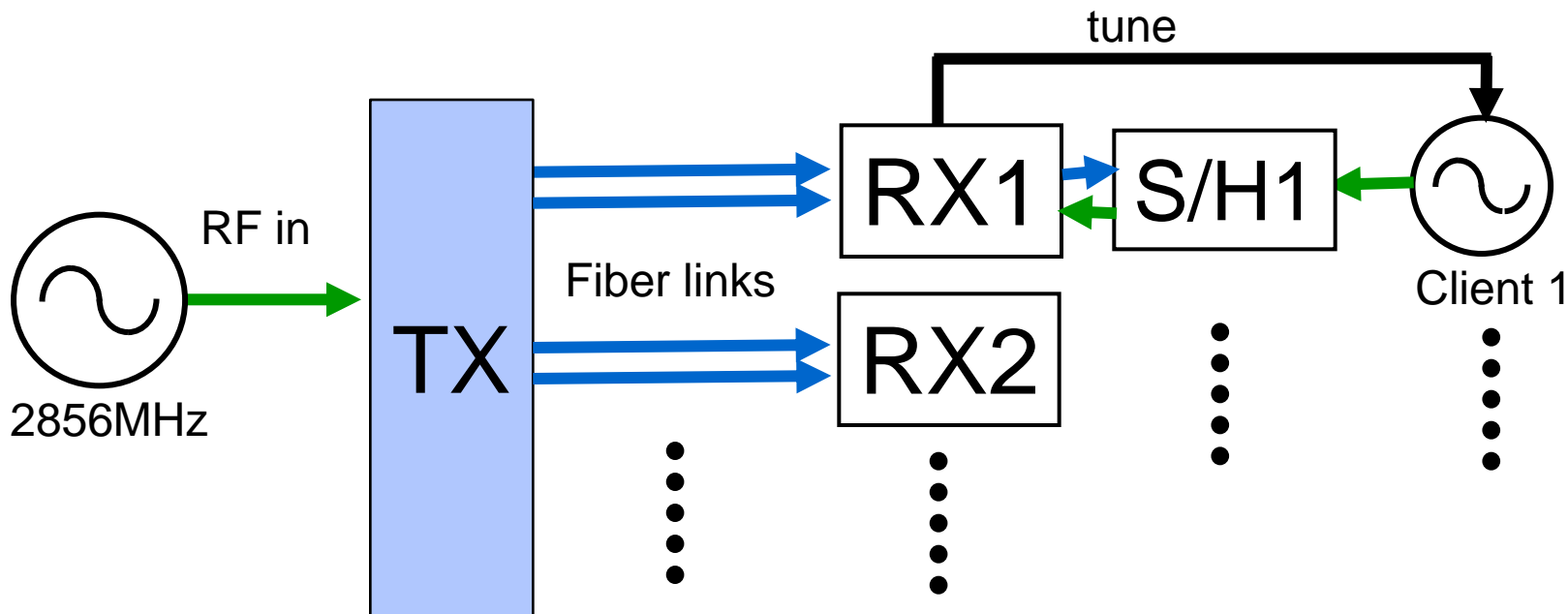
- Problem: coaxial cables and optical fiber have a temperature dependence of propagation delay of about 50 psec/km/deg-C.
  - Completely unacceptable for next-gen light sources both for RF systems and lasers.
  - Temp. stabilized cables impractical for large installations.
- Solution: use optical interferometry over fiber links to measure length change and actively feedback to stabilize signal propagation delay.
  - Fiber provides THz bandwidth, low attenuation, electrical isolation. Acoustically sensitive.
  - Optical signal transmission allows very sensitive interferometry (time or frequency domain).
  - Commodity grade fiber technology relatively cheap.



# Stabilized RF transmission



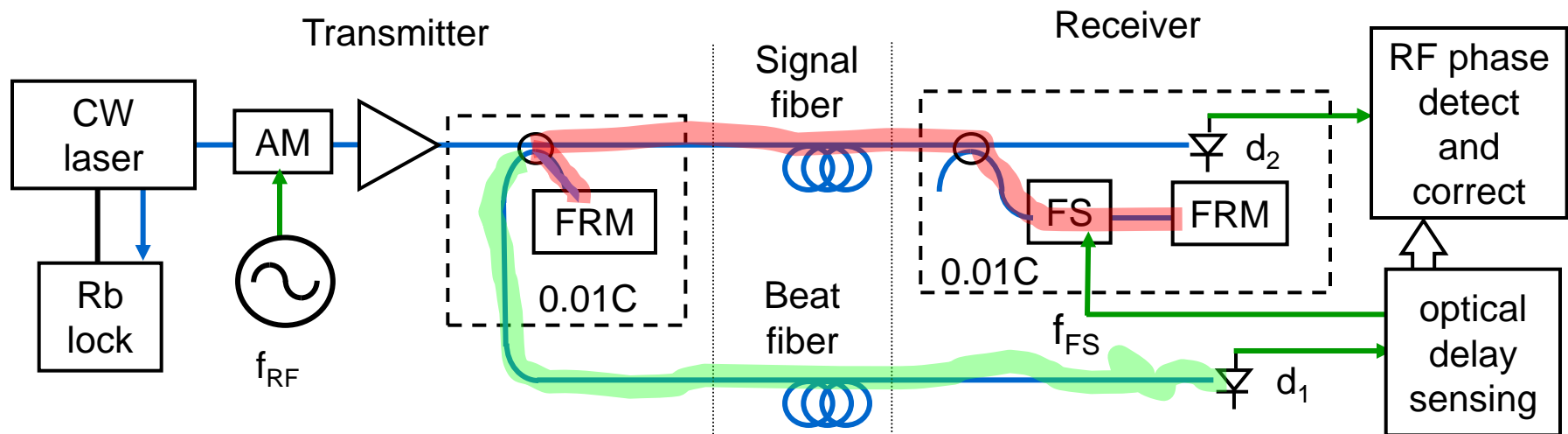
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- TX: N-channel fiber transmitter
- RX: signal receiver, signal processing, link stabilizer
- S/H: synch-head positioned as close as possible to client (e.g. laser oscillator, RF system, VCO)

# Single Channel Link

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- FRM is Faraday rotator mirror (ends of the Michelson interferometer)
- FS is optical frequency shifter
- CW laser is absolutely stabilized
- Transmitted RF frequency is 2856 MHz
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

More detail in TUPEA033

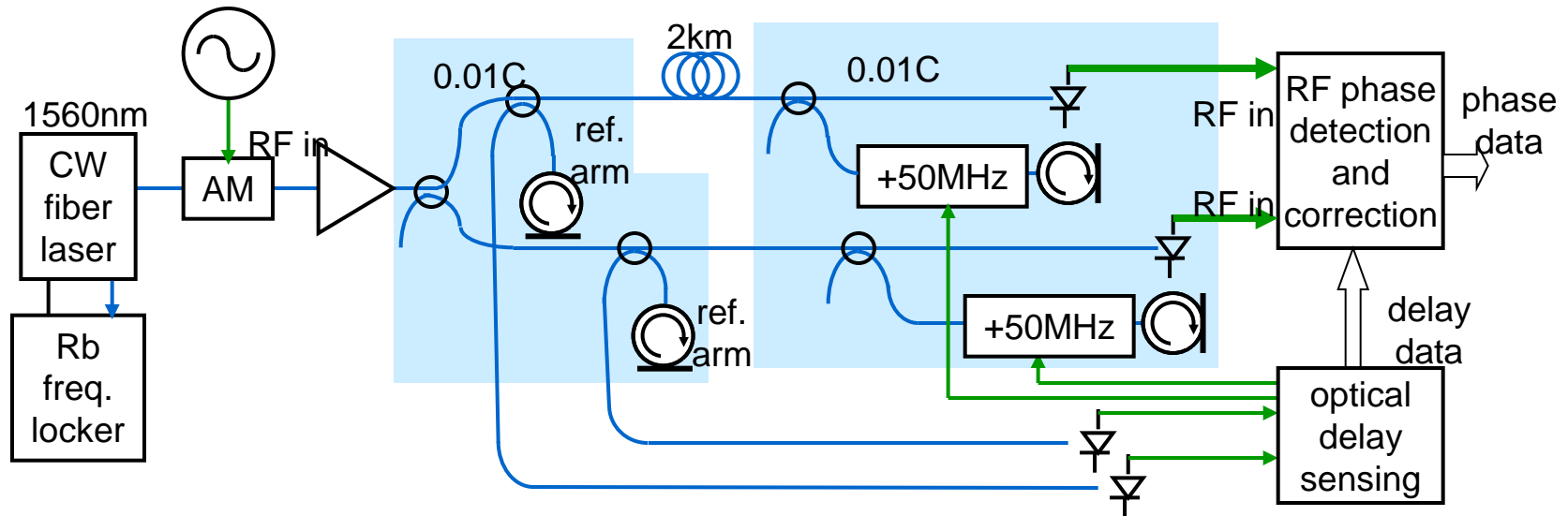
# Our recipe for stabilized RF transmission

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- Transmit master clock as modulation of optical carrier
  - Transmit RF by amplitude modulation of CW signal
  - Like cable TV transmission
- Measure link variation by Michelson interferometer using stabilized optical carrier.
  - Use heterodyne interferometer to avoid baseband phase drift.
  - High sensitivity by modulating optical phase to maintain constant number of optical wavelengths over fiber link.
  - Correct for different temperature coefficients of group and phase velocity by feeding forward an additional phase correction to RF
- Demodulate using photodiodes characterized for AM/PM conversion
  - High power diodes have a favorable characteristic
- Process RF signal using FPGA controller
  - RF components continuously calibrated.
  - Powerful processor can implement averaging and filter functions
  - Ready for integration into accelerator systems
- Phase lock remote client (laser, VCO, RF system) to reference clock.
  - Higher frequency reference more sensitive.

# RF Transmission tests



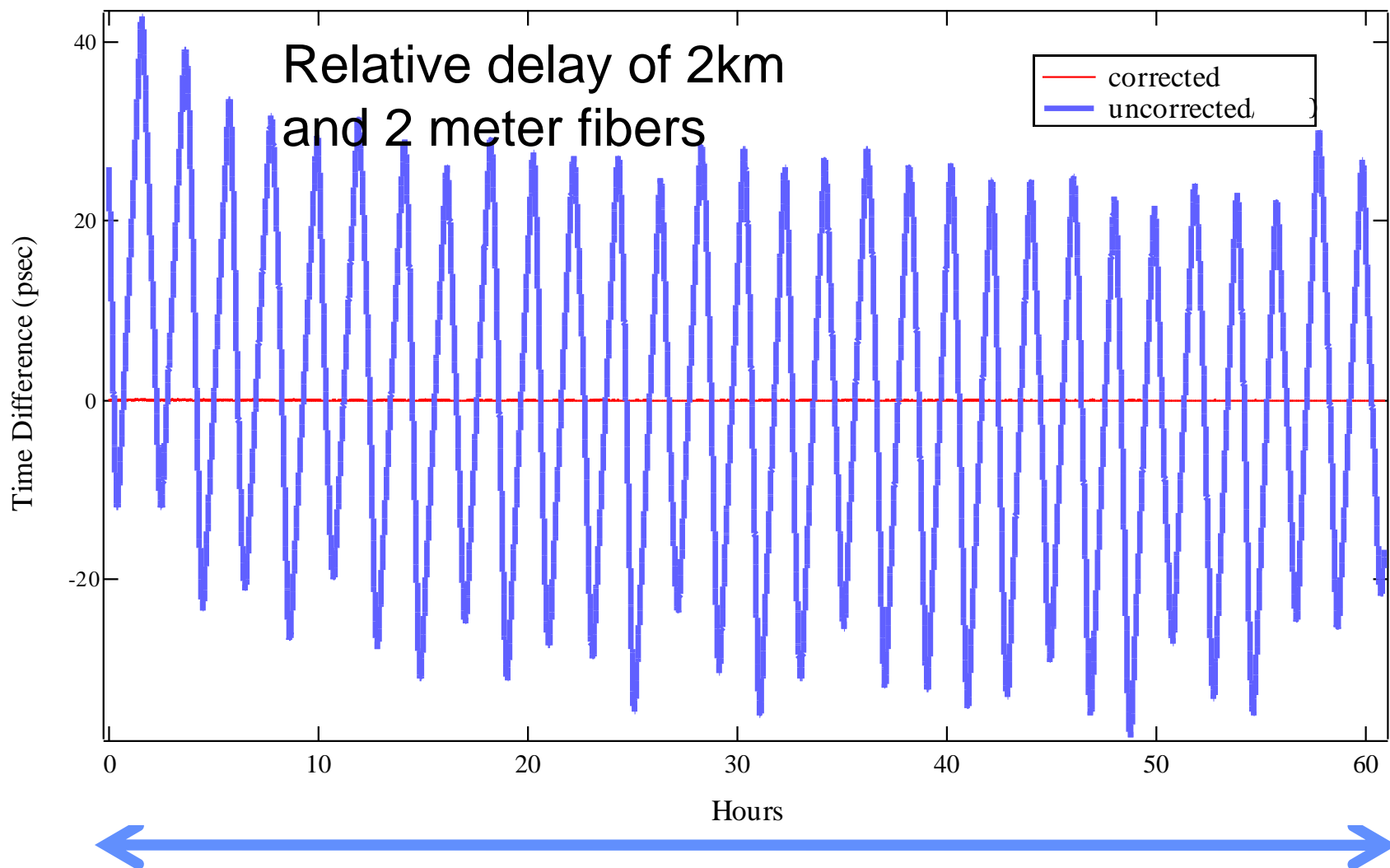
Compare relative phase of 2856 MHz transmitted long and short stabilized links.

- Shift RF phase to compensate for link variation
- Compensate for GVD correction
- Actively calibrate RF phase detection front end (mixers, splitters, etc.)

# RF Transmission results

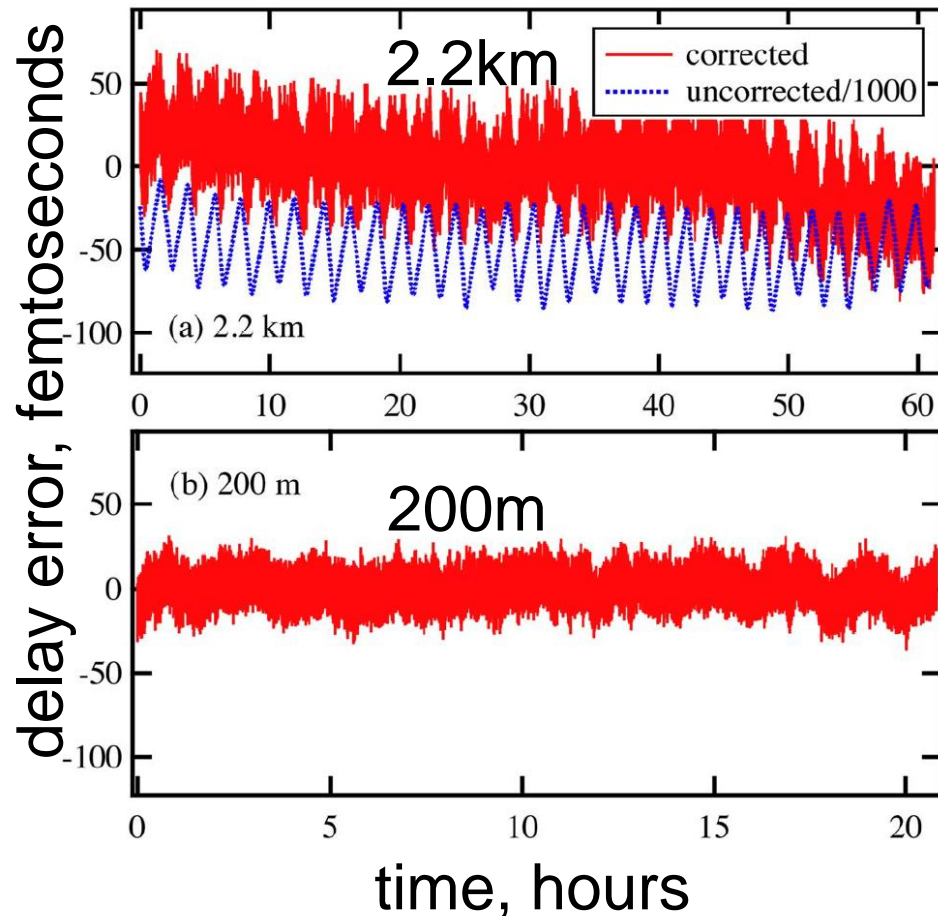


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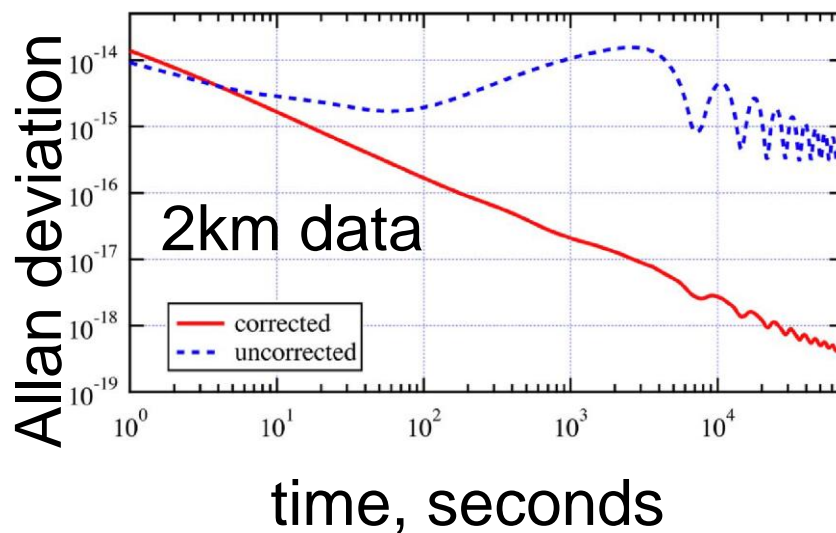


61 hours

# Detailed results



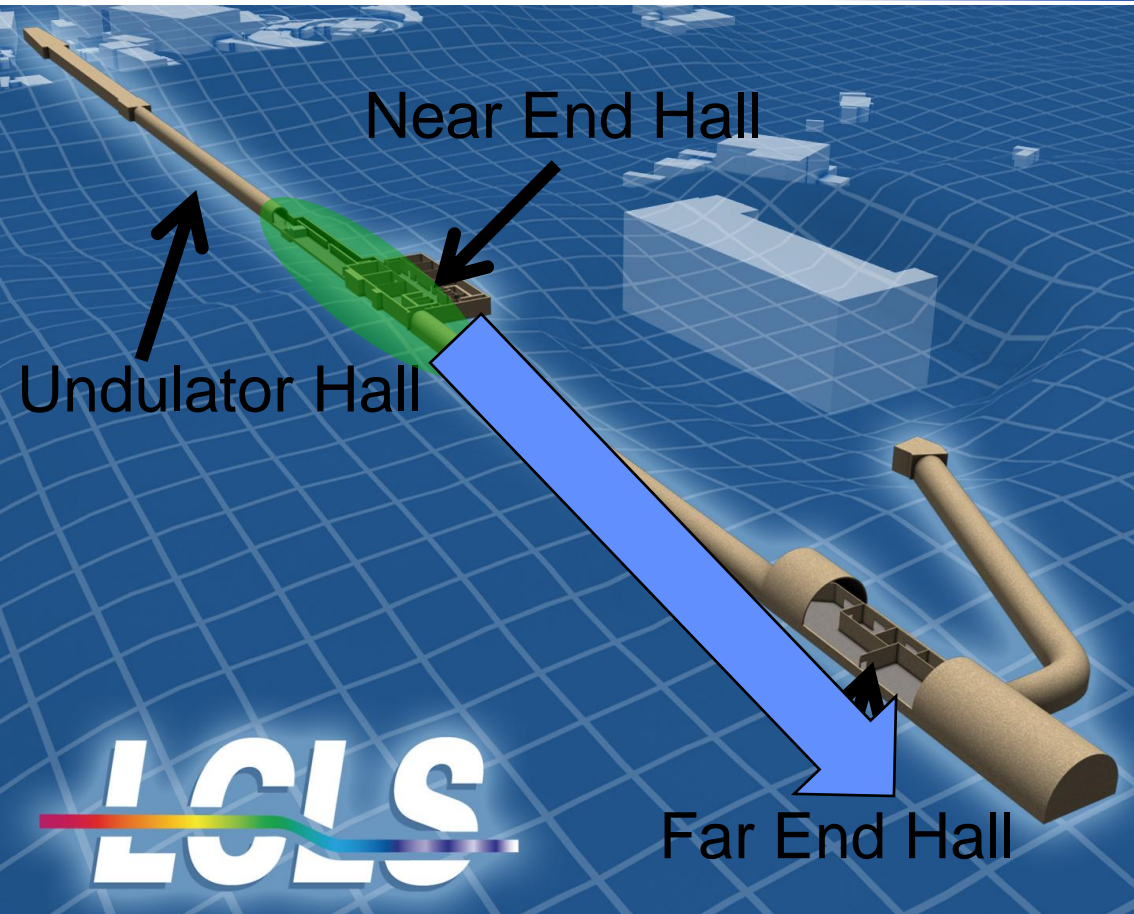
- 1kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



# LCLS: Initial Configuration

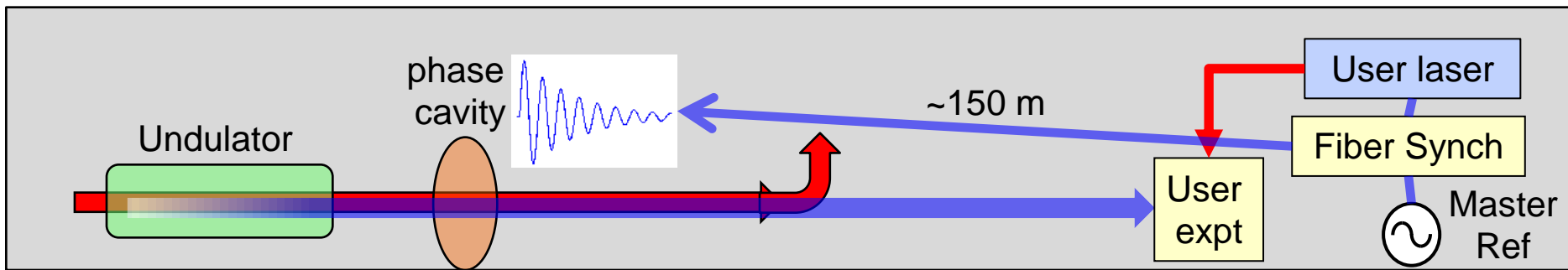


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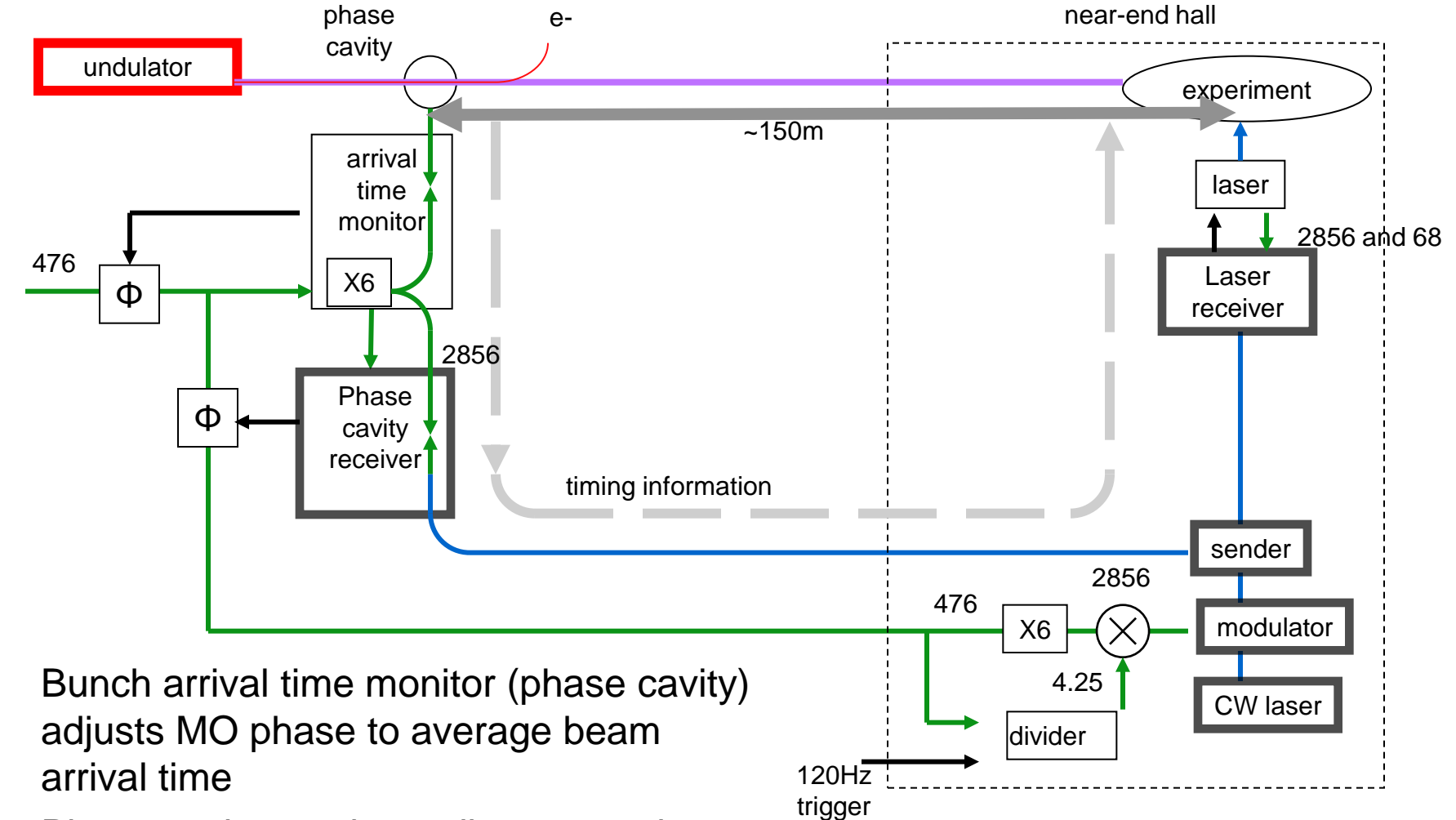
Goal: Synchronize NEH and FEH lasers to a bunch arrival time diagnostic to allow time-stamping of each beam pulse.

Initial configuration synchronizes phase cavity and one NEH laser (Ti:Sapph osc)





# LCLS Configuration

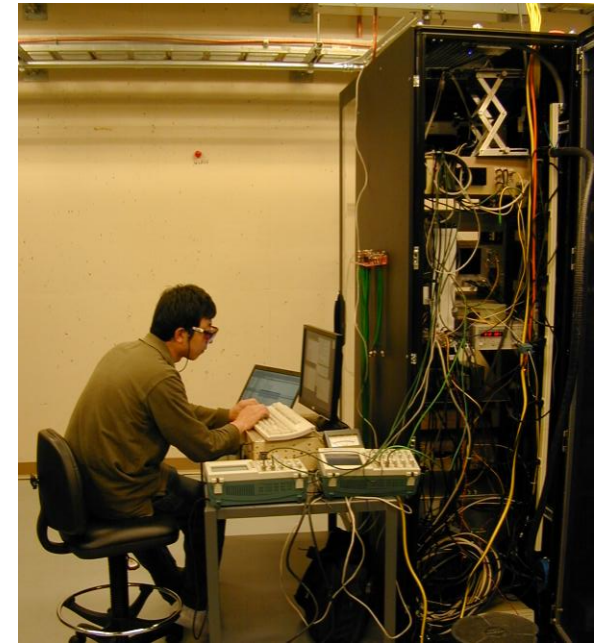
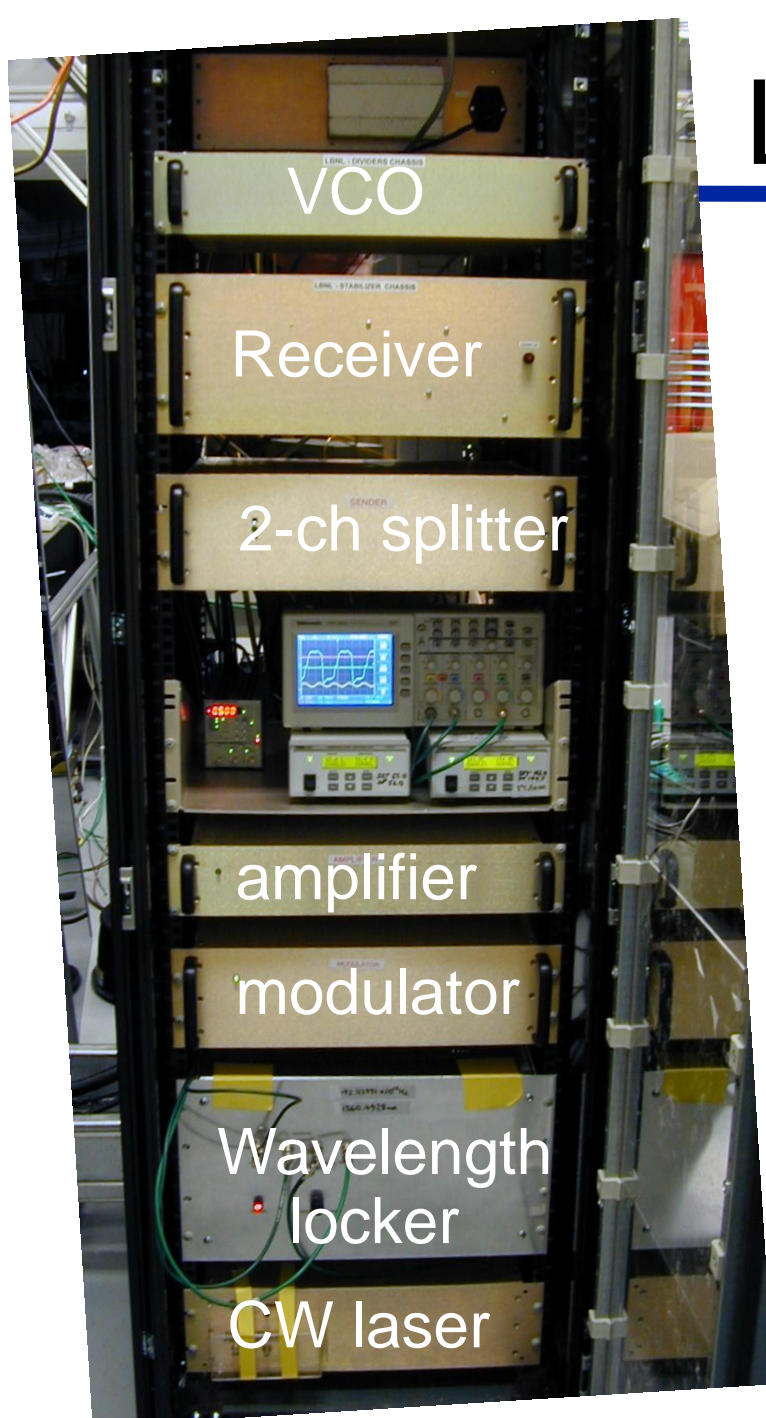


- Bunch arrival time monitor (phase cavity) adjusts MO phase to average beam arrival time
- Phase cavity receiver adjusts 476 phase to follow average beam phase.
- The laser is treated as a VCO that is locked to average beam phase.

# LCLS System

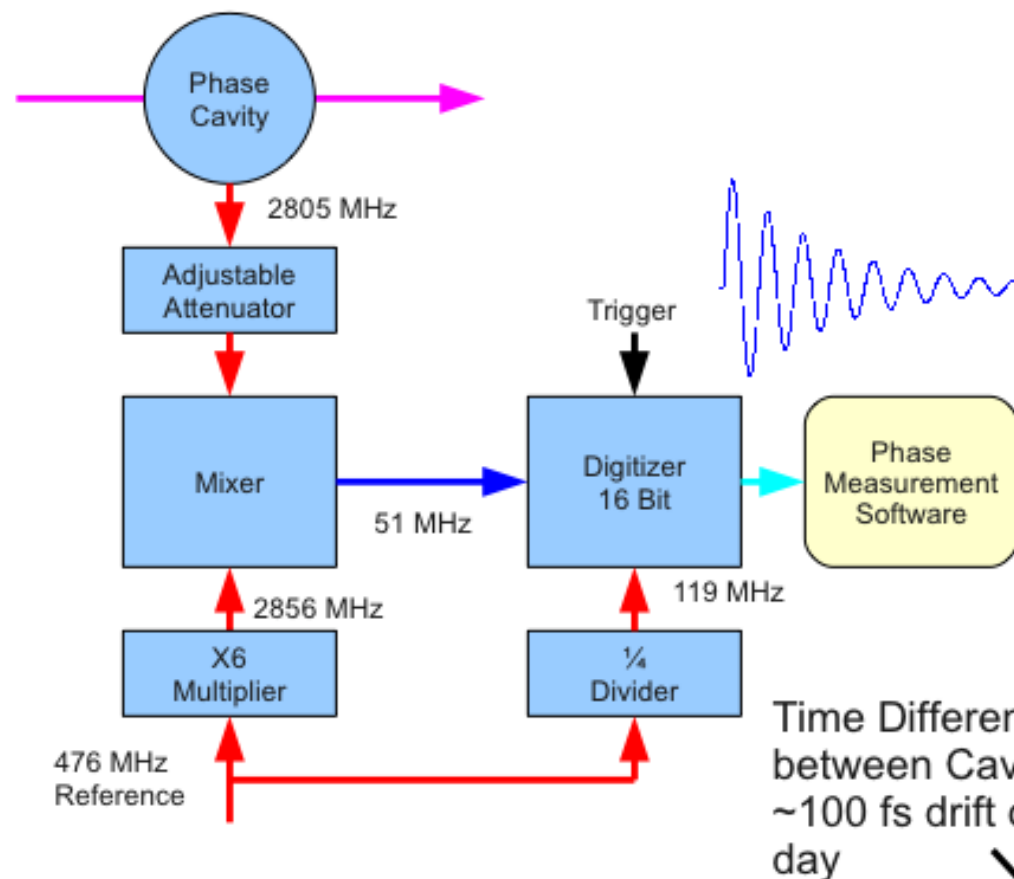


- TX occupies half of standard rack.
- Each RX has a Synch-head and stabilizer chassis. S/H sits as close as possible to client.
- Fiber links are run in SMF28 in 12 fiber cables.



# Phase Cavity System

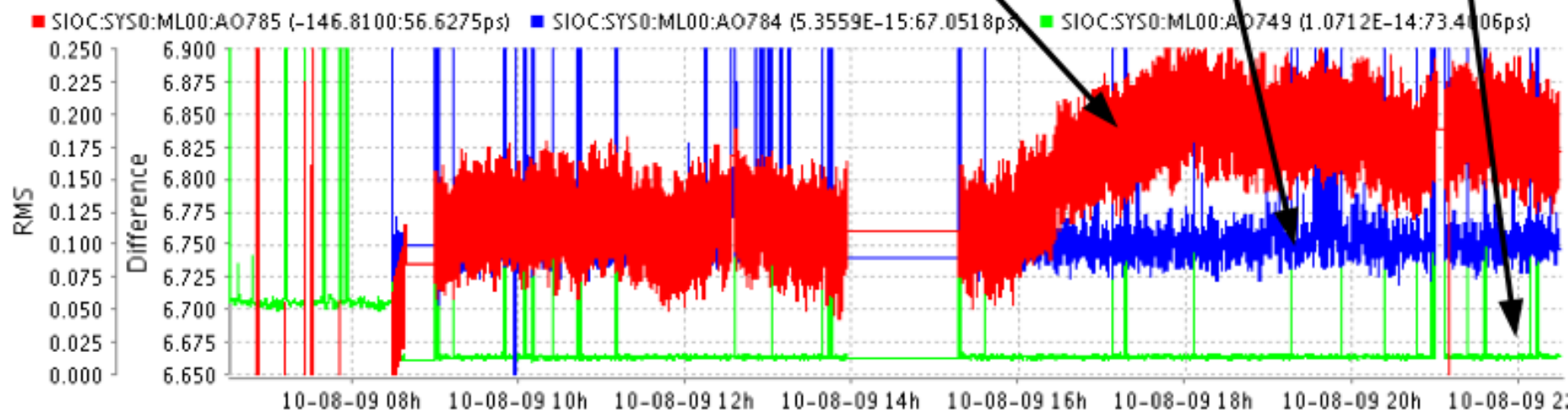
Joe Frisch, SLAC



Standard deviation of difference between cavities ~15 fs RMS

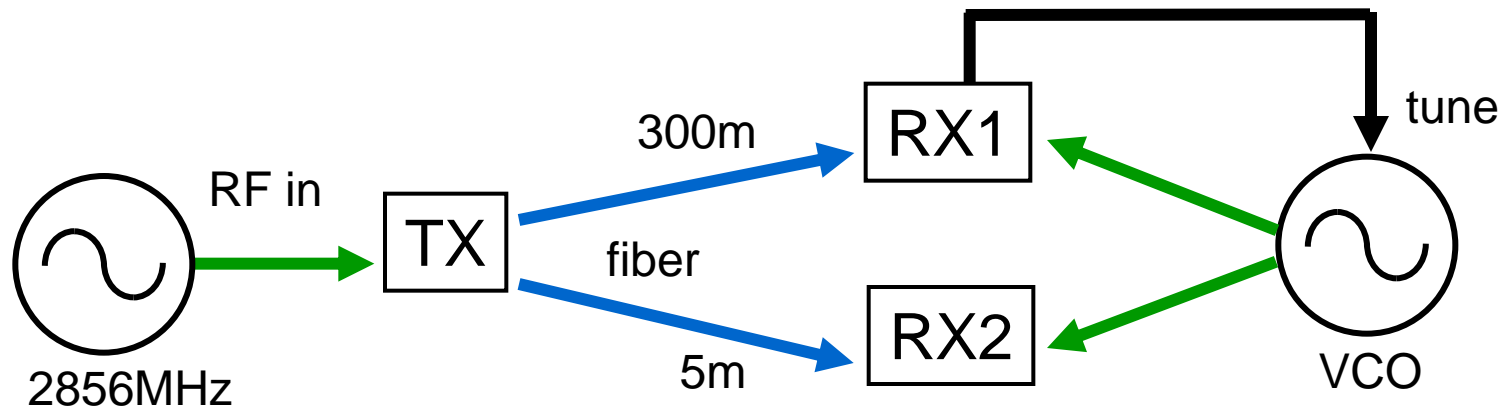
Time Difference between Cavities ~100 fs drift over 1 day

Standard Deviation of single cavity ~100fs RMS

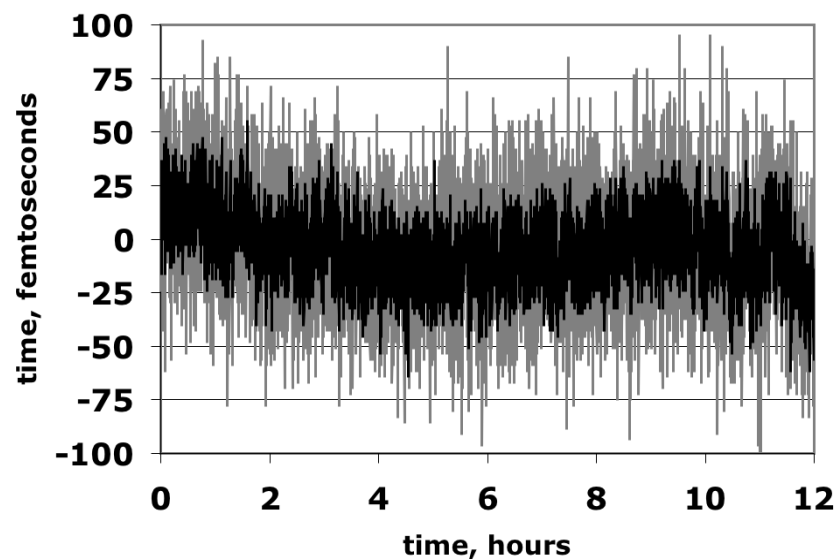


# LCLS RF Transmission Results

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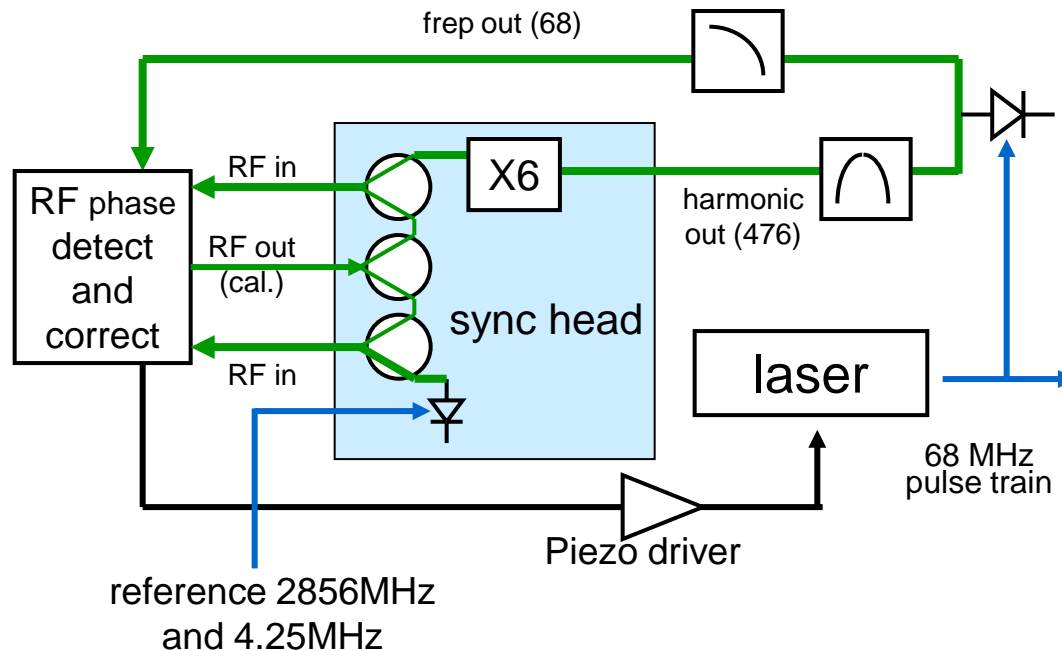
- 27fs RMS in 125kHz BW
- 16fs RMS in 1kHz BW
- Long fiber is looped back from tunnel.
- Drift is due to short cable between receivers, room temperature



# Laser locking configuration

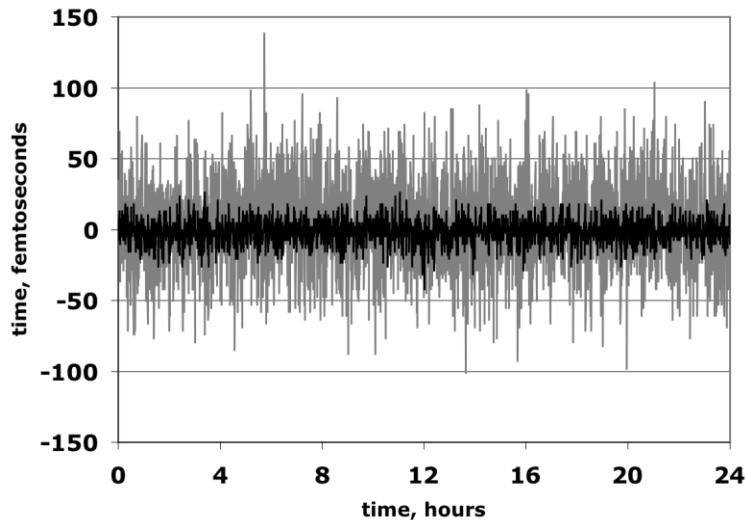


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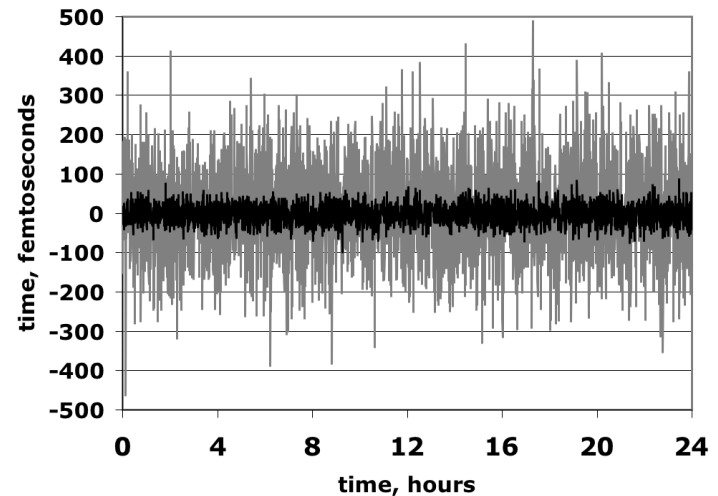


- Phase compare at 2856MHz
- Sync first to 68MHz to remove “bucket ambiguity”
- Works better than the commercial lockbox
- New arrangement uses faster diode, eliminates X6 multiplier

# Laser lock results



RF control error signal  
1kHz BW (black): 8fs RMS



Laser control error signal  
1kHz BW (black): 25fs RMS

- Improvements to the laser should decrease high frequency noise
  - Acoustic and vibration isolation
  - Lower noise pump laser

# Summary



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- We have demonstrated a stabilized fiber link system for high precision distribution of RF signals
  - 16fs between two RF channels
  - Easily manufacturable, expandable
  - First commercially produced subsystems being tested
- System allows synchronization between laser system and electron beam
  - Direct locking to laser oscillator (25fs laser loop error (1kHz))
  - **Enabled first LCLS pump-probe experiment!**
- LCLS is engineering production receivers (8 channels), upgrading transmitter to 16 channel capability
- Future work
  - Improve laser control
  - Better synchronization measurements
  - Try higher frequencies



# Next challenge...

- We are presently working on a fiber distribution system for controlling the phase of accelerating sections of a linac for the Fermi@Elettra project. Combines stabilized links with precision RF control.

