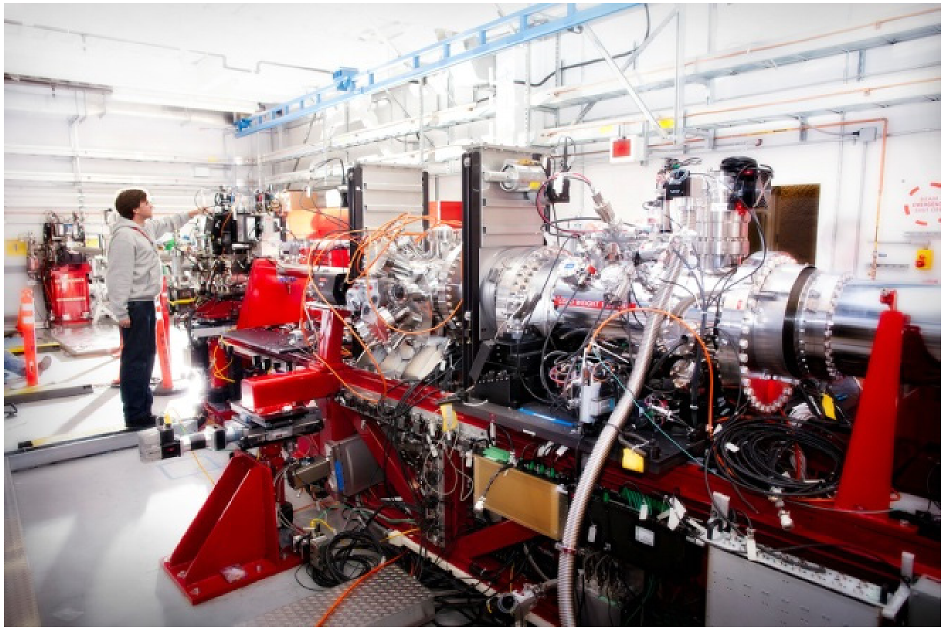
Beam Arrival Time Monitors

Josef Frisch, IBIC Sept. 15, 2015

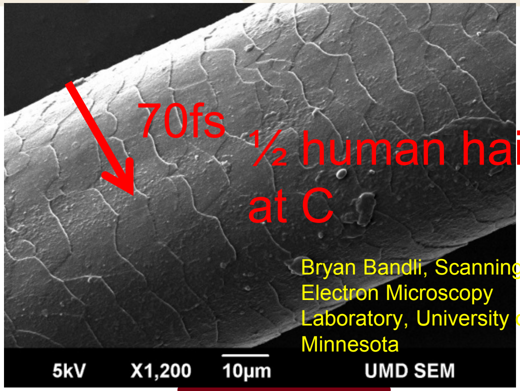
Arrival Time Monitors

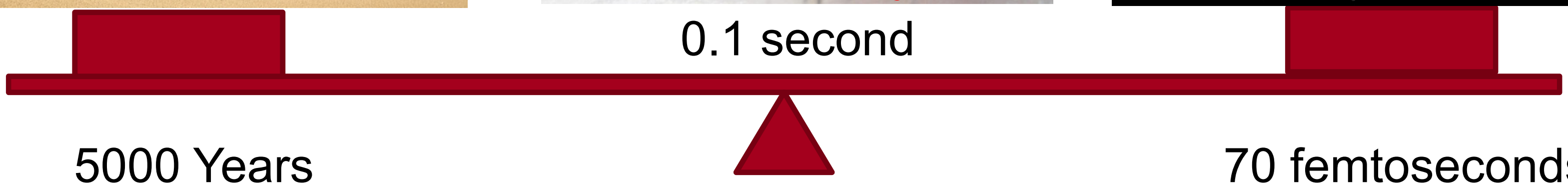
- Timing is only meaningful relative to some reference, and in general what matters is the relative timing of two different systems
- Pump / Probe experiments (FELs, UED etc.) are generally the most critical, with requirements down to a few femtoseconds.
- Proton HEP experiments can require few picosecond coincidence detection, but bunch lengths are typically long, so precision arrival times are not needed.



CXI experiment at SLAC
Laser pump / XFEL probe

Femtoseconds are REALLY SMALL





0.1 second

5000 Years

70 femtoseconds

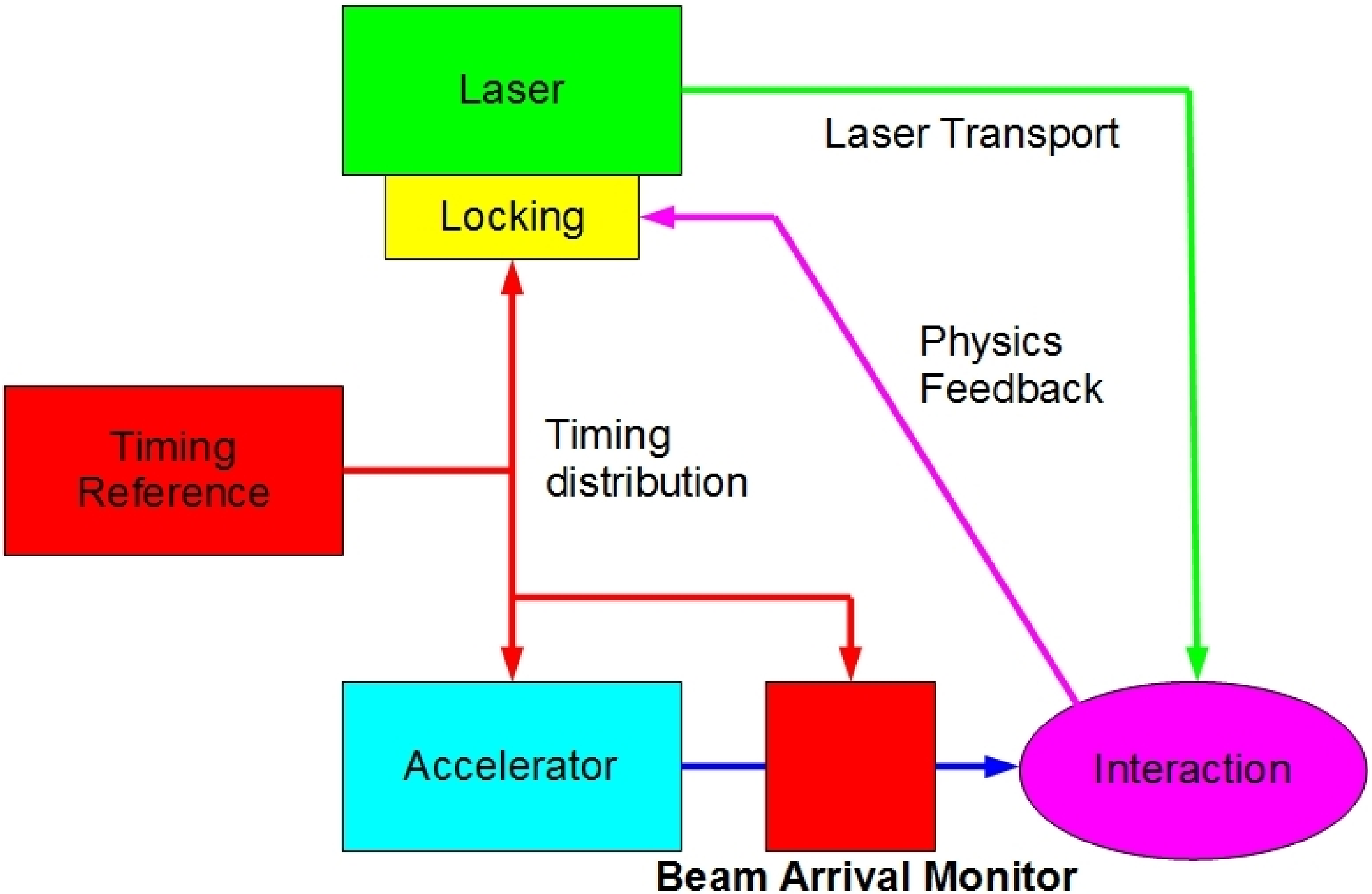
1 Meter of typical engineering material will change length by 30fs/°C. Optical fibers change path length by ~50fs/°C

Ultra-relativistic beams and photons in vacuum are the only things where timing stabilization is not required for long distances

Fortunately accelerator tunnel lengths are quite stable – the bedrock temperature changes very slowly.

Engineering tradeoffs! You don’t need the “best”.

Typical Timing System



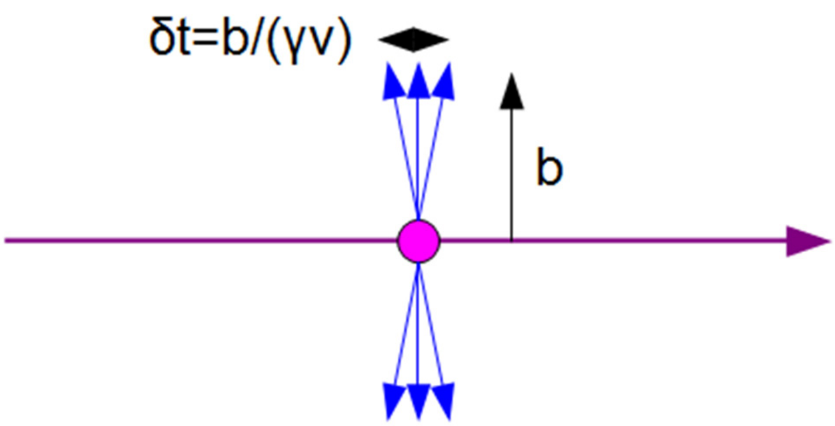
Beam arrival monitor can provide timing feedback and / or pulse tagging for offline experiment data correction

Arrival Time Monitor Use

- Used for feedback to reduce the timing jitter of the accelerator
  - Needs a high frequency machine – superconducting
  - Used at DESY / FLASH
- Used to correct for timing drifts in the reference signal from the accelerator to the experiments .
  - Used at SLAC / LCLS
- Used to correct experiment data for accelerator timing jitter.
  - On low rate machines like LCLS (120Hz) the shot to shot jitter cannot be corrected but the arrival time monitor can record the timing for offline data correction.

Detect timing from the beam electric or magnetic field.

- Electron bunches are usually shorter than the response time of conventional electronics.
- Relativistic effects usually allow the high frequency signals to get to the beampipe.



For 6GeV (XFEL), 1cm beam pipe:
Pulse width = 2 fs
For 6 MeV (UED) 1cm beam pipe
Pulse Width = 2ps

For conventional electronics we need to low pass filter.
Signal pickoffs to cables are typically limited to ~<50 GHz.
For pulsed laser fiber systems can in principal use bandwidth to ~100fs.

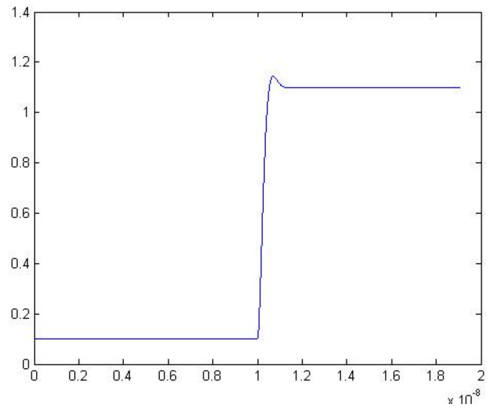
Signal Levels

- A beam pickoff has a characteristic impedance (geometric impedance is called "R/Q") to describe its interaction with the beam. Scale is $Z_0 = 377\Omega$ (free space impedance). Actual impedance usually lower, ~100Ω for a cavity, much lower for a pickoff.
- Single pulse energy deposition is $E = q^2\left(\frac{\omega_0}{2}\right)\left(\frac{R}{Q}\right)$
  - 100pC, f=3GHz, 100Ω gives 10nJ
  - Thermal noise is $k_b T/2$ or 2×10^{-21}J
  - Energy signal to noise is 5×10^{12} (!)
  - Corresponds to 20 attoseconds
  - **Thermal signal to noise is rarely the problem with strongly coupled pickoffs like cavities!**
  - Button type probes may have much lower signals.
- Higher frequencies improve the signal to noise as ω^2, but it is usually better than you need anyway.

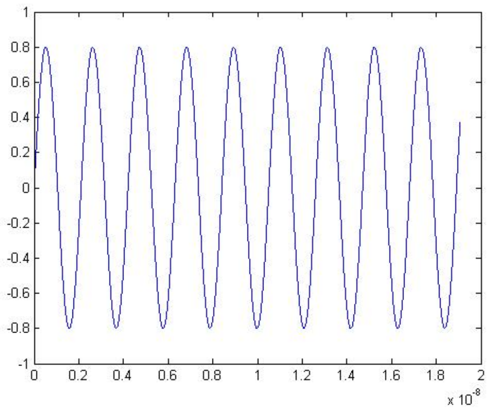
Broadband vs Narrowband

Conventional electronic triggers only good to ~1ps.

Laser based systems can measure to femtoseconds



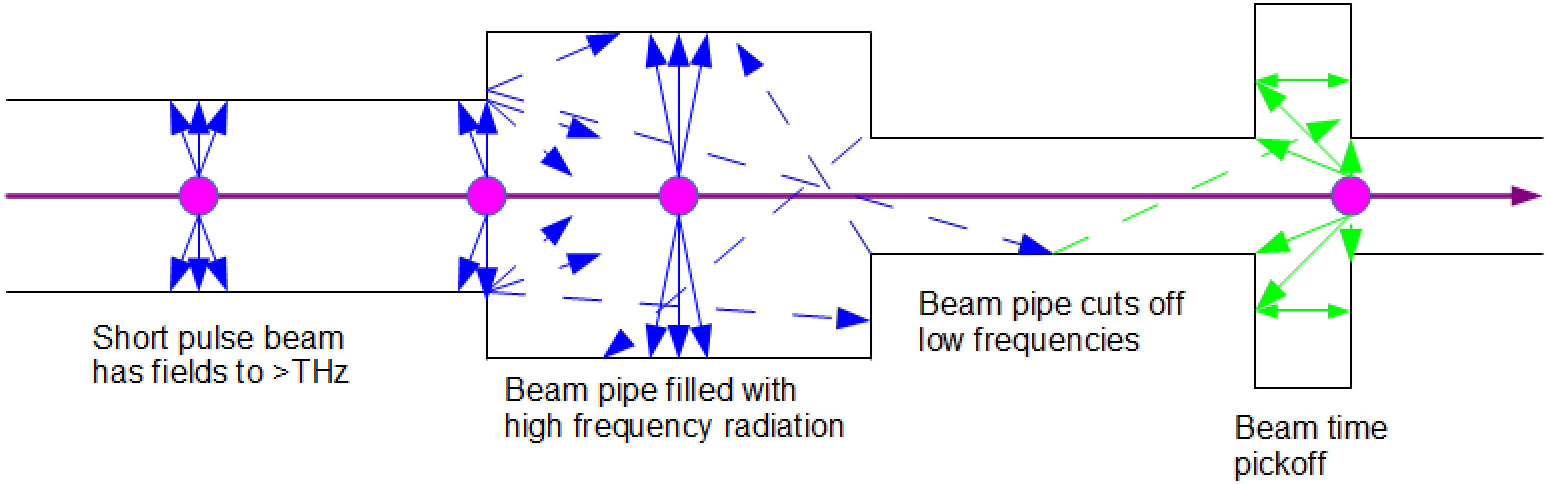
Using repetitive signals to average timing measurements on millisecond timescales will allow X1000 improvement using GHz clocks



Selection of frequency and bandwidth have a strong impact on the system design

Where to the fields come from [IMPORTANT]

- Fields generated by the beam can propagate down the beam pipe if they are above cutoff : 1.8412C/(2πR) = 9GHz for a 1cm radius pipe.
- Signal seen at a pickoff is a combination of local fields from the beam, and propagating fields.
- Some of these fields depend on the beam position upstream, so a measurement will combine position and timing -> useless.
- Working below cutoff solves all this but limits you to frequencies around a few GHz
  - Very small beam pipes are usually not allowed for wakefield / stay-clear issues

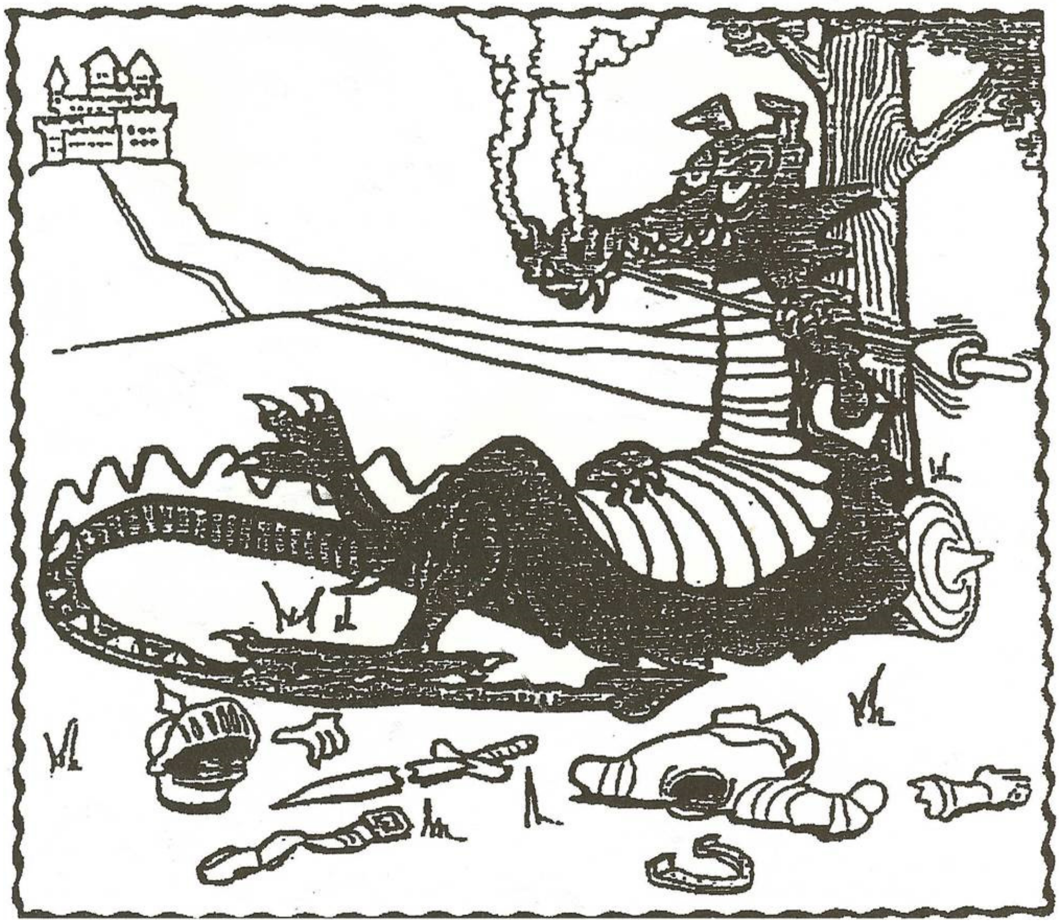


High Frequency: Working above cutoff

- Arrival time monitors commonly need resolution in the 10^{-2} (pulsed optical systems) to 10^{-5} (RF systems) of a wavelength.
  - It doesn't take a lot of interfering signal to degrade the arrival time monitor performance
  - The same problem exists for BPMs
- If you are near cutoff the group velocity for upstream signals is << C: $V_g = c\sqrt{\left(1-\left(\frac{f_c}{f}\right)^2\right)}$ So signals from the local beam will be ahead of signals generated upstream
  - **But not by much** – measurement cannot be very narrow-band or it will be contaminated by upstream signals.
- If you operate far above cutoff, the propagation frequency ~c.
  - Consider 1cm radius beampipe, 1M upstream interference
  - 10x cutoff -> 90GHz .995C propagation speed -> 16ps delay (1 cycle)
- Geometry doesn't help much. Path difference is only 50um (150fs) between straight ahead and edge of beam pipe.
- **Systems that rely on looking at the rising edge of the beam fields must be broadband (not just high frequency)**
  - If pickoffs and cables are used, care must be taken to avoid dispersion that can mix signals from different times.

Above Cutoff – Here there be Dragons!

- Has been done successfully at DESY with some of the best performance in any system. F. Loehl et. al, “Electron Bunch Timing with Femtosecond Precision in a Superconducting Free-Electron Laser” Phys. Rev. Lett. 104, 144801 – Published 5 April 2010
- But great care is required in order to design a broadband system that can work on the very rising edge of the pulse.



The instrumentation landscape is littered with failed attempts to work above beam pipe cutoff for RF beam instrumentation.

Frequencies and Bandwidths

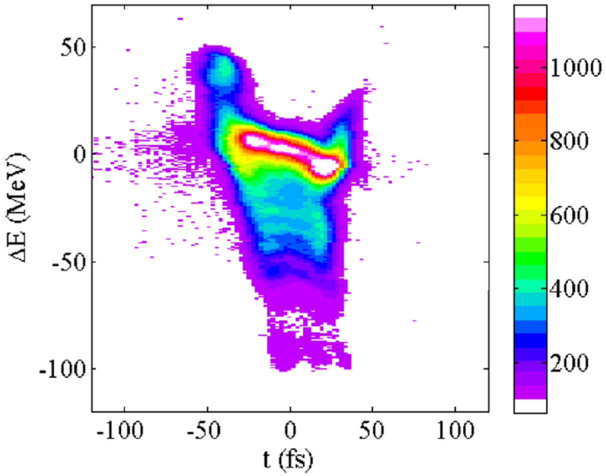
- High frequency operation
  - Implies operation above beam pipe cutoff.
  - Operation above cutoff -> broadband detection to see the signal before all the junk from upstream arrives
  - Use a Broadband pickoff to highest practical frequency measurement.
- Low frequency operation
  - Requires narrow bandwidth to get enough signal averaging for good resolution
  - High Q resonant cavities provide beam coupling and filtering.
    - Temperature sensitivity is a big issue – more on this later.
- Medium frequency operation:
  - Probably a bad place to be
  - Above cutoff, so forced to use broadband detection
  - Frequency not high enough for good single shot measurements.

If you are going to go above cutoff, go FAR above cutoff.

Dark Current and Halo

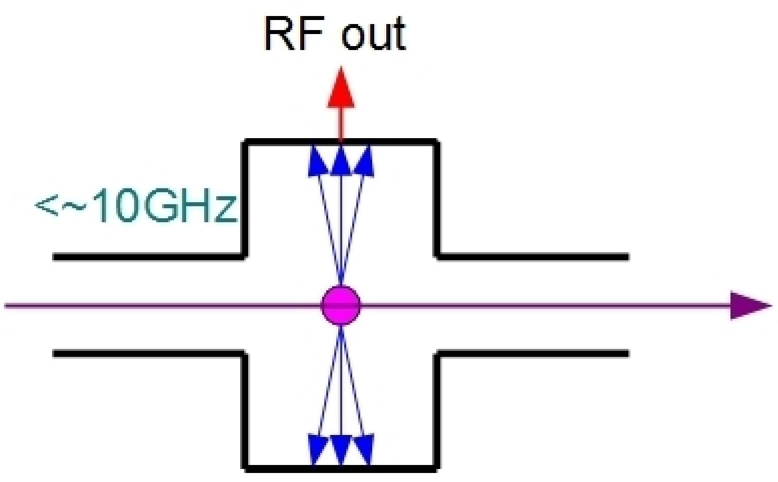
- Most accelerators produce some unwanted beam
  - Charge in incorrect buckets from gun or structure field emission
  - Charge in a defocused halo or tails that may arrive at a different time.
- Beam pickups will see this dark current and it can interfere with the timing measurement.
  - 10^{-3} charge out of time in a 3GHz arrival time monitor can produce a 50 femtosecond error.
- Generally we don't really want the average of the entire beam, just the "useful" part
- Narrowband and low frequency systems are more susceptible to dark current / halo issues.

TCAV image from SLAC / LCLS showing that the centroid of the energy extraction (X-ray pulse) is not at the centroid of the charge

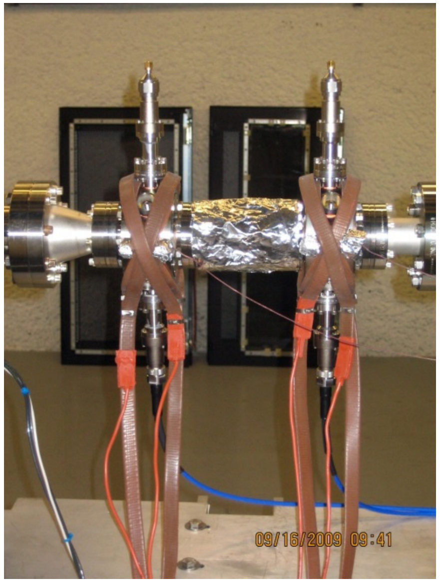


Beam Pickup - Cavity

- Generally limited to <10GHz to stay below beam pipe cutoff with an acceptable beam aperture
- Cavity provides high Q ~10,000 and good beam coupling
- Mechanically robust and reliable
- High dynamic range
- Modest frequency electronics uses conventional RF engineering.
- Extreme temperature sensitivity requires compensation algorithm



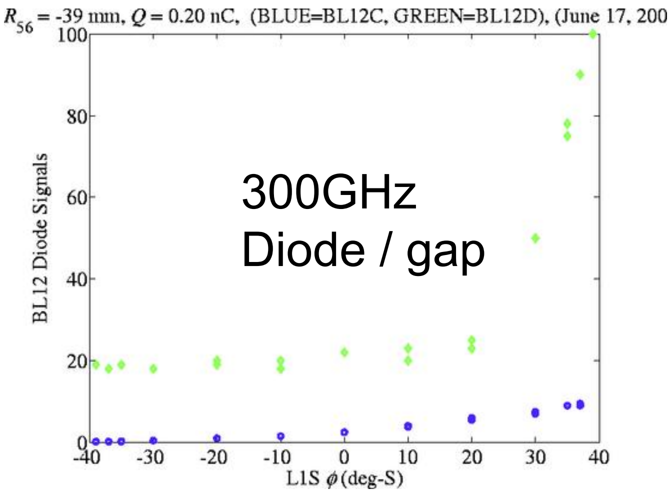
RF cavity pickup



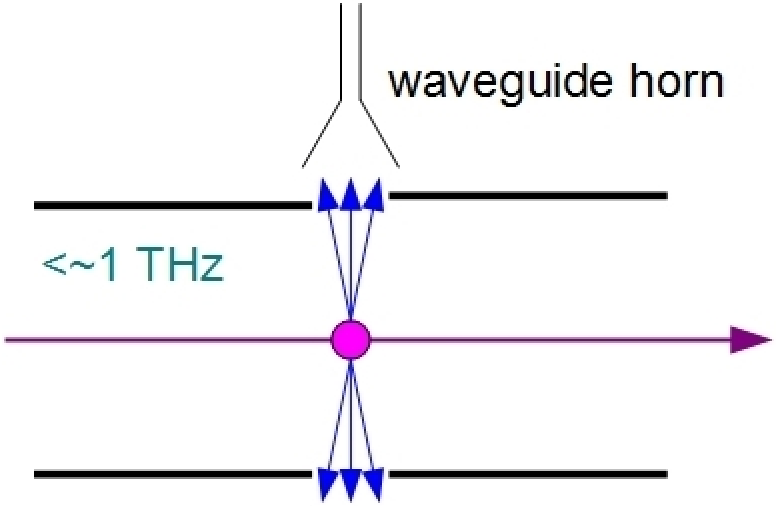
SLAC / LCLS

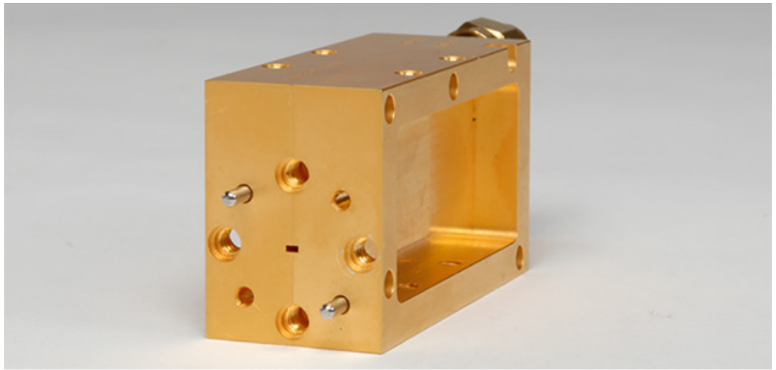
Beam Pickup – High Frequency Waveguide

- Millimeter wave mixers are available (up to ~1THz)
- Mm-wave signals from gaps have been used at LCLS for bunch length measurement.



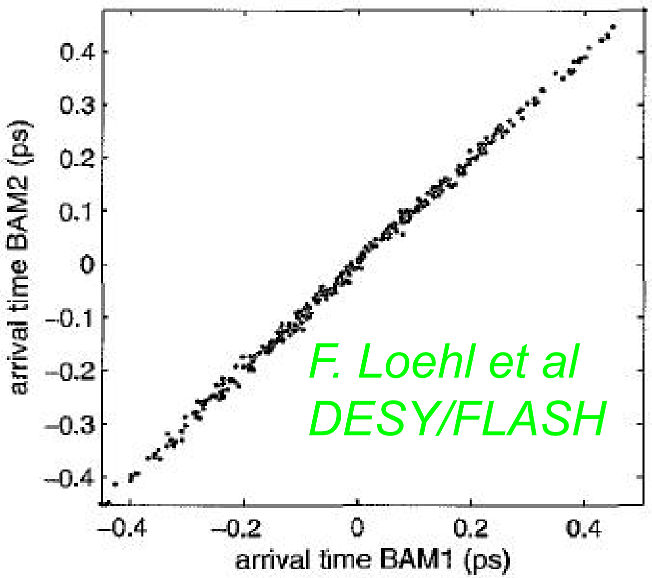
- Potential application for arrival time monitor working above beampipe cutoff
- Usual cautions about above-cutoff apply!
- Not aware of this having been tested

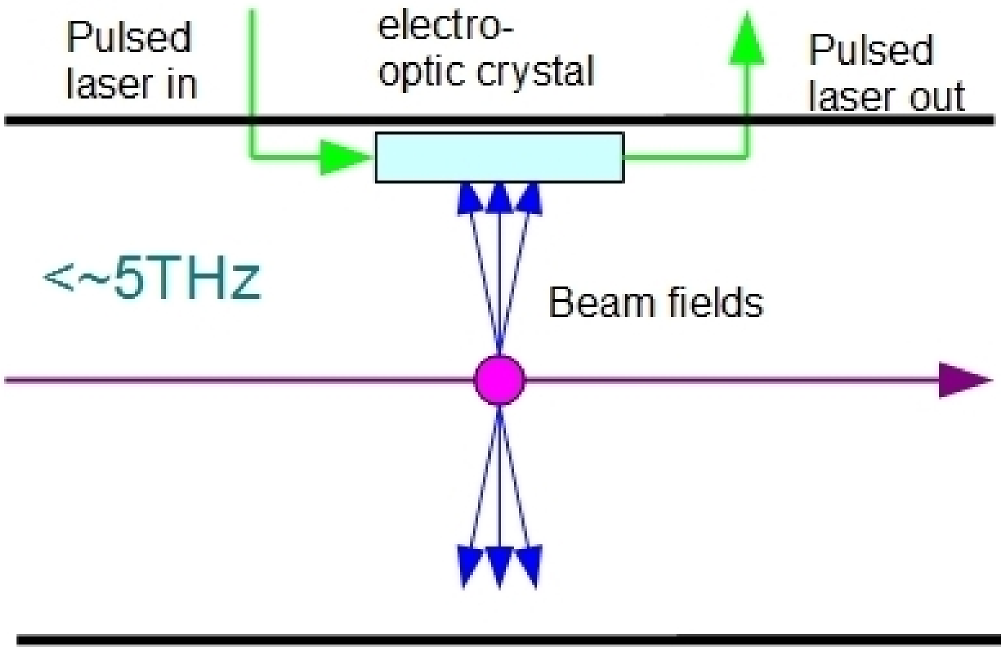




Beam Pickup – Electro Optical

- Bandwidth is limited by available electro-optical materials and the electron bunch length.
- Readout is by interacting with a femtosecond laser
  - Direct intensity modulation through crossed polarizers
  - Spectral modulation of a chirped pulse
- Extremely high bandwidth!
- Directly interfaces to fiber timing system
- Electro-optical crystal near the beam presents challenges
  - Radiation damage
  - Dynamic range

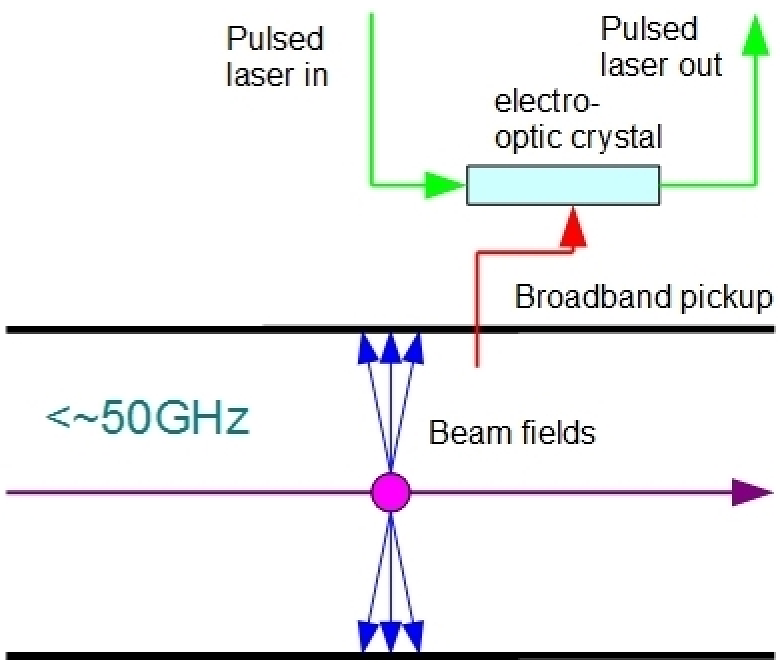


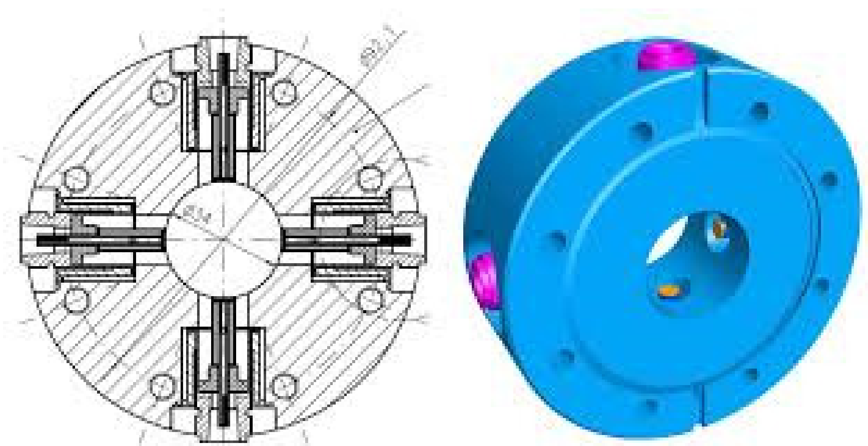


6fs RMS (maybe 3 achieved?)

Indirect Electro Optical pickoff

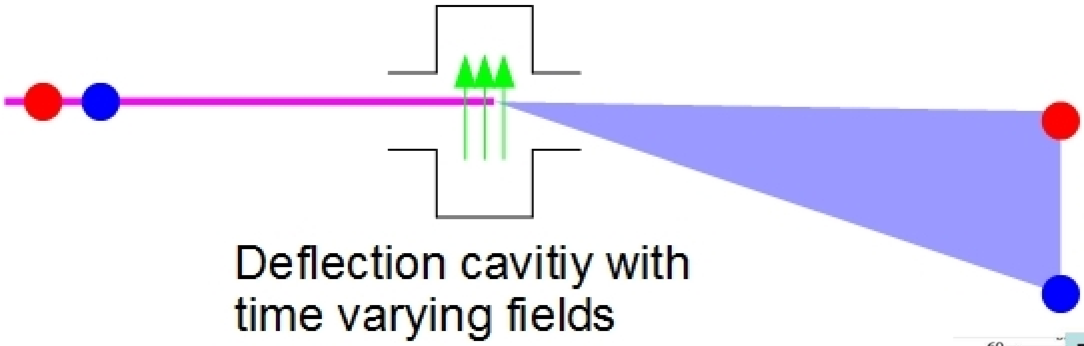
- Use a high frequency pickup and cable, and an external electro-optical modulator.
- Reduces bandwidth to <50GHz for practical feedthroughs
- Eliminates radiation and beam stay-clear issues.
- Directly interfaces to fiber timing system
- Planned for the EURO XFEL

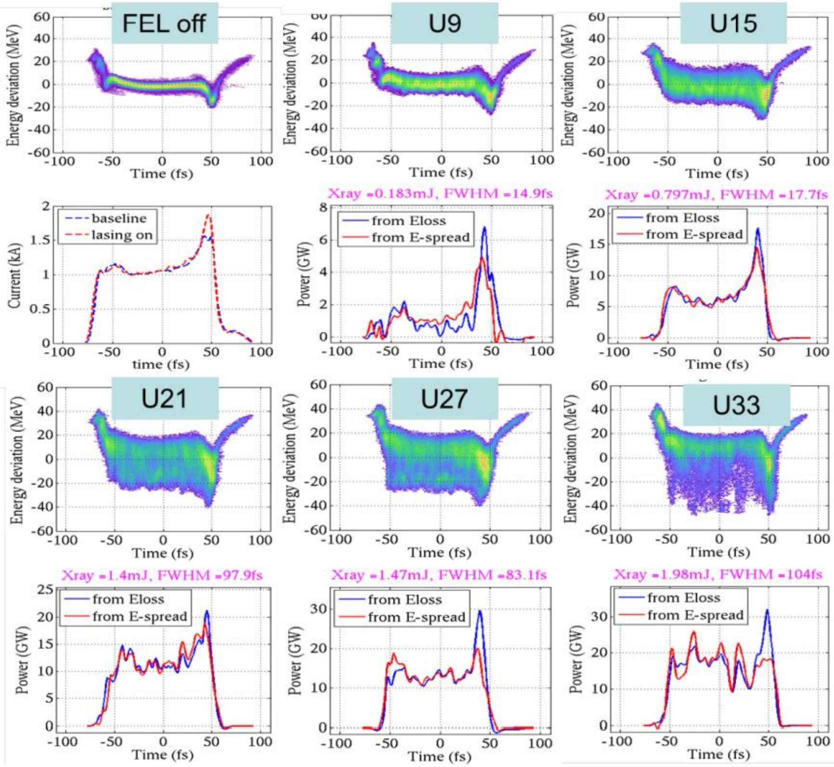




M. K. Block et al. DESY

Transverse Deflection Cavities

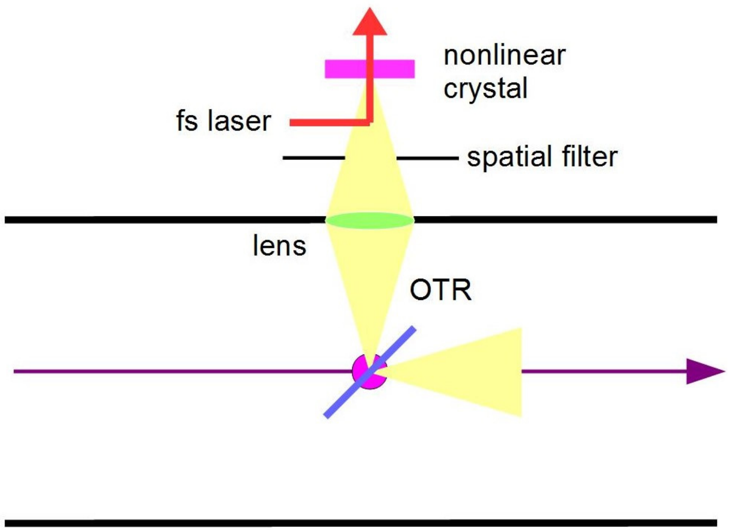




- Single shot temporal imaging resolution to <1fs demonstrated.
- Timing measurement limited by stability of RF in the cavity
  - **In most cases this is no better than the ability to measure the beam induced signal**
  - For very low charge beams this can have better resolution than a beam pickup
- If combined with an energy spectrometer, a TCAV can provide additional information – for example what part of a bunch is lasing in a FEL
- VERY EXPENSIVE – Usually not worth building as a timing diagnostic, but can be used for that if it is already needed for other functions.

Free Space Radiation

- The electron beam can be made to radiate into free space through the use of Optical Transition Radiation or an Undulator.
  - This allows the a signal with the full bandwidth of the beam to interact with a femtosecond laser
  - Typical FEL electron beams will be radiating in a 1-100THz band that is not very convenient for optical techniques
  - Spatial filtering can be used to reduce interference from upstream radiation.
- OTR
  - Simple and broad bandwidth, can be optically filtered to narrow-band
  - Invasive
- Undulator
  - Provides a narrow band at the desired wavelength
  - Expensive., Parameters may not be practical for high energy beams
  - May be invasive due to coherent effects.



- Potential for very high resolution measurements
- More complex than conventional EO systems.

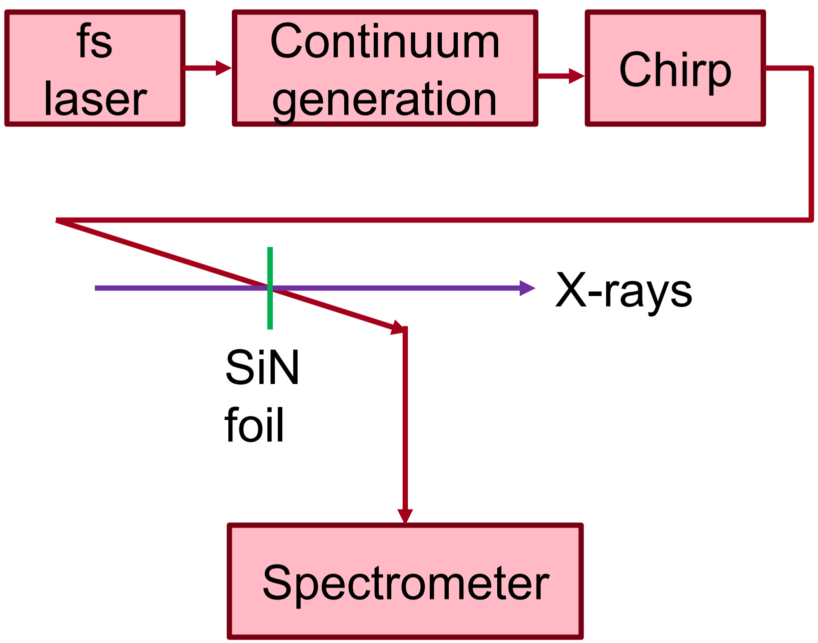
(see S. Kovalev's talk)

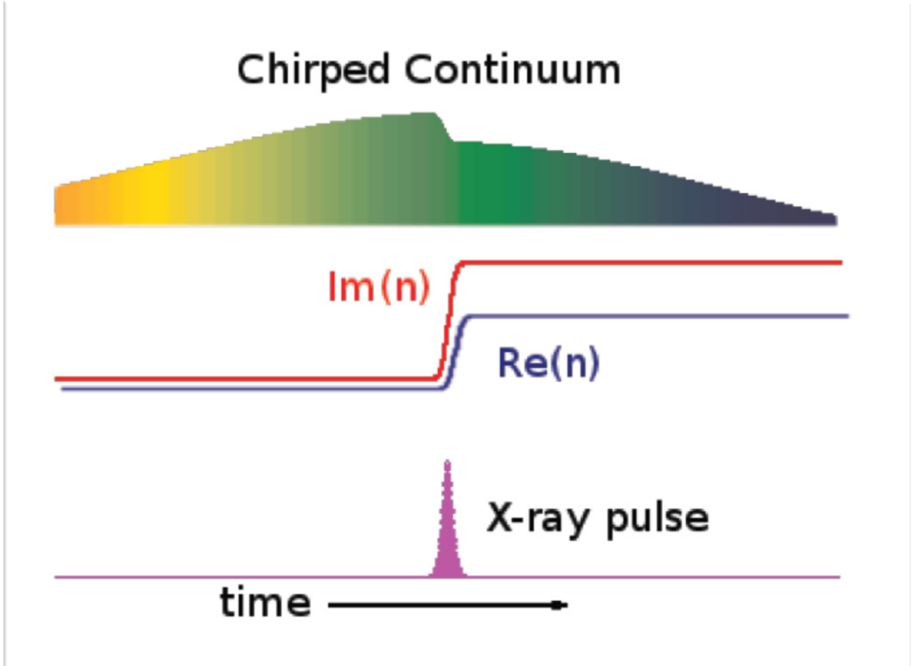
X-ray vs. Laser Timing

- For X-ray FELs we can directly measure the quantity of interest: X-ray vs experiment laser time
  - Provide feedback to beam timing
  - Provide shot by shot data for offline correction
- Still need a conventional arrival time monitor
  - Temporal range is usually small, so these systems have to be used in conjunction with a conventional arrival time monitor
  - Greatly reduces the requirements on the conventional system.
  - These systems may not work under all FEL operating conditions.
- When usable, direct X-ray / optical measurement will generally provide the highest performance.
- The design of these systems is beyond the scope of this talk – will just give an example.

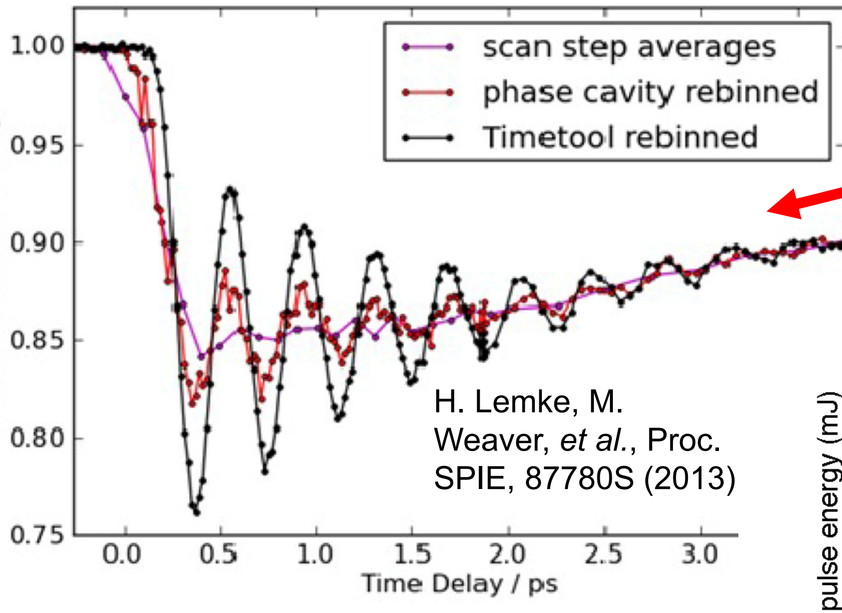
X-ray / Optical timing at SLAC / LCLS

- Multiple labs have used these techniques, using SLAC / LCLS design as an example.
- X-rays change the transmission and refractive index of a foil.
- This change is detected as a spectral change on a chirped continuum pulse generated from the experiment laser

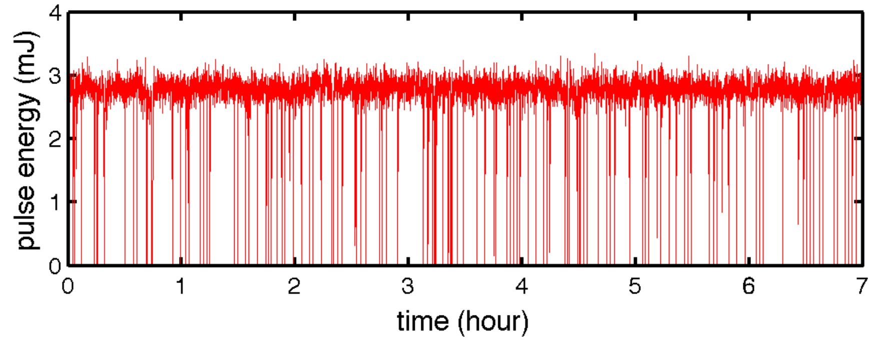




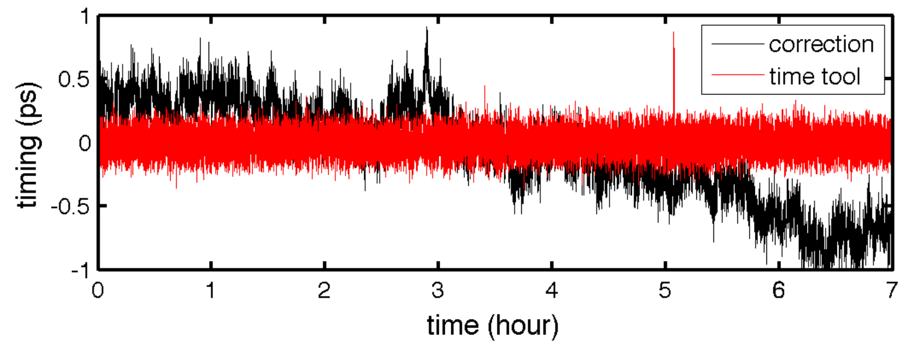
"Time Tool" X-ray / Optical cross correlator results



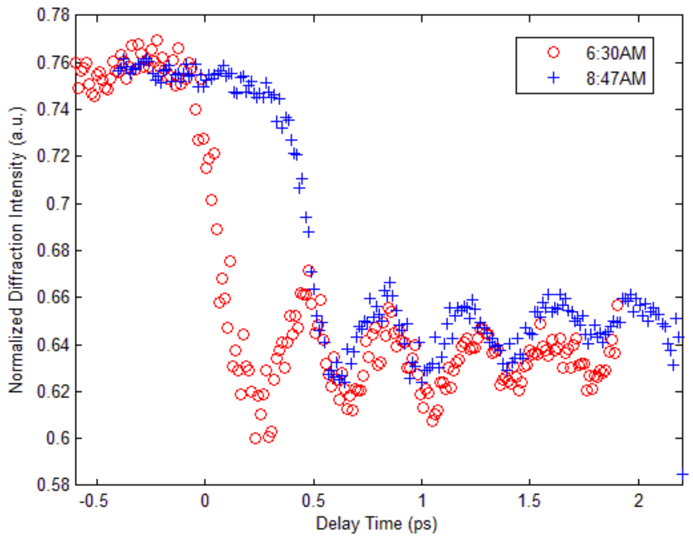
- Phase cavity (Bunch Arrival Monitor) improves jitter.
- Time tool makes a large additional improvement.



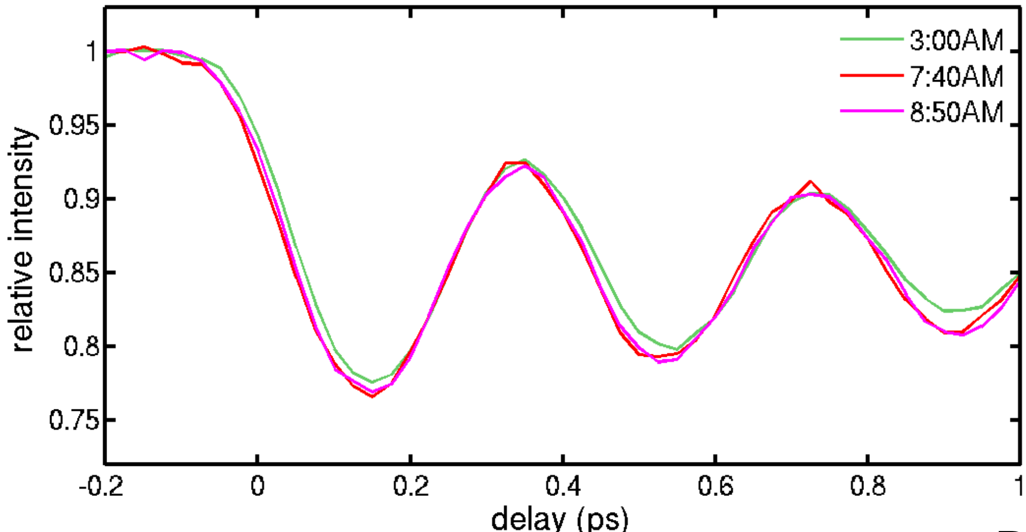
- Time tool data used in feedback to eliminate drift from the conventional timing system.



LCLS Timing System With and Without Time Tool



- Without time tool, 100fs/hour drifts are seen on experiments from a combination of
  - Arrival Monitor
  - Timing Distribution System
  - Laser Locking System
  - Laser Transport System



With Time Tool active the drift is <15fs

D. Zhu et al

Selecting an Arrival Time Monitor - Guidelines

SLAC

- The Arrival Monitor is rarely the performance limiting, or most expensive part of a precision timing system: Evaluate the entire design of your timing system.
- For low frequency systems operating below beam pipe cutoff, RF cavities are very attractive.
- For high frequency systems:
  - Operating above cutoff requires careful thought to avoid contamination from upstream signals
  - Optical systems generally have the highest bandwidth
  - Its not worth going a little above cutoff
  - These systems can be very high performance, but it is easy to get it wrong!
- Other schemes like TCAVS, undulators etc, may be useful in unusual situations.
- A physics based arrival time monitor at the experimental chamber will be better than ANY external timing system.
  - This is the best option if available.

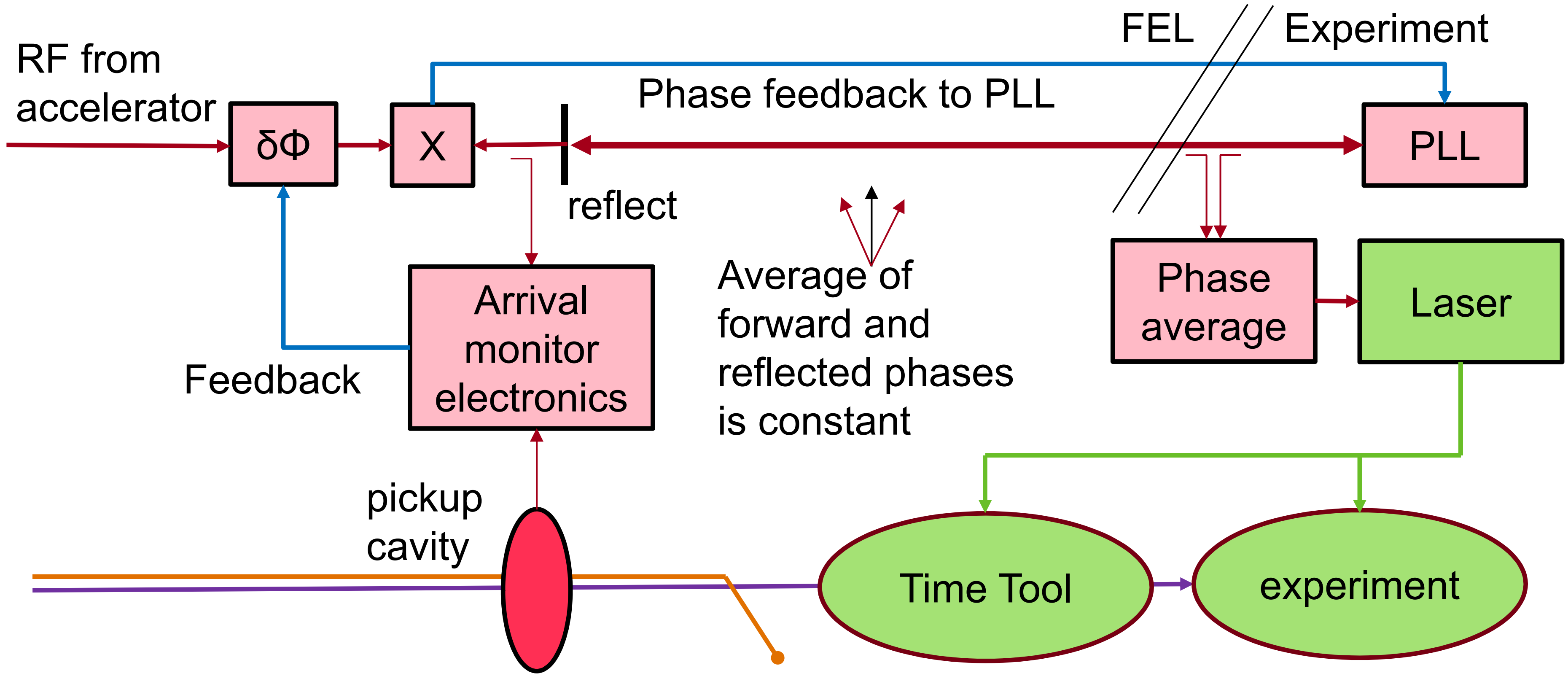
This is a job for Engineers, not Students (and not Scientists!).

Its like building a bridge – you don't want to have to re-invent engineering!

RF Cavity Arrival Time Monitor: SLAC / LCLS

- Example of a RF cavity based arrival time monitor
  - LCLS is a X-ray FEL facility, operating since 2007
    - 15 GeV electron beam from 1/3 of the old SLAC high energy physics LINAC
    - New gun and bunch compressors
    - 1.7km total length
    - Undulator
    - 15GeV, 20-250pC, 10-100 fs electron bunches, 120Hz.
- Arrival time monitor located after the undulator.
  - Provides femtosecond timing to the X-ray experiments.
  - In use since 2007

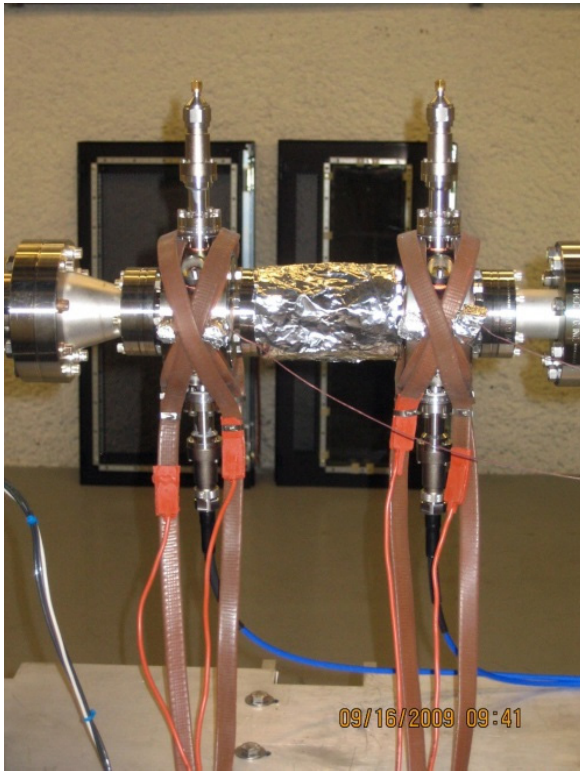
SLAC / LCLS Timing System



The RF reference from the accelerator is stabilized by the arrival time monitor. The resulting signal is transmitted to the experiment by a bi-directional RF line using phase averaging to correct for drift. The “time tool” X-ray / optical cross correlator provides precision timing. All long distance transmission is at 476MHz. 1/6 of the main accelerator frequency

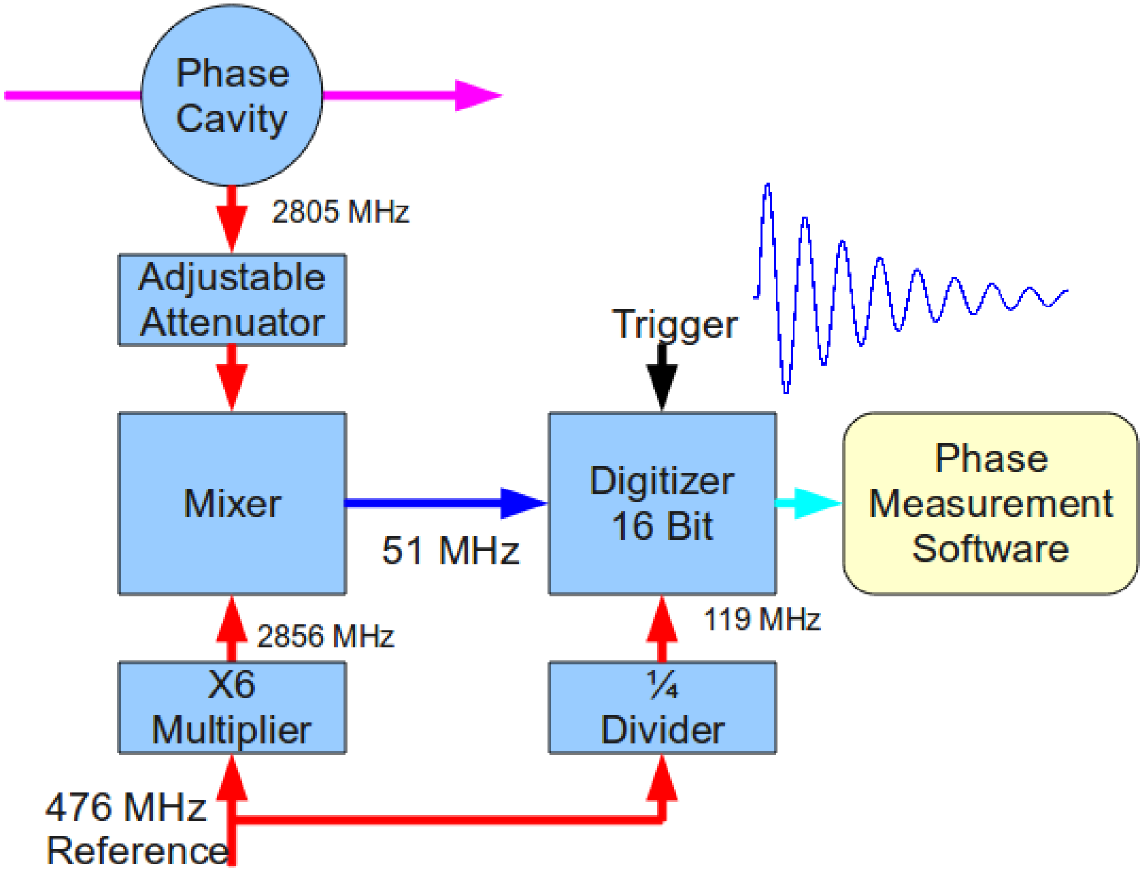
Arrival Time Monitor Cavities

- The LCLS uses beam pickup cavities at S-band, 2805MHz
  - Different from the GUN and Accelerator RF of 2856MHz to avoid measuring dark current
- Cavities are high Q (~7000) copper.
  - Couplers are NOT designed to reject dipole modes – no measurement of position sensitivity has been performed. (expected to be fairly small, and cavities are located after the undulator where the orbit is very stable).
  - Two cavities are used, each has a heater for calibration.



Arrival Time Monitor Electronics

- The electronics mixes the 2805MHz from the cavity with 2856 (6X the 476MHz reference).
- The resulting IF is digitized at 119MHz (locked to the reference).
- High linearity electronics used throughout to reduce amplitude -> phase conversion.
- Electronics is 8 years old, could be improved, but it is not the performance limiting part of the timing system.



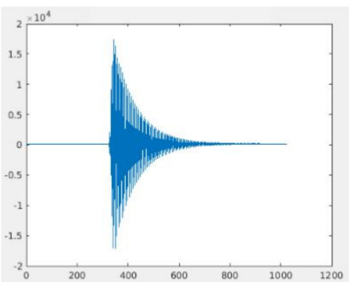
Note that the frequencies were chosen based on available hardware and are not optimal.

Temperature Correction

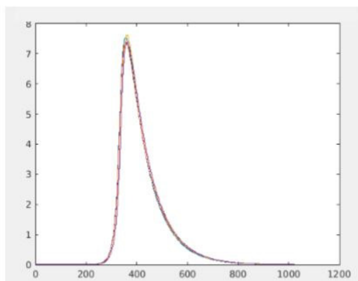
- Temperature coefficient of timing:
  - The high Q cavities ring at ~3GHz for ~10^4 radians
  - The thermal expansion of Copper is ~2×10^{-5}/℃
  - **Expect 10ps/℃ temperature sensitivity without correction!**
- The ringing frequency is directly proportional to temperature, in fact it is the change in frequency that is causing the problem in the first place
- Measure the changing resonant frequency and use it to correct the timing
- Calibrate the effect by heating first one cavity, then the other, and fitting the change in delay times relative to measured cavity frequencies.
- See poster "Implementation of Phase Cavity Algorithm for Beam Arrival Time Monitoring System for LCLS", MOPB076, K. H, Kim et al.
  - Unfortunately that was yesterday so you will need a time machine....

Correction Algorithm

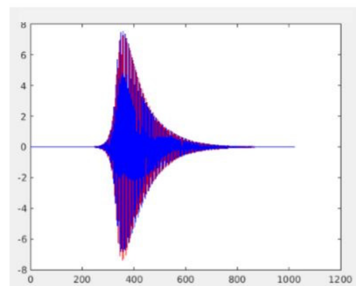
- Data Collecting for Calibration
  - temperature ramp up and down for two cavities serially
  - collecting RF raw waveforms for more than 6 hours , ~14k samples
  - offline analysis to get calibration parameters:
    window function, phase slope, frequency slope, initial frequency, centroid position and threshold for a good RF signal



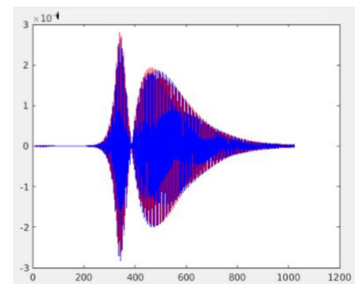
RF pulse signal



Window function

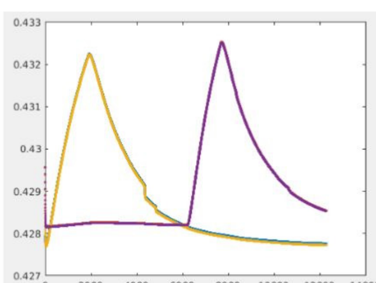


Phase Detection Waveform

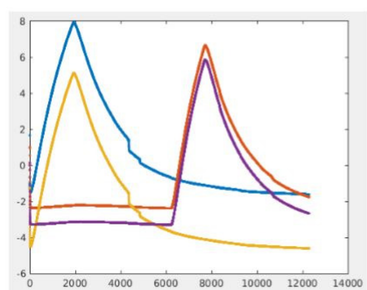


Frequency Detection Waveform

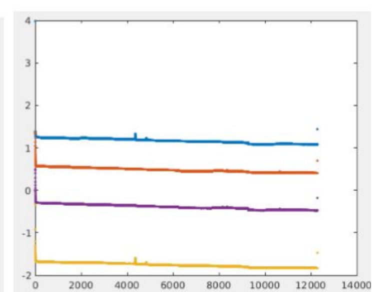
Frequency Error
Imaginary part of scalar product of RF signal and frequency detection waveform



Corrected Frequency



Phase Measurement before the phase correction

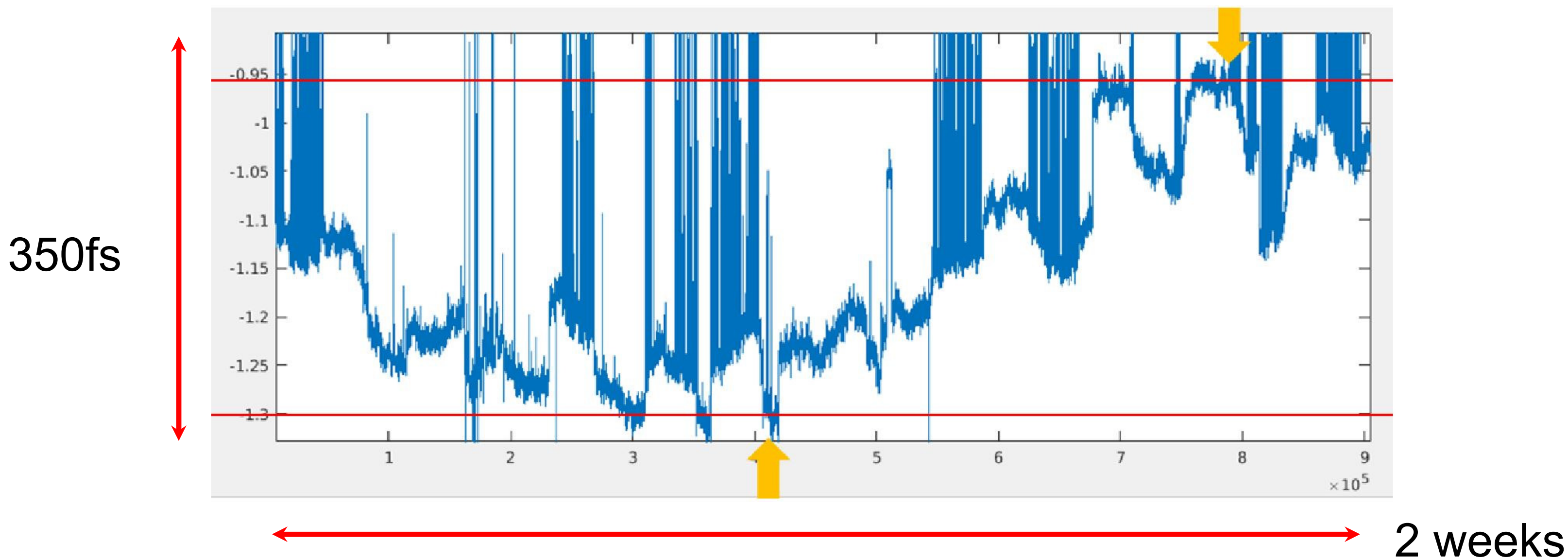


Corrected Phase

K.H. Kim

Arrival Time Monitor Performance

- RMS difference between measured timings for two cavities: 13fs RMS for a 1 minute measurement.
- Drift difference between timings for two cavities: 340fs pk-pk for 2 week measurement.
- (note the LCLS tunnel temperature is very stable ~0.1℃)



Note that the drift is not diurnal, typically < 100fs / day.

Where Does the Remaining Drift Come From?

- The drift is not diurnal and does not match the time structure of the temperature in the undulator hall:
- Humidity: Water has a high dielectric constant at RF frequencies. Water absorption in cables can change their phase length
- Physical motion: The 300fs drift corresponds to 100um motion. The cavity mounts could move due to changes in air pressure acting on bellows
- Beam conditions: changing satellite bunches, dark current etc. could cause timing changes.

In the end it doesn't matter – Other timing drifts are larger and the Time Tool fixes everything.

RF Arrival Time Monitor Reliability

- The SLAC / LCLS arrival time monitor has been in near continuous use since 2007.
- One hardware failure (loose connector caused 100fs jitter increase)
  - Automatic fail-over to redundant system allowed experiments to continue without loss of performance.
- Significant problems with real time communication of the measured arrival times to the experiment data acquisition system.
- Overall the system has been very robust and maintenance free!

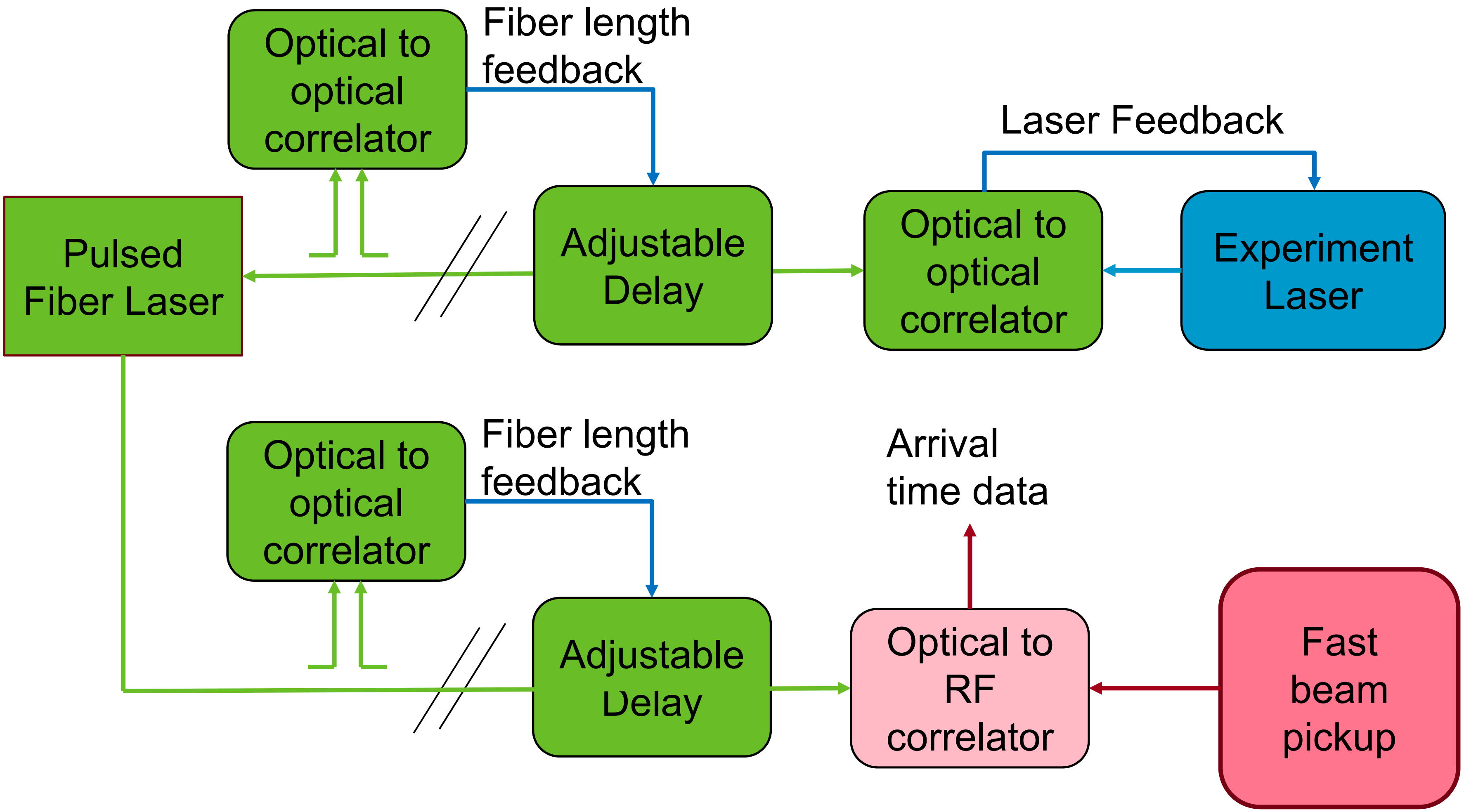
Pulsed Fiber Arrival Time Monitor – DESY / FLASH / European-FEL

- Several variants of a common design concept have been used or are under development for FLASH and the European FEL.
    - Will show a “generic” version
- System uses a pulsed fiber laser as a master source.
- Arrival time monitor uses high frequency RF pickups which drive commercial electro-optical modulators
- Designed for 20pC to 1nC, with beam burst rates to MHz.

This is the result the work of many groups at a wide variety of laboratories around the world.

F. Lohl et al, “Electron Bunch Timing with Femtosecond Precision in a Superconducting Free-Electron Laser” Phys. Rev. Lett. 104, 144801

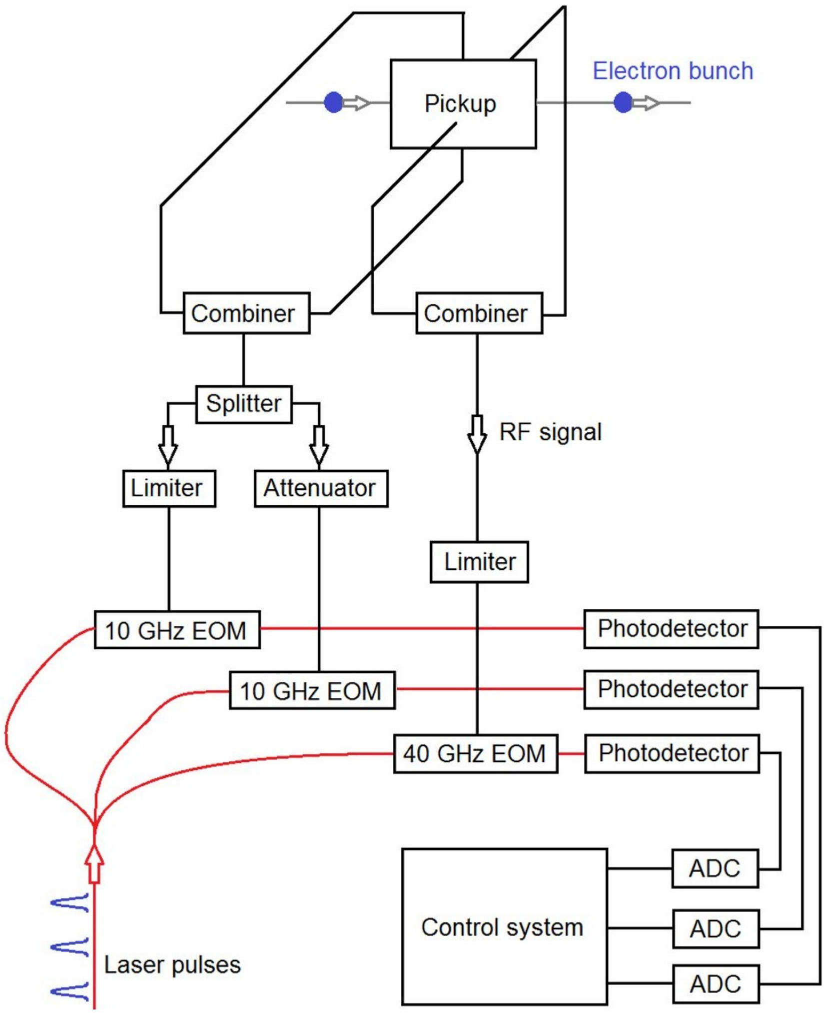
Pulsed Fiber Timing System



Fiber lengths are stabilized by comparing the forward and reflected pulse times with an optical correlator (nonlinear crystal)

Fiber Arrival Time Monitor Front End

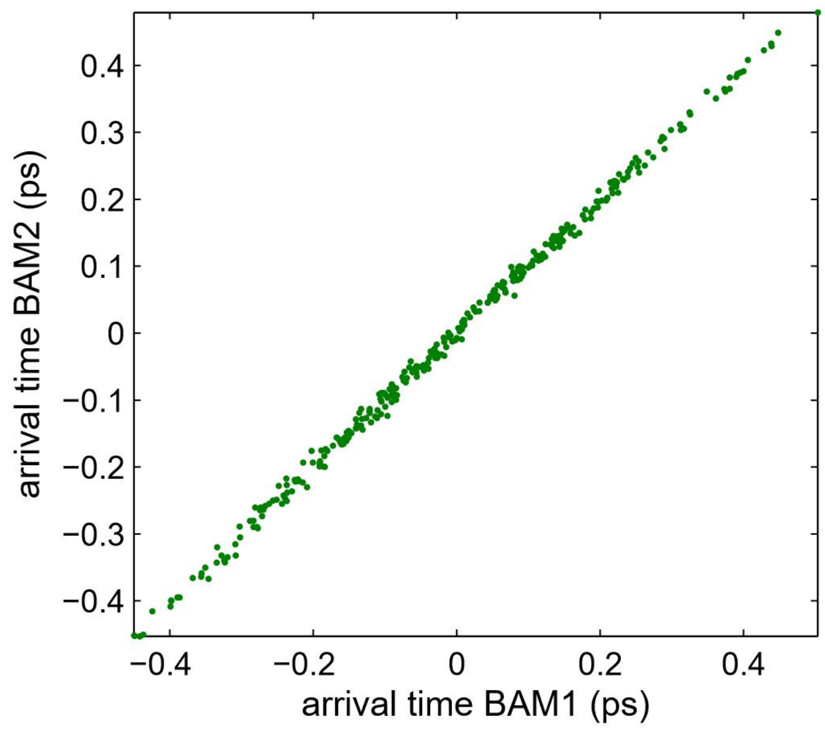
- "Coarse" 10GHz Channel
- "Fine" 40GHz Channel
- High frequency EO modulation of pulsed fiber laser intensity by the beam signal
- Intensity modulation detected by low bandwidth photo receivers.
- High bandwidth allows detection of the first zero-crossing of the 40GHz RF and reduces sensitivity to propagating beam pipe modes
- Large dynamic range requires the use of limiters / attenuators.
  - Care is needed to maintain good linearity and avoid amplitude -> phase conversion.



A. Kuhl et al.

Fiber Arrival Time Monitor Results

- Results from 2008 gave 9.5fs RMS difference between two monitors over 1 minute.
  - This was for an earlier lower bandwidth system, the 40GHz system is expected to have better performance.
- Long term drift is expected to be good.



F. Loehl et al

Fiber vs RF

- RF based systems
  - Simple and low cost
  - Straightforward RF engineering.
  - Very rugged with excellent reliability
  - Performance sufficient for many applications (<15fs jitter, <500fs multi-week drift)
- Electro-optical systems
  - Very good performance. <10fs jitter (3fs? – discussed but can't find in the literature).
  - Couple directly to high performance pulsed timing distribution systems.
- Experiment timing: X-ray / optical correlators
  - This changes everything. These will be better than any indirect system, but may not be applicable everywhere.

The Timing Chain – Conclusions

- Are the electrons you are measuring the ones that contribute to the physics?
  - Dark current? Tails? Does the entire beam laser in the FEL?
- Arrival Time Monitor?
- Timing transport system?
- Laser locker?
- Laser amplifier and compression chain?
- Laser transport of the experiment?

It is easy (and good) to get excited about building the best possible arrival monitor.

Just remember that it is experiment timing that matters, and the BAM is usually not the limit.