Laser-Based Synchronisation & BAMs

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on behalf of the LbSync-Team

FEL Seminar
03. May 2016
What You Can Expect From This Talk...

1. Overview

2. Synchronisation System & FLASH Facility.

3. Infrastructure & Synchronisation Lab.

4. Building Blocks of the Optical Synchronisation System.

5. Synchronised Sub-Systems

6. Summary

7. Bibliography
People Involved...

- Laser-Based Synchronisation & Special Diagnostics: (alphabetic order)
  Dinter, Felber, Janaz, Gerth, Kozak, Lamb, Me, Müller, Predki, Sydlo, Steffen,
  Titberidze, Viti, Zummack

- Support for HW:
  Fenner, Ludwig, Przygoda, Wedel ..

- Support for FW:
  Butkowski, Kay, Rybaniec, ..

- Support in Feedback Systems:
  Heuer, Pfeiffer, Schmidt
LbSync@FLASH

FLASH accelerator facility
LbSync@FLASH

FLASH accelerator facility & laser-based synchronisation system

Legend
- actively stabilized link fibre
- passively stable fibre (PSOF)
- external laser beam
- pickup with RF cable

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4 / 20
Optical Fiber Distribution

1. Synchronisation signals distributed via optical fibres:
   - Currently, 7 active links via Single-Mode Fibre (SMF-28e)

2. Infrastructure for Timing, MPS, Diagnostics ...
   - in total: 672 optical (SMF) p-2-p connections installed at FLASH

3. Upgrade of Synchronised Links (17+4 in total, but only space for 20)
   - started Jan.’16: Installation of Polarisation-Maintaining Fibre (PMF)
## Optical Fiber Distribution

### FLASH 1

<table>
<thead>
<tr>
<th>Patchfield</th>
<th>Rack (target)</th>
<th>No. of Cables</th>
<th>Required Length (m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1.ACC1</td>
<td>Tunnel, 12m : PF</td>
<td>1</td>
<td>44</td>
<td>done</td>
</tr>
<tr>
<td>P2.BC2</td>
<td>Tunnel, 21m : PF</td>
<td>2</td>
<td>2x 54</td>
<td>done</td>
</tr>
<tr>
<td>P3.ACC23</td>
<td>Tunnel, 49.5m : PF</td>
<td>1</td>
<td>94</td>
<td>done</td>
</tr>
<tr>
<td>P4.BC3</td>
<td>Tunnel, 76m : PF</td>
<td>1</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>P5a.KryoAnbau</td>
<td>KryoAnbau : LLRF Rack</td>
<td>1</td>
<td>169</td>
<td>continue JUN'16</td>
</tr>
<tr>
<td>P6.ACC7</td>
<td>Tunnel, 134m : PF</td>
<td>1</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>P7.OCAS</td>
<td>28g, Rm.006 : Patchbox an Wand</td>
<td>1</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>P8.ORS5</td>
<td>Tunnel, 191m : PF</td>
<td>1</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>P10.PP-Laser</td>
<td>28c, laser labor : PF (Box an Wand)</td>
<td>1</td>
<td>363</td>
<td></td>
</tr>
</tbody>
</table>

**Total 10** 1556 m

### FLASH 2

<table>
<thead>
<tr>
<th>Patchfield</th>
<th>Rack (target)</th>
<th>No. of Cables</th>
<th>Required Length (m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>P11.SEED</td>
<td>(P12) 28m O1.005 (Technik Raum)</td>
<td>1</td>
<td>O(P12) = x + 326</td>
<td></td>
</tr>
<tr>
<td>P12lab + P12.FLASHFwd</td>
<td>28M O2.005 (Laser Labor)</td>
<td>1</td>
<td>44 + 326</td>
<td></td>
</tr>
<tr>
<td>P13.FL2EXTR</td>
<td>28m rack 02</td>
<td>2</td>
<td>2x 240</td>
<td></td>
</tr>
<tr>
<td>P14.FL2BURN</td>
<td>28l rack 80</td>
<td>1</td>
<td>344</td>
<td></td>
</tr>
<tr>
<td>P15a.FLPPL</td>
<td>... pending</td>
<td>1</td>
<td>? = O(P15c) –473m</td>
<td></td>
</tr>
</tbody>
</table>

**Sub-Total (Original Planning) 6**

| FEL beamlines / additional lasers | ... pending | 4 | x m, x = O(400m) | in NOV'16 |

**Total 10** O(3200m)
• **19 + 1** ports foreseen for individual stabilised fibre-links
  
  1. **8**: BAMs (3/8 in operation)
  2. **6**: Laser-2-Laser (OXC or RF)
  3. **3**: REFM-Opt (0/3) in operation: 1st REFM-Opt in June/’16
  4. **2**: Active Links to FEL-Beamlines at FLASH2
  5. **1**: Spare

• 2 more links to lasers at FEL beamlines FLASH2 required: new concept needed

• in 2017: completely replace FSD optics for better drift stability
- Optical Cross-Correlation (OXC) for detecting changes in transit time
- sensitivity typically ≤ 300 as/mV
- regulation with ≤ 3 kHz BW & slow compensation of drifts
- reported out-of-loop timing jitter (for 300 m SMF link) ≤ 1 fs RMS

Details: [Schulz et al.2013]
Link-Stabiliser Units (LSU)

- no more spare for VME & with MTCA.4 less space consumption
- up to 20 LSUs required: not enough space on table with old design
- better performance with new electronics
- change of optical components with Upgrade to PMF
- with PMF better drift performance: demonstrated (3600m link): Residual Drift $\leq 5$ fs (rms) over 24h, i.e. improvement by more than factor 10.

For details contact: C. Sydlo.
## Link-Stabiliser Units (LSU)

### Space allocation on optical table in sync.hutch/hall3

(shifted for better visibility; numbers in brackets mark potential space for vertical ODLs as long as FD-Boxes are still present)

1...16 = old numbering
1...20 = new numbering

<table>
<thead>
<tr>
<th>Old Numbering</th>
<th>New Numbering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 (4) 5 6 7 (8)</td>
<td>1 2 3 (4) 5 6 7 (8)</td>
</tr>
<tr>
<td>9 10 11 (12) 13 14 15 (16) 17 18 19 (20)</td>
<td>9 10 11 (12) 13 14 15 (16) 17 18 19 (20)</td>
</tr>
</tbody>
</table>
Electronics Upgrade in 2017

1. One MTCA.4 card set will handle 4 LSUs
2. Status boards: final revisions done & boards in production
3. Firmware development on-going:
   new, generalised FW concept for Laser & Link Lock
4. Server development in parallel:
   new generalised Server concept (based on control system independent libs); modular design
5. 1st complete set-up to be installed & commissioned at XFEL.
Ongoing Work at Various Client Systems

1. New RF-Resynchronisation at LLRF Rack GUN/ACC1/ACC39
2. Upgrades for Laser-to-Laser Synchronisation Setups at FLASH1/FLASH2/FLASHFwd
3. Progress on Bunch Arrival Time Monitors & Intra-Train Feedback
REFM-Opt: RF Re - Synchronisation

- optical reference module (REFM-Opt)
- balanced scheme with dual-output Electro-Optical Modulator (EOM)
- correcting phase drifts of 1.3 GHz signal by use of a VM (vector modulator) or phase shifter
- reported performance: 3.6 fs peak-to-peak drift over 24h

Details: [Lamb et al.2013] For details contact: Thorsten Lamb

- Installation in June (mini-shutdown) - optionally only as feedthrough box, depending on progress with Firmware development
- Jun’16: Commissioning of PMF link to REFM-Opt
Upgrades for Laser-2-Laser Synchronisation

1. OXC@Injector laser 1: Installation Jun’16 or end ’16
   - New IR-OXC with latest, engineered design + 4ns ODL
   - All infrastructure (electronics) are prepared

2. @FLASHFwd laser: on-going, installation of new OXC + new MTCA.4 electronics

3. @FLASH 1, 2nd Pump-Probe Ti:Sa-Laser: Planned for end ’16, earliest
   - New OXC + new MTCA.4 electronics
   - Keep redundant VME system in parallel

4. @FLASH 2: Pump-Probe Laser, currently in Bldg.49, i.e. w/o synchronised link
   - New MTCA.4 electronics for RF-sync. + OXC, one for both PP Lasers (as in final setup)
   - Preparation on-going

For details contact: Jost Müller, Matthias Felber
Bunch Arrival Time Monitors: Generation 3

1. new electro-optical unit ("BAM-box"): 4U, 19-inch module with all electro-optics, RF parts, electronics
   8x boxes ready for FLASH in Aug/Sep.'16.

2. new RF-frontend: produced, tested & demonstrated usability for down to 40 pC Details: [Czwalinna et al. 2014]

3. new electronics for read-out & control
   - read-out electronics (dual FMC on MTCA.4): newest revision in production
   - very good progress on FW & server dev. (w/ DOOCS interface & GUIs)
Backup

Bunch Arrival Time Monitors: Generation 3

1. New electro-optical unit ("BAM-box") - 4U, 19-inch module with all electro-optics, RF parts, electronics
   - 8 boxes ready for FLASH in Aug/Sep.'16.

2. New RF-frontend - produced, tested & demonstrated usability for down to 40 pC
   - Details: [Czwalinna et al. 2014]

3. New electronics for read-out & control
   - Read-out electronics (dual FMC on MTCA.4): newest revision in production
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Revival of Intra-Train Feeback

Schematic of control loops for the Fast, Intra-Train RF feedback. Set-Point Modulation w/ beam-based information:
Revival of Intra-Train Feedback

Feedback on ACC1 using BAM.3DBC2 (on MTCA.4 electronics)
Out-of-loop monitor : BAM.4DBC3 : down to 25fs RMS (not optimised!)

![Graph 1](image1)

![Graph 2](image2)
Goals for end of 2016/mid of 2017

- Continue PMF Installation (IT, IMD, Kellner-Telecom)
- Jun’16 : install REFM-Opt in ACC1 Rack
- by Jun/Jul’16:
  - BAM.1UBC2,3DBC2 & 4DBC3 permanently running on MTCA.4 system
  - intra-train FB tested with ACC1, later on ACC23
- end 2016 : BAM-Box
  - exchange of BAM.4DBC3 "BAM-Box" by new Gen.3 module
- in 2016: upgrades of Laser-2-laser systems
  - New OXC setups : Inj.Laser, PP-Laser, FLASHFwd
  - Laser-Locking electronics on MTCA.4 : PPLs for FLASH1&2
- beginning of 2017: commission 2x FL2-BAMs with complete new setup
  - RF Cabling (during shutdown Nov/Dec’16)
  - latest BAM-Box module (during shutdown Nov/Dec’16)
  - MTCA.4 electronics
- in 2017 : Sync.Lab
  - start to migrate to MTCA.4 & stand-alone electr. for laser & link locking
- in 2017: needs new cabling in Sync. Lab


• concept for shielding: is crucial due to accoustics, vibrations & EMI:
  • copper ground & optical table resting on its own concrete fundament
  • cover for optical table: not sufficient for accoustic isolation

• temperature stabilisation: upgraded in 2010:
  • cover of optical table: “low-pass filter” for ambient temperature
  • stability on optical table: 30mK pk-to-pk
  • additional, actively stabilised rel. humidity: 2 % pk-to-pk

• mandatory effort because of coefficients of RF & optical cables:
  • 35 - 50 fs/Km
  • 2 - 5 fs/%m
General Layout

- **master laser oscillator (MLO):**
  - pulsed SESAM-based laser (Origami-15 from OneFive)
  - 200 fs pulses @ 216.667 MHz repetition rate
  - 1550 nm central wavelength (telecommunication standard)

- **link stabilisation unit (Link Box):**
  - at end-station: out-of-loop jitter ≤ 1 fs
lately, upgraded and improved locking mechanism by firmware update
server and firmware are capable of automatically finding locking position again after the low-jitter lock has been lost
but, instabilities from laser oscillator can impede a stable locking state
  • OXC has high sensitivity, but small dynamic range
  • RF-Locking setup sensitive to EMI and vibration
EMI problems in laser labs deteriorate the synchronisation performance
lately, immense improvement of phase & amplitude noise of the TiSa oscillator
  • in turn, the jitter characteristic of the RF & lock improved by a factor of 2

<table>
<thead>
<tr>
<th>Frequency Offset [Hz]</th>
<th>SSB Phase Noise [dBc/Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^3</td>
<td>-145</td>
</tr>
<tr>
<td>10^4</td>
<td>-140</td>
</tr>
<tr>
<td>10^5</td>
<td>-135</td>
</tr>
<tr>
<td>10^6</td>
<td>-130</td>
</tr>
</tbody>
</table>

![Graph](image.png)
RF-Lock Box setup:
- Optical power monitoring
- RF signal generation & phase comparison
- generation of RF signal from stabilised, optical pulse train
- phase comparison between converted RF and reference RF
- error signal to controller electronics (VME)

RF-Locking of external laser:
- cascaded loops: 108 MHz, 1.3 GHz, 9.1 GHz
- low phase noise, high precision versus small dynamic range
- stabilising repetition rate (cavity length) of the external laser oscillator
- two-color optical cross-correlation (sum or difference frequency generation), balanced detection scheme
- currently, still optical bread-board design
- engineered version in development
- sensitivity typically between 30 mV/fs and 5 mV/fs
- slightly different setups installed at FLASH lasers:
  - Injector Laser 2 (IR)
  - Injector Laser 1 (UV) : in development
  - Seed Laser (28g)
  - Pump-Probe Laser (28c)