Linac Timing, Synchronization & Active Stabilization

PAC11 Conference

Florian Loehl, Cornell University
Outline

• Femtosecond timing needs in linear accelerators

• Femtosecond stable…
  • …Timing signal distribution
  • …RF signal generation
  • …Laser synchronization
  • …Electron bunch arrival-time detection
  • …Electron bunch shape detection
  • …Active bunch arrival-time and shape stabilization
  • …Photon pulse arrival-time detection
High gain FEL facilities, like the LCLS

- 6 MeV: $\sigma_z \approx 0.83$ mm, $\sigma_\delta \approx 0.05$ %
- 135 MeV: $\sigma_z \approx 0.83$ mm, $\sigma_\delta \approx 0.10$ %
- 250 MeV: $\sigma_z \approx 0.19$ mm, $\sigma_\delta \approx 1.6$ %
- 4.30 GeV: $\sigma_z \approx 0.022$ mm, $\sigma_\delta \approx 0.71$ %
- 13.6 GeV: $\sigma_z \approx 0.022$ mm, $\sigma_\delta \approx 0.01$ %
ERL facilities, like the Cornell ERL project
Linear Accelerators

Linear Collider Projects: ILC & CLIC

International Linear Collider
Timing Needs in an X-ray FEL

- Laser synchronization
- RF signal distribution
- Bunch arrival-time measurements
Timing Needs in an X-ray FEL

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

**Arrival Time Monitor**

- Photo cathode laser
- Booster
- Magnetic chicane
- Acc. modules
- Undulator
- Target
- Pump-probe laser
- RF gun
Timing Needs in an X-ray FEL

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

RF gun → booster → magnetic chicane → acc. modules → undulator → target

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

photo cathode laser → seed laser → pump-probe laser

Arrival Time Monitor
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

$$\Sigma^2_t \approx \left( \frac{R_{56}}{c_0} \frac{\sigma_A}{A} \right)^2 + \left( \frac{C-1}{C} \right)^2 \left( \frac{\sigma_R}{2\pi f_{RF}} \right)^2 + \left( \frac{1}{C} \right)^2 \Sigma^2_{i,t}$$

- timing jitter after compressor
- cavity field amplitude jitter
- cavity phase jitter
- injector timing jitter

- photo cathode laser
- seed laser
- pump-probe laser
Which level of accuracy is required?

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

\[ \sum_{t}^{2} \approx \left( \frac{R_{56}}{c_{0}} \frac{\sigma_{A}}{A} \right)^{2} + \left( \frac{C-1}{C} \right)^{2} \left( \frac{\sigma_{\phi}}{2\pi f_{RF}} \right)^{2} + \left( \frac{1}{C} \right)^{2} \sum_{i,t}^{2} \]

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

\(< 1.5 \times 10^{-5} \) field amplitude stability of vector sum
\(< 0.005^\circ \) phase stability of vector sum

See DESY-TESLA-FEL-2009-08 for detailed timing jitter analysis for FLASH
Ultra-short pulse mode in x-ray ERLs:

- Significant higher repetition rate (~GHz)
  - Beam stabilization mandatory  
    (instead of just measuring timing variations)
  - Beam arrival-time monitors can average over many bunches

- A bunch compression at full beam energy leads to a significant larger number of cavities upstream of the bunch compressor

Linear Collider:

- Very long distribution distances (tens of kilometers)
- Very large number of cavities
- Timing requirements driven by luminosity loss  
  & requirements can be as tight as in FELs

See, e.g.: D. Schulte and R. Tomas, “Dynamic effects in the new CLIC main linac”, PAC 20009
Femtosecond Stable Timing Distribution

Optical synchronization schemes

→ Lower transmission loss
→ Higher resolution timing detection
<table>
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<th>CW</th>
<th>Pulsed</th>
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<td>Transmission of ‘single’ frequency laser light</td>
<td>Transmission of ~100 - 200 fs long laser pulses</td>
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<td>Interferometric stabilization of an optical fiber</td>
<td>Stabilization of an optical fiber based on cross-correlation techniques</td>
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| 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  

**WEOBS2**

stability: < 10 fs

stability: < 10 fs
CW Optical Synchronization Scheme

- **Continuous-wave Er-doped laser**
  - **ω_{opt}**
  - Stabilization of ω_{opt}
- **Remote RF device**
  - Control
  - Remote RF error signal
- **100 MHz oscillator**
- **Freq. shifter**
- **BP**
- **FRM1**
- **FRM2**
  - Fiber 1
  - Fiber 2
- **Target end-points**

- **Amplitude modulator**
  - **ω_{RF}**
- **Distribution unit**
Difficult: (temperature dependent) difference between the phase velocity of the optical carrier frequency and the group velocity of modulated RF signal

$\Rightarrow$ Additional feed-forward term added in digital controller to correct for this.

data from R. Wilcox et. al. (Berkeley synchronization team)
Stability of RF signal transmission:

- 200 m fiber $\rightarrow$ 8.4 fs (rms)
- 2 km fiber $\rightarrow$ 17.7 fs (rms)

Pulsed Optical Synchronization Scheme
Fiber Link Stabilization

mode-locked Er-doped laser

optical pulse train

to other end-points

distribution unit

low-bandwidth lock

cross-correlator

piezo actuator

ingo loop

dispersion compensated fiber-link

long-term stable frequency source

partially reflecting (Faraday rotator) mirror

device to be synchronized

Florian Loehl (Cornell University)
Particle Accelerator Conference 2011 (PAC11)
New York City, USA
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 pulsed & CW scheme)

\[ \frac{\Delta L}{L_0} \approx -\frac{\Delta f}{f_0} \]

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:

\[ f_{\text{RF}} = n f_{\text{rep}} \]

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
RF signal generation and probing

Phase detection in the optical domain:

\[ \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop} \]

Output power

\[ \Phi = \pi \]

No phase modulation

Courtesy of J. Kim (MIT)
Phase detection in the optical domain:

- Pulse train input, $T_R = 1/f_R$
- Frequency divided by 2
- Phase Modulator
- 50:50 coupler
- Modulation voltage: $f_{rep} / 2$

Output power

$\Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop}$

Courtesy of J. Kim (MIT)
Phase detection in the optical domain:

- Pulse train input $T_R = 1/f_R$
- Amplitude modulation depth is proportional to the phase error.
- VCO signal to stabilize $(n*f_{rep})$

When a phase error between pulses and RF-source exists.

$\Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop}$

Modulation voltage: $f_{rep} / 2$

Courtesy of J. Kim (MIT)
Phase detection in the optical domain:

- **Pulse train input** $T_R = 1/f_R$
- **Amplitude modulation depth** is proportional to the phase error.
- **Freq divided by 2**
- **50:50 coupler**
- **Output**
- **Phase Modulator**
- **$f_{R/2}$**
- **$\sim Nf_R$**
- **$\sim VCO$**

**To read out amplitude modulation depth in the baseband.**

**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

Sagnac Loop PD

$\theta_e$

$V_{out} \propto \theta_e$

Loop filter

Control signal

Phase shifter

BPF

$Nf_R$

From

Regerated microwave signal ($f = Nf_R$)

10-GHz

$S_\phi(f)$

$S_\phi(f)$

Courtesy of F. X. Kaertner, MIT & CFEL

Florian Loehl (Cornell University)
Particle Accelerator Conference 2011 (PAC11)
New York City, USA
Sagnac Loop Interferometer

Delay-locked loop (DLL) for excess noise suppression

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

Synchronization of Lasers to the optical reference

**CW scheme:** See John Byrd’s talk: WEOBS2

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

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)

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
(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 WEOBS2
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.

Femtosecond Bunch Arrival-Time Monitors
Bunch Arrival-time w.r.t. Pump-Probe Laser

F. Tavella et al., Nature Photonics 5, p. 162 (2011)
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)
Electro-optic scheme utilizing pulses from optical synchronization
→ No additional jitter added

Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

RF gun

MLO

photo cathode laser

ACC1

ACC2

ACC3

ACC4

ACC5

bypass

seeded undulators

SASE

undulators

photon beam

dump

experiment

pump probe laser

seed laser

ACC6
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 as measured by both monitors

![Graph showing bunch arrival times for BAM1 and BAM2 vs. time (min).](image-url)
Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

Performance Benchmark of Optical Synchronization & Bunch Arrival-Time Detection

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)

Detecting Variations of the Bunch Shape

- Possibility of using EO-monitors mentioned before

Ideal monitor for feedback applications:
- 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 of the Bunch Shape
Detection of Integrated THz Power

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

![Diagram of bunch shape stabilization at the LCLS](image)

Courtesy of H. Loos, SLAC
Fast intra bunch train feedbacks based on the timing reference from the optical synchronization system.

Active Bunch Arrival-Time &
Bunch Shape Stabilization

Achieved 25 fs bunch arrival-time stability
→ Important for laser based seeding and manipulation schemes (see WEOCN6)

Achieved 0.025 deg beam phase stabilization

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

Most arrival-time and bunch compression monitors have a dependence on the bunch charge. 

→ Better bunch charge stability can improve the resolution of both of these monitors.

![Graphs showing beam current over time with and without feedback control.](image)

- Without FB
- With FB: stability much better than 1%
Photon Pulse Arrival-time Detectors

40 – 50 fs arrival-time resolution

see also: C. Gahl et al., Nature Photonics 2, pp. 165 - 169 (2008)
Summary / Outlook

- Femtosecond timing is a very active field of development and many technologies already exist
- 10 fs electron beam stability is almost reached
- Very strong potential for reaching sub-fs photon pulse stability with laser seeding / manipulation schemes
- Still missing: Highest resolution photon pulse arrival-time detectors

Thank you for your attention!