HOM measurements at FLASH & SVD data analysis

12th December, 2007

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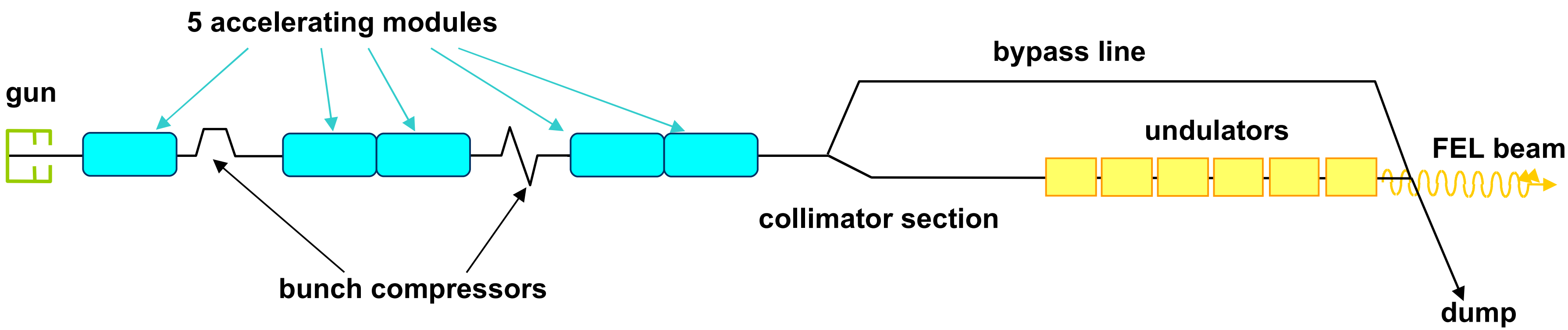
SLAC

Quick introduction to FLASH



- **1.3 GHz superconducting linac**
  - **5 accelerating modules during our runs.**
  - **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.**

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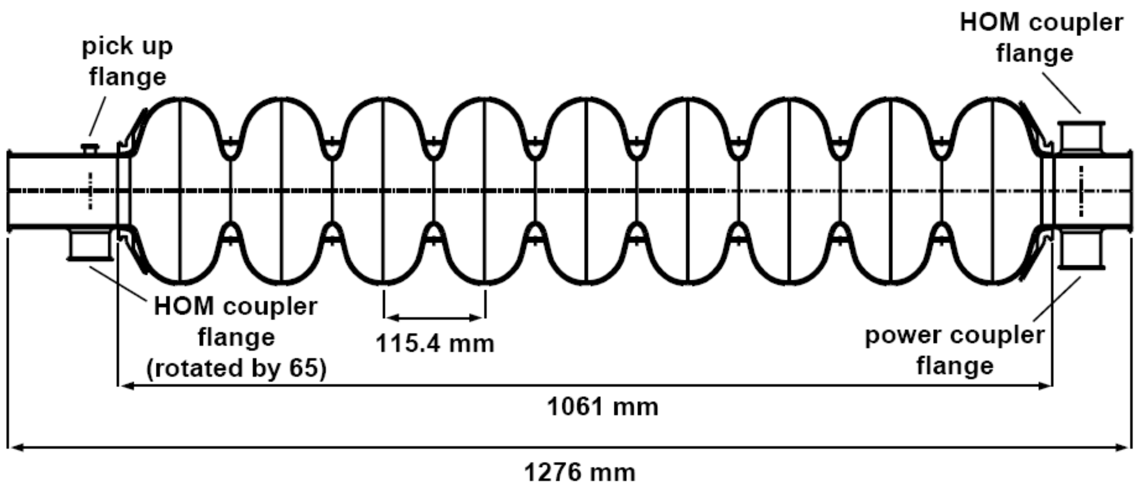
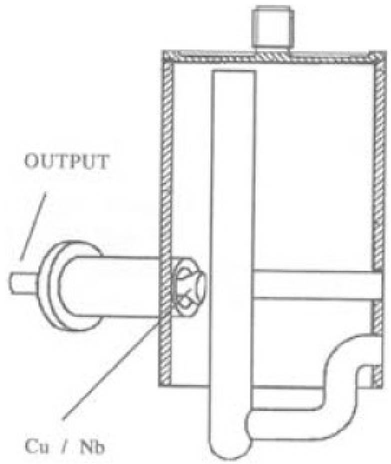
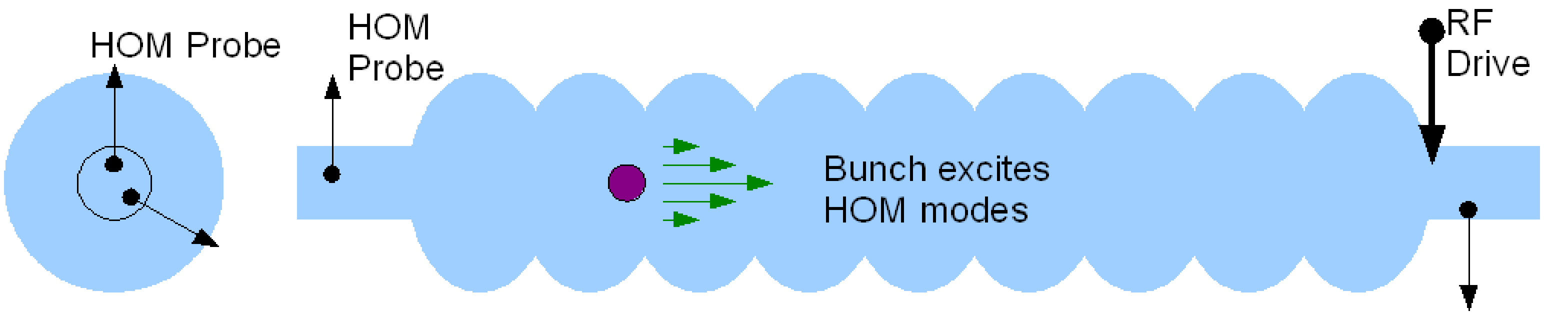
TESLA Cavities



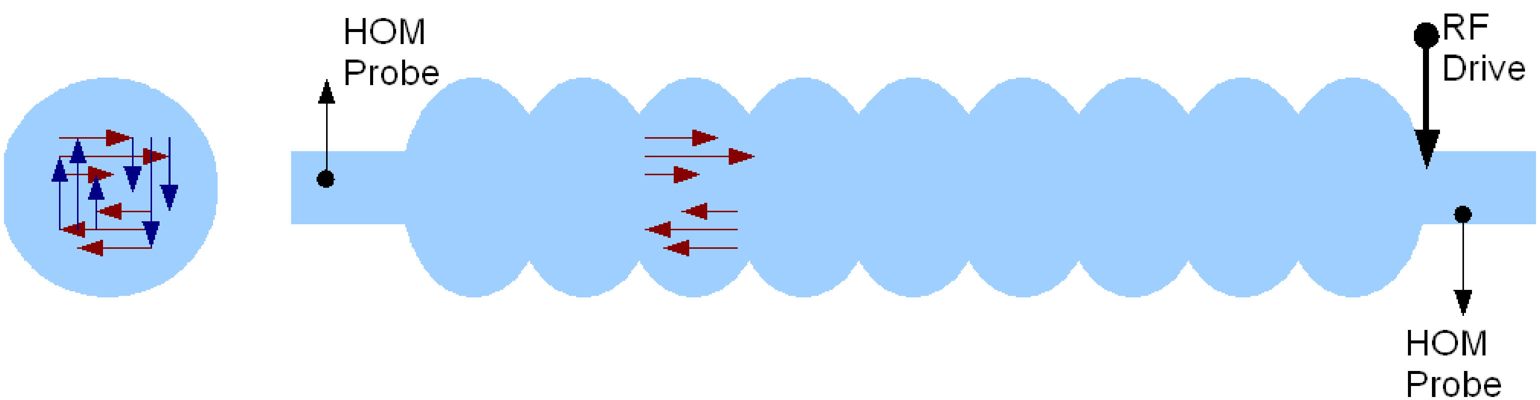


- **Nine cell superconducting cavities.**
- **1.3 GHz standing wave used for acceleration.**
- **Gradient of up to 25 MV/m.**
  - **Addition of piezo-tuners and improvement of manufacturing technique intended to increase this to ~35 MV/m.**
- **HOM couplers with a tunable notch filter to reject fundamental.**
  - **One upstream and one downstream, separated by 115degrees azimuthally.**
  - **Couple electrically and magnetically to the cavity fields.**

Response of HOM modes to beam

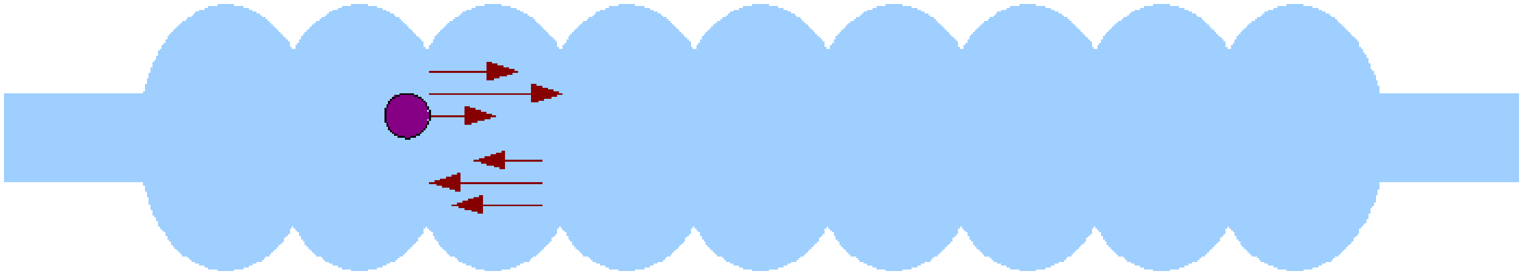


Monopole mode: Amplitude first order independent of beam position
Phase of mode determined by bunch arrival time

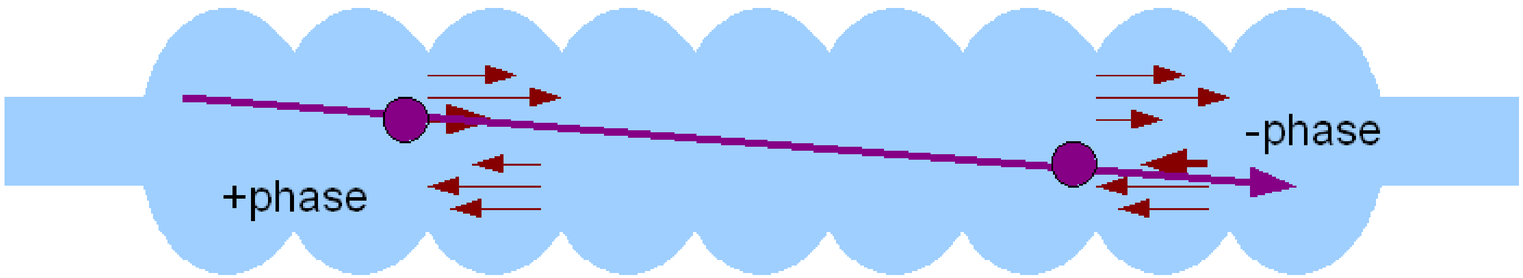


Dipole Modes: Each mode has 2 polarizations
Frequencies degenerate for ideal cavities
Frequency degeneracy broken by power coupler and fabrication errors

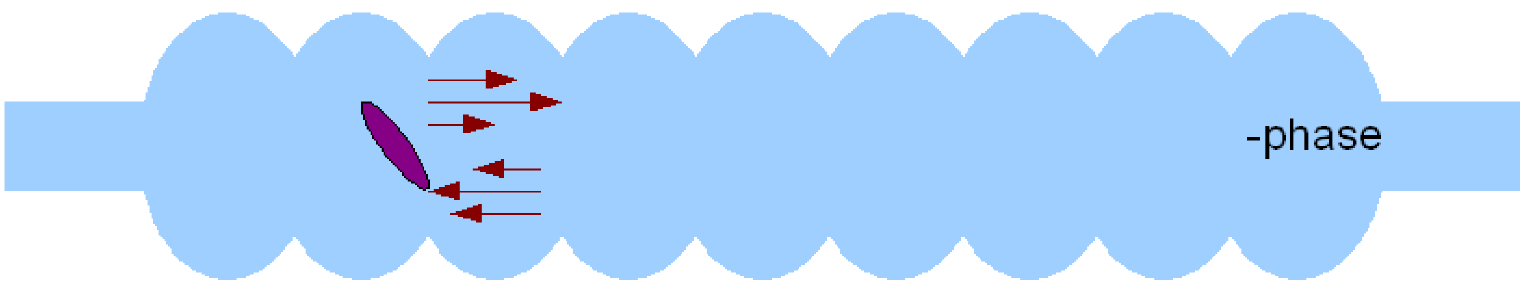
If frequency splitting is < line width, Need both couplers to separate polarizations



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~~)

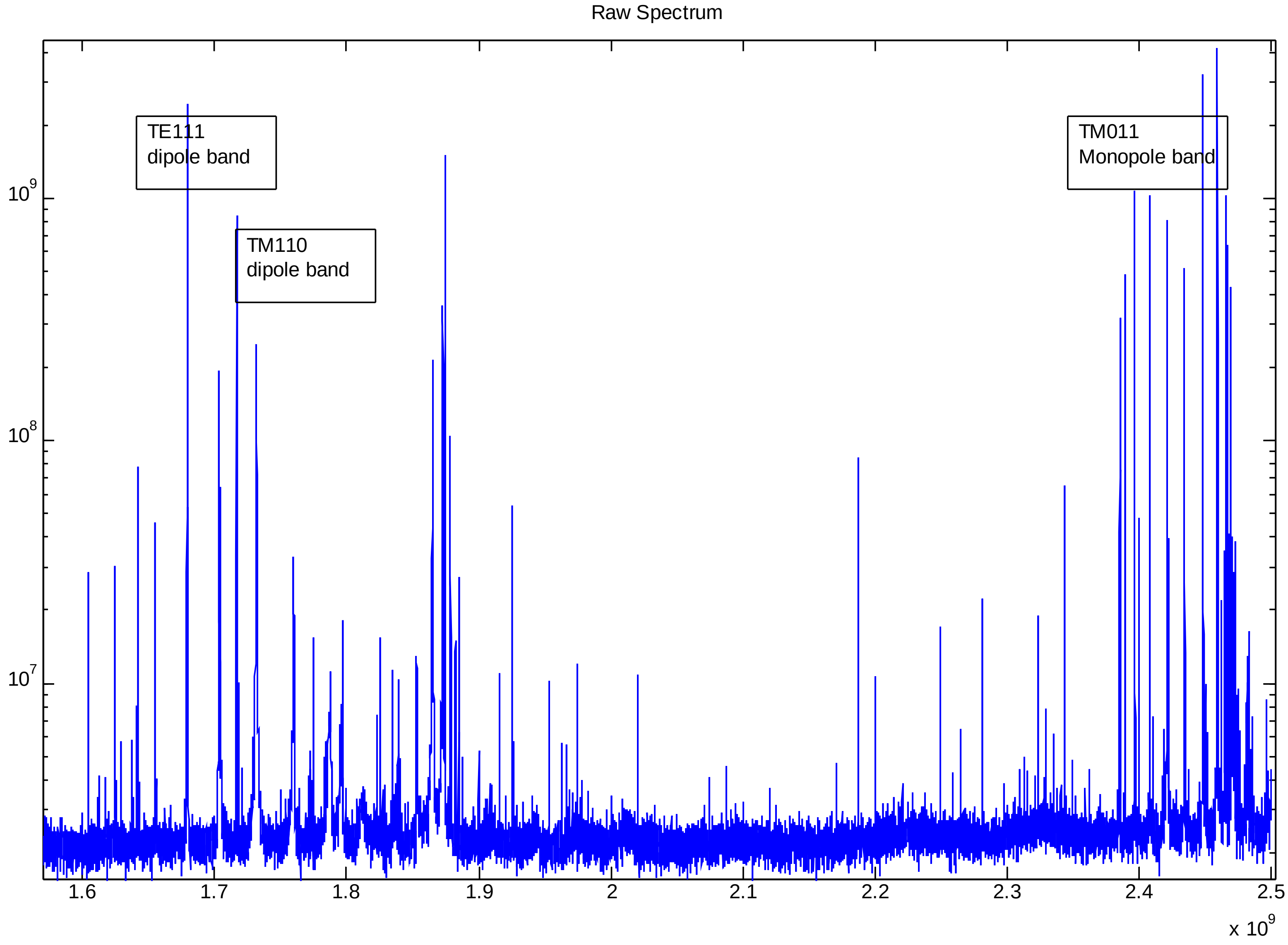


Tilted bunch will also excite signal at 90 degrees, amplitude proportional to bunch length and tilt: Not significant for short TTF bunches

Higher Order Modes

- The 9 cells of the cavities act like coupled resonators.
  - Each standard mode can have 9 different longitudinal distributions.
    - i.e. Different passbands with 9 modes each.
  - Modes distinguished by differing phase advance per cell.
- Modes synchronous with the beam (i.e. phase velocity = *c*) have strongest coupling to the beam,
  - Indicated by a large R/Q.
- 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.

Sample HOM Spectrum



HOMs as a Beam Diagnostic

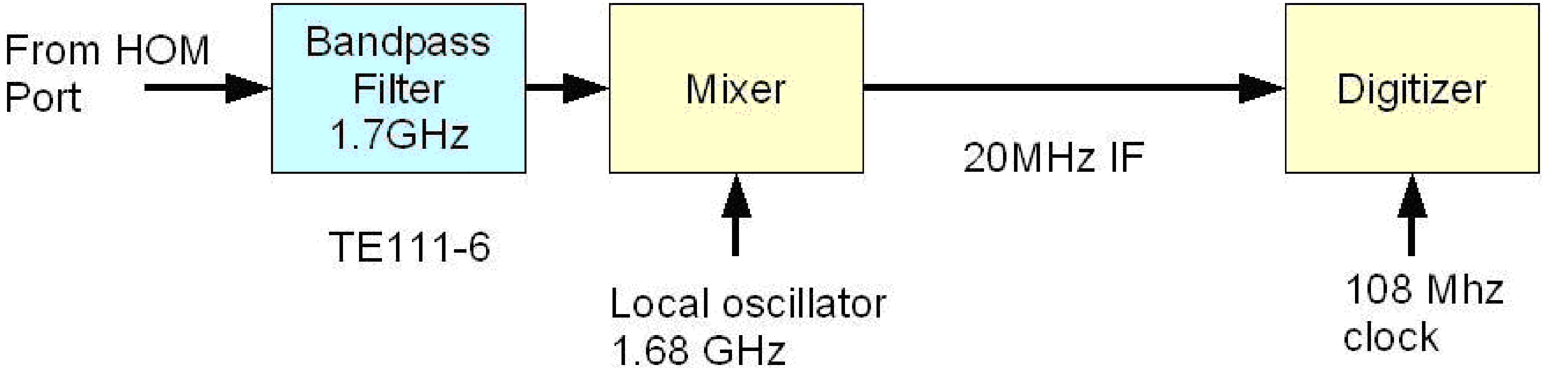
- **Beam Position Monitoring**
  - **Dipole mode amplitude is a function of the bunch charge and transverse offset.**
  - **Exist in two polarisations corresponding to two transverse orthogonal directions.**
    - Not necessarily coincident with horizontal and vertical directions due to perturbations 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 HOM monopole mode.**

Benefits of using HOMs as Diagnostics

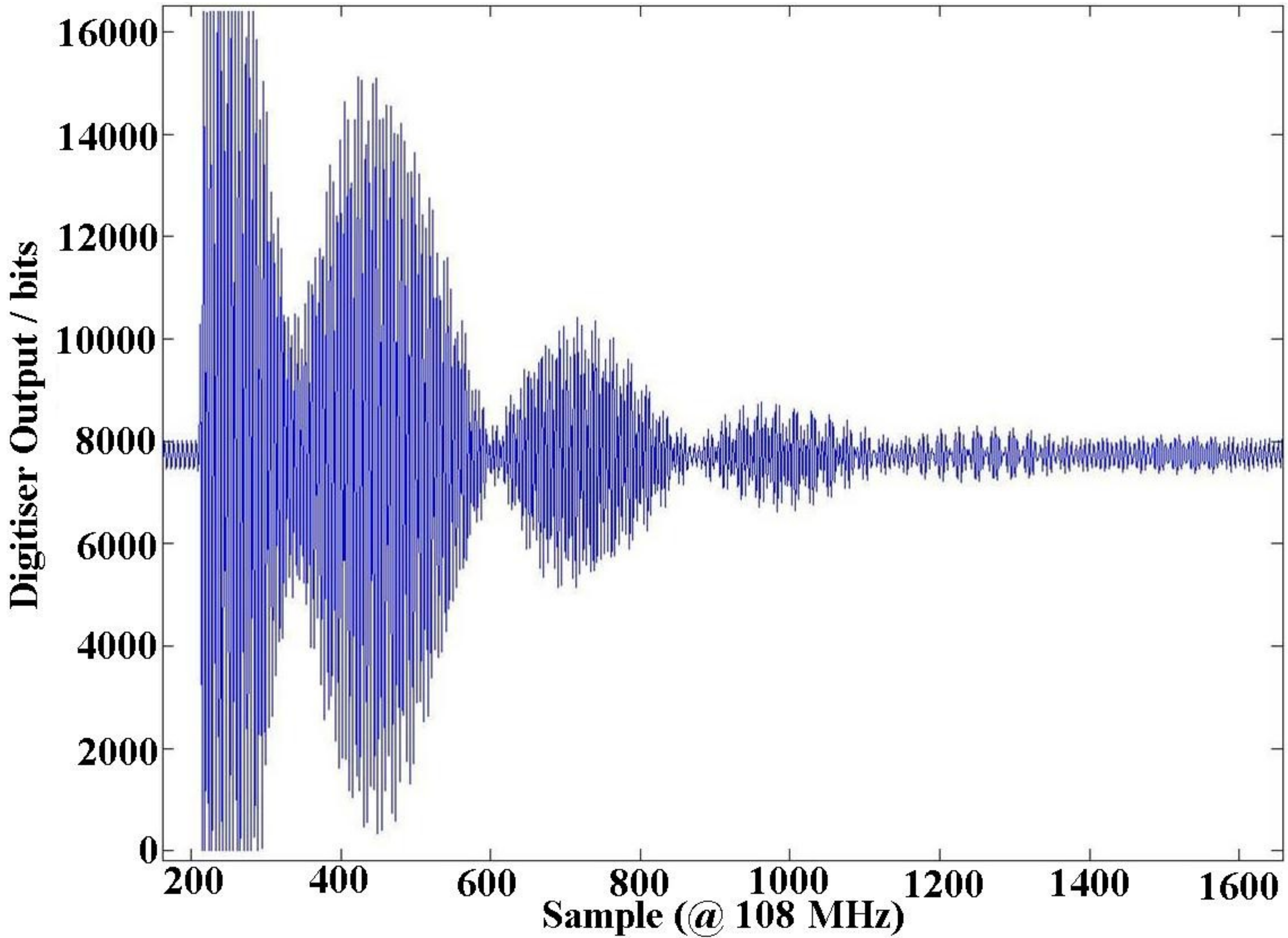
- No need to install new beamline hardware
  - HOM power must be coupled out of the cavities to prevent BBU, etc.
  - Therefore beamline and cryogenic hardware already exists.
- Large proportion of linac length occupied by structures.

Dipole Mode Measurement

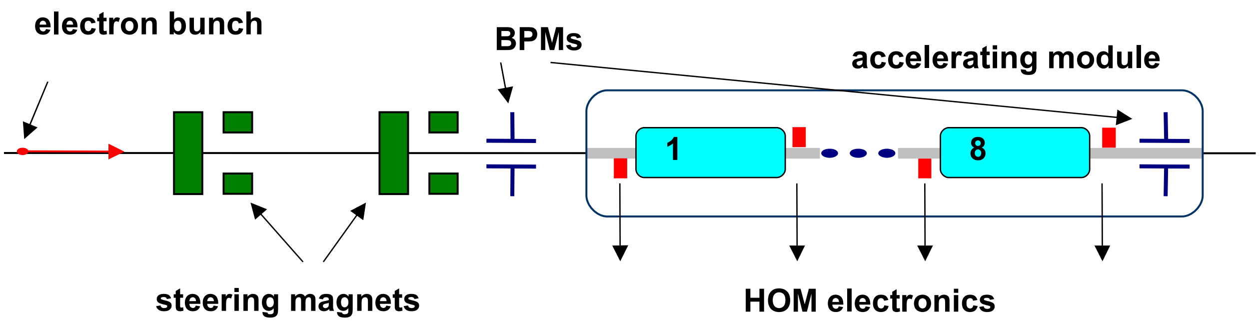
- **Simulations show that the 6th mode in the 1st passband has a strong coupling to the beam,**
  - **R/Q = ~5.5 Ohms/cm^2**
  - **Frequency = ~1.7 GHz**
- **Design narrow band electronics to observe this mode only.**
  - **Filter around 1.7 GHz (20 MHz bandwidth)**
  - **Mix with 1.679 GHz LO**
  -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



Example Waveform



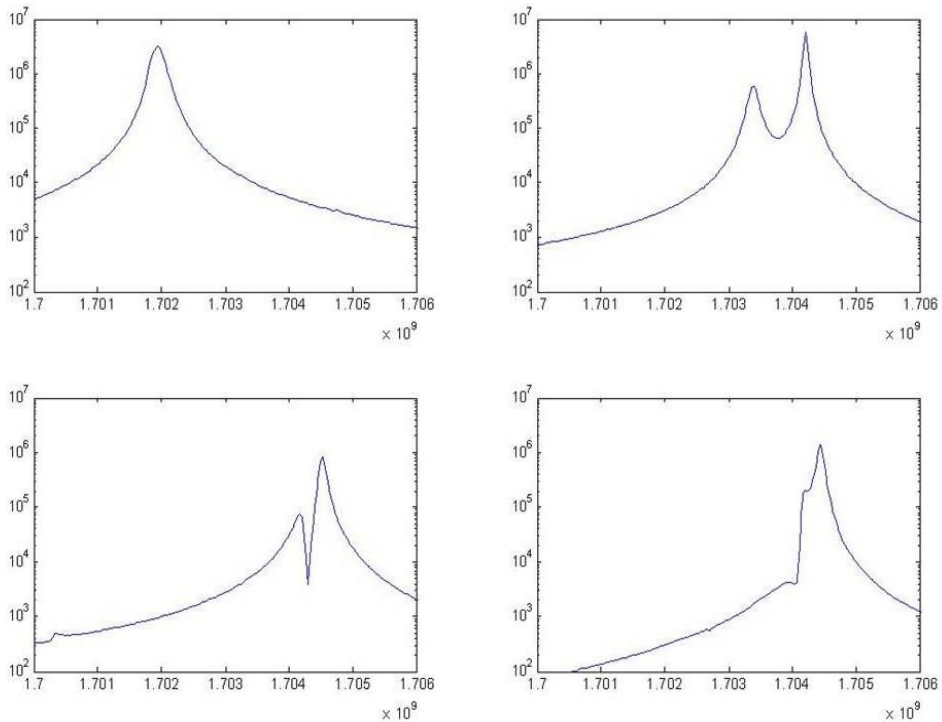
HOM calibration method



- 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.

Standard Analysis

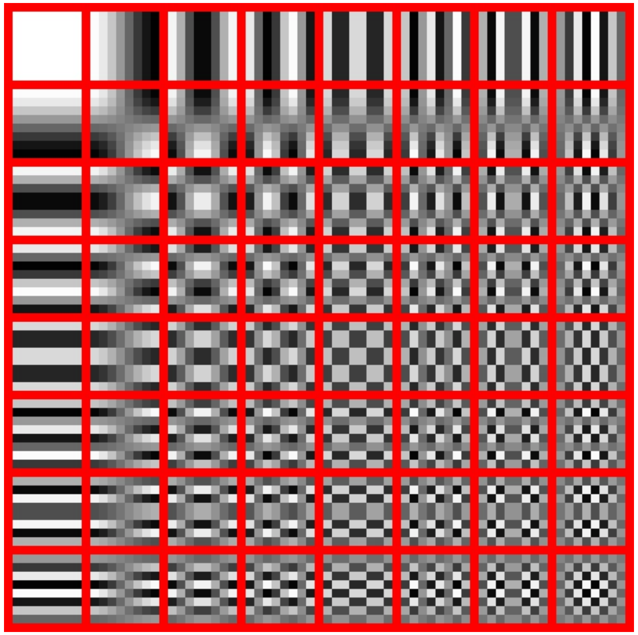
- **Measure amplitude and phase at peak frequency of each polarisation.**
- **Correlate with position interpolated from BPMs.**



- Problematic due to varying degrees of frequency degeneracy in the cavities.
  - Simple to determine 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.

JPEG encoding – Using "modes" to represent data

- The bitmap is split into 8x8 blocks.
- Each block is compared with the official JPEG modes.
  - The amplitude of each mode can be found for each block.
- 64 numbers now used to represent each block.
  - Compression is achieved by discarding high frequency information.



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 a Model Independent Analysis.

How does SVD calculate modes?

Definition: $X \equiv U \cdot S \cdot V^T$

U and *V* are unitary. *S* is diagonal.

Therefore → $X^T \cdot X = V \cdot S \cdot U^T \cdot U \cdot S \cdot V^T$

$X^T \cdot X = V \cdot S^2 \cdot V^T$

Autocorrelation matrix

How does SVD calculate modes?

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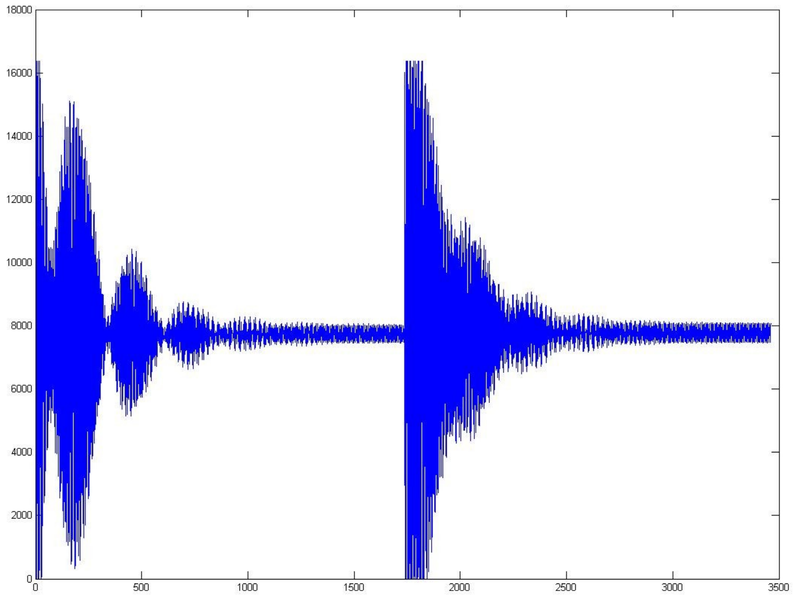
U and *V* are unitary. *S* is diagonal.

Therefore → $X^T \cdot X = V \cdot S \cdot U^T \cdot U \cdot S \cdot V^T$

$$X^T \cdot X = V \cdot S^2 \cdot V^T$$

Eigenvalue equation

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)

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Using SVD (1)

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

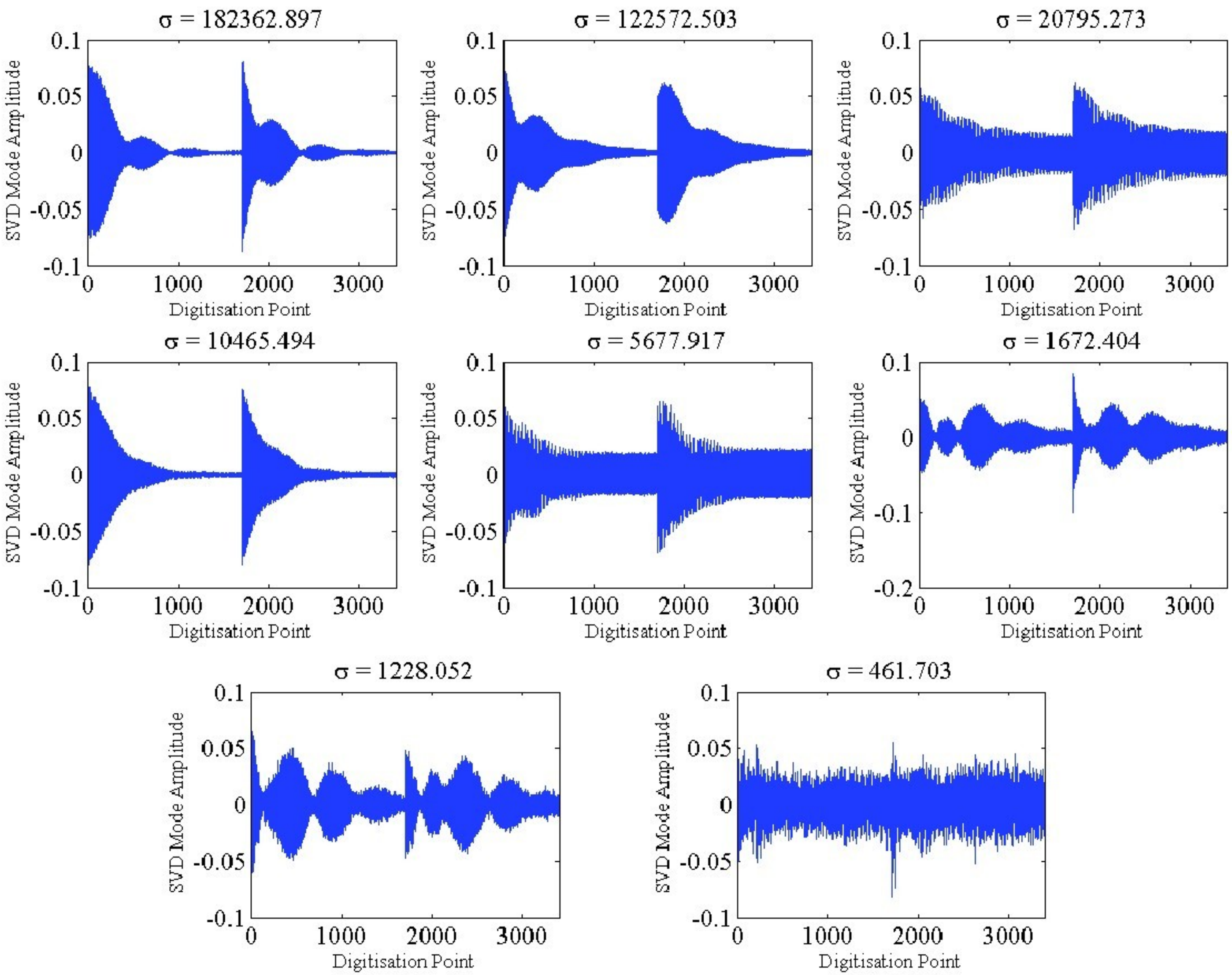
- **Using SVD on the (n x j) cavity output matrix, *X*, produces three matrices.**
  - ***U*** **(n x j),** ***S*** **(j x j, diagonal), and** ***V*** **(j x j)**
- ***V*** **contains** ***j*** **modes.**
  - **These are the orthonormal eigenvectors.**
  - **“Intuitive” modes will be linear combinations 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.**
- ***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.**
- **It can be shown that the largest *k* eigenvalues found by SVD are the largest** possible **eigenvalues.**
- **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 to do the calculation.**

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

Example modes (acc5, cav5)



Calibrating HOMs (1)

- **Steer beam in x, x', y, and y'.**
  - **An optics model now exists for TTF, so it's possible to 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.**

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

Calibrating HOMs (2)

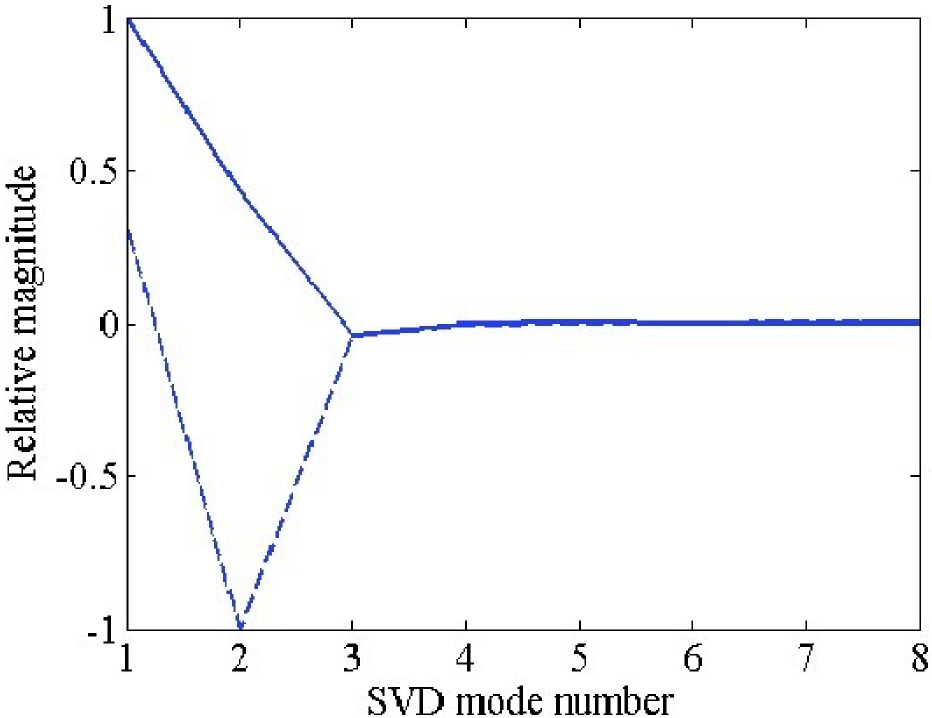
$$\begin{pmatrix} M_{11} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & M_{1,k+1} \\ \vdots & & & & & & & & \vdots \\ M_{41} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & M_{4,k+1} \end{pmatrix} \cdot \begin{pmatrix} A_{11} & \cdots & \cdots & \cdots & A_{1n} \\ \vdots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

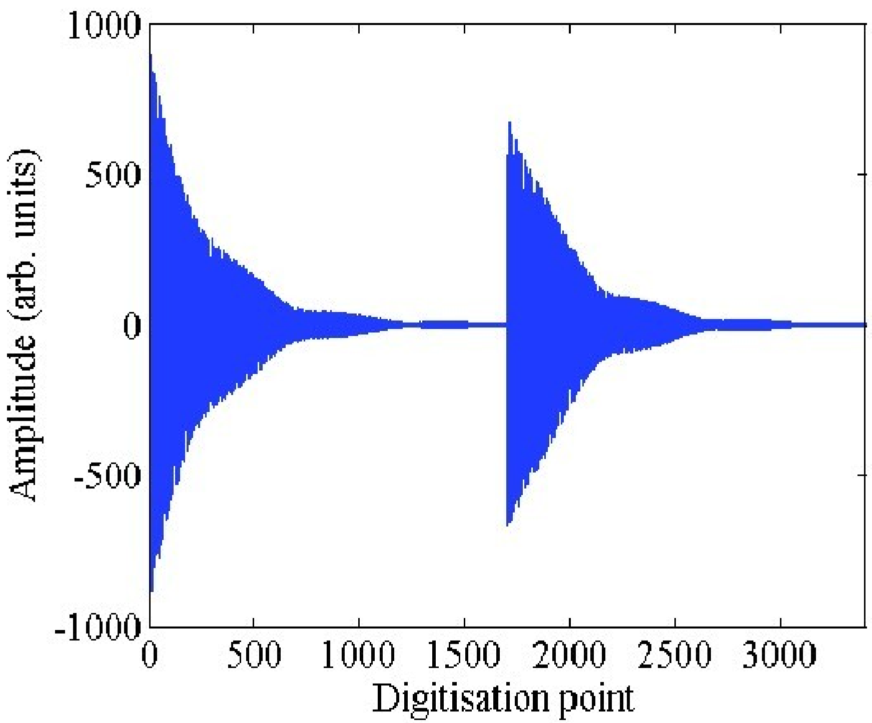
- **Regress the mode amplitudes, *A,* against beam position & angle.**
  - **Position/angle interpolated from adjacent BPMs.**
- **The slash operator performs a least-squares fit to the data**
  - **Results in a (4 x (*k*+1)) calibration matrix, *M*.**

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

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…

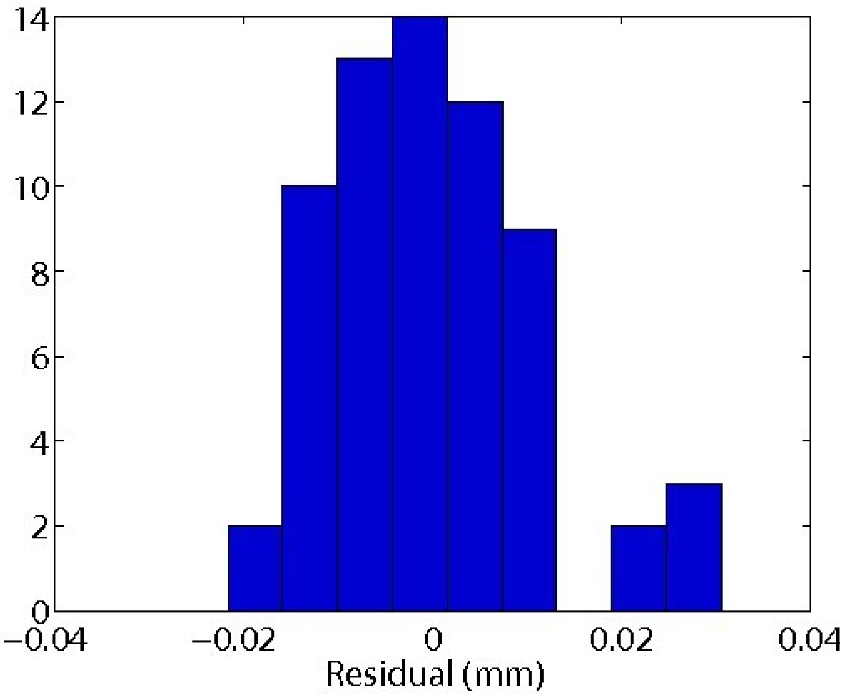




Resolution

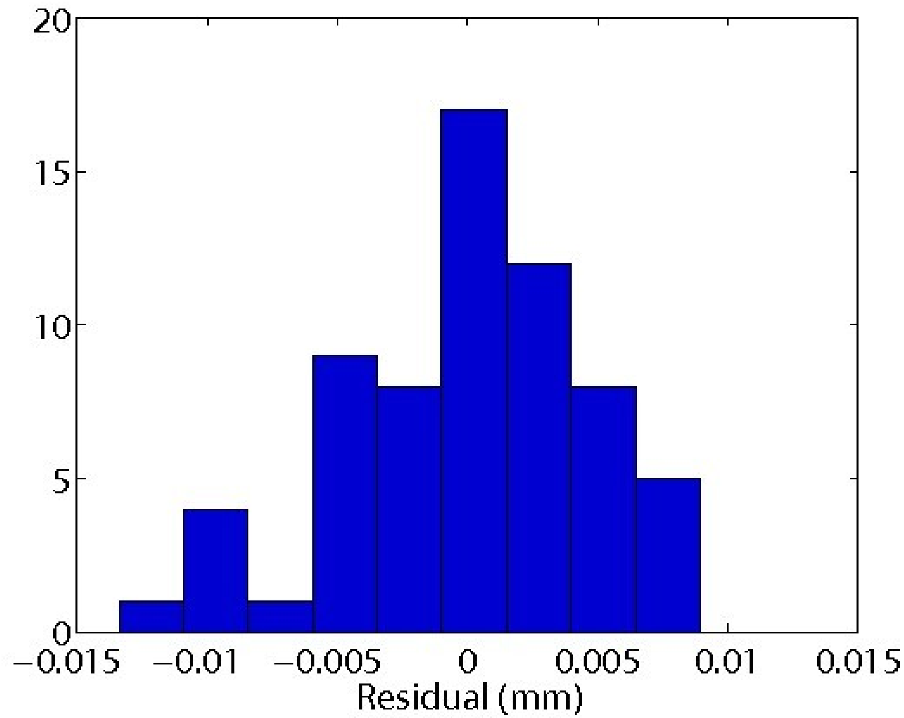
- **Standard resolution calculation technique**
- **Calibrate against position and angle in both planes.**
  - **Straight line interpolation between BPMs.**
    - Incorrect for ACC1 due to significant energy gain…
  - **Angle calibrated against beam trajectory.**
    - Bunch tilt (if any) will appear as the mean of the residuals.

Distribution of (position) Residuals



X Measurement:
RMS = 11 microns

Resolution == 9 microns

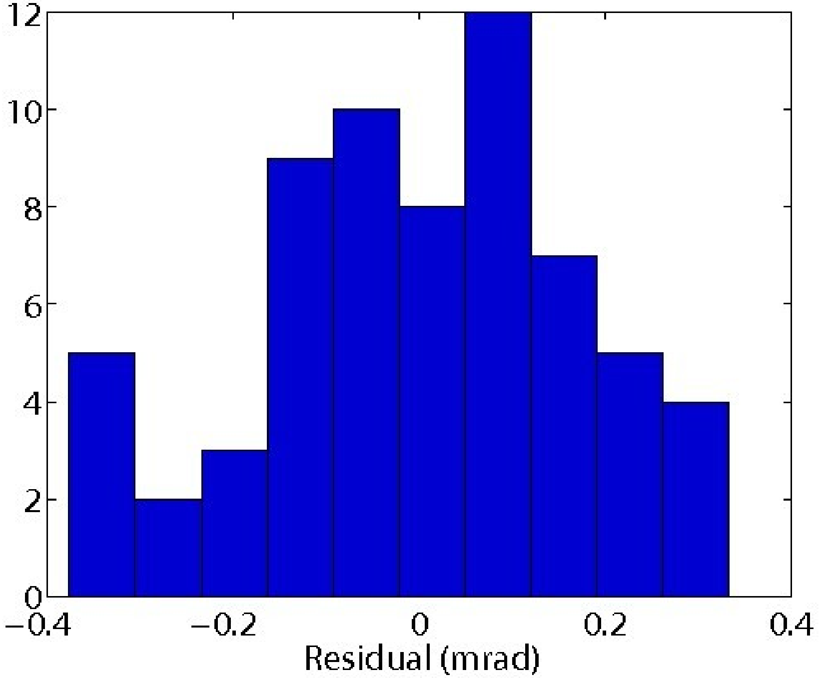


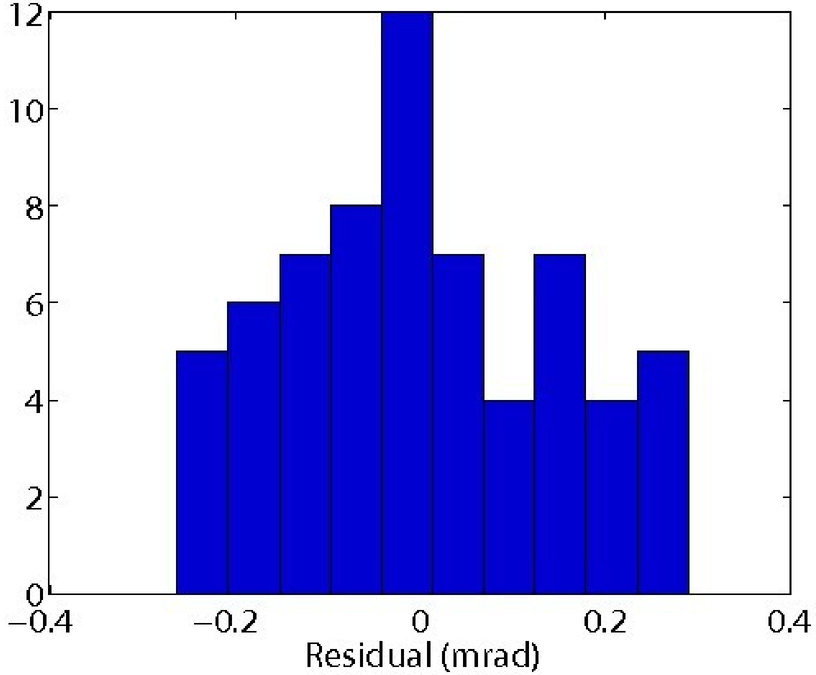
Y Measurement:
RMS = 5 microns

Resolution == 4 microns

Note: No cavity-related reason for better y resolution. Simply due to lower beam jitter and better BPM resolution in that plane.

Distribution of (angle) Residuals





X' Measurement:

Resolution == 175 microrad

Y' Measurement:

Resolution == 140 microrad

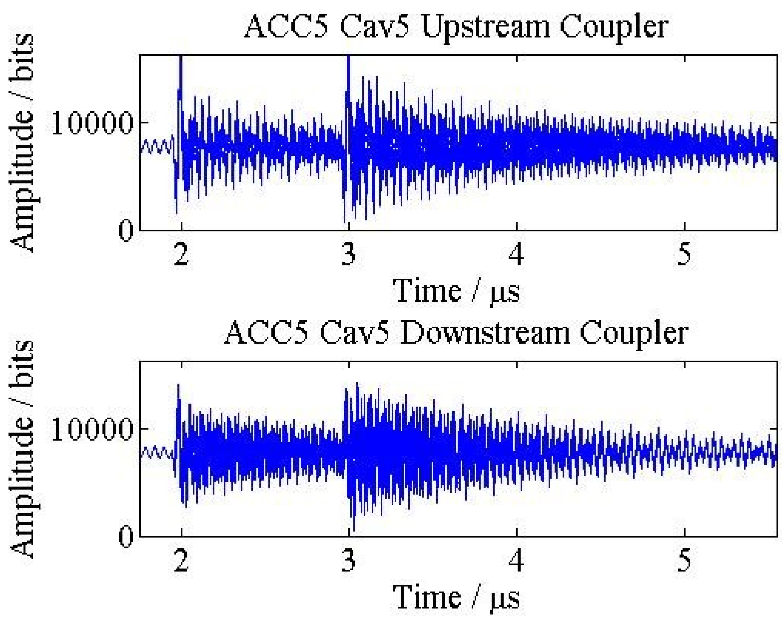
Theoretical Resolution

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

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

- Corresponds to a limit of ~65 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.

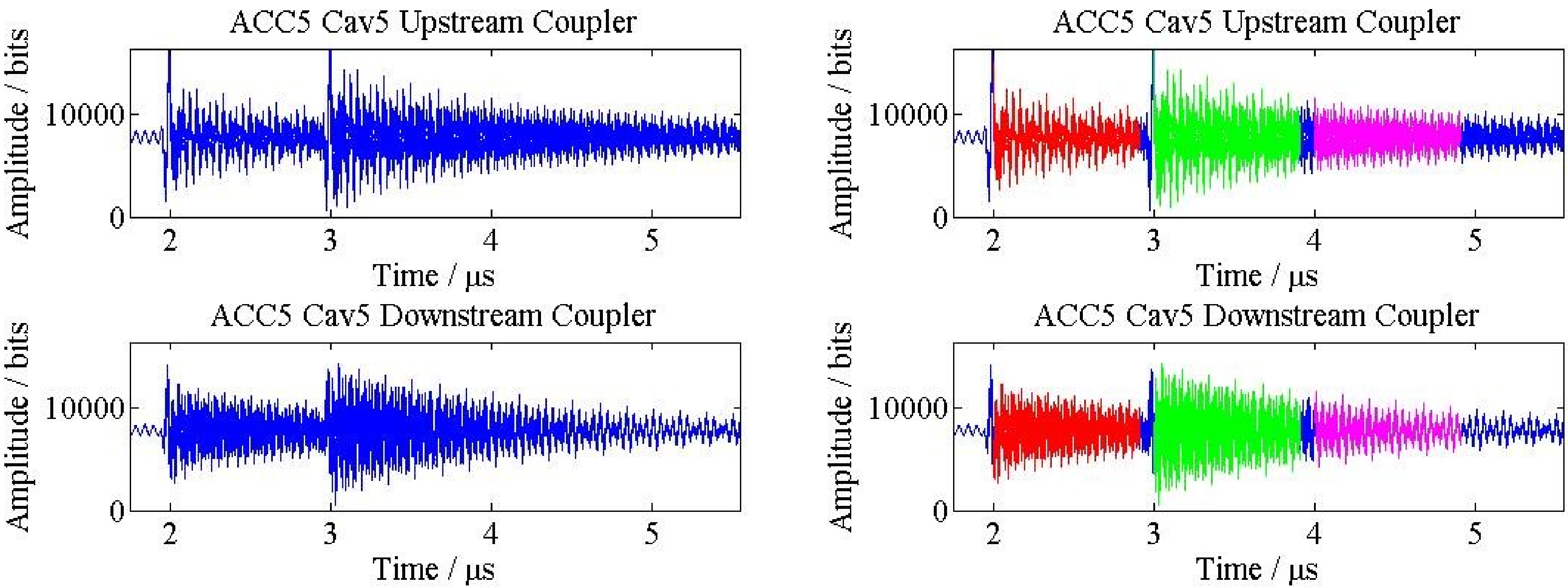
Multi-bunch operation



- **HOM decay time**
  - **a few µs**
- **Interbunch spacing**
  - **ILC: ~300 ns**
  - **FLASH (minimum): 1 µs**
- **HOM signals will interfere**
  - **If constructive, then the strong resonant signal will saturate the electronics.**
    - Cavity design will try to avoid resonances
  - **Can bunch-by-bunch info be extracted?**

Calibrating multi-bunch

- **How to unwind each bunch from interfering signals?**
  - **Subtract the effect of previous bunches one by one?**
    - No! Results in large errors!
- **Use the single-bunch SVD modes.**
  - **Measure the single bunch mode amplitudes in one time window.**
  - **Measure the mode amplitudes in the second time window**
    - **No beam in this window!**
  - **Calculate the transformation matrix**


ACC5 Cav5 Upstream Coupler
Amplitude / bits
Time / µs
ACC5 Cav5 Upstream Coupler
Amplitude / bits
Time / µs
ACC5 Cav5 Downstream Coupler
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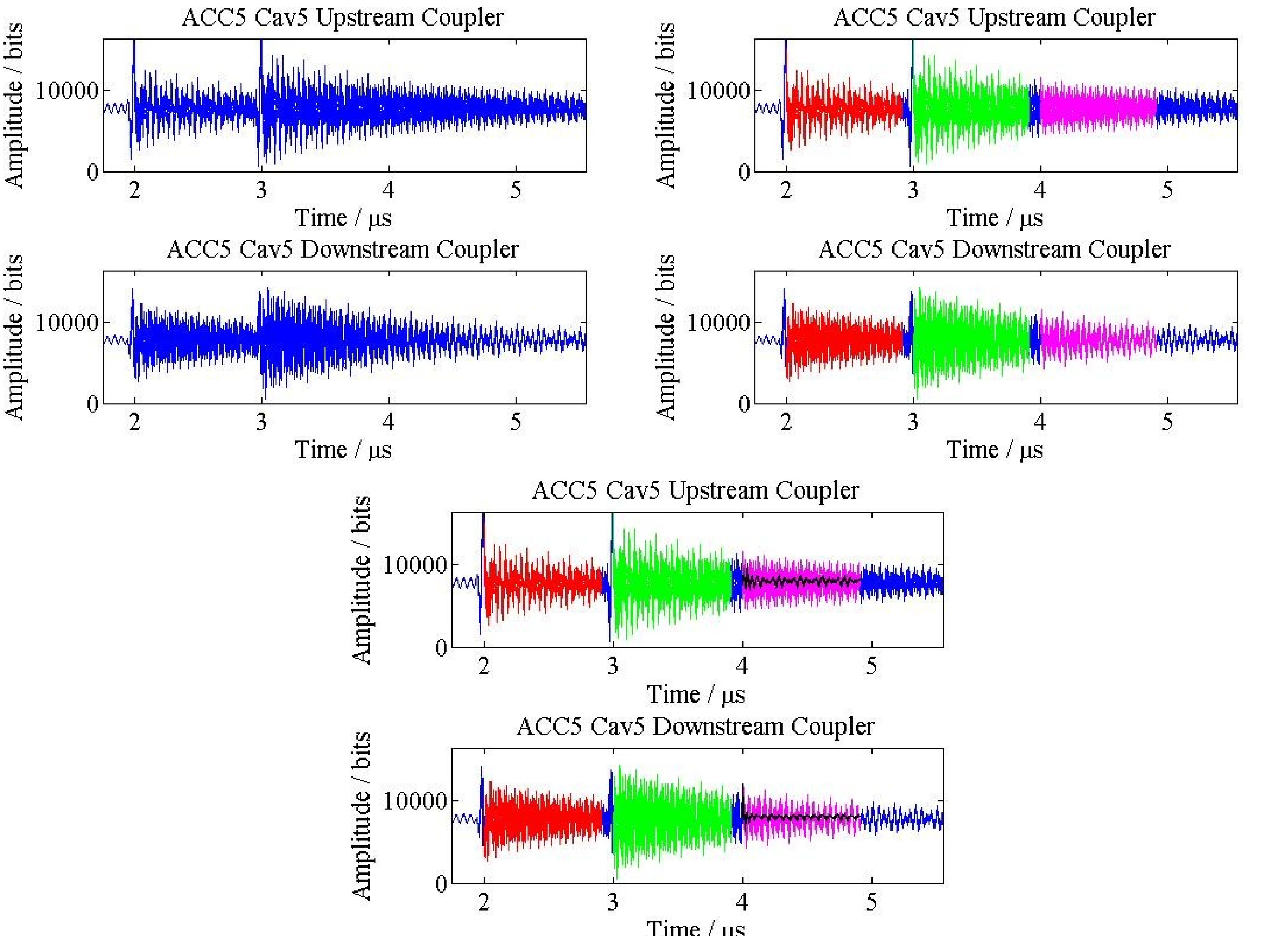
Time / µs
ACC5 Cav5 Downstream Coupler
Amplitude / bits
Time / µs


ACC5 Cav5 Upstream Coupler
Amplitude / bits
Time / µs
ACC5 Cav5 Upstream Coupler
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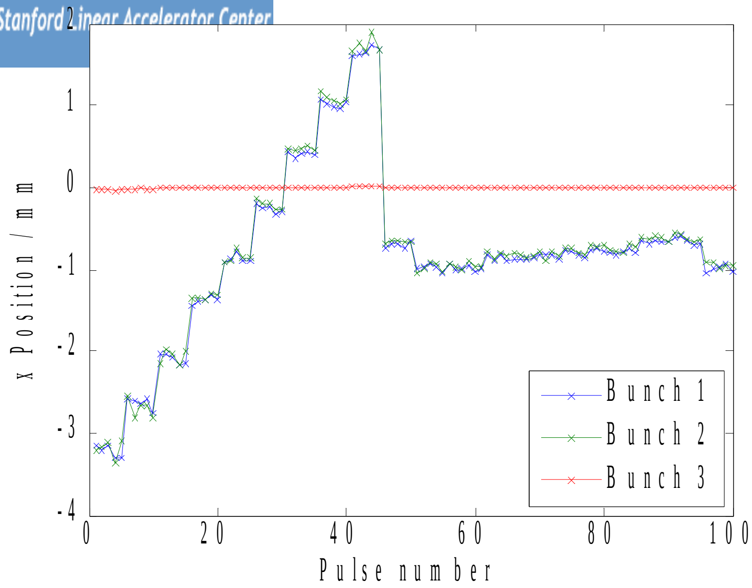
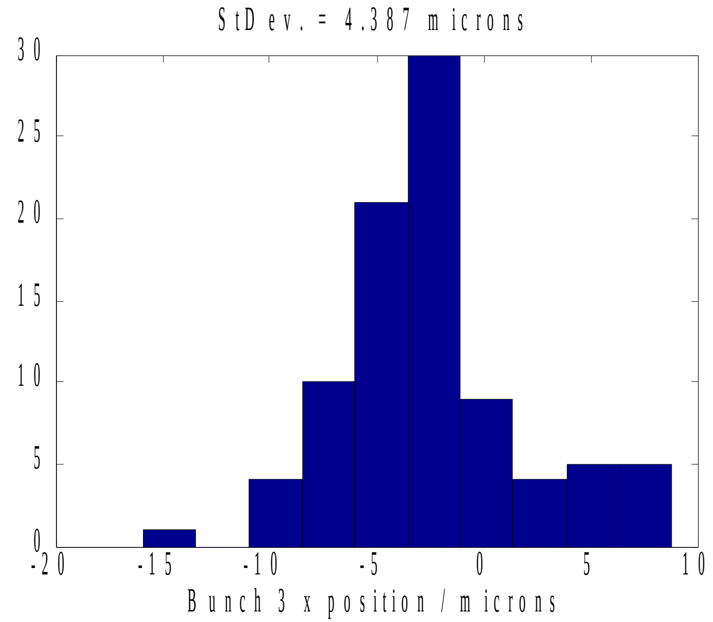
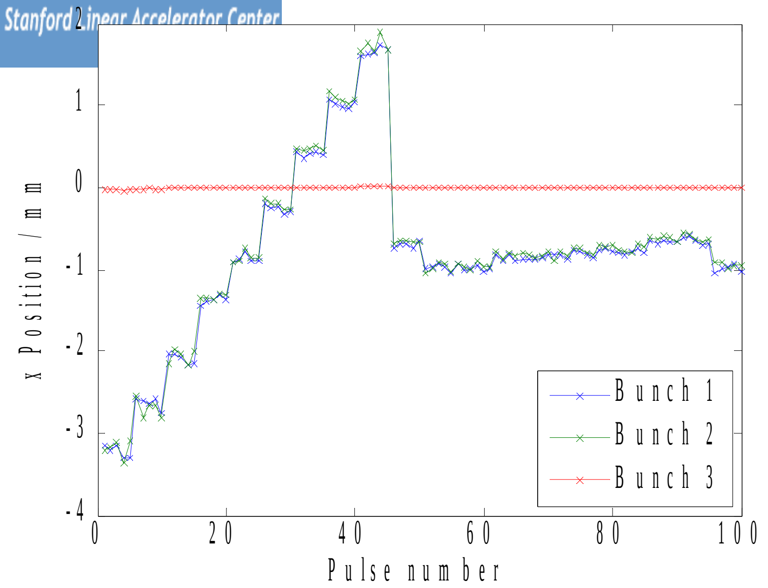
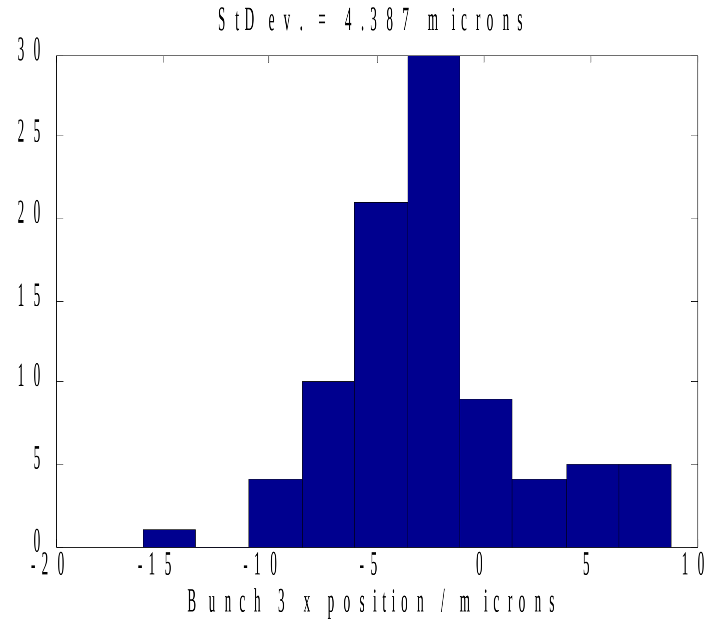
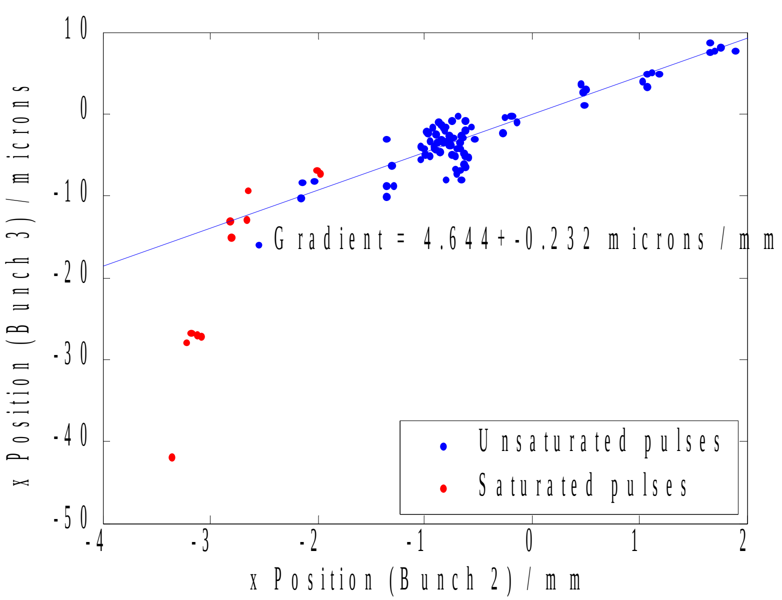
Amplitude / bits
Time / µs

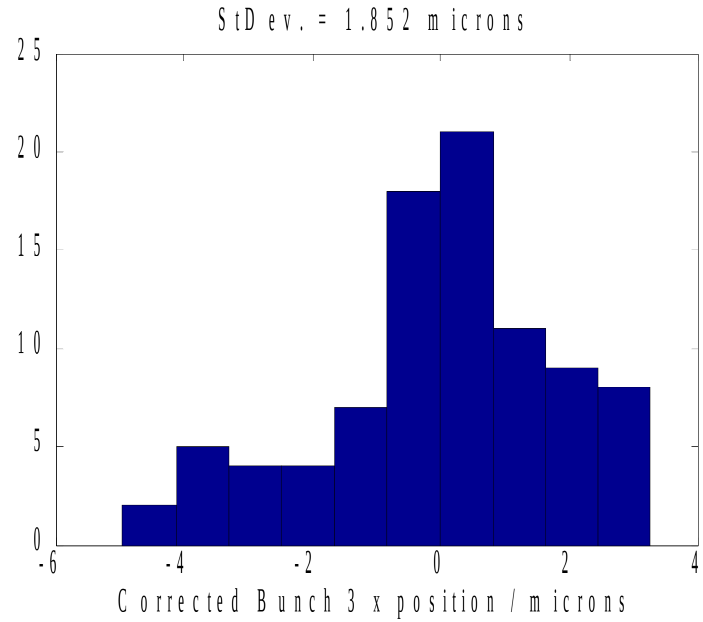

x Position / mm
Pulse number
Bunch 1
Bunch 2
Bunch 3
2
1
0
-1
-2
-3
-4
0
20
40
60
80
100


StDev. = 4.387 microns
Bunch 3 x position / microns
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10


x Position / mm
Pulse number
Bunch 1
Bunch 2
Bunch 3


StDev. = 4.387 microns
Bunch 3 x position / microns


x Position (Bunch 3) / microns
x Position (Bunch 2) / mm
Gradient = 4.644+-0.232 microns / mm
Unsaturated pulses
Saturated pulses


StDev. = 1.852 microns
Corrected Bunch 3 x position / microns

Summary

- HOMs have been used to monitor the position of the FLASH beam
- Due to their potentially destructive nature, these modes must be coupled out anyway
  - Thus, beamline hardware already exists
- "Standard" cavity analysis is troublesome (please see next talk)
  - SVD provides a way to extract the information
- Analysis works for multibunch beam
  - Despite high Q / short interbunch time
- Successfully implemented at FLASH as part of their control system

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High precision SC cavity alignment measurements with higher order modes

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Abstract
Experiments at the FLASH linac at DESY have demonstr
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Keywords: higher order modes, BPM, superconducting ca

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High precision superconducting cavity diagnostics with higher order mode measurements

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Experiments at the FLASH facility at DESY have demonstrated that the higher order modes induced in superconducting cavities can be used to provide a variety of beam and cavity diagnostics. The axes of the modes can be determined from the beam orbit that produces minimum power in the dipole HOM modes. The phase and amplitude of the dipole modes can be used to obtain high resolution beam position information, and the phase of the monopole modes to measure the beam phase relative to the accelerator rf. For most superconducting accelerators, the existing higher order mode couplers provide the necessary signals, and the downmix and digitizing electronics are straightforward, similar to those for a conventional beam position monitor.

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