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

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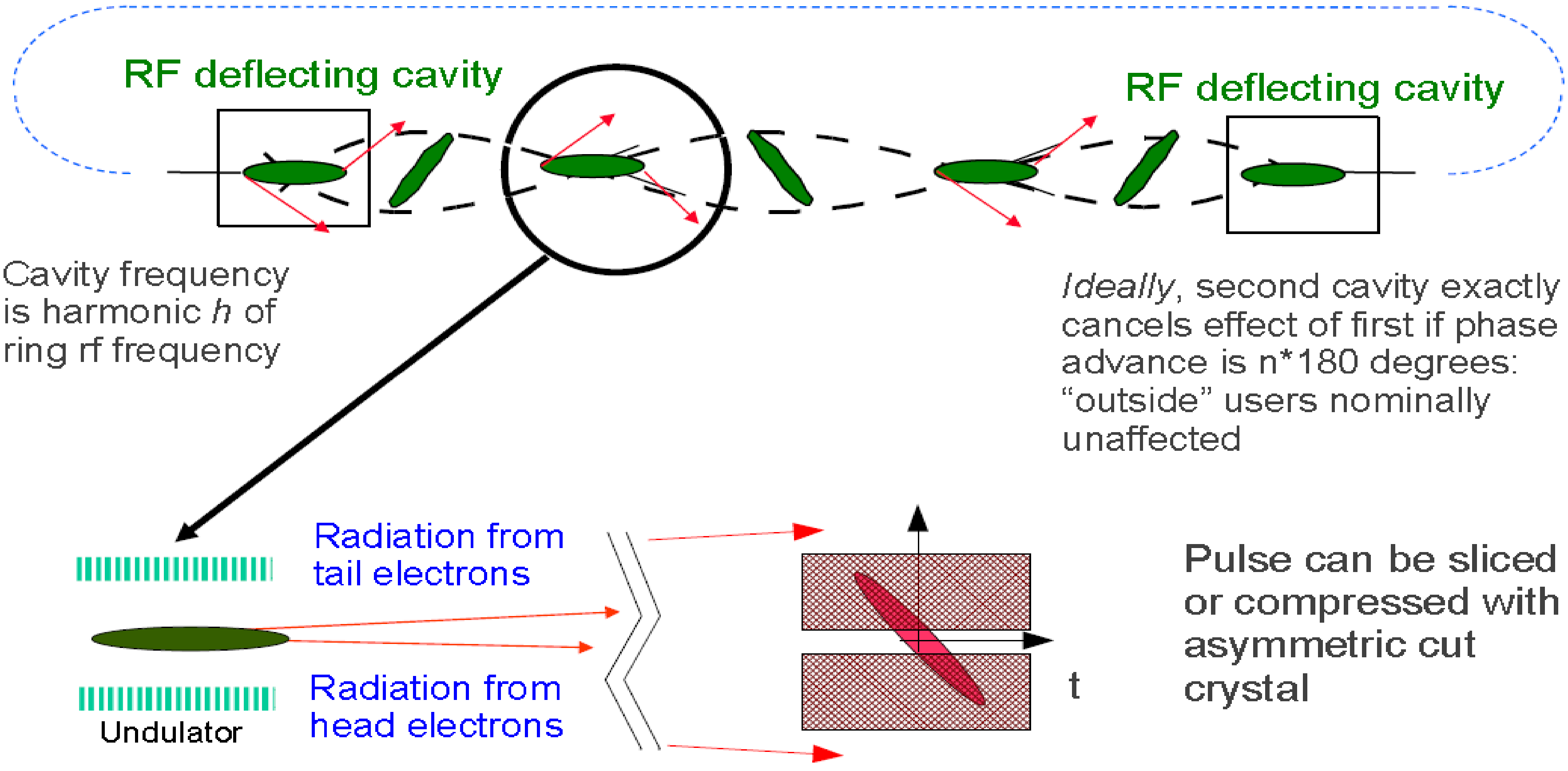
Outline

- Specifications
- The Problem
- The Team
- The Solution
- Solution applied to SPX

The SPX Deflecting Cavity Scheme to Produce Short X-Ray Pulses



A. Zholents, et. al., NIM A 425, 385 (1999).

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

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

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: ***~50 femtoseconds/degC***

At 2815 MHz: 1 degree of phase ~ 1 picosecond

The Team

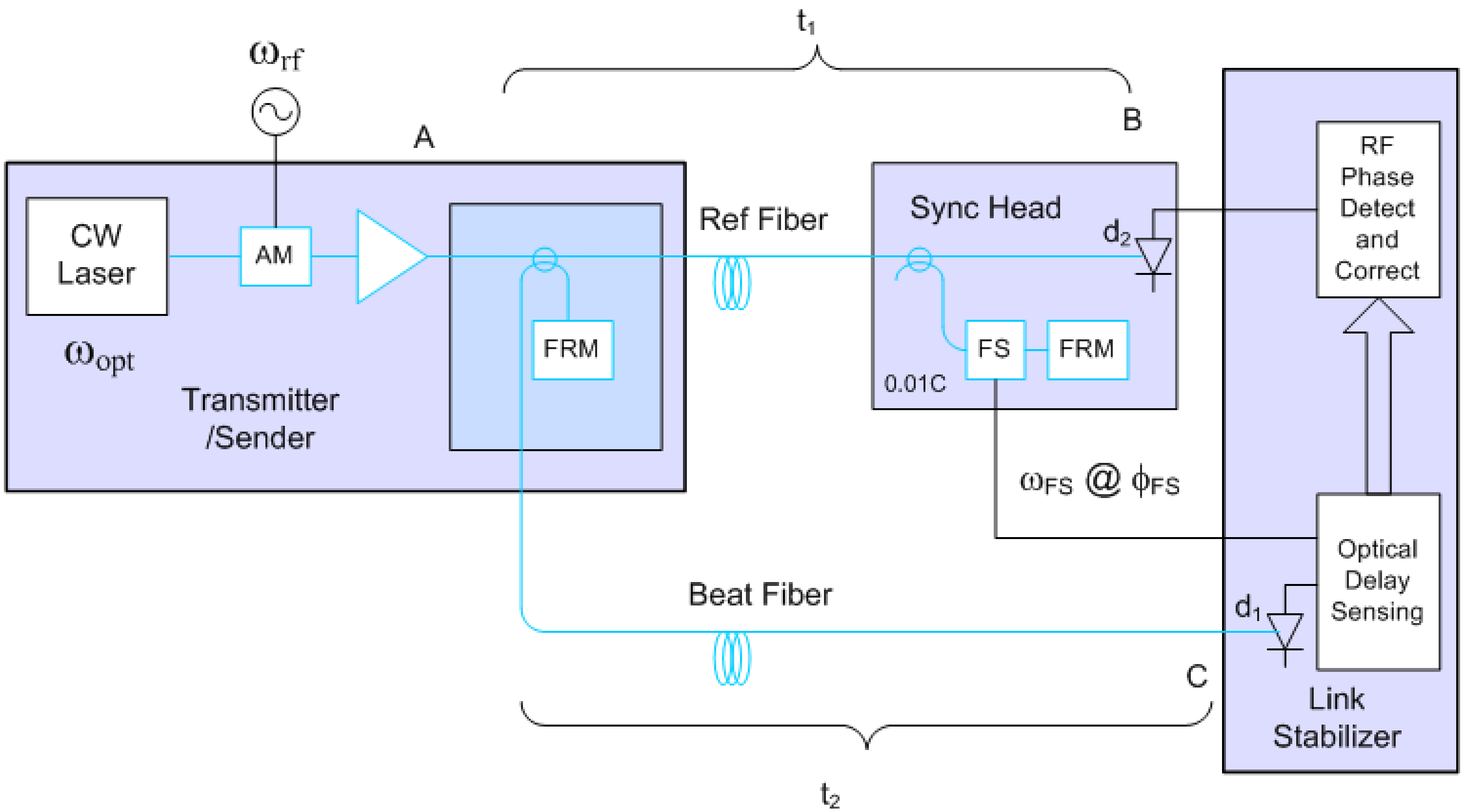
- Entered into a collaboration with LBNL to apply their femtosecond synchronization system to the SPX requirements
- The team
  - ANL
    - Frank Lenkszus
    - Tim Berenc
    - Ned Arnold
    - Hangjie Ma
    - Tom Fors
  - LBNL
    - John Byrd
    - Russell Wilcox
    - Larry Doolittle
    - Gang Huang
    - 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

$$E_{long} = \cos\left(\omega_{opt}(t - 2t_1 - t_2) + 2(\omega_{FS}(t - t_1 - t_2) + \phi_{FS})\right)$$

Electric Field for A -> C

$$E_{short} = \cos\left(\omega_{opt}(t - t_2)\right)$$

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

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

Since $\omega_{opt} >> \omega_{FS}$ this term is negligible

We have:

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

Reference: "Stable transmission of radio frequency signals on fiber links using interferometric delay sensing", R. Wilcox, J. Byrd, L. Doolittle, G Huang, J. Staples, Optics Letters, Vol 34, No. 20, pp 3050-3052 (Oct 15, 2009)

LBL Results

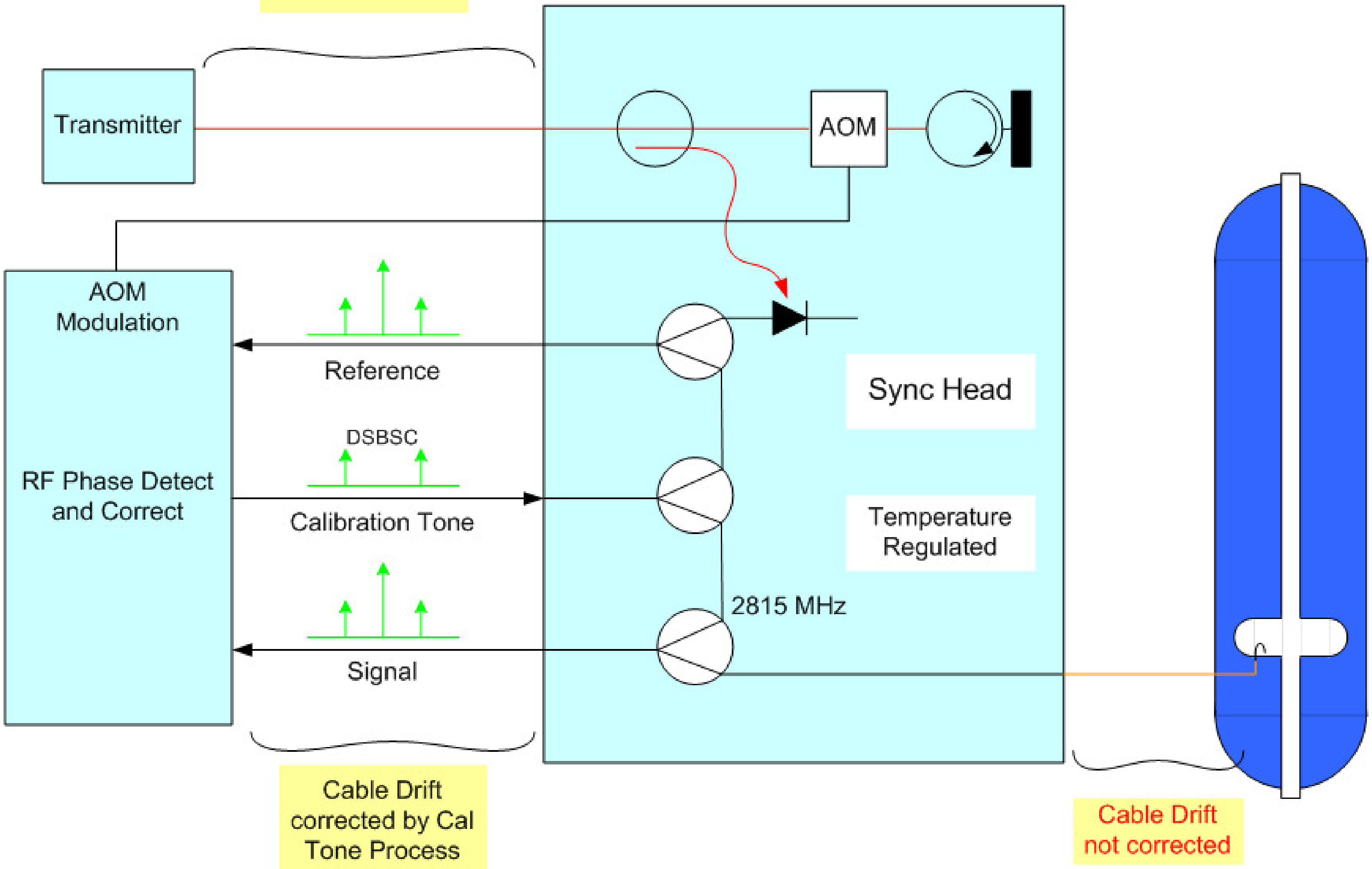
- 2.2 km fiber
  - 19.4 fs rms @ 2850 MHz (60 hours)
  - Variation ~1000 greater without correction
- 200 m fiber
  - 8.4 fs rms @ 2850 MHz (20 hours)

Reference: "Stable transmission of radio frequency signals on fiber links using interferometric delay sensing", R. Wilcox, J. Byrd, L. Doolittle, G Huang, J. Staples, Optics Letters, Vol 34, No. 20, pp 3050-3052 (Oct 15, 2009)

Calibration Process

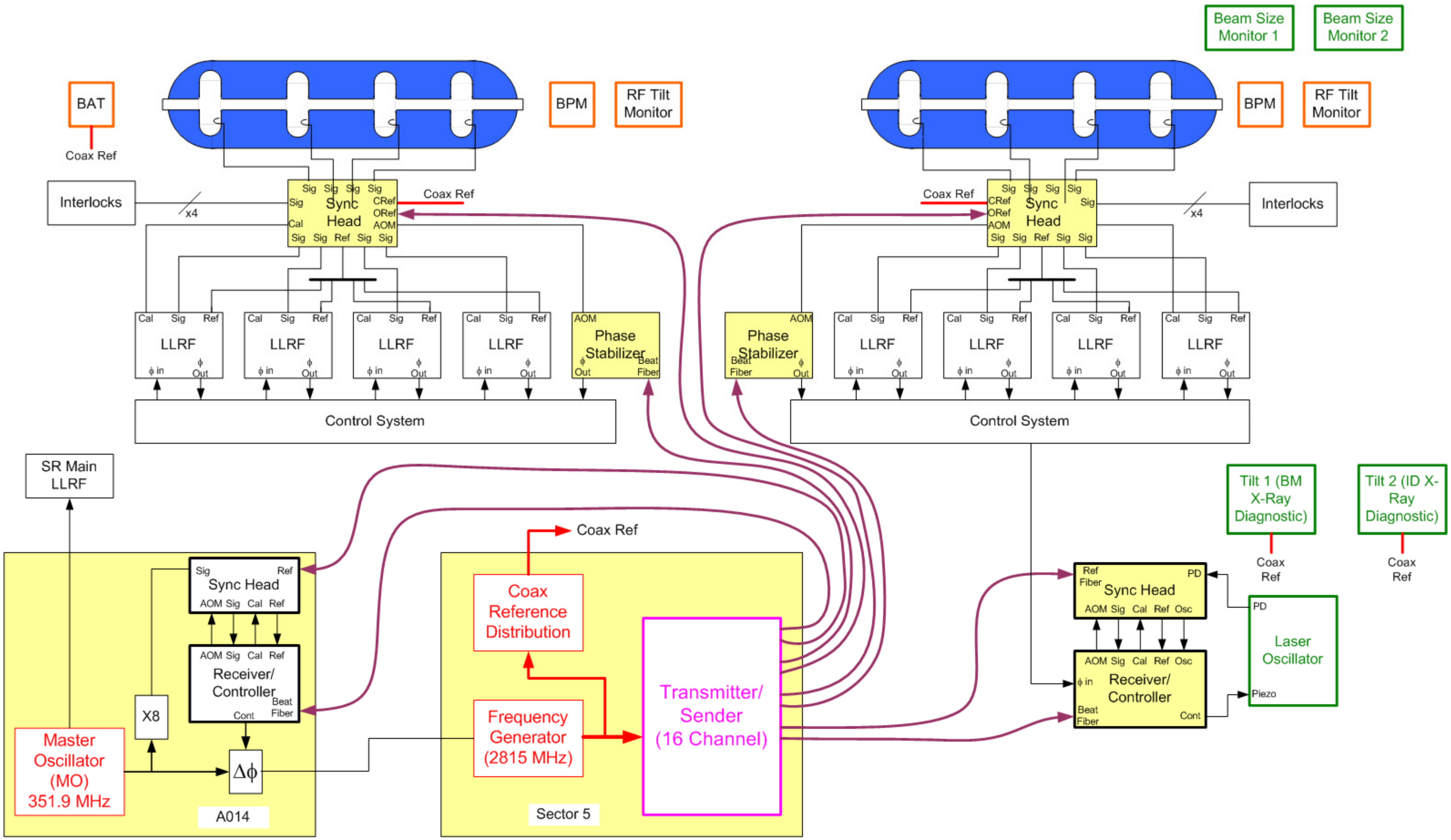
Cable Drift corrected by phase stabilizer

$$\emptyset_{ref,sig} = (\emptyset_{rf,ref} - \emptyset_{rf,sig}) - (\emptyset_{rf,calur} - \emptyset_{rf,calus})/2 - (\emptyset_{rf,callr} - \emptyset_{rf,calls})/2$$

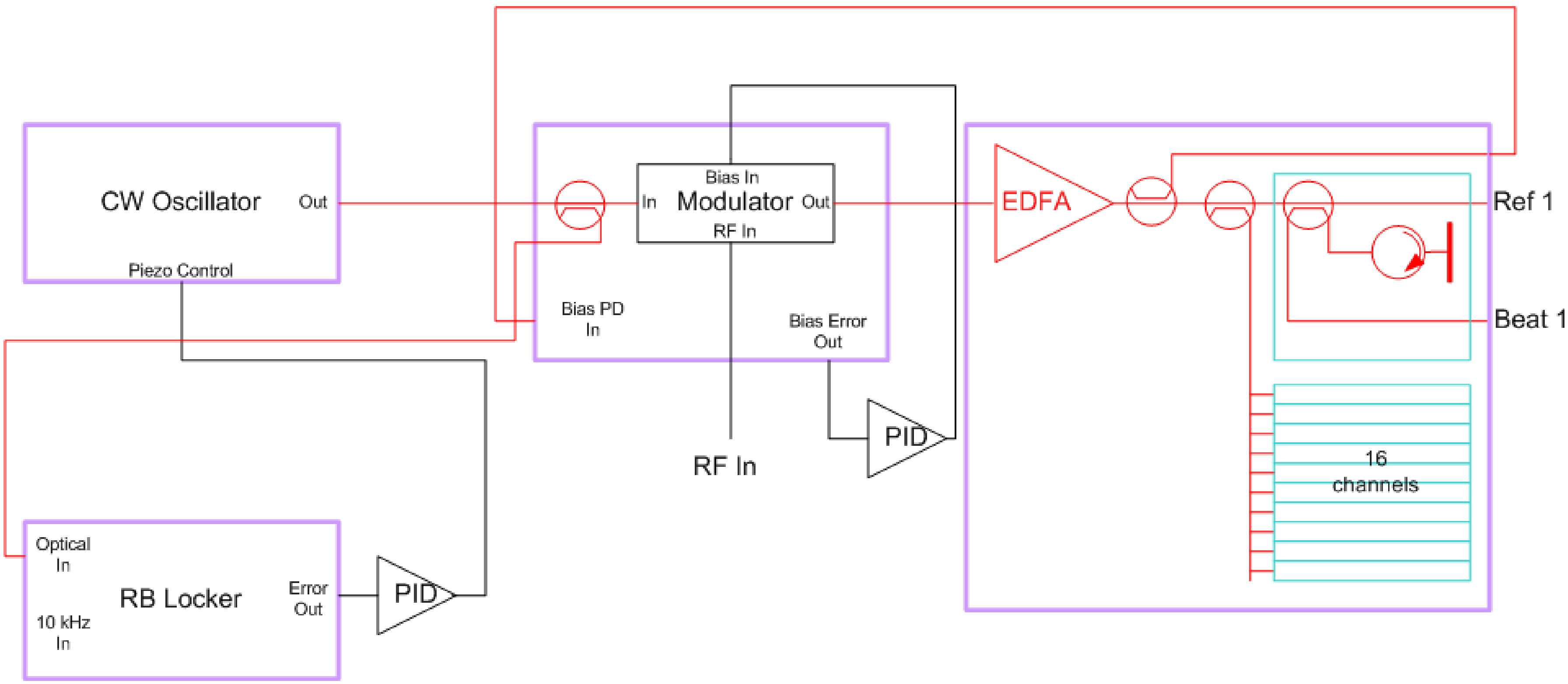


"Signal Processing for High Precision Phase Measurements", G. Huang et.al., Proceedings BIW10, Santa Fe, NM (2010)

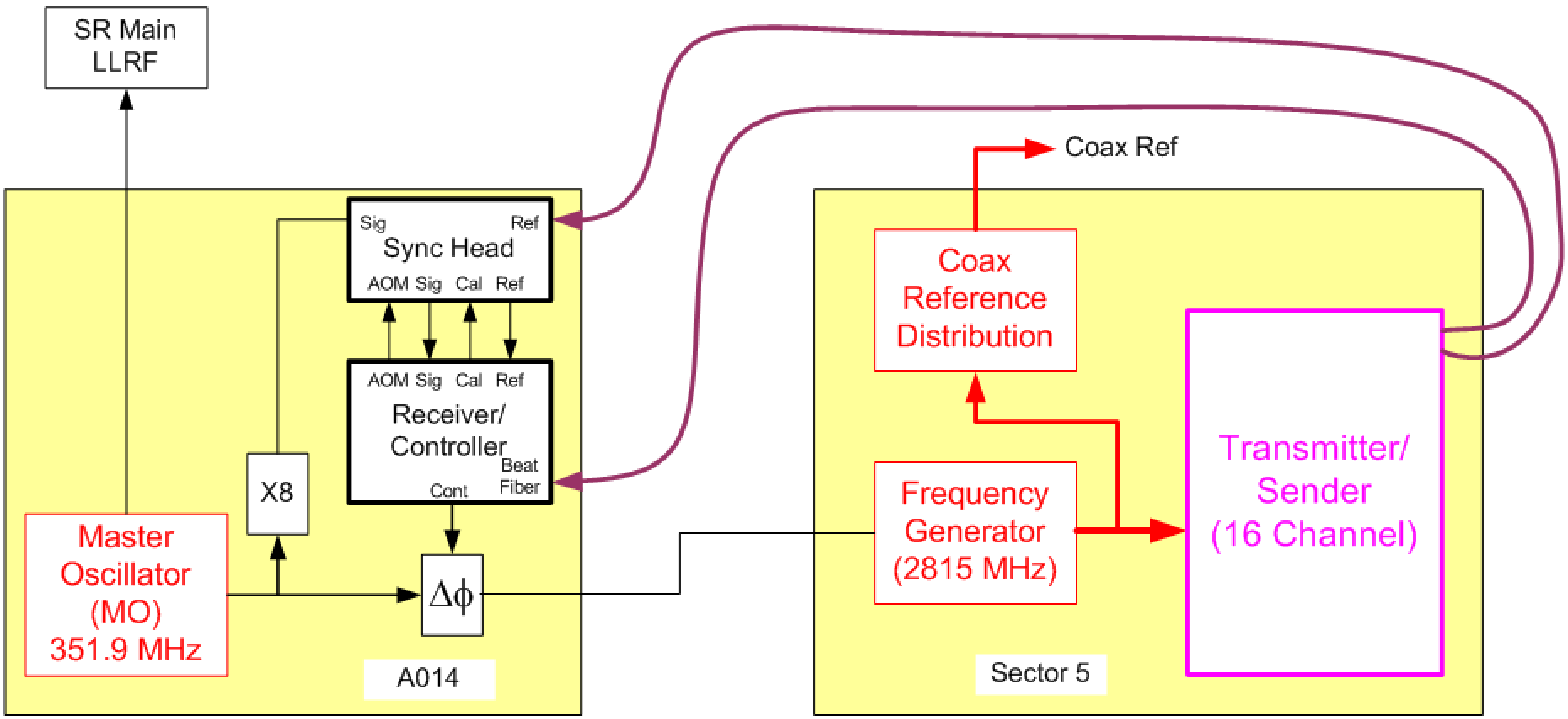
SPX Timing/Synchronization Block Diagram



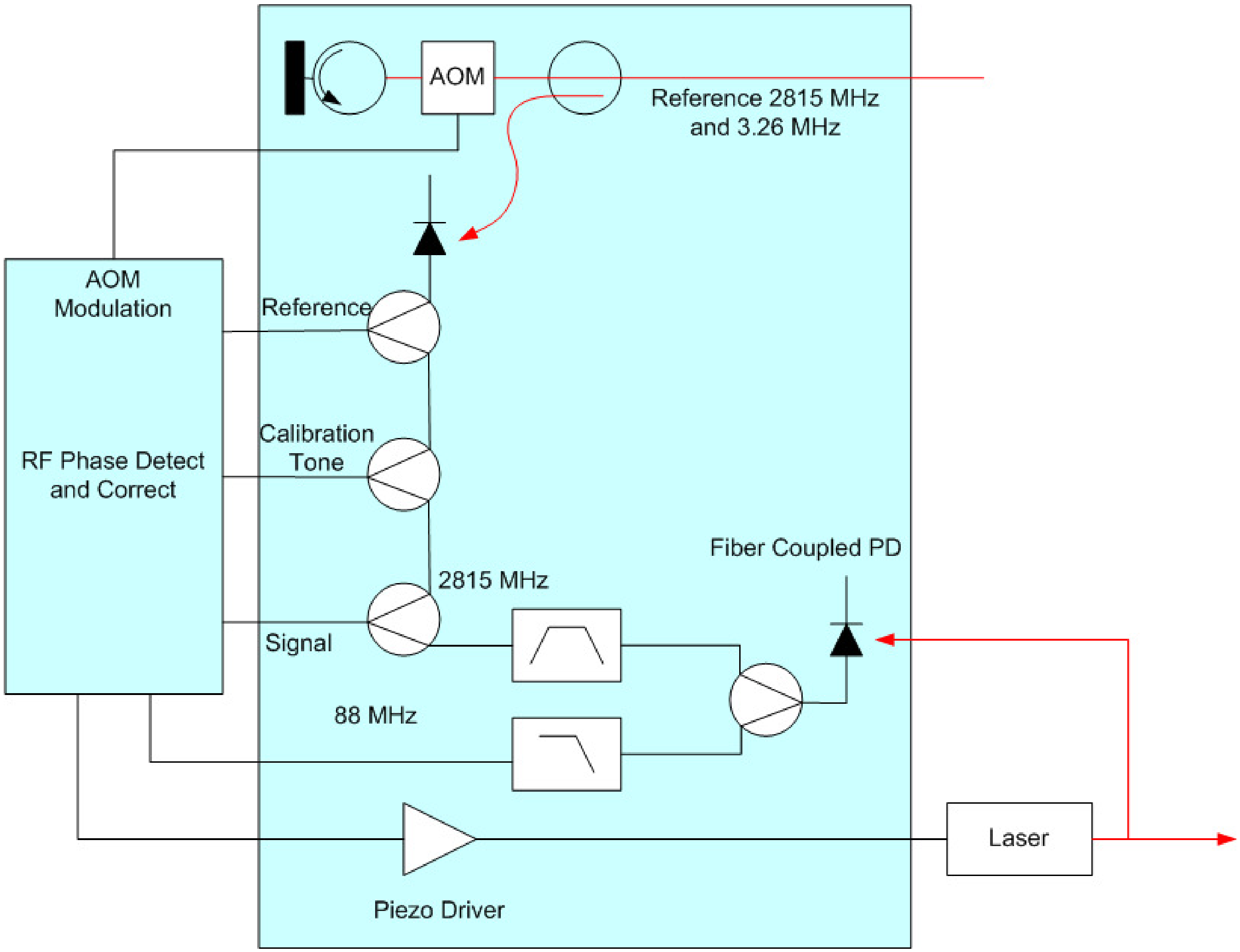
Transmitter/Sender



Reference Line Stabilization



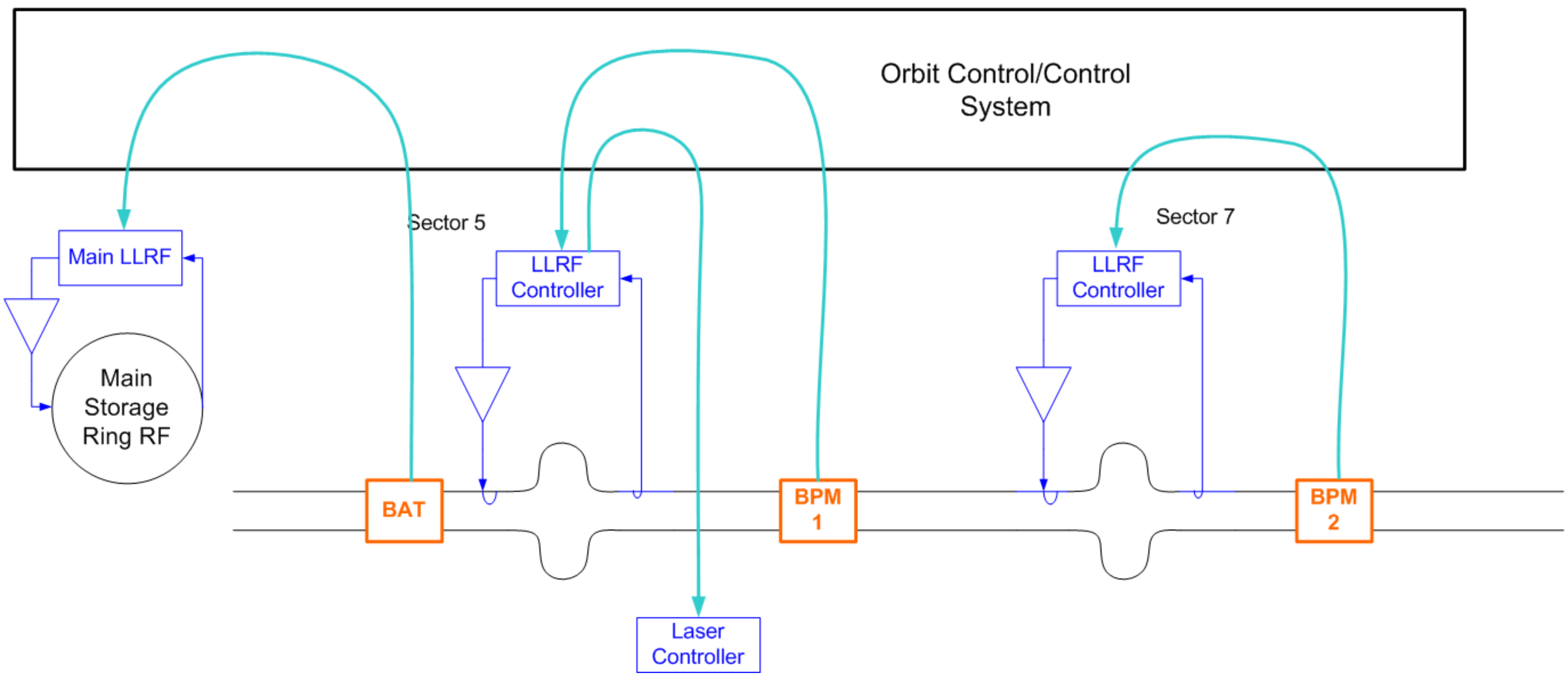
Laser Control



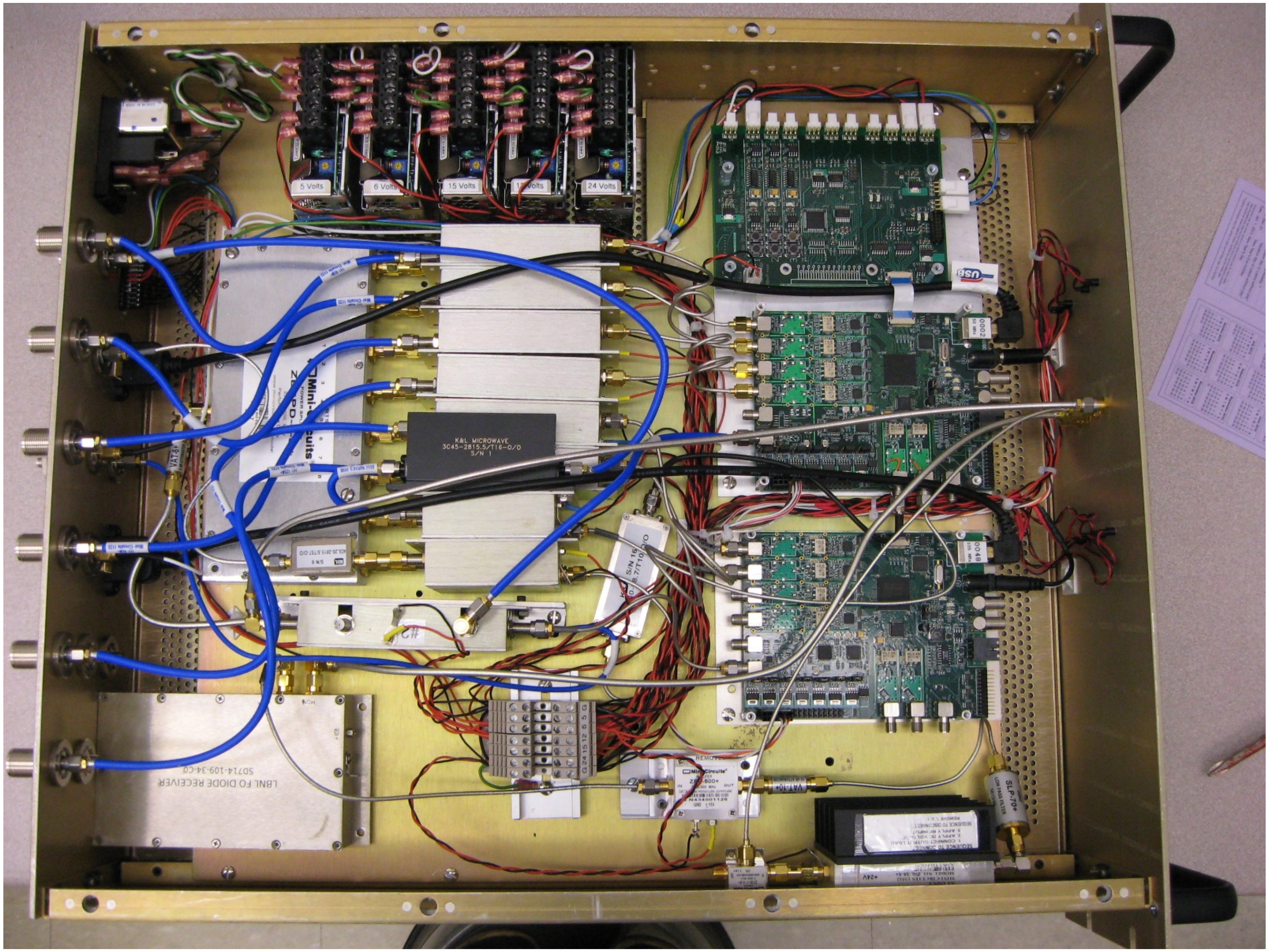
Feedback

- 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 bpms 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

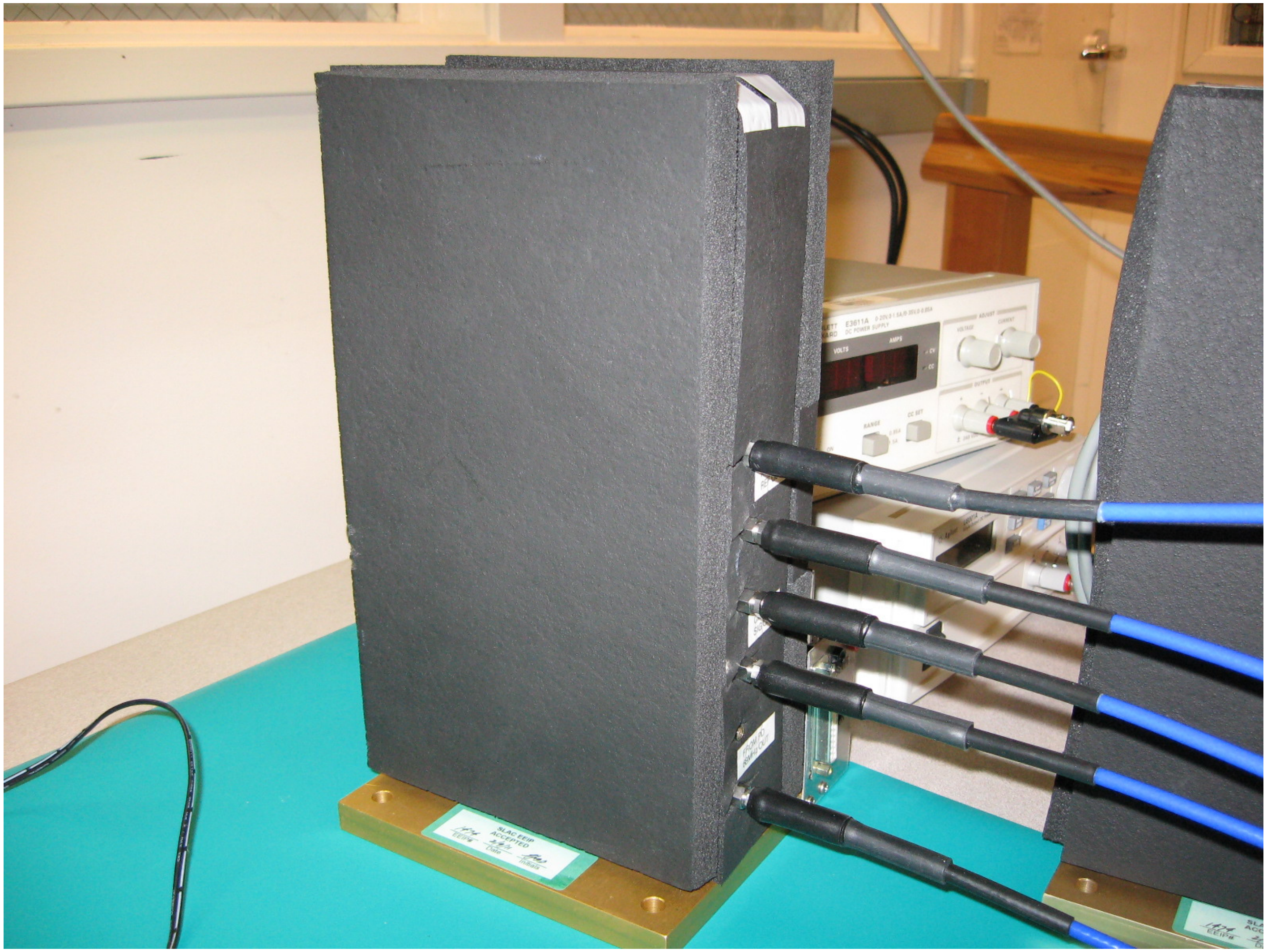
Feedback


Orbit Control/Control System
Sector 5
Sector 7
Main LLRF
LLRF Controller
LLRF Controller
Main Storage Ring RF
BAT
BPM 1
BPM 2
Laser Controller

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