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A Beam Timing Monitor for the SLC Final Focus*

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A BEAM-TIMING MONITOR FOR THE SLC FINAL FOCUS*

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Abstract

The relative timing of electron and positron bunches at the SLC interaction point (IP) is affected by phase and energy fluctuations in various upstream systems. By shifting the collision point, IP timing variation may degrade the luminosity and hinder IP spot-size tuning. To monitor the timing stability, in 1997 a novel rf monitor was installed in the South Final Focus, which measures the relative arrival time of the two bunches on every beam pulse. The monitor is based on narrow-band filtering of the beam-induced signal from a common pickup, delay of the first beam waveform into coincidence with the second, and homodyne mixing.

1 INTRODUCTION

In this note we describe an apparatus for monitoring the relative timing of the two colliding electron and positron bunches in the Stanford Linear Collider, by means of a phase-measurement on microwave signals induced by the two beams on a common pickup, about 50 m from the interaction point. As each beam passes through the pickup it radiates into a waveguide. The relative phase between the two electromagnetic pulses travelling down the waveguide is sensitive to changes in the time delay between the arrival of the first beam (e^+) and the second beam (e^-) at the pickup. The pickup is located in the South Final Focus of the SLC. Since the momentum compaction between the monitor location and the interaction point is negligibly small, jitter in the observed time delay is a direct measure of the jitter in the collision point.

Hitherto, beam timing at the IP was not monitored at all. Yet it is a critical factor for IP spot-size tuning, spot-size stability and the luminosity. If the collision point shifts in time, it will no longer coincide with the beam waists. A shift by an amount β^* will cause a factor of two reduction in luminosity. The present values of the beta functions are of the order $\beta_x^* \approx$ 2.2–2.9 mm and $\beta_y^* \approx$ 1.4–1.7 mm, the length-equivalents of 5–10 degree at S-Band (2856 MHz). Phase shifts of this order are not necessarily recognized, since the beam energy is held constant by dedicated feedback loops. To maintain the optimum energy spread at the end of the SLAC linac, it is necessary to vary the injection time by about 3 degree S-Band diurnally. Fortunately, timing changes on such long time scales, even if they are different for both beams, are not thought to be a problem, as the four waists (x and y for both beams) are scanned and corrected regularly. However, changes on shorter time scales—such as pulse-to-pulse variation ('jitter') or drifts over a few minutes—would be uncorrectable and could seriously degrade the average luminosity.

In the SLC, there are many potential sources of IP timing drifts and timing jitter: (1) changes of the extraction time from the damping rings, (2) variation of the bunch-compressor rf phase relative to the damping-ring phase, and (3) beam energy and profile fluctuations in the linac:

A beam-timing monitor with a resolution of 20° X-Band (5° S-Band), could detect timing errors corresponding to a 10% luminosity reduction. Preliminary measurements suggest that, in fact, our monitor achieves a much better resolution, at the level of 5° X-Band, over relevant time scales.

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2 APPARATUS

Previous reports describe the SLC Fouth Final Focus bunch length monitor (BLM) assembly and BLM signal analysis, *e.g.*, Ref. [1]. The setup for the beam timing monitor (BTM) is illustrated in Fig. 1.

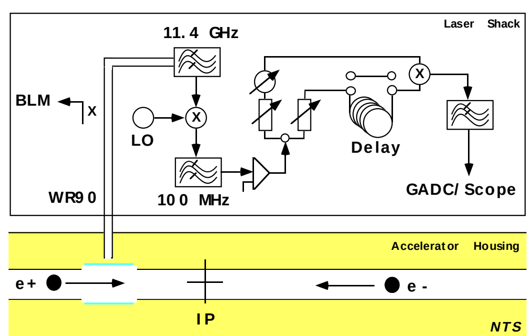

Figure 1: Schematic of BTM signal processing.

The first bandpass filter has center at 11.39 GHz, with full width of ±50 MHz. The LO is an HP8350B synthesizing signal generator, set to 11.49 GHz. Its stability, as measured with a frequency counter, is about ± 0.1 MHz, after thermal insulation. The output of the W-J M85C mixer is passed through a 5% bandwidth filter tuned to 100 MHz. The filtered IF signal is then passed through a Qbit-258 47dB amplifier (2.4 db NF), and a benchtop amplifier

(HP8447E, 27 dB gain, 11 dB NF). The signal is then split with a tee. One arm passes through a trombone phase-shifter permitting a full phase shift of 20° with a 0.002° dial indicator. The second arm is delayed. The delay cable consists of 38 meters of 3/8" Heliax cable, providing a delay of 194 ns. The arms of the tee are passed through variable attenuators and combined in a Minicircuits ZAD-6 mixer. The final IF output is then low-pass filtered with a Minicircuits BLP-21.4, and can be viewed on a scope, acquired with Labview, or passed to a LeCroy 2249A gated analog to digital converter for acquisition by the SLC control system.

3 SIMPLIFIED SIGNAL ANALYSIS

Let us analyze the signal as it proceeds through this circuit. In a first approximation, the voltage phasor at the output of the first filter is

$$\begin{aligned} V_A(t) &\approx \tilde{V}_1 e^{(j\omega_1-\nu_1)(t-T_1)} H(t-T_1) \\ &+ \tilde{V}_2 e^{(j\omega_1-\nu_1)(t-T_2)} H(t-T_2) \end{aligned} \quad (1)$$

with $\tilde{V}_k$ the voltage waveform induced by the k-th bunch, arriving at time T_k, and $k = 1, 2$ for e^+ and e^-. We neglect the geometrical asymmetry in our pickup (assuming beam centroid jitter is small compared to the 1" pipe diameter) and take $\tilde{V}_k = Q_k$, with Q_k the charge of bunch no. k, discarding a coupling factor that we may restore later for checks of signals levels. We are also discarding a form factor (due to the finite bunch length) as this is a small correction for a 1 mm rms bunch length at X-Band.

In this approximate expression for the phasor at the output of the first filter, the first filter is treated as a single-pole filter with center angular frequency ω_1 and half-width at half-maximum ν_1. The step-function is H. This expression is just what one gets with a shock excitation of a harmonic oscillator, and neglects the finite width (due to waveguide dispersion) of the incident waveform compared to the damping time of the oscillator. This is a crude approximation, but provides results consistent with a more refined numerical analysis. Next, with the LO waveform taking the form $V_L(t) = \tilde{V}_L e^{j\omega_L t}$ at the output of the mixer we have components that will subsequently be filtered out, and a phasor of the form

$$\begin{aligned} V_B(t) &\approx V_A(t) V_L^*(t) \\ &\approx \tilde{V}_1 \tilde{V}_L^* e^{-j\omega_L T_1} e^{(j\omega_1-\nu_1)(t-T_1)} H(t-T_1) \\ &+ \tilde{V}_2 \tilde{V}_L^* e^{-j\omega_L T_2} e^{(j\omega_1-\nu_1)(t-T_2)} H(t-T_1) \end{aligned} \quad (2)$$

where we have linearized in V_L for the sake of brevity. The intermediate frequency is $\omega_{IF} = (\omega_1 - \omega_L)$. At the output of the second filter we have the phasor

$$V_C = V_{C1} + V_{C2} \quad (3)$$

where $V_{Ck}(t) \equiv \tilde{T} \tilde{V}_k \tilde{V}_L^* e^{-j\omega_L T_k} e^{(j\omega_{IF}-\nu_2)(t-T_k)} H(t-T_k)$ with $k = 1, 2$ and, in a single-pole approximation, $\tilde{T} = \cos\Psi \exp(j\Psi)$ with $\Psi = \arctan(Q(\omega_{IF}/\omega_2 - \omega_2/\omega_{IF})$ and $Q = 2\omega_2/\nu_2$.

Next we split the signal with a 3 dB hybrid, and consider the signal in each arm. Up to an overall factor at the output of the undelayed arm we have $V_{D1}(t) = V_C(t)e^{j\phi}$ where we allow for an insertable, adjustable phase shift ϕ, and at the output of the second arm we have $V_{D2}(t) = V_C(t - T_D)$. The down-mixed output of the second mixer is, after low-pass filtering, $V_E(t) = V_{D2}(t) V_{D1}^*(t)$. The signal, as it would appear on a scope, is then $V_s(t) = \mathrm{Re} V_E(t)$, and the counts registered in a gated analog-to-digital converter are then $\int_{T_{trig}}^{T_{trig}+T_{gate}} dt\, V_S(t)$ + pedestal, up to an overall constant. The trigger time is T_{trig} and the gate width T_{gate} is 50 ns.

Let us consider explicitly the limit in which the decay time of the output from the first filter is much less than the delay $(T_2 - T_1) \approx 200$ ns between the two bunches. We are considering then the time-interval where the undelayed signal from the second bunch, $V_{D1}(t) = V_{C2}(t)e^{j\phi}$ overlaps the delayed signal of the first bunch, $V_{D2}(t) = V_{C1}(t - T_D)$. The mixer output is then determined from $V_E(t) = V_{C1}(t - T_D) V_{C2}^*(t) e^{-j\phi}$, or, abbreviating

$$\Delta T \equiv T_2 - T_1, \quad t' \equiv t - T_2 + \Delta T - T_D, \quad (4)$$

we can write

$$\begin{aligned} V_E(t) = |\tilde{T}|^2 |\tilde{V}_L|^2 \tilde{V}_1 \tilde{V}_2^* \times \\ e^{-j\phi - j\omega_{IF} T_D} e^{j(\omega_L+\omega_{IF})\Delta T} e^{-\nu_2(2t'-\Delta T)} \end{aligned} \quad (5)$$

The scope waveform then takes the form

$$\begin{aligned} V_s(t) \approx \left\{ |\tilde{V}_L|^2 \cos^2\Psi \right\} Q_1 Q_2 \times \\ e^{\nu_2 \Delta T} \cos(\omega_1 \Delta T - \omega_{IF} T_D - \phi) e^{-2\nu_2 t'} \end{aligned} \quad (6)$$

Systematic features relating to LO drift in amplitude and frequency are quantified in the bracketed term. Notice that the delay cable should be phase stable to a small fraction of the intermediate-frequency wavelength. Notice too that one is interested in looking at timing jitter much smaller than the natural decrement time associated with the second filter. Let us define relative beam phase as

$$\theta \equiv \omega_1 \Delta T - \omega_{IF} T_D - \phi + \pi/2 \quad (7)$$

in terms of which the signal is expressed as

$$V_s(t) \approx k Q_1 Q_2 \sin\theta \qquad \text{with} \qquad k = |V_L|^2 \cos^2\Psi \quad (8)$$

Whatever the nominal beam delay $(T_2 - T_1)$ may be, one may adjust ϕ to put the scope signal at a null. In practice this also requires a choice of gate position. In this case, maximum sensitivity is attained and the nominal relative beam phase is 0. For small variations in relative beam phase, one has

$$V_s(t) \approx k Q_1 Q_2 \theta \quad (9)$$

Small jitter in relative beam timing then correlates linearly with $V_s/(Q_1 Q_2)$. Conversely this normalized signal should correlate linearly with small changes in phase-ramp, or energy setpoint.

A refined numerical model of the signal waveforms has also been developed, taking into account the filter characteristics as measured with the network analyzer, and the numerically computed waveforms incident on the first filter (including the dispersion characteristics of the waveguide). As an example, Fig. 2 shows the delayed and undelayed intermediate-frequency signals prior to the second mixer, obtained from this model.

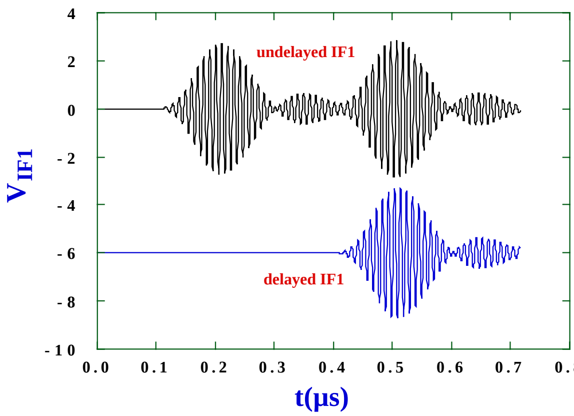

Figure 2: Computed IF signals prior to the second mixer.

4 CALIBRATION AND FIRST RESULTS

The raw signal is normalized by first subtracting the pedestal and then dividing by the product of the e^+ and e^- intensities (particles per bunch in units of 10^{10}). Typically, a change of the normalized signal by 1 unit corresponds to a timing change of 4 degree X-band or 1 degree S-band (about 300 μm). This is illustrated by the two calibration curves in Fig. 3 showing the BTM signal as a function of the delay time (in units of degree X-band) in one of the two arms, which was varied using the phase trombone. The first picture is an autophase measurement (one beam only, delay cable removed); the second is an actual two-beam measurement (with delay cable). The fitted slope can be used to convert a measured signal change into degree X-band (or time). The much larger scattering of the data in the two-beam measurement (right picture) appears to represent real beam-timing jitter, as large as 14° X-band peak to peak.

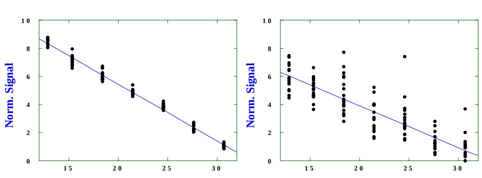

Figure 3: Calibration measurements: normalized timing-monitor signal versus the trombone phase difference in degree X-band; (left) signal for one beam with cable delay removed; (right) signal for two beams including cable delay.

Figure 4 shows the BTM signal as a function of the electron energy at the end of the linac, varied using the `FB31' energy feedback setpoint. From this measurement and from the phase calibration performed at the same time, we can estimate the R_{56} of the SLC North arc as $R_{56} \approx 120$ mm, which agrees to within 20% with the theoretical value (145 mm).

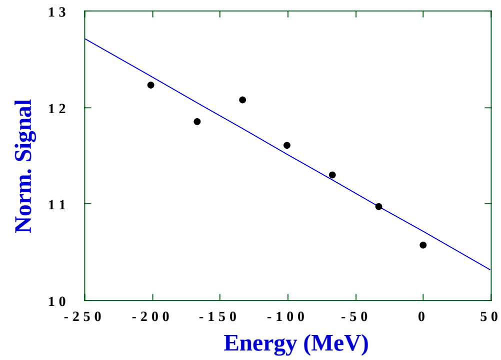

Figure 4: BTM signal versus e^- linac energy; the slope is proportional to the momentum compaction factor (R_{56}) of the North arc and agrees within 20% with the predicted value.

5 CONCLUSION AND OUTLOOK

Since fall 1997, an rf-based beam-timing monitor has become available for monitoring changes in the relative arrival time of electron and positron bunches at the SLC interaction point, with a short-term resolution better than $5°$ X-band. For a more precise calibration of this instrument and also for studying the phase-jitter propagation from the damping rings to the IP, we intend to measure the sensitivity of the collision timing signal to different controlled perturbations, in particular, its response to changes in the linac energy, the linac injection time, and the two bunch-compressor phases.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] F. Zimmermann, G. Yocky, D.H. Whittum, D. McCormick, C.K. Ng, P. Raimondi, M. Seidel, "An RF Bunch-Length Monitor for the SLC Final Focus", Proc. of the 17th IEEE Particle Accelerator Conference (PAC 97), Vancouver, Canada, 12–17 May, 1997, and SLAC-PUB-7456 (1997).