Installation Progress of the Laser-based Synchronization System at FLASH.
Overview, Experiences, Performance and Outlook

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Outline.

1. Introduction and Overview

2. Progress and Results of Selected Subsystems
   - Master Laser Oscillator
   - Fiber Links
   - Laser-to-Laser Synchronization
   - Infrastructure and Electronics

3. Latest Development
   - Photoinjector Laser Synchronization

4. Summary and Outlook
Optical Synchronization Systems.

Overview

- projected point-to-point stability: \( 10 \text{ fs} \)
- enable the **implementation** of a longitudinal feedback system
The Laser-based Synchronization System at FLASH.

Layout, Implementation and Upgrades

- last user run (till September 2009)
  → MLO with distribution and 4 fiber links, 3 BAMs, 1 EBPM (3 front-ends), standard BCMs, EO with Ti:sapphire laser
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- **After the FLASH upgrade** (just finished, now in commissioning phase) . . .
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- upgraded MLO and distribution, 3 more fiber links, 1 new BAM, 1 new EBPM, new BCM setups, new EO station, new OXC-IL2, improved infrastructure, and more
Master Laser Oscillator I.
Overview and Current Status

Specifications/Requirements

- topology: EDFL in $\sigma$-configuration
- repetition rate: $216.66 \text{ MHz}$
- average power: $\approx 100 \text{ mW}$
- pulse duration $< 100 \text{ fs (rms)}$
- integrated timing jitter $< 15 \text{ fs}$ in the interval $[1 \text{ kHz}, 10 \text{ MHz}]$
- mechanically robust, easy to maintain

$\Rightarrow$ established additional diagnostics to ensure single-pulse operation
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- back to breadboard design (severe issues with engineered versions)
- prepared for further automatization, exception handling
- in operation for $> 6$ months without major problems
Master Laser Oscillator II.

Some Recent Results

- integrated timing jitter 11.5 fs in the interval [1 kHz, 10 MHz]
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- amplitude drift over 240 h:
  - < 2% (peak-to-peak),
  - ~ 0.4% (rms)
  → no active stabilization
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Some Recent Results

- integrated timing jitter $11.5 \text{ fs}$ in the interval $[1 \text{ kHz}, 10 \text{ MHz}]$
- amplitude drift over 240 h: $< 2\%$ (peak-to-peak), $\sim 0.4\%$ (rms) → no active stabilization
- pulse duration $\tau_p = 87 \text{ fs}$, from $\text{sech}^2(t/\tau_p)$-fit → important for fiber link dispersion compensation
Master Laser Oscillator III.

Alternative Concept: Investigation of a Commercial Laser System

Promising: OneFive ORIGAMI-15

- topology: unknown (SESAM, soliton)
- repetition rate: 216.66 MHz
- average power: > 100 mW
- pulse duration: $\tau_p < 150$ fs
- integrated timing jitter < 5 fs in the interval [1 kHz, 10 MHz]
- mechanically robust, easy to maintain (sealed housing, one button)

⇒ ordered custom system
⇒ delivery/installation: April 2010
⇒ PSI enabled progress on direct conversion
⇒ November 2009 – ...
⇒ open questions: long-term stability, life-time
Actively Length-Stabilized Fiber Links 1.
Experiences with the Engineered Version

*Design: 3 Layers*
- free-space optics
Actively Length-Stabilized Fiber Links

Experiences with the Engineered Version

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Experiences with the Engineered Version

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*Problems*

- motorized delay stage
- telescope design  
  → incoupling efficiency
- optical isolation of EDFA
- ∼ 20 minor issues

⇒ solved, taken into account for in first redesign (manufacturing now)
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⇒ easy: dispersion compensated EDFA (between FSD and link box)
⇒ advantageous: new pre-spliced DCF (lower insertion loss)
⇒ major redesign considerations in progress → end-of-year
Actively Length-Stabilized Fiber Links II.

Performance Example: Long-Term Drift

**LINK09 → BAM UBC2**
- ≈ 165 m
- FRM link-end
- returning pulses $\tau_p = 115$ fs

**LINK15 → OXC EO**
- ≈ 440 m
- loop-mirror link-end
- returning pulses $\tau_p = 200$ fs

- engineered fiber link boxes ensure reliable operation
- timing distribution to the femtosecond level over long periods
- out-of-loop measurement setup currently under consideration
Laser-to-Laser Synchronization I.

Idea and First Implementation

**RF Synchronization**
- based on a RF down-mixing scheme
- timing jitter \( \gtrsim 35 \text{ fs} \)
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Optical Synchronization
- basis: non-linear optics
  \( \Rightarrow \) more precise measurements
  \( \Rightarrow \) timing jitter \( \ll 10 \text{ fs} \)
- issues:
  \( \rightarrow \) two individual oscillators
  \( \rightarrow \) different repetition rates
  \( \rightarrow \) different wavelengths
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Laser-to-Laser Synchronization II.

Single-Crystal Two-Color Balanced Optical Cross-Correlator

- sum frequency generation (SFG) in type-$I^{-}$ phase-matched BBO crystal
- group delay, then again SFG
- measurement of SFG intensities
  - difference signal highly sensitive to timing changes
  - (nearly) independent on amplitude noise of the lasers (“balanced”)
  - input signal for PLL
Laser-to-Laser Synchronization III.

Performance of the Optical Lock of the EO experiment’s Ti:Sapphire Laser

- used to lock, i.e. first cross-correlator
- measured by scanning an optical delay stage

→ challenging task to reproduce routinely/automatically
Infrastructure and Electronics.

Some Important and Critical Points

**Infrastructure**

- new climatization in the synchronization hutch
- new power supplies with battery backup for optical table and critical rack-chassis
- new power supplies for BAM/EBPM installations in the tunnel
- improved BCM, VME & cabling installations in the tunnel

⇒ Important for a robust and reliable system
⇒ Time-consuming and expensive
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**Electronics & Software**

- addressed all issues of the fast ADC for BAM and EBPM readout
- improved VME laser diode drivers
- extension of the RF-lock server *(exception handling!)*
- polarization/amplitude feedback for the fiber links
- better failure detection and remote control
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Photoinjector Laser Synchronization

Motivation

New BAM upstream of First Chicane

- timing change:
  \[ \delta t_{\text{beam}} = G_{\text{gun}} \delta t_{\text{gun}} + G_{\text{laser}} \delta t_{\text{laser}} \]
  with
  \[ \delta t_{\text{gun}} = \frac{\delta \phi_{\text{gun}}}{\omega_{\text{RF}}} \quad \text{and} \quad \delta t_{\text{laser}} = \frac{\delta \phi_{\text{laser}}}{\omega_{\text{RF}}} \]

- variation of gun and laser phase:
  \[ \Rightarrow \delta t_{\text{gun}} + \delta t_{\text{laser}} = 2.12 \text{ ps/deg} \]
  \[ (32\% + 68\%) \]

- variation of RF-gun phase slope:
  \[ \Rightarrow \delta t_{\text{max}} = 0.52 \text{ ps} \]
  \[ \Rightarrow \text{RF-gun phase feed-forward or feedback requires arrival-time information of photoinjector laser pulses on cathode!} \]

\[ \rightarrow \text{optical cross-correlator} \]
Photoinjector Laser Synchronization II.
Prototype Implementation at FLASH

- MLO delivers precise timing information over an optical fiber.
- Measuring timing jitter between PTO and reference on $O(10\, \text{fs})$ level with the optical cross-correlator.
- Stabilize 1.3 GHz phase of the PTO’s EOM by a feed-forward algorithm or a control loop.

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Photoinjector Laser Synchronization III.

Single-Crystal Two-Color Balanced Optical Cross-Correlator

- one short pulse (126 fs) and one long pulse (∼4 ps)
- sum frequency generation (SFG) in type-$I^(-)$ phase-matched BBO crystal
- separation of pulses, delay with mirror, then again SFG
- measure sum frequency intensity shot-by-shot with fast detectors and ADCs ($\nu_{rep} = 27$ MHz)
Photoinjector Laser Synchronization III.

Single-Crystal Two-Color Balanced Optical Cross-Correlator
First Results

- scan delay between MLO and PTO pulse → SFG in both directions of OXC
- measure for PTO pulse duration ⇒ 4.9 ps (rms)
- delay with mirror for second SFG not adjusted correctly
Summary and Outlook.

Current Status of Upgrades to the Optical Synchronization System

1. many new components and subsystems
2. considerable progress towards a robust, reliable and engineered system
3. implementation of a longitudinal feedback
Acknowledgements.

Thank you for your attention!

The FLASH LbSyn Team

and its former members
V. Arsov, F. Loehl, A. Winter, J. Zemella

with its many collaborators, technicians and people of other groups
RF-Lock Electronics for Ti:Sapphire Lasers

Extended RF Circuit with 81 MHz, 1.3 GHz and 9.1 GHz Phase-Detectors
Laser-to-Laser Synchronization

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Laser-to-Laser Synchronization

Implementation using the FLASH EO Ti:Sapphire Laser System – Layout
Actively Length-Stabilized Fiber Links

Principle of Operation

Link Box on Optical Table (called "Tx" in the measurements)

- BPF 2.6 GHz
  - SMA
  - Power Amplifier
- splitting 1:16
- LNA
- LPF 1.9 MHz
  - SLP-1.9+
- Photo Diode ET3010 (1.5 GHz)
- Phase Detector
  - ADR302
- Amp 2X50-35LM-5+
- Splitter ??? (minicircuits)
- Photo Diode ET3010 (1.5 GHz)
- piezo stretcher
- coupler 95/5
- coll.
- L4 (motorized)
- L2
- L4 motorized delay
- balanced optical X-correlator
- controller
- 2x Sub-D 9 (male & female)
- Sub-D 26 (male) combined motor

SAGNAC loop or ShortLink?
- distribution 1 to 16
- EDFA
- MLO
- EDFA
- Gain fiber
- link fiber, up to 350 m
- EDFA
- Faraday Rotating Mirror

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FLASH Optical Synchronization
FLS Workshop 2010

Actively Length-Stabilized Fiber Links A-I.

Principle of Operation

- sum frequency generation (SFG) of reference and reflected pulses in type-II phase-matched PPKTP crystal, delay, then again SFG
- measurement of SFG intensities
  - difference signal highly sensitive to timing changes
  - (nearly) independent on amplitude noise of the lasers ("balanced")
  - input signal for PLL (acting on piezo stretcher and delay stage)
Free-Space Distribution A-I.

Schematics and Implementation

- designed for redundant two laser operation
- allows for setting optical power per device
- no dispersive pulse broadening
Free-Space Distribution A-I.

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Free-Space Distribution A-II.

Measurements

Transmission and Reflection of Newport 05FC16BC.9 at 1550 nm

- beam cubes do not meet specs (to a small amount)
- use only the best (→ QA)

Optical Power Drift

- 0.3% (peak-to-peak) over 14 h
- but: cannot distinguish between temperature and pointing stability
Free-Space Distribution A-II.

Measurements

Transmission and Reflection of Newport 05FC16BC.9 at 1550 nm

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⇒ consider also alternative schemes:
  → dispersion compensated high-power EDFA
  → hybrid design: free-space + fiber splitter(s)

Optical Power Drift

- 0.3% (peak-to-peak) over 14 h
- but: cannot distinguish between temperature and pointing stability
- can it be done better?