ELECTRON BUNCH PATTERN MONITORING VIA SINGLE PHOTON COUNTING AT SPEAR3[*]

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Abstract

In recent years the synchrotron radiation program at SPEAR3 has moved toward laser/x-ray pump-probe experiments which utilize a single timing 'probe' bunch isolated by a ± 60 ns dark space on either side. In order to quantify bunch purity in the region near the timing bunch, time-correlated single photon counting is used. In this paper we investigate methods to optimize the fill pattern and resolve satellite bunches in the region near the timing bunch. Integration of the Matlab measurement and data processing software into EPICS is reported.

INTRODUCTION

SPEAR3 is a 234 m circumference electron storage ring with a 476MHz RF frequency. The electron beam can be injected into any of 372 RF buckets separated by 2.1 ns. As shown in Fig. 1, the 500 mA electron beam is configured in four electron bunch 'trains' each containing 70 bunches. The 30 ns gap between bunch trains allows for ion clearing to optimize beam lifetime. By design, the bunches in the four bunch trains contain equal charge. The single isolated timing bunch seen to the right is separated by ±60 ns dark space for time-resolved pump/probe experiments. With a 9 hr beam lifetime, the 1% beam loss is replenished every 5 min by a 10 Hz injector delivering single-bunches with ~50 pC charge/pulse.

For the injection process, a linear accelerator (linac) with a thermionic cathode gun transfers 120 MeV electrons to a booster ring which by design accelerates a single bunch of charge to 3 GeV prior to injection into SPEAR3. To avoid charge spill, the timing of each charge transfer process must be accurate to the sub-nanosecond level.

A visible-light diagnostic beam line on SPEAR3 is used to measure beam cross section, bunch length and injected beam dynamics. Time-Correlated Single Photon Counting (TCSPC) was added to monitor electron charge stored in each bunch [1-7]. With TCSPC, the bunch charge can be resolved with high dynamic range. The TCSPC data is used to monitor satellite bunches adjacent to the pump-probe timing bunch and to monitor evenness of charge in the bunch trains. The TCSPC system reported here uses a combination of Matlab for data acquisition and processing and EPICS for control. In this paper we report on recent developments with the data processing algorithm and the software environment.

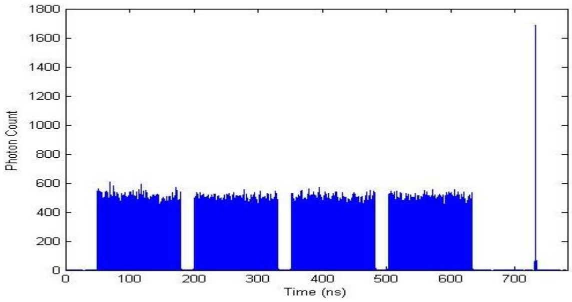

Figure 1: SPEAR3 timing bunch pattern with 4 bunch trains and 1 timing bunch (tall spike at right).

SPEAR3 TCSPC SYSTEM

Time Correlated Single Photon Counting is a slow yet accurate measurement process that can provide the dynamic range needed to detect low-charge bunches. The measurement depends on the fact that the rate of SR photon emission is proportional to the total charge in each bunch, and produces much higher resolution compared to conventional techniques such as oscilloscope sampling of a beam position monitor.

The SPEAR3 TCSPC detection system uses a PMA Hybrid single-photon detector with a PicoHarp300 pulse detector, both manufactured by PicoQuant [8]. The PicoHarp300 operates by detecting the arrival time of single photon emission events relative to a trigger, in this case the periodic beam revolution clock. For SPEAR3, the beam revolution time is 781 ns and the corresponding revolution rate is f=c/L=1.28 MHz. At each trigger event, the first photon arrival event is recorded in one of 65535 discrete 16 ps time bins which is sufficient to resolve the 2.1 ps bunch separations. The accumulation of counts in each time bin integrated over the total measurement interval generates a histogram of the electron beam bunch pattern in time.

Since the PicoHarp300 only records the first photon arrival event each trigger cycle, it is important to reduce the single photon arrival rate to avoid measurement pileup [5, 9]. An average photon arrival rate of one count per every 10 beam revolution triggers provides high accuracy.

SATELLITE ELECTRON BUNCHES

In practice, small inaccuracies in the charge acceleration process can cause electrons to be captured in RF buckets adjacent to the target bunch, a process referred to charge spill. These 'satellite' bunches can grow over time with repeated topup cycles.

The plot in Fig. 2 shows TCSPC data expanded around the timing bunch after approximately 10 days of periodic

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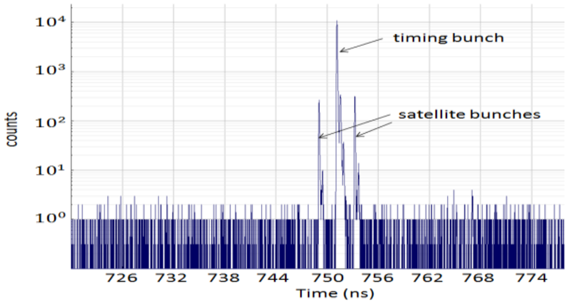


Figure 2: Zoom image of TCSPC data illustrating satellite bunches adjacent to the timing bunch.

top-up injection. In this case charge has accumulated in the upstream and downstream satellite bunches at the few percent level.

At SPEAR3 it is difficult to inject a 'pure' isolated timing bunch into the main storage ring because of imperfections in the charge transfer process between the 2856 MHz s-band linac and the 358 MHz booster synchrotron. As illustrated in Fig. 3, at each 10 Hz injection cycle a thermionic RF gun generates a 2 µs s-band bunch train with bunches separated by 350ps. A synchronized 'chopper' module is designed to select approximately 7 s-band bunches from the 2 µs bunch train, or ~2.5 ns of charge. Ideally, this charge is captured a single 2.8 ns booster RF bucket.

In practice, however, more than 7 s-band bunches pass through the chopper which can lead to charge spill into adjacent booster buckets (Fig. 4). As illustrated in Fig. 5, when the booster charge is transferred to SPEAR3, satellite bunches are generated.

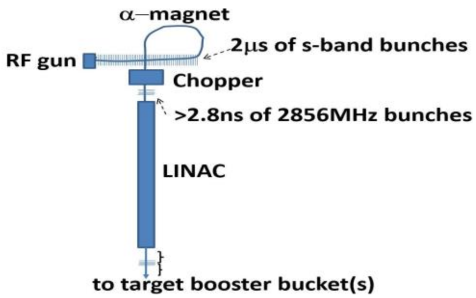


Figure 3: SPEAR3 pre-injector showing charge transfer from the electron gun to linac and booster.

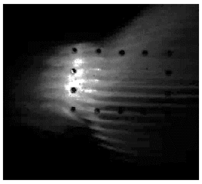


Figure 4: Camera image of the linac output beam prior to injection into the booster. s-band bunches are dispersed vertically due to action of the chopper and horizontally by dipole dispersion.

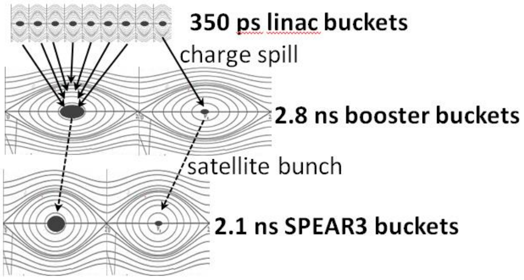


Figure 5: Charge spill from the linac bunch train generates satellite electron bunches in SPEAR3.

By adjusting the time between the linac and the booster, it is possible to minimize but not eliminate satellite bunches. Figure 6 shows measurements of the charge in the early and late satellite bunches in SPEAR3 as the SPEAR-to-Booster RF timing was adjusted. Jitter in the timing system and charge diffusion in longitudinal phase space can also lead to satellite bunches. When the bunch-by-bunch feedback system becomes operational in 2018 it will be possible to study charge diffusion directly [10].

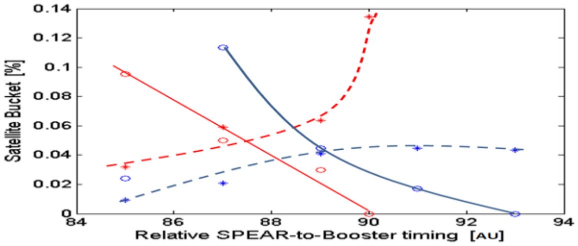
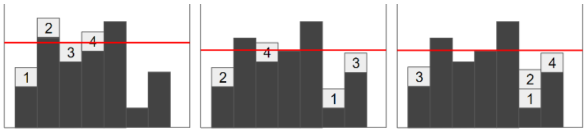


Figure 6: Early ('o') and late ('*') satellite bunch charge by percentage as a function of SPEAR-to-booster timing as for two linac timing settings (blue, red).

TOP-UP CONTROL

The current software algorithm used for charge topup targets numerically consecutive RF buckets in SPEAR3 during injection Fig. 7 (a). Although the total beam current is restored each top-up cycle, injection irregularities can create high and low charge bunches. To reduce or eliminate this effect, the bunch current pattern measured with TCSPC can be used to re-specify the injection filling sequence to achieve the desired result.

The simplest algorithm is to sequentially inject into bunches sorted from lowest to highest charge Fig. 7 (b). A more robust algorithm is to pre-calculate the impact of multiple injection shots into charge-deficient buckets Fig. 7 (c).



(a) (b) (c)

Figure 7: Results of using the consecutive refill pattern (a), the sorted refill pattern (b), and multi-shot refill pattern (c). Red lines indicate median bunch current after four refill shots.

Since TCSPC measures the bunch pattern in the terms of photon arrival events, the average number of counts per injector pulse can be calculated from

$$\frac{Count}{Shot} = \frac{Count}{Charge} * Q_{shot} = \frac{Count}{Charge} * (I_{shot} * t_{rev})$$

where

$$\frac{Count}{Charge} = \left(\sum_{buckets} x_i\right)(I_B * t_{acq})^{-1}$$

with I_{shot} the injected electron current per shot, t_{rev} the SPEAR3 revolution time, χ_i the TCSPC counts per bucket, I_B the total current and t_{acq} the acquisition time.

To evaluate efficiency of a topup algorithm, the standard deviation in charge across all bunches can be used as a metric. A Monte Carlo algorithm was used to compare the standard deviation in randomized bunch patterns for different top-up scenarios: the simulator artificially generated different bunch patterns and the injection algorithm attempted to reduce the rms spread of bunch charge [5]. As expected, the multi-shot algorithm is able to out-perform the single-shot sorting algorithm.

SOFTWARE ARCHITECTURE

In order to automate data acquisition and processing, the PicoHarp300 has been integrated into a Matlab/EPICS software architecture. The Matlab portion contains an outside 'wrapper' that provides a heartbeat to the EPICS control system (Fig. 8). At each heartbeat cycle, the wrapper software also calls a 'core' Matlab program that acquires and processes the data. In practice, the heartbeat operates at 1 Hz and the data is acquired every 5 sec. An additional, time-integrated histogram is accumulated every nth iteration of the 5 sec measurements where the accumulation variable 'n' is user-selectable.

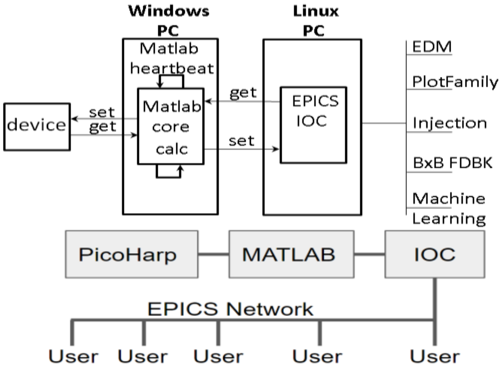
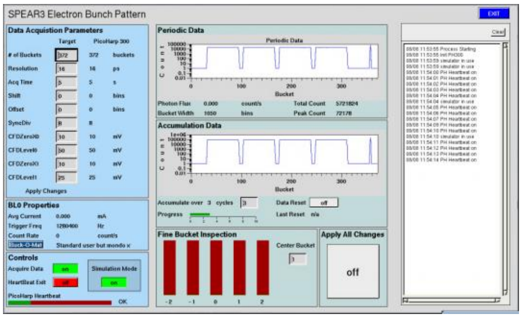


Figure 8: Schematic of the software architecture.

At each heartbeat cycle the PicoHarp300 data acquisition parameters are downloaded from EPICS, and at each 5 sec cycle both the full histogram waveform and the bunch current in all 372 buckets are uploaded to EPICs. The Matlab code can be compiled to increase operational stability.

On the EPICS side, a stand-alone input-output controller (IOC) was constructed to act as a server with a custom EPICS database. Figure 9 shows the EPICS EDM panel used to control the measurement parameters and display the raw data. External users can also acquire the raw or processed data using Channel Access (C/A) to query the IOC. Control of the PicoHarp300 data acquisition system is possible through either Matlab or EPICS using C/A. For instance, a separate TCSPC analysis application can instruct the bunch-by-bunch feedback system to remove charge from unwanted satellite bunches or the bunch pattern can be plotted in the MML Plotfamily interface. At each 5 sec heartbeat cycle, key parameters are stored in the EPICS history buffer database.


SPEAR3 Electron Bunch Pattern

Data Acquistion Parameters

	Target	PicoHarp 300	
# of Buckets	372	372	buckets
Resolution	16	16	ps
Acq Time	5	5	s
Shift	0	0	bins
Offset	0	0	bins
SyncDiv	8	8	
CFDZero0	10	10	mV
CFDLevel0	50	50	mV
CFDZero1	10	10	mV
CFDLevel1	25	25	mV

Periodic Data

Photon Flux 0.000 count/s
Total Count 5721824
Bucket Width 1050 bins
Peak Count 72178

Accumulation Data

Accumulate over 3 cycles 3
Data Reset off
Last Reset n/a

BL0 Properties

Avg Current 0.000 mA
Trigger Freq 1280400 Hz
Count Rate 0 count/s
Standard user but mondo x

Controls

Acquire Data on
HeartBeat Exit off
Simulation Mode on
PicoHarp Heartbeat OK

Fine Bucket Inspection

Center Bucket 1

Apply All Changes off

Figure 9: EPICS EDM panel to control and monitor Matlab software.

Overall, the Matlab/EPICS software connection is one instance of several systems at SPEAR3 utilizing similar machine-independent software for the Matlab heartbeat and EPICS EDM panel for software uniformity. A Unix Watchdog system monitors the heartbeat communication of all applications running on the Unix servers including the Matlab/EPICS processes described here [7]. When an abnormal event occurs, audio and visual alarms are raised and the event is recorded in an error log.

SUMMARY

By recording single photon arrival events synchronized to the storage ring revolution clock, the TCSPC histogram measurement can reveal the bunch pattern with high dynamic range. The bunch pattern data can be used to specify when to remove unwanted satellite bunches or specify the next top-up injection sequence.

To facilitate operations, the data acquisition system is controlled by a Matlab program to acquire and process the raw data and maintain a monitored heartbeat for the EPICS control system. By choosing Matlab for the data processing, complex algorithms are easy to test and deploy in either native m-file or compiled format.

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