POSITION DETERMINATION OF CLOSELY SPACED BUNCHES USING CAVITY BPMs*

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Abstract

Radio Frequency (RF) Cavity Beam Position Monitor (BPM) systems form a major part of precision position measurement diagnostics for linear accelerators with low emittance beams. Using cavity BPMs, a position resolution of less than 100 nm has been demonstrated in single bunch mode operation. In the case of closely spaced bunches, where the decay time of the cavity is comparable to the time separation between bunches, the BPM signal from a bunch is polluted by the signal induced by the previous bunches in the same bunch-train. This paper discusses our ongoing work to develop the methods to extract the position of closely spaced bunches using cavity BPMs. A signal subtraction code is being developed to remove the signal pollution from previous bunches and to determine the individual bunch position. Another code has been developed to simulate the BPM data for the cross check. Performance of the code is studied on the experimental and simulated data. Application of the analysis techniques to the linear colliders, such as International Linear Collider (ILC) and Compact LInear Collider (CLIC), is briefly discussed.

INTRODUCTION

When a bunch of charged particles passes through a resonant cavity, it induces oscillating electromagnetic (EM) fields over various resonant modes [1]. Among all modes, the amplitude of the field induced in the dipole mode has a strong dependence on the position offset from the center of the cavity, and the excitation is linear around the center. The phase indicates the direction of the offset. Even after the bunch leaves the cavity, the induced EM fields continue oscillating, with their amplitudes decaying exponentially in time. The decay time of each mode is defined by the internal losses and coupling. The RF signal of the dipole mode is extracted through couplers into the electronics. It is down converted to intermediate frequency (IF) for digitisation and further digital processing.

The ATF2 extraction line of the Accelerator Test Facility (ATF) at KEK (Japan) [2] is equipped with a total of 37 resonant cavities mounted on the quadrupole magnets throughout the beamline [3, 4]. Position resolution of 250 nm is typical, with 27 nm measured in the best performing cavities [3].

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The ILC and CLIC will operate with typical bunch spacing of 300 and 0.5 ns respectively. That makes it essential to understand the processing of the overlayed signals. We operated the BPM system in multi-bunch (technically, multi-train) mode during December 2010 run, using 3 bunches of around $0.4 \cdot 10^{10}$ particles per bunch separated by Δt_b =154 ns. This separation is short compared to the decay time of the cavities (τ = 150 ns for Q_L = 6000). We report the first analysis of that data below.

MULTI-BUNCH MEASUREMENTS

When bunches are closely spaced, their signals overlay as shown in Fig. 1, resulting in a false measurement if processed the same way as single-bunch data. This pollution needs to be removed in the processing.

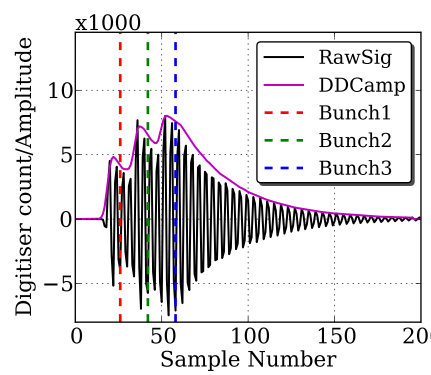

Figure 1: Digitised BPM signal.

Signal Subtraction

The initial processing of the multi-bunch data is the same as for the single-bunch data: the amplitude and phase of the digitised IF signal are extracted in the process of digital down conversion (DDC) [3, 1]. Figure 1 shows the processed amplitude. The amplitude and phase are sampled at a single point for each bunch. We color-code all the plots as Red, Green and Blue for bunches 1, 2 and 3 respectively throughout the paper.

The signal $\mathbf{V}_j$ at a time after the j^{th} bunch arrives can be written as a phasor:

$$\mathbf{V}_j = \sum_{k=1}^{j} A_k \, e^{-\frac{\Delta t_b (j-k)}{\tau}} \, e^{i(\omega \Delta t_b (j-k) + \phi_0)} \quad (1)$$

where ω is the angular frequency of the signal. The phasor generated just by this bunch can be found as a difference

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of the phasors measured at the current and the previous bunches:

$$\mathbf{V}'_j = \mathbf{V}_j - \mathbf{V}_{j-1}\, e^{-\frac{\Delta t_b}{\tau}} e^{i\omega \Delta t_b}. \quad (2)$$

As long as the linearity is preserved in the processing, the same applies to the DDC phasors.

Since a filter is applied to the down-converted signals, samples corresponding to different bunches are convolved introducing an error. We set the width of the filter window to be the same as the bunch separation and the sampling point in the middle between the arrivals of consecutive bunches to minimize the pollution. This, however, constraints the minimum filter bandwidth to a value larger than normally used for single-bunch processing, resulting in higher contributions from noise and up-converted components.

Beam Measurements

The multi-bunch data was collected parasitically while ATF was operating in the multi-bunch mode. BPM MQM13FF was moved in y-direction together with its quadrupole using the mover supporting the quadrupole. BPM signals were recorded at each mover position for several machine pulses. A data cut was applied on pulses during which the digitiser was saturated.

To complement beam data, a BPM signal simulation code has been developed. Multi-bunch BPM signals are simulated using a simple model: signals are generated for different bunches according to their positions and arrival times as decaying sine-waves, and then added linearly. The beam jitter is simulated by adding a random position and angle variation. All the processing was tested on both, the beam and simulated, data.

Pollution from previous bunches is subtracted using Eq. 2 on DDC phasors. In phase (I) and Quadrature (Q) values for each bunch are then calculated as:

$$I_j = \frac{A_j}{A_{r,j}} \cos\left(\phi_j - \phi_{r,j}\right) \quad (3a)$$

$$Q_j = \frac{A_j}{A_{r,j}} \sin\left(\phi_j - \phi_{r,j}\right), \quad (3b)$$

where r denotes the reference cavity.

Figure 2 shows IQ diagrams for the multi-bunch data before and after the subtraction. Clearly, no subtraction is applied to IQ phasors corresponding to the first bunch as they are no different to single-bunch data. The amplitudes of the phasors for the second and third bunches are expected to be of a similar magnitude as of the first bunch, because the position of the three consecutive bunches from the same extraction should be similar. Indeed, after the subtraction this is the case. Before the subtraction, they are roughly 20 and 60% for the second and the third bunches respectively. After subtraction, the difference in positions is around 2%.

As can be seen in Fig. 2, the phasors corresponding to the consecutive bunches, have a phase advance with respect to each other. This is due to two reasons. Firstly, a small difference of the position and reference cavity frequencies ($\Delta\omega$) gives a phase offset when the phasors are propagated in time:

$$\Delta\phi = \Delta\omega\, \Delta t_b\,. \quad (4)$$

Secondly, the phase of the contribution from previous bunches also depends on the bunch spacing, see Eq. 2. This latter part is removed during subtraction, leaving a phase advance of 1.09 rad, which is in good agreement with the expected $2\pi\times$ 1.2 MHz $\times$ 154 ns $=$ 1.16 rad.

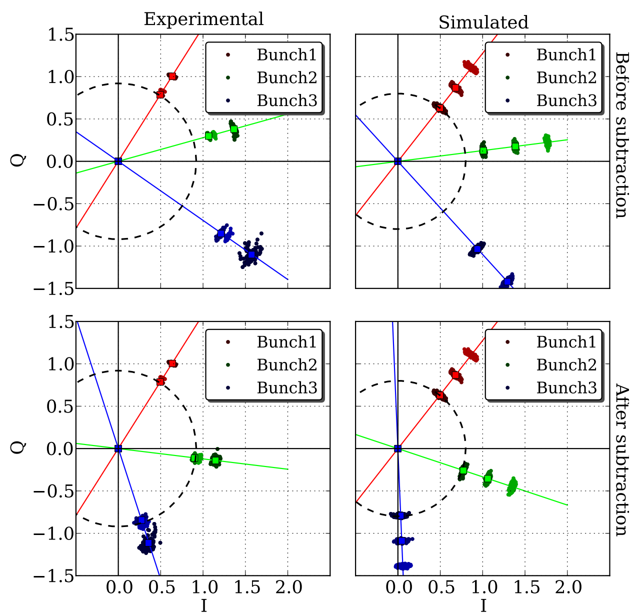

Figure 2: IQ diagrams: experimental and simulated data before (top left and right, respectively) and after the signal subtraction (bottom left and right, respectively).

Figure 2 also shows results for the simulated data. The mean offset is assumed to be the same for all three bunches. Applying the subtraction yields equal amplitudes and phase advance of the phasors for all three bunches, which confirms that the algorithm works correctly.

Removing the measured phase advance between the bunches and using single bunch calibration [3], we converted the measured I and Q values into positions. Figure 3 shows the position data relative to the mean for each mover position, i.e. the beam jitter (measured and simulated). The measured jitter grows with the bunch number, while simulated data shows no increase. This can also be seen in the IQ diagrams, Fig. 2. As the simulation currently does not include non-linear effects, it has been suspected that saturation occurs when the amplitude grows due to addition of the signals. The electronics saturates around 11 dBm, corresponding to 0.8 V or 6500 digitiser counts.

Figure 4 shows the amplitude ratio at two sampling points separated by 16 clock cycles, starting at samples 58, 62 and 66 – all corresponding to bunch 3. It can be seen

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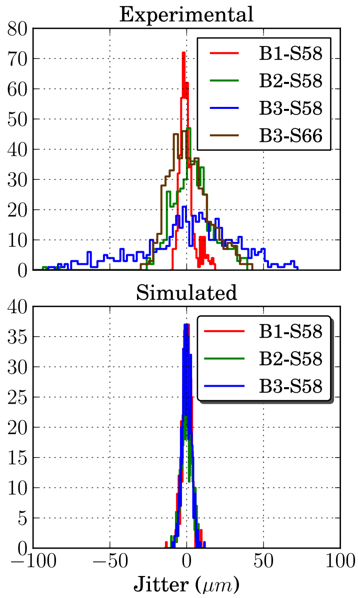

Figure 3: Position jitter observed in the experimental and simulated data.

that, when sampled at sample 58, the amplitude goes into saturation with a threshold of around 7000 digitiser counts. This is very close to the expected saturation threshold of the electronics. Sampling at a later time allows to avoid this problem either partially (sample 62) or completely (sample 66) in our data. The same subtraction algorithm was applied with the third bunch sampled at sample number 66. The position scale had to be altered accordingly assuming an exponential decay. As shown in Fig. 3, the residual for the third bunch decreases to the same level as for the second bunch. Table 1 summarises the RMS values of the measured jitter. Although avoiding electronics saturation improves the jitter measurement for bunch 3, RMS jitter measured for bunches 2 and 3 are almost four times larger than that for bunch 1. Further investigations involving multiple BPMs using dedicated beam time are required in order to understand whether this is a systematic effect introduced in the subtraction algorithm, or a feature of the mode in which the machine was operated at the time the measurements were taken.

Table 1: RMS Jitter Measured for Three Bunches

Bunch No	RMS residual (μm) 3^{rd} Bunch Sample no 58	66
1	3.51	3.51
2	13.06	13.06
3	40.98	12.99

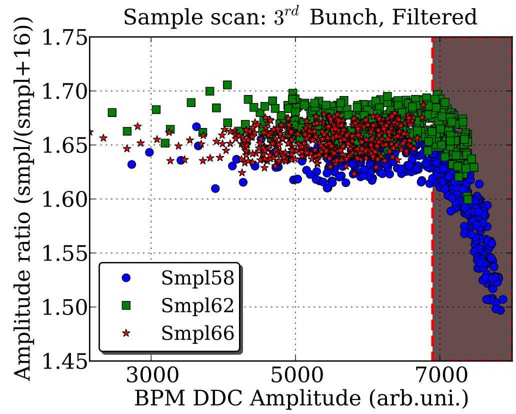

Figure 4: Effect of the saturation at different sampling points.

SUMMARY AND FUTURE WORK

We tested the signal subtraction code on experimental and simulated BPM data for three consecutive bunches with 154 ns spacing. The position error due to signal pollution from previous bunches was reduced to around 2% from 20 and 60% for the second and third bunches of the train respectively. Single bunch calibration factors were successfully applied to the multi-bunch data after removing the phase advance due to frequency difference between the position and the reference cavities. Increased jitter for the third bunch was attributed to the non-linearity in the processing electronics and rectified by sampling at a later time. Although the subtraction technique provides a reasonable position reading for bunches 2 and 3, an increased jitter compared to bunch 1 is observed. Simulated data does not show such an artefact. We are planning to acquire additional data for multiple BPMs at different locations in the beam line in order to determine whether the increased jitter was caused by the particular mode of machine operation or the algorithm needs substantial redevelopment. Studies including higher digitisation rate and varying the bunch separation are foreseen to aid the understanding of the signal subtraction.

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