High Precision SC Cavity Diagnostics with HOM Measurements

Stephen Molloy, Nicoleta Baboi, Nathan Eddy, Josef Frisch, Linda Hendrickson, Olaf Hensler, Douglas McCormick, Justin May, Sergei Nagaitsev, Olivier Napoly, Rita Paparella, Lyudvig Petrosyan, Marc Ross, Claire Simon, Tonee Smith

CEA, DESY, FNAL, SLAC

Or,

How I learned to stop worrying and love the HOMs

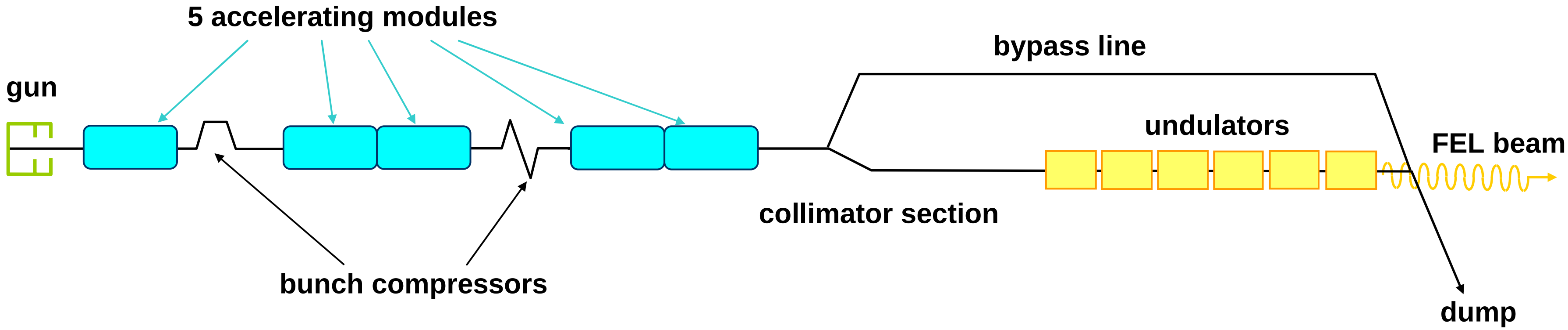
Stephen Molloy, Nicoleta Baboi, Nathan Eddy, Josef Frisch, Linda Hendrickson, Olaf Hensler, Douglas McCormick, Justin May, Sergei Nagaitsev, Olivier Napoly, Rita Paparella, Lyudvig Petrosyan, Marc Ross, Claire Simon, Tonee Smith

CEA, DESY, FNAL, SLAC

Introduction

- FLASH
- Higher Order Modes in Cavities
- HOMs as Diagnostics

FLASH Facility (formerly TTF2)

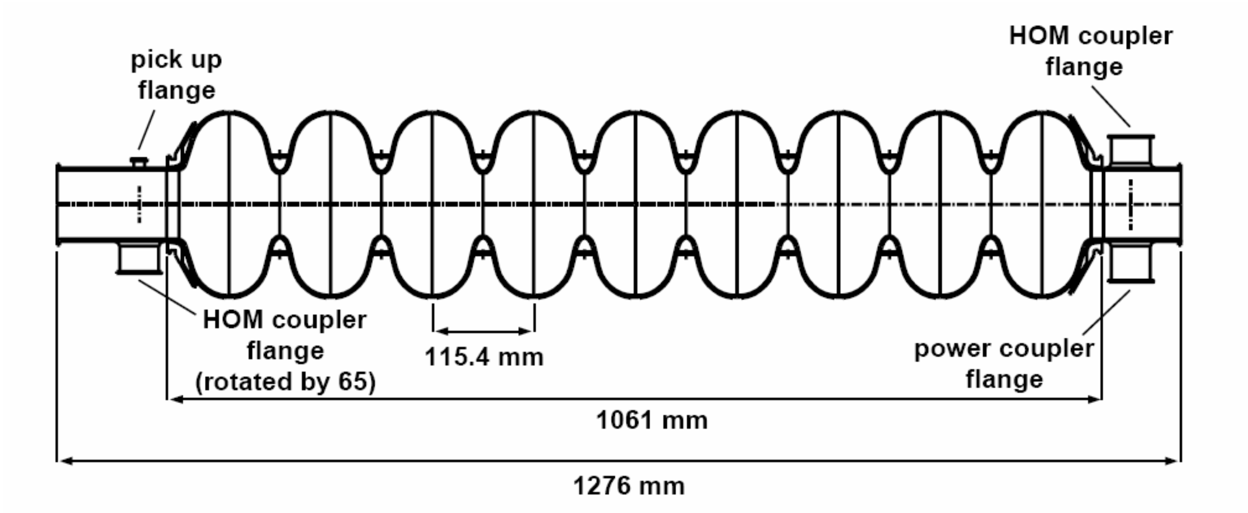


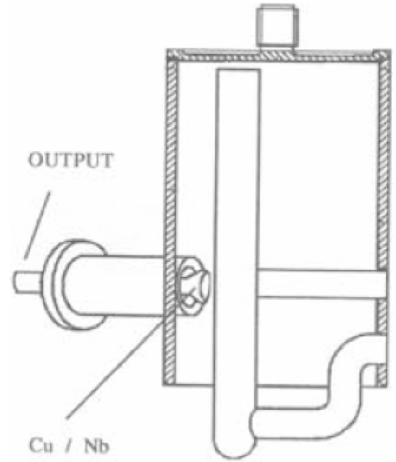
- 1.3 GHz superconducting linac
  - 5 current accelerating modules, with a further two planned for installation.
  - Typical energy of 400 – 750 MeV.
- Bunch compressors create a ~10 fs spike in the charge profile.
  - This generates intense VUV light when passed through the undulator section (SASE).
- Used for ILC and XFEL studies, as well as VUV-FEL generation for users.

Higher Order Modes in Cavities

- In addition to the fundamental accelerating mode, cavities can support a spectrum of higher order modes.
- Traditionally they are seen as “bad”.
  - Beam breakup (BBU), HOM heating, …
- Here we investigate their usefulness,
  - Beam diagnostics
  - Cavity alignment
  - Cavity diagnostics

TESLA Cavities





- Nine cell superconducting cavities.
- 1.3 GHz standing wave used for acceleration.
- Gradient of up to 35 MV/m.
  - Addition of piezo-tuners and improvement of manufacturing technique intended to make 35 MV/m gradient easier to achieve.
- HOM couplers with a tunable notch filter to reject fundamental.
  - One upstream and one downstream, separated by 115degrees azimuthally.
  - Couple electrically and magnetically to the cavity fields.

Higher Order Modes

- The 9 cells of the cavities leads to 9 different longitudinal distributions with similar radial field geometry
  - i.e. Different passbands with 9 modes each.
- Monopole modes,
  - First monopole passband is TM-like, and contains the 1.3 GHz accelerating mode.
  - First higher order monopole band lies between 2.38 – 2.46 GHz.
- Dipole modes,
  - TE-like between 1.6 – 1.8 GHz.
  - TM-like between 1.8 – 1.9 GHz.
- Quadrupole modes,
  - First quadrupole band is at ~2.3 GHz.
- Modes synchronous with the beam (i.e. phase velocity = *c*) have strongest coupling to the beam,
  - Indicated by a large R/Q.

HOMs as Diagnostics

- No need to install new beamline hardware
  - HOM power must be coupled out of the cavities to prevent BBU, etc.
  - Therefore beamline and cryogenic hardware already exists.
    - Even the cables existed at FLASH!
- Large proportion of linac length occupied by structures.

HOMs as a Beam Diagnostic

- Beam Position Monitoring
  - Dipole mode amplitude is a linear function of the bunch charge and transverse offset.
  - Exist in two polarisations corresponding to two transverse orthogonal directions.
    - Not necessarily coincident with horizontal and vertical directions due to perturbations from cavity imperfections and the couplers.
    - Problem – polarisations not necessarily degenerate in frequency.
      - Frequency splitting <1 MHz (of same size as the resonance width).
- Beam Phase Monitoring
  - Power leakage of the 1.3 GHz accelerating mode through the HOM coupler is approximately the same amplitude as the HOM signals.
    - i.e. Accelerating RF and beam induced monopole modes exist on same cables.
  - Compare phase of 1.3 GHz and a monopole HOM.

HOMs as a Cavity Diagnostic

- Analyse the response of a dipole mode to different beam trajectories.
  - Can find the trajectory corresponding to the lowest power output from that mode.
  - This is the centre of that dipole mode in that cavity.
- Measure the axis of a dipole mode for many cavities within a structure.
  - Can compare the centre of a particular mode in many cavities.
  - Gives in situ alignment data on the internals of the accelerating module.

HOMs as a Cavity Diagnostic

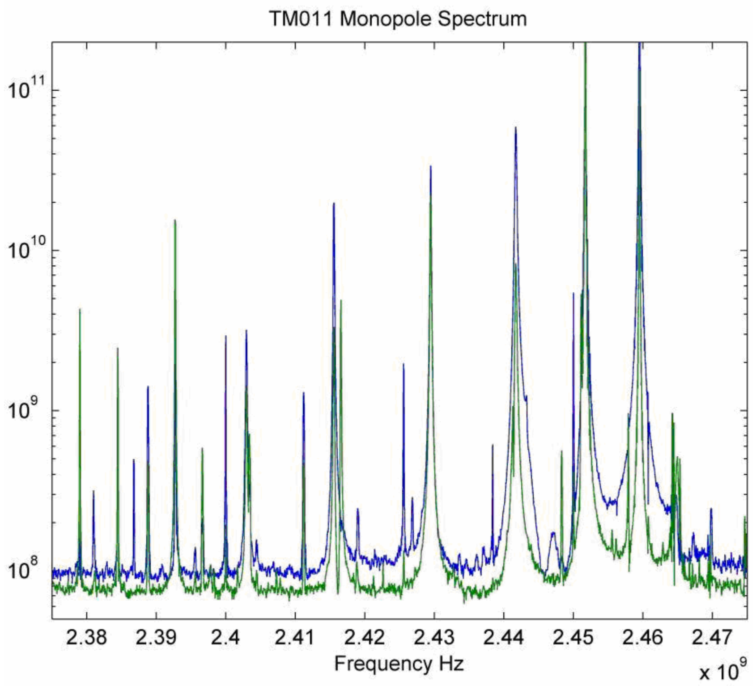
- Many modes in the spectrum.
  - Monopole, dipole, quadrupole, etc.
  - Frequency, Q, R/Q, etc. dependent on cavity construction.
- HOM spectrum directly influenced by the internal cavity shape.
  - The low frequency HOMs studied here are not strongly affected by the iris positions.
  - Effect of couplers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

Measuring HOMs

- Broadband
- Narrowband

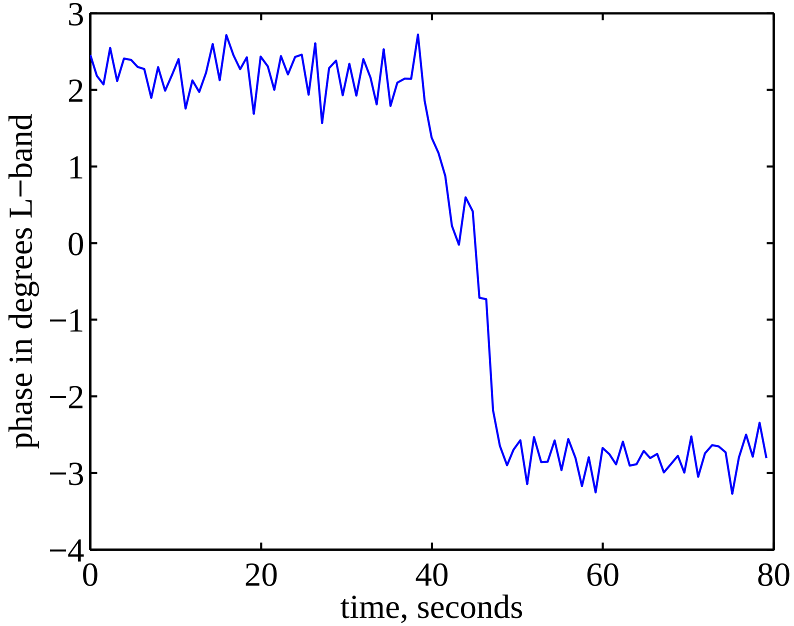
Broadband Measurements

Monopole Mode Measurements



- Digitise the HOM signal with a broadband scope,
  - 5 GS/s, 2.5 GHz
- Can measure phase of beam induced monopole lines.
- HOM coupler allows a small amount of the fundamental to leak through.
  - Accelerating RF and beam induced HOMs exist on same cable.
  - No cable expansion issues.

Monopole Mode Measurements



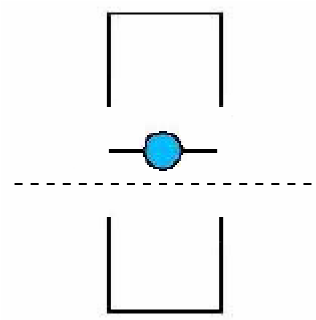
- Measurement of the 1.3 GHz phase
  - 5 degree phase change command from the RF control system.
- Noise is 0.08 degrees at 1.3 GHz (~170 fs)
  - Estimated by comparing the measurement from two couplers from the same cavity.
- When the beam phase is compared to the RF phase of two cavities on the same klystron, an RMS of 0.3 degrees is measured.
  - Microphonics?

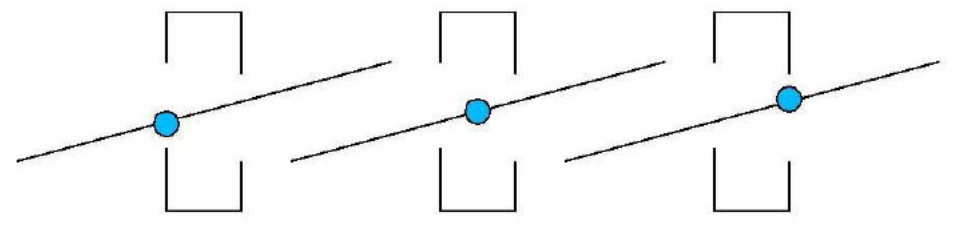
Future

- Many modes, with many free parameters
  - Potentially a lot of information in the HOM spectrum.
  - Simulate and compare with measurements
    - Perfect cavities.
    - Perturbations in cavity shape, couplers, …
  - Attempt to measure cavity shape from HOM spectrum.
- More exotic effects
  - Elliptical modes, corkscrew modes, …
  - Implications for beam dynamics, and cavity construction.

Narrow band Measurements

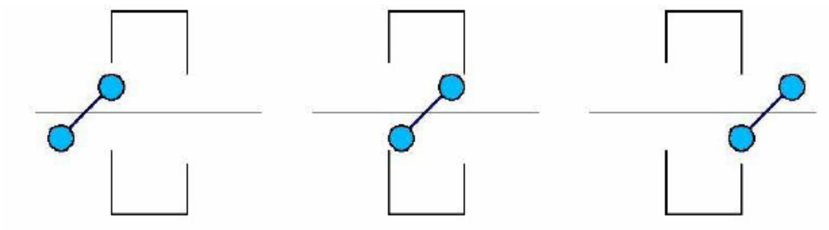
Dipole Mode Response





Tilted trajectory

- Mode excited by bunch offset from mode centre.
- Amplitude goes with offset
- Phase changes going through zero

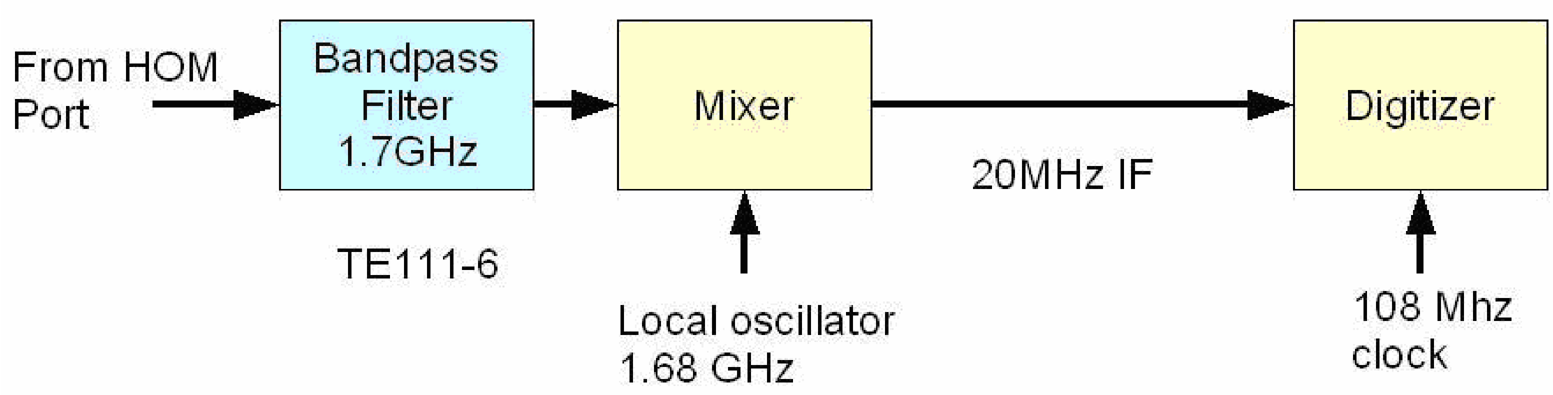


Tilted bunch

Information on tilt of trajectory/bunch.

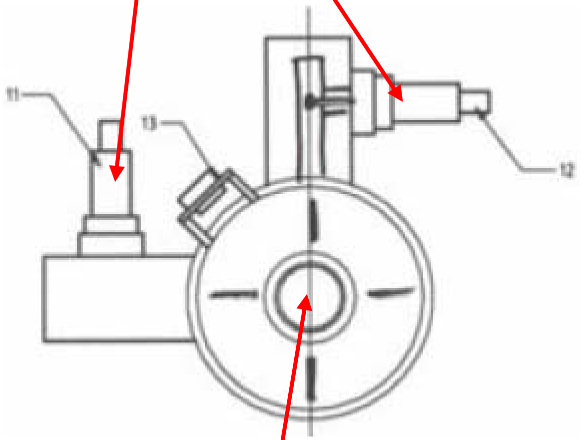
Dipole Mode Measurement

- Simulations show that the 6th mode in the 1st passband has a strong coupling to the beam,
  - R/Q = ~5.5 Ohms/cm^2
  - Frequency = ~1.7 GHz
- Design narrow band electronics to observe this mode only.
  - Filter around 1.7 GHz (20 MHz bandwidth)
  - Mix with 1.679 GHz LO
  - Digitise at 108 MHz
- 1.697 GHz tone added before mixer to provide a constant amplitude, 18 MHz, calibration signal.

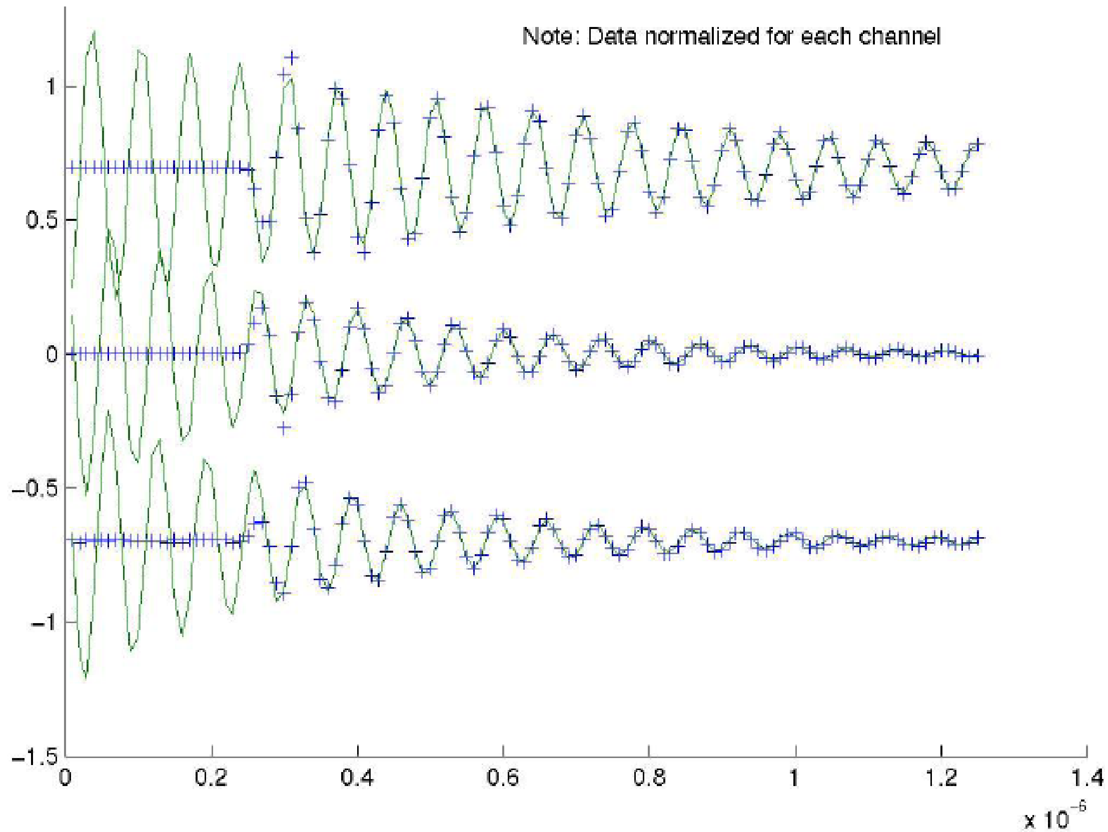


Standard Cavity BPM

Couplers



Beam pipe



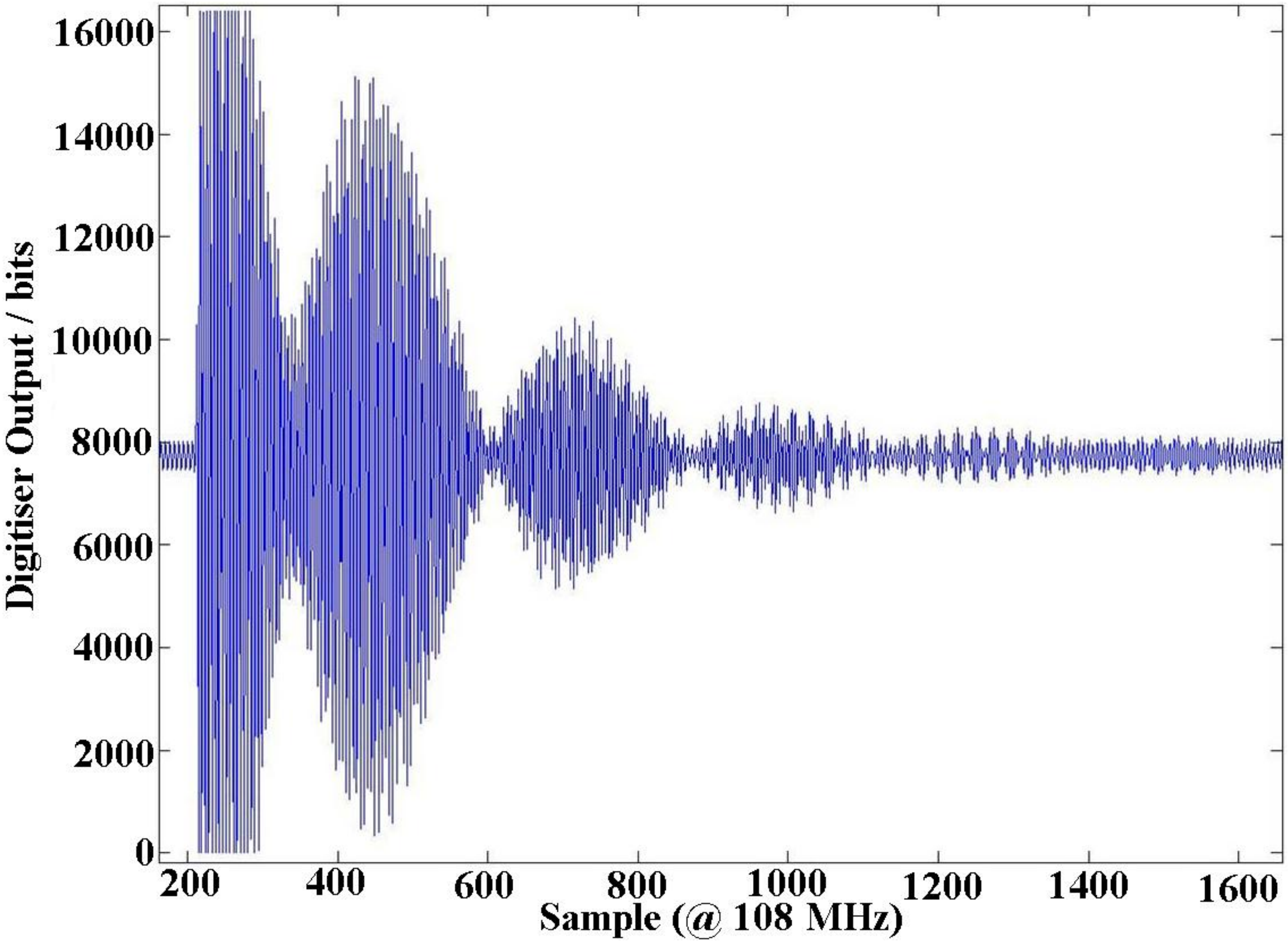
Standard Cavity BPM

- Two coupling ports
  - Each sensitive to orthogonal signals (x or y)
- Output is decaying sine wave
- Analysis
  - Fit to signal with known frequency and Q.
    - Determine bunch offset and tilt from fitted amplitude and phase.
  - Digital Down Conversion (DDC)
    - Multiply by sine and cosine-like signals.
    - Digitally filter to leave only low frequency information
    - Amplitude of I and Q components gives phase and amplitude of original signal.

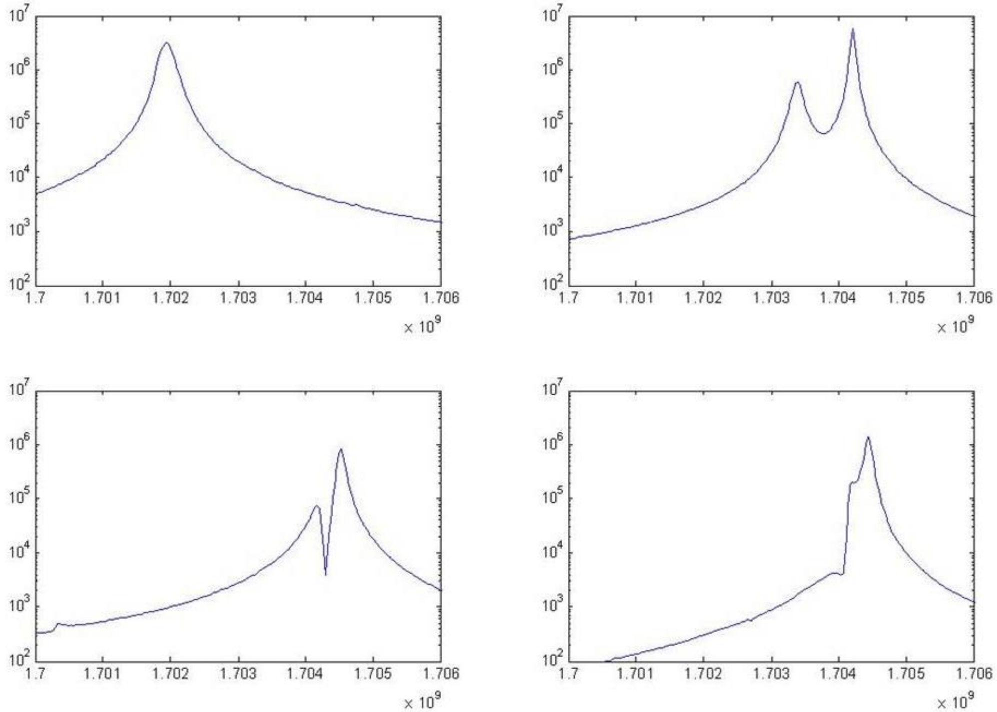
TTF RF Cavities as BPMs

- Couplers are not orthogonal.
  - Separated by 115 degrees azimuthally.
- Instead, use the fact that each dipole mode exists in two orthogonal polarisations.
  - The axis of these polarisations not necessarily coincident with x,y axis.
  - Must look at signals from both couplers to observe both polarisations.
  - Polarisation frequencies may be different.
    - Signal no longer simple decaying sine wave as the polarisations will beat against each other.

Example Waveform



Analysis



- Standard cavity BPM analysis techniques are problematic due to varying degrees of frequency degeneracy in the cavities.
    - Simple to determine amplitude and phase if the frequency split is greater than the line width, or if they are identical.
    - Non-trivial when the splitting is on the same scale as the width.

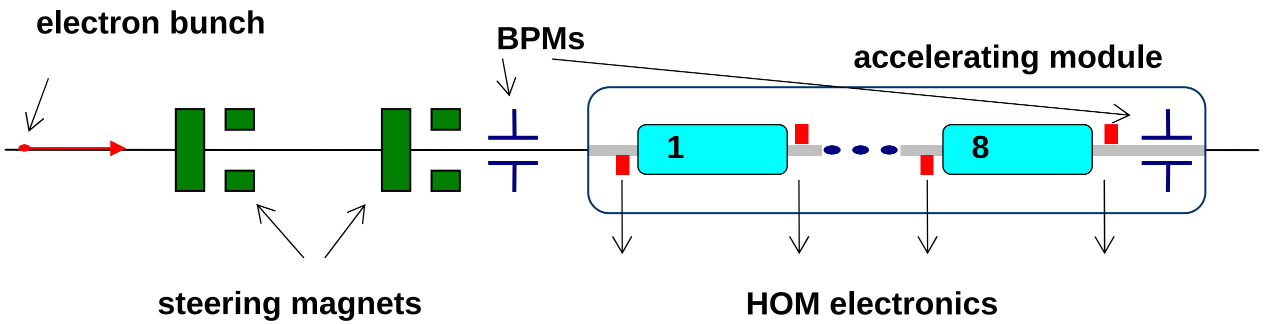
Alternative

- Rely on the fact that the four degrees of freedom (x, x', y, and y') generate four orthogonal signals.
- Move the beam through a wide range of phase space, and analyse output.
  - Try to find four orthogonal modes corresponding to the four degrees of freedom.
  - With a large dataset, this could be done in a "least squares" way.
- Singular Value Decomposition (SVD) finds the predominant modes in a dataset.
  - Therefore the top 4 SVD modes should be linear combinations of the x, x', y, y' modes.
  - Can find the amplitude of each of the SVD modes in each output pulse.
  - Then find the correlation between these amplitudes and the beam position.

Analysis – Singular Value Decomposition

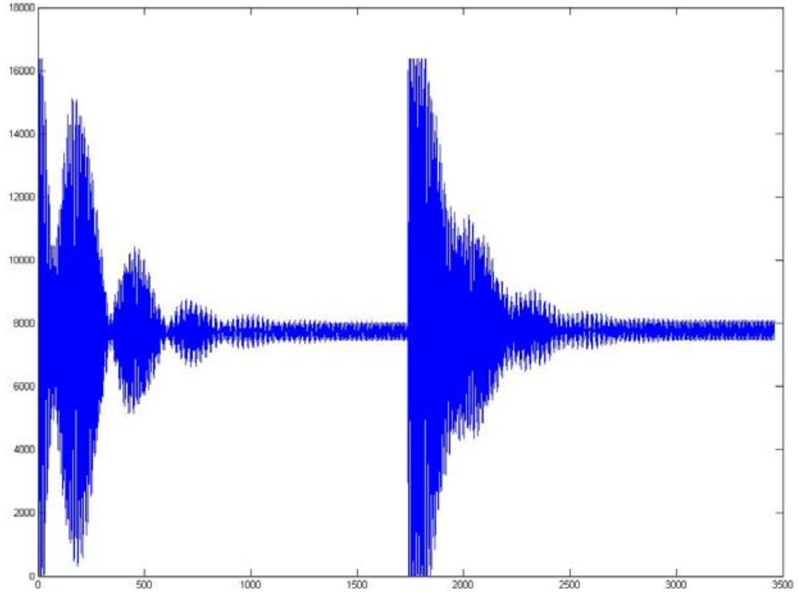
- SVD decomposes a matrix, *X*, into the product of three matrices, *U*, *S*, and *V*.
  - *U* and *V* are unitary.
  - *S* is diagonal.
- It finds the "normal eigenvectors" of the dataset.
  - i.e. "modes" whose amplitude changes independently of each other.
  - These may be linear combinations of the expected modes.
- Use a large number of pulses for each cavity.
  - Make sure the beam was moved a significant amount in x, x', y, and y'.
- Does not need *a priori* knowledge of resonance frequency, Q, etc.
  - Similar to Model Independent Analysis.

Method



- Develop model for the machine
- Steer beam using two correctors upstream of the accelerating module.
  - Try to choose a large range of values in (*x*,*x'*) and (*y*,*y'*) phase space.
- Record the response of the mixed-down dipole mode at each steerer setting.

Data preparation



- Cut saturated pulses.
- Cut on low charge pulses (using toroid information).
- Cut on excessive (>1 cm) beam motion in BPMs.
- Cut pulses that contain BPM failures (i.e. toroids show sufficient charge, but BPM readout failed).

- Combine output of both couplers into one waveform.
  - Start of pulse will have transient effects, so cut this.
- Make (n x j) matrix. (I'll call this matrix "*X*")
  - n = number of pulses (≤250)
  - j = samples in each waveform (~3500)

Using SVD (1)

$$X = \begin{pmatrix} U_{11} & \cdots & \cdots & \cdots & \cdots & U_{1j} \\ \vdots & & & & & \vdots \\ \vdots & & & & & \vdots \\ U_{n1} & \cdots & \cdots & \cdots & \cdots & U_{nj} \end{pmatrix} \bullet \begin{pmatrix} S_{11} & & 0 \\ & \ddots & \\ 0 & & S_{jj} \end{pmatrix} \bullet \begin{pmatrix} V_{11} & \cdots & V_{1j} \\ \vdots & \ddots & \vdots \\ V_{j1} & \cdots & V_{jj} \end{pmatrix}$$

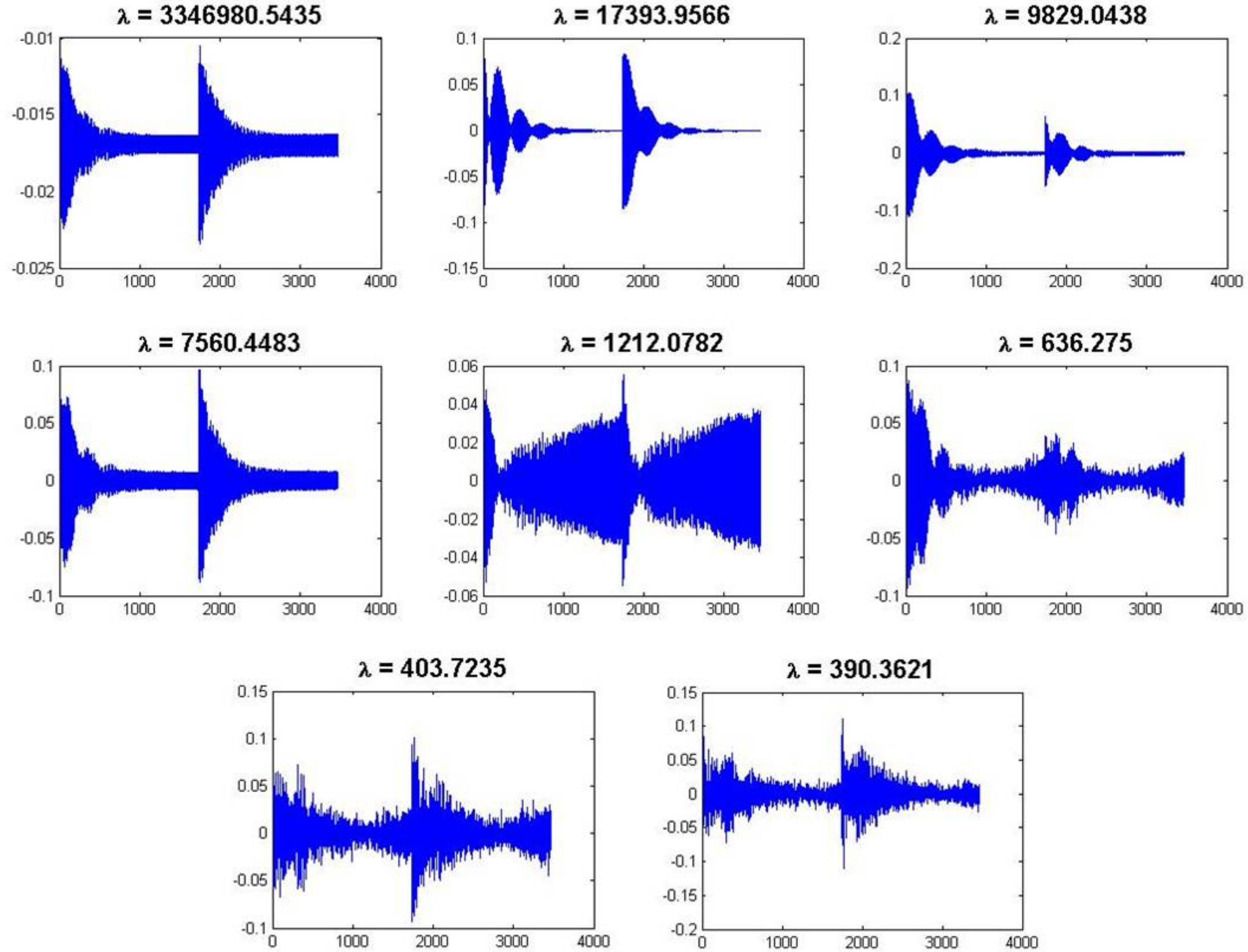
- Using SVD on the (n x j) cavity output matrix, *X*, produces three matrices.
  - *U* (n x j), *S* (j x j, diagonal), and *V* (j x j)
- *V* contains *j* modes.
  - These are the orthonormal eigenvectors.
  - “Intuitive” modes will be linear combinations of these.
- The diagonal elements of *S* are the eigenvalues of the eigenvectors.
  - i.e. the amount with which the associated eigenvector contributes to the average coupler output.
  - It can be shown that the largest eigenvalues found by SVD are the largest **possible** eigenvalues.
- *U* gives the amplitude of each eigenvector for each beam pulse.

Using SVD (2)

- Performing full SVD analysis on multiple ~100 x 3500 matrices is very time consuming.
- Instead find only first *k* eigenvectors (*k* ~ 4 – 8).
  - i.e. *k* largest eigenvalues
  - CPU time is dominated by the SVD, so this greatly reduces the time taken for the calculation.

$$X \cong \begin{pmatrix} U_{11} & \cdots & \cdots & U_{1k} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ U_{n1} & \cdots & \cdots & U_{nk} \end{pmatrix} \bullet \begin{pmatrix} S_{11} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & S_{kk} \end{pmatrix} \bullet \begin{pmatrix} V_{11} & \cdots & \cdots & \cdots & \cdots & V_{1j} \\ \vdots & & & & & \vdots \\ \vdots & & & & & \vdots \\ V_{k1} & \cdots & \cdots & \cdots & \cdots & V_{kj} \end{pmatrix}$$

Example modes (acc5, cav5)



Calibrating HOMs (1)

- Steer beam in x, x', y, and y'.
  - Generate multi-knobs for this purpose.
- Normalise by charge read from toroids.
- Extract eigenvectors using SVD.
- Find amplitude of each eigenvector for each beam pulse.
  - Dot product of *k* eigenvectors with *n* beam pulses.
  - Results in *k* x *n* matrix, *A*.

$$\begin{pmatrix} V_{11} & \cdots & \cdots & \cdots & \cdots & \cdots & V_{1j} \\ \vdots & & & & & & \vdots \\ \vdots & & & & & & \vdots \\ V_{k1} & \cdots & \cdots & \cdots & \cdots & \cdots & V_{kj} \end{pmatrix} \bullet \begin{pmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \vdots & & \vdots \\ X_{j1} & \cdots & X_{jn} \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & & \vdots \\ \vdots & & \vdots \\ A_{k1} & \cdots & A_{kn} \end{pmatrix}$$

Calibrating HOMs (2)

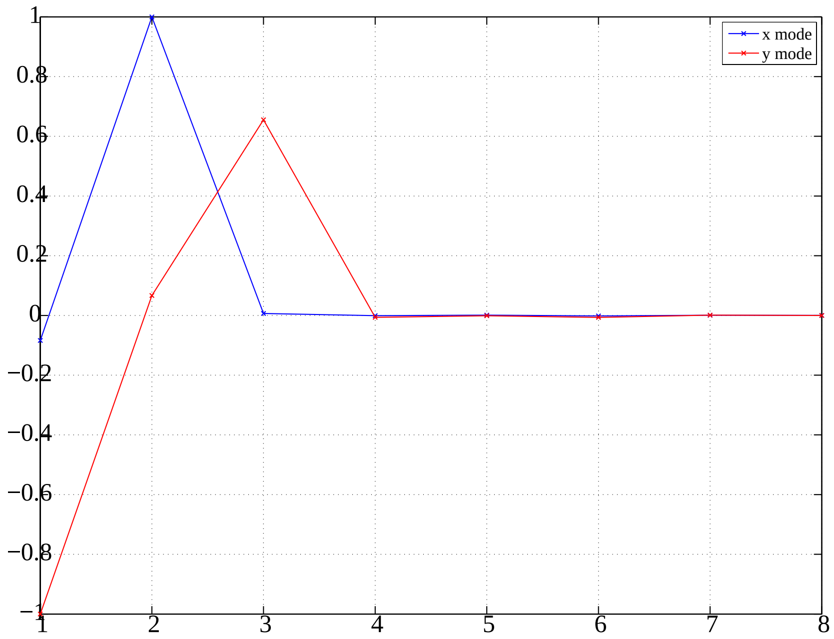
$$\begin{pmatrix} M_{11} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & M_{1,k+1} \\ \vdots & & & & & & & & \vdots \\ \vdots & & & & & & & & \vdots \\ M_{41} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & M_{4,k+1} \end{pmatrix} \bullet \begin{pmatrix} A_{11} & \cdots & \cdots & \cdots & A_{1n} \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ A_{k1} & \cdots & \cdots & \cdots & A_{kn} \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} x_1 & \cdots & \cdots & \cdots & x_n \\ x'_1 & \cdots & \cdots & \cdots & x'_n \\ y_1 & \cdots & \cdots & \cdots & y_n \\ y'_1 & \cdots & \cdots & \cdots & y'_n \end{pmatrix}$$

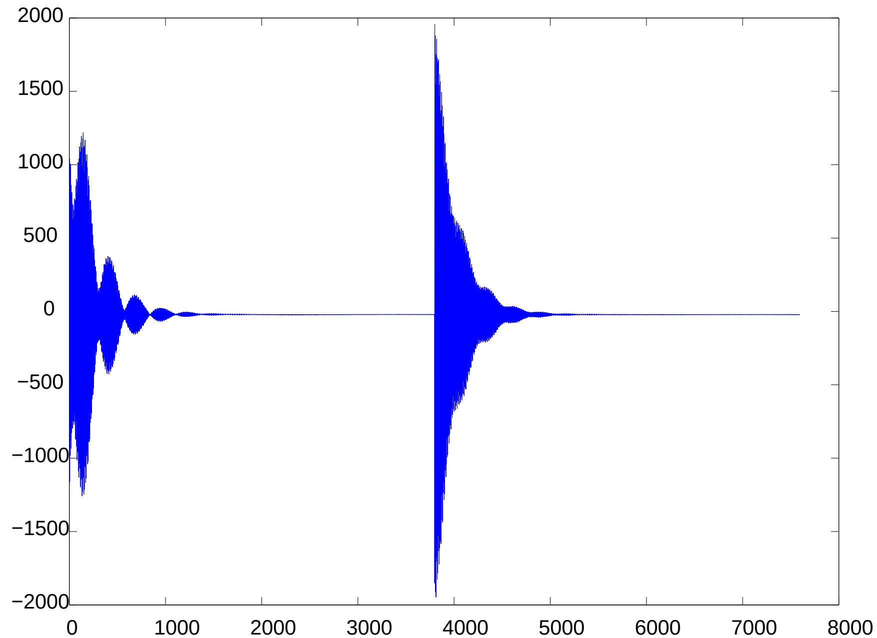
- Use Matlab "slash" operator to regress the mode amplitudes, *A,* against beam position & angle.
  - Position/angle interpolated from adjacent BPMs.
- The slash operator performs a least-squares fit to the data
  - Results in a (4 x (*k*+1)) calibration matrix, *M*.

$$M = \begin{pmatrix} x_1 & \cdots & \cdots & \cdots & x_n \\ x'_1 & \cdots & \cdots & \cdots & x'_n \\ y_1 & \cdots & \cdots & \cdots & y_n \\ y'_1 & \cdots & \cdots & \cdots & y'_n \end{pmatrix} / A$$

Intuitive modes?

- This calibration matrix, *M*, shows how much of each SVD mode contributes to the modes corresponding to *x, x', y, y'*.
- Therefore, can sum the SVD modes to find the intuitive modes.
  - Lack of calibration tone in the reconstructed modes, as expected.
  - Beating indicates presence of two frequencies, i.e. actual cavity modes are rotated with respect to *x* and *y*.
  - Could rotate these modes to find orientation of polarisation vectors in the cavity…

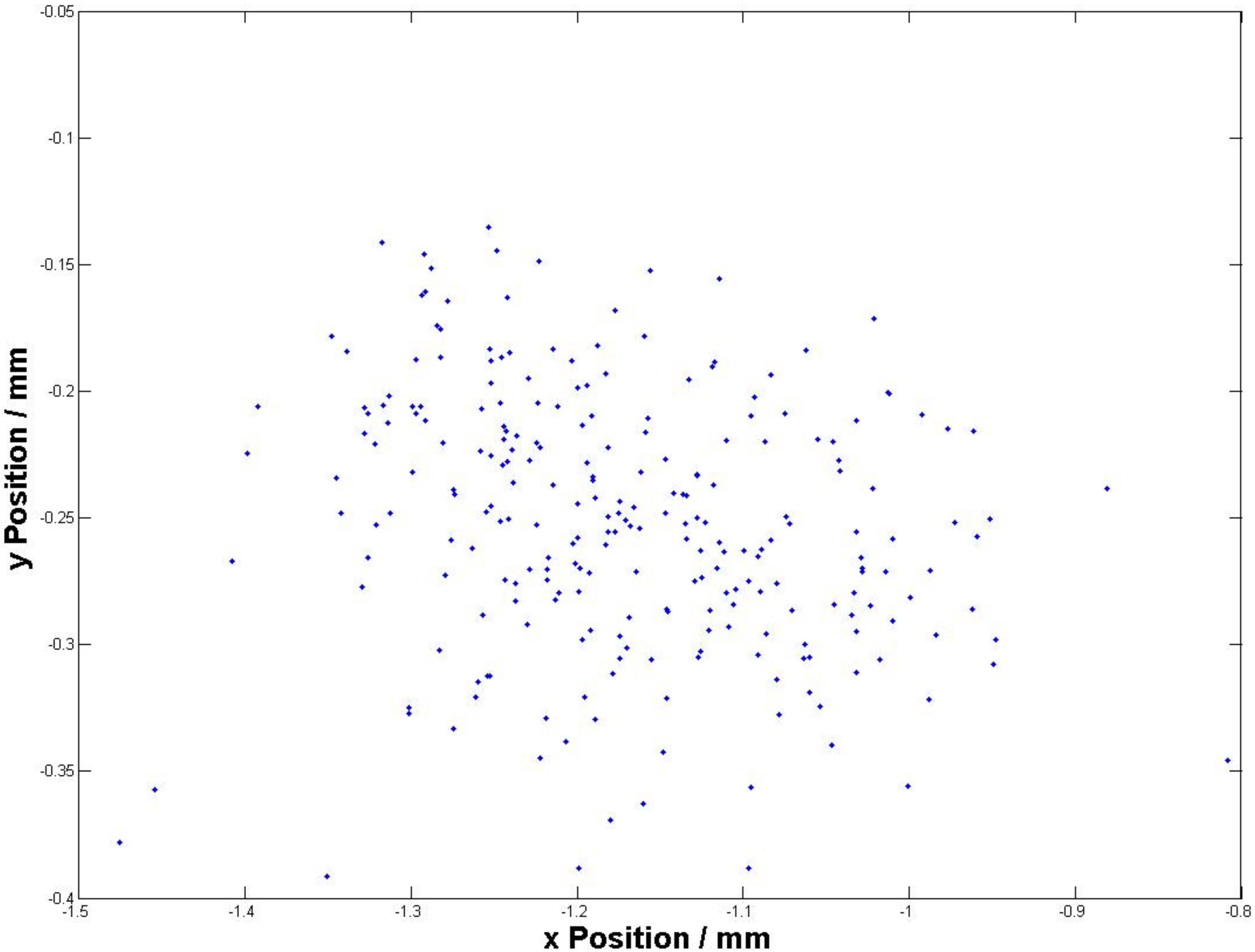




Resolution

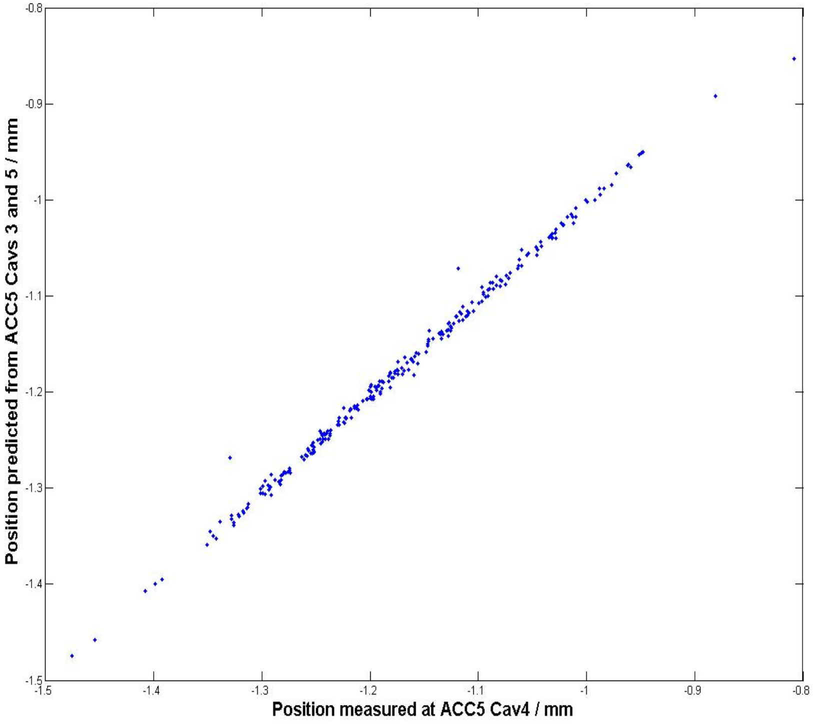
- Calibrate against position and angle in both planes.
  - Straight line interpolation between BPMs.
    - Incorrect for ACC1 due to significant energy gain…
  - Angle calibrated against beam trajectory.
    - Bunch tilt (small) will appear as the mean of the residuals.
- Use "figure of merit" to determine quality of dataset.
  - $\sqrt{X_{rms} \times Y_{rms}} \Big/ \sqrt{\sigma_x \times \sigma_y}$
  - Turns out best dataset is achieved by calibrating on jitter! (Have yet to fully analyse data from this run.)

250 point run – no steering

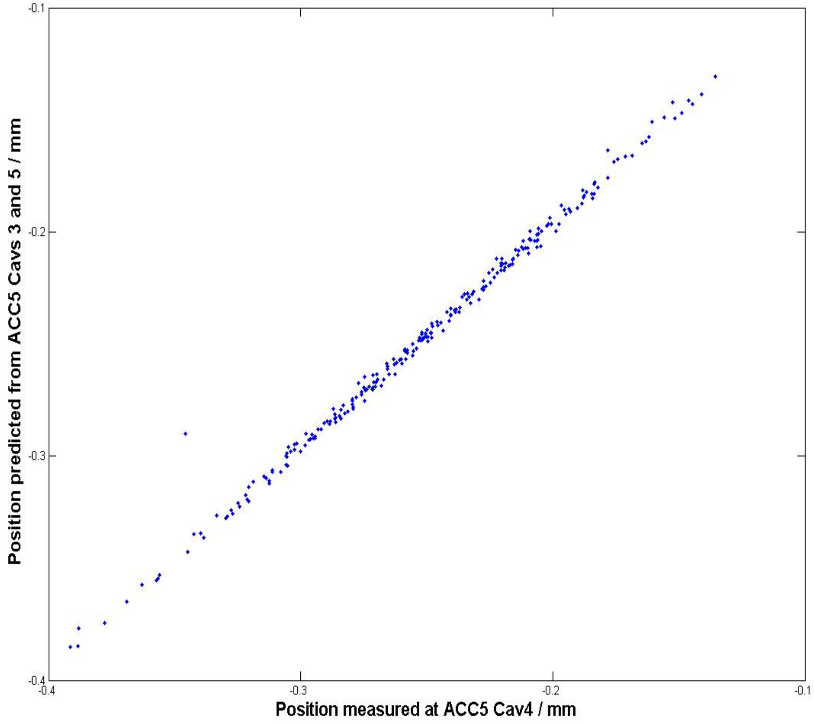


Predict position at one cavity from positions at adjacent cavities

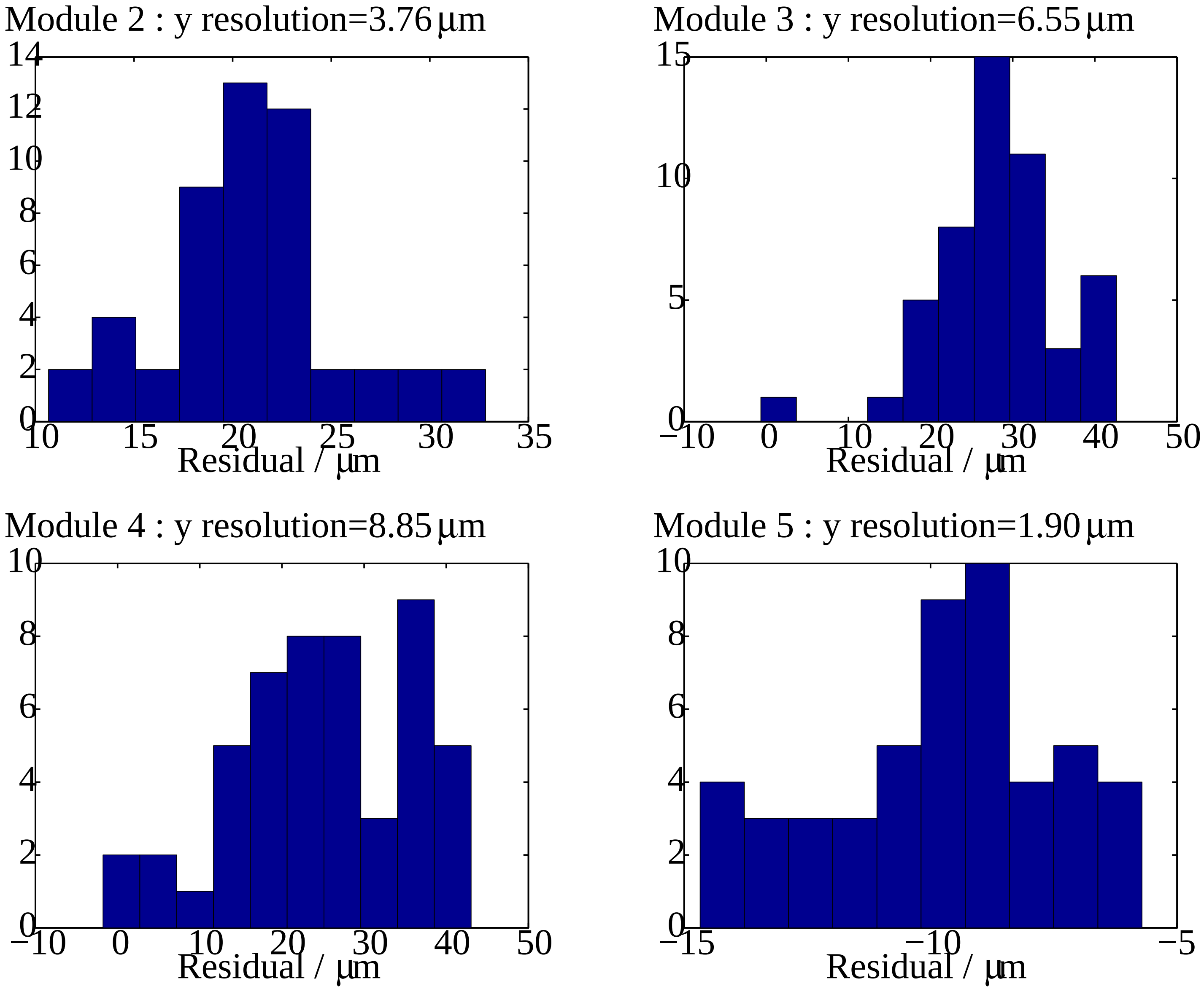
X resolution ~ 6.1μm



Y resolution ~ 3.3 μm



Apply calibration to a different dataset



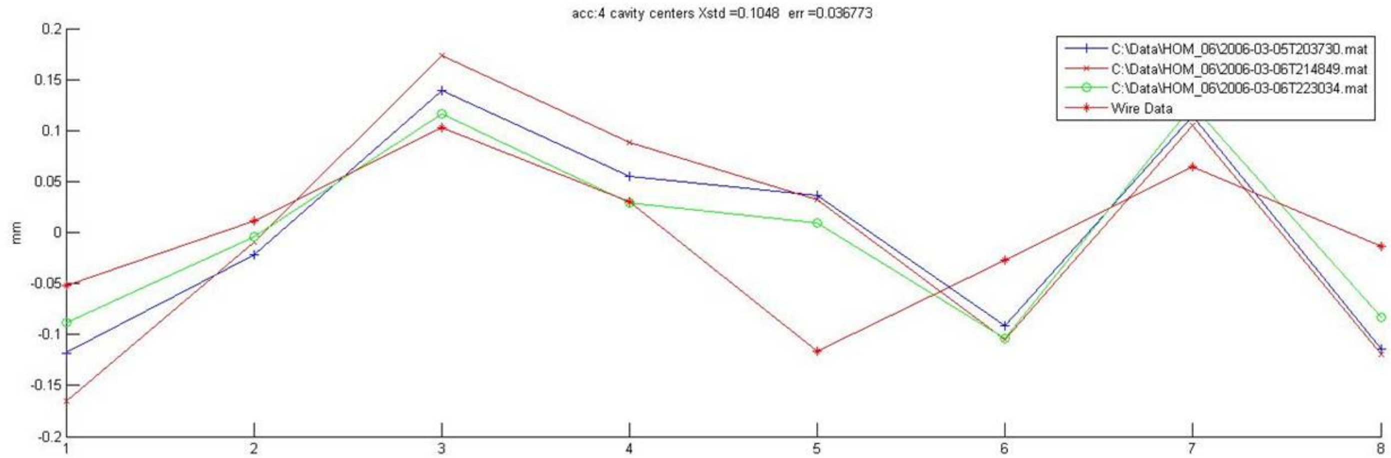
Theoretical Resolution

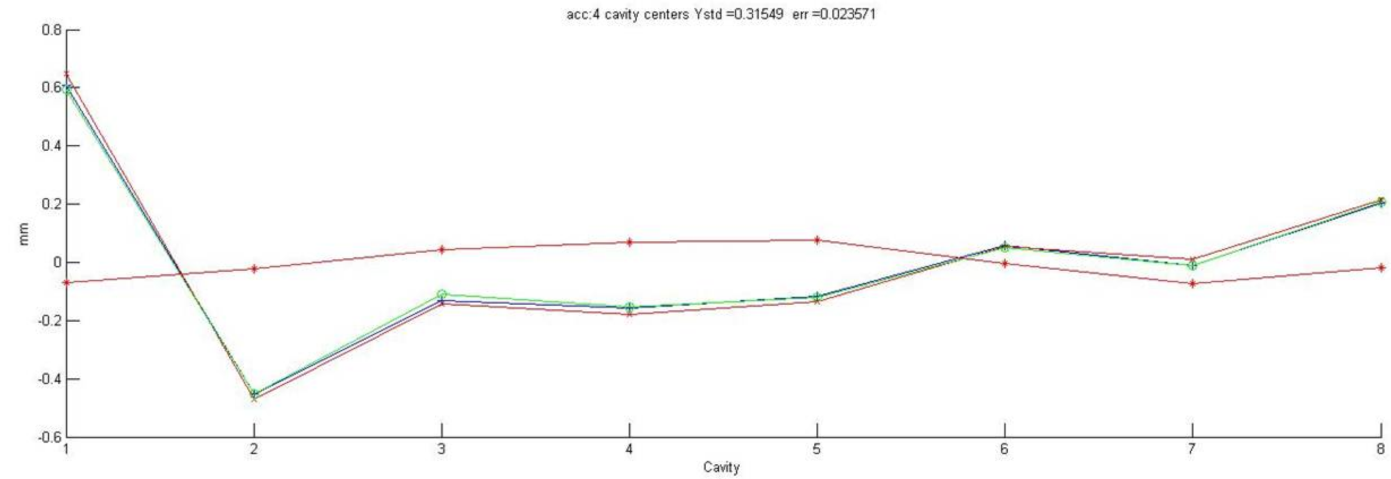
Energy in mode – $U = \beta \cdot \left(\frac{R}{Q} \right) \cdot \frac{\omega}{2} \cdot q^2$

Thermal noise – $U_{th} = \frac{1}{2} k_b T$

- Corresponds to a limit of ~165 nm
  - Included 10 dB cable losses, 6.5 dB noise figure, and 10 dB attenuator in electronics.
- Need good charge measurement to perform normalisation.
  - 0.1% stability of toroids, to achieve 1 um at 1 mm offset.
  - Not the case with the FLASH toroids.
- LO has a measured phase noise of ~1 degree RMS.
  - This will mix angle and position, and will degrade resolution.
  - LO and calibration tone have a similar circuit, and cal. tone has much better phase noise.
    - Therefore, should be simple to improve.

Cavity centre determination

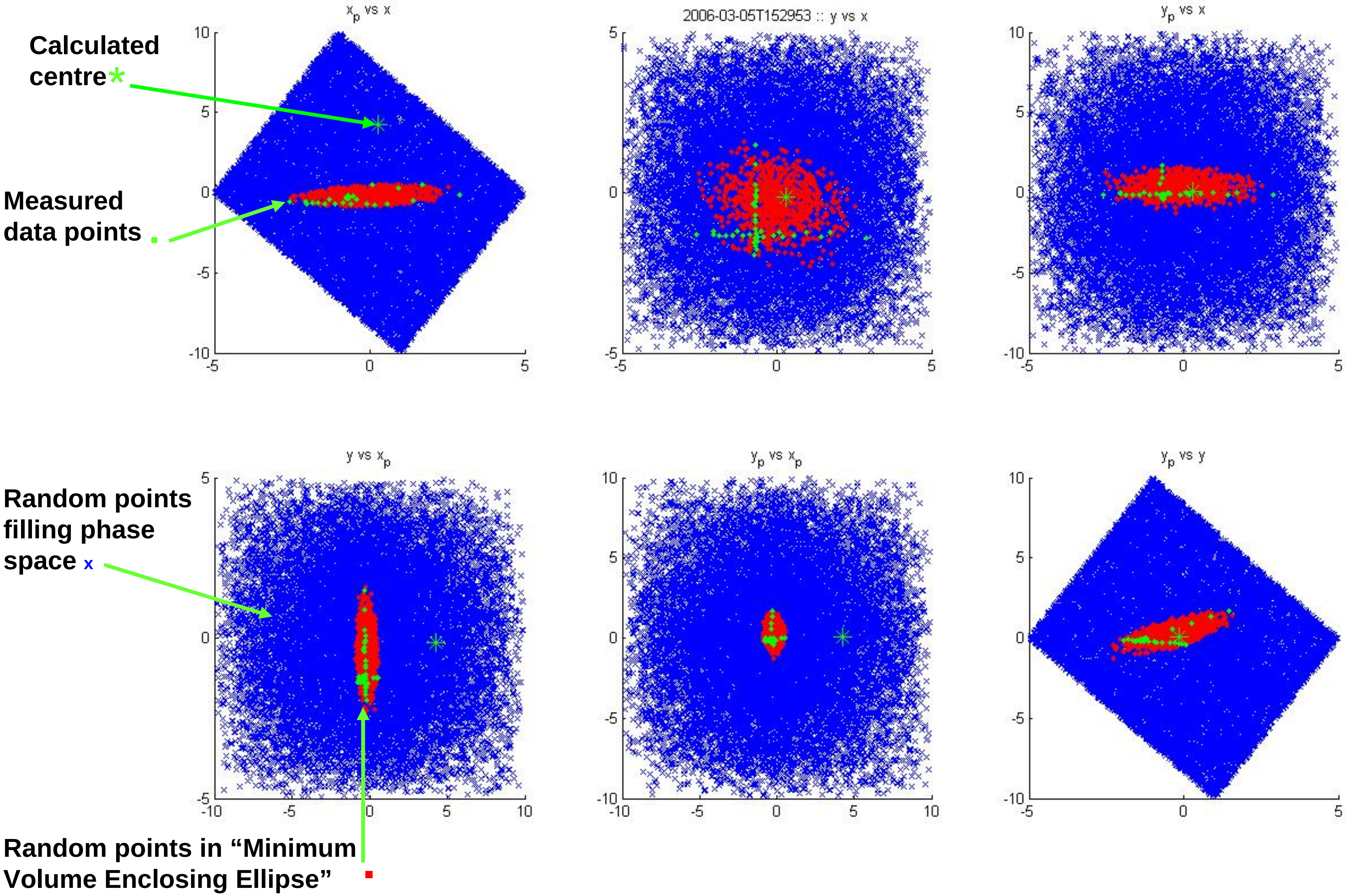




Cavity centre determination

- ACC4 alignment:
  - X: 105 um +- 37 um
  - Y: 215 um +- 24 um
- ACC5 alignment:
  - X: 241 um +- 9 um
  - Y: 203 um +- 5 um
- This calculation was performed using x and y offset data only. No angle information used.
  - It is necessary to use all 4 degrees of freedom.
  - Not enough of the x and y angle space was covered in previous data runs, resulting in noisy data.

Illustration of phase space



Summary

- HOMs are useful for diagnostic purposes.
  - Beamline hardware already exists.
  - Large proportion of linac occupied with structures.
- Cavity/Structure diagnostics.
  - Alignment of cavities within supercooled structure.
  - Possibility of exploring inner cavity geometry by examining HOM output and comparing to simulation.
- Beam diagnostics.
  - Accelerating RF and beam induced monopole HOM exist on same cable.
    - No effect from thermal expansion of cables.
    - Can find beam phase with respect to machine RF.
  - Dipole modes respond strongly to beam position.
    - Can use these to measure transverse beam position.
    - ~2 um demonstrated, (~165 nm thermal limit)
    - Large proportion of FLASH and ILC occupied by cavities, therefore this results in **many** extra high resolution BPMs for these machines.