Synchronization of Accelerator Sub-Systems with Ultimate Precision

Holger Schlarb

MSK/DESY

- Sources of arrival time jitter
- Synchronization systems
- Low level RF controls
- Beam based feedbacks
Increasing demands on synchronization …

… is driven by stability requirements

⇒ Bunch scale has changed from ns/ps to fs
⇒ High accelerator frequencies (e.g. CLIC)
⇒ Accelerator facility length increased ~ 100 m – e.g. 3.5 km

Free Electron Lasers:
- Compression control (exponential growth)
- Energy control (self seeding)
- Pump-probe experiments (fs-evolution)
- External seeding (efficiency)

External injection in laser plasma wakefield
- Plasma wavelength

Picosecond/femtosecond photon sources
- THz / Thomson radiation

fs-synchronization pre-requisite for new accelerator applications
Scope of synchronization …

Synchronization reach into many different physics & engineering disciplines and requires wide range of know-how and technologies

Radio Frequency:
- RF Master Oscillator and distribution (cables)
- High power RF (modulator, preamp., klystron, waveguide,…)
- Low level RF (field detection, driver, digital feedback loops,…)
- RF accelerator structure (reflection, cooling, phase advance,…)

Wide range of components: phase detectors / mixer / multiplier / divider / low noise amplifier / …

Optics & Lasers:
- Laser oscillator / amplifier (phase noise, piezo resonance, pump source,…)
- Laser pulse shaping & wavelength conversion & transport
- Optical reference & distribution (fiber optics, opto-electronics, photo-detection)

Environmental control:
- temperature / humidity / air pressure / vibration / ground motion / EMI / EMC

Controls & control theory:
- multiple feedbacks / PLL theory / automation / SISO / MIMO / …

Longitudinal electron beam dynamics
Sources of timing jitter in accelerator

Arrival time of electron bunch at seed source
Arrival time at entrance to undulator

Sources of timing jitter (uncorrelated): $\sigma_t = \left[ \sum (w_j \sigma_j)^2 \right]^{1/2}$

- Photo–cathode laser: $w \sim 40–60\%$
- RF phase of RF gun (non–relativistic electrons): $w \sim 60–40\%$
- Seed and Pump–probe laser: $w \sim 100\%$
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Arrival time at entrance to undulator

Sources of timing jitter (uncorrelated): \( \sigma_t = [\sum (w_j \sigma_j)^2]^{1/2} \)

Energy chirp + energy dependent path length

\( V_{acc} \)

\( z/c \)
Sources of timing jitter in accelerator

Arrival time of electron bunch at seed source
Arrival time at entrance to undulator

Sources of timing jitter (uncorrelated): $\sigma_t = \left[ \sum (w \sigma_{t,i})^2 \right]^{1/2}$

- Photo-cathode laser: $w < 5\%$
- RF phase of RF gun (non-relativistic electrons): $w < 5\%$
- RF amplitude and phase: $w \sim 100\%$
- Seed and Pump-probe laser: $w \sim 100\%$

Timing jitter behind BC

Voltage: $\Sigma_{t,f}^2 = \left( \frac{R_{56}}{c_0} \right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left( \frac{C - 1}{C} \right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2} + \left( \frac{1}{C} \right)^2 \cdot \Sigma_{t,i}^2$

Phase

Incoming compression factor

C $\sim$ 5 ... 20

- XFEL: 3.3 ps/%
- FLASH: 5.5 ps/%
- 2 ps/deg
- L-band
- 0.05 ps/ps
- C=20
Sources of timing jitter in accelerator

Several compressor stages

Case 0: $E_0 \ll E_1$ and $E'_0 \ll E'_1$

$$\Sigma^2_{t,1} = \left( \frac{R_{56}}{c_0} \right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left( \frac{C_1 - 1}{C_1} \right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega^2_{rf}} + \left( \frac{1}{C_1} \right)^2 \cdot \Sigma^2_{t,0}$$
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RF gun \rightarrow Accelerator \rightarrow BC1 \rightarrow Accelerator \rightarrow BC2 \rightarrow Main Linac

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Various approaches:

1) RF distribution

\[ f \sim 100\text{MHz} \ldots \text{GHz} \]
Synchronization schemes …

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f ~ 100MHz …GHz
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   $f \sim 100\text{MHz} \ldots \text{GHz}$

2) Carrier is optically
   $f \sim \text{GHz}$
Synchronization schemes …

Various approaches:

1) RF distribution

$\text{LO} \rightarrow \text{MZT} \rightarrow \text{standard} \rightarrow \text{interferometer} \rightarrow \text{MO}$

$f \sim 100\text{MHz} \ldots \text{GHz}$

2) Carrier is optically

$\text{LO} \rightarrow \text{MZT} \rightarrow \text{f} \sim \text{GHz}$

3) Carrier is optically + detection

$\text{LO} \rightarrow \text{MZT} \rightarrow \text{f} \sim 200\text{ THz}$
Various approaches:

1) RF distribution
   - $f \sim 100\text{MHz} \ldots \text{GHz}$

2) Carrier is optically
   - $f \sim \text{GHz}$

3) Carrier is optically + detection
   - $f \sim 200\text{THz}$

4) Pulsed optical source
   - $\Delta f \sim 5\text{THz}$

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Synchronization schemes …

Various approaches:

1) RF distribution

\[ \Delta t \approx \frac{\Delta f}{f} \]

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3) Carrier is optically + detection

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H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Pulsed optical synchronization system

EDFL, soliton, $\Delta t<200\text{fs}$, $f=216\text{MHz}$
saturable absorber, $P > 100\text{mW}$,
phase noise $<10\text{fs}$ ($\geq1\text{kHz}$)

Free space distribution
+ EDFA

Dispersion comp.,
Polarization contr.,
Collinear bal. opt.
cross-corr.

Other lasers
Two color bal.
Opt. cross-corr.

Laser pulse

Laser MLO

MO-RF

Narrow Band.

Distribution

Optical link
<5fs

Direct
Optical link
<5fs

Optical link
<5fs

LO-RF

Direct/Interferometer

DWC/Kly

FB

A & $\phi$ cavity

Desired point-to-point stability $\sim 10\ \text{fs}$

Main issue: robustness, stability and maintainability $\Rightarrow$ Prototype at FLASH
Master Laser Oscillator (MLO)

- Commercial: OneFive ORIGAMI-15
- Repetition rate: 216,66 MHz
- Average power: > 100 mW
- Pulse duration: < 200 fs
- Mechanically robust, easy to maintain
- Phase noise ~ 5 fs rms [1 kHz-10 MHz]

Courtesy: S. Schulz
Master Laser Oscillator (MLO)

Optical lock of two laser oscillators

Balance, background free detection

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High sensitivity at low noise

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- Fast actuator (PZT/driver)

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Out-of-loop

Jitter
< 3 fs (1Hz-1MHz)

Drift: 6 fs pkpk @ 30h

High sensitivity at low noise

14 as/mV
meanwhile rather reliable operation (still babysitting required) 
switch from 10GHz -> 40GHz bandwidth for low charge operation  
new front-end with improved thermal stability  

reduced dependency on beam orbit 
reduced dependency on bunch charge 
sensitivity in terms of  
% modulation per fs timing change
Bunch Arrival Monitor

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pick-up design drawing, courtesy: K. Hacker

 Courtesy: M. Bock, DESY
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uncorrelated jitter over 4300 shots:
8.4 fs (rms)

Courtesy: M. Bock, DESY
Example: Arrival stability at FLASH

 Arrival time measurements

Typically values

- 60-100fs rms from injector
- 50-60fs rms behind BC2
- 40-50fs rms exit LINAC

Global slow feedback implemented

Intra-train repetitive error correction implemented

Fast feedback reduce Bunch-to-bunch jitter ~ 20 fs
RF generation from optical pulses

Direct conversion with photo detector (PD)
- Low phase noise (to be proven at end-station)
- Temperature drifts (0.4ps/C°)
- AM to PM conversion (0.5-4ps/W)
- Potential for improvement (corporation with PSI)

\[ T = \frac{5\text{ns}}{f_{\text{rep}}} \]

\[ f_{\text{rep}} = \frac{n\times f_{\text{rep}}}{2\pi} \]

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Time domain

Frequency domain

\[ T = \frac{5}{f_{\text{rep}}} = \frac{1}{f_{\text{rep}}} \]

\[ f = nf_{\text{rep}} \]

\[ \Delta \Phi = \text{phase difference between counter-propagating pulses in the Sagnac-loop} \]
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Sagnac loop interferometer
- balanced optical mixer to lock RF osc.
- insensitive against laser fluctuation
- Very low temperature drifts

f=1.3GHz jitter & drift < 10 fs rms limited by detection
Remark: much easier at higher frequencies …
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MZI based balanced RF lock
- new scheme, under investigation
MZI based balanced laser-to-RF phase detector

Locking low-noise microwave oscillator to laser (or visa versa)

RF Oscillator $f_{VCO} = n f_r$, split and delayed

See: Accelerator 2011, Highlights and Annual Report, DESY
http://www.desy.de/ueber_desy/jahresberichte/index_ger.html

Sketch of effect due to VCO phase shift
MZI based balanced laser-to-RF phase detector

Locking low-noise microwave oscillator to laser (or visa versa)

RF Oscillator $f_{\text{VCO}} = n f_r$, split and delayed

See: Accelerator 2011, Highlights and Annual Report, DESY
http://www.desy.de/ueber_desy/jahresberichte/index_ger.html

Sketch of effect due to VCO phase shift

Residual jitter

Out-of-loop

Residual drift

Drift < 14 fs pkpk (3.8 fs rms)

Courtesy: T. Lamb, DESY
Sketch of the controller structure

- Real-time FPGA processing of 8/16 RF channels and microsecond latency
- Generator driven Multiple-in-Multiple-out feedback controller, with adaptive feed forward drive
- Super-conducting RF cavities with ~300 Hz bandwidth
Precision RF field detection (noise limitation)

Non-IQ sampling field detection limited by:
- Receiver active (< 4 fs)
- Receiver passive (< 2 fs)
- LO-Generation (< 2 fs)
- ADC (limitation) (~5 fs)

at 1.3 GHz. Can be better at high frequencies.

Measurement with ADC

ΔA/A = 3.2E-5

ΔP/P = 0.0022° (5 fs)

Courtesy: F. Ludwig, DESY

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Problem:
- Mixer phase drifts $\sim 0.2^\circ/K$
- Mixer amplitude drifts $\sim 0.2\%/K$
+ dependence also on humidity
+ mixer drift not equal (one PCB)

$\Rightarrow$ Reference tracking for mixer drift removal

Figure 3: Measured (a) amplitude and (b) phase deviation for the injected corrected signal (blue marked) and uncorrected (green marked) over 60 hours.

Courtesy: F. Ludwig, DESY
MTCA.4 crate system used as LLRF hardware platform

Integration to low-noise, high processing power environment

LN Power Modules

Timing/Interlock

EMC/EMI

RF Backplane

Grounding!

Controller

Controller

Instrumentation Technologies

- 2 channel vector modulator
  (108MHz, 2.5GHz, 1.3GHz, 3.3GHz)
- 16 bit
- LLRF Controller, 6 Fiber-Ports, 2 GB-Links
- FPGA(70), DSP

EMC/EMI

- Klystron Driver

RF Backplane

Integration to low-noise, high processing power environment

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Calibrated controller gain

System gain w/o notch

Amplitude stability $\sigma_A$

1/T ~ 800 kHz

No impact on beam but causes instabilities of regulation

Digital notch filter

System gain with notch

1/T ~ 3 MHz

Has impact on beam and causes instabilities of regulation

MTCA.4 crate system used as LLRF hardware platform

8/9 pi modes

7/9 pi modes

THPM086
New Beam Based Feedbacks algorithm

- Arrival FB on ACC1 only using monitors after BC1 \( \Rightarrow \) \( \sim 20 \text{ fs routine} \)
- Arrival FB on ACC2 (was not active) Test this week \( \Rightarrow \) \( \sim 10-15 \text{ fs expected} \)
- Ultimate: broadband NRF cavity & ultra-low latency digital feedback system From simulations \( \Rightarrow \) \( \sim 5 \text{ fs expected} \)

Achieved arrival time stability

Latency of system

X 4 \( \sim 20 \text{fs} \)

Courtesy: Ch. Schmidt, S. Pfeiffer, DESY

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Thanks you for attention
Intra-train beam based feedbacks (FLASH)

Beam Based Feedbacks:
- Arrival time (BAM) and bunch compression (BCM) after chicane BC1 are simultaneously correct amplitude and phase in ACC1
- BAM and BCM after BC2 correct amplitude and phase in ACC23
- Charge measurement used for beam loading compensation

Courtesy: Ch. Schmidt, S. Pfeiffer, DESY
Intra-train beam based feedbacks (FLASH)

Beam Based Feedbacks:
• Arrival time (BAM) and bunch compression (BCM) after chicane BC1 are simultaneously correct amplitude and phase in ACC1 /39
• BAM and BCM after BC2 correct amplitude and phase in ACC23
• Charge measurement used for beam loading compensation

Courtesy: Ch. Schmidt, S. Pfeiffer, DESY
H. SchlARB, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Beam Based Feedbacks:
• Arrival time (BAM) and bunch compression (BCM) after chicane BC1 are simultaneously correct amplitude and phase in ACC1/39
• BAM and BCM after BC2 correct amplitude and phase in ACC23
• Charge measurement used for beam loading compensation

Achieved arrival time stability

- Both intra-train FB on
- MIMO controller
- Repetitive pkpk deviation < 100fs

< 22 fs

Latency of system

Courtesy: Ch. Schmidt, S. Pfeiffer, DESY

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Fiber Link Stabilization (optically)

216 MHz Er-doped fiber laser

Fiber Link Stabilization (optically)

216 MHz Er-doped fiber laser

Balanced optical cross-correlator


H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012
Fiber Link Stabilization (out-of-loop)

For 400m link !!!
3.5 km will be considerably more difficult!
⇒ Dispersion management
⇒ Accumulated delays
⇒ PMD/spurious SPM
⇒ Polarization control

360 as (rms) timing jitter from 1 Hz to 100 kHz
3.3 fs (rms) timing jitter from 35 μHz to 100 kHz

H. Schlarb, LINAC12, Tel Aviv, Israel, September 9-14, 2012

Courtesy: F. Kaertner
Fiber Link Stabilization (optically)

3rd generation of opto-mechanics
typical in loop jitter ~ 1-2 fs rms (also smaller)

Courtesy: Bock/Schultz/Lamb
Fiber Link Stabilization (optically)

3rd generation of opto-mechanics
typical in loop jitter ~ 1-2 fs rms (also smaller)

Experience:
- Operate reliably
- Some links fast AM noise observed

Recent developments:
- Matching optics
- Retro-reflector delay line with precision stepper motor
- Isolation to FSD
- Link layout changed

Current developments 2011/12:
- PCB for readout electronics
- Low noise balanced detector
- Ultra-low noise LDD driver
- uTCA based digital FB controller

XFEL:
- Dispersion management need to be improved (2 test links in 26a for 3.5km)
- Delay stage too short for long links and large temp. changes (PSOF fibers)

Courtesy: Bock/Schultz/Lamb