Synchronization of X-Rays and Lasers for Pump-Probe Experiments at Next Generation Light Sources

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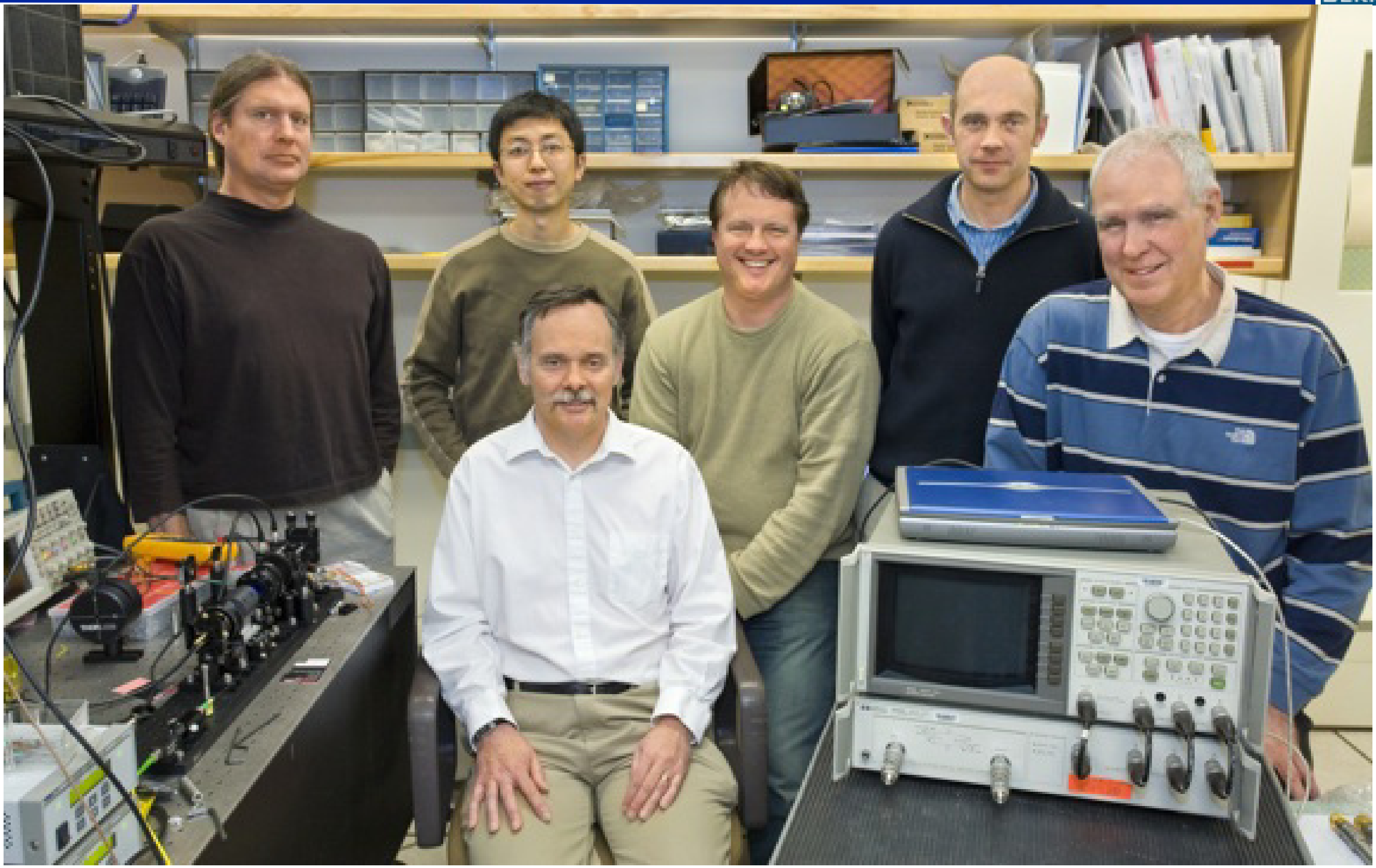
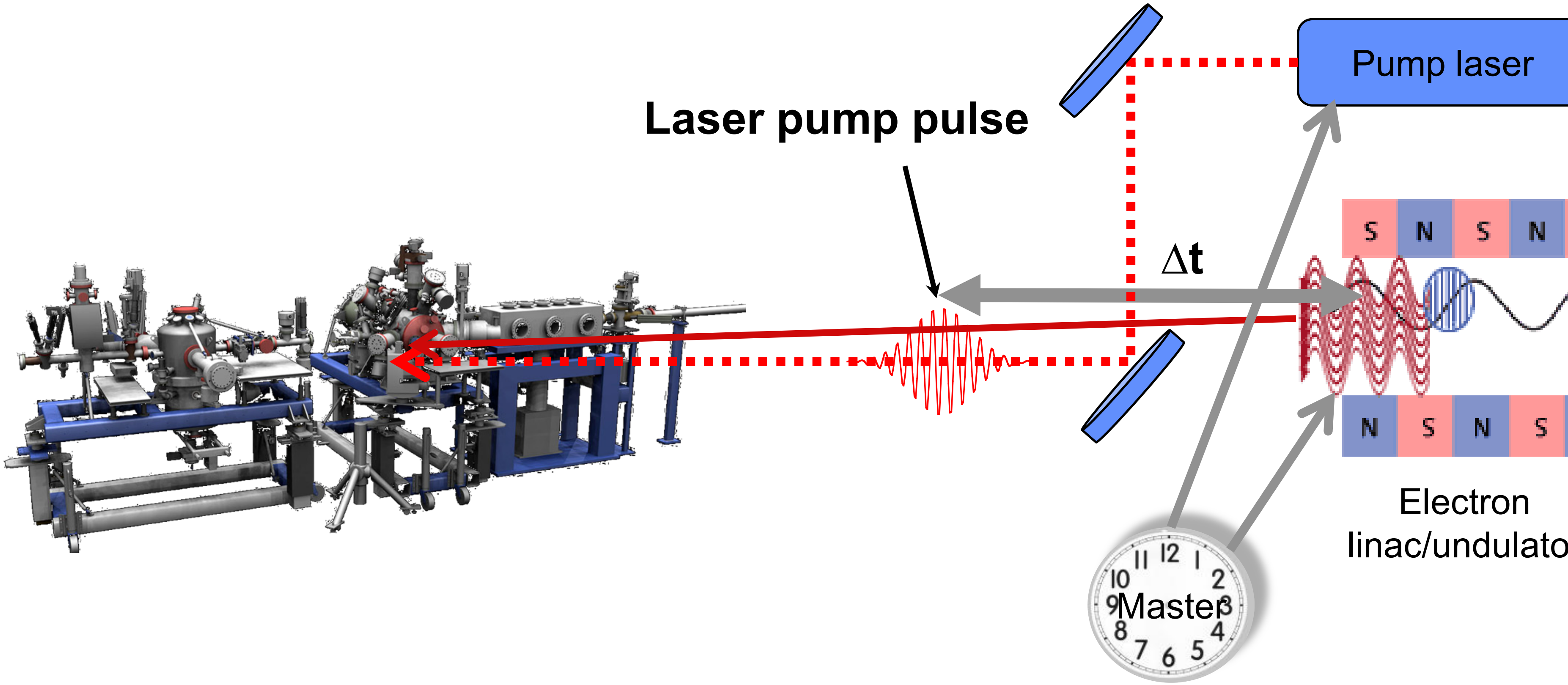


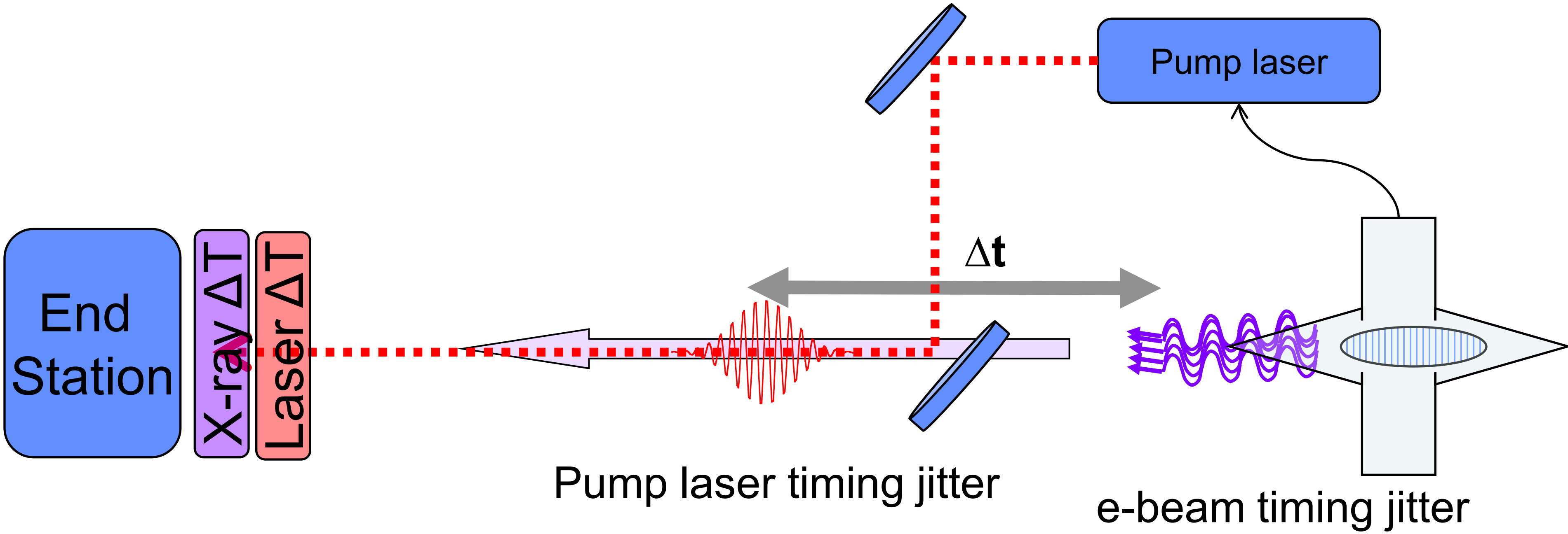
Russell Wilcox, Gang Huang, Larry Doolittle, John Byrd, Alex Ratti, John Staples

X-ray/optical Pump-probe



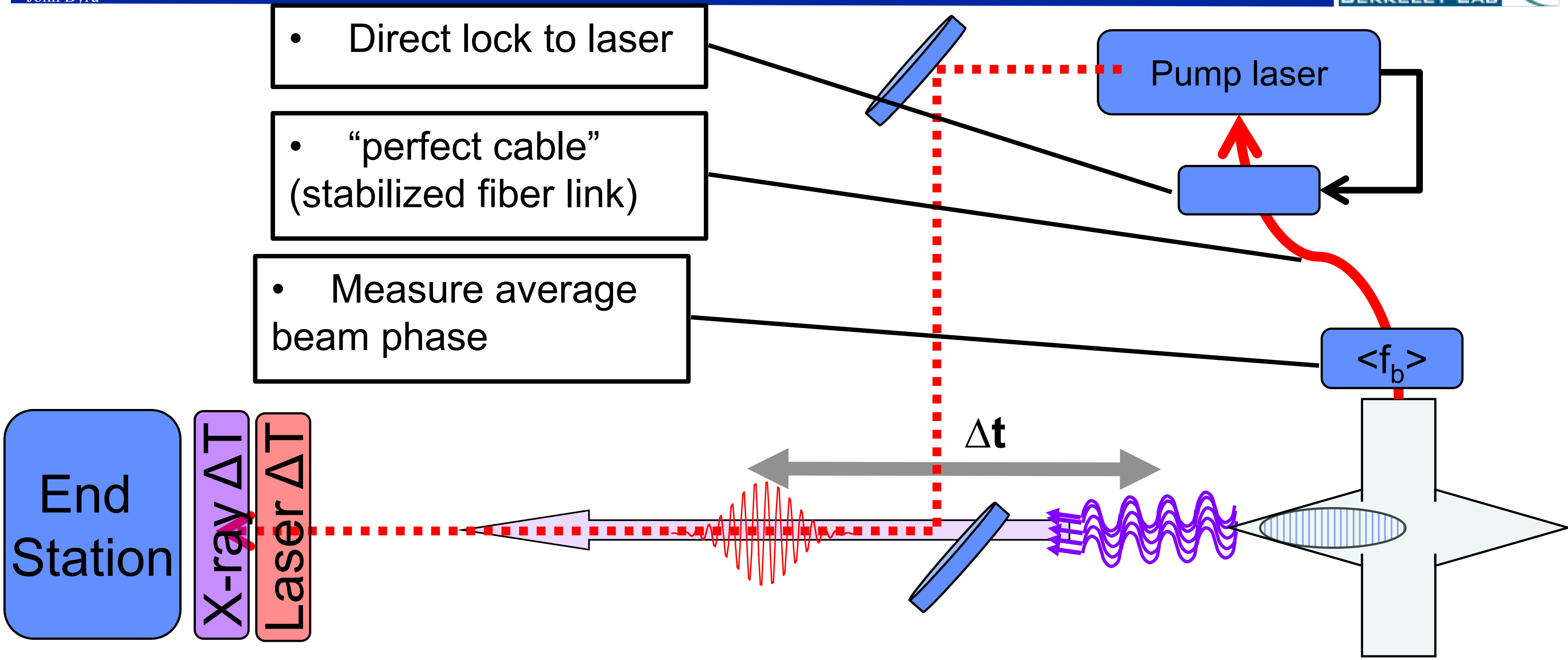
- Ultrafast laser pulse "pumps" a process in the sample
- Ultrafast x-ray pulse "probes" the sample after time Δt
- By varying the time Δt, one can make a "movie" of the dynamics in a sample.
- Synchronism is achieved by locking the x-rays and laser to a common clock.

FEL Timing is not perfect



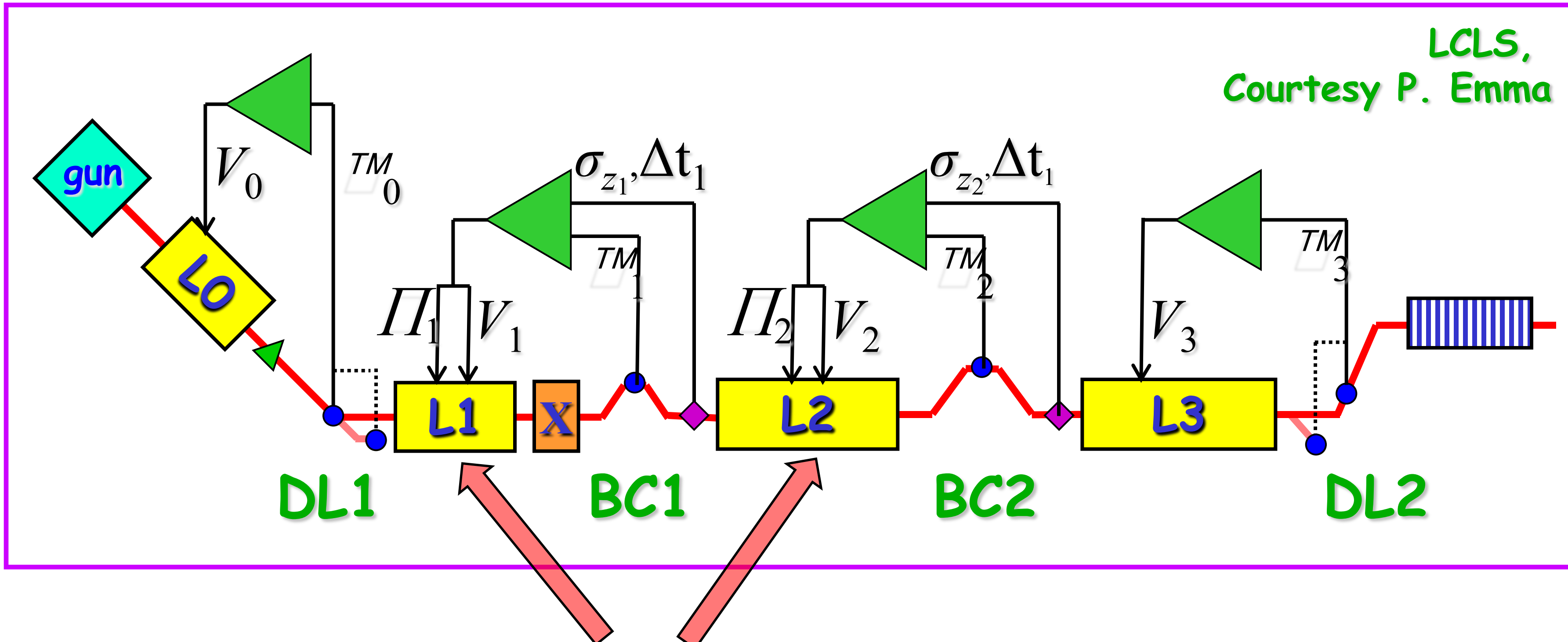
- Ideal Solution: Measure the relative x-ray and pump arrival times and use it to bin the experimental data.
- Present LCLS Solution: Measure the electron arrival time and lock the pump laser to the average electron arrival time.

Synchronize Pump and Probe



- Ability to lock laser to beam driven by
  - Precision measurement of beam phase
  - Transmission of beam phase to laser hutch over 100s of meters
  - Ability of laser to follow beam phase

Sources of electron jitter



- Timing jitter results primarily from amplitude and phase jitter of linac accelerating sections before a bunch compressor.
- RF and beam-based feedback can be used to reduce jitter.

Three Challenges

- Provide long-term stable clock over entire accelerator complex: injector, linac, diagnostics, and lasers
  - Use stabilized links to maintain stable relative phase

- Lock remote clients to stable clock
  - Advanced digital controllers (RF and mode-locked laser oscillators)
  - Direct seeding of remote lasers

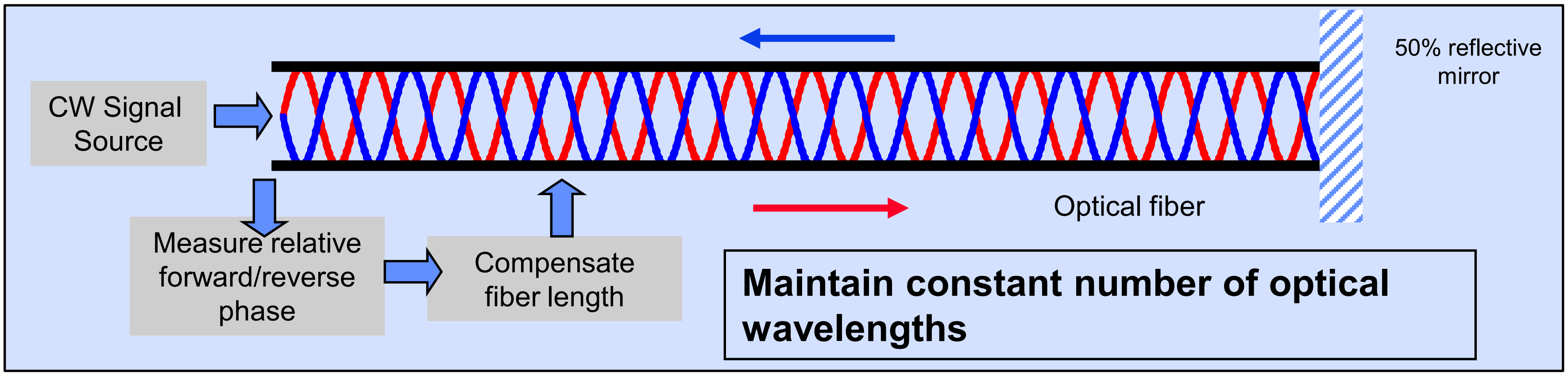
- Measure resulting electron and photon timing stability
  - Femtosecond electron arrival time and bunch length and energy spread monitors
  - Femtosecond x-ray arrival time, pulse length, spectrometer

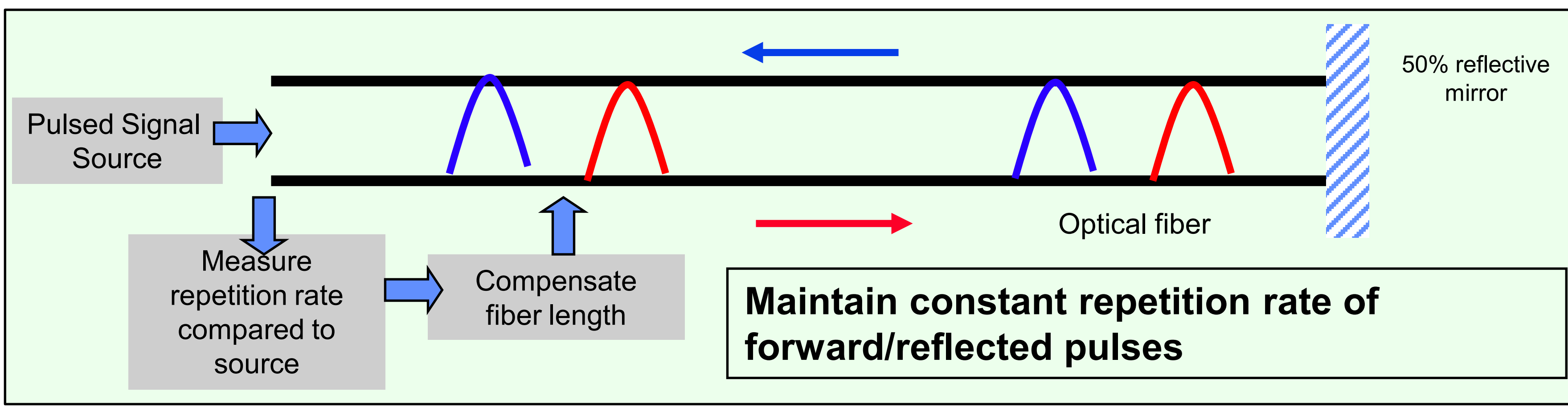
Why optical fiber links?

- 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

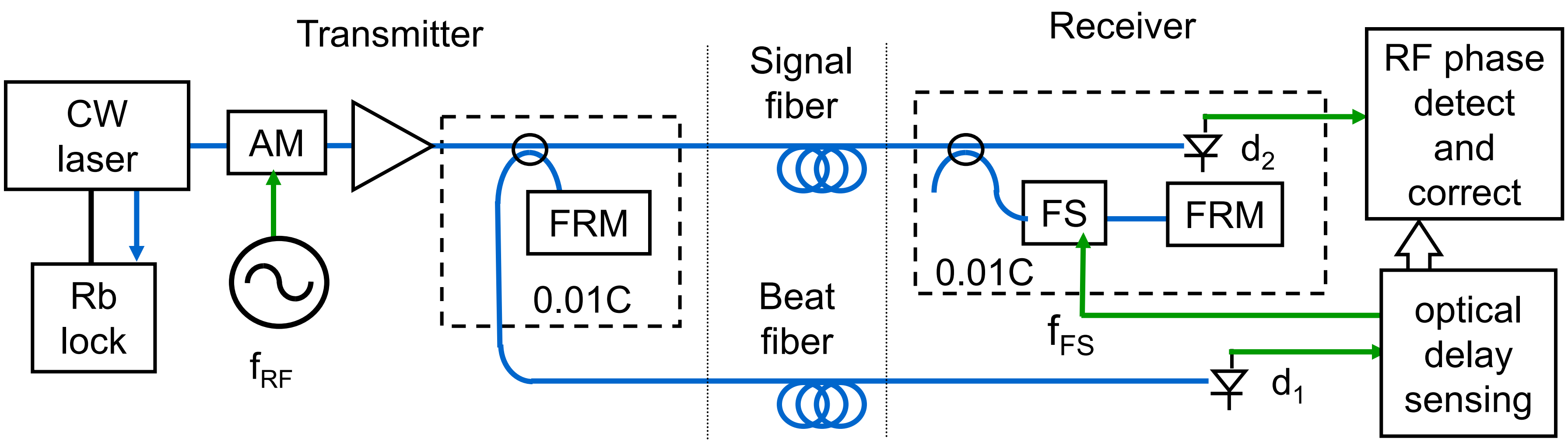
- Fiber links can be stabilized based on the revolution in metrology time and wavelength standards over the past decade.





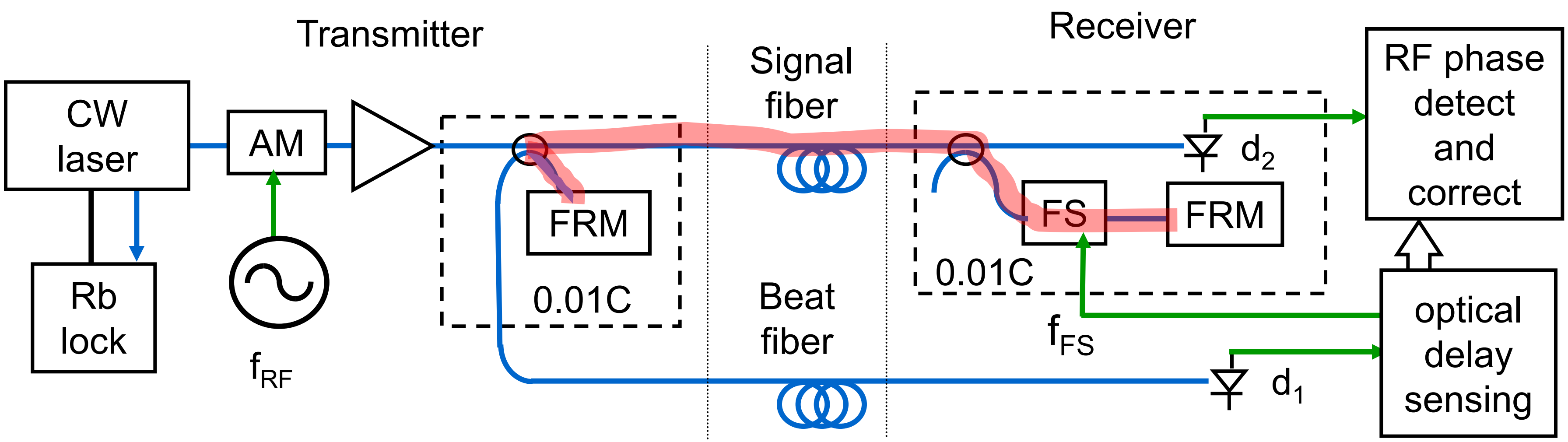
Correction BW limited to R/T travel time on fiber (e.g. 1 km fiber gives 100 kHz)

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 fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

Single Channel Link



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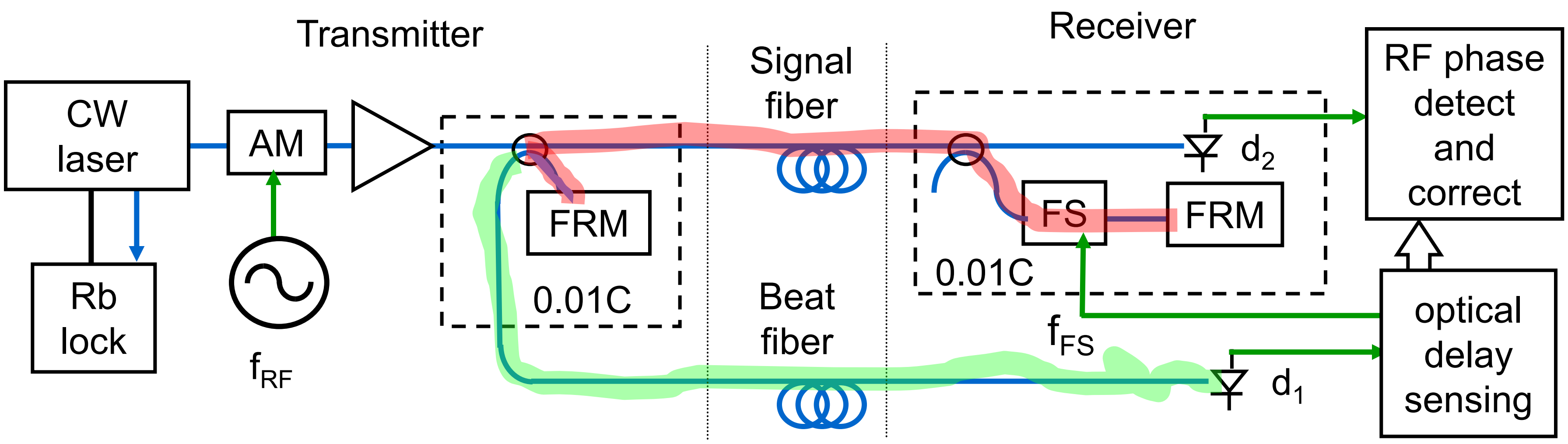

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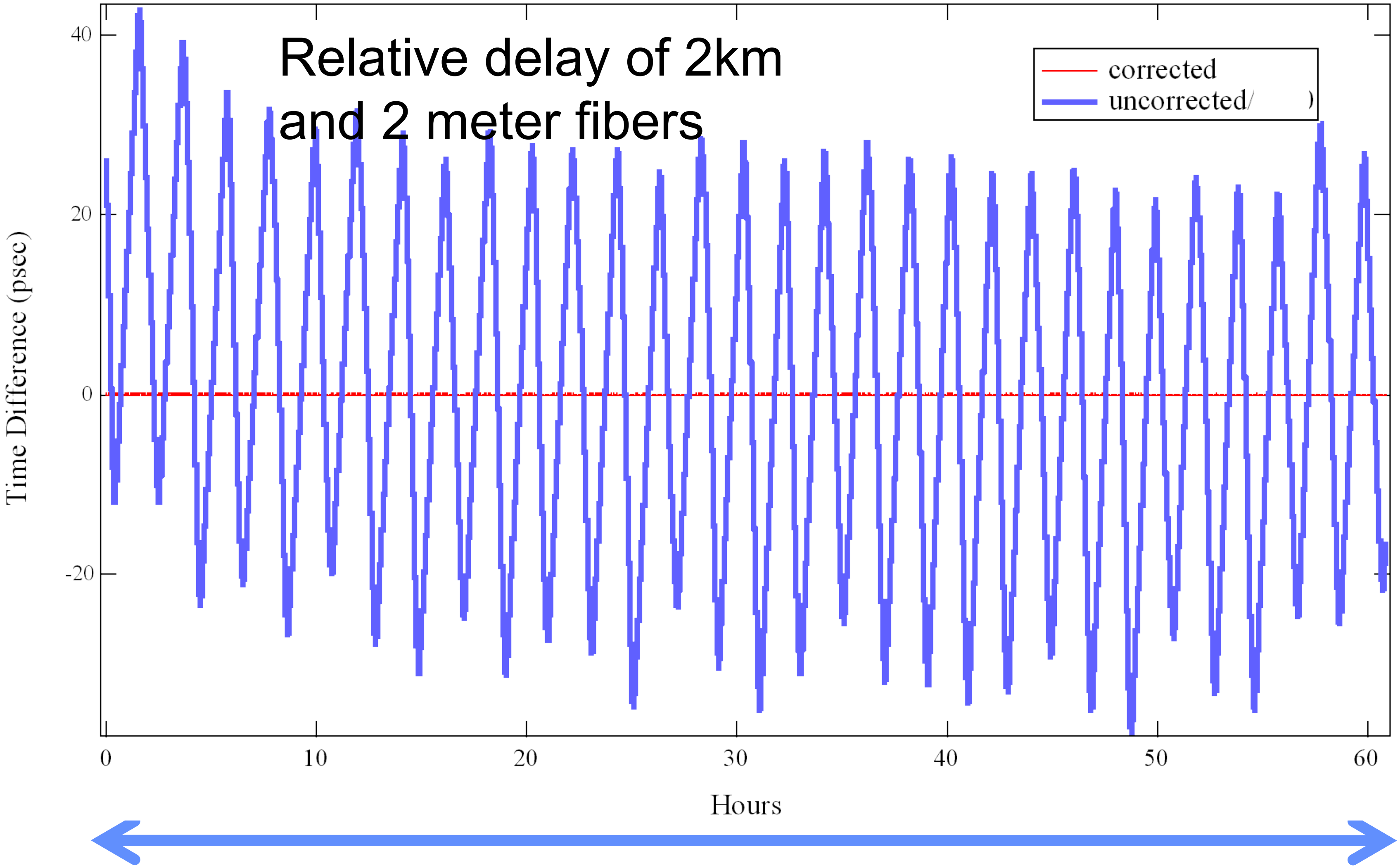
Our recipe for stabilized RF transmission

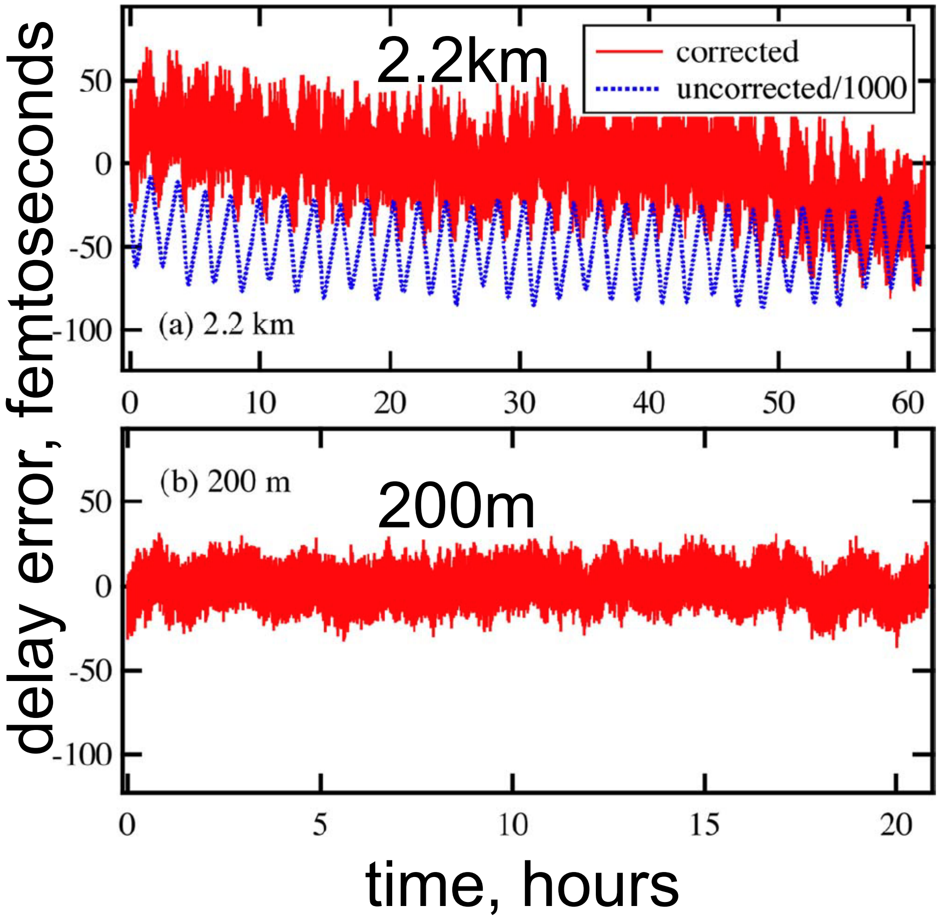
- Transmit master clock as modulation of optical carrier
  - Transmit RF by amplitude modulation of CW signal
  - Like cable TV transmission
- Measure link variation by Michelson interferometer using stabilized optical carrier.
  - Use heterodyne interferometer to avoid baseband phase drift.
  - High 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.

RF Transmission results

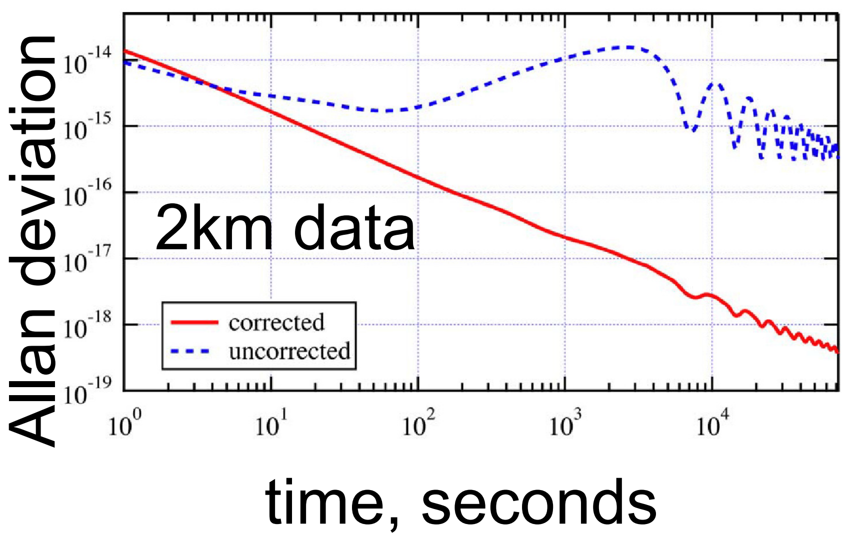


61 hours

Detailed results

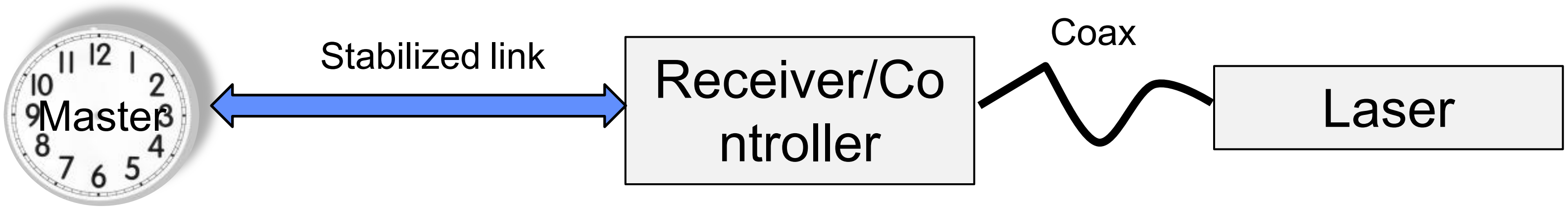


- 1 kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



The timing commandment

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



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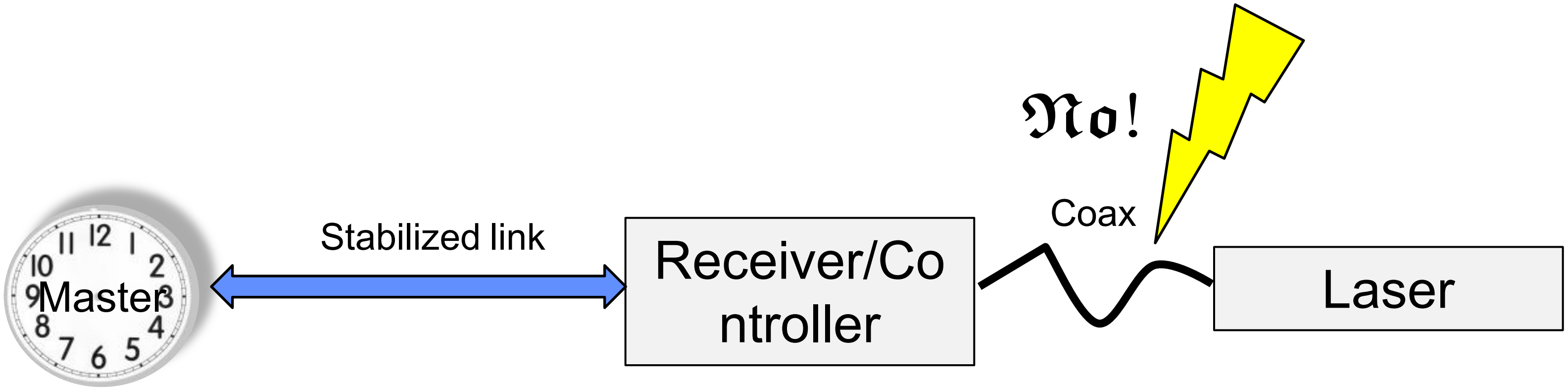

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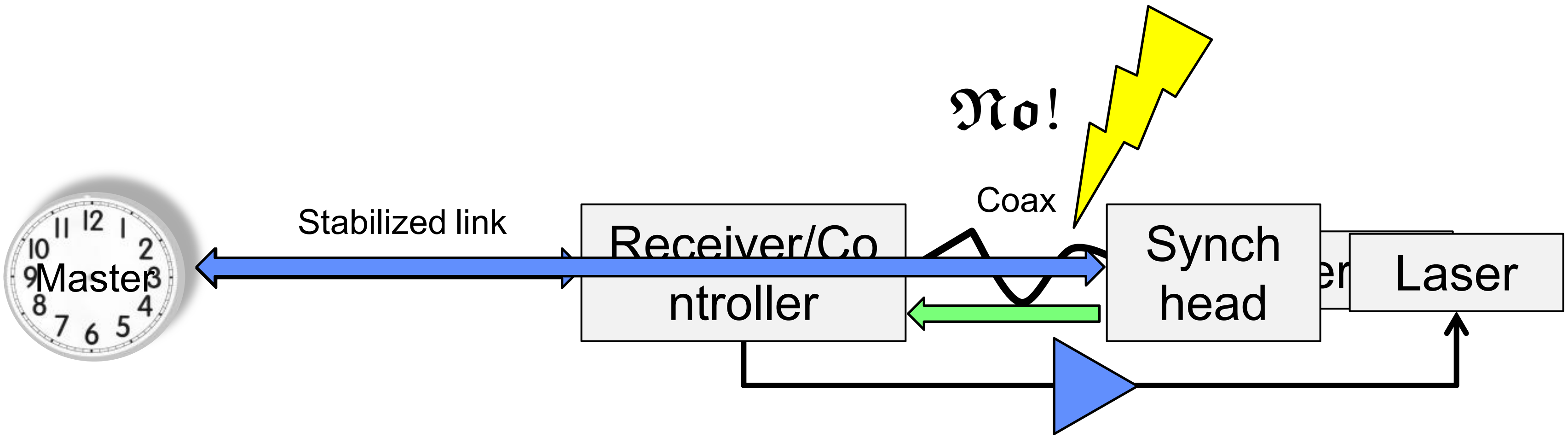
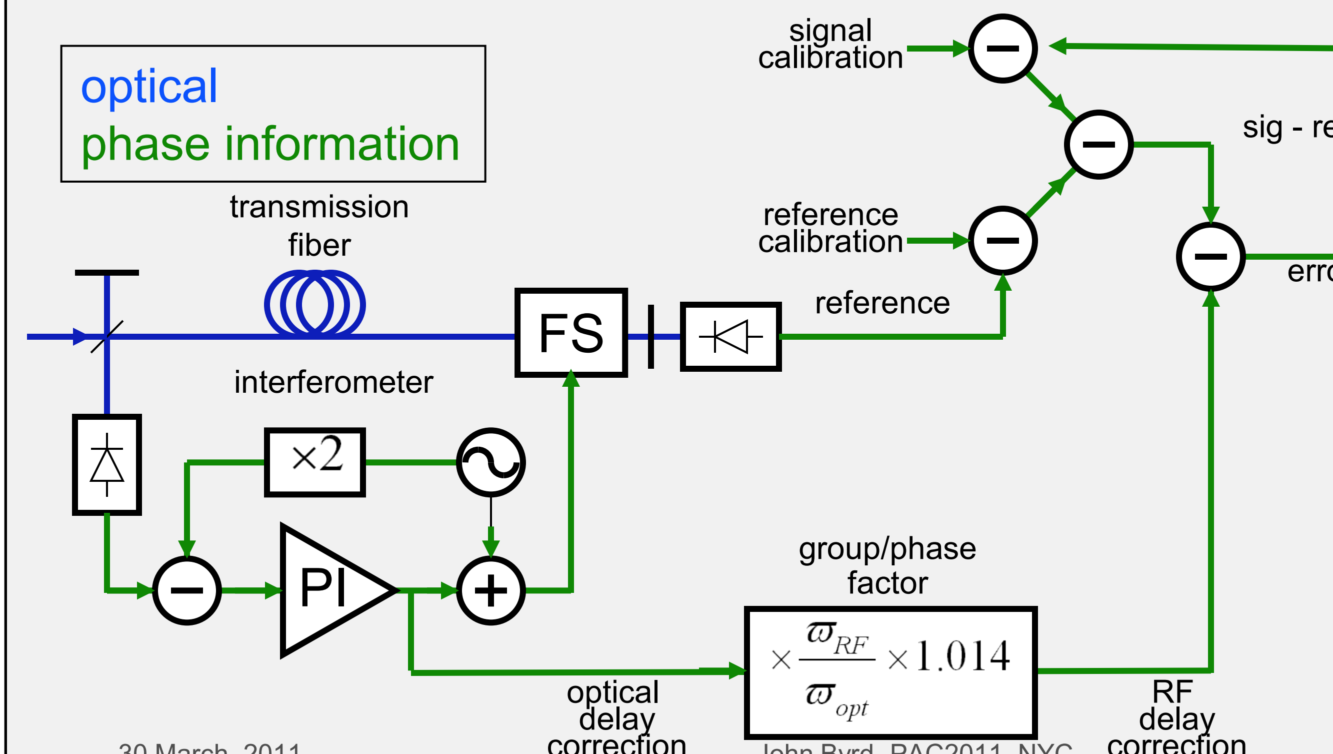


- Bring the stable phase signal as close as possible to the client by extending the fiber to a "synch-head".
- Lock the client (i.e. laser/VCO) directly to the stabilized RF phase. We use the same controller to lock the client as the fiber.

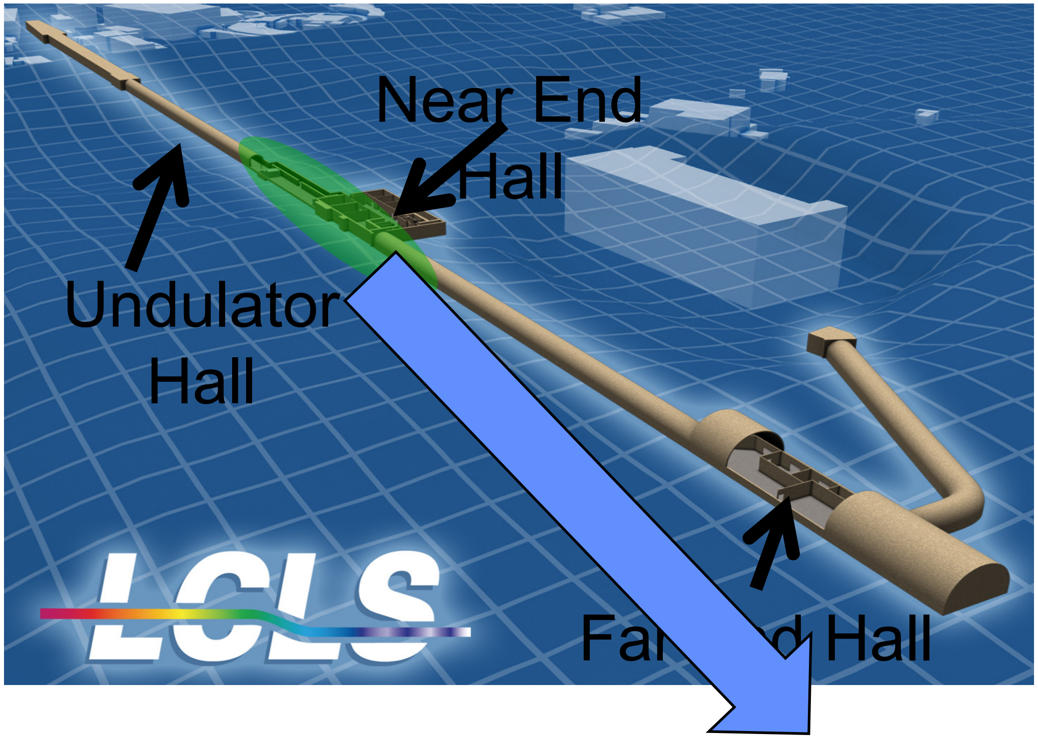
"I am in control here"

- 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



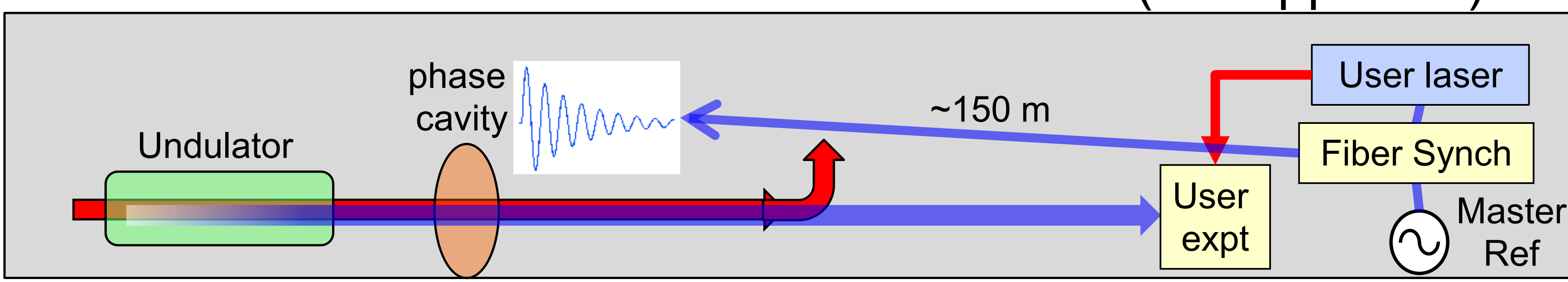
Client can be:
- Laser
- RF system
- VCO
- Phase shifter
- …

LCLS: Initial Configuration

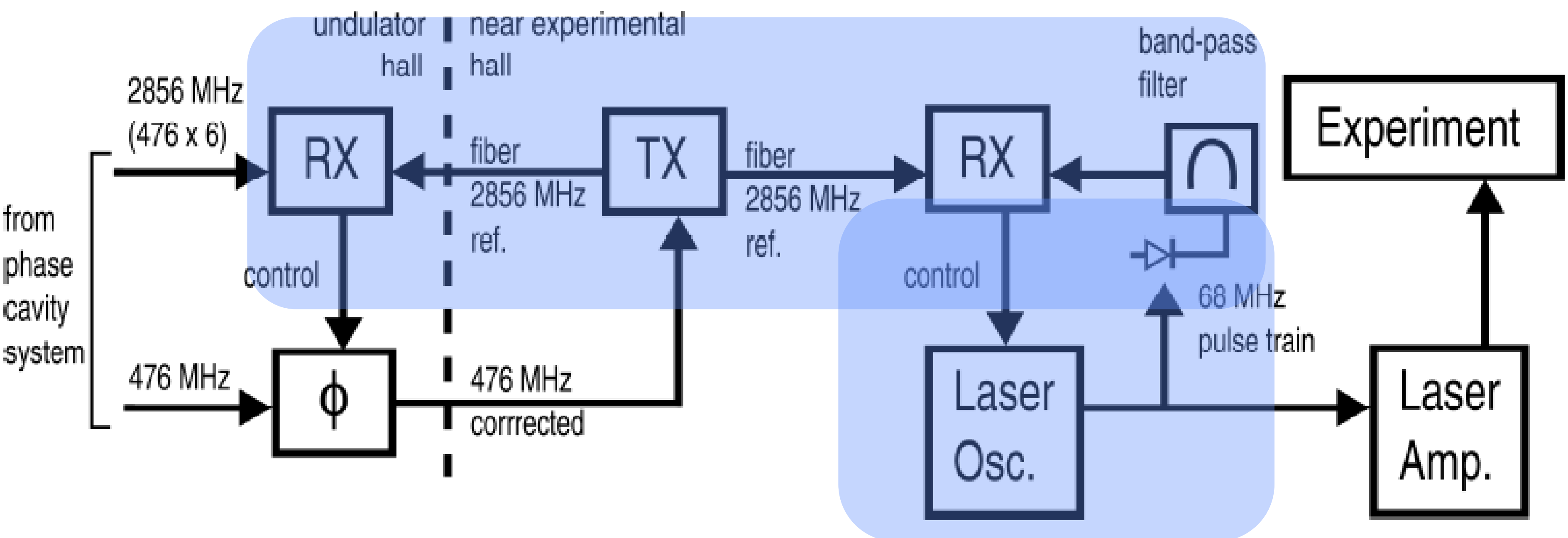


Goal: Synchronize NEH and FEH lasers to a bunch arrival time diagnostic to allow time-stamping of each beam pulse.

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



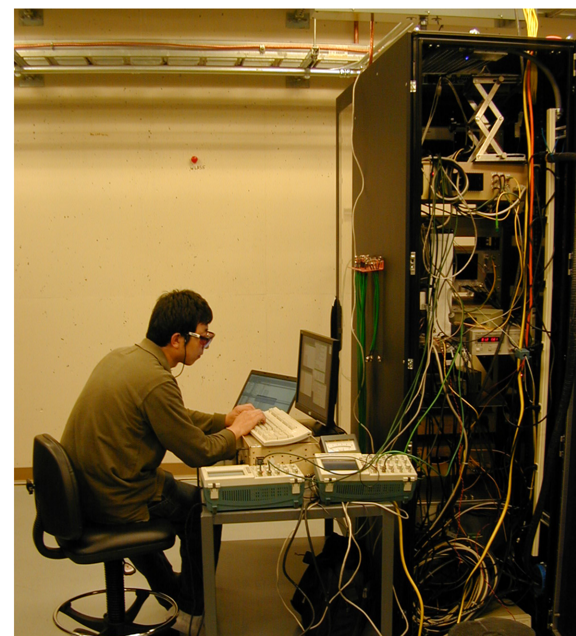
Detailed LCLS Configuration



- Controlled transmission from e-beam phase cavity to NEH laser oscillator.

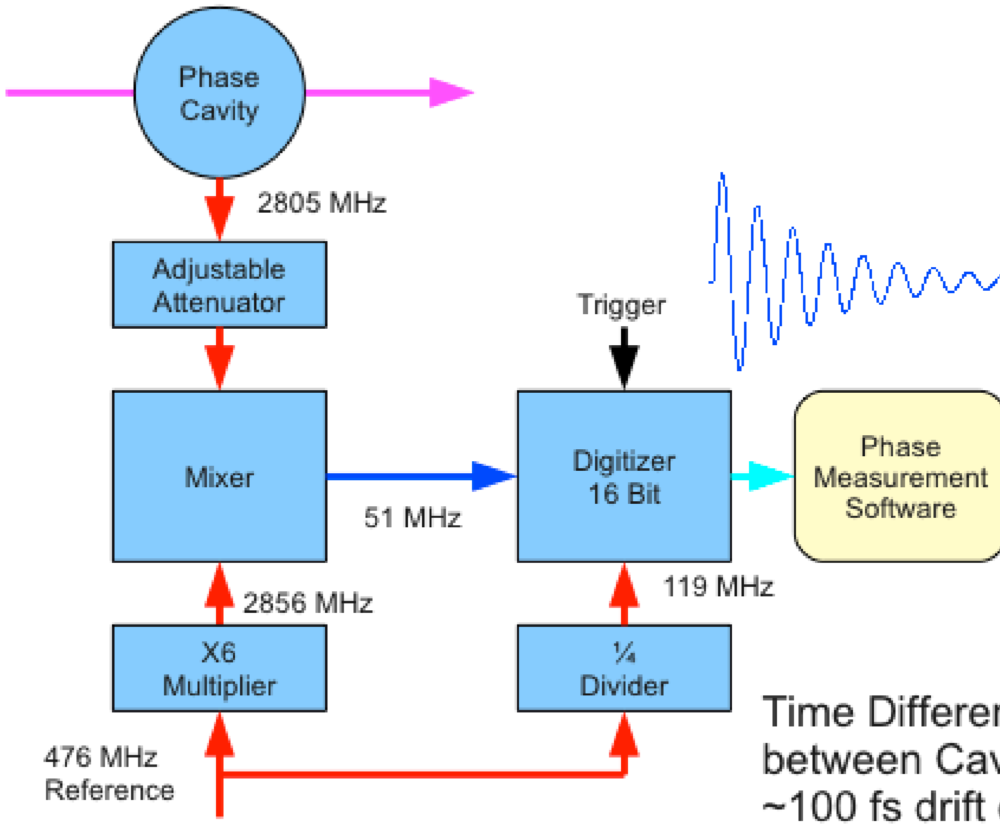
LCLS System

- 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

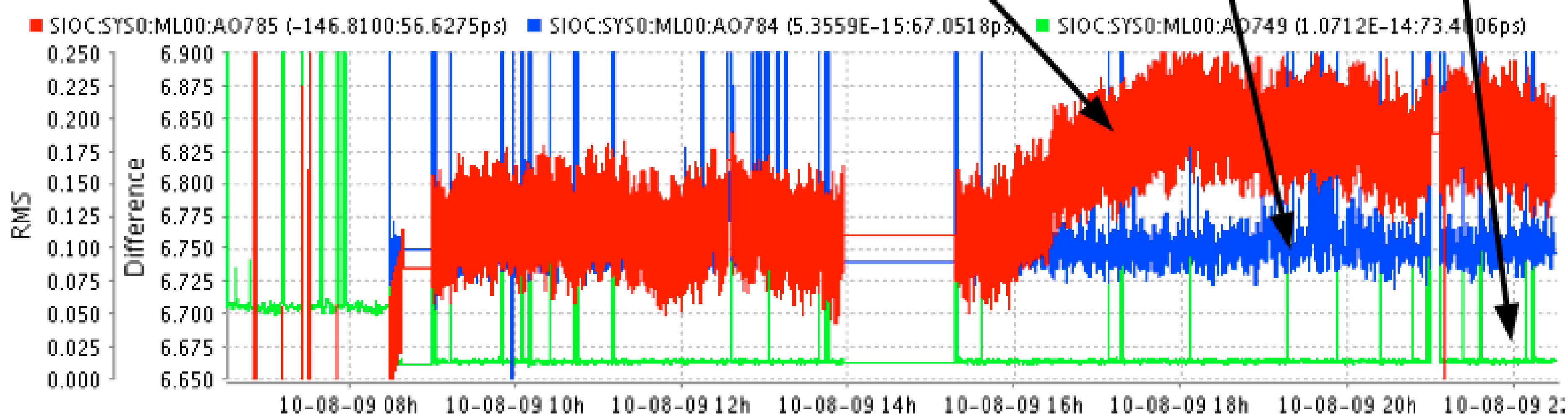
Joe Frisch, SLAC



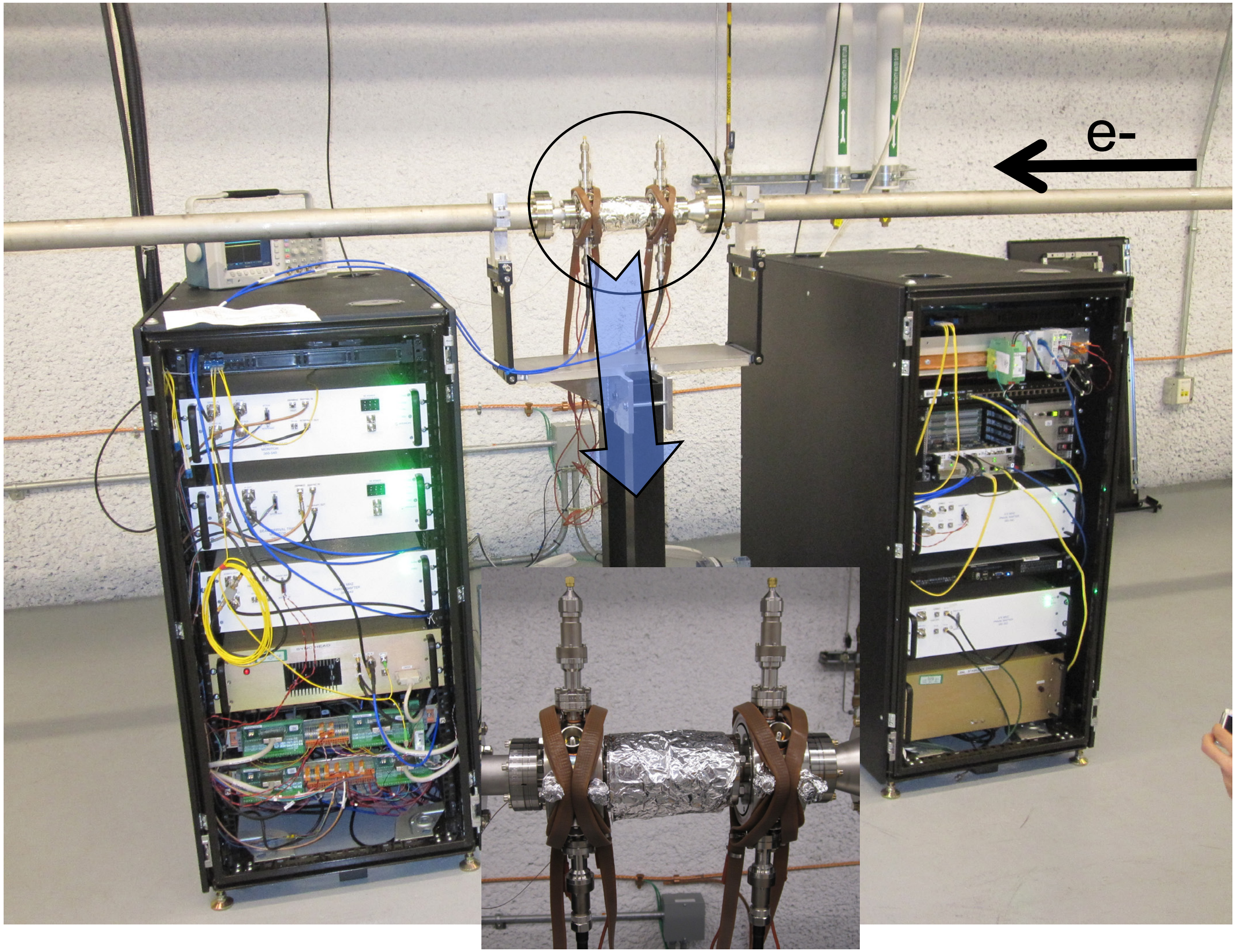
Standard deviation of difference between cavities ~15 fs RMS

Time Difference between Cavities ~100 fs drift over 1 day

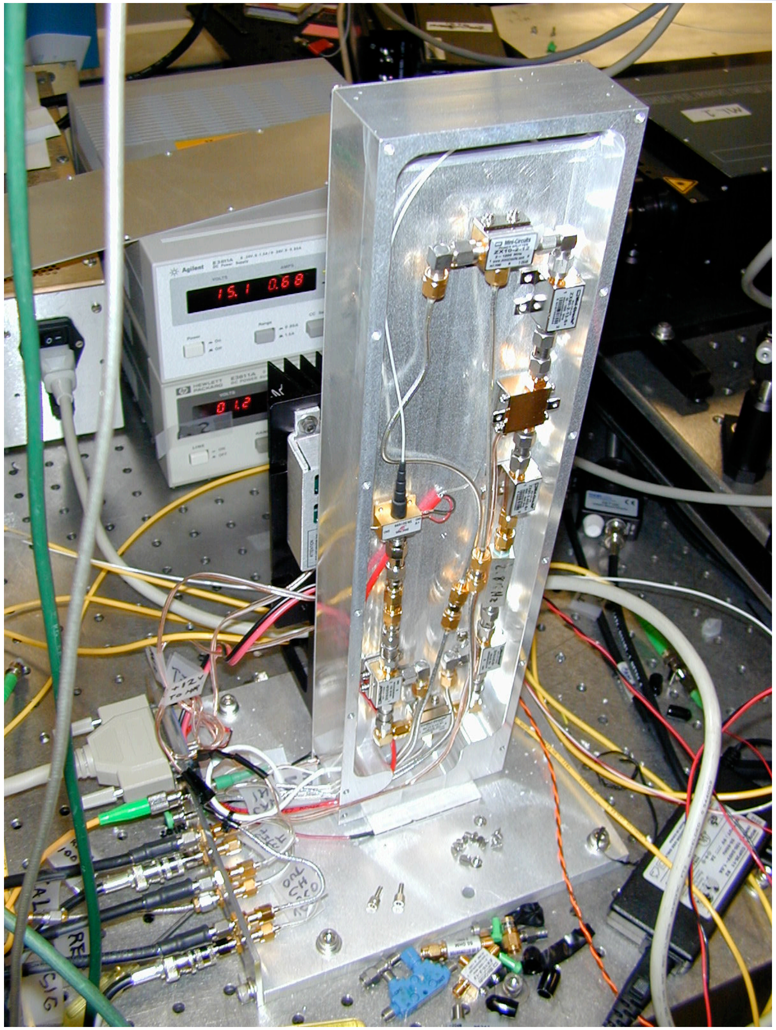
Standard Deviation of single cavity ~100fs RMS



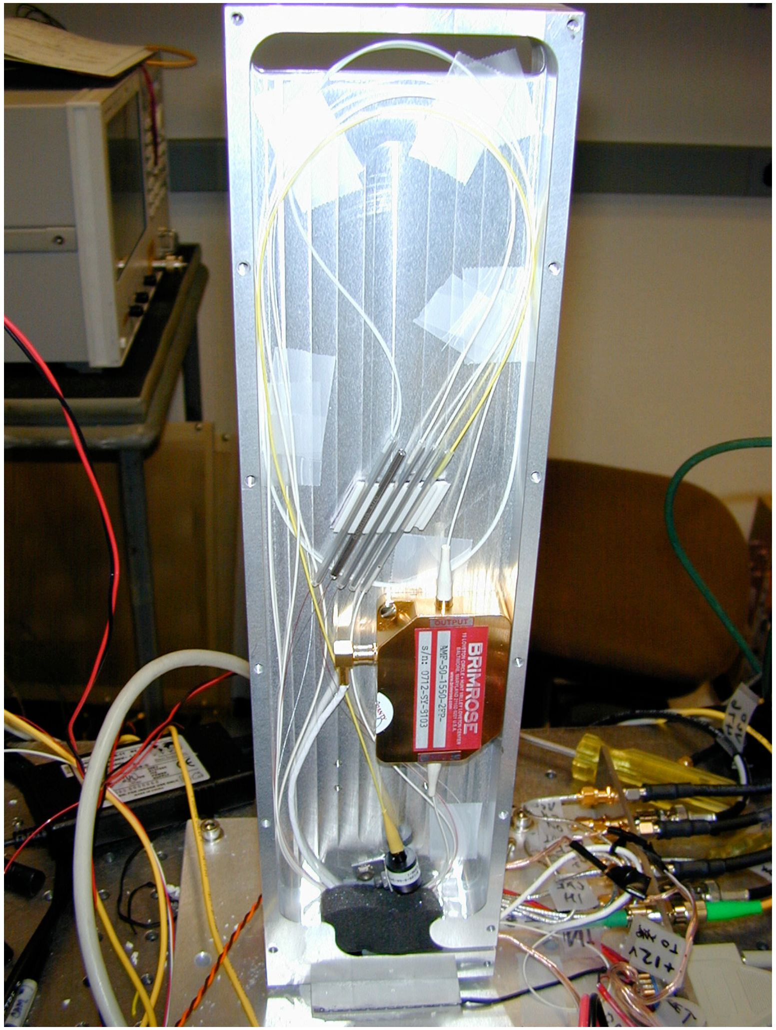
LCLS Phase Cavities



Synch/Head



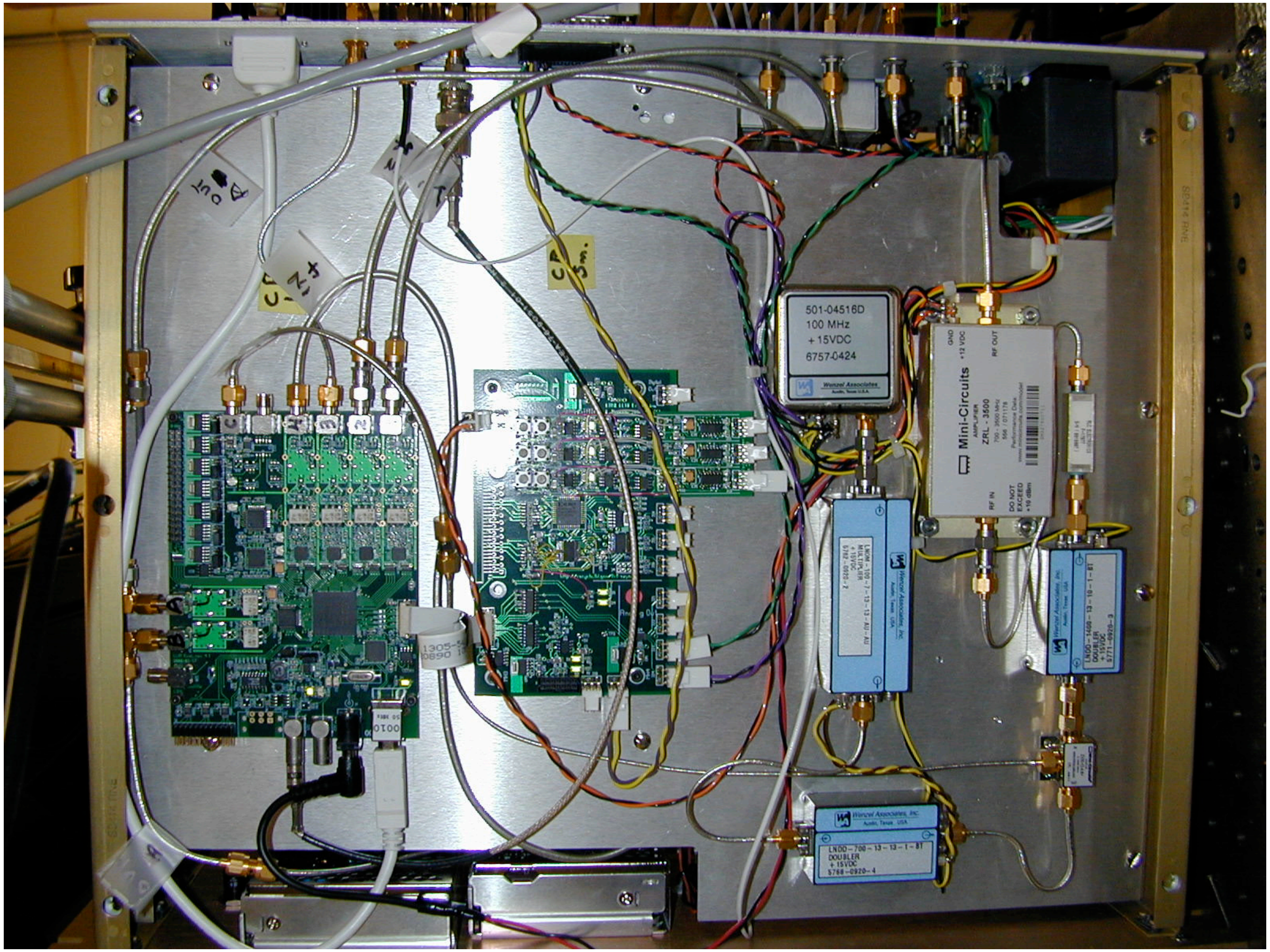
Electronic side



Optical side

Receiver

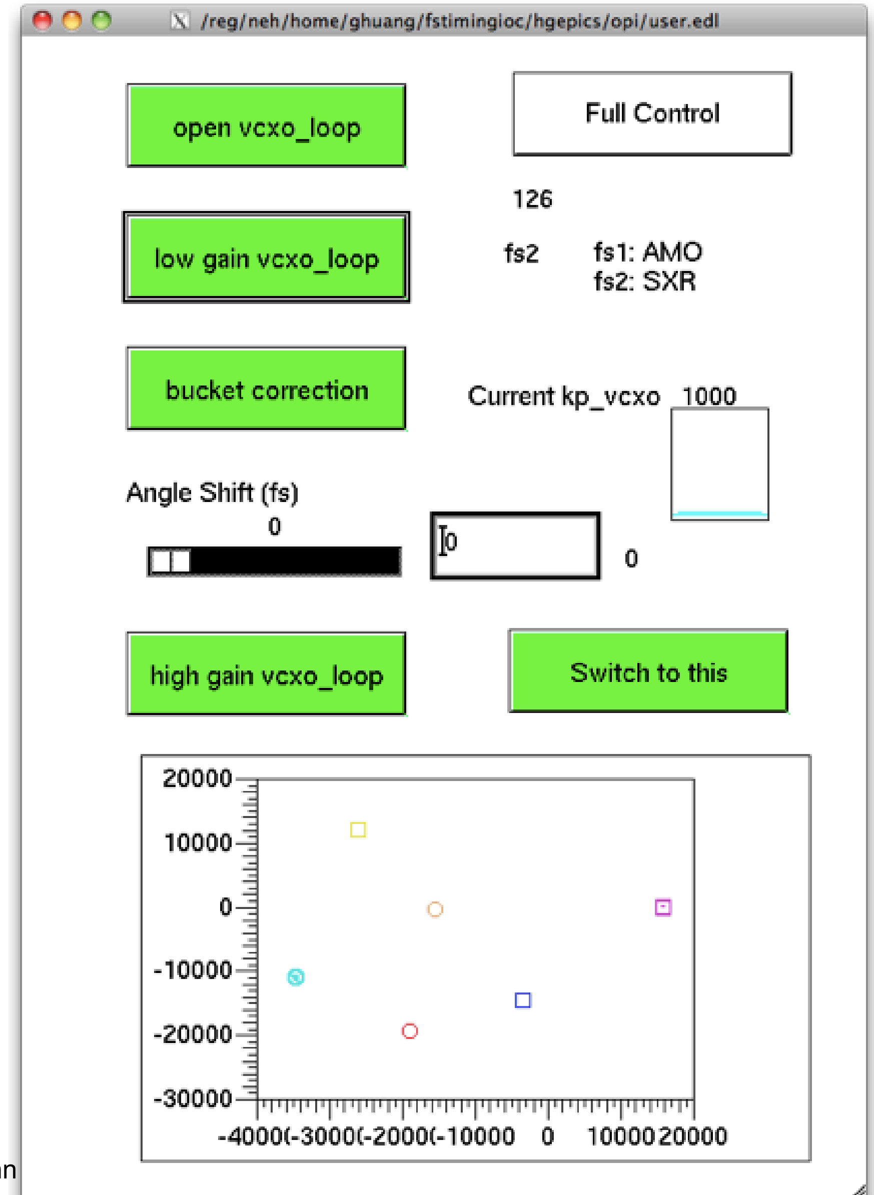
BERKELEY LAB



FPGA side (RF receiver on other side)

User control

- Digital controller allows user adjust of relative laser phase to stabilized reference.



Present status

- Femtosecond synchronization has become an enabling technology for new science using optical pump/x-ray probe at xFELs.
- High precision bunch arrival time alleviates effect of linac timing jitter. Systems available with precisions of 5-10 fsec.
- We have demonstrated a stabilized fiber link system for high precision distribution of RF signals
  - 10-20fs between two RF channels
  - Rack-mounted chassis packaging, easily expandable.
  - Subsystems commercially available.
  - Expansion to 16 channel system in progress.
- LCLS presently dominated by laser jitter w.r.t. beam reference
  - 50-100 fsec RMS. Noise sources under investigation: laser pump, acoustic noise, etc.
  - Improving cavity lock loop: higher bandwidth, lower noise amplifier.

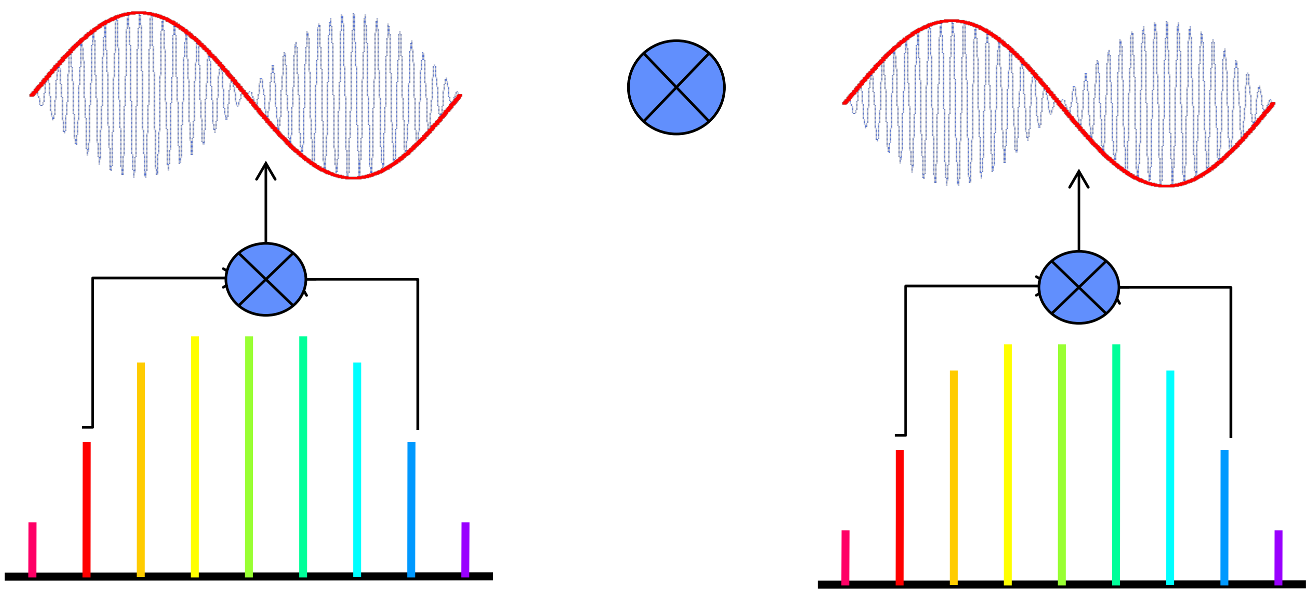
Future directions

A few examples at Berkeley and SLAC

- All optical laser synchronization
  - Locking optical comb spectral lines
- E-beam arrival time/bunch length monitors
  - Electro-optic modulation of THz beat wave
- X-ray/laser arrival time monitor
  - X-ray/optical cross-correlation
  - X-ray phase cavity

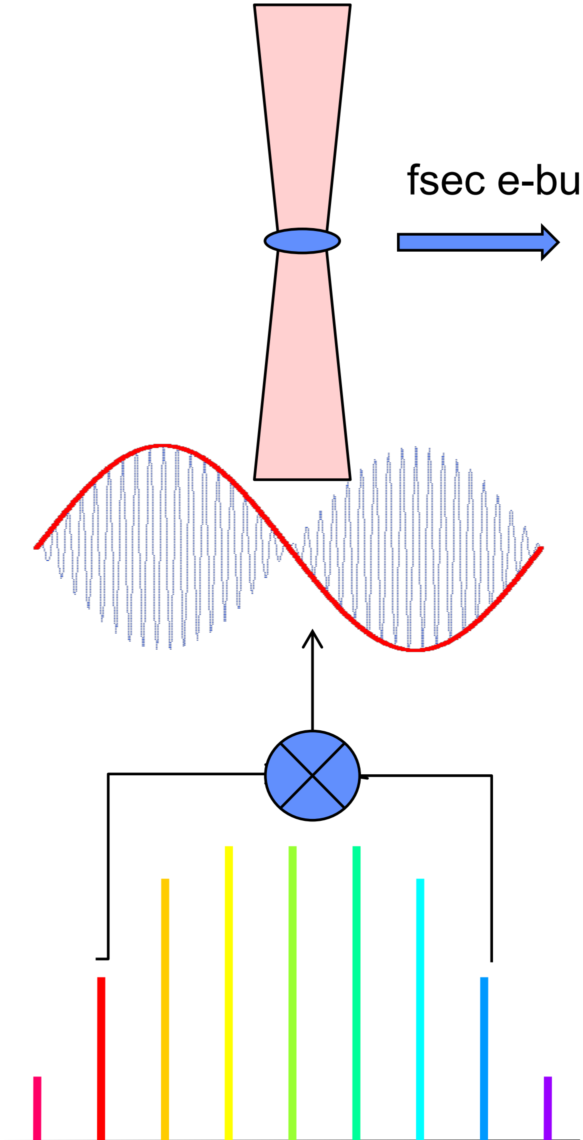
All-optical lock schemes

- Synchronization of lasers with RF signals limited by resolution in phase(0.01 deg@3GHz=10 fsec)
- Go to optical frequencies…



- Create a beat wave generated from two mode-locked comb lines (up to a few THz)
- Lock the beat wave of one laser with a remote laser

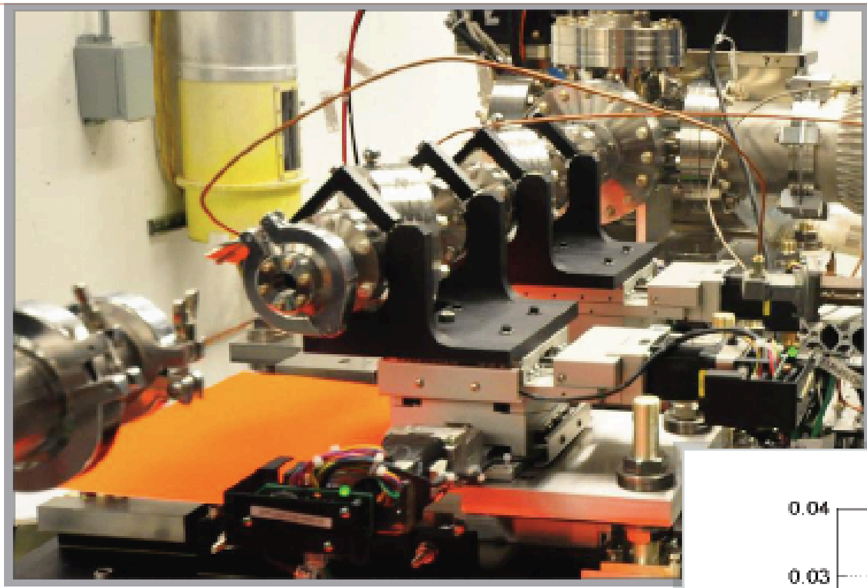
Sub-fsec arrival monitor



- Sensitivity of e-beam arrival monitors proportional to reference frequency.
- Use THz beat wave as a reference frequency.
- Electro-optically modulate beat wave with e-beam electric field.

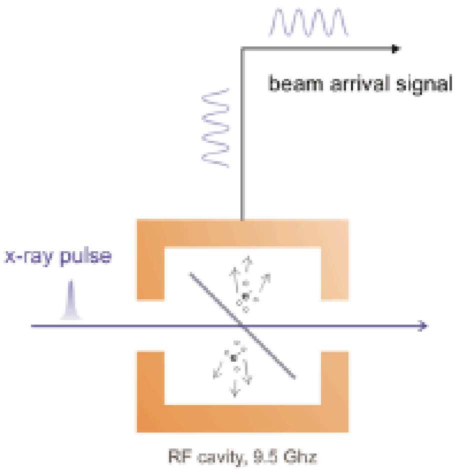
X-ray Pulse Arrival Time Measurement using RF Phase Cavities

John Byrd

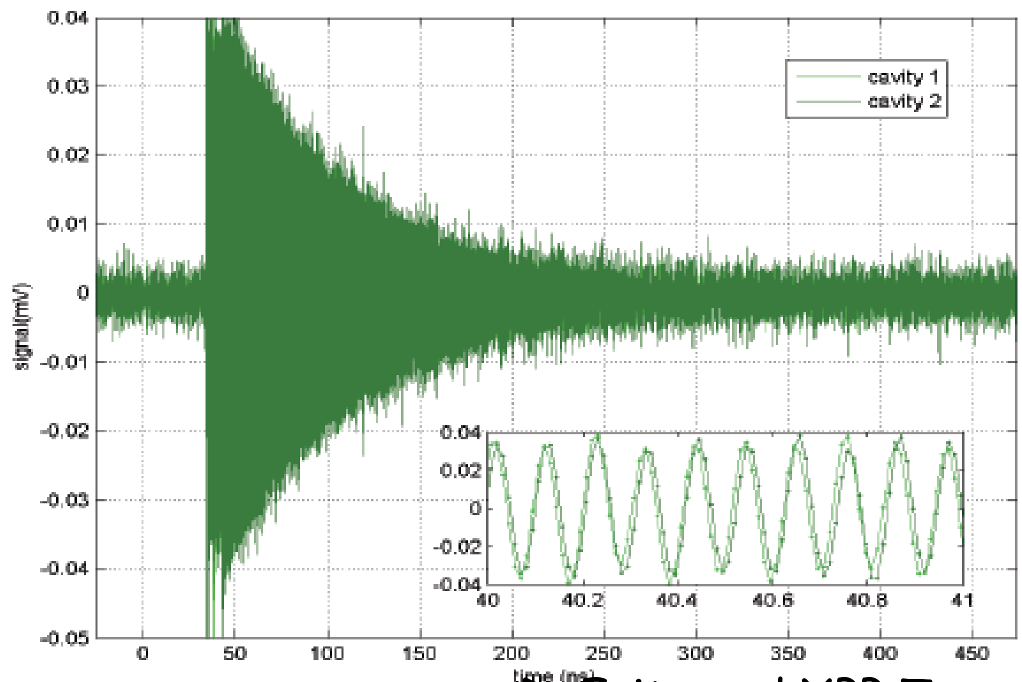


- photoelectrons induced by the x-ray pulse from a thin film target (30 nm silicon nitride membrane) excites the 9.5GHz RF cavity. The timing information is encoded in the phase of the cavity oscillation.

- A first test experiment was performed during LCLS Run 3. Cavity ring down signal was observed as expected from both cavities, as shown below.

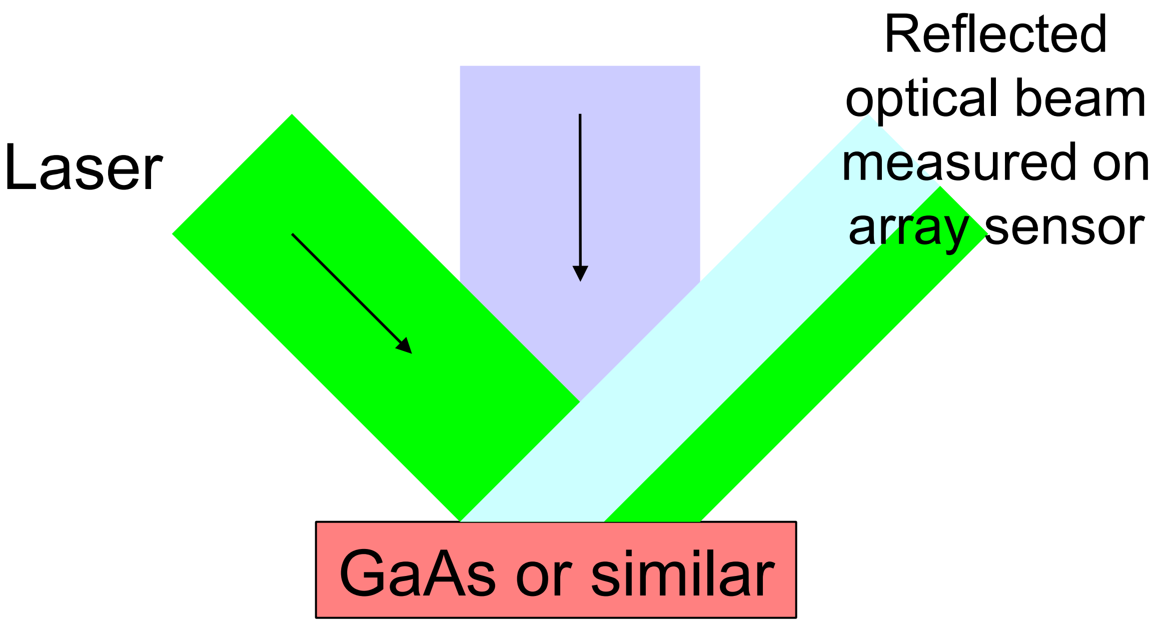


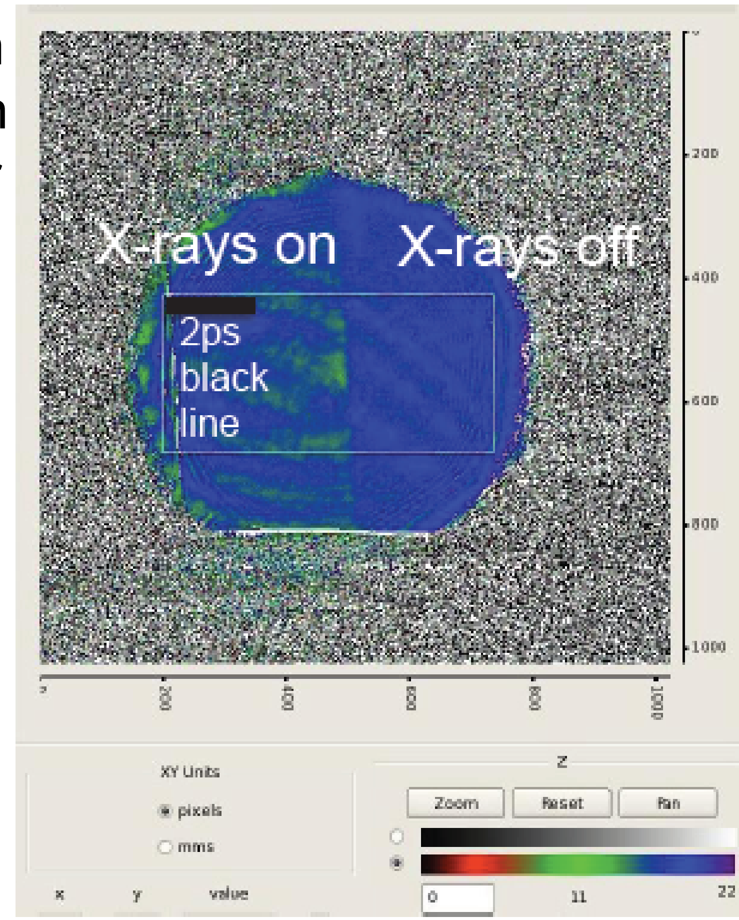
The inner working mechanism of the X-ray Cavity



D. Fritz and XPP Team

X-ray/optical cross-correlator

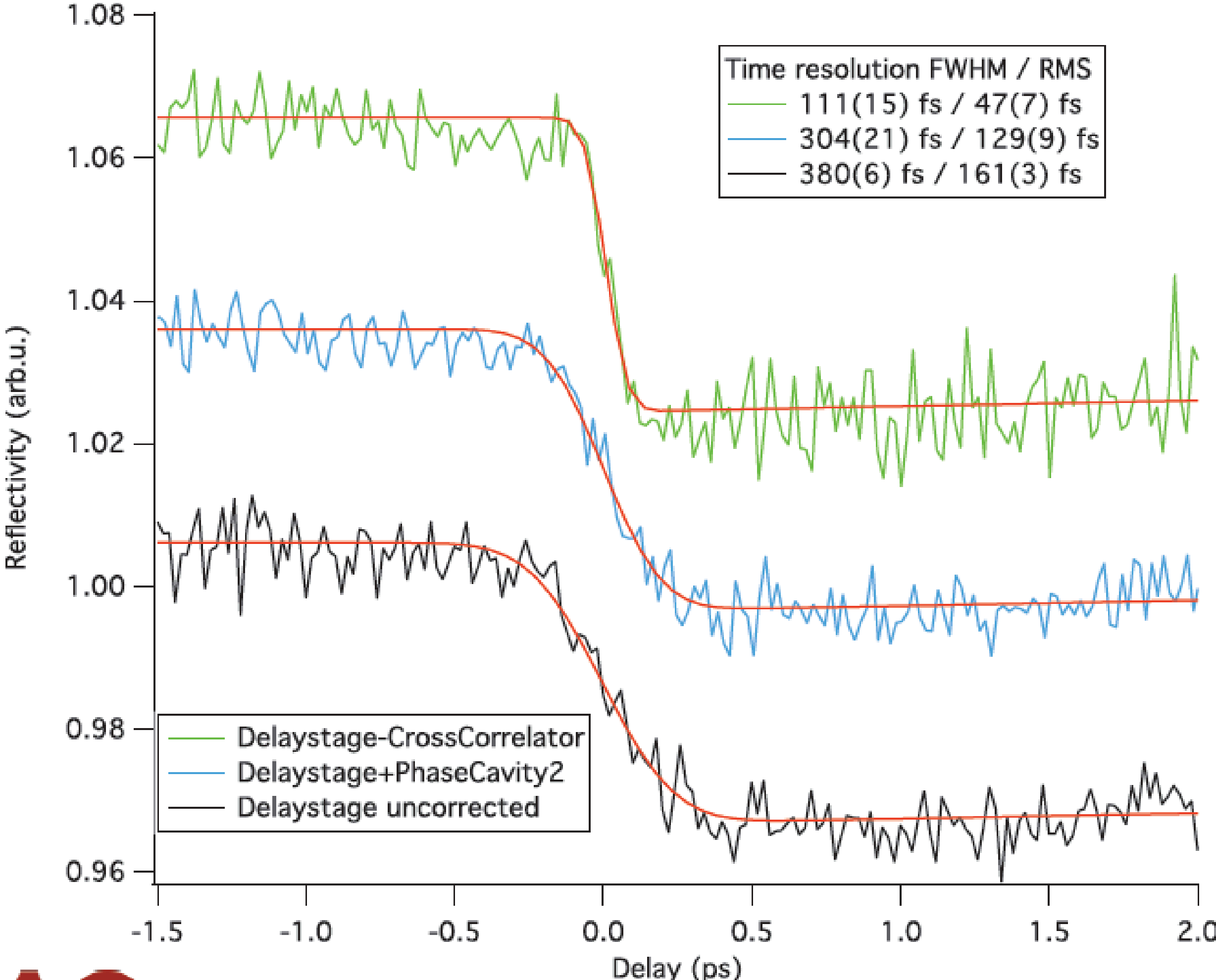




- Use the x-ray induced change in reflectivity on GaAs as a cross correlator

0 ps
143.3 mm on delay stage

X-ray induced reflectivity (very recent results)



Martin Beye

With correlator
111 fs FWHM

With phase cavity
304 fs FWHM

Intrinsic
380 fs FWHM

Summary

- Femtosecond synchronization is an exciting area and critical for the success of present and future FELs.
- New ideas and results every week….
- Thanks to colleagues at Berkeley, SLAC, DESY, Trieste, and elsewhere for many ideas and contributions.