

Laser Timing for Accelerators (Femtosecond Timing)

Josef Frisch

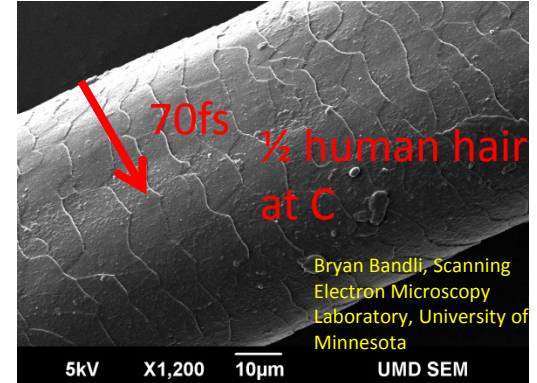
SLAC

Femtoseconds

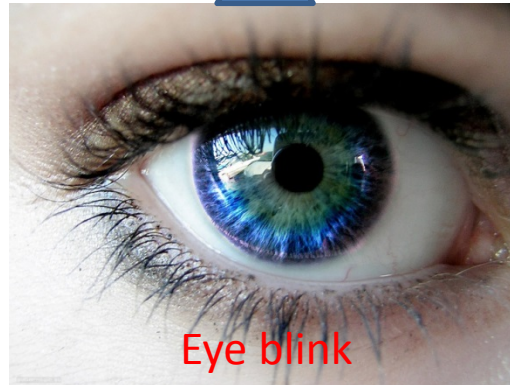


5000 Years

0.1 second

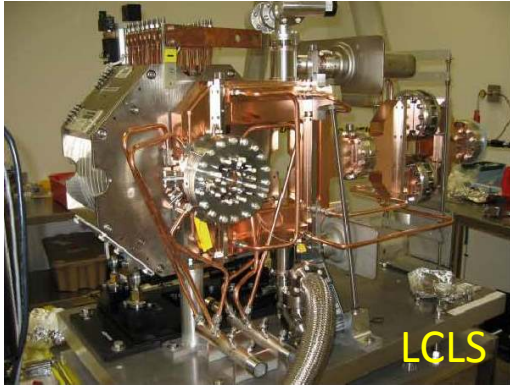


70 femtoseconds

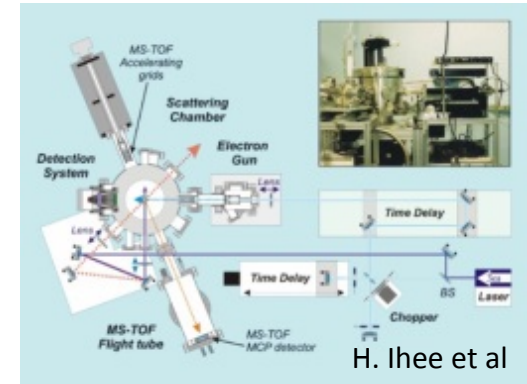


1 Meter of typical engineering material will change length by 30fs/°C

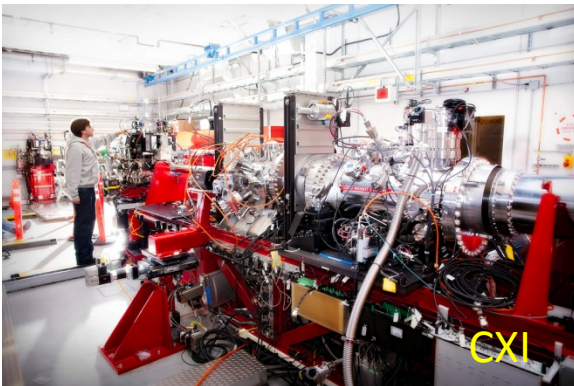
Applications of Accelerator / Laser Timing



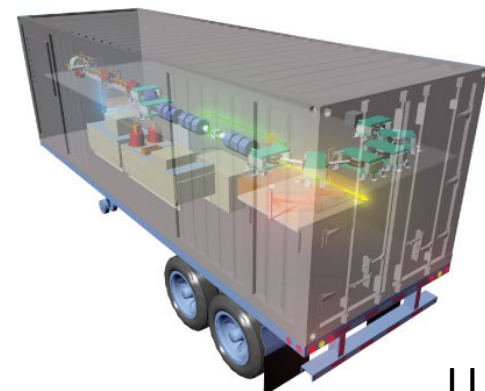
Drive laser for RF guns



Ultra-fast electron diffraction

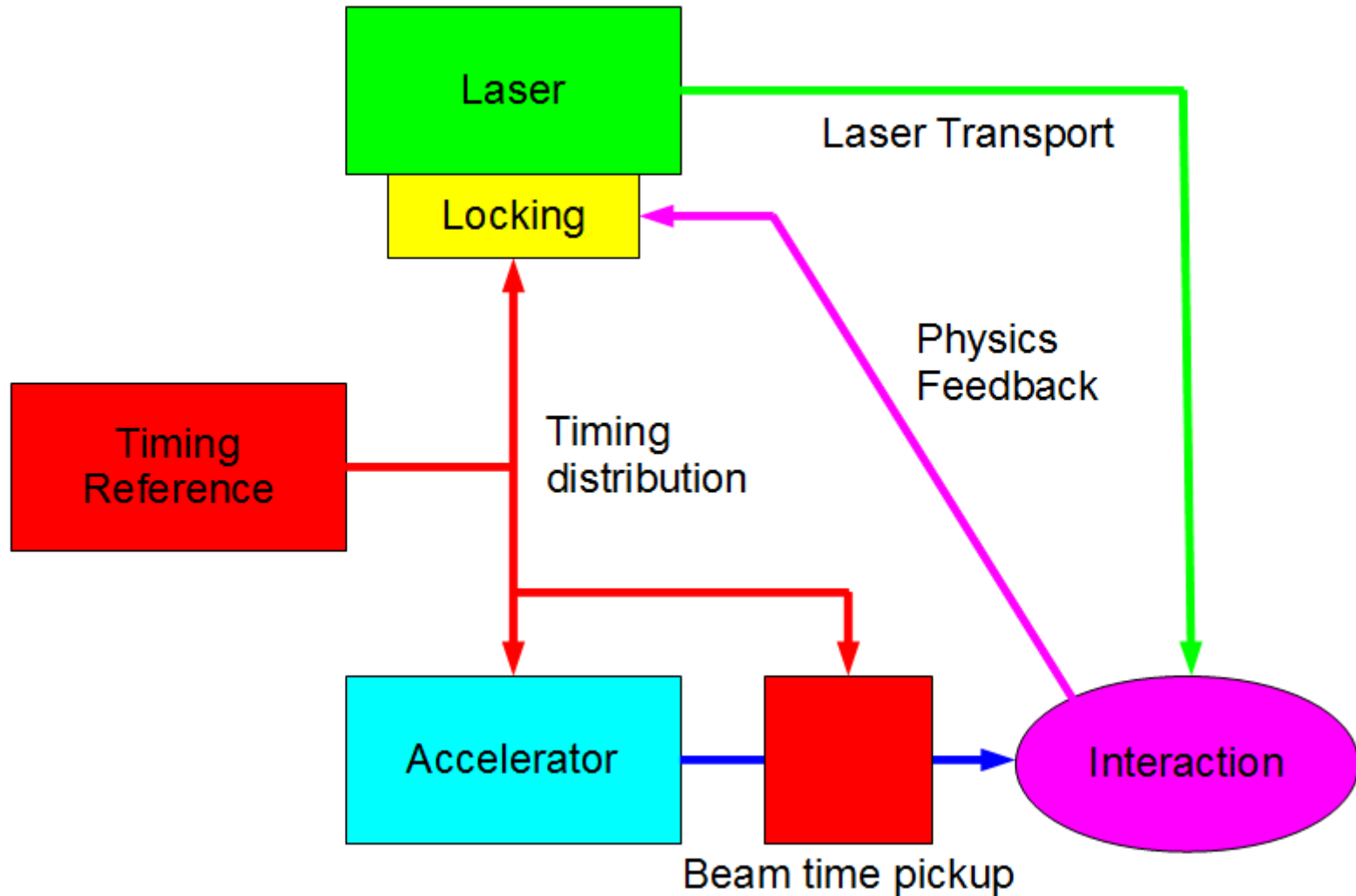


X-ray / laser pump
probe experiments



Compton backscatter sources

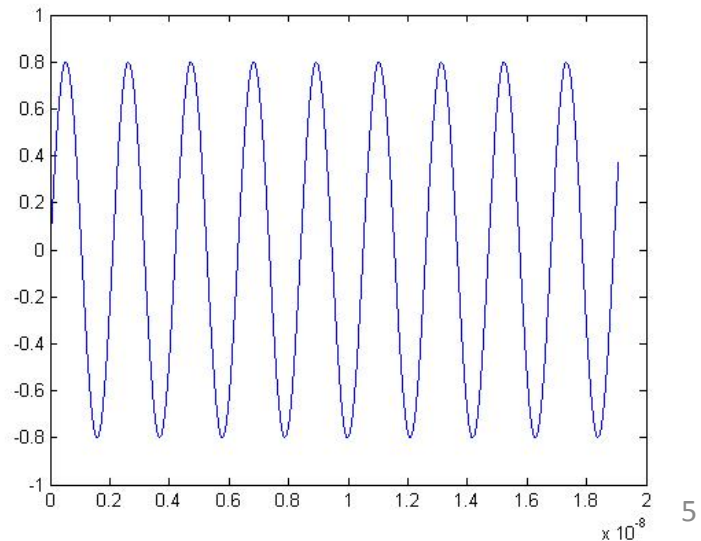
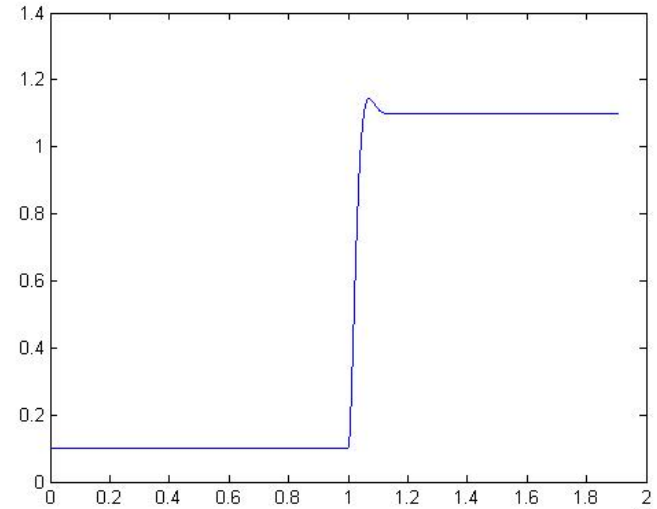
Subsystems



Measuring Femtoseconds - Narrow Band Clocks

Conventional electronic triggers only good to $\sim 1\text{ps}$.

Use repetitive clock to average timing measurements on millisecond timescales to allow X1000 improvement using GHz clocks



RF Systems

Terminology

dB is a log ratio of power: $\text{dB} = 10 \cdot \log_{10}(P1/P2)$

dBm is a power measurement – dB relative to a 1 milli-Watt source.

0dBm = 1mW, 20dBm = 100mW

Noise figure is the ratio (in dB) of the noise of the actual device to thermal noise. Typical well designed RF systems have noise figures of <10dB, individual components can have noise figures < 1dB.

Why Use RF?

Thermal noise (at room temperature) is -174dBm in a 1Hz bandwidth

So in a 1 KHz bandwidth, thermal noise is -144dBm or **4 Attowatts**

A 1 mW , 1KHz bandwidth, 10dB noise figure system would have a signal to noise of 134dBm, corresponding to an amplitude signal to noise of 2×10^{-7} . For a 1GHz system this is a timing noise of **30 attoseconds**

RF Mixers

Any non-linear combination of 2 signals will produce sum and difference frequencies:

$$A = \sin(w_1 t + \varphi), \quad B = \sin(w_2 t + \phi)$$

$$Y = C_1 A + C_2 B + C_3 A^2 + C_4 B^2 + C_5 AB + \dots$$

$$\sin(w_1 t + \varphi) \sin(w_2 t + \phi) = \frac{1}{2} [\sin((w_1 + w_2 + \varphi + \phi)t) + \sin((w_1 - w_2 + \varphi - \phi)t)]$$

- Contains frequency and phase difference.
- Useful way to translate phase from frequency to low frequency
- “Magnifies” time : 1° at 10GHz is converted to 1° at 10MHz expands time X1000

Low cost commercial units available

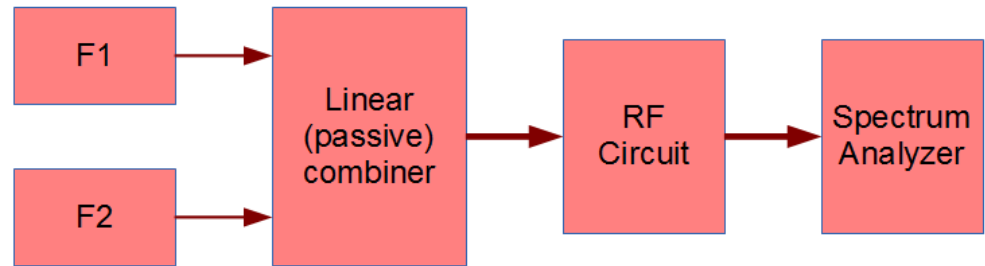
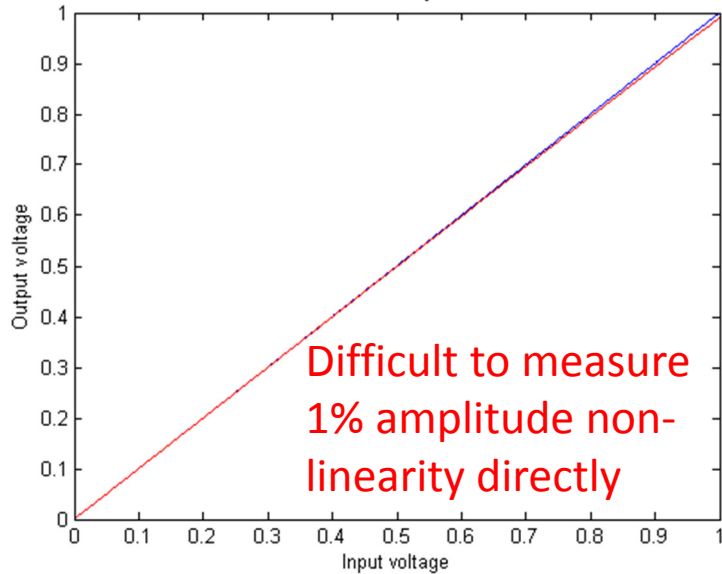


RF Linearity

- Amplitude to phase conversion is a major source of timing drift and noise
 - Typical phase detection frequencies are $\sim 2\text{GHz}$ ($\omega=10\text{GHz}$), so 100fs represents only 10^{-3} Radian
- Very difficult to measure AM- $\rightarrow$ PM due to the lack of a method to produce amplitude variation without associated phase variation.
- AM- $\rightarrow$ PM is a form of nonlinearity, so it is possible to make an estimate by measuring other nonlinear terms (amplitude nonlinearity).

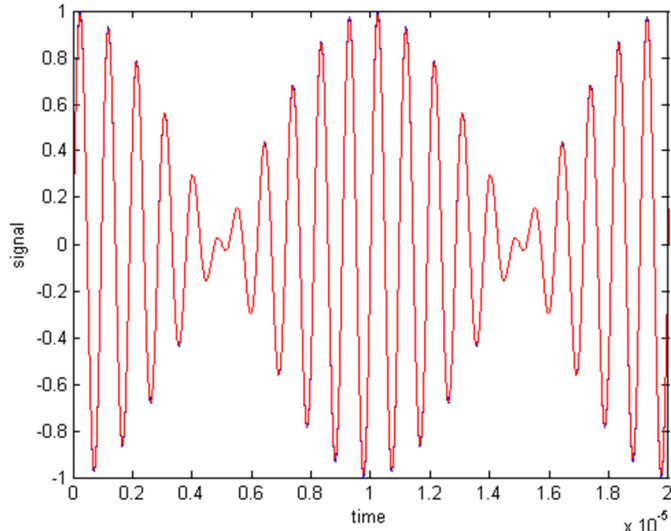
Measuring Nonlinearity: IP3

Nonlinear response 1%

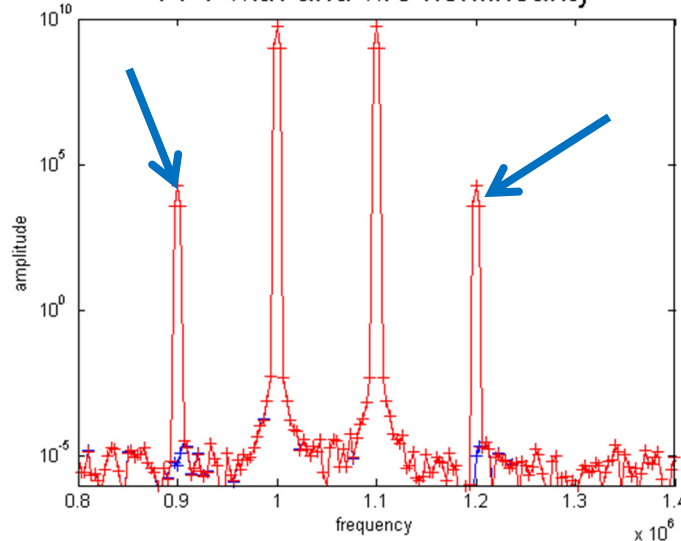


Instead, use the beating of 2 sources to generate amplitude modulation

Sum of sine waves with and w/o nonlinearity



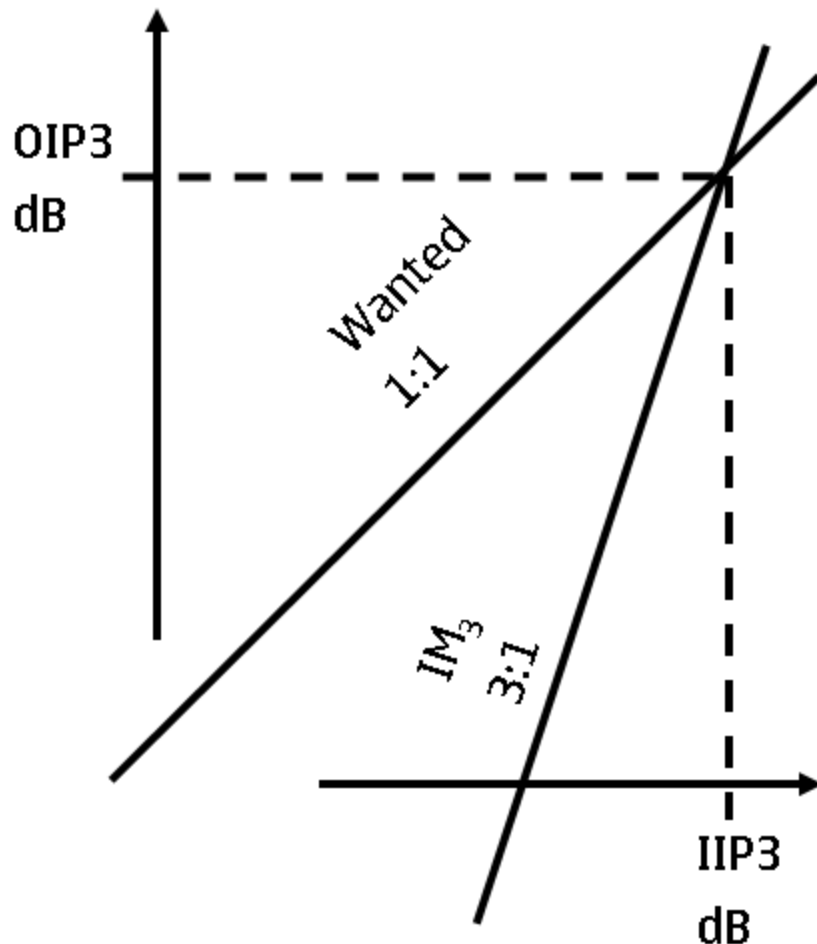
FFT with and w/o nonlinearity



Nonlinearity
visible in
spectrum

IP3 and Signal Levels

READ THIS!



Signal level is a trade-off between linearity and noise

Imagine an amplifier with:
14dB noise figure (-160dBm/Hz)
20dBm IP3
1MHz signal bandwidth

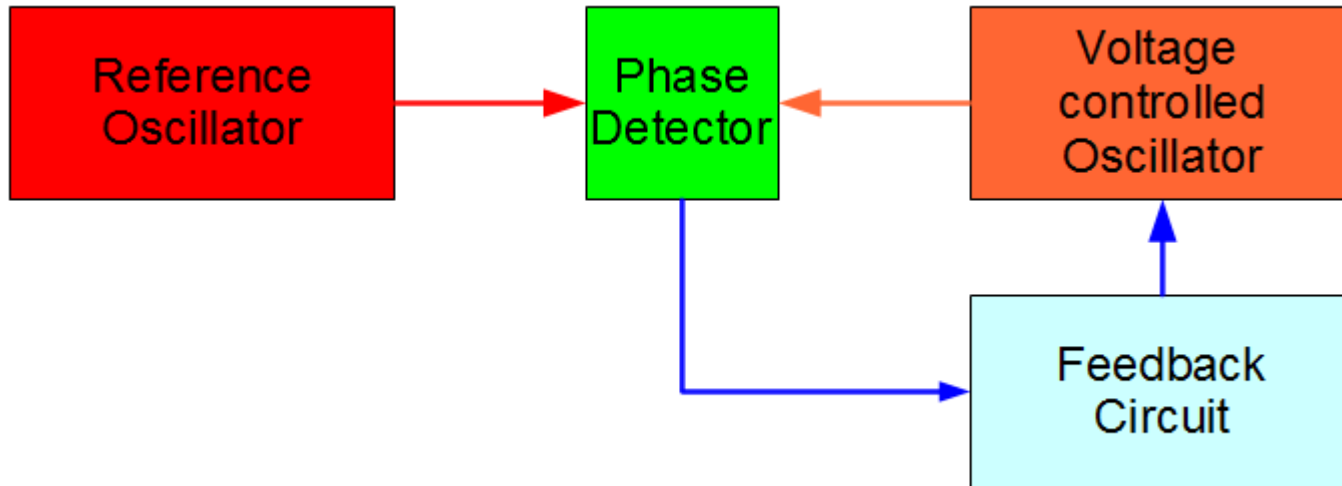
Noise level: -100dBm
Signal level of -20dBm:
80dB signal to noise
80dB nonlinearity to noise.

(If amplitude is stable, higher signal level might be better)

Input vs. output IP3 specification:
manufacturers use whatever
gives the higher number!

DO NOT USE MORE GAIN THAN YOU NEED!

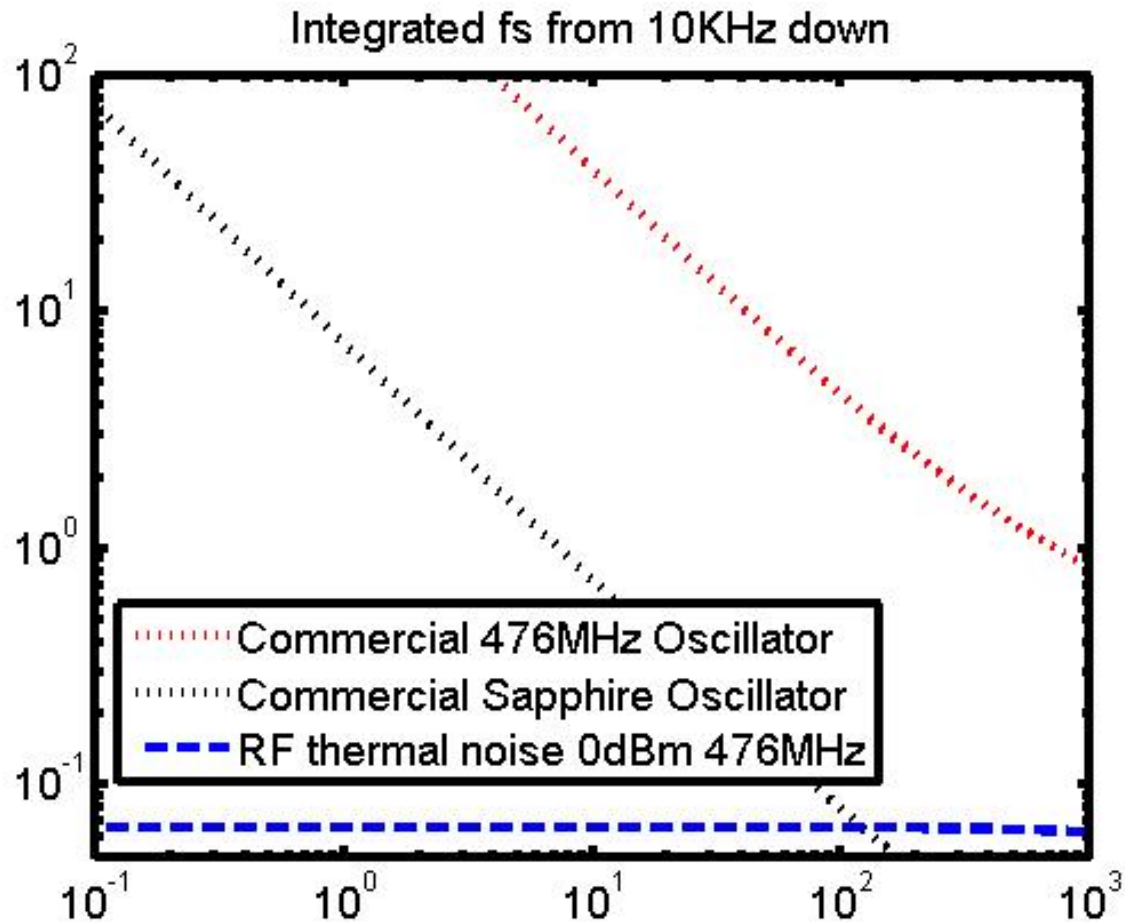
Phase Locked Loops



- Typically design the feedback for infinite gain at DC
- Gain reduced at higher frequency
- For long timescale the VCO follows the phase changes of the reference oscillator
- For short timescales the VCO is essentially free-running

VCO can be an electronic oscillator or a laser oscillator

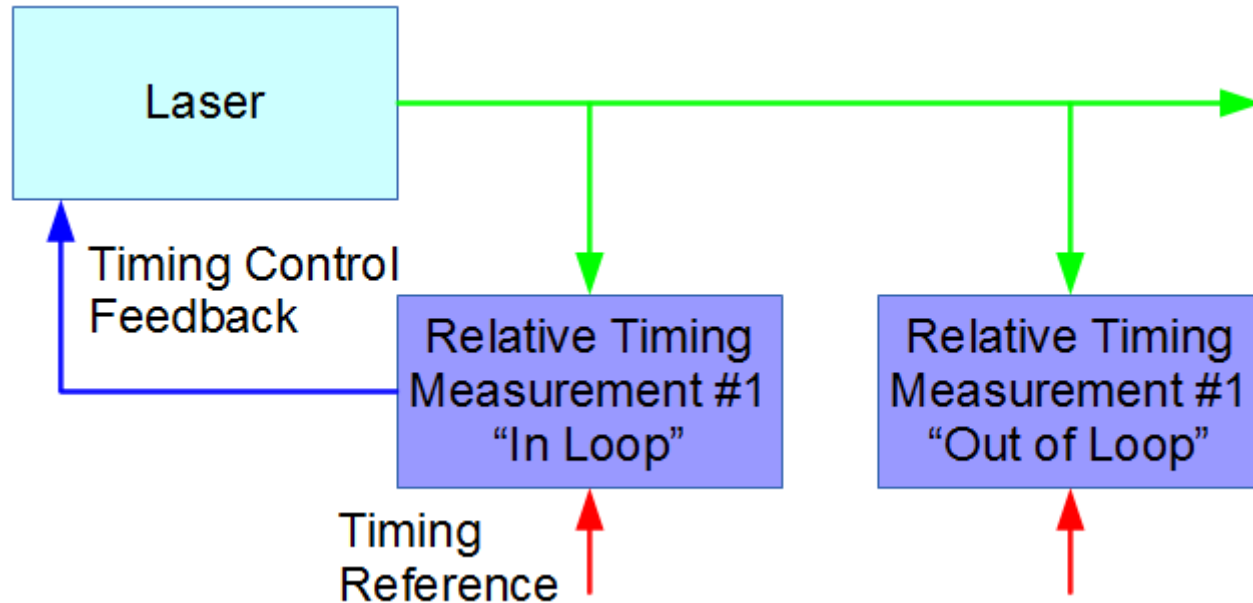
Oscillator Phase Noise



Good quality commercial oscillators can “remember” phase to 10s of femtoseconds at 10-100Hz (Wenzel, Pascal)

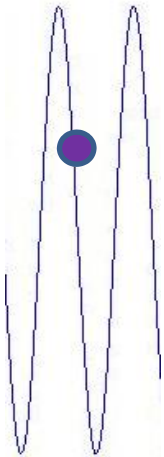
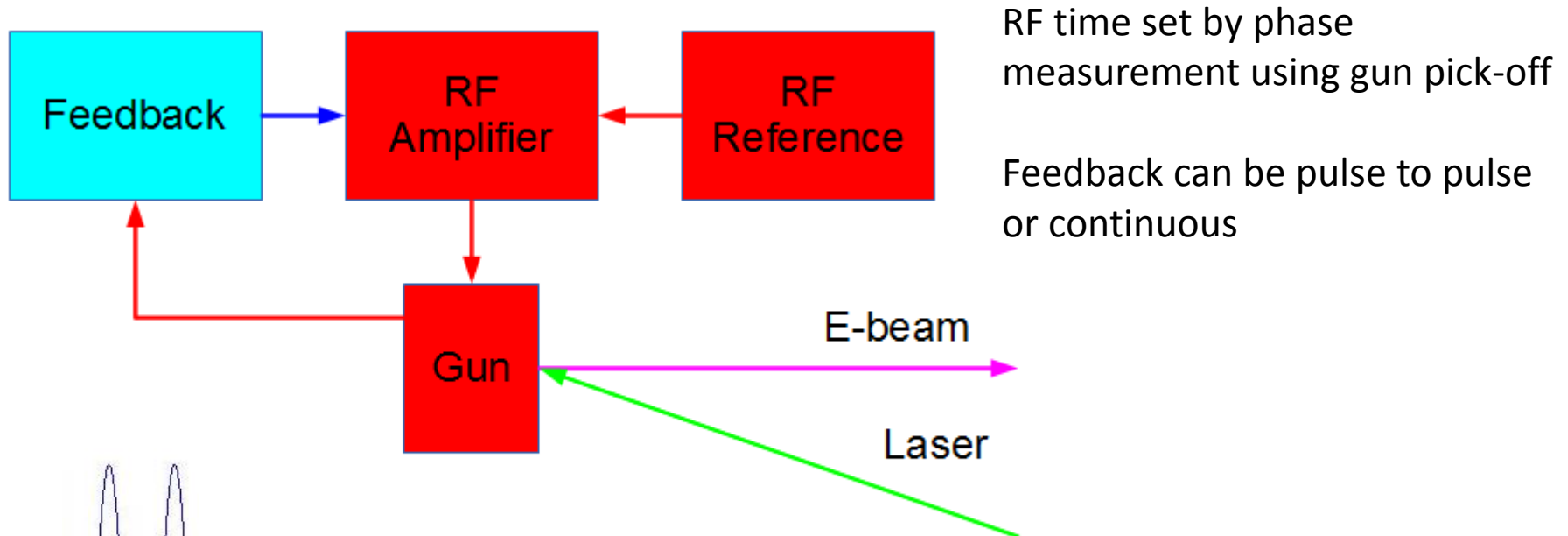
Very expensive Sapphire oscillators can “remember” 10s of femtoseconds at 1-10Hz. 12

In loop / Out-of-loop Measurements



- Feedback systems (typically) have infinite gain at DC, so the “in loop” detector cannot measure drift. Low frequency noise will also be attenuated by the loop gain
- Need an independent “out of loop” detector to know how well your system is actually working

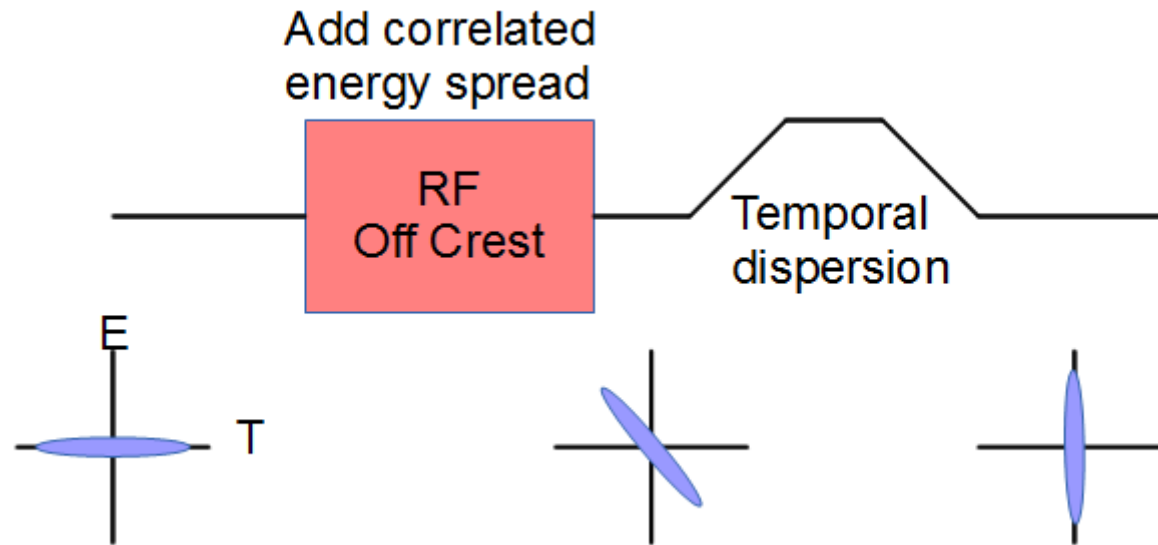
Accelerator Timing – RF Gun



- Photo-emission typically off crest
- Energy spread produces compression
- For LCLS gun, beam time is equally controlled by laser and RF timing

Beam time is not completely determined by laser time

Electron Beam Compression

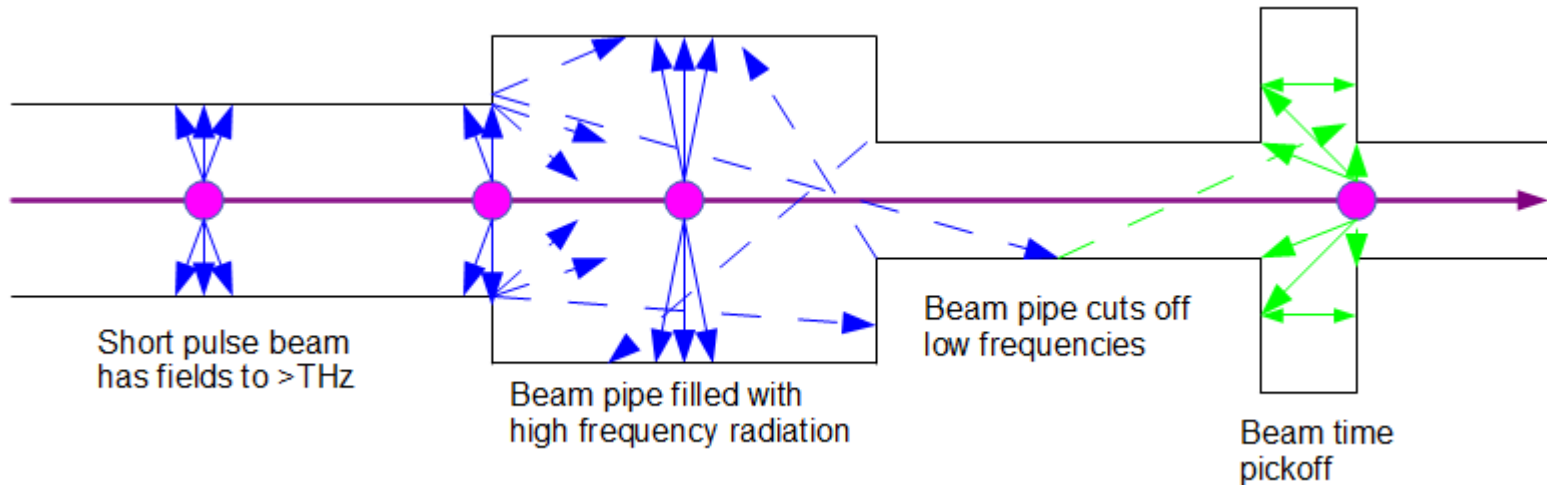


- Changes in input beam time are compressed to smaller changes in output time
- RF phase changes directly change output beam time.
- Input energy changes will change output time
- Beam is (typically) ultra-relativistic, so it is possible to measure the orbit in the compression chicane to determine the output beam time.

Beam Arrival Time Monitors

- Rely on electromagnetic fields from beam
 - Generally THz bandwidths
- RF systems use GHz fields induced in cavities or other pickups
- Optical systems use beam fields to drive electro-optical modulators of fiber-coupled picosecond pulses
- Mechanics: 10fs stability implies 3 micron mechanical stability of pickoff!

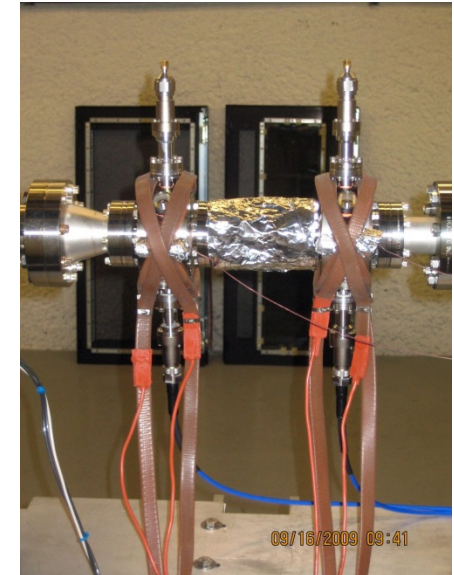
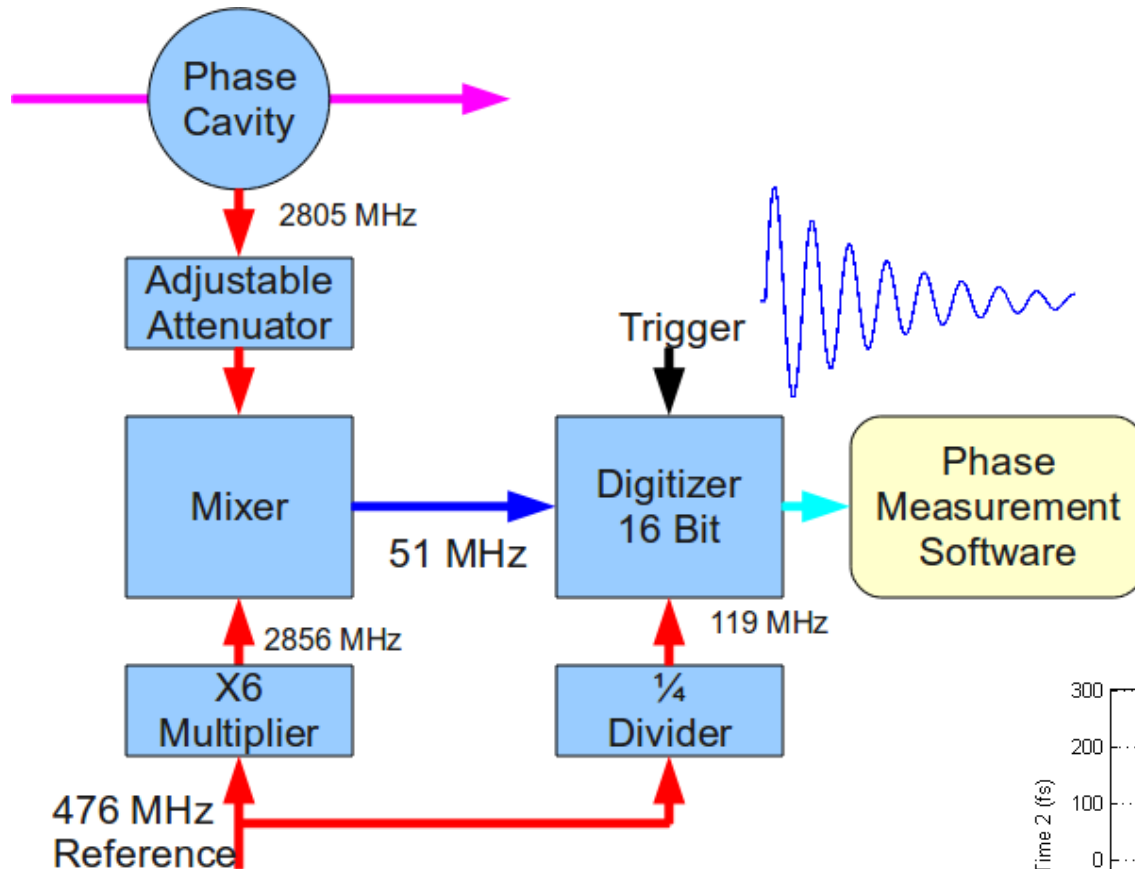
RF Beam Fields



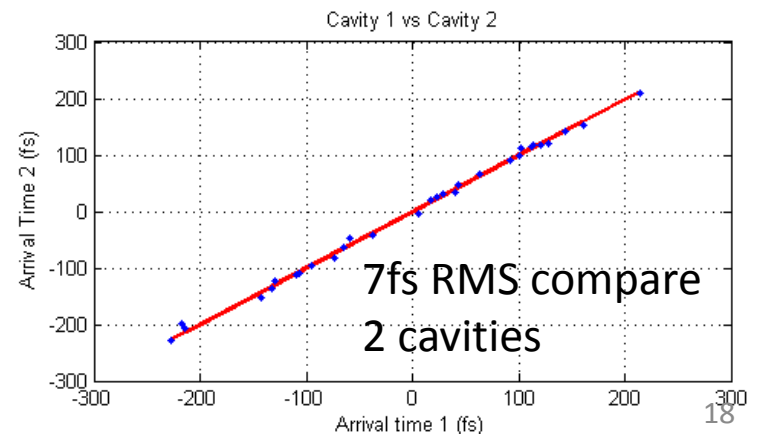
- Accelerator beam-pipes are filled with electromagnetic radiation from upstream discontinuities.
- If the beam time pickoff is operated below the beam-pipe cutoff, upstream signals will not interfere with the measurement
- Operation above beam-pipe cutoff may be possible IF the detection system is broad-band and can detect local beam fields before the fields from upstream arrive. **Extreme care must be taken with high frequency measurements.**

RF Beam Time Measurement

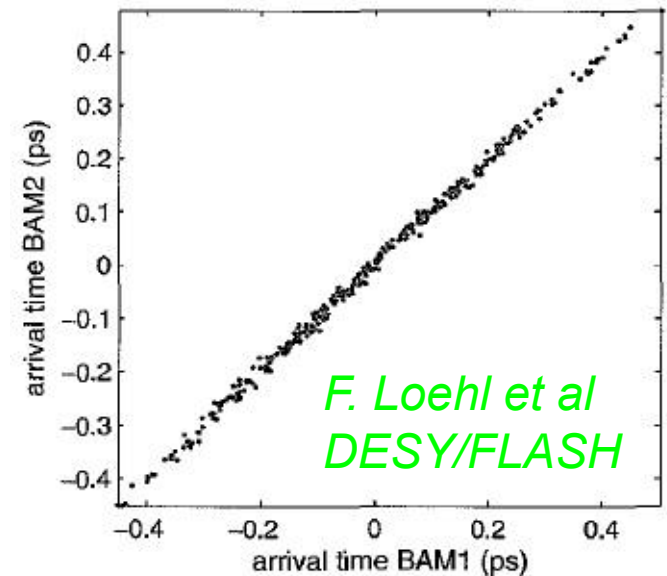
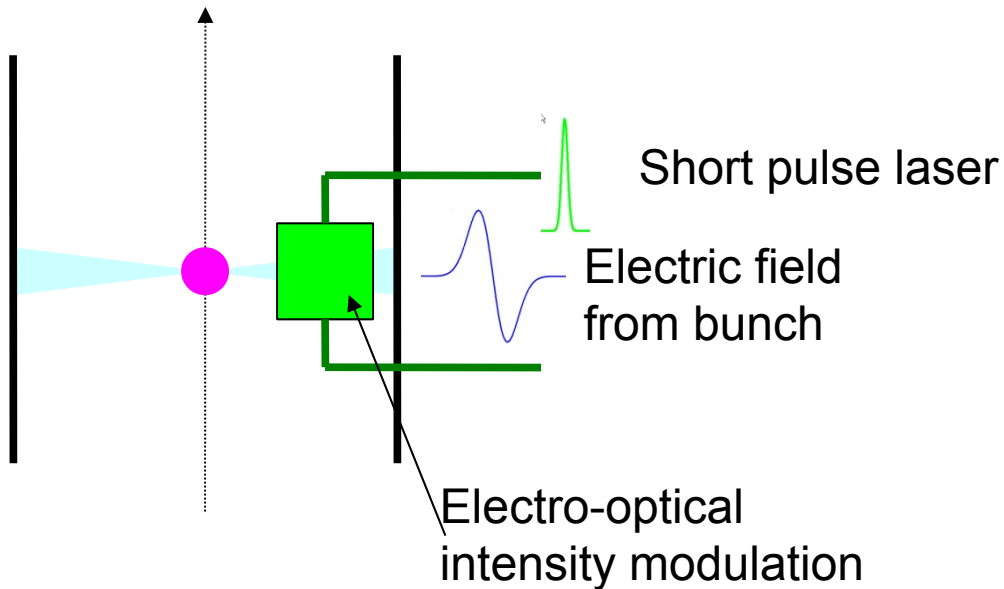
Phase Cavity



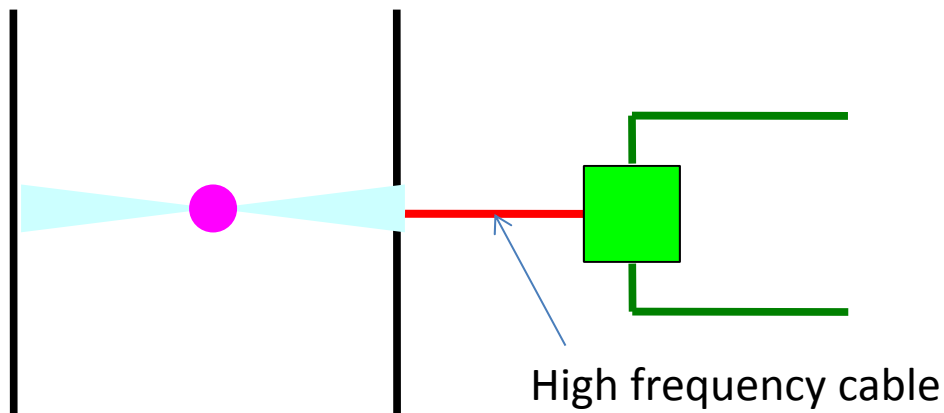
Algorithm must correct for phase shifts from temperature changes



Electro-optical beam time monitor



6 femtosecond timing noise
published (Believe ~3 fs achieved)



Use of RF pickoff simplifies mechanical
design, but care is needed to avoid
picking up signals from upstream.

Timing Transmission

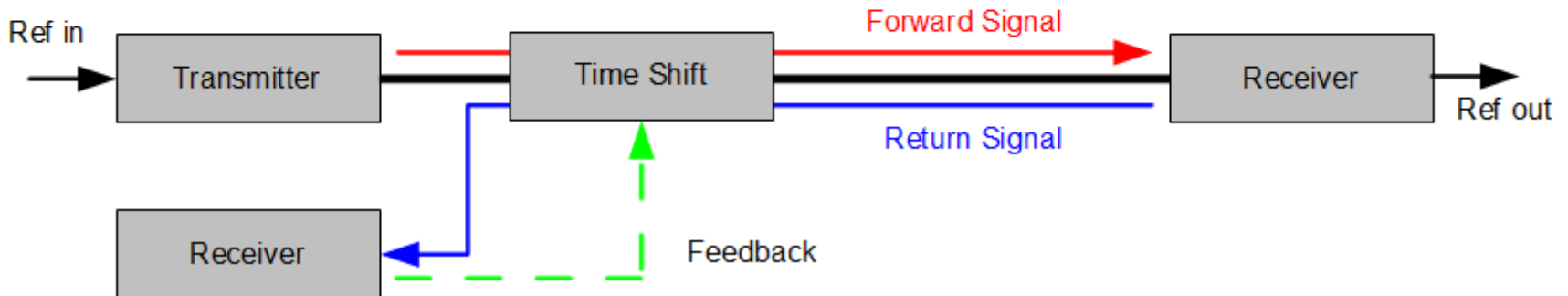
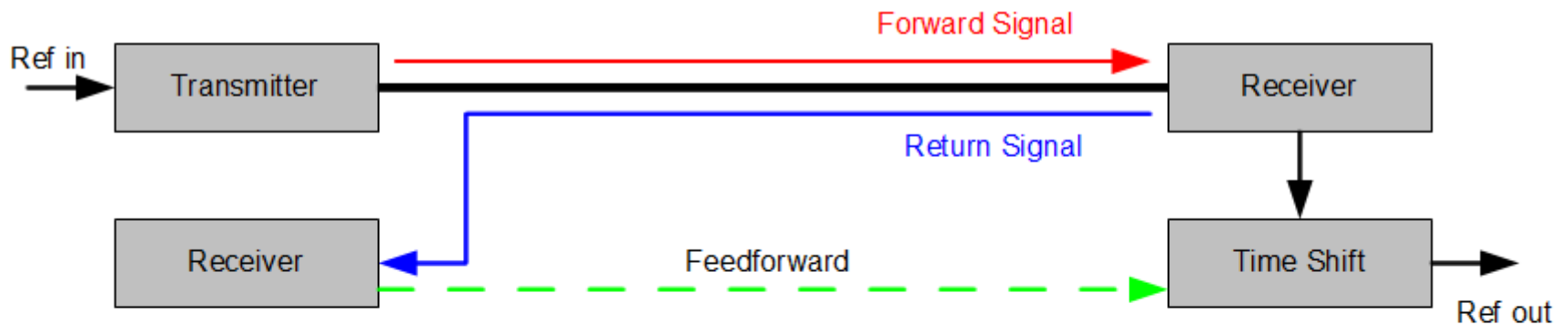
- Need to transmit timing $\sim 100\text{M}$ with $\sim 100\text{fs}$ stability $\sim 10^{-7}$.
- Temperature coefficient of delay of RF coax and optical fibers both $\sim 10^{-5}/^{\circ}\text{C}$
 - Fused silica thermal expansion is very low but the index of refraction has a significant temperature coefficient.
- Humidity effects can be as large as temperature effects.
- Lower thermal coefficient specialty cables and fibers exist, but usually not good enough to avoid the requirement for feedback
- Work done at many labs around the world
 - This is a favorite topic of timing research – probably because it doesn't require a giant accelerator facility.
- Will only give a very brief overview here!
- State of the art: 10s of femtoseconds stability (better in R&D programs, worse in installed systems)

World's Best Timing System



**LIGO: $<10^{-28}$ seconds noise over 4km!
Spectacular achievement!
Useless for laser / accelerator timing!**

Timing Transport



Feedforward requires a very accurate measurement of timing shifts

Feedback only requires a stable measurement, but requires a bi-directional timing shift

Fiber vs. Coax

Coax

- Limited bandwidth – GHz over 100M.
- Thermal noise - $\sim 1/40\text{eV}$
- Bulky, expensive - $>1''$ sizes often needed
- Simple, Rugged, Common diagnostics

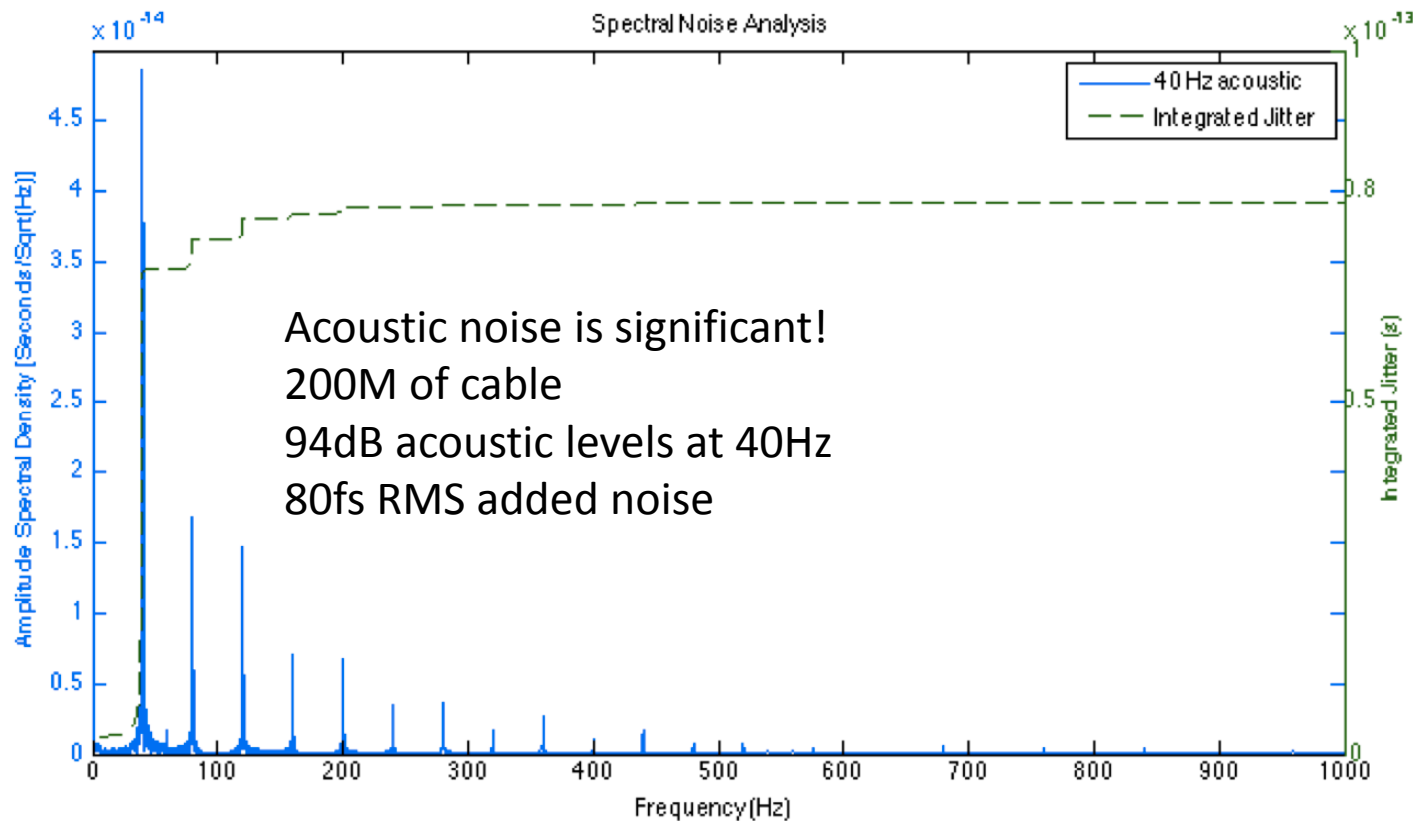
Fiber

- High Bandwidth – $>\text{THz}$ with dispersion compensation
- Photon noise $\sim 1\text{eV}$
- Commercial SMF-28 inexpensive, compact
- Delicate, needs special instrumentation

Both used successfully for accelerator timing systems.
Choice will depend on the design of the rest of the system

Sources of Noise - Coax

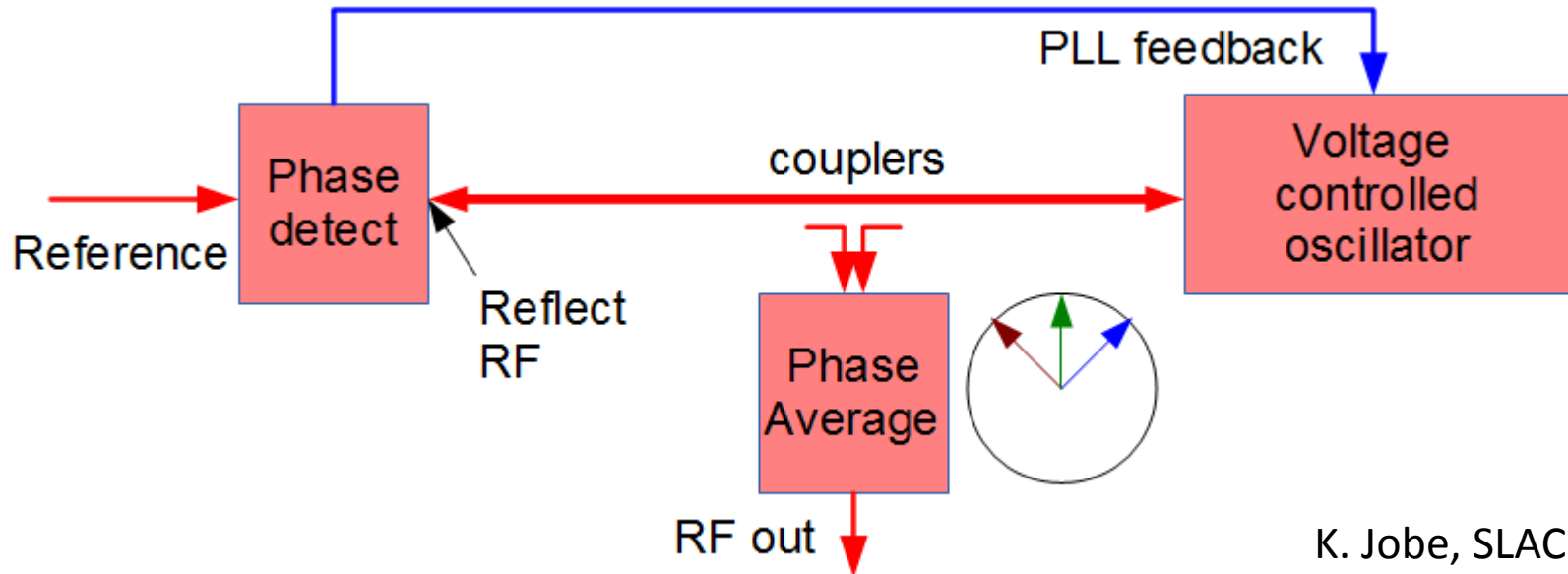
- RF (thermal noise), Real systems have $\sim 10\text{dB}$ noise figure
- Generally not a limit with normal power levels and bandwidths



Sources of Noise – Fibers

- Photon shot noise and detector noise (at low optical powers)
- Laser wavelength variations -> dispersion -> timing variations
 - Usually this is bidirectional
 - Can be used to advantage as a fiber delay control with a tunable laser.
- Amplitude variations -> nonlinearity -> wavelength variations (at high optical powers)
 - May not be bidirectional
- Polarization mode dispersion in conventional fiber
 - Not bidirectional
 - Can be fixed with PM fiber, but very expensive and specialized hardware.
- May be sensitive to acoustic noise

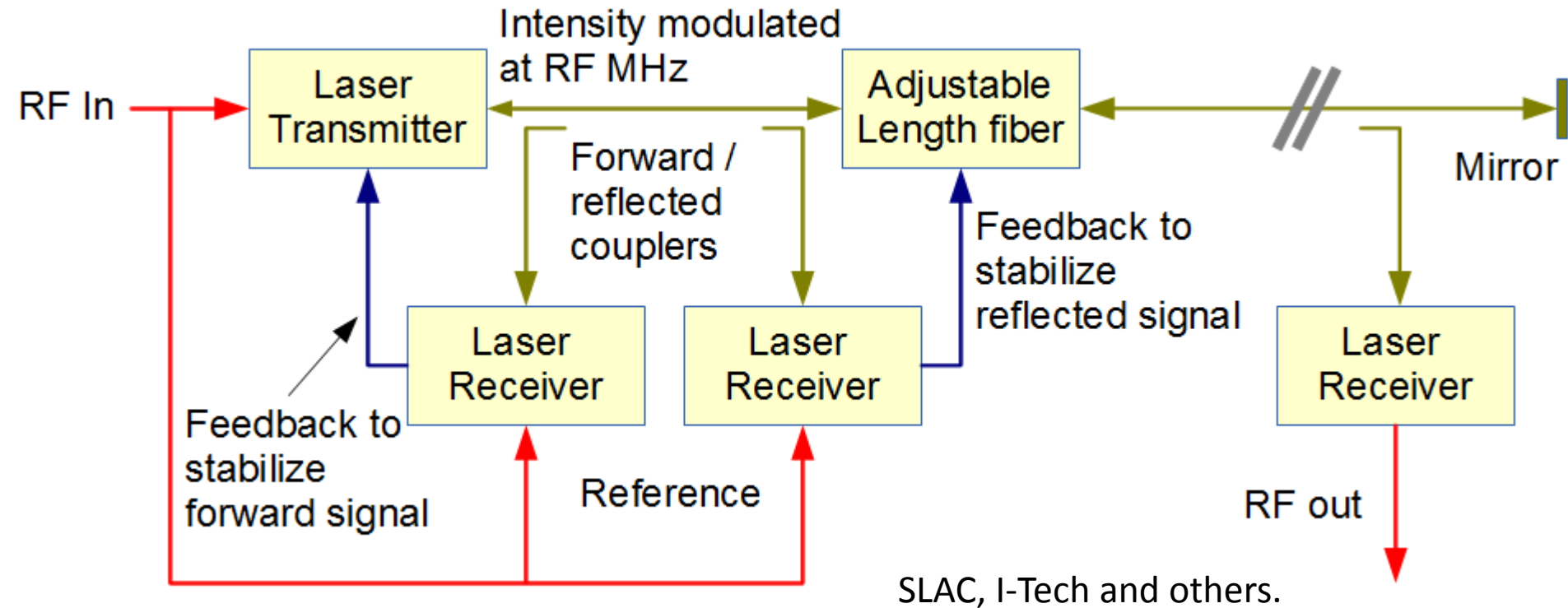
RF Feed-Forward Link



K. Jobe, SLAC

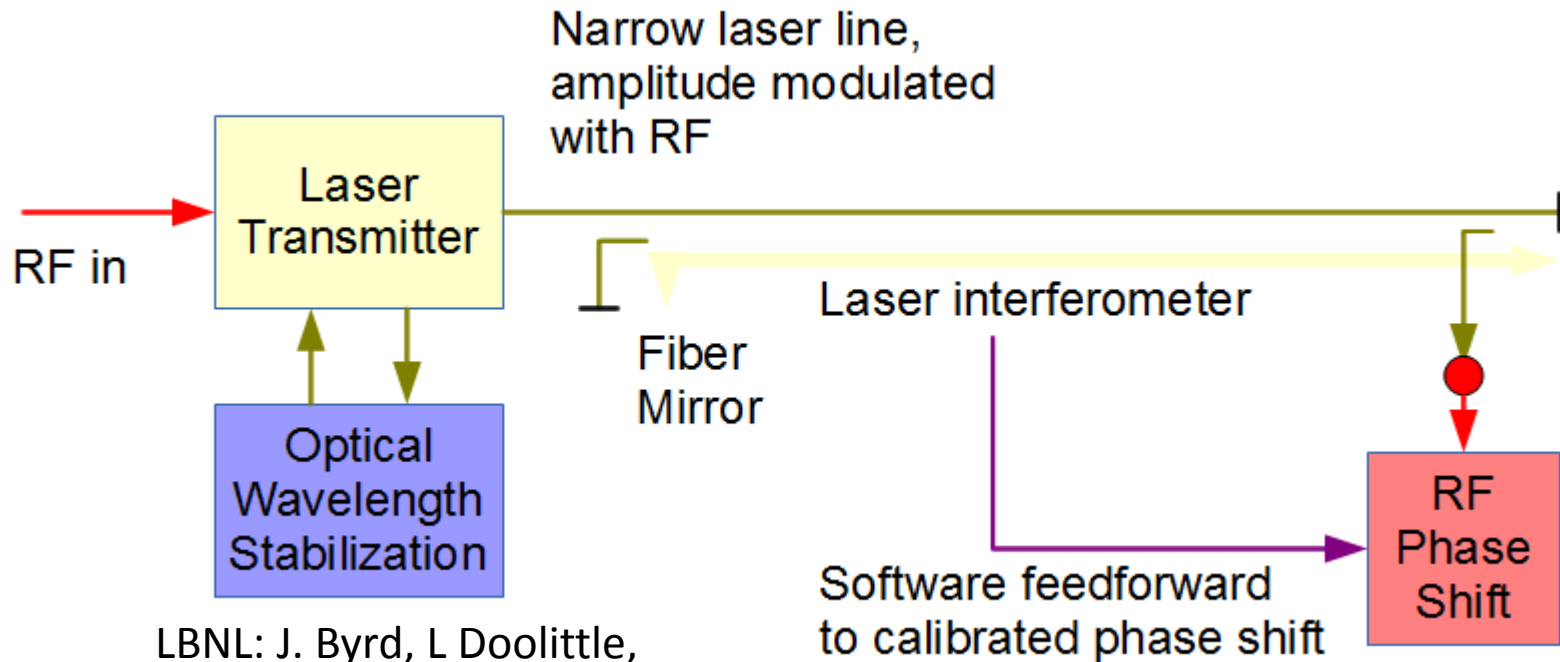
- Average phase is first order independent of cable length
- Multi-drop capability
- Very simple / rugged.
- Feed forward, not feed back: in practice only see X10-X20 improvement
- Reflections limit performance even in an “ideal” system

CW RF over fiber feedback



- Fiber length feedback options:
 - Piezo stretcher: fast, limited range, causes polarization shifts
 - Fiber oven (Kilometer fiber with temperature control): long range, slow
 - Wavelength tuning (use fiber dispersion)

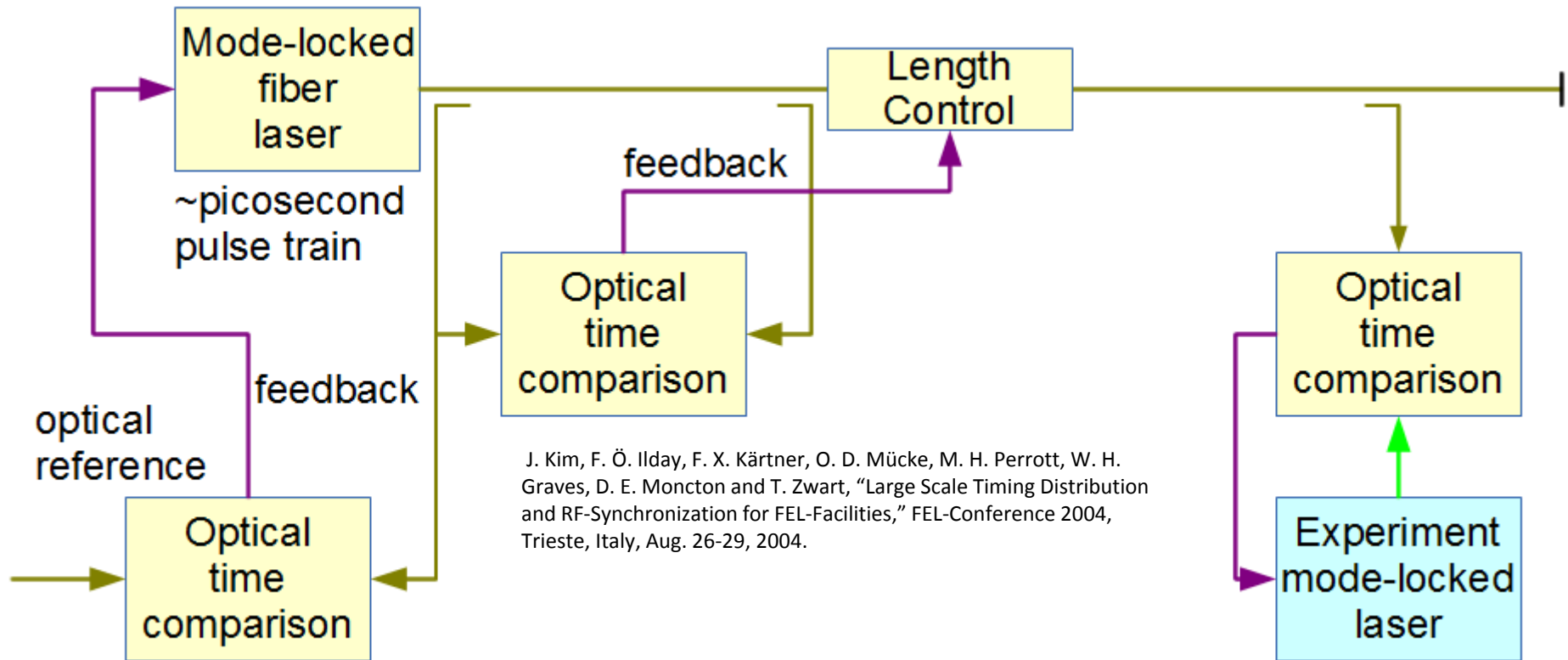
Interferometer Fiber / RF



LBNL: J. Byrd, L Doolittle,
G. Huang, R. Wilcox,

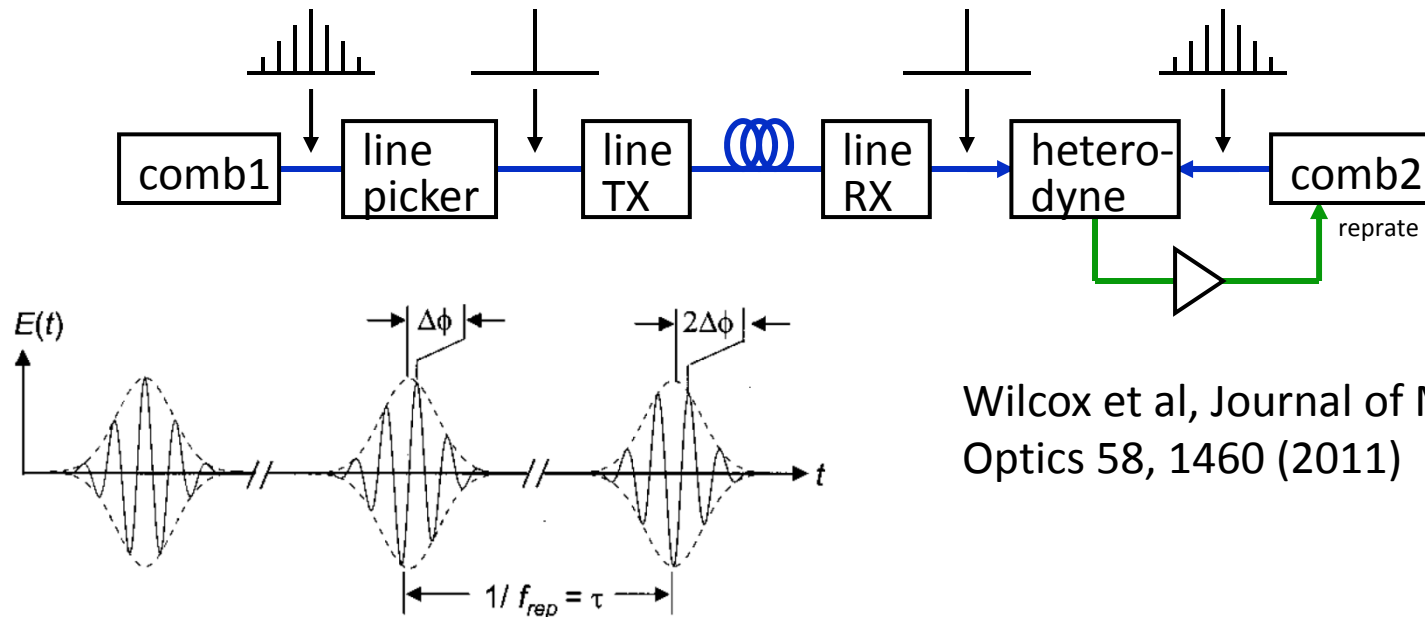
- Use an (optical) frequency stabilized laser to drive an fiber optical interferometer which measures the transmission fiber length
- Laser is modulated with RF and detected by a photodiode at the far end of the fiber
- A calibrated (digital) RF phase shifter corrects the RF phase based on the interferometer measurement

Pulsed Fiber System



- Timing is carried by picosecond optical pulses
- Timing comparison by optical techniques (nonlinear interaction of pulses)
- Work by many groups: MIT, DESY, IdestaQE, etc.

Direct Optical Phase Transmission



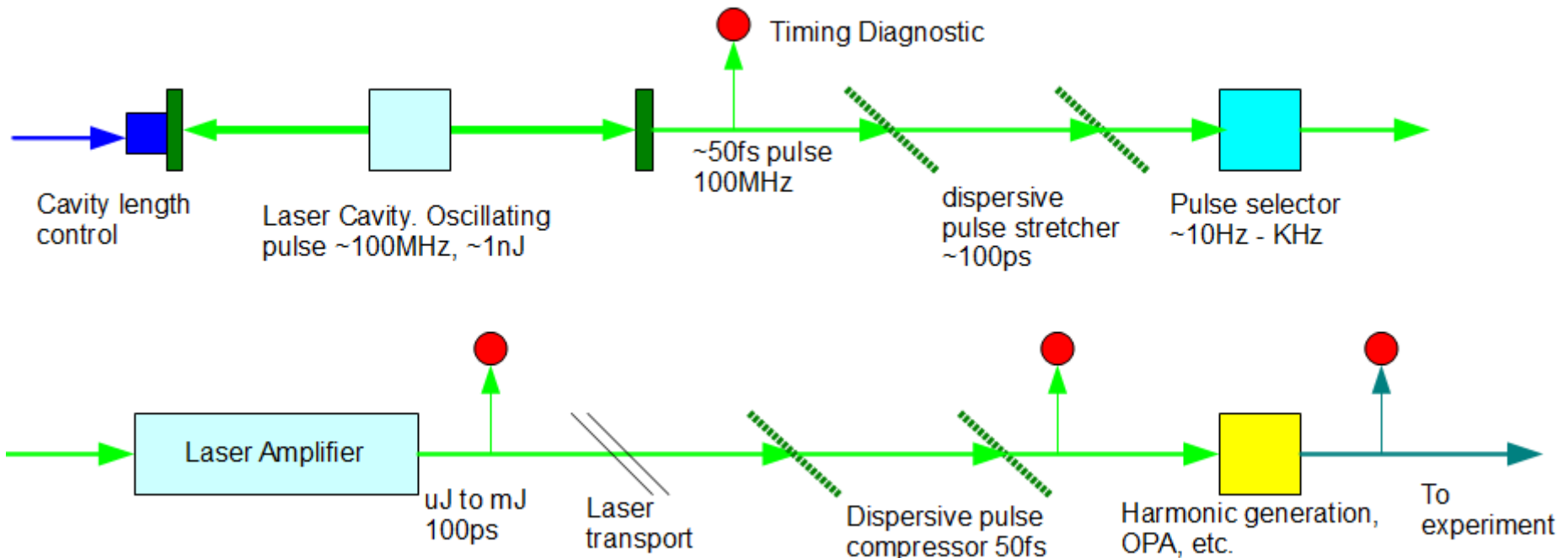
Wilcox et al, Journal of Modern Optics 58, 1460 (2011)

- Timing carried by the OPTICAL phase – 300THz carrier!
- Single cycle is 3fs, so easy to imagine $\ll 1$ fs timing
- Newer design does not require carrier / envelope locked lasers (simplifies laser system).
- Still a very complex system, not yet fully demonstrated in the lab.

Laser Locking Systems

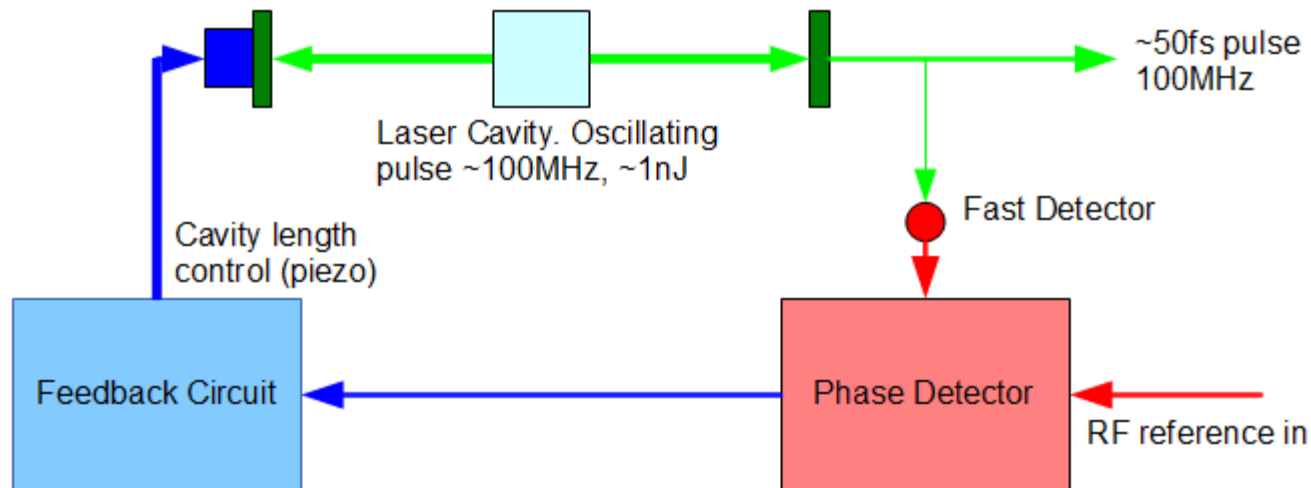
- Most rely on locking the $\sim 100\text{MHz}$ mode-locked laser oscillator to a reference signal
- Commercial laser $\rightarrow$ RF locking systems available at the $\sim 100\text{s fs}$ noise level
 - Can do better with custom systems
- Ti:Sapphire lasers are the most commonly used, but fiber lasers are gaining popularity.
- Significant variation in the unlocked noise of different laser oscillators – directly impacts locked performance

Laser Systems



- Mode locked laser frequency -> phase determined by optical cavity length
- Optical cavity length usually controlled with piezo-electric mirror
- Pulses are stretched before amplification to avoid peak power damage

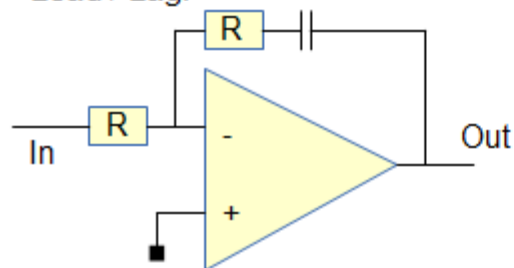
Laser Locking



Typical Designs:

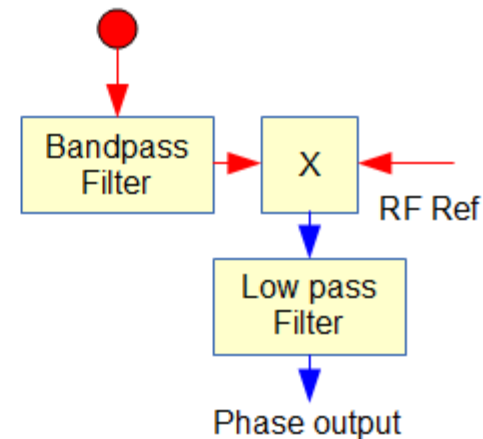
PID: $A \cdot X + B \cdot \text{integral}(X) + C \cdot \frac{dX}{dt}$
Or

Lead / Lag:



Both provide infinite gain at DC, roll off to make loop stable

Laser acts as a harmonic PLL loop: it already has one integration term



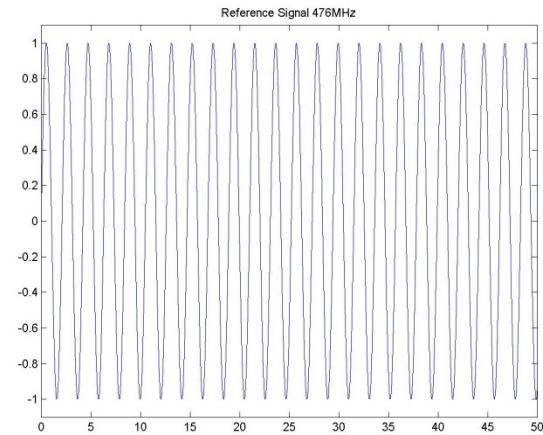
Phase detector circuit using a mixer

Output is linear in phase near zero

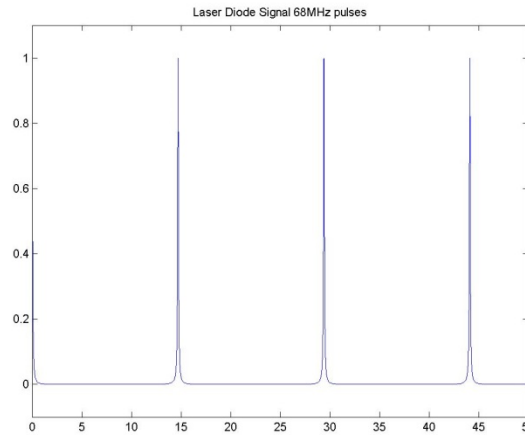
Phase Detection

- Generally the most challenging part of the laser locking system
- Laser diodes produce short ($\sim 100\text{ps}$) pulses at fairly low rate ($\sim 100\text{MHz}$)
 - Use bandpass filters to ring the signal into a near continuous RF tone
- Use a mixer to compare the phase with the reference system

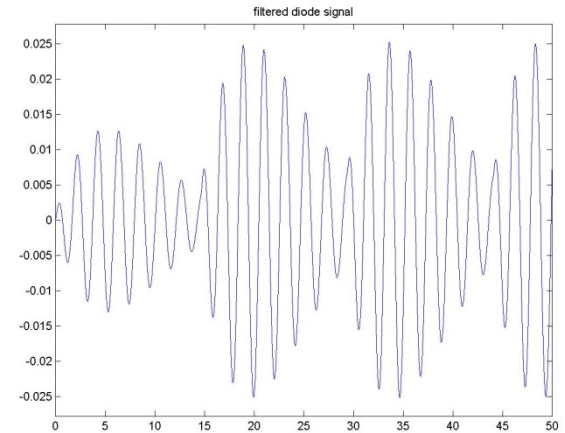
Photodiode Phase Detection Signals



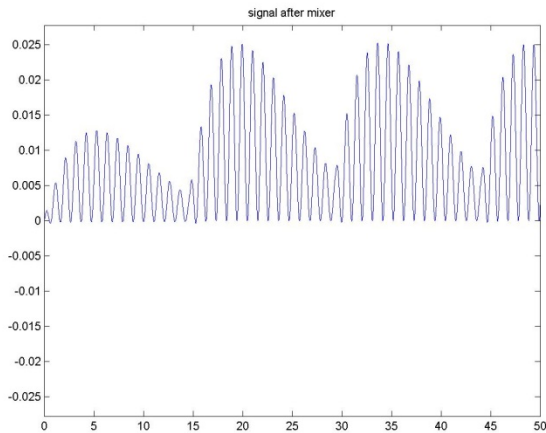
Reference



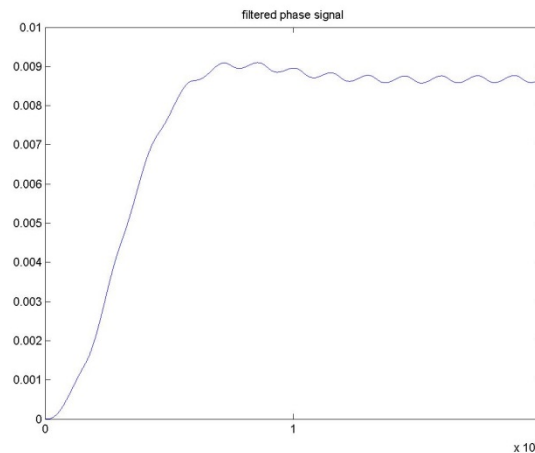
Laser diode out



Filtered laser diode



Mixer output



LP filter output

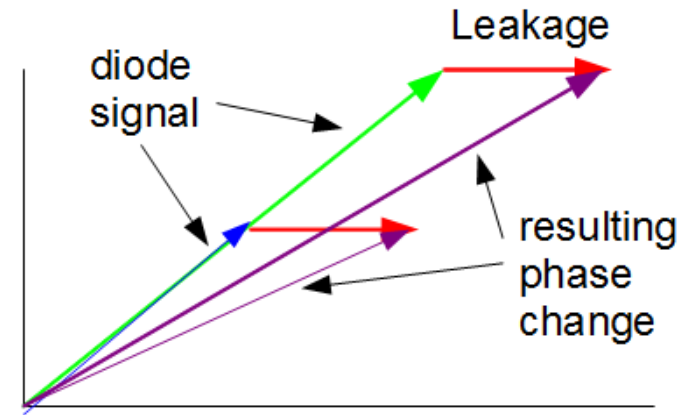
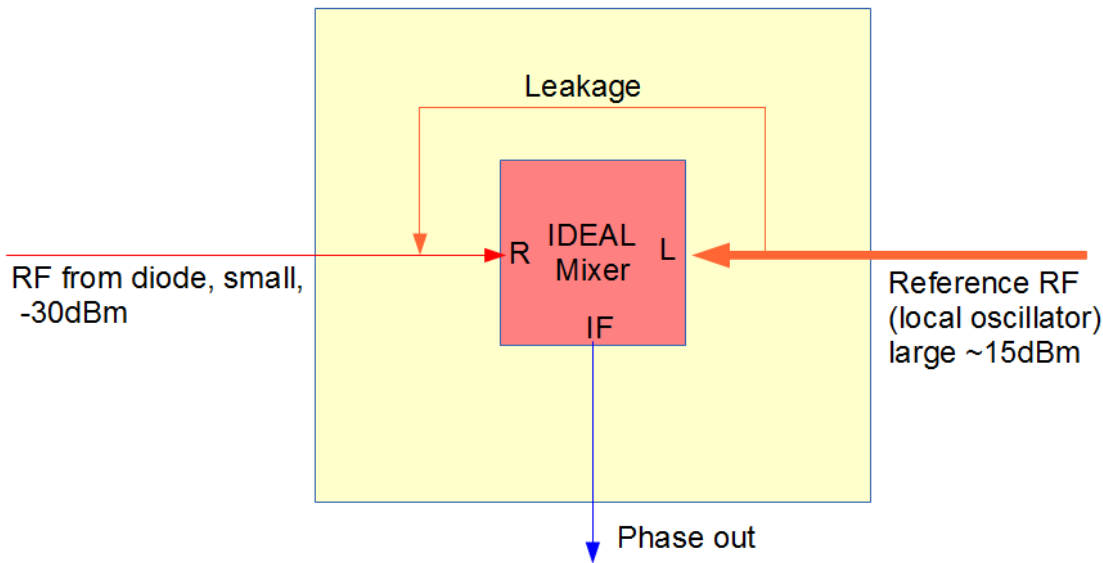
Matlab calculation with
68MHz laser frequency
and 476MHz locking
frequency

Photodiode Error Sources

- Amplitude -> phase conversion
 - 10GHz diodes typically biased at 5V
 - If peak output voltage becomes comparable to the bias, the capacitance of the diode can change and cause a phase shift
 - Remember that we are looking at timing shifts on the order of $<1/1000$ of the diode pulse width.
- Position sensitivity
 - Typical 10GHz photodiode (ET-4000) has a 40micron diameter – corresponds to about 500fs for signals to cross the diode!
- Improved diodes: High linearity fiber coupled diodes available.
 - Looks like an overall improvement
 - Needs care to have long term stable coupling to single mode optical fiber
 - Available from **Discovery Semiconductor**. (IP3 > 40dBm!)

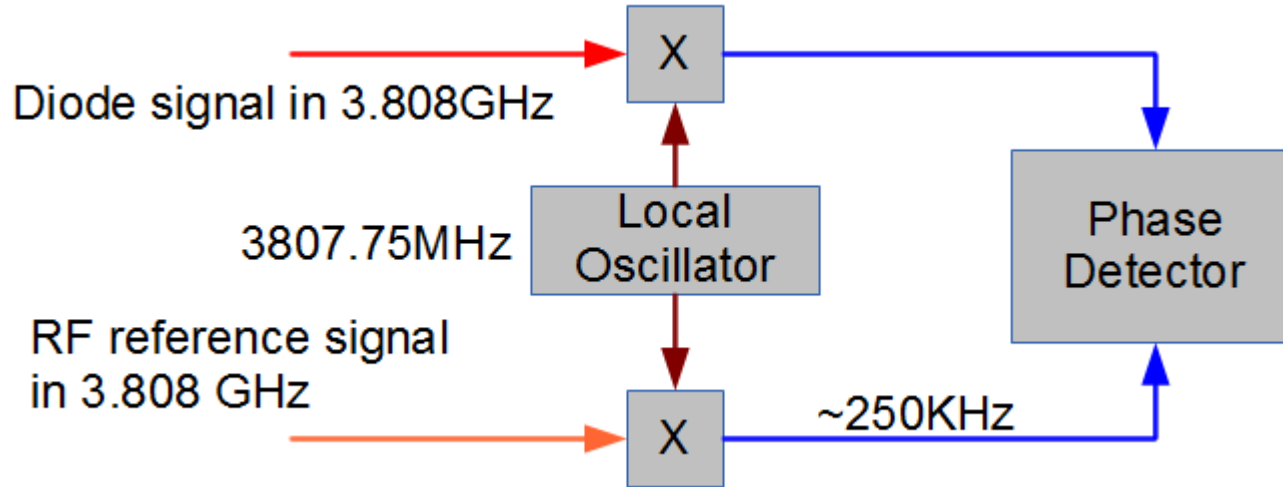


Mixer LO Leakage



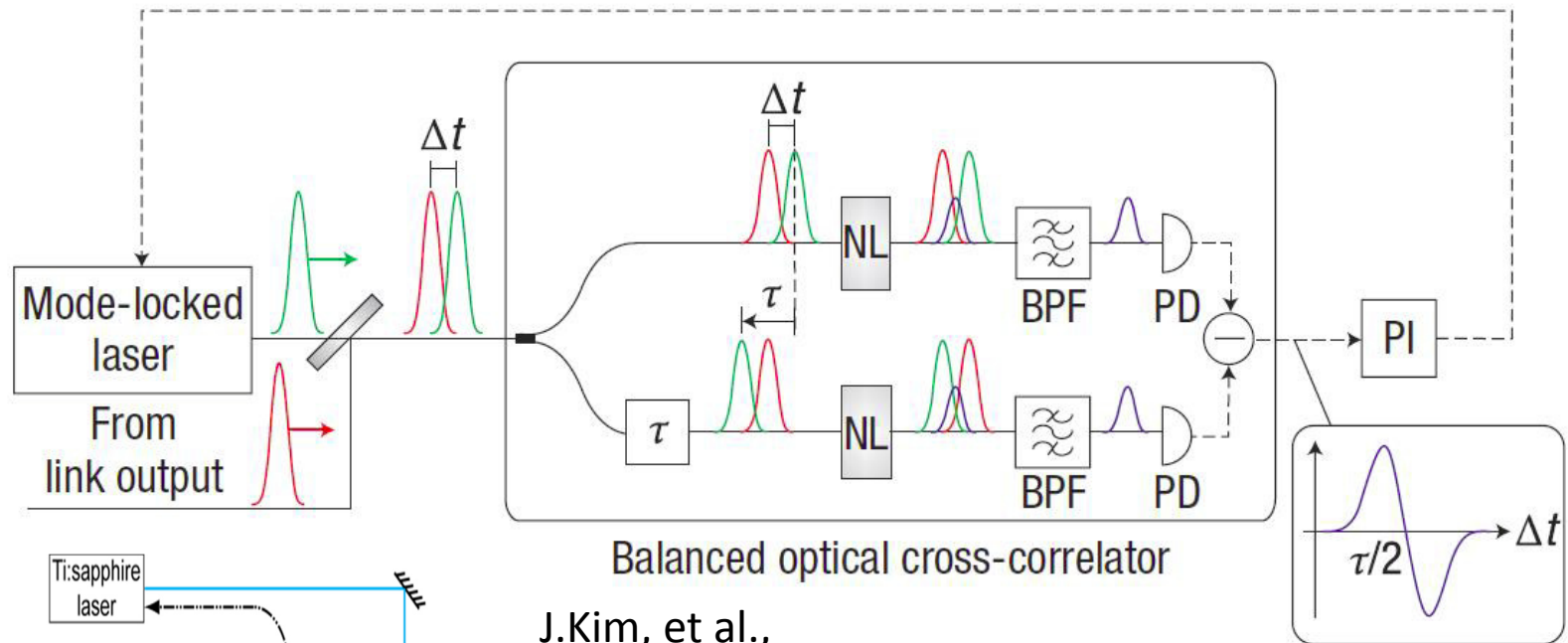
- A small amount ($\sim -30\text{dB}$ coupling) of the high power LO reference will leak into the low power RF input
- This causes a shift in phase of the input RF signal from the diode that depends on the amplitude of the 2 signals
- Results in significant amplitude $\rightarrow$ phase conversion.
- Can improve by using high gain amplifiers on the diode signal, **BUT**
 - IP3 limits in the mixer
 - High gain systems can have cross talk from other signals
- 3GHz $\rightarrow \tau = 50\text{ps}$, so need 1/1000 interference (-60dB interference) for 50fs

Heterodyne System



- Mix to an intermediate frequency rather than DC (frequencies from SLAC system)
- Low frequency phase detection much easier:
 - Can easily digitize and calculate relative phase in software
 - Can use low frequency mixer or analog multiplier with much better performance than RF mixer
- Signal levels small until RF mixer, then put gain at low frequency where cross talk is less significant.
- Technique used in radio receivers (R. Fessenden , 1901 (!!!!))

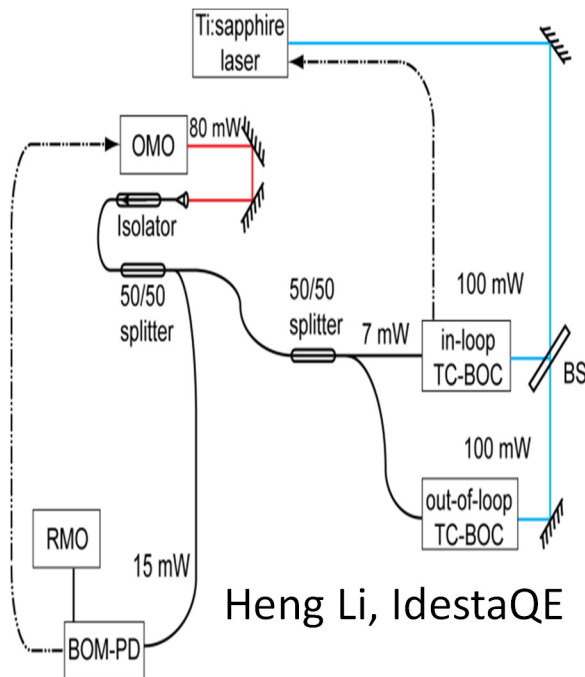
Direct Optical Pulse Locking



Balanced optical cross-correlator

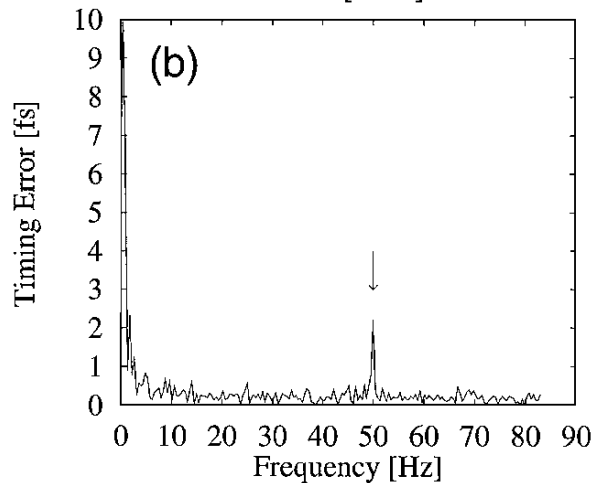
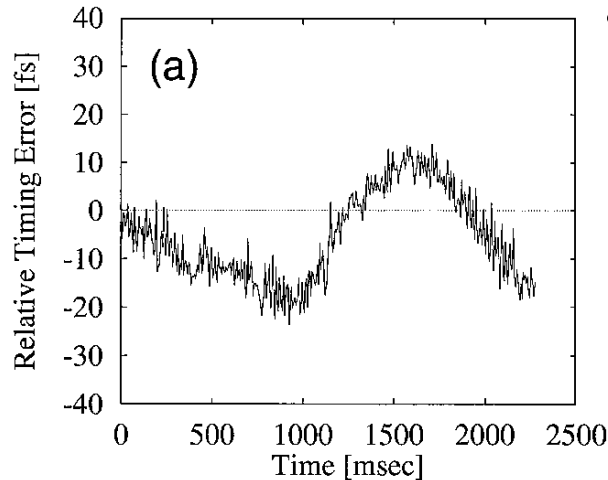
J.Kim, et al.,
Nat. Photonics 2, 733-736 (2008)

- All-optical timing system operates with picosecond pulses $\rightarrow$ 100GHz bandwidths
- Very low noise/ drift measurements for laser feedback



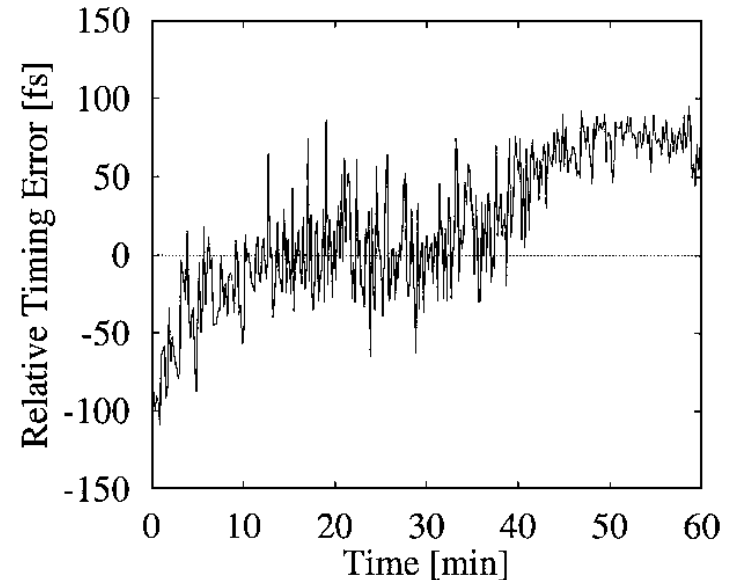
Heng Li, IdestaQE

Laser Amplifier and Transport



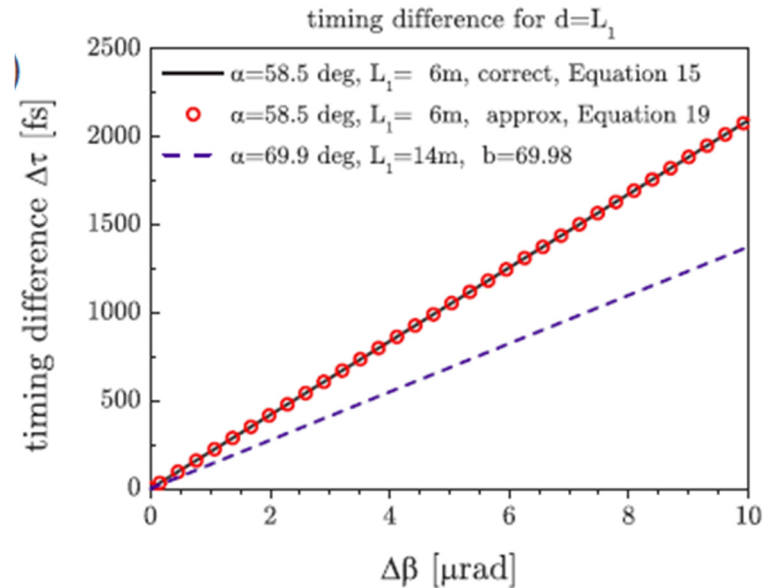
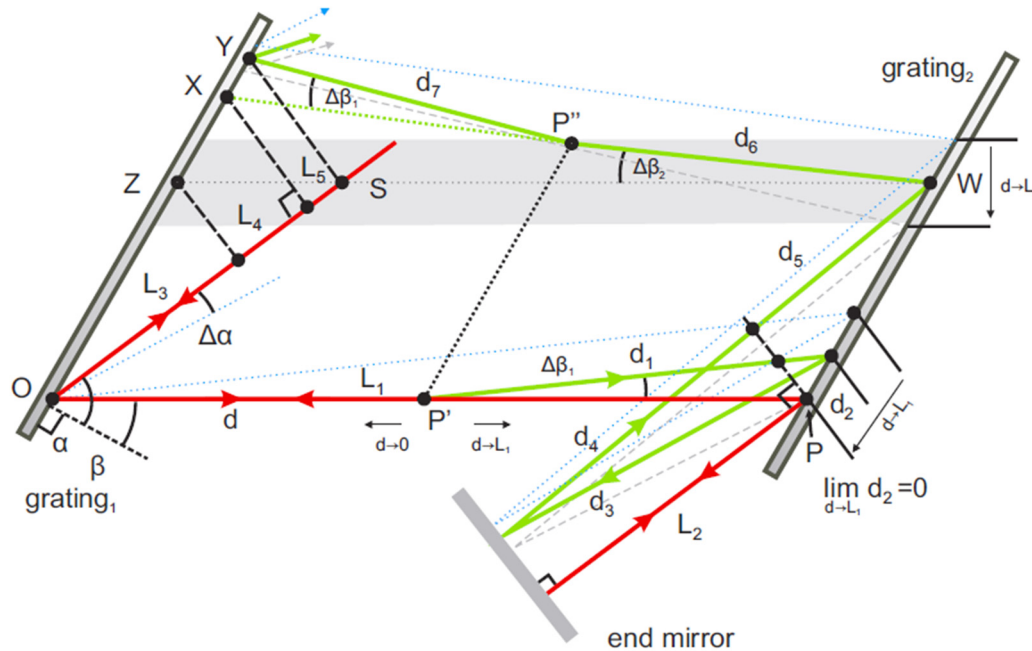
- In installed systems the laser amplifier / transport chain appears to add substantial jitter:
 - SLAC / MEC: oscillator / FEL jitter < 100fs, but measured optical to X-ray jitter >150fs
 - PSI: Oscillator jitter < 30fs, amplified pulse jitter >150fs (Divall Marta et al)
 - 100s of fs increased jitter seen at Max Plank

Short term jitter
relative to mode-
locked laser ~10fs



Long term drift 100fs/hour 40

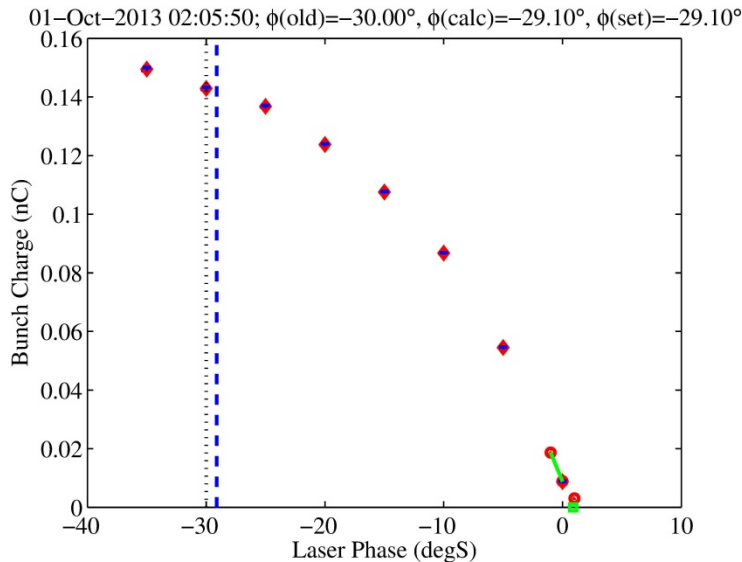
Compressor / Expander



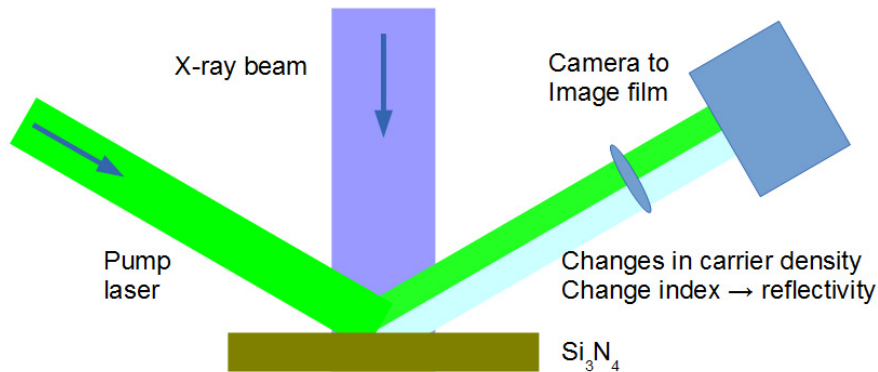
Steering due to air currents in compressor can cause
 $\sim 100\text{fs}/\text{microradian}$ timing shifts.

Experimental and theoretical investigation of timing jitter inside a stretcher-compressor setup. Sandro Klingebiel, *et al*, 13 February 2012 / Vol. 20, No. 4 / OPTICS EXPRESS 3443

“Physics” Timing



- For RF guns, the charge depends on the relative phase of the RF fields and the laser
- If QE is stable, you could feedback laser time on photocathode current!
- Can move to zero-current phase (Schottky edge) to find “zero” time in a few seconds (done at LCLS)



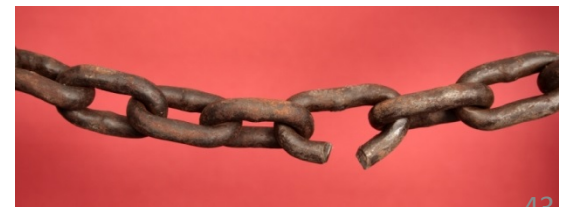
- For X-ray FELS can use a separate “experiment” to measure relative X-ray and optical timing
- LCLS:
 - X-ray induced changes in index of refraction in thin films
 - Index measured with optical laser
 - $<10\text{fs}$ resolution

Solution for electron diffraction and Compton scattering not obvious

Timing System Architecture Guidelines

- Figure out what you need to time – be specific e.g. :
 - Laser pulse in gun vs. RF phase in gun
 - Laser pulse in experimental chamber vs. X-ray pulse in experimental chamber
- What is the most direct signal you can measure:
 - Schottky edge? Cross Correlator?
 - Can you use this for slow drift or jitter correction?
- Create a chain of timing between the 2 signals you need to time:
 - Electron beam in undulator -> beam time monitor -> timing transmission system -> laser locking system -> laser amplifier system -> laser transport system -> experimental chamber <- X-ray transport <- FEL process in undulator.
 - Find the WEAKEST link and work on that.
 - Resist the temptation to work on the most “exciting” part

The most important improvement to timing stability at the LCLS was an upgrade to the laser room air conditioning system!



Timing System Engineering

- You can't afford to buy or operate the “best possible” timing system – there is a price / performance / reliability trade-off: **This is engineering** , not science.
- Understand the requirements: do the experiments REALLY need $<10\text{fs}$ jitter on a 50fs laser pulse?
- Consider the entire system design and how it interacts with your accelerator and laser systems before deciding on RF or Fiber (or both).
- This is part of a user facility, not an experiment itself. The system needs to have high reliability and be maintained by your staff.