DEVELOPMENT OF A TURN-BY-TURN BEAM POSITION MONITORING SYSTEM FOR MULTIPLE BUNCH OPERATION OF THE ATF DAMPING RING

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Abstract

An FPGA-based monitoring system has been developed to study multi-bunch beam instabilities in the damping ring (DR) of the KEK Accelerator Test Facility (ATF). The system utilises a stripline beam position monitor (BPM) and single-stage down-mixing BPM processor. The system is designed to record the horizontal and/or vertical positions of up to three bunches in the DR with c. 150ns bunch spacing, or the head bunch of up to three trains in a multi-bunch mode with a bunch spacing of 5.6 ns. The FPGA firmware and data acquisition software allow the recording of turn-by-turn data. An overview of the system and performance results will be presented.

INTRODUCTION

The next generation of high energy linear lepton colliders, such as the International Linear Collider (ILC) [1] and the Compact Linear Collider [2], will require ultra-stable low-emittance multi-bunch beams to be preserved up to the Interaction Point. The KEK Accelerator Test Facility (ATF) [3], was originally constructed to demonstrate the generation of ultra-low emittance beams in the Damping Ring (DR). The ATF consists of a 1.3 GeV S-band linac, a 138 m circumference damping ring, and extraction line. Up to three trains can be injected into the DR at any time, with up to ten bunches per train at 5.6 ns bunch spacing.

A monitoring system has been developed for multi-bunch operation of the ATF DR, using an available stripline beam position monitor (BPM) in the DR, and BPM processing and digitisation hardware originally designed for the upstream feedback system in the extraction line [4]. The original motivation was to study multi-bunch instabilities, associated with beam-size blow-up in the DR, especially in the context of the fast extraction kicker studies for the ILC [5] where up to 30 bunches could be damped together and extracted individually. The system has the ability to monitor up to three bunches in the DR on a turn-by-turn basis in multi-train single-bunch mode, or the leading bunch of each train in multi-bunch mode. The existing ATF DR turn-by-turn BPM system [6], based on 96 button-style BPMs, is not capable of bunch-by-bunch measurement within a given turn. The bunch-by-bunch monitoring system was installed at the ATF and demonstrated in November and December 2010, and the design and initial tests were presented in [7, 8].

The system was recently used at ATF, in November 2011, to study the limitations of the down-mixing BPM processing scheme, for example stability of the clocks and timing signals used in the processing with respect to the bunch, making use of the turn-by-turn capability of the system. These studies demonstrated the effect of longitudinal bunch dynamics on the apparent BPM resolution. An overview of the key design parameters, system performance and the results from the recent measurements is presented in the following sections.

SYSTEM OVERVIEW

Hardware

The hardware for the turn-by-turn system consists of a stripline BPM in the ATF DR (pairs of pickoffs in the horizontal and vertical plane are used), and a front-end analogue BPM processor and FPGA-based digital signal processor, both of which were designed for use in the upstream position and angle feedback system in the ATF extraction line.

One BPM processor is used for each transverse plane; the function being to convert the high frequency stripline impulse signals to baseband ($<$100 MHz). This produces a sum signal, proportional to beam intensity, and a difference signal, proportional to beam position and intensity, from the two opposing strips. These signals are then band-pass filtered and mixed with a 714 MHz local oscillator (LO) phase-locked to the beam, and finally low-pass filtered to remove the high frequency component of the mixer output.

The digital processor centres around a Xilinx Virtex-5 FPGA, clocked with both an external source of 357 MHz, synchronised to the ATF master oscillator, for high speed logic including timing and synchronisation, and a 40 MHz from an on-board crystal oscillator for slower ancillary logic. High speed Analog Devices ADCs, also clocked at 357 MHz, digitise up to 9 channels of sum and difference signals from the front-end processors.

Firmware and Data Acquisition

Table 1 shows the key system design parameters. The FPGA firmware and DAQ software were based on that developed for the beam-based feedback system in the ATF extraction line [4]. To maximise the number of turns recorded

Table 1: DR Turn-by-Turn Monitor Design Parameters

System clock speed	357 MHz
Sampling resolution	14-bit
Max no. channels	6
Max no. samples per channel per turn	3
Max no. of turns collected	131071

for turn-by-turn acquisition, it was decided to record only the peak value for each bunch and reduce the maximum number of channels recorded to six (allowing for horizontal and vertical position from a maximum of two BPMs in the DR.) Samples from each required channel are interleaved in a single large first-in, first-out (FIFO) memory allowing a total of 131071 14-bit samples to be recorded per cycle.

The sampling logic is run at 357 MHz, but the bulk turn-by-turn data acquisition and transmission logic is run at 40 MHz. A 2.16 MHz signal, synchronised to the DR revolution period, is generated from a counter running on the 357 MHz and is used as a turn counter. The turn counter allows for the acquisition of n turns in every m in order to increase the range of the time window across the damping cycle, whilst retaining the flexibility to record batches of consecutive turns within the window.

RECENT RESULTS

System Performance

Without any additional attenuation, the dynamic range of the measurement system is $\sim \pm 500\mu$m for bunch intensities of ∼0.5 x $10^{10}e^-$. However, the system can work with large mean position offsets in the DR, without having to sacrifice resolution for dynamic range, by adding attenuation asymmetrically to the stripline signals before subtraction. To allow for varying this attenuation, the BPM processors and digitiser were located outside of the DR enclosure, and the stripline signals were brought out on 40 m long cables. Fixed attenuation, initially of 8 dB, was also added to the BPM pickoffs in-tunnel to reduce reflections from the cables passing back to the striplines. With 8 dB attenuation in-tunnel and no additional attenuation at the processor the measurement noise of ∼1.4 ADC counts corresponds to a minimum resolution of ∼1.3 μm on the position measurements. The measurement noise is estimated from the measured spread of the sum signal over several thousand turns.

The system was used in November 2011 for studying the stability of the 714 MHz local oscillator signal, derived from the damping ring RF, with respect to the bunch. For this purpose, just the in-phase and residual quadrature-phase sum signals, from the vertical pickoffs, were measured. The BPM processor is nominally phased such that the in-phase sum signal (Σ_I) is maximised and the quadrature-phase (Σ_Q) is minimised, and the nominal phase is given by $\phi = \Sigma_Q/\Sigma_I$ for small values of the phase, ϕ. For this study additional attenuation was unnecessary and the in-tunnel attenuation was also removed to maximise sensitivity to phase variations, with the measurement noise corresponding to a phase resolution of less than 0.1 degrees.

Bunch Phase Measurements with Respect to LO

Fig. 1 shows phase variations over the last c. 12000 consecutive turns before extraction for three bunch operation of the DR, with a bunch spacing of 154 ns. The three bunches are each single-bunch trains injected into the DR on subsequent machine pulses. Several frequencies are present in the data; an FFT is shown in Fig. 2. The most prominent peak at 10.8 kHz can be identified as the synchrotron frequency, arising due to the longitudinal motion of the bunch with respect to the machine RF. Two other main features are a slowly varying component at around 434 Hz and a high frequency oscillation at 735 kHz, although this frequency is approaching the Nyquist limit for the system and so may be aliased down from an even higher frequency. The origins of these two frequencies are unknown. To separate out the three components, three different software filters were applied: a band-pass filter, with pass-band 5–15 kHz; a 5 kHz low-pass filter; and a 15 kHz high pass filter. Fig. 3 shows the raw data (red) and band-pass filtered data (blue) for bunch 1. Variation in the amplitude of the synchrotron oscillation can be seen in this example. This behaviour had been observed previously in the ATF DR and attempts made to mitigate against it [9, 10].

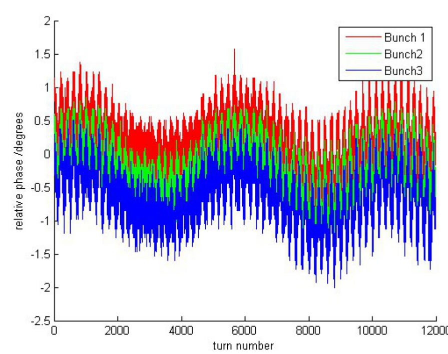

Figure 1: Bunch phase with respect to the LO, for the last c. 12000 turns before extraction for three bunches separated by 154 ns.

Figure 4 shows the last ∼200 turns for the band-pass filtered data for bunch 1 for 43 pulses recorded in short succession, although not consecutively. The time for the system to transmit the turn-by-turn data and be ready for subsequent operation is around 6 seconds, corresponding to every third extracted pulse in three-train mode. The figure illustrates that the synchrotron oscillation is occurring with a random phase at extraction. This will manifest as an additional source of jitter in the stripline BPMs in the extraction line. The different BPMs exhibit differing sensitivity to phase jitter, and so the synchrotron motion of the bunch will appear as position jitter and hence degrade the apparent position resolution. Fortunately this effect can

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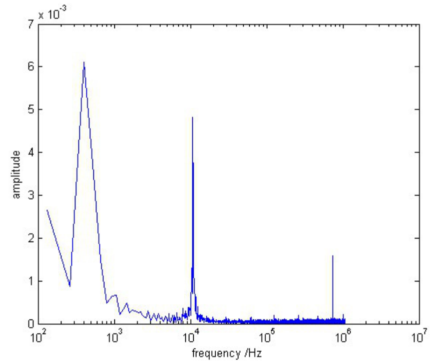

Figure 2: Fourier transform of the relative phase of bunch 1. Bunches 2 and 3 show very similar behaviour.

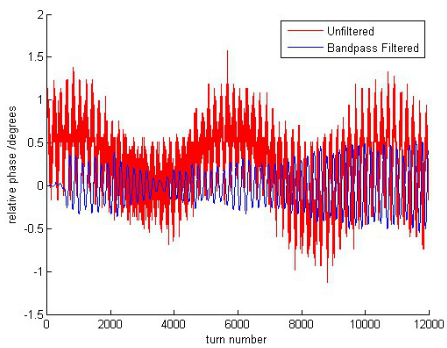

Figure 3: Comparison of unfiltered (red) and band-pass filtered (blue) data for bunch 1. The bursting nature of the synchrotron oscillation can be seen clearly in the filtered data.

be removed, both in the BPM processor offline data analysis, and online in the feedback calculation, see [11]. The bunch-to-bunch correlation is, however, very high at extraction and, in general, the bunches all oscillate together. Table 2 gives the contributions of the three principal components to the total observed jitter in bunch phase with respect to the LO. Larger variation is seen with the band-pass filtered data, due to the bursting nature of the synchrotron oscillation, where some pulses appear to have little phase jitter at 10.8 kHz whereas for others this frequency dominates.

Table 2: Mean Contribution to the Total Phase Jitter for Three Principal Components, over 43 Pulses

Total jitter		$0.34° \pm 0.07°$
Band-pass	10.8 kHz	$0.25° \pm 0.09°$
Low-pass	434 Hz	$0.14° \pm 0.04°$
High-pass	735 kHz	$0.18° \pm 0.01°$

CONCLUSIONS

A measurement system has been developed and deployed in the ATF damping ring for multi-bunch, multi-turn beam position monitoring. The system has a position resolution of around 1 micron, and a phase resolution of below 0.1 degrees, depending on the level of attenuation required to keep large offsets within the measurement range of the system. It was used in November 2011 to investigate the performance limitations of the down-mix stripline BPM processors used for the beam-based feedback system in the ATF extraction line. This study identified several frequencies in the spectrum of the bunch phase with respect to the local oscillator, including the synchrotron oscillation at 10.8 KHz, and contributed to the understanding of the effects of the longitudinal bunch motion on the apparent BPM resolution as measured in the extraction line.

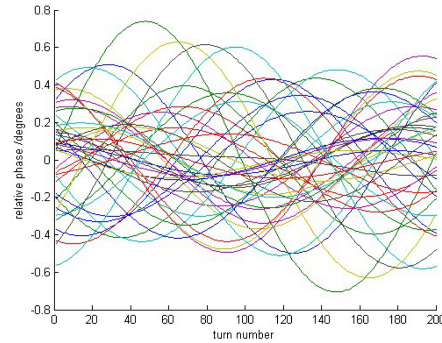

Figure 4: Last 200 turns (one synchrotron period) before extraction for band-pass filtered data for bunch 1. Data for 43 successive pulses is overlaid, showing that the phase of the bunch at extraction is random.

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