Measurement of the beam's trajectory using the higher order modes it generates in a superconducting accelerating cavity.

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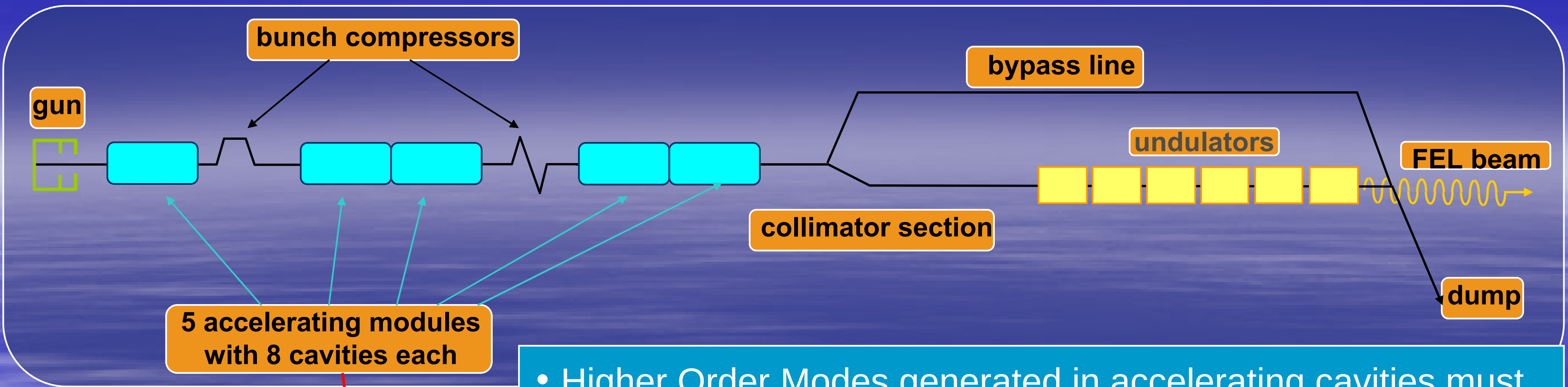
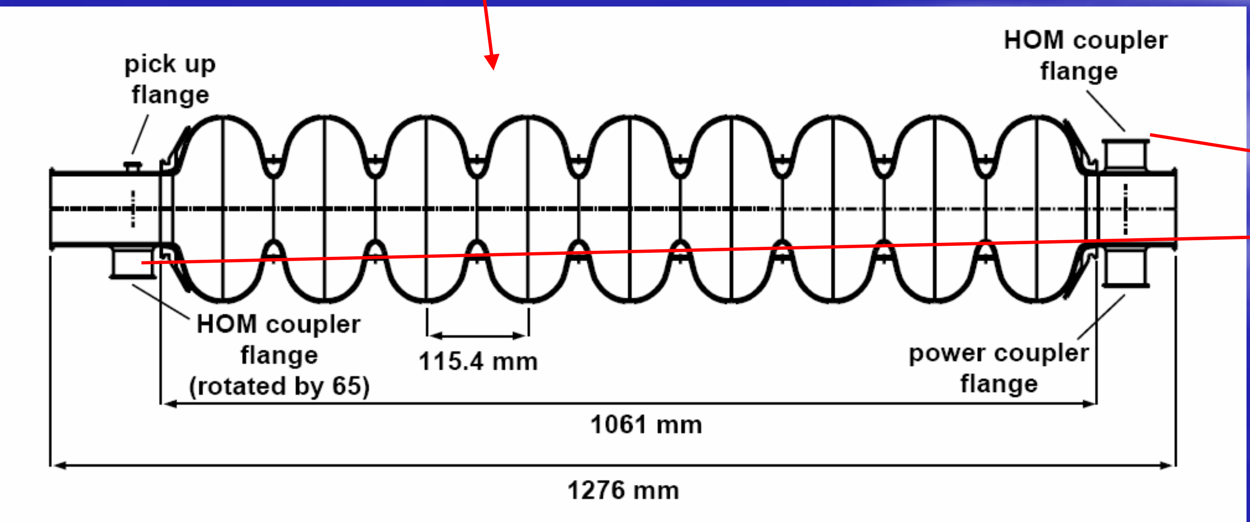
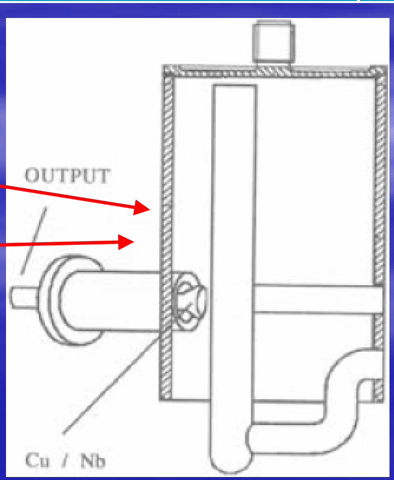
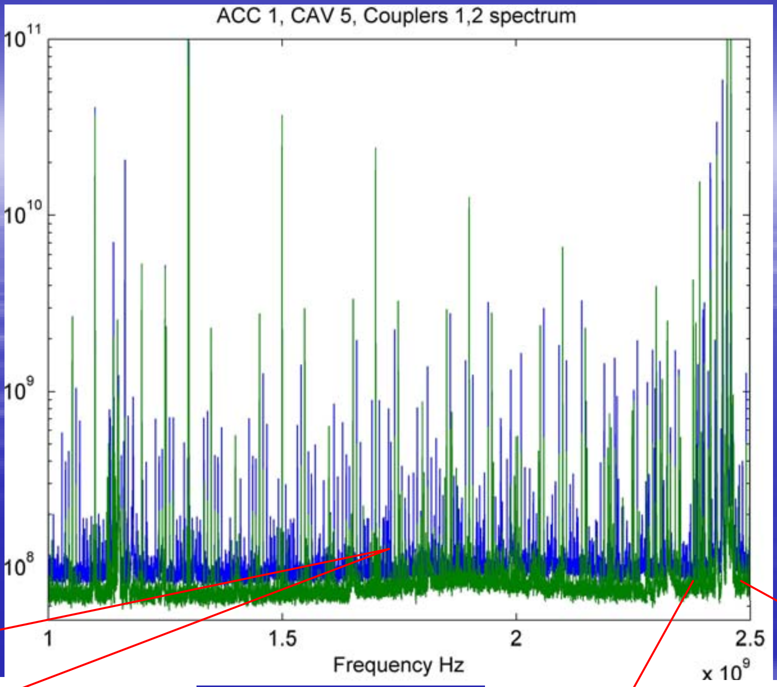


- Higher Order Modes generated in accelerating cavities must be damped.
- These HOMs may also be monitored to obtain beam/cavity information.
- Forty cavities exist at FLASH.
  - Couplers/cables already exist.
  - Electronics installed to monitor HOMs (wideband and narrowband response).



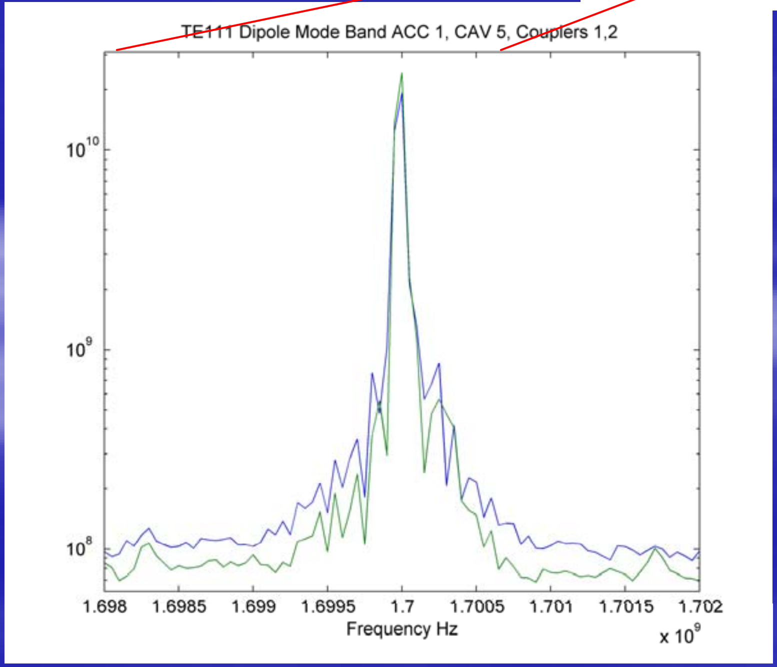


HOM Signals

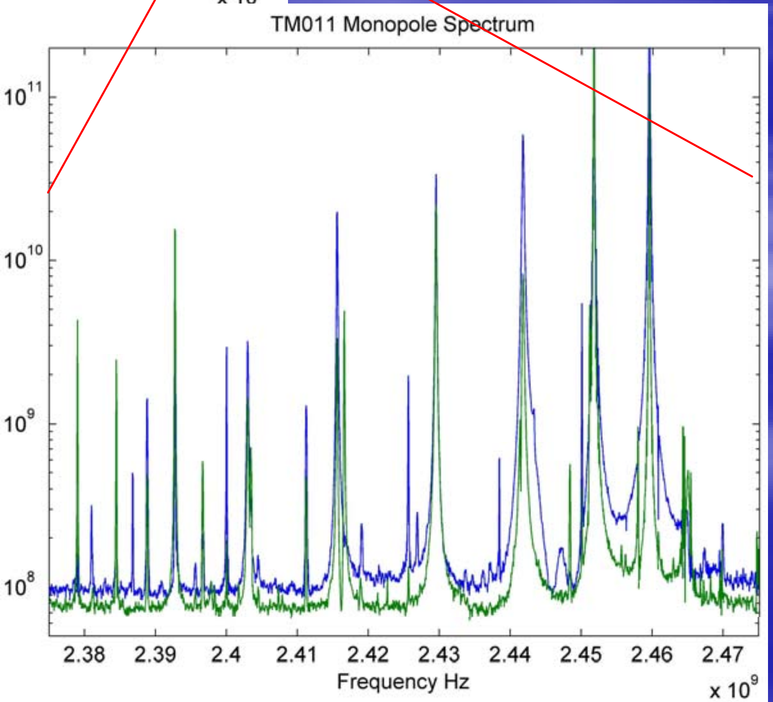


Broadband system data

Dipole Mode 1.7GHz
4 MHz frequency span shown

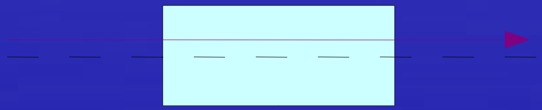


Monopole Modes
100 MHz frequency span shown

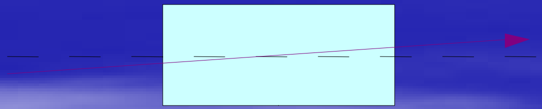


Beam Measurements

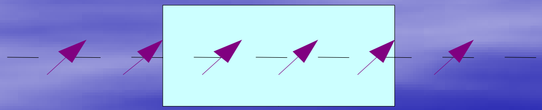
- Transverse.
  - Dipole modes couple to transverse beam offsets.
  - Use narrowband electronics to monitor a particular dipole line.



Pure offset



Angled trajectory

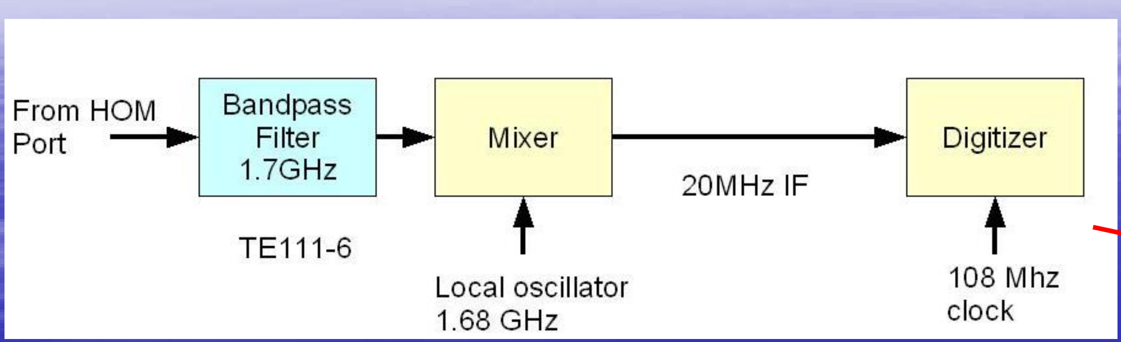


Tilted bunch

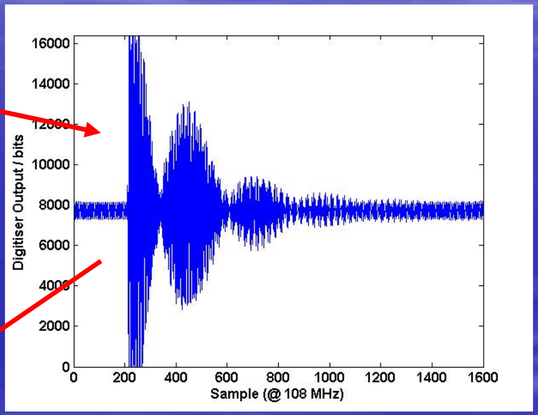
• Magnitude of angle response may be reduced by cell to cell cancellation.

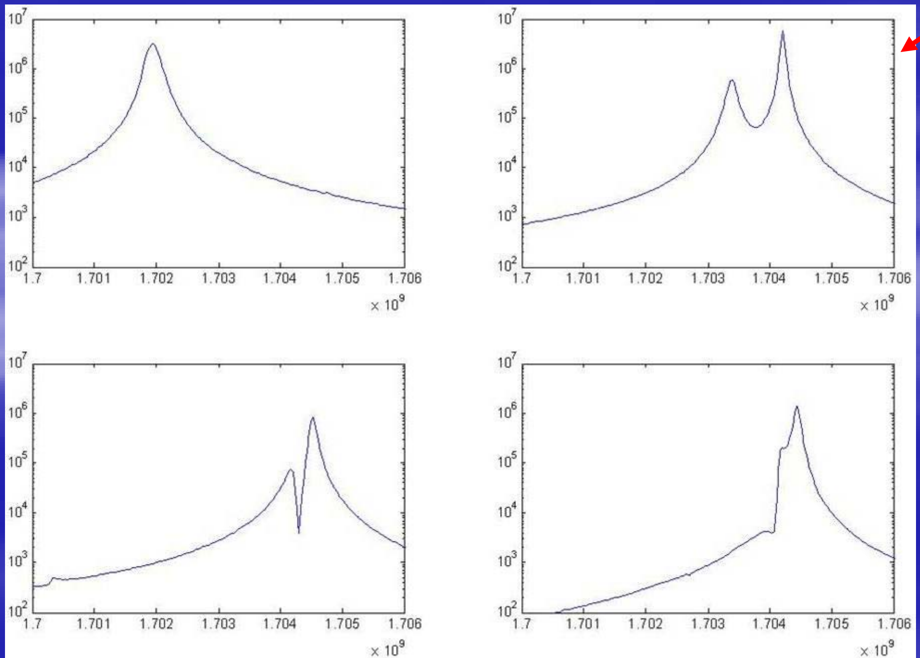
- Longitudinal
  - HOM coupler tuned to reject accelerating mode.
  - Rejection not perfect, and amplitude is approx equal to high *R/Q* monopole modes.
  - Beam phase and accelerating phase information therefore exist on the **same cable.**
  - Use a broadband system to measure 1.3 GHz (accelerating mode) and a strong monopole mode.

Narrow-band Measurements



- ~1.7 GHz tone added for calibration purposes.
- Cal tone, LO, and digitiser clock all locked to accelerator reference.



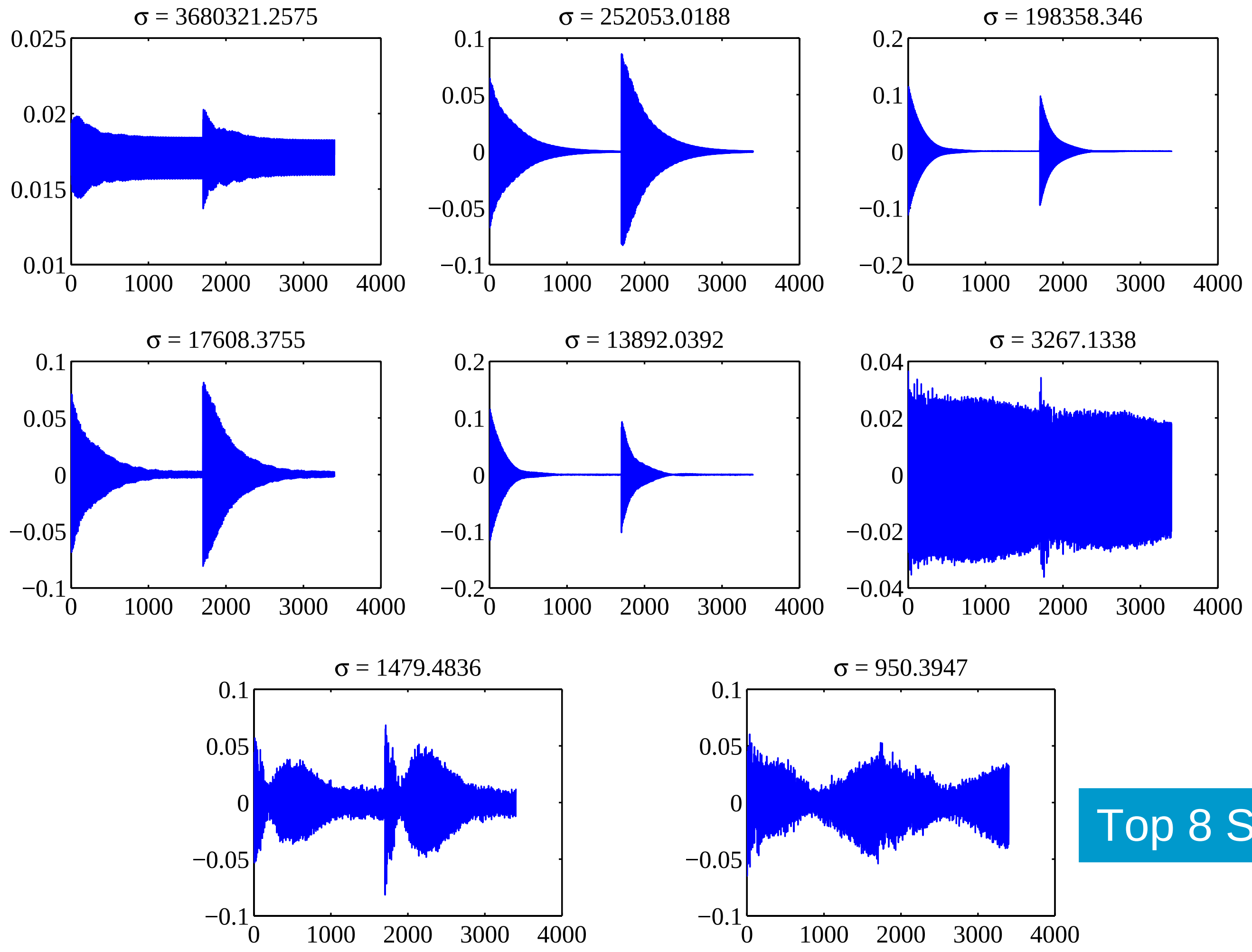


- Dipole modes exist in two polarisations corresponding to orthogonal transverse directions.
- The polarisations may be degenerate in frequency, or may be split by the perturbing affect of the couplers, cavity imperfections, etc.
- May be difficult to determine their frequencies.

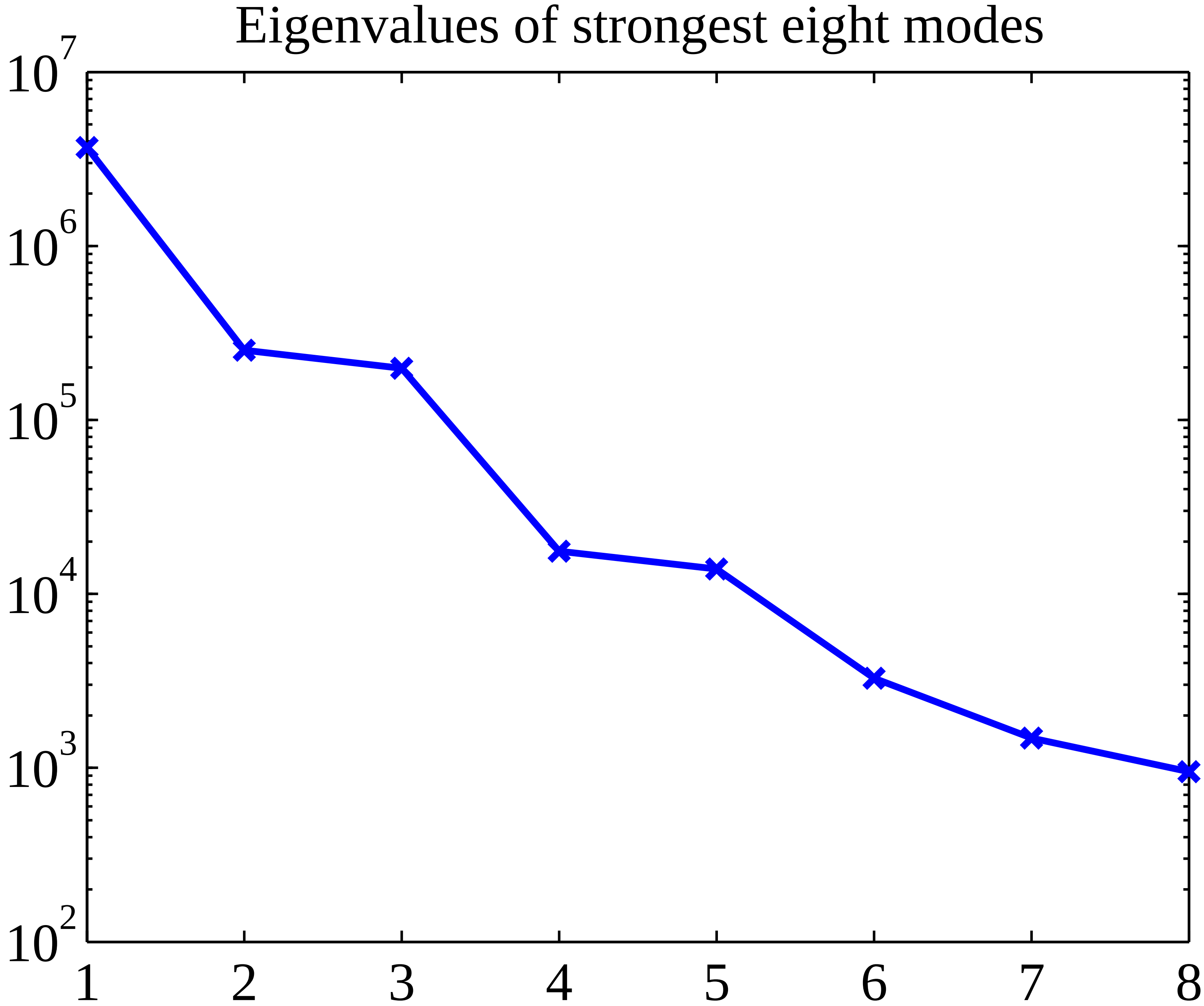
Analysis of Narrowband Signals – Beam Position (1)

- Small differences in each cavity lead to differing values of the frequency split, etc.
- With eighty signals to analyse (40 cavities with 2 couplers each), it is difficult to find the frequency and *Q* for each one.
- Instead, use SVD to find major "modes" for each cavity.
  - Must find ≥4 SVD modes as the beam has 4 transverse degrees of freedom.
- Find correlation between the amplitude of each of these modes and the transverse position of the beam.

Analysis of Narrowband Signals – Beam Position (2)



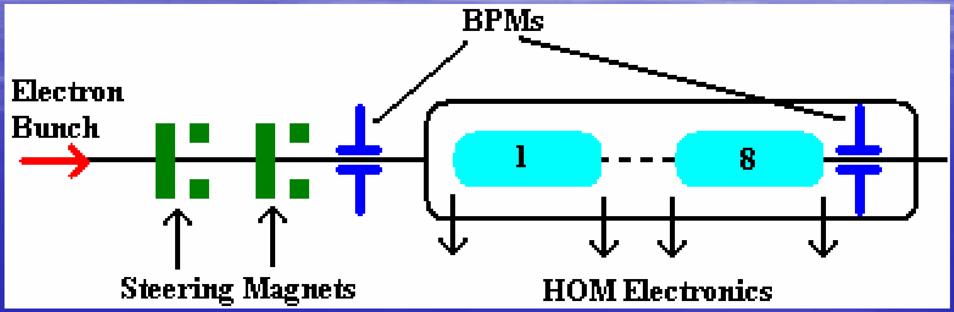
Top 8 SVD modes.



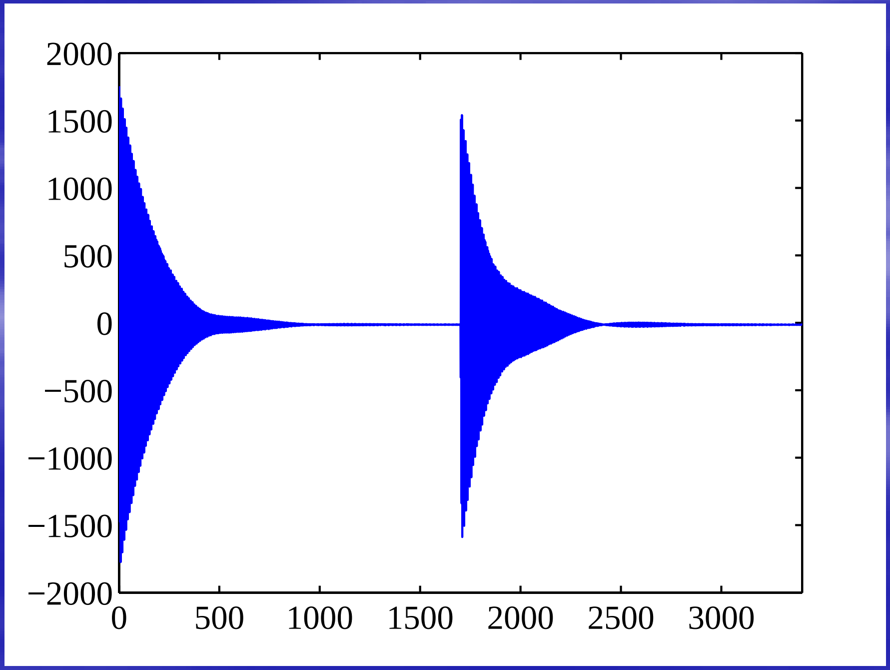
Eigenvalues of strongest eight modes
10^7
10^6
10^5
10^4
10^3
10^2
1
2
3
4
5
6
7
8

Analysis of Narrowband Signals – Beam Position (3)

- Steer beam through a large region of transverse 4D space.
  - Systematic scans in 1 dimension at a time resulted in spurious position-angle correlations.
    - Position-angle mixing due to imperfect BPMs also introduced spurious correlations, resulting in an artificially high angle resolution.
  - Instead picked random 4D positions and calculated corrector moves to achieve these.
- Correlate SVD mode amplitude with 4D beam position.
- Can use the regression matrix to reconstruct cavity modes.

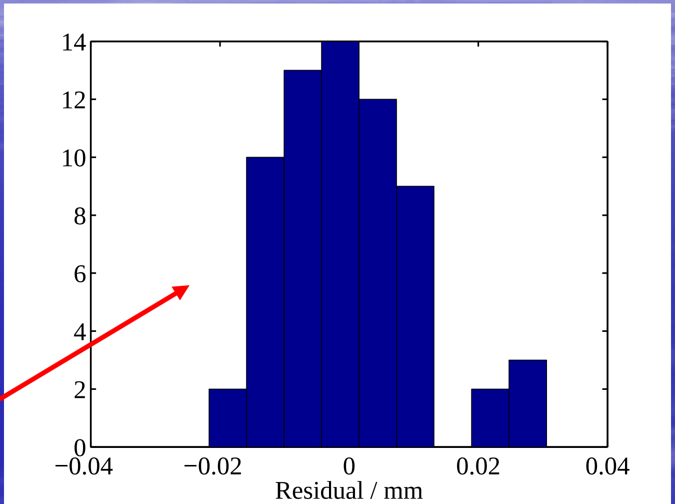


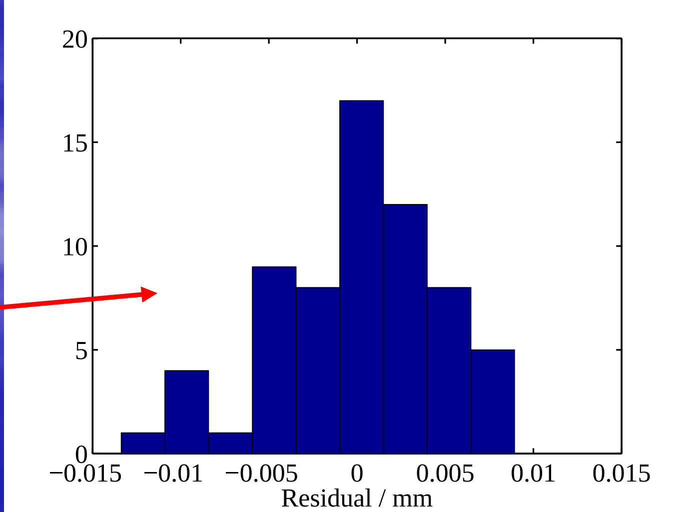
Reconstructed *x* mode



Analysis of Narrowband Signals – Beam Position (4)

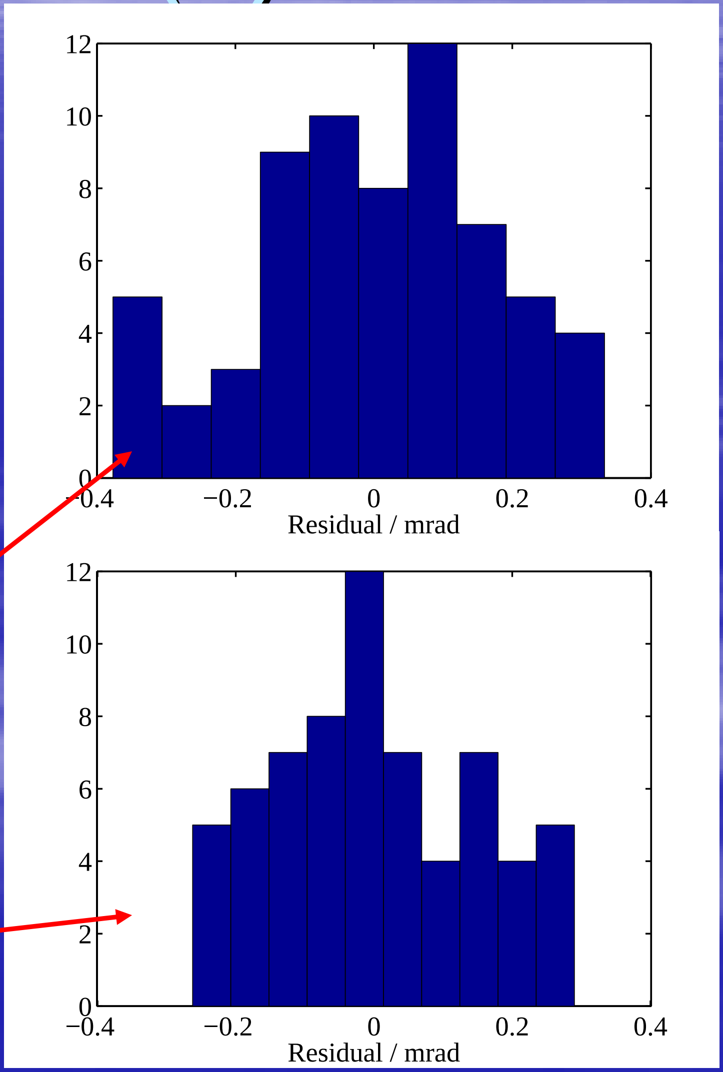
- Resolution of position measurement.
  - Predict the position at cavity 5 from the measurements at cavities 4 and 6.
  - Compare with the measured value.
- X resolution
  - 9 microns
- Y resolution
  - 4 microns





Analysis of Narrowband Signals – Beam Position (5)

- Angle resolution measurement.
  - Predict angle from positions and compare with measurement.
- Angle signal from entire cavity will cancel as the mode is synchronous with the beam.
  - Signals from the first and last cavities will cancel.
- Angle signals from each cell will remain.
  - Mode will have small angle sensitivity.
- X angle resolution
  - 175 u.rad
- Y angle resolution
  - 140 u.rad



Resolution

Energy coupled into a mode:

$$U = \left(\frac{R}{Q}\right) \cdot \frac{\omega}{2} \cdot c^2$$

Minimum detectable energy is dominated by thermal noise:

$$U = \frac{1}{2} k_b T$$

Theoretical best position resolution is ~6 nm.

Given the cable losses, the protective attenuator in the circuit, and the noise factor, the theoretical res is ~130 nm.

The theoretical angle resolution is ~2 u.rad.

The measured resolutions are ~5 um and ~150 u.rad

There are two main reasons for this disparity:

The amplitude of the HOMs are proportional to the beam charge, so the signals must be normalised by the toroid output. The FLASH toroids have a noise of ~0.6%, and so contribute strongly to the measurement error.

The LO signal in the electronics has a phase error of ~1 degree. This causes mixing between position and angle, and leads to a degradation in their resolution.

Conclusions

- It has been demonstrated that strong dipole HOMs may be used as a beam diagnostic.
- A position measurement of ~5 um has been shown
  - This may be significantly improved by using a more stable LO, and a higher resolution charge measurement (perhaps using the monopole amplitude?).
- This system has been deployed on five accelerating modules at FLASH, DESY, and the measurement system has been integrated into the control system.
- A first attempt at a multibunch position measurement has been made with promising results.
  - Work on this system is ongoing.