NanoBPMs: Analysis Experience

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NanoBPM Collaboration

• Collaboration between SLAC, KEK, LLNL, UCB

• Ambitious goals
  - Position resolution for a single pulse at ~ nm scale
  - Similar accuracy and position stability of the BPM structure
  - Demonstrate beam tilt measurement with tens of mrad resolution

• Operational experience with precision devices
  - Nanometer resolution: push technology to the limit
  - Mechanical stability: Final focus, beam energy spectrometer
  - Tilt measurement: find (and correct for) sources of emittance growth in the linac → luminosity optimization.
NanoBPM Project

- Test facility: extraction line at ATF (KEK)
  - Long (~mm) single bunches, small jitter (few µm)
- 3 existing C-band cavities constructed at BINP
  - Another set being constructed at KEK/Tohoku
- SLAC/KEK: infrastructure & electronics
- LLNL: BPM mounting, position stabilization and metrology system
- UCB: DAQ, analysis, electronics
- Funding: LC support @ SLAC, LDRD @ LLNL, LCRD grant at UCB
RF BPMs (cont.)

RF voltage induced by a beam parallel to BPM axis:

\[ V(t) = C q x_0 \exp \left( j(\omega t + \phi) \right) \]

To measure position \( x_0 \), need to know amplitude independently of phase shift \( \phi \) or keep phase shifts stable.

RF voltage induced by a tilted beam:

\[ V(t) = C q \exp \left( j(\omega t + \phi) \right) \left[ x_0 - j\delta\omega / 16c \right] \]

Beam tilt induces an additional signal, shifted by 90° wrt position signal.

Tilt of ~2 µm (5 mrad) equivalent to offset of ~13 nm for X band.

High precision, X-band BPM.

Need to measure both amplitude and phase of RF signal (0.7° phase resolution).
ATF extraction line
C-band cavity
L = 12mm, Radius = 26mm, f = 6426MHz,
λ=46.6mm
Movers – x, y, pitch (v-z)
ATF Cavity assembly

3 cavities on individual (X,Y,X’,Y’) movers: allow independent calibration and resolution measurements.
BPM Cavities

• C-band cavities constructed at BINP (V. Vogel)
  - Resonant at 6426 MHz
  - Q ~ 5100 internal, 3300 external
  - Monopole mode suppression
  - Coupling $1.4 \cdot 10^{10} \text{ J/C}^2/\text{mm}^2$
  - Idealized resolution of ~0.5 nm for ~1 nC

• Digital IF readout
  - Mix signal down to 15 MHz, digitize using a 14 bit 100 MHz sampling ADC
Readout Concept

Digital IF readout provides information on both amplitude and phase of the Signal (I/Q)

In many cases, high resolution, fast rad-hard FADCs needed (see KK Gan’s talk)
Signal Decoding

- Digital down conversion (S. Smith)
  - Multiply signal by $\exp(j\omega t + \phi)$, filter out high-frequency harmonics (this is what a mixer does), then integrate result
  - In the simplest implementation, have to fix frequency, phase, integration window
Signal Decoding

• Fit to decaying oscillation
  - Fit for amplitude, decay constant, phase, pedestal offset
  - In theory, more powerful
    - Look for environmental variations of fit parameters
    - Look at residuals and study sources of noise
  - But have to rely on cavity response model
  - Amplitude and phase are referenced relative to a beam-derived trigger signal
    - Could avoid that by phase-locking LO and digitizer to beam
Sample Waveforms

Sampled BPM Waveform

Fit here

Fit Residuals

Fit Over Fit Window

Chi2 / ndf = 171.7 / 185
Prob = 0.7492
Ped  = 8544±3.995
Amp  = 2.389±0.04±303.7
GammaInv= 0.03336±0.0002203
O   = 18.76±0
Omega = 0.9479±0.0002205
Phase = 10.43±0.01283
Saturated Waveforms

Digitizer saturation

Still some phase info

01/09/2004
Residuals: Time and Frequency Domains

Information on noise and systematics

2 MHz beating?
Parameter Stability

Reference cavity

Position cavity

01/09/2004

Yury Kolomensky, NanoBPM Analysis
Temperature Regulation

ref: 1e-fold Decay Time (us)

ref: Freq (MHz)
Calibration

- Use precision movers (0.5 μm precision) to sweep each cavity through the beam
  - Determine position sensitivity of I and Q channels for each cavity, decouple position and tilt signals
  - Need quick calibration to make sure beam does not drift
  - During June run at KEK, calibration repeated several times a day over ~ ±20 μm in a few minutes
- Repeatability (hysterisis, beam drifts) an issue
  - Need to center beam manually, better online tools useful
Calibration: raw
Calibration: position signal

\[ y_3: l \text{ vs. } Q \]

- \( \text{Chi}^2 / \text{ndf} = 8.273 / 8 \)
- \( \text{Prob} = 0.4073 \)
- \( p_0 = -0.5278 \pm 0.009792 \)
- \( p_1 = 0.00329 \pm 0.00329 \)

\[ y_3: l \text{ vs. Mover} \]

- \( \text{Chi}^2 / \text{ndf} = 8.341 / 8 \)
- \( \text{Prob} = 0.4089 \)
- \( p_0 = -0.523 \pm 0.000535 \)
- \( p_1 = 0.00102 \pm 0.001057 \)

\[ y_3: Q \text{ vs. Mover} \]

- \( \text{Chi}^2 / \text{ndf} = 8.297 / 8 \)
- \( \text{Prob} = 0.465 \)
- \( p_0 = 0.0701 \pm 0.04233 \)
- \( p_1 = 0.3213 \pm 0.003425 \)
Position drifts
Resolution (crude)

- Use cavities 1 and 3 to predict position of beam in 2, then compare
- Good linearity over large dynamic range (even past digitizer saturation)
- Resolution of 170 nm near cavity center
  - SLAC analysis sees better results, different dataset
  - Still significantly above thermal noise limit
Future Directions

• Preparing for next beam test in March at KEK
  - New supports/movers: See Jeff’s talk
  - Upgraded electronics (low noise amplification should gain x3)
  - Will look at other sources of noise (ground loops?)

• Operational improvements
  - DAQ: read data from ATF BPMs for correlations
  - Online displays and stripcharts: online monitoring, beam centering
Future Plans

• Test resolution limit
  □ Position and beam tilt

• Mechanical stability: two girders
  □ Simulate FF doublet

• Multibunch operations
  □ Understanding cavity response, resolution
  □ Fast feedback (FONT)

• Radiation issues
  □ ESA beam tests