



for Particle, Astroparticle and Synchrotron Radiation Experiments



Beam Position Monitors with Nanometer-Scale Resolution

International Symposium on the Development of Detectors

April 3-6, 2006

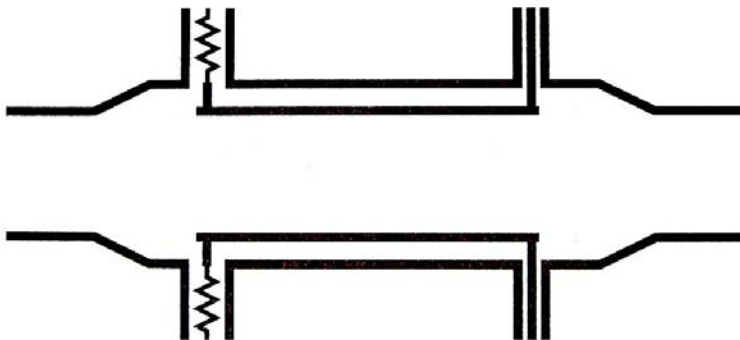
**Steve Smith
Stanford Linear Accelerator Center**

Outline

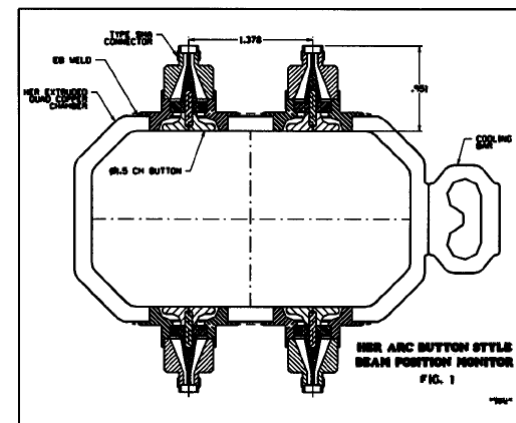
- What is a Beam Position Monitor?
- Why nanometer-scale resolution?
- How to get nm resolution
- Results
- Future

Beam Position Monitors

- What's a BPM?
 - Locate a beam of charged particles in a beam pipe
 - Non-destructively
 - Sense the electromagnetic fields of beam
- Differencing Techniques
 - Beam couples more to the near wall than the far wall
 - Examples:
 - Split-ring pickups
 - Opposing striplines
 - Button pickups



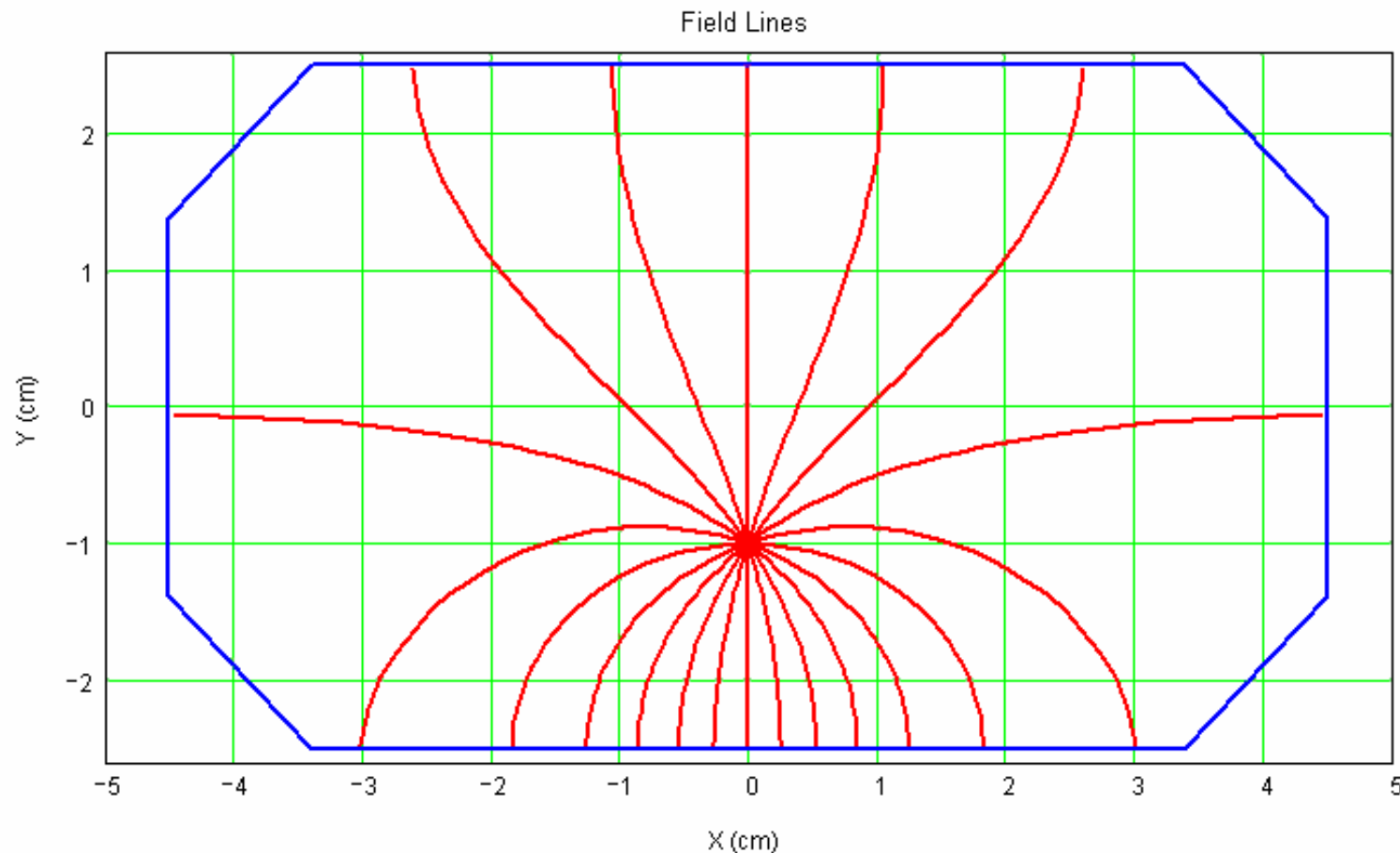
Stripline BPM



Button BPM

Beam Position Monitors

- Differencing Techniques
 - Beam couples more to the near wall than the far wall
 - $Y = R/2 * (V_{up} - V_{down}) / (V_{up} + V_{down})$
 - High resolution → small differences of large numbers
 - Scale set by size of beam duct
 - Very difficult to get $\sigma = 10^{-4}$ of radius



Steve Smith - 2011 Symposium on the Development of Detectors

Resolution Requirements

- Why nanometer resolution?
 - Colliders need small beam spots for luminosity
- International Linear Collider (ILC) parameters:
 - Typical linac beam size ~ micron
 - Beam size at interaction point
 - $\sigma_x \sim 600$ nm
 - $\sigma_y \sim 6$ nm (some options call for $\sigma_y \sim 3.5$ nm)
- Collision accuracy must be much less than spot size
- Stability of components, beam position jitter sources critical
- Can use beam-beam deflection to measure IP beam offsets
 - Feedback to control steering
 - Only need micron resolution
 - Beam-beam deflection focal length ~ 100 microns!
 - Measures beam properties at a single point
 - Does not help identify sources of beam motion
 - Only works while colliding
- How can we establish nm-level stability of beamline components before we build the collider?
- ➔ nanometer resolution beam position monitor

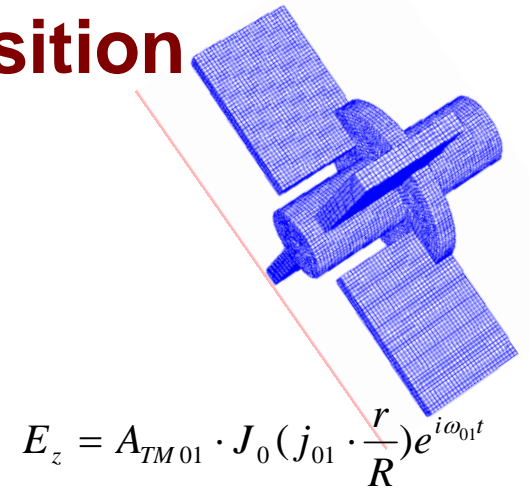
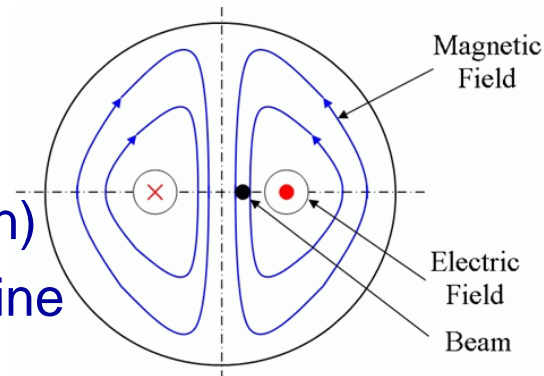
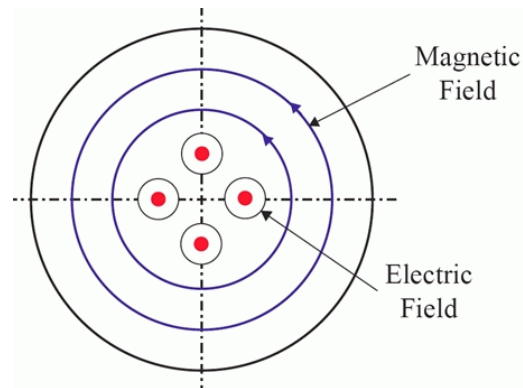
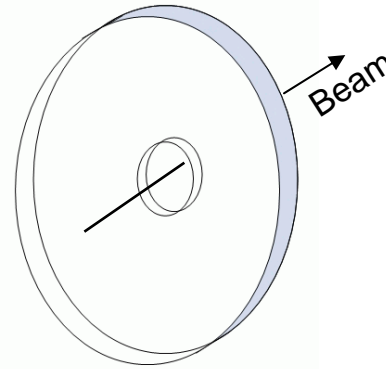
How to Couple Directly to Position

Resonant cavity position monitor

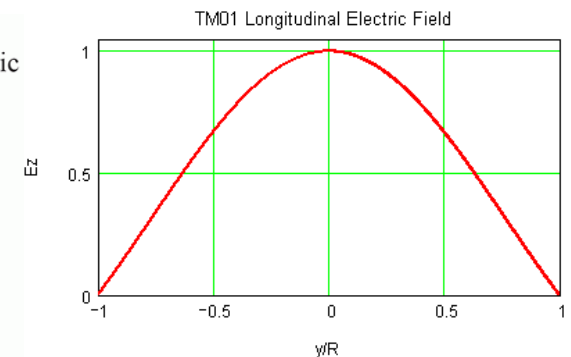
- Assume pillbox cavity
- Beam passes through cavity
- Couples to longitudinal electric field of cavity modes

Cavity modes:

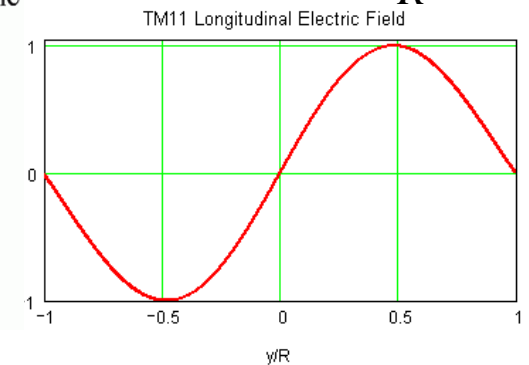
- Lowest frequency mode
 - Monopole
 - Couples to bunch charge
 - (not position)
- Next higher modes are dipole
 - Couple to (Charge x Position)
 - Linear coupling near nodal line



$$E_z = A_{TM01} \cdot J_0(j_{01} \cdot \frac{r}{R}) e^{i\omega_{01}t}$$

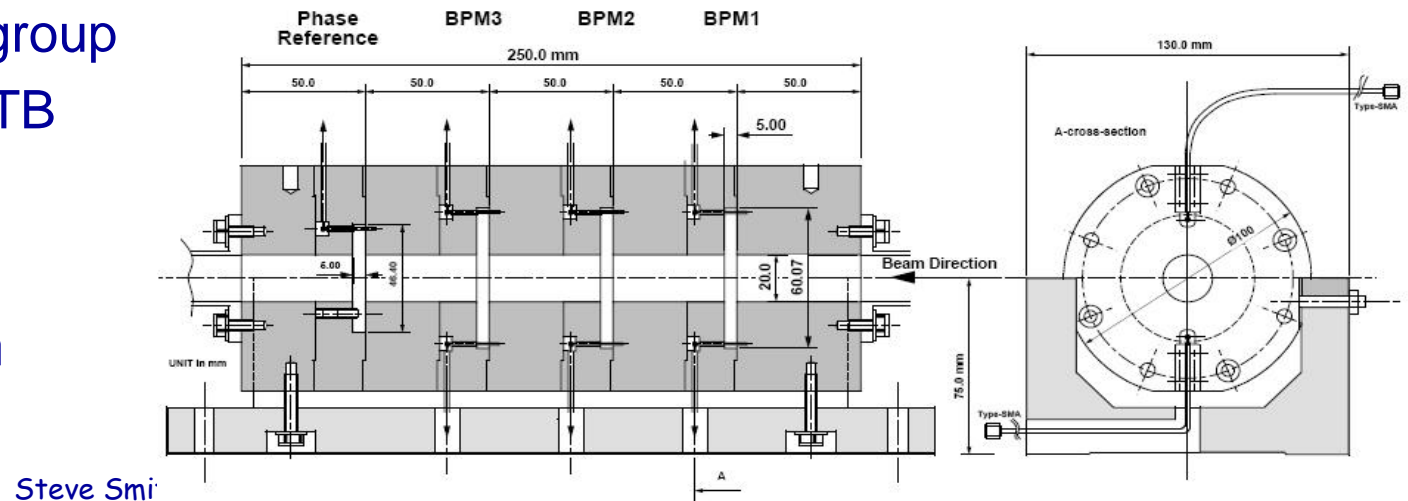


$$E_z = A_{TM11} \cdot J_1(j_{11} \cdot \frac{r}{R}) e^{i\omega_{11}t}$$



How to Demonstrate nm Resolution?

- In the presence of:
 - Noise
 - Beam motion
 - Ground motion
 - Simplest approach:
 - 3 BPMs rigidly mounted to each other
 - No beam optical elements between them
 - Predict beam position in each from measured positions in other two
 - Pulse-by-pulse
 - Shintake '95
 - KEK-SLAC group
 - At SLAC FFTB
 - 3 cavities
 - Single block
 - $\sigma_y \sim 26$ nm
-
- UNIT In mm



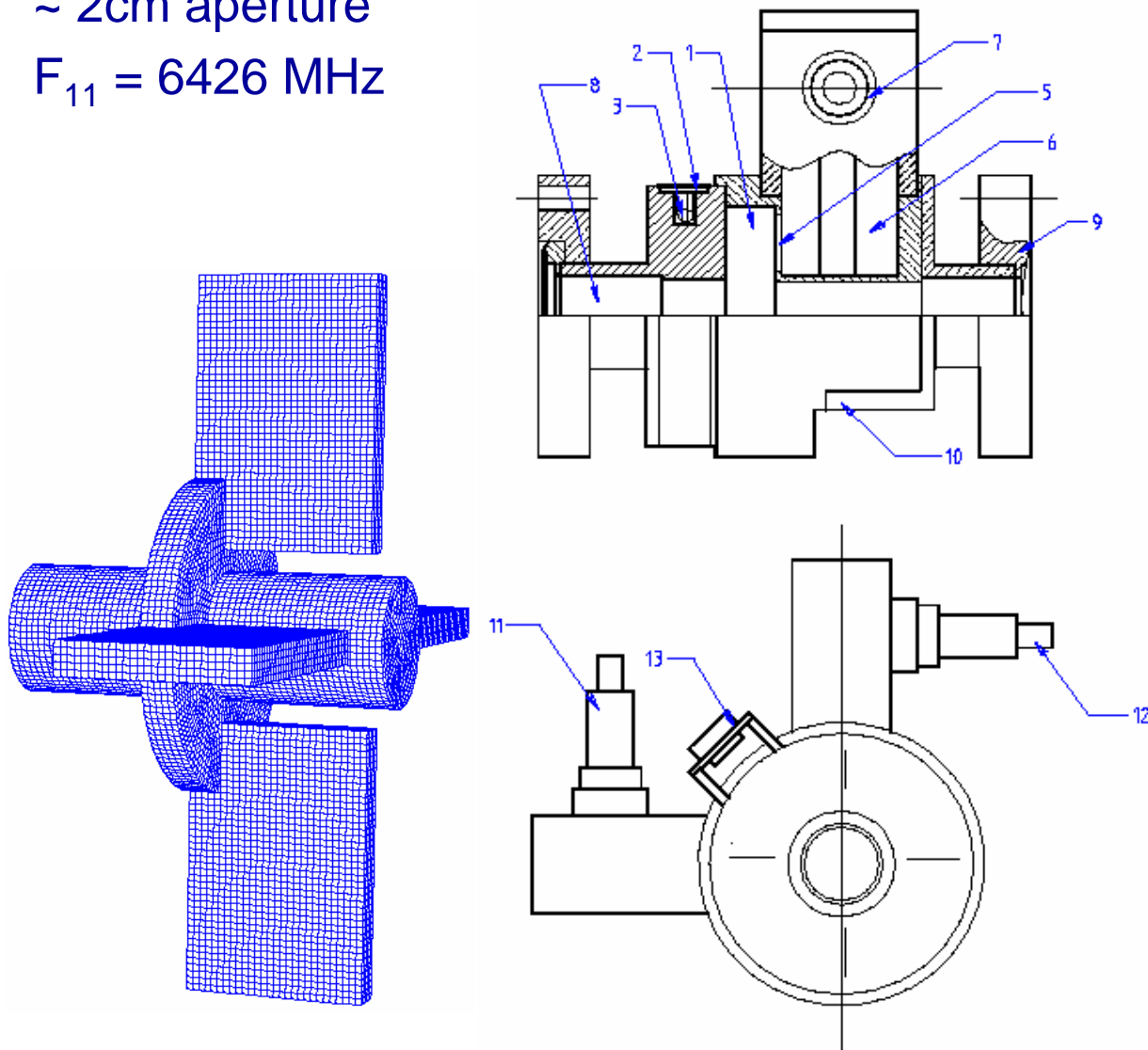
Common-Mode Free Cavities

Cavities from Budker Institute Nuclear Physics, V. Vogel, *et al.*

Dipole-mode selective couplers

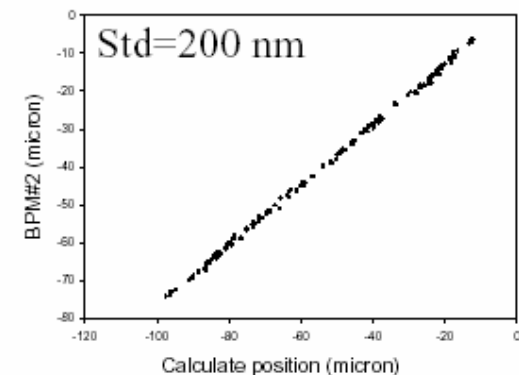
~ 2cm aperture

$F_{11} = 6426$ MHz



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.



Beam Test of nanometer-scale BPMs

- Accelerator Test Facility (ATF) at KEK – Tsukuba, Japan
- ATF is a prototype damping ring for linear collider
- Adding a test of linear collider final focus (ATF2)

Vladimir Vogel, Mark Slater, David Ward, Hitoshi Hayano, Yosuke Honda, Nobuhiro Terunuma, Junji Urakawa, Yury Kolomensky, Toyoko Orimoto, Carl Chung, Pete Fitsos, Jeff Gronberg, Sean Walston, Glen White, Joe Frisch, Justin May, Douglas McCormick, Marc Ross, Steve Smith, Tonee Smith, Stewart Boogert, Alexey Lyapin, Stephen Malton, David Miller

SLAC, KEK, Lawrence Livermore National Lab, Lawrence Berkeley National Lab, University College London, Cambridge Univ.

Signal / Noise

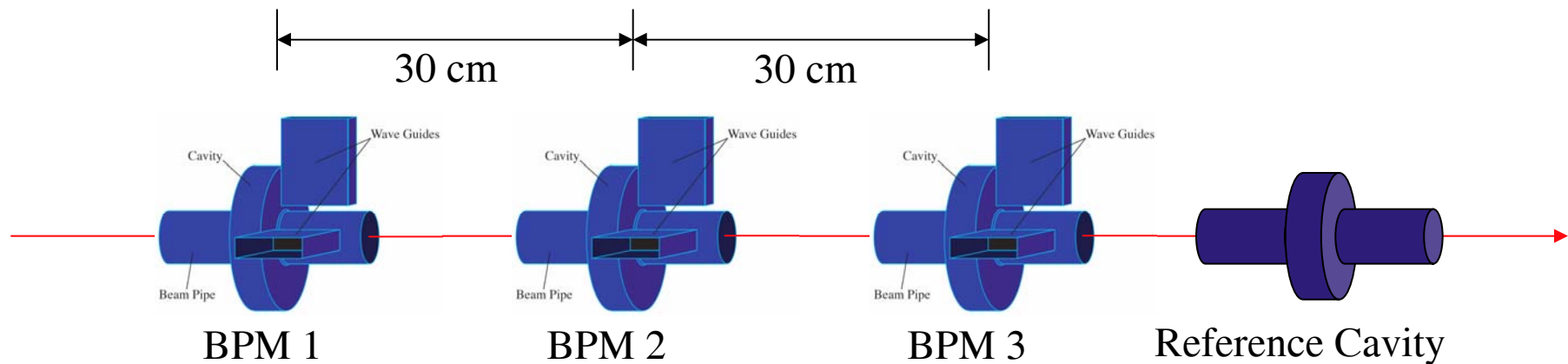
- Loss factor (Energy left in cavity by beam)
 $k_{11} = 10^{-19} \text{ Joule}/(10^{10}e^-)^2/(\text{nm})^2$
- Decay time $\tau = 350 \text{ ns}$
- Cavity Power $dE/dt = 0.28 \text{ pW}/(\text{nm})^2$ for $10^{10}e^-$
- Coupling $\beta = 0.3$
- Power Out $P_{\text{out}} = 65 \text{ fW} = \frac{\beta}{1+\beta} \cdot dE/dt$ at 1 nm
- Thermal noise $kTB = 12 \text{ fW}$
- Electronics noise figure $\sim 3 \text{ dB}$
→ Noise factor = 2
- Noise power = 24 fW
- Signal/Noise (power) = 2.7
- Signal/noise (position) = 1.6 at 1 nm
- → should be able to resolve 1 nm

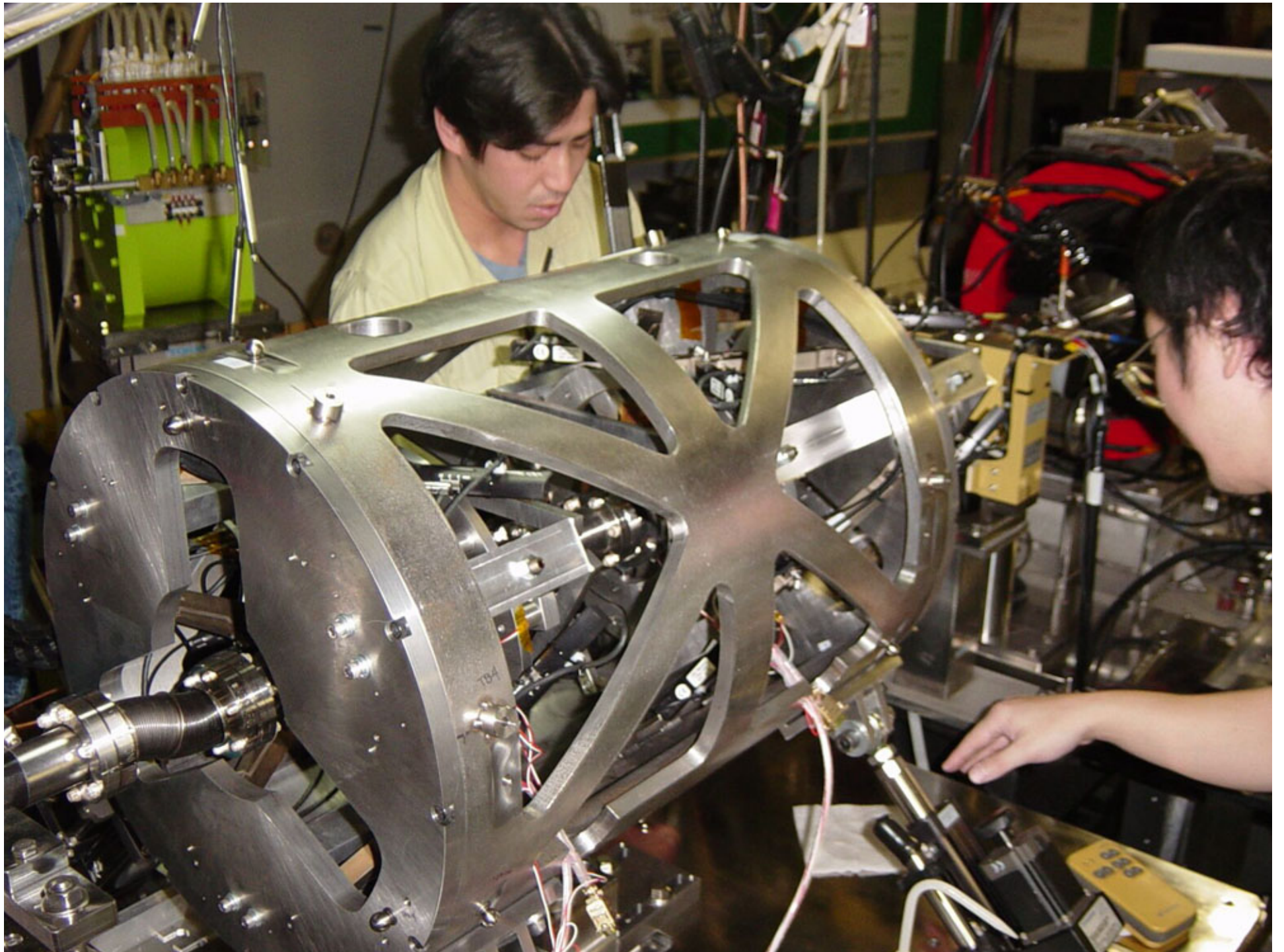
Beam Parameters

- Energy 1.28 GeV
- Bunch Charge $10^{10} e^-$
- Bunch rate: $\sim 1\text{ Hz}$
- Energy jitter $\delta \sim 1e-3$; $\Delta E/E \sim 5e-4$
- Beam size:
 - $\sigma_x = 80\text{ }\mu\text{m}$
 - $\sigma_y = 8\text{ }\mu\text{m}$
 - $\sigma_z = 8\text{ mm}$ (comparable to dipole mode frequency)
- Position & angle jitter:
 - $\sigma_x \sim 20\text{ }\mu\text{m}$
 - $\sigma_y \sim 3.5\text{ }\mu\text{m}$
 - $\sigma_x' \sim 1000\text{ }\mu\text{rad}$
 - $\sigma_y' \sim 2\text{ }\mu\text{rad}$

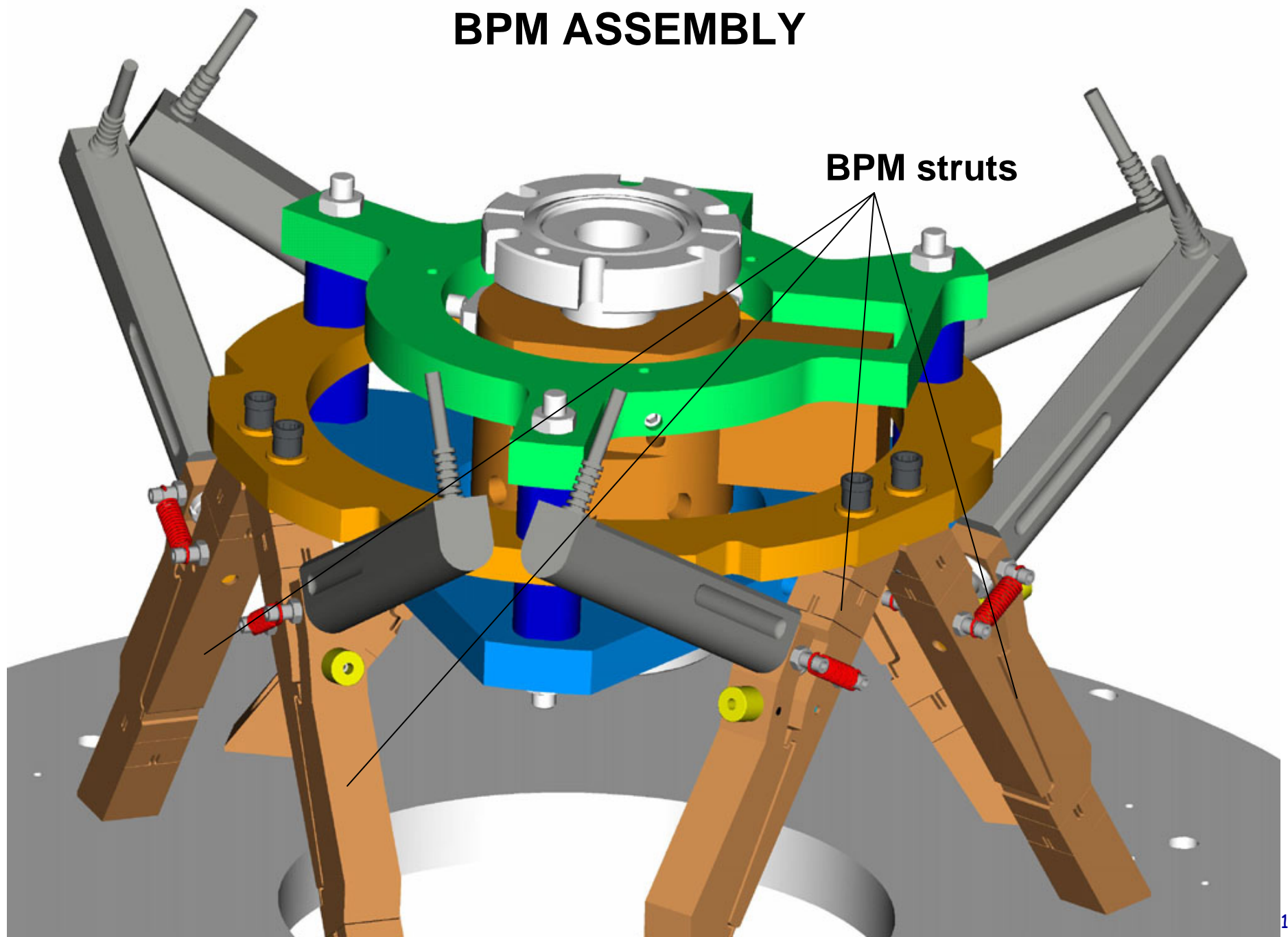
Cavity Beam Position Monitors

- 3 Cavity BPMs
 - C-band (6426 MHz nominal)
 - Dipole-mode couplers
 - Good rejection of symmetric (common) mode
 - Vogel, *et al*
- 1 Reference cavity
 - Fundamental mode at 6426 MHz
 - Phase and beam charge normalization
- All BPMs mounted on X, Y, X', Y' movers

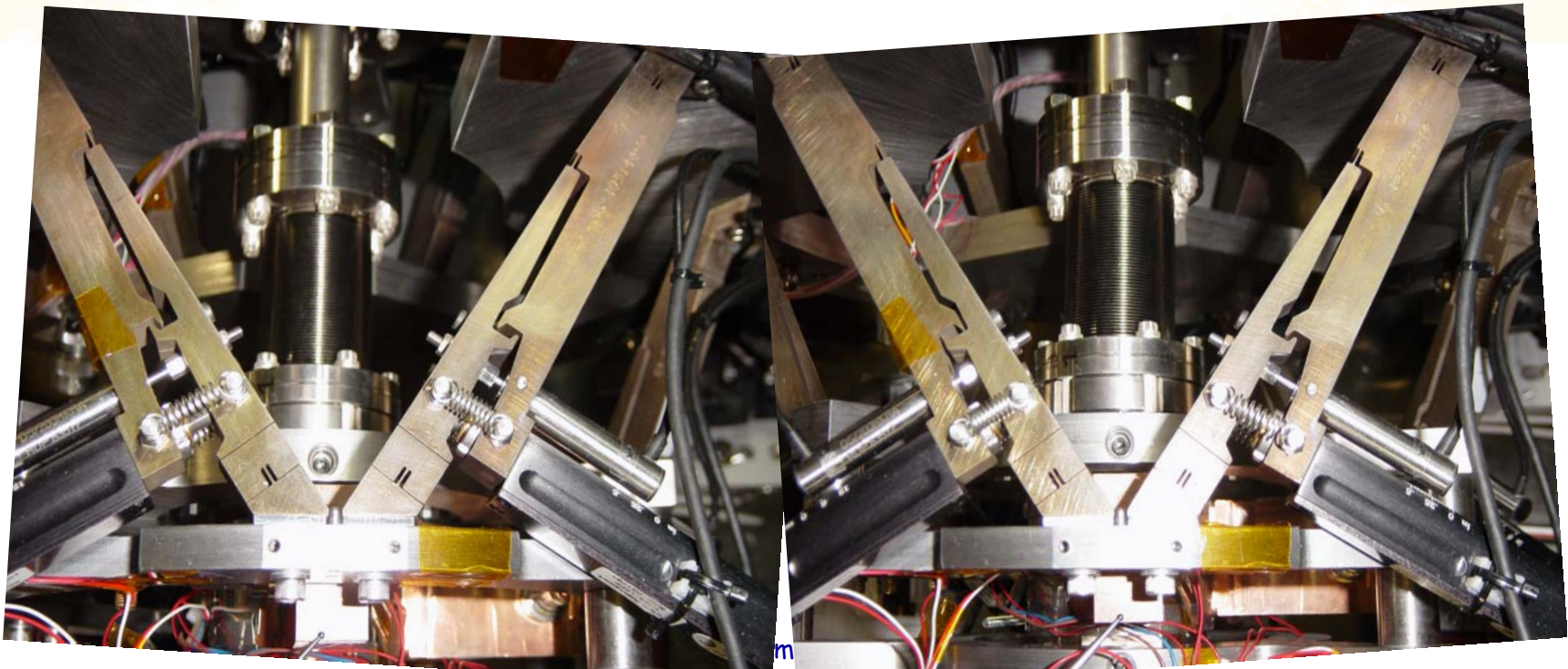
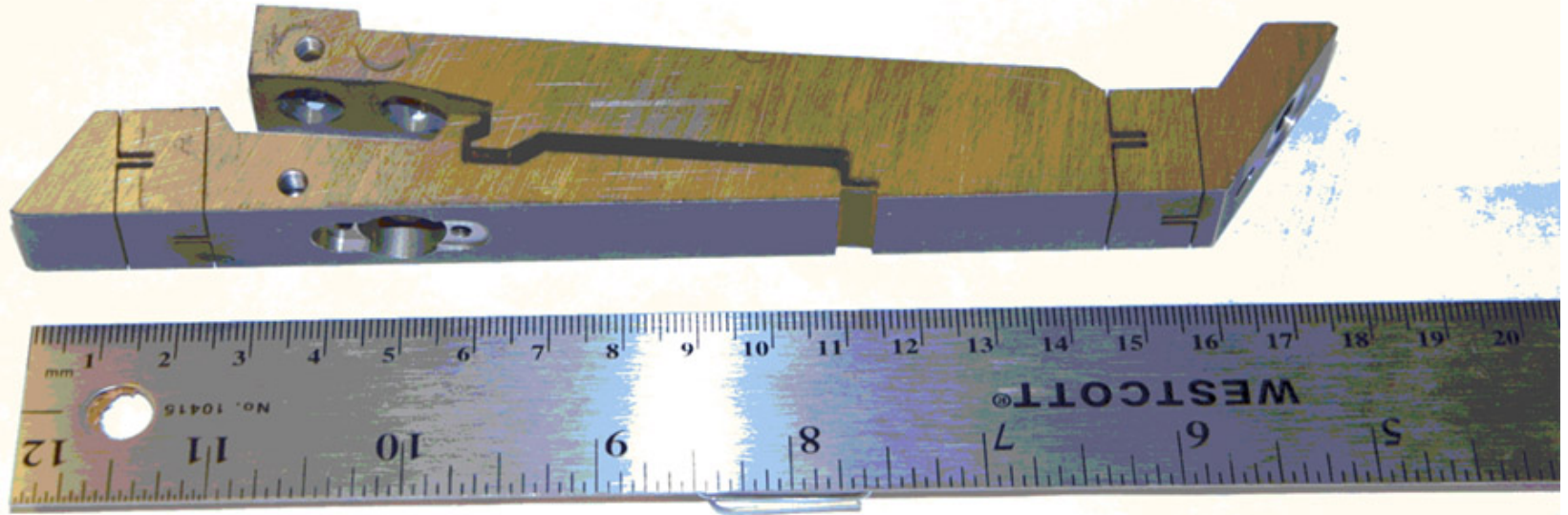




BPM ASSEMBLY

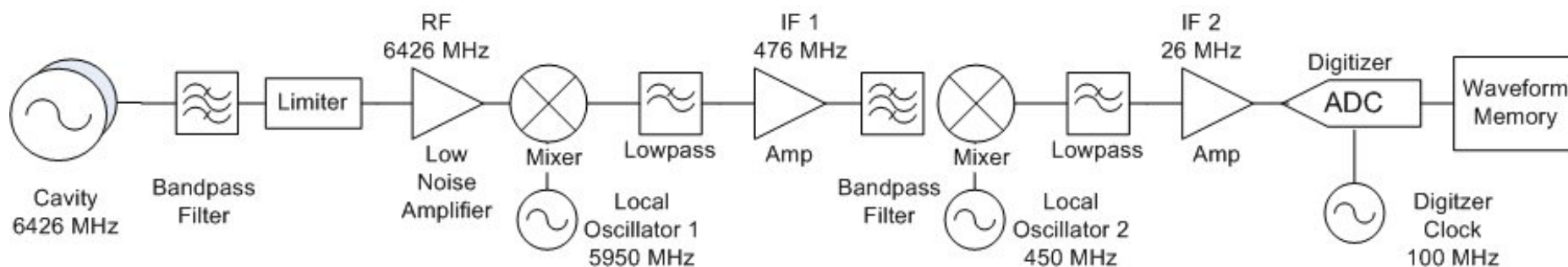


Flexure Legs



Electronics

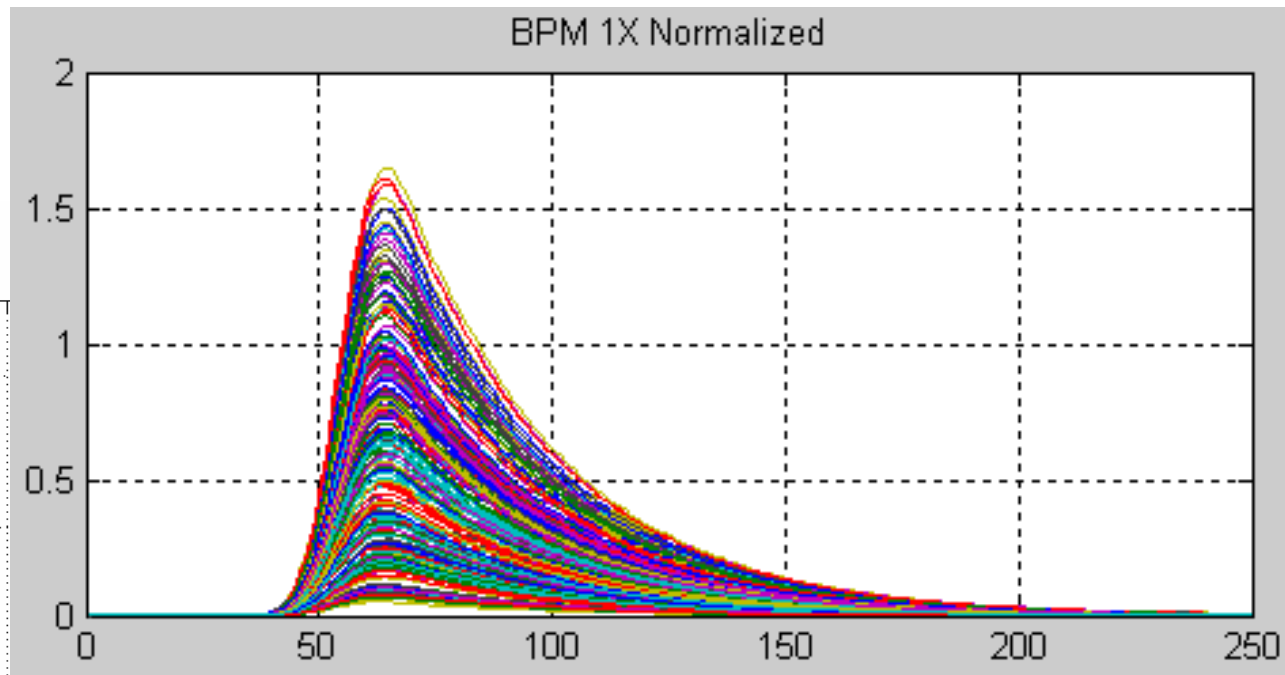
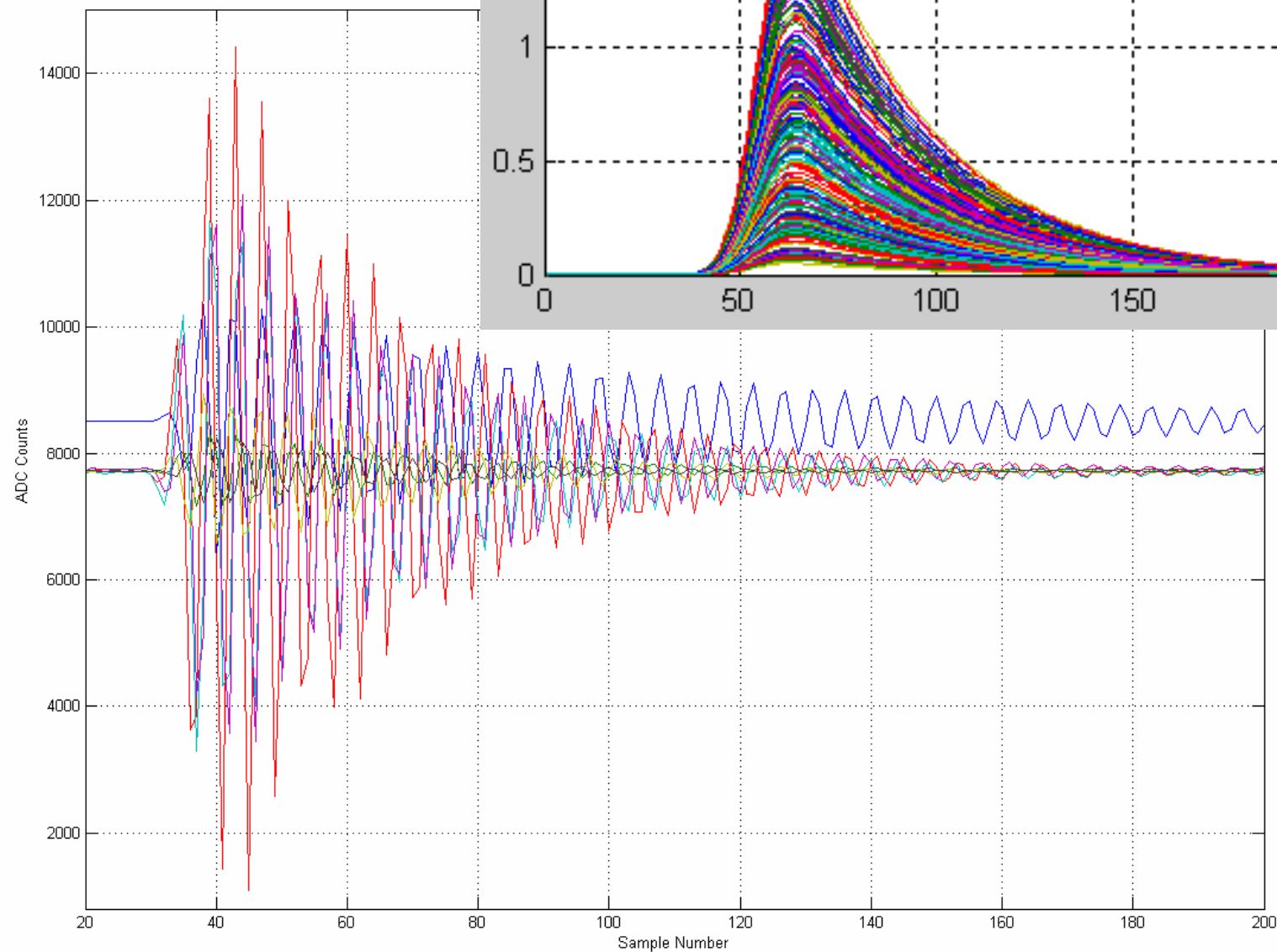
- Low noise: Noise Figure ~ 3 dB
- High dynamic range
 - Expect noise floor ~ 1 nm
 - Full scale ~ 20 microns
- Protected against overdrive
 - beam can go anywhere in aperture!
 - Saturating signal is OK
 - Damaging electronics is not OK
- Final down-conversion left for digital processing
- Implemented here in 2-stage downconversion
- High-speed, high resolution ADC
 - 100 M samples/sec
 - 14 bits



Processing Algorithm

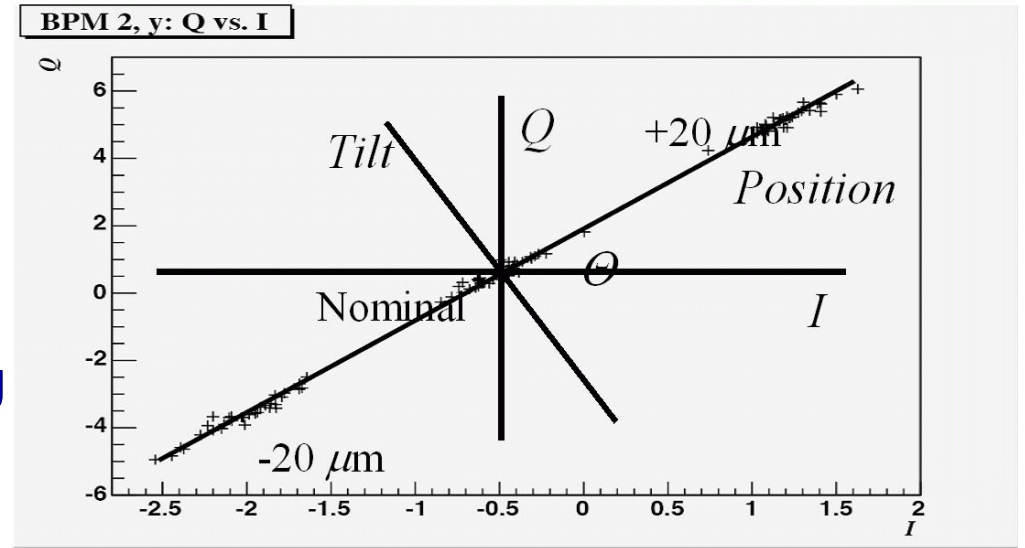
- Digital Downconversion:
 - Multiply digital waveform by complex “local oscillator” $e^{i\omega t}$
 - *i.e.* shift frequency
 - Low-pass filter (approximately match cavity bandwidth)
- Sample complex amplitude of position cavity at “peak”
- Divide by complex amplitude from reference cavity
 - Normalizes charge variation
 - And phase variation
- Scale by calibration constants
- Refine calibration with linear least-squares fit to other BPM measurements
 - Removes rotations, calibration errors.

Data: Raw & Demodulated



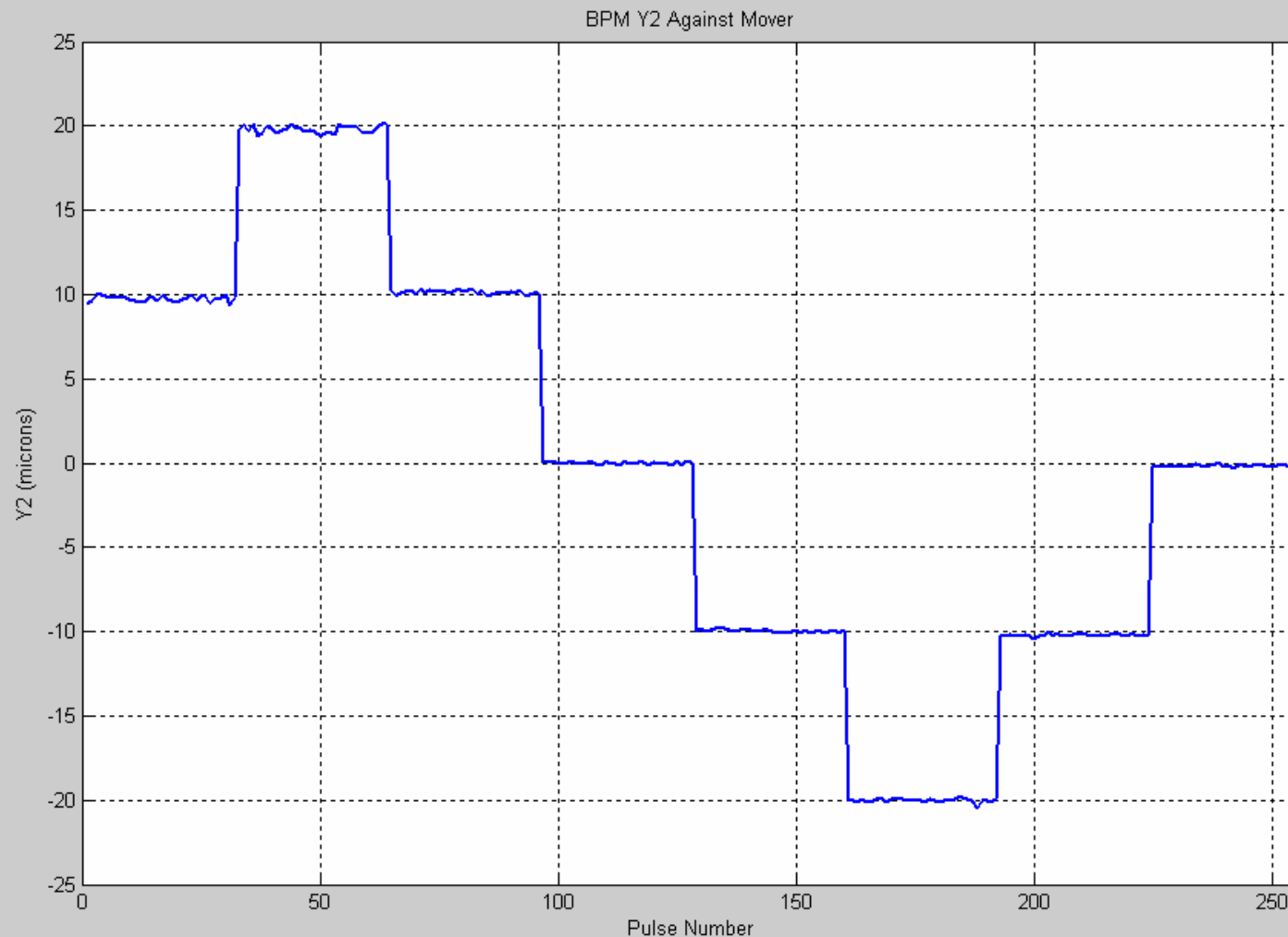
Calibration

- Calibrate:
 - Move 1 BPM
 - Normalize BPM response to Reference cavity response
 - Fit BPM (complex) amplitude vs. mover setting
- Yields:
 - Offset (complex)
 - Gain (complex, *i.e.* phase and gain)
- Evaluate:
 - Normalize measured BPM (complex) amplitude to reference cavity.
 - Compare each BPM to linear least-squares best fit prediction from all other BPMs

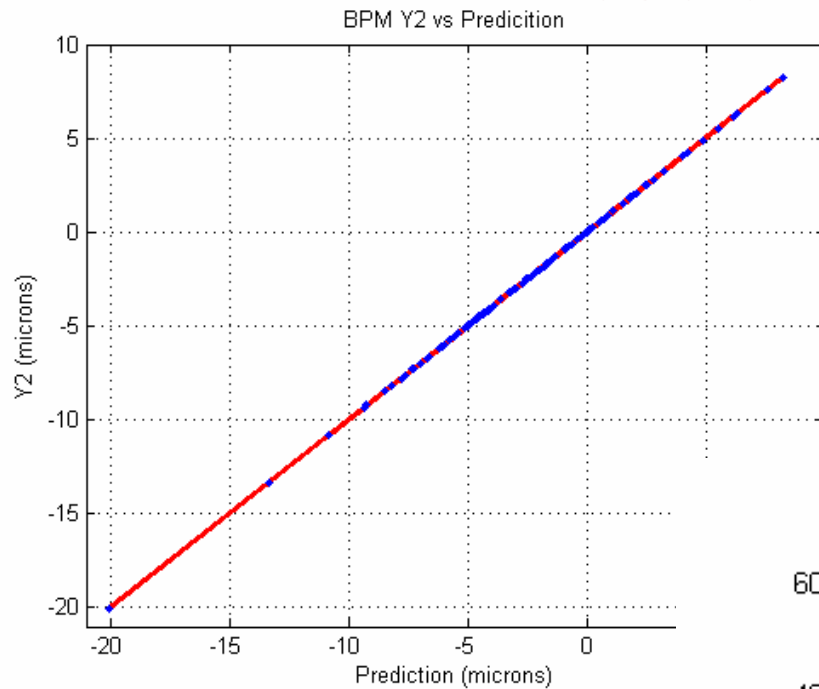


Calibrate

- 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.

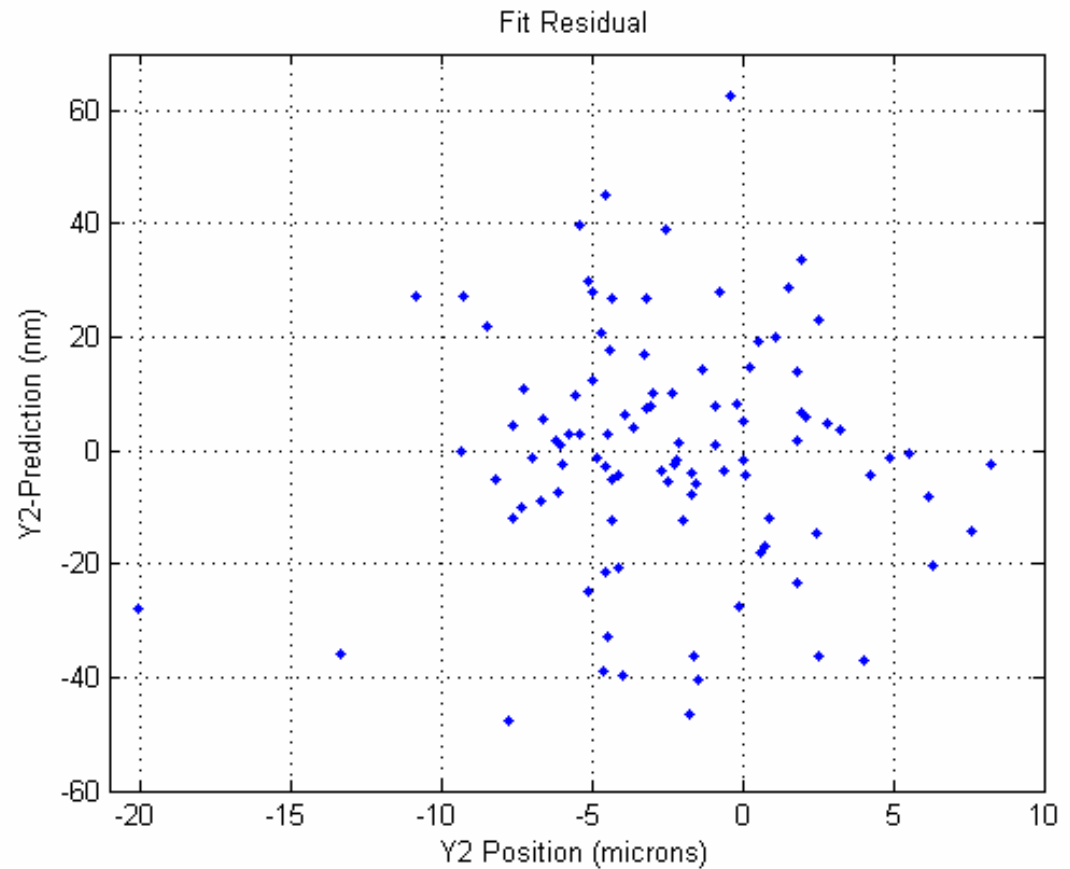


Resolution

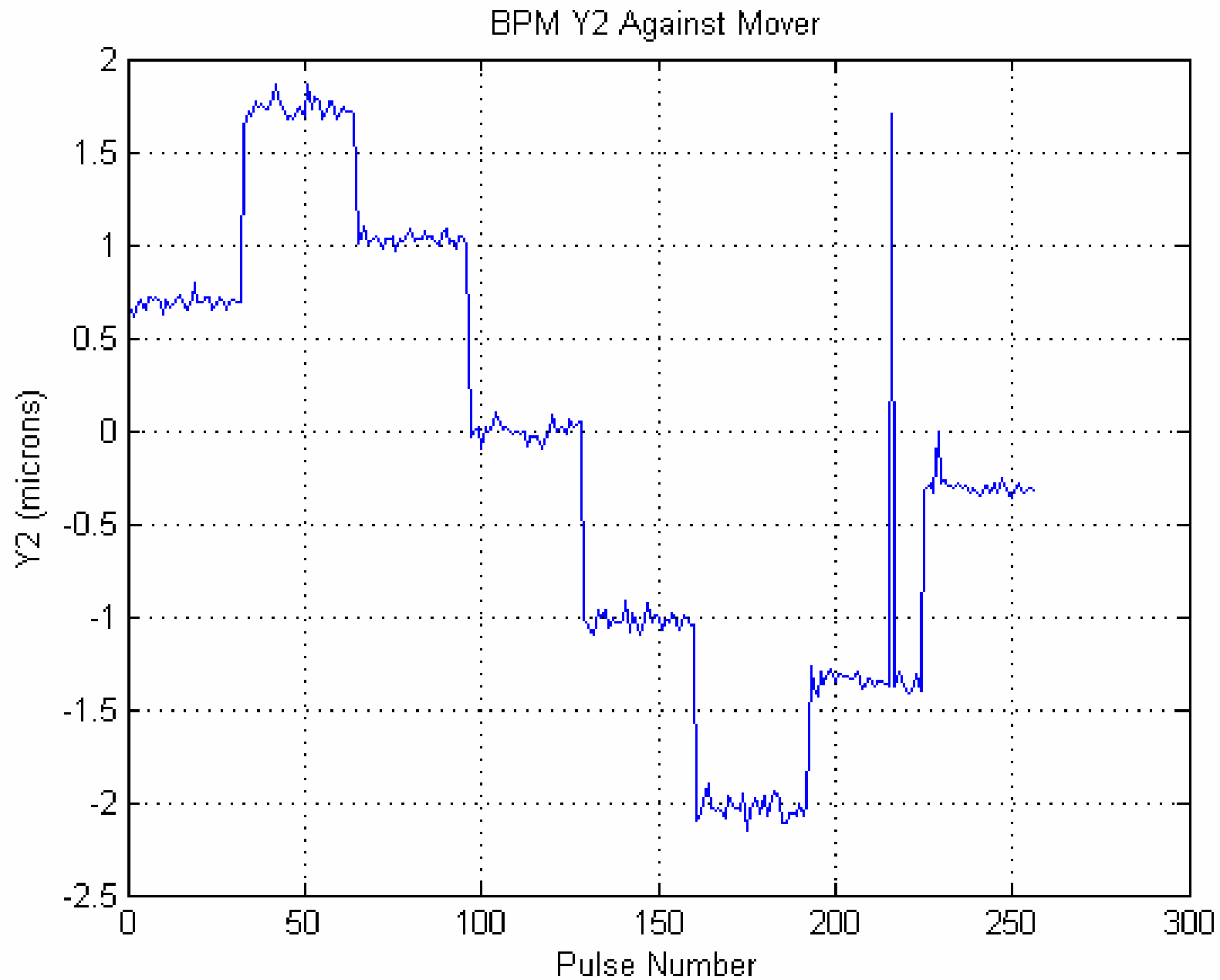


Predict Y2 from other BPMs
Linear least-squares fit to (x, y, x', y')
At BPMs 1&3

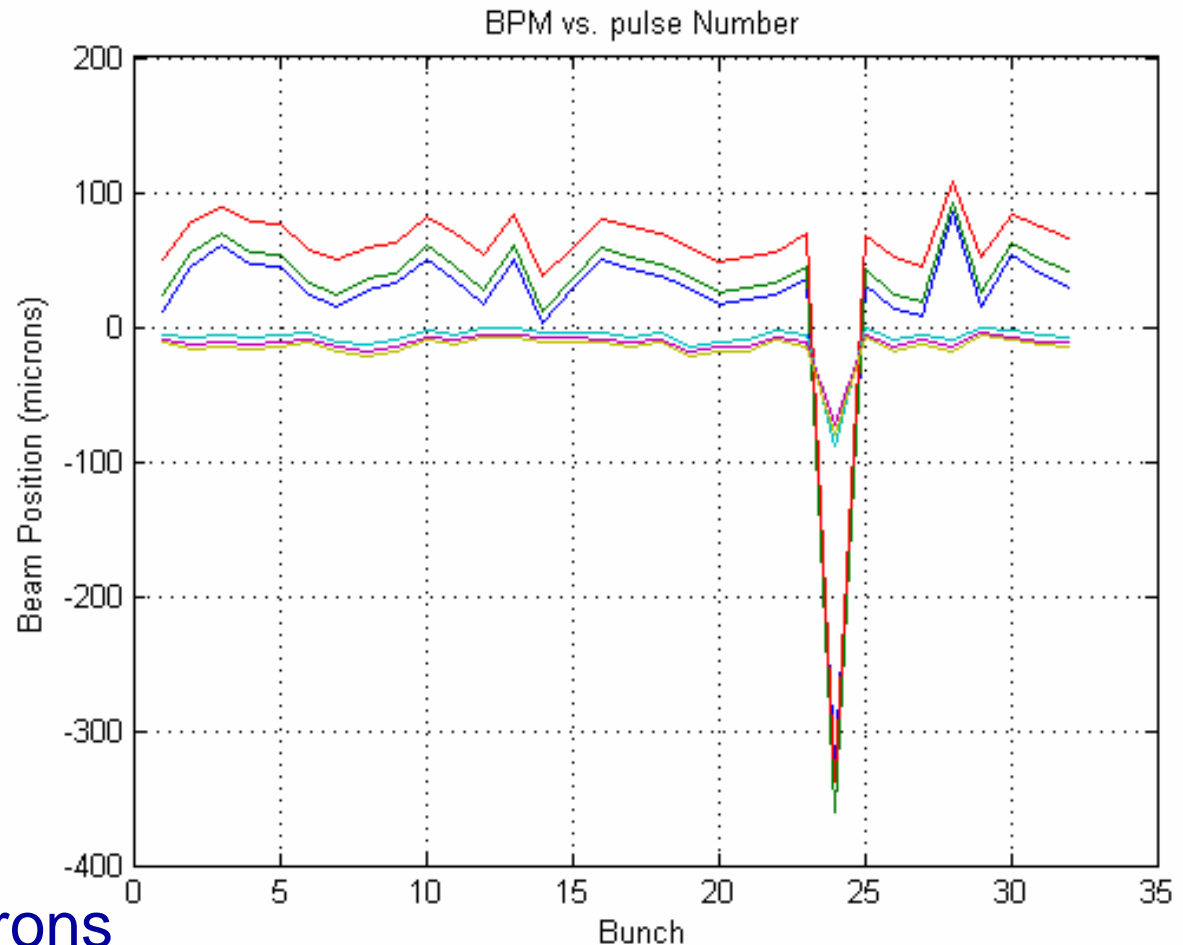
- 1 minute
- 100 pulses
- $\sigma = 17$ nm
- Is it real?
- Check against mover



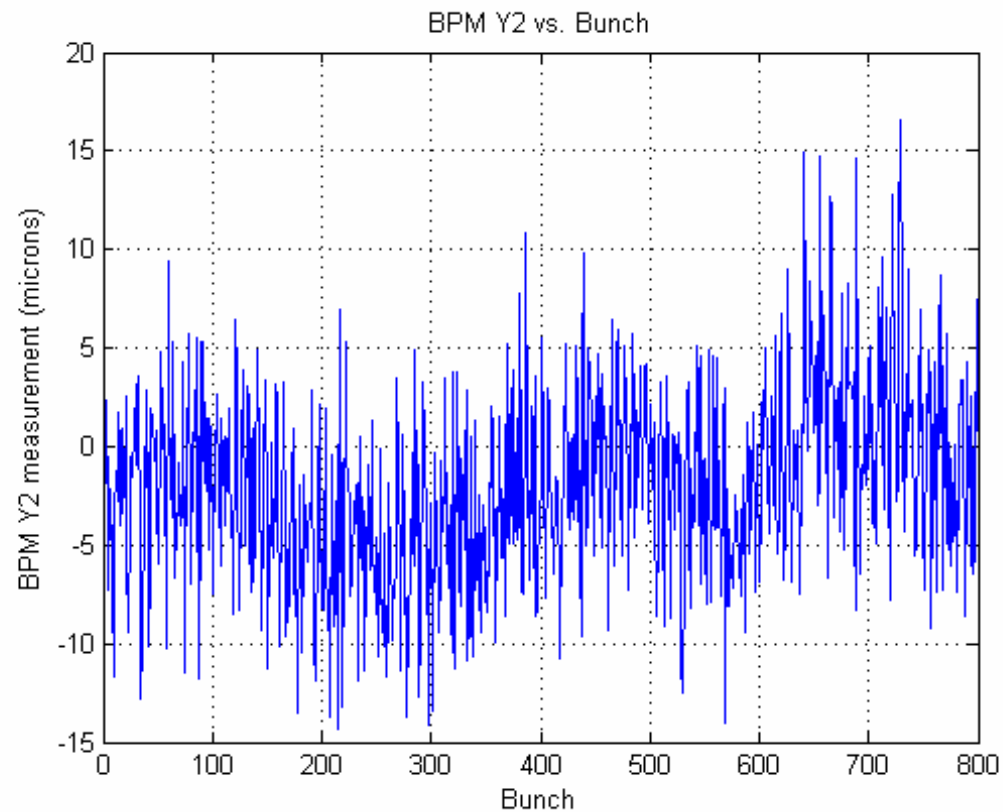
Move BPM in 1 μm Steps



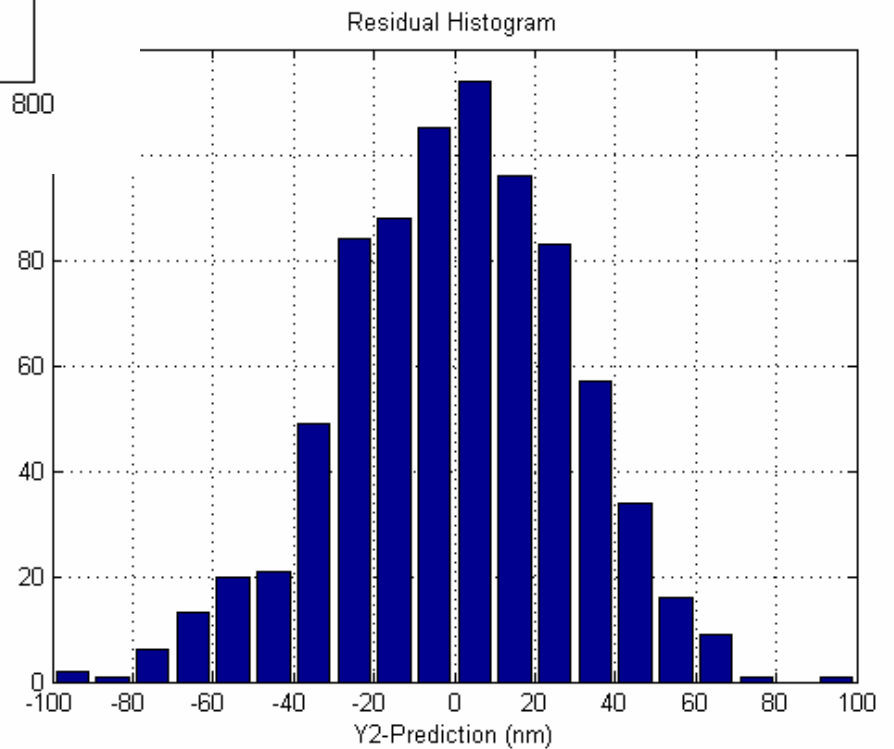
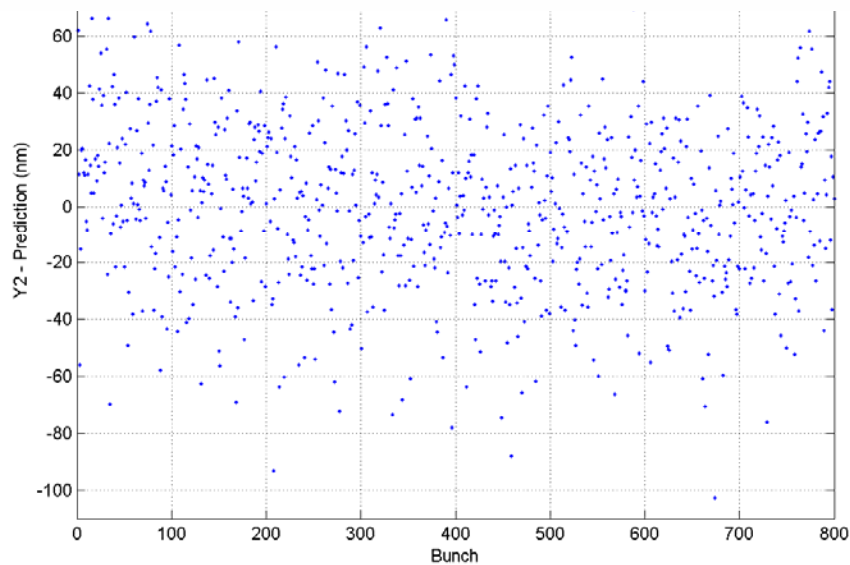
Flier



- 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

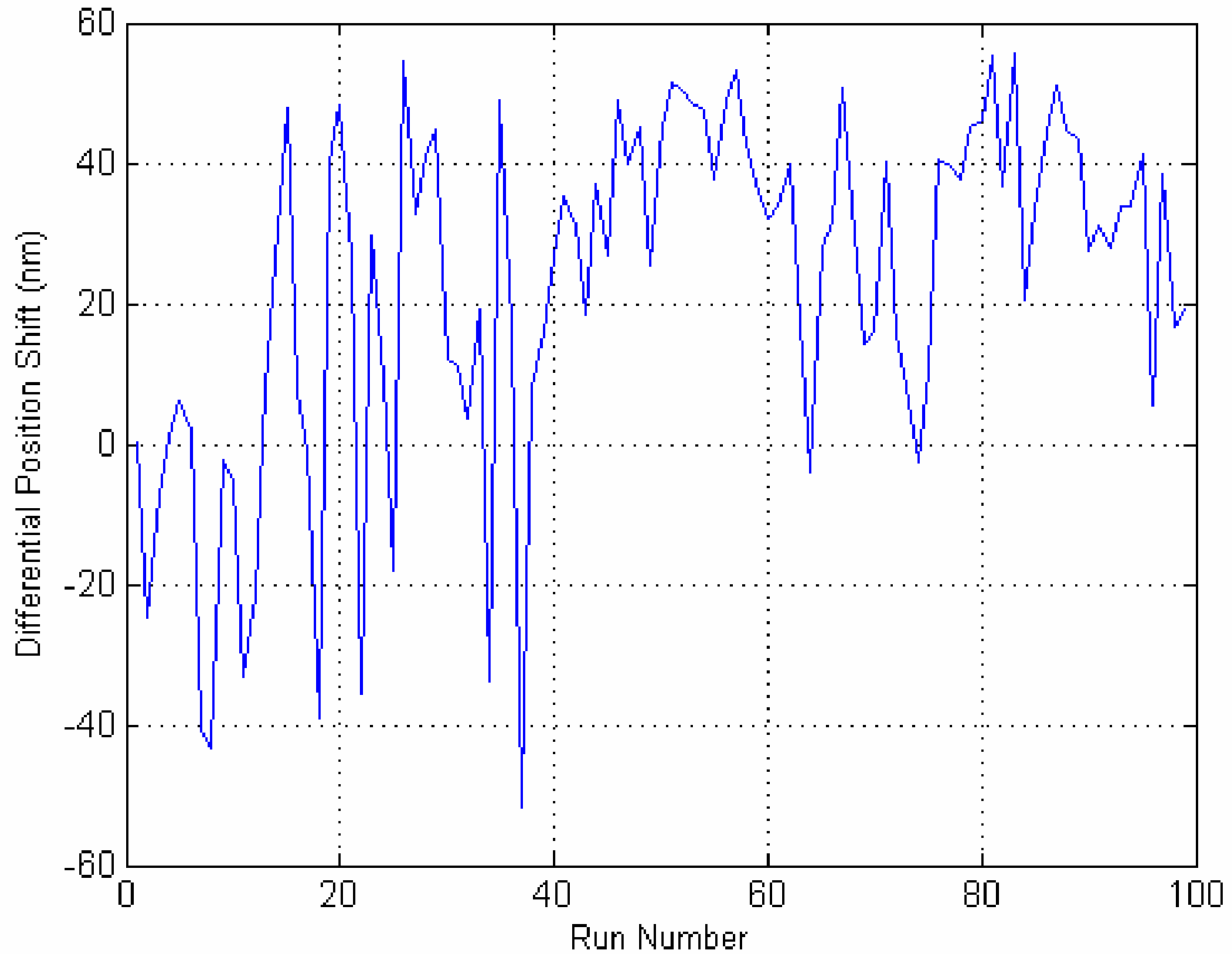


- Ten minute run
- 800 events
- $\sigma \sim 24$ nm
- Few-minute drift
- Thermal?
- Characteristic of ATF water temperature variation



Stability Check

BPM Drift Over 2 Hours

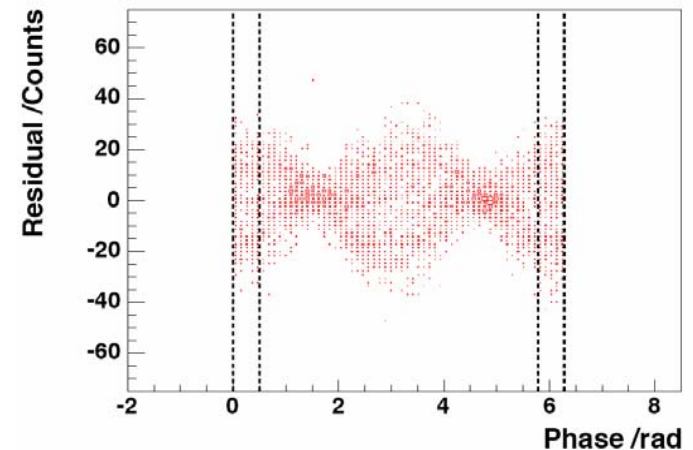


Stability

- 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

Why don't we get nm resolution?

- Measured resolution explained by observed signal & noise
- Calculated loss factor in dispute
 - Power per Coulomb per mm^2
- Re-analyze cavity: loss factor reduced a factor of 10
 - Must incorporate waveguide and coupler into simulation
 - (factor of 3 in resolution)
 - Measured loss factor somewhere between
- Bunch length is significant
- Measure noise
 - “Amplitude” noise in absence of input signal
 - Find 4 ADC counts rms
 - “Phase noise” from residual of fit to CW.
 - RF & clock distribution not clean enough
- Frame drive motors holding current vibrates structure at ~20 nm level
 - In principle this is coherent across all 3 BPMs
 - But some may appear differentially (not known how much)



Status

- Resolution is excellent
 - but not as good as expected
- In terms of ILC needs:
 - Much better than needed to operate ILC
 - Not enough to demonstrate needed component stability
- Have not yet established:
 - absolute accuracy
 - Long-term stability (\gg 2hrs)

Review: Why Cavity BPMs?

- Resolution
 - Its reasonable 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
 - Avoid critical timing stability requirements
- Accuracy
 - Centering established by reasonable machining tolerances.

Conclusions

- Cavity BPMs offer:
 - Resolution
 - Accuracy
 - Stability
- Require:
 - Solid (and stable) mounting, alignment techniques
 - Careful analysis of design choices
- It's difficult to establish: resolution at the nm level!!
 - Or accuracy at the micron level