Laser Synchronization for the LCLS XFEL

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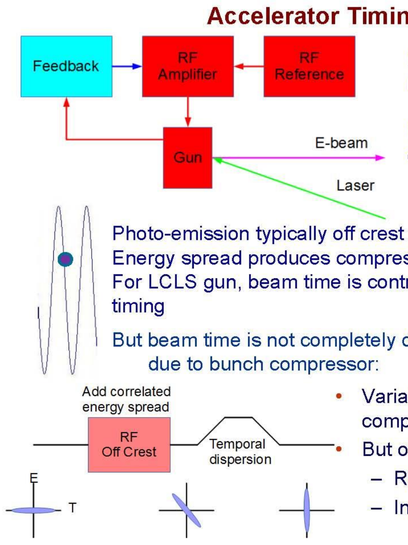
The Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Lab requires many short pulse lasers to be synchronized to the XFEL on the scale of femtoseconds. This is accomplished in several ways, by locking to the electron beam arrival time after the undulator, or to the accelerator RF system. We discuss several of the tools used, and some of the lessons learned in the process.

Accelerator Timing – RF Gun



RF time set by phase measurement using gun probe

Feedback can be pulse to pulse or continuous

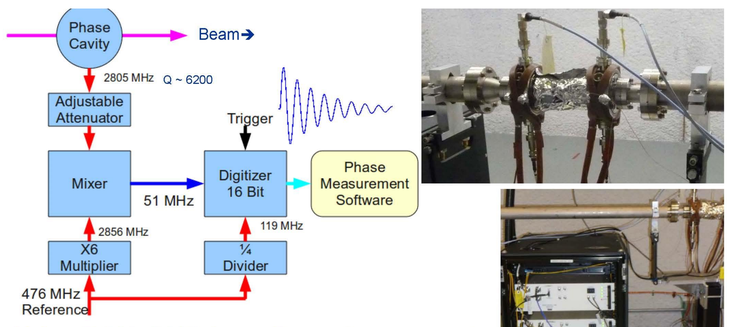
Photo-emission typically off crest
Energy spread produces compression
For LCLS gun, beam time is controlled both by laser and RF timing

But beam time is not completely determined by laser time due to bunch compressor:

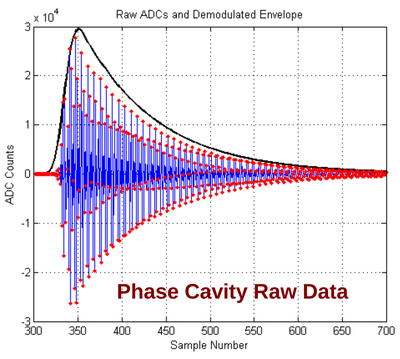
- Variation of input beam time compressed to smaller output variation
- But output time varies with:
  - RF phase
  - Input energy

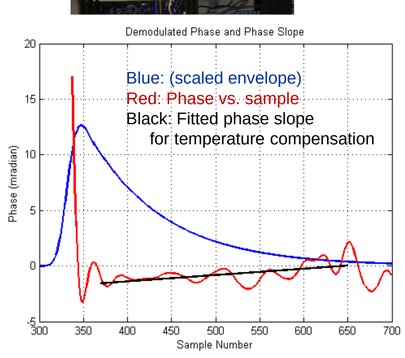
RF Phase Pickups

- Use narrow band pickups below beam-pipe cutoff (~<10GHz)
  - RF cavity around beampipe to "trap" beam fields.
  - Average phase over many cycles ➔ reduce noise
- Disadvantage of narrow band signals: Thermal sensitivity
  - Small frequency changes in pickup cavity result in large phase shifts: 1us decay time requires ~10^{-7} frequency stability for 100fs timing stability
  - Temperature control at the required 0.01°C level not practical.
  - ➔ Constantly measure cavity frequency and correct the measurement.
- Generally limited by linearity, not noise for beam charges above ~10pC
- Dark Current Issues:
  - Narrow band timing pickups average signals over many RF cycles.
  - Pickup cavities should operate away from accelerator frequency to avoid dark current sensitivity
  - SLAC uses 2805MHz cavities with an accelerator that operates at 2856MHz
  - Measuring phase away from the accelerator reference frequency requires more complex electronics

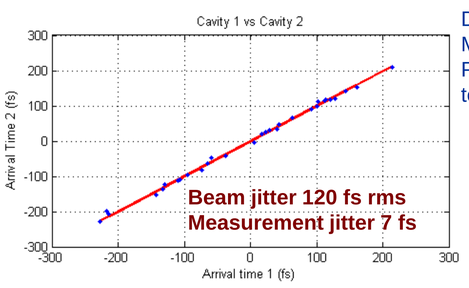


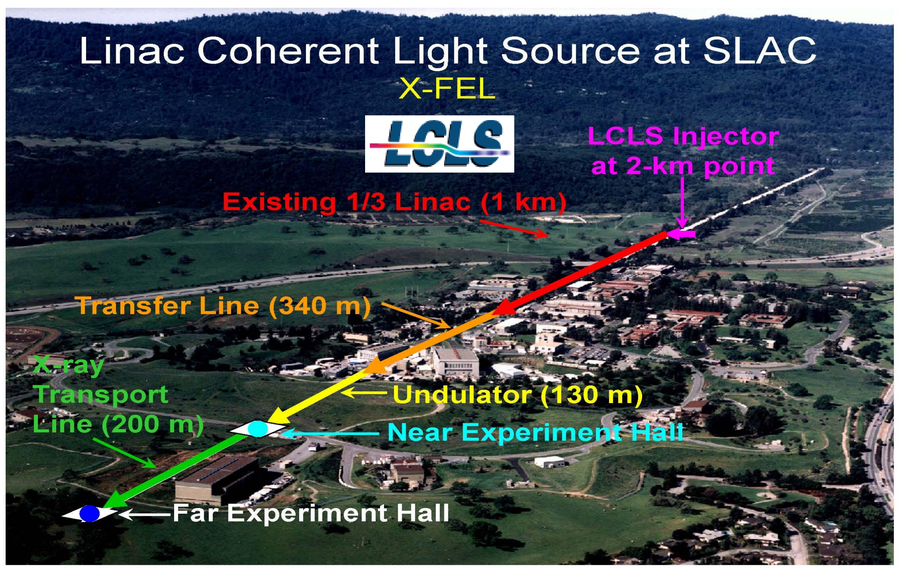
Noise: 7-20fs RMS depending on beam current
Drift ~100fs after frequency (cavity temperature) correction





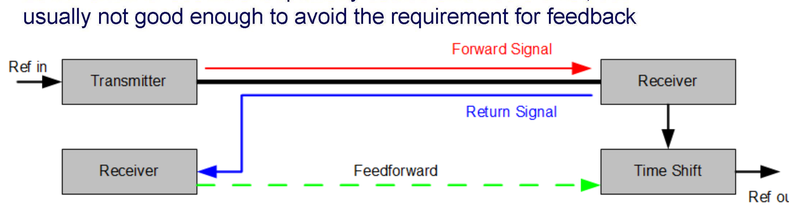
Digital Downconversion to get phase vs. time
Mean phase➔ t_0
Phase slope ➔ frequency offset ➔ temperature correction



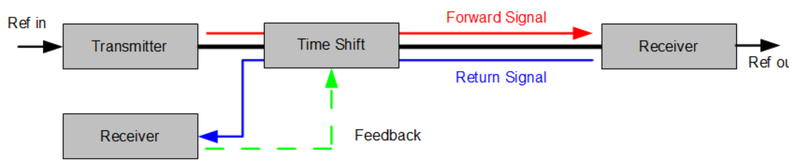


Phase Transmission

- Transmit timing ~100m with ~100fs stability ➔~10^{-7} relative stability
- Temperature coefficient of delay of RF coax and optical fibers both ~10^{-5}/°C
  - Fused silica thermal expansion is very low but the index of refraction has a significant temperature coefficient.
- Lower thermal coefficient specialty cables and fibers exist, but usually not good enough to avoid the requirement for feedback



Feedforward requires a very accurate measurement of timing shifts



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

Timing distribution – Devil in the Details

- Unwanted reflections disturb accuracy of feedback / feedforward
  - 1ppm reflected RF power causes 100fs timing shifts.
- Bi-directional phase shifters are difficult to realize electronically if signal levels are different
- Directional couplers have limited directivity
  - Better for fiber than for coax
- Normal telecom fibers do not maintain polarization – extra degree of freedom can cause problems.

Fiber vs. Coax

Coax	Fiber
• Limited bandwidth – GHz over 100m	• High Bandwidth >THz with dispersion compensation
• Thermal noise ~1/40eV	• Photon noise ~1eV
• Bulky, expensive >1" sizes often needed	• Commercial SMF-28 inexpensive, compact
• Simple, Rugged, Common diagnostics	• Delicate, needs special instrumentation

Both used here
Choice depends on specific needs

Sources of Noise – CW Fibers

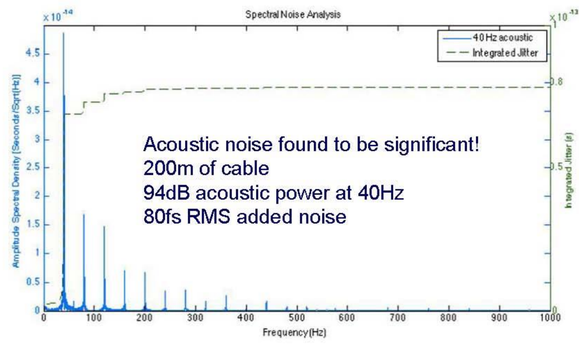
- Photon shot noise and detector noise (at low optical powers)
- Laser wavelength variations -> dispersion -> timing variations
  - Usually this is bidirectional
  - Can be used to advantage as a fiber delay control with a tunable laser.
- Amplitude variations -> nonlinearity -> wavelength variations (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

Types of fiber systems

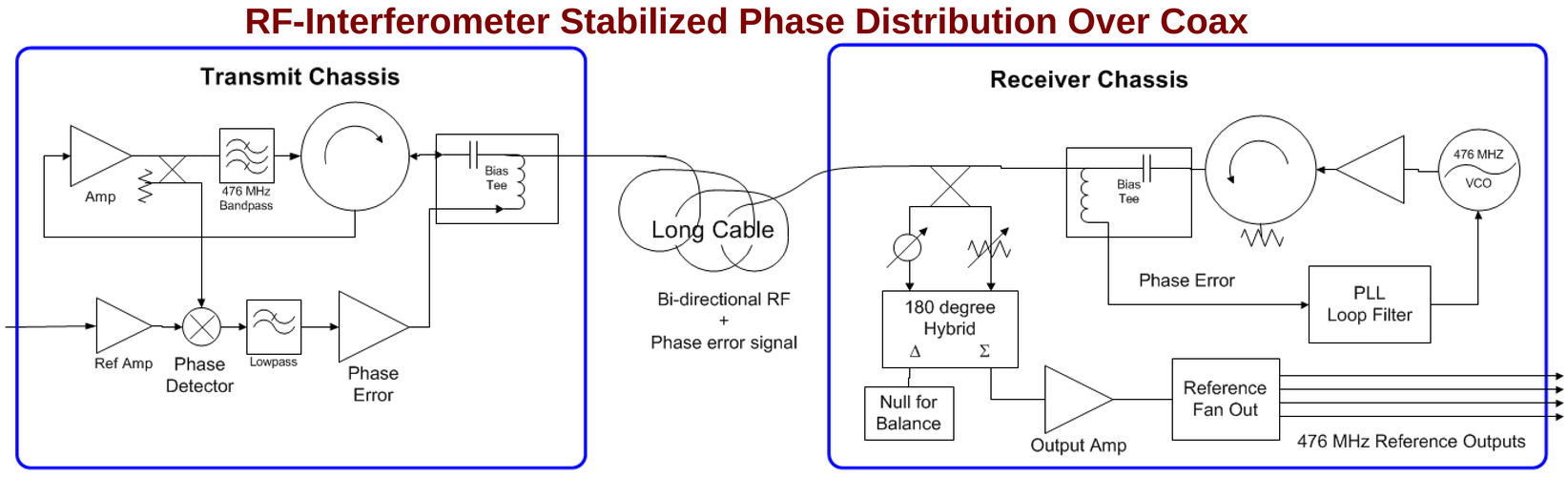
- CW Optical signal modulated with RF (typically GHz)
  - Takes advantage of low loss in fiber at high modulation frequencies
  - Takes advantage of high directivity couplers and low back-reflection fiber connectors (~60-70dB, compared to ~40dB for Coax.
  - High noise is the primary disadvantage
- Pulsed fiber systems
  - Very high bandwidth ~THz for very low noise
  - Broadband systems mostly immune from reflections
  - Dispersion will rapidly broaden pulses without special dispersion compensated fibers
  - Nonlinearity from high peak optical power can modify spectrum and produce amplitude -> timing conversion.
  - Picosecond laser systems are complex
  - Potentially very high performance!

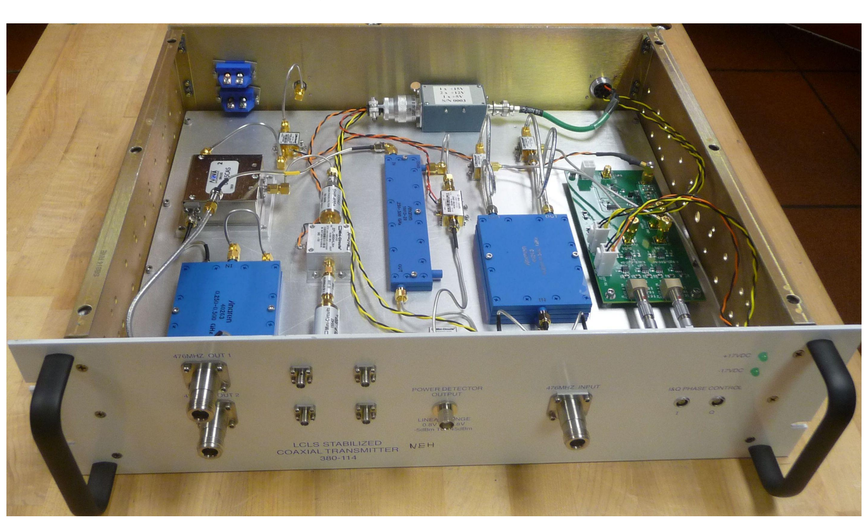
Phase Noise in Coax

RF (thermal noise)
Real systems have ~10dB noise figure
Generally not a limit with normal power and bandwidth

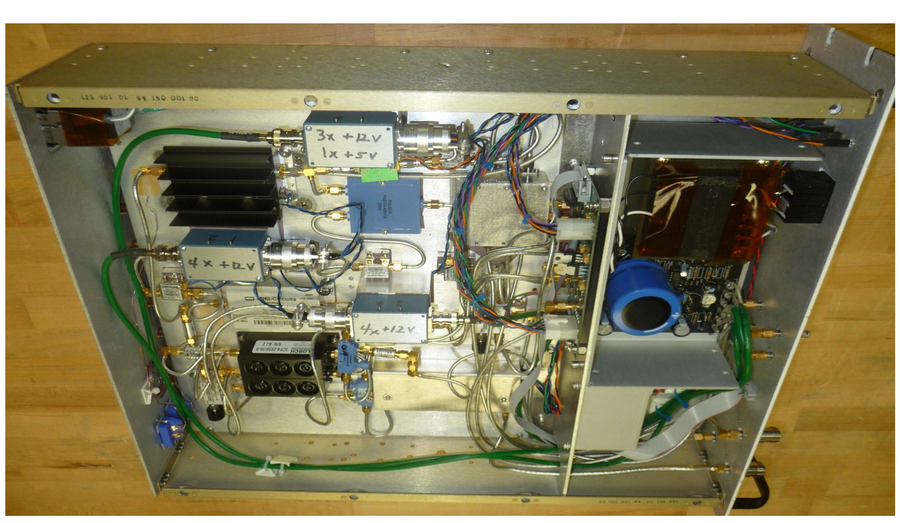


RF-Interferometer Stabilized Phase Distribution Over Coax

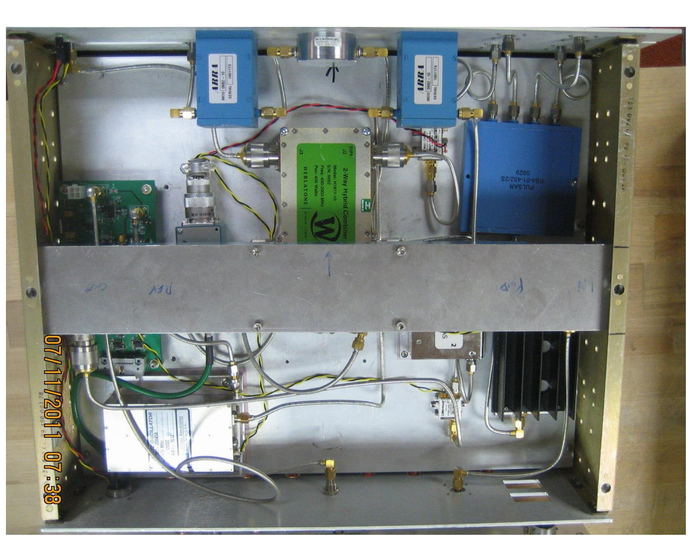




Beam Arrival Time Monitor



Cable Stabilizer Transmitter



Cable Stabilizer Reciever