Recent results of RF synchronization at LBL

Russell Wilcox

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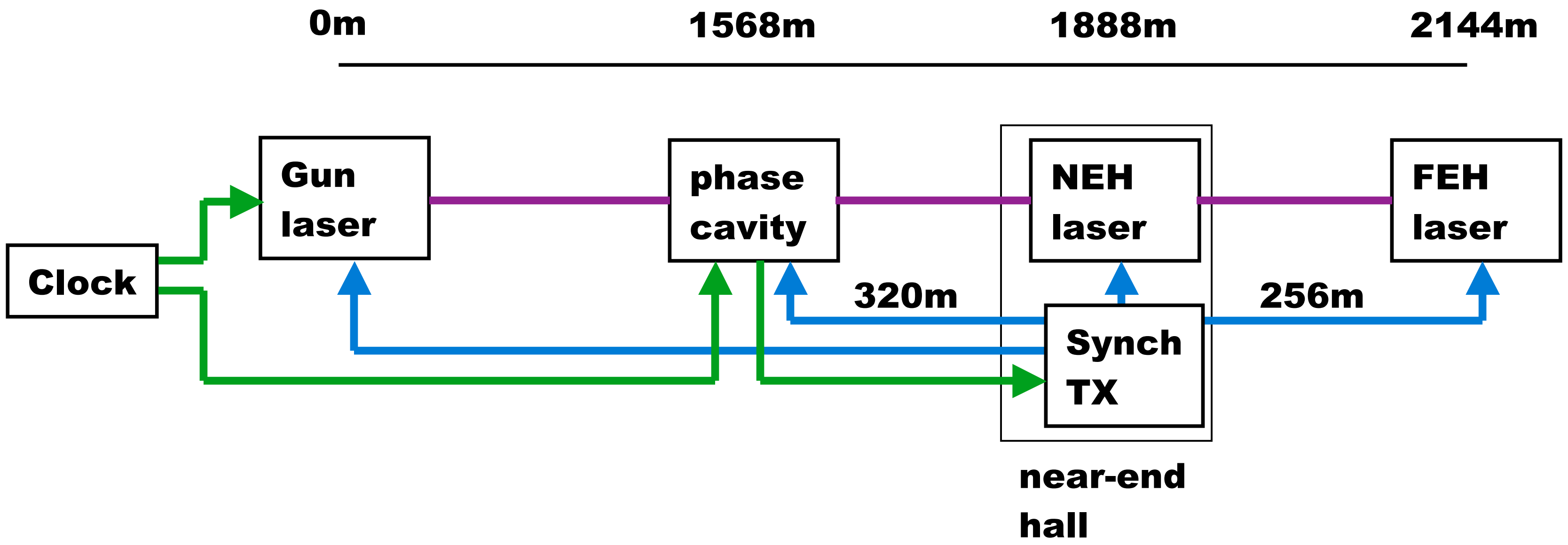
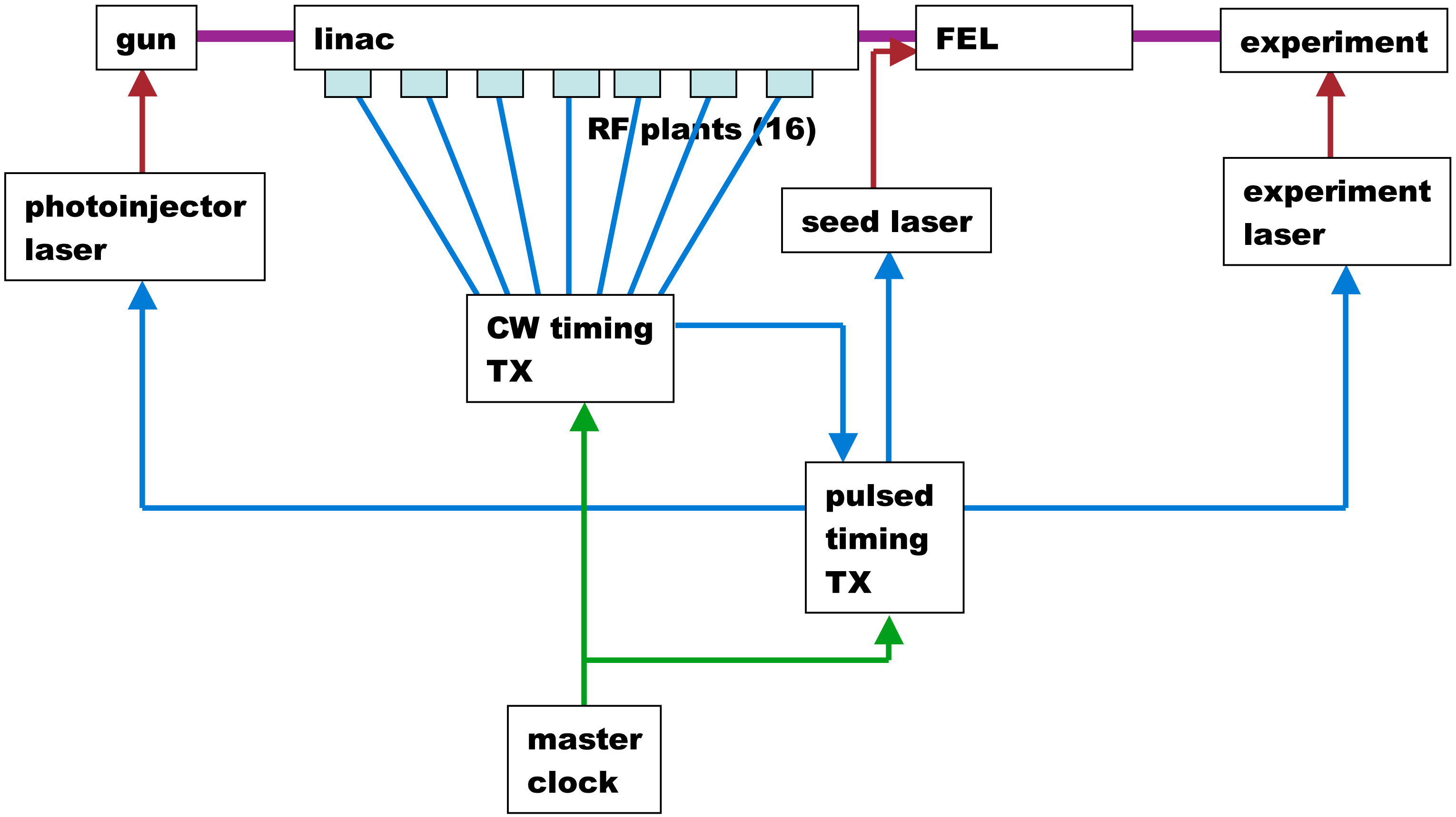
In LCLS we will synch lasers with RF



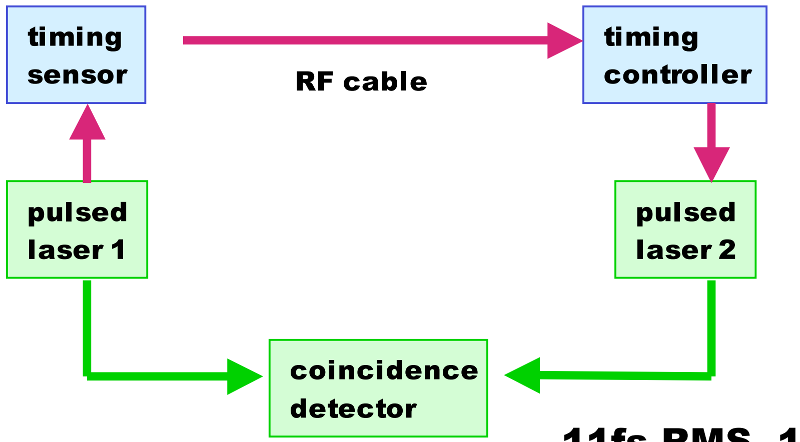
- 4 lines, expandable to 16
- <100fs RMS error over 24h
- Continuous operation over one week
- Deliver signals capable of synching modelocked laser
  - 0dBm RF, 476 and 68MHz

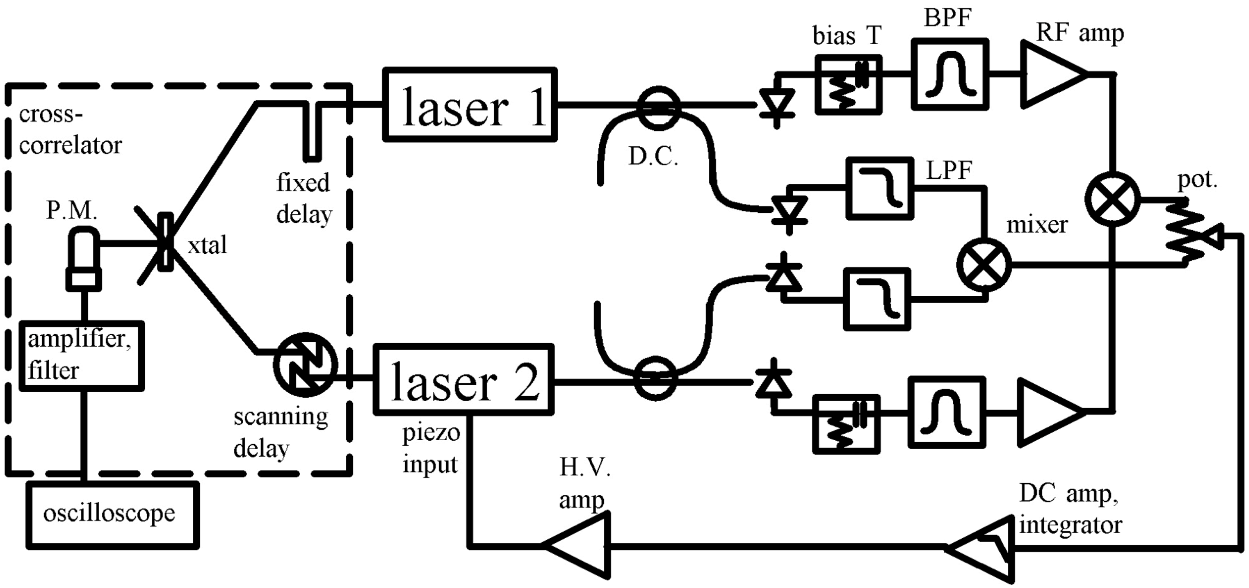
In Fermi, RF cavities are synchronized with each other and with laser pulses



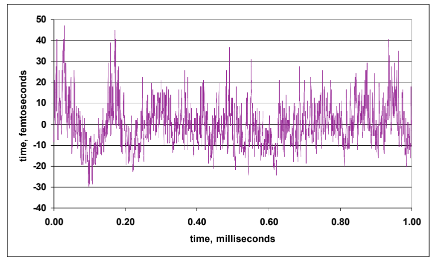
Lasers can be well synchronized using RF

- We stabilized two lasers at 100MHz and 2200MHz
- Our decision to use 2856MHz is based on this result
- Typical scheme, but higher frequency than commercial lock electronics (~500MHz)

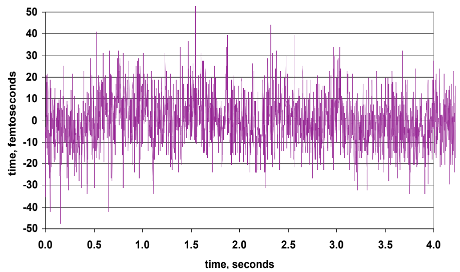




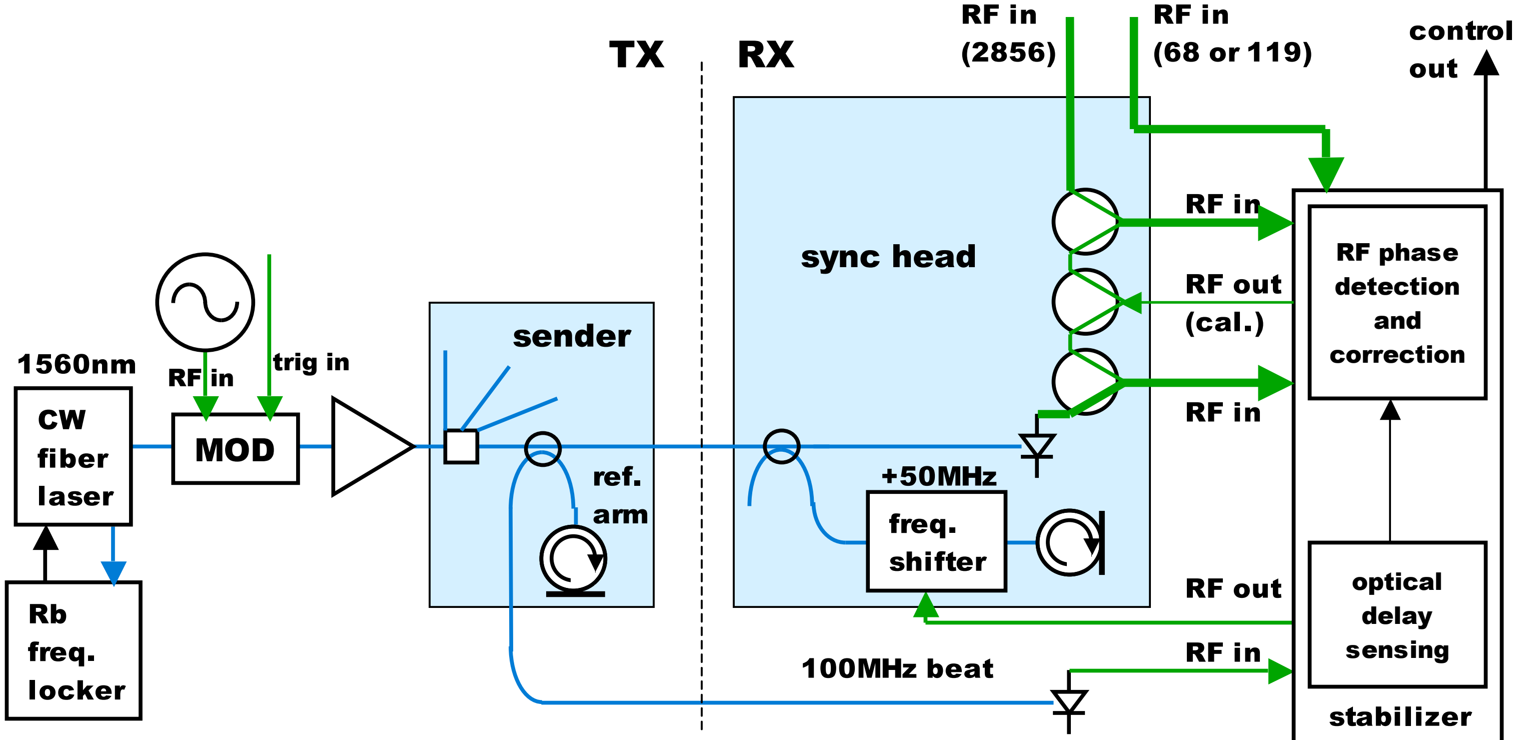
11fs RMS, 1kHz-1.25MHz



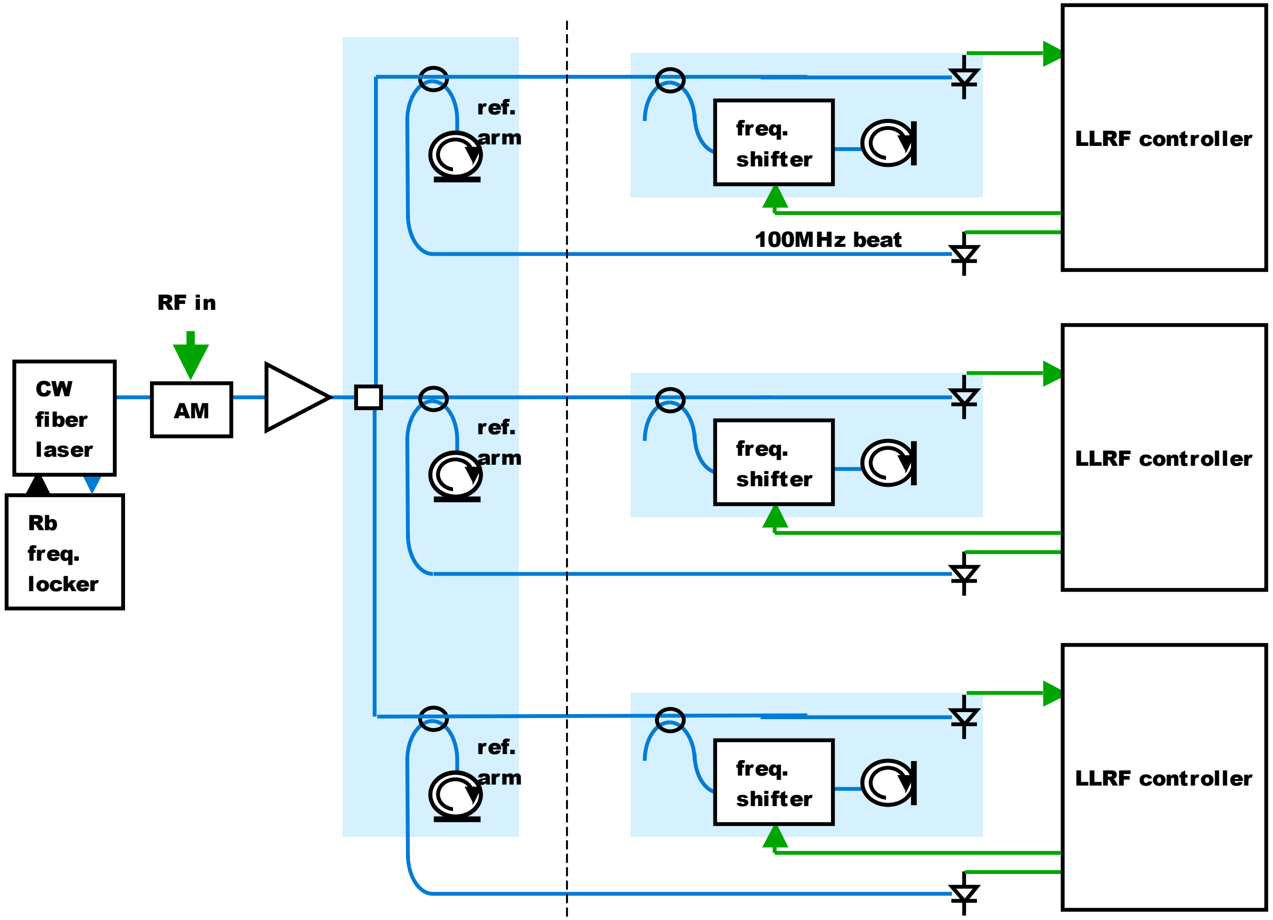
12fs RMS, 4 seconds



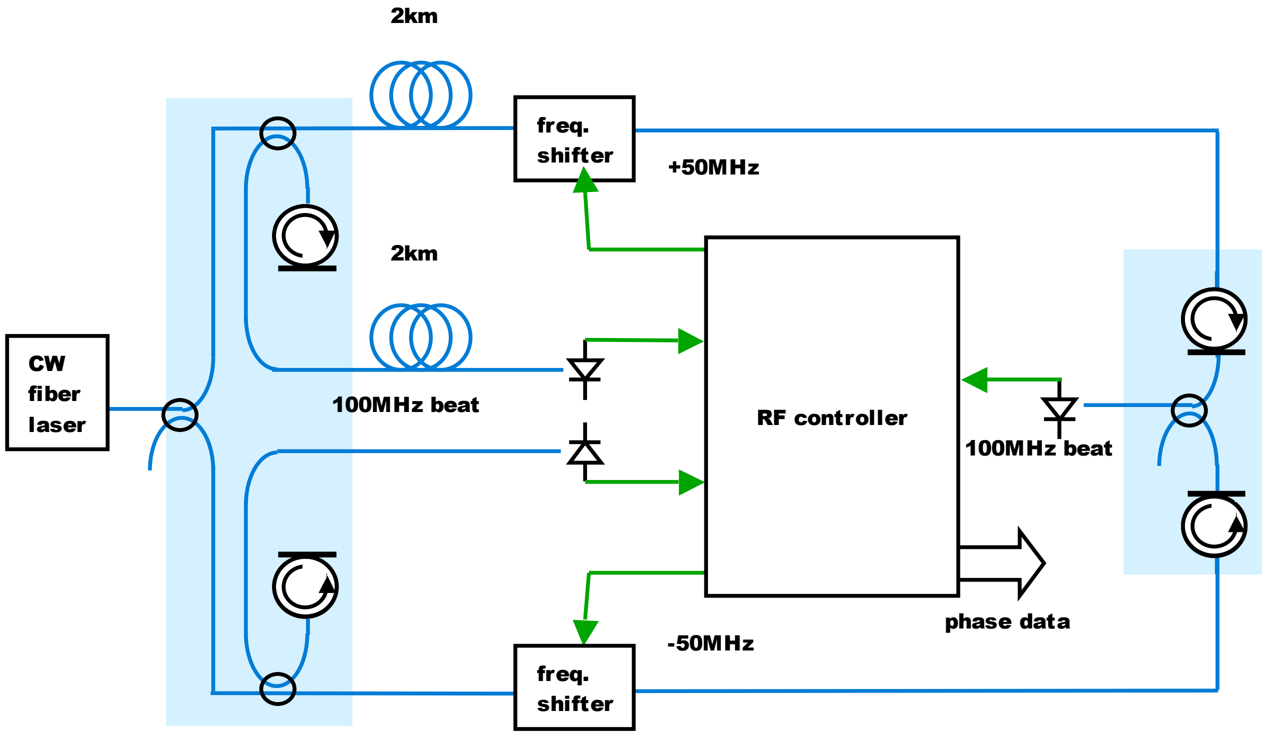
How our RF transmission scheme works



System is easily expanded to many channels, since transmitter is simple



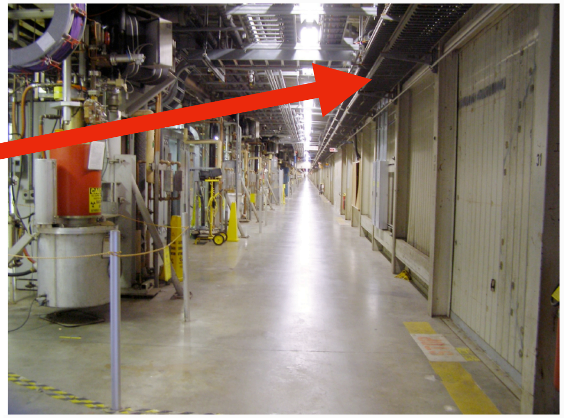
Our tool for measuring perturbations was a dual channel interferometer

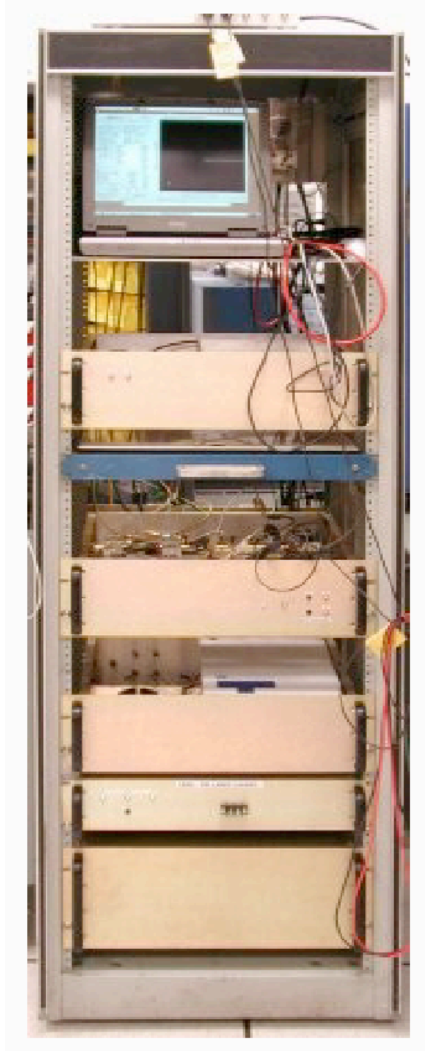


- Made of two single channel Michelsons in a Mach-Zehnder configuration
- The heterodyne Michelson interferometer is the backbone of the synch system
  - Robust, precise, thoroughly tested
  - Our unique configuration has advantages over typical designs

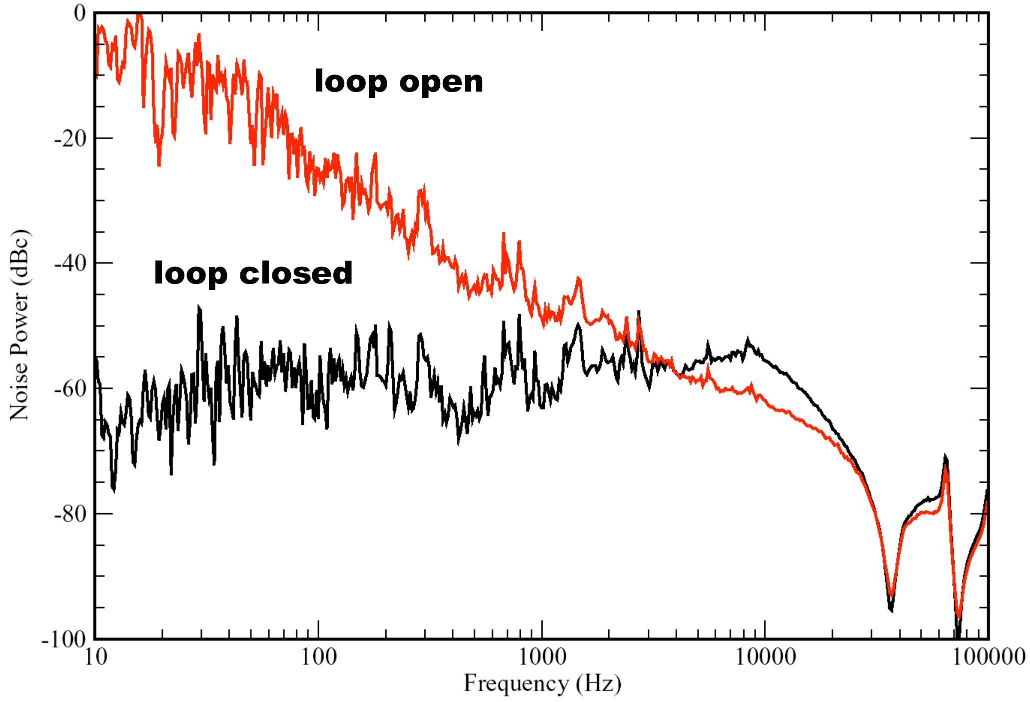
We packaged a dual-channel interferometer for tests at SLAC

- Tunnel fiber was two 2.8km long loops
- Fiber was plain network cable, 12 strand, run in open cable conduit
- Goal was to demonstrate this location is OK, since it is cheaper to install here
  - (for earlier location in laser room)



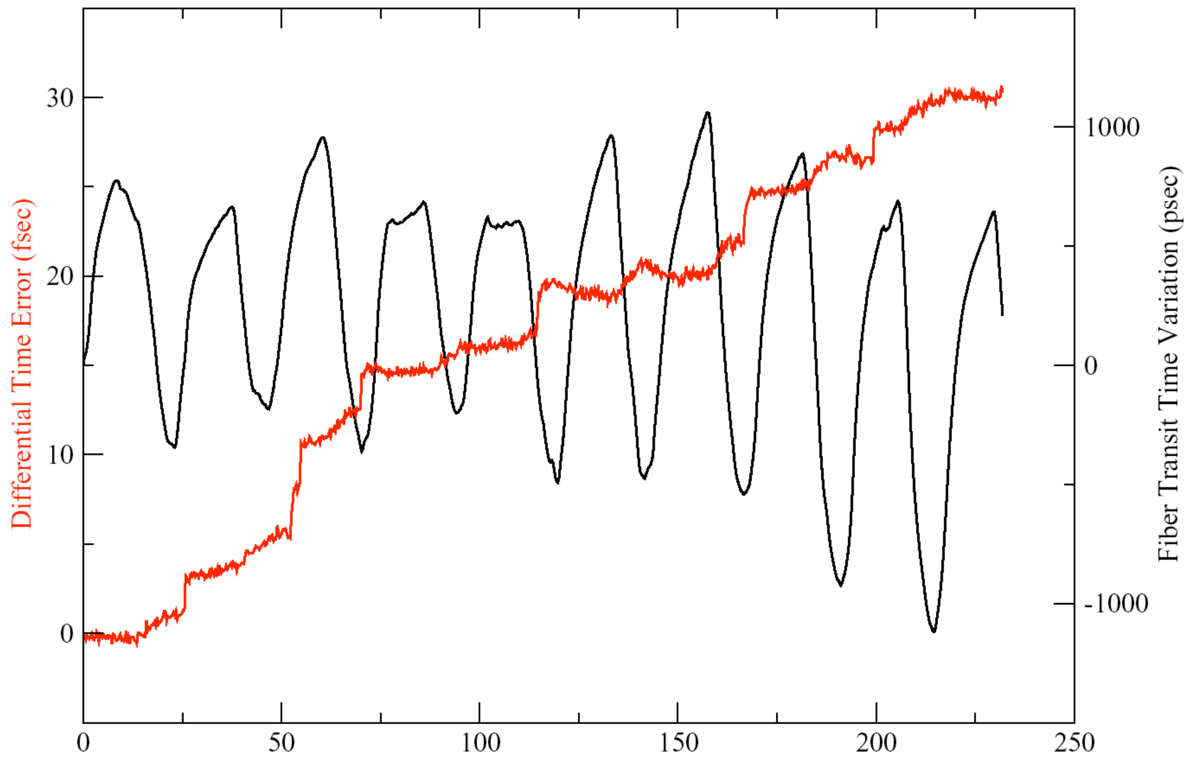


Jitter in SLAC tests was <1fs



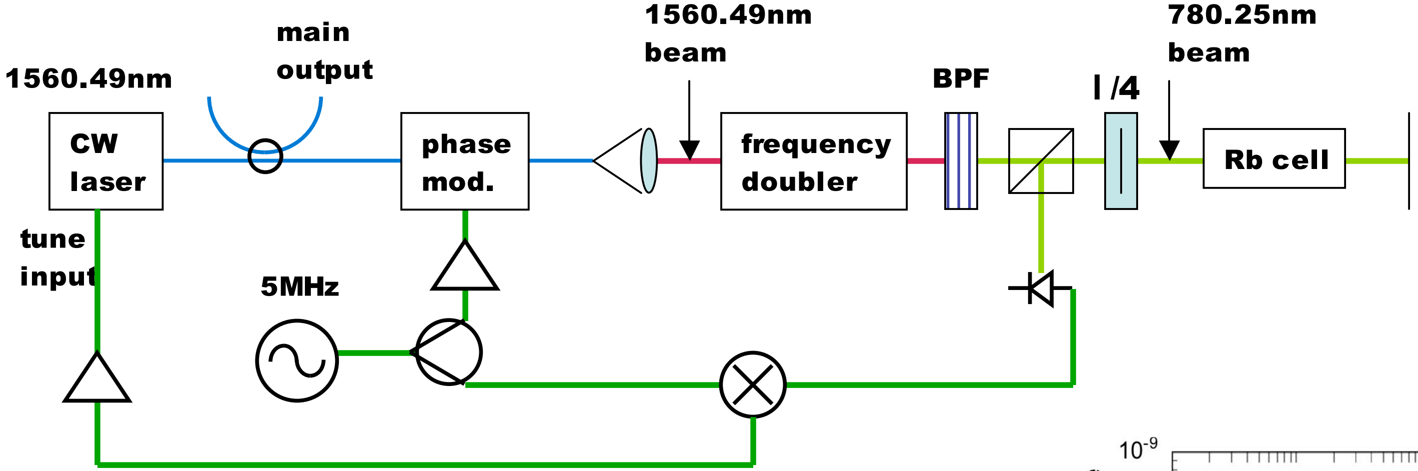
- Noise plot of 110MHz interferometer signal, comparing two lines (gallery)
- Integrated jitter from 10Hz to 40MHz is ~0.25fs at optical frequency
- Loop bandwidth is limited by transit time though fiber
- We saw no spurs at klystron frequencies, indicating no acoustic problem

Results of SLAC gallery tests, long term

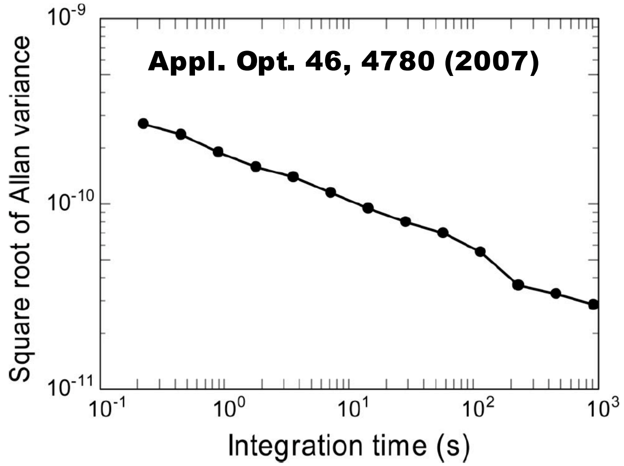


225 hour run.
Total correction: black
Differential error: red
Slope is found to be a computation artifact. "Jumps" are not instantaneous, and not multiples of the optical period

Frequency stabilization of the CW laser

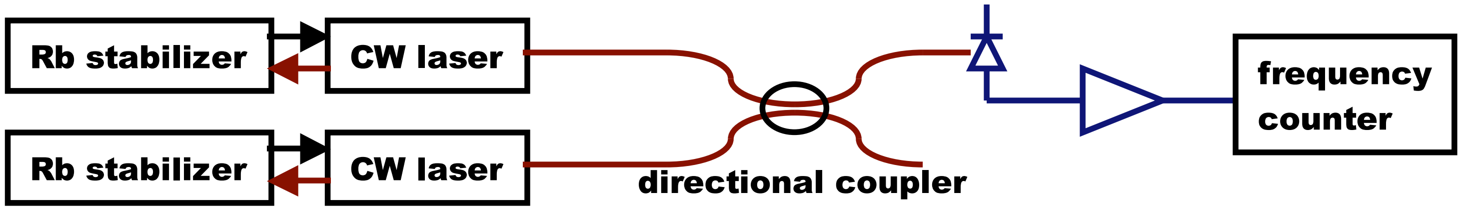


- Need 10^{-9} for 2km link, 10fs uncertainty
- Stabilizing to line center of saturated absorption in Rb can achieve ~2×10^{-10} in 1sec
- Saturation creates a narrow notch in the Doppler broadened line
  - 20MHz notch in 500MHz line
  - Lock to notch

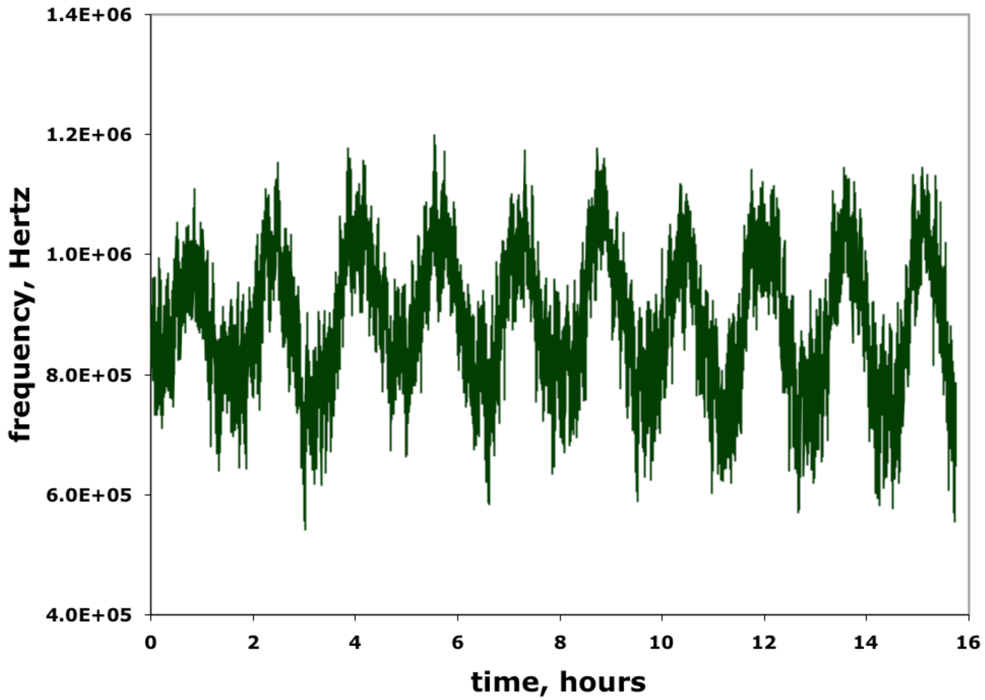


Beating two stabilized lasers to test stability

- Two Rb-stabilized lasers are mixed on a photodiode, producing a beat which varies in time. Fractional stability is beat variation divided by optical frequency

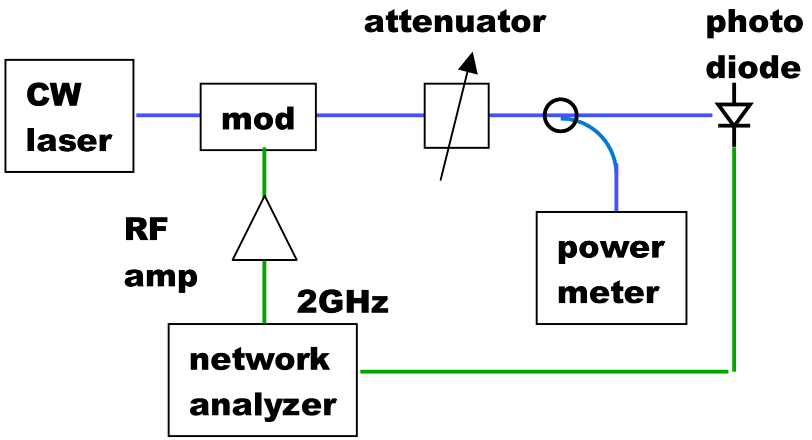


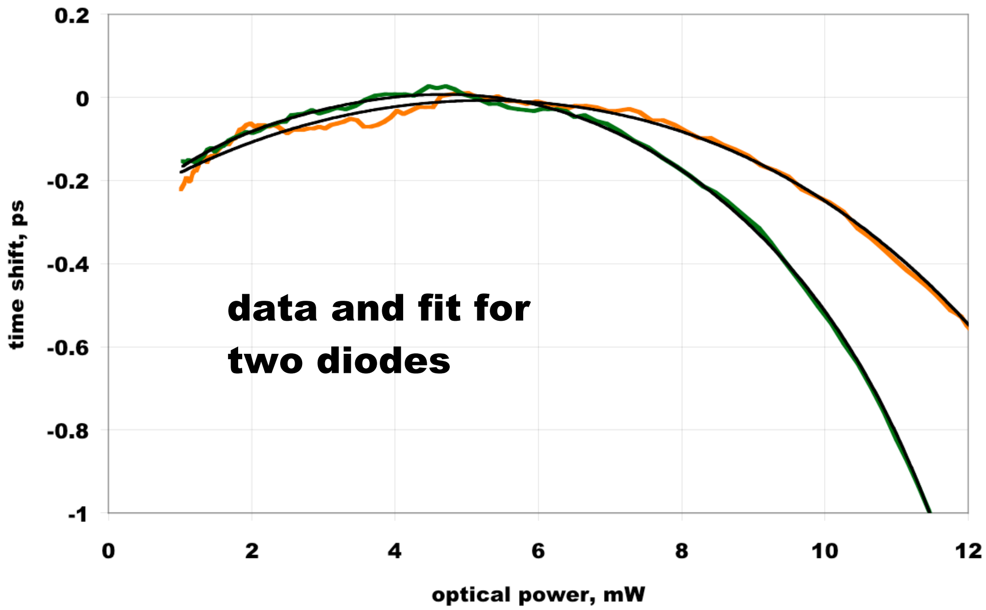
- Slow variations are correlated to room temperature
  - We suspect a mechanism that can be easily controlled
- RMS, long term: 5.0e-10
- RMS, short term: 2.0e-10
- P-P variation: 3.2e-9



Our operating signal levels are adjusted to minimize phase error

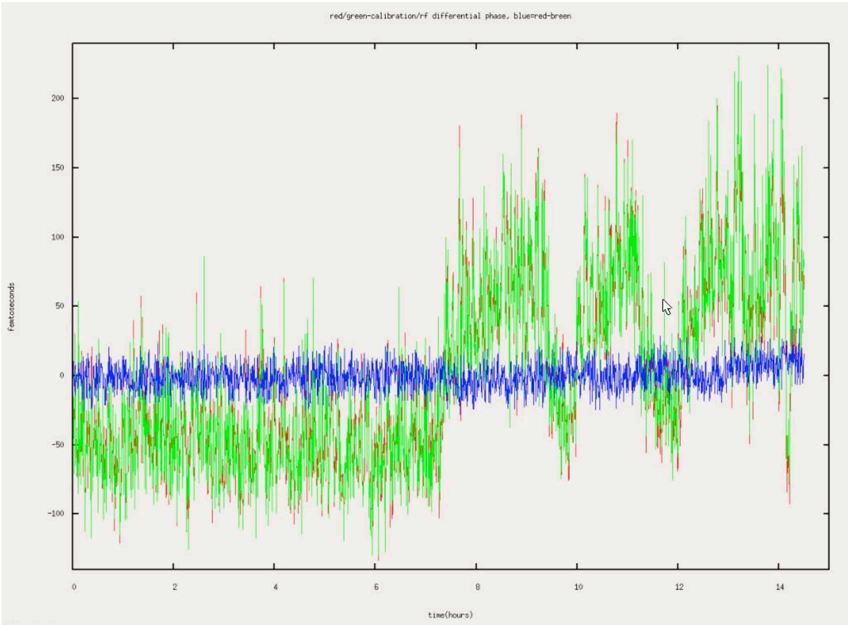
– **As average optical power to diode is varied, phase of detected RF shifts**

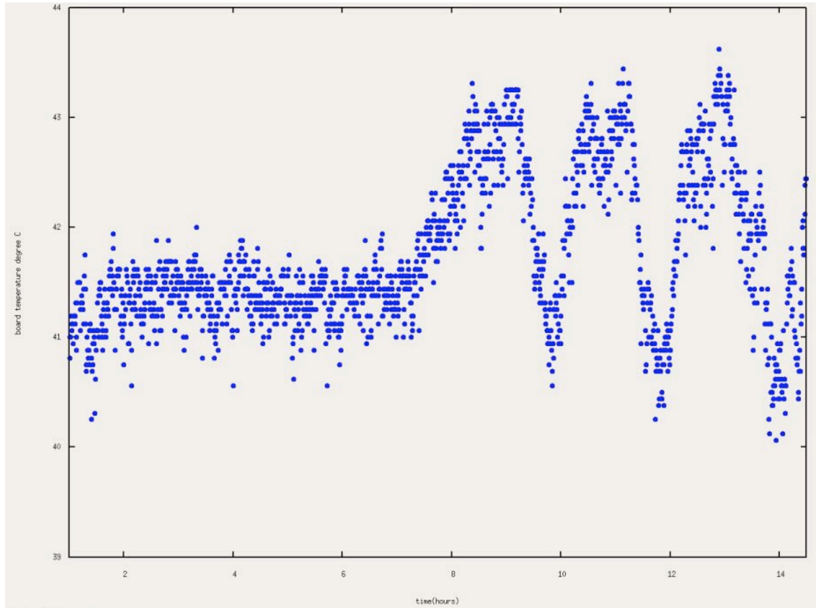




- **Peak in AM/PM curve provides "zero-slope" operating point**
  - **+/- 10% in power produces <10fs timing shift**
- **This operating point is a convenient power, provides high signal**

Differential measurements of RF detection system showed ~10fs uncertainty

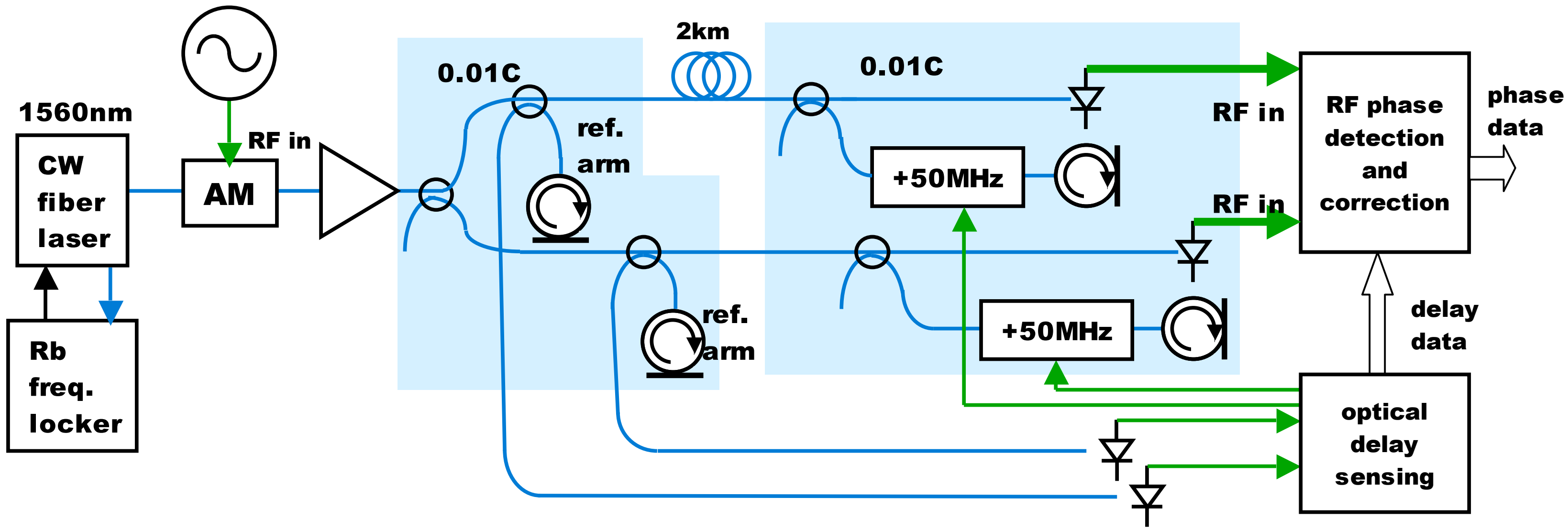




14-hour run.
Green, red are 2-channel differential phase of RF and calibration signal.
Blue is RF/cal phase difference (corrected RF phase). RMS error is ~10fs

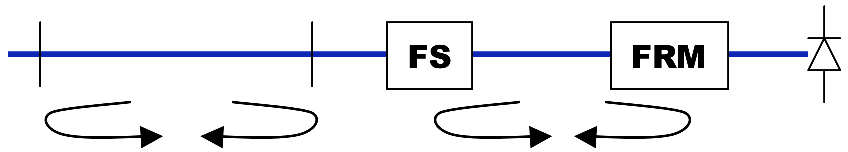
Temperature during run.
Peak-to-peak is ~2 degrees C.
Air conditioning was turned on halfway through run

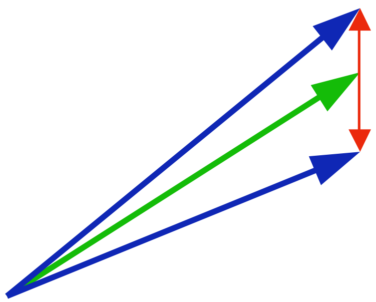
Our current experiment uses two LLRF boards to make a dual-channel receiver



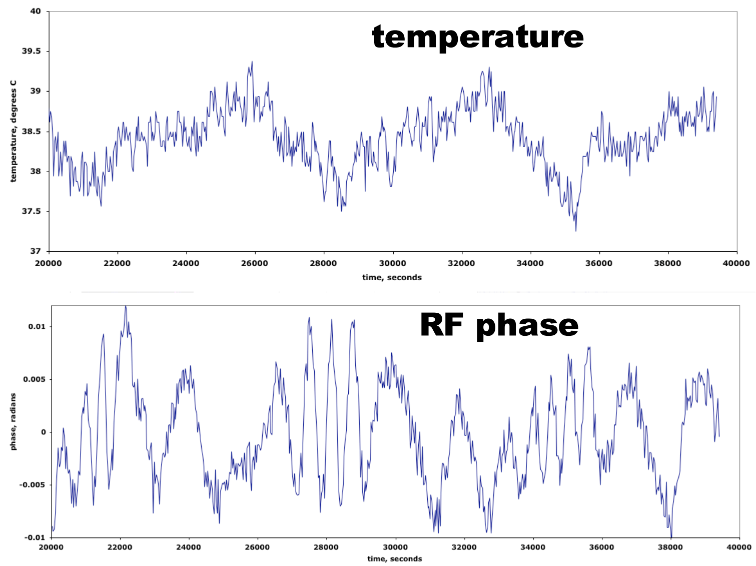
Optical reflections have to be carefully managed

- **Issue: small retroreflections add coherently with signal, add to RF phase**



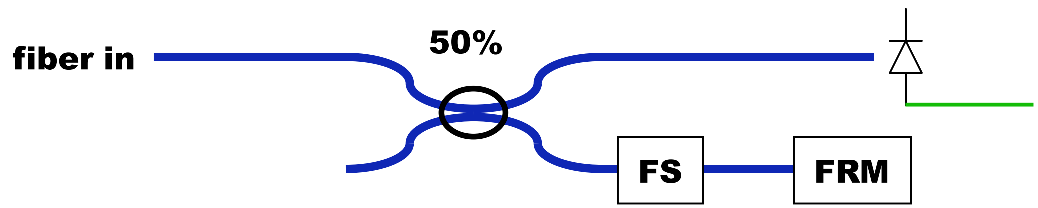


$$\tau_{error} = \frac{\sqrt{2R_p}}{\pi f_{sig}}$$

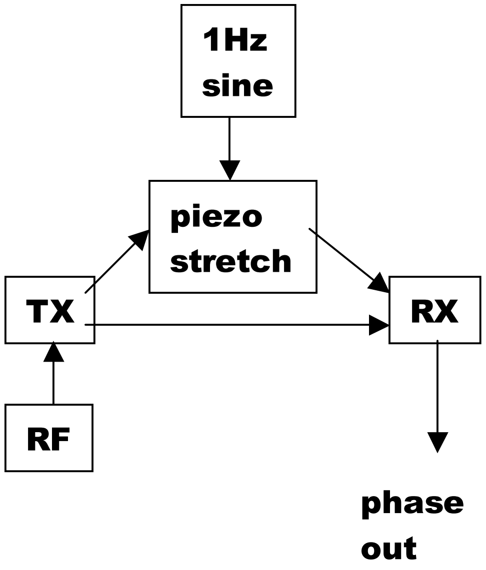


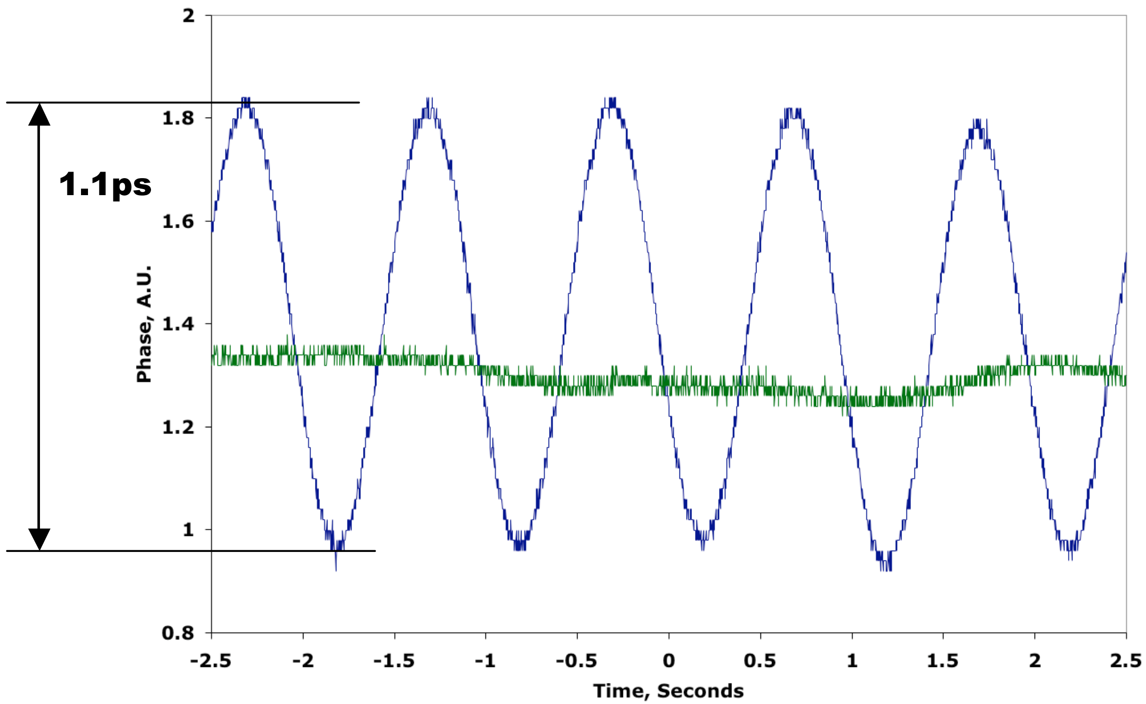
Example: 60dB back reflection produces ~150fs error.
Spec for major components is ~30dB (~4ps)

- **Solution: keep large reflections (including interferometer end mirror) out of signal path, and make sure others are >40db down**



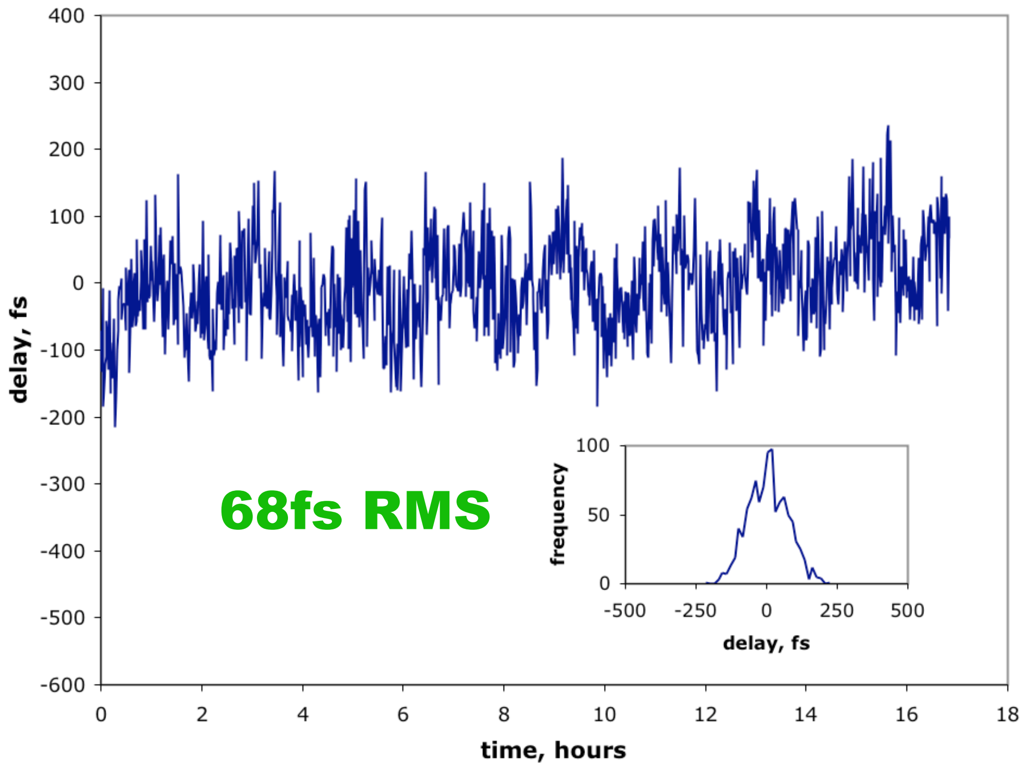
The feed-forward scheme eliminates short term length perturbations





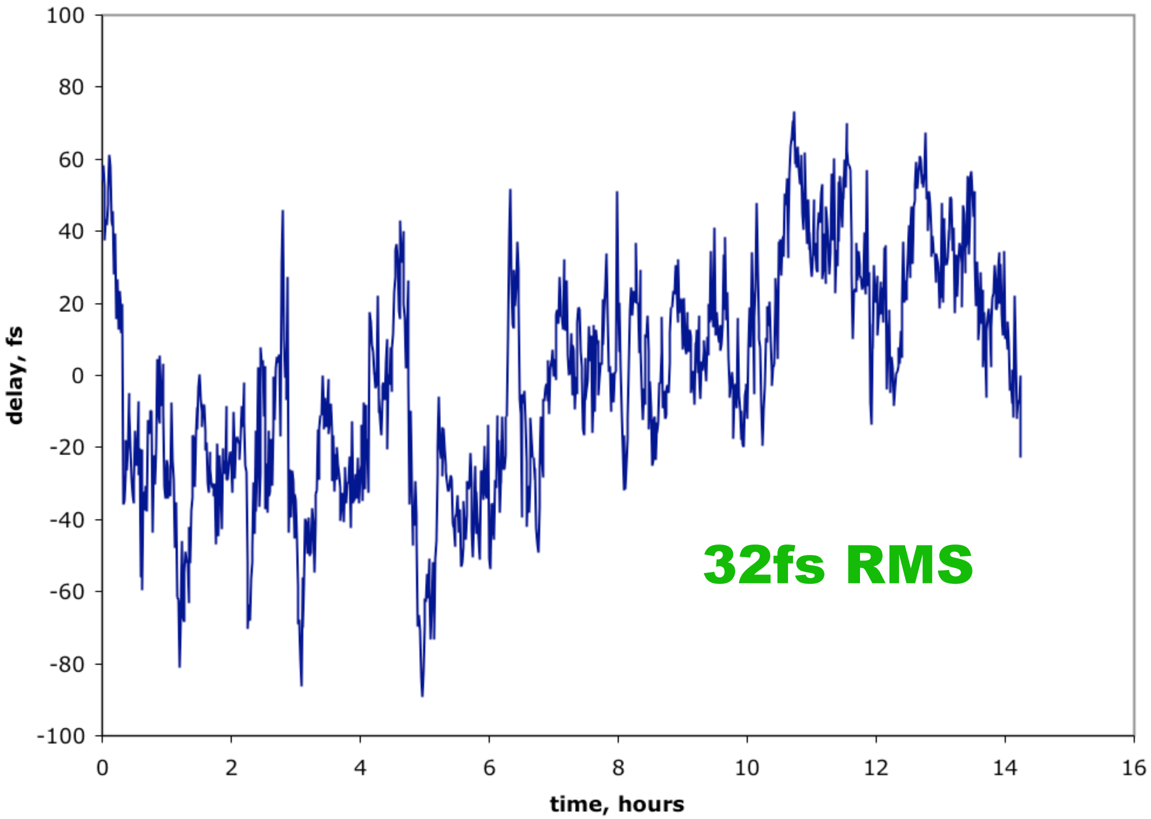
- We perturbed one fiber path with a ~1ps, 1Hz signal, and observed the relative phase between the two channels
- We could null the effect of this perturbation by adjusting one factor, with perturbations from other effects remaining
- This proves the "measure and feed forward" scheme

We observe sub-100fs long term error over 2km



- 68fs RMS delay error between two channels, one 2km the other 2m
- LAN fiber under test has large reflections at PC connectors, so the "fast" errors will be less if better connectors are used (as in LCLS gallery)

For 200m, error is 32fs RMS over 14h



- **200m of fiber with better connectors, less temperature swing (all in lab)**
- **This result indicates the performance of the near term LCLS and Fermi systems**

Upcoming developments

- Build a two channel synch system for operation at LCLS in July, to synch one laser with bunch arrival
- Build two more channels for November delivery to LCLS
- Build a three channel system for demonstration at Fermi in Q1 of 2010
  - Possible early operation using these channels
- Engineering to optimize cost and manufacturability
  - Deployment of ~20 channels at Fermi in late 2010
- Continue to improve performance
  - Software improvements
  - Mechanical engineering
  - Higher frequencies