LOSS FACTOR MEASUREMENT USING TIME CORRELATED SINGLE PHOTON COUNTING OF SYNCHROTRON RADIATION

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Abstract

A method to derive the total loss factor from the variation of SR photon arrival times with bunch charge has been developed. A time correlated single photon counting system is used operationally for fill pattern and bunch purity measurements. By fitting the individual peaks in the photon arrival time histogram, their relative timing can be retrieved with ps resolution and reproducibility. For a measurement of the loss factor, a fill pattern comprising a range of different bunch charges is stored and then their timing relative to the RF buckets is charted against charge. Examples of measurements illustrate the variation of loss factor with RF voltage and change in Insertion Device gap.

INTRODUCTION

Measurement of the loss factor is a useful diagnostic to calculate the total RF power lost due to longitudinal coupling impedance. It requires a measurement of the change of synchronous phase with increase of the stored charge. In the past this measurement has been performed either by directly measuring the phase of a single bunch against the RF phase using a mixer [1], or by looking at the relative timing of a reference bunch and other bunches of varying charge using a streak camera [2].

We have managed to retrieve the required highly precise relative timing of bunches from the Time Correlated Single Photon Counting (TCSPC) instrument we use to measure fill pattern and bunch purity at Diamond [3]. This offers the ability to measure bunches of many different charges at the same time. Mixer measurement could only measure one charge at a time (thus require stable conditions over the time needed to vary the charge) and streak camera measurements could only measure a few bunches at the same time.

EXPERIMENTAL SETUP AND METHODOLOGY

We are using a PicoHarp 300 TCSPC with an Id Quantique Id100-20 STD: Single-Photon Detector to generate an arrival time histogram from visible light photons off a bending magnet relative to a storage ring revolution clock. In the past, we have analysed these histograms only in terms of the number of photons arriving within each 2ns RF bucket to measure the fill pattern of the storage ring.

We found, that even though the histogram bins of the PicoHarp are set to a width of 32ps (so that we cover the 1872 ns revolution period with the 65536 bins available), we can retrieve much more precise timing information of the individual bunches by fitting the count distribution of each individual bunch with a Gaussian (Fig. 1). It can be seen that the Gaussian is not a perfect match for the recorded distribution which is almost entirely due to the transit time spread of the detector, but we found it good enough to get a reliable measurement of the bunch centroid longitudinal position.

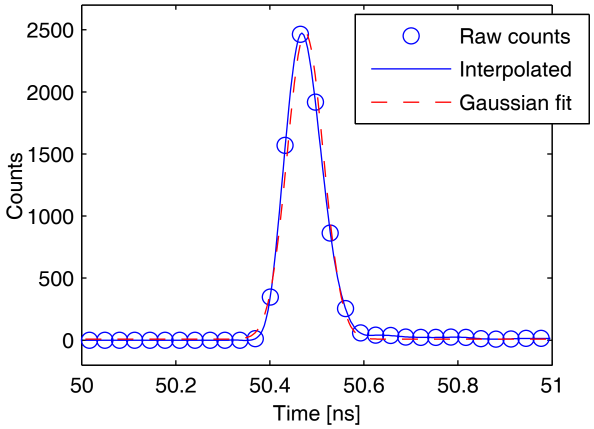

Figure 1: TCSPC counts of one bunch together with a spline interpolation of the data and a Gaussian fit.

This process is repeated for each of the filled bunches. To estimate the uncertainty of this method we have calculated the longitudinal position of all the bunches in a 900 bunch fill of roughly equal charge from 5 minutes of photon counting. The result in Fig. 2 shows the presence of a systematic deviation of the timing for bunches 300-400, which we believe to due to electric crosstalk between the clock and photon pulse input channels. However, this and the general slope across all bunches are entirely reproducible and not related to the fill pattern (which in this case has its gap around bunch 100).

Measurement Error

Figure 3 illustrates how we have attempted to separate the random measurement error from systematic contributions. To this end we concentrate on bunches 400 to 900 in the previously shown measurement where the systematic deviation is characterised by the upward slope.

After removal of this slope, the data still exhibits a correlation with bunch charge, which varied between 0.45

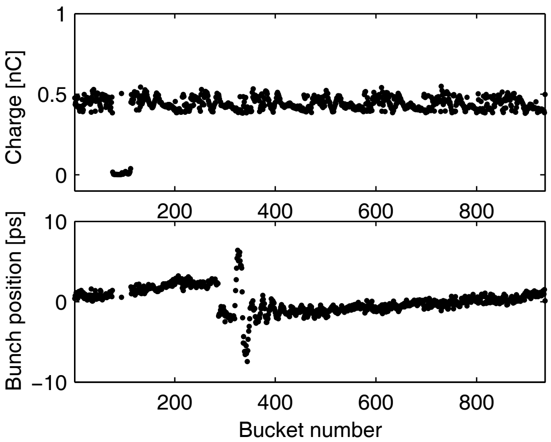

Figure 2: Fill pattern (top) with roughly equal charge in 900 of the 936 RF buckets. Relative longitudinal bunch position (bottom) of the stored bunches within each RF bucket.

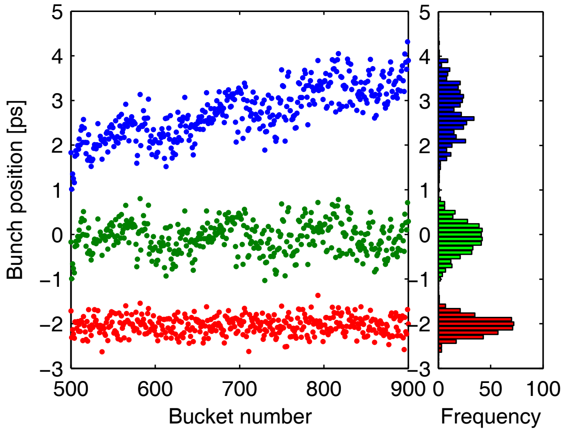

Figure 3: Separation of systematic and random variation components of the bunch timing measurement: top/blue raw data of bunch positions, middle/green slope of systematic error removed, bottom/red correlation with bunch charge removed.

and 0.55 nC in these bunches. Subtraction of the correlated component leads to the final data set which has a standard deviation of only 200 fs.

LOSS FACTOR MEASUREMENT

To derive the loss factor from the longitudinal positions of bunches and minimise the influence of any systematic errors, we use a fill pattern consisting of a ramp of charges in individual bunches with reference bunches of a low charge between. After retrieving the longitudinal position by the fitting as described above (see result in Fig. 4), we can calculate the difference in time between each bunch and its adjacent reference bunch and plot this against charge.

We have then repeated this process with different

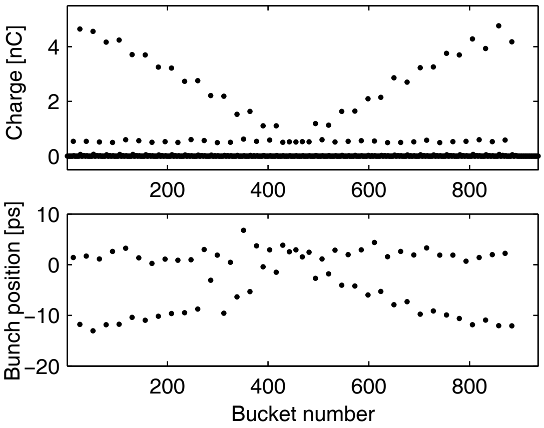

Figure 4: Fill pattern (top) with a ramp in bunch charge and reference bunches of a low charge between. Relative longitudinal bunch position (bottom) of the stored bunches within each RF bucket.

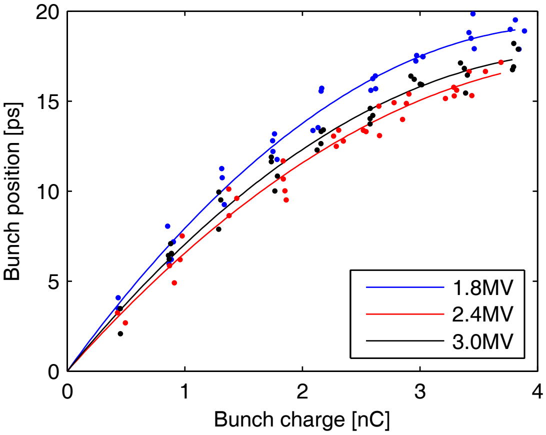

Figure 5: Corrected relative longitudinal bunch positions plotted against bunch charge for 3 different total RF cavity voltages.

RF cavity voltages to see how the variations in bunch length influence the loss factor. Figure 5 shows the measurements for three different cavity voltages, where each measurement was from only 5 s of photon counting. The curvature of the synchronous phase offset is due to the bunch lengthening caused by the high single bunch charge and is approximated by a quadratic fit.

The total loss factor is given by the following equation:

$$k_{loss} = V_{RF}\cos(\phi_s)\frac{\mathrm{d}\phi_s}{\mathrm{d}Q} \qquad (1)$$

with $\phi_s = \arcsin(U/V_{RF})$ the electron synchronous phase, V_{RF} the RF cavity voltage, Q the bunch charge, and U the electron energy loss in a turn, which for Diamond is $U \simeq 1.003$ MeV.

With ϕ_s written as function of U and V_{RF}, and with t_s the longitudinal bunch position in the bucket used to

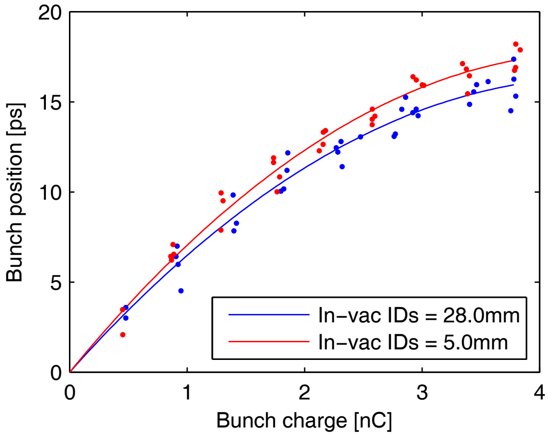

Figure 6: Corrected relative longitudinal bunch positions plotted against bunch charge with all in-vacuum undulators at open gap (28 mm) and closed gap (5 mm).

express $\mathrm{d}\phi_s = \omega_{RF}\mathrm{d}t_s$ one reaches:

$$k_{loss} = \omega_{RF}\sqrt{V_{RF}^2 - U^2}\frac{\mathrm{d}t_s}{\mathrm{d}Q} \quad (2)$$

The slope $\mathrm{d}t_s/\mathrm{d}Q$ is taken from the quadratic fit at the origin in Fig. 5.

We have also done measurements with a variation of the gap of 9 in-vacuum undulators between their fully open state at 28 mm and their fully closed state at 5 mm to see how this change in geometry near the beam influences the total loss factor (see Fig. 6). All results are summarised in Table 1.

Table 1: Loss Factor Measurement Results. The values for k_{loss} are the mean and standard deviation (scaled by $1/\sqrt{N}$) of N repeated measurements

V_{RF} [MV]	ID gaps [mm]	k_{loss} [V/pC]
1.8	5	42.5±1.6
2.4	5	50.2±1.4
3.0	5	71.8±3.4
3.0	28	51.7±3.1

CONCLUSIONS

We have derived a method and provided example measurements to calculate the precise longitudinal position of bunches from histograms of the arrival time of synchrotron light photons. These histograms are available from a Time Correlated Single Photon Counting setup which has been originally designed and used for the purpose of fill pattern and bunch purity measurement. Despite the relatively large bin size of 32ps and a FWHM of the photon arrival time distribution of about 110 ps, we have shown that the centroid position can be reproducibly measured with a standard deviation of 200 fs.

We have then used measurements of the longitudinal bunch position to determine the synchronous phase shift with varying charge in the bunch to measure the loss factor. These measurements have been repeated to give an estimate of the variability of the result.

This new method has the unique capability to measure bunches of many different charges simultaneously and rapidly (within a few seconds of counting time). It is even conceivable to add a few ‘probe bunches’ to the fill pattern used normal user operation to allow a continuous online measurement of the loss factor.

REFERENCES

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