

Precision RF Beam Position Monitors for Measuring Beam Position and Tilt Progress Report

UC Berkeley Senior Personnel

Yury G. Kolomensky

Collaborating Institutions

Stanford Linear Accelerator Center: Marc Ross, Steve Smith, Joseph Frisch, Michael Woods

University of Notre Dame: Michael D. Hildreth

Contact Person:

Yury G. Kolomensky

yury@physics.berkeley.edu

(510)642-9619

1. Objectives

Controlling beam emittance is important for future linear colliders as well as high-brightness light sources. Transverse wakefields (from beam-to-RF-structure misalignments) and dispersion (from beam-to-quadrupole misalignments) in the linac could lead to an emittance dilution that is correlated along the bunch length (*i.e.*, the tail of the bunch is deflected relative to the head). The ability to detect beam pitch is important in order to identify the primary sources of emittance dilution. For single beam bunches at the ILC, 2 – 15 mrad beam tilt would correspond to 10% emittance growth.^[1]

In addition to measurements of the transverse beam offsets along the linac, measurements of the beam position and energy near the interaction point are of great importance for the physics program of the future linear collider. Energy spectrometers at the interaction point aim at measuring the energy of the colliding beams with the precision of 10^{-4} or better.^[2] Such precision will require a measurement of the beam position before and after the spectrometer magnets with the resolution of $\mathcal{O}(50\text{ nm})$, and comparable stability.

Resonant RF cavity beam position monitors^[3] can be used to measure the average position of the bunch train with high precision, as well as determine the bunch-to-bunch variations. In a single-bunch mode, *i.e.* in the mode where the time interval between the bunches is larger than the fill time of the cavity, the same cavities can be also used to measure the head-to-tail position differences, or bunch tilts. The cavity BPMs are a good match for the precision beam diagnostics at the ILC due to their narrow bandwidth and clean separation between resonant modes. In the following, we will briefly describe the RF beam position monitors, report our R&D activities last year, and outline plans for the cavity system.

2. Beam Position Monitors

A typical beam position monitor consists of three copper cavities, two (X and Y) cavities for monitoring the horizontal and vertical displacements of the beam, a Q cavity to provide an *in-situ* measurement of beam charge and phase. The position cavities are typically tuned to the dipole TM_{210} mode while the Q cavity

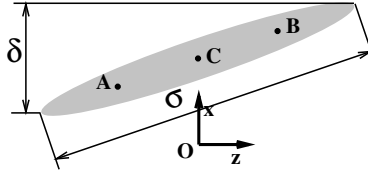


Fig. 1. Tilt of the bunch relative to the z axis of the cavity.

uses the monopole TM_{110} mode. The BPMs constructed at SLAC in 1960s^[3] use three independent cavities which are easy to manufacture and tune. On the other hand, new C- and X-band monitors constructed at KEK and BINP as a prototype for the NLC use a more compact single-cavity design.^[4]

The resonance frequency of the cavities is typically a multiple of the carrier RF frequency. To achieve good position resolution and stability, the cavities are tuned to a high value of $Q > 1000$ which increases the resonant pickup. Custom RF electronics with I/Q demodulation^[5] provides information on both amplitude and phase of the beam-induced signals. Measuring both amplitude and phase of the RF signals reduces systematic effects and increases position sensitivity.

3. Beam Tilt Measurement

One of the main objectives of this proposal is to demonstrate that the RF cavities can be used for measuring small tilts of individual beam bunches. This can be done by measuring the imaginary part of the beam-induced RF pulse, or a phase difference between the RF signals from a dipole and Q cavities.

A short beam bunch of charge q centered the distance x_0 from the electrical center O of the cavity (point O in Fig. 1) induces an RF pulse with voltage

$$V(t) = Cqx_0 \exp(j\omega t) \quad (1)$$

where C is some calibration constant, ω is the resonant frequency of the cavity, and time t is computed from the time the center of the pulse passed through the cavity. If the bunch is pitched by amount δ from head to tail, the RF voltage is instead

$$V(t) = Cq \exp(j\omega t) \left[x_0 - j \frac{\delta \sigma \omega}{16c} \right] \quad (2)$$

The beam tilt introduces a phase shift

$$\Delta\phi = \frac{\Delta x}{x_0} = - \frac{\delta \sigma \omega}{16cx_0} \quad (3)$$

equivalent to an offset of $\Delta x \approx 10$ nm for a typical ILC beam size of $\sigma = 300$ μm and a tilt of $\delta = 2$ μm . For small offsets of $x_0 \sim 1$ μm , the phase shifts of $\approx 0.7^\circ$ should be measurable. It is clear that for this measurement the phase information is vital: it would be hard to extract the small offset from the amplitude signal alone (*e.g.* by measuring the RF power). For the phase measurement, the challenge is to be able to keep the beam centered at the cavity with high accuracy, and to be able to maintain the phase stability. The former requires being able to position the electrical center of the cavity near the beam axis (by either moving the beam or the cavity), and the latter requires precise temperature and environment control, as well as good cancellation of the dominant monopole mode in the dipole X cavity.^[5]

4. Scope of the Project

A set of high-resolution C-band beam position monitors have been constructed at BINP and is currently being tested at the Accelerator Test Facility (ATF) at KEK by the NanoBPM Collaboration.^[6] The monitors

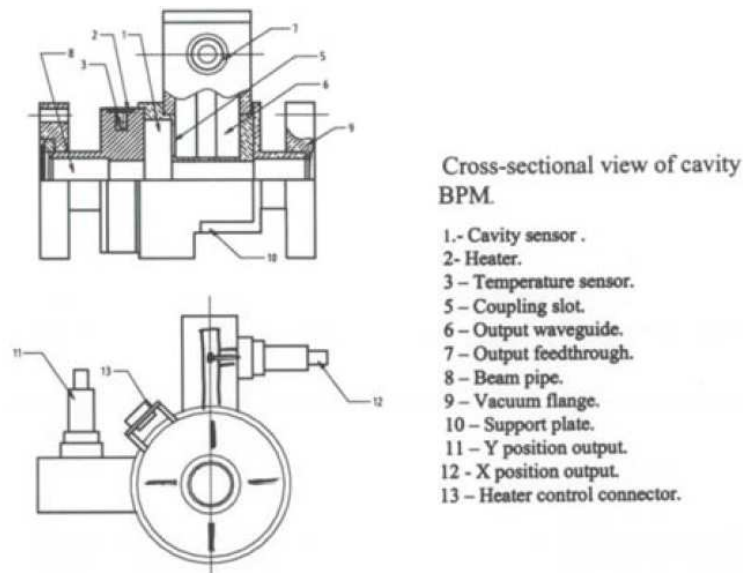


Fig. 2. C-band position monitor constructed at BINP for the NanoBPM collaboration.

use a single-cavity circular design, with transverse coupling slots for the position-sensitive X- and Y-dipole modes (see Fig. 2). The demodulation scheme employed by the SLAC group involves down-mixing the RF pulse to an intermediate frequency of 15-20 MHz and digitizing the IF signals with a 100 MHz sampling ADC. Information on the amplitude and phase of the RF pulse is then obtained in the offline analysis of the IF data, shown in Fig. 3.

We are taking part in the NanoBPM project, and are responsible for the online monitoring and offline analysis of the data. The main objective of the work at KEK is to gain operational experience with the precision BPM hardware and demonstrate nanometer-scale position resolution and sensitivity of the beam-induced RF signals in the position cavities to beam tilt.

Application of the precision RF BPMs to measuring beam parameters (*e.g.*, beam energy) near the interaction point of the linear collider requires high position resolution and high stability, possibly in the presence of synchrotron radiation from the spectrometer dipoles and other adverse environmental effects. These aspects of the precision monitor operation will be tested in the test experiments being developed at SLAC.^[9] Berkeley group is part of the experiment T-474^[10] which aims to develop a working prototype of the energy spectrometer with resolution and stability suitable for achieving a 100 part per million measurement of beam energy at the ILC. We are also contributing to the design and optimization of the BPM hardware and electronics for the beam tests being planned in FY06-07.

5. Progress Report and Future Schedule

This project is part of the national Linear Collider R&D program which is described in detail in “*A University Program of Accelerator and Detector Research for the Linear Collider*”^[7] by the US Linear Collider Research and Development Group.^[8] The project received funding from DOE for FY03 and FY04-06 under DOE contract DE-FG02-03ER41279.

In the first two years of the project (2004-2005), we are working in collaboration with groups at SLAC, LLNL, and KEK in developing the prototype of the nanometer precision beam position monitor. The NanoBPM Collaboration^[6] has completed several beam tests at the ATF facility at KEK with the precision C-band cavities constructed at BINP. The present structure consists of a reference (charge-sensitive)

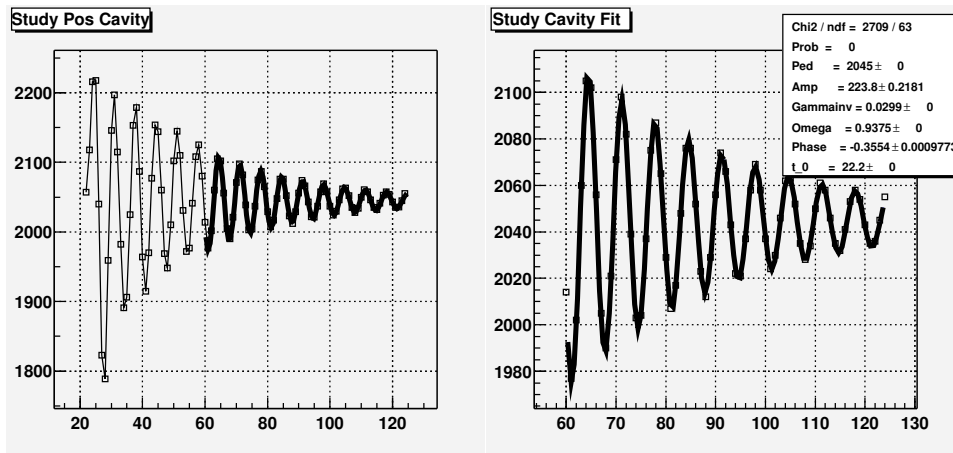


Fig. 3. Intermediate frequency signals produced by a single beam bunch at the ATF from BINP position cavities. A fit to the data produces information about the amplitude and phase of the beam-induced signals.

cavity and three pairs of (X, Y) BPMs^[4] mounted on precision movers, and allows for the measurement of the position and tilt resolution. The best resolution from the latest run in December 2004 was found to be in the range of 20 – 30 nm

The position and tilt sensitivity of each cavity was calibrated against known mover offsets, as shown in Fig. 4. After calibration, the position error for the middle cavity is computed for each pulse as

$$\Delta y_2 = y_1 \cdot \left(\frac{z_3 - z_2}{z_3 - z_1} \right) + y_3 \cdot \left(\frac{z_2 - z_1}{z_3 - z_1} \right) - y_2 \quad (4)$$

where $z_{1,2,3}$ are z locations of electrical centers of the BPMs, and $y_{1,2,3}$ are BPM measurements. The RMS of the distribution in Eq. (4) measures the BPM resolution, while the mean of the distribution is a measure of relative misalignments and electronic and mechanical stability.

Fig. 5 shows the measured resolution as a function of time in during a two-hour run. The top plot shows the resolution computed from Eq. (4), and it ranges typically between 50 and 100 nm. The raw resolution is limited by the cross-talk between X and Y dipole modes in the cavities. Linear regression against tilt signals and X positions improves the resolution in Y direction to 20 – 40 nm (bottom plot in Fig. 5), although occasional outliers, possibly due to changes in beam conditions, are visible.

More beam tests are scheduled for 2005 at the ATF. In addition to the existing NanoBPM structure, three more position monitors have been installed approximately 5 meters downstream. Build by the KEK group, these cavities employ a completely different mechanical support system and electronics, and as such present an independent option for precision beam monitoring. More importantly however, demonstrating stability of electrical and mechanical offsets between the two systems would go a long way towards achieving stringent requirements for the energy spectrometry at the linear collider.

The milestones for the future KEK tests include

- Demonstrating sensitivity of the BPMs to beam tilts in 10 mrad range.
- Demonstrating the stability of the BPM position measurements of below 50 nm over several hours.
- Demonstrating the stability of the relative offset between the SLAC-LLNL and KEK structures.

A related project of demonstrating the performance of BPM-based energy spectrometer in the presence of large beam-induced backgrounds and other systematic effects has been proposed at End Station A (ESA)

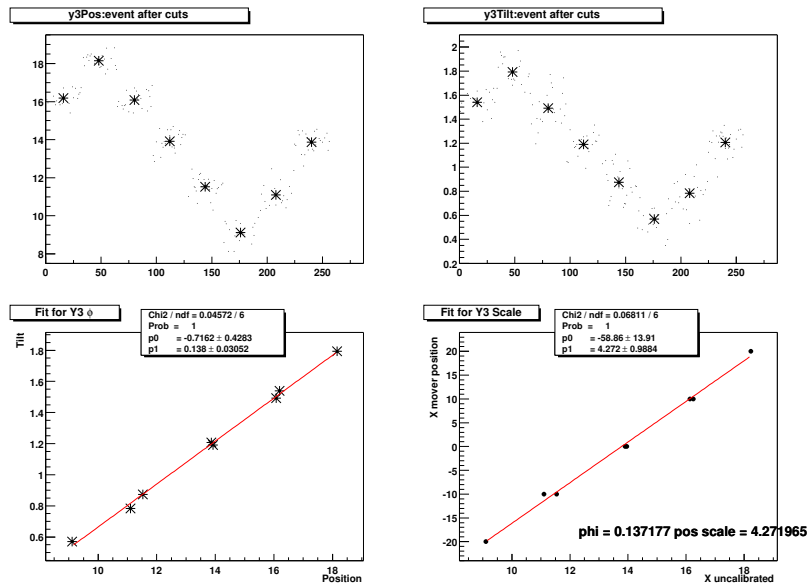


Fig. 4. Calibration of cavity Y3 against known mover offsets. The cavity was moved vertically from -20 to $+20 \mu\text{m}$ relative to the nominal position in $10 \mu\text{m}$ steps. The top plots show the raw data for the position and tilt signals as a function of time, where dots represent individual pulses and stars show the average BPM measurement for each mover position. The slope of the plot in the lower left determines the relative phase shift of the position signal relative to the reference cavity, and the slope of the plot in lower right determines the position calibration constant.

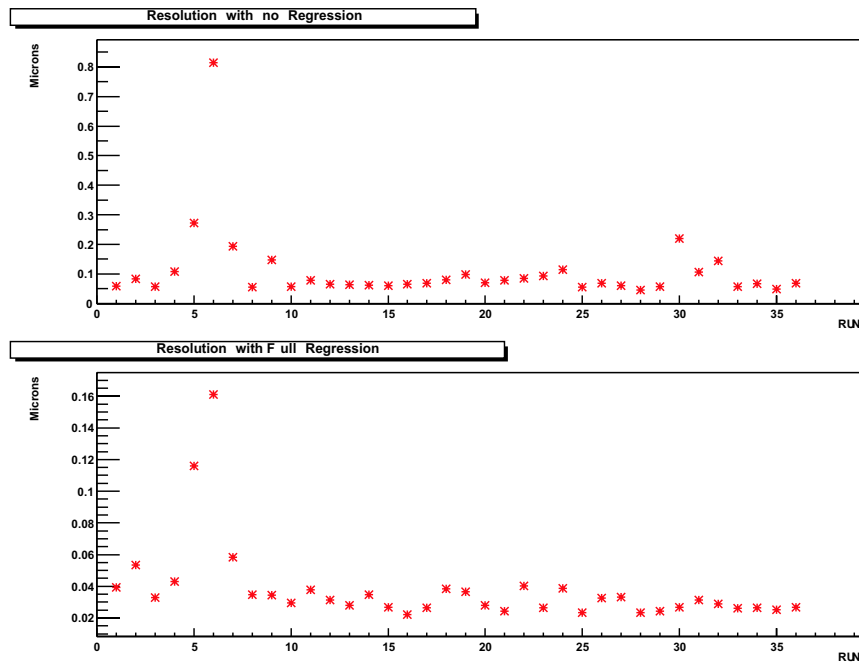


Fig. 5. Beam position resolution in Y direction (μm) as a function of time. Each data point corresponds to approximately one minute of beam data. Top plot shows the raw position resolution, and the bottom plot shows the resolution after linear regression against beam positions in X and beam tilts in X and Y directions.

at SLAC for FY05 and beyond.^[9,10] We will be involved in assembling a set of precision cavities with associated RF processing electronics for beam tests in 2005-2006. The resolution and stability requirements for the energy spectrometer are similar to what is aimed at by the NanoBPM project. However, the beam and environmental properties in End Station A, in particular RF interference, beam-induced backgrounds, beam spot size and beam energy, are more closely matched to the ILC design. In addition, we plan to use rectangular S-band cavities,^[3] which suppress X/Y coupling. Thus, ESA tests are complementary to the NanoBPM program at the ATF. Ultimately, the two beam test programs will converge on the common design of the beam position monitors suitable for precision linac beam diagnostics and for the energy spectrometer.

References

1. P. Tenenbaum *et al.*, preprint SLAC-PUB-9265 (2002).
2. M. Hildreth, "A Demonstration of the Electronic and Mechanical Stability of a BPM-Based Energy Spectrometer for an $e+e-$ Linear Collider, in Ref. [7].
3. Z. D. Farkas *et al.*, preprint SLAC-PUB-1823 (1976).
4. M. Ross *et al.*, preprint SLAC-PUB-9887 (2003).
5. D. H. Whittum, Yu. G. Kolomensky, *Rev. Sci. Instrum.* **70**, 2300 (1999).
6. NanoBPM Collaboration,
<http://www-project.slac.stanford.edu/lc/local/nanoBPM/nanoBPM.htm>.
7. University Consortium for Linear Collider R&D and Linear Collider Research and Development Working Group: "A University Program of Accelerator and Detector Research for the Linear Collider", http://www.hep.uiuc.edu/LCRD/pdf_docs/LCRD_UCLC_Big_Doc/ (2003).
8. Linear Collider Research and Development Working Group, <http://www.hep.uiuc.edu/LCRD/> (2002).
9. Yu. Kolomensky *et al.*, "Beam Instrumentation Tests for the Linear Collider using the SLAC A-Line and End Station A", SLAC-LOI-2003.2 (2003).
10. M. Hildreth *et al.*, SLAC Test Beam Request T-474, "Linear Collider - BPM-based energy spectrometer 2" (2004).