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PERFORMANCE OF A NANOMETER RESOLUTION BPM SYSTEM *

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Abstract

International Linear Collider (ILC) interaction region beam sizes and component position stability requirements will be as small as a few nanometers. It is important to the ILC design effort to demonstrate that these tolerances can be achieved – ideally using beam-based stability measurements. It has been estimated that RF cavity beam position monitors (BPMs) could provide position measurement resolutions of less than one nanometer and could form the basis of the desired beam-based stability measurement. We have developed a high resolution RF cavity BPM system. A triplet of these BPMs has been installed in the extraction line of the KEK Accelerator Test Facility (ATF) for testing with its ultra-low emittance beam. The three BPMs are rigidly mounted inside an alignment frame on variable-length struts which allow movement in position and angle. We have developed novel methods for extracting the position and tilt information from the BPM signals including a calibration algorithm which is immune to beam jitter. To date, we have been able to demonstrate a resolution of approximately 20 nm over a dynamic range of +/- 20 microns. We report on the progress of these ongoing tests.

INTRODUCTION

The design for the International Linear Collider (ILC) calls for beams which are focused down to a few nanometers at the interaction point. This poses unique engineering challenges which must be overcome. To wit, final focus components must be effectively stabilized at the level of a few nanometers. With nanometer resolution beam position monitors (BPMs), mechanical stability can be measured relative to the particle beam itself. The intent of our experiment is to understand the limits of BPM performance and to evaluate their role in overcoming some of the thorny engineering issues the interaction region of the ILC presents.

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THEORY OF CAVITY BPMS

When a bunch transits a cavity BPM, the field of the bunch excites the eigenmodes of the electromagnetic fields within the cavity. For beams near the center of the cavity, the transverse magnetic TM_{010} or monopole mode has the highest excitation of all the modes, is symmetric, and is proportional to the charge of the bunch. The TM_{110} or dipole mode, however, is antisymmetric and its amplitude has a strong linear dependence on the transverse offset of the beam relative to the electrical center of the cavity; the power thus has a quadratic dependence on the offset. The phase depends on the direction of the offset.

The intrinsic resolution of a BPM is limited by the signal to noise ratio of the system: The signal voltage of the BPM is determined by the beam's energy loss to the antisymmetric TM_{110} mode and by the external coupling of the waveguide; the overall noise of the system comes from thermal noise as well as contamination from the symmetric TM_{010} mode. It has been estimated that an RF cavity BPM along with state-of-the-art waveform processing could have a resolution below one nanometer [1].

EXPERIMENTAL SETUP

This experiment employed three identical cavity BPMs designed at Budker Institute of Nuclear Physics (BINP) [2]. The resonant frequency of the dipole TM_{110} mode was 6426 MHz. The dipole mode – whose amplitude is comparatively small when the beam passes near the electrical center of the cavity – was selectively coupled out by two orthogonal slots – one each for x and y – which exploited the difference in the field structure of the monopole and dipole modes to reject the monopole mode – and in particular the side bands which reside at or near the dipole mode frequency. A quarter view of the inside surface of the BPM is illustrated in figure 1.

To these three BPMs must be added a fourth "reference" cavity whose monopole TM_{010} mode had a resonant frequency of 6426 MHz. This reference cavity signal was used to normalize the amplitudes of the signals from the three directional cavities to remove the effects of variations

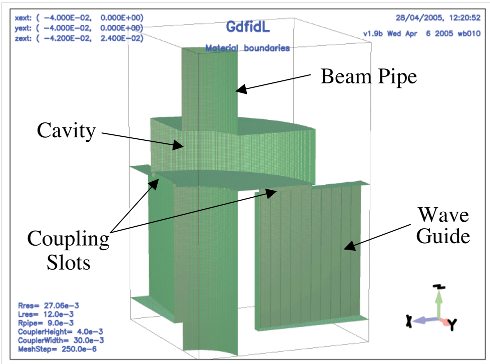

Figure 1: A quarter view of the inside surface of a BINP BPM.

in the bunch charge; this signal also provided a single reference for comparing the phases of the signals from the three directional cavities.

The three BPMs were each rigidly mounted to the endplates of an alignment frame by six variable length struts which allowed each BPM to be moved by small amounts in x, y, z, yaw, pitch, and roll. The entire alignment frame assembly was mounted by four variable length motorized legs which allowed the entire experiment to be moved in x, y, yaw, pitch, and roll to steer it onto the beam. This is illustrated in figure 2.

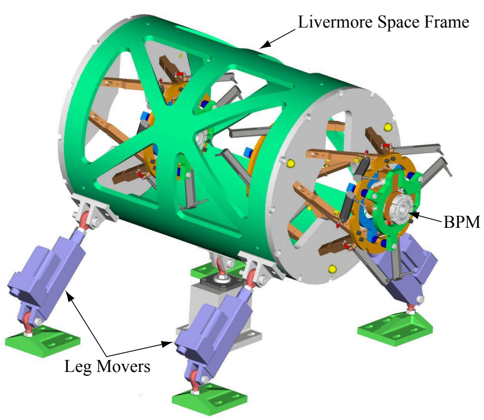

Figure 2: The Livermore alignment frame held the entire three-BPM assembly rigid. The first vibrational mode was at 200 Hz. Each BPM is mounted by six variable length struts which allow the BPM to be moved in x, y, z, yaw, pitch, and roll. This facilitated both the steering of an individual BPM onto the beam and also calibration of each BPM. The leg movers allowed the entire experiment to be steered onto the beam.

Single bunch extractions from the ATF ring were used for all of our tests. Each ATF extraction contained between 6 and 7×10^9 e^- at an energy of 1.28 GeV. The machine repetition rate was ~ 1 Hz.

The electronics used to process the raw signals from the BPMs employed a two-stage down-mix to go from 6426 MHz to 20 MHz before being digitized at 100 Megasamples per second by a 14 bit ADC.

Two methods were employed to calculate the amplitude and phase from the digitized waveforms: Fitting and digital down-conversion. In the fitting algorithm, the waveforms were fitted using the equation

$$V \quad = \quad V_0 + Ae^{-\Gamma(t-t_0)} sin[\omega(t-t_0)+\varphi], \qquad (1)$$

considering the amplitude A and phase φ as free parameters. In the digital down-conversion (DDC) algorithm, the raw waveform was first multiplied by a local oscillator (LO) of the same frequency to yield a zero intermediate frequency (IF). The real and imaginary parts of each IF were then multiplied by a 39 coefficient, symmetric, finite impulse response (FIR), low-pass filter with 2.5 MHz 3 dB bandwidth. The value of the complex amplitude at t_0 was then determined by extrapolation using the decay constant. In both algorithms, the amplitudes and phases were determined from the non-saturated portion of the waveforms.

After normalization by the reference cavity amplitude and phase, the complex amplitude of the BPM waveform was related to the beam's position and tilt by a simple rotation in the complex plane, followed by a scaling to get the units correct. The calibration procedure entailed moving an individual BPM a known amount with the hexapod strut movers and considering how the response of that BPM changed. The information from the calibration provided both the rotation angle and the scale constants needed to determine the beam's position and tilt.

RESULTS

Because the beam passed through the apparatus in a straight line, the position in BPM 2 was related in a linear way to the beam's position in BPMs 1 and 3,

$$y_2 \quad = \quad a + b_{1x}x_1 + b_{1y}y_1 + b_{3x}x_3 + b_{3y}y_3. \qquad (2)$$

Repeated application of equation 2 over many ATF extractions yielded a matrix equation which was evaluated using the method of Singular Value Decomposition to determine the coefficients a and b. (It should be noted that terms for $x'_{1,3}$ and $y'_{1,3}$ could be and sometimes were added to the right hand side of equation 2.)

BPM resolution was determined by measuring the residual – that is the difference between the position of the beam as measured by BPM 2 and the predicted position as calculated from equation 2 by applying the regression coefficients a and b. The resolution was then proportional to the standard deviation of the distribution of the residuals over many ATF extractions. The constant of proportionality was a geometric weight factor (equal to $\sqrt{2/3}$ for BPM 2).

Figure 3 shows the distribution of the residuals for 2300 ATF extractions from the evening of 11 March 2005, 18:38 JST. This data set was analyzed using the waveform-fitting algorithm. Four events were subsequently removed as being missing pulses, and a further two flier events were removed yielding a total of 2294 events. The standard deviation of the distribution was 28.9 nm and yielded a resolution of 23.6 nm.

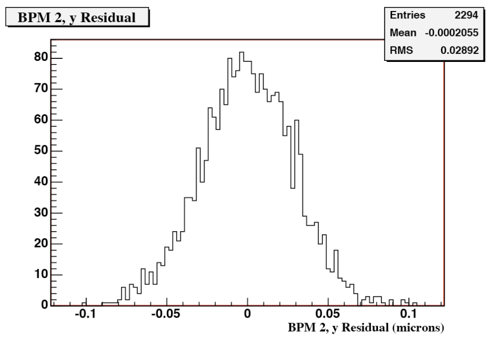

Figure 3: The residuals for 2300 ATF extractions from a period spanning approximately half an hour on the evening of 11 March 2005, 18:38 JST. Four events were removed on account of low reference cavity amplitude, which usually signifies either a missing bunch or at least a very low current bunch, and a further two flier events were removed for a total of 2294 events. The standard deviation of the distribution was 28.9 nm and yielded a resolution of 23.6 nm.

Figure 4 shows the distribution of the residuals for 800 ATF extractions from 27 May 2005. This data set was analyzed using the digital down-conversion algorithm, and the calculation of the residual included additional terms for x_1', y_1', x_3', and y_3' in equation 2. The data here covered a roughly 9 minute time period. The standard deviation of the distribution was 29.4 nm and yielded a resolution of 24.0 nm.

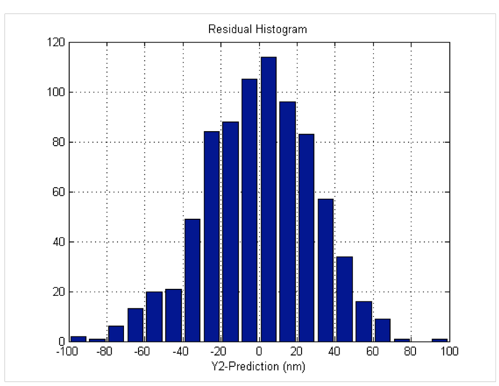

Figure 4: The residuals for 800 ATF extractions from a period spanning roughly 9 minutes on 27 May 2005. The standard deviation of the distribution was 29.4 nm and yielded a resolution of 24.0 nm.

For the period of data-taking in April 2006, attenuation was removed from the output of the reference cavity to increase the signal levels and improve the signal to noise ratio. Furthermore, the two local oscillators used to downmix the BPM signals as well as the digitizer clock were phase-locked. Lastly, an improved thermal insulating enclosure was added. These combined effects improved the resolution a noticeable amount. Figure 5 shows the distribution of the residuals for 1108 ATF extractions from 12 April 2006, 02:16 JST. This data set was analyzed using the digital down-conversion algorithm, and the calculation of the residual included additional terms for x_1', y_1', x_3', and y_3' in equation 2. The data here covered a roughly 13 minute time period. The standard deviation of the distribution was 20.7 nm and yielded a resolution of 16.9 nm.

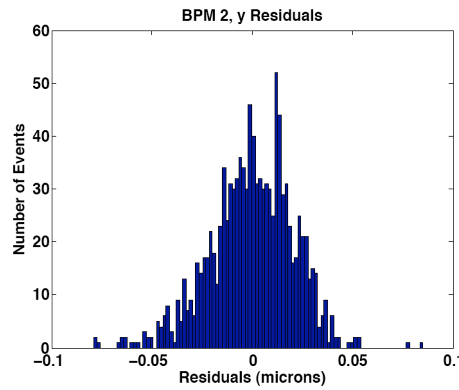

Figure 5: The residuals for 1108 ATF extractions from a period spanning roughly 13 minutes on the morning of 12 April 2006, 02:16 JST. The standard deviation of the distribution was 20.7 nm and yielded a resolution of 16.9 nm.

CONCLUSIONS AND FUTURE PLANS

We have achieved a resolution of 16.9 nm to date. The alignment frame and hexapod mounting arrangement of the BPMs has provided both excellent stability and range of motion. Analysis has shown that our resolution is currently limited by electronic noise.

We recently installed a metrology system to account for the relative motion of the three BPMs, nominally from temperature fluctuations. On each BPM are attached three encoder-based optical xy-position sensors which measure the six degrees of freedom of each BPM. A carbon fiber metrology frame with a zero coefficient of thermal expansion supports all of the optical encoder grids (three per BPM) for all of the BPMs, thus providing the frame of reference for the position measurements. Data and analysis with the new metrology system will be forthcoming soon.

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[2] V. Balakin et al., "Discussion of Nanobeam Summaries and Areas for Future Collaboration," http://www.vlepp.serpukhov.su/engl/bnl/bpm.html.