PROGRESS REPORT

Precision RF Beam Position Monitors for Measuring Beam Position and Tilt

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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.[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 $\mathcal{O}(100 \text{ nm})$, and comparable stability.

Resonant RF cavity beam position monitors[3] 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 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

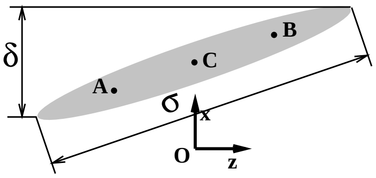

Fig. 1. Tilt of the bunch relative to the **z** axis of the cavity.

describe the RF beam position monitors, report our R&D activities last year, and outline plans for the cavity system.

Beam Position Monitors

A classic beam position monitor[3] 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. Modern cavity designs employ highly symmetric magnetic coupling to suppress the leakage of the position-independent TM_{110} "monopole" mode into the frequency band of the position-sensitive TM_{210} and TM_{120} "dipole" modes. A single cavity provides measurements in both X and Y directions.[6]

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[4] 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 my 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

$$V(t) = Cqx_0 \exp(j\omega t) \tag{1}$$

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

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

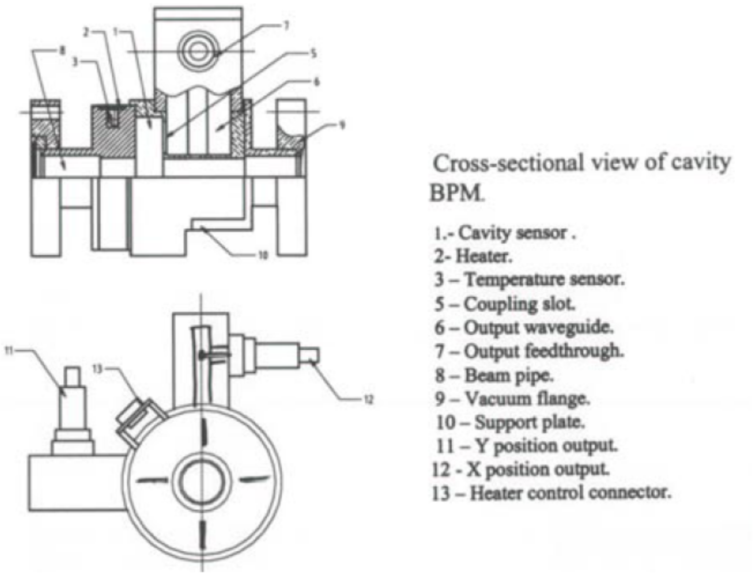

Fig. 2. C-band position monitor constructed at BINP for the NanoBPM collaboration.

The beam tilt introduces a phase shift

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

equivalent to an offset of $\Delta x \approx 10$ nm for a typical ILC beam size of $\sigma = 300\ \mu$m and a tilt of $\delta = 2\ \mu$m. For small offsets of $x_0 \sim 1\ \mu$m, the phase shifts of $\approx 0.7^o$ 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.[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.[5] 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.

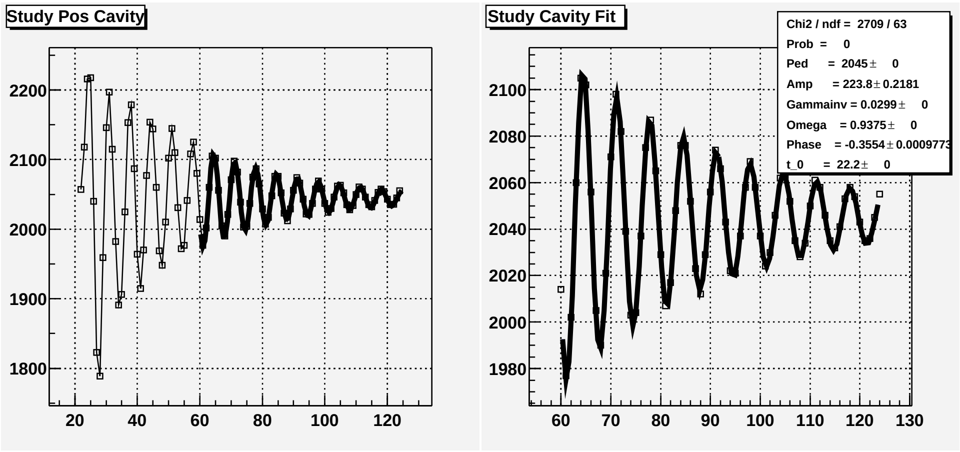

Fig. 3. Intermediate frequency signals produced by a single beam bunch at the ATF from BINP position cavities. A fit to the data produces information about the amplitude and phase of the beam-induced signals.

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.[10] Berkeley group is part of the experiment T-474[11] 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 2007, includes Prof. Kolomensky, Junior Specialist Mahsa Sadre-Bazzaz, and undergraduates Maria Chistiakova and Erik Petigura. Over the past three years, we have trained one graduate student (Toyoko Orimoto, Ph.D. 2006) and six undergraduates. The students have participated in every aspect of the project, from building and testing electronics components, to taking part in data taking runs, to the data analysis.

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"*[8] by the US Linear Collider Research and Development Group.[9] 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[5] 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[6] mounted on precision

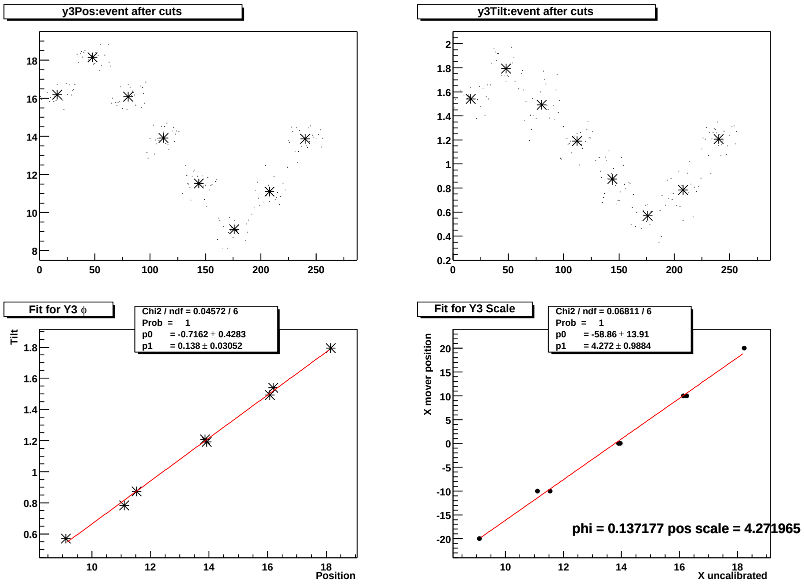

Fig. 4. Calibration of cavity Y3 against known mover offsets. The cavity was moved vertically from -20 to $+20$ μm relative to the nominal position in 10 μm steps. The top plots show the raw data for the position and tilt signals as a function of time, where dots represent individual pulses and stars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

movers, and allows for the measurement of the position and tilt resolution. The BPM signals are amplified and down-converted to the intermediate frequency of about 25 MHz by a heterodyne receiver circuit, and digitized at 100 MHz sampling rate by a commercial digitizer board.[7] The positions and tilts for each cavity are extracted by the offline software.

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

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

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.

Our graduate student, Toyoko Orimoto, has been participating in the NanoBPM tests since 2004. She has been responsible for the online monitoring software, daily operations, and online and offline data analysis. 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. 5.

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

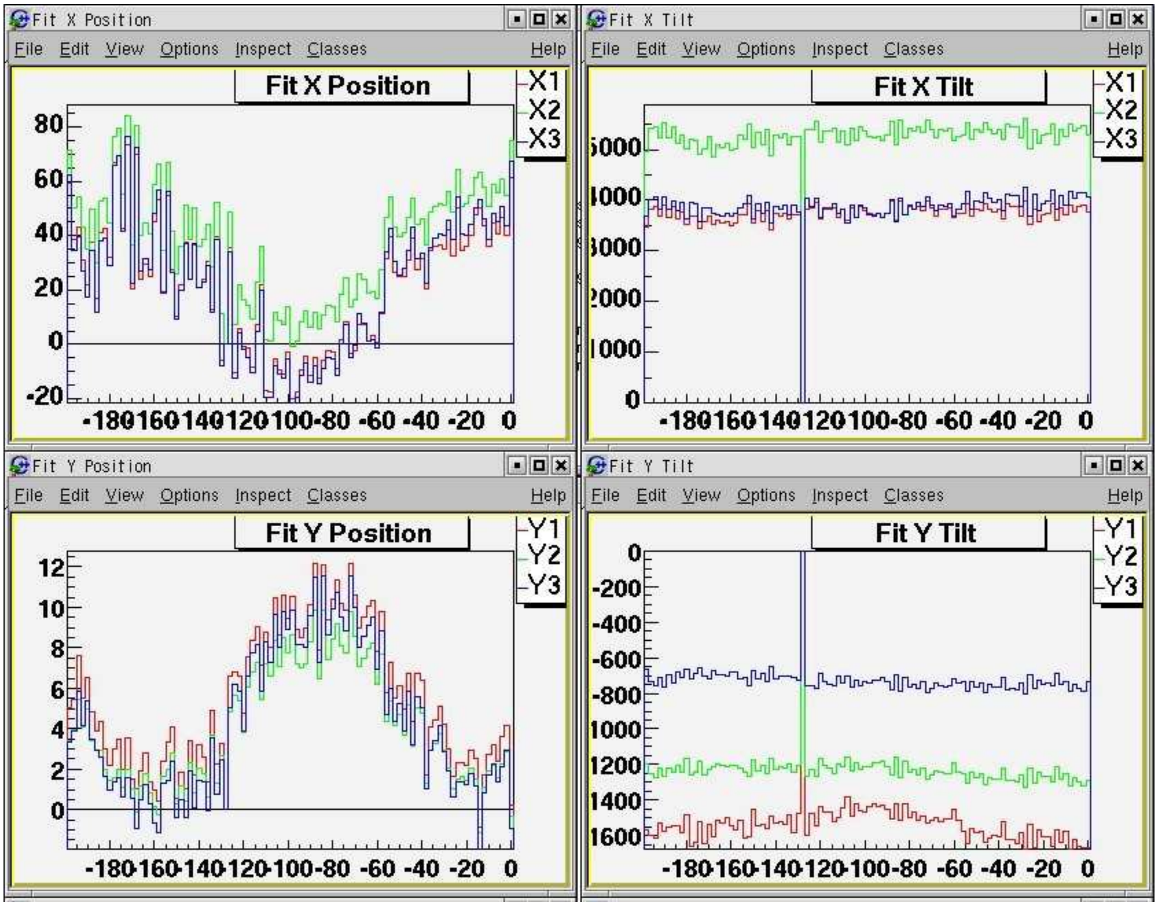

Fig. 5. Real-time output of the online monitoring stripcharts. The plots show instantaneous beam position (in μm) in three BINP cavities in X (top left) and Y (bottom left) as a function of pulse number, and the instantaneous tilt (in arbitrary units) in X (top right) and Y (bottom right).

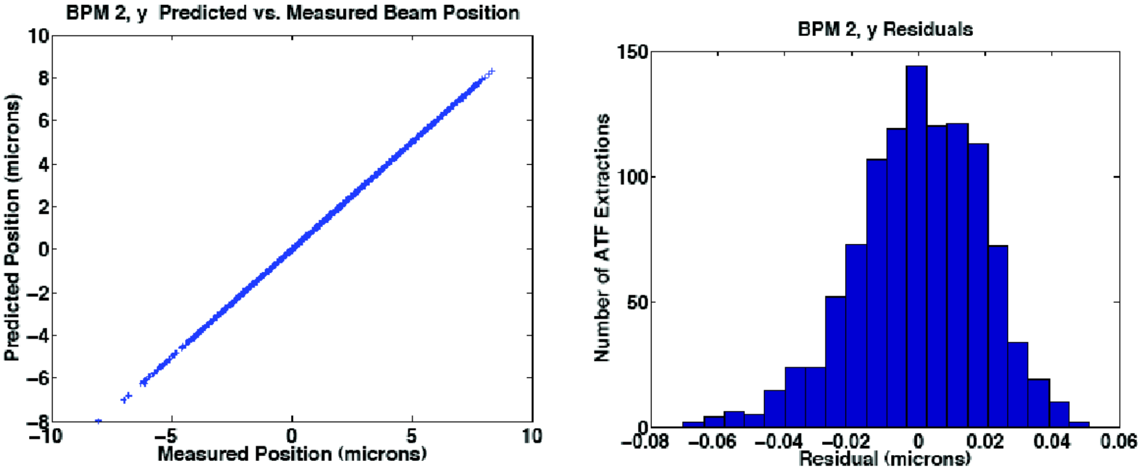

Fig. 6. Measured vs predicted position of the beam (left) and the difference between the measured and predicted positions showing the RMS width of 15.6 nm (right) in the cavity BPMs. Data from the NanoBPM experiment at KEK.[7]

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 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.

So far NanoBPM collaboration has achieved position resolution of 16 nm for single bunches of 2 nC (Fig. 6) and the dynamic range of about 20 μm and simultaneous measurement of beam angles (tilts) with a precision of 2.1 μrad.[7] Given the measured amplitude and phase noise of the RF electronics, resolutions of 3 nm could potentially be achievable. Part of the extra noise may be coming from the mechanical vibrations of the BPM support structure, which are monitored by the NanoGrid fringe interferometers, but are not currently incorporated in the analysis. Other sources of noise, including common-mode pickups, calibration errors and thermal instabilities are being investigated.

Energy Spectrometer Prototype at SLAC

We are collaborating with several groups from the US and the UK on the SLAC test experiments T-474 and T-491[11,12] which aim 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 is also used to test the prototypes of the beam position monitors for the main ILC linac. T-474 had three data runs in the calendar year 2006, in which we commissioned the system of 12 BPMs. In 2007, the full magnetic spectrometer has been installed and commissioned; the full data run to measure energy resolutions and stability is planned for July 2007.

For T-474/T-491, 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. Prof. Kolomensky is a co-spokesperson of T-491.

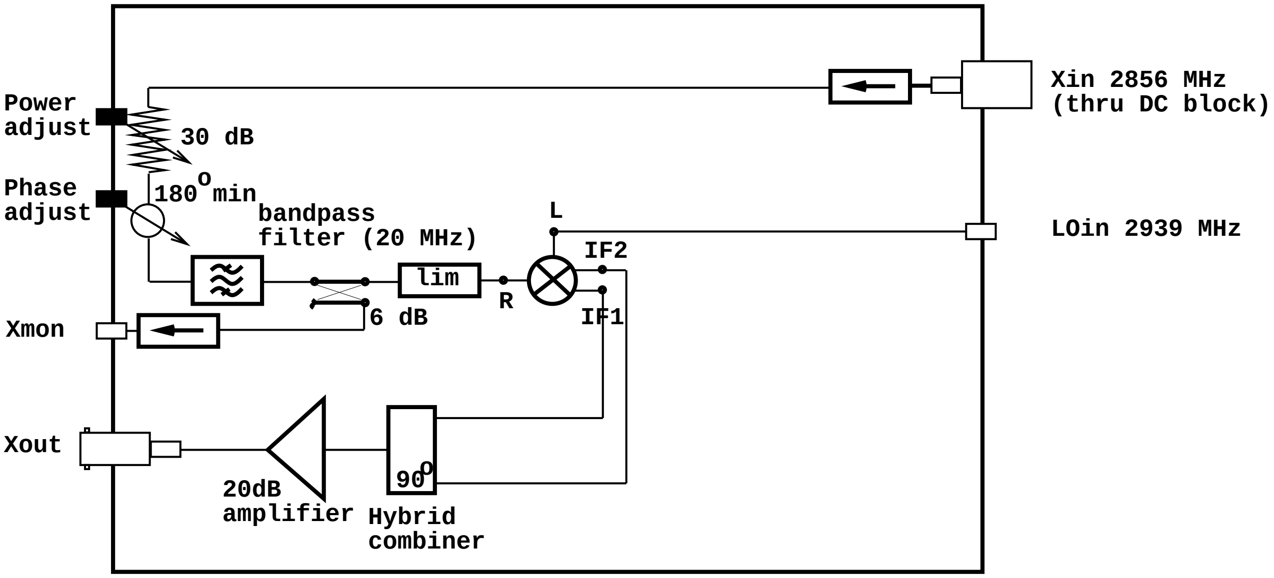

Fig. 7. Schematics of the custom BPM signal processor.

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. We employ nine S-band BPM stations from the SLAC linac and A-line.[3] 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. We also use three sets of new cylindrical cavities, designed at SLAC for the ILC linac.[13] These cavities were successfully tested for the first time by T-474 in 2006. The groups of BPMs are 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 83 MHz. The IF signals are recorded by commercial SIS3301 14-bit 120 MHz waveform digitizers from Struck Innovative Systeme.

Our group has built and tested 33 processor channels for T-474/T-491. A sample waveform recorded from a position cavity is shown in Fig. 8. The response of the cavities and electronics is calibrated by rastering the beam position at the BPMs using upstream corrector magnets. An example of such calibration run is shown in Fig. 9. We have achieved position resolution of below 1 μm over 1 mm dynamic range for all BPMs in the T-491 magnetic spectrometer, including new cavities designed at SLAC. The best resolution (over a short period of time) of below 200 nm was seen in the recent T-491 run in April 2007 (Fig. 10). We have also demonstrated that the drifts in the measured positions are within ±100 nm for time periods of about an hour (Fig. 11). Such stability is close to the requirements for the energy spectrometer prototypes, and further improvements are possible.

The drifts in the measured beam position are dominated by the changes in the gain and phase

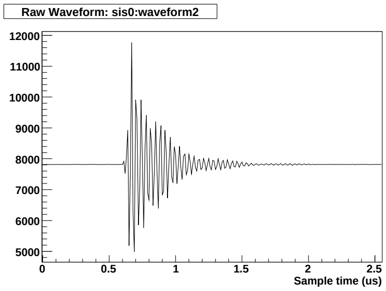

Fig. 8. A sample waveform recorded in one of the dipole (X) cavities in January 2006 runs of T-474.

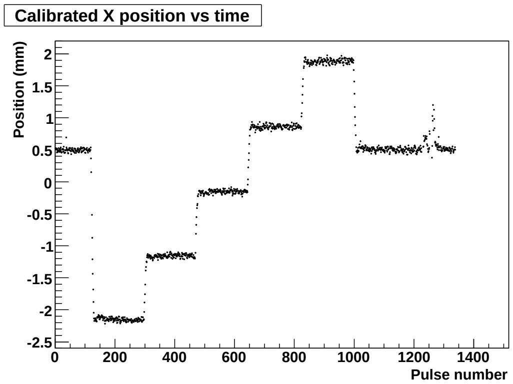

Fig. 9. An example of the position calibration run. Beam position in X direction is rastered in 5 steps over the range of ±2 mm. The plot shows the reconstructed beam position (in mm) as a function of pulse number, and corresponds to approximately 140 seconds of real time.

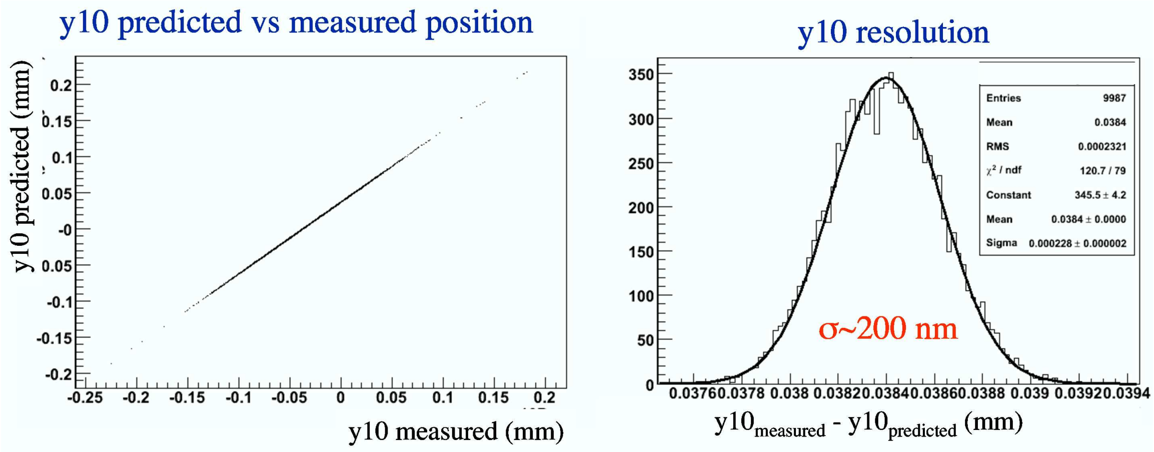

Fig. 10. Position resolution of the S-band BPMs from T-491 run in March 2007. The position in one of the cavities (y_{10}) is compared to the prediction from fit to the beam trajectory through the monitors y_9 and y_{11} (left). The difference between the measured and predicted beam positions are also shown (right). Assuming roughly equal resolutions for each of the BPM in the triplet, the width of the distribution of 230 nm corresponds to a single-monitor resolution of $230/\sqrt{1.5} = 190$ nm.

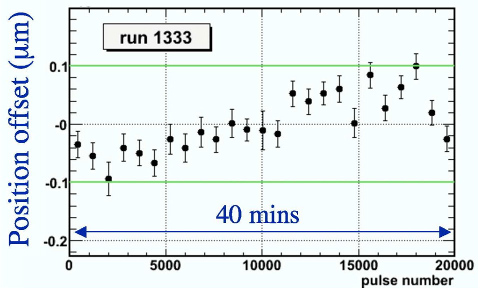

Fig. 11. Average residual between the measured and predicted beam positions over approximately 40 min interval. Data from July 2006.

shifts of the RF electronics. In order to monitor these changes precisely, we are implementing an in-situ calibration system. The relative gain of each position channel would be calibrated with a stable RF pulse, activated every 10 seconds between the beam pulses. A small-scale prototype calibration system was tested in the March 2007 run, and the full system will be implemented by July 2007.

Summary

The NanoBPM collaboration has developed precision beam position monitors and has demonstrated position resolution of 16 nm for single bunches of 2 nC and the dynamic range of about 20 μm, and simultaneous measurement of beam angles (tilts) with a precision of 2.1 μrad. This is the first demonstration of simultaneous measurements of both position and angle of the beam in a single device, and the smallest, to date, achieved position resolution.

The T-474/T-491 experiments have successfully commissioned a BPM-based magnetic spectrometer, and is gearing up for the physics run in July 2007. The resolution, dynamic range, and stability of position measurements are within specs, and further improvements are in the works. Future use of the ESA facility in parallel with LCLS operations is currently under discussion.

Our group is playing an important role in both the NanoBPM and T-474/T-491 collaborations: we have designed and built RF processing electronics, developed online and offline analysis software for both experiments, and contributed to the daily operations and data analysis. Students in our group have developed a valuable expertise and several of them have gone on to successful professional and graduate careers in physics.

FY06 is the last year our group is supported under DOE contract DE-FG02-03ER41279.

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