In this note we set down the concept for a beam timing monitor, making parasitic use of the bunch length monitor network installed above the SLC south final focus prior to the ’97 run. Analysis of the signal processing is provided, with an assessment of systematic sources of error. Preliminary tests have begun and will be reported elsewhere.

Motivation

In this note we describe an apparatus for monitoring the relative timing of the SLC’s two production bunches, by means of a phase-measurement on microwave signals induced by the two beams on a common pickup, 150’ 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. Since the pickup is located in the south final focus of the SLC, after the arcs, jitter in this time delay is a direct measure of the jitter in the collision point.

The interest in such a beam timing monitor arises from the concern that beam timing at the IP is not monitored on a shot-to-shot basis, nor over time-scales of minutes to hours. Yet it is a critical factor for IP spot-size tuning, and in determining luminosity. In practice, phase-ramp knobs are adjusted based on energy “stripes” in the beam switchyard (after the exit of the linac proper), and in this way, the phase of each beam in the linac is adjusted to account for all other contributors to energy spread in an empirical fashion: beam-induced longitudinal wakefields (dependent on the charge and bunch length, with cross-talk from e⁺ to e⁻ in the fundamental mode of the structures), compressor phase-errors, collimator wakefields with jaw settings as is, linac phase-profile as is.

Each of these effects is in principle time-dependent as phases wander, collimator jaws are moved, charge jitters and drifts, bunch length may in principle jitter and drift, and phase-ramp itself may in principle drift. [quantify best estimates in each case]. After phase-ramp adjustment, operators scan the waist at the IP in order to locate the adjusted collision point, and set the waist at this collision point. In the hours following, and prior to the next waist scan, beam timing may in principle change, causing the collision point to drift away from the waist. Drift by an amount \( \beta \), will cause a factor of two reduction in luminosity. This corresponds to 4 mm, or 13 ps, the equivalent of 13 S-Band degrees. Drift by 1.3 mm will cause a 10% reduction in luminosity and this corresponds to 4 S-Band degrees. The collision point may also fluctuate from pulse-to-pulse (e.g., due to time-slot). This would be undetectable and could seriously impede the optimal tuning of the IP spot-size. The BTM apparatus we describe here is intended to provide a reliable relative measure of the timing of the two beams, by means of a phase-measurement at X-Band. If we can achieve resolution of 20° X-Band (5° S-Band) we can observe timing errors corresponding to a 10% luminosity reduction. This does not mean we can fix such errors, but it is a first step to be able to diagnose them. We are aiming for resolution at the level of 5° X-Band.

An additional effect arises from \( R_{56} \) in the arcs, of order 150 mm, combined with motion in the beam center energy. While this is less of an operational concern, given the efficacy of the energy feedbacks, it is, for our purposes a useful effect. The implication is that a 100 MeV energy change (\( \delta = 2 \times 10^{-3} \)) in one beam will move the collision point by

\[
R_{56} \delta \approx 0.3 \text{ mm} = 1^\circ \text{ S-Band} = 4^\circ \text{ X-Band}.
\]

This provides us with two separate means of testing a beam timing monitor: adjustment of phase-
ramp, and adjustment of the energy feedback setpoint.

**Apparatus**

Previous reports describe the SLC south final focus bunch length monitor (BLM) assembly and BLM signal analysis. The setup for beam timing monitor (BTM) is illustrated in Fig. 1.

The first bandpass filter has center at 11.39 GHz, with full width of ±50 MHz. The LO is an HP8684D frequency and amplitude adjustable synthesizing signal generator. The LO is set at a nominal 3.3 dBm and 11.49 GHz, and is stable to xx. The first mixer is a xx. The second filter is a Telonic Model No. 95-5-5ee bandpass filter (“Telonic #2” in the logbook), tunable over 63-125 MHz with a 5% bandwidth. It is adjusted to 100 MHz. The amplifier indicated in the schematic consists actually of two amplifiers. The first is a Qbit Model No. 258, operating at 15 V, with a nominal gain of 47 dB and a noise figure of 2.4 dB (nominal operating range 10-250 MHz). The second is an HP 8447E benchtop amplifier with nominal gain of 27 dB, and noise figure of xx dB (nominal operating range 0.1-1300 MHz). The tee is a xx. The adjustable attenuators are xx. The phase-shifter is a trombone permitting a full phase shift of xx, and a dial indicator with xx precision. The delay cable consists of xx feet of 3/8“ Heliax cable. The second mixer is a Minicircuits Model No. ZAD-6 (RF 0.003-100 MHz, IF DC-100 MHz), and the IF output is low-pass filtered with a Minicircuits BLP-21.4. This output can be viewed on a scope, acquired with Labview, or passed to a LeCroy 2249A gated analog to digital converter for acquisition to the

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Simplified Signal Analysis

Let us analyze the signal as it proceeds through this circuit. We first take the simplest, analytic approach. After that we may proceed to a more precise numerical model taking account of the filter characteristics as measured with the network analyzer, and the numerically computed waveforms incident on the first filter (taking account of the dispersion characteristics of the waveguide).

In the first approximation, the voltage phasor at the output of the first filter is

\[ V_A(t) = \tilde{V}_1 e^{(j\omega_1 - \nu_1)(t - T_1)} H(t - T_1) + \tilde{V}_2 e^{(j\omega_1 - \nu_1)(t - T_2)} H(t - T_2), \]

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 output 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 \#\( k \), 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 (indeed the smallness of this correction at X-Band is the motivation for looking at higher frequencies for the bunch length monitor).

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 \( \omega_1 \) and half-width at half-maximum \( \nu_1 \). 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 of the incident waveform compared to the damping time of the oscillator. This is not a great approximation, but will do for now.

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

\[ V_B(t) = V_A(t)V_L(t) = \tilde{V}_1 \tilde{V}_L e^{-j\omega_L T_1} e^{(j\omega_1 - \nu_1)(t - T_1)} H(t - T_1) + \tilde{V}_2 \tilde{V}_L e^{-j\omega_L T_2} e^{(j\omega_1 - \nu_1)(t - T_2)} H(t - T_2), \]

except that we are typically running the LO at or above 3 dBm, where the amplitude response of the mixer would require use of the \( I_1 \) Bessel function. We omit this detail for now, for simplicity, although it will enter in assessing the sensitivity of results to fluctuations in LO amplitude. The intermediate frequency is

\[ \omega_I = \omega_1 - \omega_L. \]

At the output of the second filter we have the phasor

\[ V_C(t) = \tilde{T}\tilde{V}_1 \tilde{V}_L e^{-j\omega_L T_1} e^{(j\omega_1 - \nu_2)(t - T_1)} H(t - T_1) + \tilde{T}\tilde{V}_2 \tilde{V}_L e^{-j\omega_L T_2} e^{(j\omega_1 - \nu_2)(t - T_2)} H(t - T_2), \]

where, in the single-pole approximation, discarding an amplitude factor, and neglecting mismatch, we have
\[
\tilde{T} = \frac{j\omega_1\omega_2/Q}{(\omega_1^2 - \omega_2^2) + j\omega_1\omega_2/Q} = \cos \psi e^{j\psi},
\]
where \( Q = 2\omega_2/\nu_2 \) and the tuning angle is given by
\[
\tan \psi = Q \left( \frac{\omega_1}{\omega_2} - \frac{\omega_2}{\omega_1} \right) \approx 2Q \left( \frac{\omega_1 - \omega_2}{\omega_1} \right).
\]

The center angular frequency of the second filter is \( \omega_2 \) and the half-width at half-maximum is \( \nu_2 \).

It will be helpful to express this phasor as \( V_c = V_{c1} + V_{c2} \), with
\[
V_{c1}(t) = T V_k V_L e^{-j\omega_k T_k} e^{(j\omega_2 - \nu_2)(t - T_k)} H(t - T_k).
\]

Next let us suppose that the amplifier in Fig. 1 is perfectly linear, noise free, with flat frequency response over the 15 MHz or so of interest. Then the output is simply
\[
V_D(t) = V_c(t),
\]
up to an overall factor.

Next we split the signal with a 3 dB hybrid, and consider the signal in each arm. At the output of the undelayed arm we have
\[
V_{D1}(t) = V_D(t)e^{j\phi},
\]
where we allow for an insertable, adjustable phase-shift \( \varphi \). At the output of the second arm we have
\[
V_{D2}(t) = V_D(t - T_D).
\]

It is not necessary here, but we may as well note that for our application, if we had an unknown constant phase-shift, we would be happy to set it to zero, accepting that phases later inferred are relative and not absolute. We are cavalier about this, as the absolute time-delay between the two beams is of no particular interest to us, insofar as it includes the transit time (2 ×) from the IP to the pickup. The absolute value of this transit time has no particular relevance to luminosity. Rather it is the deviation in timing relative to the IP waist-tuned condition that is of concern. As is, however, one could, with detailed measurements on the cable assembly, determine the absolute timing of the two beams at the pickup. We have no interest in pursuing this, but simply make a note of it. Insofar as the technique employs a common pickup and network, temperature drifts outside the laser shack are of no relevance to the measurement.

Let us next suppose that the signal amplitudes are sufficiently attenuated that the response of the second mixer is linear. The down-mixed output of the second mixer is, after low-pass filtering,
\[
V_E(t) = V_{D2}(t)V_{D1}^*(t) = V_D(t - T_D)V_D^*(t)e^{-j\phi}.
\]

The signal as it would appear on a scope is then
\[ V_s(t) = \Re V_E(t), \]

and the counts registered in a gated analog to digital convertor are then

\[ G = \int_{T_{\text{trig}}}^{T_{\text{trig}}+T_{\text{gate}}} dt V_s(t) + \text{pedestal}, \]

up to an overall constant corresponding to the product of the various discarded normalization factors, and a coefficient for the GADC. For the LeCroy 2249A this corresponds to $1/4$ pC per bit from 50 \( \Omega \). Pedestal might be 120 counts. The trigger time is \( T_{\text{trig}} \) and the gate width \( T_{\text{gate}} \) 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 \( T_2 - T_1 \) (300 ns) between the two bunches. We consider times \( t \) such that the second mixer output is non-zero. We are considering then the time-interval where the undelayed signal overlaps the delayed signal. The undelayed signal is then due to the second bunch (\( e^- \)) and is given by

\[ V_{D_1}(t) = V_C(t) e^{j\phi}, \]

while the delayed signal is due to the first bunch (\( e^+ \)) and is given by

\[ V_{D_2}(t) = V_C(t - T_D). \]

The mixer output is then determined from

\[ V_E(t) = V_{C_1}(t - T_D) V_{C_2}^*(t) e^{-j\phi} = \left\{ \bar{V}_1 \bar{V}_2 e^{-j\omega_L T_1} e^{i\omega_H v_2}(t-T_D-T_1) \right\} \left\{ \bar{V}_1 \bar{V}_2 e^{-j\omega_L T_2} e^{i\omega_H v_2}(t-T_2) \right\}^* e^{-j\phi}. \]

Simplifying this we have

\[ V_E(t) = |T_L|^2 |\bar{V}_2|^2 \bar{V}_1 \bar{V}_2^* e^{-j\phi} e^{i\omega_L(T_2-T_1)} e^{i\omega_H(T_2-T_D)} e^{-v_2(2t-T_D-T_2-T_1)}. \]

Let us abbreviate

\[ \Delta T = T_2 - T_1 - T_D, \quad t' = t - T_1 - T_D = t - T_2 + \Delta T, \]

so that

\[ V_E(t) = |T_L|^2 |\bar{V}_2|^2 \bar{V}_1 \bar{V}_2^* e^{-j\phi+2\omega_LT_D} e^{i(\omega_L+\omega_H)\Delta T} e^{-v_2(2t'-\Delta T)}. \]

By assumption, we have taken the cable delay \( T_D \) to be rather close to the absolute bunch delay \( T_2 - T_1 \), so the phase \( \omega_L \Delta T \) is small. We are encouraged then, to treat this term as a small constant and absorb it into the phase \( \phi \) (from which we seek to derive no absolute information anyway). For example, if the bunch timing should change by 10 ps, then this 100 MHz term contributes a phase-shift of 0.4°. Meanwhile, the X-Band term contributes a phase-shift of 40°.

The scope waveform then takes the form
Systematic features relating to LO drift in amplitude and frequency are quantified in the bracketed term. Notice that one wants the delay cable to be phase-stable to a small fraction of the high-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

\[ \theta = \omega_L \Delta T + \omega_1 T_D - \varphi + \frac{\pi}{2}. \]

In terms of relative beam phase

\[ V_s (t) \approx k Q_1 Q_2 \sin \theta, \]

where

\[ k = |\tilde{V}_L|^2 \cos^2 \psi. \]

Whatever the nominal beam delay \( T_2 - T_1 \) may be, one may adjust \( \varphi \) 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

\[ V_s (t) \approx k Q_1 Q_2 \theta. \]

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.

**Numerical Signal Analysis**

The foregoing analysis made a number of approximations that are easily removed with the help of a computer code.

[to be continued]

**Operational Features**

The following equipment must be turned on and set for the device to work. Amplifier power supply turned on and set to 15 V, checked by multimeter. Benchtop amplifier turned on. LO turned on, set to 11.49 GHz. Output of final mixer connected to Channel 4 of ARRY, FB69, 616 (i.e., the channel labelled “3” in the LeCroy 2249A in slot 16 of “the BLM crate”, in the Laser Shack). For the time-being, prior to studies involving real beam time (as opposed to parasitic jitter studies), a trombone calibration with two-beams present should be performed as mentioned below.

The apparatus requires either one or two beams reaching the IP. With one beam, and cable delay removed, one can study the phase of one beam with respect to itself. This should be a constant when pedestal and charge normalization are correctly accounted for, and for ideal components. Thus auto-phase measurement amounts to a check of the apparatus. One such study has been performed, with results as illustrated in Fig. 2.
With two beams to the IP, one can perform studies of the 2-beam phase-difference. Using the trombone, the phase-difference signal in units of counts may be compared to actual phase-difference in units of ° X-Band. This provides a check of the charge normalization, a calibration of the slope in meaningful units. Such a calibration assumes constant settings for relevant control variables: phase-ramp, and energy setpoint. Such a calibration, and inspection of scope waveforms, conducted at various intervals over days serves as a check of the long-term consistency of the apparatus. Several such studies have been performed with results as illustrated in Fig.3. Consistency is not yet established, however it appears that some knobs have been played with by anonymous BTM afficionados between studies, and we will continue to study the matter. (Relevant primarily for evaluation of the usefulness of history-buffered data, and for determination of the proper setup procedure for eventual routine use of the instrument.)

**FIGURE 2.** Example autophase measurement

**FIGURE 3.** Example beam phase jitter measurement.

**FIGURE 4.** Example beam phase jitter measurement while someone was tweaking the energy setpoint.

**Next Plans**
Request for dedicated beam time has been submitted. Intent is to study correlation of the BTM signal with $\phi_{\text{comp}}$, FB31 Energy, phasramp. First correlation with FB31 Energy has been demonstrated parasitically as shown in Fig.3. In the event of the most likely outcome, good correlations, an immediate recommendation will be to replace the signal generator currently being used as LO for one with better frequency stability.

**Appendix A: Waveforms**
For the record let us note some typical waveforms corresponding to the various voltage phasors mentioned in the analysis.

**FIGURE A1.** X-Band waveform prior to first filter.

**FIGURE A2.** X-Band waveform after first filter.

**FIGURE A3.** 100 MHz waveform after first mixer

**FIGURE A4.** 100 MHz waveform after amplifier

**FIGURE A5.** 100 MHz waveform after filter

**FIGURE A6.** 100 MHz waveform after amplifier

**FIGURE A7.** Low-pass filtered output of final mixer, autophase.

**FIGURE A8.** Low-pass filtered output of final mixer, one arm delayed.

**FIGURE A9.** Effect of trombone adjustment by, one arm delayed.

**FIGURE A10.** Good choice of gate position given waveforms as in Fig. A9.

**Appendix B: LeCroy 2249A**