SLAC–PUB–12631
July 2007

STRIPLINE TRANSVERSAL FILTER TECHNIQUES FOR SUB-PICOSECOND BUNCH TIMING MEASUREMENTS*

John D. Fox†,Themis Mastorides, Claudio Hector Rivetta and Daniel Van Winkle
Stanford Linear Accelerator Center, Stanford University,2575 Sand Hill Road, Menlo Park, CA 94025

Abstract

Measurement of time of arrival of a particle bunch is a fundamental beam diagnostic. The PEP-II/ALS/BESSY/PLS longitudinal feedback systems use a planar stripline circuit to convert a 30 ps beam BPM impulse signal into a 4 cycle tone burst at the 6th harmonic of the accelerator RF frequency (2.856 GHz). A phase-detection technique is used to measure the arrival time of these BPM impulses with 200 fs rms single-shot resolution (out of a 330 ps dynamic range). Scaled in frequency, this approach is directly applicable to FEL and other sub-ps regime pulse and timing measurements. The transversal circuit structure is applicable to measurement of microbunches or closely spaced bunches (the PEP-II/ALS/BESSY/PLS examples make independent measurements at 2 ns bunch spacing) and opens up some new diagnostic and control possibilities.

This paper reviews the principles of the technique, and uses data from PEP-II operations to predict the limits of performance of this measurement scheme for arrival phase measurement. These predictions are compared with results in the literature from electro-optic sub-picosecond beam timing and phasing diagnostics.

Presented at
DIPAC 2007
Venice,Italy
May 20-23 , 2007

*Work supported by Department of Energy contract DE–AC02–76SF00515
†jdfox@slac.stanford.edu

1 Introduction

The longitudinal feedback systems developed to control instabilities in high current factory colliders and light sources must measure the oscillation coordinate of every bunch in order to compute a correction signal. These oscillation displacements are measured relative to a master oscillator. For a 1 cm bunch stabilized to 2% of its' length, the system must sense the time of arrival of the bunch with better than 1 ps resolution and noise.

Instrument techniques to measure bunch longitudinal (time of arrival) coordinates are also of increasing interest for FEL diagnostics, recirculating LINAC applications, and time-resolved photon science experiments.

2 Instrument System

Signals from a button BPM are processed via a planar stripline circuit band-pass filter which has a $sin(x)/x$ frequency response (figure 1). The output signal is a band-limited tone burst of finite duration (here 4 cycles at 2856 MHz). For multi-bunch applications the finite time response allows an independent measurement 2 ns later of the subsequent bunch (a resonant filter would have to be very low-Q to completely decay in this short interval)[1].

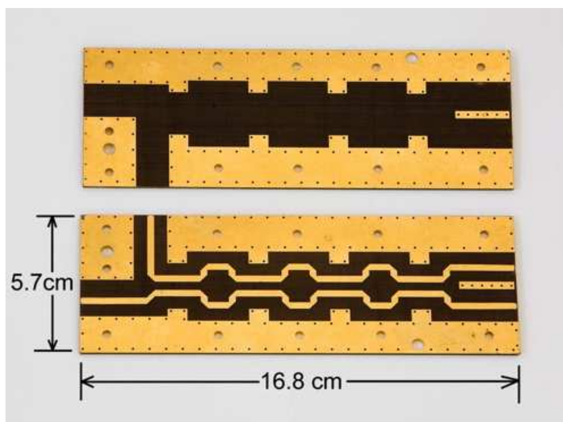

Figure 1: Photo of 4 cycle 2856 Mhz Comb Generator

This tone burst is phase detected against a phase-locked accelerator reference and the baseband phase information is digitized. The wideband processing is implemented with RF gain at the detection frequency and DC-coupled baseband gain after the phase detector. A baseband Bessel low pass filter defines a processing bandwidth (either 400 MHz or 800 MHz) [2]. The baseband detector voltage is of the form:

$V_{out} = kQ_bSin(\phi_{beam} - \phi_{ref}) + V_{offset}$ where k is a system specific gain factor, Q_b the charge in the sensed bucket, and $\phi_{beam} - \phi_{ref}$ is the phase difference of the bunch-derived tone burst and a reference oscillator.

The sensitivity scales directly with detection frequency and signal level (per bunch charge and the processing gain).

3 Beam Phase Detector Performance

We use operating feedback systems (ALS, DAΦNE E-, PEP-II LER and HER) to get a sense of the resolution and noise of the beam phase measurement via recordings of of the baseband phase signal [3]. We can then use offline tools to look at rms noise in the signals, and compute power spectra and other diagnostic measurements [4, 5]. The transient record is a two dimensional matrix of ADC samples, for each bucket a sequence of consecutive samples is recorded. The samples/bucket varies from 661 for the PEP-II systems (with 1740 controlled bunches) to 4031 for the DAΦNE systems (with 120 controlled bunches).

As the basic hardware at each installation is identical, we can see the impact of some of the dynamic range and gain selection trade-offs. In Table 1 the noise and beam measurements are computed in rms counts, where the rms values are first computed along the bunch sample axis (after removing the mean), then the bunch rms values are quadrature weighted along the turn axis resulting in a single weighted rms value.

Table 1: A/D RMS Noise at 4 installations (rms counts)

Parameter	**ALS**	**DAΦNE**	**HER**	**LER**
Terminated A/D	0.68	0.63	0.63	0.66
Receiver no Beam	0.74	0.96	0.81	0.82
Receiver no beam , no mixer LO			0.75	0.71
Controlled Beam	1.70	4.53	1.97	1.88
I for control study mA	131	890	1740	2700

The baseband channel noise includes contributions from Johnson noise in the pickups and terminations, noise in the RF processing amplifiers, noise mechanisms in the RF mixer, and noise in the baseband stages. There is also contribution from the phase noise of the local reference oscillator. Finally, the system has some spurious signals, some originating in the high-speed logic, which are detectable.

Table 1 shows the noise contribution of the fast sampler and quantizing noise in the A/D with terminated input. The multiple systems are similar, with noise of roughly 0.6 counts averaged over the full recording. This noise can be compared to a perfect quantizer of 0.29 rms counts ($1/\sqrt{12}$). Of greater importance is the measured noise in the systems with no beam, but with the full operating receiver channel. This measurement shows the contributions of the RF and baseband sources within the sampler bandwidth, and the various installations show noise levels in the range of 0.8 to 0.9 counts rms. This base noise floor is the limit we should use in estimating the performance of the measurement. We can understand the relative noise contributions from the baseband and RF signal paths in a measurement of the receiver with the LO power at zero in the mixer. For PEP-II the baseband path contributes roughly 0.1 count rms in quadrature.

Table 1 also shows operating machines with populated bunches. This increased rms level is the fluctuating beam motion plus oscillator phase noise within the sampler bandwidth. Using the calibration factors ‡ and typical bucket currents we can estimate the measurement noise floor in RF phase or time units (Table 2).

Table 2: Receiver Noise (rms counts) converted to Beam Phase resolution

Parameter	**ALS**	**DAΦNE**	**HER**	**LER**
Receiver no Beam	0.74	0.96	0.81	0.82
Current for estimate	400	890	2200	4000
I/bunch (mA)	1.22	9.9	1.3	2.3
C/bunch (C)	8E-10	3.2E-9	9.2E-9	1.6E-8
Calibration (counts/mA/deg@RF)	5.8		18.9	5.36
est. resolution (ps)	0.57		0.20	0.39

A power spectrum computed from the beam samples is insightful. Figure 2 presents PEP-II LER data at 2700 mA. The power spectrum shows considerable beam motion at 720 Hz and low frequencies which originate in the RF system klystron power supplies. Harmonics of this excitation are present on the beam from the modulation of the accelerating voltages in the RF cavities. In the narrow band near the 4.3 KHz synchrotron frequency we see that the beam spectral noise power drops to near the receiver noise due to the action of the coupled-bunch feedback system. What is happening is that the feedback loop reduces the fluctuations on the beam signal by $1/(1 + \textit{loop gain})$. The channel has high gain in the DSP filter (maximized at the synchrotron frequency) and the resonant response of the beam further increases the loop gain at the synchrotron frequency.

It is also possible to compute the amplitude of the beam signals as modal motion, where the motion of the individual bunches are transformed to a modal basis. As seen in figure 3, the data from the HER at 1700 mA is decomposed into even fill basis eigenmodes. This modal amplitude plot shows the motion at the synchrotron frequency, is very small at less than 0.005 degrees per eigenmode, and well below the individual sample noise floor.The largest motion is mode zero from noise in the RF system. Each individual bunch is still moving in a superposition of the contributions of each modal eigenmode.

One observation from this study is that the A/D converter resolution does not dominate this system noise floor, as the noise from the receiver channel is of the same order. If we require better resolution on the instantaneous beam samples we need to improve the receiver

‡these are found by modulating the phase reference through 2π at a low frequency and fitting a sinusoid to the response

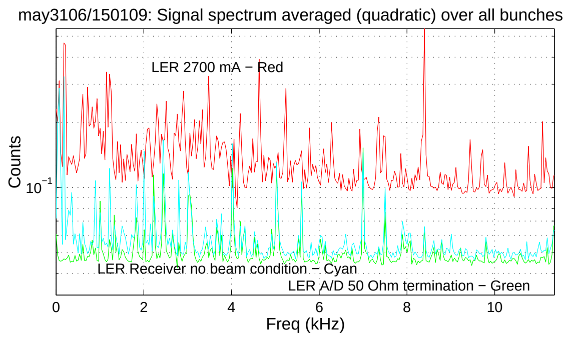

Figure 2: Power Spectrum of beam phase signal, showing noise floors and the controlled beam

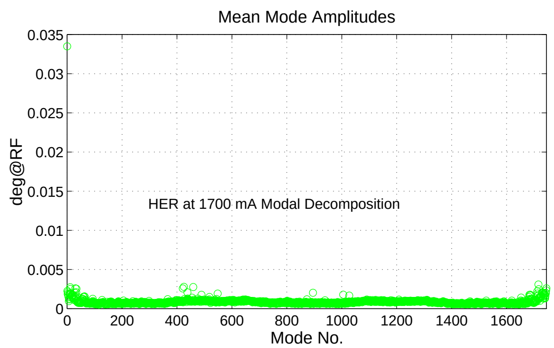

Figure 3: Modal plot of the HER at 1700 mA, showing the controlled noise floor is below 0.005 Degrees at 476 Mhz

noise figure before any improvement from additional resolution in the A/D converter could be significant. §

4 Summary and Scaling to Other Applications

It is interesting to estimate the limits of this bunch arrival technique. The most direct method to increase the sensitivity is to detect at a higher frequency, with a reduction in measurement range (the phase detector is periodic every 2π). For cm bunched beams there are significant signal components out to 30 GHz and higher. The pick-up electrodes would need clean response at this higher frequency. Similarly, these higher frequencies would likely propagate in a practical vacuum chamber, and if there are resonant structures or HOMs in the vacuum system it may not be feasible to operate at arbitrary detection frequencies. Another factor would be the implementation of the stripline comb generator, and at frequencies above 15 or 20 GHz it likely would have to be fabricated on a sapphire or alumina substrate. It may be helpful to place the comb generator inside the vacuum chamber to reduce the required

§ this is also true for the transverse feedback systems studied, as the noise in the transverse motion receiver is also greater than the quantizing noise in the A/D of the feedback channel

Table 3: Estimated RMS Resolution of 3 Measurement Channels - Scaled from 2200 mA PEP-II HER

Parameter	**3 GHz**	**10 GHz**	**30 GHz**
Channel Noise (rms)	0.8	0.8	0.8
Bunch Charge (C)	1E8	1E8	1E8
Estimated resolution	0.2 ps	0.06 ps	0.02 ps

feedthrough bandwidth.

The systems examined have noise floors which are set by the RF/Baseband receiver processing and have additonal contribution from the wideband samplers. The choice of detection frequency (operating frequency of the phase detector) is independent of this noise floor estimate for systems with similar processing bandwidths (e.g. the thermal noise in a 400 MHz band around 3 GHz would be the same as 400 MHz around 30 GHZ). The noise figure of the RF processing amplifier would not differ significantly. However, the phase noise component of the reference oscillator would likely be worse for similar technical implementation. Additionally, we would expect greater losses in a cable plant which would require increased RF gain.

Table 3 presents a speculative design of 10 and 30 GHz processing channels, with the same scaled noise contribution as from the 3 GHz implementation. Using the 2.2A PEP-II HER design current we estimate the single shot measurement resolution as 200 fs for the implemented system, scaling to 20 fs for the 30 GHz detection frequency . This is comparable to the electro-optic technique described by Loehl, et al in the literature.[6]

One interesting difference between this technique and electro-optical techniques is applicability to bunch train measurements. The comb generator technique allows independent measurements of closely spaced bunches. If a mode-locked laser is used to generate a short sampling pulse, the repetition rate of the laser may be a factor in design, or complexity, of a bunch train diagnostic (Loehl, et al used a 40 MHz sampling rate).

Both of these techniques are measuring the product of bunch current and time displacement. To make a general channel, which measures both quantities, a quadrature technique could be implemented, with the measurement of sine and cosine components. Subsequent processing would then offer both charge and displacement data.

5 Acknowledgements

We thank Dan Van Winkle for his comments and RF engineering expertise, and the cumulative efforts of Dmitry Teytelman and Shyam Prabhakar in the MATLAB analysis codes. Andrew Young contributed much of the phase detection channel. Allessandro Drago (LNF-INFN) and Greg Stover(LBL) contributed the measurements from DAΦNE and the ALS.

References

[1] Briggs, D., et al, ”Prompt Bunch by Bunch Synchrotron Oscillation Detection by a Fast Phase Measurement”, Proceedings of the IEEE Particle Accelerator Conference, 5/91, 1404-1406.

[2] A. Young, J. Fox, D. Teytelman “VXI based multibunch detector and QPSK modulator for the PEP-II / ALS / DAΦNE longitudinal feedback system.” (PAC 97)

[3] J. Fox, et al,“Multi-Bunch Instability Diagnostics via Digital Feedback Systems at PEP-II, DAΦNE, ALS and SPEAR”, Proc. IEEE Particle Accelerator Conference, 1999.

[4] D. Teytelman et al, “Accelerator diagnostic techniques using time domain data from a bunch-by-bunch longitudinal feedback system.” Presented at 3rd European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 97), Frascati, Italy, 12-14 Oct 1997.

[5] D. Teytelman et al, “Beam diagnostics based on time-domain bunch-by-bunch data.” Presented at 8th Beam Instrumentation Workshop (BIW 98), Stanford, California, 4-7 May 1998.

[6] F. Loehl, K.E. Hacker, F. Ludwig, H. Schlarb, B. Schmidt A. Winter, ‘’ A Sub 100 fs Electron Bunch Arrival-time Monitor System for FLASH”, EPAC 2006 Proceedings pp.2781 - 2783