ILC Cavity BPMs

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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 Spectrometry

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 $\ll$ 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.
4. Coupling slot.
5. Output waveguide.
6. Output feedthrough.
7. Beam pipe.
8. Vacuum flange.
10. Y position output.
11. X position output.

Std~200 nm
Incoming Beam Parameters

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

- 1 minute
- 100 pulses
- $\sigma = 17 \text{ nm}$
- Is it real?

Predict $Y_2$ from other BPMs
Linear least-squares fit to $(x, y, x', y')$ at BPMs 1&3
- Longer run
- 800 events
- $\sim 10$ minutes
- $\sigma \sim 24$ nm
- Few-minute drift
- Thermal?
Move BPM in 1 μm Steps

BPM Y2 Against Mover

Y2 (microns)
Pulse Number
• 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

X channels have -20dB pad before electronics

RMS residual = 235 nm
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 \( \sim 4 \) ADC counts rms
  - Measure phase noise by injecting cw tone in frontend
  - Seems to explain observed resolution
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
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
• 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

Power Spectrum of Sink 66 (dBm 50 ohms)

Frequency in Hz (dF = 762.9e+3 Hz)
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

![Graph showing simulation of an inband monopole signal with time in seconds on the x-axis and amplitude on the y-axis. The graph displays multiple peaks and troughs, with the time scale ranging from 0 to 0.5 microseconds.]
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 Processing
  - 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…