BUNCH PATTERN MEASUREMENT VIA SINGLE PHOTON COUNTING AT SPEAR3*

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Abstract

SPEAR3 is a 3GeV storage ring light source with 500mA circulating beam current and a 5 minute top-up cycle. The bunch pattern contains 4 bunch 'trains' and a single timing pulse isolated by ±60ns dark space for laser pump/x-ray probe applications. In order to quantify the bunch pattern and charge purity of the probe pulse, a time-correlated single-photon counting system has been installed (TCSPC). In this paper we report on preliminary results using a photomultiplier tube with a commercial PicoHarp300 TCSPC device to identify bunch charge purity, afterpulse effects and top-up performance.

INTRODUCTION

SPEAR3 is an 18-cell, 234m circumference storage ring light source servicing 16 photon beam lines with up to 30 experimental endstations. The 476MHz RF system produces 372 RF buckets of which typically 280 contain charge bunches distributed in 4 bunch 'trains' separated by 30ns to minimize ion accumulation [1]. A single isolated timing pulse separated by ±60ns is available for time resolved pump/probe experiments using fast-gated detectors [2].

Charge injection into the 500mA electron beam takes place on a fixed 5 minute time interval. During each injection period the 10Hz booster synchrotron injects single-bunch pulses into consecutive SPEAR3 buckets until full current is restored. Each circulating bunch contains 1.4nC, or about 30 injection pulses (3% per shot). With a 9 hour electron beam lifetime, the periodic 1% beam loss is replenished by ~50 charge pulses containing 50pC each. Of significance, the arrival time of injected charge must be sufficiently accurate to avoid charge spill into adjacent buckets. The time separation between buckets is 2.1ns and the beam revolution time is 781ns (1.28MHz).

Historically a control room oscilloscope connected to a dedicated BPM was used to monitor the bunch pattern. More recently a PicoScope [3] was installed to enable remote viewing site wide. Although the 'scope solutions provide rough monitoring of the charge pattern, a more precise system is needed to measure bunch purity of the timing pulse and to study injector performance on a more quantitative basis. Furthermore, to remove unwanted charge, plans are underway to install x-y kicker magnets driven by the bunch-by-bunch feedback system [4].

In this paper we report on preliminary bunch pattern measurements using a Hamamatsu photomultiplier tube in conjunction with the PicoHarp300 TCSPC module [5].

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The work follows directly from previous authors [6,7,8]. In short, for TCSPC, the PicoHarp300 records the time difference between the 1.28MHz storage ring orbit clock synchronization pulse (SROC) and single photon detection events. Upon integration, the resulting histogram displays the electron bunch pattern with potentially high resolution.

TCSPC DETECTOR CONFIGURATION

The PicoHarp300 was installed in the visible beam diagnostic laboratory at SPEAR3 [9]. At 500mA, the visible beam power is 0.5mW or about 10^{15} photons/sec. In order to reduce the count rate to ~1 count every 10 turns (7.8μs) the beam power incident on the PMT must be attenuated by 10 orders of magnitude. Most of the reduction was achieved by placing a small translatable pick-off mirror in the far beam halo. This arrangement also permits operation of other beam diagnostics in parallel. As shown in Fig. 1, redirected photons then pass through an ND filter and a 10nm bandpass filter inside a double-walled optical isolation box. A series of mirrors and irises serve to reduce background photon counts from ambient room light.

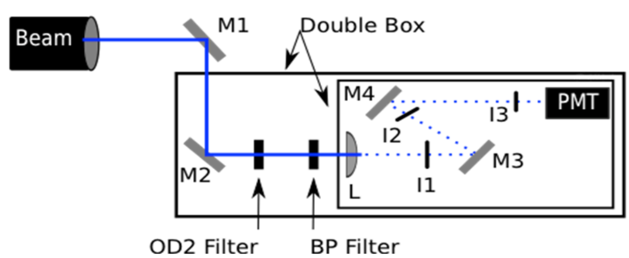

Figure 1: Schematic optical input system. The PMT has a dark count rate of 15 cps.

The PicoHarp300 was selected because it has two independent channels which can read up to 10^6 counts per second with 4ps time resolution [10]. Each channel requires a negative-going input pulse between 0V and -1V, and has a high resolution constant-fraction discriminator followed by time-to-digital conversion electronics (TDC) [10]. The 1.28MHz SROC is connected to Channel 1 as a timing reference (Sync port) after conversion from TTL to NIM in a commercial CAEN module.

Single photon detection was carried out using a Hamamatsu H7360-01 photon counting head [11]. The H7360-01 was selected based on experience with laser/SR cross-correlation bunch length measurements previously made in the diagnostics laboratory [12].

For each detected photon event, the H7360-01 outputs a single TTL pulse which is again converted to NIM and subsequently connected to PicoHarp300 Channel 2 (Signal port). Figure 2 shows the circuit schematic.

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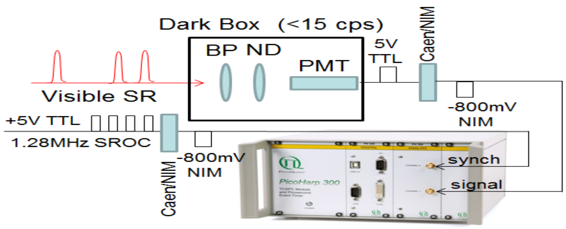

Figure 2: SROC and PMT input to PicoHarp300.

Operationally, the bin width of the PicoHarp300 histogram time axis can be set to multiples of 2ps across the 2^{16} wide horizontal time axis. For the 781ns one-turn time interval in SPEAR3, 16ps is the smallest bin size possible to record the entire beam profile in a single histogram.

Ideally, each pulse seen on the PicoHarp300 would be an exact, narrow spike localized in time; however, the counts actually 'land' in time distributed across a range of digitized bins. In order to maximize the number of counts in each bin while maintaining accuracy, a bin width of 32ps was typically used [13]. The maximum number of counts per bin is 2^{16} yielding in principle $1.5x10^{-5}$ contrast resolution. Operating with 3.3×10^{5} cps and 32ps bin width, the peak number of counts/bin was about 9,000 for 120s acquisition with the current detector configuration.

As an initial test of the TCSPC system, a single bunch was injected into SPEAR3. Figure 3 shows the resulting histograms for beam current values of 2, 4 and 6 mA. The narrow spike seen in the center was obtained by splitting the SROC signal, routing each copy through independent TTL-to-NIM conversion channels and detecting SROC 'counts' without the uncertainty of the PMT. This measurement indicates an overall 'impulse response' of approximately 32ps FWHM including timing jitter in the TTL-to-NIM conversion modules.

The actual bunch profile measurements exhibit a much wider profile of 800ps FWHM, and surprisingly a broad tail prior to the anticipated photon arrival time (Fig. 3). After conducting a series of tests it was determined the pulse broadening is due either to pulse conversion to TTL within the H7360-01 PMT electronics, or timing jitter on the SROC. When beam returns to the experimental station the source of pulse broadening will be further investigated and a higher time resolution detector acquired as needed.

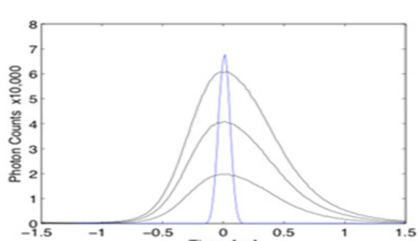

Figure 3: Histo gram for impulse response (32ps FWHM and single bunch measurement (800ps).

NOMINAL SPEAR3 BUNCH PATTERN

A typical measurement of the nominal 500ma bunch pattern is shown in Fig. 4 in both linear and logarithmic scale. As seen in Fig. 5, an 'afterpulse' is present 10ns following each electron bunch. The afterpulse is an electronic artifact located at a non-integer multiple of the 2.1ns bucket separation time and has 4ns duration. As a test, bunch patterns were generated by filling pairs of buckets at varying 2.1ns bucket intervals. By numerically identifying the afterpulse signature the artifact can be removed from the raw histogram data in software.

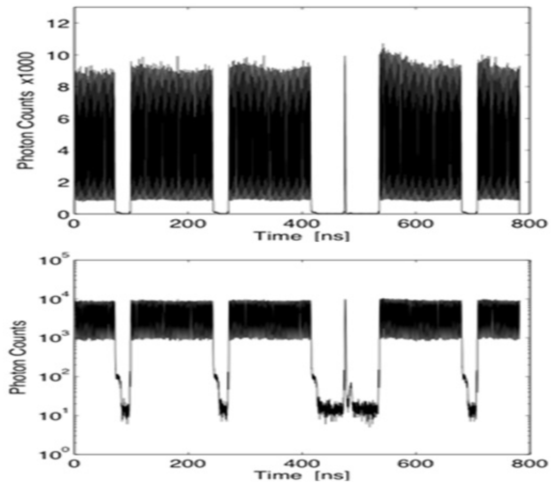

Figure 4: Nominal bunch pattern with four bunch trains and timing pulse. Linear scale (top) and log scale (bottom).

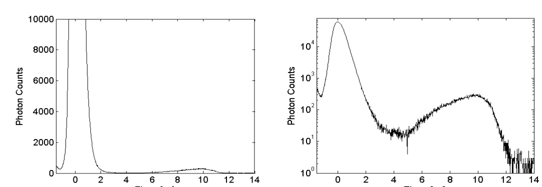

Figure 5: Afterpulse in linear and log scale.

DOUBLE-BUCKET INJECTION

Further examination of the timing bunch also reveals a second, upstream pulse with almost 1% amplitude relative to the timing bunch. Figure 6 shows the 'pre-pulse' in closer detail. In this case the pre-pulse is located exactly 2.1ns prior to the timing bunch and easily identified as charge spill during the injection process. To further study the source of the pre-pulse, the relative RF phase between SPEAR3 and the injector was varied.

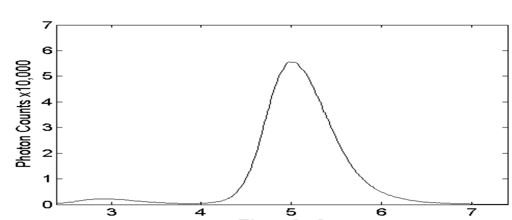

Figure 6: Injection charge spill into upstream bucket.

At first it was hypothesized the 'correct' phase setting would line up the injected charge exactly with the target SPEAR3 bucket and the pre-bunch would disappear. To the contrary, as the injection timing changed the spilled

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charge remained on one side or both sides of the target bunch depending on the injection time (Fig. 7).

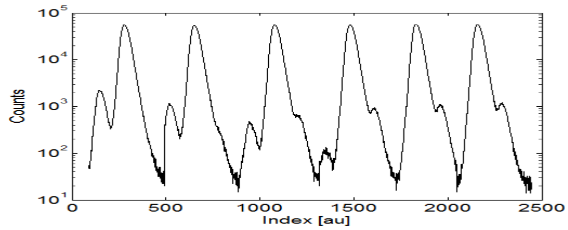

Figure 7: Evolution of double-bucket injection with varible timing between the injector and SPEAR3.

Archived oscilloscope images of the bunch fill pattern revealed the 'double bucket' was not present only days prior to the first PicoHarp300 measurements. Possible sources for the double bucket are outlined in Fig. 8. Likely candidates include jitter in the SPEAR3-to- injector timing system or multiple injector buckets. A less likely possibility the injector output pulse length may be longer than design causing charge injection into adjacent SPEAR3 buckets. Due to the observed systematic response to changes in injection timing it is unlikely the double buckets are due to steady-state diffusion between potential wells in longitudinal phase space. Longitudinal beam dynamics at injection is known to be complex [14] so the charge transfer could take place during the initial 5ms inject/damp cycle. Further tests will be made to correct the charge spill when beam operations resume.

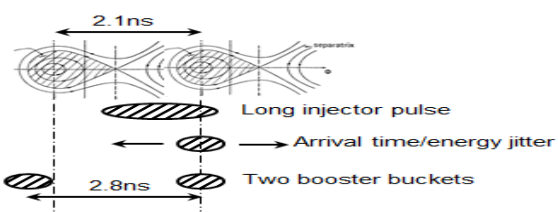

Figure 8: Potential double-bucket injection scenarios.

TOP-UP INJECTION

Injector performance across top-up cycles can be difficult to diagnose due to low bunch charge differential at each fill cycle. With present operating conditions, during each 5 min 'coasting beam' interval about 1% of the stored current is lost. Distributed across 280 buckets, each bunch loses 14pC or about 1/3 of the charge contained in a single injection pulse. Furthermore, with single-photon counting, the data integration time is of order 120 seconds or almost half the time interval between consecutive injection cycles.

In order to optimize the measurement, we positioned the TCSPC integration time to occur prior to each top-up cycle. In this way all 280 bunches decay for a full 5 minutes or more while the fresh 'top-up' charge decays at most 3-5 min. A schematic of the data acquisition timing is shown in Fig. 9.

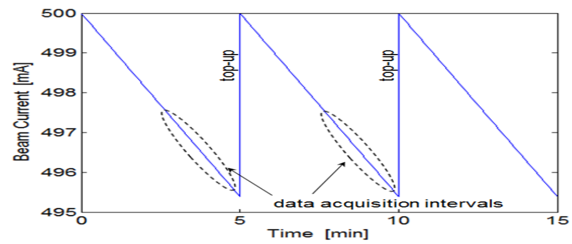

Figure 9: Timing diagram for top-up data acquisition.

A typical top-up data set is plotted in Fig. 10. The histogram in blue was acquired just before a top-up cycle while the red portion indicates target buckets after injection. By summing histogram bin counts across each 2.1ns bucket interval, a measure of differential bunch charge loss/gain can be found before and after top-up. The resulting change in integrated bin counts is plotted to the right in Fig. 10. Here the blue data indicates charge loss over a 5 minute time interval (bunches with no charge injection). The red data reflects top-up into ~50 target bunches followed by several minutes decay. The data are clearly quantitatively correct and will be further evaluated taking into account beam loss throughout the data acquisition time and enhanced intra-beam scattering in the top-up buckets which contain additional current.

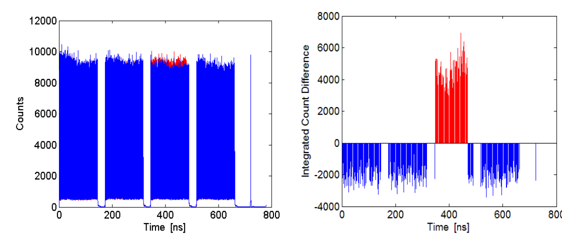

Figure 10: Bunch charge histogram before (blue) and afte topoff (red). Differential change in histogram count shown to right.

GUI DEVELOPMENT

The PicoHarp300 comes with both a graphical user interface and programming library compatible with a variety of languages. In order to provide additional interface functionality for operations staff, a complementary interface was developed in Matlab [15]. The gui mimics (see Fig. 11) the 'PlotFamily' interface used in conjuction with the Matlab Middlelayer for high level machine control [16]. Features of the interface include:

- Machine independence
- PicoHarp300 control
- data smoothing
- afterpulse deconvolution
- histogram difference capability
- display of desired bucket pattern
- intra-bucket histogram integration
- before/after top-up measurements
- measured bucket pattern report to EPICS
- pause/continue and additional data for histogram
- software timing shift to line up measurements with buckets as defined by main control system

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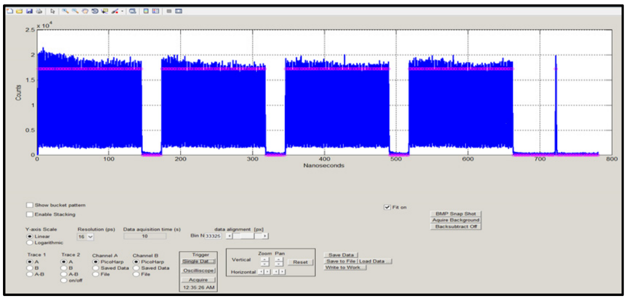

Figure 11: Matlab interface to PicoHarp300 for storage ring bunch pattern analysis.

SUMMARY

The PicoHarp300 accumulating real-time processor has been installed at SPEAR3 in conjunction with a Hamamatsu H7360-01 single photon counting PMT to measure the stored bunch pattern. Overall system performance is excellent. Histogram accumulation durations of 120sec with 32ps bin size were chosen make use of the PicoHarp300 dynamic range while maintaining good timing resolution and reasonable data acquisition times. Initial results produced a 800ps FWHM single-bucket histogram with the present PMT and timing system configuration. In the future this number must be decreased by at least a factor of 2 to better resolve individual buckets.

Preliminary measurements also revealed and error in the timing system leading to injected charge spill into adjacent buckets. By adjusting the relative RF phase between the injector and SPEAR3, the charge spill was observed to move from early- to late buckets. This problem will be corrected when beam operations resume.

Top-up measurements show that the TCSPC system can resolve both charge loss in coasting beam buckets over a single top-up cycle and single-pulse injection into target top-up buckets. Development of a machine-independent Matlab gui allows control of the PicoHarp300 with added functionality for storage ring operations. Individual bunch charge data can be posted to EPICS for history buffers, top-up control, single-bunch cleanout and monitoring of the probe pulse amplitude for pump/probe research.

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