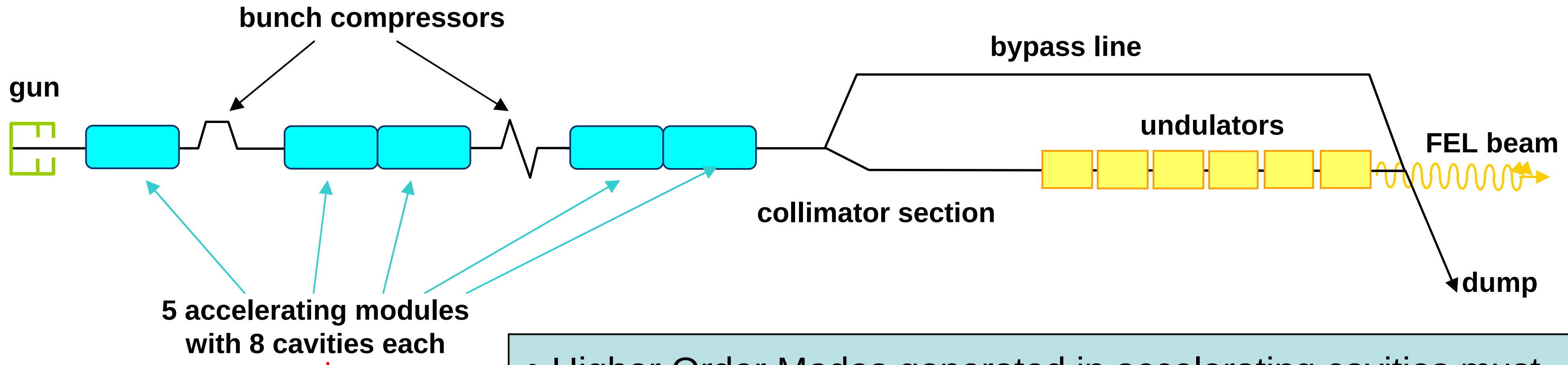
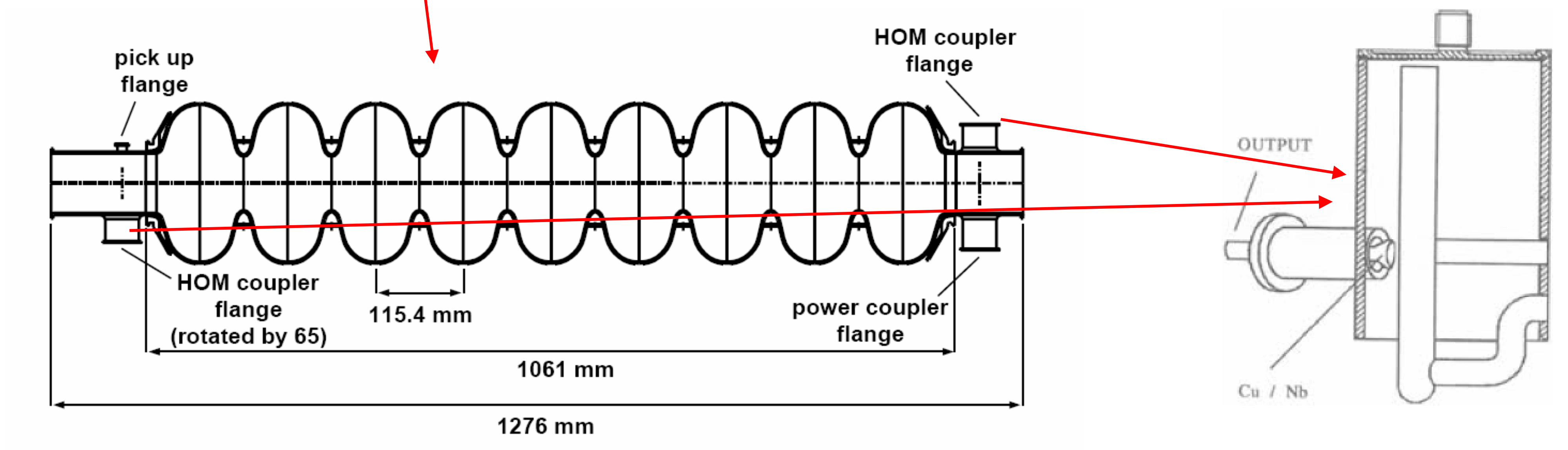
# HOMs as a beam and cavity diagnostic

*CEA, DESY, FNAL, SLAC, Cockroft*




- 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).

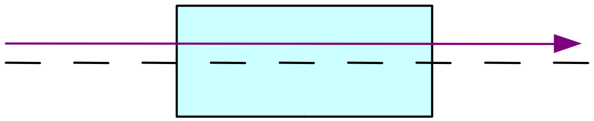


# HOMs as Diagnostics

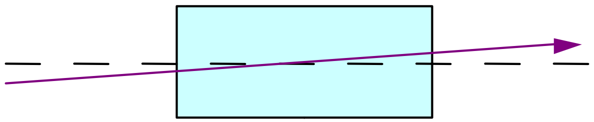
- No need to install new beamline hardware
  - HOM power must be coupled out of the cavities to prevent BBU, etc.
  - Therefore beamline and cryogenic hardware already exists.
- Large proportion of linac length occupied by structures.

# Beam Measurements

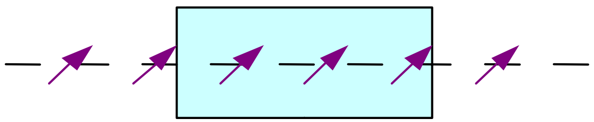
- Transverse.
  - Dipole modes couple to transverse beam offsets.
  - Use narrowband electronics to monitor a particular dipole line.



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.

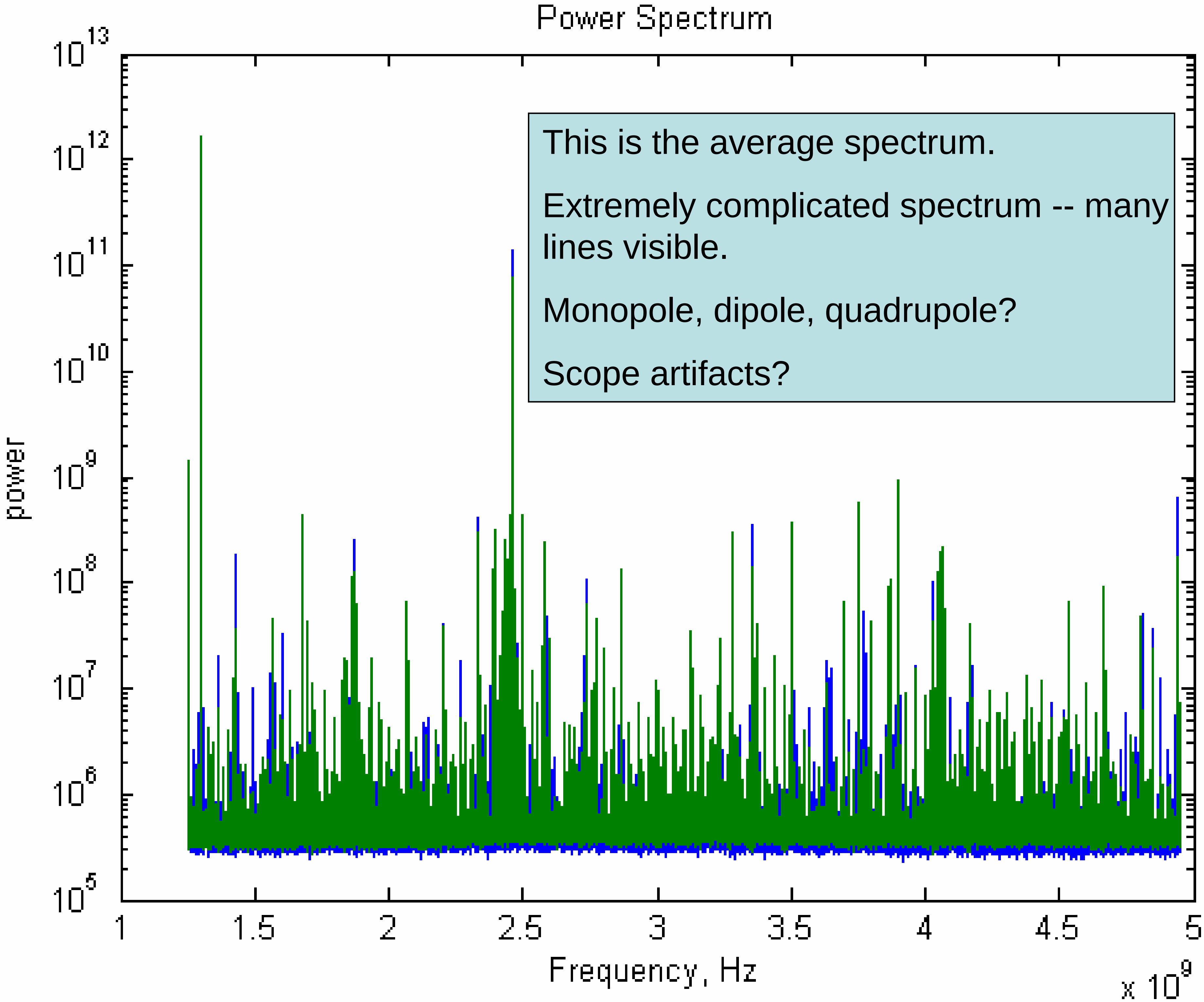
# HOMs as a Cavity Diagnostic

- 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 affected by the iris positions.
  - Effect of couplers can offset the modes from the cavity centre.

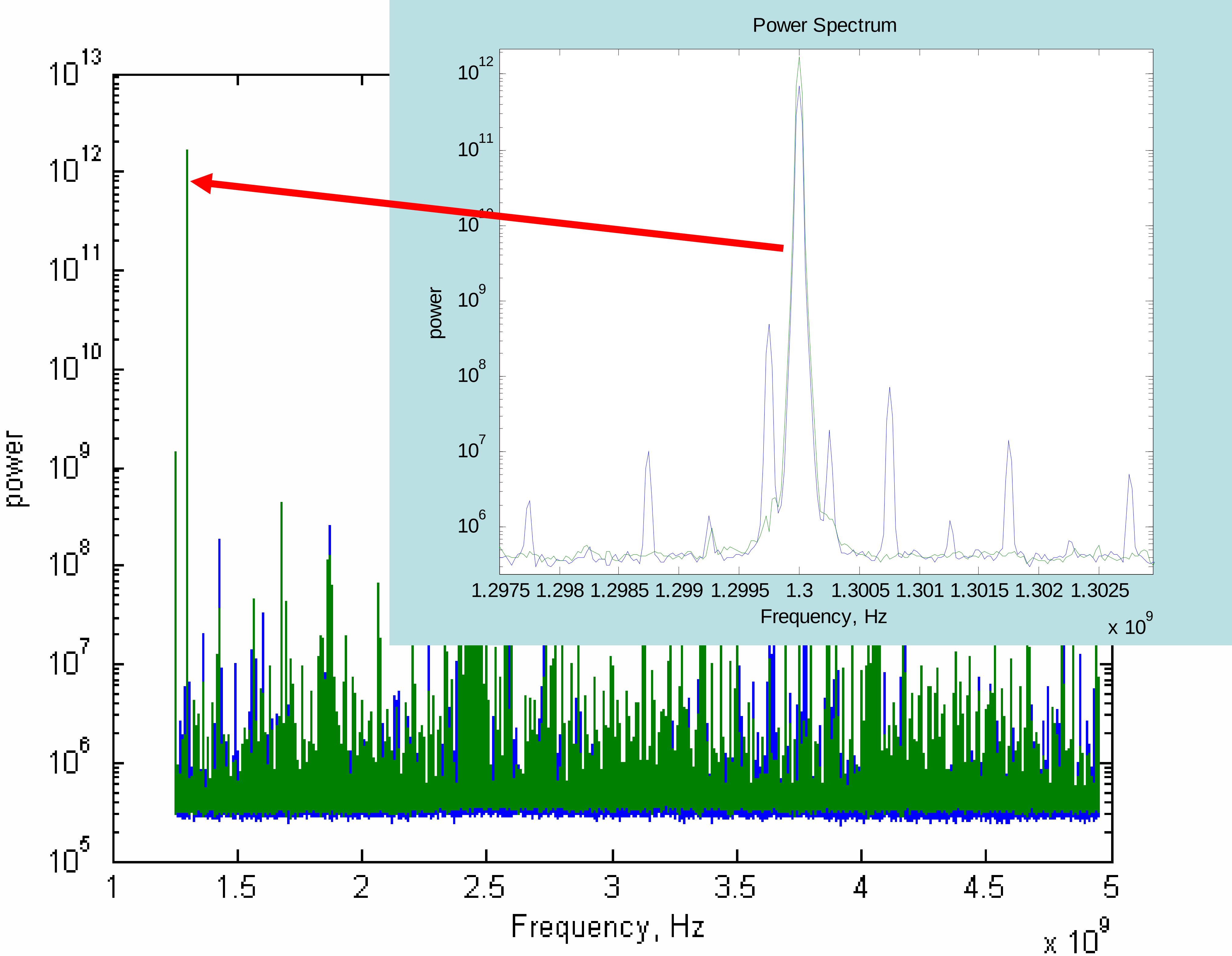
# Broadband Measurements

# Broadband HOM Measurements at TTF

- Both couplers on ACC5 cavity #4 connected to a 10 GS/s, 6 GHz scope.
- Beam was steered to 130 random points in x, x’, y, y’ in order to calibrate our narrowband HOM system.
  - +-2 mm, +- 1mrad range.
  - The broadband measurements were parasitic.
  - Unfortunately the scope acquisition was not necessarily on the same pulse as the BPM acquisition.
    - Position & angle were calculated from the corrector settings.



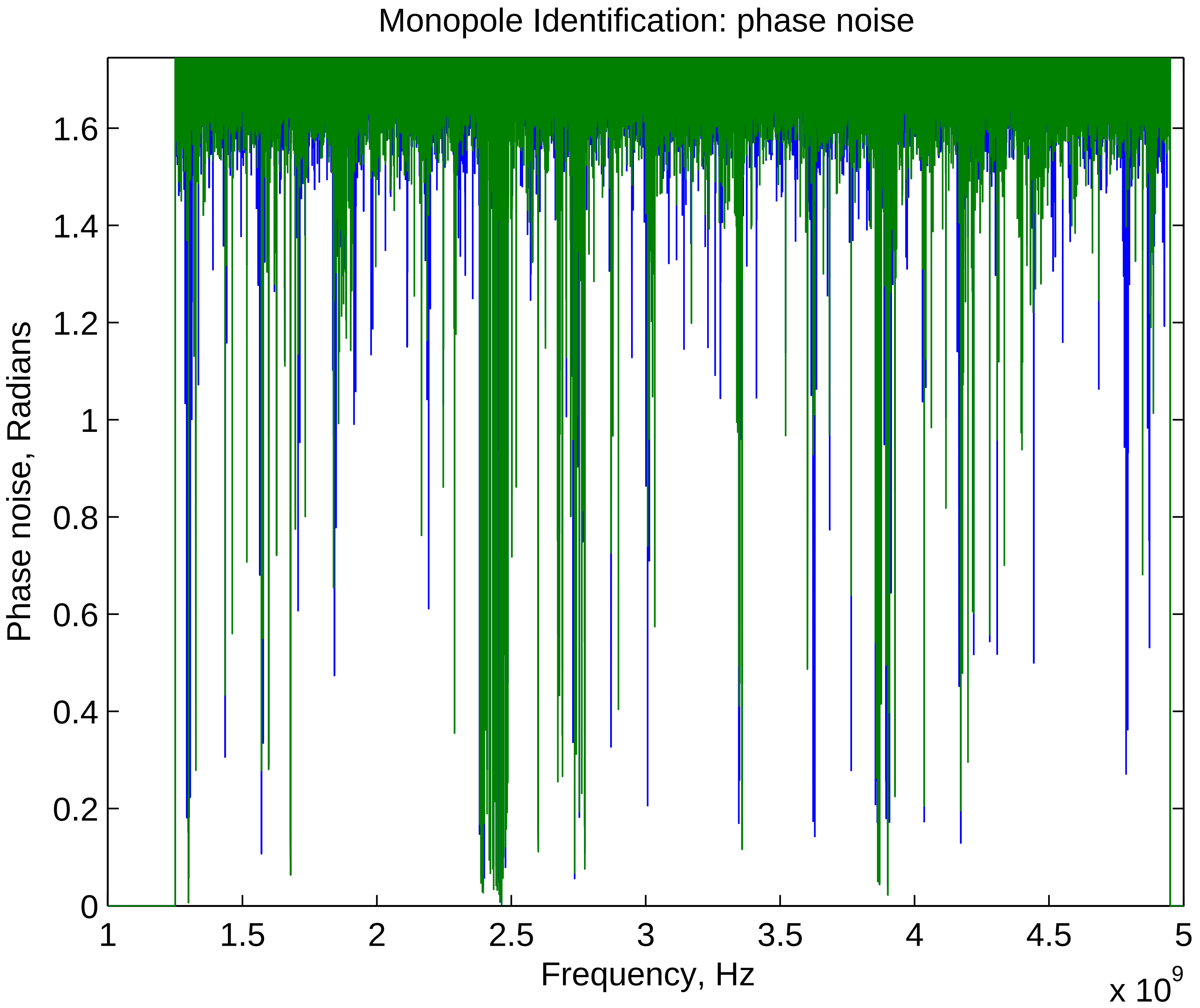
Power Spectrum
This is the average spectrum.
Extremely complicated spectrum -- many lines visible.
Monopole, dipole, quadrupole?
Scope artifacts?
power
Frequency, Hz
x 10^9



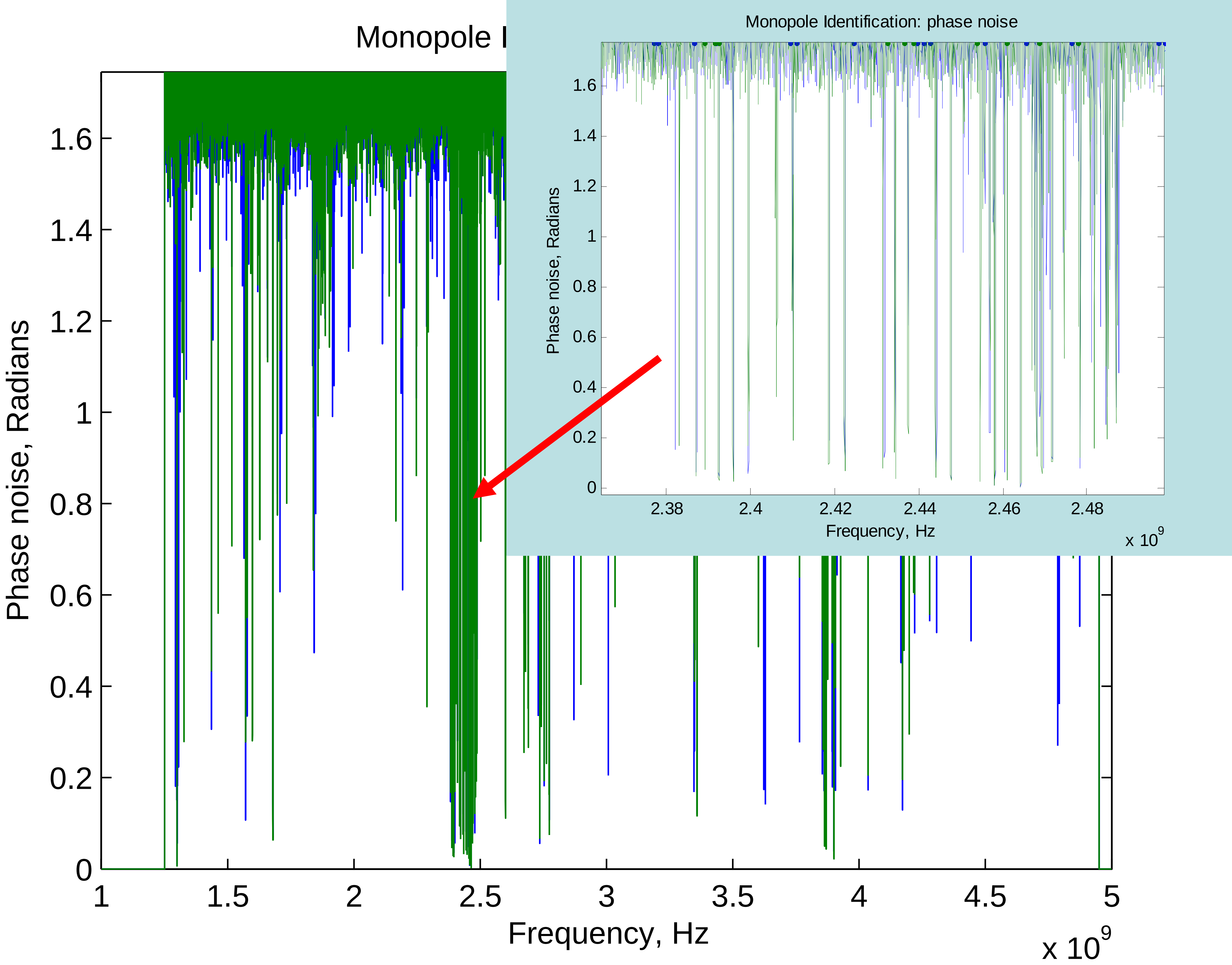
Power Spectrum
power
Frequency, Hz
x 10^9
1.2975 1.298 1.2985 1.299 1.2995 1.3 1.3005 1.301 1.3015 1.302 1.3025
10^12 10^11 10^10 10^9 10^8 10^7 10^6
10^13 10^12 10^11 10^10 10^9 10^8 10^7 10^6 10^5
1 1.5 2 2.5 3 3.5 4 4.5 5

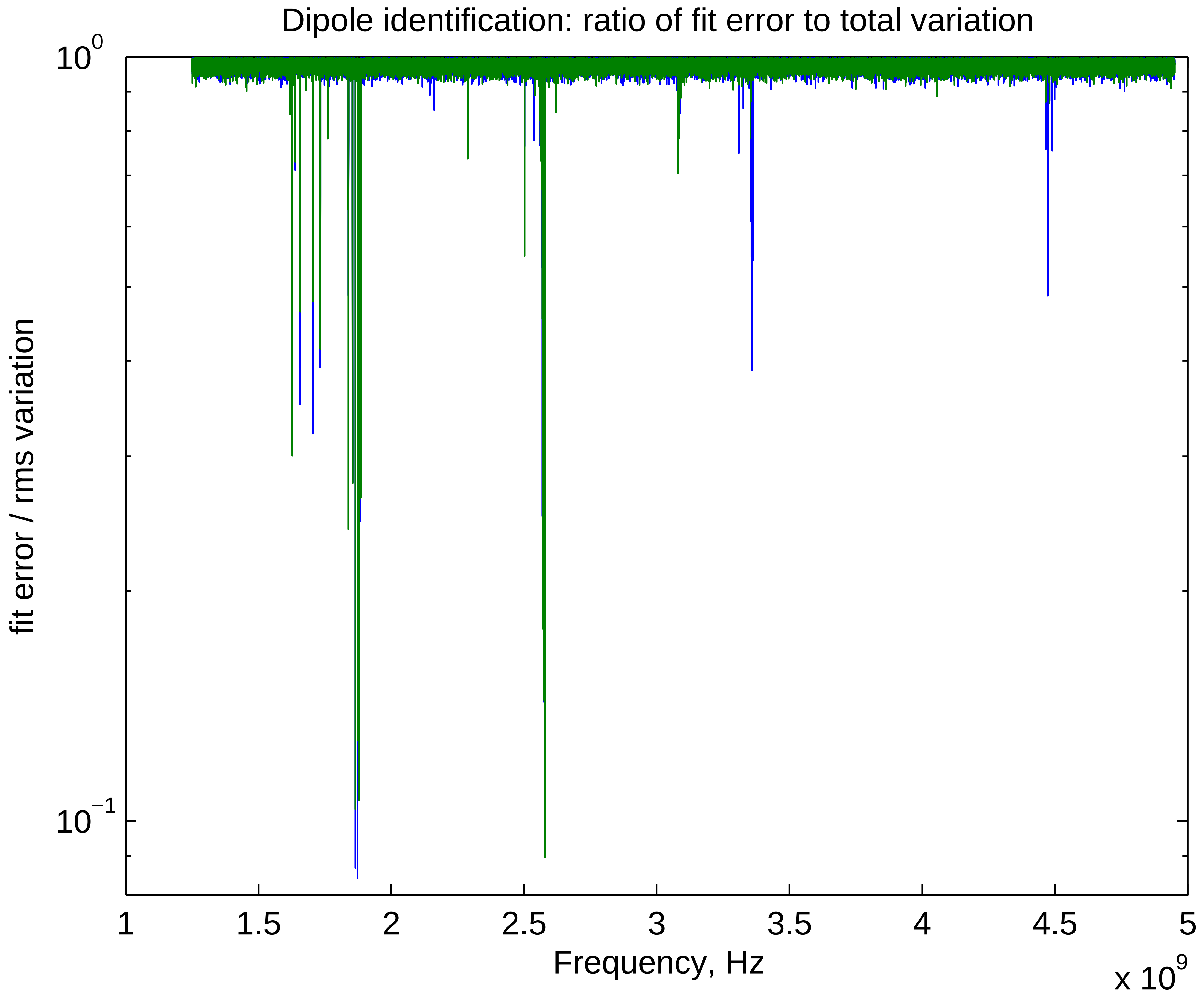
# Interpreting the spectrum

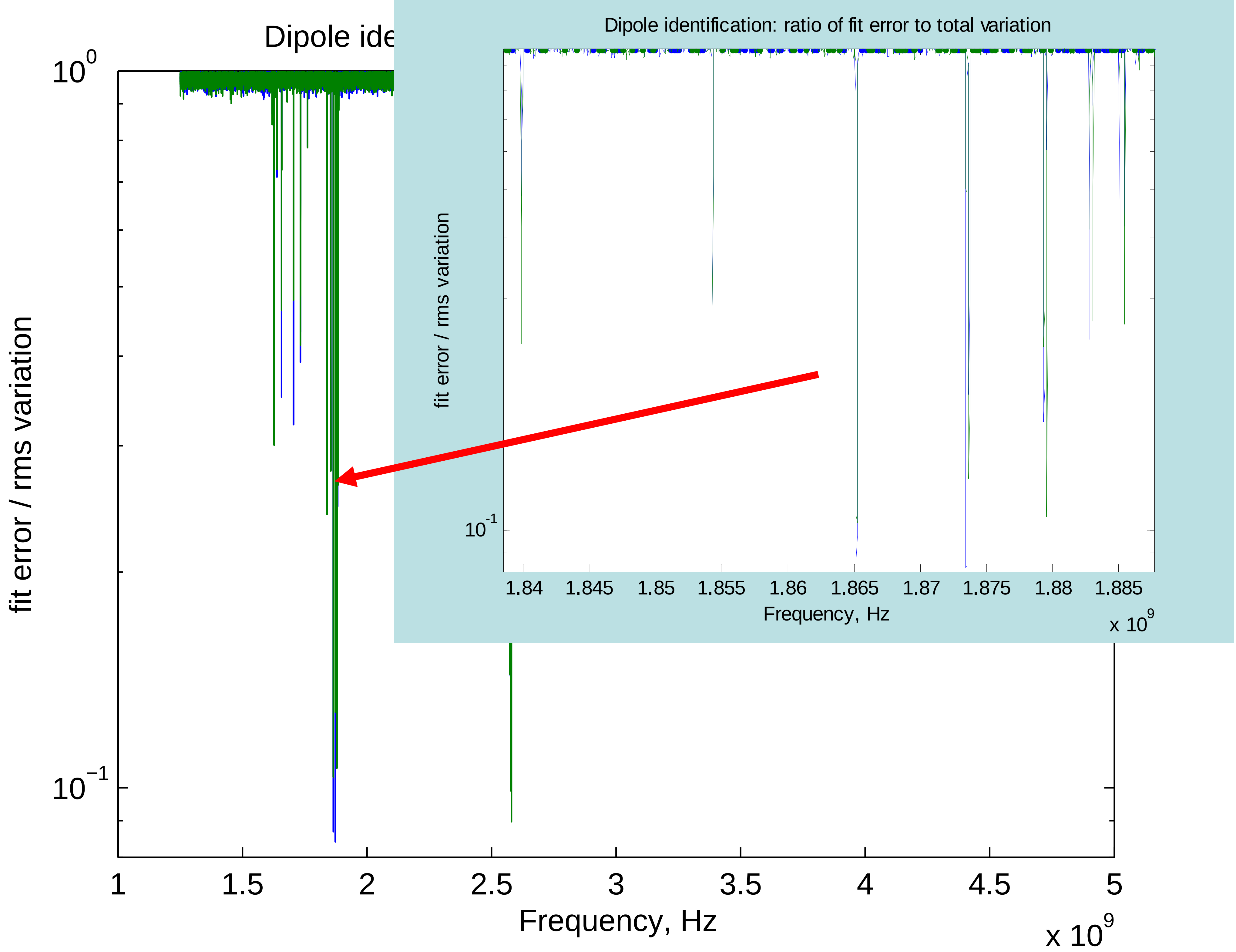
- How to distinguish modes from scope artifacts?
- How to distinguish different types of modes?
- Monopole
  - Should have a fixed phase relationship with 1.3 GHz, while scope artifacts will not.
  - Correct for random scope phase, and compare the phase of each frequency with the phase of the 1.3 GHz.
- Dipole
  - Should have a strong relationship with the beam position.
  - Predict beam position from corrector settings, and regress against complex amplitude of each frequency.



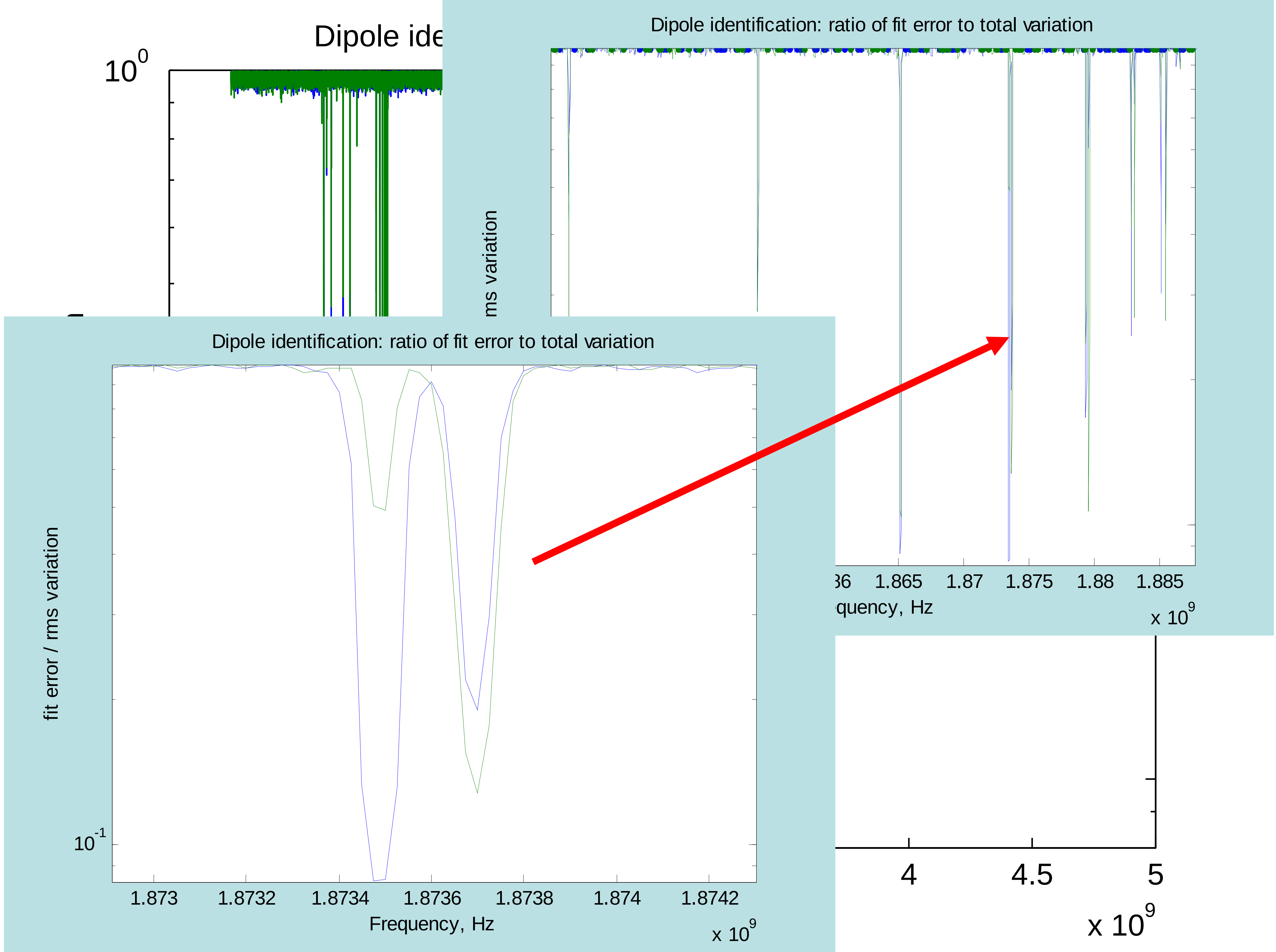
Monopole Identification: phase noise
Phase noise, Radians
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency, Hz
x 10^9


Monopole I
Phase noise, Radians
Frequency, Hz
x 10^9
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
1.5
2
2.5
3
3.5
4
4.5
5
Monopole Identification: phase noise
Phase noise, Radians
Frequency, Hz
x 10^9
2.38
2.4
2.42
2.44
2.46
2.48


Dipole identification: ratio of fit error to total variation
$10^0$
$10^{-1}$
fit error / rms variation
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency, Hz
x $10^9$



Dipole ide
10^0
10^−1
fit error / rms variation
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency, Hz
x 10^9
Dipole identification: ratio of fit error to total variation
fit error / rms variation
10^-1
1.84
1.845
1.85
1.855
1.86
1.865
1.87
1.875
1.88
1.885
Frequency, Hz
x 10^9



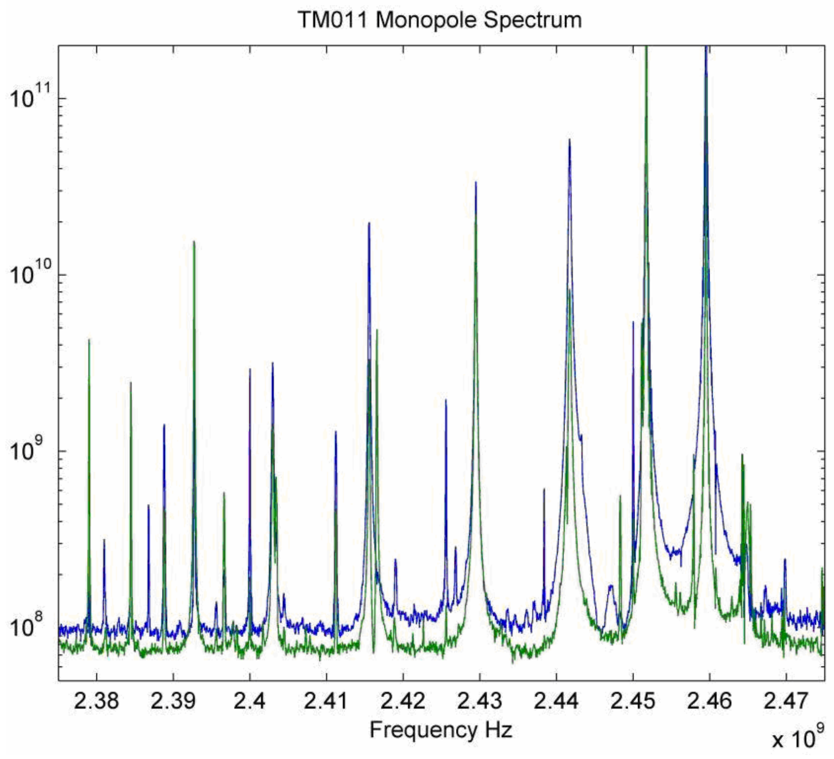
Dipole ide
10^0
4
4.5
5
x 10^9
Dipole identification: ratio of fit error to total variation
ms variation
36
1.865
1.87
1.875
1.88
1.885
quency, Hz
x 10^9
Dipole identification: ratio of fit error to total variation
fit error / rms variation
10^-1
1.873
1.8732
1.8734
1.8736
1.8738
1.874
1.8742
Frequency, Hz
x 10^9

# Preliminary Mode Centres

| Freq / Hz | x Centre / mm | y Centre / mm |
|---|---|---|
| 1.6269E+9 | 0.001 | 0.018 |
| 1.6272E+9 | 2.447 | 0.385 |
| 1.6391E+9 | 0.061 | -0.484 |
| 1.6574E+9 | 0.002 | -0.040 |
| 1.6576E+9 | 1.247 | 0.238 |
| 1.7052E+9 | 0.044 | -0.428 |
| 1.7056E+9 | -0.085 | -0.010 |
| 1.7334E+9 | -0.002 | -0.270 |
| 1.7614E+9 | 0.016 | -0.005 |
| 1.8399E+9 | 0.621 | 0.273 |
| 1.8543E+9 | 0.125 | -0.952 |
| 1.8652E+9 | 1.613 | -1.486 |
| 1.8735E+9 | 0.579 | -1.227 |
| 1.8737E+9 | 0.747 | 0.378 |
| 1.8794E+9 | 1.373 | -0.619 |
| 1.8796E+9 | 0.020 | -0.003 |
| 1.8828E+9 | -0.007 | 0.008 |
| 1.8831E+9 | 0.047 | 0.110 |
| 1.8851E+9 | 0.051 | -0.253 |
| 1.8855E+9 | 2.133 | 0.933 |
| 2.2893E+9 | 0.025 | 0.015 |
| 2.5024E+9 | 0.047 | -0.972 |
| 2.5383E+9 | -0.019 | 0.016 |
| 2.5615E+9 | 0.028 | -0.351 |
| 2.5628E+9 | 0.000 | -0.003 |
| 2.5640E+9 | -0.026 | -0.078 |

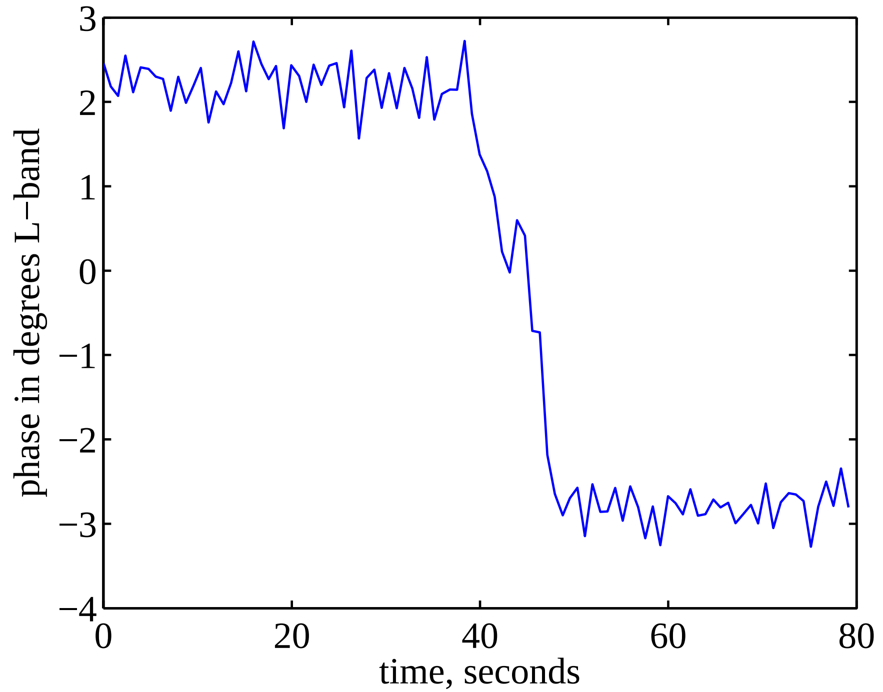
| Freq / Hz | x Centre / mm | y Centre / mm |
|---|---|---|
| 2.5678E+9 | 0.047 | 0.013 |
| 2.5691E+9 | -0.001 | 0.005 |
| 2.5699E+9 | 0.014 | 0.019 |
| 2.5706E+9 | 0.006 | -0.266 |
| 2.5726E+9 | 0.001 | -0.038 |
| 2.5730E+9 | 0.000 | 0.001 |
| 2.5737E+9 | 0.011 | 0.024 |
| 2.5753E+9 | -0.006 | 0.030 |
| 2.5757E+9 | 0.001 | -0.006 |
| 2.5761E+9 | -0.011 | -0.019 |
| 2.5764E+9 | 0.001 | -0.040 |
| 2.5775E+9 | -0.008 | 0.152 |
| 2.5780E+9 | -0.006 | 0.031 |
| 2.5801E+9 | 0.178 | -1.549 |
| 3.0807E+9 | 0.066 | -0.001 |
| 3.0824E+9 | -0.002 | -0.074 |
| 3.0837E+9 | 0.071 | -0.027 |
| 3.3092E+9 | 0.131 | -0.303 |
| 3.3538E+9 | 0.047 | -0.517 |
| 3.3539E+9 | 0.297 | -0.099 |
| 3.3558E+9 | 8.299 | -8.022 |
| 3.3561E+9 | 0.251 | 0.468 |
| 3.3592E+9 | -0.388 | 0.397 |
| 3.3629E+9 | -0.593 | -0.907 |
| 4.4652E+9 | 1.235 | -0.421 |
| 4.4735E+9 | 0.816 | -2.129 |

# Monopole Mode Measurements




- Digitise the HOM signal with a broadband scope,
  - 10 GS/s, 6 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.

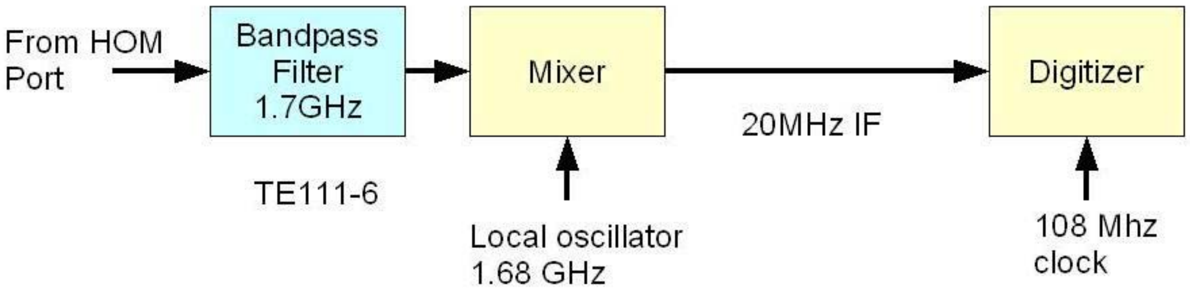
# Monopole Mode Measurements

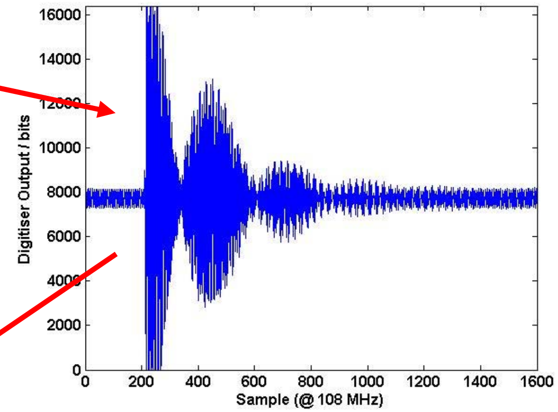



- Measurement of the 1.3 GHz phase
  - 5 degree phase change command from the RF control system.
- Noise is 0.08 degrees at 1.3 GHz
  - Estimated by comparing the measurement from two couplers from the same cavity.
- When the beam phase is compared to the RF phase of two cavities on the same klystron,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

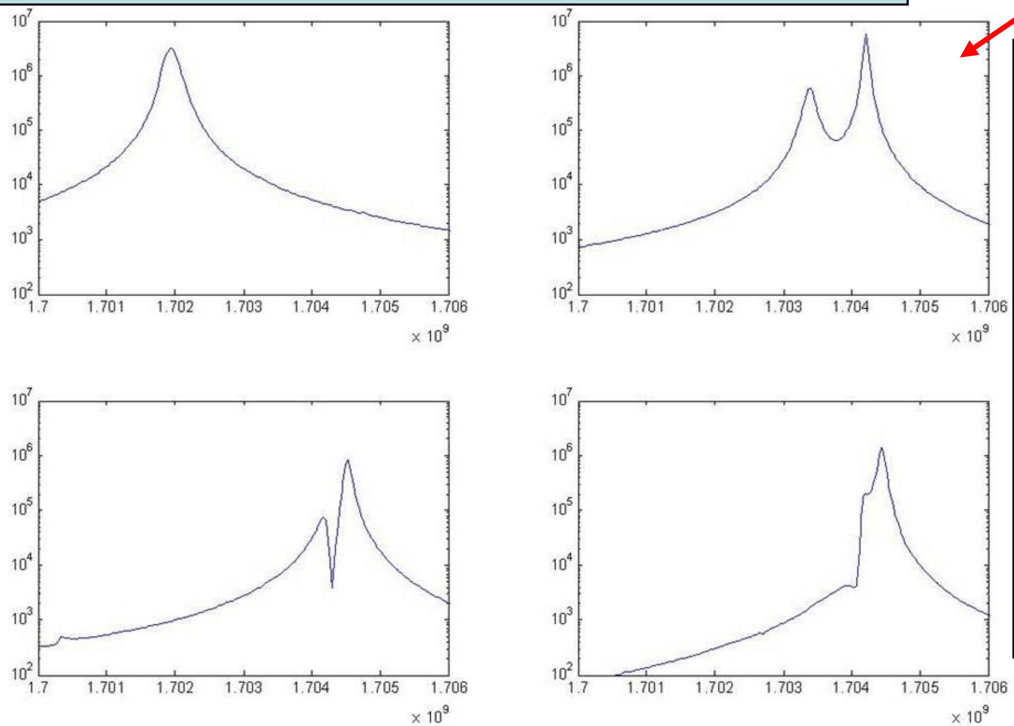
# Narrow band Measurements

# Narrow-band Measurements



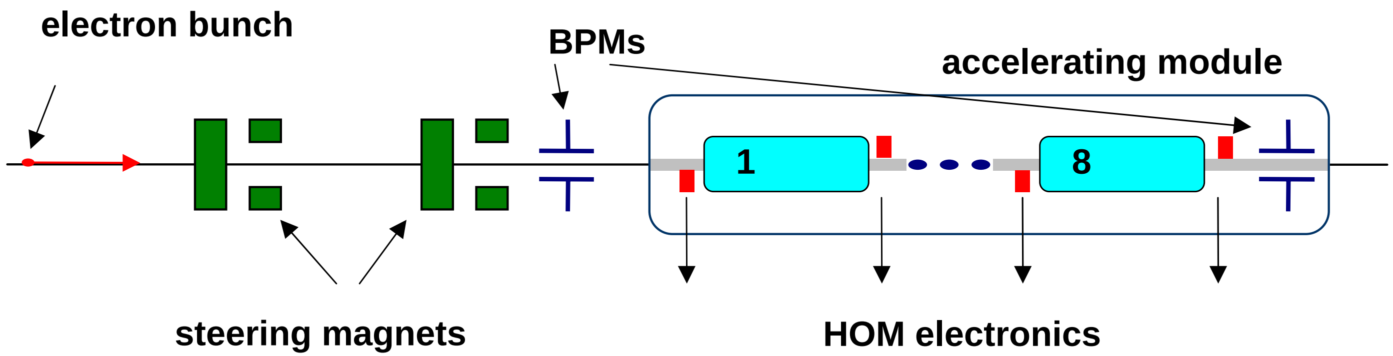




- ~1.7 GHz tone added for calibration purposes.
- Cal tone, LO, and digitiser clock all locked to accelerator reference.




- 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.

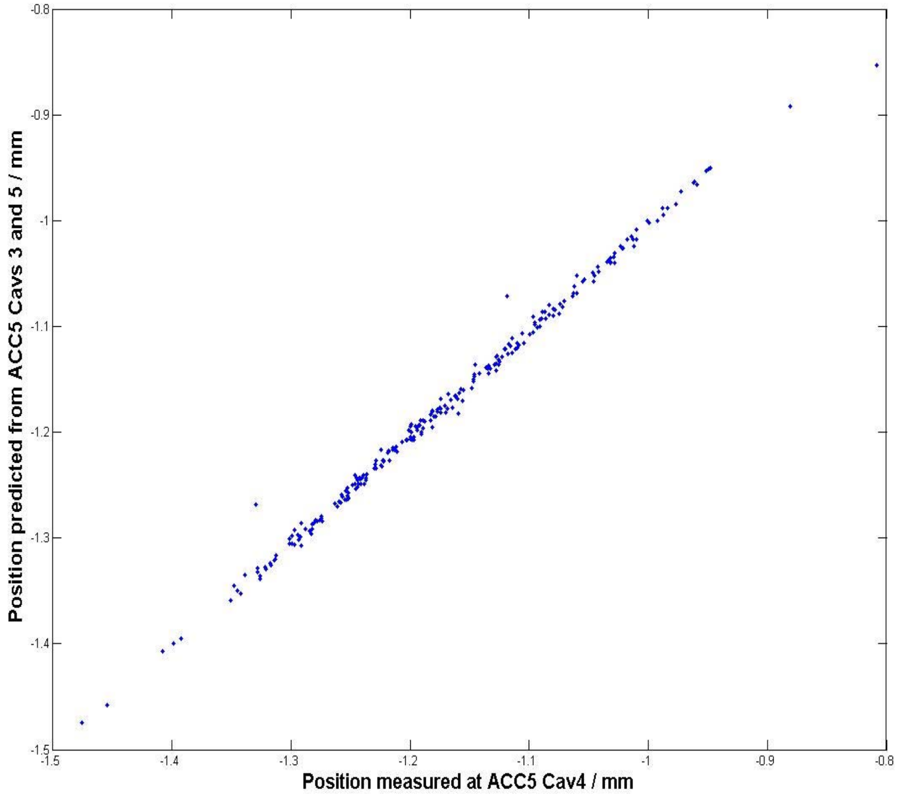
# Method



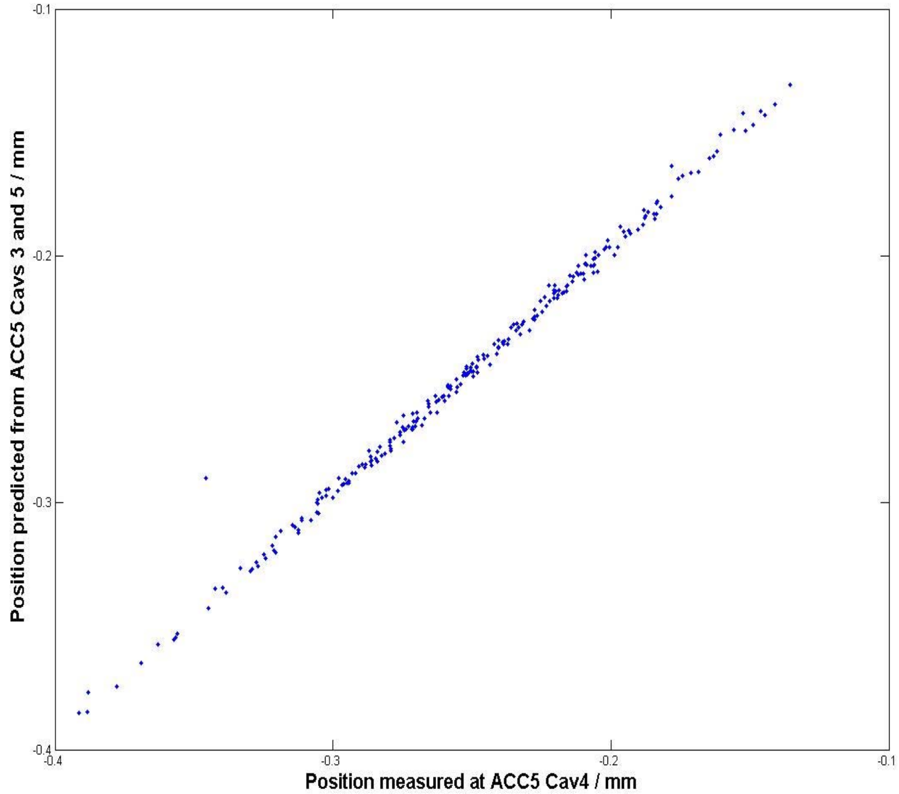

- Develop model for the machine
- Steer beam using two correctors upstream of the accelerating module.
- Record the response of the mixed-down dipole mode at each steerer setting.
- Data analysed using SVD method to reconstruct waveforms due to motion in each dimension.

# Predict position at one cavity from positions at adjacent cavities

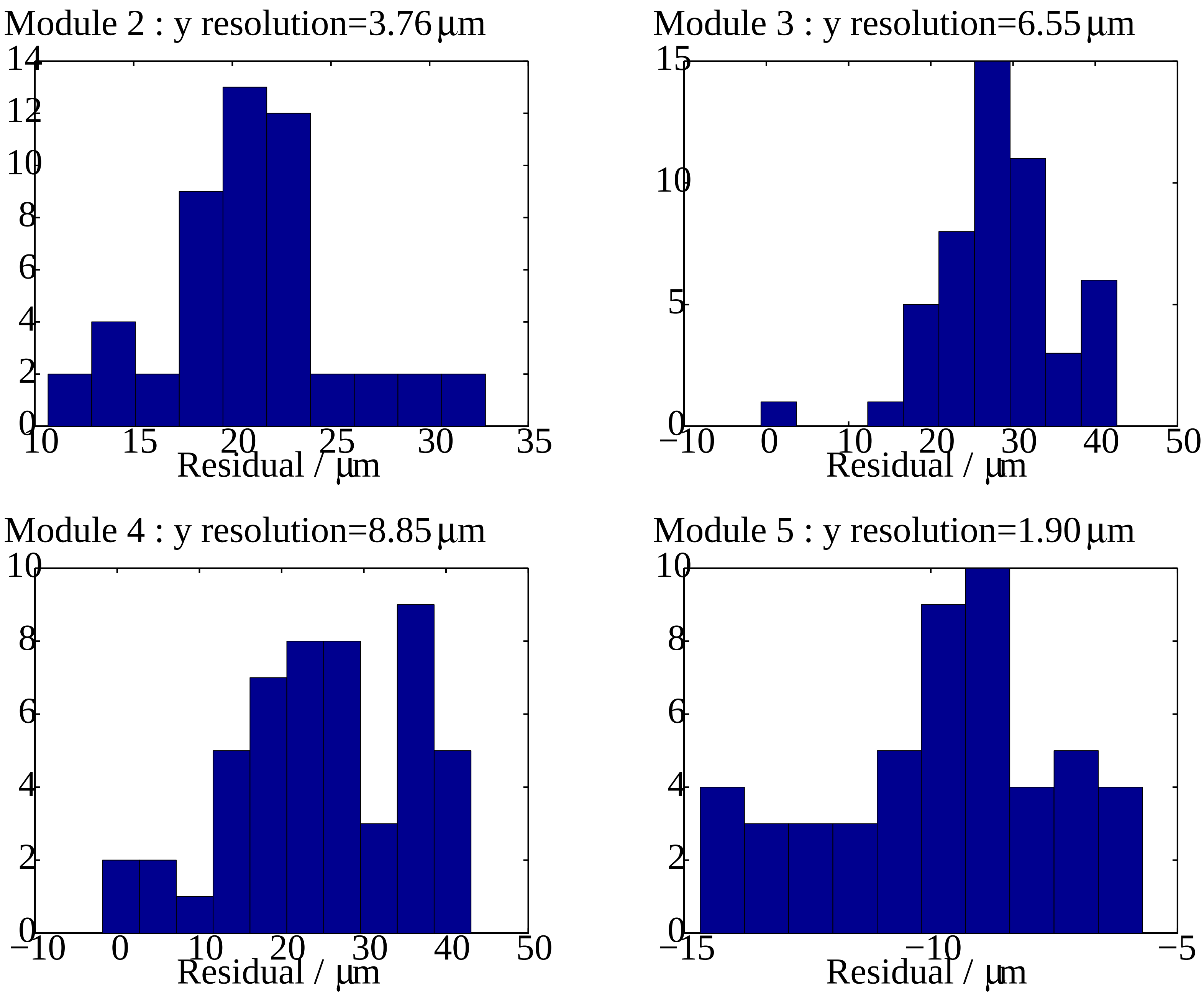
*X* resolution ~ 6.1µm




*Y* resolution ~ 3.3 µm



# Apply calibration to a different dataset



# Theoretical Resolution

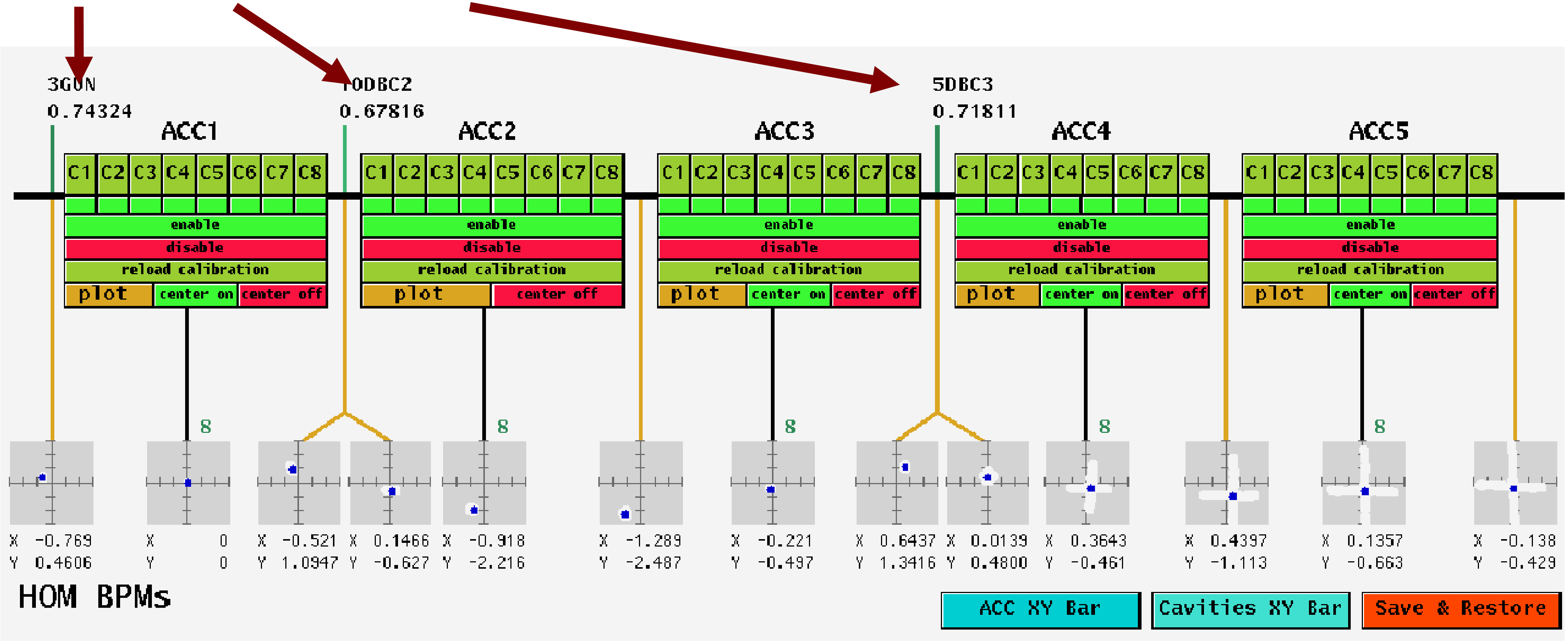
Energy in mode – $U = \left(\frac{R}{Q}\right) \cdot \frac{\omega}{2} \cdot q^2$

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

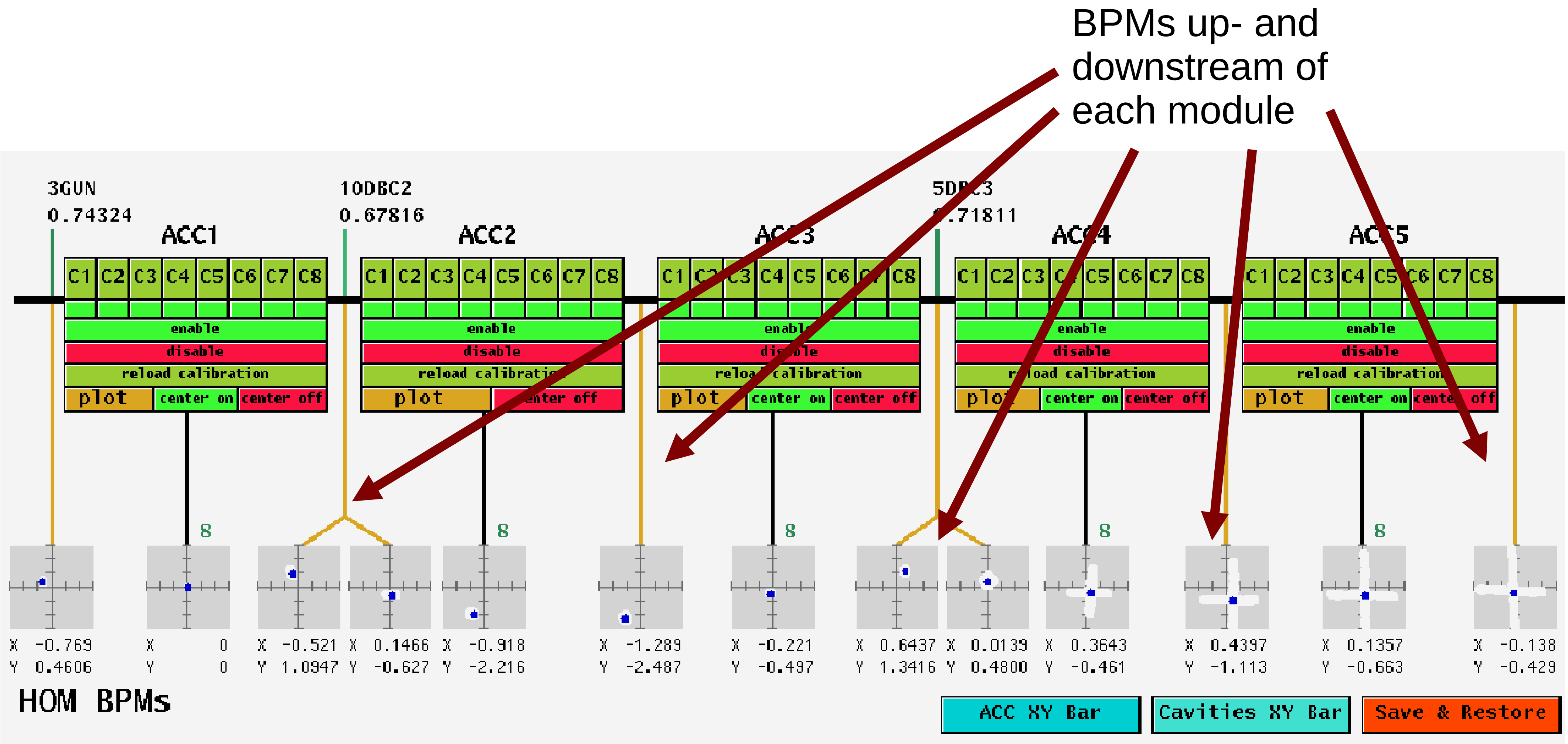
- Corresponds to a limit of ~100 nm
  - Included 10 dB cable losses, 6.5 dB noise figure, and 10 dB attenuator in electronics.
- Need good charge measurement to perform normalisation.
  - 0.1% stability of toroids, to achieve 1 um at 1 mm offset.
  - Not the case with the FLASH toroids.
- LO has a measured 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.

# Integrated with DOOCS

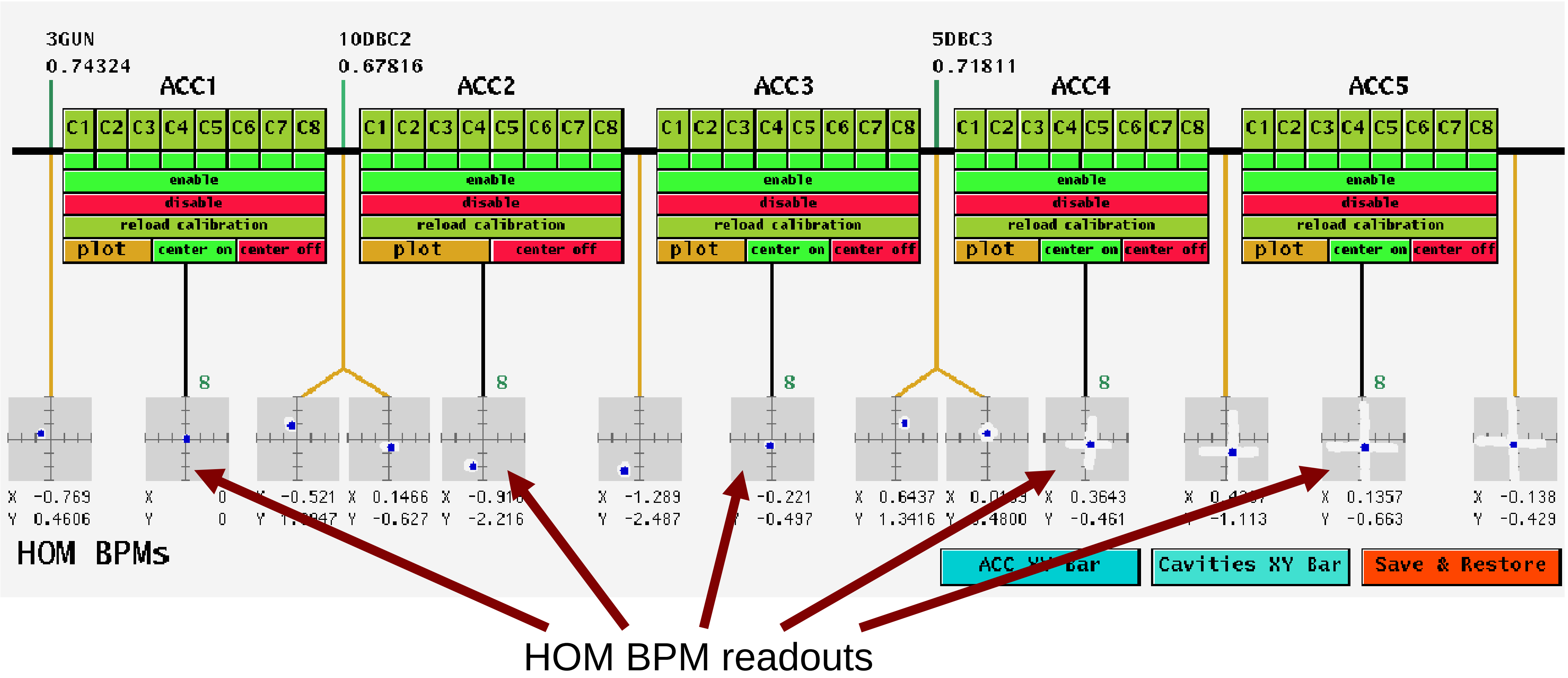
Toroids immediately upstream of the modules



# Integrated with DOOCS



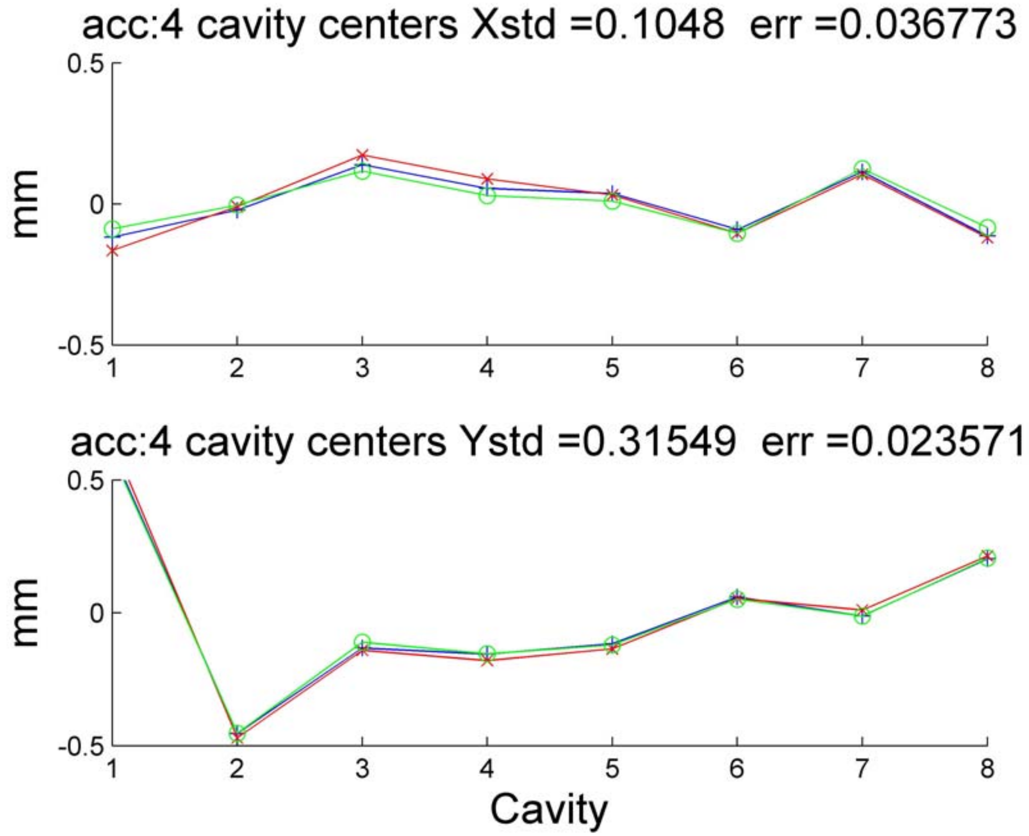
# Integrated with DOOCS




- Output is the average of all enabled HOM BPMs in each module.

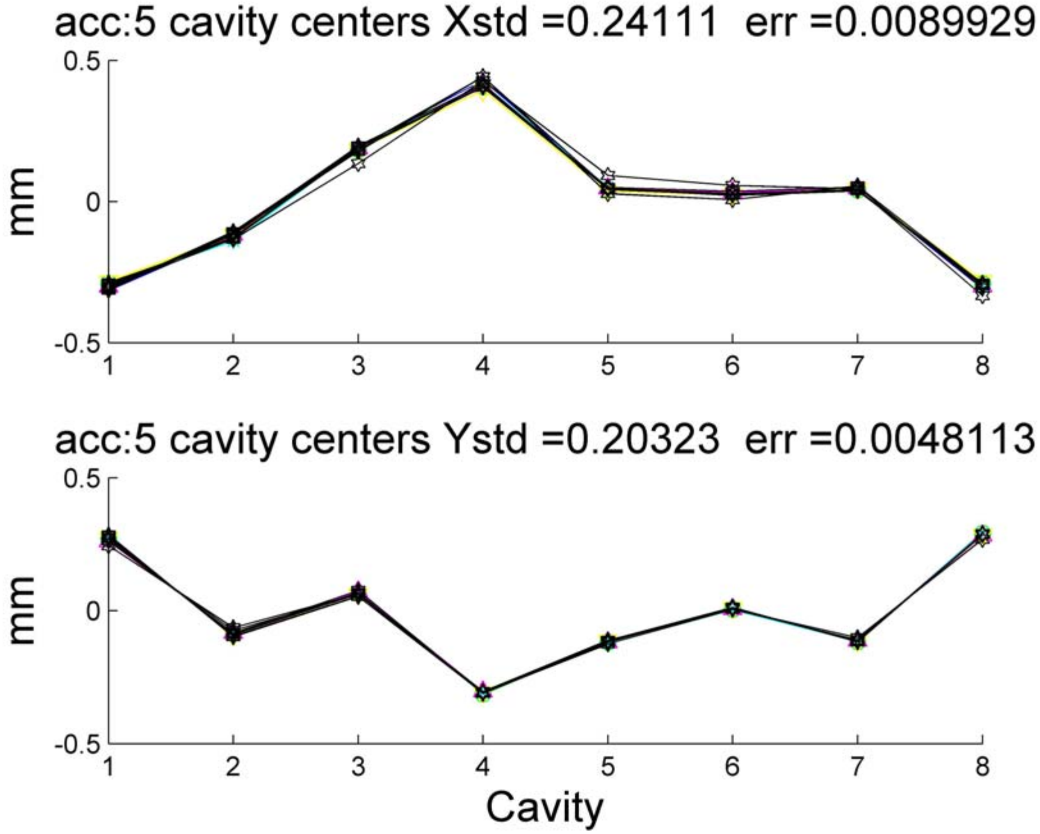
# Cavity Alignment ACC4

- X: 100 microns RMS misalignment, 37 micron measurement reproducibility
- Y: 215 micron RMS misalignment, 23 micron measurement reproducibility



# Cavity Alignment ACC5

- X: 240 micron misalignment, 9 micron reproducibility
- Y: 200 micron misalignment, 5 micron reproducibility



# 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, (65 nm thermal limit)