Timing and Synchronization for the APS Short Pulse X-Ray (SPX) Project

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Outline

- Specifications
- The Problem
- The Team
- The Solution
- Solution applied to SPX
The SPX Deflecting Cavity Scheme to Produce Short X-Ray Pulses

Cavity frequency is harmonic $h$ of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is $n \times 180$ degrees: “outside” users nominally unaffected

Radiation from tail electrons

Radiation from head electrons

Pulse can be sliced or compressed with asymmetric cut crystal

See “Status of the Short-Pulse X-Ray (SPX) Project at the Advanced Photon Source” Ali Nassiri, et. al. WEPPC038


Figure Courtesy of Ali Nassiri
SPX Phase Tolerance Specifications

Cavity Phase Tolerances

<table>
<thead>
<tr>
<th>Specification Name</th>
<th>RMS Value</th>
<th>Bandwidth</th>
<th>Driving Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common-mode phase Variation</td>
<td>10 deg</td>
<td>0.01 Hz – 271 kHz</td>
<td>Intensity Variation under 10% rms</td>
</tr>
<tr>
<td>Differential mode phase variation between sectors</td>
<td>&lt; 0.077 deg</td>
<td>0.01 Hz – 1 kHz</td>
<td>Keep rms beam motion outside of SPX under 10% of beam size/divergence for SPX</td>
</tr>
<tr>
<td>Differential mode phase variation between sectors</td>
<td>&lt; 0.28 deg</td>
<td>1 kHz – 271 kHz</td>
<td>Limit effective emittance growth to below 1.5 pm</td>
</tr>
</tbody>
</table>

Beam-Line Laser Synchronization

Beam-Line laser needs to be synchronized to the x-ray pulse to 400 femtoseconds rms
Keep time resolution degradation under 10% of x-ray pulse width
The Problem

- One Meter of cable with
  - 7 ppm/degC
  - V/C = 67%
- Result: \( \sim 50 \text{ femtoseconds/degC} \)

At 2815 MHz: 1 degree of phase \( \sim 1 \text{ picosecond} \)
The Team

- Entered into a collaboration with LBNL to apply their femtosecond synchronization system to the SPX requirements

- The team
  - ANL
    - Frank Lenkszus
    - Tim Berenc
    - Ned Arnold
    - Hangjie Ma
    - Tom Fors
  - LBNL
    - John Byrd
    - Russell Wilcox
    - Larry Doolittle
    - Gang Huang
    - Jim Greer
    - Kerri Campbell
The LBNL Femtosecond-Phase Stabilization System

- Measures the optical phase delay through a fiber with a heterodyne interferometer.
  - The optical frequency is offset by an RF frequency (~100 MHz)
  - The original optical frequency is heterodyned (mixed) with the offset optical frequency to produce an RF beat signal of 100 MHz
  - Changes in optical phase translate to identical changes in the 100 MHz beat signal
  - Offers a large leverage over stabilization in the RF domain (six-order-of-magnitude)
  - One degree of phase change in the 1560 nm optical domain (~ 21 attoseconds) translates to 1 degree of phase change in the RF domain (~25 picoseconds).

“Demonstration of Femtosecond-Phase Stabilization in 2 km Optical Fiber”, J. Staples, R. Wilcox, J. Byrd, LBNL, Proceedings of PAC07 (MOPAS028)
LBL Scheme for stable transmission of RF signals
The Math

Electric Field for A -> B -> A -> C

\[ E_{\text{long}} = \cos(\omega_{\text{opt}}(t - 2t_1 - t_2) + 2(\omega_{\text{FS}}(t - t_1 - t_2) + \phi_{\text{FS}})) \]

Electric Field for A -> C

\[ E_{\text{short}} = \cos(\omega_{\text{opt}}(t - t_2)) \]

After low-pass filtering to remove \( \omega_{\text{opt}} \) and mixing with \( 2\omega_{\text{FS}} \) we have the phase of the detected RF

\[ \phi_{\text{det}} = -2\omega_{\text{opt}}t_1 - 2\omega_{\text{FS}}(t_1 + t_2) + 2\phi_{\text{FS}} \]

Since \( \omega_{\text{opt}} \gg \omega_{\text{FS}} \) this term is negligible

We have:

\[ \phi_{\text{det}} = -2\omega_{\text{opt}}t_1 + 2\phi_{\text{FS}} \]

LBL Results

- 2.2 km fiber
  - 19.4 fs rms @ 2850 MHz (60 hours)
  - Variation ~1000 greater without correction
- 200 m fiber
  - 8.4 fs rms @ 2850 MHz (20 hours)

Calibration Process

\[ \phi_{\text{ref,sig}} = (\phi_{\text{ref,ref}} - \phi_{\text{ref,sig}}) - (\phi_{\text{ref,calur}} - \phi_{\text{ref,calus}})/2 - (\phi_{\text{ref,callr}} - \phi_{\text{ref,call}})/2 \]

“Signal Processing for High Precision Phase Measurements”, G. Huang et.al., Proceedings BIW10, Santa Fe, NM (2010)
SPX Timing/Synchronization Block Diagram
Transmitter/Sender
Reference Line Stabilization
Laser Control
Feedback

- Cavity phase errors cause a vertical kick to the beam
  - Detected as orbit distortion by BPMs
- A Beam Arrival Time Monitor (BAT) located at the upstream cavity will feedback to the main LLRF to stabilize beam arrival time.
  - But the BAT will not be specified to be stable below 0.01 Hz.
- Uncompensated beam arrival time errors will cause a common mode phase error at the upstream cavity.
- Feedback to the upstream LLRF phase from the BPMs will cause the upstream cavity phase to track the beam arrival time to correct for common mode phase errors
- Feedback to the down stream LLRF phase from bpm will correct for differential phase errors
- Feed forward from the upstream cavity phase to the Laser controller will cause the laser to track the x-ray pulse phase
Feedback
Receiver/Link Stabilizer
SYNC Head (LCLS version)
Status

- **R&D**
  - Four receiver chassis built
  - Frequency generation chassis built
  - Order in process for transmitter/sender
  - Sync head development underway

- **CD2: December 2012**
Summary

- Entered into collaboration with LBNL to apply their femtosecond timing/synchronization system to the SPX project.
  - LBNL technology is being transferred
- LBNL’s system should allow stringent timing/synchronization requirements to be met