Bunch Arrival Synchronization

• Arrival time detector overview
• Optical synchronization system using a pulsed reference laser
  – Distribution system
  – Synchronization of laser oscillators
  – Measurement and generation of RF signals
  – Arrival time detector
• Sources for arrival time changes
  – Arrival time stabilization at FLASH
• Summary of arrival time detectors
ERL requirements

<table>
<thead>
<tr>
<th>Modes</th>
<th>(A) Hi-flux</th>
<th>(B) Coherence</th>
<th>(C) Small Charge, Short Bunch, Hi-Rep Rate</th>
<th>(D) High Charge, Short Bunch, Lo-Rep Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>100</td>
<td>25</td>
<td>TBD&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.1</td>
</tr>
<tr>
<td>Bunch Charge (pC)</td>
<td>77</td>
<td>19</td>
<td>TBD&lt;sup&gt;1&lt;/sup&gt;</td>
<td>1000</td>
</tr>
<tr>
<td>Repetition Rate (MHz)</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>0.1</td>
</tr>
<tr>
<td>Geom. Emittance, both Horiz. &amp; Vert. (pm)</td>
<td>30</td>
<td>8</td>
<td>TBD&lt;sup&gt;1&lt;/sup&gt;</td>
<td>500</td>
</tr>
<tr>
<td>RMS Bunch Length (fs)</td>
<td>2000</td>
<td>2000</td>
<td>&lt;100&lt;sup&gt;2&lt;/sup&gt;</td>
<td>&lt;100&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Relative electron energy spread (x10&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

In short pulse modes, an electron bunch arrival time stability of 10 fs is required.
Arrival time detection by RF methods
Simplified principle

**Measurement of beam phase relative to RF reference**

+ relative simple setup
+ high resolution possible at high frequencies
+ single bunch measurement possible
  - demonstrated at 2 ns bunch spacing (J. Fox et al.)

- long-term stability hard to achieve
  - band pass filter / cavity and mixer tend to drift
  - drift free generation of high frequency reference signal is challenging
- no information on bunch shape
Arrival time detection by RF methods
PEP-II / ALS / BESSY / PLS system

Planar stripline circuit band-pass filter
- generates 4 cycle output signal at 2856 MHz from a button BPM signal
- Finite time response allows for single bunch detection at small bunch spacings (here: 2 ns)

Single shot resolution: 200 fs.

Estimated resolutions for a higher frequency design:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3 GHz</th>
<th>10 GHz</th>
<th>30 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Noise (rms)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Bunch Charge (C)</td>
<td>1E8</td>
<td>1E8</td>
<td>1E8</td>
</tr>
<tr>
<td>Estimated resolution</td>
<td>0.2 ps</td>
<td>0.06 ps</td>
<td>0.02 ps</td>
</tr>
</tbody>
</table>

bunch charge: 10 nC
ERL: 0.077 nC

Courtesy of J. Fox (SLAC), et al.
• detection scheme at 30 GHz
• less than 10 fs resolution in 250 MHz bandwidth
• bunch spacing: 333 ps

Courtesy of A. Andersson, J.P.H. Sladen (CERN)
Detection of electron arrival time with respect to reference beam.

- Mapping of electron bunch profile into polarization of a short laser pulse using an electro-optical crystal.
- Different arrival times correspond to different spatial positions of the laser pulse.

- 30 fs resolution for bunch centroid
- Single bunch measurement
- Sample rate limited by readout system (and laser repetition rate)
- Bunch profile information available

Courtesy of A. Cavalieri
Electro-optical arrival time detection: Spectral decoding

- Mapping of electron bunch profile into optical spectrum of a broad-band laser pulse using an electro-optical crystal.

Similar performance as previous scheme.

Courtesy of G. Berden et al. (FELIX)
Arrival time measurement with a transverse deflecting structure

Measurement of the bunch arrival time with respect to the RF field in the cavity

- highest temporal resolution of the discussed methods (sub 20 fs within the longitudinal profile)
- single shot detection possible
- small bunch spacing possible when paired with BPM readout system

- Streaked bunches are lost
  - Knowledge of the timing of the cavity RF field determines arrival time resolution
„Synchronization“ of arrival time monitors

- „Single frequency detection“
  - provide stable RF signal with respect to reference
  - phase detection of RF signal with respect to reference

- Electro-optical methods with external lasers
  - synchronize laser to reference

- Transverse deflecting cavity
  - provide stable RF signal with respect to reference
  - phase detection of RF signal with respect to reference
Layout of the optical synchronization system at FLASH

Master Laser Oscillator (erbium-doped fiber laser)

- Optical length stabilized fiber links
- Fiber couplers
- Phase lock loop
- Low-noise microwave oscillator

Laser to RF conversion to low level RF

Direct use of laser pulses:
- Bunch arrival-time monitors
- Synchronization of external lasers (cross-correlation)
- Beam position monitors
- Optical down-converters
- Electro-optical methods (e.g. photon beam arrival time)
- Seeding of amplifiers
- ...

Development in collaboration with MIT (F.X. Kaertners group)
The fiber laser system

A low noise, Erbium-doped, modelocked, 216 MHz soliton laser is used as the timing reference for the accelerator.
Prototype of a 216 MHz laser and a small distribution unit. The second iteration is on its way.
Laser distribution unit
Schematic layout

- Laser 1
  - Fiber link 1+2
  - Fiber link 3+4
  - Fiber link 5+6
  - Fiber link 7+8
  - Laser 2
  - Fiber link 9+10
  - Fiber link 11+12
  - Spare
  - Sagnac loop
  - PM - EDFA

- Laser 2
  - Fiber link 1+2
  - Fiber link 3+4
  - Fiber link 5+6
  - Fiber link 7+8
  - Laser 1
  - Fiber link 9+10
  - Fiber link 11+12
  - Spare
  - Sagnac loop
  - PM - EDFA
Fiber link stabilization:
Schematic setup

216 MHz Er-doped fiber laser

end station

EDFA

50:50 Faraday Rotating Mirror

balanced cross-correlator

Piezo-driver

Loop filter

Piezo-stretcher

Optical delay stage

HWP

HWP

QWP

Mirror

Fiber link stabilization:
Balanced optical cross-correlator

Development in collaboration with MIT
Fiber link stabilization: Schematic setup

216 MHz Er-doped fiber laser

end station

EDFA

50:50 Faraday Rotating Mirror

Balanced cross-correlator

Piezo-stretcher

Optical delay stage

Piezo driver

Loop filter

QWP

Mirror

HWP

HWP
Fiber link stabilization:
Schematic setup to determine fiber link stability

216 MHz Er-doped fiber laser
Fiber link stabilization
Frequency distribution of fiber link timing changes

![Frequency distribution of fiber link timing changes](image-url)
Fiber link stabilization
Long term stability

rms timing jitter over 2 minutes: (4.4 ± 1.1) fs
timing drift over 12 hours: 25 fs (rms over this time: 7.5 ± 1.8 fs)
measurement bandwidth: 200 kHz
Fiber link stabilization
Timing drift a measurement artifact?

- polarization changes inside the fiber-link!
  - amplitude entering out-of-loop cross-correlator is changed
Prototypes of master laser and fiber link stabilization
Construction of fiber link mechanics together with K. Jähnke (DESY).
Locking of external lasers
Scheme of optical cross-correlator

A similar scheme as for the fiber link cross-correlator will be used:

DGD: differential group delay
Locking of external lasers
First setup

Courtesy of S. Schulz, V. Arsov
Locking of external lasers
First signal

- TiSa
- EDFL
- RF lock
- balanced cross-correlator

Courtesy of S. Schulz, V. Arsov

Error signal (mV)

Time (ps)
Laser to RF conversion
Possible schemes

Optical division of distributed frequency

Direct conversion with PD
- temperature drifts
- AM to PM conversion*
- noise limitation due to low power in spectral line of PD output

Injection Locking
- temperature drifts of PD
- AM to PM conversion of PD*
+ DRO determines high frequency noise
+ entire photo detector signal used

(*) typical AM to PM conversion: 1-10ps/mW
RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:

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

Output power

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

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

modulation voltage: \( f_{\text{rep}} / 2 \)

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

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

modulation voltage: $f_{rep} / 2$

Courtesy of J. Kim (MIT)
RF extraction and measurement with a Sagnac loop interferometer

Phase detection in the optical domain:

First results with a DRO (dielectric resonance oscillator) frequency of 10 GHz are very promising (6.8 fs over 10 h). Next step: Transition to 1.3 GHz DRO.

VCO signal to stabilize \((n \cdot f_{\text{rep}})\)

modulation voltage: \(f_{\text{rep}} / 2\)

 Courtesy of J. Kim (MIT)
Bunch arrival time monitor (BAM)
Detection principle

The timing information of the electron bunch is transferred into a laser amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.
Bunch arrival time monitor (BAM)
Schematic setup
During last summer, a new beam pick-up (design: K. Hacker) was installed instead of ring electrodes to improve the pick-up performance.

**old ring electrode:**

**new design:**

14.5mm

17mm

6.2mm

1.2mm thick

Alumina disk
Bunch arrival time monitor (BAM)
shot-to-shot fluctuations and intra bunch train pattern
An upper limit for the BAM resolution can be estimated by correlating the arrival time of two adjacent bunches in the bunch train:

The resolution estimated from the laser amplitude noise and the slope steepness is about 5-6 fs.
Goal: generate and compensate arrival time slopes with the beam loading amplitude of ACC1
Bunch arrival time monitor (BAM)
Positions of the BAMs in the FLASH linac

Synch Lab with master laser system

fiber links of synchronization system
Arrival time correlation between two BAMs

Arrival time measurement with two BAMs, separated by 60 m drift space.
Arrival time difference contains:
- high frequency laser noise (~1.7 MHz – 216 Mhz)
- two fiber link stabilizations
- two BAMs

Single bunch resolution of entire measurement chain: 7.5 fs (rms)
300 shots in 60 seconds

not yet published
Main sources for arrival-time changes of the FEL radiation

- arrival-time of the photo cathode laser pulses
- phase of the RF gun
- amplitude and phase of booster module
- arrival-time of potential seed lasers
Timing changes in a FEL

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

- photo cathode laser
- pump-probe laser

RF requirements for 10 fs arrival time stability at FLASH:
- phase stability < 0.005° @ 1.3 GHz (= 10 fs)
- amplitude stability < 1.6 * 10^{-5}

\[ \sum_t^2 \approx \left( \frac{R_{56}}{c_0} \frac{\sigma_A}{A} \right)^2 + \left( \frac{C-1}{C} \right)^2 \left( \frac{\sigma_{\phi}}{2\pi f_{RF}} \right)^2 + \left( \frac{1}{C} \right)^2 \sum_{i,t}^2 \]
Bunch arrival time monitor (BAM) intra bunch-train arrival time feedback

- Photo Cathode Laser
- RF Gun
- ACC1
- ACC23
- BAM
- SIMCON DSP
- ACB2.1
- Digital cavity
- Controller board
- FPGA + DSP
- Rocket IO
- 4 channel 108 MHz ADC board
- 16 bit resolution
- FPGA for data processing
- Rocket IO
Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback
Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

arrival time for 1200 shots:

jitter w.o. FB:
~1.5 ps pk-pk
~240 fs rms

jitter with FB:
~300 fs pk-pk
~40 fs rms

not yet published
Bunch arrival time monitor (BAM)
intra bunch-train arrival time feedback

rms over 1200 shots

arrival time jitter [fs]

time [us]

not yet published
Bunch arrival time monitor (BAM) 
intra bunch-train arrival time feedback

Generation of well defined arrival time slopes over the bunch train: 
(this allows complete pump-probe experiments within a single bunch train)

![Graph showing relative arrival time over time (us)]
Outlook: complete longitudinal feedback

Detection of main arrival-time jitter sources
- Arrival time of photo cathode laser pulses (CC / 1st arrival time monitor)
- Phase of RF gun (difference between 1st and 2nd arrival time monitor)
- Amplitude of ACC1 (BPM in magnetic chicane)
- Phase of ACC1 (Bunch Compression Monitor)
- Arrival time of pump-probe lasers (cross-correlation with timing system)
## Summary of bunch arrival time detectors

<table>
<thead>
<tr>
<th>Measurement Bandwidth</th>
<th>RF mixing</th>
<th>„BAM“</th>
<th>„EO“</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single shot</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Sample rate</td>
<td>GHz</td>
<td>~200 MHz</td>
<td>~10 – 100 kHz</td>
<td>GHz</td>
</tr>
<tr>
<td>Pros</td>
<td>- no optics</td>
<td>- high resolution</td>
<td>- high resolution</td>
<td>-highest resolution information</td>
</tr>
<tr>
<td></td>
<td>- simple setup</td>
<td>- easy and fast data processing</td>
<td>- profile information</td>
<td>profile information</td>
</tr>
<tr>
<td></td>
<td>- easy and fast data processing</td>
<td>- absolute reference</td>
<td>- drift free</td>
<td>data processing</td>
</tr>
<tr>
<td>Cons</td>
<td>- may drift</td>
<td>- no profile infos</td>
<td>- complicated</td>
<td>-expensive</td>
</tr>
<tr>
<td></td>
<td>- single shot resolution</td>
<td>- small bunch spacing requires fast pick-up</td>
<td>- slow data acquisition</td>
<td>-invasive</td>
</tr>
<tr>
<td></td>
<td>- no profile infos</td>
<td>- data processing</td>
<td>- drift free</td>
<td>-may drift</td>
</tr>
</tbody>
</table>

**Develop. for ERL**
- pick-up
- drifts
- pick-up
- fast detector
- data processing
Summary

• Four different schemes for the arrival time detection were discussed. None of these schemes meets all ERL requirements (i.e. 1.3 GHz data acquisition, low bunch charge).

• The reference signal and its distribution go hand in hand with the arrival-time detection.

• The timing stability of a machine depends sensitively on the design of the bunch compressor scheme.
Contributing People

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Thank you for your attention!