Optical Synchronization Techniques for VUV and X-Ray Free Electron Lasers

F. Loehl*¹, V. Arsov¹, M. Felber¹, K. Hacker¹, F. Ludwig¹, B. Lorbeer, K. Matthiesen¹, Holger Schlarb¹, B. Schmidt¹, S. Schulz², A. Winter², J. Zemella²

¹ Deutsches Elektronen Synchrotron (DESY), Hamburg
² Hamburg University

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Outline

• Motivation

• The synchronization system at FLASH
  – laser system
  – distribution unit
  – fiber links, Er-doped fiber amplifiers
  – endstations:
    • bunch arrival time monitor
    • locking of external lasers
    • laser to RF conversion
Synchronization needs in an FEL facility

**Goal:**
- measure and stabilize timing jitter + drift between FEL and pump-probe laser on the 10 fs scale

**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
Layout of the optical synchronization system

- **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
- ...
The fiber laser system

A redundant 216 MHz soliton laser will be used as a reference oscillator. The higher repetition rate compared to the previous 54 MHz stretched pulse laser system has several advantages for the subsystems.
First prototype of a 216 MHz laser and a small distribution unit. The second iteration is on its way.
Distribution unit
Schematic layout

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

216 MHz Er-doped fiber laser

HWP

HWP

QWP

Mirror

Balanced cross-correlator

Loop filter

Piezo stretcher

Optical delay stage

EDFA

50:50 Faraday Rotating 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-driver

loop filter

Optical delay stage

Piezo-stretcher

HWP

QWP

Mirror

0.01
Fiber link stabilization:
Schematic setup to determine fiber link stability

216 MHz Er-doped fiber laser

HWP QWP HWP QWP

Piezo-stretcher

Optical delay stage

Balanced cross-correlator

Loop filter

EDFA

HWP QWP

50:50 Faraday Rotating Mirror

Out-of-loop Balanced cross-correlator

Out-of-loop timing jitter measurement
Fiber link stabilization
Frequency distribution of fiber link timing changes

![Graph showing frequency distribution of fiber link timing changes](image)
Fiber link stabilization
Long term stability

rms timing jitter over 2 minutes: $(4.4 \pm 1.1)$ fs
Timing drift over 12 hours: 25 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
Characterization of Er-doped fiber amplifiers

Florian Löhl

GFA seminar, PSI

March 4th, 2008
Prototypes of master laser and fiber link stabilization
Fiber link stabilization
Mechanical design

Construction of fiber link mechanics together with K. Jaehnke (ZM1).
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)
Positions of the BAMs in the FLASH linac

Synch Lab with master laser system

fiber links of synchronization system
During last summer, a new beam pick-up (design: K. Hacker) was installed instead of the 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)

BAM signals

\[
\text{mean(baseline)} = (59.128 \pm 2.190) \text{ mV}
\]

\[
\text{mean(signal)} = (455.729 \pm 48.832) \text{ mV}
\]

\[
\text{mean(laser amp)} = (514.856 \pm 49.034) \text{ mV}
\]

\[
\text{mean(laser amp norm)} = 1.00386 \pm 0.08946
\]

amplitude noise = 0.183%
The laser pulses are scanned over the beam pick-up signal to map it onto the laser amplitude. The slope at the zero-crossing is used for the measurement. A calibration run can be made “online” and a continuous calibration update is foreseen in case operation conditions are changed (already implemented in DOOCS server).

(slope measured with old beam pick-up)
Bunch arrival time monitor (BAM)
Dependence of the pick-up signal slope on the beam position

There is basically no dependence!
Bunch arrival time monitor (BAM)

Dependence of the pick-up zero-crossing on the beam position

horizontal channels combined:

- Symmetric curve with zero slope at \( y = 0 \) expected!

- possible reasons:
  - misalignment of BPM 16ACC7
  - misalignment of BAM 18ACC7 and OTR chamber
  - different coupling efficiency of different pick-up electrodes
Bunch arrival time monitor (BAM)
Dependence of the pick-up signal slope on the bunch charge

Slope does not get steeper with increasing charge!
Bunch arrival time monitor (BAM)
Dependence of the measured bunch arrival time on the charge

Arrival time dependence on the bunch charge is much higher for the BAM than for LOLA!
Bunch arrival time monitor (BAM)
Dependence of the measured bunch arrival time on the charge

Do the BPMs have a charge dependence?

orbit feedback switched off
Bunch arrival time monitor (BAM)
Change of the bunch length with charge (on-crest)

charge = 0.27 nC  sigma(t) = 3.85 ps  charge = 0.48 nC  sigma(t) = 5.52 ps  charge = 0.70 nC  sigma(t) = 7.19 ps  charge = 1.60 nC  sigma(t) = 10.19 ps

The bunch length is changed almost by a factor of three!
The longitudinal pulse shape is changed significantly!
→ Intra bunch train charge feedback needed.
Superposition of “wavelets” for each longitudinal slice.
Free parameter: wavelet duration.
Bunch arrival time monitor (BAM)
Simple model to understand the BAM charge dependence

For a compressed bunch, the dependency is strongly suppressed.
The previous considerations seem to explain the charge dependence...

BUT: This is the frequency spectrum of the shortest wavelet:
(bandwidth of EOM: 20 GHz)
Expansion of the model by a low pass filter.
Behavior of the BAM can still be described by the model.
(wavelet pkpk ~ 6 ps)
Goal: generate and compensate arrival time slopes with the beam loading amplitude of ACC1

The different colors represent different settings of the beam loading compensation.
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 well below 10 fs.
Bunch arrival time monitor (BAM)
Arrival time manipulation over the bunch train

Arrival time flattened by applying arrival time readings to ACC1 amplitude set point tables.
Bunch arrival time monitor (BAM)
Next step: intra bunch-train arrival time feedback

- Photo Cathode Laser
- RF Gun
- ACC1
- ACC23
- SIMCON
- ACB2.1
- BAM
The bunch arrival time monitors can be used for many different kinds of diagnostics, e.g.:

- Beam position measurement as difference of two arrival time measurements

- Laser timing measurement by sampling of photo detector signals

- Phase and amplitude measurements of RF signals

- …
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 laser (cross-correlation with timing system)
A similar scheme as for the fiber link cross-correlator will be used:
Locking of external lasers
First setup

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

Courtesy of S. Schulz, V. Arsov

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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
Laser to RF conversion
Sagnac loop

Phase detection in the optical domain:

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

Courtesy of J. Kim
Laser to RF conversion
Sagnac loop

Phase detection in the optical domain:

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

- Pulse train input
- \( T_R = 1/f_R \)
- 50:50 coupler
- Phase Modulator
- \( f_R/2 \)
- Modulation voltage: \( f_{\text{rep}}/2 \)

Courtesy of J. Kim

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Phase detection in the optical domain:

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

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

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

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

First results with a DRO frequency of 10 GHz are very promising (< 10 fs drift over 12h, J. Kim et. al.). Next step: Transition to 1.3 GHz DRO.

Courtesy of J. Kim
Conclusion

• Most subsystems have been prototyped and proven to have a resolution / stability of ~ 10 fs.

• A complete system consisting of a fiber laser, a fiber link and a bunch arrival time monitor is running and provides the expected resolution.

• The ultimate machine stabilization will be done using beam based measurements.

Next steps:
• Consistency studies:
  – comparison measurement of two BAMs
  – comparison measurement BAM ↔ EO
• Implementation of arrival time feedback
• Upgrade of synchronization system to reach more end-stations

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