Femtosecond Synchronization of Laser Systems for the LCLS

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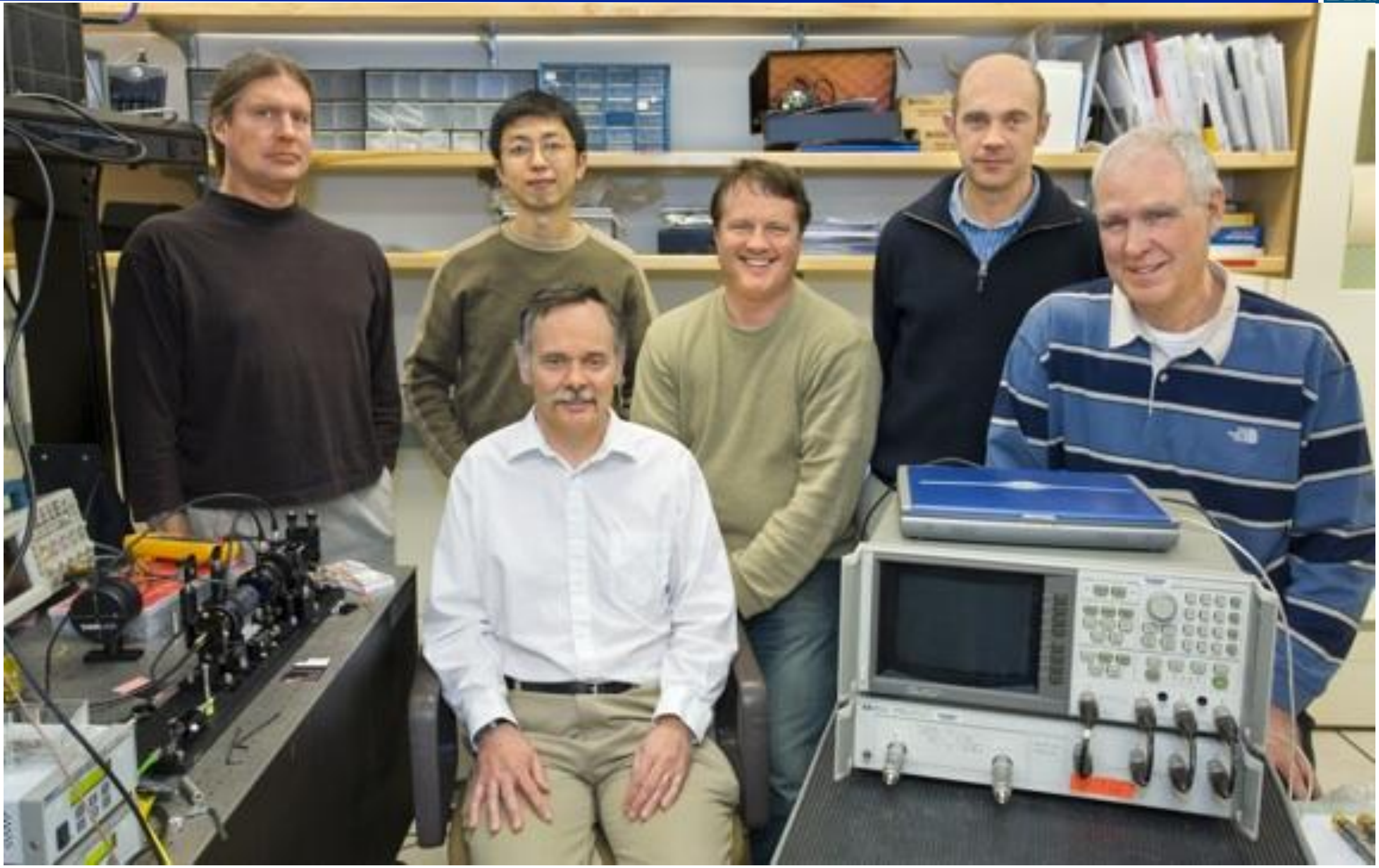
Berkeley Timing Group



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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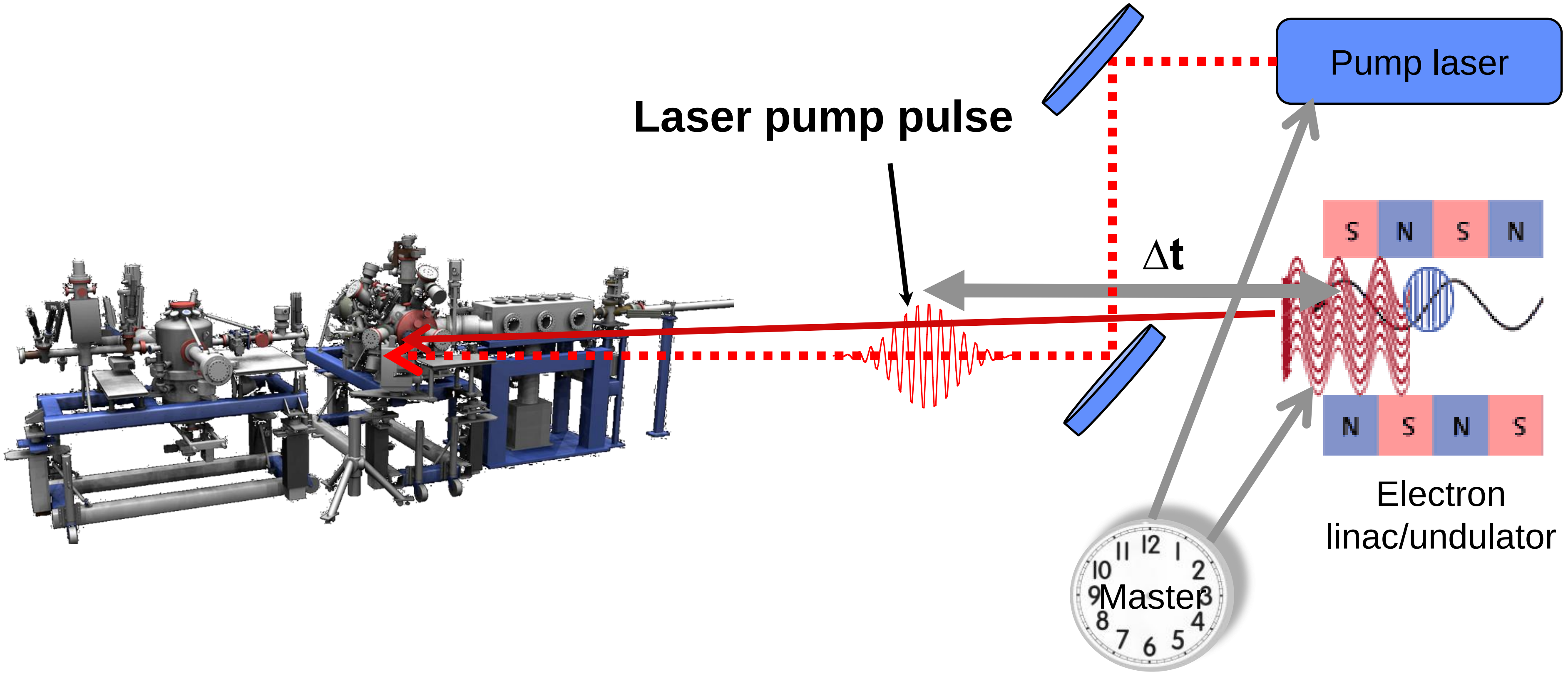
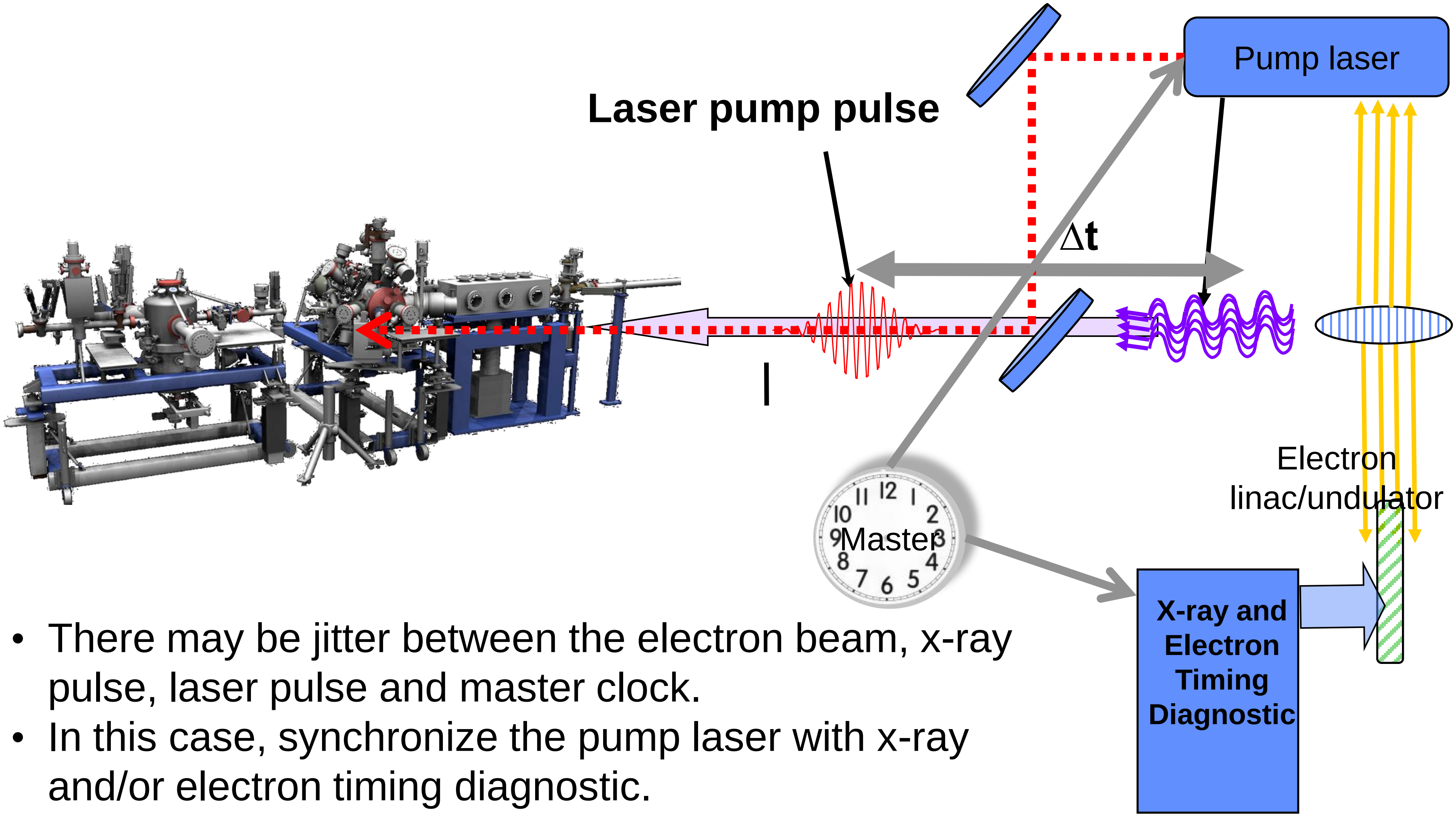
X-ray/optical Pump-probe



- Ultrafast laser pulse "pumps" a process in the sample
- Ultrafast x-ray pulse "probes" the sample after time Δt
- By varying the time Δt, 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.

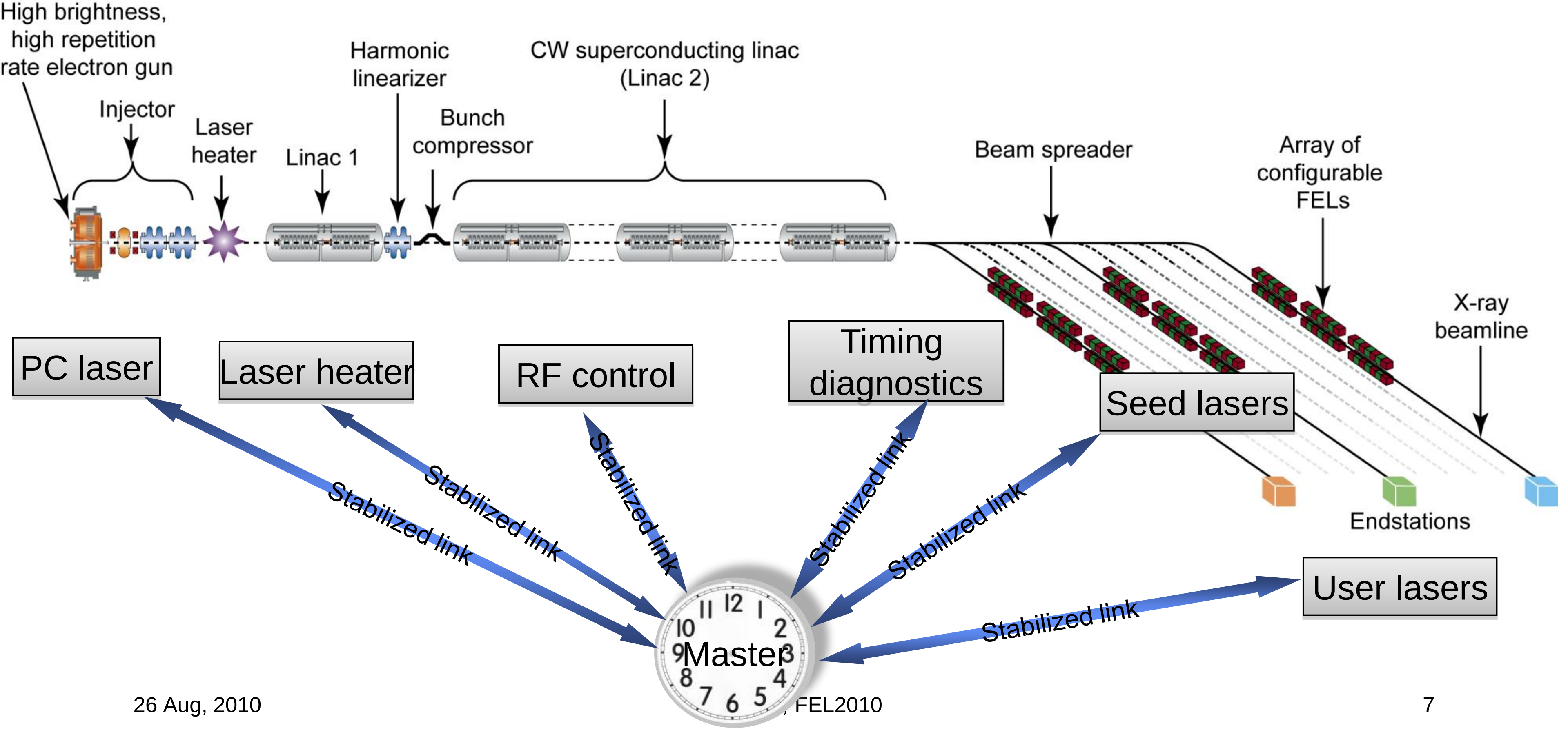
With respect to what?



- There may be jitter between the electron beam, x-ray pulse, laser pulse and master clock.
- In this case, synchronize the pump laser with x-ray and/or electron timing diagnostic.
- Allows best possible characterization of Δt on each pulse.

Establishing "Railroad Time"

- The eventual goal is to accurately distribute a master clock over the entire accelerator complex and 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

- 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 <1 fsec).
  - 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

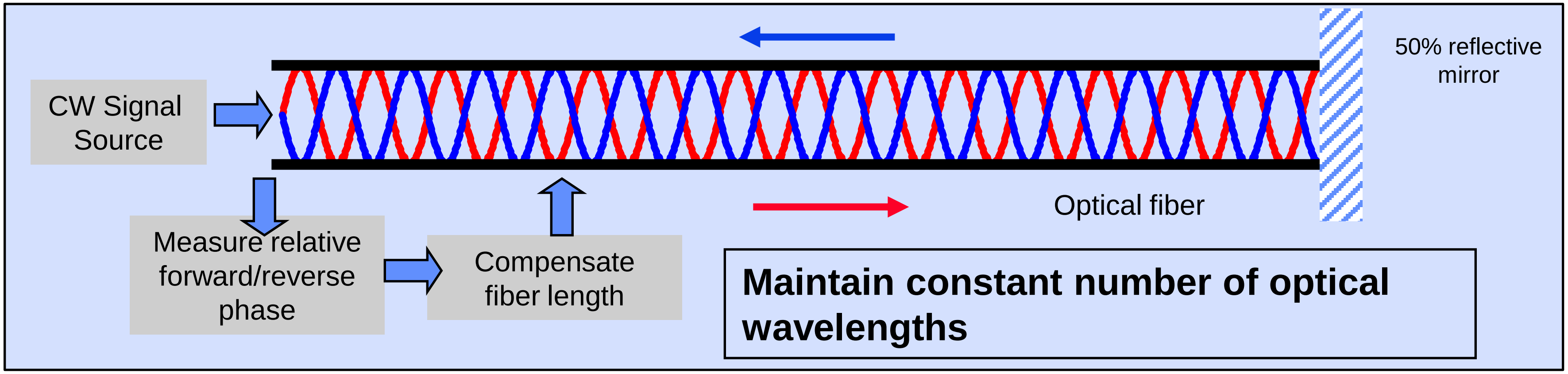
- Measure resulting electron and photon timing stability
  - Femtosecond electron arrival time and bunch length and energy spread monitors
  - Femtosecond x-ray arrival time, pulse length, spectrometer

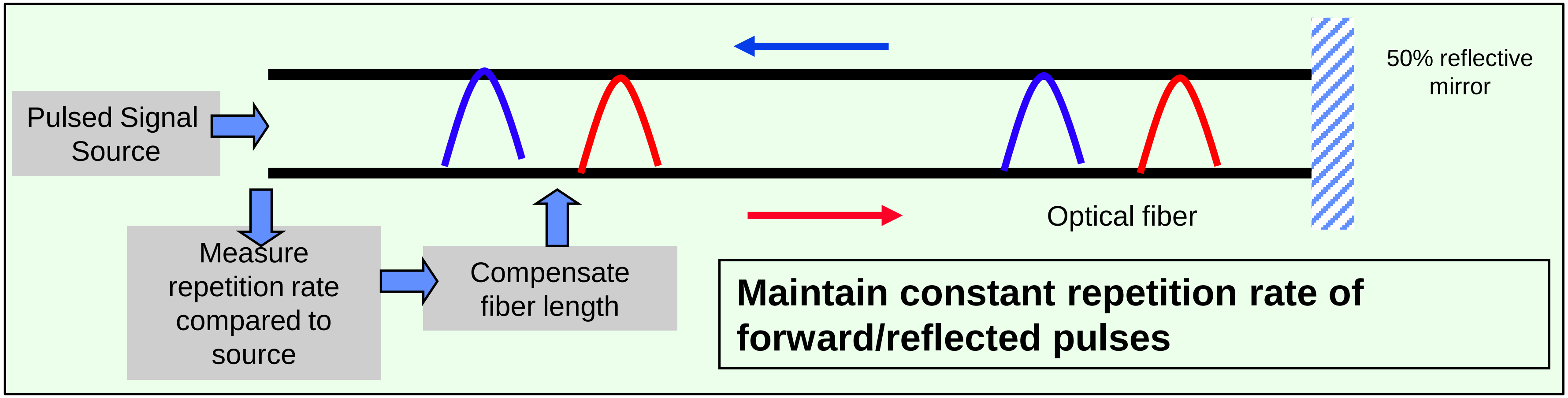
Why optical fiber links?

- 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.

Time and Frequency Domain Stabilized Links

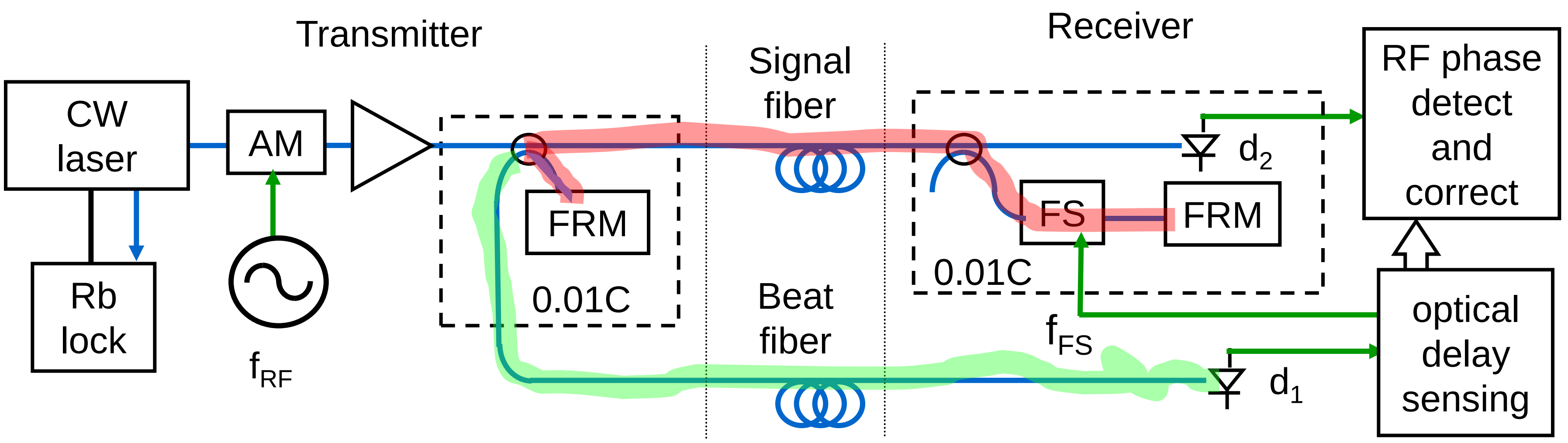
- Fiber links can be stabilized based on the revolution in metrology time and wavelength standards over the past decade.





Correction BW limited to R/T travel time on fiber (e.g. 1 km fiber gives 100 kHz)

Single Channel Link



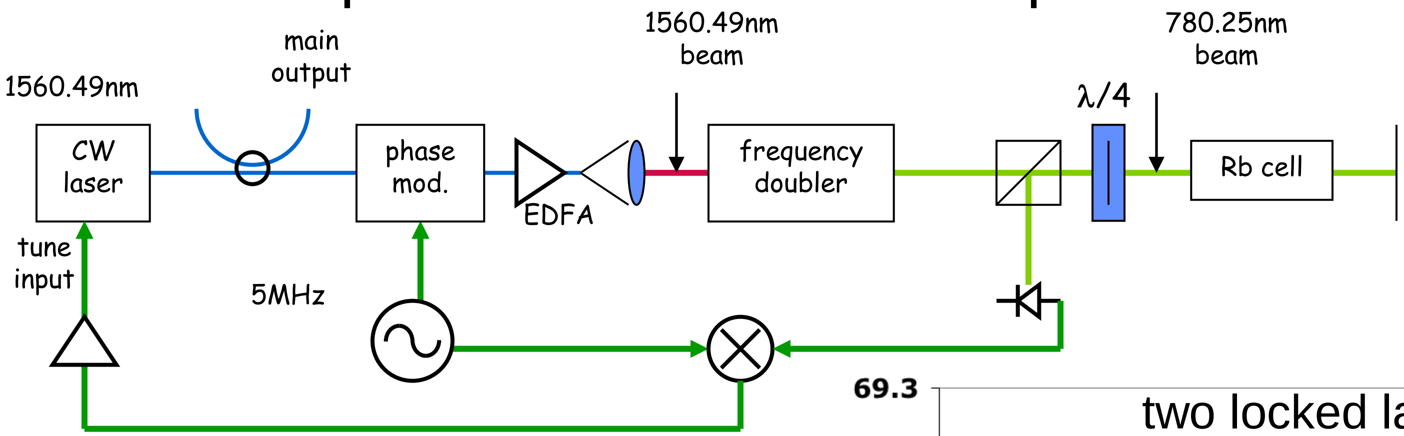
- FRM is Faraday rotator mirror (ends of the Michelson interferometer)
- FS is optical frequency shifter
- CW laser is absolutely stabilized
- Transmitted RF frequency is 2856 MHz
- Detection of beat signal is at receiver
- Signal paths not actively stabilized are temperature controlled

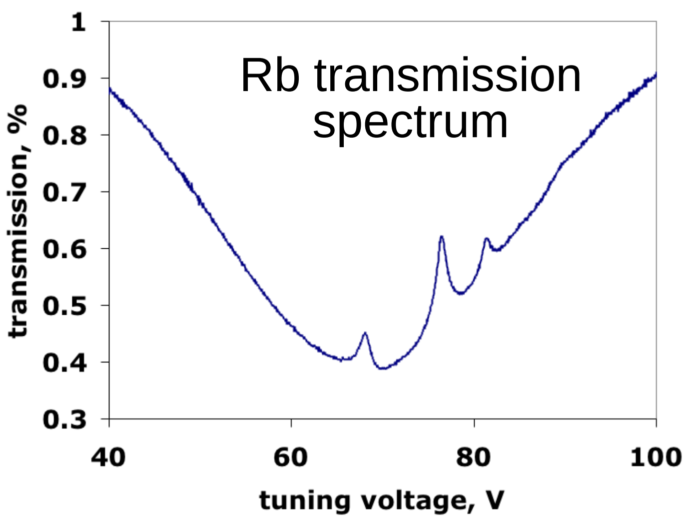
Our recipe for stabilized RF transmission

- 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.
  - PLL implemented using FPGA controller.

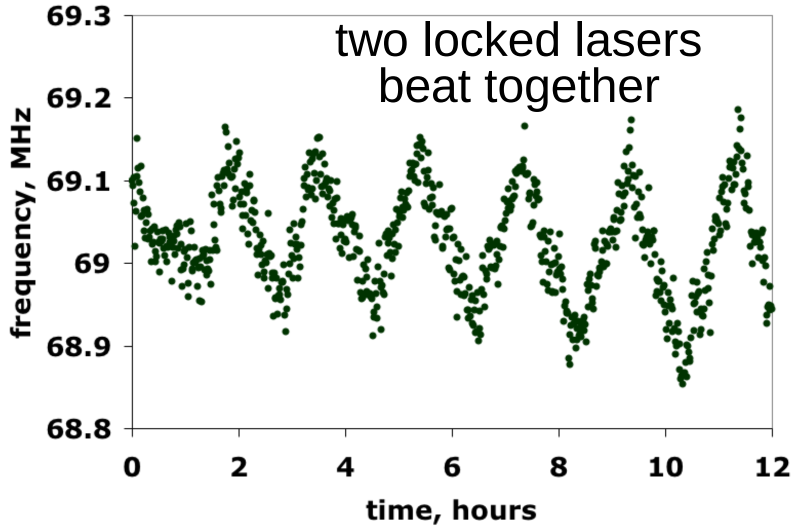
Wavelength standard

Lock CW optical carrier to an absorption line in Rb





Saturation spectroscopy reveals sub-Doppler lines

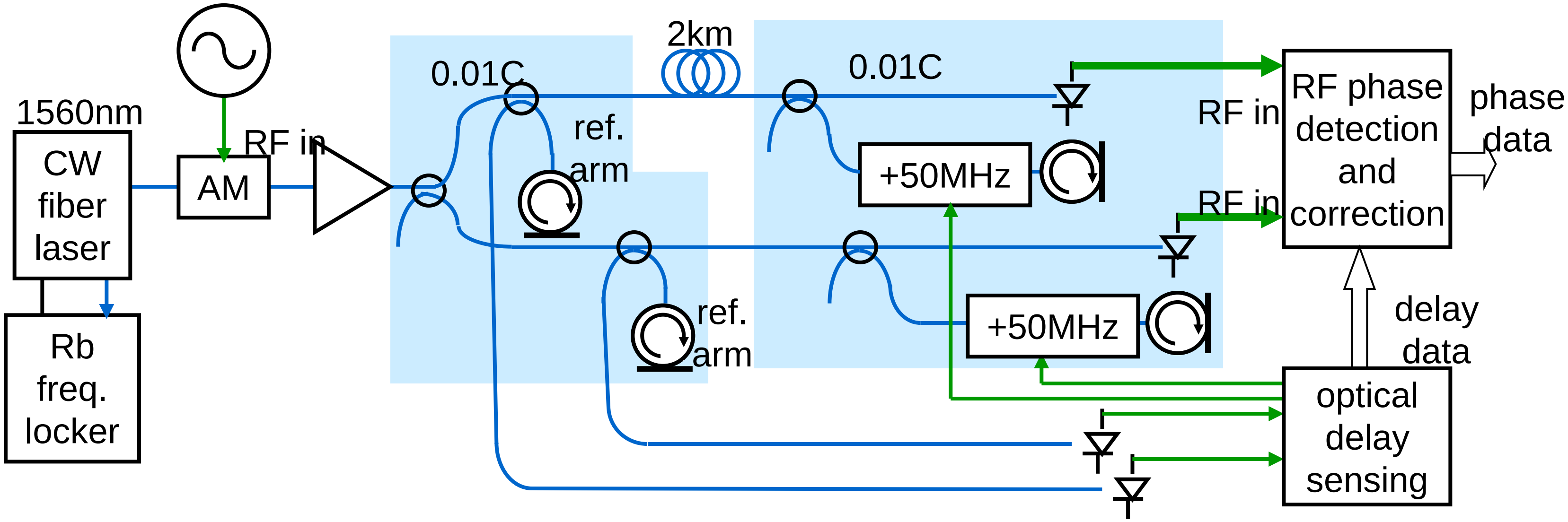


Gate time: 1s

Long term variation: 1.7E-9 p-p

Error for 200m: 1.7fs p-p

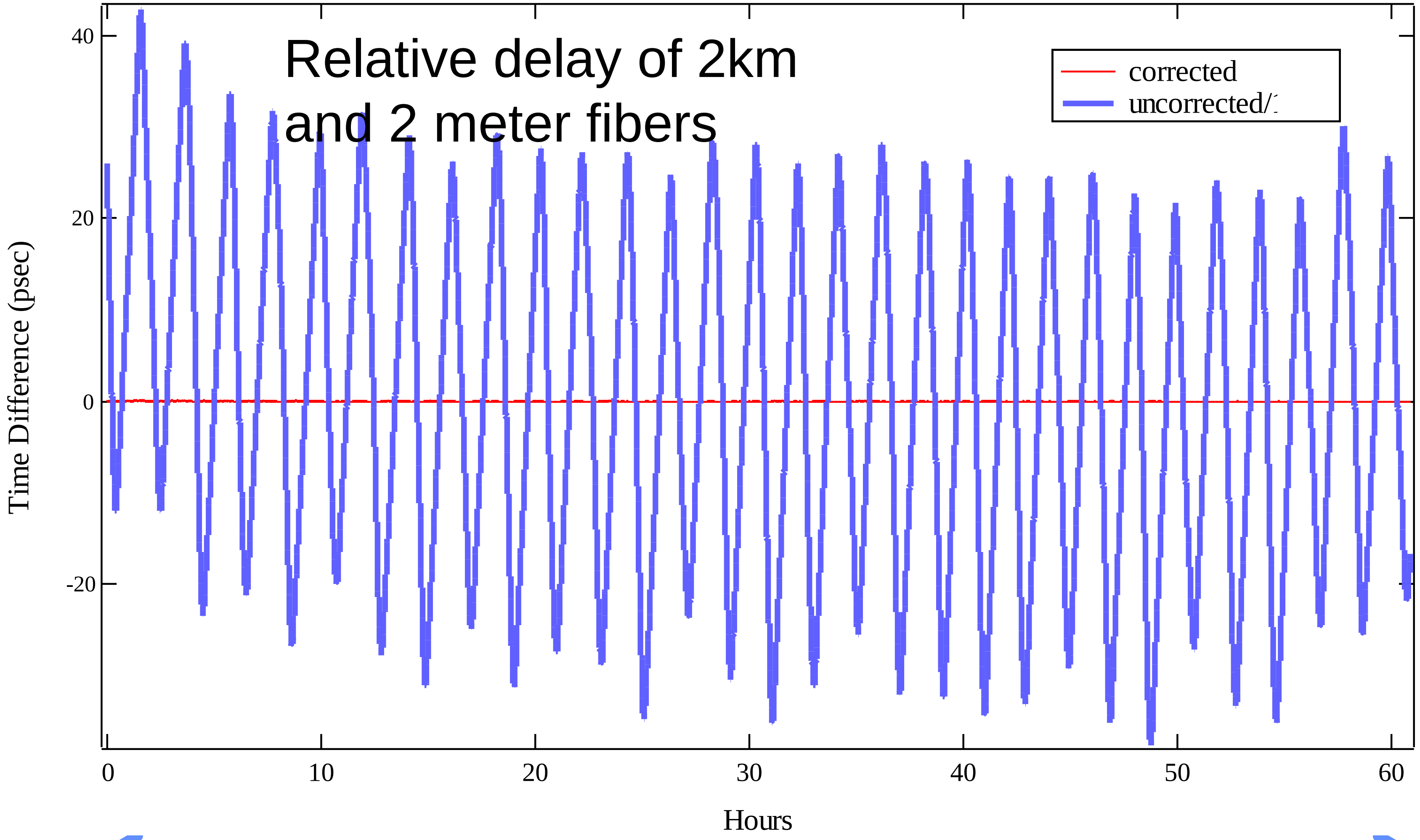
RF Transmission tests



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

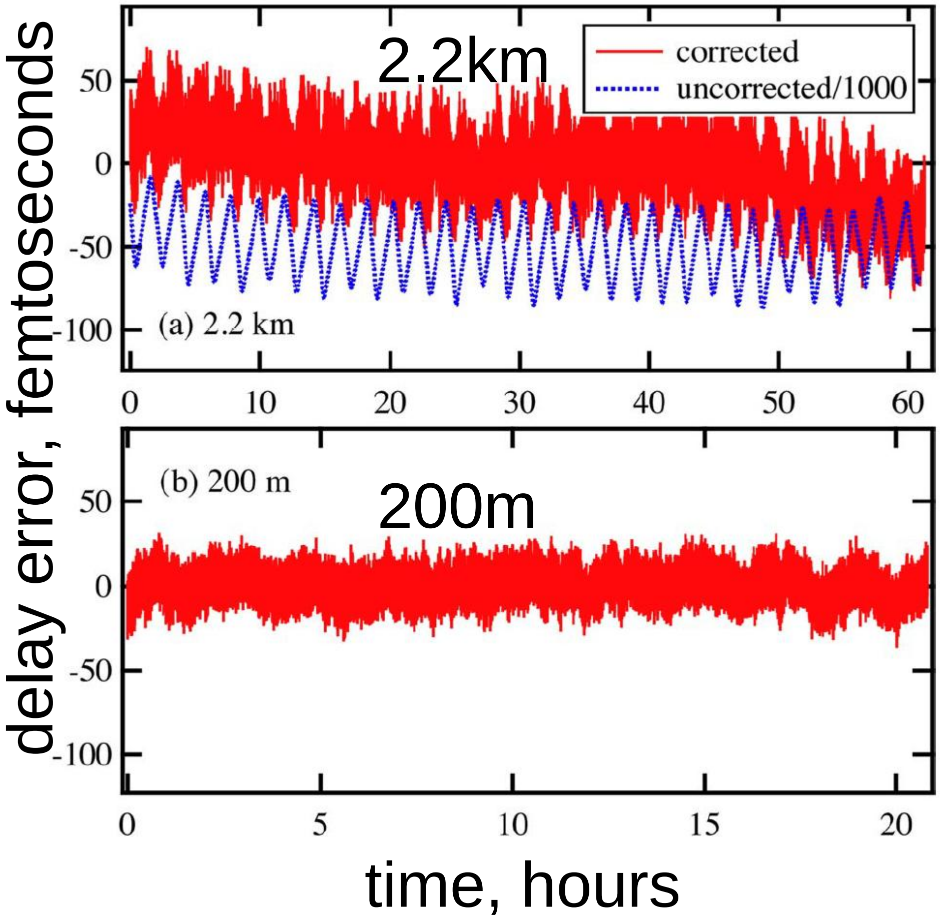
- Shift RF phase to compensate for link variation
- Compensate for GVD correction
- Actively calibrate RF phase detection front end (mixers, splitters, etc.)

RF Transmission results

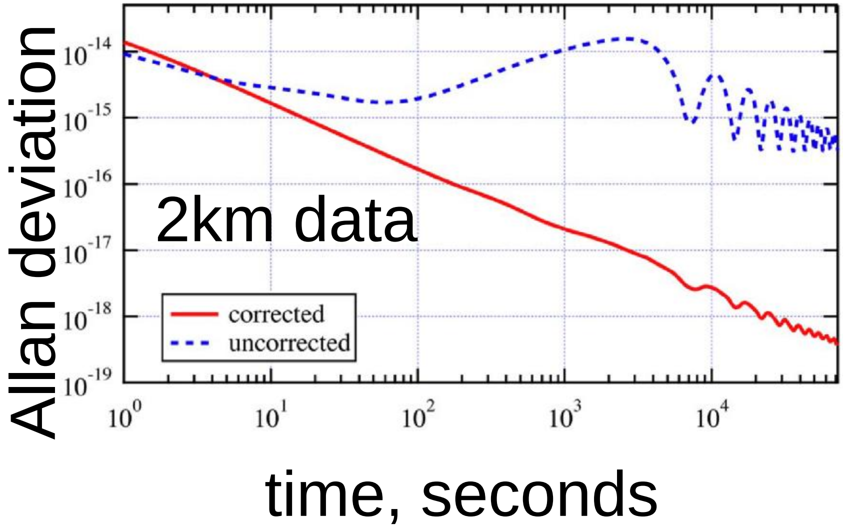


61 hours

Detailed results

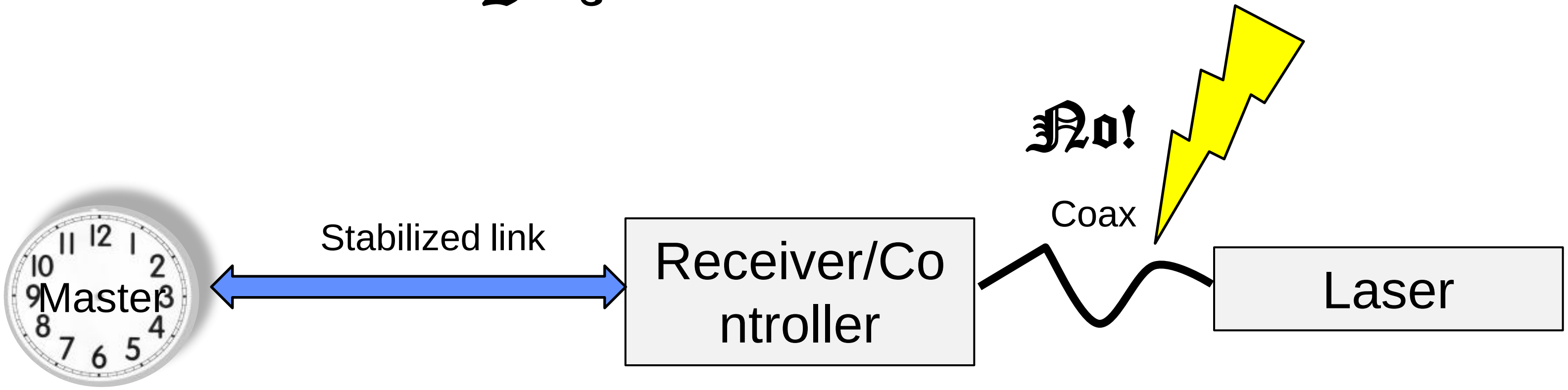


- 1kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



The timing commandment

Thou shalt not have any uncontrolled path lengths in a femtosecond timing system



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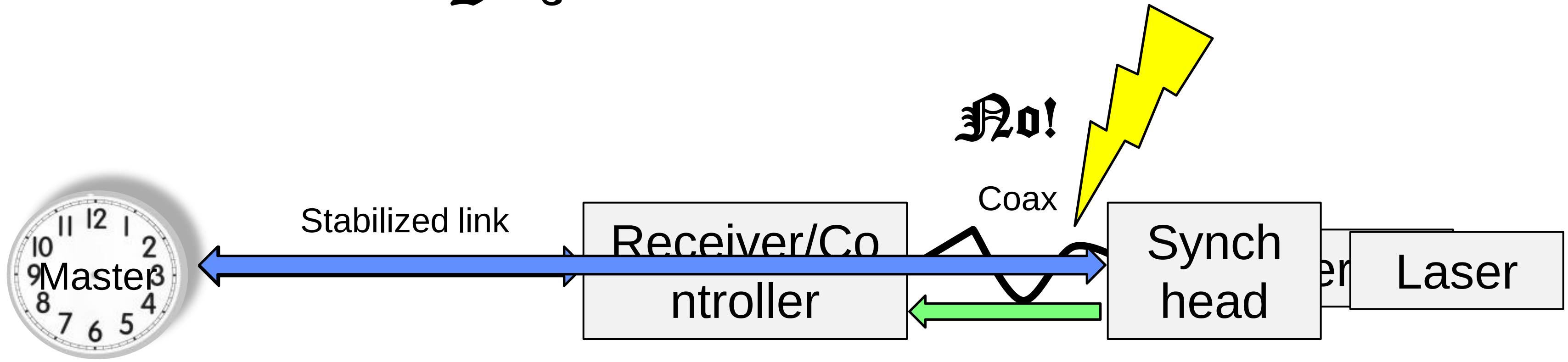

•Bring the stable phase signal as close as possible to the client by extending the fiber to a “synch-head”.
•Lock the client (i.e. laser/VCO) directly to the stabilized RF phase. We use the same controller to lock the client as the fiber.

The timing commandment

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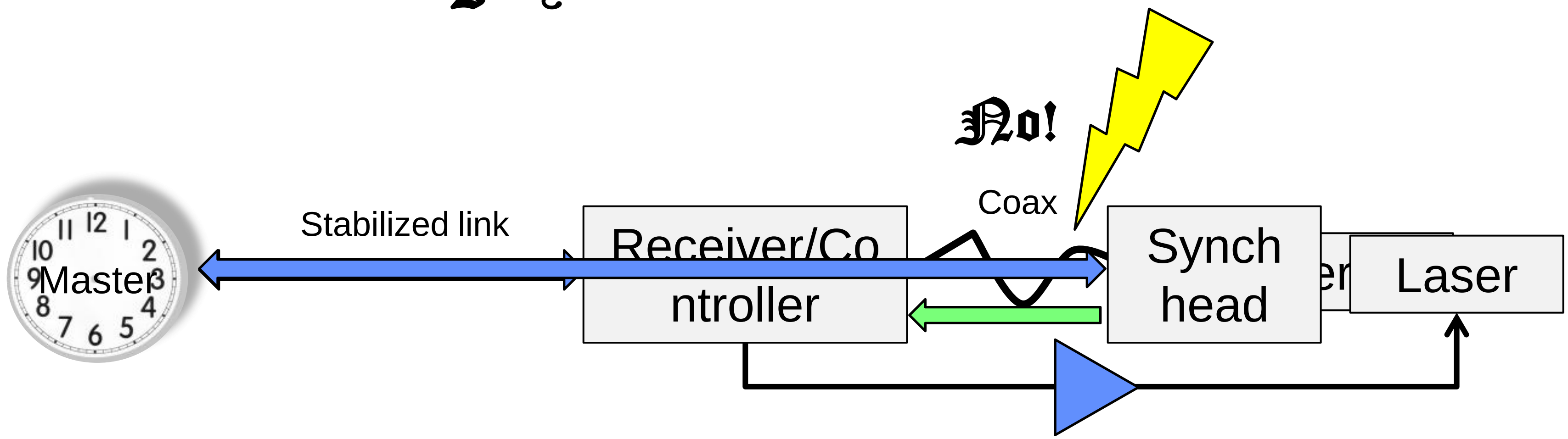

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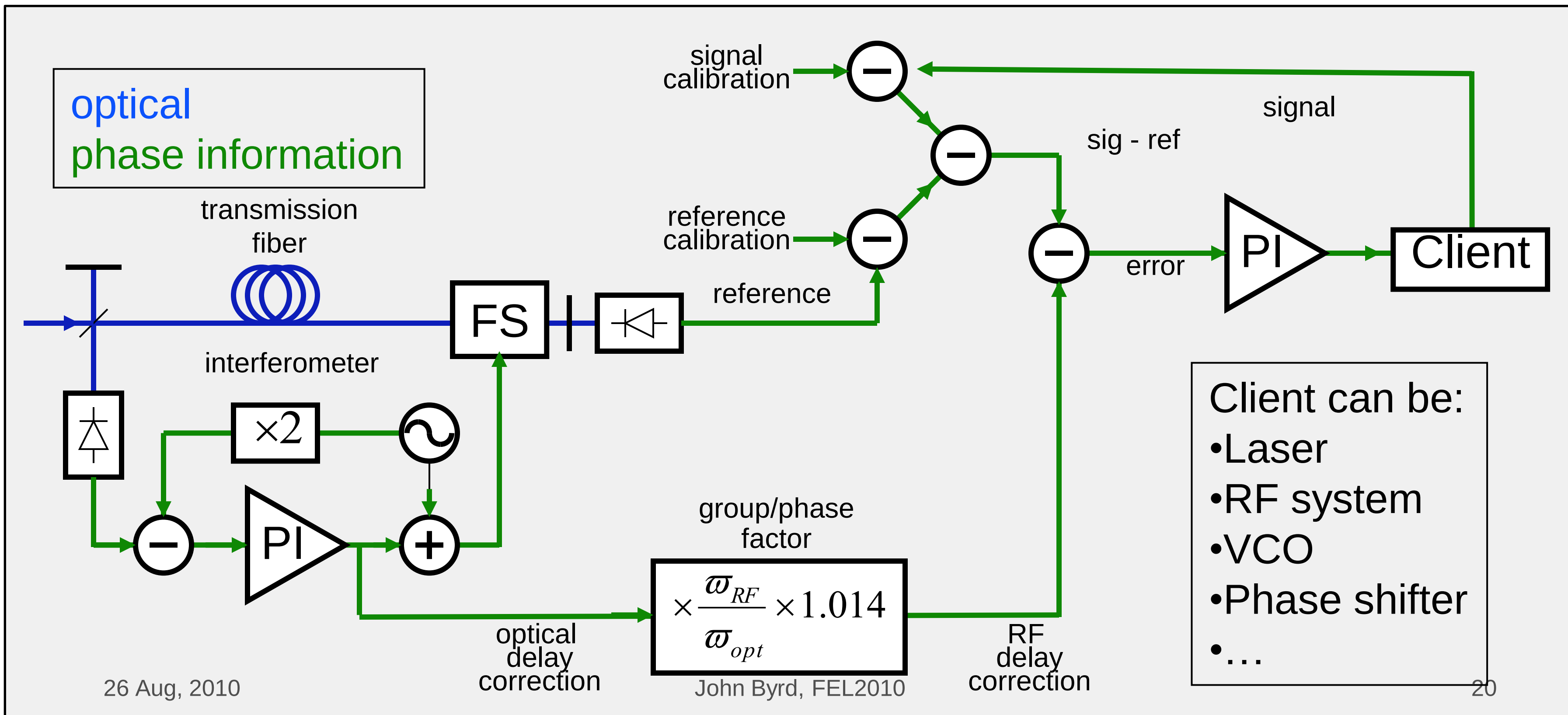
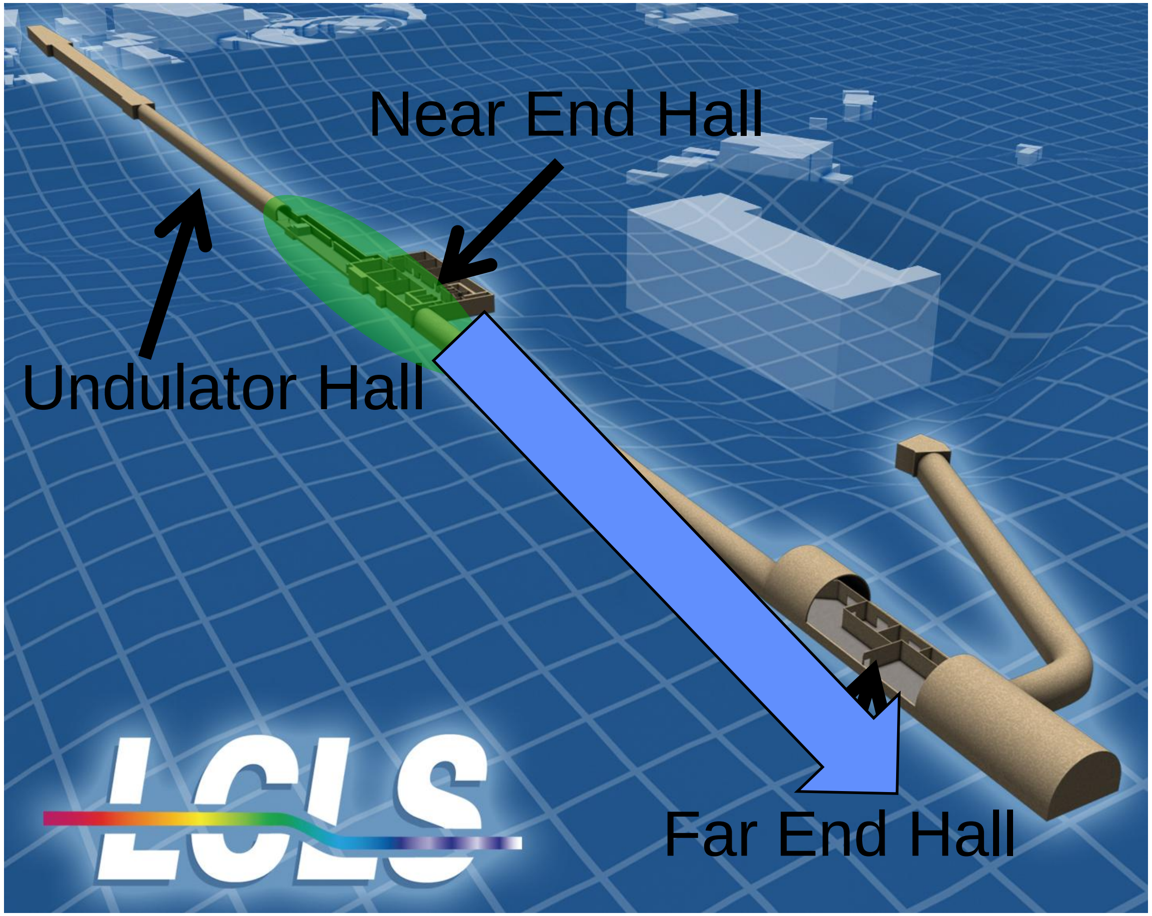
“I am in control here”

- All possible drift sources from the master to the client must be either actively compensated or thermally stabilized.
  - Thermal effects of cables and RF components are actively compensated via calibration signals
  - Group delay is compensated via feed-forward



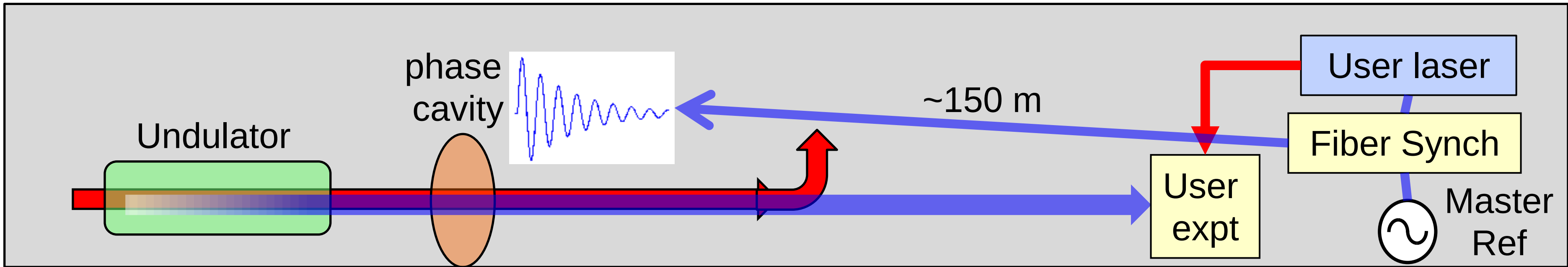
LCLS: Initial Configuration

John Byrd

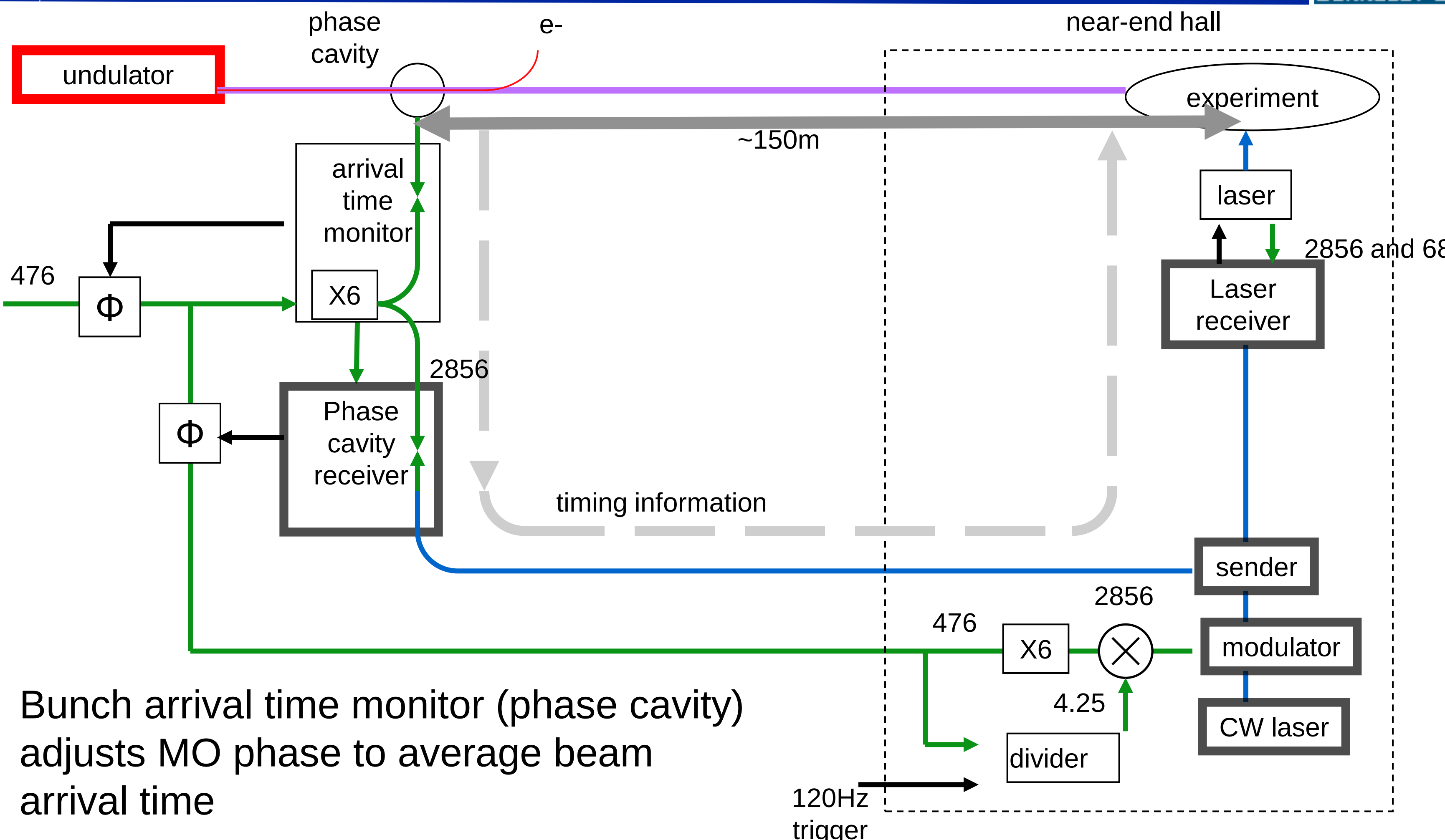


Goal: Synchronize NEH and FEH lasers to a bunch arrival time diagnostic to allow time-stamping of each beam pulse.

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

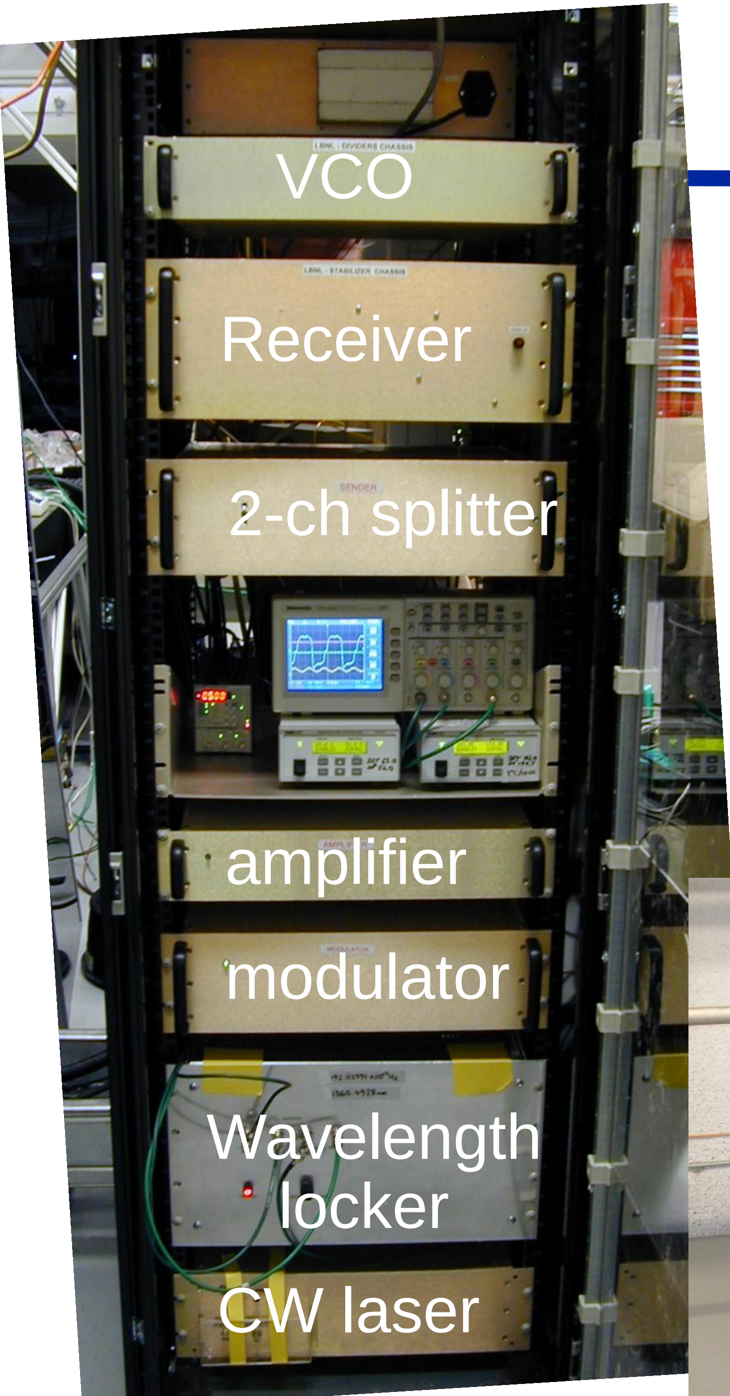


LCLS Configuration

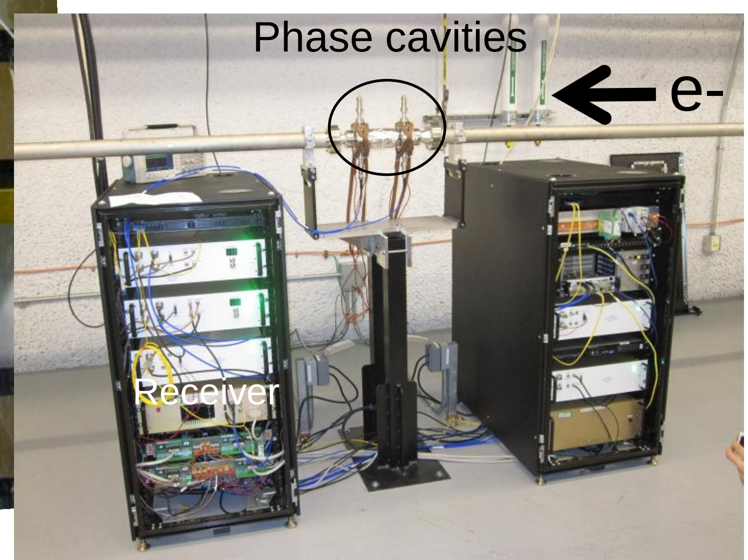


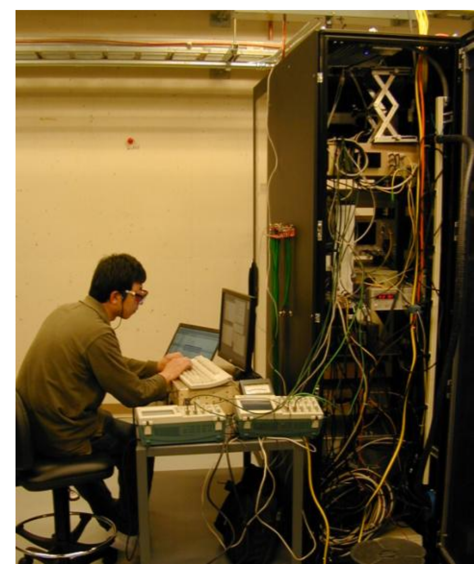
- Bunch arrival time monitor (phase cavity) adjusts MO phase to average beam arrival time
- Phase cavity receiver adjusts 476 phase to follow average beam phase.
- The laser is treated as a VCO that is locked to average beam phase.

LCLS System

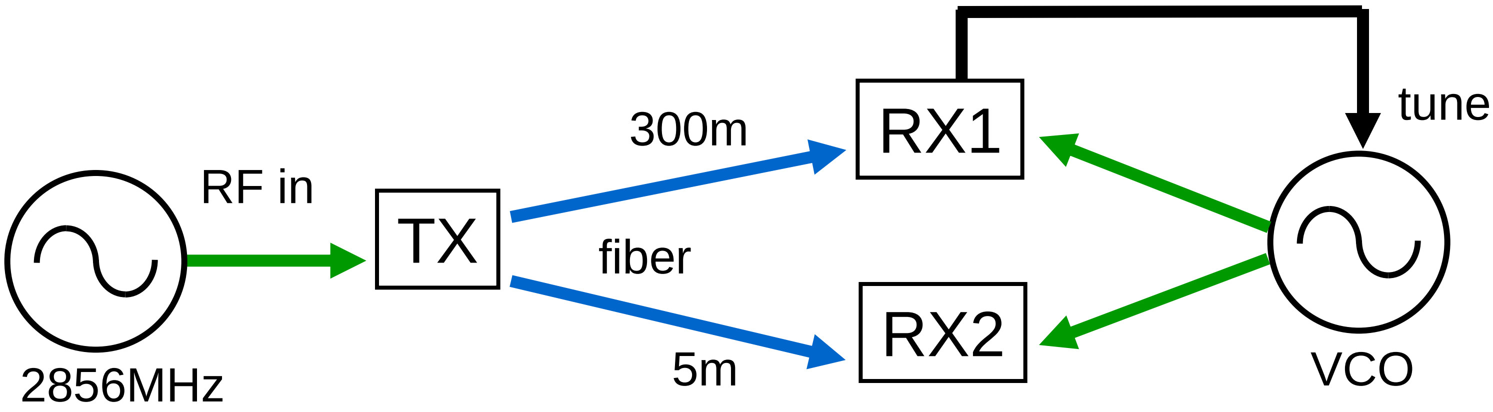


- TX occupies half of standard rack.
- Each RX has a Synch-head and stabilizer chassis. S/H sits as close as possible to client.
- Fiber links are run in SMF28 in 12 fiber cables.

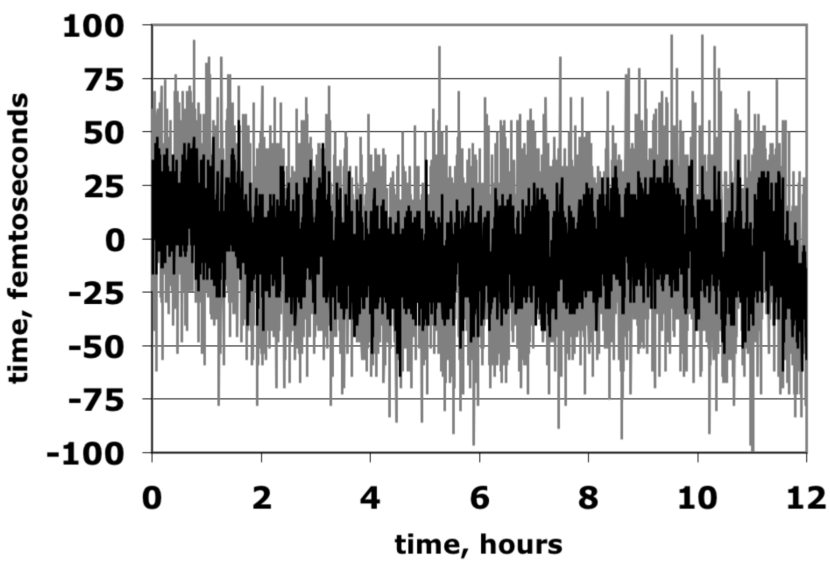




LCLS RF Transmission Results

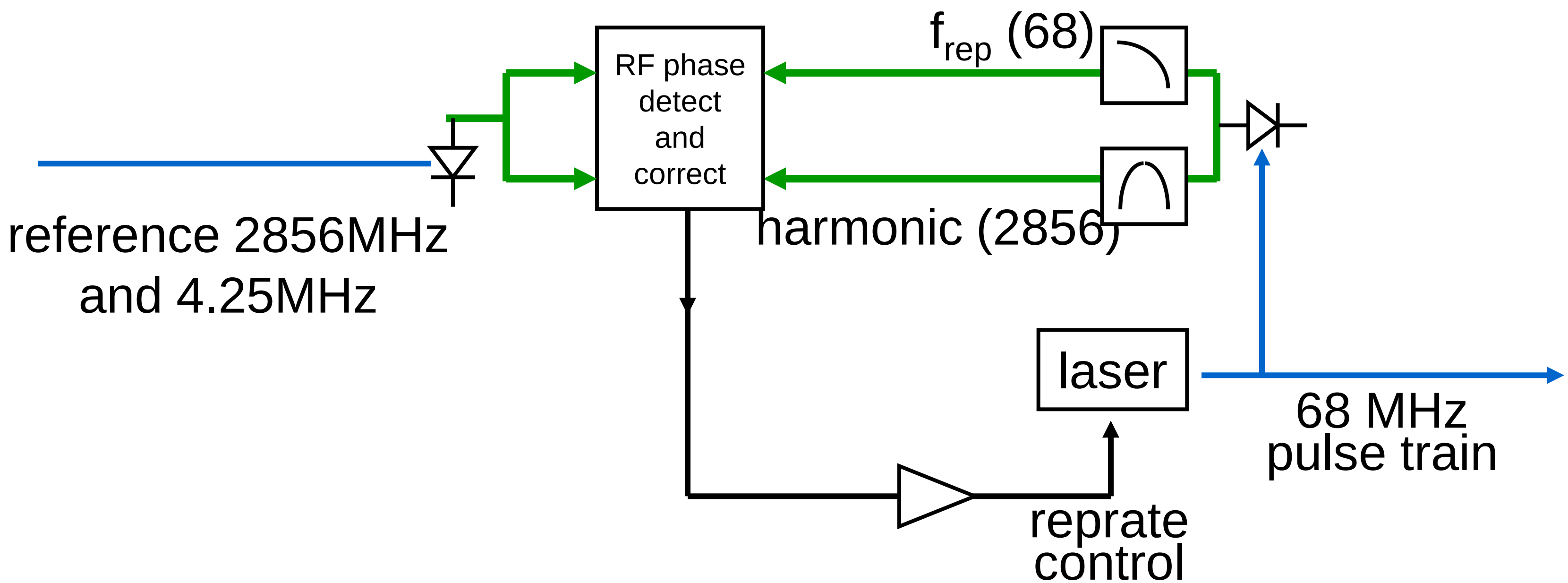


- 27fs RMS in 125kHz BW
- 16fs RMS in 1kHz BW
- Long fiber is looped back from tunnel.
- Drift is due to short cable between receivers, room temperature

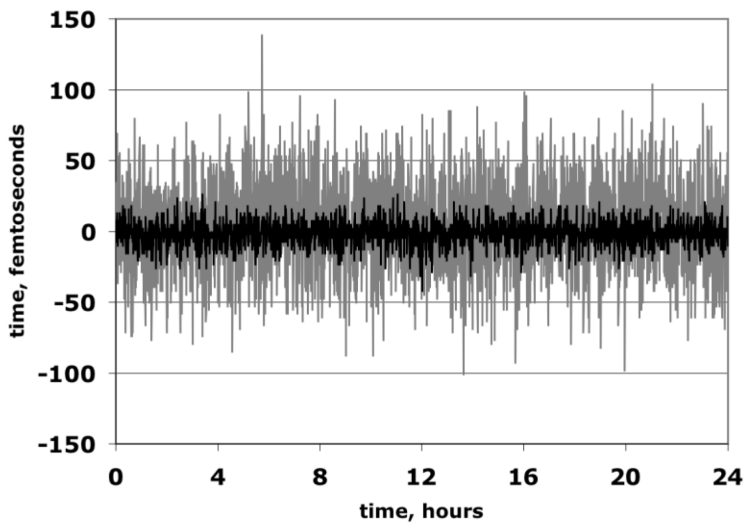


Laser locking configuration

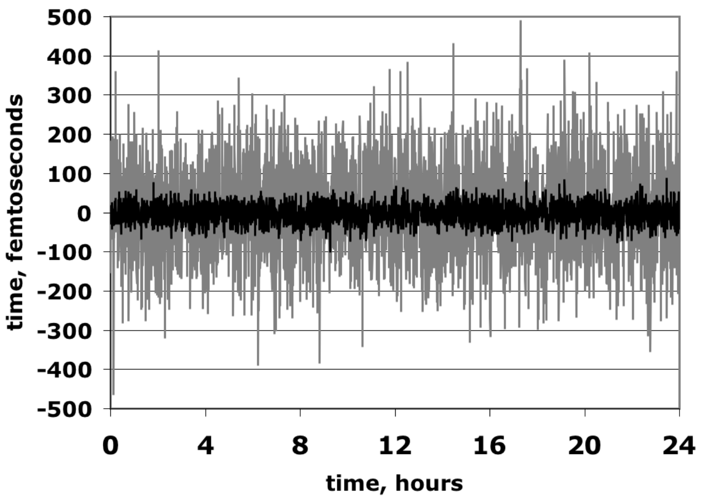
- At 3GHz, 0.01 degree phase uncertainty = 10fs temporal uncertainty
- Quiet lasers can be locked to <15fs RMS at this frequency
- Need to lock at repetition frequency also, to remove “bucket ambiguity”
- Replaces commercial “lockbox”



Laser lock results



RF control error signal
125kHz BW (gray): 31fs RMS
1kHz BW (black): 8fs RMS



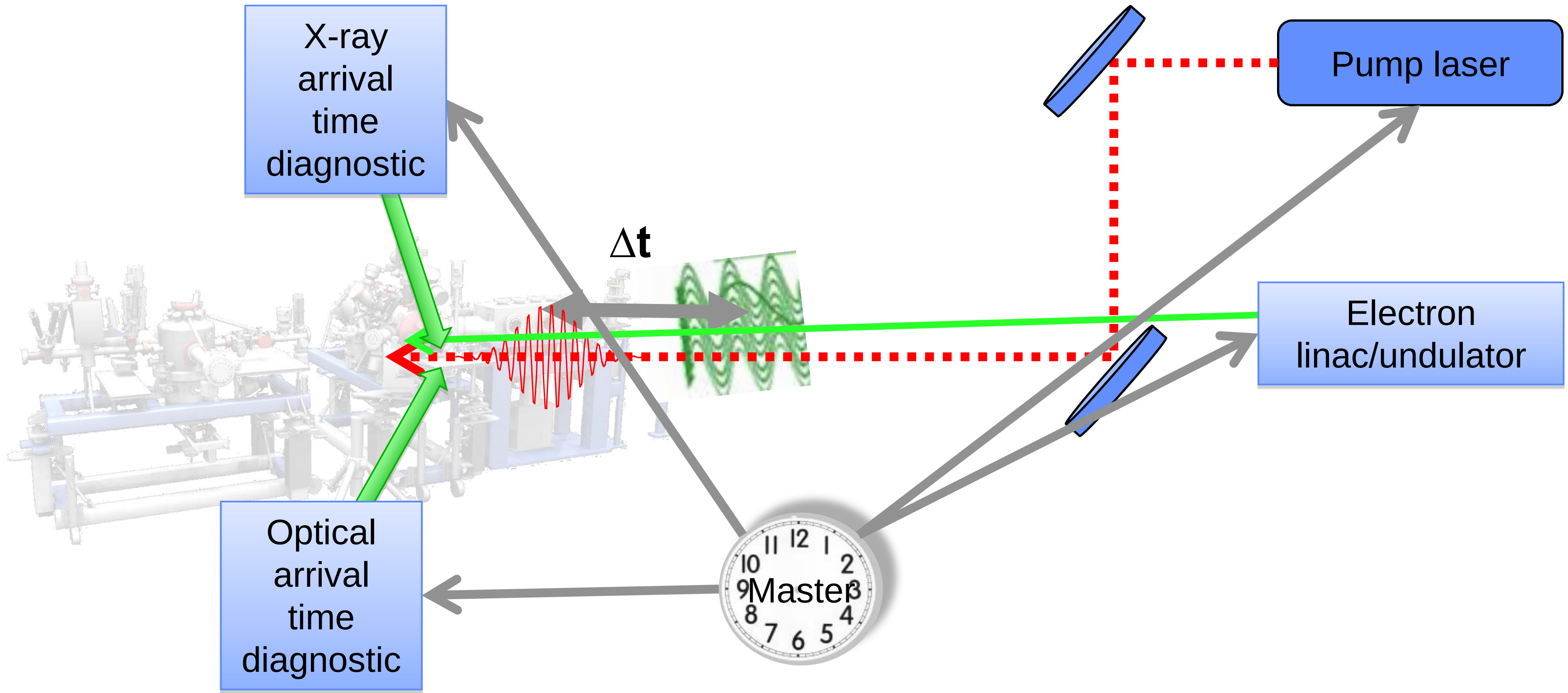
Laser control error signal
125kHz BW (gray): 60fs RMS
1kHz BW (black): 25fs RMS

- Improvements to the laser should decrease high frequency noise
  - Acoustic and vibration isolation
  - Lower noise pump laser
  - Increase control loop bandwidth and gain

Summary

- 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
  - **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

Ideal Configuration



- Measure pump and x-ray arrival time ***at the experiment*** relative to stabilized reference phase.

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.