

# **High Precision SC Cavity Alignment Diagnostics with HOM Measurements**

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# HOMs in SC Accelerator Cavities

- In addition to the fundamental accelerating mode, SC cavities support a spectrum of higher order modes
- In accelerator physics HOM modes are generally considered a source of problems: Beam breakup, HOM heating, etc.

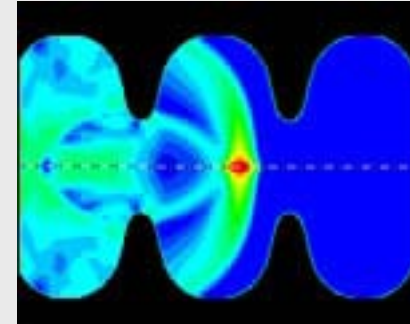


# HOMs for Diagnostics

- Here we attempt to harness the HOMs
  - Beam Diagnostics (position and phase)
  - Structure Diagnostics (cavity alignment)
  - Cavity diagnostics (cavity shape).

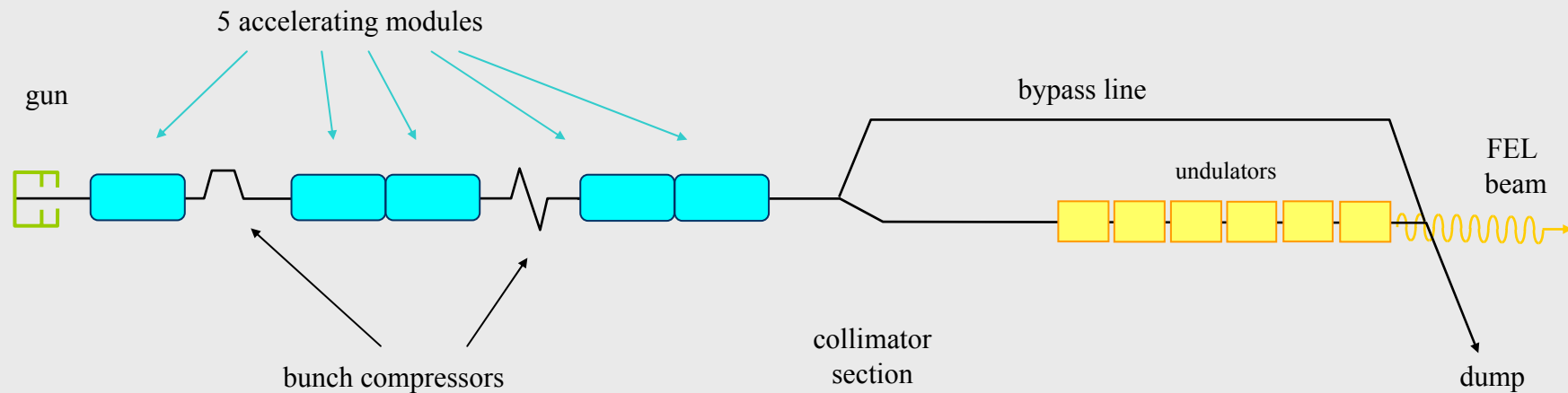


# Why Use HOM Modes



- Beam Diagnostics:
  - HOM Modes must be coupled, and signals brought out to room temperature for damping
    - Beam line and Cryogenic components already present
    - Electronics is low cost
  - Large fraction of the linac length is occupied by structures
  - Measures beam relative to structures: this may be an advantage or disadvantage
- Structure Diagnostics:
  - HOM modes measure interior of structure
  - **Disadvantages**
    - Low frequency HOM modes do not accurately measure Iris positions
    - HOM mode centers can be offset by couplers – not directly tied to cavity center (typically at 100 micron level).

# FLASH at DESY (formerly TTF2)



- 1.3GHz Superconducting Linac, Typically 450-700MeV, 1 nC charge
- 5 Accelerating Structures
  - Each structure contains 8 Cavities
    - Each cavity contains 9 cells
- Used for VUV-FEL, XFEL studies, ILC studies

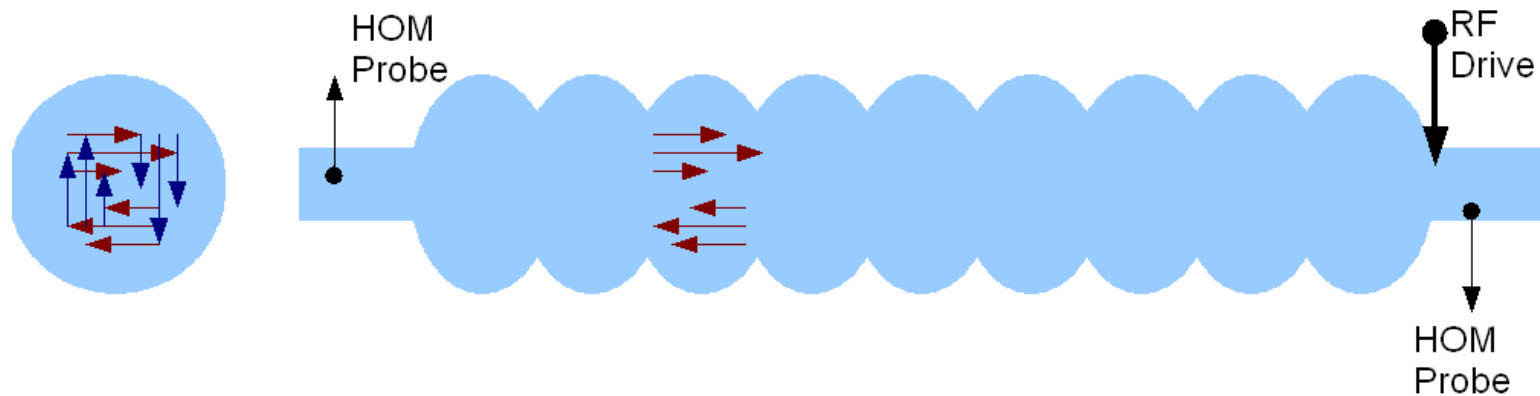
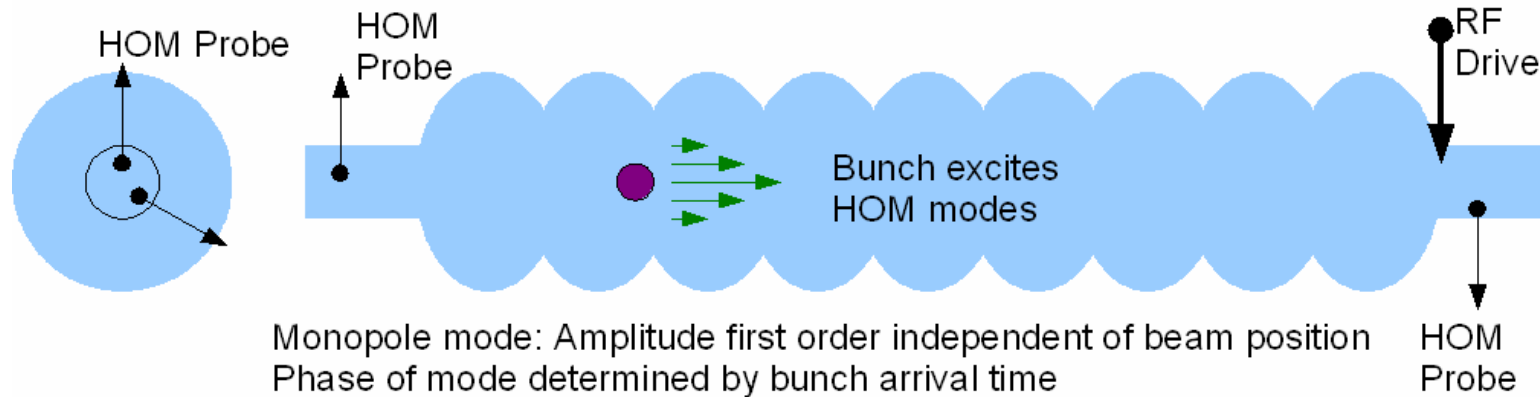
# HOM modes in the FLASH SC Structures

- Monopole, Dipole, and higher order bands
- Near speed of light modes have strongest coupling to beam.
- Frequencies from simulations in

R. Wanzenberg “Monopole, Dipole and Quadrupole Passbands of the TESLA 8-cell Cavity”, TESLA 2001-33.

- Monopole bands
  - 1.28 to 1.3 GHz
    - Includes accelerating mode at 1.3GHz (R/Q 511 Ohms)
    - Low R/Q for other modes
  - 2.38 – 2.45 GHz
    - Some modes with R/Q ~75 Ohms.
    - Used here for phase measurements
- Dipole Bands
  - 1.63-1.8 GHz
    - TE111-6, at 1.7GHz has strong coupling to beam
    - Used for beam position measurements
  - 1.84-1.89 GHz
    - 2 modes also have strong coupling to beam
    - Not currently used for position measurements, but available

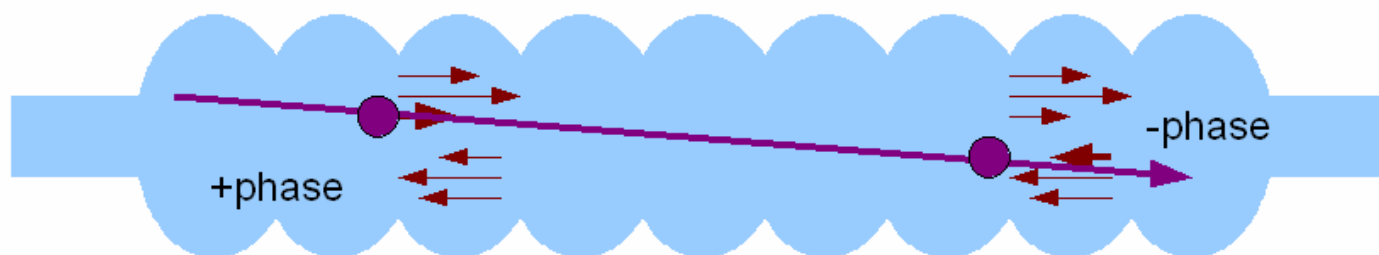
# Response of HOM modes to beam



If frequency splitting is  $<$  line width, Need both couplers to separate polarizations



Dipole mode: Amplitude proportional to bunch transverse position  
Phase determined by bunch arrival time for position offset



Beam at an angle will excite dipole mode with 90 degree phase shift  
relative to signal from position offset  
Amplitude proportional to angle X effective mode length (~ 1 Meter)



Tilted bunch will also excite signal at 90 degrees, amplitude proportional  
to bunch length and tilt: Not significant for short TTF bunches



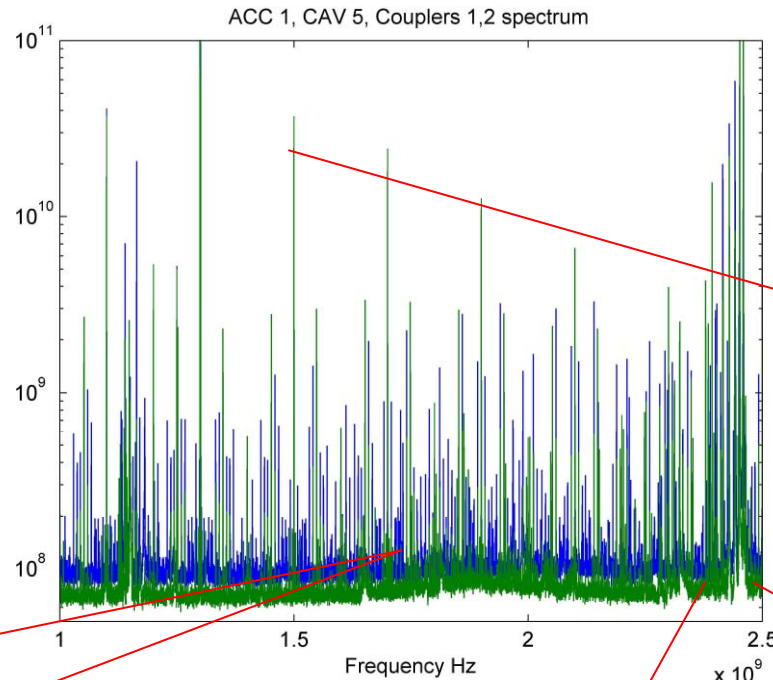
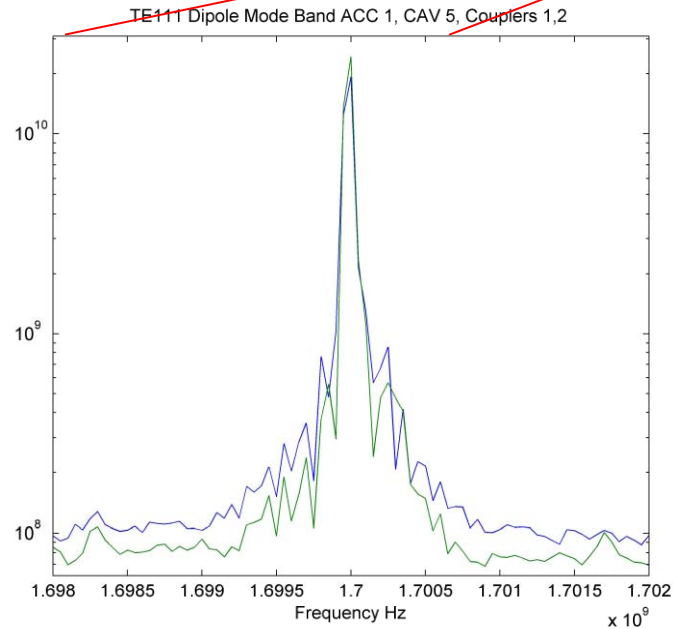
# HOM Measurement Systems: 2 Systems in Use

- **Broadband system**
  - 2.5 GHz bandwidth, 5 Gs/s 8 bit digitization, 4 simultaneous channels
  - Based on high bandwidth oscilloscopes
  - Used with 200MHz bandwidth filter for monopole measurements
- **Narrowband system**
  - 20MHz Bandwidth, 108Ms/s 14 bit digitization, 80 simultaneous channels
  - Frequency centered on TE<sub>111-6</sub> mode (1.7 GHz)
  - Based on frequency down conversion electronics
  - Used for dipole mode measurements

# HOM Signals

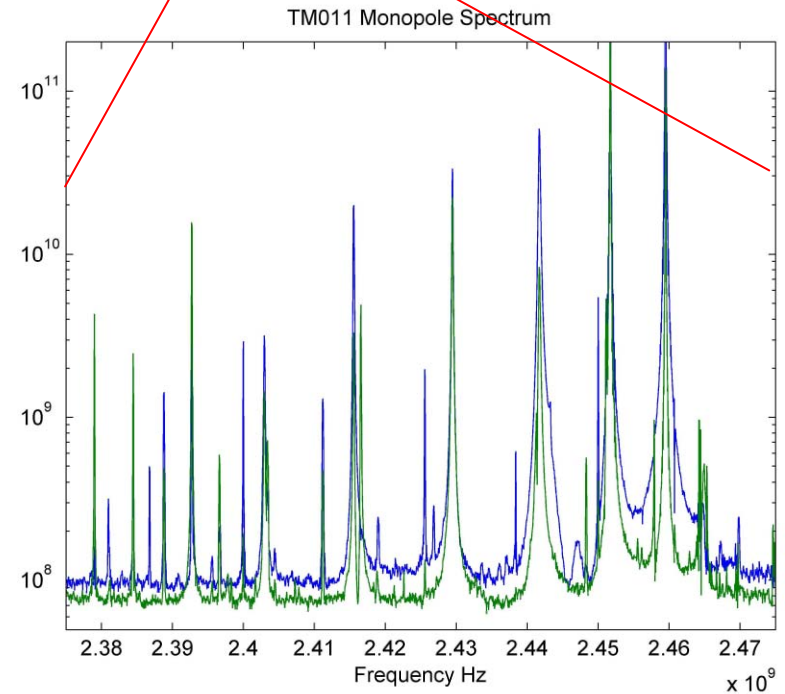
**Broadband system  
data**

Dipole Mode 1.7GHz  
4 MHz frequency  
span shown



Note spurious lines  
Data acquisition system

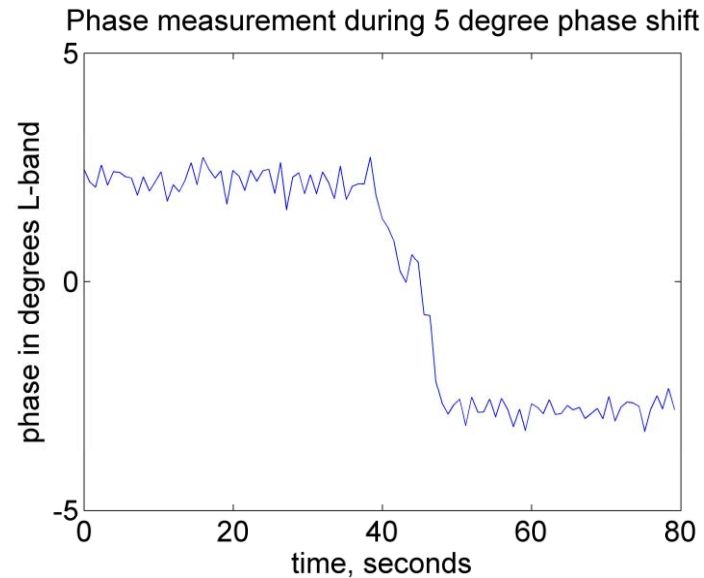
Monopole Modes  
100 MHz frequency  
span shown



# Monopole Modes for Beam Phase Measurement

- For FELs and for the Linear Collider beam phase relative to RF is important at the  $< 0.1$  degree L-band ( $< 200$  femtosecond level)
- Monopole HOM mode phase determined by beam arrival time
- HOM couplers measure both HOM and fundamental RF fields in cavity
  - High power accelerating fields blocked by superconducting filter, but significant power leaks through
- Can use same coupler, cable, and electronics to measure accelerator RF and HOM modes
- Allows low drift measurement of beam vs. RF phase.

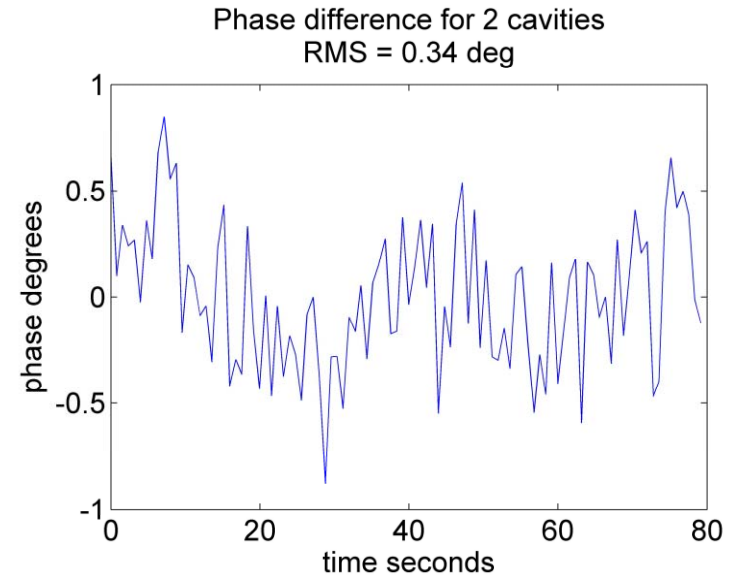
# Phase Measurement Results



RF Phase measurement over 80 seconds

5 degree L-band phase measurement commanded by RF system

Measured phase shift 5 degrees



Comparison of phases for 2 cavities during measurement

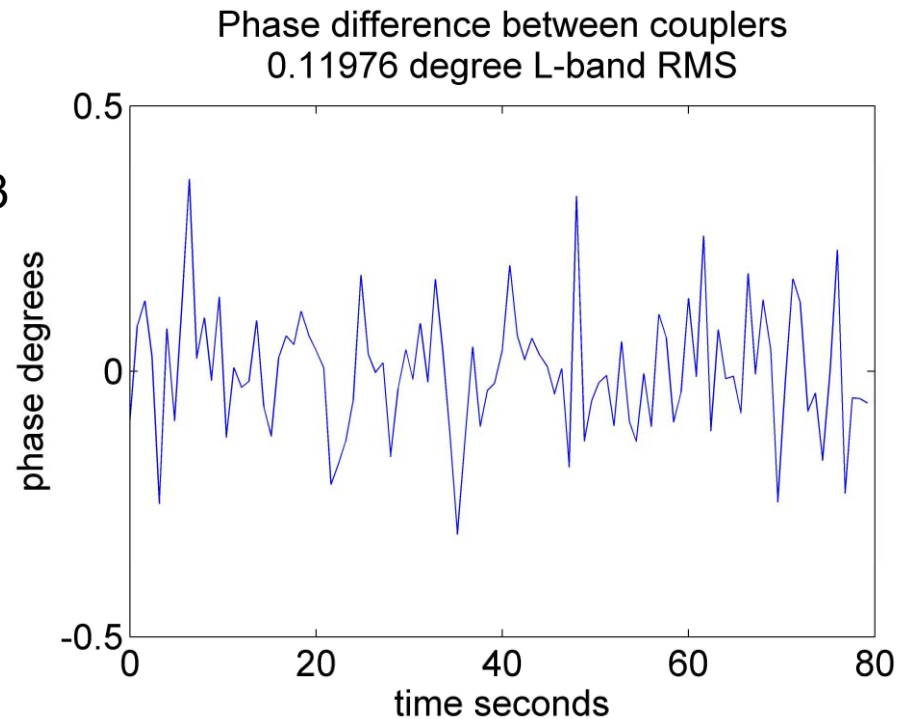
RMS difference 0.34 degrees L-band

# Phase Measurement Noise

- Measured difference between 2 couplers 0.12 degrees L-band (corresponds to 0.08 deg RMS / measurement)

Coupler to coupler measurement error  
~ 0.12 degrees consistently smaller  
than cavity to cavity measurement ~0.3  
degrees

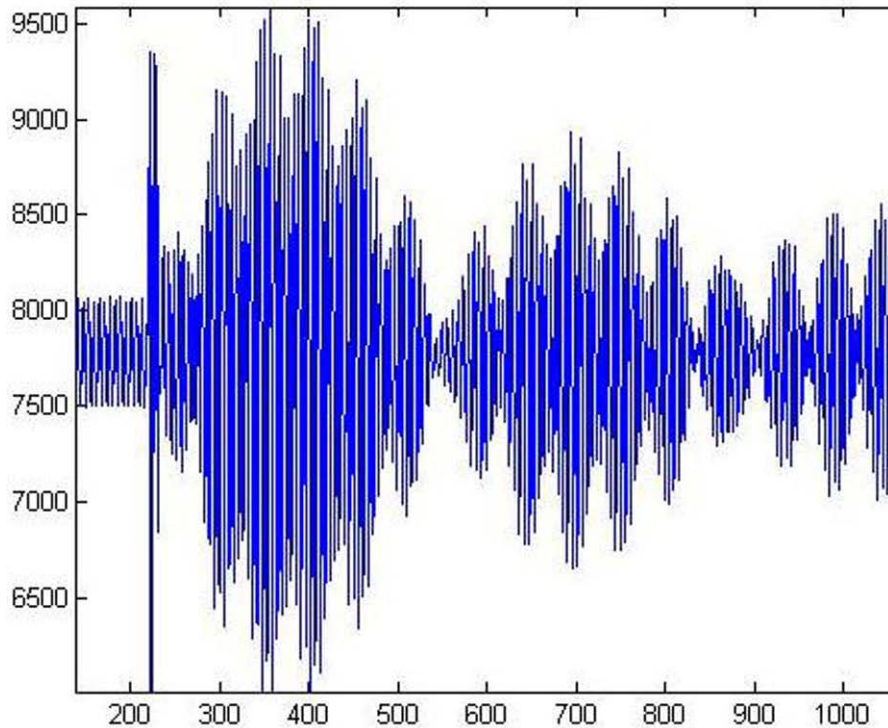
Possibly due to cavity microphonics?



# HOMs for Beam Position Measurement

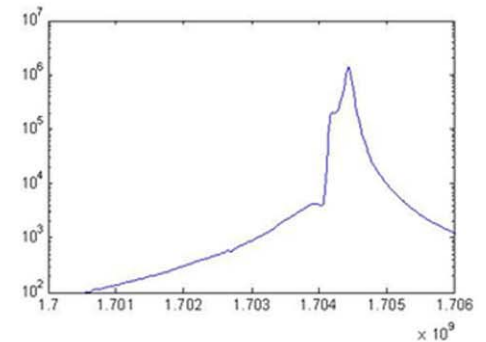
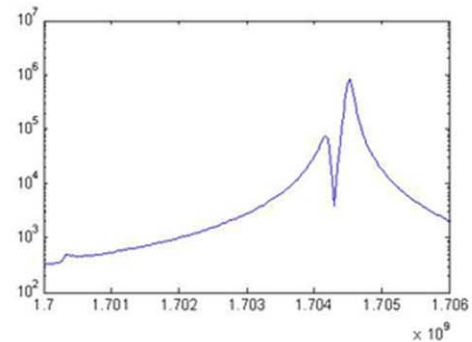
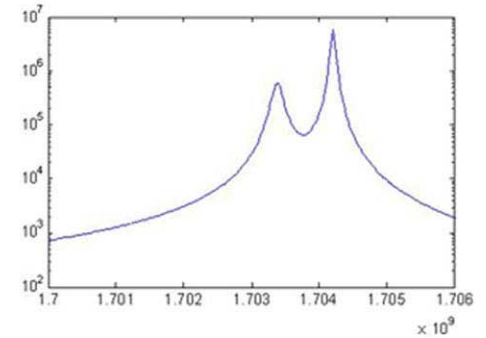
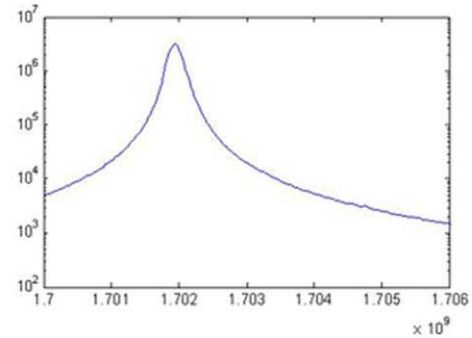
- Micron level beam position measurement required in ILC linac and FELs.
- Can use HOM dipole modes in accelerator cavities
  - Accelerator cavities comprise most of the linac length
  - Dipole mode amplitudes directly related to long range wake fields
  - **Not obvious how to reference position to quadrupoles**
- Experiments done with narrowband system, looking at TE<sub>111-6</sub> mode (1.7 GHz)
- Experiments done with single bunch beam – will extend to multi-bunch for future run.

# HOM Dipole Mode Signals



Raw HOM signal (band pass filtered at 1.7GHz)

Beat is from two mode polarizations



Mode separation varies between cavities.

So far unsuccessful at finding separate mode frequencies

# Singular Value Decomposition (SVD) to Find Modes

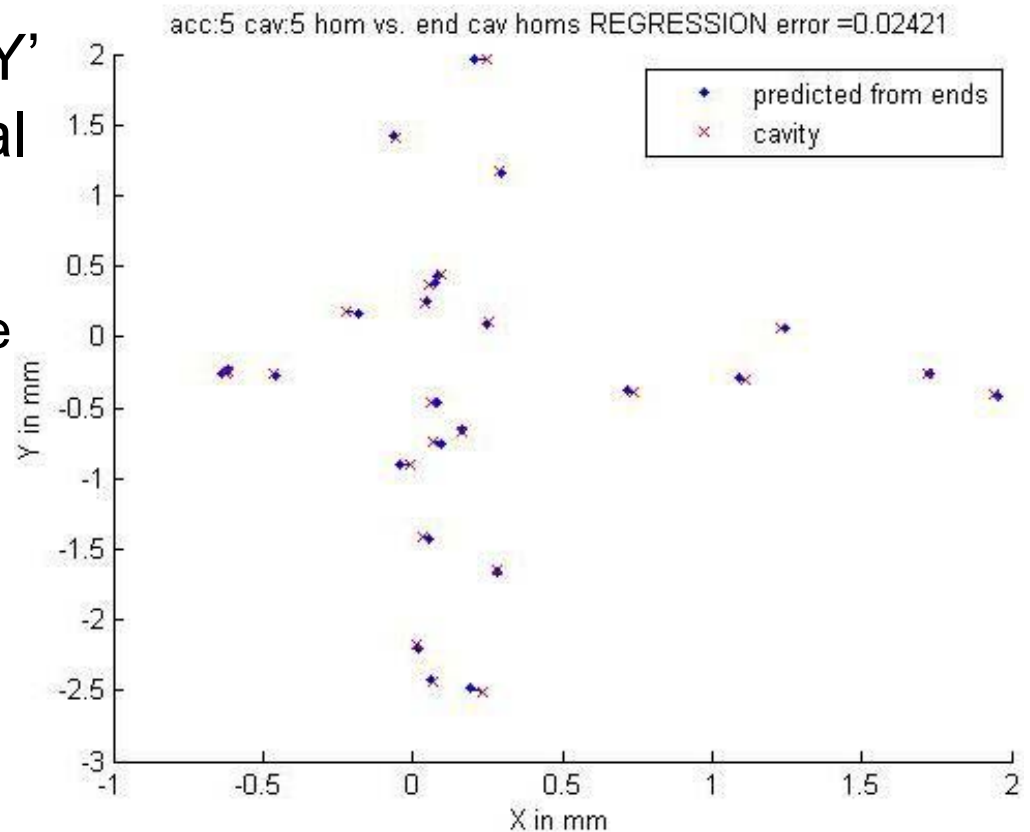
- Collect HOM data for series of machine pulses with varying beam orbits
- Use SVD to find an orthonormal basis set.
  - Select 6 largest amplitude modes\*
  - Calculate mode amplitudes
- Linear regression to find matrices to correlate beam orbit ( $X, X', Y, Y'$ ), and mode amplitudes
- Use SVD modes and amplitudes to measure position on subsequent pulses

\* 8 modes used for some tests



# Position Measurement

- Beam steering in X,Y,X',Y'
- Electronics with additional 10dB attenuation
  - Increase dynamic range
  - Reduce chance of damage from breakdowns
- 5mm steering Range
- RMS (circular error) 24 microns



# Theoretical Resolution Limit

TE111 - 6 calculated  $(R/Q) = 5.5\Omega / cm^2$

$$\text{deposited energy } U = \left(\frac{R}{Q}\right) \frac{\omega}{2} q^2$$

$$\text{Minimum detectable energy } U_{th} = \frac{1}{2} k_b t$$

Where  $t$  is the detection electronics temperature  
assumed to be 300K

Corresponds to 3 nanometers RMS for a 1nC (typical)  
bunch charge

Angle resolution proportional to effective length of  
mode  $\sim 1$  Meter

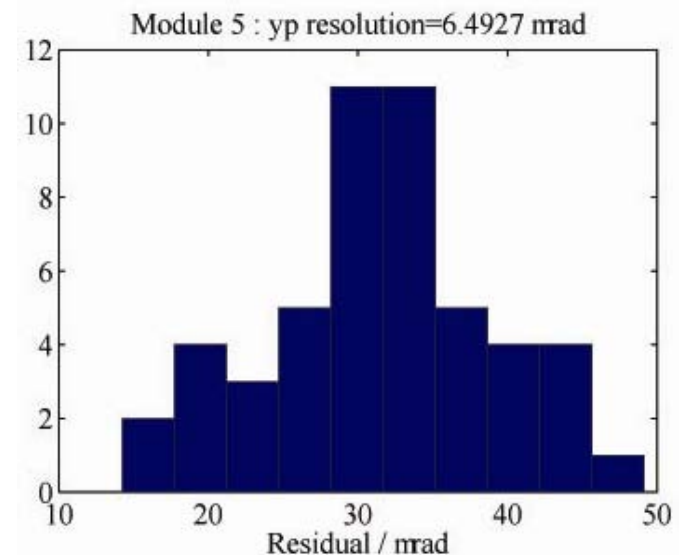
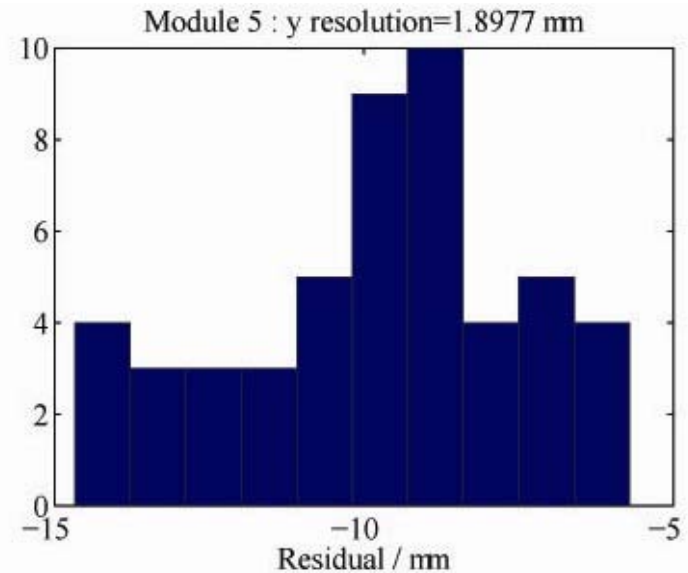
# Realistic Resolution – TTF2

- Cable losses to electronics: 10dB
  - 9 nm
- Electronics noise figure 6.5dB (measured)
  - 18 nm
- External 10dB attenuators (used to increase dynamic range, may not be necessary)
  - 60 nm
- Non-ideal algorithm: This has not been studied.

**Expect resolution < 100nm**

# Measured Resolution

- Best measured resolution was 1.5 microns, and 5 micro-radians.
  - Compare positions measured with 3 neighboring cavities
- Resolution believed to be limited by:
  - Noisy Local Oscillator electronics
  - Charge normalization
- Both problems amenable to straightforward electronics improvements.

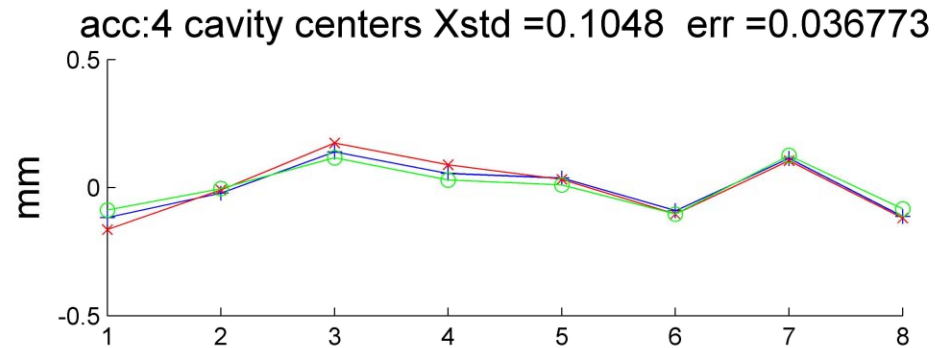


# Cavity Alignment Within a Structure

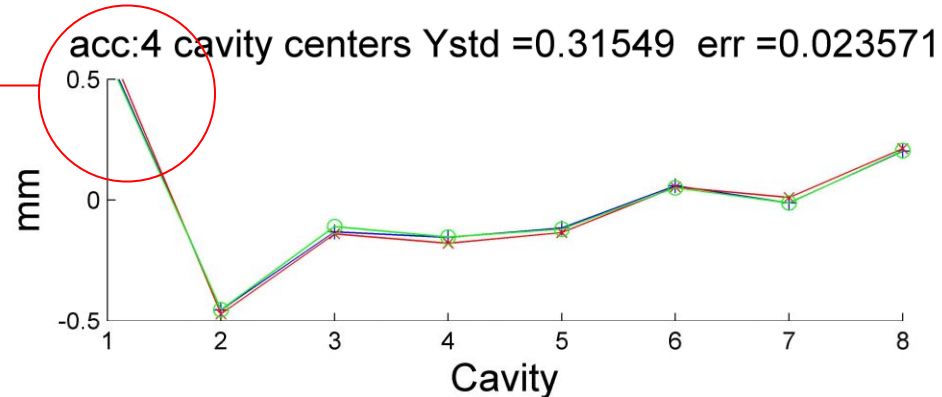
- Find correlation between HOM mode amplitudes and position (from conventional BPMs).
- Calculate position corresponding to minimum HOM power in cavity
- Ideally would like to find position AND angle corresponding to minimum HOM power for each cavity
  - Beam position / angle scans did not cover full range – will fix in future run
- Plot position for minimum HOM power for multiple data runs

# Cavity Alignment ACC4

- X: 100 microns RMS misalignment, 37 micron measurement reproducibility
- Y: 215 micron RMS misalignment, 23 micron measurement reproducibility

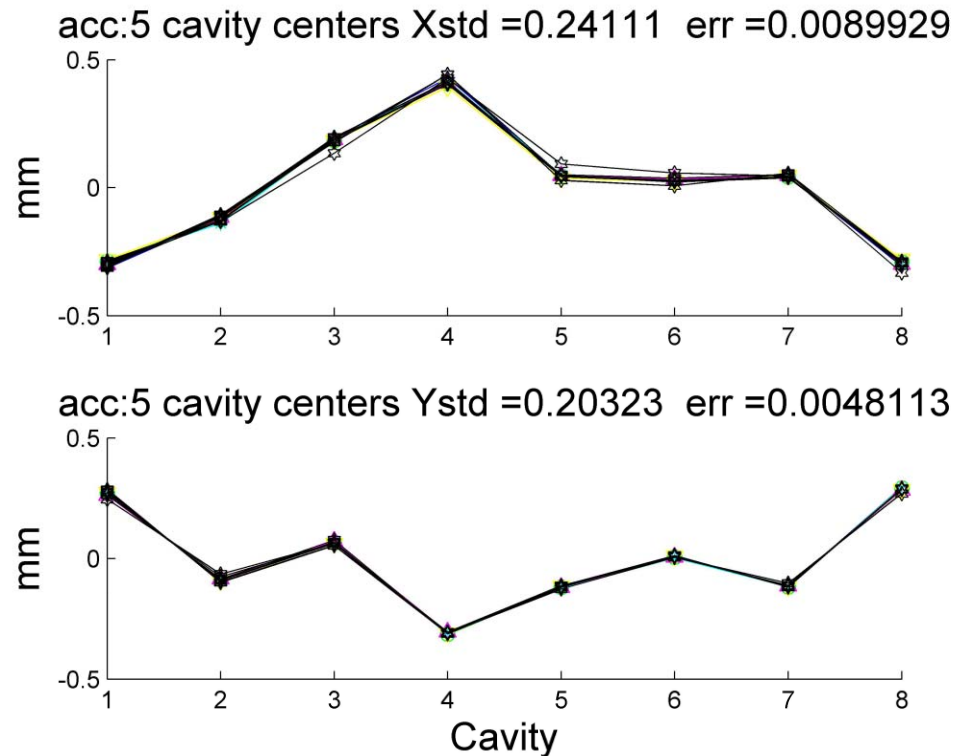


Is this real?



# Cavity Alignment ACC5

- X: 240 micron misalignment, 9 micron reproducibility
- Y: 200 micron misalignment, 5 micron reproducibility

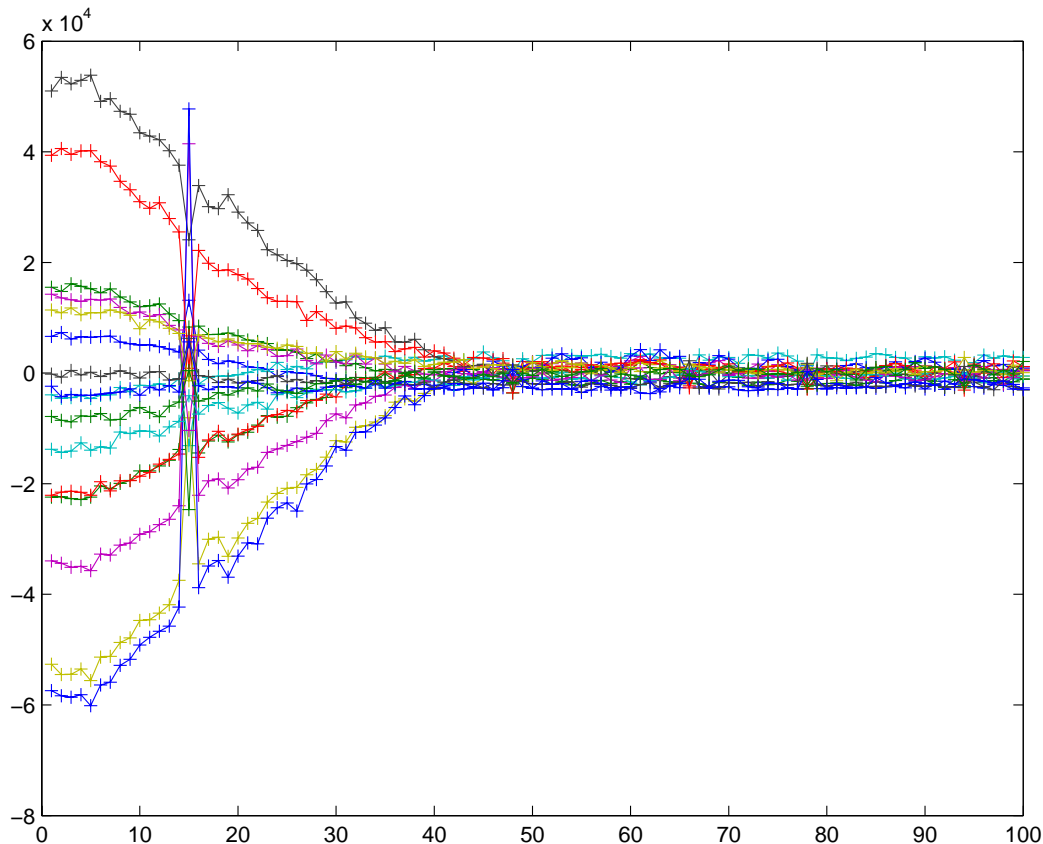


# HOM based Feedback

- Feedback to minimize HOM mode power in first structure at TTF (linear algorithm)

Plot of HOM mode amplitudes for 100 machine cycles after feedback is turned on

Earlier version of data acquisition system used.





# Multi-Bunch Operation (Future)

- For low repetition rate machines (bunch rate comparable to HOM mode decay time)
  - System is linear
  - Data acquisition system can be synchronous with bunch rate
  - Possible to de-convolve signal to get single bunch response
    - Measure single bunch response
    - Subtract signals from previous bunches to measure beam on each bunch.
  - Will test at DESY FLASH.
  - Should work for XFEL and ILC.
- For high repetition rate (near CW) machines
  - Need signal at HOM frequency
  - In principal can slightly modulate beam intensity at HOM frequency
  - Needs more study

# Cavity Diagnostics (Future)

- Using broadband system can measure HOM mode amplitudes and phases as a function of beam orbit for all cavities in a structure
- Cavity shape diagnostic
- Measure relative centers of Dipole (and possibly Quadrupole) HOMs
- Possibly measure Lorentz force detuning in high gradient structures
  - Could this be a problem for HOM measurements?

# Summary

- Demonstrated
  - Beam phase vs. main RF phase measurement at the  $<0.1$  degree level
  - Beam position with 1.5 micron, 5 micro-radian resolution
    - Expect significant improvement with upgraded local oscillator source
  - Cavity alignment measurement with  $\sim 10$  micron reproducibility
  - HOM based feedback to minimize dipole HOM power
- Future
  - Multi-bunch operation
  - Cavity diagnostics