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FILLING PATTERN MEASUREMENTS USING DEAD-TIME CORRECTED SINGLE PHOTON COUNTING

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Abstract

Time-correlated single photon counting (TCSPC) is a versatile tool for various accelerator diagnostics aspects. Amongst others it allows a precise determination of the filling pattern. At the visible light diagnostics port at the Karlsruhe Research Accelerator (KARA), the KIT storage ring, a Single-Photon Avalanche Diode (SPAD) in combination with a histogramming device (PicoHarp) is used. To compensate for possible dead-time effects, a correction scheme was developed and tested successfully. The compensation increases the dynamic range in which accurate measurements are possible and avoids distortion of the measured filling pattern. This contribution presents the experimental setup, as well as a series of benchmark measurements.

INTRODUCTION

A precise determination of the filling pattern in a storage ring is important for several reasons. For some time-resolved studies using synchrotron radiation, it must be ensured that there are no spurious bunches in the storage ring (*bunch purity*). Another motivation are studies of current dependent effects in multi-bunch operation, e.g. during the micro-bunching instability. This instability occurs when the electron bunches are compressed longitudinally until they emit coherent synchrotron radiation (CSR) and start to interact with their own radiation. At KARA this instability is studied extensively [1–3], pushing the need for a precise determination of the filling pattern.

A versatile tool for all kinds of accelerator diagnostics is the incoherent synchrotron radiation as its intensity is proportional to the emitting charge.

TIME-CORRELATED SINGLE PHOTON COUNTING

The temporal distribution of the incoherent synchrotron radiation represents the filling pattern and can be used for measurements in various ways. One possibility is the usage of fast photodetectors and DAQ systems with a sufficient electrical bandwidth to resolve single bunches. At KARA, the bunch spacing is 2 ns. In this case, averaging over many turns has to be applied to increase the signal-to-noise ratio.

The technique of time-correlated single photon counting (TCSPC) is a cost-efficient alternative [4]. There, the light intensity is lowered to be able to distinguish between single photons. The temporal profile of the light signal is then reconstructed by histogramming the arrival times of the single photons relative to a fixed reference signal, e.g. a revolution trigger. Being originally a tool for spectroscopy studies, TCSPC can also be used for precise filling pattern measurements at synchrotron light sources (e.g. at Diamond [5] and BESSY-II [6]). At KARA, we also make use of this technique since 2011 [7] and upgraded our setup stepwise since then [8].

EXPERIMENTAL SETUP

Our experimental setup is located at the visible light diagnostics port [8] where we use synchrotron radiation from a dipole magnet. As detector we use a single photon avalanche diode (SPAD) from idQuantique (id100-20 ULN, [9]) and a PicoHarp 300 as histogramming device [10]. We operate the SPAD with a wavelength of 400 nm as for short wavelengths the penetration depth of light in silicon is reduced. This reduces the probability to create electron-hole pairs outside of the depletion zone which then diffuse into the depletion zone where they trigger an avalanche after a statistically fluctuating delay [11]. As a consequence, the *diffusion tail* in the histogram peaks is minimized [8, Fig.2]. In addition, a small iris lens is mounted directly in front of the detector. Together with the small diameter of the sensor (20 µm), this leads to a very small angular acceptance. Thus it acts as an optical discriminator which blocks almost all background light and allows to operate the setup without any additional shielding.

As KARA has a revolution time of 368 ns, the PicoHarp is operated with a bin width of 8 ps to cover one revolution with the available 65536 bins.

Data Analysis

The aim of the data analysis is to determine the relative distribution of the current on the 184 RF buckets from the raw histogram. The whole data analysis (as well as the dead-time correction scheme discussed in the following section) is written in Python.

As first step, the first 368 ns of the histogram are grouped in 184 intervals for the 184 RF buckets. For each interval, the local maximum is determined and the bins of the adjacent bins are summed. Monte-Carlo studies showed, that the best performance is achieved, if the 25 preceding and the 25 successive bins are taken into account. This is illustrated in Fig. 1.

After a normalisation of the 184 values to a sum of 1, this relative filling pattern is multiplied with the average beam current measured using a DC current transformer (DCCT) [12] before and after the histogram acquisition. For the error

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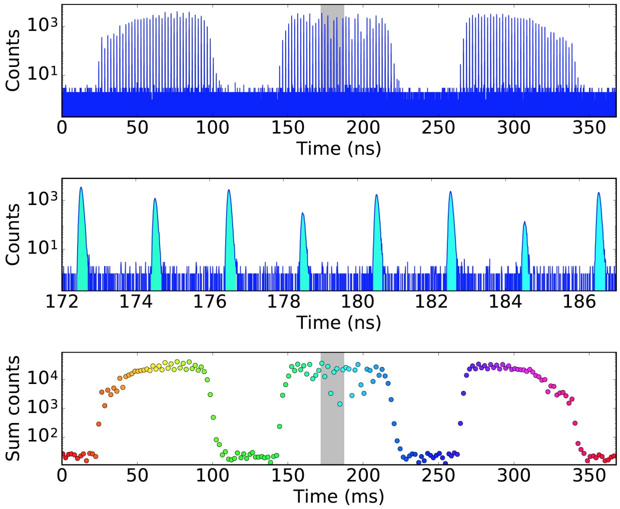
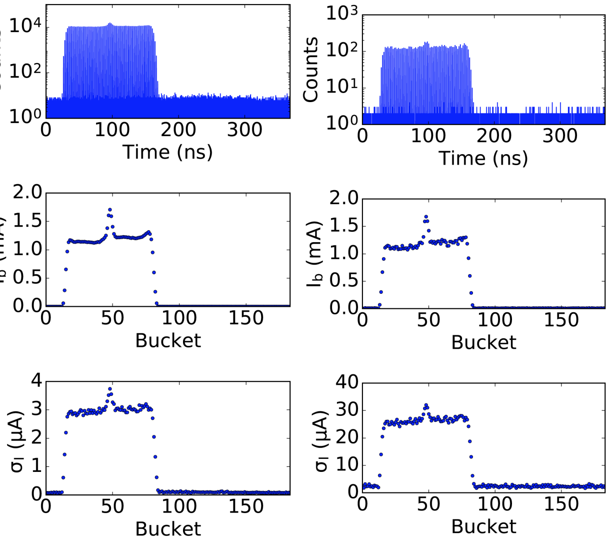


Figure 1: Top: Raw data histogram, Center: Zoom into the raw data histogram (indicated by the grey bar), the light blue area below the peaks indicates the bins used for integrating the counts to calculate the filling pattern. Bottom: Integrated counts for the 184 RF buckets.

on the bunch currents, two contributions are assumed: The first is the counting error per bin σ_i assuming Poisson's statistics $\sigma_i = \sqrt{n_i}$ with n_i as number of counts per bin. The second is the error of the beam current measurement from the DCCT given by the quadratic sum of the standard deviation of the beam current and the measurement error of the DCCT of 0.5 µA [13].

Monte-Carlo studies are used to determine the error on the bunch currents. There, the data analysis is repeated many times and the input parameter (raw data histogram and beam current) are varied according to their error as standard deviation.



(a) 1.0×10^5 photons/s

(b) 1.3×10^3 photons/s

Figure 2: Comparison of two datasets with a high (2a) and a low photon rate (2b). Top: Raw data histograms. Center: Corresponding bunch currents. Bottom: Bunch current errors.

Two measurements for the same filling pattern with different photon rates are shown in comparison in Fig. 2. The reduction of the photon rate was achieved by inserting a neutral density filter into the optical beam path.

A reduction of the photon rate from 1.0×10^5 to 1.3×10^3 increases the error on the individual bunch currents by approximately one order of magnitude. Thus, the photon rate should be as high as possible to achieve a good resolution. On the other hand, a high count rate can lead to a distortion of the measured histogram due to dead-time effects. To study and handle these distortions, a dedicated dead-time correction scheme was developed and tested.

Dead-Time Correction Scheme

Both, the SPAD and the PicoHarp, have a certain dead-time during which they cannot process incoming events. When a photon is detected by the SPAD and an avalanche has been triggered and detected, the bias voltage of the pn-junction is reversed to quench the avalanche before it is restored and the next photon can be detected. This quenching takes a certain amount of time in which the detector is blind. The dead-time of the PicoHarp, in which the device is insensitive to logical pulses from the SPAD, is defined by its electronics. Both dead-times were measured, for the PicoHarp it is (86.8 ± 0.2) ns while for the SPAD it is (37 ± 1) ns.

Under certain conditions, the effect of the dead-time induced distortion can be estimated from the measured values and compensated as well. Based on the ansatz discussed in [14], we adjusted the proposed correction scheme according to the needs of a synchrotron light source. The scheme was already briefly introduced in [3]:

The *real* number of photons per bin ν_i can be calculated to be

$$\nu_i = \frac{n_i}{\prod\limits_{j=i-n_{\tau_{\mathrm{d,\,PH}}}}^{i-b}\left(1-\frac{n_j}{N}\right)} \approx \frac{n_i}{1-\sum\limits_{j=i-n_{\tau_{\mathrm{d,\,PH}}}}^{i-b}\frac{n_j}{N}} \qquad (1)$$

with the parameters given by Table 1.

This method is based on the following assumptions:

- The dead-time of the PicoHarp dominates, Monte-Carlo studies showed that the dead-time of the SPAD is a second order effect and neglected.
- The probability $p_i = n_i/N$ for an event to be detected in bin i is small (typically 1×10^{-4}), allowing to replace the product in Eq. 1 by a sum. This also leads to a higher numerical stability as higher order terms are neglected.
- There is only one photon emitted per bunch and turn and thus the correction scheme only takes the photons from the previous bunches into account (sum ends at $i - 50$).

Table 1: Parameter for the Dead-Time Correction

Variable	Meaning	Value
ν_i	*Real* number of photons / bin	
n_i, n_j	Measured counts / bin	
$\tau_{\text{d, PH}}$	PicoHarp dead-time	86.8 ns
$n_{\tau_{\text{d, PH}}}$	Bins per PicoHarp dead-time	10850
b	Bins per bunch	50
T_{Acq}	Acquisition time	Typically 30 s
T_{Rev}	Revolution time	368 ns
N	Number of excitation cycles	$T_{\text{Acq}}/T_{\text{Rev}}$

TEST MEASUREMENTS

To test the dead-time correction scheme, two histograms were taken with different photon rates. From the one with the lower rate (1.9×10^4 counts/s), the reference filling pattern is calculated. In the histogram with the high count rate (1.2×10^6 counts/s), dead-time effects induce a distortion which is corrected using the correction scheme discussed above. From the distorted as well as the corrected histograms, filling patterns are determined, which are finally compared to the reference pattern. This comparison is illustrated in Fig. 3.

There, the top panel shows three filling patterns: The first one, plotted in blue, is the reference filling pattern recorded with a low count rate while the green and the red curve show two filling patterns recorded with a high count rate. For the red curve, the dead-time correction was applied. As the effect of the distortion and the dead-time correction are *relatively* small, they are illustrated in the bottom panel in more detail. It shows the bunch current differences between the reference, distorted and the corrected filling pattern, respectively.

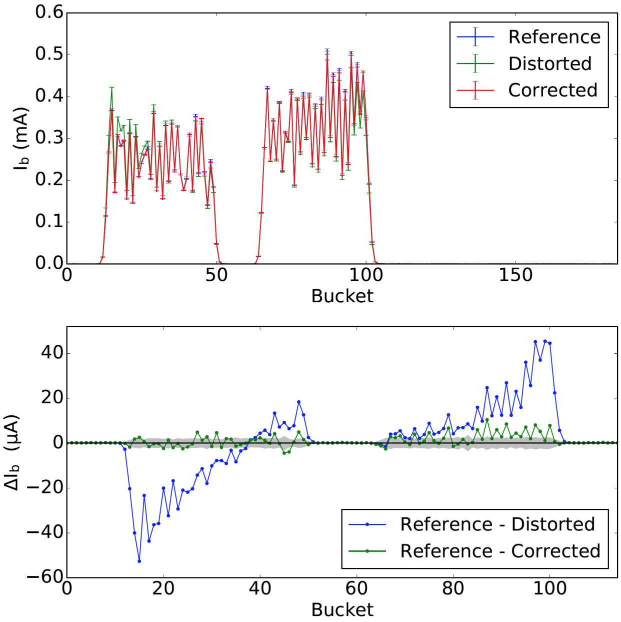


Figure 3: Top: Reference (blue), dead-time distorted (green) and dead-time corrected (red) filling pattern. Bottom: Difference between reference and distorted (blue) and reference and corrected filling pattern (red), respectively. The grey area depicts the bunch current error of the reference filling pattern.

While the dead-time distortion of the histogram leads to bunch current differences of up to 50 µA, they are reduced significantly by the correction to values of below 10 µA. The corrected and the reference filling pattern then coincides mostly within the uncertainty of the reference filling pattern which is given by the estimated bunch current error using Monte-Carlo studies. This is indicated by the grey area.

This shows that the dead-time correction scheme is able to reduce the distortion induced by the PicoHarp dead-time significantly.

SUMMARY

The technique of time-correlated single photon counting is a useful tool for precise measurements of the filling pattern of a storage ring. At KARA, we use a setup based on a SPAD and a PicoHarp 300 as histogramming device. To prevent distortions of the measured filling pattern due to dead-time effects, we successfully implemented and tested a dead-time correction scheme. This increases the dynamic range of the system e.g. for bunch purity studies as a higher photon rate can be handled and furthermore it allows a reduction of the acquisition time.

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