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

Raw Spectrum

- TE111 dipole band
- TM011 Monopole band
- TM110 dipole band
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 relative 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 $U, S, \text{ and } V$ 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 Eigenvalues (the contribution of each mode in $V$).
- Can then multiply new data by these vectors to find amplitudes of these modes. $A = VX$
  - $C = \text{cycle}$
  - $M = \text{mode}$
  - $P = \text{datapoint}$

\[
X = \begin{bmatrix}
  x_{1,1} & x_{1,2} & x_{1,p} & x_{1,4000} \\
  x_{2,1} & \ldots & \ldots & \ldots \\
  x_{c,1} & \ldots & \ldots & \ldots \\
  x_{100,1} & \ldots & \ldots & x_{100,4000}
\end{bmatrix}
\]

\[
V = \begin{bmatrix}
  Mode_{-1} & Mode_{-2} & Mode_{m} & Mode_{100} \\
  Mode_{-1} & \ldots & \ldots & \ldots \\
  Mode_{-1} & \ldots & \ldots & \ldots \\
  Mode_{14000} & \ldots & \ldots & Mode_{1004000}
\end{bmatrix}
\]

\[
A = XV
\]

\[
A_{c,m} = \sum_p X_{c,p} V_{p,m}
\]
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
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.

![Graph 1](image1.png)

![Graph 2](image2.png)
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”, \( = \sqrt{X_{\text{rms}} \times Y_{\text{rms}}} \).
  - 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).
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

acc:4 cavity centers Ystd = 0.31549  err = 0.023571
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:

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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

1.3GHz time from hom pickoff rms = 1.4ps
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.