Femtosecond Optical Synchronization System for FLASH

Achievements and challenges during the first implementation phase of an engineered version in the accelerator

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Agenda

➢ Short Introduction to FLASH

➢ Synchronization Needs and System Layout

➢ The Basic Components of the System

➢ Arrival Time Measurements and Feedback

➢ RF Generation from Optical Pulse Train

➢ Closing Remarks
Started as test facility for the TESLA project

- Superconducting cavities at 1.3 GHz (~25 MV/m)
- 3\textsuperscript{rd} Harmonic Module at 3.9 GHz
- Two dispersive sections for high peak currents
- First user facility for VUV and soft X-ray laser pulses
- Photon pulses have few 10 fs length
- Pump-Probe experiments require synchronization on a 10 fs scale
Synchronization needs in an FEL facility

Goal
- Measure and stabilize (feedback) timing jitter + drifts
- Lock various lasers (pump-probe, diagnostic, seed, …)
- Provide extremely stable RF reference signals

Main sources for arrival-time changes
- Arrival-time of the photo cathode laser pulses
- Phase of the RF gun
- Amplitude and phase of the booster module(s)

RF requirements for 10 fs arrival stability:
\[ \Delta \varphi < 0.005^\circ @ 1.3 \text{ GHz} \]
\[ \Delta A/A < 1.6 \times 10^{-5} \]
The reference timing information is encoded in the precise repetition rate of an optical pulse train.
Schematic of the optical synchronization system at FLASH

- beam based feedback stabilization of arrival-time
- high precision synchronization of lasers
- synchronization of all timing critical devices (up to 14)

⇒ Point-to-point synchronization ~ 10 fs rms (< 30 fs rms to beam)
⇒ Permanent operation and long term stability / availability investigation
The synchronization lab at FLASH

> Optical table (full expansion state)

- two MLOs for redundancy
- free-space distribution
- four fiber (EDFA) distribution units
- up to 14 link stabilization units (‘Fiber Links‘)
- RF-lock unit for MLO
- RF based link stabilization unit

> Four electronic racks

- four VME crates (in future μTCA)
- 18 DSP controls (feedback loops)
- 18 piezo drivers (± 300 V)
- 20 pump laser diode drivers
- 16 stepper motor drivers
- > 40 temperature readouts
- tons of monitor signals
- ~ 300 cables to/from optical table
Master laser oscillator (MLO)

Properties

- mode-locked erbium-doped fiber laser
- 1550nm telecommunication wavelength
- repetition rate of 216.66 MHz (1.3 GHz /6)
- average power > 60 mW
- pulse duration < 100 fs (FWHM)
- Integr. timing jitter ~15 fs [1 kHz, 10 MHz] (limited by measurement)
- amplitude noise < 2 \cdot 10^{-4} [10 Hz, 40 MHz]

NPR type laser maybe not the best solution?

Original design:
Distribution to up to 16 outputs

Properties

- baseplate made of Invar
- two free space inputs, 16 collimator outputs
- same pathlength for each output
- 4-5 mW per output
- ~ 85% incoupling efficiency at all collimators

S. Schulz, FEL09, WEPC72
Fiber link stabilization

216 MHz Er-doped fiber laser


End station

EDFA

50:50 Faraday Rotating Mirror

Balanced cross-correlator

Piezo-stretcher

Mirror

Piezo driver

Optical delay stage

HWP

QWP

Courtesy F. Loehl
Balanced optical cross-correlator (OCC)

(Development in collaboration with MIT)

F. Loehl, FEL08, THBAU02

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Beam arrival-time monitor (BAM)

M. Bock, FEL09, WEPC66

Patented 2006 by DESY
Arrival time correlation between two BAMs

Arrival time difference contains:
  • high frequency laser noise (~3 MHz – 108 MHz)
  • stability of two fiber links
  • two BAMs

Single bunch resolution of entire measurement chain: < 6 fs (rms)

Goal: Achieve stable arrival time, energy and compression

Need: Many (different) monitor systems and complex regulation algorithms needed

Beam based injector feedback

Photo Cathode Laser (PCL)

1 arrival-time monitors

RF Gun

Booster

Energy BPM (EBPM)

BPMs

3 bunch compr. monitor

2 synchrotron light monitor SLM

Machine parameter:
Arrival-time of PCL
Phase of RF gun
Amplitude of booster
Phase of booster module

Monitor:
1st arrival time monitor
difference 1st and 2nd arrival-time monitor
EBPM + BPMs / difference 3rd and 2nd arrival-time monitor (/ SLM)
(bunch compression monitor / fiber laser + EO)
Intra bunch-train arrival time feedback

1200 shots:

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

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

Intra-pulse arrival jitter reduction by a factor of 5!

F. Loehl, FEL08, THBAU02
> **Direct Conversion**

- Drift: 10.7 fs over >15 h @ 1.3 GHz  
  (*M. Felber, PAC09, TH6REP088*)
- Jitter: 3.3 fs [1kHz,10MHz] @ 3 GHz  
  (*S. Hunziker, DIPAC09, TUPB43*)
- small and robust
- 10 mW $P_{\text{opt}}$ sufficient
- relatively cheap (<2k€)
  - Small output power vs. amplifier drift
  - Amplitude to phase conversion: 1-4 ps/mW
  - Temperature dependency $\sim$350 fs/°C
RF generation from optical pulse train

> Balanced optical-microwave phase detector ➔ PLL feedback loop

- High power output (amplifier can be included in feedback)
- Balanced scheme ➔ potential for ultra-low drift: <7 fs over 7 h (*M. Felber, PAC09, TH6REP088*)

![Diagram of RF generation from optical pulse train](image)

*J. Kim et al., Nature Photonics 225: 733-736, 2008*
> Many more projects at LbSyn...

- **RF-based fiber (short)link stabilization**
  - RF based measurement of link length change <5 fs over 50 h
    (J. Zemella, FEL09, FROA05)

- **Two-color optical cross-correlator**
  - locking lasers of different wavelength, e.g. Ti:Sa (800 nm)
    (S. Schulz, PAC09, TH6REP091)

- **Energy BPM (EBPM)**
  - use orbit dependency of pickup signal in chicane + two BAM setups
    (K. Hacker, FEL09, WEPC70)

- ...
Requirements for developing a synchronization system

❯ Infrastructure
  ▪ Environment
    Temperature stabilization
    Vibration suppression
    EMI shielding
  ▪ Typical laboratory equipment
    Optical spectrum analyzer
    Autocorrelator
    RF Phase- and amplitude noise analyzer
    Baseband analyzer
    Fast scopes (≥8 GHz)
    RF spectrum analyzer (≥26 GHz desired)
    Splicer + PM splicing equipment
    etc…

❯ Engineering skills
  Optics (Free space- and fiber)
  Electronics (low noise analog / fast digital)
  FPGA programming
  Software (Control system integration / feedback)
  Mechanical (small and precise / big and robust)
  RF

❯ Time, Money and Manpower
Prototypes for all subsystems have been built and demonstrated <10 fs stability

Engineered versions of key components have been developed, some with major problems (MLO), some with good performance (Links)

At FLASH, the system is in the commissioning phase (2 MLOs, 4 Link stabilizations, 3 BAMs, and 1 EBPM in operation)

Robustness and long-term (>month) reliability tests underway

Installation of two more BAMs planned, till the end of the current shutdown (March 2010)

Still a lot of development to do…
During the past five years many fruitful collaborations contributed to the progress

Thank you for your attention!
BAM Layout

laser laboratory

MLO  
ADC 108 MHz 16 bit clock  
ADC clock generation  

MLO  
laser pulse distribution  
fibre link  

pulse shaping

optical BAM front-end

EDFA  
FRM  
EDFA  

EOM 2  
attenuator  
lIMITER  

EOM 1  

ODL 2  
ODL 1

95/5  
50/50

pick-ups on beam pipe:

① vertical, fine  
② horizontal, coarse

Courtesy M. Bock
BAM measurements – arrival time dependencies

M. Bock et al., FEL09, WEPC66

Most critical at FLASH 4.8 ps/%

Gun

Amplitude

Phase

Acc1

Acc23

Acc456 no effect
Shot-to-shot fluctuations and intra bunch train pattern