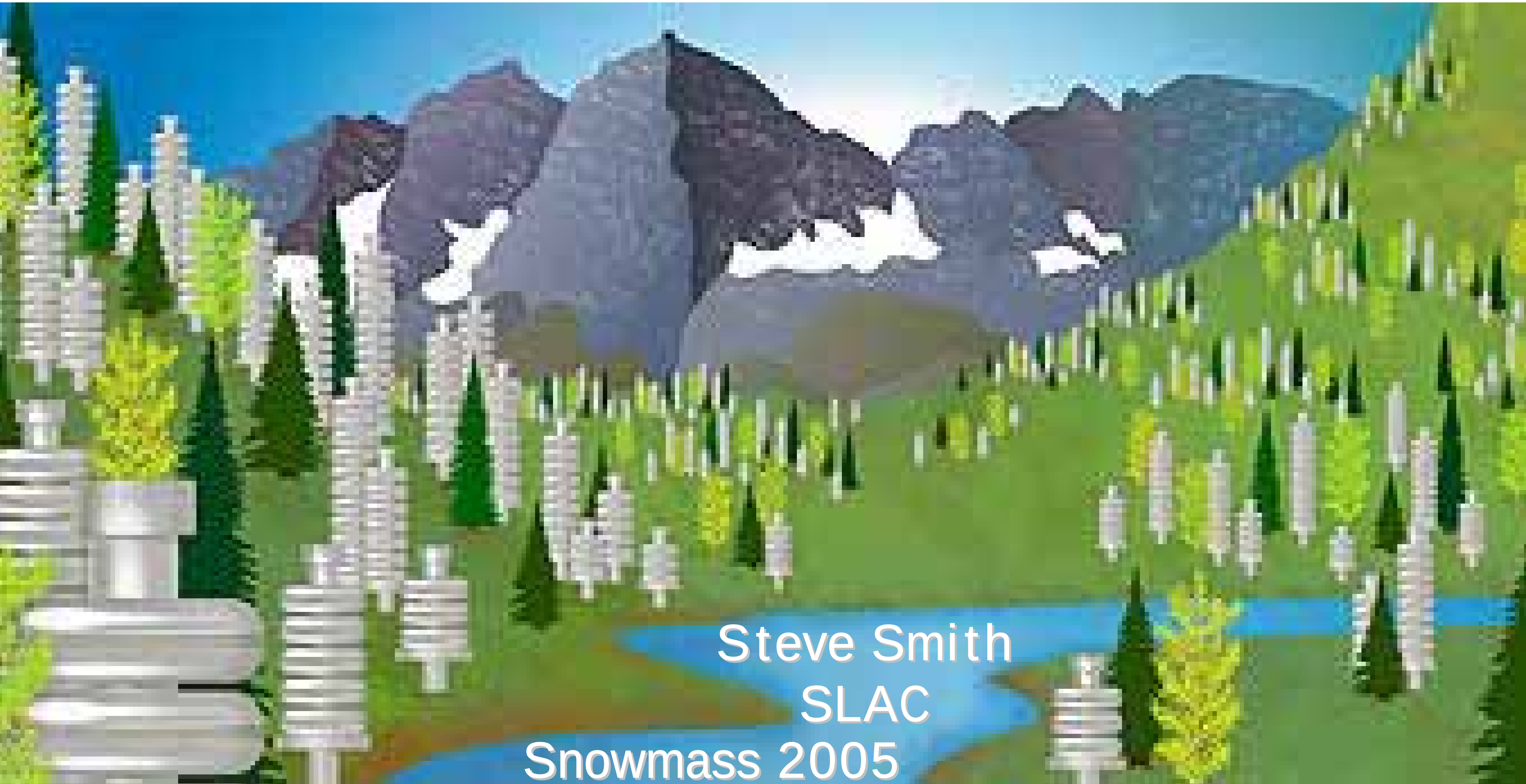
ILC Cavity BPMs



Outline

- Goal:
  - Compare ILC requirements to “state-of-the-art”
- What are ILC Requirements?
- What kinds of BPMs?
  - Q BPMs
  - HOM BPM
  - Diagnostic BPMs
  - “Specials”
  - Energy Spectrometery
- Detailed Example: KEK ATF cavity BPM work
  - BINP Cavity BPMs
  - KEK Cavity BPM
  - ATF2 BPM

ILC Beam Position Monitor Requirements

- Aperture
- Resolution
  - Spatial
    - Few microns?
    - Or « beam spot size
      - In order to find source of jitter
  - Temporal
    - Bunch-by-bunch
    - Average over some/all bunches in a train?
- Accuracy (*i.e.* where is center of BPM with respect to alignment fiducials?
- Stability
- **Need solid requirements on which to base design**

Why Cavity BPMs?

- Resolution
  - It is easy to get adequate beam signal in a reasonable processing bandwidth
- Bandwidth
  - Easy to design cavity for bandwidth low enough for conventional signal processing
  - High enough for bunch-bunch separation
- Processing Scheme
  - Want to digitize and process signals in conventional manner
  - processing bandwidth where COTS chips are
  - i.e. <20 MHz processing bandwidth
- Stability
  - Avoid techniques involving small differences of large signals
  - Gnat's eyelash timing stability
- Accuracy
  - Centering established by reasonable machining tolerances.

Why not stripline or buttons?

- Signal is small difference of large numbers
- Differences taken externally to transducer
  - Analog difference (hybrid or difference amp) OR
  - Digital difference (after separate analog processing chains)
- Subject to mismatch, drifts
- Impacts
  - accuracy
  - stability
  - dynamic range
- Cavity BPMs reject common mode several ways:
  - Frequency discrimination
  - Spatial discrimination
  - Residual common mode can be microns
  - Stripline/Button: $\Delta = \Sigma$ when $Y \sim R/2$

Example: KEK-ATF Cavity BPM

- C-Band Cavities from BINP (Vogel, et al)
  - Nominally 6426 MHz
  - Dipole-mode selective couplers
- Livermore Spaceframe
  - 3 cavities fixed with respect to each other
  - Hexapods for 6 degrees of freedom of alignment
  - flexure legs
- Dual Downconversion Electronics:
  - First IF at 476 MHz
  - Second IF at 25 MHz
- Digitize 14 bits at 100 MSamples/sec
- Expect few nm resolution
- Compare consistency of three BPMs

C-Band Cavities

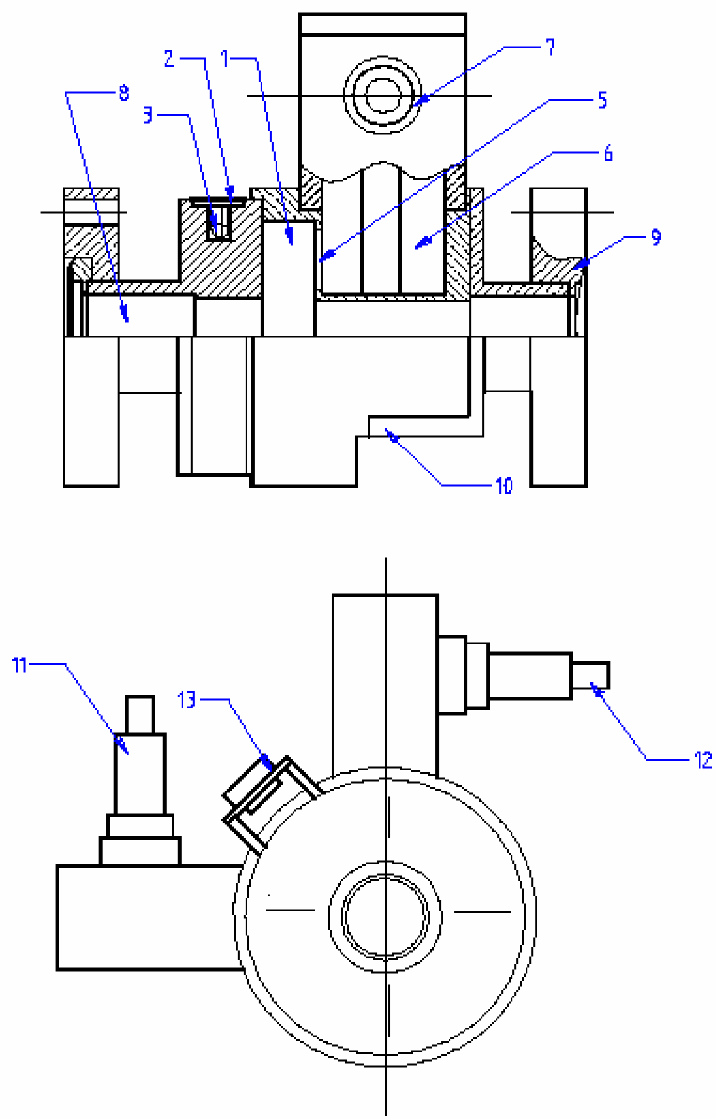
BINP Cavities (Vogel, *et al.*)

~ 2cm aperture

Dipole-mode

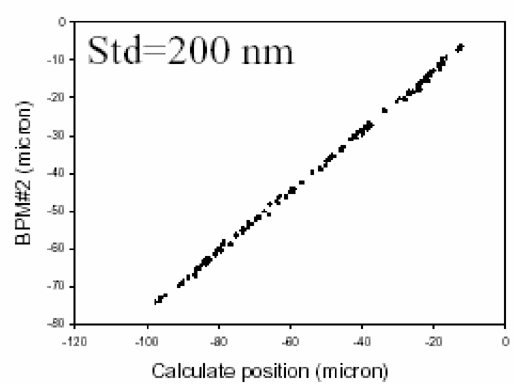
selective

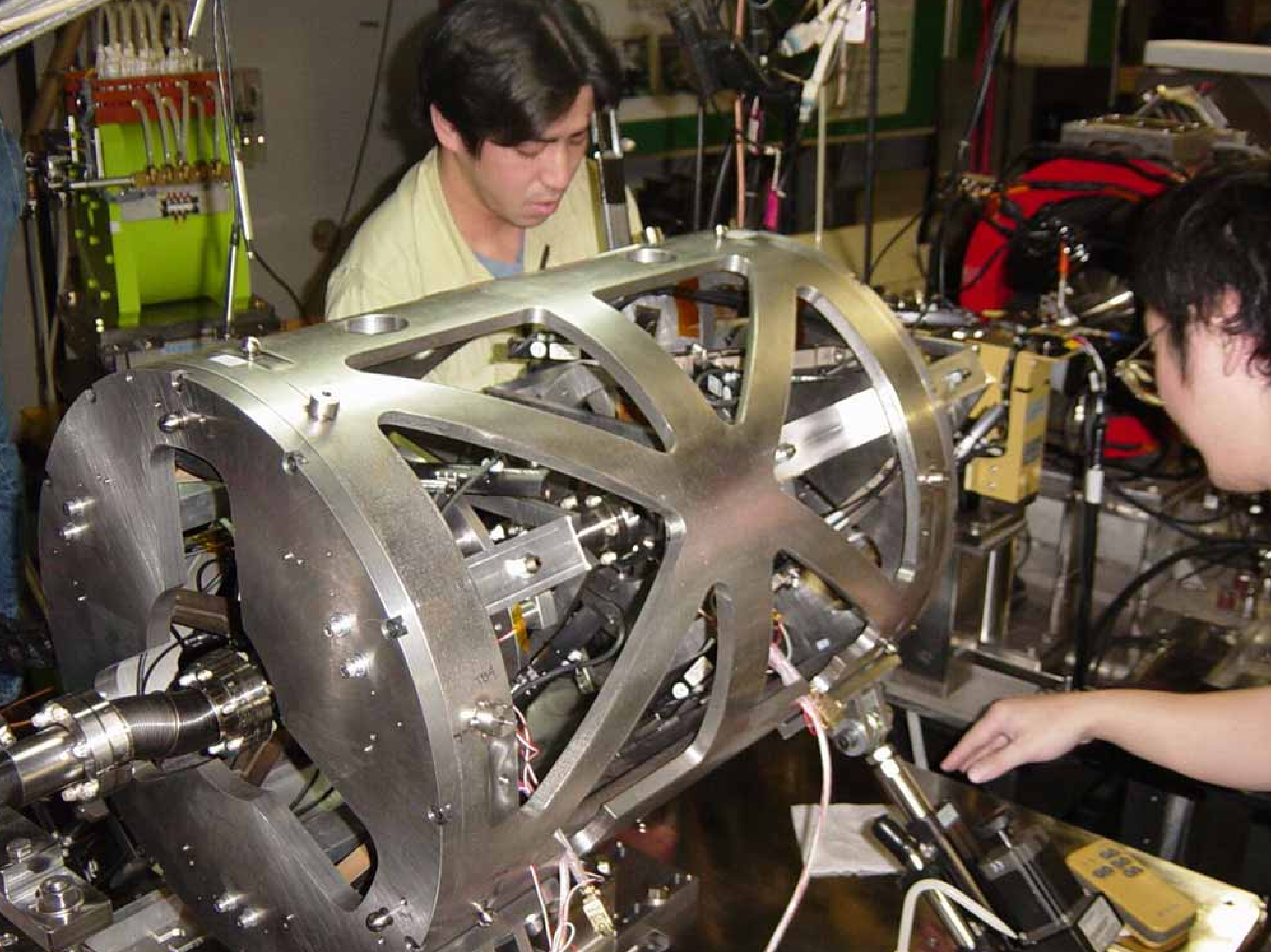
couplers



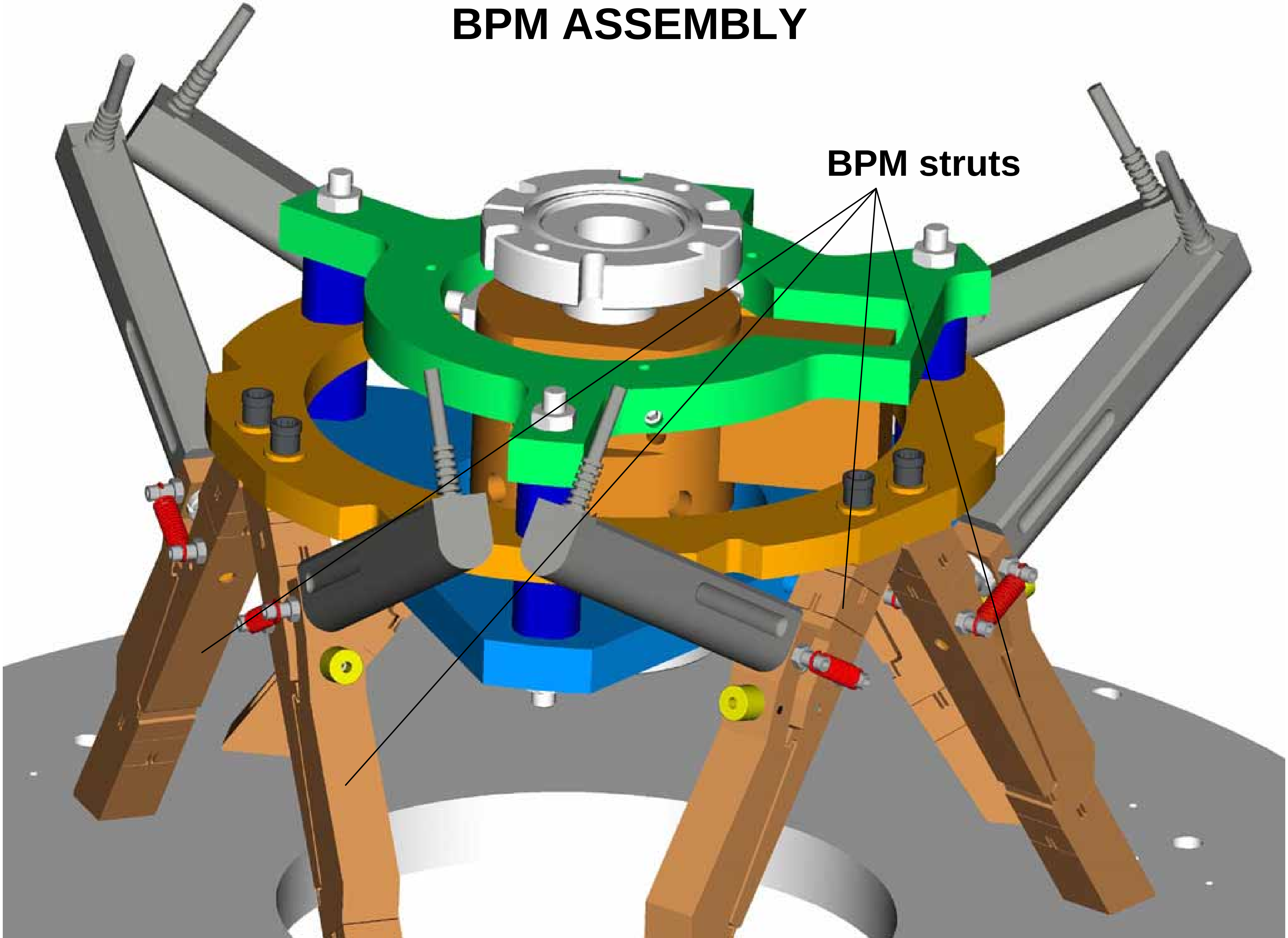
Cross-sectional view of BINP cavity BPM 6426 MHz, (5p. in KEK ATF + 1p.). 2000.

1.- Cavity sensor .
2- Heater.
3 – Temperature sensor.
5 – Coupling slot.
6 – Output waveguide.
7 – Output feedthrough.
8 – Beam pipe.
9 – Vacuum flange.
10 – Support plate.
11 – Y position output.
12 - X position output.
13 – Heater control connector.





BPM ASSEMBLY



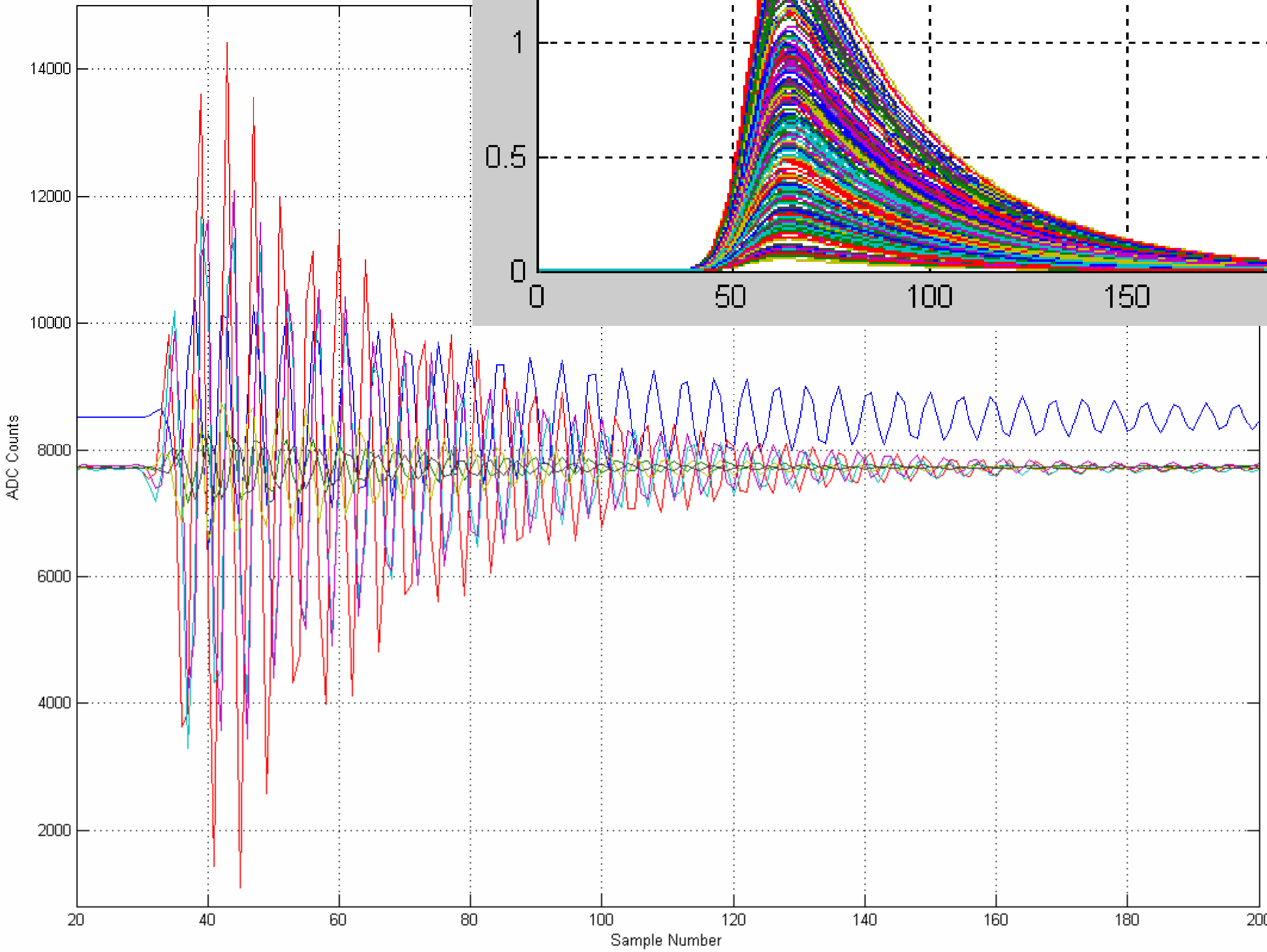
Incoming Beam Parameters

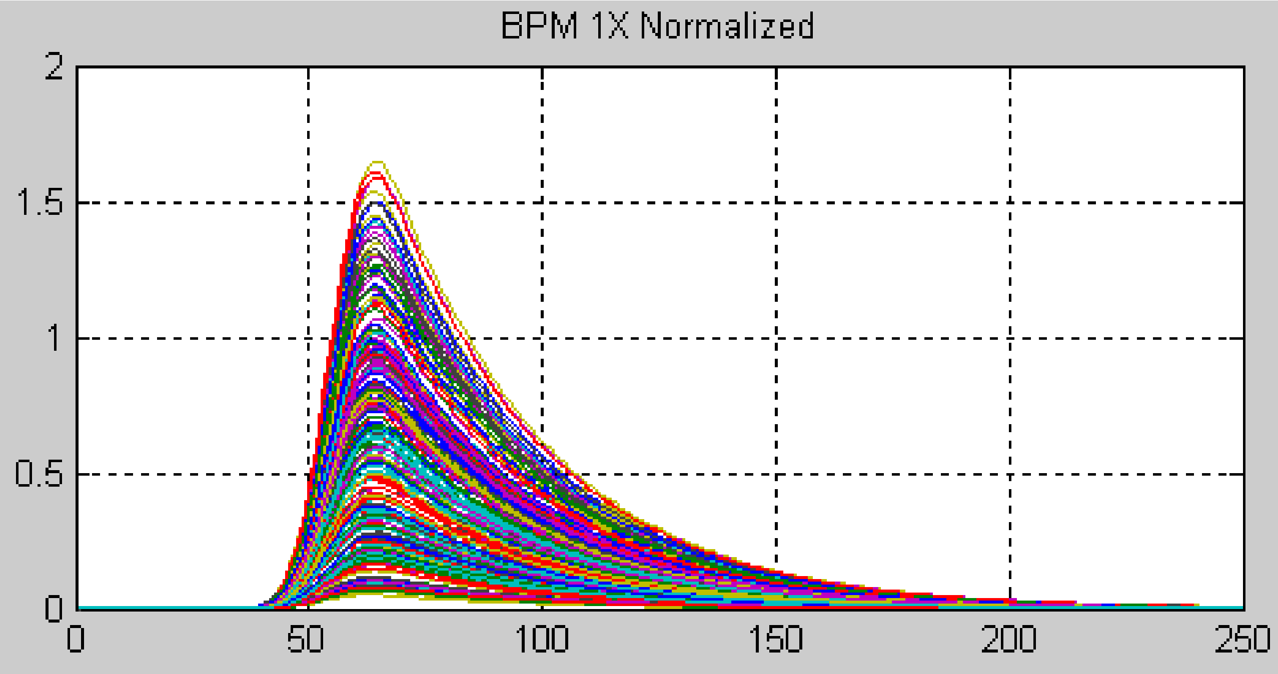
- Charge Q ~ 1.5 nC
- Spot size:
  - $\sigma_x \sim 80\ \mu m$
  - $\sigma_y \sim\ 8\ \mu m$
  - $\sigma_z \sim 8mm$ (!)
- Energy
  - dispersion ~ 1e-3
  - $\Delta E/E \sim 5e\text{-}4$
- Position & angle jitter:
  - $\sigma_x\ 20\ \mu m$
  - $\sigma_y\ 3.5\ \mu m$
  - $\sigma_x'\ 1000\ \mu rad$
  - $\sigma_y'\ 2\ \mu rad$

Processing Algorithm

- Digital Downconversion:
  - Multiply digital waveform by complex "local oscillator" $e^{i\omega t}$
  - Low-pass filter (currently 2.5 MHz B/W)
- Sample complex amplitude of position cavity at "peak"
- Divide by complex amplitude from reference cavity
- Scale/rotate by calibration constants
- Refine calibration with linear least-squares fit to other BPM measurements, e.g. $y_2^{pred} = f(y_1, y_3, x_2)$
  - Removes
    - Beam jitter
    - Rotations
    - calibration errors.
  - Monopole modes appear as offset in (I,Q) space
    - As do mixer offsets, rf leakage

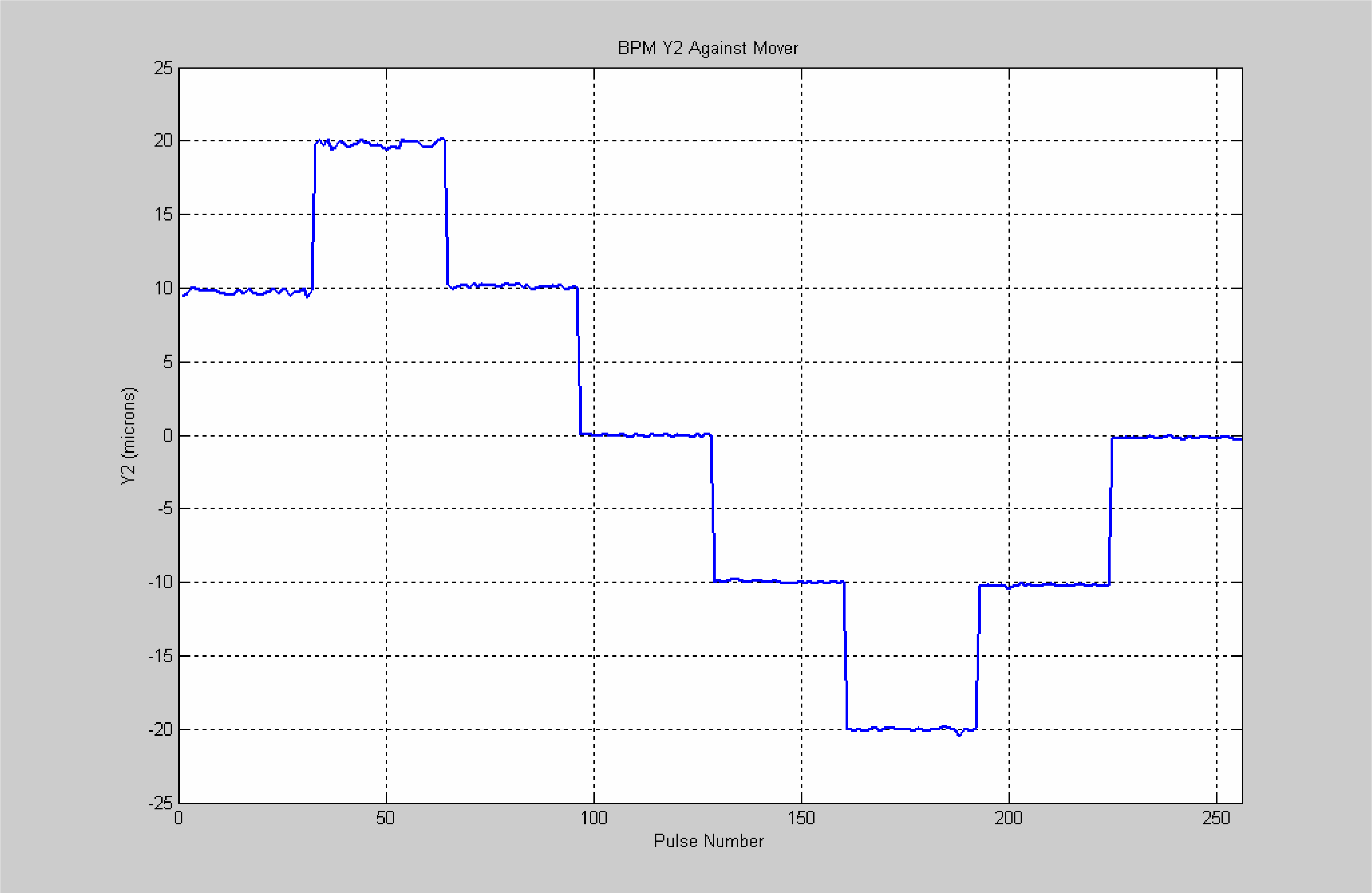
Data: Raw & Demodulated



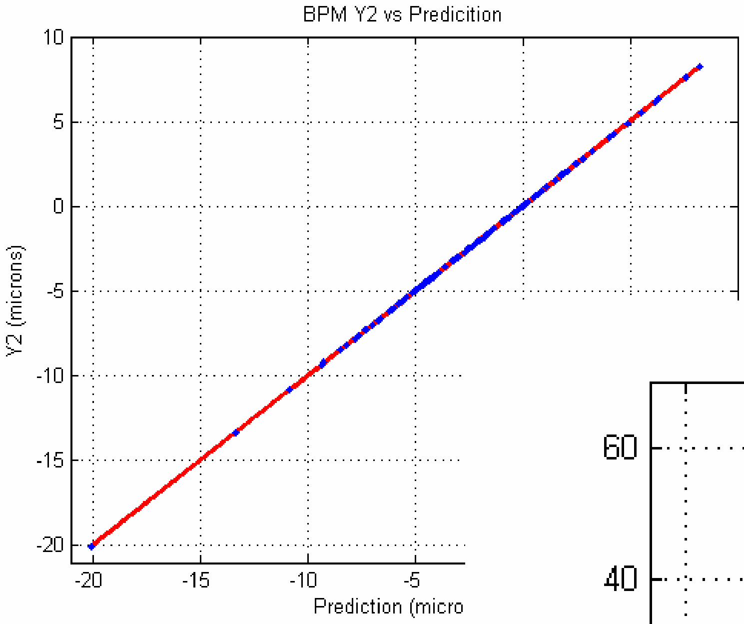


Calibrate

- Move one BPM at a time with movers
- Extract BPM phase, scale, offset as well as beam motion by linear regression of BPM reading against mover + all other BPM readings.

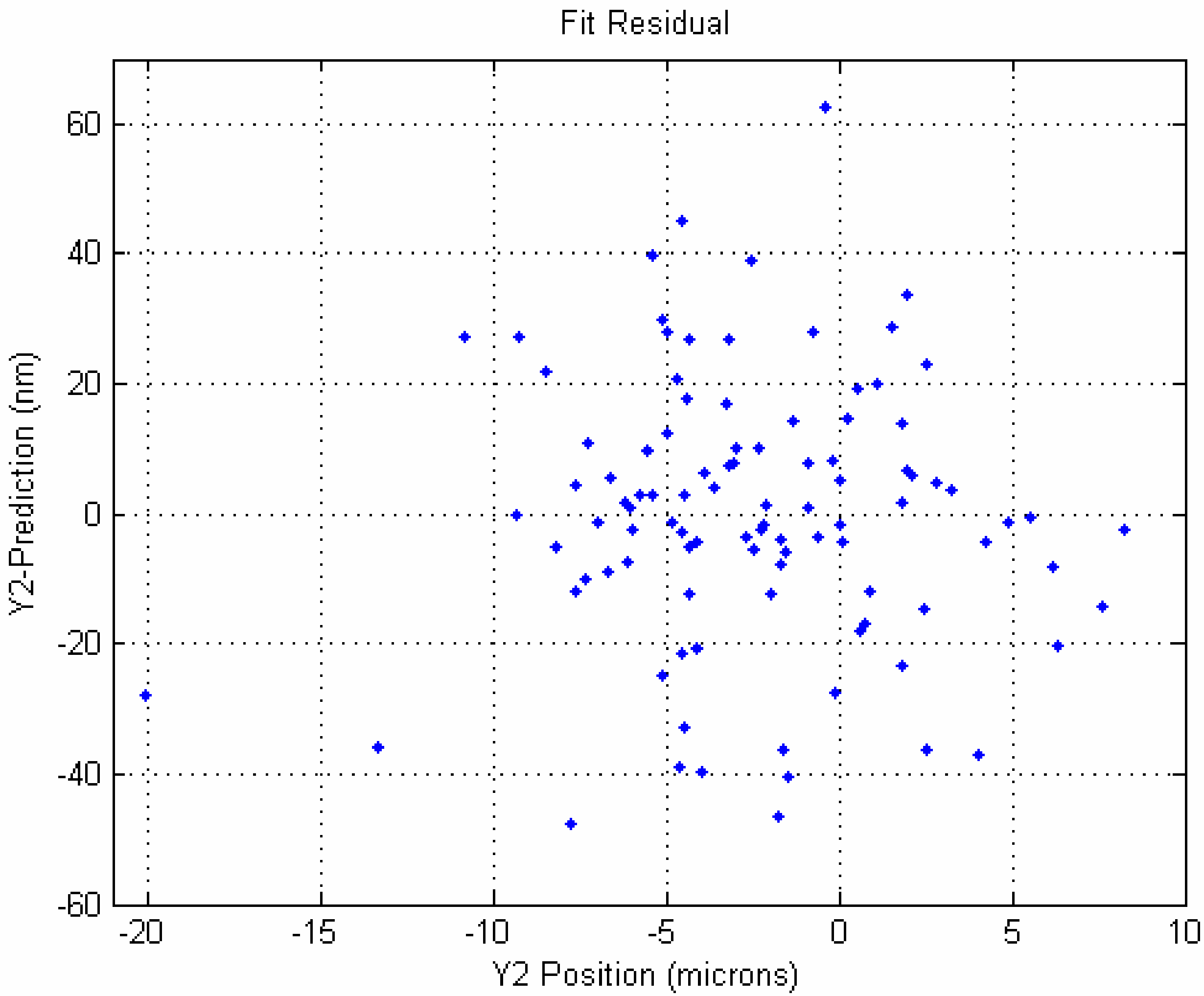


Short Term Resolution

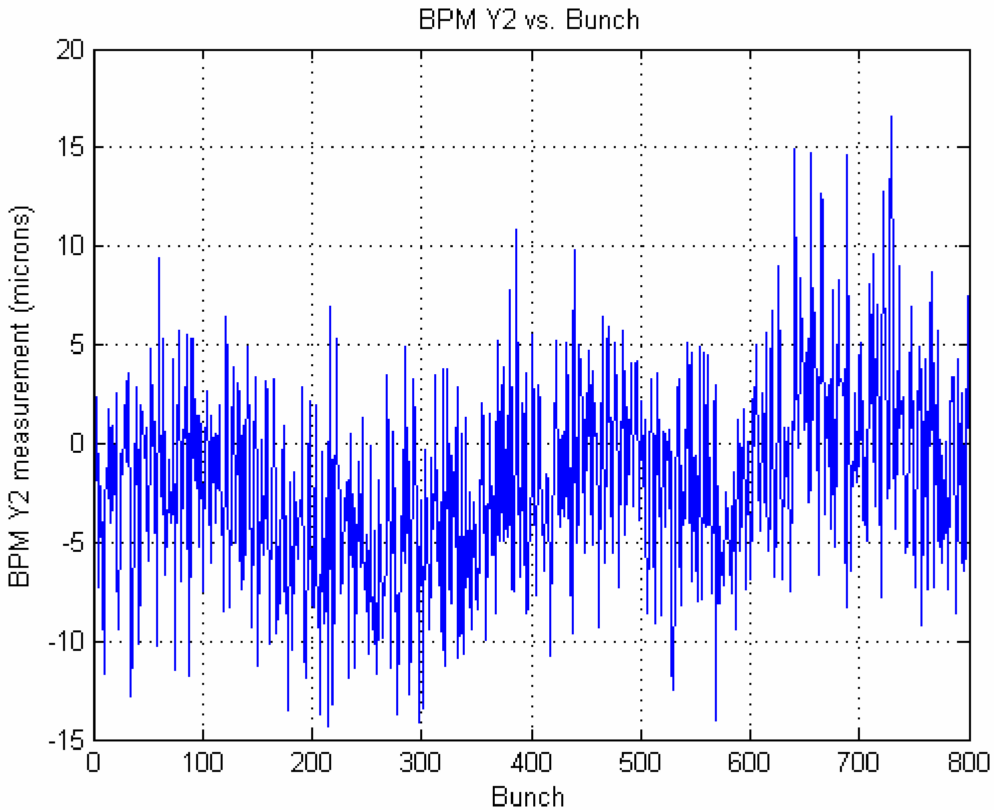


Predict Y2 from other BPMs

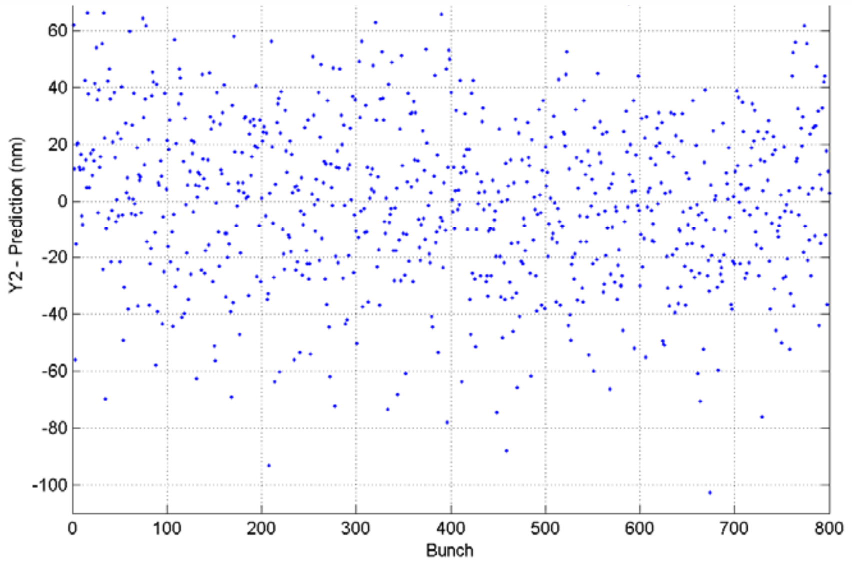
Linear least-squares fit to (x, y, x', y') at BPMs 1&3

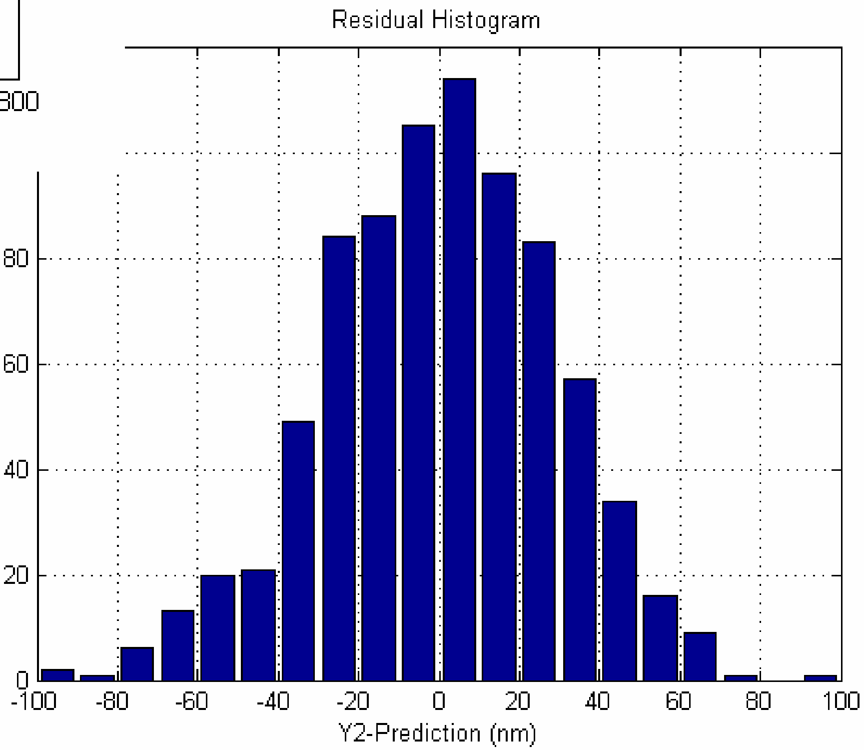


- 1 minute
- 100 pulses
- σ = 17 nm
- Is it real?

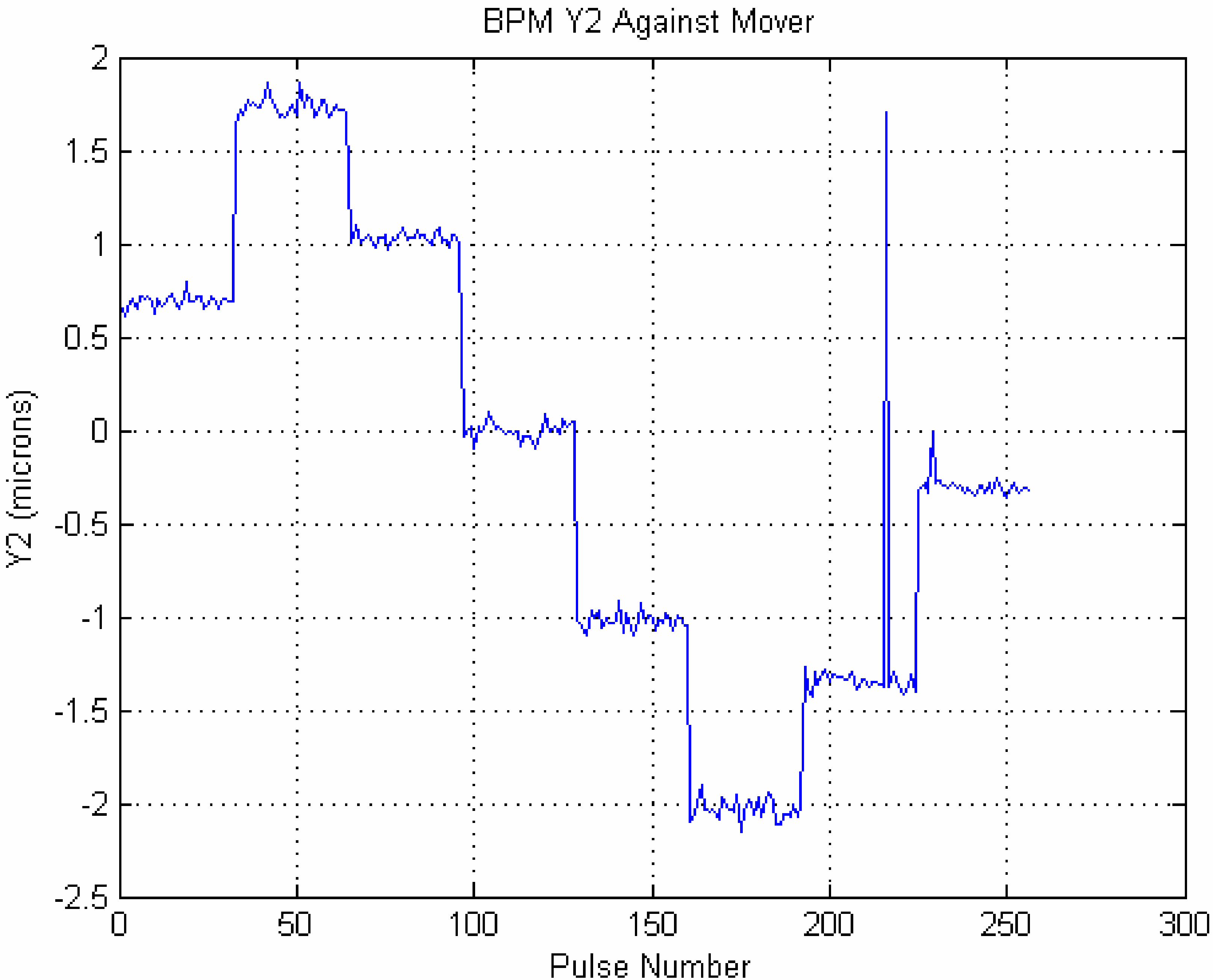


- Longer run
- 800 events
- ~10 minutes
- σ ~ 24 nm
- Few-minute drift
- Thermal?

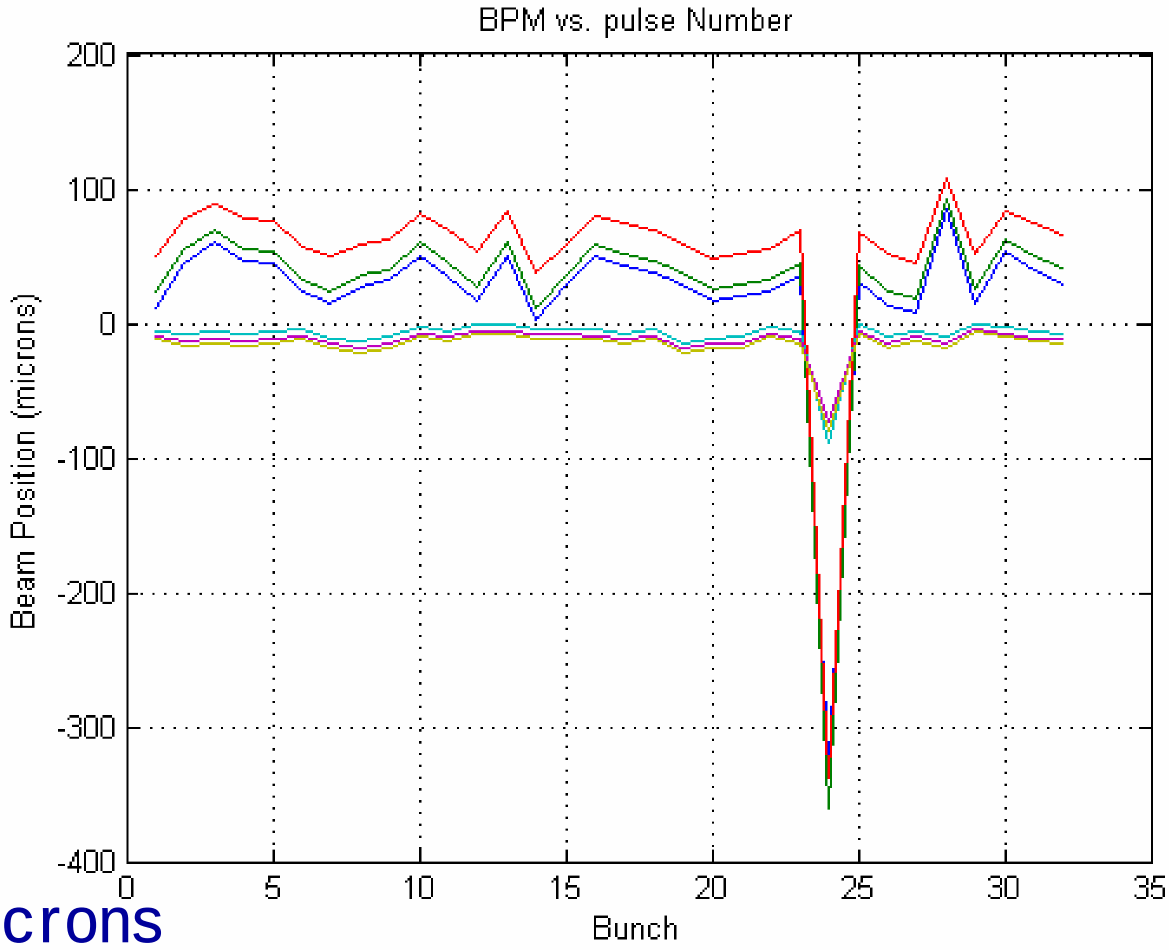




Move BPM in 1 μm Steps

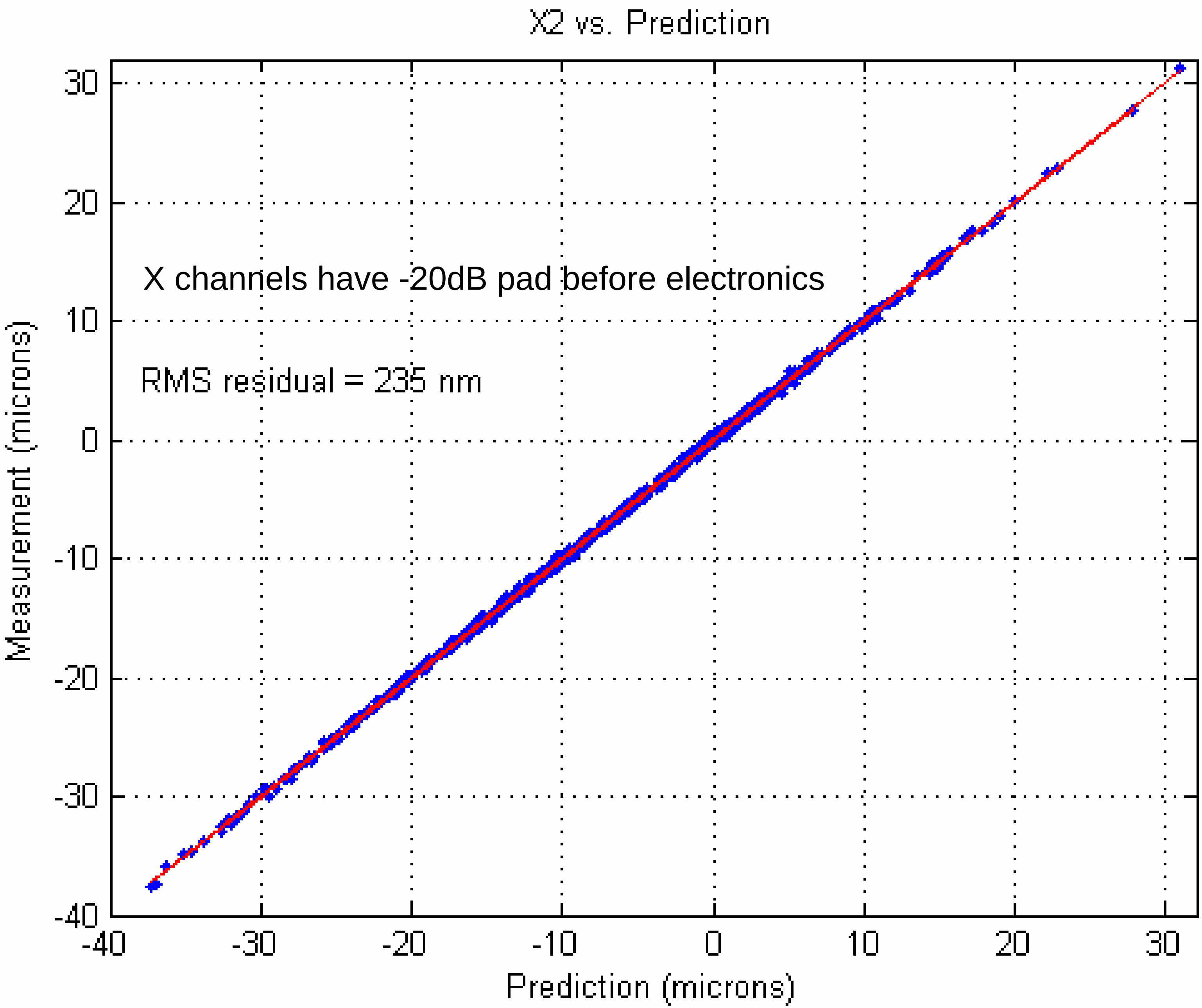


Flier



- Charge 20% low
- X off by 300 microns
- Y off by 80 microns
- ADCs heavily saturated
- Got Y trajectory consistent to within 1 micron of 80
- Should do better

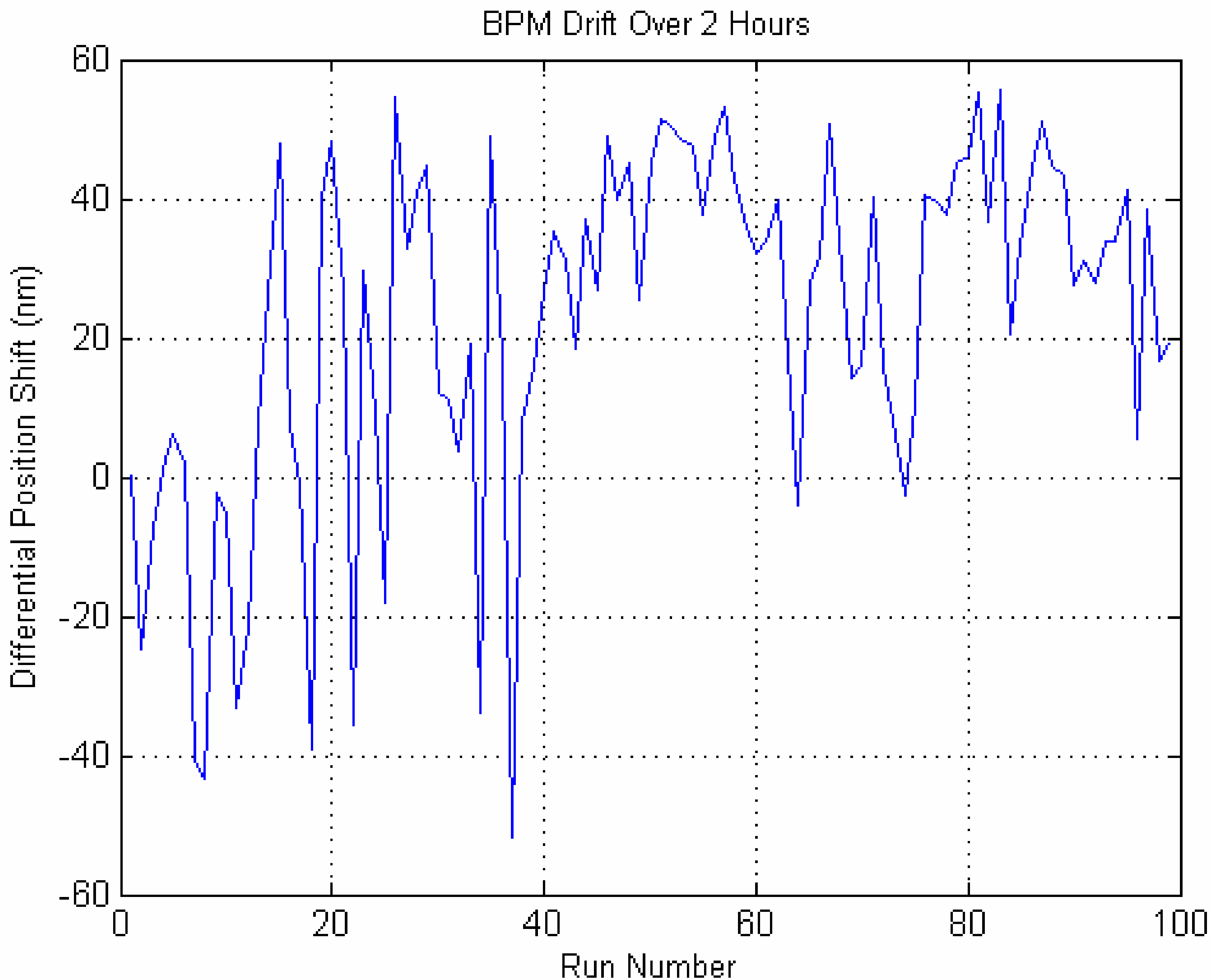
X Resolution



What limits resolution?

- Why don't we get 2 nm rms?
- Calculated loss factor in dispute
  - Power per Coulomb per mm
- Re-analysis of cavity revised loss factor down by factor of 10
  - Incorporate waveguide and coupler into simulation
  - (factor of 3 in resolution)
  - Measured loss factor somewhere between
- Compare resolution to that calculated from measured noise
  - Measure broadband electronics noise in samples digitized before beam arrival ~ 4 ADC counts rms
  - Measure phase noise by injecting cw tone in frontend
  - Seems to explain observed resolution

Stability Check



Stability

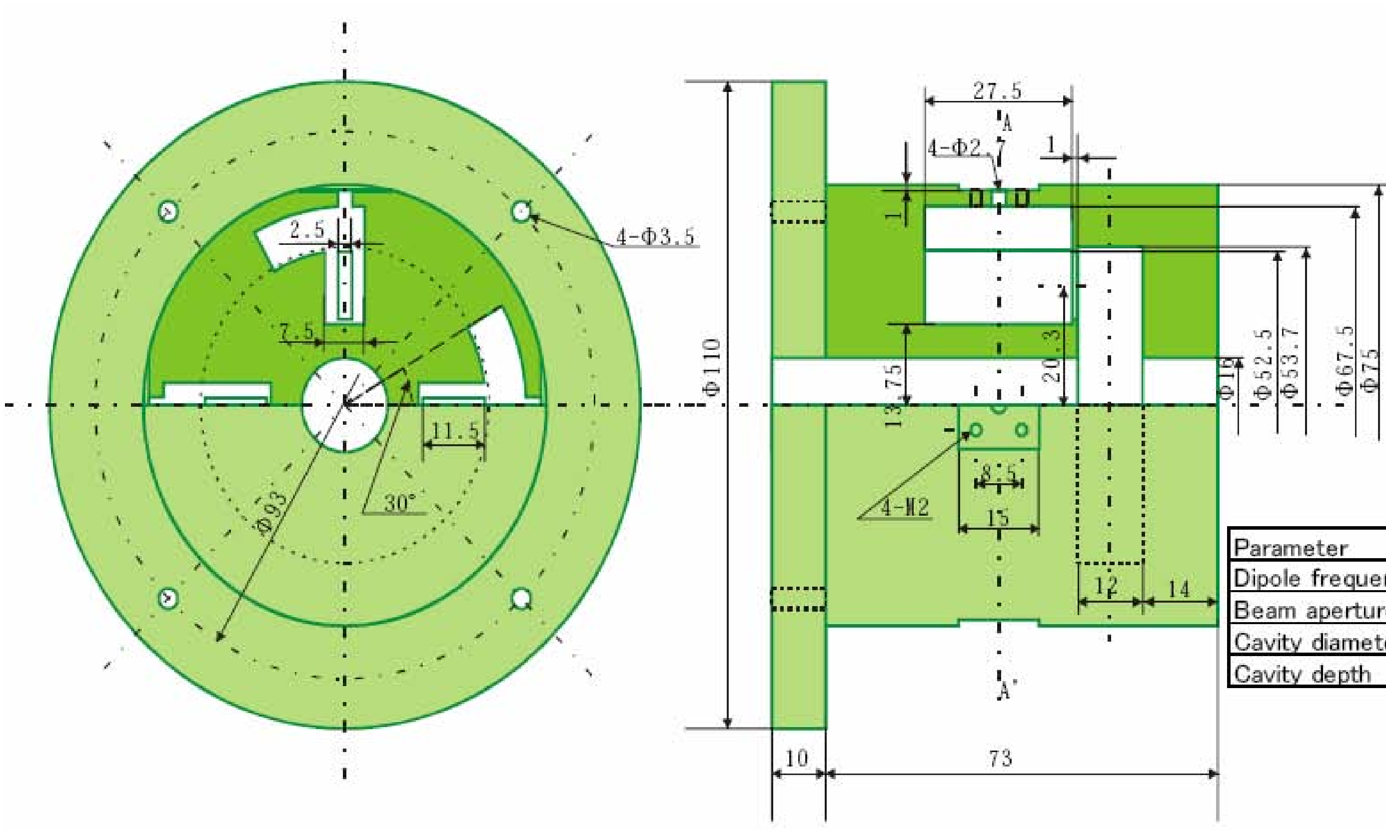
- Stability excellent
  - At least BPM to BPM
- Good running periods were only a few hours
  - Sporadic shifts for BPM studies
  - We moved BPMs (as a unit) a lot to chase the beam
- Drifts look very small over short term (~ 2 hours)
  - Need to look at data to see when movers have been touched
    - (get unbiased estimate of stability)
- Watch out for mechanical drifts in the cavity supports
  - After all a micron is rather small mechanical motion

Status

- Resolution is excellent
  - but not as good as expected
  - We don't yet understand our noise in detail
- Have not yet established:
  - absolute accuracy
  - Long-term stability (>> 2hrs)

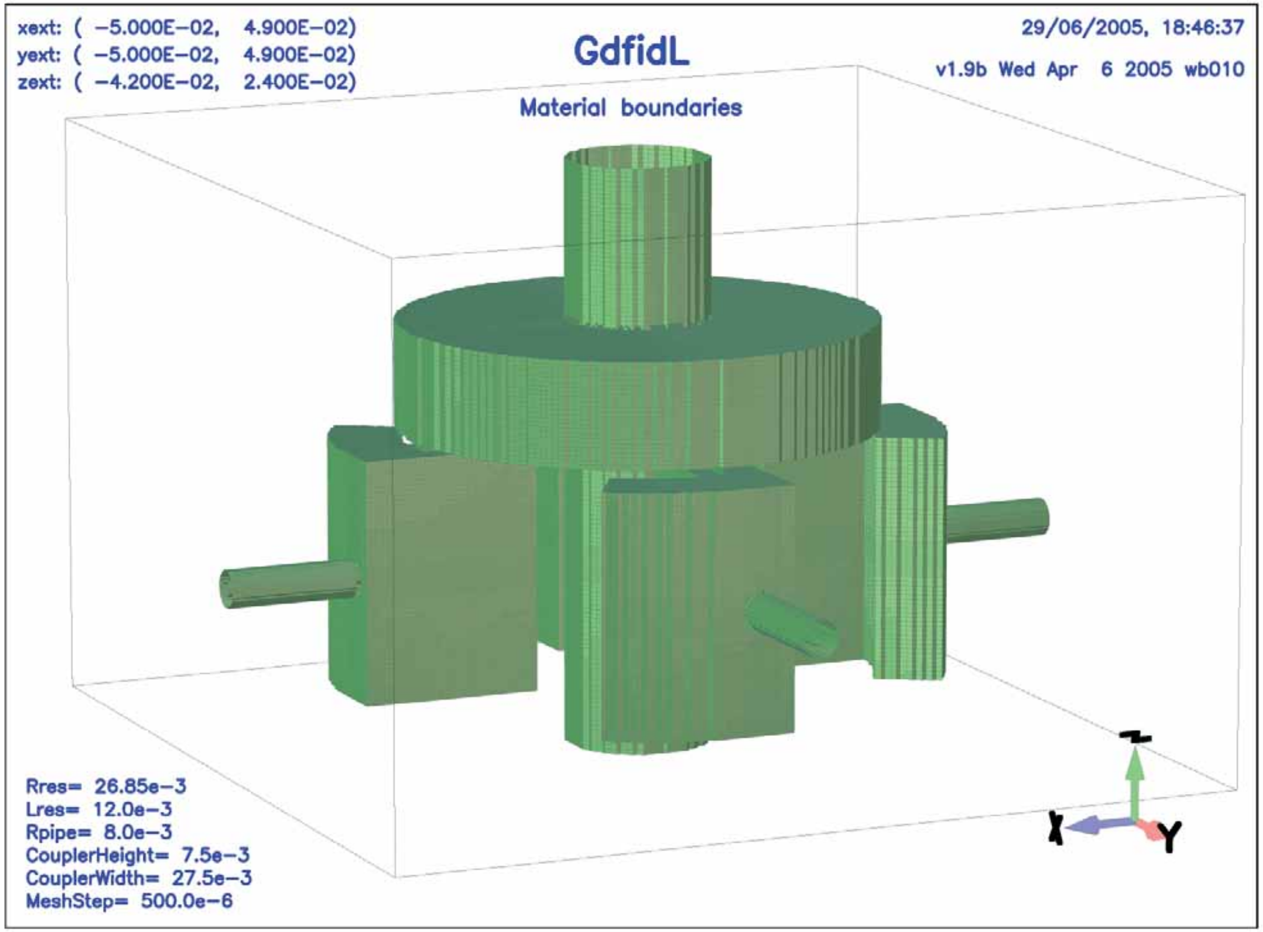
KEK Cavity BPM

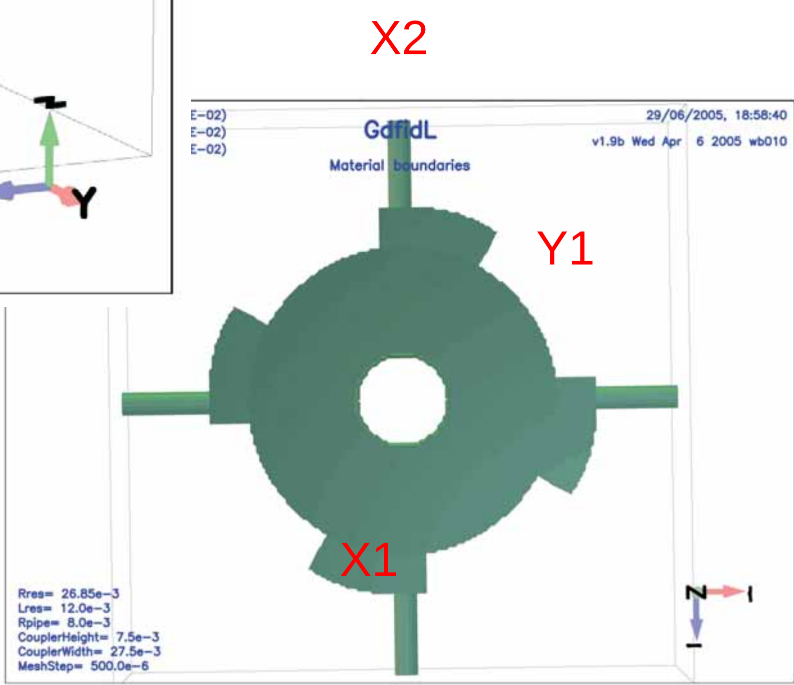
- Very compact design to save space
  - Waveguide has fold, asymmetry
- Differs from BINP design
  - BINP BPM has long waveguide taper to coax adapter
  - KEK coax adapter is very close to cavity



Parameter	Value
Dipole frequency	6.54GHz
Beam aperture diameter	16mm
Cavity diameter	53.7mm
Cavity depth	12mm

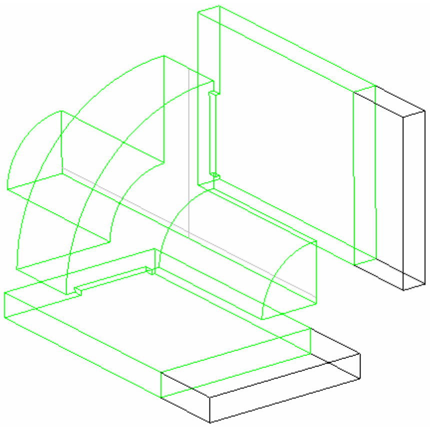
Structure – KEK BPM



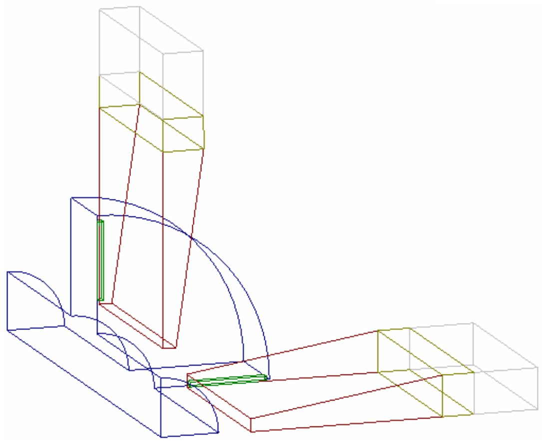


- KEK group sees ~ 70 nm resolution
- Also X-Y coupling
- Monopole mode leakage

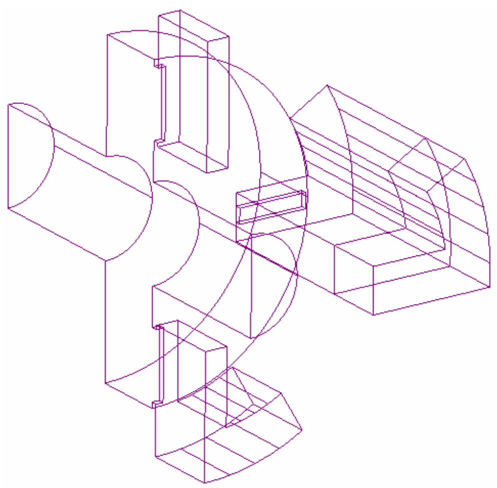
Cavity Geometry Choices



ATF2 BPM



BINP BPM



KEK BPM

C. Nantista

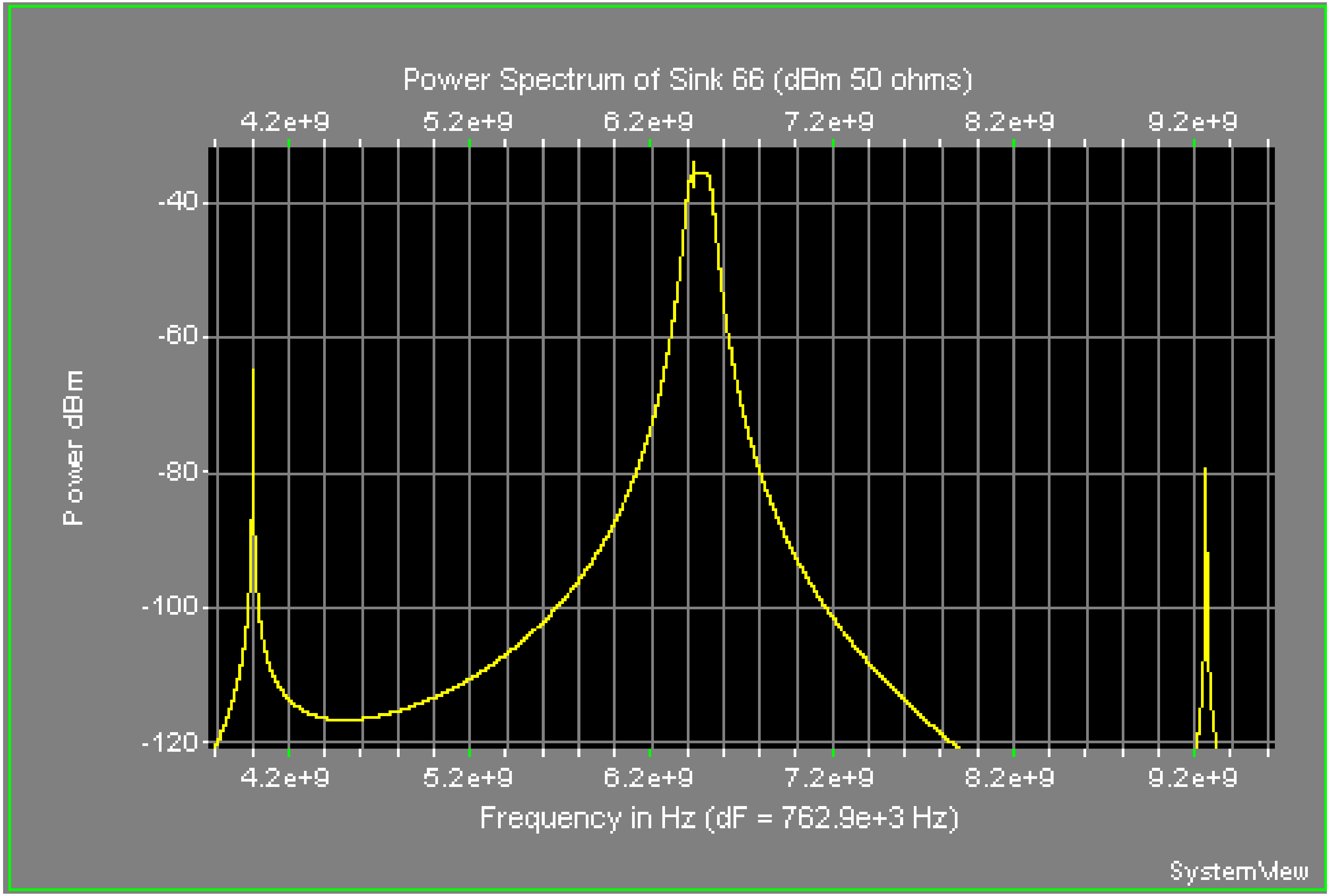
Cavity Design Lessons

- Must treat as coherent system:
  - Cavity
  - coupling slots
  - Waveguide
  - coax adapters
  - Electronics
    - In particular: reflections from first element of electronics
    - Circulator? (SLAC E158)
- Mitigate latter 3 effects by under-coupling cavity?
  - Reflections/distortions induced by coupler, etc have reduced influence on modes in cavity
  - Design for higher loss factor to maintain resolution
  - LCLS Cavity BPM

Discussion Topics (more talks?)

- Common mode effects
  - Signatures
  - Tolerance
  - processing scheme, algorithm dependence
- Degenerate modes
  - Parameters
  - Tolerances
  - processing scheme, algorithm dependence
  - Consequences of breaking degeneracy
    - Is the medicine worse than the disease?
- Bunch-Bunch Measurements
  - Temporal resolution required to cleanly extract information from adjacent bunches?
  - Definition of “clean”
    - Correlated error between bunch measurements
    - Or just the increase in noise due to signal subtraction
  - Measure every bunch, or running average over a few bunches?

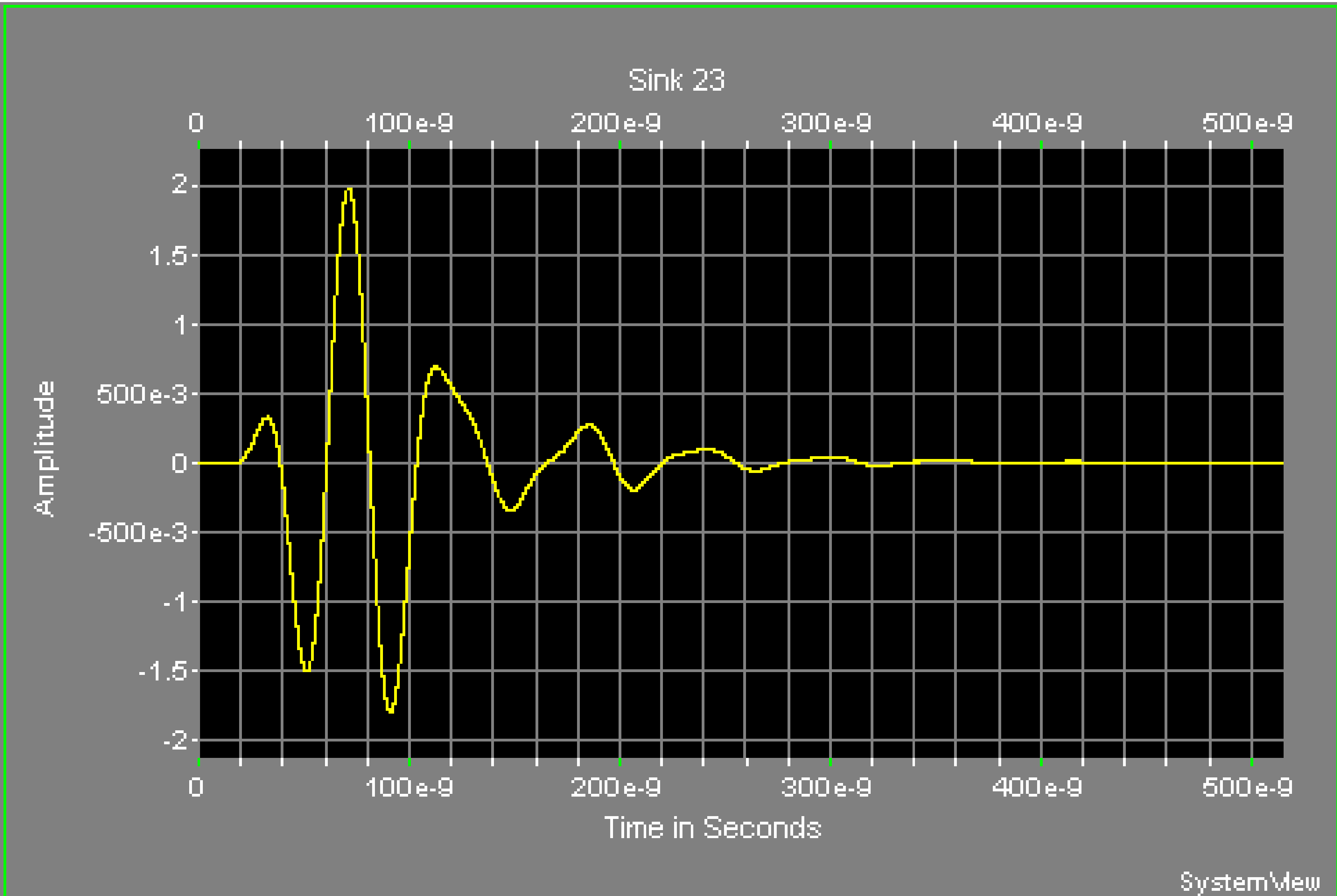
Monopole + Dipole Spectrum



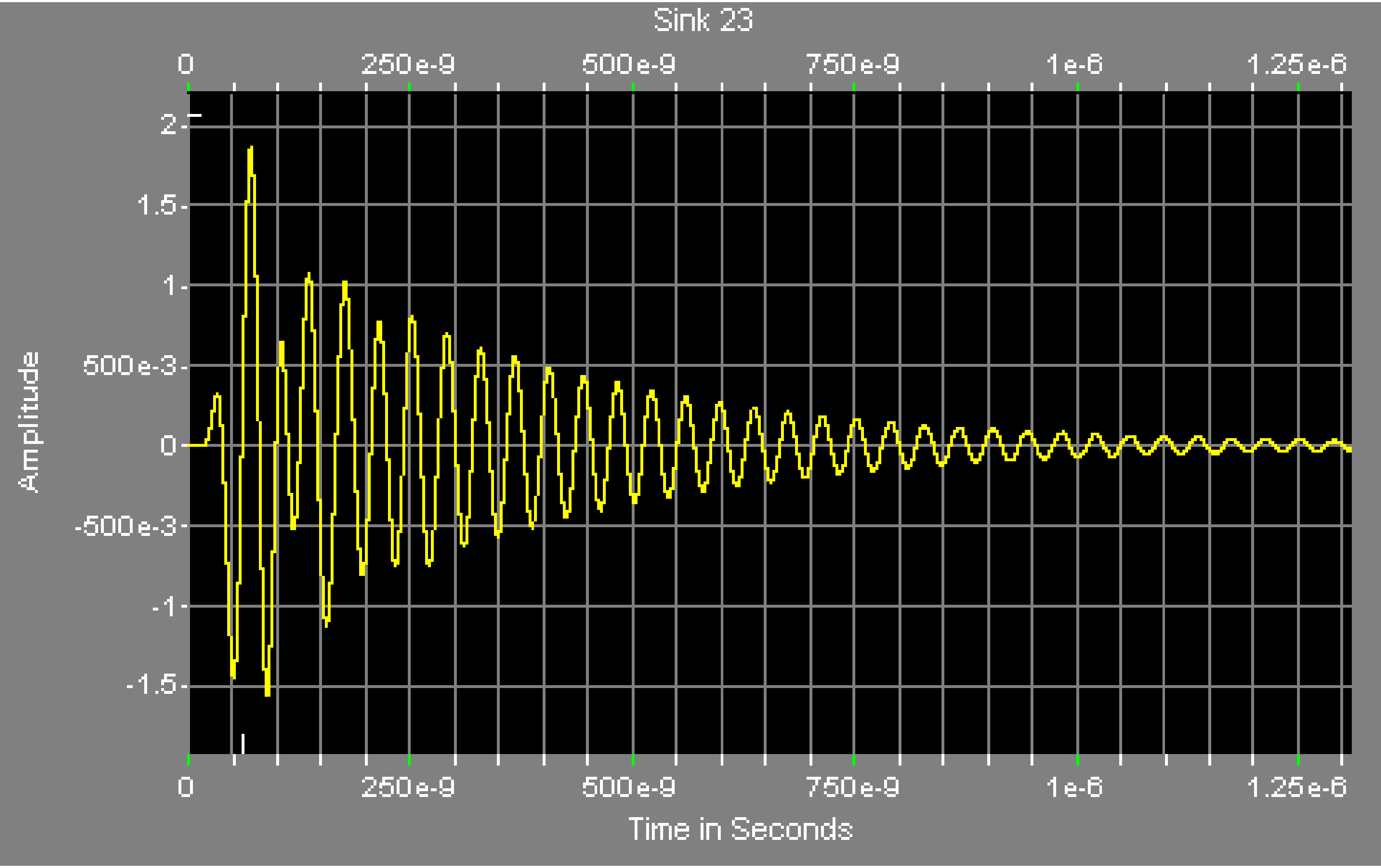
Monopole + Dipole Spectrum

- Spectrum simulated at input to first amplifier (LNA)
- Left spike is first monopole mode as suppressed by front-end filter
- Right spike is second monopole mode
- Middle plateau is the tail of the monopole mode in the bandwidth of the first filter
- Tiny glitch on top of plateau is dipole signal
  - It is extracted cleanly after down-conversion and filtering
- But first amp must deal with the power of the entire bandwidth input

Simulation of Inband Monopole Signal



Simulation of Dipole + Monopole



Analysis of Degenerate Mode Effects

- Excitation
  - Beam passes through cavity
  - Excites many cavity modes
- Evolution
  - Modes evolve in time
  - Phase of each mode evolves at its frequency
  - Amplitude decays with mode's time
- Extraction
  - Output couplers extract energy
  - Each output port is linear combination of modes
- Evaluation
  - Process the data
  - Estimate Charge, Position, Pitch, Yaw, Quadrupole moment, ...

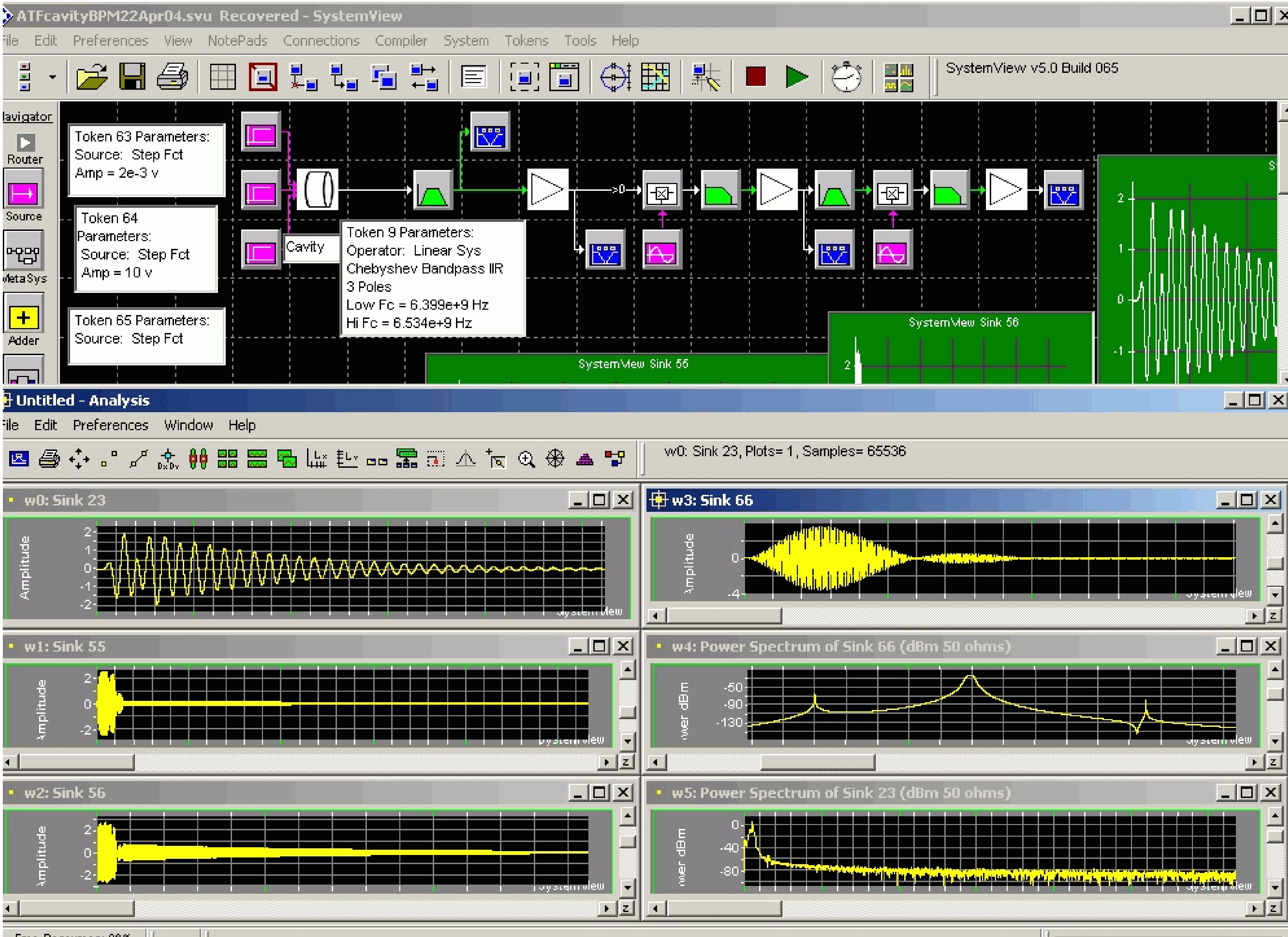
More Discussion Topics

- Electronics Requirements
  - Noise
  - Dynamic Range
  - Input protection
  - Processor for SLAC linac cavities (~40 years old) now have input protection to ~1kW (!)
  - Linearity
    - Impacts
      - resolution
      - Common mode / degenerate mode rejection
      - Accuracy
      - stability

Even More Discussion Topics

- Modeling/Simulation
  - EM Field solvers
  - Cavity/coupler
  - Waveguides/caox adapter
  - MAFIA,...
- Whole System
  - Parameterized cavity
  - Electronics
  - Digital Procesing
  - Simulink, SystemView, Matlab, ROOT,...

SystemView Model



Conclusions

- Cavity BPMs offer:
  - Resolution
  - Accuracy
  - Stability
  - Simplicity

- Need:
  - Solid requirements on which to base design
  - Careful analysis of design choices
  - Beam test to validate analysis
    - Analysis to understand beam tests, etc…