

# PROGRESS REPORT

## Precision RF Beam Position Monitors for Measuring Beam Position and Tilt

### Personnel and Institution(s) requesting funding

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### Project Leader

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### Project Overview

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.<sup>[1]</sup>

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.<sup>[2]</sup> Such precision will require a measurement of the beam position before and after the spectrometer magnets with the resolution of  $\mathcal{O}(100\text{ nm})$ , and comparable stability.

Resonant RF cavity beam position monitors<sup>[3]</sup> can be used to measure the average position of a long 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 (which would be the case at the ILC), 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.

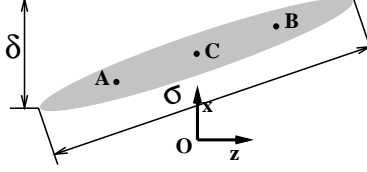


Fig. 1. Tilt of the bunch relative to the  $\mathbf{z}$  axis of the cavity.

### *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 uses the monopole  $TM_{110}$  mode. The BPMs constructed at SLAC in 1960s<sup>[3]</sup> 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.<sup>[4]</sup>

The resonance frequency of a cavity depends on its dimensions, and is often driven by external constraints, such as the minimum size of the beam port, limits in the kick factors from the beam dynamics in the linac or beam delivery system, mechanical supports and mounting, etc. The old SLAC cavities were designed to operate in S band, at the RF carrier frequency of 2856 MHz. On the other hand, BPMs constructed at BINP and KEK are more compact and operate in the C band. To achieve good position resolution and stability, the cavities are tuned to a high value of  $Q > 1000$  which decreases the bandwidth and improves signal-to-noise ratio. Custom RF electronics with I/Q demodulation<sup>[5]</sup> 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.

### *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,  $\omega$  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  $\delta$  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

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

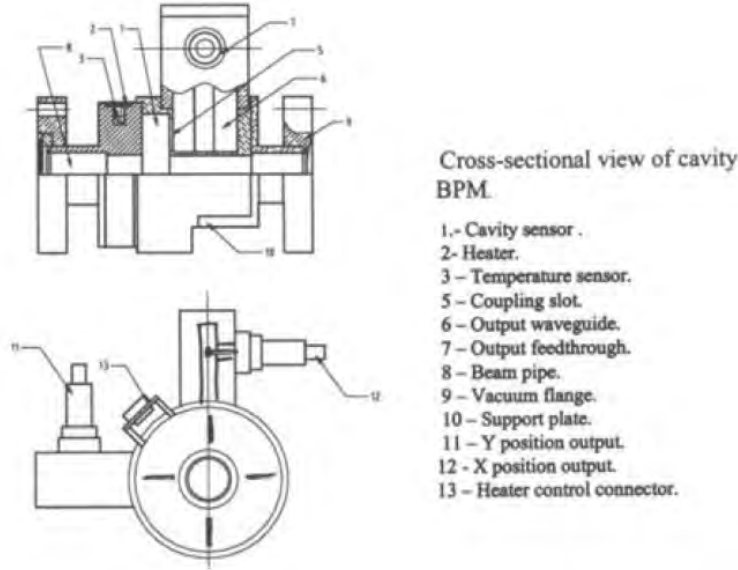


Fig. 2. C-band position monitor constructed at BINP for the NanoBPM collaboration.

equivalent to an offset of  $\Delta x \approx 10$  nm for a typical ILC beam size of  $\sigma = 300$   $\mu\text{m}$  and a tilt of  $\delta = 2$   $\mu\text{m}$ . For small offsets of  $x_0 \sim 1$   $\mu\text{m}$ , 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.<sup>[5]</sup>

### 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.<sup>[6]</sup> The monitors 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

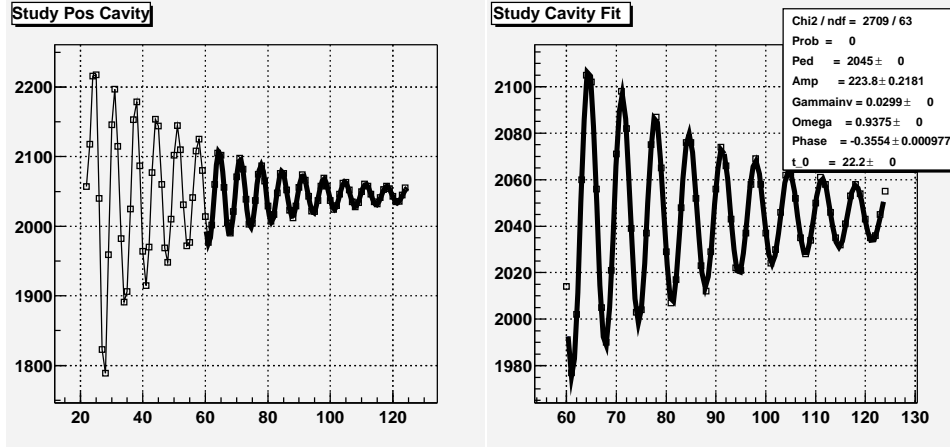


Fig. 3. Intermediate frequency signals produced by a single beam bunch at the ATF from BINP position cavities. A fit to the data produces information about the amplitude and phase of the beam-induced signals.

be tested in the test experiments being developed at SLAC.<sup>[9]</sup> Berkeley group is part of the experiment T-474<sup>[10]</sup> 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. For T-474, we are responsible to the design and construction of the BPM electronics, online software, and data analysis.

## Personnel

The Berkeley group, as of January 2006, includes Prof. Kolomensky and graduate student Toyoko Orimoto, and a number of UCB undergraduates, who have contributed to several aspects of this project. In 2005 and 2006, undergraduates William Chickering, Chit Thu Hlaing, Oleg Khainovski and Peter Loscutoff have taken part in both NanoBPM and SLAC-ESA activities, and are listed as co-authors in this report.

## Progress Report

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*”<sup>[7]</sup> by the US Linear Collider Research and Development Group.<sup>[8]</sup> The project received funding from DOE for FY03 and FY04-06 under DOE contract DE-FG02-03ER41279.

### *NanoBPM Experiment*

Since 2003, we have been working in collaboration with groups at SLAC, LLNL, and KEK in developing the prototype of the nanometer precision beam position monitor. The NanoBPM Collaboration<sup>[6]</sup> has completed several beam tests at the ATF facility at KEK with the precision C-band cavities constructed at BINP and KEK. The present structure consists of a reference (charge-sensitive) cavity and three pairs of (X, Y) BPMs<sup>[4]</sup> mounted on precision movers, and allows for the measurement of the position and tilt resolution. The best resolution from a 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

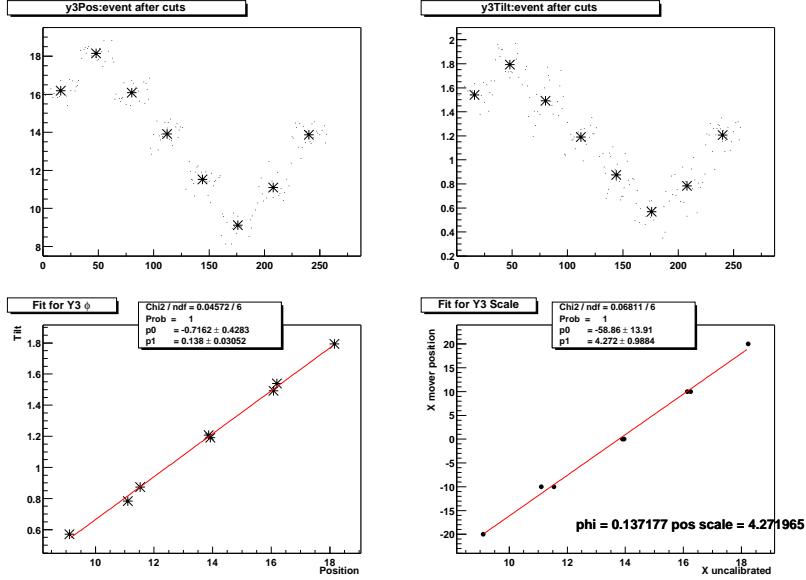


Fig. 4. Calibration of cavity Y3 against known mover offsets. The cavity was moved vertically from  $-20$  to  $+20 \mu\text{m}$  relative to the nominal position in  $10 \mu\text{m}$  steps. The top plots show the raw data for the position and tilt signals as a function of time, where dots represent 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.

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.

In 2005, 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.

During the runs in 2005, the KEK monitors have been extensively studied and debugged. Unfortunately, they show a fairly large coupling between  $X$  and  $Y$  modes, and a significant

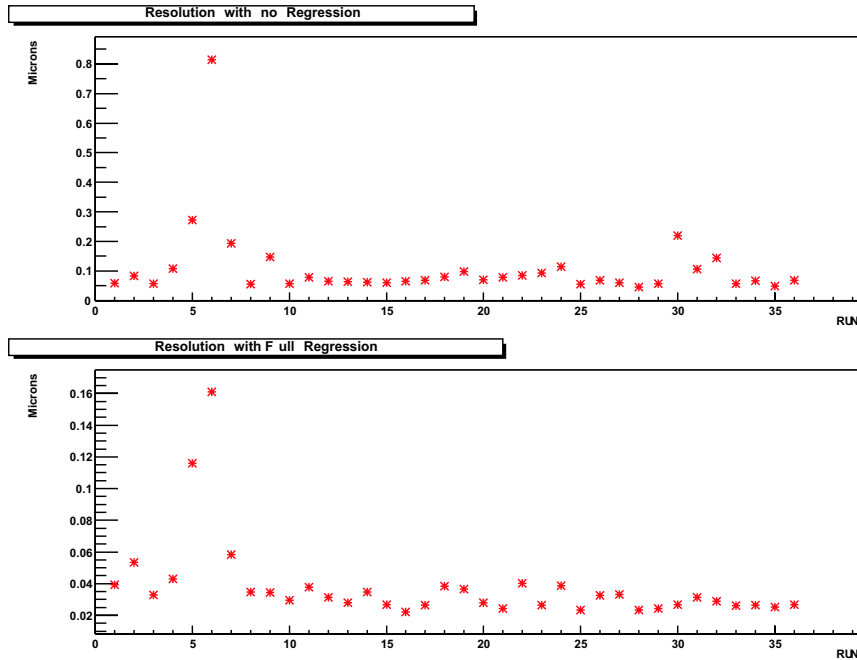


Fig. 5. Beam position resolution in  $Y$  direction ( $\mu\text{m}$ ) as a function of time. Each data point corresponds to approximately one minute of beam data. Top plot shows the raw position resolution, and the bottom plot shows the resolution after linear regression against beam positions in  $X$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

interference from the monopole mode, which limit the resolution of the cavities. An attempt to remedy these problems was made before the Dec. 2005 run, the data from this run are currently being analyzed.

Our graduate student, Toyoko Orimoto, has been participating in the NanoBPM tests since 2004. She has been responsible for the online monitoring software and the data analysis. In the latest run in December 2005, she ran day-to-day operations of the experiment, including daily planning of activities, shift assignments, etc. The online data processing software we have developed provides the real-time feedback to the shifters about beam conditions, helps align the beam near the centers of the cavities, and monitors stability of the beam trajectories and resolutions. A snapshot of the real-time “stripcharts”, developed in ROOT with a shared memory interface to the online analysis program, are shown in Fig. 6.

In addition, two of our undergraduate students, Oleg Khainovski and Peter Loscutoff, have developed readout software for the NanoGrid fringe interferometers. LLNL group have assembled a set of nine NanoGrids, produced by Optra, Inc., to measure nanometer-scale vibrations of the cavities in the NanoBPM experiment. The readout was developed using a LabView data acquisition system with an EPICS interface to the main Unix-based DAQ. It includes fast readout and data logging, monitoring of the hardware status, and linear transformation from the local coordinate systems to the 3-dimensional positions and tilts of each BINP cavity. The NanoGrids have been installed at KEK this January, and will be tested in the upcoming run in March-April 2006. The NanoGrids will monitor the mechanical position of the cavities, so that we can correct the observed position resolution of the BPMs for the motion of the electrical centers of the cavities.

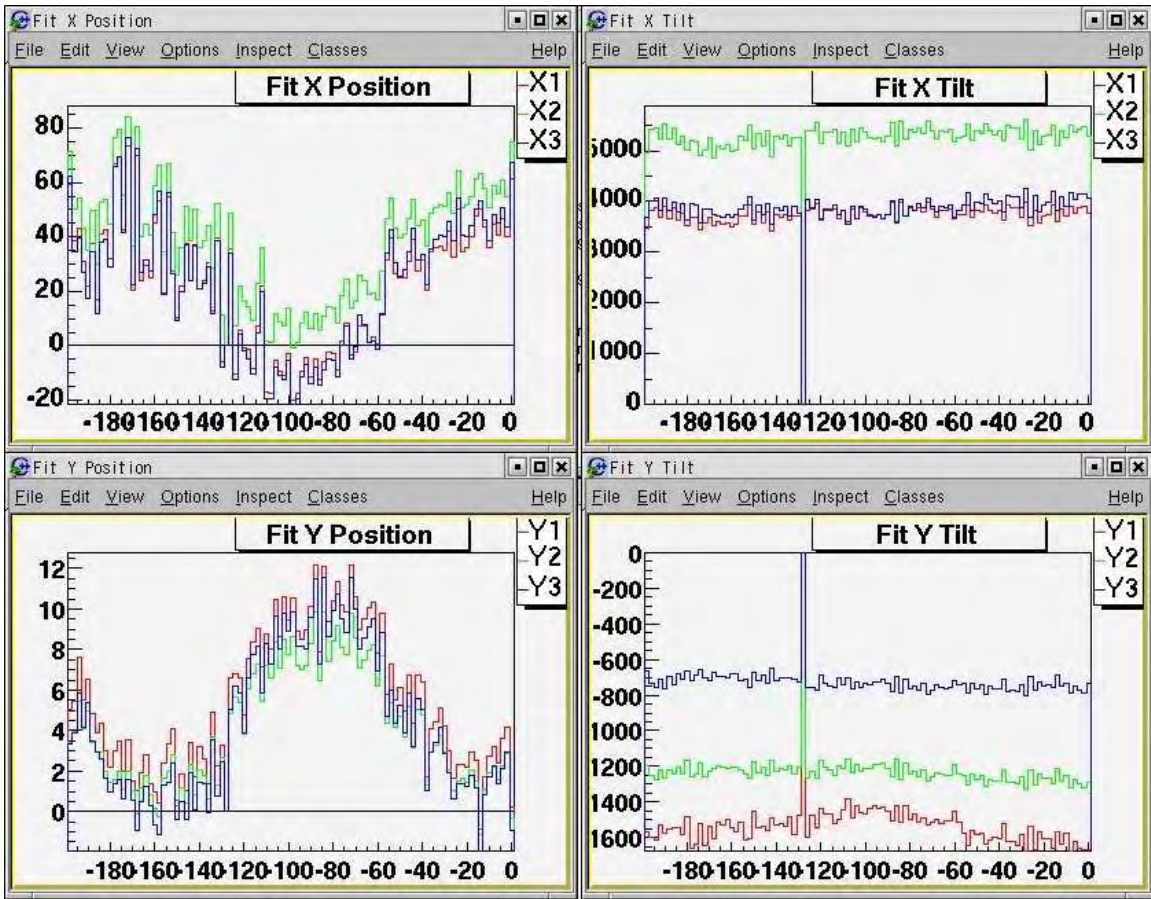


Fig. 6. Real-time output of the online monitoring stripcharts. The plots show instantaneous beam position (in  $\mu\text{m}$ ) in three BINP cavities in  $X$  (top left) and  $Y$  (bottom left) as a function of pulse number, and the instantaneous tilt (in arbitrary units) in  $X$  (top right) and  $Y$  (bottom right).

### *Energy Spectrometer Prototype at SLAC*

We are collaborating with several groups from the US and the UK on the SLAC test experiment T-474<sup>[10]</sup> 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. The beamline in the End Station A will also be used to test the prototypes of the beam position monitors for the main ILC linac. T-474 has three runs tentatively scheduled for the calendar year 2006: a short 4-day period just completed in January 2006, and two-week runs in March and June 2006.

For T-474, we are responsible for design and construction of the BPM electronics. We also provide support for both online and offline software, and perform analysis of the collected data.

T-474 uses a set of S-band cavities to study stability of position measurements under the realistic conditions that would exist in the ILC beam delivery system. For the “Stage 1” run in January 2006, we used two S-band BPM stations from the SLAC linac.<sup>[3]</sup> Each station consists of two rectangular pillbox position-sensitive cavities (“X” and “Y”), and a cylindrical “Q” cavity for beam charge and phase measurements. The resonant frequencies for the modes of interests are near 2856 MHz. For the Stage 2 and 3 runs, in the spring and summer 2006, we will use three additional SLAC stations, also designed in the 1960s, and three sets of new cylindrical cavities, being designed at SLAC for the ILC linac.<sup>[11]</sup> The groups of BPMs will be separated by 10-20 meters, similar to the lever arms in an ILC BPM-based energy spectrometer.

The signals from the BPMs are read out using single stage mixer circuits designed for the E158 experiment at SLAC, and modified by our group for T-474. A schematic diagram of the processor is shown in Fig. 7. A combination of the I/Q mixer and a 90° hybrid combiner provides single sideband downconversion to the intermediate frequency of 73 MHz. The IF signals are recorded by commercial SIS3301 14-bit 100 MHz waveform digitizers from Struck Innovative Systeme.

Our group has built and tested 16 processor channels, and successfully tested them in the January 2005 “Stage 1” run of T-474. A sample waveform recorded from a position cavity is shown in Fig. 8. The response of the cavities and electronics was calibrated by rastering the beam position at the BPMs using upstream corrector magnets. An example of such calibration run is shown in Fig. 9. A detailed analysis of the data is ongoing, but we expect to demonstrate position resolution of a few microns with a dynamic range of several millimeters from the old SLAC cavities. Such resolution is sufficient to probe long-term stability of the electronics and mechanical supports at the scale of 100 nm over a period of an hour.

The resolution of the old SLAC BPMs is limited by a large contribution of the monopole mode, which interferes with the dipole (position-sensitive) signal in the frequency band of interest. The new cavities being designed at SLAC<sup>[11]</sup> will be essentially free of the monopole contamination, and are expected to perform significantly better. They will be tested in the subsequent runs of T-474.

### **Next year Project Activities and Deliverables**

The resolution and stability requirements for the ILC 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. Thus, ESA tests are complementary to

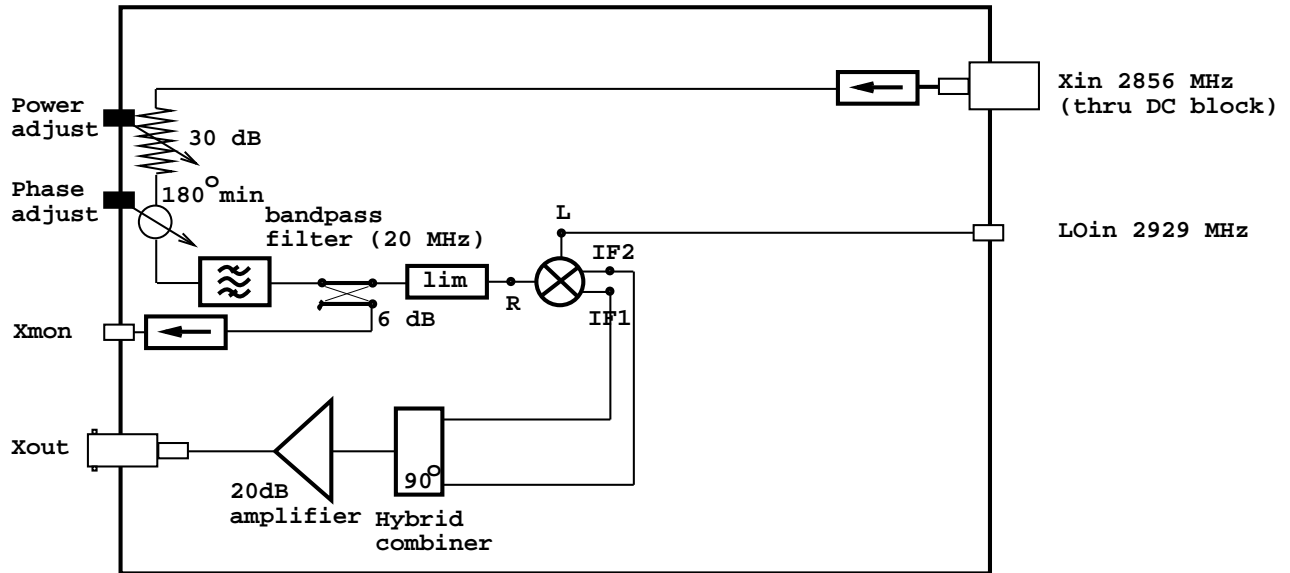


Fig. 7. Schematics of the custom BPM signal processor.

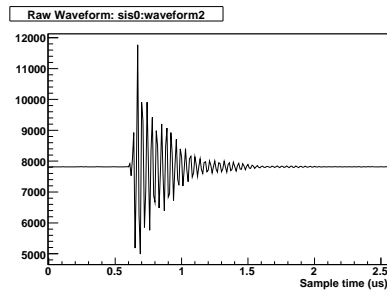


Fig. 8. A sample waveform recorded in one of the dipole (X) cavities in January 2006 runs of T-474.

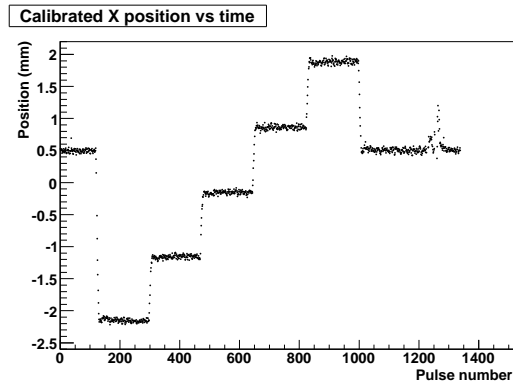


Fig. 9. An example of the position calibration run. Beam position in X direction is rastered in 5 steps over the range of  $\pm 2$  mm. The plot shows the reconstructed beam position (in mm) as a function of pulse number, and corresponds to approximately 140 seconds of real time.

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.

#### *NanoBPM experiment*

The milestones for the future KEK tests include

- Demonstrating the stability of the BPM position measurements of below 50 nm over several hours, using the triplet of BINP BPMs and external corrections for the position jitter using the new interferometer system.
- Demonstrating the stability of the relative offset between the SLAC-LLNL and KEK structures.

At least two three-week runs are planned at the ATF facility for 2006. Toyoko Orimoto will continue taking an active role in running the NanoBPM experiments at KEK.

#### *Energy Spectrometer Prototype at SLAC (T-474)*

Two beam test runs are currently scheduled at SLAC End Station A for the calendar year 2006, and more may be scheduled in 2007, as needed. The goals for the SLAC tests are:

- Demonstrating sub- $\mu\text{m}$  resolution of the BPM position measurement with new S-band BPMs and electronics constructed at Berkeley.
- Demonstrating stability of the position measurement between BPM stations at the level of 100 nm.
- Studying the impact of machine backgrounds, RF interference, and other adverse conditions on the beam position measurements

The Berkeley group, including on average two undergraduate students each year, will continue to play an active role in the ESA program: electronics development, operations, online monitoring, and data analysis.

#### **Budget justification:**

##### **Personnel:**

Personnel includes two undergraduate student researchers each year at 25% for 9 month during the academic year and at 100% during the summer break. The undergraduate stipend is based on an monthly rate \$1,698/month with anticipated cost of living increases of 2%/year.

##### **Benefits:**

USR benefits: 1.3% of gross salary for the academic year and 3% during the summer.

##### **Travel:**

Funds requested to travel to the experimental site at the ATF facility at KEK, Japan (\$2,500) in FY04. Funds to travel to the experimental site at SLAC and to the Linear Collider workshops and meetings in FY05-06 are requested in the amount of \$2,292.34 for FY04, \$2,190.40 for FY05, and \$2,483.18 in FY06.

##### **Other Direct costs:**

We are requesting funds in the amount of \$5,000 in FY04, \$3,000 in FY05, and \$2,000 in FY06 for custom RF electronics for NanoBPM project at KEK and the energy spectrometer

beam tests at SLAC. The amounts are based on the prior experience of purchases similar items for the E158 experiment at SLAC.

**Two-year budget, in then-year K\$**

**Institution:** University of California, Berkeley

Item	FY04	FY05	FY06	Total
Undergraduate Students	\$17,829	\$18,186	\$18,543	\$54,558
Benefits, tuition and fees	\$405	\$413.08	\$421	\$1,239
Travel	\$4,792	\$2,190	\$2,483	\$9,466
Materials and supplies	\$5,000	\$3,000	\$2,000	\$10,000
Total direct costs	\$28,026	\$23,789	\$23,447	\$75,263
Indirect costs (52% MTDC)	\$11,974	\$10,811	\$11,153	\$33,937
Total	\$40,000	\$34,600	\$34,600	\$109,200

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