BEAM TILT SIGNALS AS EMITTANCE DIAGNOSTIC IN THE NEXT LINEAR COLLIDER MAIN LINAC *

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Abstract

High frequency cavity beam position monitors (BPMs) can also provide information on the *xz* or *yz* correlation of the beam (yaw or pitch, respectively). Such a diagnostic is particularly desirable in the Next Linear Collider (NLC) main linacs, where the principal sources of emittance dilution generate such a correlation. Test results from the extremely low emittance beam at the KEK Accelerator Test Facility (ATF) [1] are described. The formalism of beam-tilt signal generation and detection are reviewed, and studies of possible emittance correction schemes based on the beam tilt signals are presented.

1 INTRODUCTION

In high performance linear accelerators, such as the Stanford Linear Collider (SLC) linac and the linacs proposed for the Next Linear Collider (NLC), the principal diagnostic tools for emittance control are beam position monitors (BPMs) and profile monitors of various types. The profile monitors can measure the beam size, which is closely related to the parameter of greatest interest (normalized transverse emittance). Unfortunately, profile monitors tend to be expensive, difficult to use, relatively invasive, and unable to produce useful data for accelerator tuning on a pulse-by-pulse basis.

Beam position monitors, by contrast, are relatively inexpensive, easy to use, non-invasive, and capable of producing useful data on each and every linac pulse. Because of these issues, the ratio of the number of BPMs to the number of profile monitors in a linac tends to be large. Despite their numerical superiority in most beamlines, BPMs have several drawbacks as well. The information they produce is much less directly correlated to the beam emittance than the information produced by a profile monitor. The absolute position reading returned by a BPM is a combination of the actual beam position and the mechanical and electrical offsets of the BPM installation itself. Because of these factors, considerable effort is invested in devising schemes that correlate the change in a BPM reading to a variable that is relevant to emittance - for example, the change in BPM readings when the centroid energy is changed reveals the dispersion at the BPM.

In the case of BPMs made from high-frequency dipole-mode resonant cavities, it is possible to extract additional information from the BPM signal component that is in quadrature with the beam position signal. This signal gives information on the *xz* or *yz* correlation within the beam, which is generically referred to here as beam tilt. The beam tilt signal is indistinguishable from the signal generated when the beam trajectory through the cavity is not parallel to the cavity axis. An angled trajectory directly generates a TE110 mode in the cavity rather than the TM110 illustrated in the next section. In practice an 'angular alignment' procedure, similar to beam-based offset alignment will be needed.

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2 GENERATION OF RF SIGNAL

Consider the system shown schematically in Figure 1: a beam of charge Q, composed of 2 macroparticles located at $\pm\sigma_z$, with a tilt angle θ, passes through a dipole-mode RF cavity with frequency f and angular frequency $\omega=2\pi f$. If the cavity response is linear, then the particles will induce a voltage signals:

$$V_+(t) = -\frac{Q}{2}\theta\sigma_z \frac{d^2V}{dQdy}\sin\left(\omega\left(t+\sigma_z c\right)\right),$$

$$V_-(t) = -\frac{Q}{2}\theta\sigma_z \frac{d^2V}{dQdy}\sin\left(\omega\left(t-\sigma_z c\right)\right)$$

respectively. The sum of these signals is:

$$V(t) = -Q\frac{d^2V}{dQdy}\theta\frac{\omega\sigma_z^2}{c}\cos\omega t$$

where we have assumed that $\omega\sigma_z$<<1. Inspection of Equations 1 and 2 shows that the remaining voltage signal is 90 degrees out of phase with the signal from a rigid offset of the beam and is proportional to the beam tilt angle. The existence and behavior of this signal was experimentally verified in beam tests of a damped and detuned acclerating structure [2].

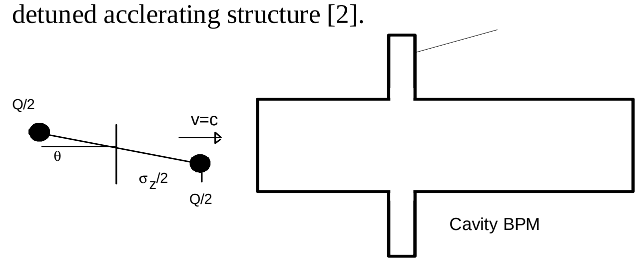

Figure 1:Schematic of tilted beam entering cavity BPM.

The peak voltage induced by a rigid offset is equal to $Q_y\, d^2V/dQdy$, while the peak voltage due to a tilted beam is equal to $Q\ \theta(\omega\sigma_z^2/c)\ d^2V/dQdy$. This indicates that, all other factors being equal, the performance of a cavity BPM as a tilt monitor improves with higher frequency and greater bunch length.

3 APPLICATION TO THE NEXT LINEAR COLLIDER MAIN LINAC

The Next Linear Collider (NLC) main linacs use approximately 11,000 RF structures to accelerate each beam from 8 GeV to 500 GeV, to achieve a center-of-mass energy of 1 TeV. The RF structures are interleaved with approximately 800 quadrupoles that are configured in a FODO array.

The NLC luminosity goals require a normalized vertical emittance at the IP of 40 nanometers, and the beam extracted from the main damping ring has a normalized emittance of 20 nanometers. Thus, the emittance growth budget for bunch compressors, linac, and beam delivery system is only 20 nm total. In the main linac, the principal sources of emittance dilution are transverse wakefields (from misaligned RF structures) and dispersion (from misaligned quadrupoles). All RF structure girders and quadrupoles in the main linacs are mounted on remote-controlled translation stages to permit alignment to the beam, but determination of the correct settings for these stages depends upon accurate and precise information from beam diagnostic devices.

By their very nature, transverse wakefields introduce a *yz* correlation when they cause vertical emittance dilution. In addition, the emittance dilution from quadrupole misalignments in the NLC main linac almost always introduces a similar *yz* correlation. This is because the linac RF is configured to produce less acceleration for the tail of the bunch than for the head, in order to produce BNS damping of the transverse wake [3]. The $z\delta$ correlation is almost total in the middle of the linac, and falls to approximately 70% at the end of the linac. Thus, when dispersive errors generate a $y\delta$ correlation in the beam, they also generate a *yz* correlation.

Consider a beam with a nominal beam size σ_0, a bunch length σ_z, and a pitch angle θ. The projected vertical beam size will be approximately $\sigma \sim \sigma_0(1+\theta^2\sigma_z^2/2\sigma_0^2)$. If we consider only points where β_y is a maximum (i.e., at the D quads), the nominal NLC beam size for 20 nm vertical emittance varies from 5.5 micrometers to 1.0 micrometers; the nominal RMS bunch length in the NLC main linac is 110 micrometers; thus, the pitch angle corresponding to 10% beam size growth thus varies from 4 milliradians to 22 milliradians.

Because the bunch length is so short in the main linac, the signal levels in the cavity BPM will be relatively small: a 1 milliradian beam pitch results in the same signal level as a 2.9 nm offset, assuming that the BPM's dipole-mode frequency is the canonical 11.424 GHz of the NLC. This implies that the cavity BPMs should have a resolution somewhat better than the prototype C-band (5.712 GHz) cavities demonstrated at the Final Focus Test Beam, which achieved a resolution of 25 nm for 0.6×10^9 bunch charge [4].

4 SIMULATION STUDIES OF TILT MONITOR TUNING ALGORITHMS

A simulation of main linac tuning was performed in which it was assumed that every BPM could be used as a beam tilt monitor with 1 mrad resolution. In this simulation, the algorithm sought to minimze the RMS tilt signal in the main linac by varying the settings of the quadrupole translation stages. In essence, the algorithm was quite similar to steering studies reported previously [5], except that the RMS beam tilt signal was used rather than the RMS beam offset reported by the BPMs. Also, the first 34 quads in the main linac were aligned using the beam position signals, since the $z\delta$ correlation required for optimal use of the tilt monitors is not established until this point in the lattice.

The tuning study showed that, for nominal NLC beam parameters, tilt monitors which operate as described above can limit vertical emittance growth to typical values of 4.2 nm.

In practice, achieving the desired beam tilt resolution in all of the NLC cavity BPMs may not be possible: detecting the signal from a 1 mrad beam pitch when it is combined with the signal from a 100 micrometer beam offset may require unreasonable dynamic range and phase stability of the processing system. An alternate approach is to install dedicated pitch monitors at a few discrete locations in the beamline. These dedicated pitch monitors can be mounted on remote controlled translation stages, in which case the offset of the montior to the beam can be kept to the level of a few micrometers.

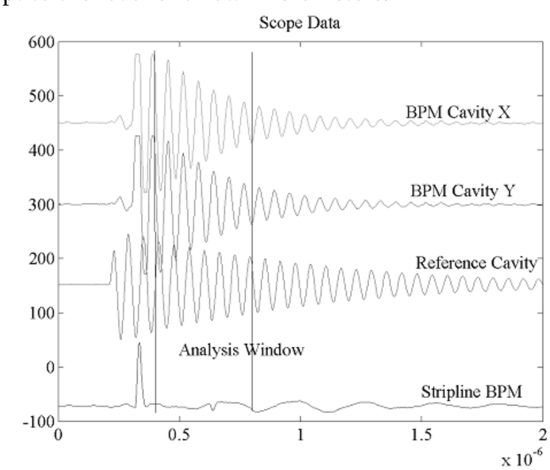

Figure 2: Mixed down (IF=16MHz) signals from the C-band reference and BPM cavities ATF.

If only a small number of pitch monitors are available, then the optimal technique for emittance control is to minimize the emittance first using a conventional, BPM-based technique such as dispersion free steering [6], and then to minimize the beam pitch signals using a limited set of global dispersion bumps. This is similar to the optimization technique used in the Stanford Linear Collider (SLC) [7], except that pitch monitors are used rather than wire scanners. A simulation of this technique indicates that an initial emittance growth of 20 nm can be reduced to about 7 nm through use of 6 sets of bumps and 12 pitch monitors. The use of pitch monitors for this procedure has two distinct advantages over the use of wire scanners. First, the pitch monitor gives a reading on every pulse, while a wire scanner requires 100 to 200 pulses to make a single measurement. Second, the amplitude and phase of the pitch monitor signal can be used to compute directly how large a dispersion bump is required, and whether the beam should be bumped upwards or downwards to minimize the pitch signal; the same optimization using a wire scanner requires that the bump be scanned through several values and an optimum value found.

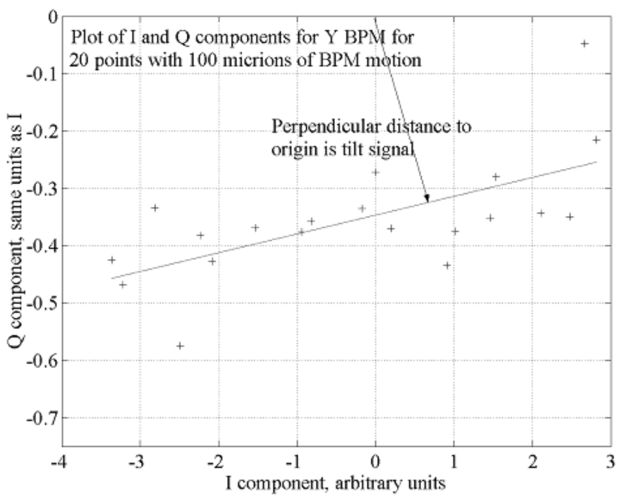

Figure 3: Cavity BPM signal for 20 pulses, separated into *I* and *Q* phases.

5 BEAM TESTS

The beam tests at the KEK ATF extraction line are intended to prove the practicality of a beam tilt monitor using the low emittance, relatively long bunch (σ_z=7mm), beam with external control of the beam tilt. To separate beam trajectory angles (or cavity pitch) and beam tilts, one of the extraction line C-band (6426 MHz) cavity BPMs was equipped with a remote controlled tilt plate support, in addition to its vertical and horizontal movers. The tilt plate controls the *yz* pitch of the cavity assembly. A separate phase reference cavity is used. Figure 2 shows the raw mixed down signals from the reference cavity and the *x* and *y* output of the cavity BPM. Since the relationship between the two cavities is arbitrary, it is not possible determine the tilt signal from this figure alone. Figure 3 shows the vertical cavity BPM signal for 20 beam pulses, separated into arbitrary in-phase (*I*) and out-of-phase (*Q*) components, while the cavity vertical mover is operated over a 100 micron range. Since the motion is known to be purely vertical, the phase of the tilt signal can be identified is the perpendicular signal of closest approach to the origin.

Figure 4 shows the calibration of the tilt signal as the *yz* pitch of the cavity is changed. The linear calibration fit residual is about 35 microradians. Using the scaling derived in section 2, and assuming that the response to a tilted trajectory and a tilted beam are of the same magnitude, this corresponds to an expected resolution of $\omega_A/\omega_N\ (\sigma_{zA}/\sigma_{zN})^2$ * 35 μrad = 13 mrad at NLC, where A and N are used to denote the parameters at ATF and NLC (f_N=11.424GHz and σ_{zN}=100μm) respectively. The resolution is somewhat larger than that used in the simulations described in section 5, but is adequate to prove the concept of the monitor.

Planned work includes an analysis of techniques to separate the beam angle and beam tilt signal and improvements to resolution.

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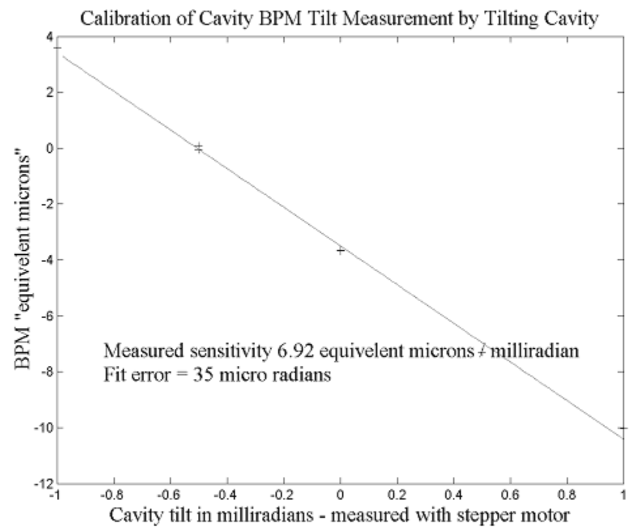

Figure 4: Tilt signal as a function of cavity pitch mover. There are 6 points in the plot.

7 REFERENCES

[1] K. Kubo et.al, Phys. Rev. Lett. **88**, 19 (2002).

[2] C. Adolphsen et al, “Wakefield and Beam Centering Measurements of a Damped and Detuned X-Band Accelerator Structure”, Proceedings *PAC-99*.

[3] V.E. Balakin, A.V. Novokhatsky, V.P. Smirnov, “VLEPP: Transverse Beam Dynamics" (1983).

[4] T. Slaton, G. Mazaheri, T. Shintake, “Development of Nanometer Resolution C-Band Radio Frequency Beam Position Monitors in the Final Focus Test Beam”, Proceedings *Linac-98* (1998).

[5] P. Tenenbaum *et.al.*, “Simulation Studies of Main Linac Steering in the Next Linear Collider,” *Proceeedings PAC-99*.

[6] T. Raubenheimer, R.D. Ruth, “A Dispersion Free Trajectory Correction Technique for Linear Colliders," NIM, **A302**:191(1991).

[7] J.T. Seeman, F.-J. Decker, I. Hsu, “The Introduction of Trajectory Oscillations to Reduce Emittance Growth in the SLC Linac”, Proceedings *HEACC-92* (1992).