Synchronization Overview

S. Simrock, DESY
Outline

• What is Synchronization

• Synchronization Requirements for RF, Laser and Beam
  • Timing stability
  • RF amplitude and phase stability

• Design of RF synchronization systems

• Measured Performance

• Conclusion
Synchronization

• Definition of Synchronization
  • [1] coordinating by causing to indicate the same time
  • [2] an adjustment that causes something to occur or recur in unison
  • [3] the relation that exists when things occur at the same time

• What is to be synchronized in accelerators:
  • RF reference signals
  • Laser pulses (Photocathode laser, seed laser, pumpe-probe laser, new: master oscillator lasers)
  • Electrical and optical timing signals
  • Charged particle beams (bunch arrival time)
Synchronisation in FELs

RF Gun \rightarrow \text{harmonic cavity} \rightarrow \text{inj. RF} \rightarrow \text{cavities} \rightarrow \text{Bunch compressor} \rightarrow \text{Linac RF} \rightarrow \text{cavities} \rightarrow \text{undulator} \rightarrow \text{experimental setup}

\begin{align*}
\sigma_Z &= 100 \text{fs} \\
\sigma_t &= 100 \text{ fs} ? \\
\sigma_E/E &= 1e-4 \\
\text{(intra & inter bunch)}
\end{align*}

\[ M.O. \approx \]

RF Reference System
Synchronisation in ERLs (example)

- **RF Gun**
- **Linac RF**
- **Undulator(s)**
- **Beam disruption**
- **Beam loss (scraping)**

- $\sigma_z = 0.1-1 \text{ ps}$
- $\sigma_t = 100 \text{ fs}$
- $\sigma_E/E = 1e^{-4}$
- $\sigma_E/E = \text{few \%}$
- $\sigma_I = 1-10 \mu\text{A}$
- $\sigma_\phi = 0.5\text{deg}$
- $(100-99.999)\text{mA}$
- $5 \text{ GeV}$
- $10 \text{ MeV}$
- $100 \text{ mA}$
- $10 \text{ MeV}$
- $1-10 \text{ mA}$
- $\sigma_z = 20 \text{ ps}$
- $\sigma_t = 1 \text{ ps}$
- $\sigma_E/E = 1e^{-4}$
- $\sigma_\phi = 0.06\text{deg}$
- $\sigma_E/E = 3e^{-4}$
- $\sigma_\phi = 0.2\text{deg}$

- **Beam dump**
- **bunch compression**
- **M56**
- **10 MeV**
- **5 GeV**
**ERL Projects in the World**

<table>
<thead>
<tr>
<th>Project</th>
<th>Beam energy (GeV)</th>
<th>Max. Current (mA)</th>
<th>Min. bunch length (ps)</th>
<th>Min. emittance (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHESS</td>
<td>5.3</td>
<td>100</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>BNL</td>
<td>3-7</td>
<td>200</td>
<td>0.1-0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>LBNL</td>
<td>2.5-3.1</td>
<td>0.04</td>
<td>0.05</td>
<td>&lt;1</td>
</tr>
<tr>
<td>BINP</td>
<td>5.4</td>
<td>1.0</td>
<td>&lt;1</td>
<td>0.003</td>
</tr>
<tr>
<td>Daresbury</td>
<td>0.6</td>
<td>100</td>
<td>0.05</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Erlangen</td>
<td>3.5</td>
<td>100</td>
<td>2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Diagram:**

- **CHESS**
- **4GLS**
Requirements

• Derived from beam parameters:
  • Energy Stability and Energy spread
  • Emittance
  • Bunch length
  • Arrival time

• Subsystem Requirements
  • Timing and Synchronization
    - Photocathode Laser, Seed laser, pump probe laser, beam diagnostics (streak camera)
    - RF reference frequencies
  • RF amplitude and phase stability (RF gun, Injector, Linac)
Error sources for timing, bunch length and energy spread in ERLs

- Laser timing jitter (reduced by bunch compressor)
- RF Stability
  - RF Gun
  - harmonic cavity
  - rf section before bunch compressor (off-crest)$^1$
  - linac rf$^2$
- Stability of magnets (bunch compression, phase for energy recovery)

1. Requires up to $1e-4$ for ampl. and up to 0.05 deg. in phase
2. Disturbed by beam disruption in beam insertion devices (undulators) and beam instabilities (BBU)
Various factors may affect beam performance.

Spatial and temporal pulse shape

Drive laser

Spatial charge, emittance comp, & photoemission

Klystrons

Wakes & rf curvature

Linac

Bunch compressor

Aberrations, ISR, & CSR

Linac

Klystrons

Timing

Power supplies

Undulator

Emittance energy spread

Energy beta match trajectory

M. Borland
Jitter budgets for LCLS and TESLA for 0.1% energy spread and 12% current modulation. *(without beam arrival timing requirement)*

P. Emma, T. Limberg

### Set up timing jitter budget, compare LCLS and TESLA XFEL

#### Table 2: A possible longitudinal jitter tolerance budget for LCLS and TESLA-XFEL.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>LCLS (Δ)</th>
<th>XFEL (Δ)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun timing jitter</td>
<td>Δτ</td>
<td>0.80</td>
<td>1.5</td>
<td>ps</td>
</tr>
<tr>
<td>Initial bunch charge</td>
<td>ΔQ/Qb</td>
<td>2.0</td>
<td>10</td>
<td>%</td>
</tr>
<tr>
<td>mean L0 rf phase</td>
<td>φ0</td>
<td>0.10</td>
<td>0.05</td>
<td>deg</td>
</tr>
<tr>
<td>mean L1 rf phase</td>
<td>φ1</td>
<td>0.10</td>
<td>0.08</td>
<td>deg</td>
</tr>
<tr>
<td>mean L2 rf phase</td>
<td>φ2</td>
<td>0.07</td>
<td>0.10</td>
<td>deg</td>
</tr>
<tr>
<td>mean L3 rf phase</td>
<td>φ3</td>
<td>0.15</td>
<td>1.0</td>
<td>deg</td>
</tr>
<tr>
<td>mean L0 rf voltage</td>
<td>ΔV0/V0</td>
<td>0.10</td>
<td>0.08</td>
<td>%</td>
</tr>
<tr>
<td>mean L1 rf voltage</td>
<td>ΔV1/V1</td>
<td>0.10</td>
<td>0.20</td>
<td>%</td>
</tr>
<tr>
<td>mean L2 rf voltage</td>
<td>ΔV2/V2</td>
<td>0.25</td>
<td>0.30</td>
<td>%</td>
</tr>
<tr>
<td>mean L3 rf voltage</td>
<td>ΔV3/V3</td>
<td>0.08</td>
<td>0.09</td>
<td>%</td>
</tr>
</tbody>
</table>

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![Diagram of LCLS and TESLA](image)
RF phase stability in some existing machines

**MIT Bates Linac RF**
Zolfaghari, Cheever, Wang, Zwart
~0.07 degree (rms) level

**Rossendorf, cw scrf, Gabriel**
~0.02 degree (rms) level

**SPPS beam results suggest this RF stability already exists in SLAC linac**

JLAB, cw scrf, ~0.01 degree rms level
0.01% rms amplitude level
RF Regulation TESLA Cavity (Simulation)
PLL Basics

- Basic idea of a phase-locked loop:
  - inject sinusoidal signal into the reference input
  - the internal oscillator locks to the reference
  - frequency and phase differences between the reference and internal sinusoid → \( k \) or 0
  - Internal sinusoid then represents a filtered version of the reference sinusoid.
  - For digital signals, Walsh functions replace sinusoids.
A phase detector (PD). This is a nonlinear device whose output contains the phase difference between the two oscillating input signals.

A voltage controlled oscillator (VCO). This is another nonlinear device which produces an oscillation whose frequency is controlled by a lower frequency input voltage.

A loop filter (LF). While this can be omitted, resulting in what is known as a first order PLL, it is always conceptually there since PLLs depend on some sort of low pass filtering in order to function properly.

A feedback interconnection. Namely the phase detector takes as its input the reference signal and the output of the VCO. The output of the phase detector, the phase error, is used as the control voltage for the VCO. The phase error may or may not be filtered.
Self Excited Loop

- Master-oscillator
- Limiters
- Loop Phase
- Phase Set Point
- Phase Detector
- Amplitude Set Point
- Amplitude Detector
- Amplitude Control
- Phase Control
- Klystron
Phase noise and timing jitter

\[ \Delta t_{\text{rms}} = \frac{\sqrt{2} \int_{f_i}^{f_2} L(f) df}{2\pi f_0} \]
Although there are very good low-noise sapphire loaded cavity oscillators

• Master oscillator phase noise within bandwidth of feedback systems can be corrected
• Residual uncontrolled phase noise plus noise outside feedback systems bandwidth results in timing jitter and synchronization limit
Performance Measured at JLAB
Bode Plot of Controller at JLAB

- Low Frequency Gain: 0 - 30 dB
- Rolloff Frequency: 1 Hz - 200 Hz
- Broadband Gain: 20 - 60 dB
- Controller + Cavity

frequency [Hz]
Noise characterization of the LLRF System (TTF2)

**RF digital feedback system (TTF2):**

- Bandwidth for transforming 250kHz squared pulses:
  \[ \Delta f \approx 10\text{MHz} \]

- Required regulation bandwidth only:
  \[ \Delta f \approx 1\text{MHz} \]

**+I,-I,+Q,-Q detection scheme:**

Rotation of the LO-signal in four 90° steps:

\[ (-I,+Q) \rightarrow (+I,+Q) \]
\[ (-I,-Q) \rightarrow (+I,-Q) \]
Noise characterization of the LLRF System (TTF2)

- **Stability requirements on phase and amplitude of the cavity field vector:**

  Amplitude stability:
  \[
  \frac{dA}{A} < 10^{-4}
  \]
  and linearity

  Phase stability:
  \[
  df < 0.01^\circ
  \]

  \[
  dU_{XFEL} < 100 \mu V
  \]
  (normalized to \( A=1V \))

- **Noise measurement at input of an ADC:**

  \[
  dU_{TTF2} \approx 1.0 mV = 10 \times dU_{XFEL}
  \]

  rms-voltage noise:
  \[
  dU = \sqrt{\int S_U(f)df} \approx \sqrt{S_U} \sqrt{\Delta f}
  \]

  - Reduce the measuring bandwidth
  - Low-noise design
  - Averaging, switched low-pass!
  - Correlation methods

  Superposition of all noise contributions:
  \[
  \sqrt{dU_{DW}^2 + dU_{IQ}^2 + dU_{MO}^2 + dU_{extern}^2 + \ldots} < 100 \mu V
  \]
Noise characterization of the LLRF System (TTF2)

\[ P_{RF} \approx [-40 \text{dBm}, -10 \text{dBm}], \quad -70 \text{dB linearity} \]

\[ dU_{DWC} \approx 2.0 \times dU_{XFEL} \]

\[ (S_{U,\otimes} + S_{U,AMP}) v^2 = S_{U,DWC} \]

\[ \sqrt{S_{U,\otimes}} \approx 4.5 \text{nV/\sqrt{Hz}}, \quad v \approx 8.5 \]

\[ \sqrt{S_{U,AMP}} \approx 7 \text{nV/\sqrt{Hz}} \]

\[ \sqrt{S_{U,DWC}} \approx 70 \text{nV/\sqrt{Hz}} \]
Noise characterization of the LLRF System (TTF2)

- Noise conversion over the LO-Signal at down-converter from master-oscillator:

\[ dU_{MO} \approx 10 \times dU_{XFEL} \]
Specifications

provide FEL pulse with some ten fs arrival time stability:

- amplitude and phase stability of RF in cavities in injector area
- stable reference distributed over 3.5 km to end of linac

Crucial are cavities up to bunch compressor. Jitter in I and Q of RF results in jitter in energy (off crest acceleration). Bunch compressor turns that into arrival time jitter.
Modelocked Fiber Laser Oscillator – RF Stabilized

- Phase-lock all lasers to master oscillator
- Derive rf signals from laser oscillator
- Fast feedback to provide local control of accelerator rf systems
  - Synchronization 10's fs
Experimental Setup for RF Locking

fs Laser 2

fs Laser 1

Delay

BBO

SHG

SFG

Phase shifter

14 GHz

100 MHz

14 GHz Loop gain

50 ps

Sampling scope

SFG intensity analysis

14 GHz Loop gain

100 MHz Loop gain

Laser 1 repetition rate control

Phase shifter

fs lasers share pump source, isolated optical table
RF phase shifter gives electronically addressable timing delay

Jun Ye’s lab in collaboration with
Henry Kapteyan and workers
Timing Jitter via Sum Frequency Generation

Cross-Correlation Amplitude

Top of cross-correlation curve (two pulses maximally overlapped)

Timing jitter 1.75 fs (2 MHz BW)

Timing jitter 0.58 fs (160 Hz BW)

(two pulses offset by ~ 1/2 pulse width)

Total time (1 s)

Mixer/Amplifier noise floor

Locking error signal

Balanced Cross-Correlator

Output
(650-1450nm)

Cr:fo

Ti:sa

Rep.-Rate Control

(1/496nm = 1/833nm+1/1225nm).

SFG

SFG

GD

Balanced Cross-Correlator

Error Signal

Mixer output [V]

Time difference [fs]
Experimental result: Residual timing-jitter

The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 0.3 fs (a tenth of an optical cycle)
RF System Response

Gradient modulator drive signals **with** and **without** energy recovery in response to 250 µsec beam pulse entering the RF cavity.
RF Instabilities

- Instabilities can arise from fluctuations of cavity fields.
- Two effects may trigger unstable behavior:
  - Beam loss which may originate from energy offset which shifts the beam centroid and leads to scraping on apertures.
  - Phase shift which may originate from energy offset coupled to $M_{56}$ in the arc.
- Instabilities predicted and observed at LANL, a potential limitation on high power recirculating, energy recovering linacs.

$M_{56}$ is the momentum compaction factor and is defined by:

$$\Delta l = M_{56} \frac{\Delta E}{E}$$
RF STABILITY FLOW CHART

- Energy Aperture
- Beam loss
- Phase shift
- Feedback
- Feedback
- $\Delta E$
- $\Delta G$
- $M_{56}$
- Frequency shift
- $\Delta V_b$
- $\Delta V_c$
- $\Delta P_{\text{light}}$
Natural extension of the original configuration.

8 times larger e-beam power.

Fitting to the concrete boundary.

Energy = 17MeV

FEL : $\lambda \approx 22\mu m$

Bunch charge = 500pC

Bunch length = $\approx 15$ps (FWHM)

Bunch rep. = 10.4MHz – 83.3MHz

Average current = 5.2mA – 40mA

after injector-upgrade
Demonstration of Energy Recovery

Beam current at the exit of the second main module.

Bunch interval is 96ns, and recirculation time is 133ns.

RF amp forward power for the 1st main module.

98% energy of e-beam is recovered.
Improvement of RF Stability — new low-level controllers and reference-signal cables

- Phase drift $\sim 3$ deg./°C
- Phase jitter $\sigma = 0.78$ deg.
- Phase drift $< 0.2$ deg.
- Phase jitter $\sigma = 0.15$ deg.
LOLA Bunch Length Measurement

Image of LOLA's screen 17ACC7

1ps
Bunch Profile and Time Jitter

Bunch profile

bunch # [~sec]

2ps

1ps

Erl Workshop 2005
Stefan Simrock
DESY
Drift ACC1 (cryomodule before BC) at TTF

Energy variation exit ACC1: 2006-02-25. $E_0 = 127$ MeV

- energy drift + jitter = 0.77%
- energy drift = 0.072%
- energy jitter = 0.028%

**energy jitter**

Time jitter due to energy jitter after BC2 (no compression BC3): 2006-02-25. $E_0 = 127$ MeV

- timing drift + jitter = 459.1 fs
- timing drift = 432.3 fs
- timing jitter = 154.8 fs

**time jitter**
Work to be done

• Develop error budget for synchronization and rf field stability.
• Precise control of the accelerating fields in presence of heavy beam loading in the injector and high loaded Q in the linac (low beam current but strong fluctuations possible).
• Synchronize Lasers and RF Systems at various frequencies separated by distances of up to a few hundred meters.
  • Develop highly stable phase reference systems.
  • Develop beam based correction schemes.
  • Develop synchronization between lasers and rf systems and demonstrate performance in the accelerator environment.