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# DEVELOPMENT OF NANOMETER RESOLUTION C-BAND RADIO FREQUENCY BEAM POSITION MONITORS IN THE FINAL FOCUS TEST BEAM*

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*Abstract*

Using a 47 GeV electron beam, the Final Focus Test Beam (FFTB) produces vertical spot sizes around 70 nm [1]. These small beam sizes introduce an excellent opportunity to develop and test high resolution Radio Frequency Beam Position Monitors (RF-BPMs). These BPMs are designed to measure pulse to pulse beam motion (jitter) at a theoretical resolution of approximately 1 nm [2]. The beam induces a $TM_{110}$ mode with an amplitude linearly proportional to its charge and displacement from the BPM's (cylindrical cavity) axis. The C-band (5712 MHz) $TM_{110}$ signal is processed and converted into beam position for use by the Stanford Linear Collider (SLC) control system. Presented are the experimental procedures, acquisition, and analysis of data demonstrating resolution of jitter near 25 nm. With the design of future $e^+e^-$ linear colliders requiring spot sizes close to 3 nm [3], understanding and developing RF-BPMs will be essential in resolving and controlling jitter.

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Using a 47 GeV electron beam, the Final Focus Test Beam (FFTB) produces vertical spot sizes around 70 nm [1]. These small beam sizes introduce an excellent opportunity to develop and test high resolution Radio Frequency Beam Position Monitors (RF-BPMs). These BPMs are designed to measure pulse to pulse beam motion (jitter) at a theoretical resolution of approximately 1 nm [2]. The beam induces a $TM_{110}$ mode with an amplitude linearly proportional to its charge and displacement from the BPM's (cylindrical cavity) axis. The C-band (5712 MHz) $TM_{110}$ signal is processed and converted into beam position for use by the Stanford Linear Collider (SLC) control system. Presented are the experimental procedures, acquisition, and analysis of data demonstrating resolution of jitter near 25 nm. With the design of future $e^+e^-$ linear colliders requiring spot sizes close to 3 nm [3], understanding and developing RF-BPMs will be essential in resolving and controlling jitter.

## 1 INTRODUCTION

Because of the small vertical spot sizes in the FFTB and a horizontal to vertical aspect ratio of almost 17 to 1, the RF-BPMs were designed to measure only vertical beam motion. At the end of the SLAC linac or entrance to the FFTB, vertical jitter is typically 30% of $\sigma y$ [4]. Assuming contribution to jitter from the FFTB is negligible, a design $\beta y^*$ of 100 μm at the Final Focal Point (FFP) and measured $\gamma\varepsilon y$ of 1.5 μm at the entrance to the FFTB would produce vertical beam jitter on the order of 20 nm. Interest in tracking and recording this jitter led to the development of these BPMs.

Although the FFTB is equipped with 34 strip-line BPMs, each with a jitter resolution of about 2 μm at a beam intensity of 6e9 [5], a direct measurement of the jitter at the FFP is very difficult. BPMs near the FFP (in the final transformer) are $n\pi/2$ out of phase measuring only angular divergence jitter. Farther away, BPMs can be found which are in phase, but are limited by their resolution and the accuracy of the transport optics model used to project the jitter to the FFP. Another concern of using BPMs which are not in the vicinity of the FFP is structural vibrations in the final transformer that could contribute to vertical jitter and would not be detected.

To make a direct measurement of the beam's motion at the FFP a single RF-BPM was installed 6.35 cm downstream of the KEK Beam Size Monitor (BSM). Because of the RF-BPM's compactness, placement close to the FFP is possible (see table 1).

Table 1. RF-BPM parameters.

| PARAMETERS OF A RF-BPM | |
|---|---|
| Frequency | 5712 MHz |
| BPM length | 50 mm |
| cavity length | 5 mm |
| BPM diameter | 96 mm |
| cavity diameter | 60.07 mm |
| beam pipe diameter | 20 mm |
| loaded Q factor | 130 |
| signal into 50 ohms | 25 μV/nC/nm |

Figure 1 shows a set of three RF-BPMs which were installed at the entrance to the final transformer, an image focal point (IMFP). The final transformer has a demagnification of 7, so the jitter will be on the order of

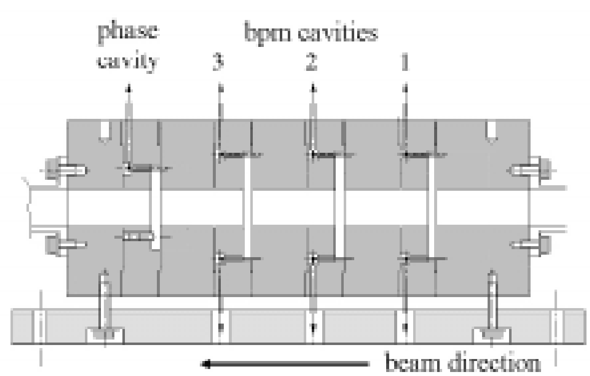


Figure 1. Mechanical drawing of the triplet RF-BPM set used for measuring the BPMs' resolutions.

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140 nm at these BPMs. This set of BPMs is used for the resolution measurement, as well as for characterizing the beam's jitter parameters before entering the final transformer.

## 2 EXPERIMENT CONFIGURATION

The RF-BPMs are a typical pill box cavity design producing a signal containing four components

$$Vrf = A1qy + jA2qy' + jA3qy^{O} + Vnoise, \qquad (1)$$

where q is the beam charge, $y$ is the beam's offset with respect to the center of the cavity, $y'$ is the beam's angle with respect to the cavity ($y'=dy/dz$), $y^{o}$ is an offset which comes from the $TM_{010}$ signal (common mode), and $j$ denotes the imaginary terms.

The signals from the RF-BPM are sent through a 180° hybrid that significantly reduces the second and third term in equation 1. The difference signal from the hybrid is passed into a RF receiver circuit. The RF receiver circuit is set up as a heterodyne synchronous detector that extracts the amplitude and polarity of the BPM signal. The beam induced waveform is filtered at 5712 MHz and mixed down to 500 MHz. The 500 MHz signal is then filtered, amplified, and mixed down to 50 MHz. This signal is again filtered and amplified and passed to a dual track and hold (NiTNH) module, a 16 bit digitizer with a ±2 volt limit and a 300 MHz bandwidth. The digital signal is converted into beam position and read by the SLC Control Program (SCP).

The measured dynamic range of the receiver is 51 dBm with measured noise of -82 dBm or 1 nm for a beam charge of 1 nC. The gain factor for the system is measured by moving the BPMs with respect to the beam (see section 3 below for this process).

## 3 DATA ACQUISITION

Before being used for data acquisition, the RF-BPMs were phased to the electron beam and a signal to position calibration constant was measured. Phasing was accomplished by using a fourth cavity which is located at the end of the triplet stack (see figure 1). Since the BPMs were phased to the beam, drifting due to timing signals were eliminated. The calibration constant was measured by moving the BPMs with respect to the beam. Calibrated linear variable differential transformers (LVDTs) measured the change in the BPM's position while the change in the BPM's signal is recorded. Within the dynamic range of the receiver, position verses signal is linear and the slope is the gain or calibration constant. This calibration constant is stored in the SCP's database for use with the BPM acquisition software. The maximum beam rate of the FFTB is 30 Hz. The signals from RF-BPMs are acquired simultaneously with the signals from standard BPMs up to the acquisition rate of 30 Hz. This allows for the comparison of the beam positions measured by the RF-BPMs to that measured by the standard BPMs.

## 4 DATA ANALYSIS

The top plot in figure 2 displays beam trajectories for approximately 300 machine pulses at an acquisition rate of 30 Hz. The beam's waist at the IMFP is close to the middle RF-BPM of the triplet set. With only drift spaces between the BPMs, the calculation of the slope and offset for each beam trajectory at the center BPM does not require knowledge of beam line optics. The bottom plot in figure 2 shows angles verses positions with a one sigma ellipse. This is a measurement of the jitter emittance which is equal to 1.533 µm. The equation for the emittance is

$$\varepsilon_{jitter} = \sqrt{\langle y \cdot y \rangle \langle y' \cdot y' \rangle - \langle y \cdot y' \rangle^2}, \qquad (2)$$

where $y$ is the measured position at the center BPM, $y'$ is the measured angle using all three BPMs ($y'=dy/dz$), and <…> means an average over a series of measurements with a fixed time limit. The jitter emittance is close to one tenth of the beam emittance, which is expected for the observed beam jitter to beam size fraction of 30% in the SLC. This is an important measurement because it shows that the RF-BPMs agree with standard BPMs.

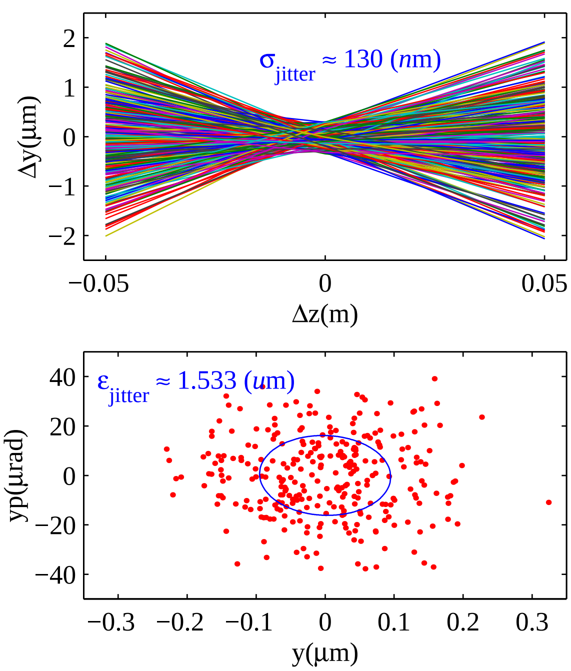


Figure 2. The top plot displays the measured beam trajectories. The bottom plot shows the calculated jitter emittance.

The resolutions of the RF-BPMs were measured using the triplet stack. With the BPMs in the triplet set being equally spaced and the beam's trajectory through them a straight line, the position from the middle BPM should equal the average of the positions from the outer BPMs. Assuming each BPM has the same resolution and uncorrelated noise, the resolution of the BPMs can be calculated from the standard deviation of the difference (residual) between the center position and the averaged positions for many beam trajectories. The equation is

$$\sigma_{bpm} = \sqrt{\frac{2}{3}}\sigma_{residual} \quad (3)$$

The first plot in figure 3 displays the distribution of the residuals with a sigma of 31 nm from a gaussian fit. This gives a BPM resolution of 25 nm for a 1 nC beam charge. The second and third plots show the time and frequency domain of the residual, respectively. It appears to be mostly white noise. The peak around 1 Hz is of some concern because it is a signature of beam motion in the SLC. The signal from the beam angle has not been completely eliminated. The fourth plot shows the integral of the residual in the frequency domain. Although the 1 Hz peak is of concern, its contribution to the overall residual is a small percentage.

If the RF-BPMs had a correlated noise source, for example a mechanical vibration or electronic noise, the resolution of the measured jitter would be understated for the rest of the beam line. To confirm the RF-BPM

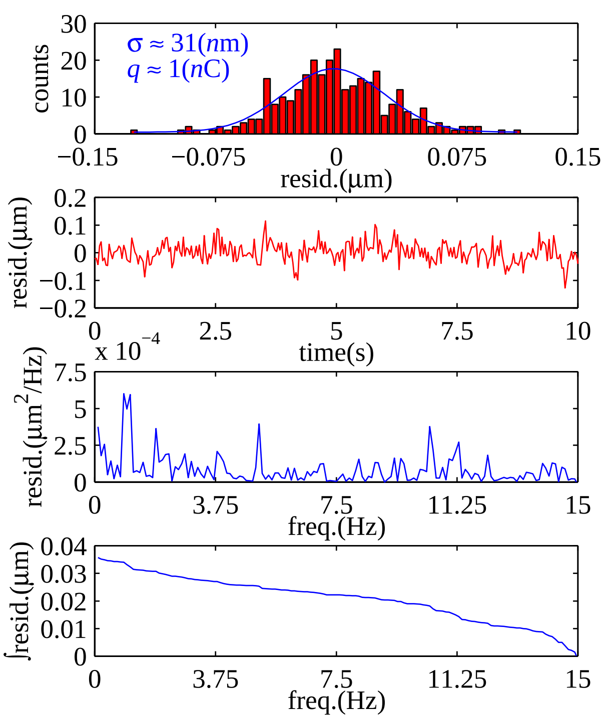


Figure 3. The histogram, time and frequency structure, and integrated amplitude of the residual from top to bottom, respectively.

resolution measured by the triplet set, standard BPMs, one before and after the triplet set, were incorporated into fitting beam trajectories. All five BPMs were simultaneously fitted to the beam line model in an iterative least squares method until the resolution of each BPM converged [6]. Displayed in table 2 are the results for the triplet set and the two strip-line BPMs. The Yrslt column gives the resolutions of the RF-BPMs (The RF-BPM names are CB02 5032, 5034, and 5036).

Table 2. RF-BPMs resolutions.

| BPMS RESOLUTIONS(µm) | | | | |
|---|---|---|---|---|
| BPMS | Yest | Yrslt | Yrsdl | Yrms |
| CB01 5020 | 0.400 | 0.400 | 0.025 | 207.8 |
| CB02 5032 | 0.045 | 0.045 | 0.040 | 1.8 |
| CB02 5034 | 0.023 | 0.023 | 0.014 | 1.3 |
| CB02 5036 | 0.054 | 0.054 | 0.051 | 1.6 |
| CB01 5030 | 2.640 | 2.640 | 2.640 | 31.4 |

## 5 DISCUSSION AND CONCLUSION

Although the resolution of approximately 25 nm was measured for the RF-BPMs from the triplet set, the measured resolution of the RF-BPM at the FFP was around 80 nm. This is attributed to the beam's large angular divergence (460 µrad) and is not completely understood. Even though the FFP BPM was not able to measure beam motion below 80 nm, it was very efficient in minimizing beam aberrations before using the KEK BSM.

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