Using HOM Signals for Measuring Cavity Alignment and Beam Position

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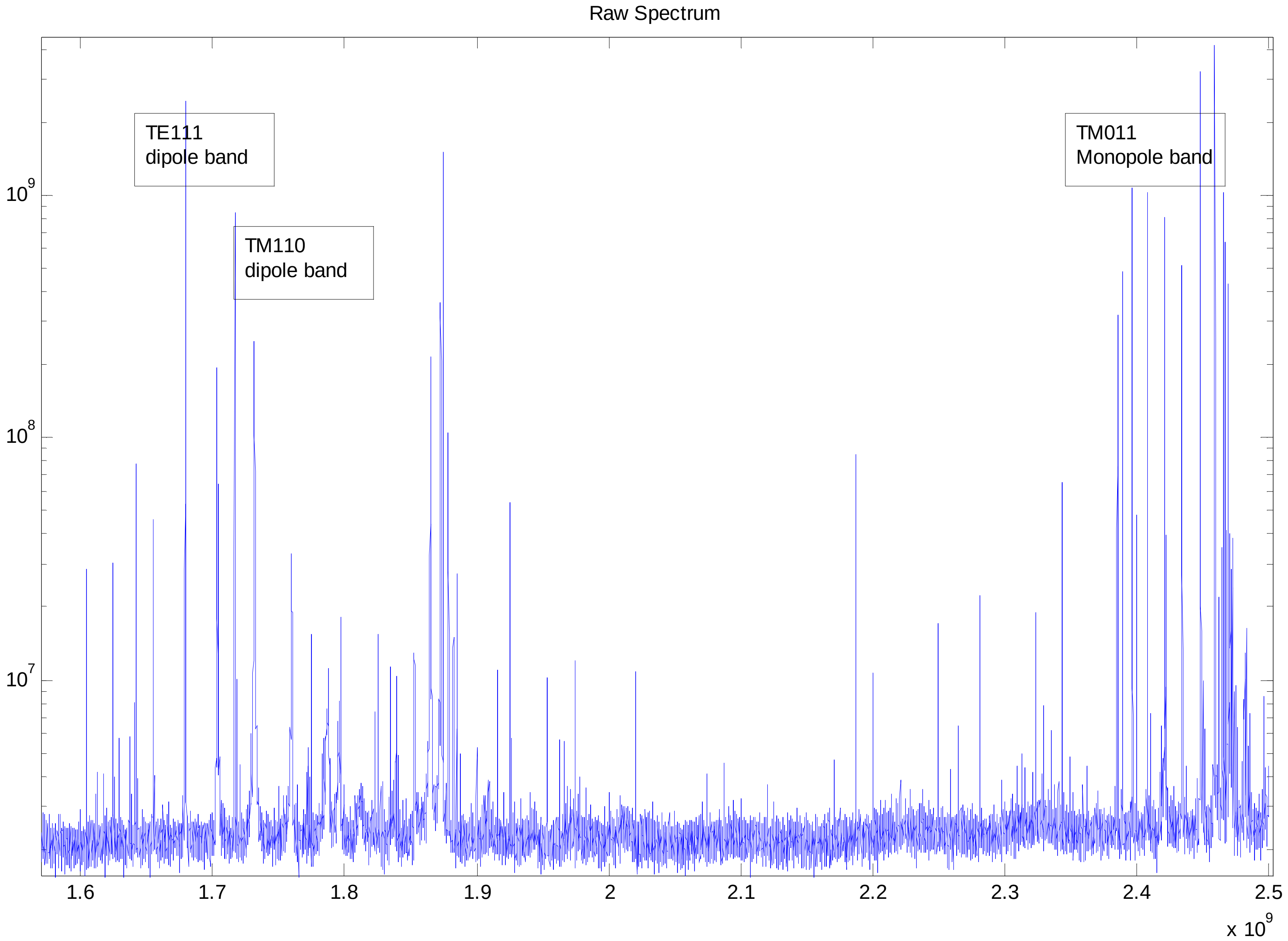
Why HOMs

- HOM signals depend directly on cavity geometry
    - Of course Interpretation can be tricky
- HOM port signals must be brought to room temperature for damping -> No new beamline hardware
- Decode electronics low cost
    – Simple down-mix and digitize

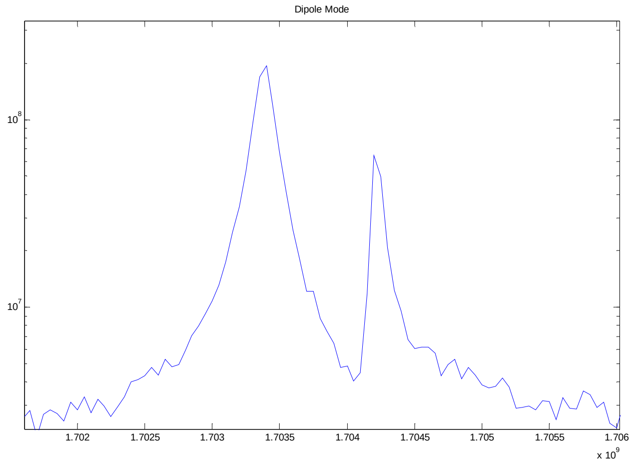
Sample HOM spectrum



Analysis Methods?

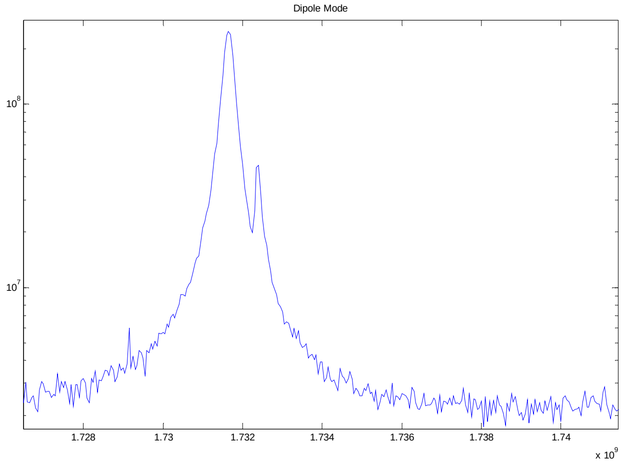
- Want to find the HOM mode amplitudes (complex) produced by bunch passage
- Most straightforward method is to directly measure phase and amplitude at “known” HOM frequencies .
- Problem is that frequencies are difficult to measure to the required accuracy (fraction of a line width).
- HOM dipole modes provide beam position realitve to cavity information. Each mode has 2 polarizations with frequencies split by cavity geometry imperfections
- Difficult to measure mode frequencies for “nearly” degenerate modes.
- Should be solvable – but so far no luck .

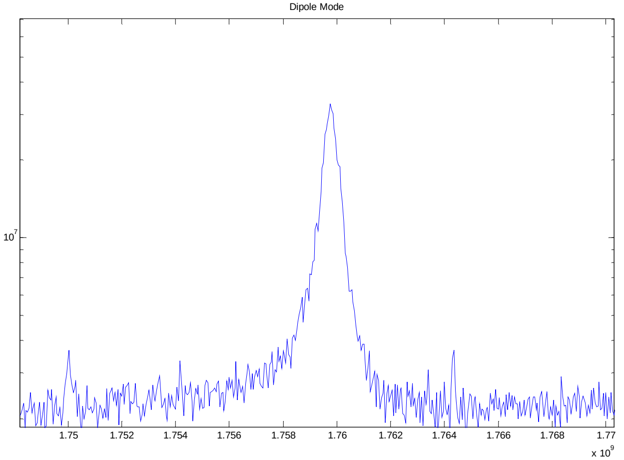
Partially Degenerate Modes



Dipole modes vary from nearly Completely separate, to indistinguishable

Difficult to fit to peaks to identify frequencies





SVD – Basic Idea

- Mathematical technique to find repetitive patterns (normal modes) in a series of data sets.
  - Example: Data consisting of a fixed frequency sine wave of random frequency: Would find 2 sine like modes with 90 degree phase difference.
- As many modes as there are data points
  - Usually only largest few are used (in our case 6). Smaller amplitude modes just represent noise
- Can then find the amplitude of these modes in any data set.

SVD Singular Value Decomposition

- Apply to a series of waveforms
  - Example is 100 acquisitions, 4,000 points each
- SVD finds matrices U,S, and V so that X = USV' with U,V unitary, S diagonal.
  - V is a matrix of the normal modes of the waveforms.
  - U (not used in this analysis), is a matrix of the normal modes with time
  - The diagonal elements of S are the Eignevalues (the contribution of each mode in V).
- Can then multiply new data by these vectors to find amplitudes of these modes. A = VX
  - C = cycle
  - M = mode
  - P = datapoint

$$X = \begin{matrix} x_{1,1} & x_{1,2} & x_{1,p} & x_{1,4000} \\ x_{2,1} & \cdots & \cdots & \cdots \\ x_{c,1} & \cdots & \cdots & \cdots \\ x_{100,1} & \cdots & \cdots & x_{100,4000} \end{matrix}$$

$$X = USV'$$

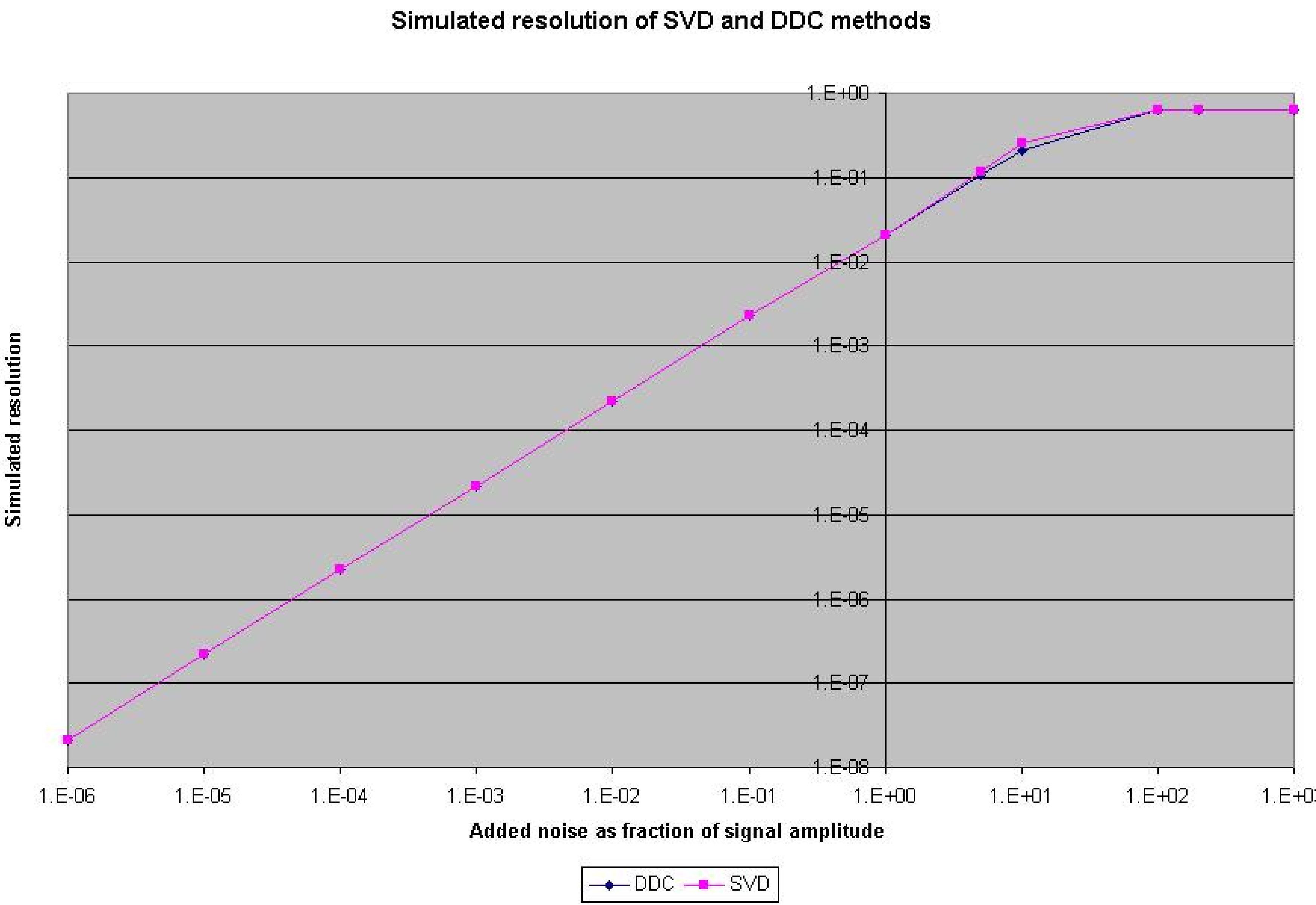
$$V = \begin{matrix} Mode\_1_1 & Mode\_2_1 & Mode\_m_1 & Mode\_100_1 \\ Mode\_1_2 & \cdots & \cdots & \cdots \\ Mode\_1_p & \cdots & \cdots & \cdots \\ Mode\_1_{4000} & \cdots & \cdots & Mode\_100_{4000} \end{matrix}$$

$$A = XV$$

$$A_{c,m} = \sum_p X_{c,p} V_{p,m}$$

SVD vs. Using Known Mode Frequencies

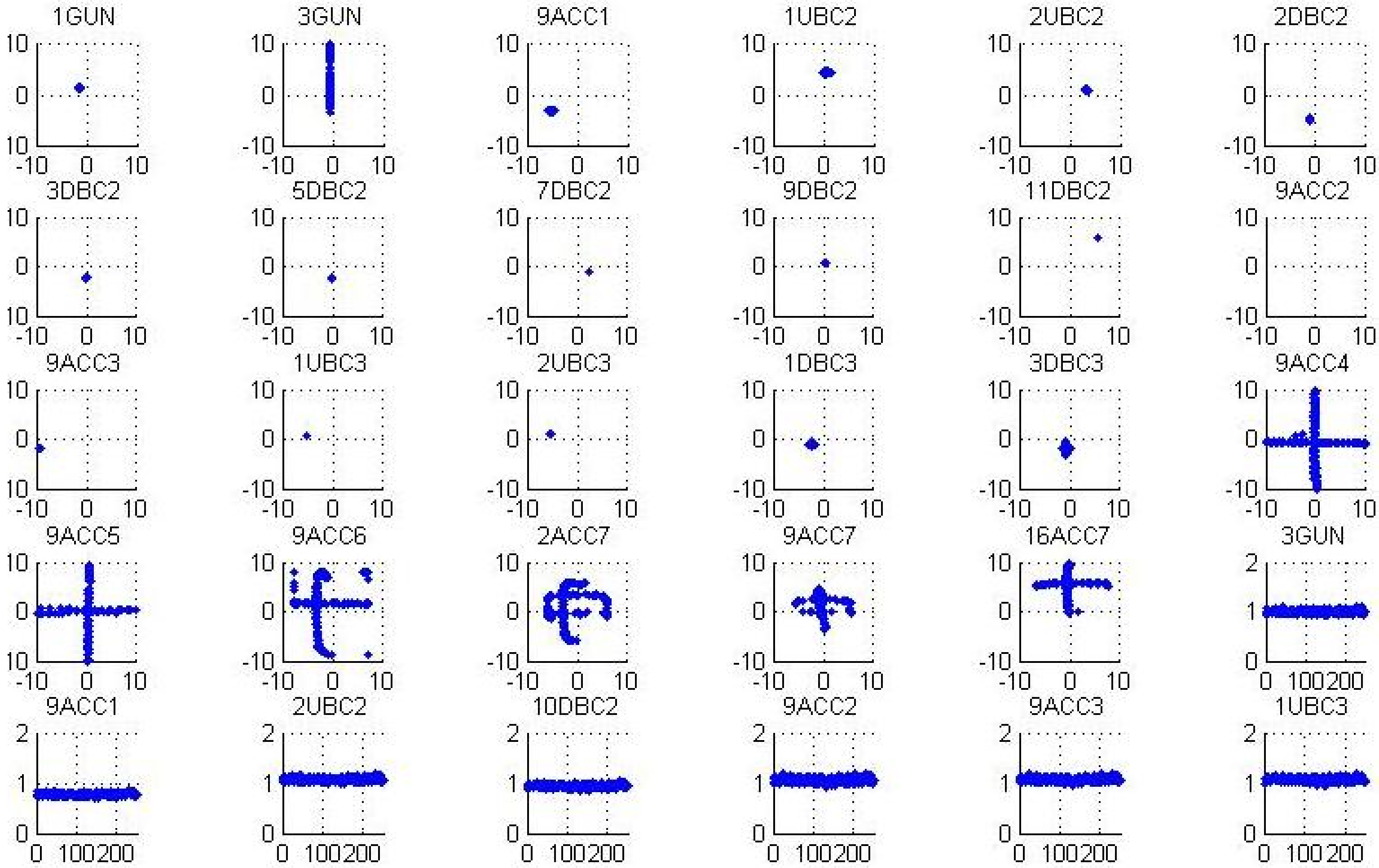
- Simple example: single sine-wave mode
- Data with random noise
- Compare measured amplitude resolution using known frequencies (DDC = Digital Down Conversion) with SVD
- For noise < 10% of signal amplitude, for this set of parameters, no significant difference.


Simulated resolution of SVD and DDC methods
Simulated resolution
Added noise as fraction of signal amplitude
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
DDC
SVD

Experiment

- Data from March 2006 experiment
- Single bunch 0.5 to 1 x 10^{10} electrons
- Beam steered at different locations to provide calibration for all structures.
- HOM modes measured with 10dB attenuators in inputs
  - Increase dynamic range
  - Reduce possibility of electronics damage from breakdown
  - Expect this to degrade resolution by approximately X3
- Very large beam steering used to ensure that the centers of all structures could be found.
  - HOM signals saturated on many pulses

Beam steering for ACC4 (TTF BPMs)

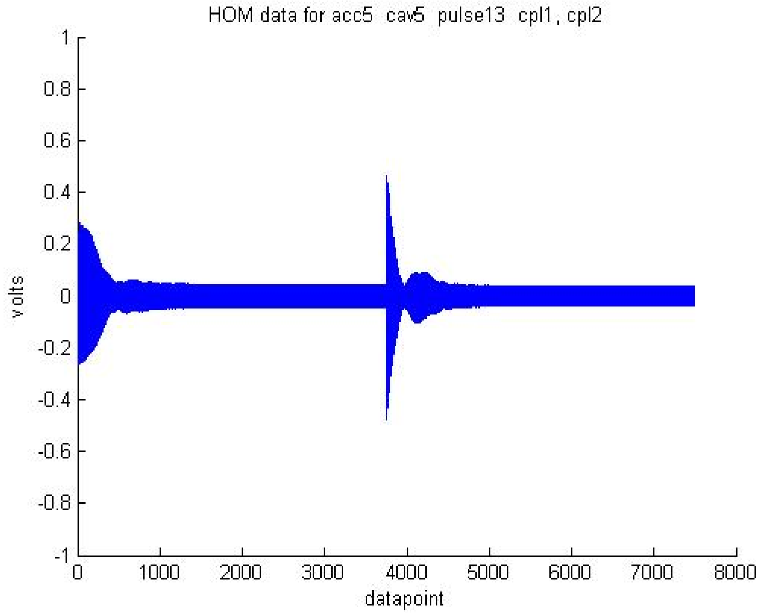


BPM Data – Selection and Cuts

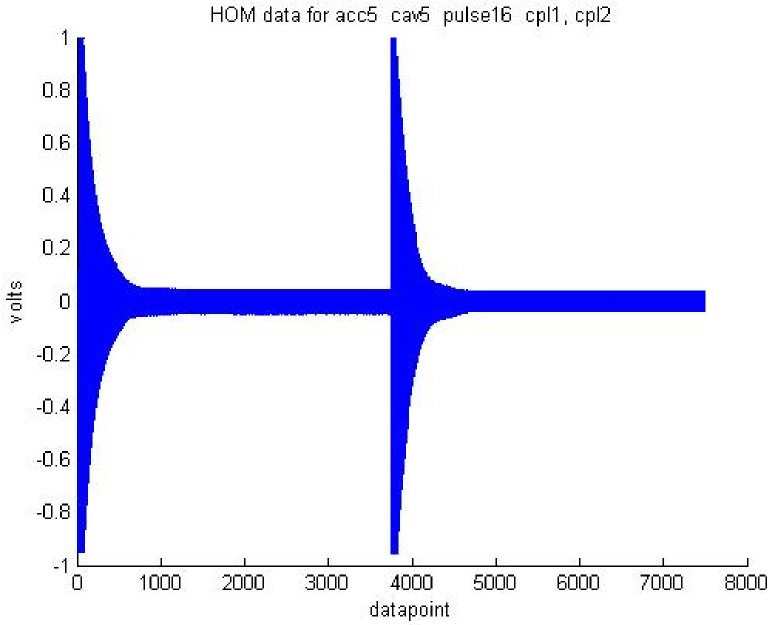
- Choose BPMs immediately upstream and downstream of cavities.
- Choose Toroid nearest cavity
  - Note: due to the way toroids are listed in the data base, in some cases BPM currents rather than real toroids were used. This may have degraded the measured resolution.
- Cut data (Independent for each structure):
  - BPM position outside +/- 5mm
  - BPM position < 5 microns (zero output)
  - Toroid current < 0.4
  - Toroid current different from median by 5%

HOM Data

- Electronics uses TE111-6 mode
- Downmixed with 1679 MHz LO (nominal 20MHz IF), Digitized with 14 bit, at 108MHz
- Look at data points 250-4000
  - Many pulses saturated ,so look late in waveform
- Data cuts
  - Done per cavity
  - Cut on saturated pulses (within analysis window) -> degrades resolution
- Note, Calibration tone at 1.7GHz included in data. This tone is designed to measure the phase and gain drifts of the electronics.



run



Data Issues

- 39 Files, (2.7GB) data analyzed.
  - Requires ~1/2 hour on fast PC for calibration (dominated by SVD).
  - After calibration ,analysis of pulses is fast
    - Just multiply / add for each point
- Approximately 4000 machine cycles analyzed.
  - Generate ~ 5 graphs / cycle,
  - Not practical to look at data by hand
  - Need automated data cuts, etc.

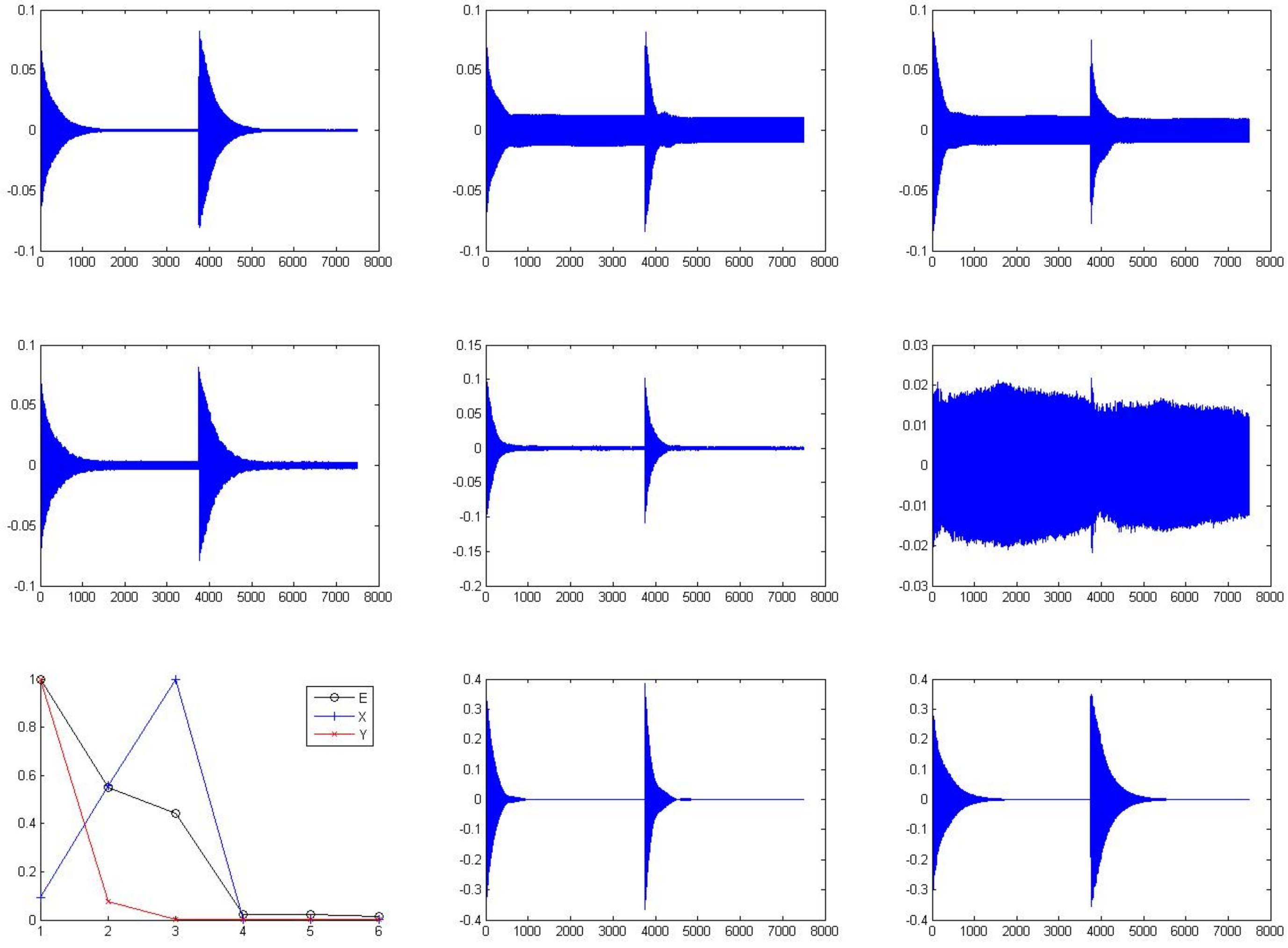
Analysis - Overall

- For each data set
  - SVD to find normal modes (6 used)
  - Find mode amplitudes
  - BPMs used with “straight line” optics to find beam position at cavity
  - Linear Regression to correlate BPM positions with HOM amplitudes.
  - Find X,Y position at cavities corresponding to minimum HOM mode power.
- For all data sets
  - Calculate figure of merit based on steering range and fit error.
  - For each cavity, use normal modes and regression coefficients from that cavity’s “best” data set.
  - Calculate positions for other data sets using normal modes and coefficients from “best” data set
- Check calibration
  - Compare conventional BPMs with positions from global calibration
  - Compare position measured by end cavities with position from middle cavities
    - Using “best” modes, and coefficients, and know cavity locations
    - Using “best” modes, and regression from end cavities to middle cavity

SVD

- Use Matlab SVDS function
  - Produces specified number of largest modes
  - Typically use 6 modes.
- Note that the modes found by SVD are linear combinations of the “physically intuitive” modes.
- Plot Eigenvalues
- Plot contribution of modes to X and Y
  - After Linear Regression against BPMs (discussed later)
- 1.7GHz calibration tone included in data
  - Note that tone appears in SVD modes, but contribution is canceled in the linear combinations corresponding to X and Y (as expected).

Modes (ACC5, CAV5)

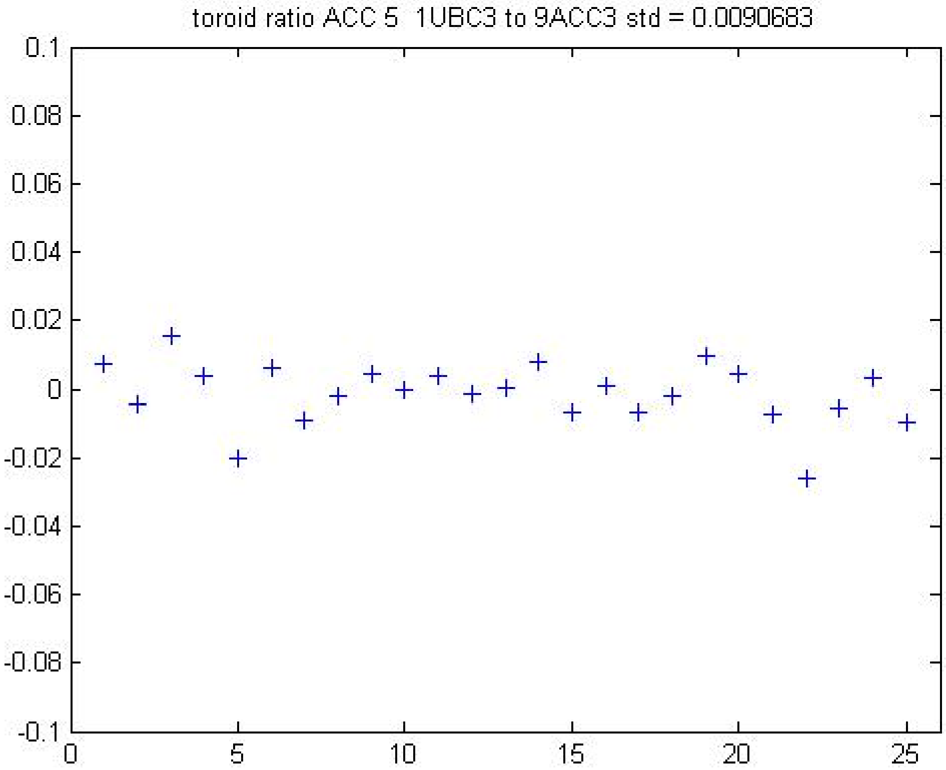


Linear Regression to Modes

- Find mode amplitudes
  - Take “modes” and multiply by data, then integrate
- Divide mode amplitudes by toroid measurement
  - Note, since we are often working at bpm offsets of several millimeters, this corresponds to a requirement of <1% measurement noise for 10 microns, 0.1% for 1 micron.
- Use BPMs closest to the structure to find the beam position within each cavity.
  - Use straight line between BPMs and linear interpolation
  - Future – need to correct for BPM rotation and offsets

Toroid correlation

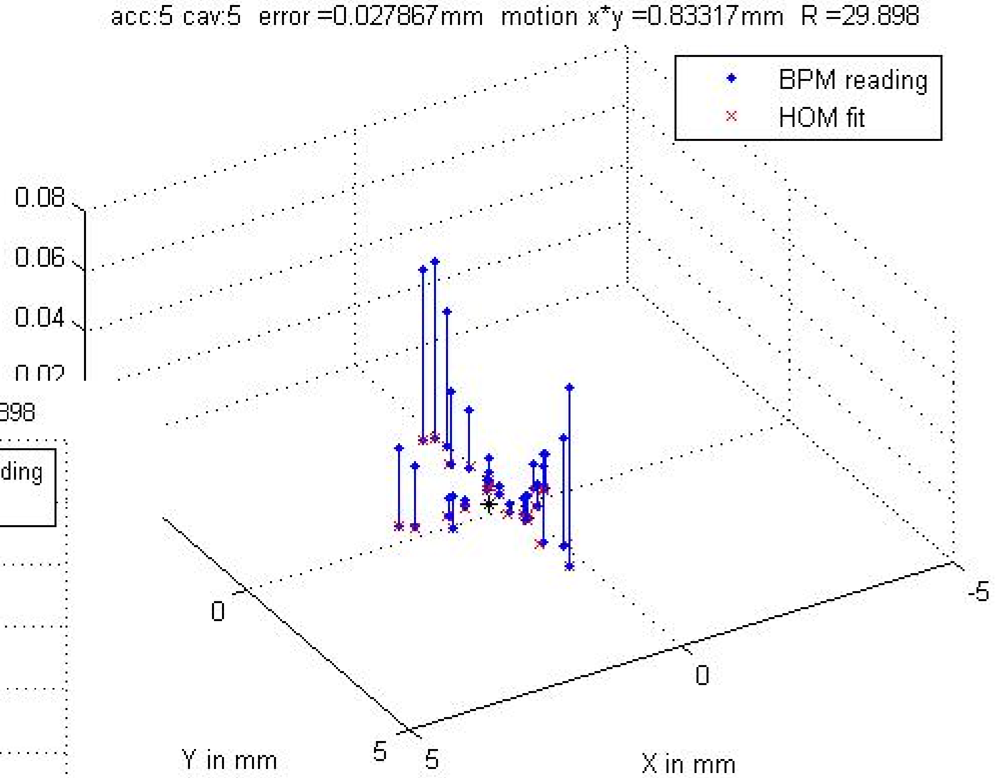
(Note, this is actually BPM sum signal)

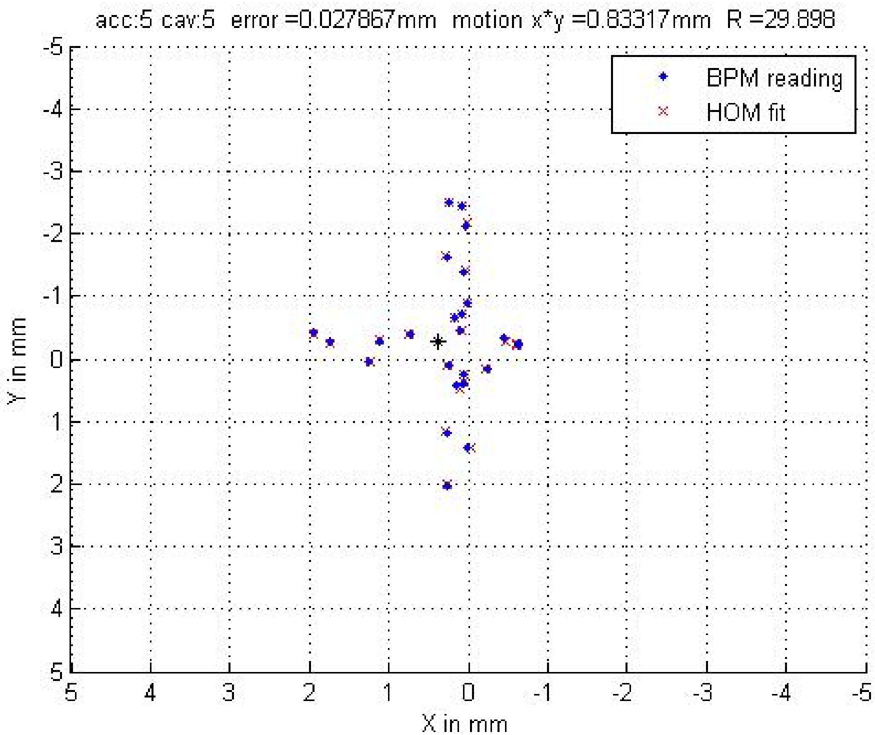


Noise of ~ 1% RMS would correspond to ~10 micron noise on the measured position

Single Cavity ACC5, CAV5, 2006-03-06T062359.mat

27 micron RMS (2-d) error





Total RMS power shown on Vertical scale

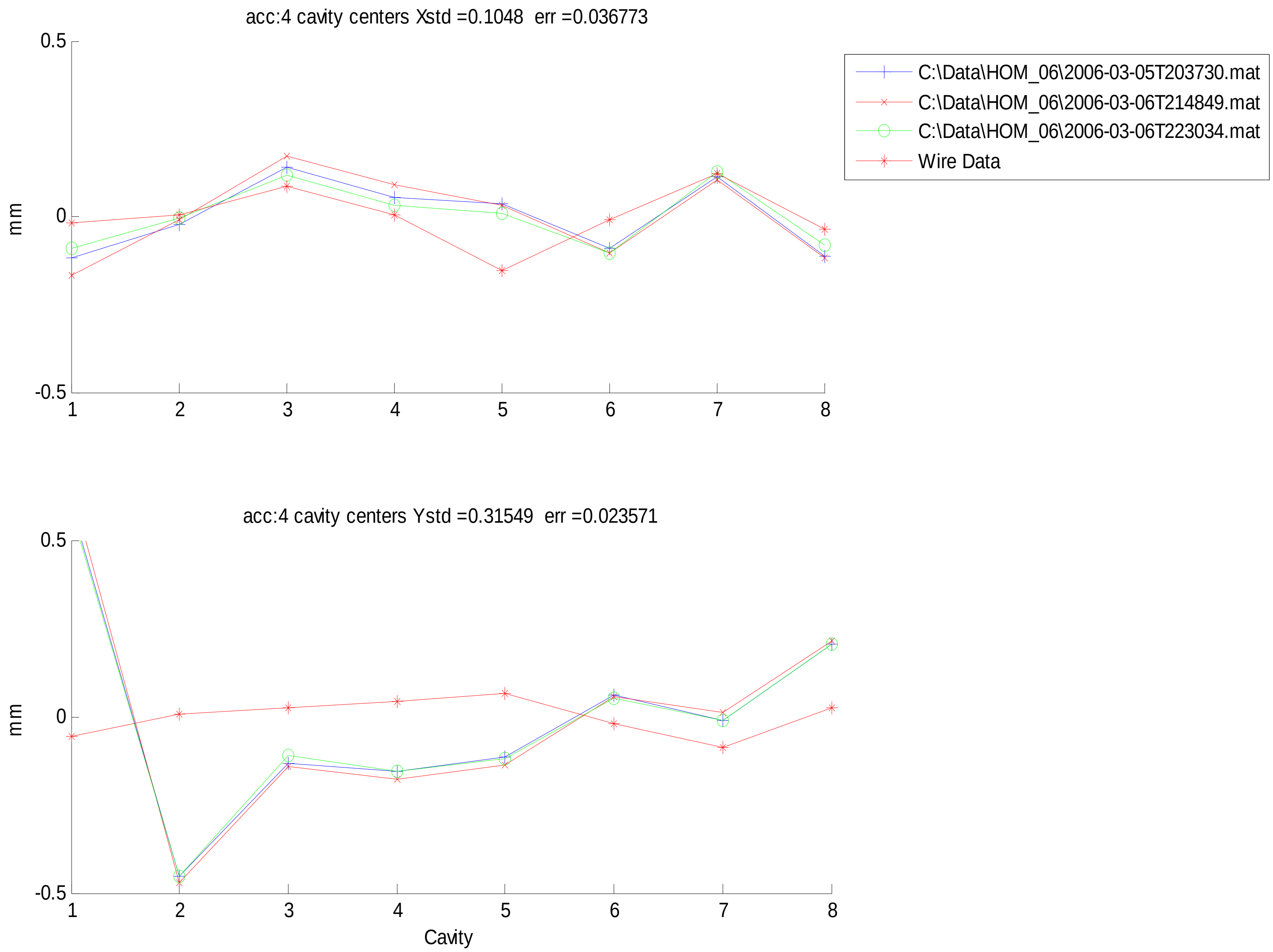
"*" mark is the found cavity center position. (see next slides)

Data “Ratio” (measure of “goodness”)

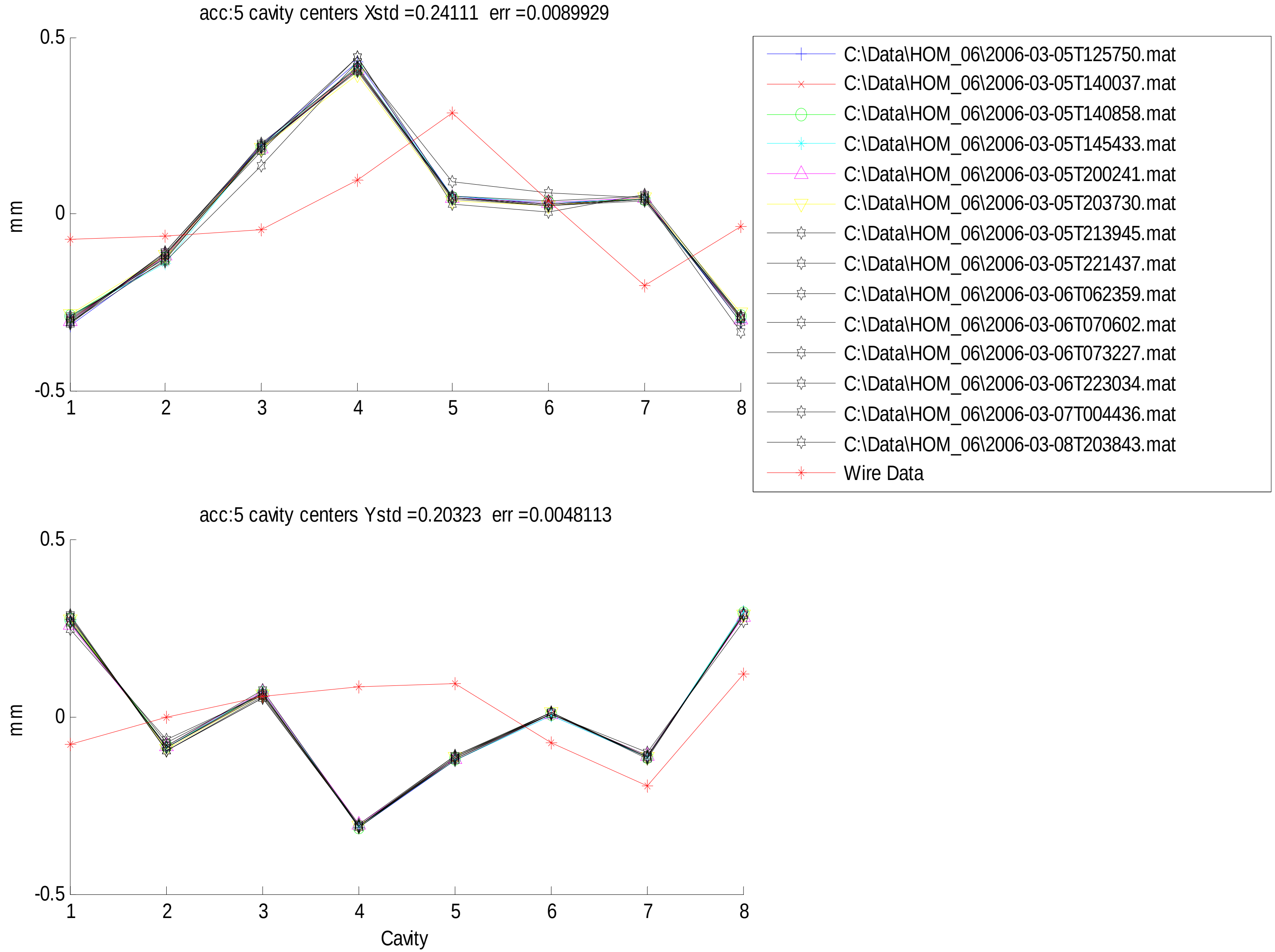
- Calculate a RMS error (sum of squares of X error, and Y error from fit).
- Calculate a “Motion”, = sqrt(Xrms * Yrms).
  - Note, do not want to use RMS position since we want to require motion in X and Y.
- Divide RMS error by “motion” to get “ratio”.
  - Unit-less, high number better.
- Other metrics could be used.

Cavity Alignment

- Use linear regression to predict the (6) HOM mode amplitudes from the X, and Y at each cavity (measured with the BPMs).
- Find the X and Y corresponding to a minimum RMS sum of the HOM mode powers in the cavity
- Require a “Ratio” (see previous slide) > 2.
- Require that the position corresponding to minimum RMS power be within the range of the position scan.
  - Errors increase if we try to project outside of the scan range
- Where data is available (ACC4, ACC5), Plot Cryo wire data
  - Linear interpolation of wire data points to find positions at each cryo module. (may not be valid)
- Plot all valid data sets for each module
  - Remove offset and slope from data (both HOM and wire).n



acc:4 cavity centers Xstd =0.1048 err =0.036773
C:\Data\HOM_06\2006-03-05T203730.mat
C:\Data\HOM_06\2006-03-06T214849.mat
C:\Data\HOM_06\2006-03-06T223034.mat
Wire Data
mm
acc:4 cavity centers Ystd =0.31549 err =0.023571
mm
Cavity


acc:5 cavity centers Xstd =0.24111 err =0.0089929
0.5
0
-0.5
mm
1
2
3
4
5
6
7
8
C:\Data\HOM_06\2006-03-05T125750.mat
C:\Data\HOM_06\2006-03-05T140037.mat
C:\Data\HOM_06\2006-03-05T140858.mat
C:\Data\HOM_06\2006-03-05T145433.mat
C:\Data\HOM_06\2006-03-05T200241.mat
C:\Data\HOM_06\2006-03-05T203730.mat
C:\Data\HOM_06\2006-03-05T213945.mat
C:\Data\HOM_06\2006-03-05T221437.mat
C:\Data\HOM_06\2006-03-06T062359.mat
C:\Data\HOM_06\2006-03-06T070602.mat
C:\Data\HOM_06\2006-03-06T073227.mat
C:\Data\HOM_06\2006-03-06T223034.mat
C:\Data\HOM_06\2006-03-07T004436.mat
C:\Data\HOM_06\2006-03-08T203843.mat
Wire Data
acc:5 cavity centers Ystd =0.20323 err =0.0048113
0.5
0
-0.5
mm
1
2
3
4
5
6
7
8
Cavity

Cavity Alignment

- HOM measurements are reproducible at the ~30 micron level
- Systematics not known
- Correlation with wire data is not very good
- Would like to measure alignment using other dipole modes
  - Can do this with broadband scope system
  - Simultaneous measurement of all cavities in a structure would require 4 high bandwidth scope
  - Scopes are available

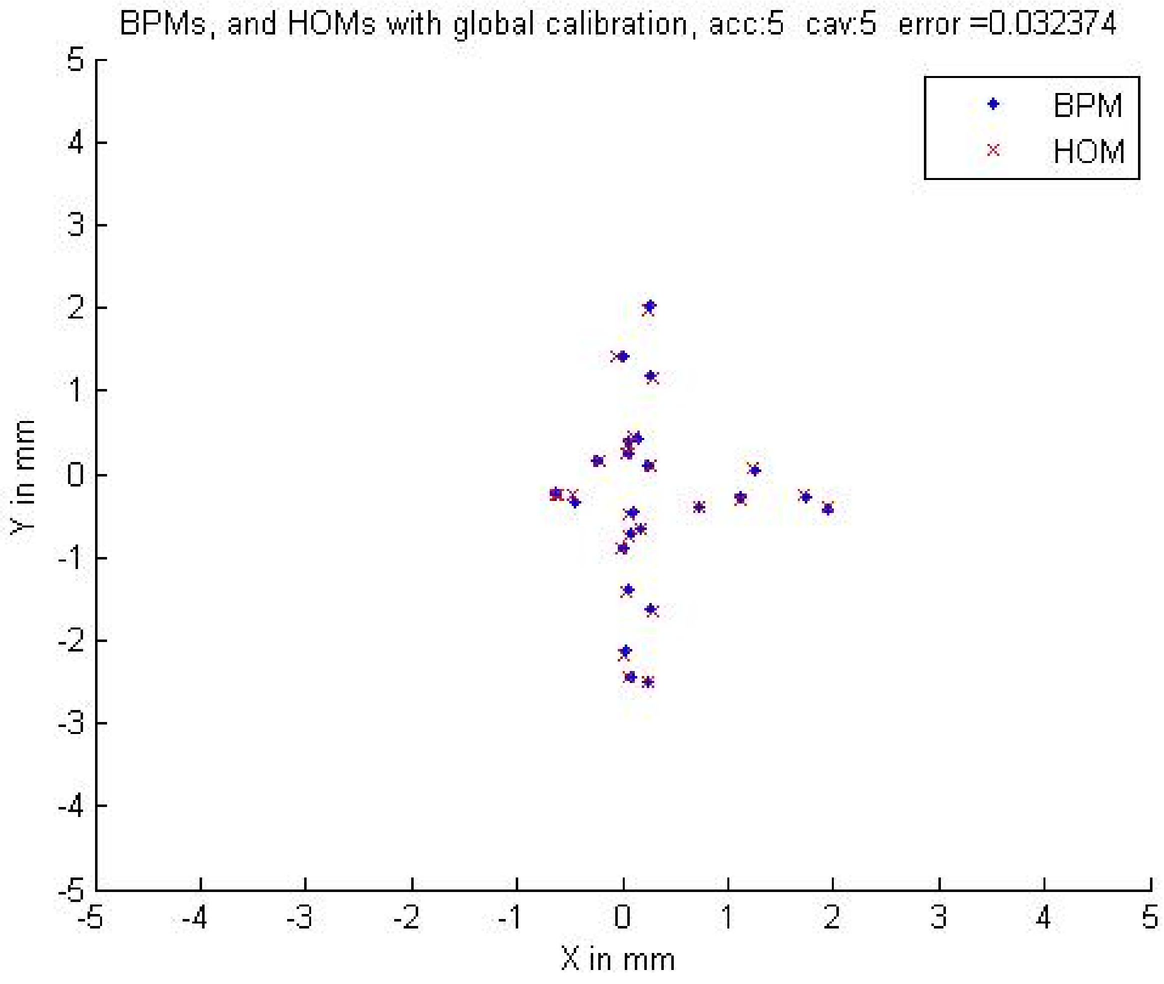
Use normal modes and coefficients from one data set to predict X and Y for others

- For each cavity, choose the data set with the highest "Ratio" for normal modes, and coefficients from modes to positions.
- Use these modes and coefficients to analyze other data sets.
  - Compare HOM positions to BPMs
  - Compare HOM positions from middle cavities to end cavities. (straight line approximation using database cavity positions)
  - Regress HOM positions from end cavity modes to predict HOM positions in middle cavities
- Data sets used:

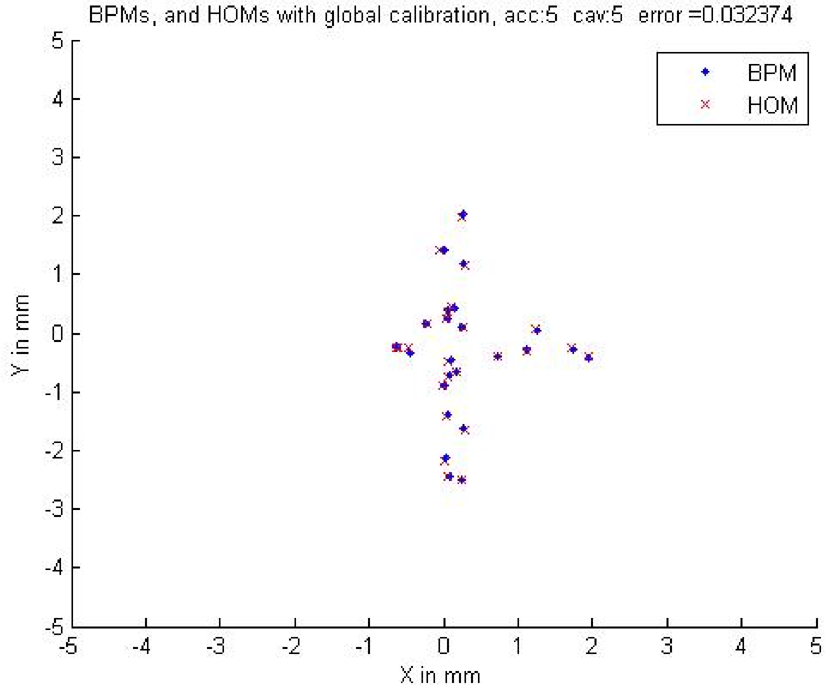
ACC1	CAV1	CAV2	CAV3	CAV4	CAV5	CAV6	CAV7	CAV8
ACC1	29	27	37	37	37	29	29	37
ACC2	34	26	24	24	24	24	34	34
ACC3	23	14	14	14	14	14	15	15
ACC4	3	3	16	16	16	16	16	7
ACC5	7	7	16	16	18	7	7	5

Graphs following are for analysis of data set 16. Note that this set is not used for calibration of cavities 1, 8, or 5 (shown)

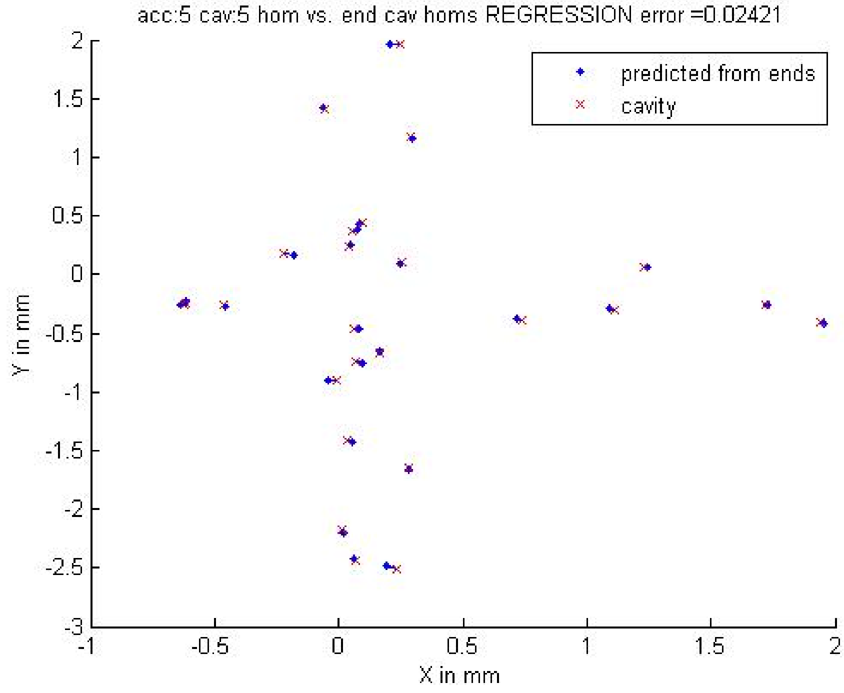
BPMs vs. HOMs using prediction from global calibration



ACC 5, CAV 5 vs. End Cavities using global calibration



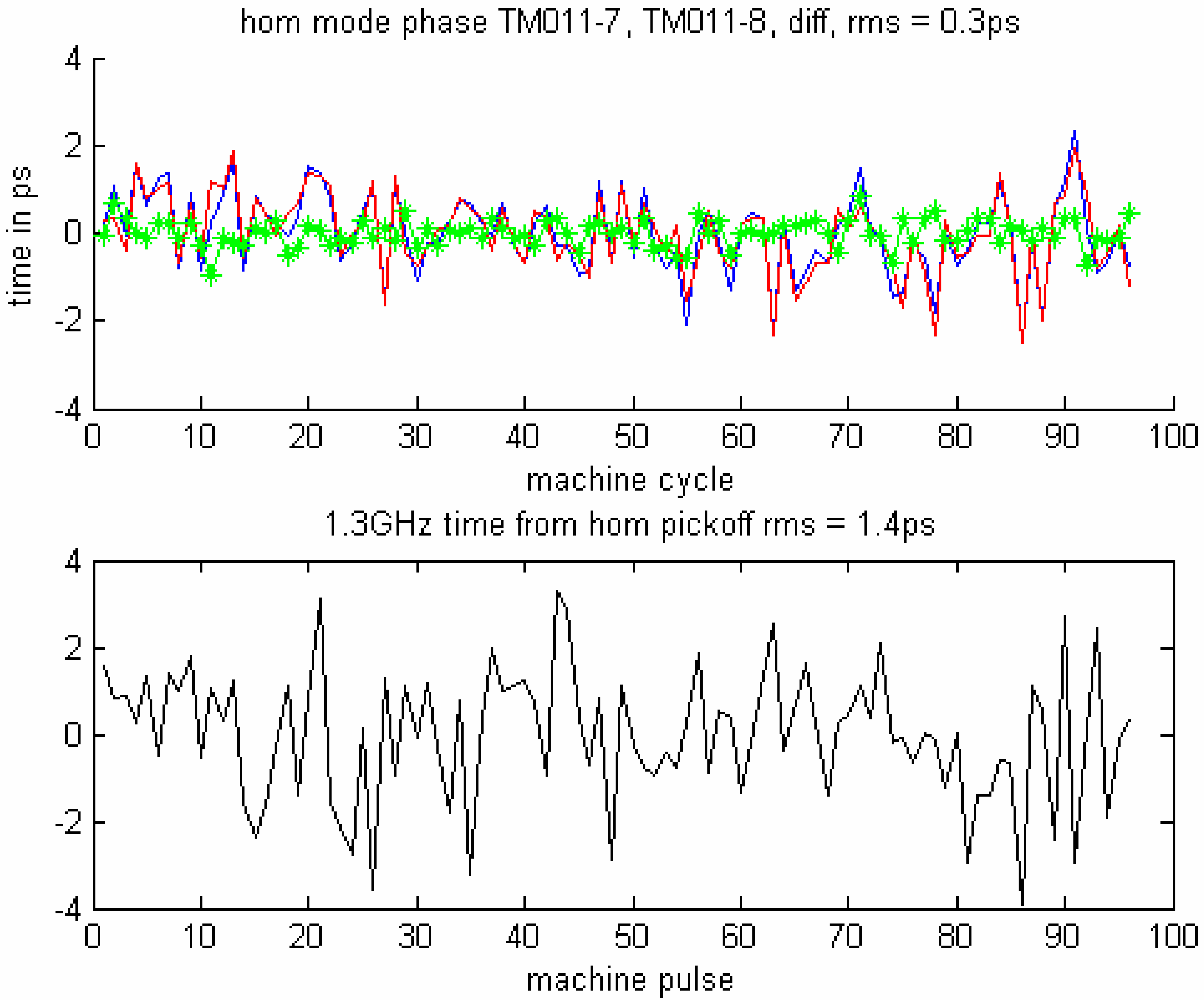
Using database cavity positions



Using regression from positions
At end cavities

Phase Measurement from Monopole modes

- Phase of monopole modes determined by beam phase.
- Use fast (5GS/s, 6GHz BW) scope directly measuring HOM signals
- Compare HOM monopole phases with 1.3 GHz reference
  - Not completely straightforward since TTF trigger jitter > 1 cycle of 1.3GHz
- Plot phase vs. machine cycle for TM011-7 and TM011-8, and phase difference between modes
- Note: measurement uses “accidental” data, taken during other experiment, not optimized.


hom mode phase TM011-7, TM011-8, diff, rms = 0.3ps
time in ps
4
2
0
-2
-4
0
10
20
30
40
50
60
70
80
90
100
machine cycle
1.3GHz time from hom pickoff rms = 1.4ps
4
2
0
-2
-4
0
10
20
30
40
50
60
70
80
90
100
machine pulse

HOM Phase Results

- 1.3 GHz reference phase vs HOM phase equivalent of 1.4 ps RMS over 100 machine cycles
- Difference between measured phases is 0.3ps RMS
- Note that data taken with very small signals on scopes (<10% of full scale)
- If we use the 1.3GHz signal leakage through the HOM port, may be able to do measurement which cancels changes in cable length, and drifts in electronics
  - **Should give very low drift measurement!**
- Experiment planned week of April 18, 2006.
  - Acquisition system and hardware ready, waiting for beam.

To Do (Analysis)

- Use “real” toroids, rather than BPM sums for normalization.
- Use calibration signals to check for gain changes in electronics.
- Modify code to allow use of alternate BPMs if no signal seen on closest BPMs
  - Will provide more good data sets
- Study angle signals as well as position signals.
- Hardware: test resolution with smaller motions, and without 10dB attenuators (expect 1 micron)

Multi-Bunch

- So far tests only done for single bunch beam
- System is linear, should be possible to separate effects of each bunch .
- Basic multibunch plan:
  – Analyze data in windows from start of one bunch to the next
  – Using single bunch data calculate the amplitude of the modes in a window that result from amplitudes measured in earlier windows.
  – Subtract amplitude generated by previous bunch to get amplitudes generated by new bunch
- Technique is straightforward for sine-line modes.
  – Should also work for SVD derived modes, but need to demonstrate this.

Other HOM Projects

- HOM beam phase monitor test
  - If successful, design / build system
- Automatic Calibration:
  - Analysis mostly automated, but would like automated steering
- Improved local oscillator generation:
  - Phase noise may be noise limit
- HOM based beam feedback
  - Successful test with old electronics, would like to automate.
- Integration of HOM beam position signals with TTF control system .