Timing and Synchronization

CERN Accelerator School
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Accelerator-based Sciences and Education (CLASSE)

Outline

- Basics

  RF signals, timing jitter, PLL, mixer, …

- Arrival-time fluctuations in free-electron lasers (FELs)

  Injector, bunch compressors, …

- Systems required to synchronize an FEL

  RF and laser based synchronization, signal distribution, arrival-time monitors, laser synchronization, photon pulse arrival-time monitors

Timing ↔ Synchronization

Goal:

- Having many systems act in sync or in a well defined sequence.
- Being able to correlate measurement data of different systems.

Timing

Event Information

- Trigger signals
- Bunch train numbering
- Beam modes, etc.

Clocks signals

- Square waves
- Adjustable delays
- Various clock frequencies

Synchronization

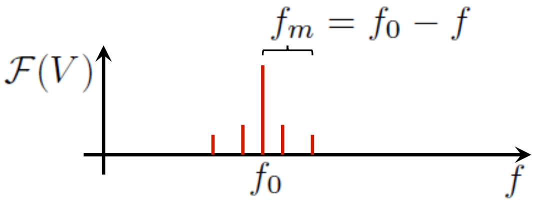
Passive:
When does an event happen with respect to a “perfect”, periodic clock?
→ “phase information”
(oscillating clock)

Active:
Apply a correction for the next event based on measurement for a previous event.

Phase noise and timing jitter

Imperfect RF signal: $$V(t) = (\underset{\substack{\uparrow \\ \text{amplitude} \\ \text{error}}}{V_0 + \alpha(t)}) \sin(2\pi f_0 t + \underset{\substack{\uparrow \\ \text{phase} \\ \text{error}}}{\phi(t)})$$

The amplitude and phase modulation leads to side-bands in the frequency spectrum.



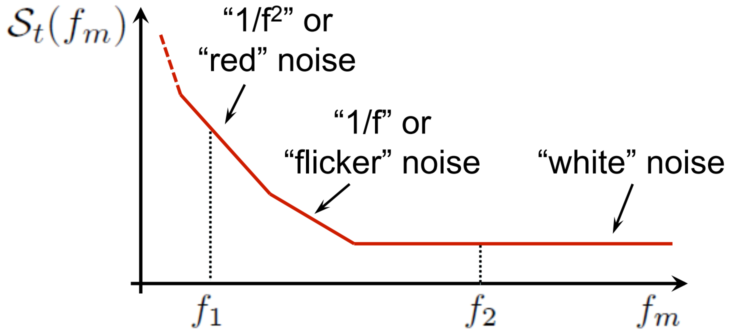
Single side-band phase noise: $$\mathcal{L}_\phi(f_m) = \frac{\phi^2_{\text{rms}}}{\Delta f}$$

ϕ^2_{rms} rms phase variation of carrier frequency f_0 occurring at offset frequency f_m

Δf measurement bandwidth

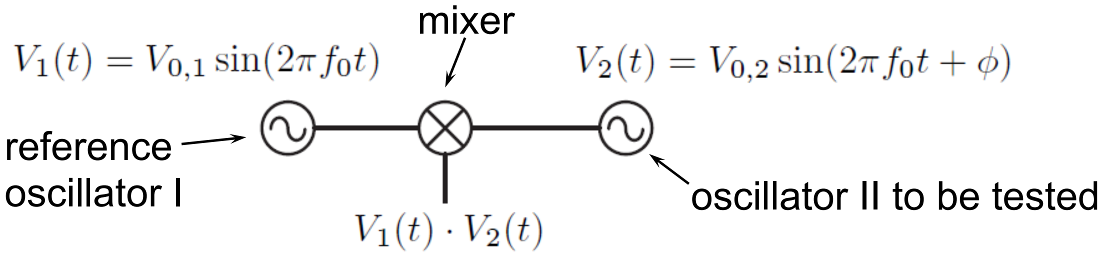
Phase noise and timing jitter

Timing jitter spectral density: $\mathcal{S}_t(f_m) = \frac{2}{(2\pi f_c)^2}\mathcal{L}_\phi(f_m)$



Integrated timing jitter: $\Delta t_{\mathrm{rms}}[f_1, f_2] = \sqrt{\int_{f1}^{f_2} \mathcal{S}_t(f_m)\mathrm{d}f_m}$

Example 1: How to measure phase / timing jitter



$V_1(t) = V_{0,1}\sin(2\pi f_0 t)$

mixer

$V_2(t) = V_{0,2}\sin(2\pi f_0 t + \phi)$

reference oscillator I

oscillator II to be tested

$V_1(t)\cdot V_2(t)$

Using trigonometry, we get:

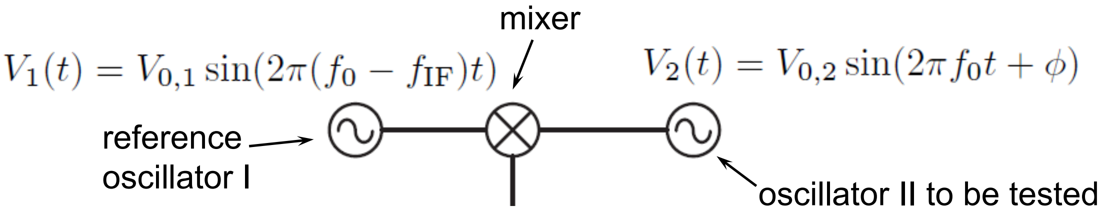
$$V_1(t){\cdot}V_2(t) = \frac{1}{2}V_{0,1}V_{0,2}\,[\underbrace{\cos(\phi)}_{\text{difference frequency}} - \cos(2\pi(\underbrace{f_0 + f_0}_{\text{sum frequency}})t + \phi)]$$

The term oscillating at twice the original frequency can be removed with a low-pass filter.

$\phi = 0$ mixer measures product of amplitudes

$\phi = \pi/2$ mixer measures phase difference

Example 2: IQ detection



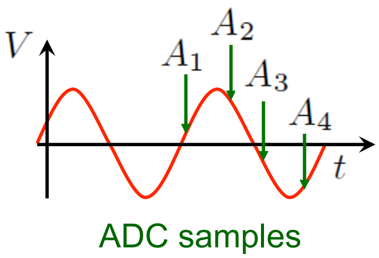
$V_1(t) = V_{0,1}\sin(2\pi(f_0 - f_{\mathrm{IF}})t)$

$V_2(t) = V_{0,2}\sin(2\pi f_0 t + \phi)$

$$V_1(t)\cdot V_2(t) = \frac{1}{2}V_{0,1}V_{0,2}\,\left[\cos(2\pi f_{\mathrm{IF}}t + \phi) - \cancel{\cos(2\pi(2f_0 - f_{\mathrm{IF}})t + \phi)}\right]$$

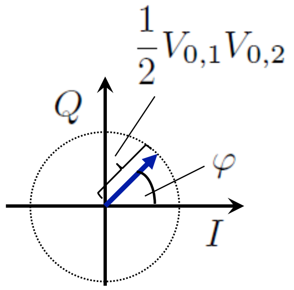
Detection of the mixer output with an ADC

Here: ADC clocked at $4f_{\mathrm{IF}}$



$$I = \frac{1}{2}(A_1 - A_3)$$

$$Q = \frac{1}{2}(A_2 - A_4)$$

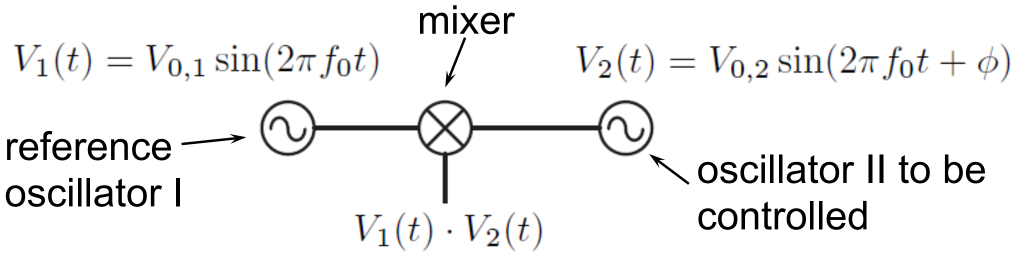


Scheme measures phase relation between ADC clock and IF signal

- φ shifts by same amount as ϕ
- Scheme sensitive to ADC clock jitter

→ Less sensitive for low IF frequency

Phase Lock Loop (PLL)



$V_1(t) = V_{0,1}\sin(2\pi f_0 t)$

$V_2(t) = V_{0,2}\sin(2\pi f_0 t + \phi)$

How do we achieve that the frequency of both oscillators is identical?

→ We need to actively adjust the frequency of oscillator II

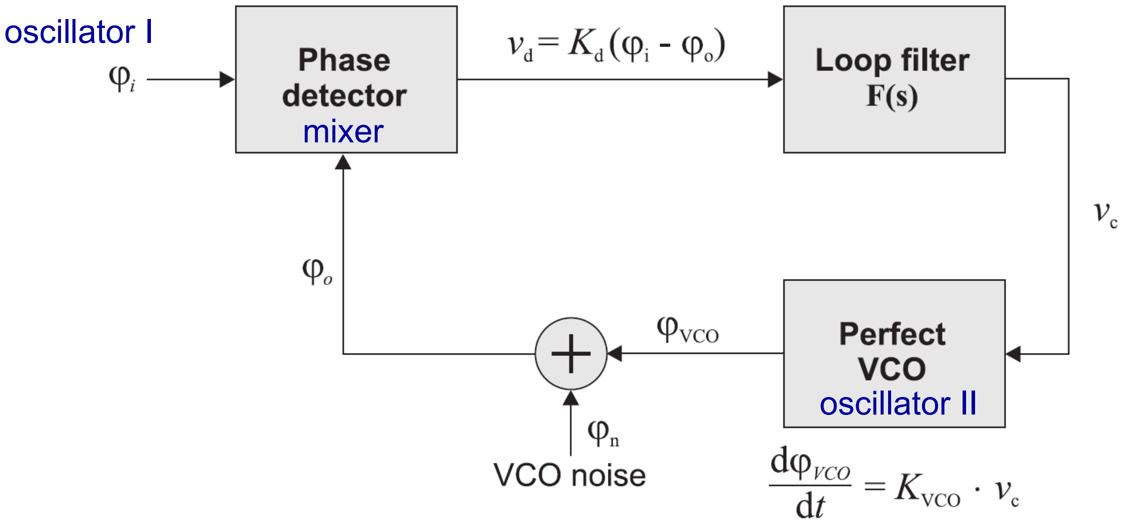
Let us assume that the frequency of oscillator II can be adjusted with a tuning voltage :

$$\Delta f = \frac{\mathrm{d}\varphi_{\mathrm{VCO}}}{\mathrm{dt}} = K_{VCO}\cdot\nu_c$$

const. tuning voltage

“voltage controlled oscillator” (VCO)

Phase Lock Loop (PLL)

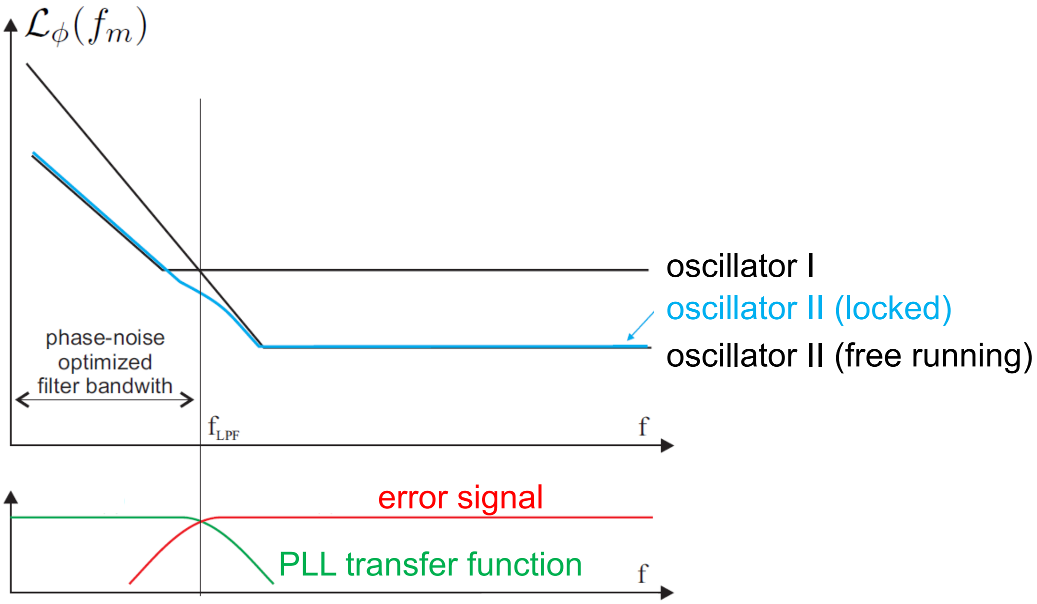


A phase lock loop stabilizes the phase relation between both oscillators.

→ This also leads to identical frequencies!

Phase lock loop (PLL)

With a PLL, two oscillators can be combined to a single ‘better’ oscillator:



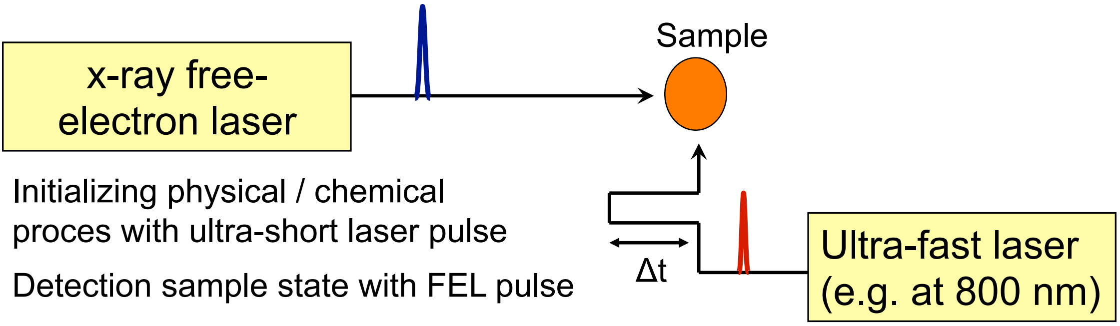
Required synchronization accuracy in accelerators

Typical bunch durations of electron accelerators

Synchrotron light sources	BESSY	σ_z = 10mm	~ 20 ps
Low-alpha Multi Bunch Hybrid Modus			**~ 2 ps**
Linac driven colliders	SLC	σ_z = 2 mm	~ 6 ps
	ILC	= 0.15 mm	~ 0.5 ps
Free-electron lasers	Eur. XFEL	σ_z = 20 um	~ 60 fs
Short pulse operation @FLASH:		FEL pulses	< 5 fs

Free-electron lasers and future linear colliders require a synchronization accuracy orders of magnitude better than in storage rings!

Pump-probe experiment in a free-electron laser



x-ray free-electron laser

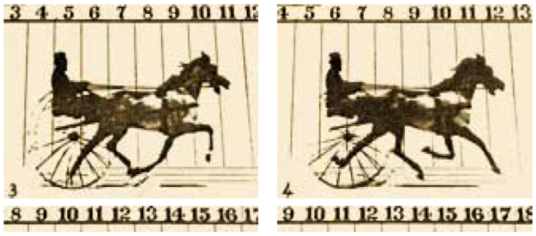
Ultra-fast laser (e.g. at 800 nm)

- Initializing physical / chemical proces with ultra-short laser pulse
- Detection sample state with FEL pulse
- Variation of relative delay between both pulses to measure dynamic of the system

→ Pulse durations determine required synchronization precision

10 fs long pulses ➡ <10 fs synchronization

Edward Muybridge (1878)
Exposure time: 2 ms
Time resolution: 40 ms



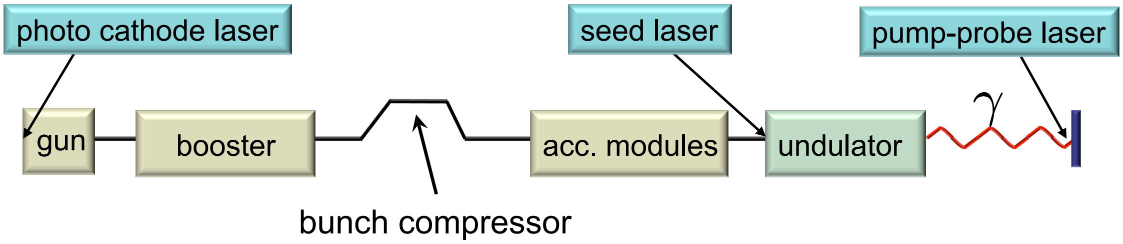
Timing needs in an x-ray FEL

Which level of accuracy is required?

Ultimate goal:

Arrival-time stability between x-ray pulses and pump-probe laser pulses: fraction of pulse duration

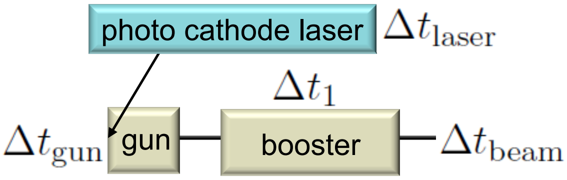
Simplified schematic of an FEL:



Bunch arrival-time jitter at the undulator has three main sources:

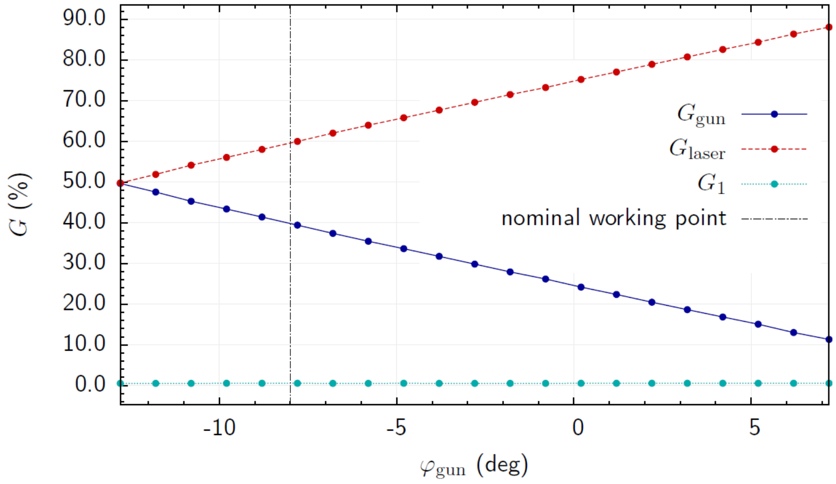
1. Arrival-time jitter generated at the beam generation
    - Photo cathode laser
    - Gun
2. Cavity field amplitude fluctuations in the booster module
3. Cavity field phase fluctuations in the booster module

Arrival-time jitter from the electron source



Example:
FLASH injector

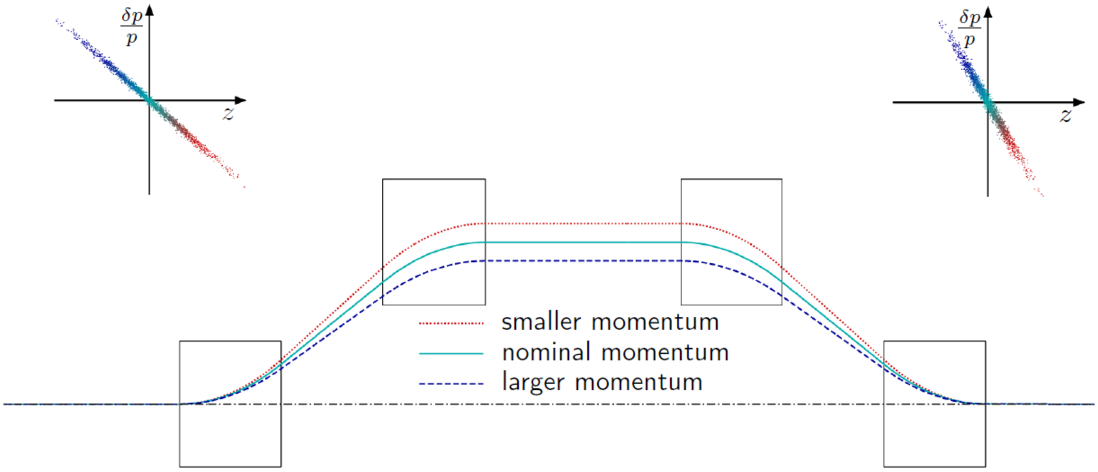
$$\Delta t_{\mathrm{beam}} = G_{\mathrm{laser}} \cdot \Delta t_{\mathrm{laser}} + G_{\mathrm{gun}} \cdot \Delta t_{\mathrm{gun}} + G_1 \cdot \Delta t_1$$



After the gun, the beam is already ultra-relativistic:

→ Almost no dependence on booster phase.

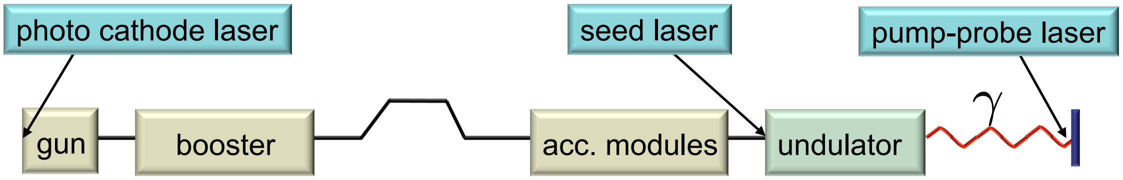
Bunch compressor principle (idealized)



- The bunch enters the compressor with an energy chirp
- Energy chirp generated by off-crest acceleration in the booster
- Longitudinal dispersion (the R_{56} matrix element) is used to compress the bunch

- Higher beam energy
→ earlier arrival-time

Arrival-time jitter after a bunch compressor



$$\underset{\substack{\uparrow\\ \text{timing jitter}\\ \text{after}\\ \text{compressor}}}{\Sigma_t^2} \approx \Big(\frac{R_{56}}{c_0}\underset{\substack{\uparrow\\ \text{cavity field}\\ \text{amplitude jitter}}}{\frac{\sigma_A}{A}}\Big)^2 + \Big(\frac{C-1}{C}\Big)^2\Big(\underset{\substack{\uparrow\\ \text{cavity phase}\\ \text{jitter}}}{\frac{\sigma_\phi}{2\pi f_{\mathrm{RF}}}}\Big)^2 + \Big(\frac{1}{C}\Big)^2\underset{\substack{\uparrow\\ \text{injector timing}\\ \text{jitter}}}{\Sigma_{i,t}^2}$$

Resulting requirements for 10 fs arrival-time stability
with FLASH parameters (R_{56} ≈ 180 mm, f_{RF} = 1.3 GHz)

< $1.5\mathrm{x}10^{-5}$	field amplitude stability of vector sum
< 0.005º	phase stability of vector sum

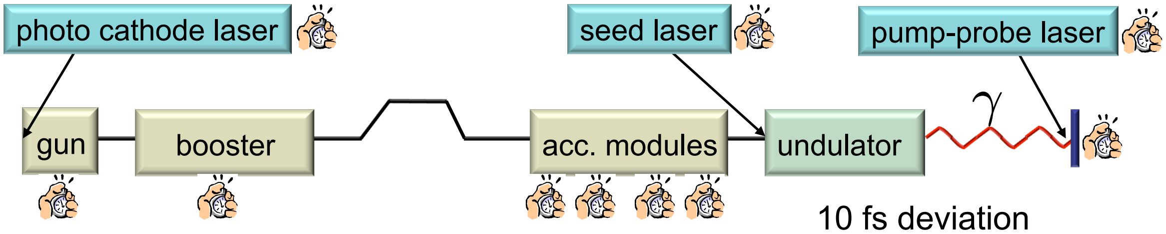
In most FELs there are multiple bunch compressors and the equation needs to be applied recursively while taking the energy gains into account.

Selected other sources of beam arrival-time changes

			arrival-time deviation
Beam energy spread			
	1000 m long, straight trajectory,	$\delta E/E < 0.1\%$	$\delta t < 0.8\,\mathrm{fs}$
Beam orbit jitter			
	1000 m long, straight trajectory, angular kick every 10 m	$\delta x < 50\,\mu\mathrm{m}$	$\delta t < 0.04\,\mathrm{fs}$
Thermal expansion			
	1000 m long, straight path 1 deg C temperature change	Concrete	$\delta t \approx 40\,\mathrm{ps}$
		Stainless steel	$\delta t \approx 58\,\mathrm{ps}$
		Invar	$\delta t \approx 4\,\mathrm{ps}$

Synchronization strategy

Can we install a high precision clock at every required location in the accelerator and reference all timings to these clocks?



10 fs deviation between clocks after:

Atomic clock: (e.g. GPS) $$\frac{\Delta t}{t} = \frac{\Delta f}{f} \approx 10^{-12}$$ 10 ms

Optical clock: $$\frac{\Delta t}{t} = \frac{\Delta f}{f} \approx 10^{-17}$$ 1000 s

→ Would require constant re-synchronization of clocks!

What do we need to achieve femtosecond stability?

- Laser synchronization
- RF signal distribution
- Bunch arrival-time measurements

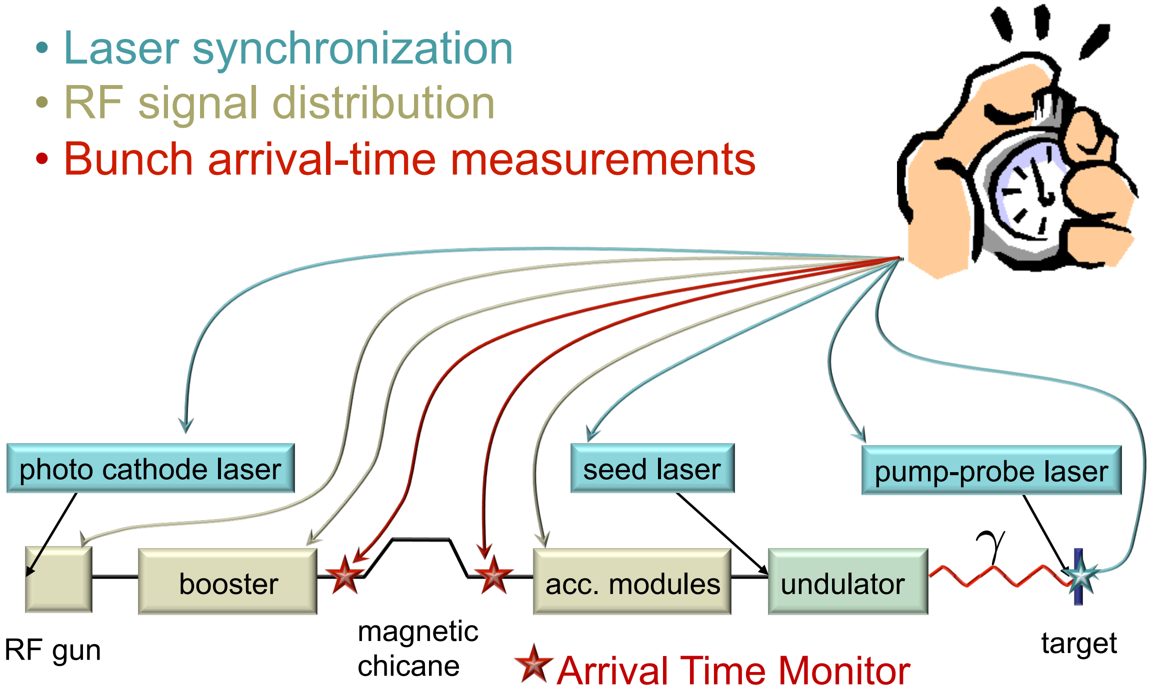


photo cathode laser

seed laser

pump-probe laser

RF gun

booster

magnetic chicane

acc. modules

undulator

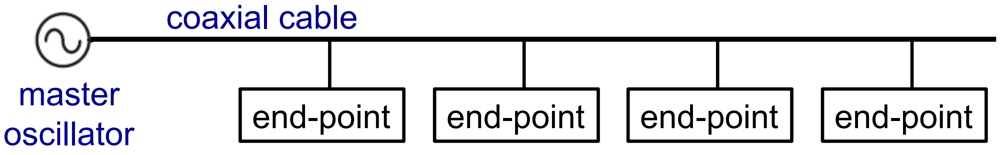
γ

target

★Arrival Time Monitor

RF based, coaxial timing distribution

Conventional RF based synchronization:



coaxial cable

master oscillator

end-point

end-point

end-point

end-point

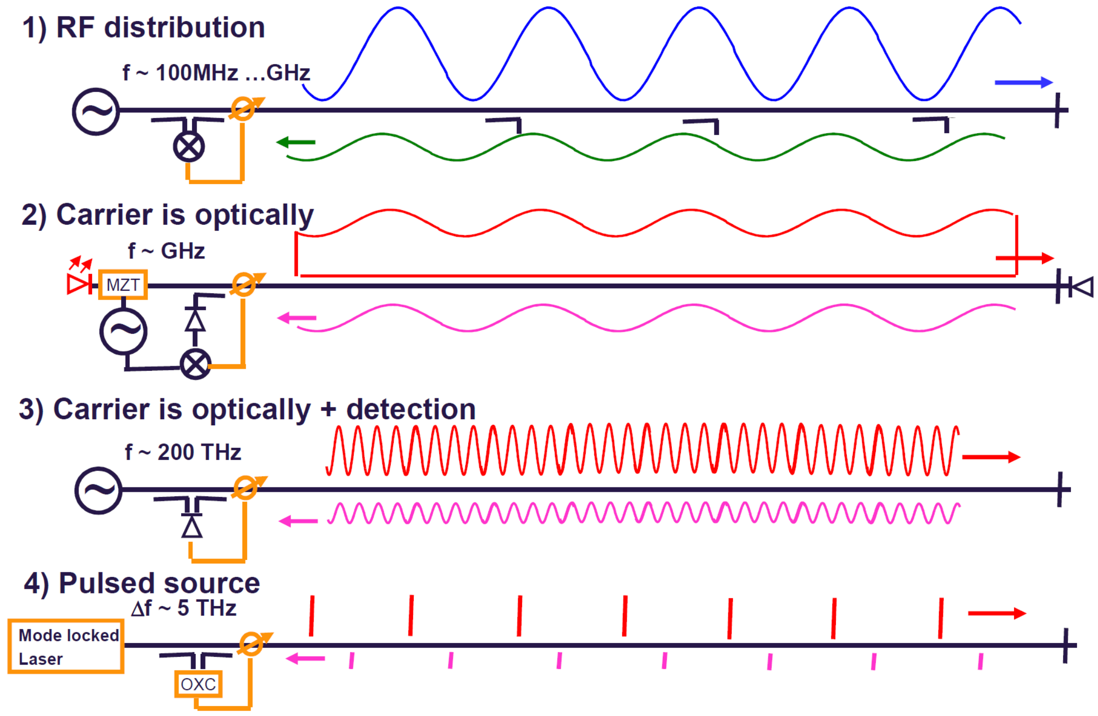
☺ High-frequency RF oscillators can be very stable
(~femtoseconds in offset-frequency range of interest)

☹ Thermal expansion of coaxial cables!
(thermal coefficient between 1 to 10 x 10^{-6})
→ Many tens of ps of drift for 1000 m long cable (ΔT = 1 ºC)

☹ Cable attenuation is very high at > 1 GHz frequencies
Limited to short cable length (hundreds of meters)
or
Limited to low frequencies (~ 100 MHz) → lower precision

Possible improvements: star-topology, active drift compensation, …

Reference signal distribution schemes

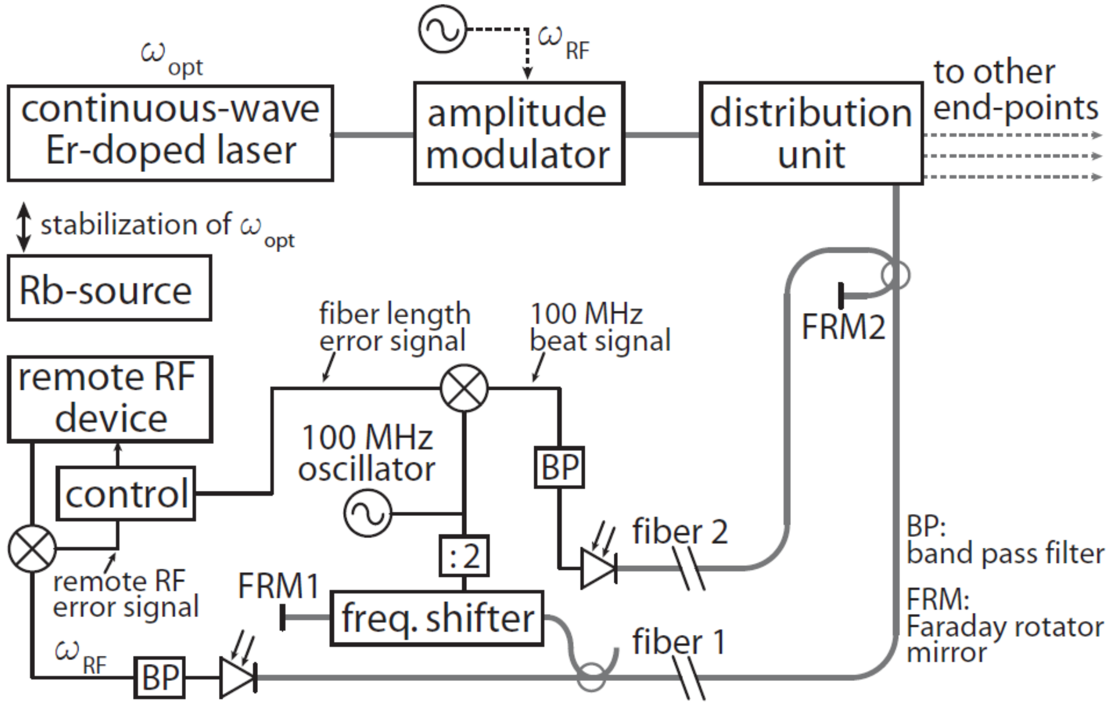


Slide from H. Schlarb

Femtosecond stable timing distribution CW & pulsed optical systems

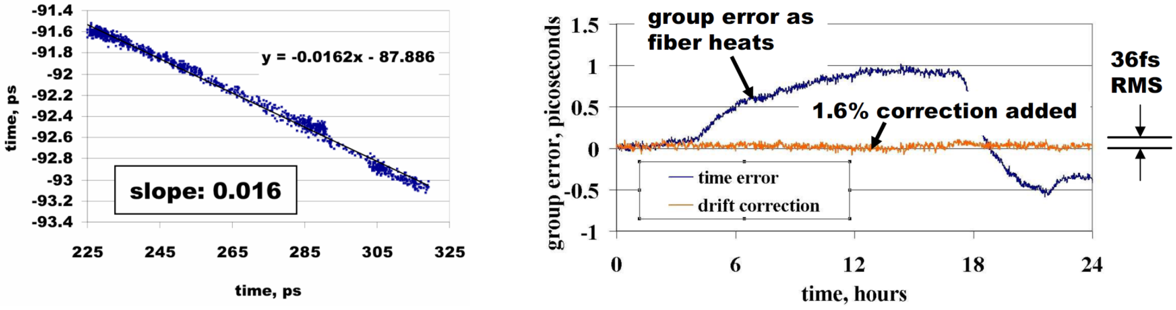
CW	Pulsed
Transmission of ‘single’ frequency laser light	Transmission of ~100 - 200 fs long laser pulses
Interferometric stabilization of an optical fiber	Stabilization of an optical fiber based on cross-correlation techniques
Transmission of RF signal through stabilized optical fiber (by modulating laser amplitude)	After transmission fiber: • generation of RF signals • direct use of laser pulses for laser based diagnostics / experiments (e.g. bunch arrival-time measurements, beam position measurements, RF phase measurements, …) • locking of lasers by cross-correlation
After transmission fiber: • extraction of RF signal	
stability: < 10 fs	stability: < 10 fs

CW optical synchronization scheme



CW optical synchronization scheme

Difficulty: (temperature dependent) difference between the phase velocity of the optical carrier frequency and the group velocity of modulated RF signal

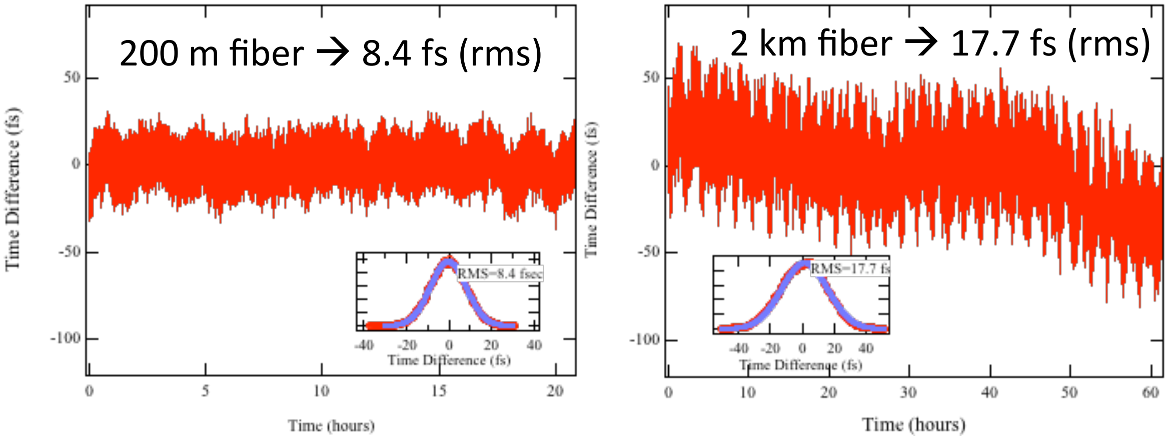


→ Additional feed-forward term added in digital controller to correct for this.

data from R. Wilcox et. al. (Berkeley synchronization team)

CW optical synchronization scheme

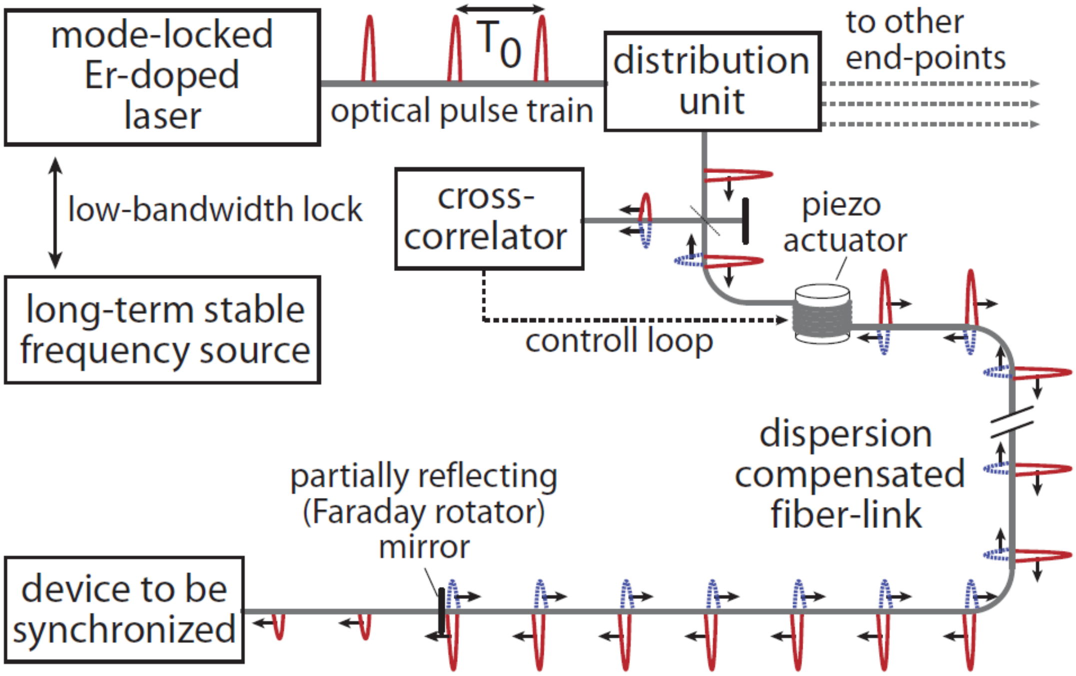
Stability of RF signal transmission:


200 m fiber → 8.4 fs (rms)

2 km fiber → 17.7 fs (rms)

R. Wilcox et. al., Opt. Lett. **34**, 20, pp. 3050-3052 (2009)

Pulsed optical synchronization scheme: Fiber link stabilization


mode-locked Er-doped laser

T_0

optical pulse train

distribution unit

to other end-points

low-bandwidth lock

long-term stable frequency source

cross-correlator

piezo actuator

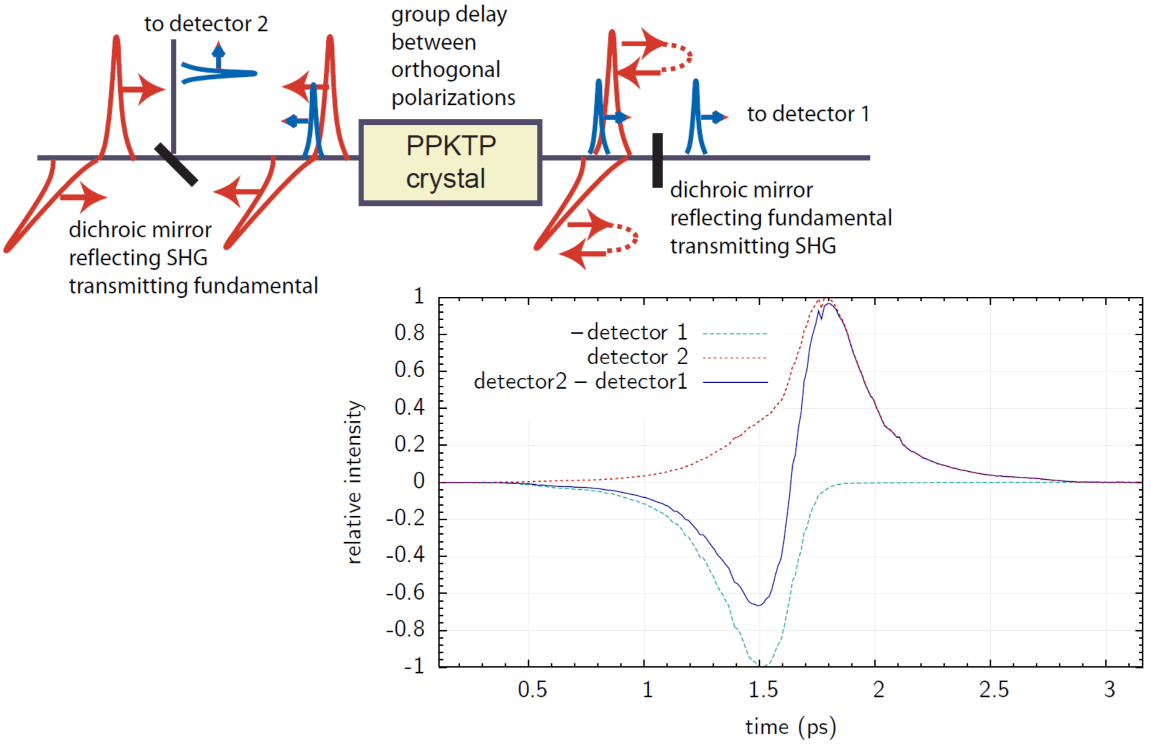
controll loop

dispersion compensated fiber-link

partially reflecting (Faraday rotator) mirror

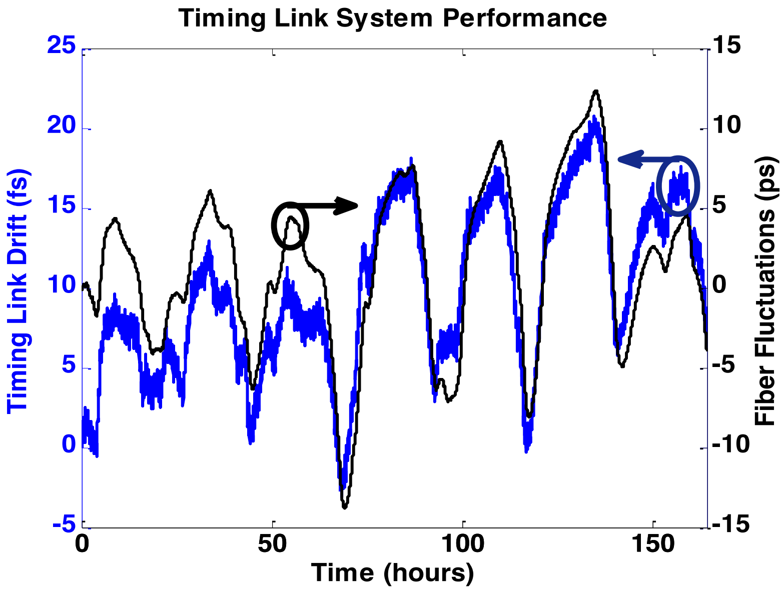
device to be synchronized

Pulsed optical synchronization scheme: Balanced optical cross-correlator



Pulsed optical synchronization scheme Fiber link stabilization (with add. polarization control)

5 fs (rms) drifts over one week of operation

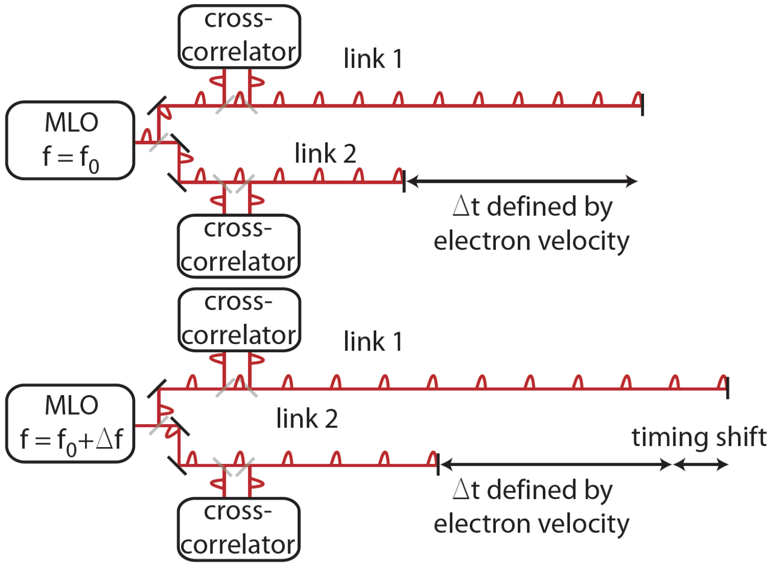


Similar links deployed at FLASH, DESY

5-link system installed at FERMI @ Trieste, 10 days < 10 fs (rms) (IdestaQE and Menlosystems GmbH)

Courtesy of F. X. Kaertner, MIT & CFEL

Required frequency stability of reference laser (Valid for all distribution schemes)

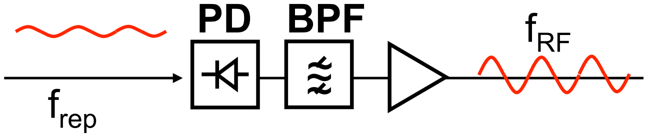


$$\frac{\Delta L}{L_0} \approx -\frac{\Delta f}{f_0}$$

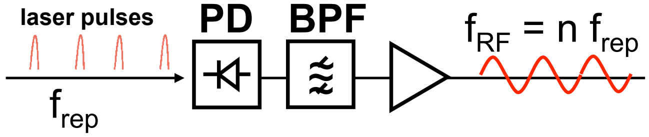
Laser frequency has to be tightly controlled for long link lengths!
→ locking of laser frequency repetition rate to Rb-transition
(or similar)

(Simple) RF signal generation

CW scheme:



Pulsed scheme:



Can deliver sub-10 fs stability for both systems.

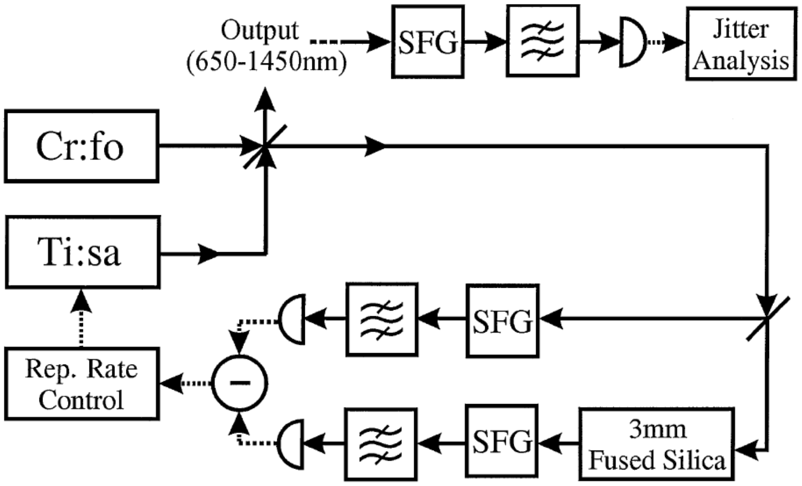
Difficulty: RF phase shifts when optical power changes!
→ Utilize well selected photo diodes
→ Operate photo detectors at optical power where shift is minimum

Alternative: Use more robust RF generation scheme
(more eventually at the end of the lecture)

Synchronization of lasers to the optical reference

CW scheme: Under development

Pulsed scheme: Highest precision by performing (two color) optical cross correlation between laser and optical reference

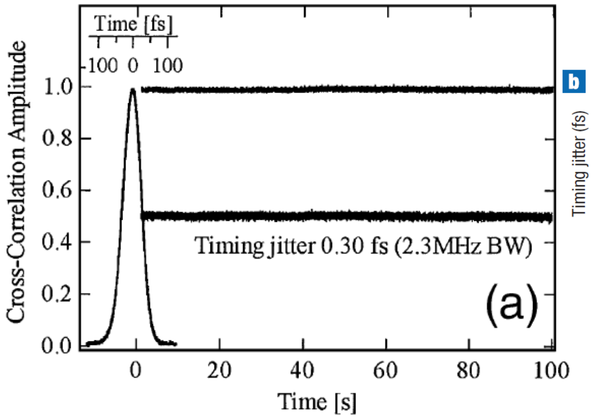


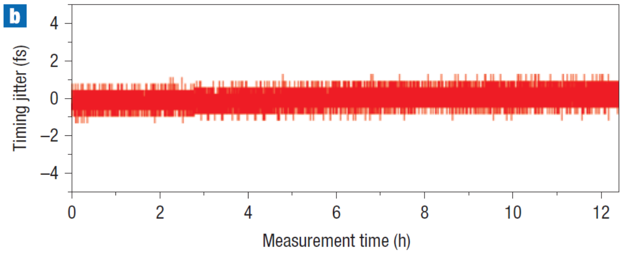
T. R. Schibli et al., Opt. Lett. **28**, p. 947 (2003)

Synchronization of lasers to the optical reference

0.3 fs stability over 100 s (2.3 MHz bandwidth)

0.4 fs stability over 12 h (2.3 MHz bandwidth)





T. R. Schibli et al., Opt. Lett. **28**, p. 947 (2003)

J. Kim et al., Nature Photonics **2**, p. 733 (2008)

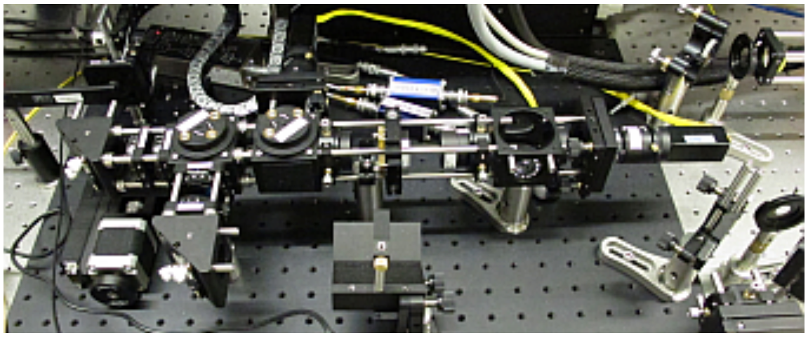
Synchronization of lasers to the optical reference

Ongoing efforts to synchronize various types of lasers to the optical reference pulse train at various laboratories like:

DESY: S. Schulz et al., PAC09, TH6REP091

Elettra: M. Danailov et al., 2nd Timing & Synchronization Workshop

PSI:



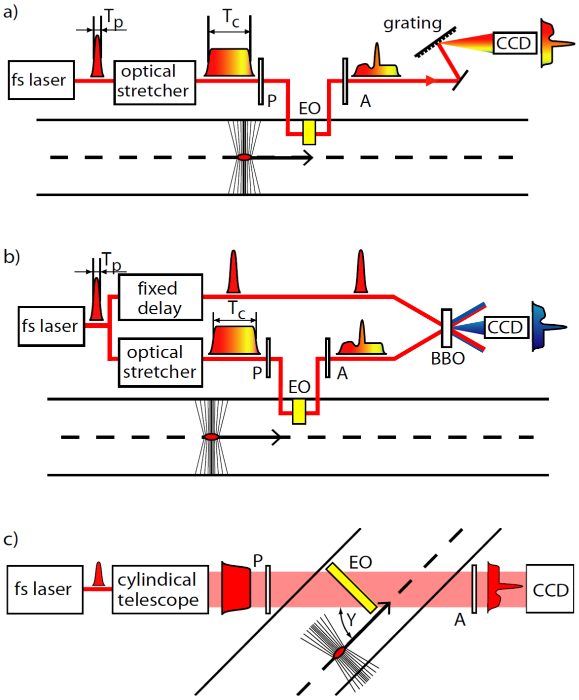
Courtesy of PSI Timing&Synch Team

Femtosecond bunch arrival-time monitors

(Sub-10) femtosecond RF based measurements are possible at

- High RF frequencies, see, for example, 30 GHz scheme tested at CTF3:
  A. Anderson et al., MOPAN066, PAC07
- Lower frequencies, when averaging over many RF cycles is possible.
  See, e.g., 'Phase Cavities' at LCLS

Femtosecond bunch arrival-time monitors
Electro-optic beam profile monitors

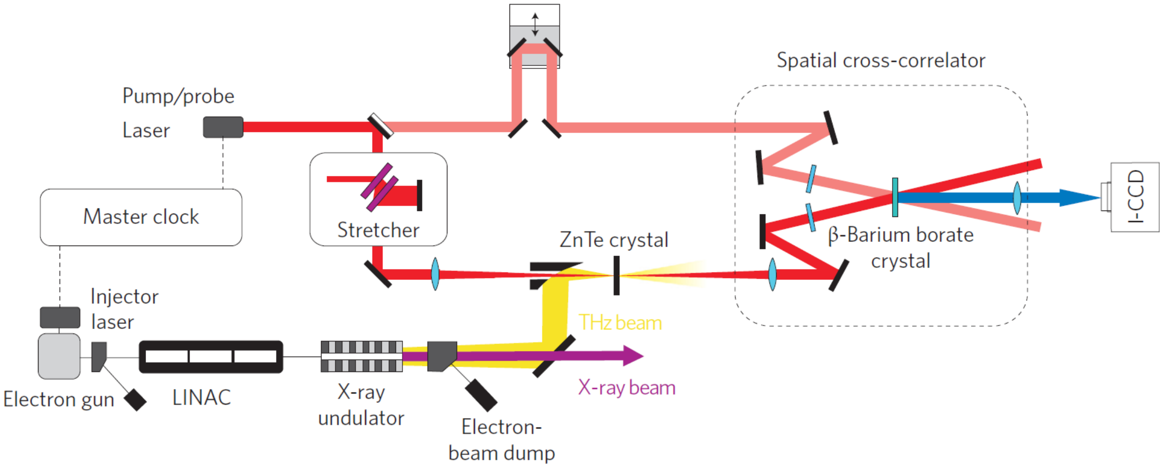


- Single bunch measurements
- Arrival-time measured with respect to a mode-locked laser
- Resolution depends on how precisely the laser is synchronized
- Long. Bunch profile & arrival-time!

But: Monitor data more difficult to analyze and thus less suited as monitors for a fast feedback.

a) I. Wilke et al., Phys. Rev. Lett. **88**, (2002)
b) G. Berden et al., Phys. Rev. Lett. **93** (2004)
c) A. L. Cavalieri et al., Phys. Rev. Lett. **94** (2005)

Femtosecond bunch arrival-time monitors
Bunch arrival-time w.r.t. pump-probe laser

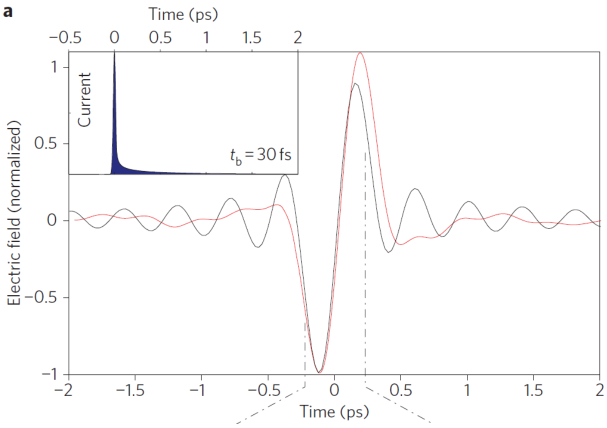


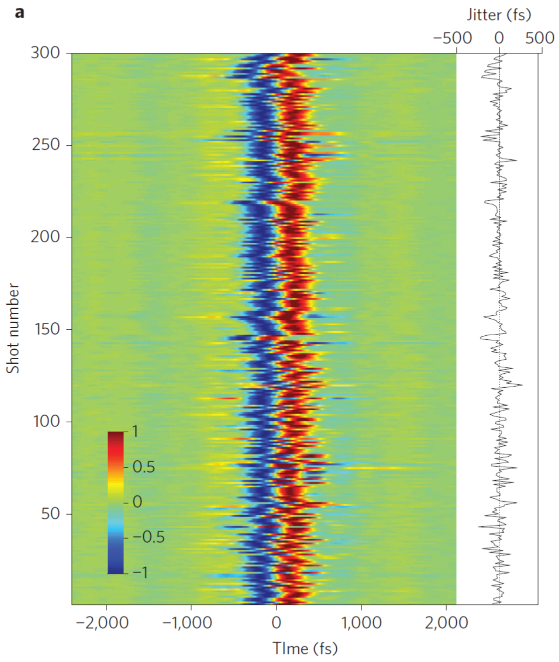
Same scheme as in G. Berden et al., Phys. Rev. Lett. **93** (2004)
But: Uses undulator edge radiation as the THz field.

F. Tavella et al., Nature Photonics **5**, p. 162 (2011)

Femtosecond bunch arrival-time monitors
Bunch arrival-time w.r.t. pump-probe laser

Electric field of the undulator edge radiation at FLASH

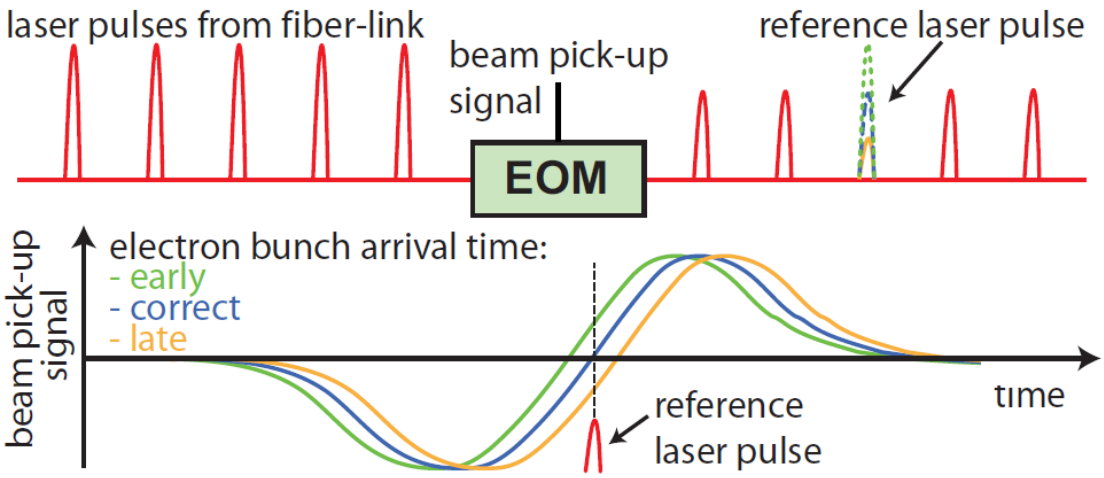




Measures bunch centroid with a resolution better than 10 fs

F. Tavella et al., Nature Photonics **5**, p. 162 (2011)

Femtosecond bunch arrival-time monitors
BAM

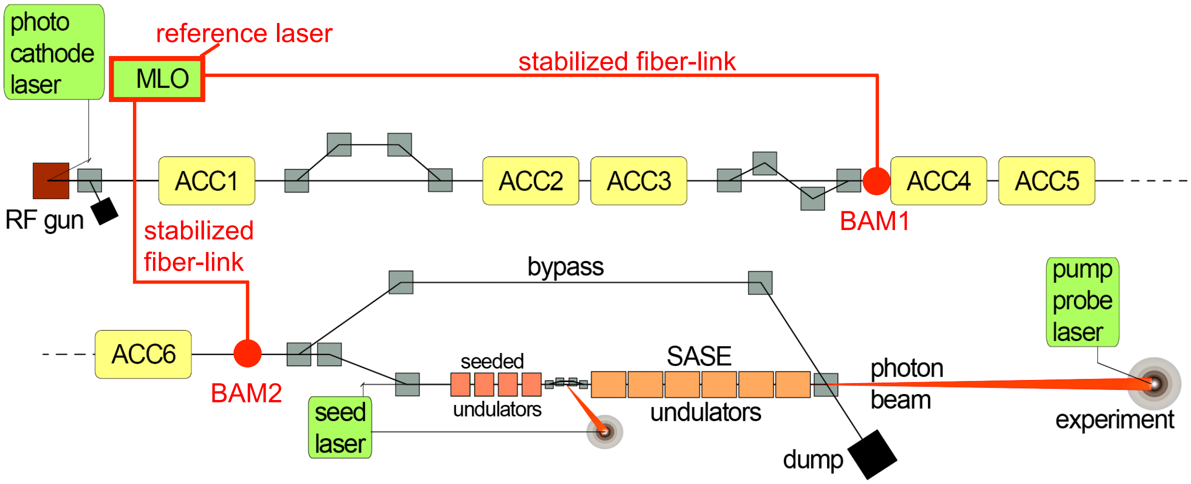


Electro-optic scheme utilizing pulses from optical synchronization

→ No additional jitter added

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

Performance benchmark of optical synchronization & bunch arrival-time detection

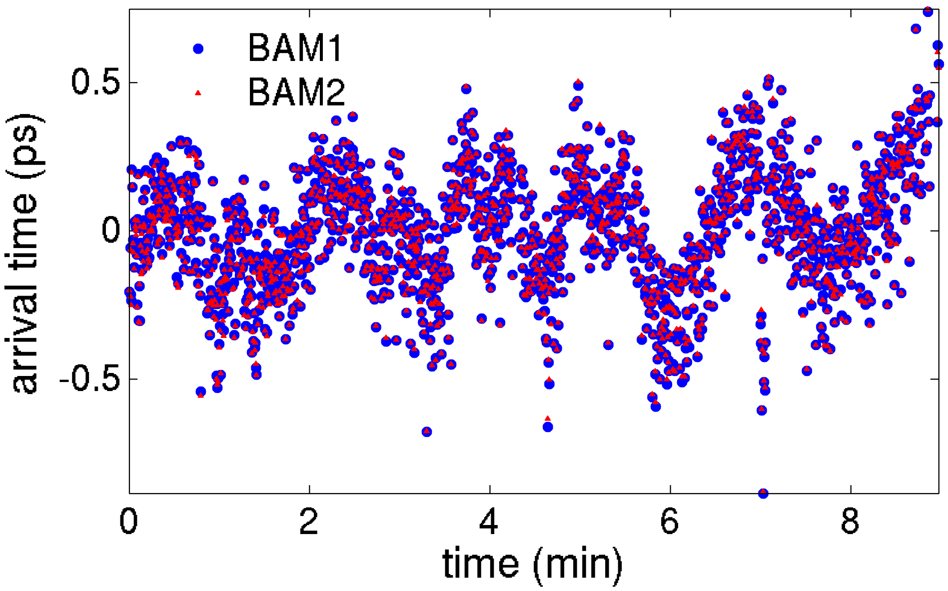


Two independent BAMs measure the arrival time of the same bunches.

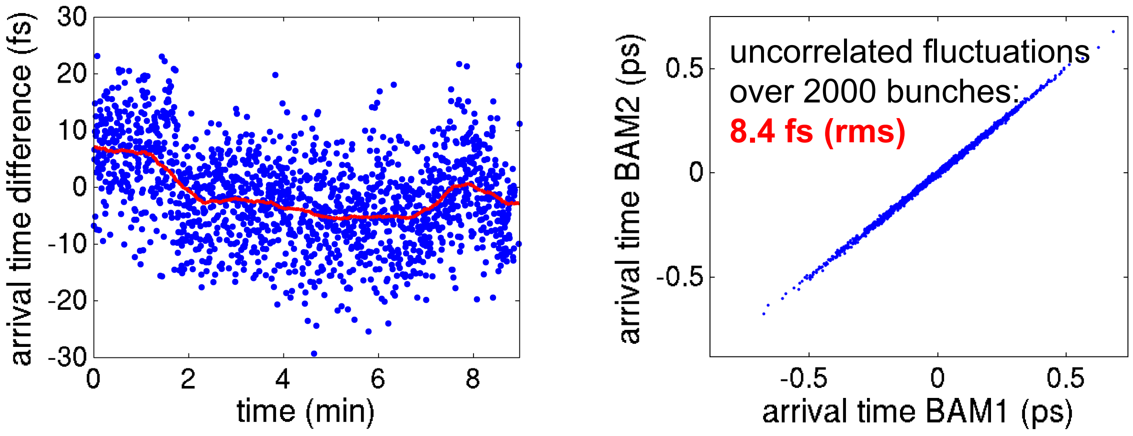
Distance between the two BAMs: 60 m

Performance benchmark of optical synchronization & bunch arrival-time detection

Bunch arrival times measured by both monitors:



Performance benchmark of optical synchronization & bunch arrival-time detection



uncorrelated fluctuations over 2000 bunches:
8.4 fs (rms)

Difference between both measurements caused by:

- BAM resolution
- Stability of fiber-links
- Fast laser timing jitter (~3 MHz – 108 MHz)

Stability of a complete measurement chain: **< 6 fs (rms)**

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

Detecting variations in the bunch shape

- Possibility of using EO-monitors mentioned before

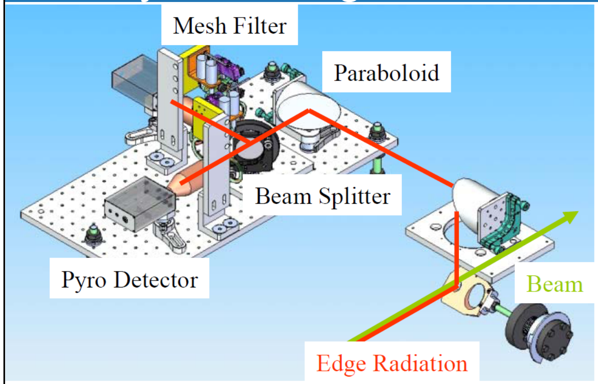
Ideal monitor for feedback applications would be:

- Non disruptive
- Fast readout
- Delivers a single number proportional to bunch duration

→ Detection of coherent beam induced THz radiation

  - Coherent Diffraction Radiation (CDR)
  - Coherent Synchrotron Radiation (CSR)
  - Coherent Edge Radiation (CER)

Detecting variations in the bunch shape by detecting beam emitted THz power (integral)

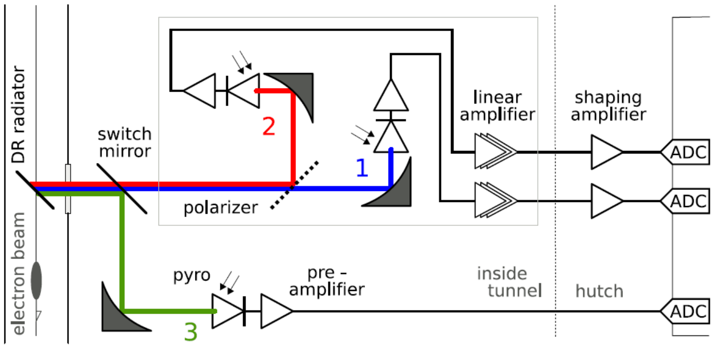


LCLS edge radiation monitor

H. Loos et al., FRPMS071, PAC07

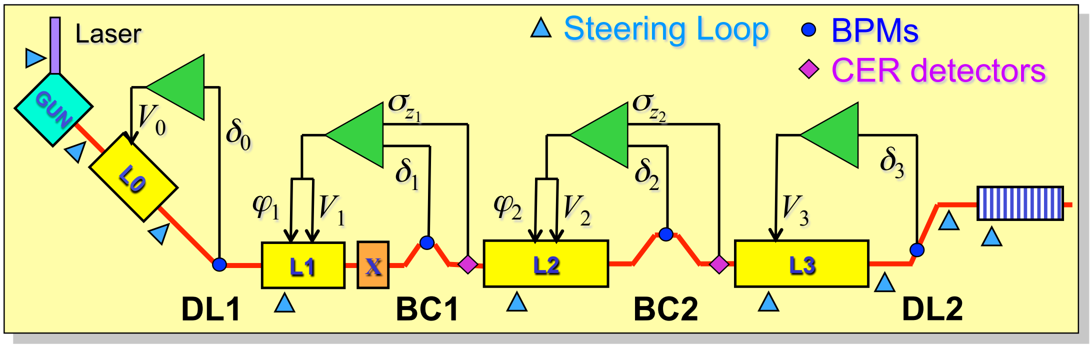
FLASH diffraction radiation monitor

C. Behrens et al., MOPD090, IPAC10



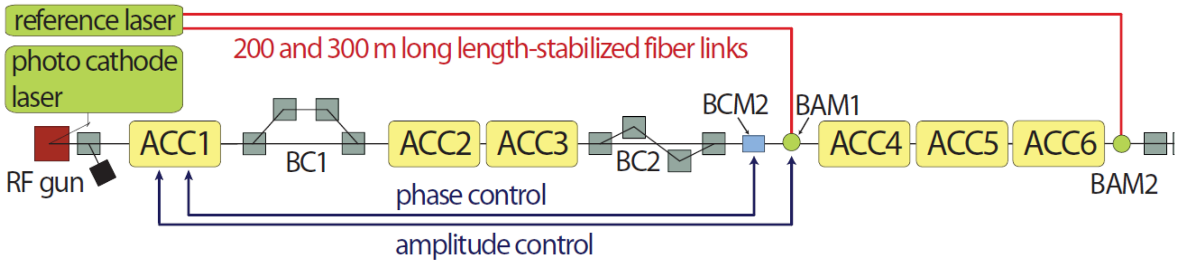
Active bunch shape stabilization at the LCLS

- Cascaded FB at 5 Hz (Matlab implementation)
- Fixed energy gain in L2 & L3 klystrons
- Change global L2 phase
- Adjust L2 & L3 energy with several klystrons at opposite phases
- Feedback uses orthogonal actuators to separate energy gain and chirp of L2



Courtesy of H. Loos, SLAC

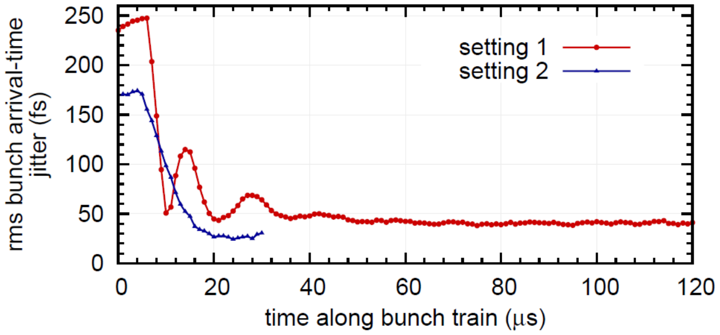
Active bunch arrival-time & bunch shape stabilization



Fast intra bunch train feedbacks based on the timing reference from the optical synchronization system.

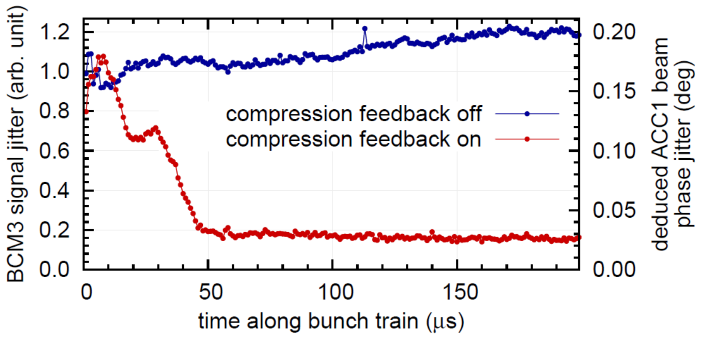
F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

Active bunch arrival-time & bunch shape stabilization



Achieved 25 fs bunch arrival-time stability

→Important for laser based seeding and manipulation schemes

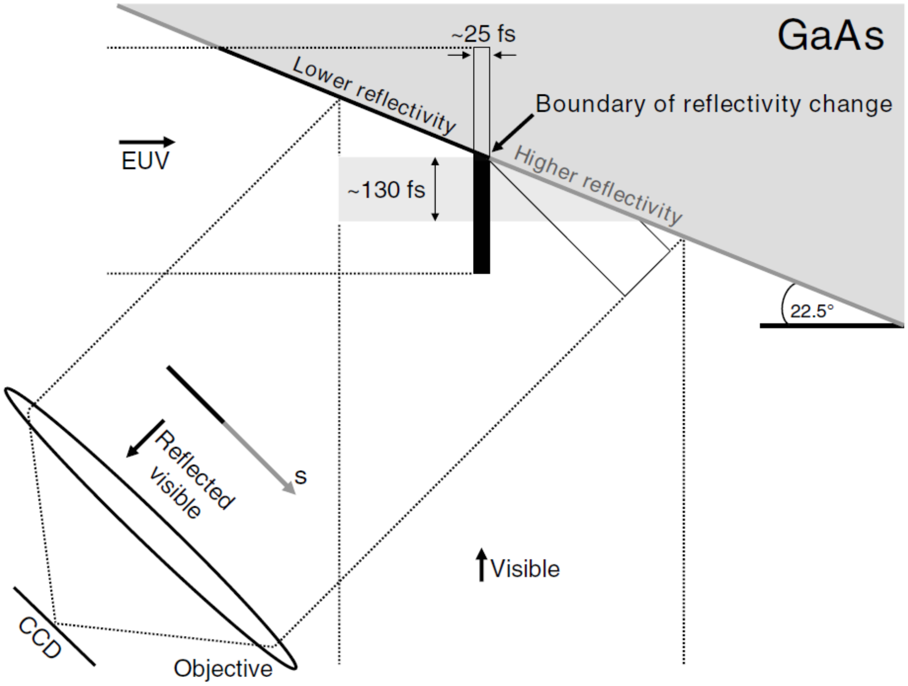


Achieved 0.025 deg beam phase stabilization

More advanced feedback scheme with more monitors and actuators under way at DESY

F. Loehl et al., Phys. Rev. Lett. **104**, 144801 (2010)

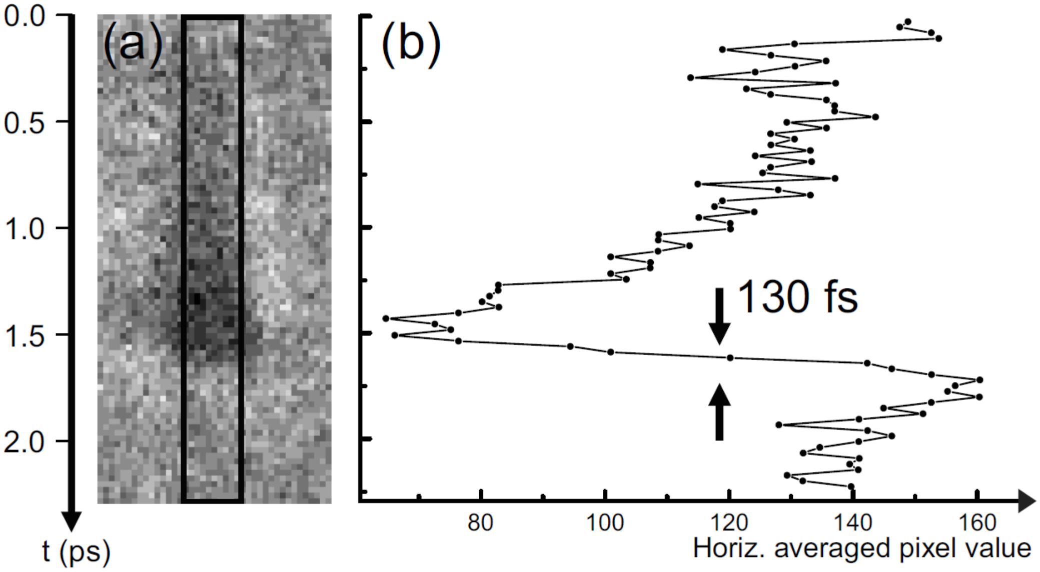
Photon pulse arrival-time detectors



T. Maltezopoulos et al., New Journal of Physics **10,** 033026 (2008)

Photon pulse arrival-time detectors

40 – 50 fs arrival-time resolution



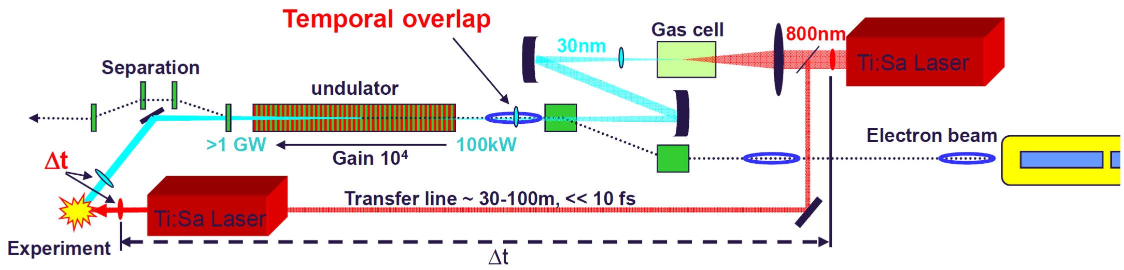
T. Maltezopoulos et al., New Journal of Physics **10,** 033026 (2008)
see also: C. Gahl et al., Nature Photonics **2**, pp. 165 - 169 (2008)

Reduction of arrival-time jitter by FEL seeding

An ultra-short laser pulse is used to select the part of the electron beam which participates in the FEL process.
(There exists many different schemes to do this.)

→ It is much easier to synchronize lasers to each other than the electron beam to a laser.
(In the simplest case, a single laser can be used.)

Example experiment currently under way at FLASH (Univ. of Hamburg):



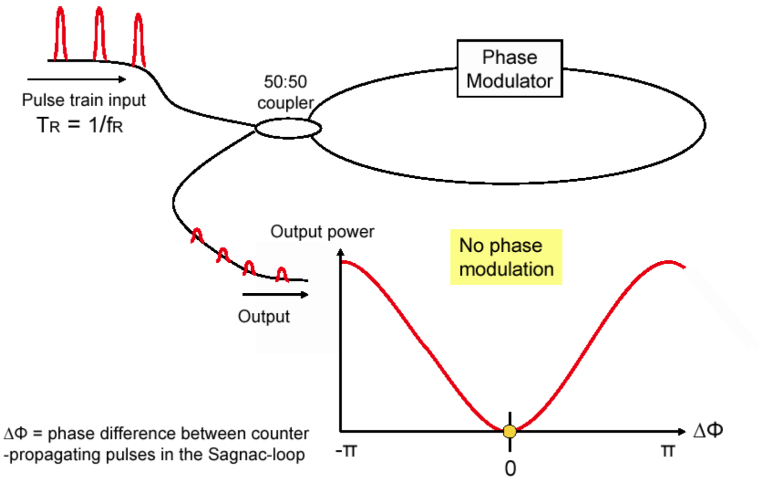
Conclusion

- Timing and synchronization is a very large field
(we covered only a very small fraction of it)
- Especially important for modern linear accelerators
(XFELs, future linear colliders, etc)
- Many challenges still remain, and the requirements get tighter with as accelerator technology evolves
(Attosecond light pulses are feasible with FELs…)

Thank you for your attention!

RF signal generation and probing

Phase detection in the optical domain:

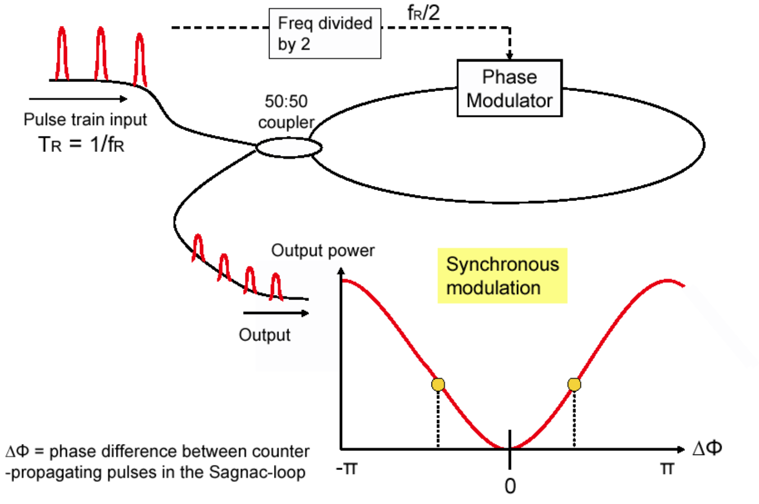


ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

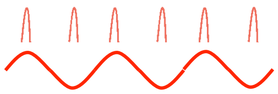
Courtesy of J. Kim (MIT)

RF signal generation and probing

Phase detection in the optical domain:



ΔΦ = phase difference between counter -propagating pulses in the Sagnac-loop

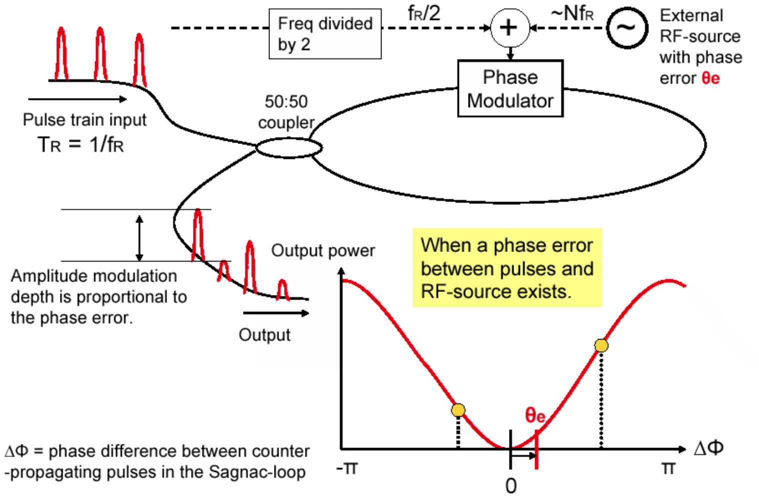


modulation voltage: $f_{rep} / 2$

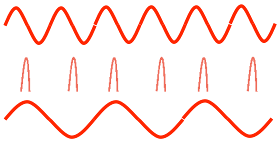
Courtesy of J. Kim (MIT)

RF signal generation and probing

Phase detection in the optical domain:



VCO signal to stabilize ($n*f_{rep}$)

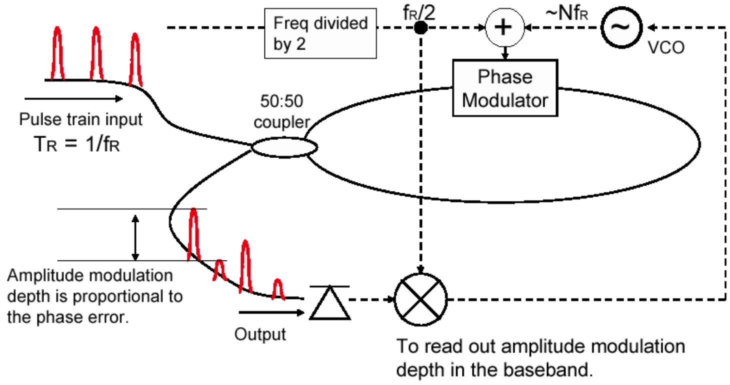


modulation voltage: f_{rep} / 2

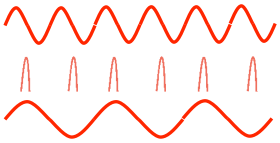
Courtesy of J. Kim (MIT)

RF signal generation and probing

Phase detection in the optical domain:



VCO signal to stabilize ($n*f_{rep}$)

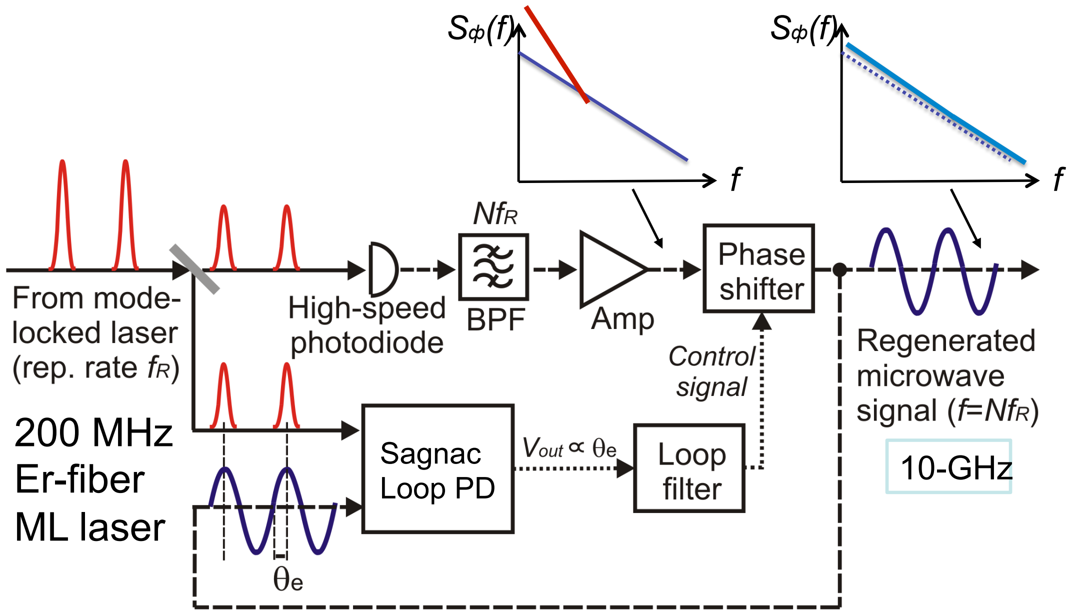


modulation voltage: f_{rep} / 2

Courtesy of J. Kim (MIT)

Sagnac Loop Interferometer

Delay-locked loop (DLL) for excess noise suppression



From mode-locked laser (rep. rate f_R)

200 MHz Er-fiber ML laser

High-speed photodiode

Nf_R

BPF

Amp

Phase shifter

Control signal

Regenerated microwave signal ($f=Nf_R$)

10-GHz

Sagnac Loop PD

$V_{out} \propto \theta_e$

Loop filter

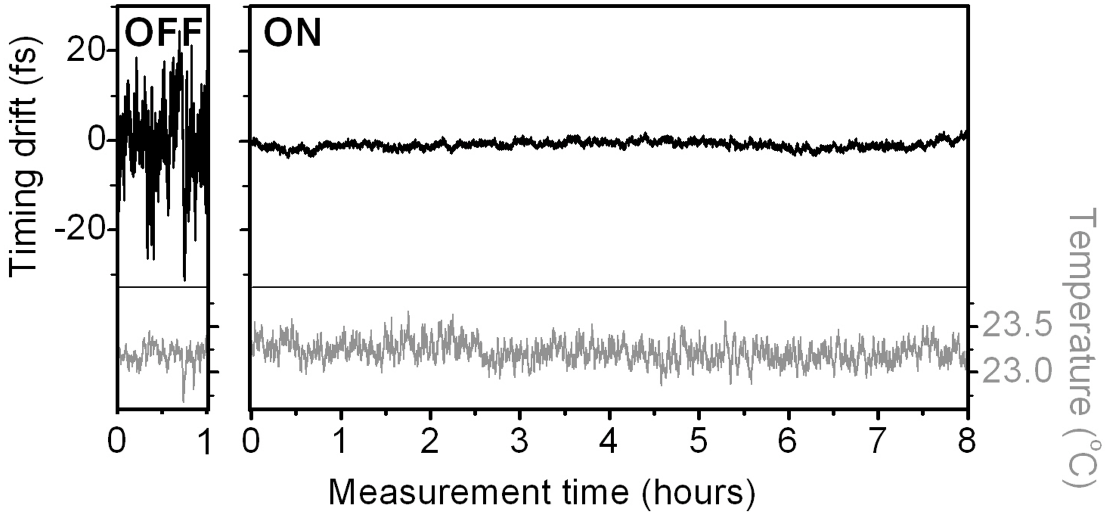
θ_e

Courtesy of F. X. Kaertner, MIT & CFEL

Sagnac loop interferometer

Delay-locked loop (DLL) for excess noise suppression

RMS timing jitter integrated in 0.1 Hz – 1MHz: 2.4 fs



J. Kim and F. X. Kaertner, Opt. Lett. **35**, p. 2022 (2010).