High Order Mode Measurements at FLASH

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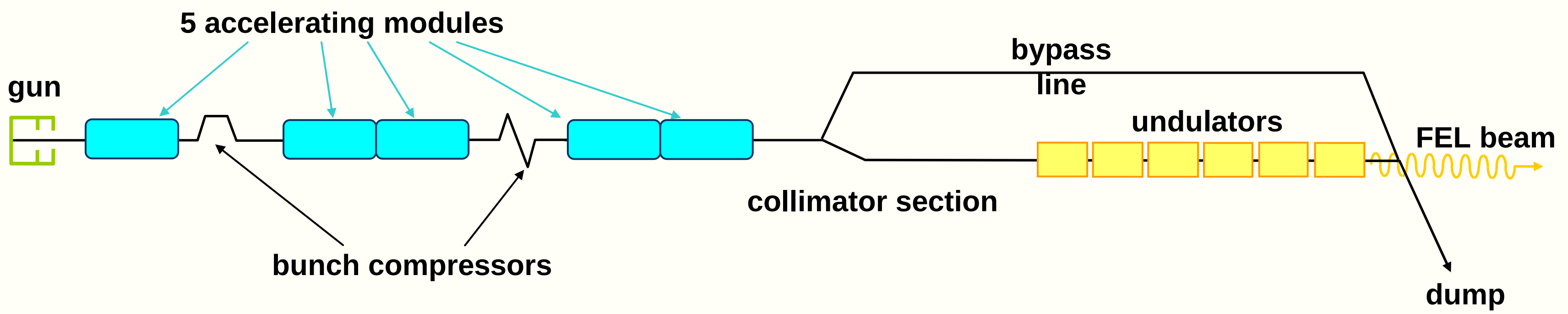
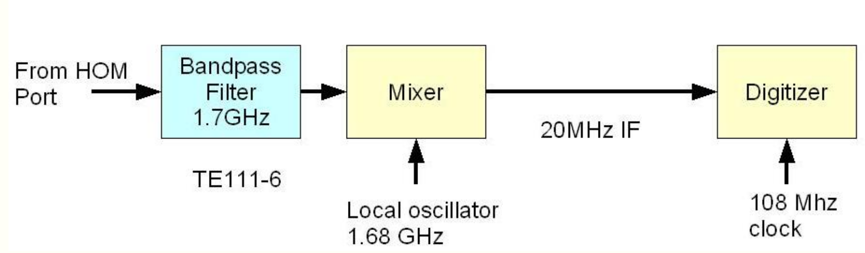
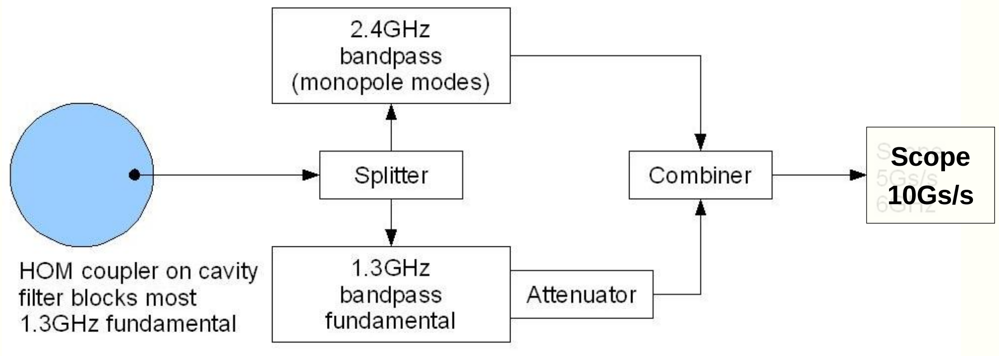
HOM Systems at FLASH



- **Narrowband (Downmix) system**
  - **Specific to TE111-6 Dipole mode (1.7GHz)**
  - **All cavities, both couplers monitored simultaneously**
  - **High dynamic range (14 bit), good linearity**
  - **High resolution HOM-based BPMs**
  - **Use for cavity alignment**



- **Broadband (scope-based) system**
  - **Monitor HOM modes up to 5GHz**
  - **Several simultaneous channels (4 or 8)**
  - **Limited dynamic range (8 bit scope)**
  - **Use for Phase measurement**
  - **In future use for cavity diagnostics**



HOM Diagnostics

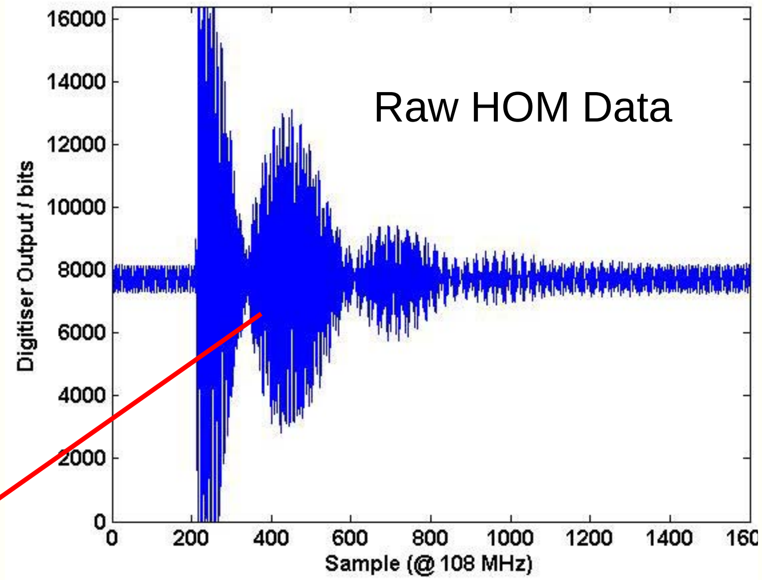
- **Beam Diagnostics**
  - Beam Position Monitoring - dipole mode amplitude is a function of the bunch charge and transverse offset
  - Beam Phase Monitoring – compare phase of 1.3 GHz and a HOM monopole mode
- **Cavity Diagnostics**
  - Cavity to cavity alignment within a cryo-module from dipole mode centers
  - Potential to study cavity imperfections within cryo-module

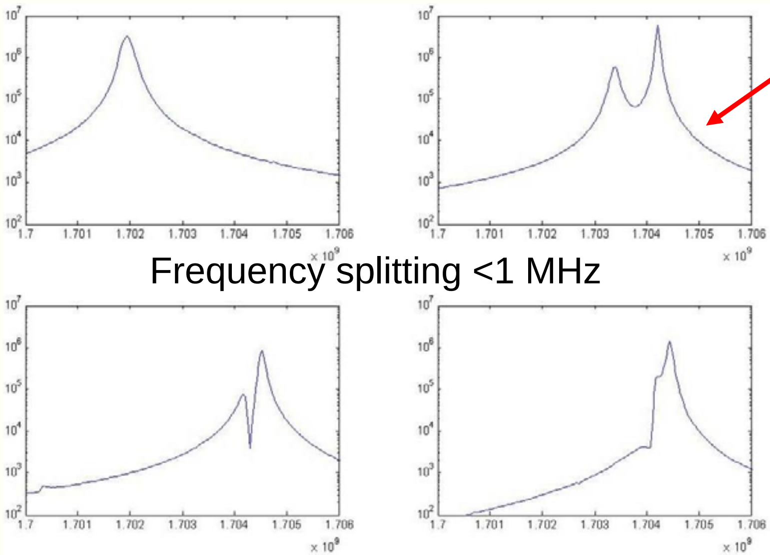
Narrow-band BPM System

• Dipole modes exist in two polarisations corresponding to orthogonal transverse directions.

• The polarisations may be degenerate in frequency, or may be split by the perturbing affect of the couplers, cavity imperfections, etc.

•Makes determination of mode amplitudes difficult using traditional techniques





Frequency splitting <1 MHz

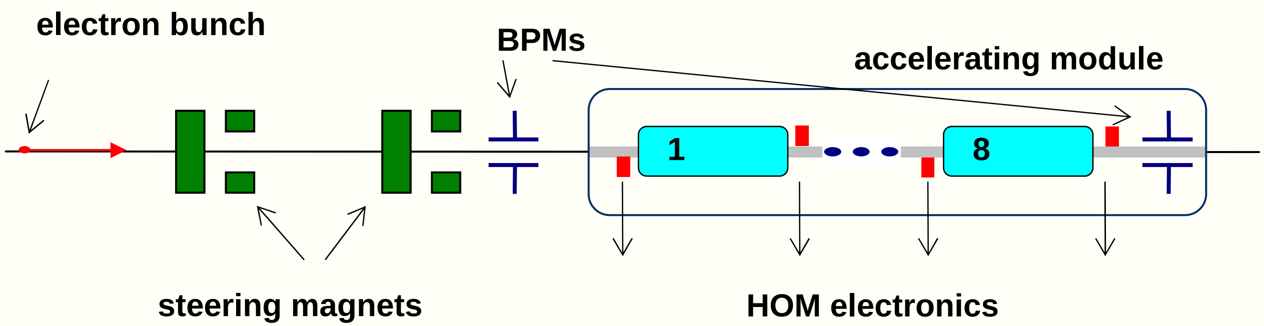
Mode Splitting in Different Cavities

• Need to calibrate the HOM response against positions from the BPMs

• Use SVD to find orthogonal modes then regress the mode amplitudes against BPMs to determine calibration matrix

•Multi-bunch data requires subtracting predicted amplitudes from previous bunch

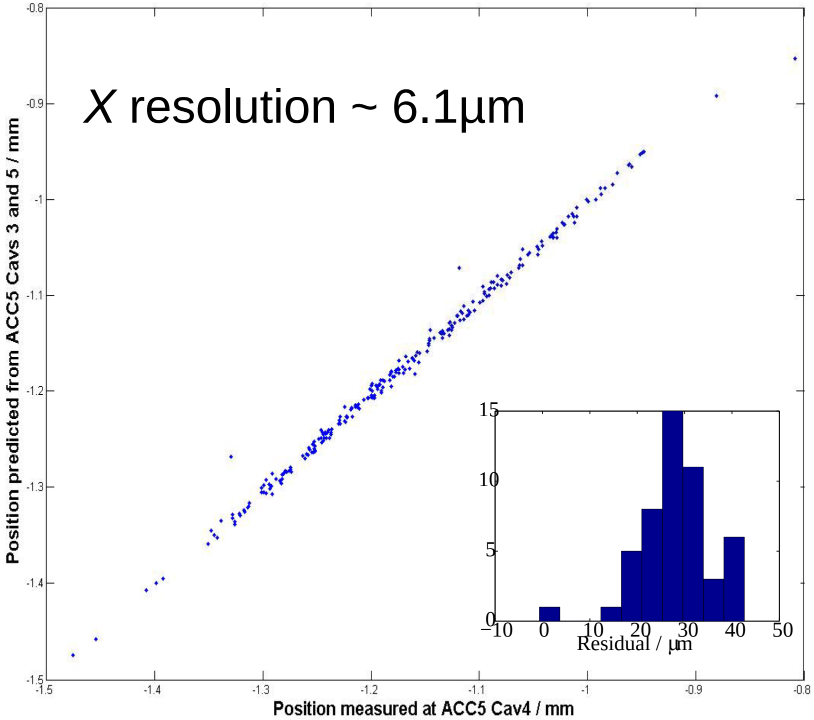
Calibration Procedure

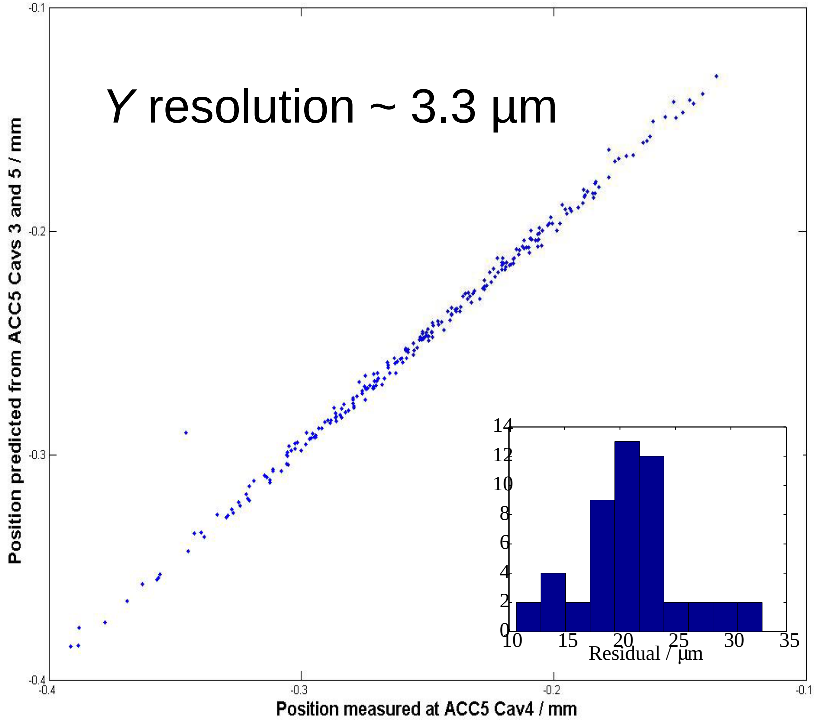


- Calibrate each module by steering the beam and recording the raw HOM signal
- Initially attempted to steer through as much of 4D phase space as possible
  - Very time consuming and often difficult to achieve X' and Y' resolution
  - Best results obtained by doing random scans
- Attempted to perform closed bumps around modules to calibrate each Module individually
  - Bumps did not close well, but found we were able to calibrate modules 2 through 5 simultaneously – only requires 15 minutes
- Work is underway to automate the calibration procedure and understand how often it is required
- Need to develop a calibration scheme for Module 1 – difficult due to trajectory and transverse kicks

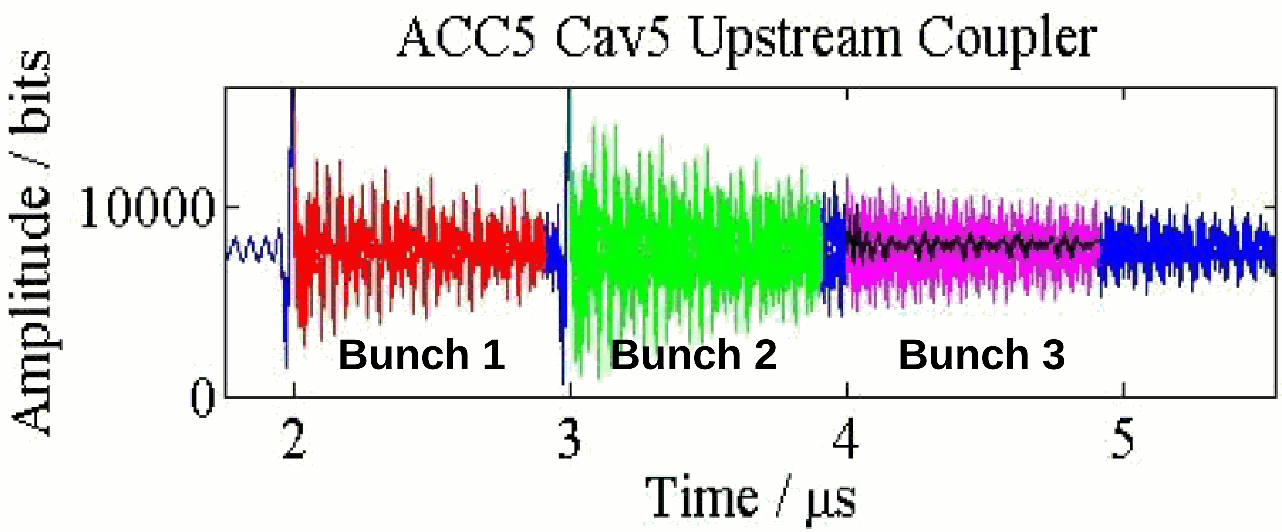
Single Bunch Results

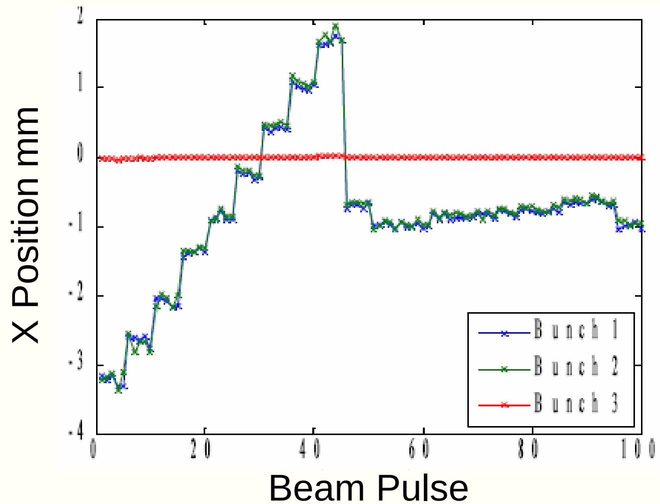
- Measured vs Predicted Position as beam is moved during scan
  - Predict position at cavity 4 from cavities 3 and 5
- Theoretical resolution of several hundred nm
  - Jitter on the LO for the downmix electronics and charge normalization



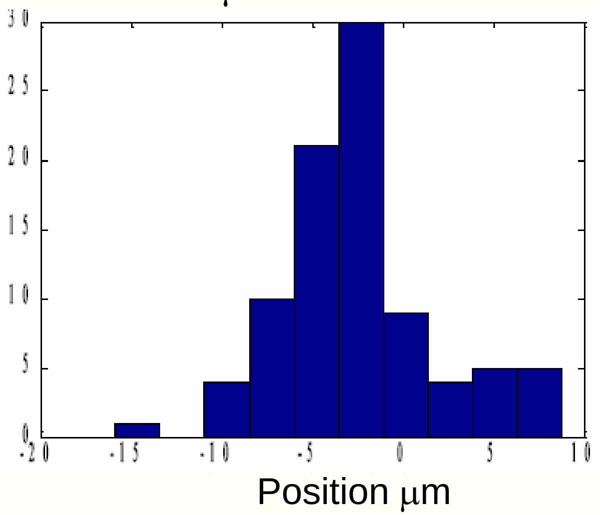


Multi-Bunch Initial Results

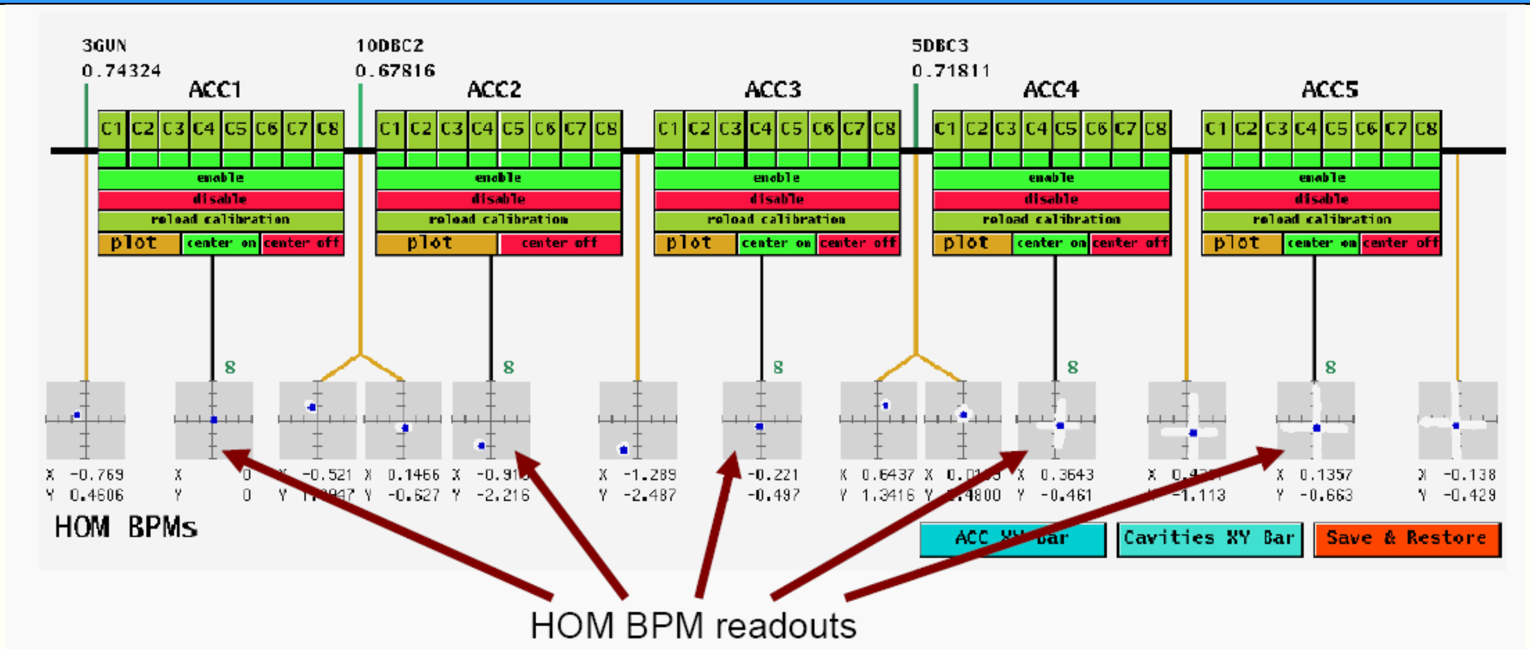




4 µm Residual



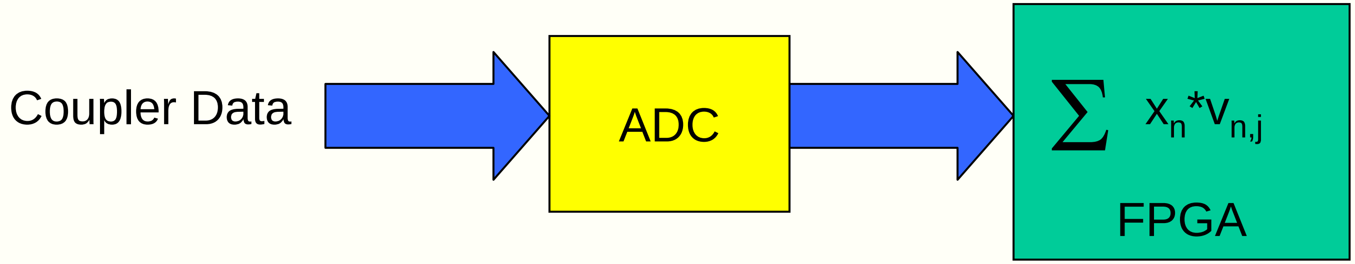
Online BPM Software



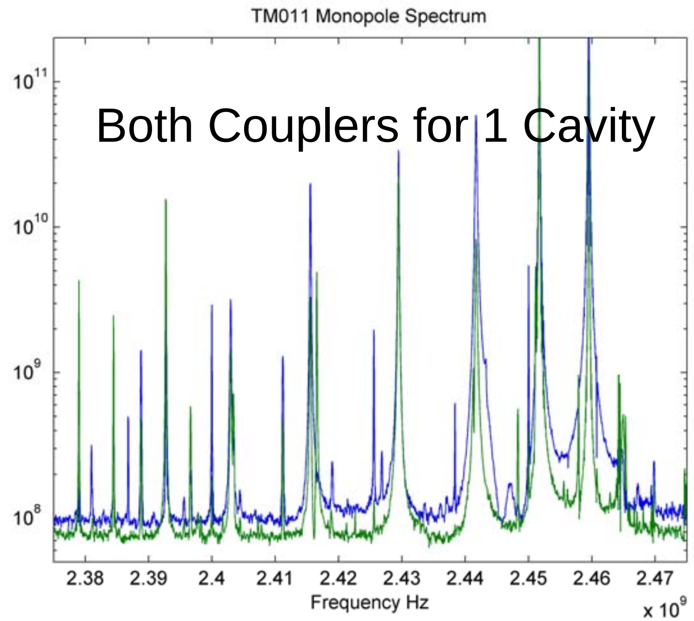
- **Code was implemented in the VME front-end to calculate the positions from the digitized HOM signals**
  - **Calibration constants are determined offline and loaded into front-end**
- **Positions are calculated for each module and reported back to the DOOCs control system in framework similar to other BPMs**
- **System is capable of both single bunch and multi-bunch**

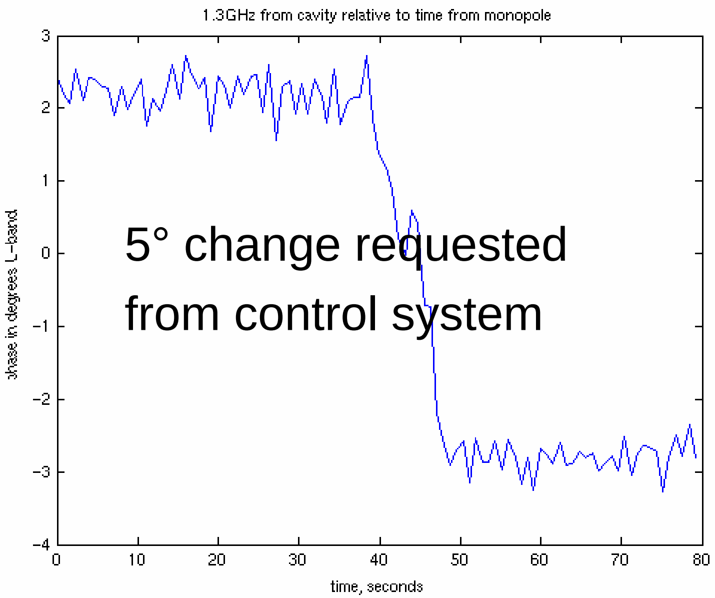
HOM Custom Digitizer

- Current online system has an I/O bottleneck in the VME front-end
  - Starts to miss beam pulses when more than a few cavities are enabled even with single bunch
  - Only gets worse for multi-bunch operation
- Can greatly increase the bandwidth of the system by calculating the mode amplitudes on the digitizer
  - Load mode vectors into FPGA and process in parallel
  - I/O still limiting factor but gain 4-5 orders of magnitude in BW
- Currently have design implemented in Proto-type board from FNAL
  - Expect to successfully test during next study period



Beam Phase Measurement

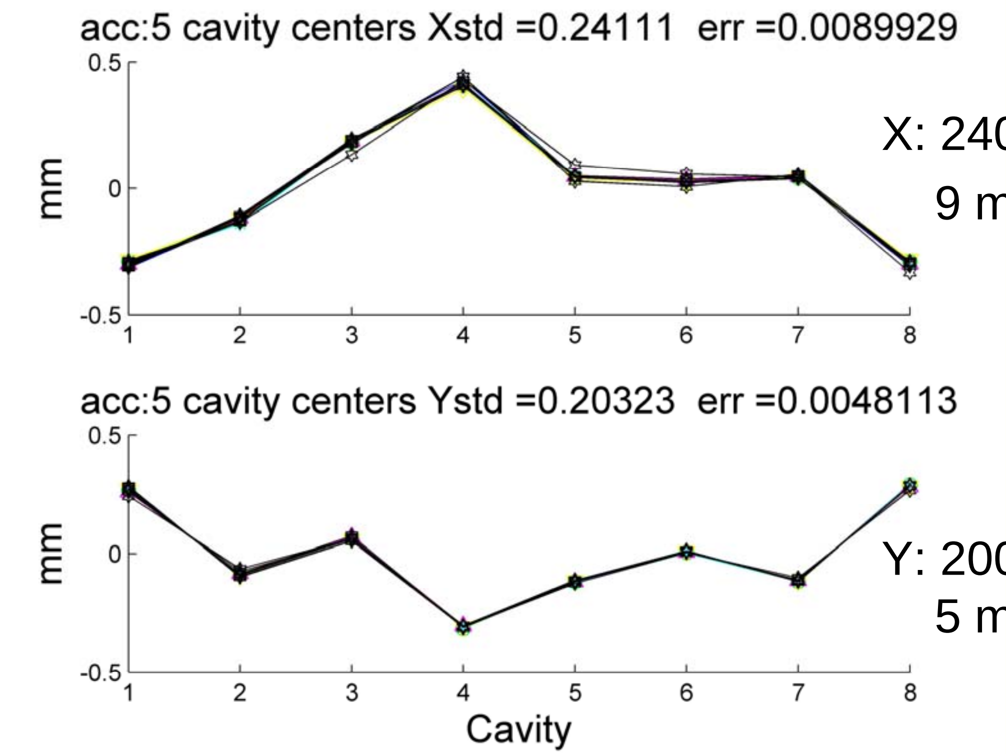




- **Able to directly measure the beam phase with respect to RF by determining beam time of arrival from monopole**
  - **The 1.3GHz drive signal leaks through the HOM coupler**
  - **Have monopole and RF signal on the same cable**
  - **Signals read out by Broadband scope system (8 bits, 10Gs/s)**
- **Initial results look very promising**
  - **Currently see about 0.1 degrees of RMS at L Band**
  - **The FLASH RF group is interested utilizing this system**

Cavity Alignment from HOMs

- **Measure the axis of a dipole mode for many cavities within a structure.**
  - **Gives in situ alignment data on the internals of the accelerating module.**

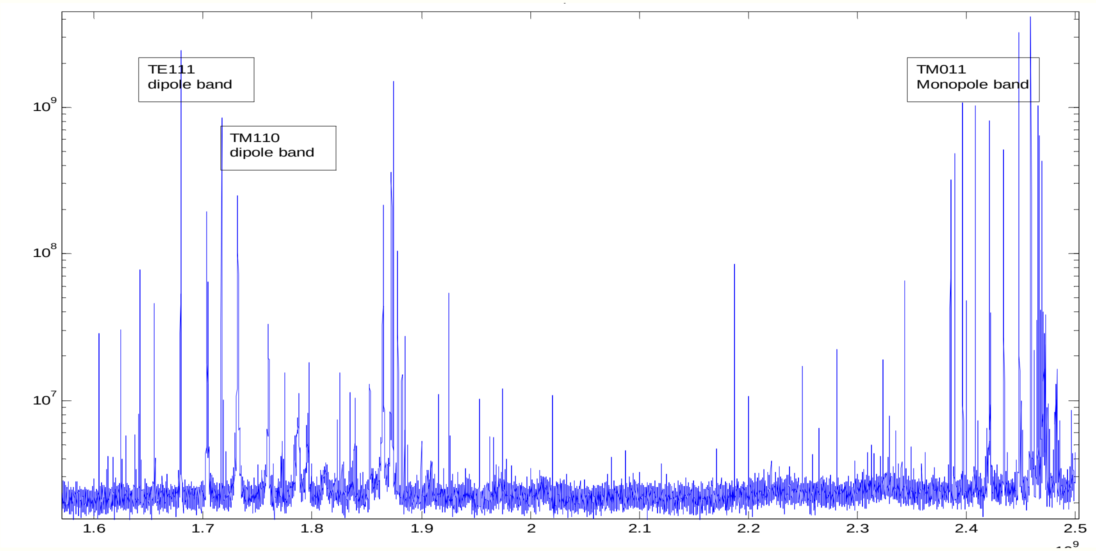


X: 240 micron misalignment
9 micron reproducibility

Y: 200 micron misalignment
5 micron reproducibility

HOMs as a Cavity Diagnostic

Raw HOM Spectrum



- **Many modes in the spectrum.**
  - **Monopole, dipole, quadrupole, etc.**
  - **Frequency, Q, R/Q, etc. dependent on cavity construction.**
- **HOM spectrum directly influenced by the internal cavity shape.**
  - **Effect of couplers can offset the modes from the cavity centre.**
  - **The low frequency HOMs studied here are not affected by the iris positions.**

Summary

- Testing and commissioning takes place during FLASH study periods
  - Typically 5-6 shifts over 2 weeks
  - Thanks to the FLASH operations team!
- Provide useful instrumentation for the FLASH operators
  - Studies suggest minimizing HOMs improves emittance
  - New online system provides better feedback for operators
  - Phase measurement may prove useful for RF stabilization
- Future studies
  - Improving calibration and resolution of narrowband system
  - Using broadband system to look at cavity distortions and predicted HOM spectrum from simulation, e.g. rotating dipole modes
- HOM Measurement Workshop was held at DESY in January
  - https://indico.desy.de/conferenceDisplay.py?confId=177