

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

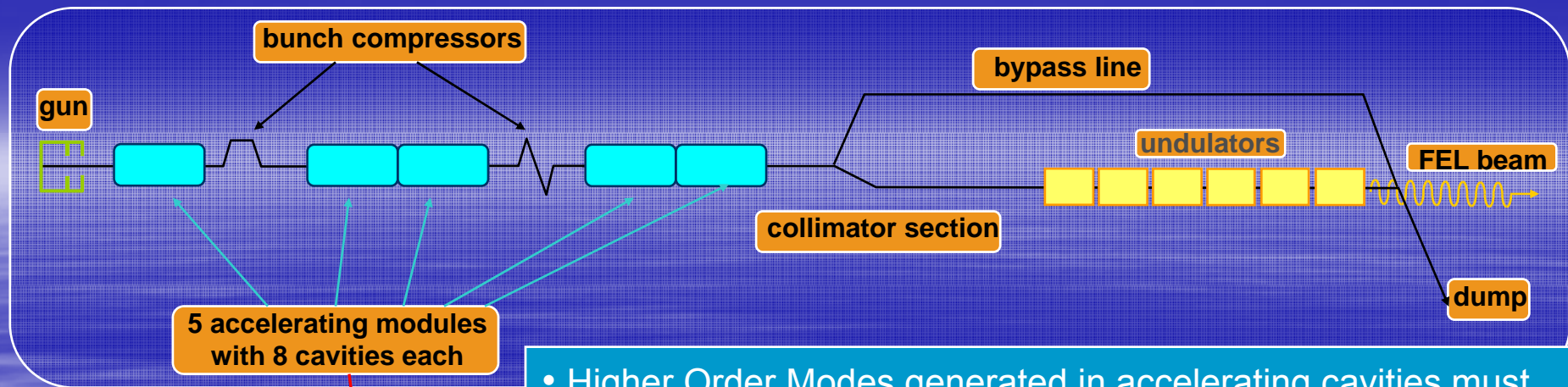
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N. Baboi, O. Hensler, L. Petrosyan, DESY, Hamburg

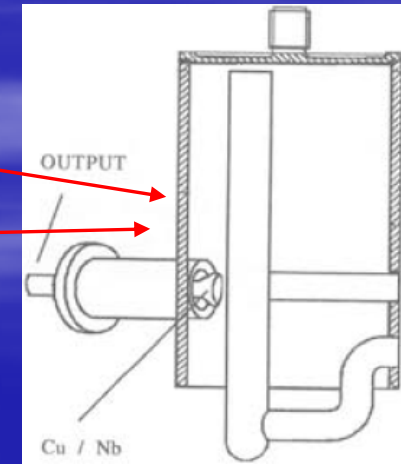
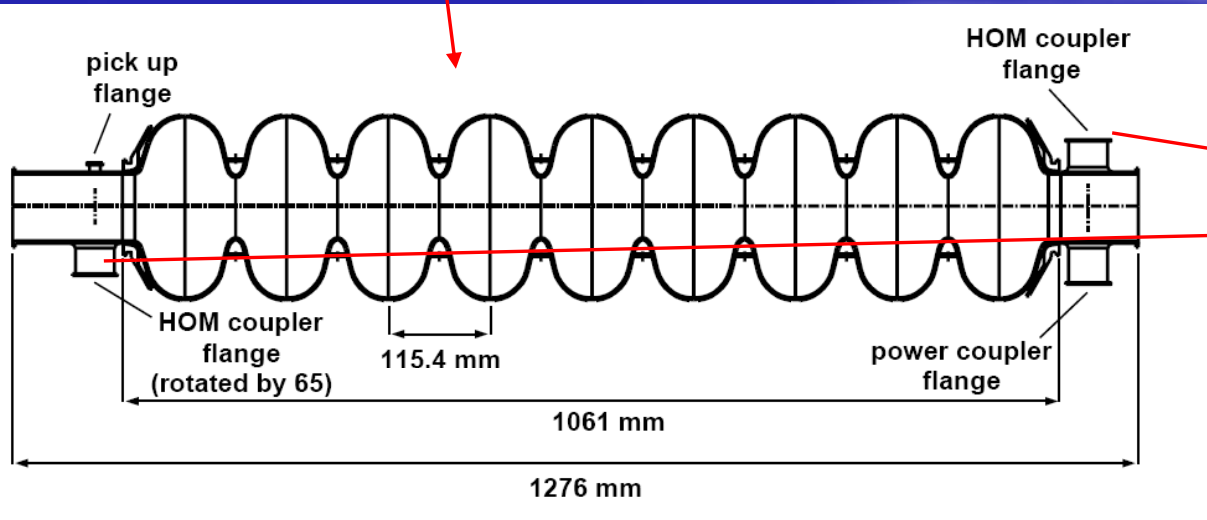
N. Eddy, L. Piccoli, R. Rechenmacher, M. Ross, M. Wendt, Fermilab, Batavia, Illinois

Olivier Napoly, Rita C Paparella, and Claire Simon, CEA, Gif-sur-Yvette, France

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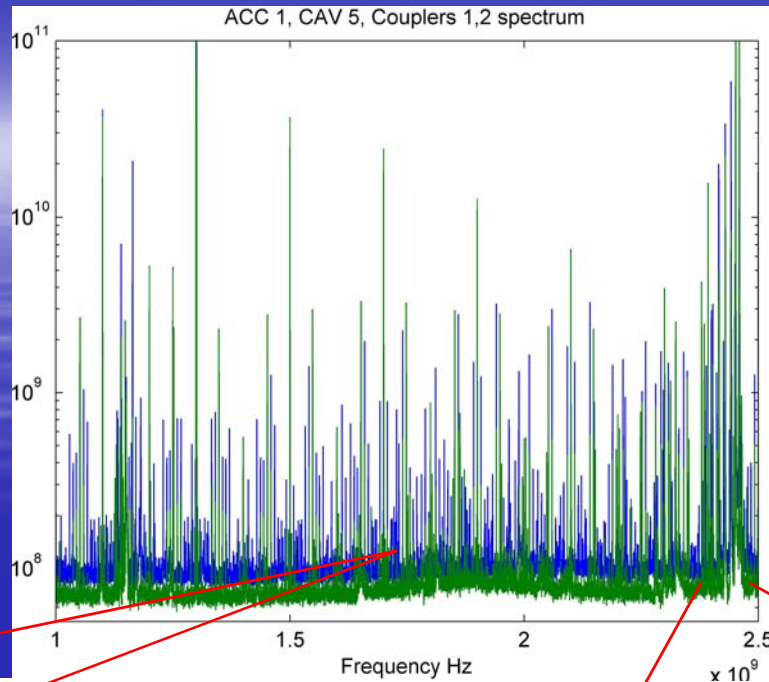


- Higher Order Modes generated in accelerating cavities must be damped.
- These HOMs may also be monitored to obtain beam/cavity information.
- Forty cavities exist at FLASH.
 - Couplers/cables already exist.
 - Electronics installed to monitor HOMs (wideband and narrowband response).



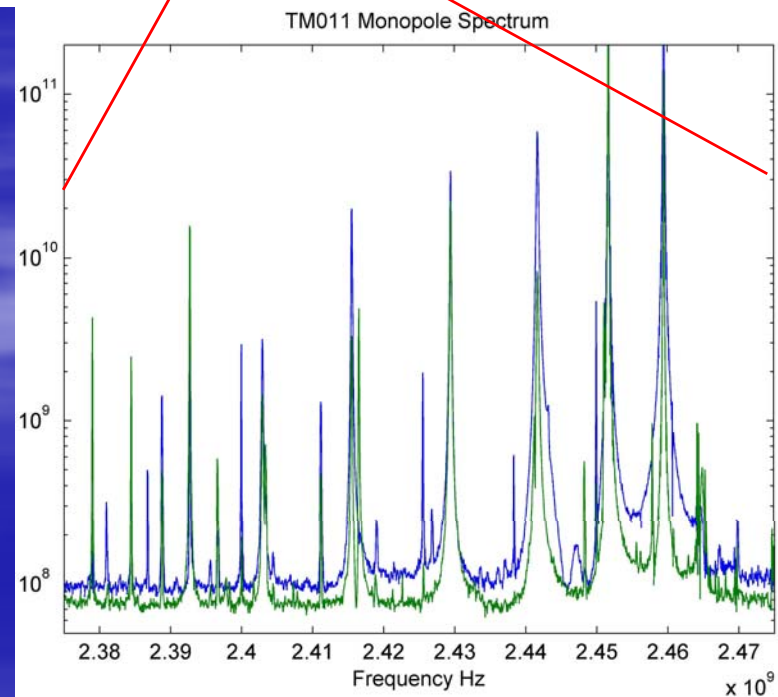
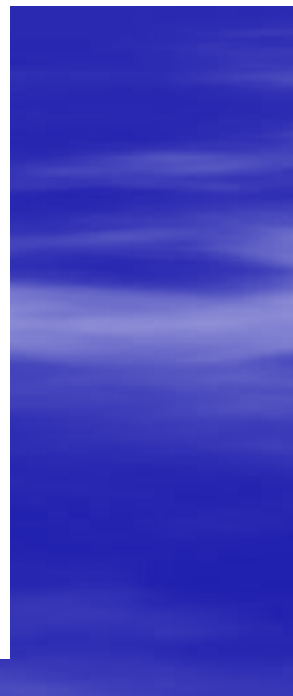
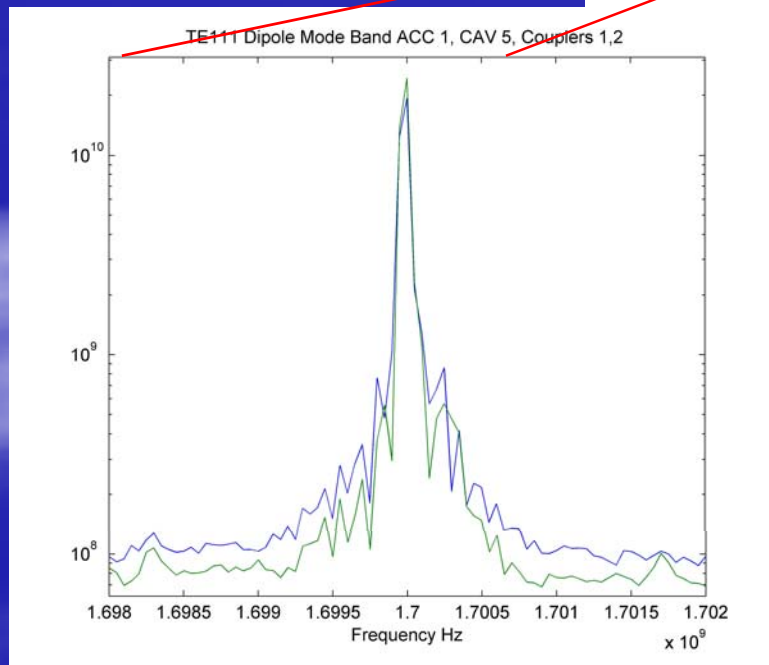
HOM Signals

Dipole Mode 1.7GHz
4 MHz frequency span shown



Broadband system data

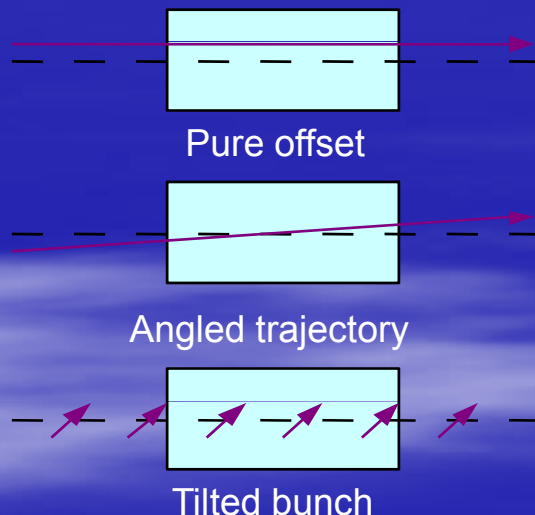
Monopole Modes
100 MHz frequency span shown



Beam Measurements

- Transverse.

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

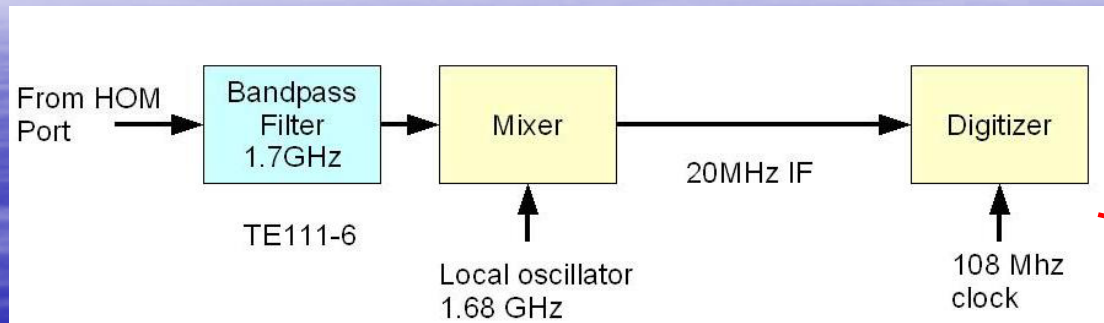


- Magnitude of angle response may be reduced by cell to cell cancellation.

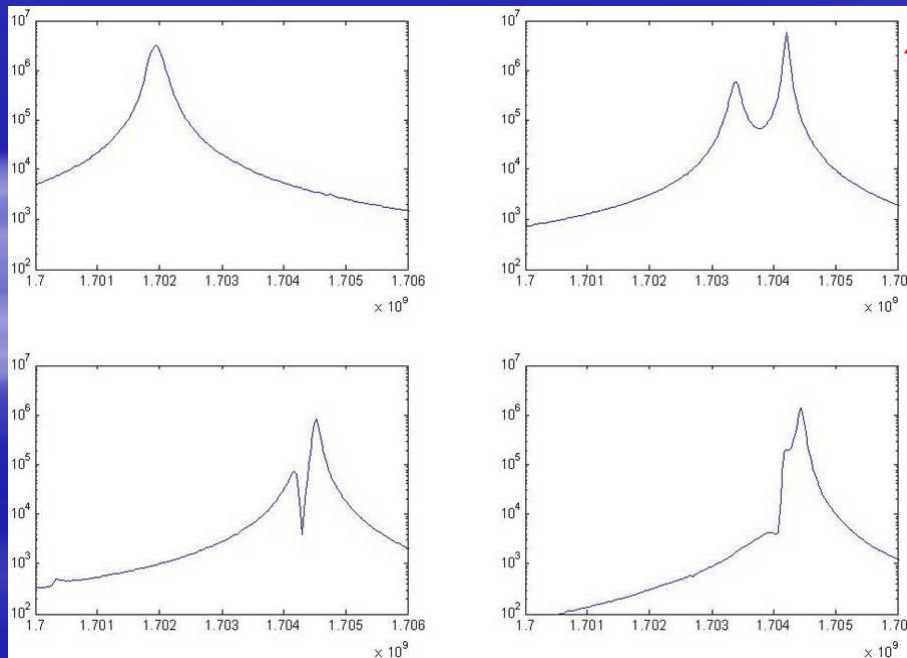
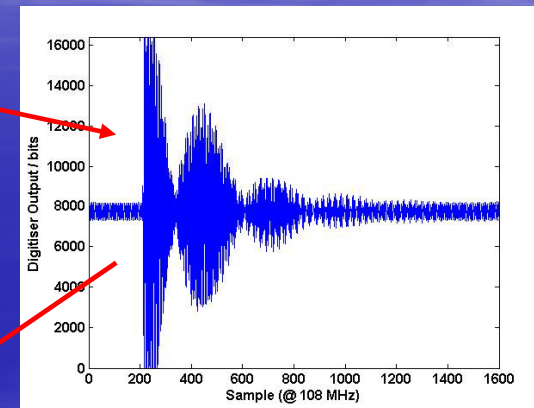
- Longitudinal

- 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.

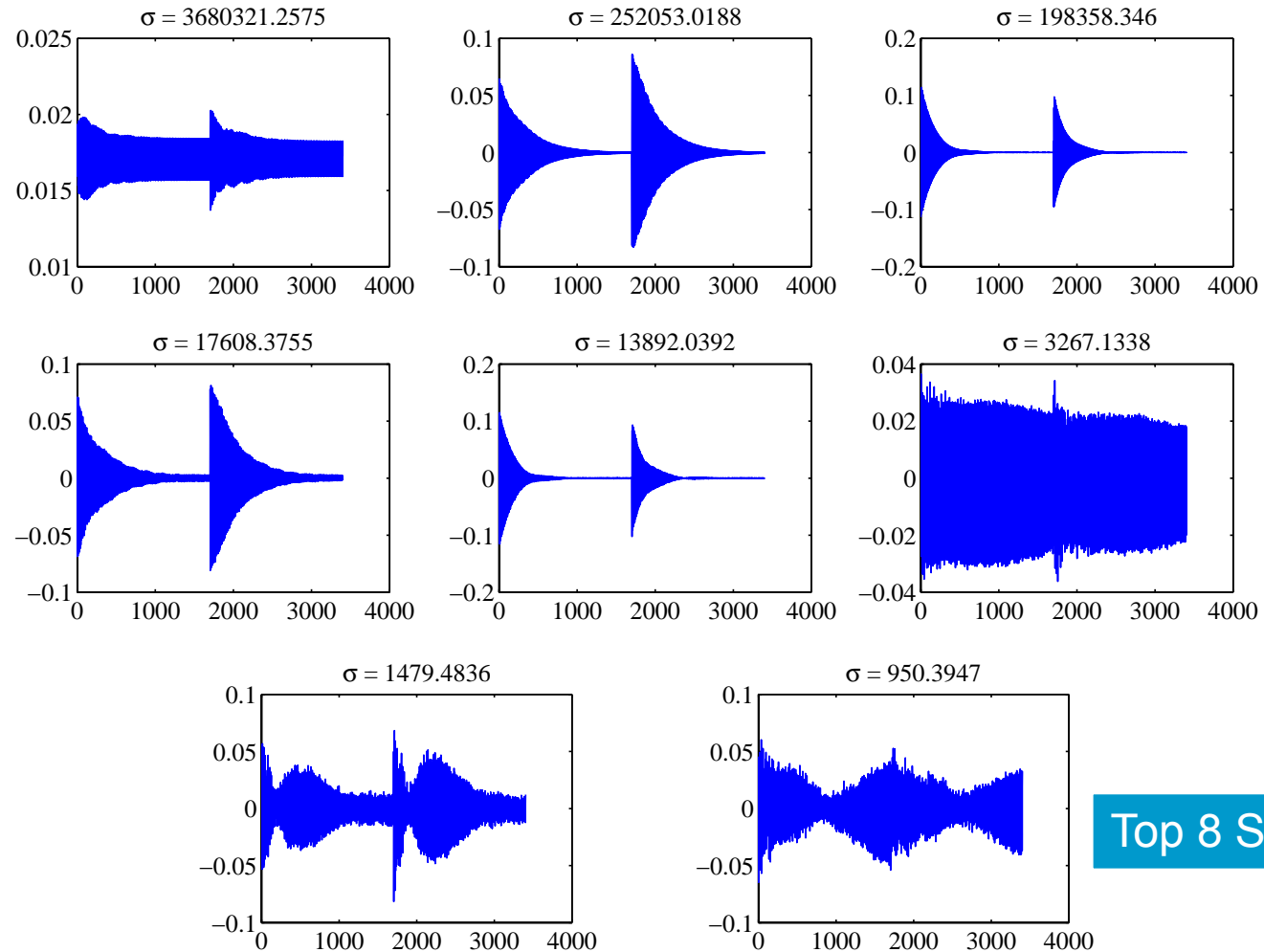


- Dipole modes exist in two polarisations corresponding to orthogonal transverse directions.
- The polarisations may be degenerate in frequency, or may be split by the perturbing affect of the couplers, cavity imperfections, etc.
- May be difficult to determine their frequencies.

Analysis of Narrowband Signals – Beam Position (1)

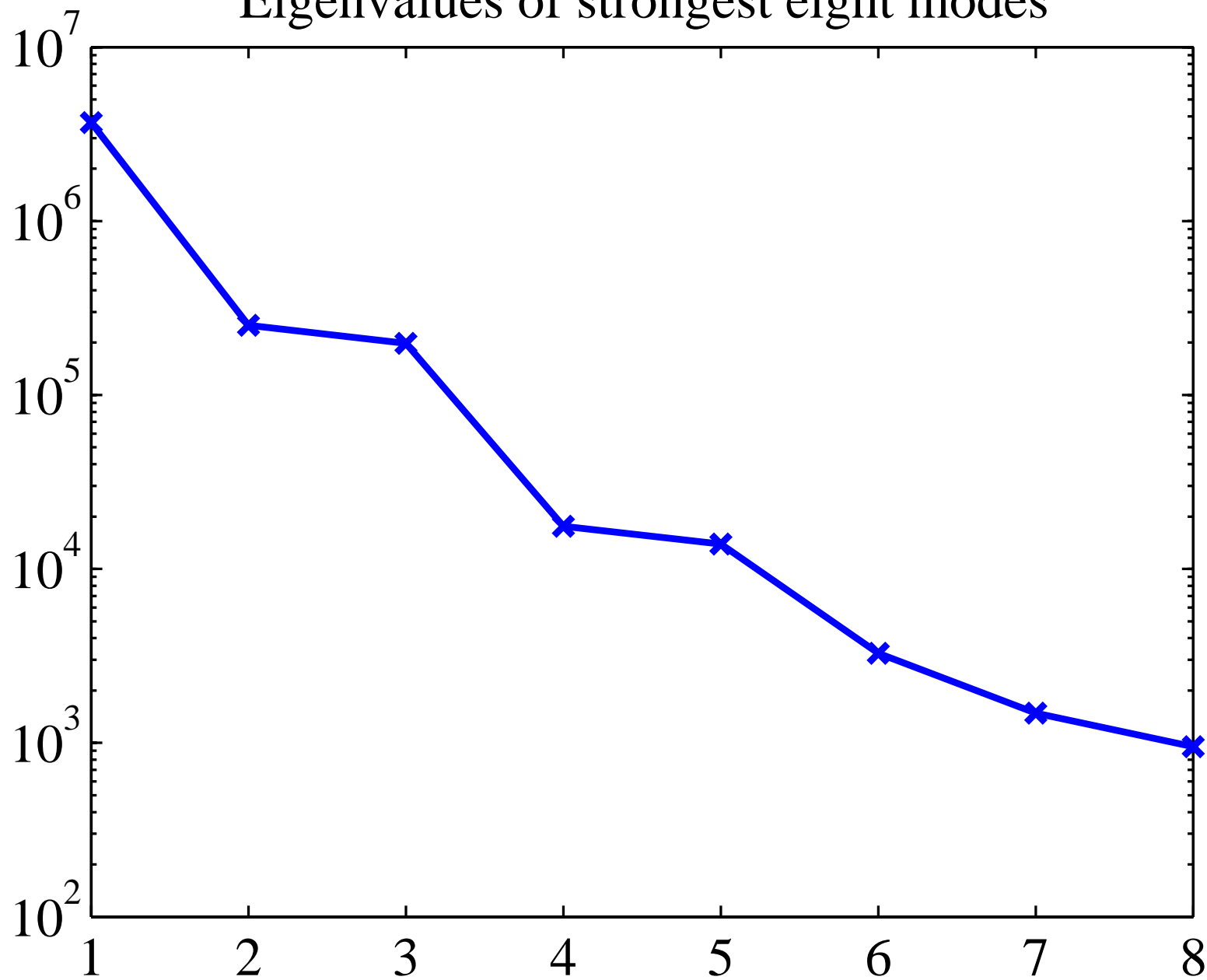
- Small differences in each cavity lead to differing values of the frequency split, etc.
- With eighty signals to analyse (40 cavities with 2 couplers each), it is difficult to find the frequency and Q for each one.
- Instead, use SVD to find major “modes” for each cavity.
 - Must find ≥ 4 SVD modes 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)



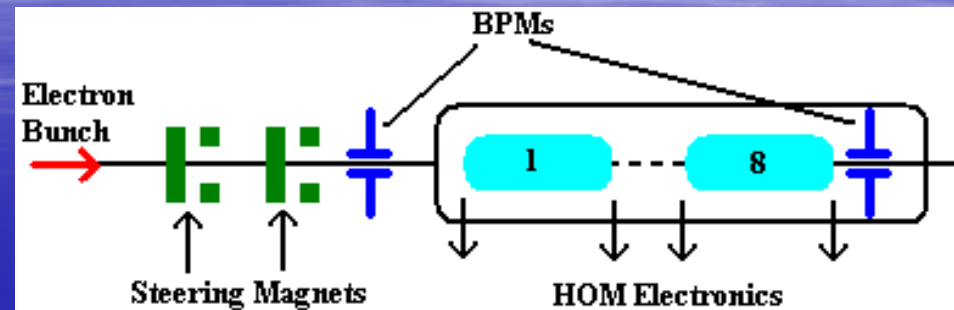
Top 8 SVD modes.

Eigenvalues of strongest eight modes

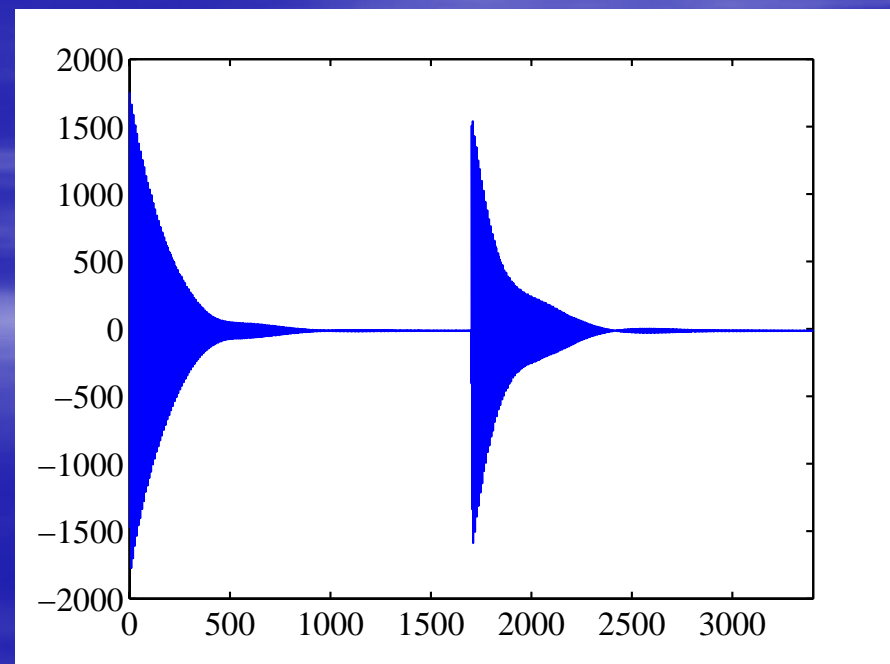


Analysis of Narrowband Signals – Beam Position (3)

- 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.

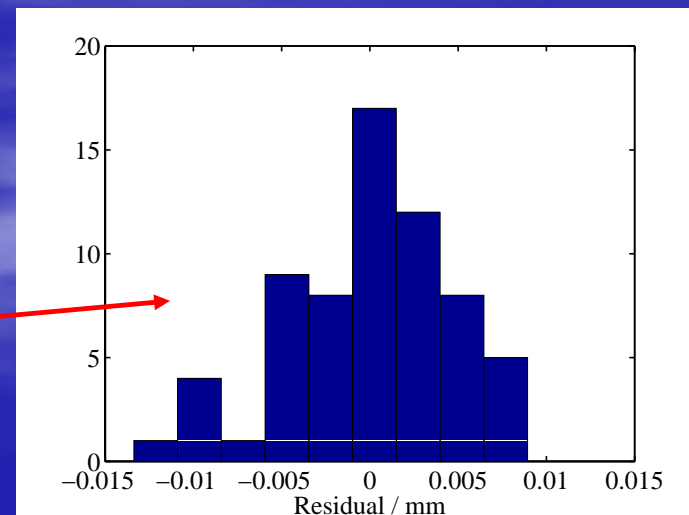
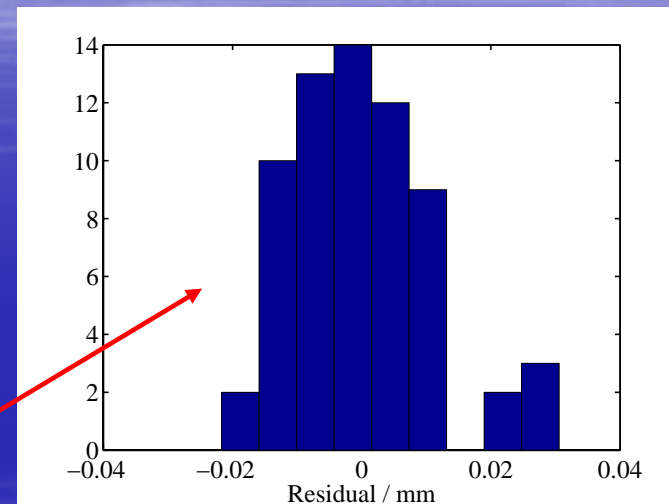


Reconstructed x mode



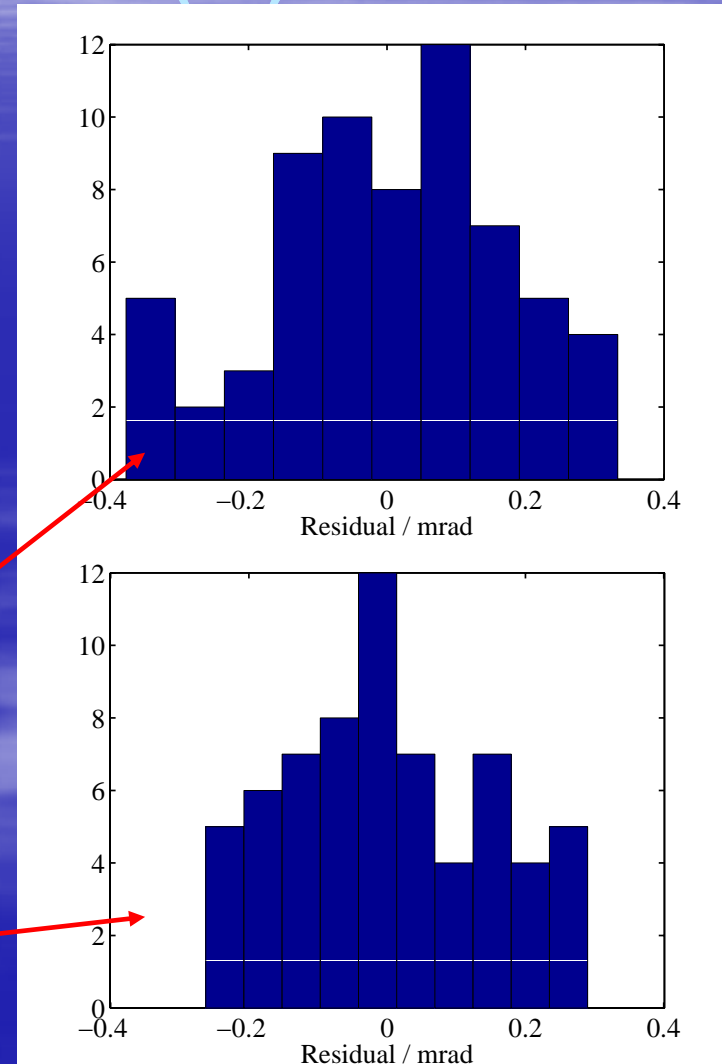
Analysis of Narrowband Signals – Beam Position (4)

- 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 μrad
- Y angle resolution
 - 140 μrad



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 μm 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.