Femto-second synchronization system for FLASH
- Prototype for XFEL -

Holger Schlarb, in collab. with MIT
March 27th 2007
Pump-probe experiments

Classical setup:

Knowledge of time delay between pump and probe is crucial!
Spatial resolution 800nm → 0.1 nm

- Atomic / Molecular Physics
  (e.g. dynamics (2 photon/meta-stable states) / nonlin. processes in VUV/XUV/X-ray)
- Solid state dynamics
  (e.g. magnetization dynamics, non-thermal melting)
- Plasma physics
  (probing high electron densities / producing “warm dense matter”)

Same source

Shot pulses fs    ps

Pump

Probe = flash

Variable delay

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Synchronization range

- Rep. rate linac
- Macro pulse
- bunch spacing
- RF period
- coherent radiation
- Optical Light (OTR)

**Time**

- 1s
- 1ms
- 1µs
- 1ns
- 1ps
- 1fs
- 1as

**Frequency**

- 1Hz
- 1kHz
- 1MHz
- 1GHz
- 1THz
- 1PHz
- 1EHz

**Length = c \cdot t**

- 3000000km
- 300km
- 300m
- 300mm
- 300µm
- 300nm
- 300A

RF Phase detector
SHG
Optical mixers

Synchronization
1. Longitudinal and transverse electron beam quality
2. Arrival time for high resolution pump-probe experiment

Sources:
1. Photo-cathode laser
2. RF gun (non-relativistic electrons)
3. Pump-probe laser/Seed laser (post ordering not possible)
4. RF phase and amplitude stability of acceleration upstream of BC

- Point to point timing jitter is relevant (100m–3km)
Source of timing jitter
- Caused by RF acceleration prior BC -

Timing jitter
Behind BC

\[ \sum_t^2 \approx \left( \frac{R_{56} \sigma_A}{c_0 A} \right)^2 + \left( \frac{C - 1}{C} \right)^2 \left( \frac{\sigma_\phi}{c_0 k_{rf}} \right)^2 + \left( \frac{1}{C} \right)^2 \sum_{i,t}^2 \]

Source of timing jitter
- Caused by RF acceleration prior BC -

- XFEL: 3.3 ps/%
- FLASH: 5.5 ps/%

C: compression factor (20)
\( R_{56} \sim 100 \text{ mm/180 mm} \)
\( k_{rf}: \) wavenumber RF acceleration (27.2/m)

Vector sum regulation of 32 cavities \Rightarrow 1 \text{ deg} \Rightarrow 1.8\% \text{ (statistic 32 cav. helps)}

But! Phase changes can be correlated due to local oscillator changes
Source of timing jitter
- characterization at FLASH -

Measurement of arrival time with LOLA

2006-02-19T171103-scan-time-jitter.mat

$dE/E = 1.28\%$ by
ACC1 gradient
variation caused
d$T = 7.32$ ps
timing change

$dT = 5.8ps/\%$
19.02.2006

• is reduced choosing smaller $R_{56}$
• or if ACC23 is operated off-crest
dE/E measurements ACC1

4.5MeV \rightarrow V = 122MV \rightarrow 127MeV

Contribution of gun:
\Rightarrow dE/E (4.5MeV) \text{ gun} < 5 \times 10^{-4} \approx 2.2\text{keV or}
\Rightarrow dE/E (127MeV) < 2 \times 10^{-5}

Using ultra low energy spread of beam!
\Rightarrow \sigma_E \approx 1 - 2 \text{keV from gun}
\Rightarrow \text{If beam would be ideally focused on screen using high energy edge about } \sigma/E/10 \text{ could be resolved } dE/E \approx 1 \times 10^{-6}
\Rightarrow \text{But finite beam size and camera resolution: } \sigma_x \approx 30 \text{um, point spread camera } \approx 10\text{um } dE/E \approx 1 \times 10^{-5} \text{ (for } R_{16} \approx 300\text{mm)}

Incoming orbit jitter \sigma_{x,jitter} \approx 30 - 50\text{um}
\Rightarrow \text{no correction: } dE/E \approx 1 \times 10^{-4}
\Rightarrow \text{when corrected } dE/E \approx 3 \times 10^{-5} \text{ (10um)}
Recent progress!

Found faulty pickup signal cavity 6 in ACC1!
Has been removed from vector sum regulation

rf control parameters: GUN: AFF gain: -0.4, FB gain: 4, Pfwd SP: 3.02 MW
ACC1: FB gain: 15, Beam Comp: ON, Ampl=12.7, Ph=-10, acc1 phase SP -146 (== 8 deg off crest)
Best results so far - but not permanent -

dE/E (ACC1) stability versus gradient OTR screen 3BC2:

Study of energy stability as function of gradient ACC1

<table>
<thead>
<tr>
<th>Gradient MV/m</th>
<th>$F_{\text{rep}}$/MHz</th>
<th>dE/E [%]</th>
<th>dE/E [%] w/o drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.8</td>
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<td>0.0188</td>
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<td>15.2</td>
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<td>15.4</td>
<td>0.04</td>
<td>0.0237</td>
<td>0.0179</td>
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<tr>
<td>15.6</td>
<td>0.04</td>
<td>0.0509</td>
<td>0.0505</td>
</tr>
</tbody>
</table>

XFEL specs.
$\sigma_t = 70\text{fs rms}$
Generic layout of laser based synchronization

- **Laser**
  - **MO-RF**
  - **Distribution**
    - **Optical link**
      - **<5fs**
    - **Other lasers**
    - **Laser pulse**
    - **Arrival beam/laser**
    - **Direct**
    - **Optical link**
      - **<5fs**
    - **LO-RF**
    - **Optical link**
      - **<5fs**
    - **DWC/Kly**
    - **FB**
    - **A & φ cavity**

**Desired point-to-point stability ~ 10 fs**
Principle

- timing information is carried by ultra-short optical pulse
  \[ \sim 200\text{fs (FWHM)} \leftrightarrow \sim 5 \text{ THz (FWHM) bandwidth} \]
- fiber length stabilization based on same principle as timing detection

\[ \Delta t = \Delta T_r - \Delta T \rightarrow 0 \Rightarrow \Delta T = \Delta T_r \]

\[ \Delta t_{\text{error}} = \Delta T \frac{\Delta f_{\text{rep}}}{f} \quad 3\text{fs} \Rightarrow \frac{\Delta f}{f} \sim 1 \times 10^{-10} \]

- timing detection to optical cross-correlation basically drift free (\(<<\sigma_t\))!

For stabilisation balanced setup is used!
Where are we now!

- Fiber oscillator – first link stab. with RF 05 – CEO stabilization to 50as –

Proceedings of the 27th International Free Electron Laser Conference

HIGH-PRECISION OPTICAL SYNCHRONIZATION SYSTEMS FOR X-RAY FREE ELECTRON LASERS

Axel Winter, Peter Schmuzer, Universität Hamburg, Hamburg, Germany,
Holger Schlarb, DESY, Hamburg, Germany,
F. Ömer Ilaş, Jung Won Kim, MIT Bates R&E Center,
D. Cheever, T.
MIT Bates R&E Center,

Abstract

Next generation free electron lasers aim to generate x-ray pulses with pulse durations down to 30 fs, and possibly even sub-fs. Synchronization of the probe system to the x-ray pulses with stability on the order of the pulse width is necessary to make maximal use of this capability. We are developing an optical timing synchronization system in order to meet this challenge. Optics has two fundamental advantages over traditional RF technologies: (i) optical frequencies are in the 100 THz range, enabling femtosecond resolution, and (ii) photons are immune to electromagnetic interferences, easing noise-free transportation of the signals. In the scheme described here, a train of short optical pulses, with a very precise repetition frequency, are generated from a mode-locked laser oscillator and distributed via a transmission line to the optical free electron laser, where they arrive simultaneously with a propagation delay of 2.8 µs, and are used to stabilize the beam position and polarization. The system also allows the stabilization of the laser pulses using the feedback from the timing signal.

Figure IV.1: Schematic of an octave-spanning Ti:sapphire frequency comb. The CE frequency $f_{CE}$ is phase-locked to $f_0/4$ using 2-to-2 self-referencing, the repetition frequency $f_{rep}$ is phase-coherently derived from an optical transition in xenon using a difference-frequency generation scheme.

50 as CEO stabilization

In-loop 66fs -> 12fs
Where are we now!

- Beam arrival monitor
- Fiber link with optical cross-correlation

Resolution ~ 30fs

Out-of-loop ~ 9.8fs

Long-Term Femtosecond Timing Link Stabilization Using a Single-Crystal Balanced Cross-Correlator

Polarization mode dispersion!
Holger Schlarb

Where are we now!

- RF generation - drift free phase detection - high precision down-converter -

**Long-Term Stable Microwave Signal Extraction from Mode-Locked Lasers**

Joseph Kuo, Frank Ludwig, Michael Fokker, Holger Schlarb, and Franz X. Klimov

Abstract: Long-term mode-locking (200 GHz to 140 GHz - 19 fs chirp-free) between two 16 fs 24.6 GHz microwave signals with $< 10^{-4}$ drift referenced to 44.1880466 Hz, employing our mode-locked laser interferometric transition into a low phase noise crystal oscillator.

**DRO lock ~ 12fs**

Good drift performance

Phase detector resolution ~ 0.8fs

(10Hz - 10MHz)

Holger Schlarb

**Drift free RF mixer**

Cortesy

F. Ludwig, J. Mueller

**Delivery Report 2006**

Task No. DSN Synchrotron: RF Amplifier and Phase Detector

Participant: Holger Schlarb, Frank Ludwig

Email address of Reporting Person: Frank.Ludwig@desy.de

Reporting Period: 01.01.06 - 31.12.06

**Figure 1:**

(a) Multi-channel DCS (Digital Counter System) device ACR 5 (Advanced Clock System) and the DCS, shielded using frequenton shielding welded structure, vacuum finished and ACR resistant. (b) Setup for averaging the ADC noise using two 16-bit ADCs. The blue, green and red curves show the direct sampled, respectively converted amplitude and phase values for an intercarrier frequency of 15MHz, sampling frequency of 150MHz by averaging over 1ps.

Figure 2 shows the latest version of the ACR20 (Advanced Clock System) based on the
Fiber link installation

Optical fiber test section will be installed in Hall 1
- test of specialty fibers
- development of fiber link stabilization

Installation status:
Installation of pipes is already done or will be done this week
Installation of first optical fibers to be done first week of January
Splicing planned for January / February

Installation of optical fibers in the TTF linac

P1-10 fiber patch panel
Synchronization hutch (start point of all links)
Installation in new synchronization lab.
Installation in development laboratory

Fiber link test bench

Drift measurements

EDFA development
<table>
<thead>
<tr>
<th>Current projects</th>
<th>(Coordinator: H. Schlarb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master laser system (MLO)</td>
<td>(A. Winter, MIT)</td>
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<tr>
<td>Fiber link stabilization</td>
<td>(F. Loehl, MIT)</td>
</tr>
<tr>
<td>Laser to RF conversion</td>
<td>(F. Ludwig, B. Lorbeer, M. Felber, MIT)</td>
</tr>
<tr>
<td>Bunch arrival time monitor</td>
<td>(F. Loehl)</td>
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<tr>
<td>BPMs in magnetic chicanes</td>
<td>(K. Hacker)</td>
</tr>
<tr>
<td>New down-converter for cavity regulation</td>
<td>(F. Ludwig, M. Hoffmann, LLRF-Group)</td>
</tr>
<tr>
<td>Laser oscillator for CPA system (ORS)</td>
<td>(N. Javahiraly, A. Winter)</td>
</tr>
<tr>
<td>Fast motor control and position encoder readout</td>
<td>(J. Thomas, …)</td>
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<tr>
<td>DOOCS compatible laser diode driver</td>
<td>(A. Winter, FEB, MVP)</td>
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<tr>
<td>Digital regulation of master laser system</td>
<td>(W. Jalmuzna, LLRF-Group)</td>
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<tr>
<td>Digital regulation of fiber links</td>
<td>(G. Petrosyan, …)</td>
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<tr>
<td>Drift characterization of photo diodes, RF comp. etc</td>
<td>(B. Lorbeer, F. Ludwig, …)</td>
</tr>
<tr>
<td>Drift reduced RF mixer</td>
<td>(J. Mueller, F. Ludwig)</td>
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<tr>
<td>DOOCS compatible polarization controller</td>
<td>(M. Felber, K. Hacker)</td>
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<tr>
<td>Fast regulation of cavities with beam based measurements</td>
<td>(LLRF-Group)</td>
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<tr>
<td>Development of precise photo diode read out</td>
<td>(K.H. Matthiesien, …)</td>
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<tr>
<td>Cross-correlation of pump-probe laser and timing system</td>
<td>(V. Arsov, …)</td>
</tr>
<tr>
<td>Development of analog PI controller / piezo driver</td>
<td>(N. Ignachine, …)</td>
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<tr>
<td>Design of 130 MHz ADC board (DWC, BAM, BPM)</td>
<td>(P.Strzalkowski, M. Hoffmann, …)</td>
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<tr>
<td>Characterization of EDFAs</td>
<td>(J. Mueller)</td>
</tr>
<tr>
<td>Simulation of optical pulse propagation</td>
<td>(H. Schlarb, F.Loehl...</td>
</tr>
</tbody>
</table>
Goals for 2007
- system design test using redundant measurements -

First monitoring and slow FB + shifts during ACC- study weeks

- 2 links + BAM at ACC3 & ACC7
- next generation of DWC + L2RF conversion unit
- Beam feedback around ACC1
- Ti:Sa system locked via opt. cross + BAM/EO timing meas.

Goal: check first prototype design, start packaging, optimization and industrialization
Goals for 2008
- complete syn. for long term stability and availability test -

- Synchronization of all timing critical devices (<100fs, ~ 10 points)
- Permanent operation and long term stability investigation
- Point-to-point synchronization ~ 10fs rms
Summary

• Most proof-of-principle for synchronization is done
  - redesign Sagnac loop at 1.3GHz
  - PMD and its limitation

• Development of accelerator compatible system is on the way
  - MLO installation and RF-MO connection May 2007
  - Splicing and patch panels June 2007
  - Link for ORS, BAM, EBPM July-Sep 2007

• First prototype are available in 2007
  - for consistency checks
  - finalize prototype design
  - start industrialization
  - cost optimize system

• 2008: extension to entire FLASH facility
  - long term reliability check
  - accepted as Prototype facility for the IRUVX consortium