BEAM ARRIVAL TIME MONITORS

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Abstract

We provide an overview of beam arrival time measurement techniques for FELs and other accelerators requiring femtosecond timing. This paper will discuss the trade-offs between the various techniques used at different facilities.

ARIVAL TIME MONITORS

Beam timing is only meaningful relative to some reference, and in general what matters is the relative timing of two different systems. Pump / Probe experiments in FELs, UEDs etc. generally have the most critical 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 required.

It should be noted that the thermal expansion of conventional materials, cables, optical fibers etc. is typically on the order of 10^{-5}/°C, corresponding to 30fs/°C. Because of this, most arrival monitors are coupled to some form of stabilized timing transmission system, and the design of that system will influence the monitor technology choice.

As the arrival monitors are typically not the "weak link" in a timing system [1], trade-offs between cost and efficiency should be considered.

Timing System Architecture

A typical timing system includes the beam arrival monitor, a timing distribution system, and an experimental laser system as shown in figure 1:

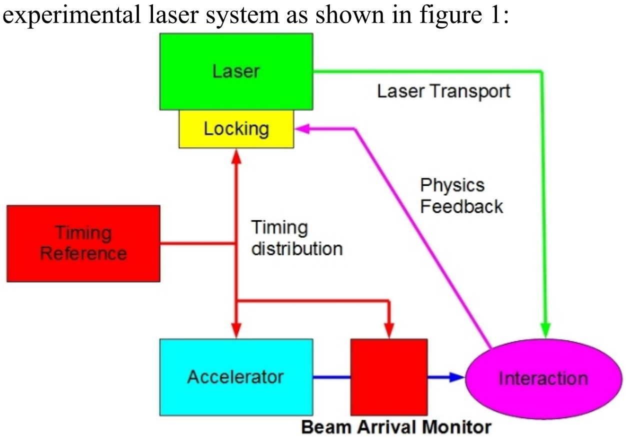

Figure 1: Typical timing system

The information from the beam arrival monitor may be used in a variety of ways:

- Provide feedback to the accelerator timing to reduce timing jitter [2]
- Correct the timing drift in the reference signal from the accelerator to the experiments [1]
- Provide offline correction of experiment data for shot to shot timing jitter [1]

DETECTING BEAM FIELDS

Frequencies

The electric fields from relativistic bunces diverge at an angle of $1/\gamma$ so that the fields at the beam pipe radius can contain high frequency components, in most cases above the maximum frequency (~50GHz) of conventional electronics. For high energy machines (γ>~300) the fields at the beam pipe will have frequency components higher than the response time of electro-optical system (~100fs).

Signal Levels

The field probes for arrival time monitors can be described as having a geometric impedance, for accelerator structures this is denoted by "R/Q", and for a cavity is typically 100Ω. The single pulse energy deposition is given by [3]

$$E = q^2 \left(\frac{\omega_0}{2}\right)\left(\frac{R}{Q}\right)$$

A 100pC bunch in a 3GHz cavity with 100Ω R/Q will deposit 10nJ. When this is compared to thermal noise of 2×10^{-21}J it corresponds to a timing resolution of 20 attoseconds. Other effects will limit the monitor resolution well before this level, and in most cases thermal noise is not the primary limitation in arrival time monitors.

Other types of beam pickoffs, including "buttons" may have much lower coupling and signal levels can be a performance limit.

Broadband vs. Narrowband Detection

Conventional electronics typically has ~1ps timing resolution for single shot measurements [4]. However if the beam electrical impulse is converted to a narrow band repetitive signal this allows multiple measurements to be averaged on a single pulse. Beamline cavities can perform this narrow-banding for low frequency systems.

Electro-optical systems can have very high bandwidths (100 fs response time) and provide few-femtosecond single shot resolution. These can be used without ringing filters.

Sources of Beam Fields – Working Above Cutoff

Electron beams will emit electromagnetic radiation whenever they encounter a change in beam pipe impedance. Components of this radiation above beam-pipe cutoff of 1.8412C/(2πR). (9GHz for a 1cm radius pipe) will propagate.

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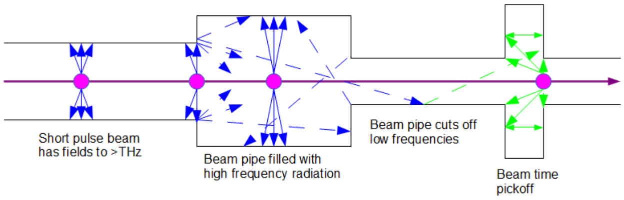

Figure 2: Fields above cutoff propagate from upstream.

The fields from upstream will have a position dependence that may interfere with the measurement of timing at the arrival time monitor. Note that most arrival time monitors have a measurement resolution that is much smaller than the operating frequency so even a small interfering signal can produce a significant timing distortion. (A 3GHz system has a time constant of ~50ps, so a -60dB interfering signal can result in 50fs errors).

Signals above cutoff will propagate with a group velocity less than C:

$$V_g = c\sqrt{\left(1-\left(\frac{f_c}{f}\right)^2\right)}$$

allowing them to be separated temporally. However, as the difference in velocities is small, using timing prevents the use of narrow band systems. The reduction in performance from using broadband detection makes operation slightly above cutoff an unattractive option in most cases.

At frequencies far above cutoff, propagation is essentially free space at the speed of light. This provides a very small delay – 150 fs for a 1cm radius beam pipe, at a distance of 1M.

Above cutoff operation has been used successfully at DESY / FLASH and other labs, [5] so provide few-femtosecond timing measurements. However, great care is needed in these systems to ensure that signals propagating from upstream do not result in position dependent time measurements.

Frequency / Bandwidth Choice

In general arrival time monitors fall into two types: Low frequency (<10GHz) cavity systems with low bandwidth that operate below cutoff, or high frequency (>10GHz – THz) systems with high bandwidth that operate above cutoff.

Dark Current, Tails and Halo

Most accelerators produce some unwanted beam charge in incorrect buckets from the gun or structure field emission. Defocused halo or tails may arrive at a different time from the main beam.

Beam pickups will see this dark current and it can interfere with the timing measurement. For example 10^{-3} charge out of time in a 3GHz arrival time monitor can produce a 50 femtosecond error.

Narrowband and low frequency systems are more susceptible to dark current / halo issues.

BEAM PICKUP TYPES

Cavities

For operation below cutoff cavities provide a narrow band high-Q beam pickup with good beam coupling. They are mechanically robust and the readout electronics use conventional RF techniques.

The largest disadvantage of cavities is their very high temperature sensitivity which needs to be corrected – described in a later section.

RF cavity based arrival time monitors have been used with few-femtosecond resolution at SLAC / LCLS. [1]

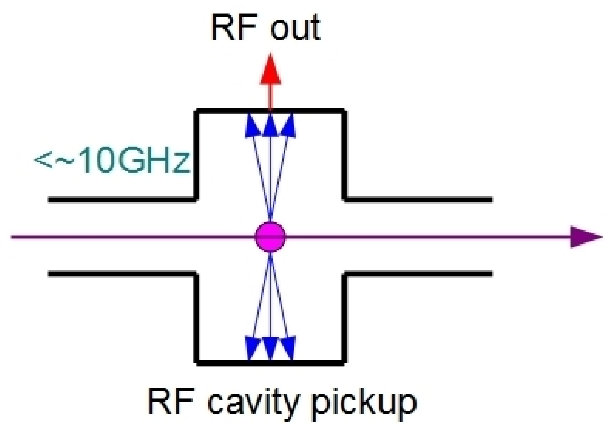

Figure 3: Cavity pickup.

Waveguide Pickup

Commercial RF waveguide components including mixers are available at frequencies up to several hundred GHz. [6] this allows high bandwidth systems to be built without optical components. However note that dispersion in the waveguide to the mm-wave mixer can prevent temporal separation of fields generated from upstream and propagating down the beam pipe.

Tests at SLAC / LCLS have shown >300GHz response from waveguide coupled systems of this type. However these have been used for bunch length, not bunch timing measurements.

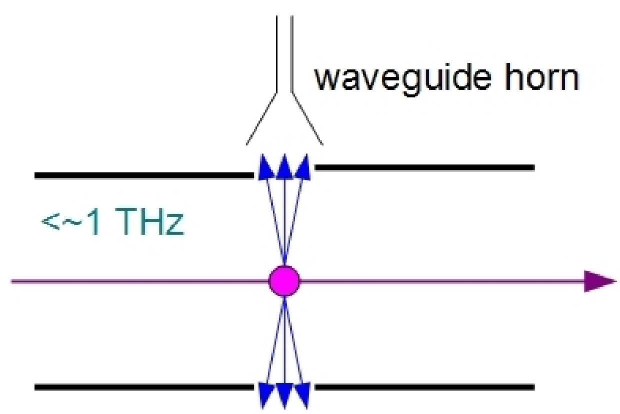

Figure 4: Waveguide based pickoff.

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Direct Electro-Optical Pickup

A fiber coupled electro-optical element placed near the beam will be directly exposed to the high bandwidth beam fields. If the electro-optical crystal is used to modulate a femtosecond optical pulse, extremely high bandwidth is available – generally limited by the phase matching requirements in the EO crystal to approximately 200fs. [7]

Direct EO systems have demonstrated few-femtosecond resolution [5], however care must be taken to avoid damage to the EO crystal from ionizing radiation or high electric fields due to its proximity to the electron beam.

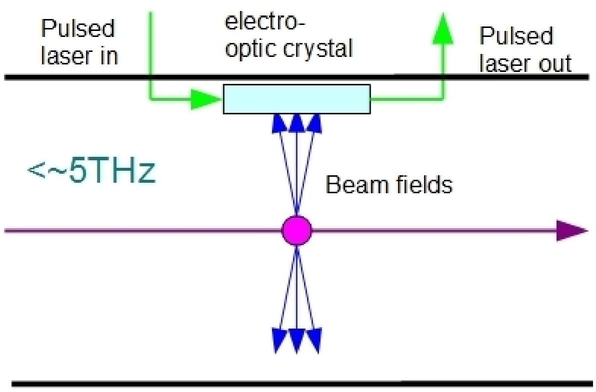

Figure 5: Direct EO sampling.

Indirect EO Sampling

The practical issues with direct EO sampling can be improved at the expense of bandwidth by using a fast electrical beam pickoff coupled to a commercial high bandwidth EO modulator. The bandwidth of such systems is typically limited to < 50GHz. A system of this type is planned for the European XFEL [8].

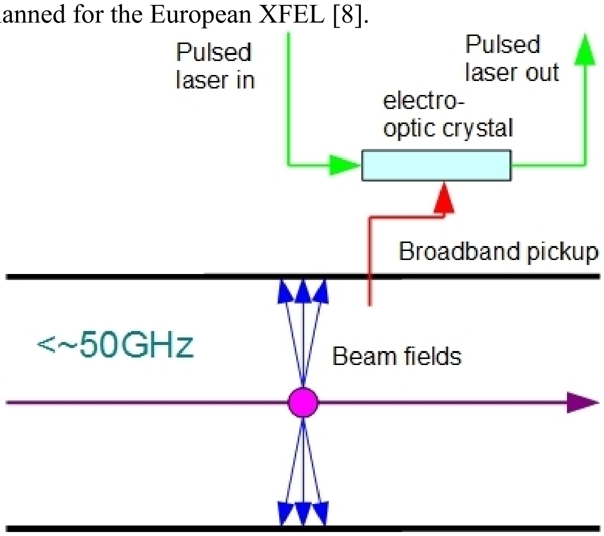

Figure 6: Indirect EO sampling.

OTHER SCHEMES

The majority of arrival time monitors rely on coupling out the beam fields, however a number of other schemes have been considered and many tested.

Transverse Deflection Cavities

Transverse deflection cavities are most commonly used to measure beam longitudinal profiles, however they can be used to measure beam arrival times. The transverse deflection of a beam in a TCAV is proportional to the relative arrival time of the beam to the cavity fields. [9]

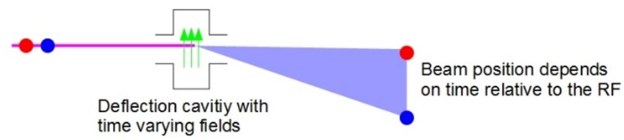

Figure 7: Transverse deflection cavity.

The fields in the TCAV are generally controlled through a feedback system based on a structure field probe. This system is very similar to a conventional cavity based arrival time monitor, so in most cases there is no performance improvement. However for very low charge beams where there is insufficient signal to noise for conventional arrival time monitors, a TCAV can provide improved resolution.

Free Space Radiation

An electron beam can radiate into free space through interaction with a foil (OTR) or undulator. Since the radiation source is well defined, spatial filtering can be used to reduce the effects of emission from upstream. The bandwidth is limited by the bunch length and can be very high. Mixing in nonlinear crystals can be used to interact the signal with a femtosecond laser to provide timing information.

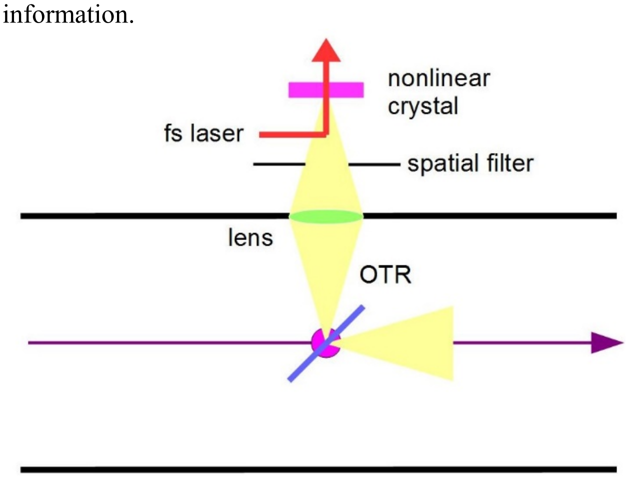

Figure 8: OTR signal generation.

Note that for an undulator it may be impractical to have a large enough K and wiggler wavelength for use with high energy electron beams.

Relative to direct EO modulation the OTR / Undulator technique has the following advantages

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- Higher signal intensity which allows the use of thinner nonlinear crystals and higher bandwidths
- Spatial and Spectral filtering can reduce interference from upstream signals
- External attenuation can provide large dynamic range.

The disadvantage is the substantially greater cost and complexity relative to conventional EO techniques. The authors are not aware of OTR being used as part of an experiment timing system.

X-ray Timing

Since the goal of X-ray FEL timing systems is to provide timing to experiments, schemes that directly measure the X-ray vs. laser timing are attractive. This type of system can provide the primary timing to experiments. Note that usually a conventional arrival time monitor is needed to keep the X-ray system within its dynamic range and for beam conditions where the X-ray system is unable to function. When available, X-ray / laser timing systems will generally provide the higher performance than other options.

In the system used at SLAC / LCLS the experiment laser is directed into an optical continuum generator and the resulting white light is temporally chirped. That chirped pulse then intersects the X-rays in a thin foil. The attenuation and index of refraction of the foil changes when it is hit by X-rays and this modified the spectrum of the transmitted light. [10]. Note that other schemes involving a special cross-correlation in an non-co-linear geometry have also been used at SLAC.

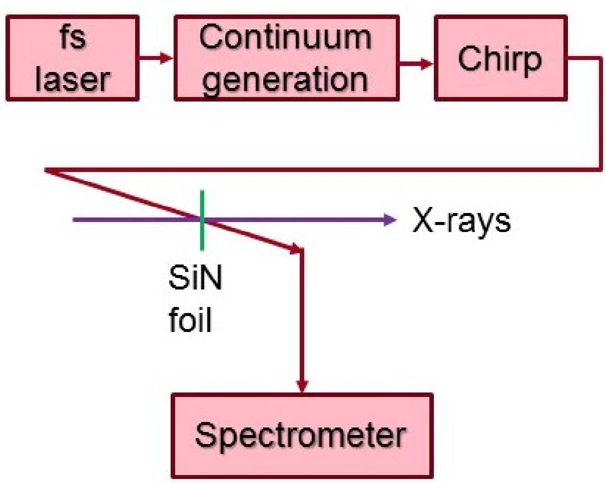

Figure 9: X-ray/optical cross correlator at SLAC/LCLS.

The improvement in timing resolution from using the X-ray / Optical arrival time monitor can be seen in figure 10 where a timing scan of the non-thermal melting of Bi is displayed. This experiment also demonstrated <15fs drift over 5 hours of operation.

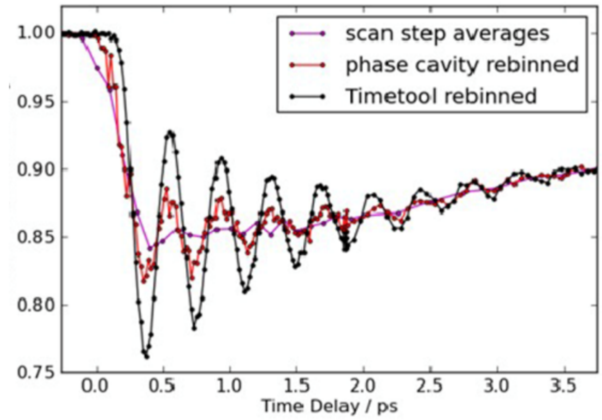

Figure 10: X-ray / Optical correlator (Time tool) improves resolution for non-thermal melting of Bi.[11]

RF CAVITY ARRIAL TIME MONITOR: SLAC / LCLS

The timing system for the LCLS is an all-RF based system. We present it as an example of the sorts of engineering to be considered in the design of a beam arrival monitor. The LCLS operates at 3-15 GeV, at 120Hz, with bunch charges from 20-250pC, and few kA peak currents.

Timing System Architecture

The LCLS timing system uses a reference signal from the accelerator transmitted through a ~1.5 km un-stabilized cable. The arrival time monitor measures the beam time in the undulator hall and corrects for the drift of the long cable. The resulting stabilized signal is then transmitted to the experiment stations using a bidirectional RF link. All long distance transmission uses 476MHz, 1/6 of the 2856 main accelerator frequency.

The bidirectional link operates as phase locked loop: The loop feedback fixes the time at the arrival time monitor. If the cable length changes (due to temperature), the change in the transmitted and reflected phases are equal and opposite, so an average of those phases is first order corrected for temperature.

Precision timing is provided by the X-ray / optical cross correlator "time tool".

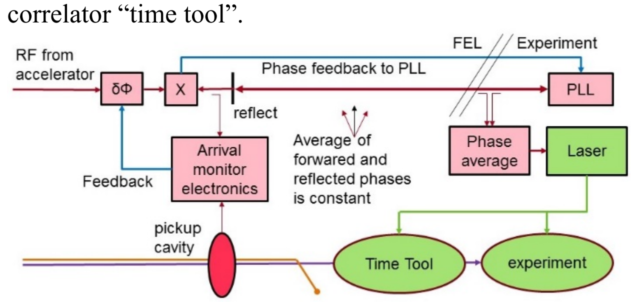

Figure 11: LCLS timing system overview.

Arrival Time Monitor Cavities

The LCLS uses beam pickup cavities at S-band, 2805MHz, different from the GUN and Accelerator RF of

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2856MHz in order to avoid measuring dark current The cavities are high Q (~7000) copper. Two cavities are used, each has a heater for calibration.

Note that he couplers are NOT designed to reject dipole modes and no measurement of position sensitivity has been performed. (This is expected to be fairly small, and cavities are located after the undulator where the orbit is very stable).

Arrival Time Monitor Electronics

The electronics mixes the 2805MHz from the cavity with 2856MHz (6X the 476MHz reference). The resulting 51MHz IF is digitized at 119MHz (locked to the reference). High linearity electronics used throughout to reduce amplitude -> phase conversion. The electronics is 8 years old, and could be improved, but it is not the performance limiting part of the timing system. Also note that the specific frequency choices were driven by the available hardware and are not optimal.

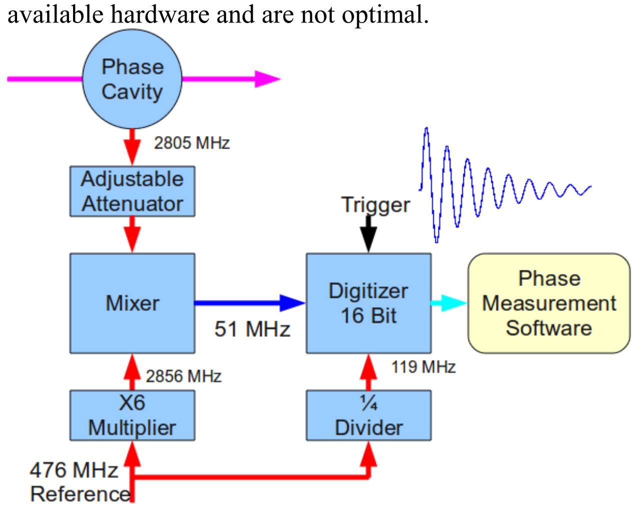

Figure 12: Arrival time processing electronics.

Temperature Coefficient Correction

The high Q cavities ring at ~3GHz for ~10^4 radians and the thermal expansion of Copper is ~$2x10^{-5}$/°C From this we expect 10ps/°C temperature sensitivity.

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. This allows us to measure the changing resonant frequency and use it to correct the timing

We calibrate by heating first one cavity, then the other, and fitting the change in delay times relative to measured cavity frequencies. For details see [12]

Note that the LCLS undulator hall where the arrival time monitor is located has a very stable temperature ~0.1 C.

Arrival Time Monitor Performance

The arrival time monitor has been in operation for approximately 8 years. After a recent upgrade to the processing algorithm the following performance was observed:

- 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 in figure 13 that the drift is not diurnal. The cause of this drift is not understood, there are a number of possible candidates:

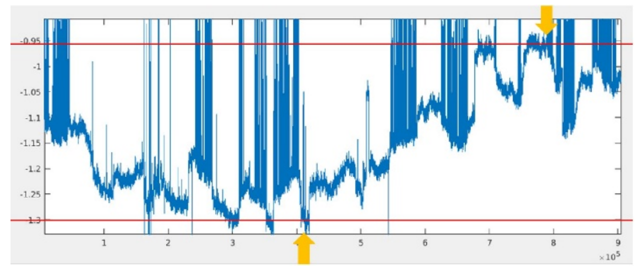

Figure 13: Drift over 2 week measurement ~340fs pk-pk.

The source of the residual drift is not understood. There are a number of possible causes that have not yet been investigated:

- 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 practice for LCLS the drift is not a significant problem as other drifts in the timing system are larger, and all are corrected by the Time Tool cross correlator for most experiments.

RF Arrival Time Monitor Reliability

Since its commissioning in 2007 the arrival time monitor has been in nearly continuous operation. It has had a single hardware failure, where automatic fail-over to the redundant system allowed experiments to continue. There have been several software / network issues, primarily related to the communication of the real-time data to the experiment data acquisition system.

PULSED FIBER ARRIVAL TIME MONITOR

Several variants of a common design concept have been used, or are under development for FLASH and the European FEL. Here we show a "generic" version.

The timing system uses a 216MHz, 100fs soliton laser as a master source and the arrival time monitors use high frequency RF pickups which drive commercial electro-optical modulator. The system is designed for 20pC to 1nC charges, with beam burst rates to MHz [13].

Fiber Timing System

The fiber timing system samples the forward and reflected laser pulses in the long haul fibers. The pulse overlap is measured by correlating in a nonlinear crystal –

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providing a measurement at the full bandwidth of the laser. Changes in delay are corrected by adjusting the length of the transmission fiber (fiber stretcher or mechanical delay line). In some variants polarization preserving fiber is used, in others a polarization feedback is used to control polarization.

This stabilized fiber backbone is used to synchronize the arrival time monitor and the experiment laser system.

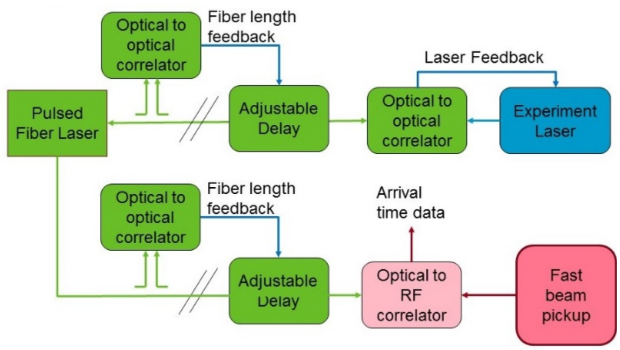

Figure 14: Fiber timing backbone.

EO Arrival Time Monitor

The electro-optical arrival time monitor uses indirect EO sampling with a broadband pickup with 10GHz (coarse) and 40GHz (fine) channels. The beam field's amplitude modulates the pulsed fiber signals whose intensity are then detected by low bandwidth receivers. The large required dynamic range necessitates the use of attenuators and limiters, so care is required to avoid amplitude -> phase conversion.

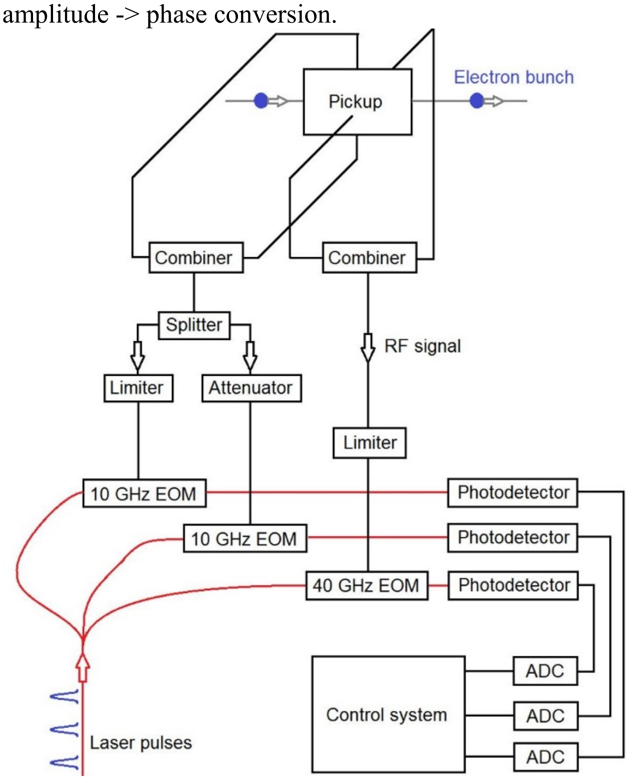

Figure 15: Fiber BAM front end. [14]

EO Arrival Time Monitor Performance

A 5GHz version of the EO system tested in 2008 at DESY FLASH where it demonstrated 9.5fs RMS difference over a 1 minute interval between two arrival monitors [13]. The long term drift was not published but is expected to be low.

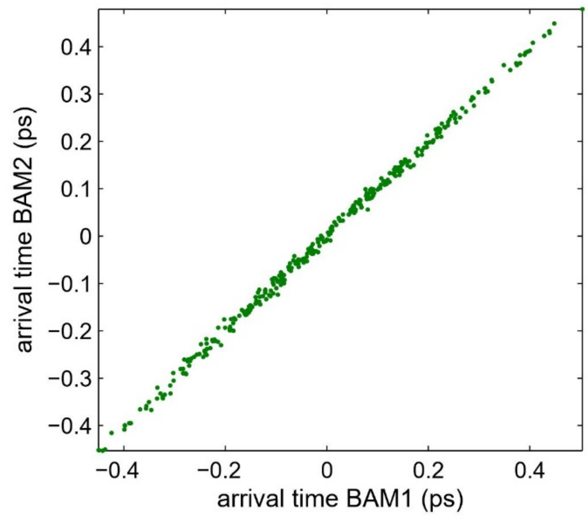

Figure 16: EO Arrival time monitor 9.5fs RMS difference over 1 minute measurement at DESY / FLASH.

DESIGN CHOICES

Fiber vs RF

Both Fiber and RF based arrival time monitors have been used successfully. RF systems generally operate below beam-pipe cutoff and are relatively simple, rugged and inexpensive. Fiber based Electro-optical systems generally operate at as high a frequency as is practical, above the beam-pipe cutoff. They in general provide better performance than RF systems, but are more complex to construct and maintain.

System Overview

The Arrival Time Monitor is just one component of an experiment timing system and many other components may be larger contributors to the overall timing error:

- 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 to the experiment?

All these sub-systems should be considered when designing a timing system.

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