Large-scale distribution of femtosecond timing for Accelerators

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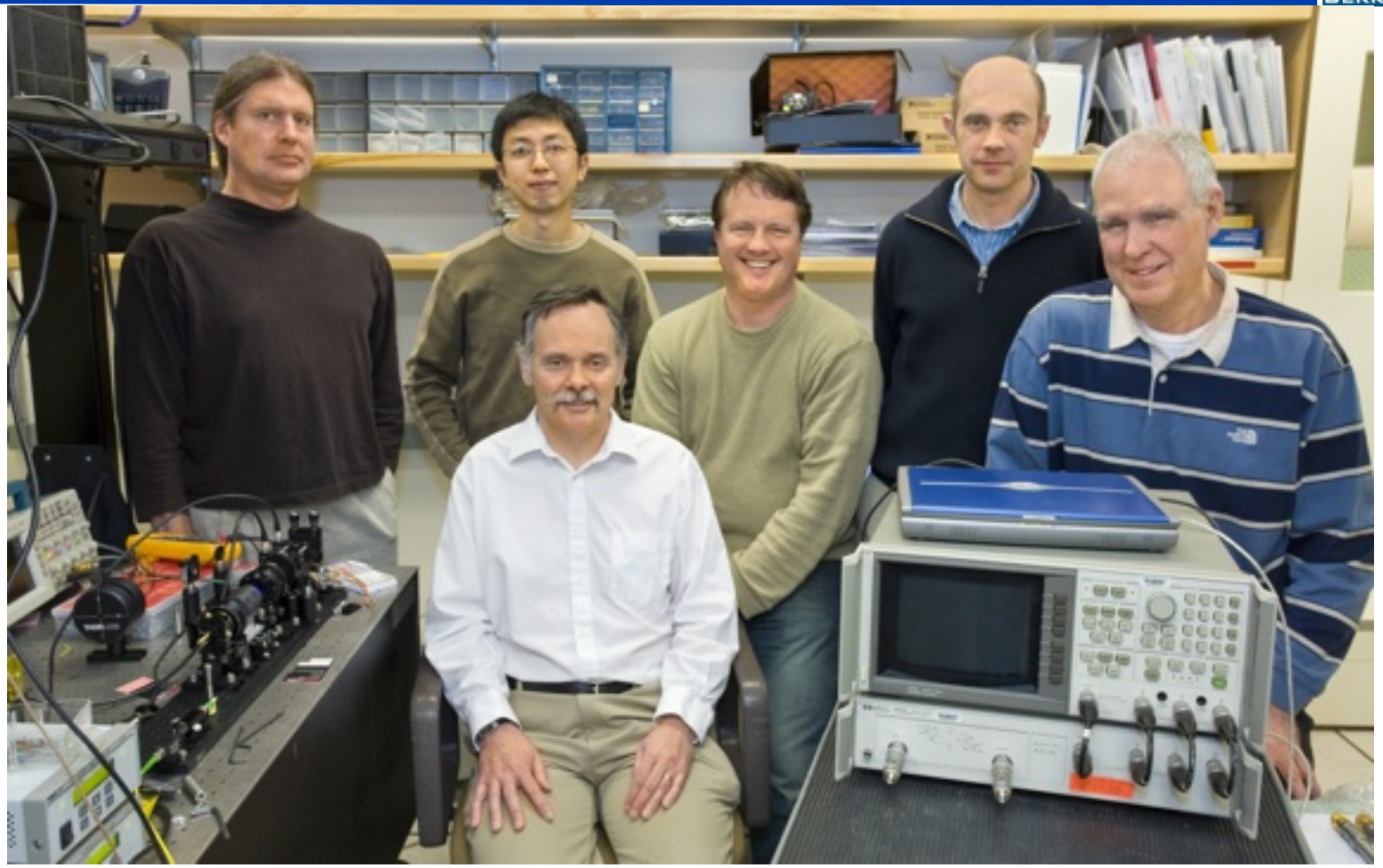

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Overview

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- Applications for femtosecond timing
- Interferometrically stabilized fiber links
- Results
  - Lab measurements
  - Linac Coherent Light Source
  - Fermi@Elettra
- Extension to >20 km links
- Summary

Application: pump/probe experiments in an ultrafast X-ray laser facility

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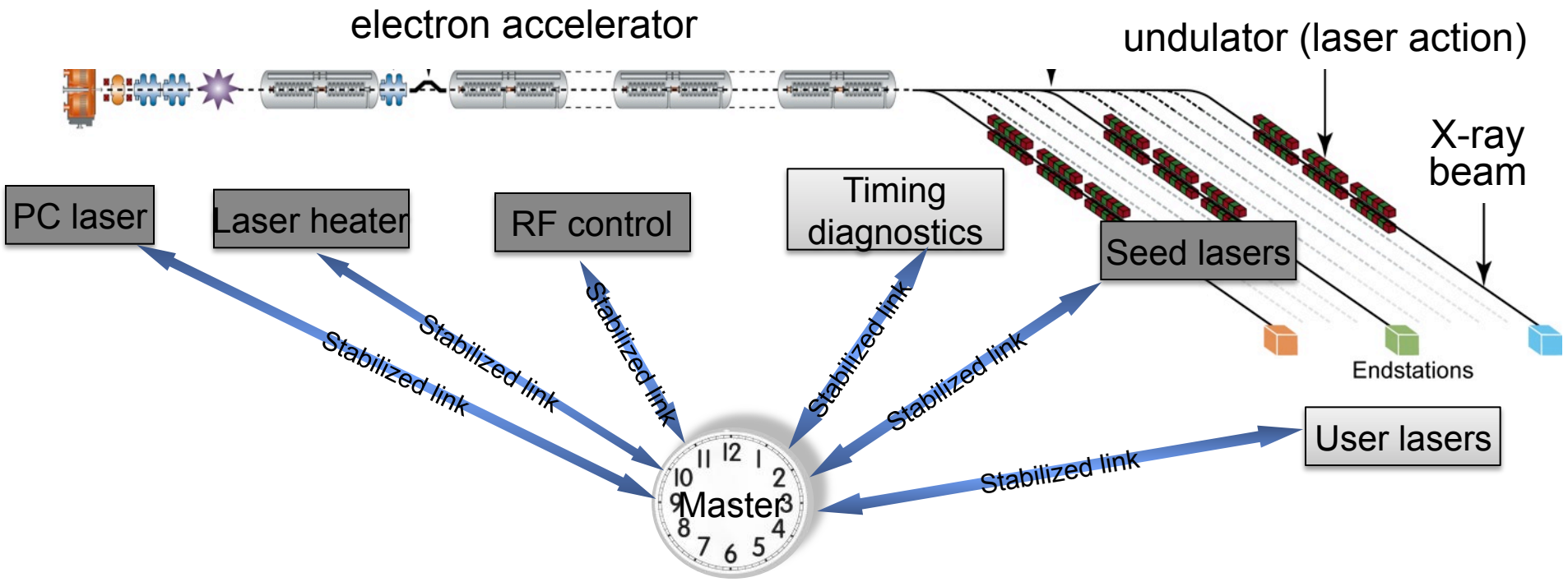
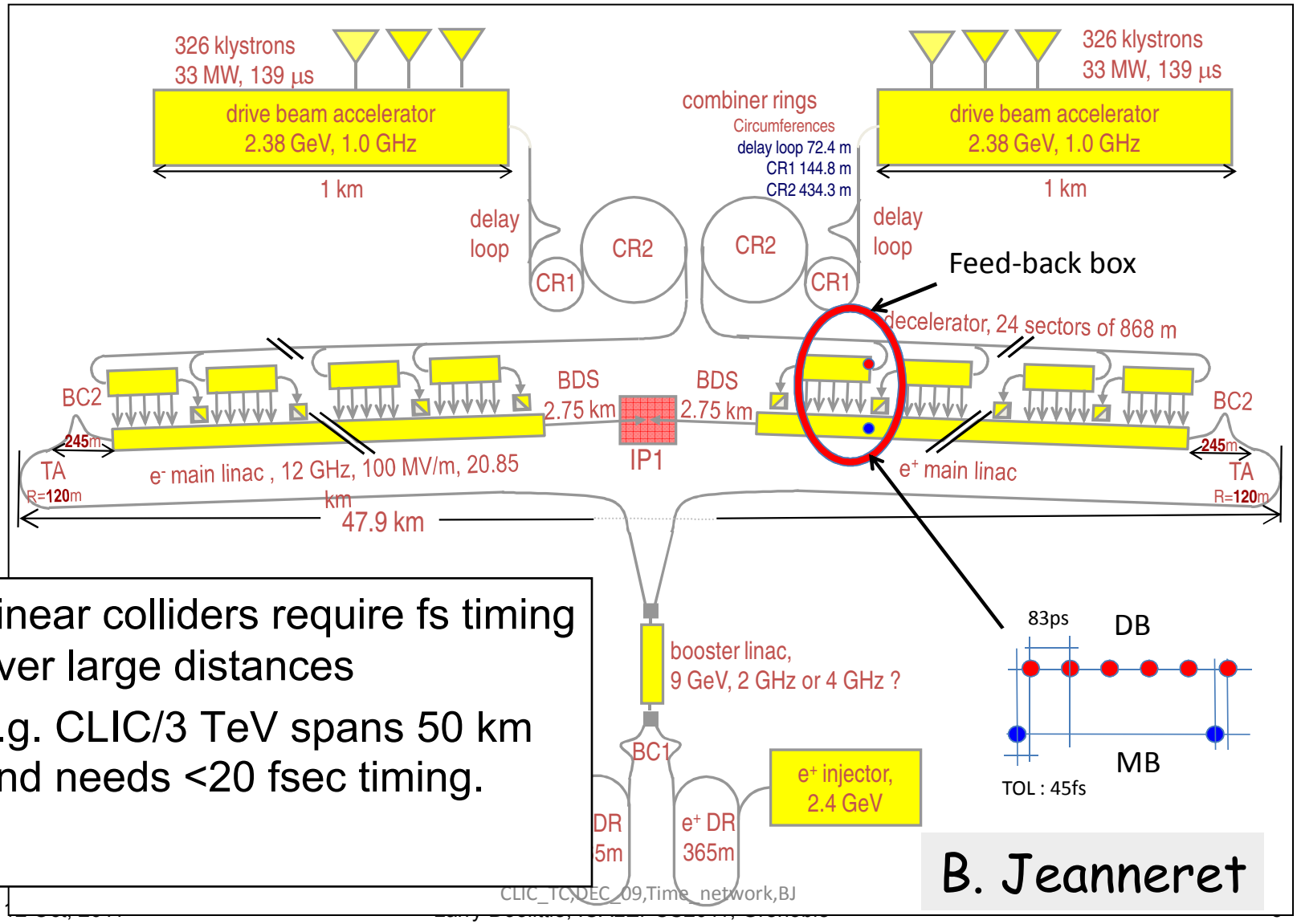
- This giant machine makes <10fs X-ray pulses!
- Pump/probe experiments require laser synchronization with electron arrival time measurements. Users want best possible synchronization.
- A "star configuration" clock distribution system provides signals for laser sync and other timing-critical functions



Application: Linear colliders



- Linear colliders require fs timing over large distances
- e.g. CLIC/3 TeV spans 50 km and needs <20 fsec timing.

Application: Large radiotelescope arrays

- The effective aperture of large telescope is set in part by the stability of the relative of the master clock signal
- Example: Atacama Large Millimeter Array

Stabilized fiber link: single channel

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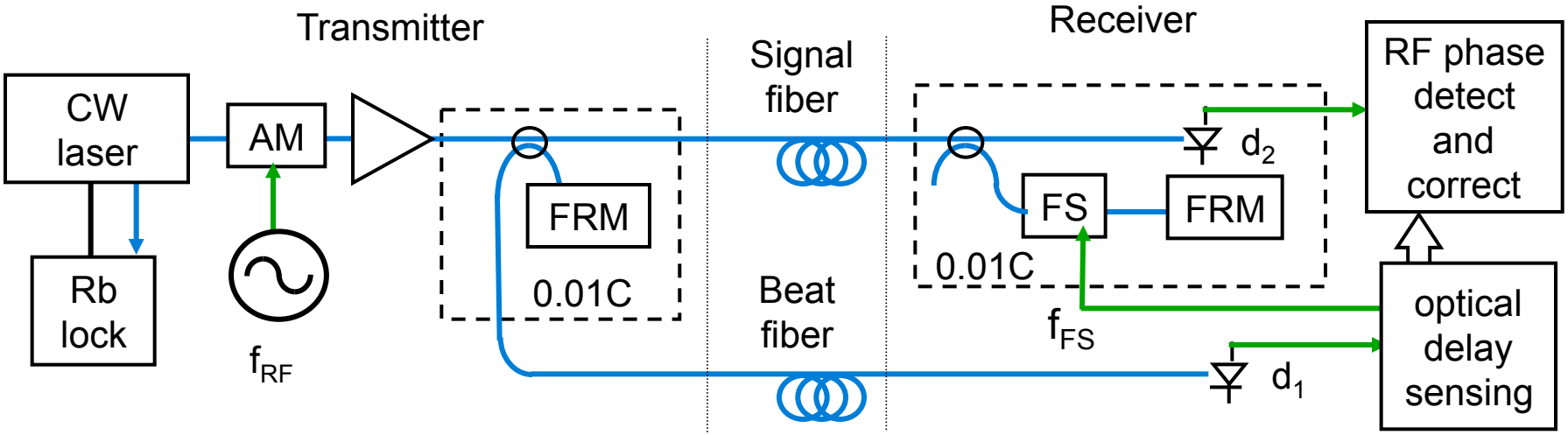
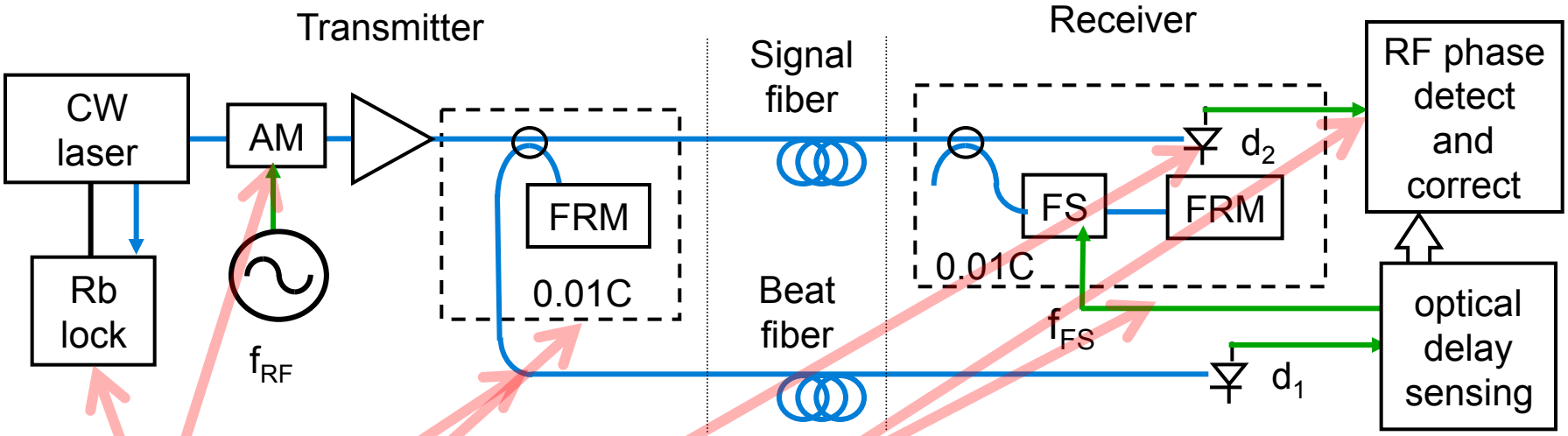


- Interferometer measures delay, reports to digital phase detector
- Easily extended to many channels by increasing fanout at transmitter.

Stabilized fiber link: error sources



1. **High stability laser frequency lock to atomic absorption line**
2. Low noise amplitude modulation at arbitrary frequency
3. Interferometric line stabilization scheme
4. Temperature and humidity controlled fan-out and reference line
5. Diodes operated to minimize amplitude-to-phase conversion
6. Feedforward correction for thermal coefficient of dispersion
7. Low noise detection of RF phase

Why optical fiber links?

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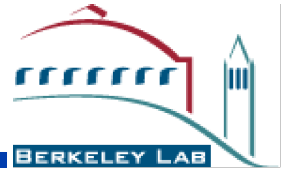

- Problem: coaxial cables and optical fiber have a temperature dependence of propagation delay of about 50 psec/km/deg-C.
  - Completely unacceptable for next-gen light sources both for RF systems and lasers.
  - Temp. stabilized cables impractical for large installations.
- Solution: use optical interferometry 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.

Time and Frequency Domain Stabilized Links

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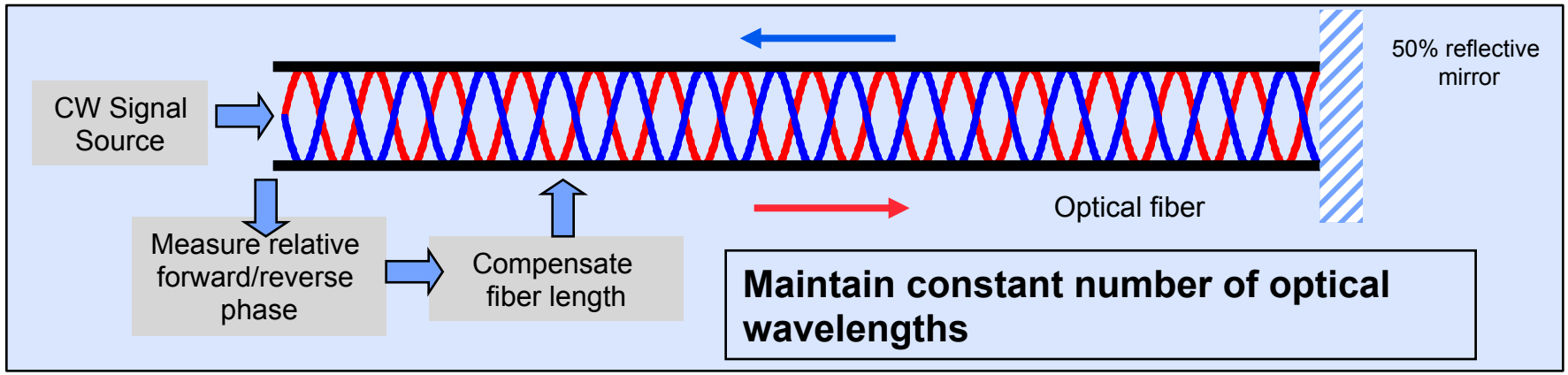
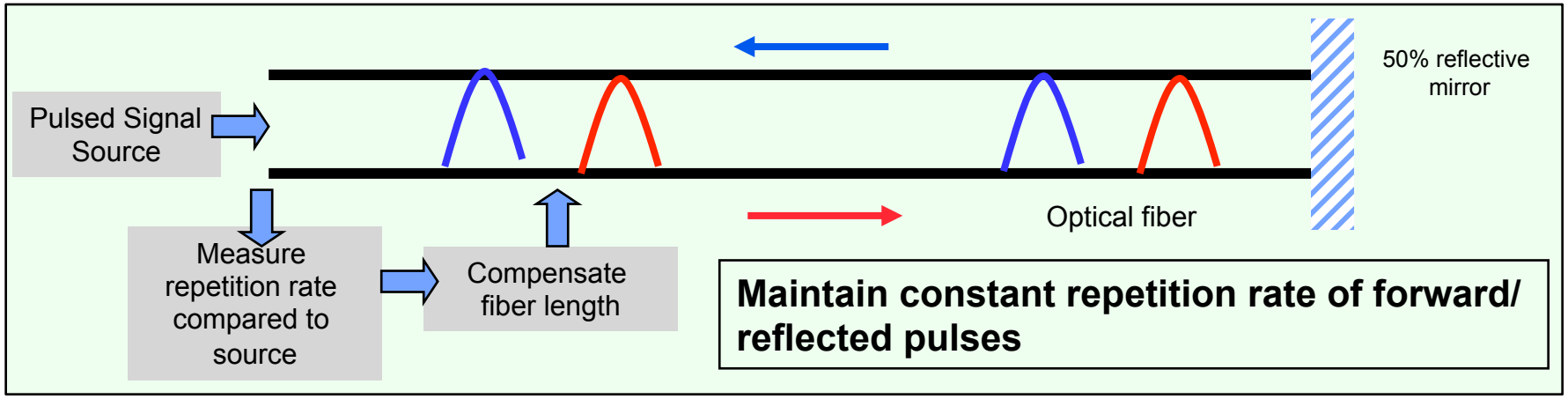
- Fiber links can be stabilized based on the revolution in metrology time and wavelength standards over the past decade.



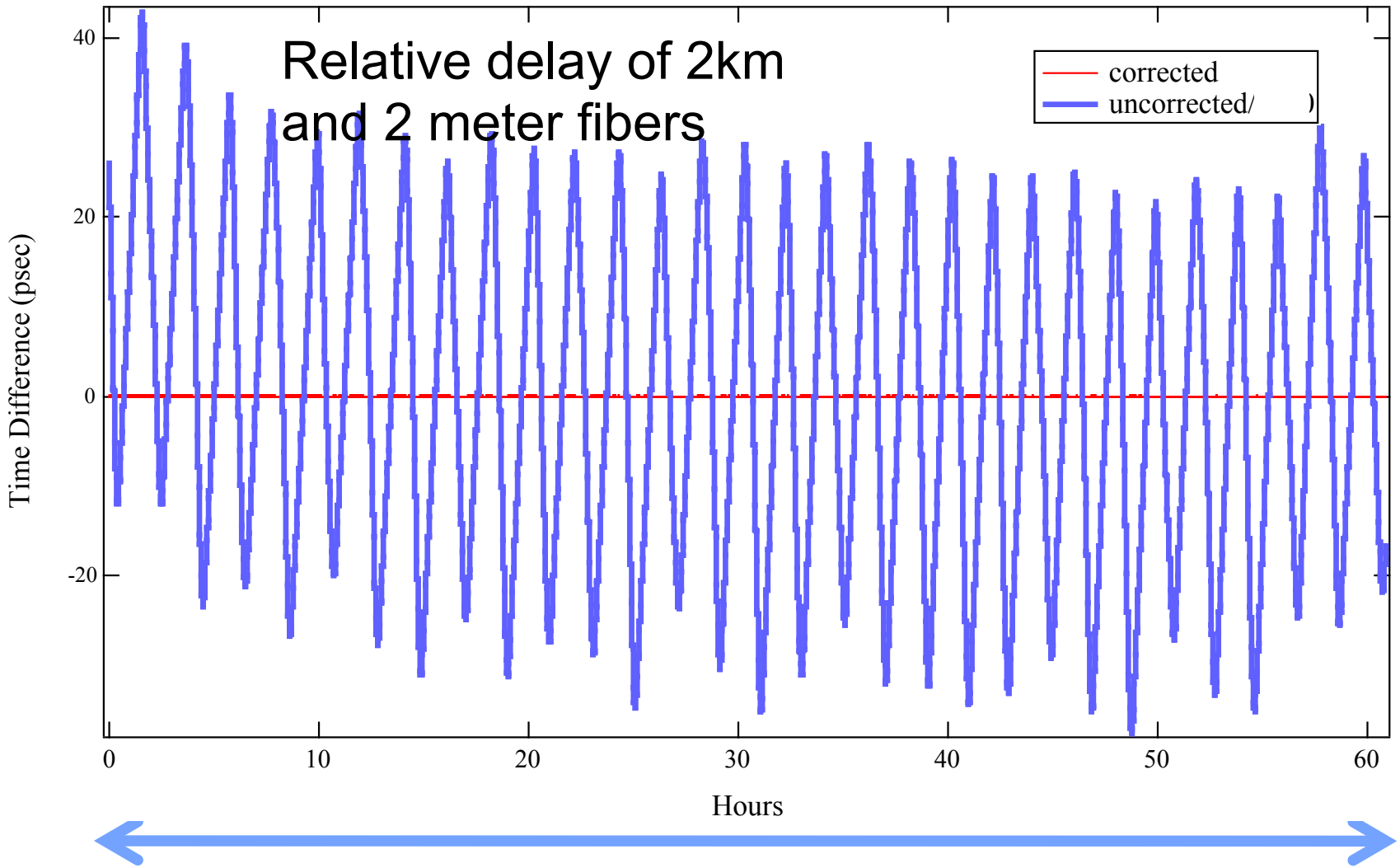


Correction BW limited to R/T travel time on fiber (e.g. 1 km fiber gives 100 kHz)

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

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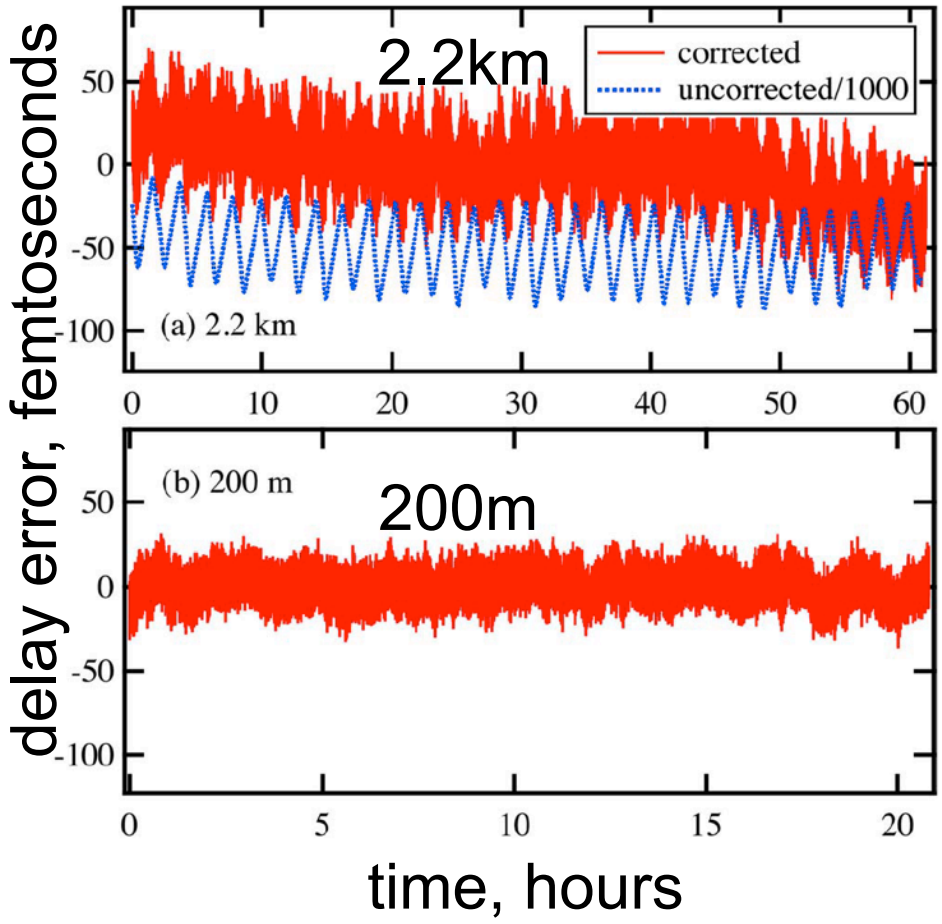
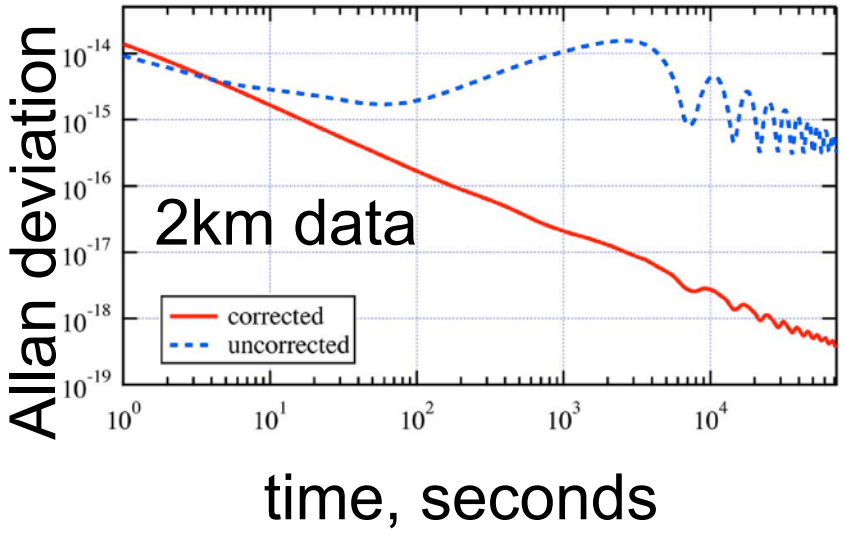


- 1 kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



RF distribution and and control device

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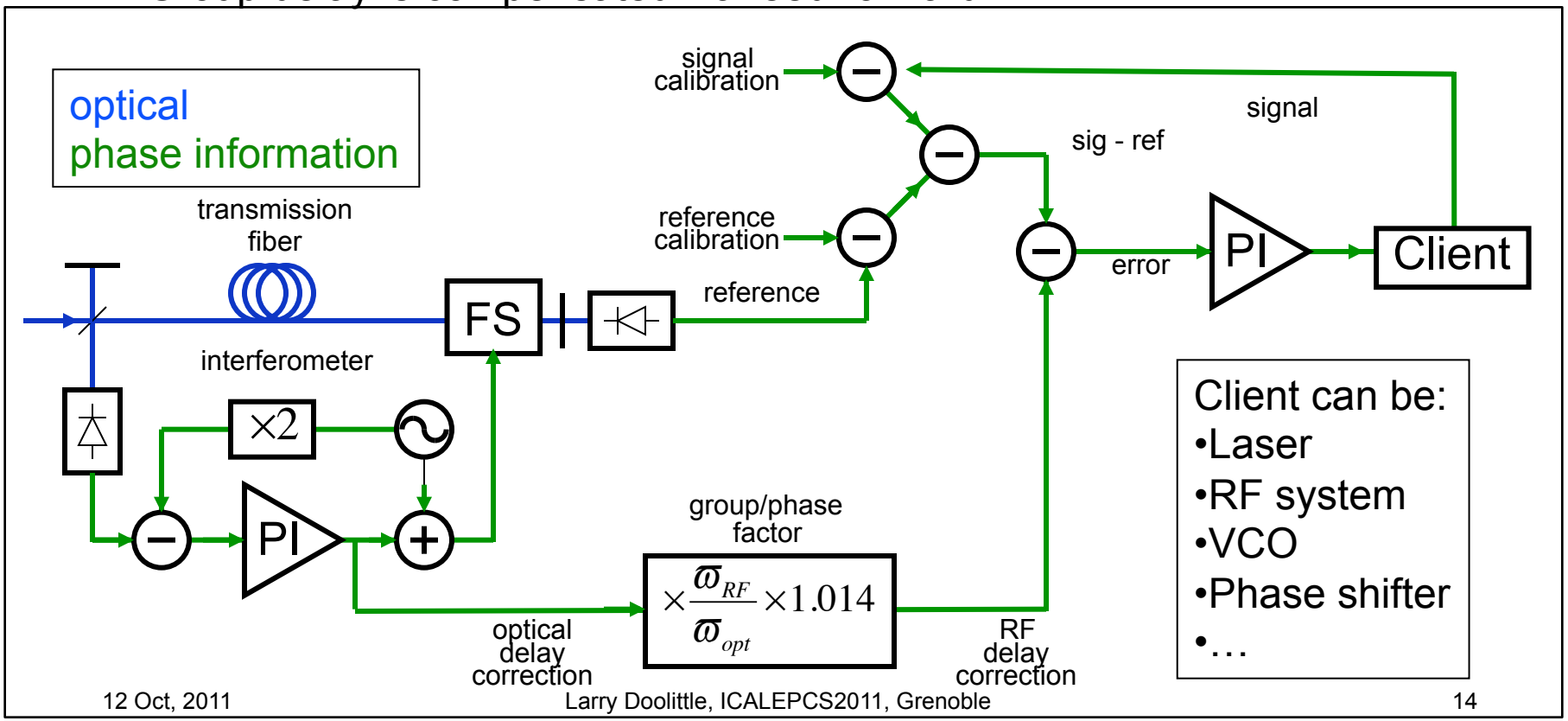
- It is critical to precisely lock the remote client to the master
- All possible drift sources from the master to the client must be either actively compensated or thermally stabilized.
  - Thermal effects of cables and RF components are actively compensated via calibration signals
  - Group delay is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



LCLS: Initial Configuration

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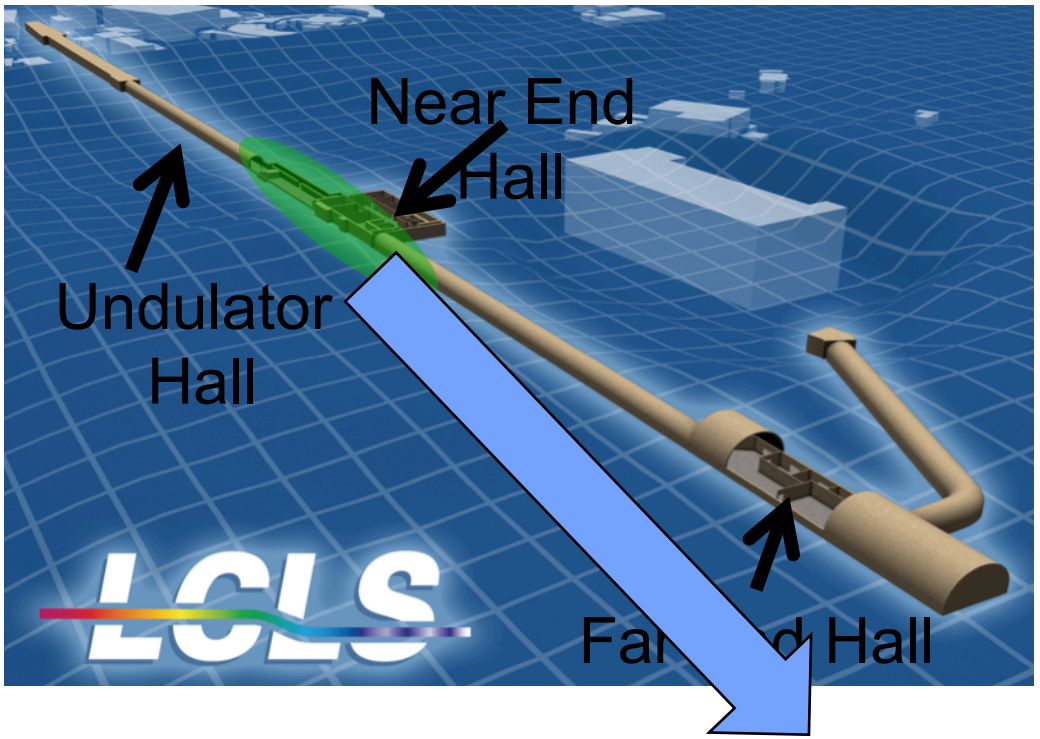
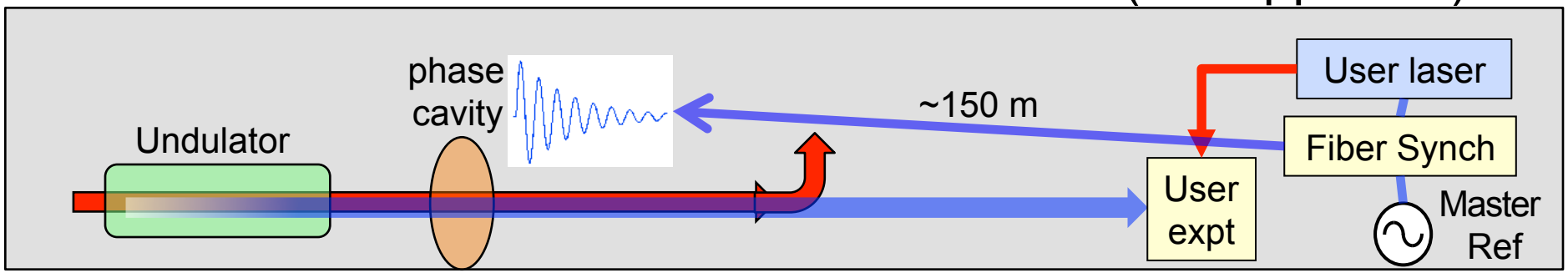


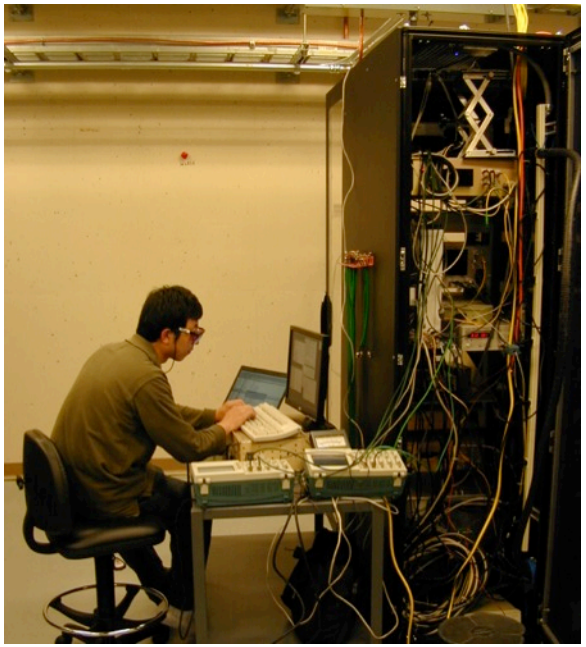
Goal: Synchronize NEH and FEH lasers to a bunch arrival time diagnostic to allow time-stamping of each beam pulse.

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



LCLS 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 Phase Cavities

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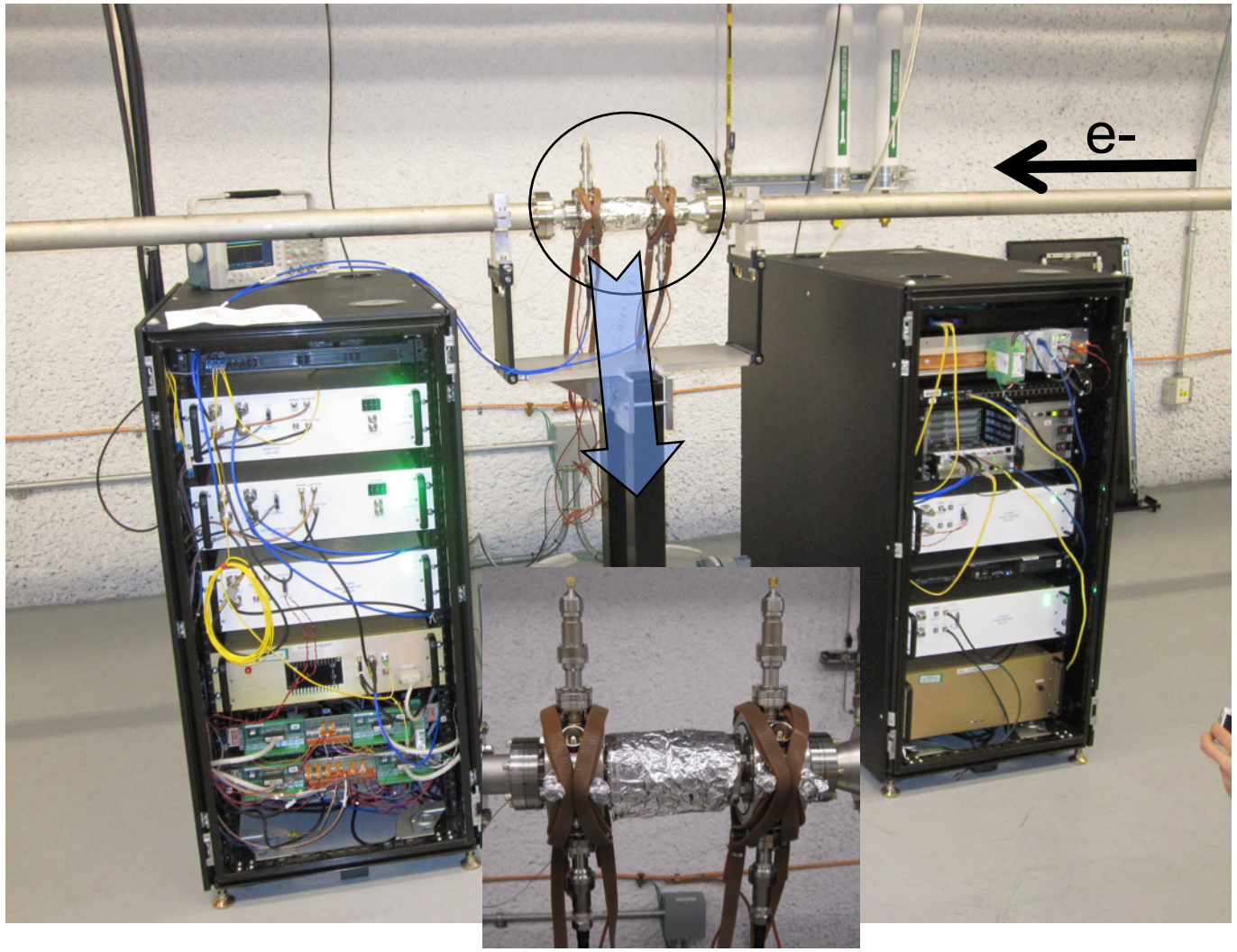

Synch/Head

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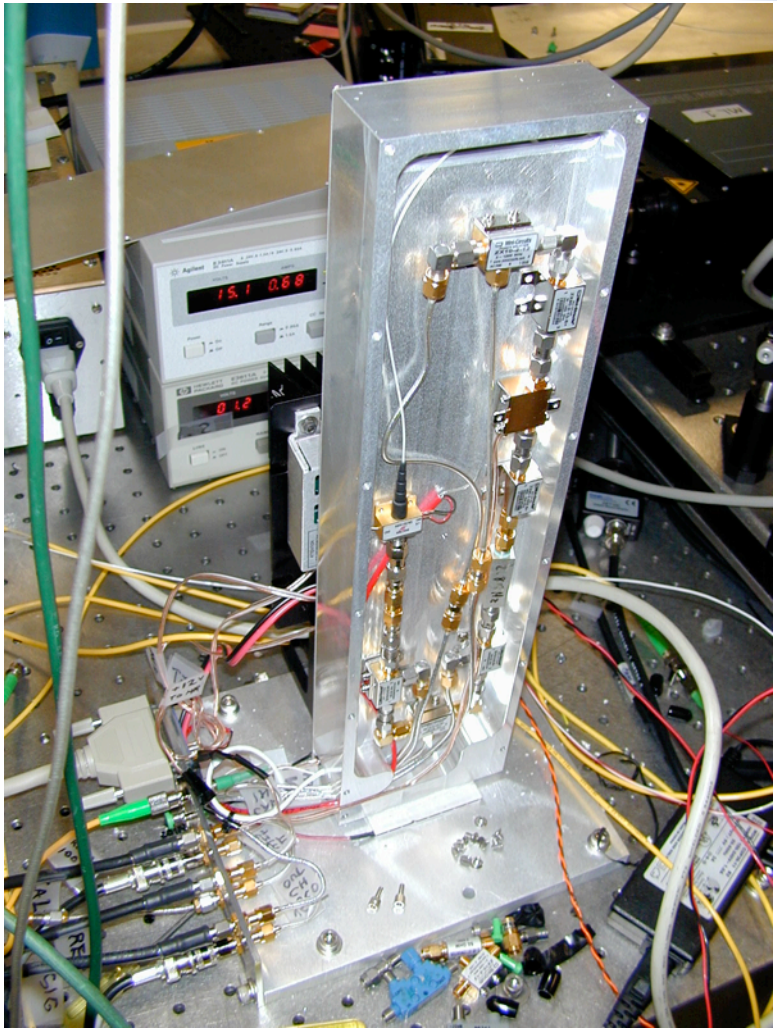
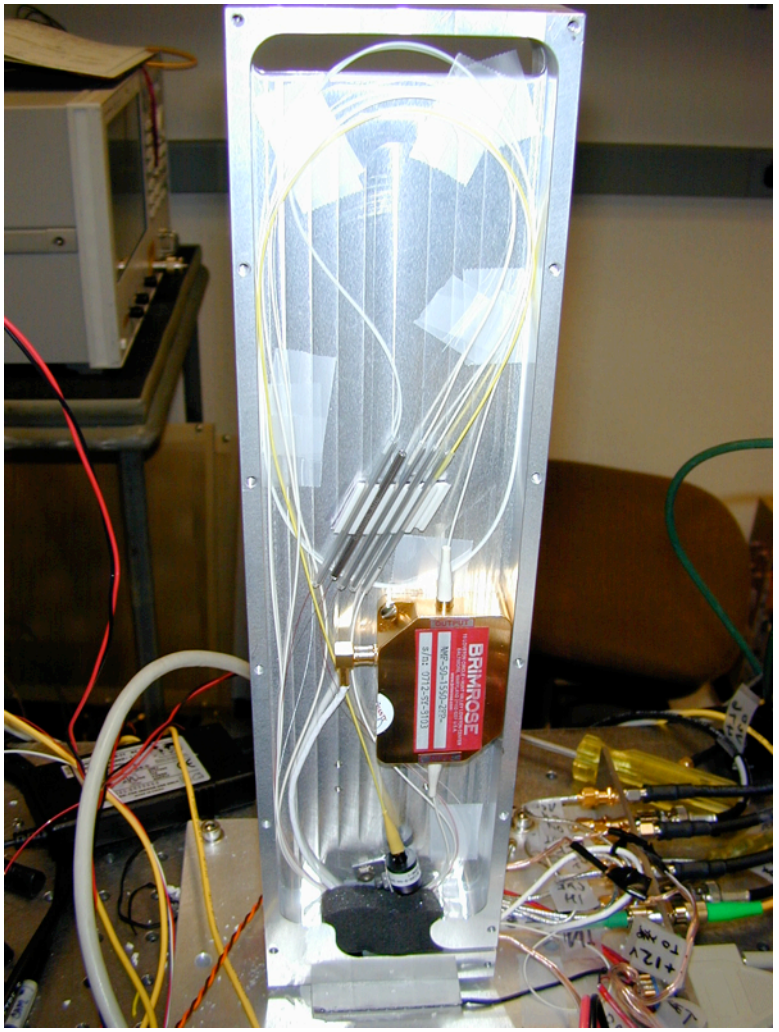


Electronic side



Optical side

Receiver

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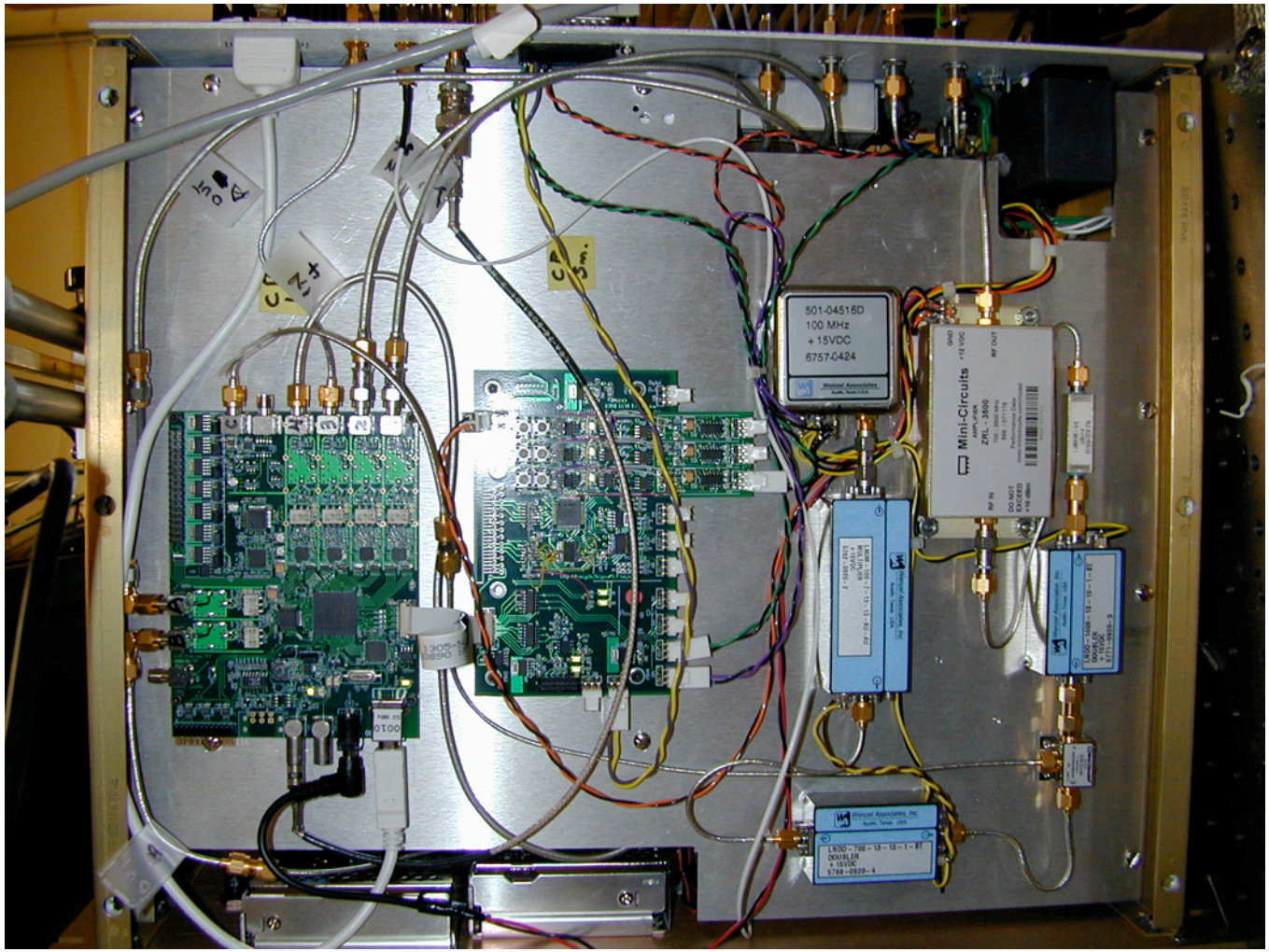
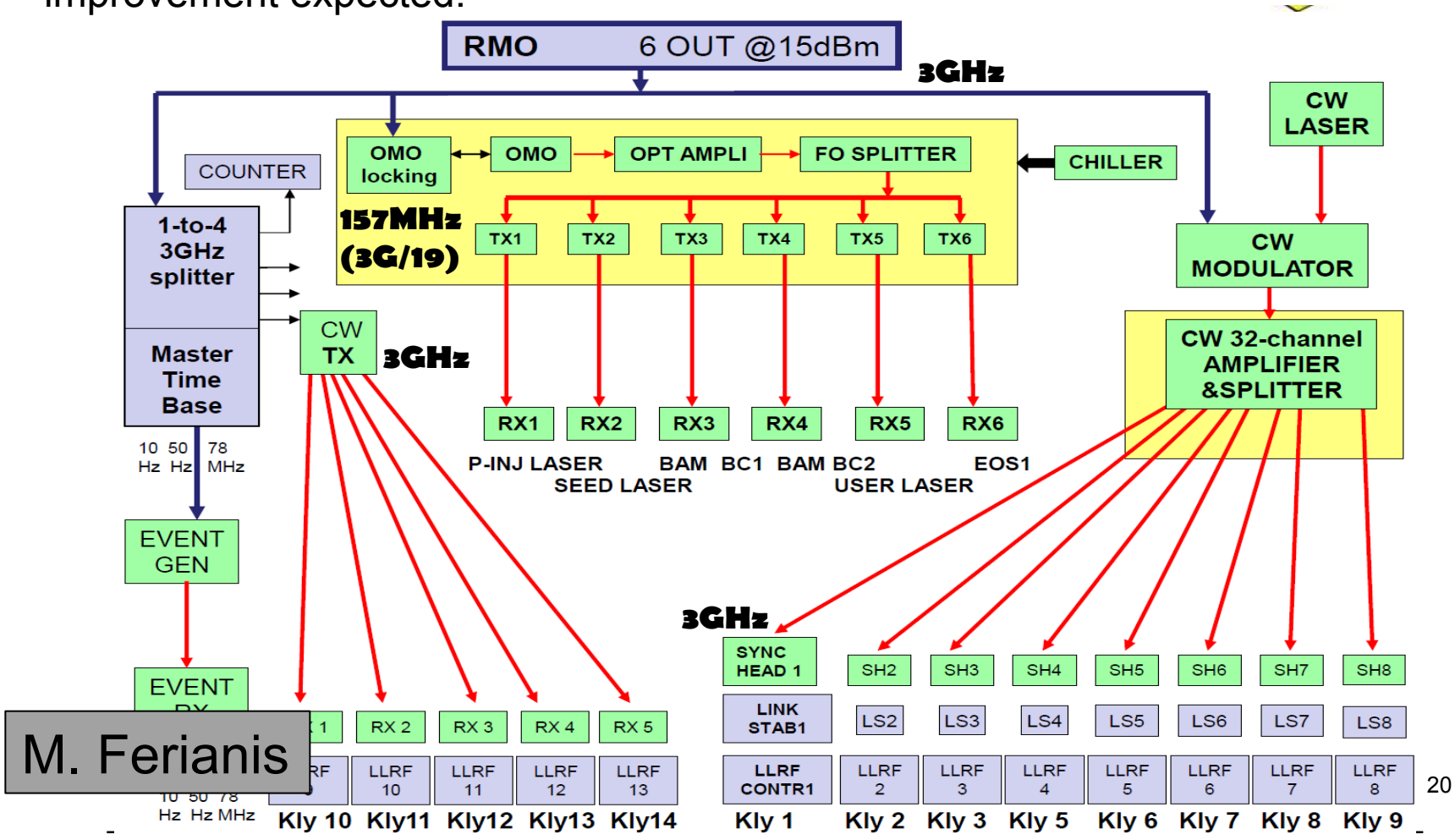


FPGA side (RF receiver on other side)

Optical Timing for Fermi@Elettra

- Stabilized links are used for distributing MO to RF stations. Each receiver also locks the RF amplitude and phase to the MO reference
- Performance is excellent. Beam jitter within spec (<75 fsec) with further improvement expected.



M. Ferianis

Extending to >20 km links

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There are a few challenges to extending the links beyond the 2 km we have demonstrated with precision of <20 fsec.

- The wavelength of the optical carrier sets the scale for measuring the link
  - Extend optical coherence length to be longer than twice link length (100 Hz line width is available.)
  - Lock optical carrier frequency to better than 10^{-11}. Several demonstrated techniques.
  - Understand polarization mode dispersion effects.
- Number of channels limited only by available optical power at transmitter.
  - 32 channels demonstrated (Fermi@Elettra).
  - Individual channel signal power is below Raman backscattering limit.

Summary

John Byrd

- Femtosecond timing distribution is now a demonstrated technology available for present and planned accelerators.
- Systems have a firm basis in technology from telecomm and digital RF controllers.
- Close to demonstrating links >20 km.
- It 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.