BPM Electronics with Self-Calibration at the ALS

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International Beam Instrumentation Conference (IBIC)

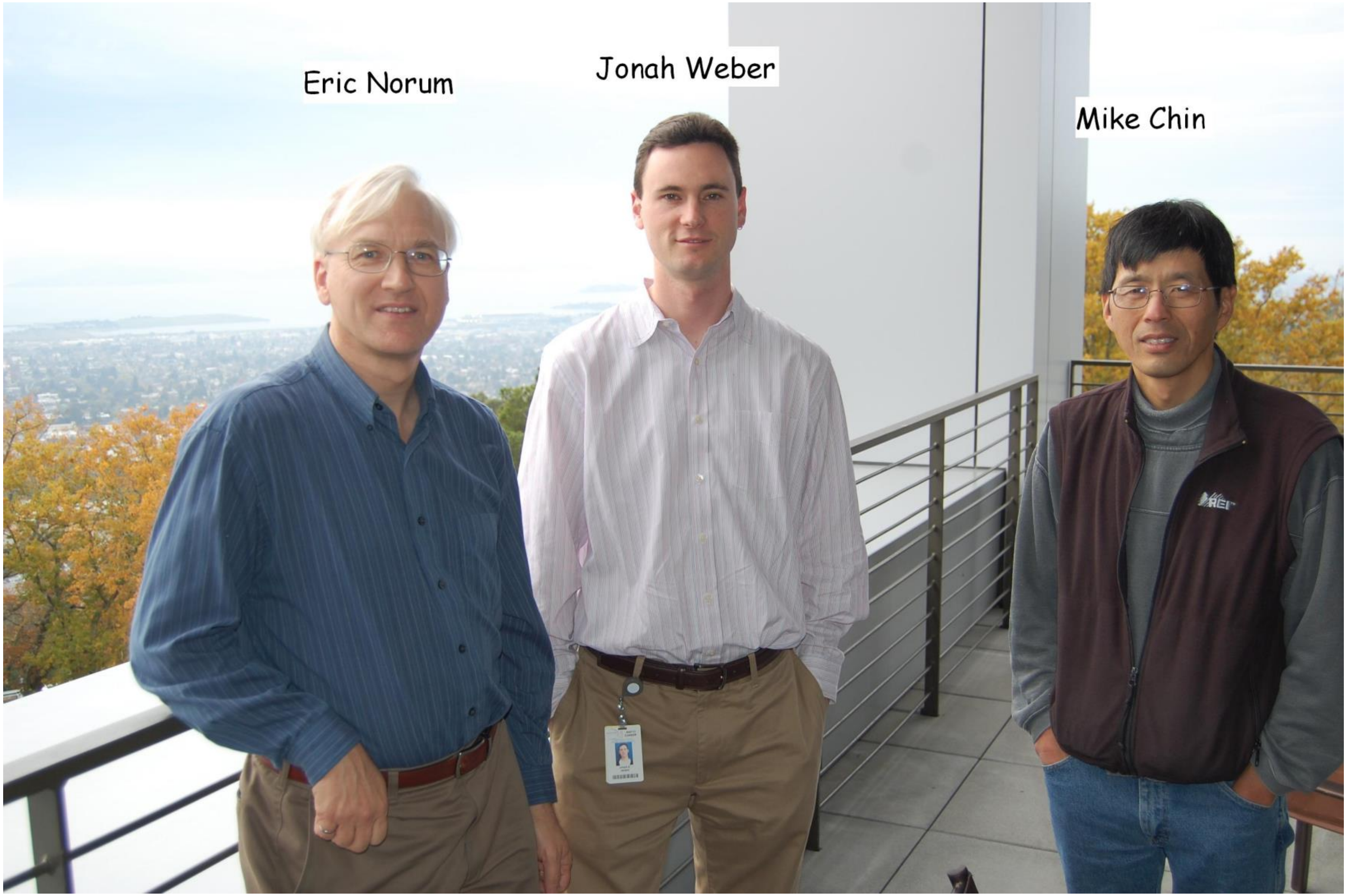
(14 – 18 September 2020)

U.S. DEPARTMENT OF ENERGY | Office of Science

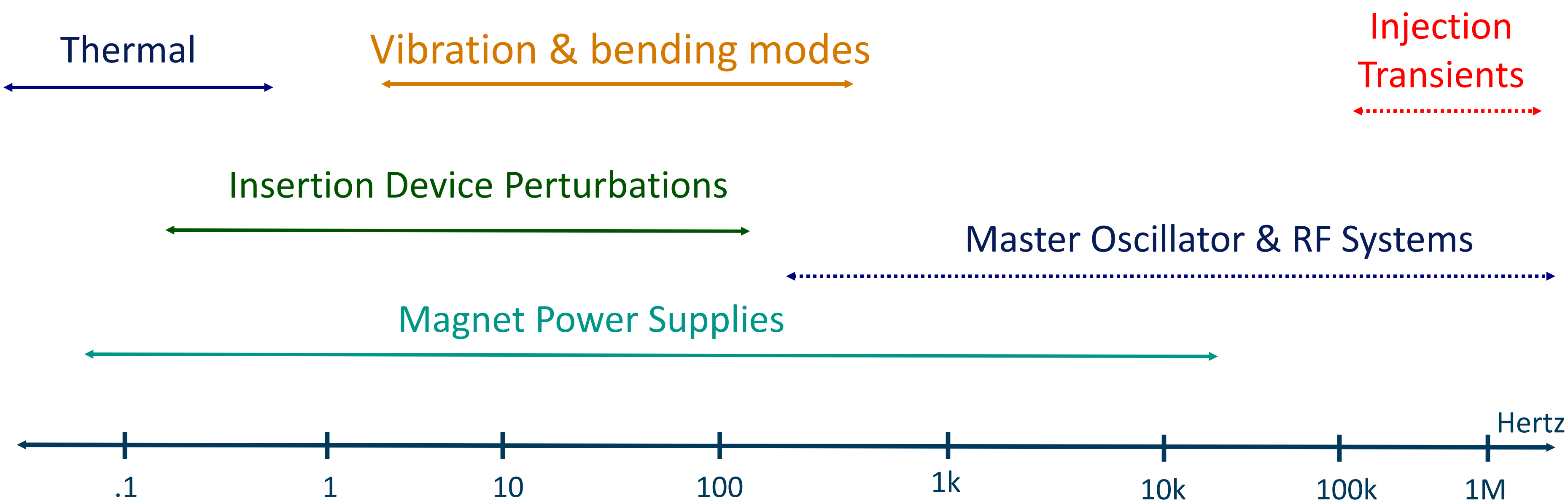
BERKELEY LAB

ALS

ALS Instrumentation Group



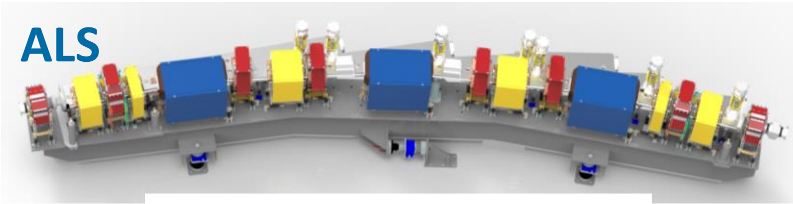
Causes of Undesirable Orbit Motions

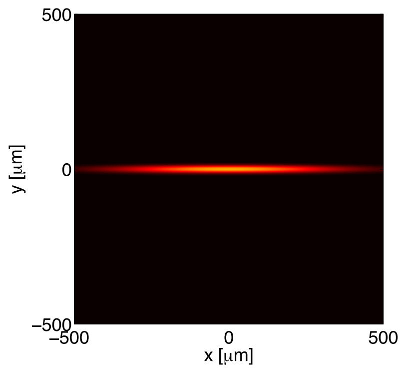


Beam Position monitors (BPMs) need to measure orbits over a large range of frequencies as well as a range of beam currents, and fill patterns (single to multi-bunch fills)

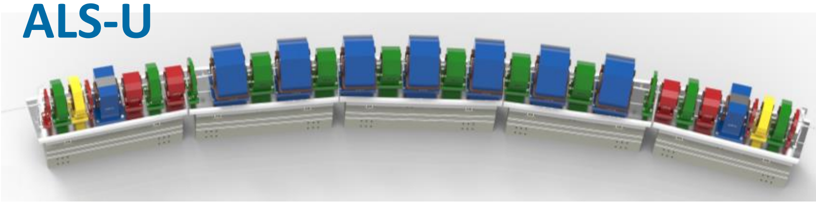
Orbit Stability Goal (ALS and ALS-U)

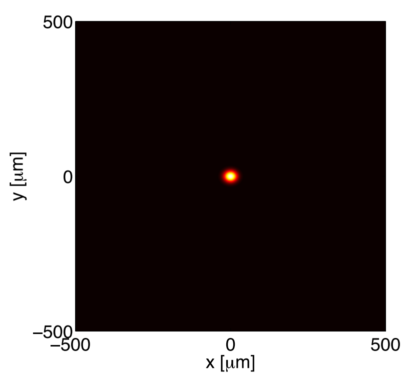
ALS





ALS-U





Storage Ring	ALS-U	ALS
Electron Energy	2.0 GeV	1.9 GeV
Horizontal Emittance (full coupling)	<75 pm (50 pm stretch goal)	2 nm
Vertical Emittance	<75 pm (full coupling)	30 pm
ID Beam Size (x/y)	<14 µm / <14 µm	251 / 10.4 µm
Bend Beam Size (x/y)	<5 µm / <10 µm	40.3 / 7.1 µm (Center bend)

- ALS has 7 to 10 µm vertical beam sizes
  ALS-U will have 5 to 14 µm beam sizes in both planes
- The requirement is 1/10 the beam size
  -> 0.5 µm @ the Bends, 1.4 µm @ the IDs
- The goal is 1/20 the beam size
  -> 0.25 µm @ the Bends, 0.7 µm @ the IDs

➔ **ALS and ALS-U have similar requirements**

➔ **The BPM development goal is 200 nm RMS from a few days to 5 kHz**

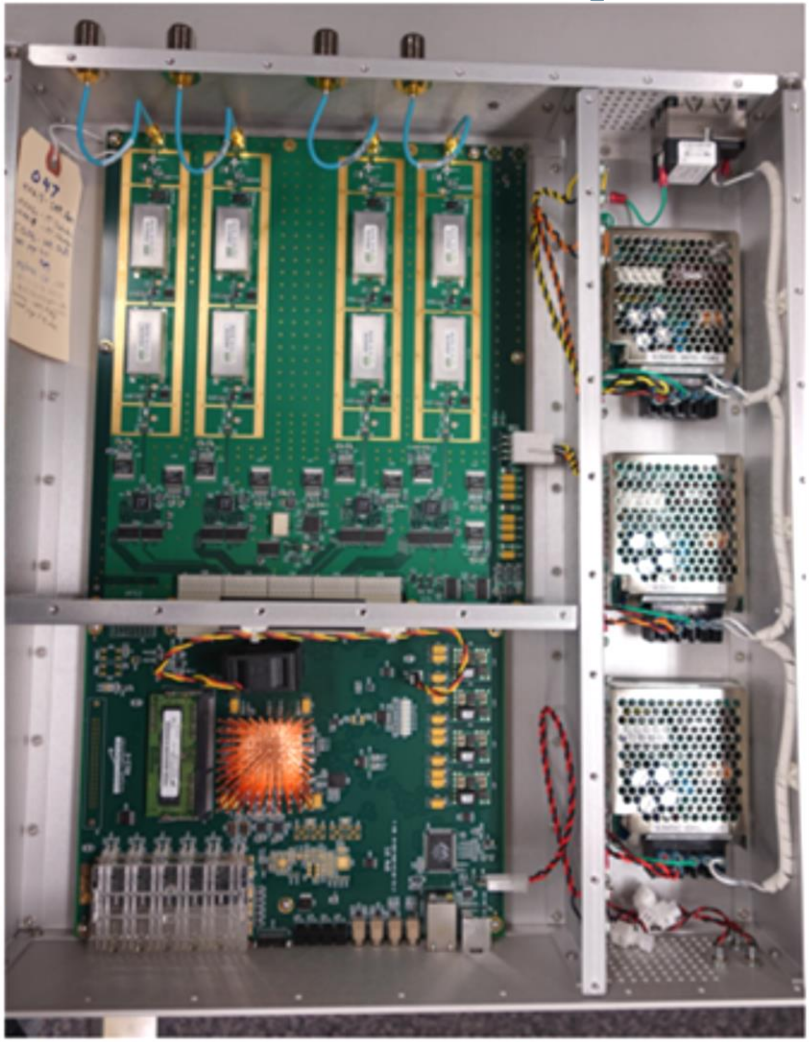
The NSLS-2 BPM

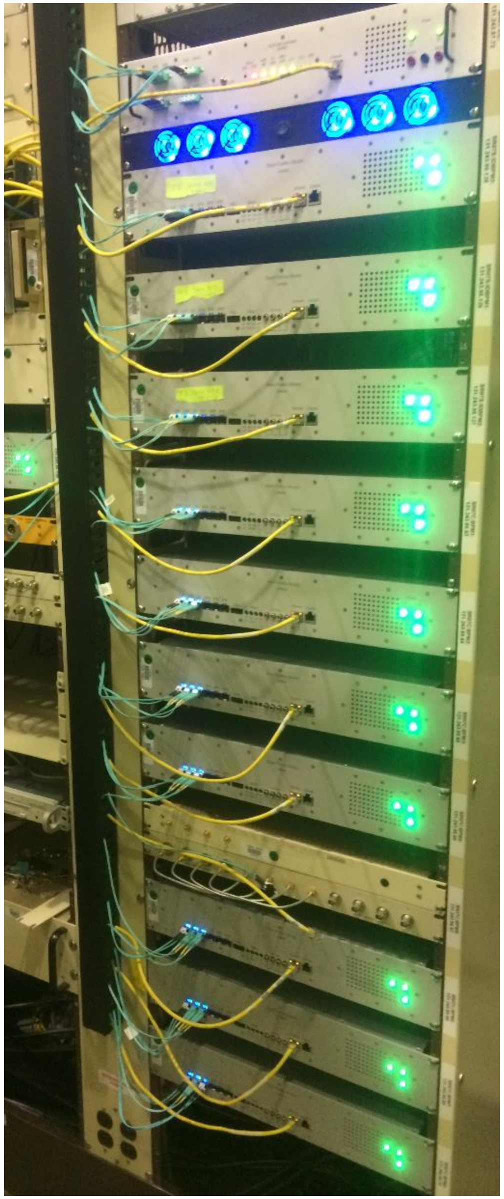
Storage Ring Thermal Racks Regulated to +-0.1C

- **BNL started a new BPM development for the NSLS-II project.**
- **We helped test this BPM at ALS before NSLS-II was built (similar RF frequencies)**
- **We leveraged this development for the new ALS BPM**
- **ALS doesn't have temperature-controlled racks, so we further developed the pilot tone compensation method that NSLS-II started.**

We are very grateful to the NSLS-II team for their openness and expertise!
Kurt Vetter, Joe Mead, Kiman Ha, Yuke Tian, Marshall Maggipinto, Joe Delong, Al Dellapenna, Danny Padrazo, … . And others including Jim Sebek at SSRL.

ALS BPM Development

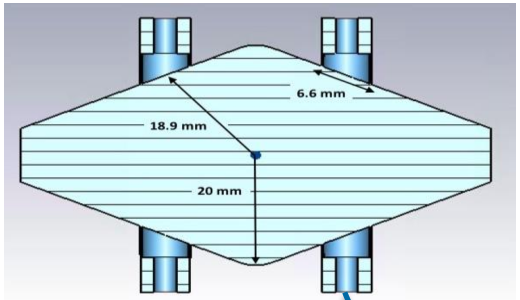




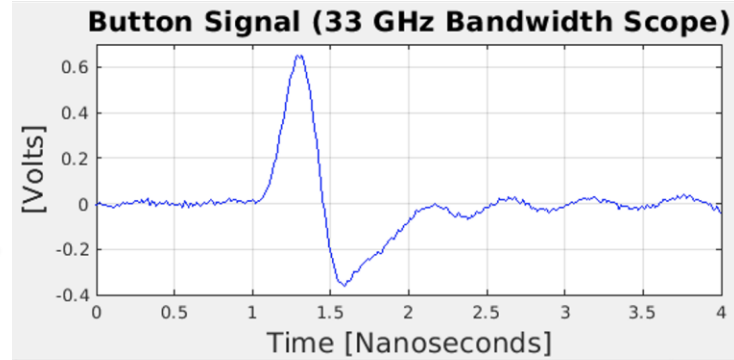
- Identical digital front end (DFE) hardware as the NSLS-II BPM, with new FPGA firmware.
- The analog front end (AFE) was modified for ALS

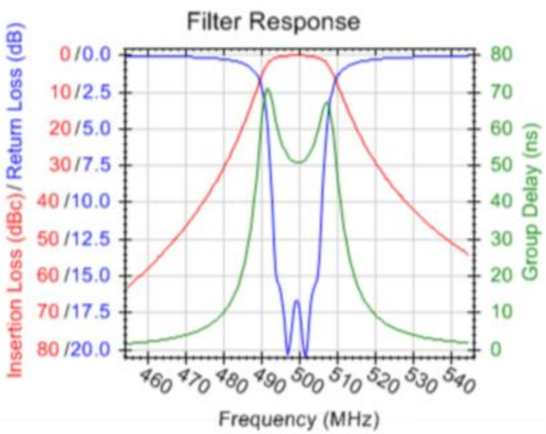
Signal Domains

ALS Arc Chamber



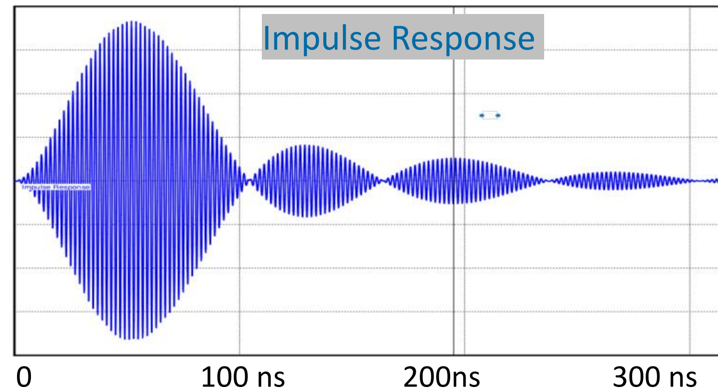
Button + Long Cable





~25MHz Bandpass Filter

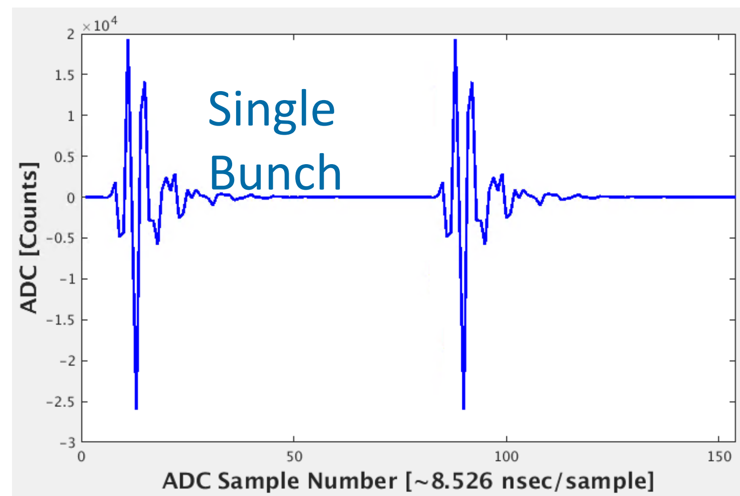
One turn in the ALS is 656ns.



ADC

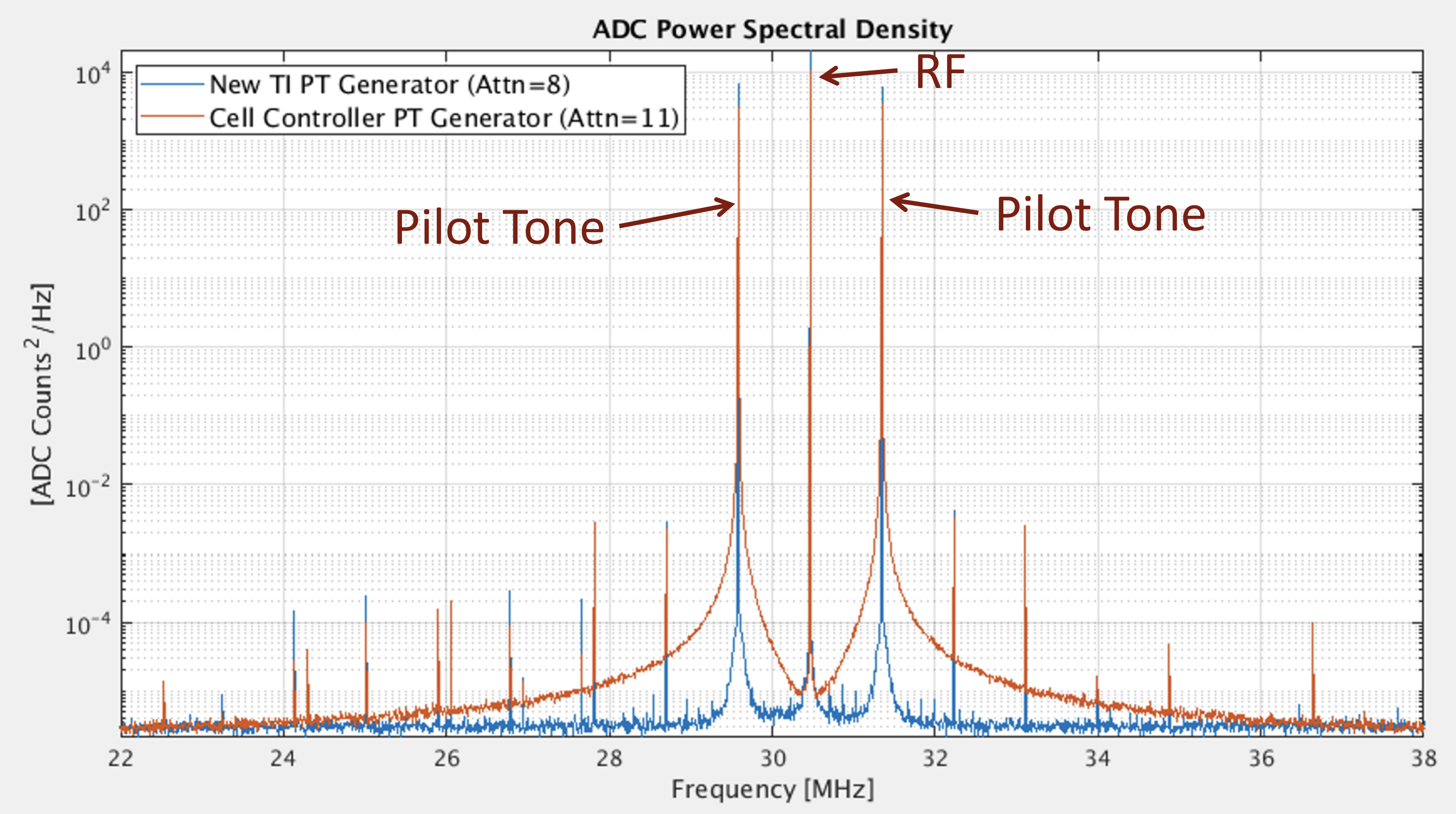
~117 MHz

Exactly 77 points/turn



ALS arc sector BPM sensitivity is 6.25 % / mm

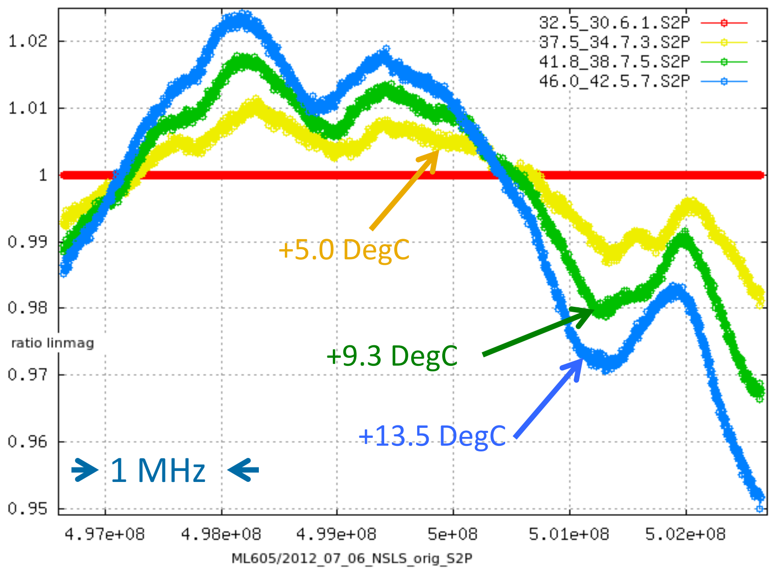
Pilot Tones



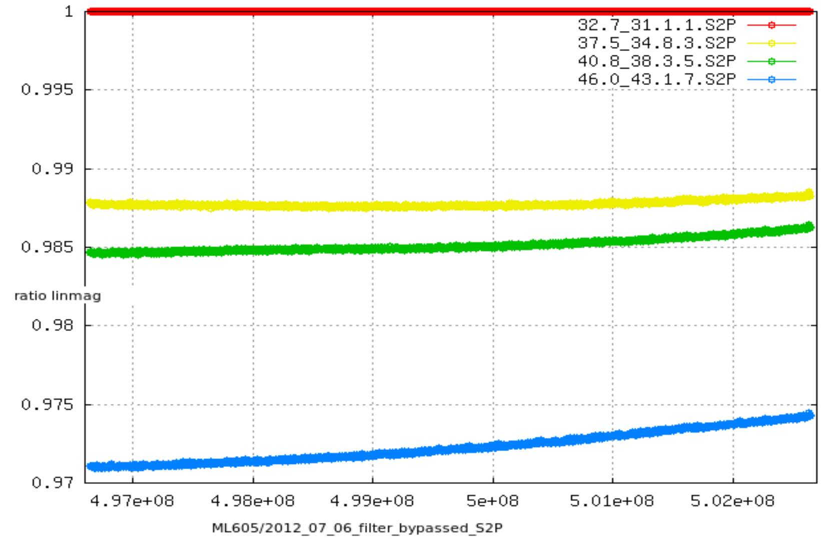
The critical assumption with pilot tone calibration is the gain changes happening at the pilot tone must correlate to the gain changes at the frequency of interest – the RF frequency for BPMs.

SAW Filter Thermal Analysis

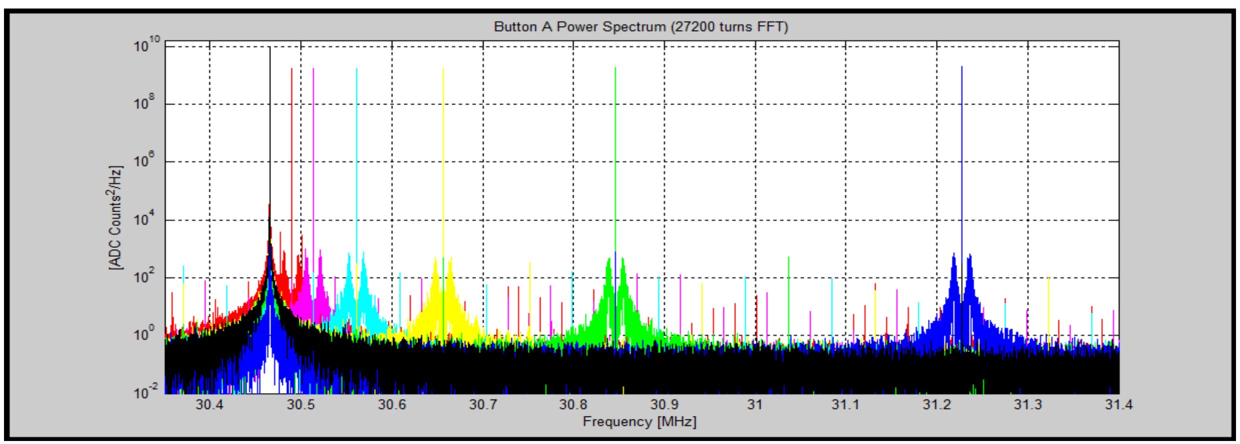
Normal BPM Channel with SAW Filters



SAW Filters Bypassed



Temperature introduces a relatively curvy response in the transfer function. This indicates that a pilot tone correction can only work if the tones are close to the RF frequency. In fact, a pilot tone at +2 MHz from at RF (~499.645 MHz) would indicate that the system gain goes down with temperature, whereas at RF the gain goes up.



RF (blk) + calibration tone at 1/64, 1/32, 1/16, 1/8, 1/4, 1/2 a revolution harmonic.

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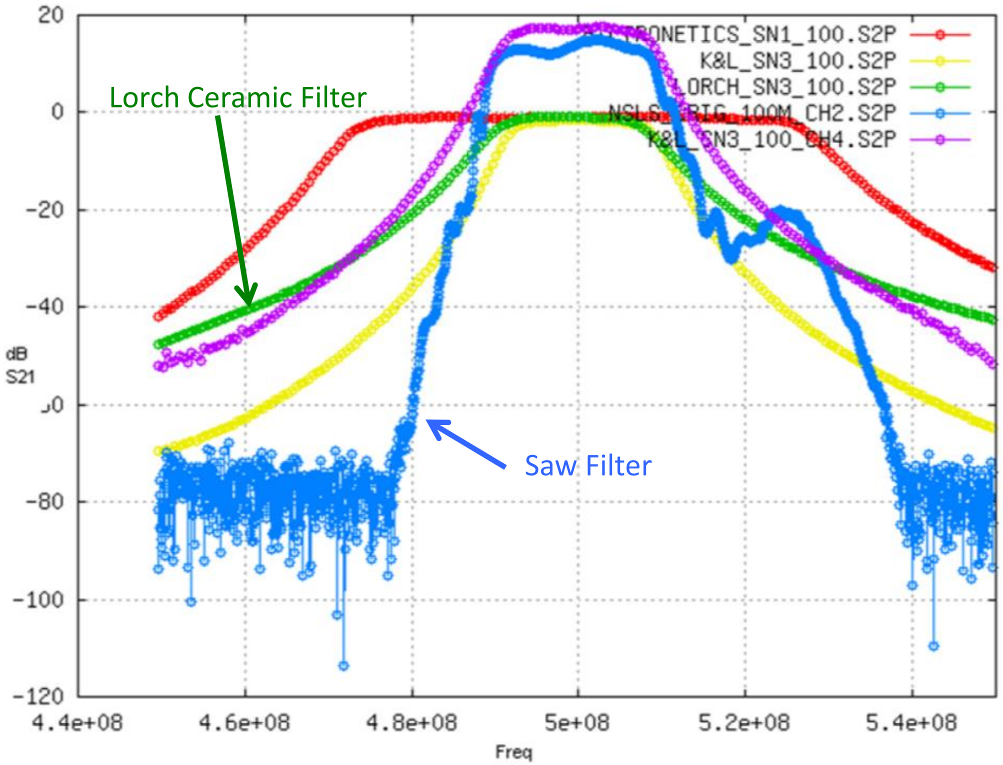
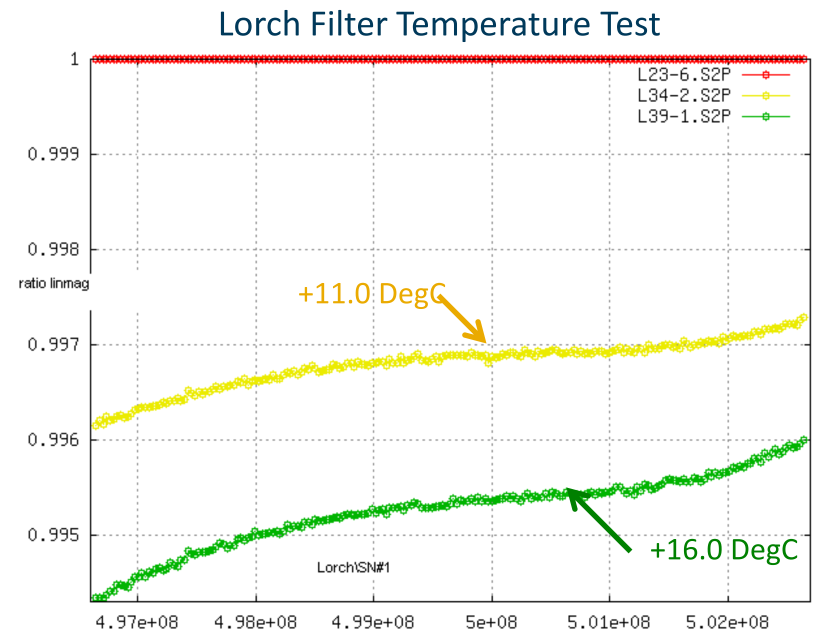
Bandpass Filter Study





The ceramic filter had an improved linear response with temperature change

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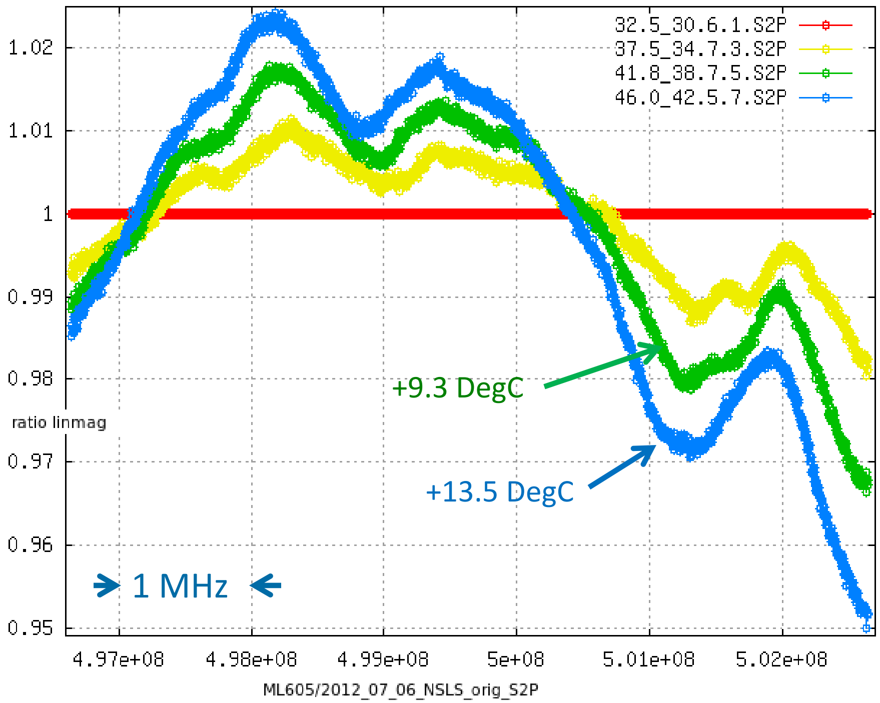
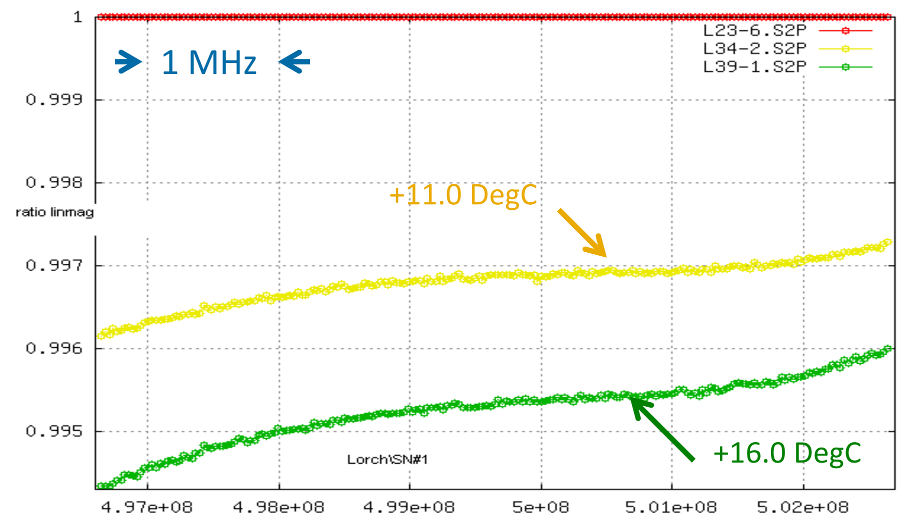
Bandpass Filter Study (Cont.)

SAW Filter Temperature Test



Lorch Filter Temperature Test



The Lorch ceramic filter is clearly much better than the SAW for pilot tone studies.

- **We original chose the Lorch ceramic filter which is assembled from 4 ceramic blocks**
- **Then we change to a mono-block ceramic filter from CTS**

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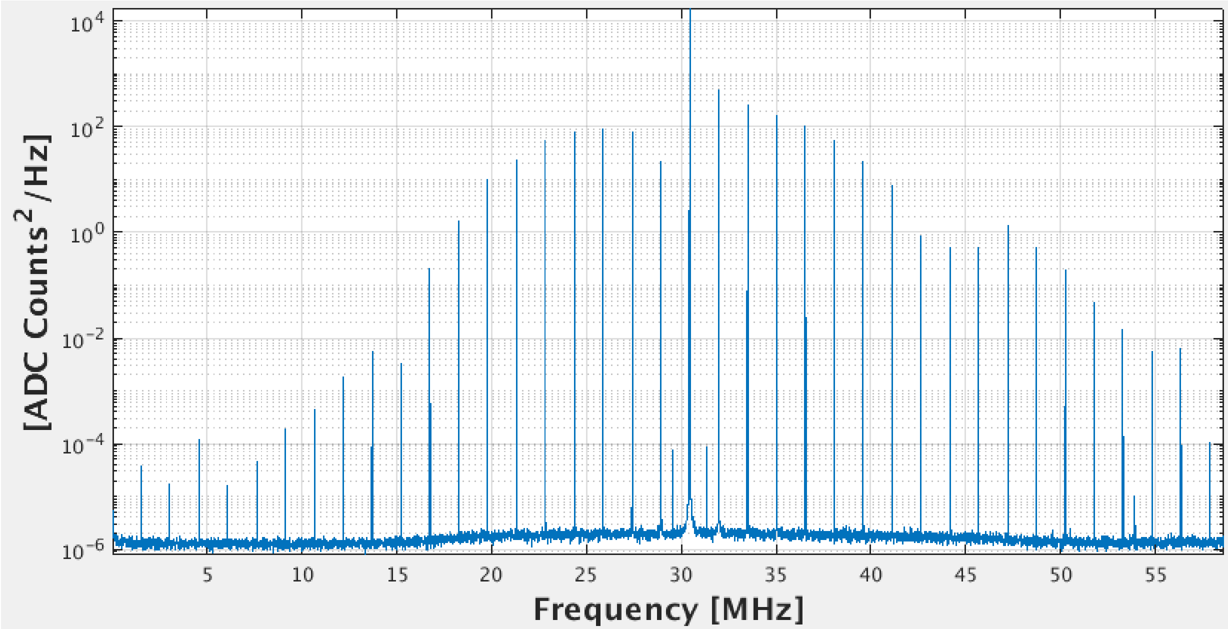
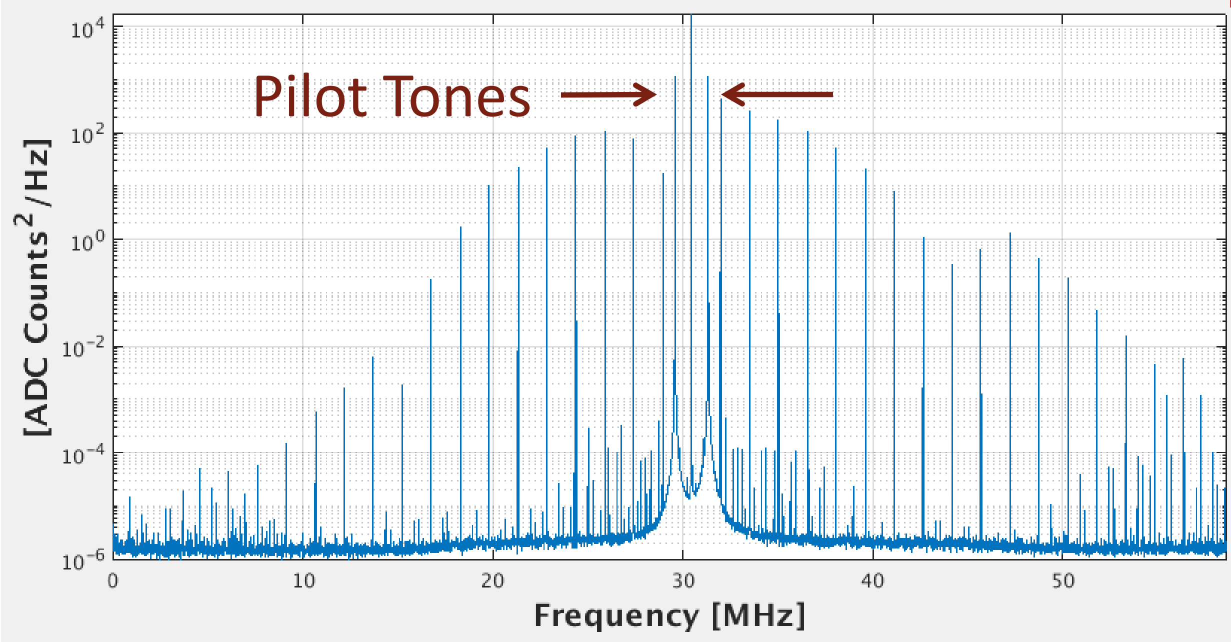
BPM ADC Spectrum w/ & w/o pilot tone





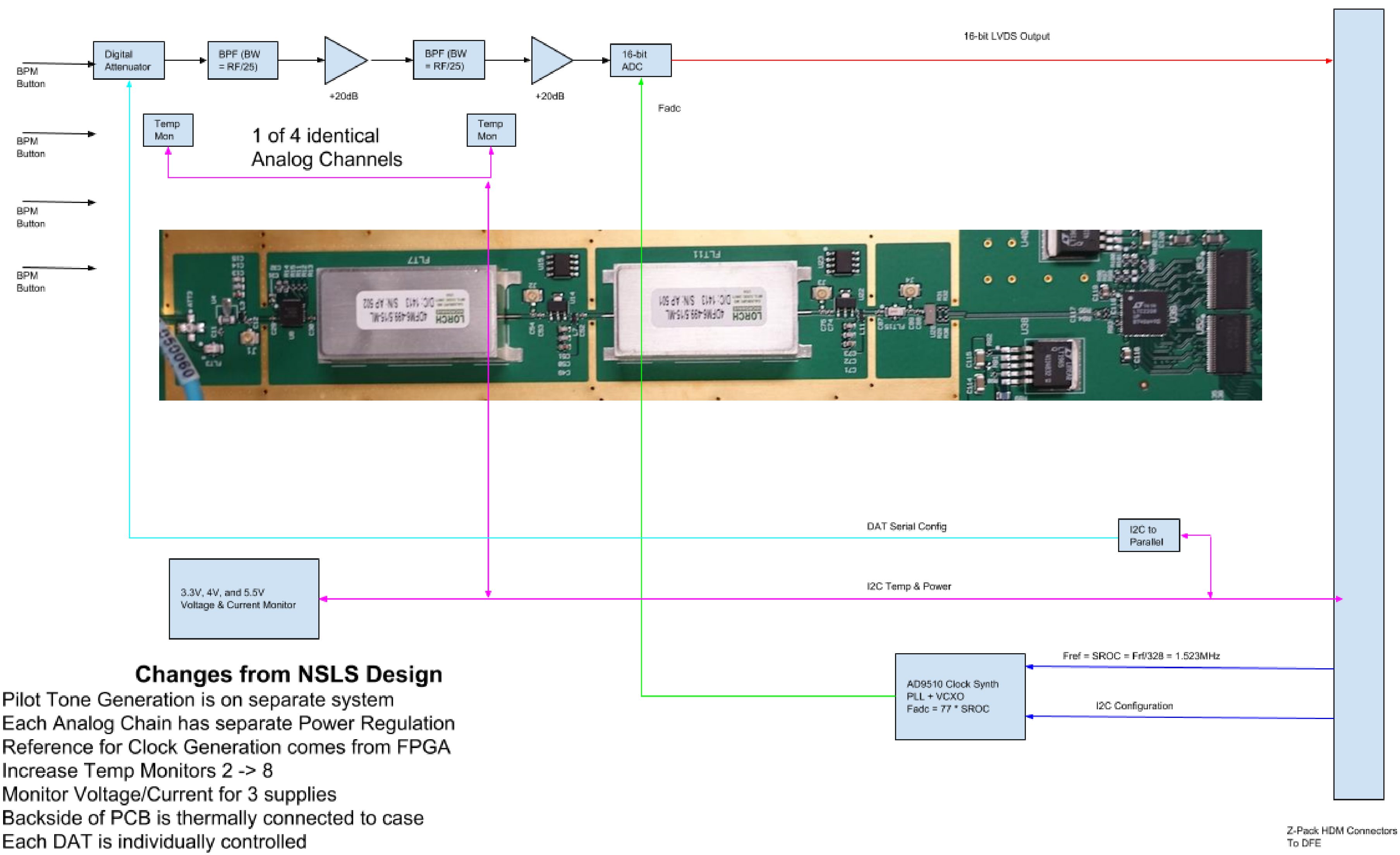
Multi-bunch Operation

- 2ns bunch spacing
- 328 Harmonic Number
- ~1.5MHz Rev Frequency

Pilot tone combiner was installed in the tunnel for temperature stability.

BPM AFE Design Changes from NSLS2

AFE Block Diagram Simplified



Changes from NSLS Design

Pilot Tone Generation is on separate system
Each Analog Chain has separate Power Regulation
Reference for Clock Generation comes from FPGA
Increase Temp Monitors 2 -> 8
Monitor Voltage/Current for 3 supplies
Backside of PCB is thermally connected to case
Each DAT is individually controlled
SAW BPFs changed to Ceramic

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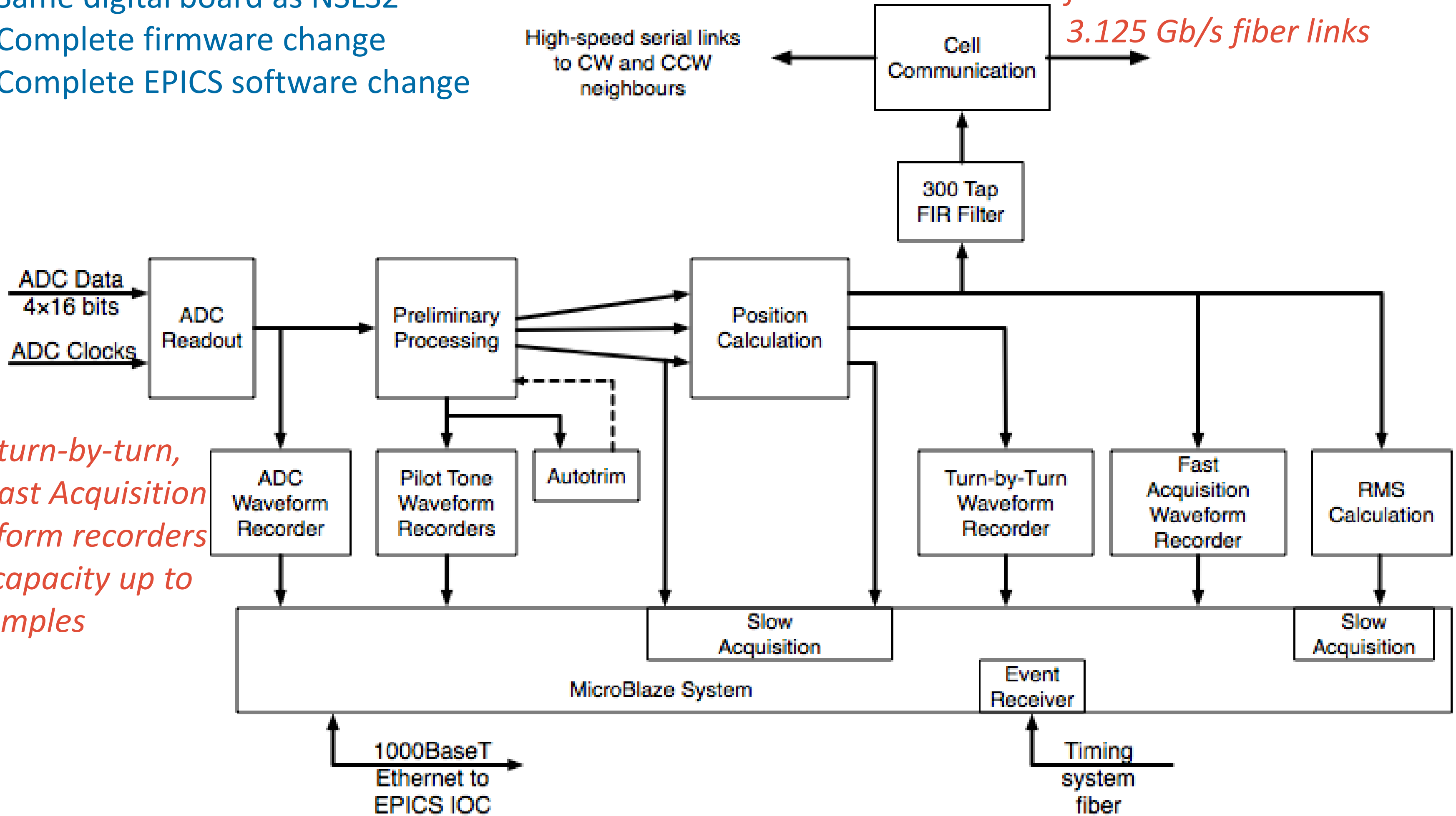
BPM Firmware

- Same digital board as NSLS2
- Complete firmware change
- Complete EPICS software change

Fast Acquisition: ~10 kHz positions to fast orbit feedback FPGAs — Dual 3.125 Gb/s fiber links



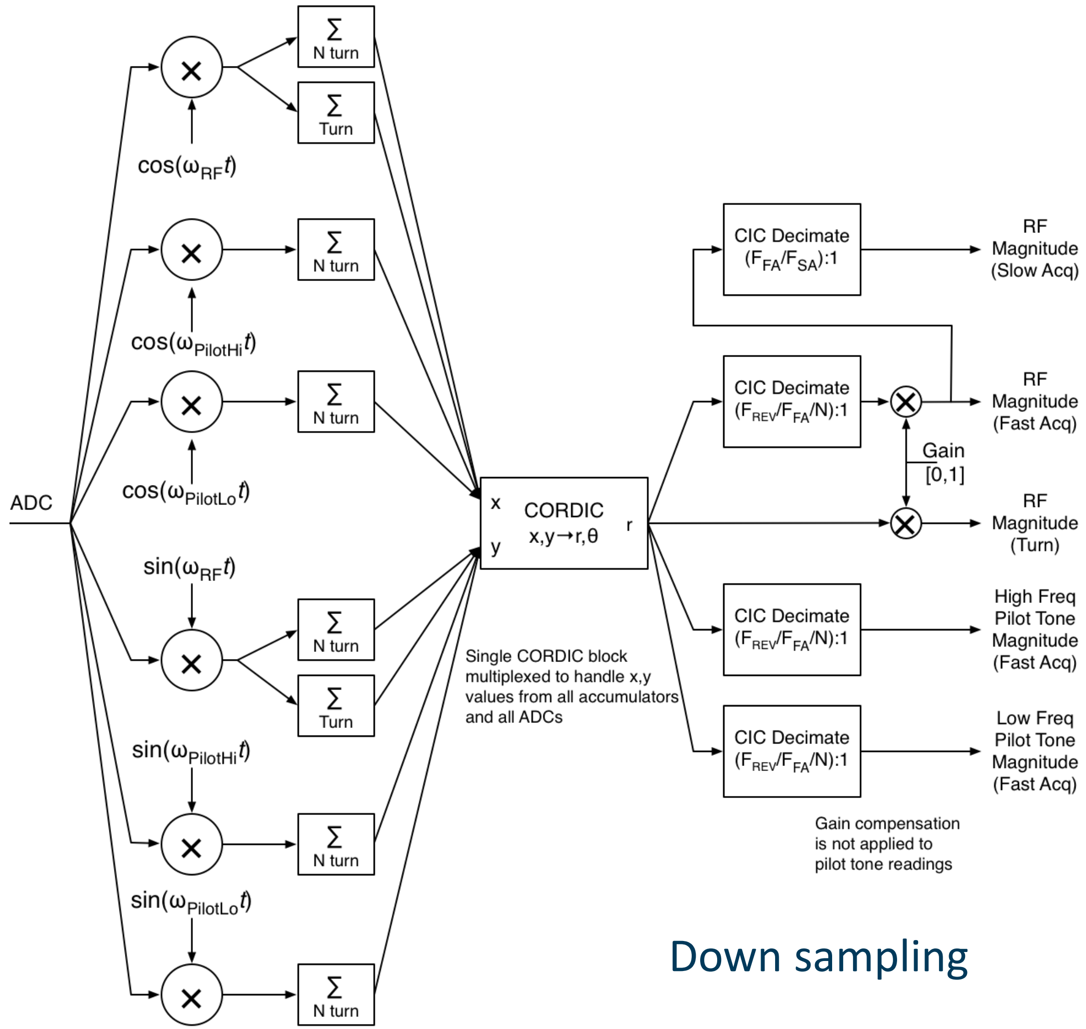
ADC, turn-by-turn, and Fast Acquisition waveform recorders with capacity up to 2^{24} samples

Slow Acquisition (~10 Hz): positions to EPICS-based orbit feedback

Acquisition clocks and triggers synchronized ALS timing system

E. Norum

BPM Firmware: Preliminary Processing Block



Down sampling

Synchronous Demodulation
(presently N = 19)

E. Norum

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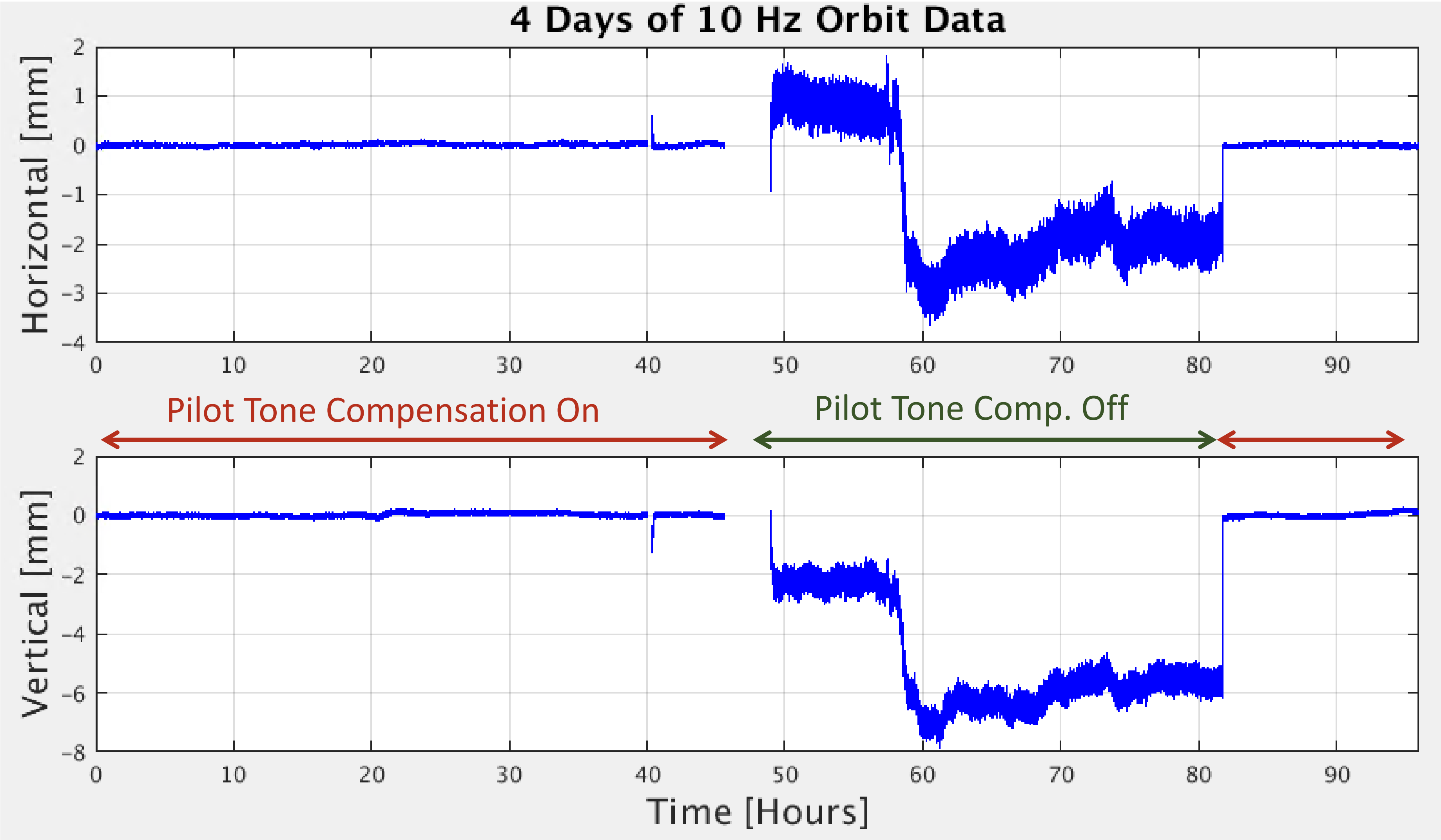
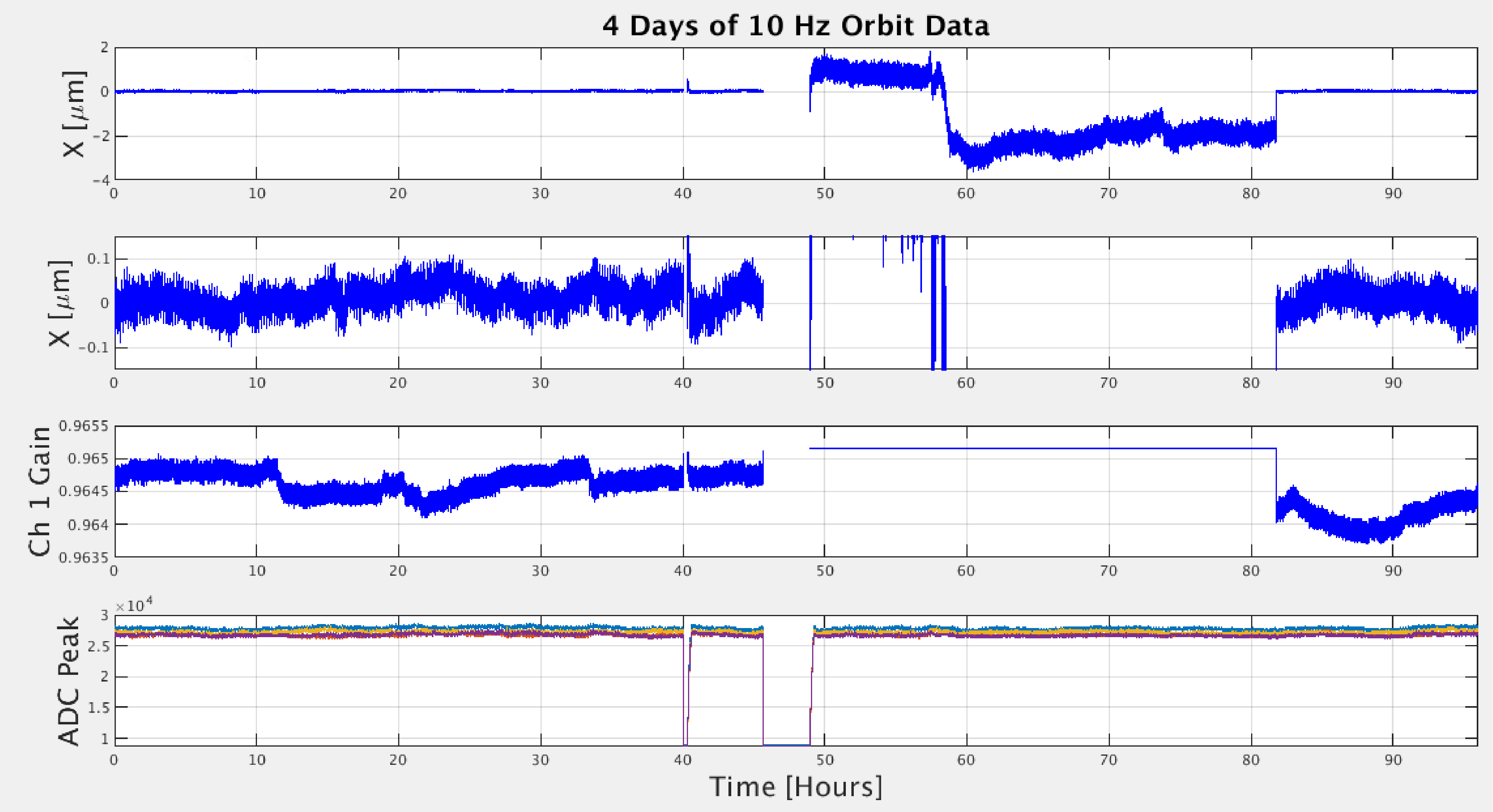
ADVANCED LIGHT SOURCE

4 Day Orbit Drift Measurement



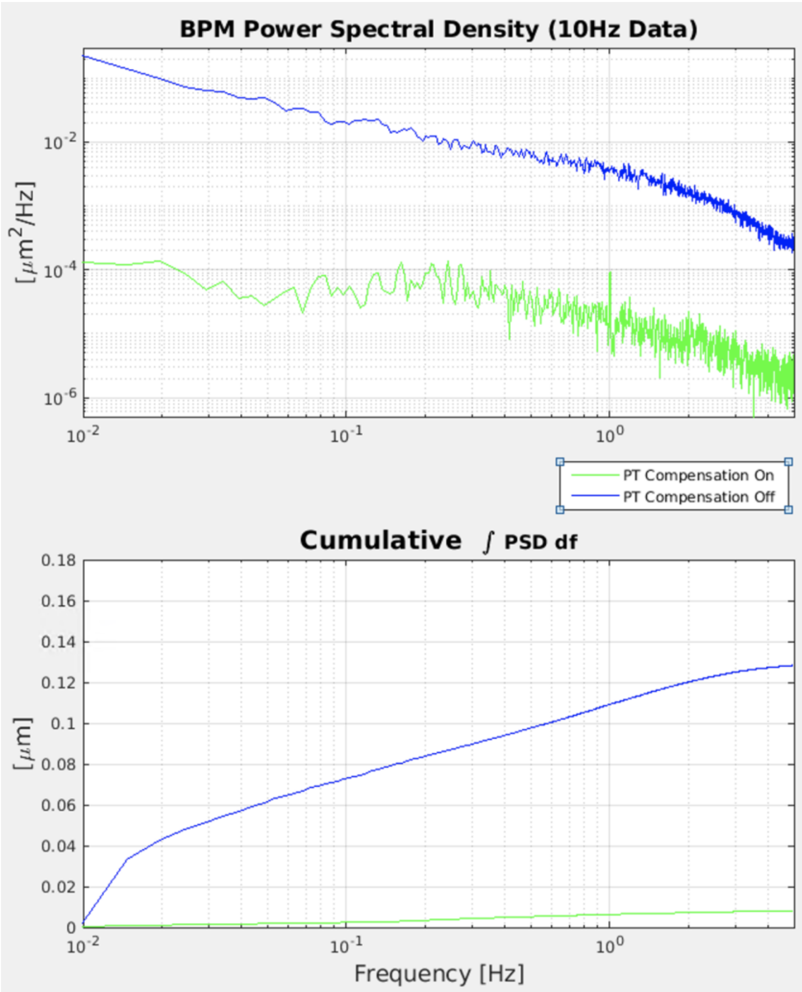
Orbit Drift Measurement (using a 4-way split button signal)

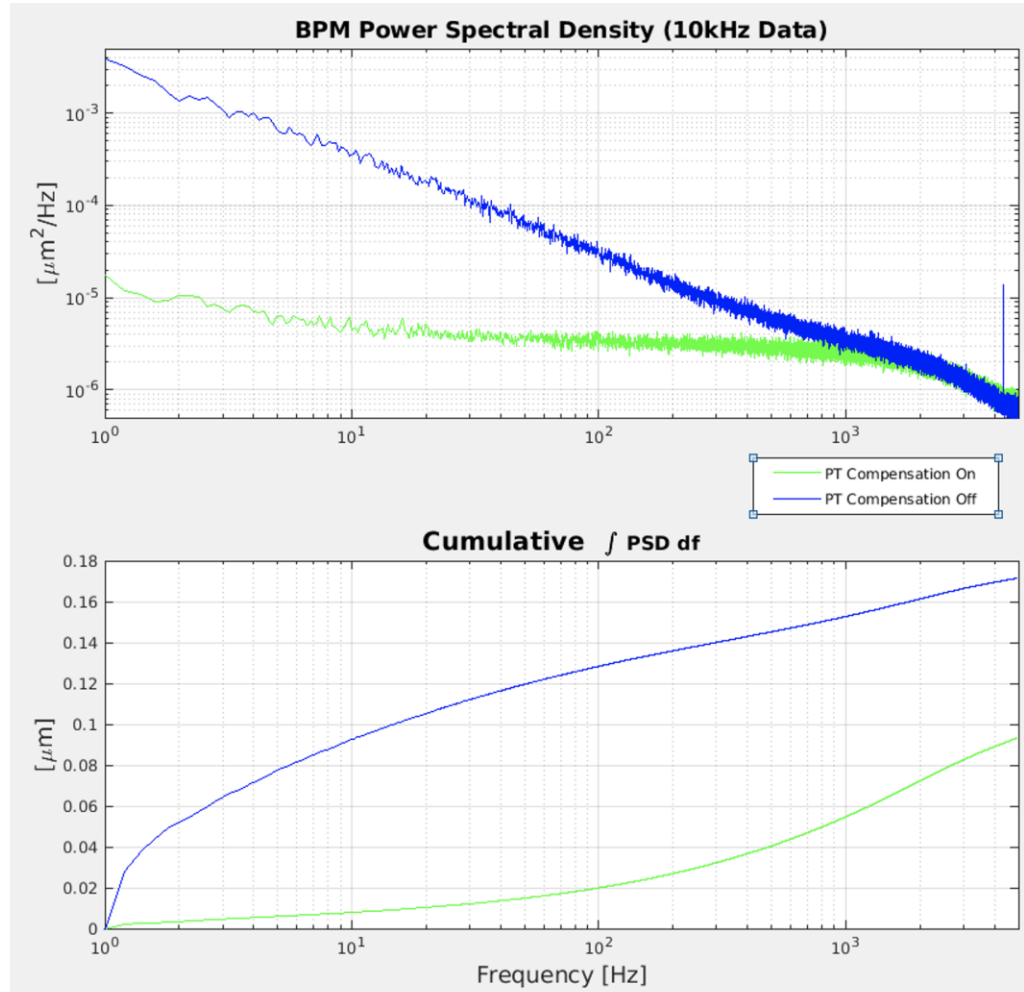
Drift measurement in more detail



- Orbit Drift Measurement (using a 4-way split button signal)
- Easily maintain our .2 μm RMS goal over 4 days with pilot tone compensation.

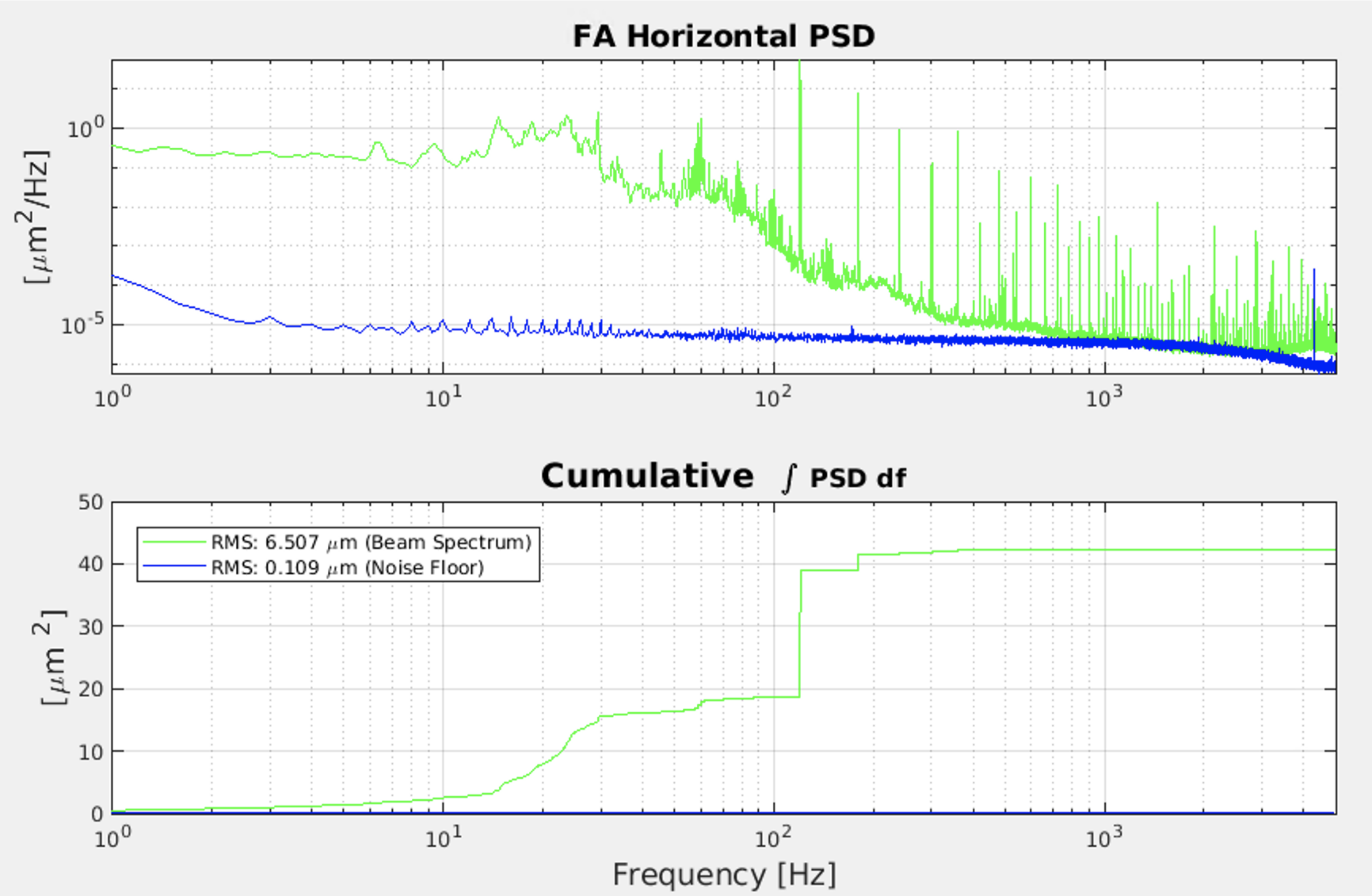
BPM Noise Floor Measurements





- Adding the spectrum in quadrature, the noise from .01Hz to 5kHz is 203nm w/o PT compensation and 93nm w/.
- This meets our 200 nm RMS noise floor goal from .01 Hz to 5 kHz basically w/ or w/o pilot tone correction.
- Pilot tone correction provides a benefit up to about 1 kHz. The fast orbit feedback bandwidth of interest is from ~1 Hz to 1 kHz where the RMS with pilot tone compensation is ~55 nm.

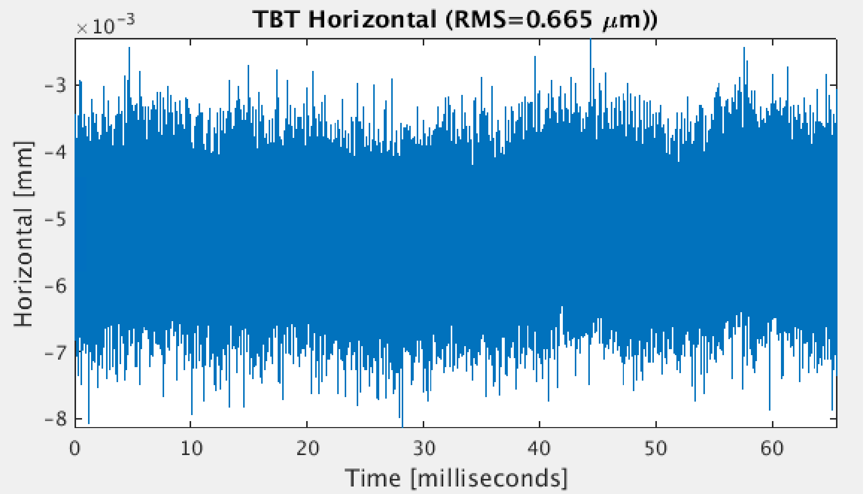
Beam & Noise Floor at 10 kHz

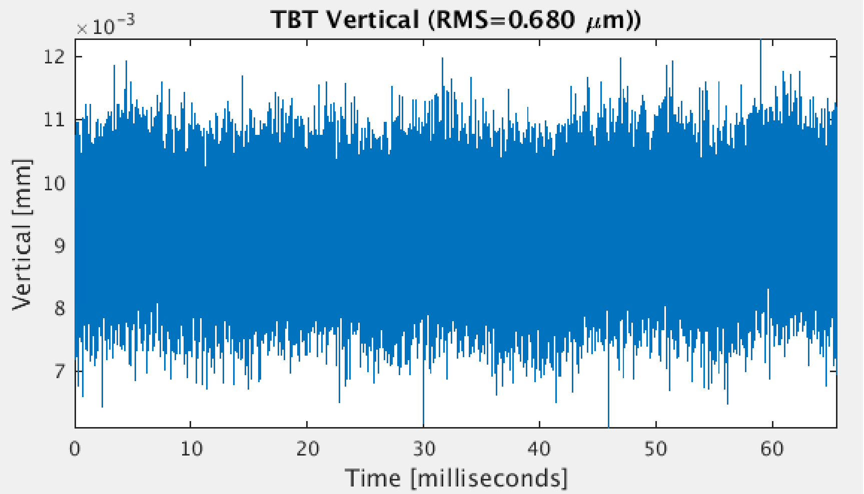


The area between the lines shows the possible improvement factor that a fast orbit feedback system could provide.

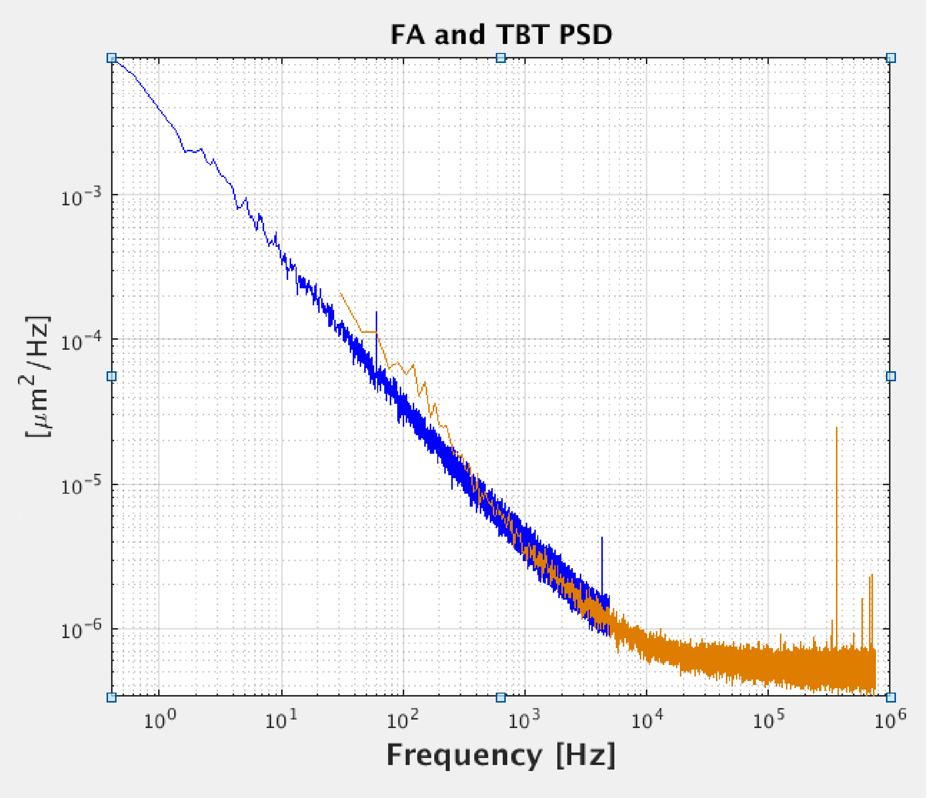
Multi-bunch Turn-By-Turn Orbit Measurement

Note: Pilot tone compensation and turn-by-turn data are not compatible!





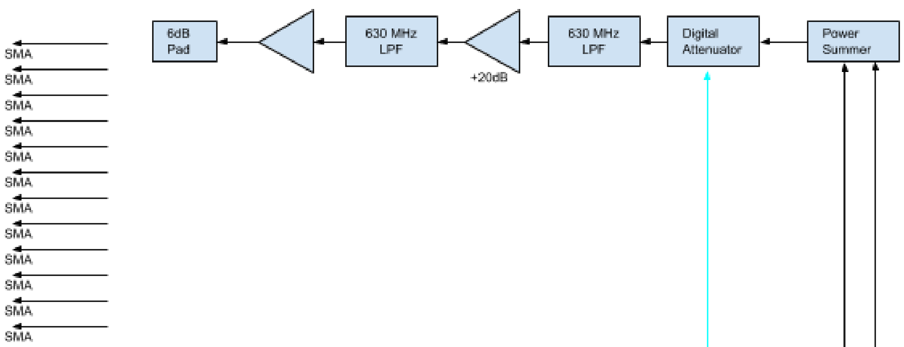
Noise measurement done at 500 mA using one button split 4-ways.



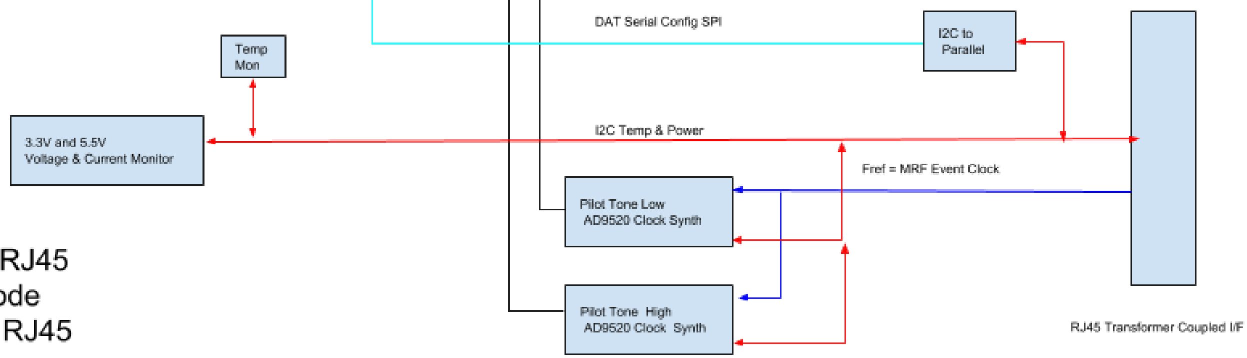
Rev. rate in ALS is 656ns (~1.5MHz)

ALS Pilot Tone Generator

Pilot Tone Generator Diagram
Simplified



- Two Tone Generators
- Presently run at ±11/19 Rev Harmonic (~882 kHz)



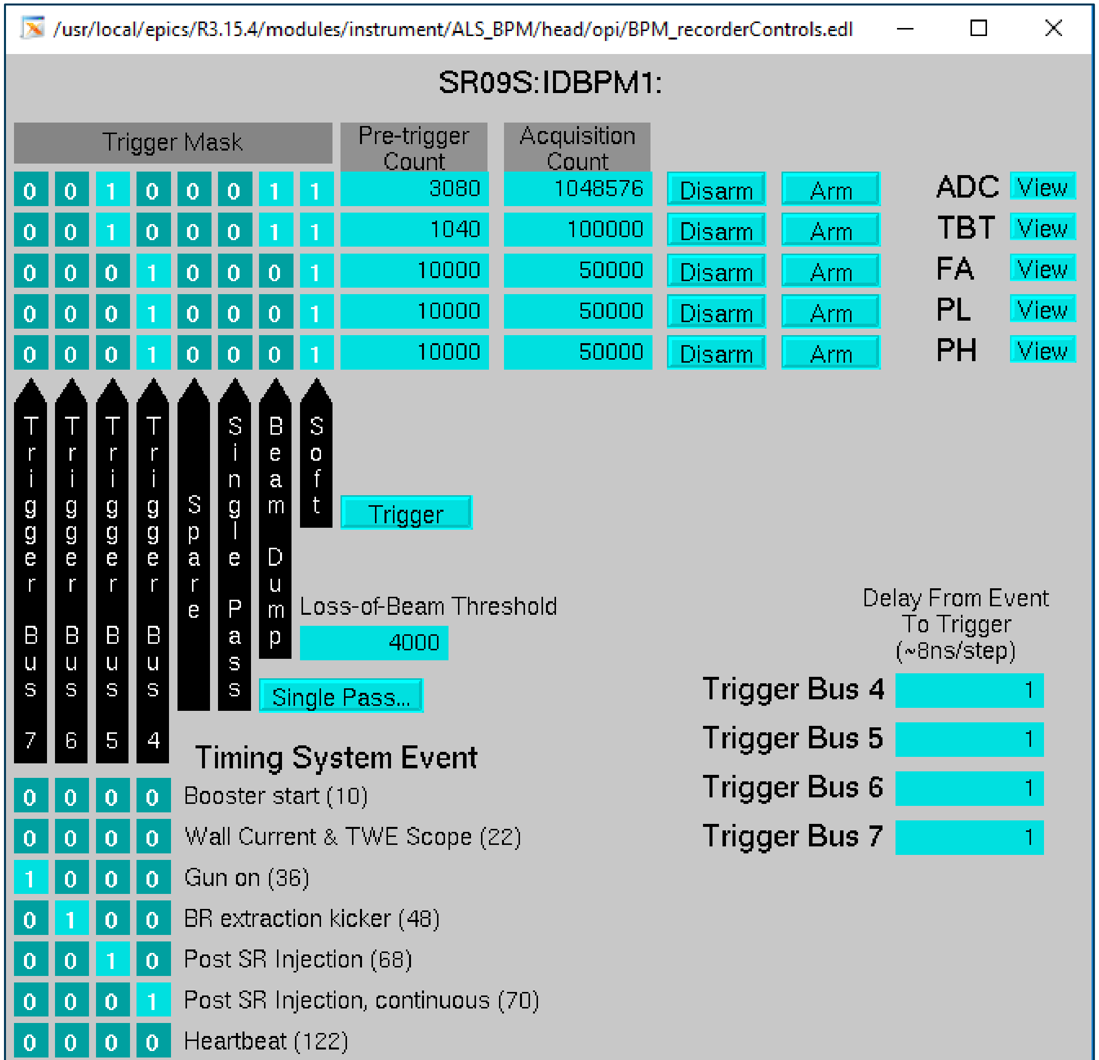
Design Highlights

Transformer coupled I2C I/F using standard RJ45
Dual AD9520 Clock Synthesizers in VCO mode
125MHz Reference for Clock Generation on RJ45
Monitor Voltage/Current for 2 supplies
Backside of PCB is thermally connected to case
Each DAT is individually controlled

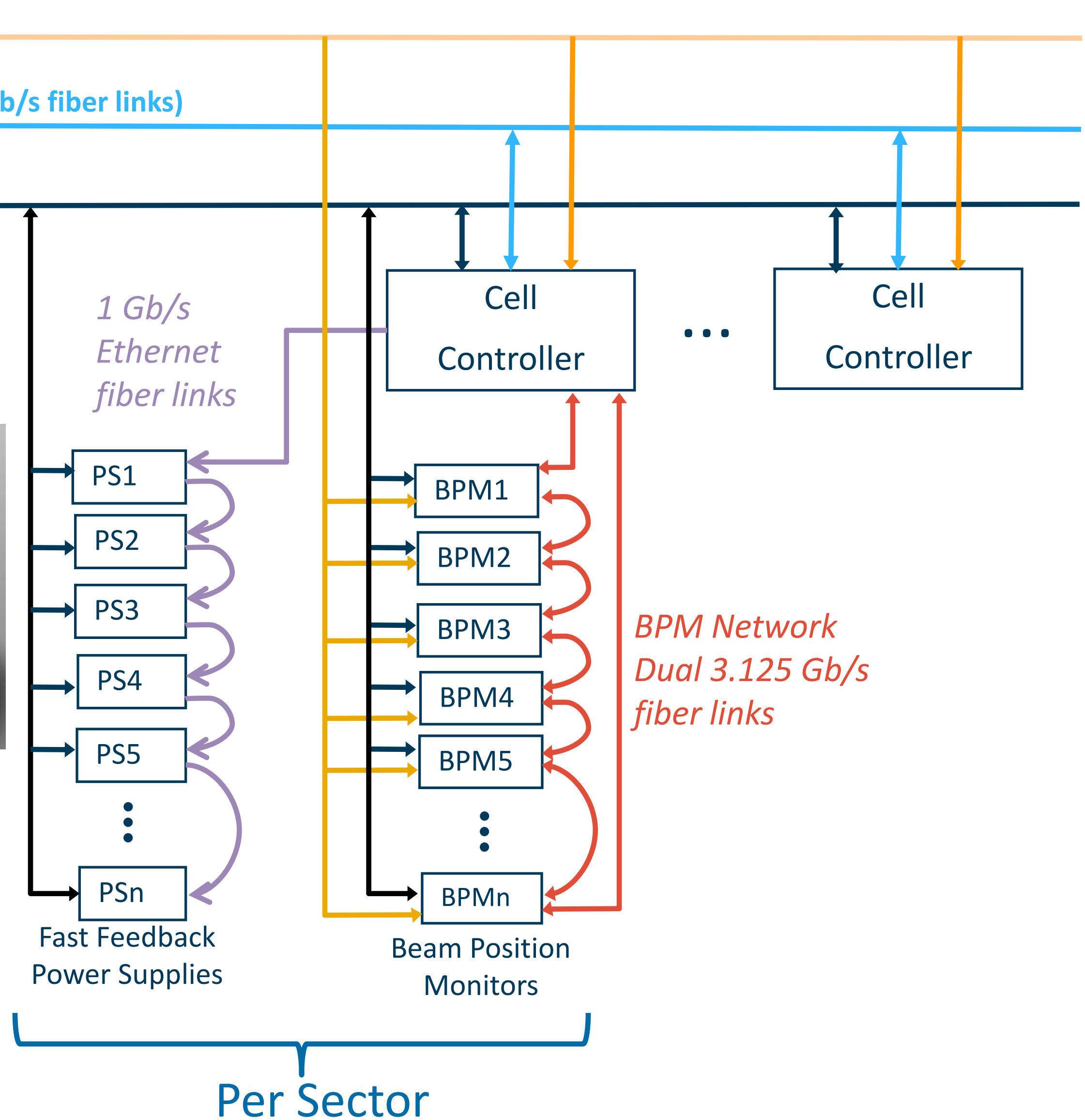
M. Chin

Data Recorder

- Data buffers for ADC, TBT, FA data streams with capacity up to 2^{24} samples (~16M)
- Trigger selection: any timing system (MRF) trigger, beam dump, single pass threshold, or software PV.

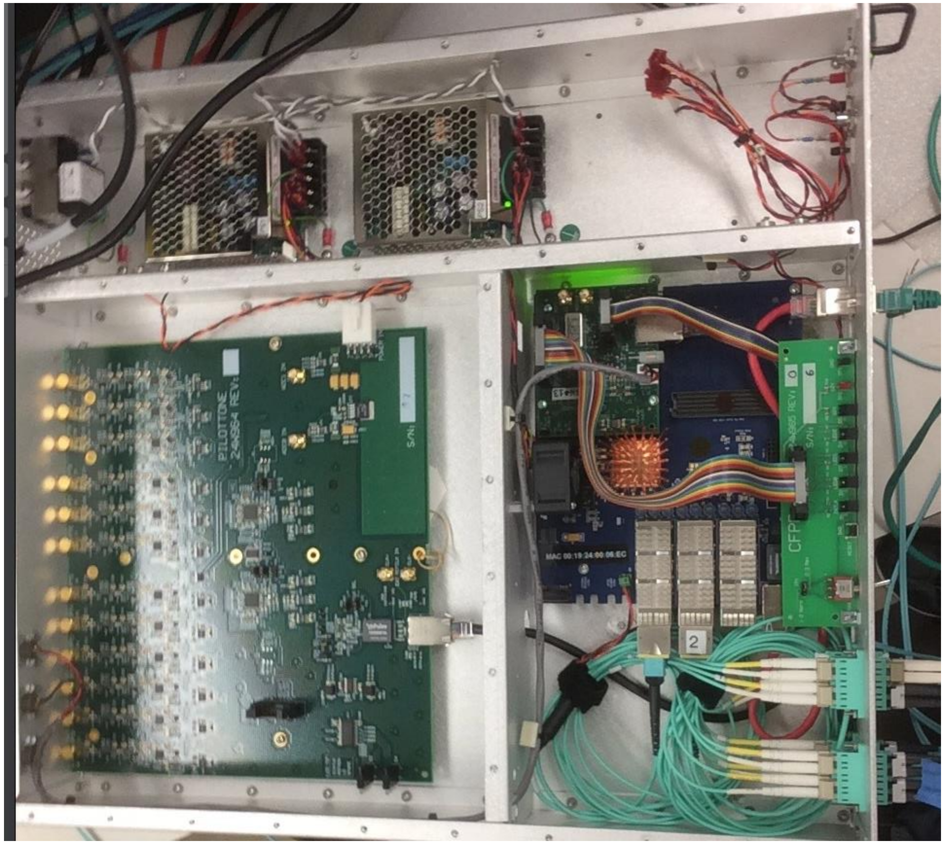


Fast orbit feedback architecture



Power Supply for FOFB (Caen Fast-PS Series, ~5kHz bandwidth)

Cell Controllers and FOFB



The ALS Cell Controller

- Conceptually similar to NSLS2 FOFB System
- Different hardware, firmware, and software

Digital frontend has multiple functions

- FOFB – Collects BPM data at 10 kHz, computes the fast orbit feedback compensation, communicates to the fast power supplies
- Controls the pilot tone generator board for the BPMs
- Fast orbit interlock (relay output daughter board)

Conclusion

- The pilot tone system is working well
  - For real-time compensation of BPM electronic errors
  - It's a great diagnostic tool for monitoring the health and performance of the beam system. On shutdown days, the pilot tone frequency can be changed to the RF frequency to mimic beam in the accelerator.
- Improvement that we're thinking about
  - Faster ADCs – less aliasing, better statistics, more bandwidth provides more room in the frequency domain for design tradeoffs.
    - More bandwidth in the bandpass is good for single bunch (more revolution harmonics in the passband -> more signal to ADC counts)
    - More filter rejection before the Nyquist frequency
  - Possibly move from 500MHz to 1GHz detection
    - Button response is good at 1GHz
    - More bandpass filter available at 1GHz
  - Move to Frac-N PLL w/VCO instead of a fixed VCXO to provide flexibility in the sample rate selection
    - Using the same electronic in different accelerators
    - Experiment with changing sampling frequency for different types of measurements, like turn-by-turn and and slow acquisition.
  - Lower noise pilot tone generators
- We'd like to thank ALS management for supporting this effort!
- We'd like to thank the NSLS-II team for providing us open access to their BPM developments.