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Bunch Purity Measurement for DIAMOND

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Abstract

Measurement of the fill pattern of synchrotron storage rings is important for several reasons, including checking the quality of the injection system and the generation of special fill patterns for time-resolved experiments. For the new national X-ray facility based on the Diamond 3GeV electron storage ring, it is planned to measure the beam quality in a short time of several minutes by using a time-correlated single photon counting method. The method has very good time resolution (50 ps) and high dynamic range (more than six orders of magnitude). In this paper, we describe our experimental setup, a series of tests to evaluate the system limitations using short pulse lasers on laboratory test benches, the existing SRS national X-ray facility, and the third-generation synchrotron radiation facility SLS. Taking all these results together, we are able to predict the system performance for Diamond.

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Technical note

Bunch purity measurement for Diamond

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Abstract

Measurement of the fill pattern of synchrotron storage rings is important for several reasons, including checking the quality of the injection system and the generation of special fill patterns for time-resolved experiments. For the new national X-ray facility based on the Diamond 3 GeV electron storage ring, it is planned to measure the beam quality in a short time of several minutes by using a time-correlated single photon counting method. The method has very good time resolution (50 ps) and high dynamic range (more than six orders of magnitude). In this paper, we describe our experimental setup, a series of tests to evaluate the system limitations using short pulse lasers on laboratory test benches, the existing SRS national X-ray facility, and the third-generation synchrotron radiation facility SLS. Taking all these results together, we are able to predict the system performance for Diamond.

Keywords: Synchrotron; Bunch purity; TCSPC; Diamond light source; Lasers

1. Introduction

The Diamond synchrotron light source is the UK third-generation light source [1]. Many electron storage rings used for X-ray and UV synchrotron radiation (SR) production have a requirement to generate bunch filling patterns with particular time structures. The so-called 'single bunch' mode for example has only a few of the available stable radio-frequency (RF) buckets populated with electrons, the others being kept empty. User experiments on these SR sources typically require the pattern to be as exact as possible, with ideally no electrons in unwanted bucket/bunch positions: a typical ratio of $>10^5:1$ between wanted/unwanted populations is desired—this ratio often being referred to as the bunch purity. The dynamic range of the instrument must of course be better than this. The requirement for Diamond bunch purity is $10^6:1$. To measure the purity of the electron bunch train for the Diamond storage ring, we use a time-correlated single photon counting (TCSPC) measurement system [2–4].

In common with other storage rings where TCSPC techniques are used [5–7], we measure the arrival time of single photons emitted by the electron bunches as they pass through a particular dipole in the storage ring. The photon arrival time is measured relative to a clock pulse which is synchronised to the bunch revolution frequency via the storage ring RF system. The TCSPC system generates a histogram of binned arrival time measurements that represents statistically the relative time distribution of electrons in the storage ring. At Diamond the primary operational mode will be a $\frac{2}{3}$ fill, where 624 consecutive RF buckets from the available 936 will be populated with electrons—the other 312 buckets will be left empty. The RF is approximately 500 MHz giving 2 ns spacing between bunches. Another important mode will be a single bunch mode where six equidistantly spaced RF buckets are populated. The bunch purity instrument should be able to measure the relative number of electrons in each of the

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936 buckets (i.e. a 1.872 μs orbit time) with a dynamic range of at least six orders of magnitude between the populated and unpopulated bunches.

Our system comprises a state-of-the-art single photon detector [8], a Hamamatsu MCP-PMT R3809U-50 microchannel plate detector, and a newly developed stand-alone TCSPC unit, the PicoHarp 300 (PicoQuant—http://www.pico-quant.com). The design of the PicoHarp 300 is different from conventional TCSPC systems as the tasks of the Time to Amplitude Converter (TAC) and the Analog to Digital Converter (ADC) are carried out by the so called Time to Digital Converter (TDC). In brief, the strength of the design is exploited by collecting the unprocessed independent arrival times as a continuous stream and permits uninterrupted data collection. In addition, it allows division of the measured arrival times into as many as 65,536 bins with bin widths from 4 to 512 ps in increments of a power of 2. A 32 ps bin width was chosen so that the full 65,536 histogram width most closely matches the revolution time of 1.872 μs. In order to achieve the best possible instrument response function (IRF), the ideal detector should have a small transit time spread (TTS) that returns fast to zero. The single photon detector currently available with the smallest TTS is the MCP-PMT R3809U-50, which has a TTS of the order of 45 ps, and decays to zero in less than 1.5 ns. We use a Hamamatsu C5594 amplifier which has 36 dB gain and (200 kHz, 1.5 GHz) bandwidth to make the pulses generated by the MCP-PMT more detectable by the PicoHarp 300. This system improves on previous instruments by providing good bunch discrimination similar to that afforded by an X-ray avalanche photodiode detector [7,9] whilst being conveniently accessible due to its use of visible photons from any convenient beamline station.

2. Instrument response function

We performed a series of measurements using short and ultra short pulsed lasers and two SR sources. The laser sources were a Spectra-Physics (Tsunami) titanium sapphire (Ti:Sapph) laser with a 110 fs pulse duration (FWHM), and a laser diode from Advanced Laser Diode Systems with two different laser heads for output at 638 and 399 nm both having pulse durations of approximately 35 ps. Fig. 1 shows the experimental setups for IRF measurement with the two lasers.

Measurements were also performed at the UK (SRS[1]) and at the Swiss (SLS[2]) synchrotron facilities, respectively. At the SRS photons were delivered to the instrument via a beamline consisting of a SiC main mirror reflecting mainly visible light, with collimation and lead glass filtration to remove residual X-rays resulting in an output bandwidth of approximately 350–850 nm.

In the optics hutch of the SLS diagnostics beamline at about 13 m from the source point (in the centre of the 05BX bending magnet of the storage ring), the visible part of the SR is coupled out of the UHV system by a photon absorber (OFHC copper), which is machined to optical quality and reflected by an angle of 45° into an optical transfer line. The TCSPC measurement set-up has been placed at the end of this transfer line (about 10 m downstream) on an optical table, where a synchroscan streak camera system for bunch length studies is also located. Following attenuation using neutral density filters, the SR was focused onto the MCP-PMT placed in a black box.

The important features of the system to be determined for Diamond were the IRF width, the time for the IRF to decay to zero, and the background noise level. Fig. 2 shows the IRF obtained using the four sources.

The minimum IRF width was measured by the laser diode (FWHM of 40 ps) as seen in Fig. 3 and showed that the MCP-PMT signal returns to zero in less than 2 ns. The background noise—laser beam off—was approximately 1 counts/s, which with an acquisition rate of 6×10^5 counts/s permit a greater than 10^6 dynamic range. Reflections are apparent in the IRF measured using the Ti:Sapph (Fig. 2), which are thought to be from the walls of the sample container black box where the MCP-PMT was mounted (see the experimental setup in Fig. 1). The Ti:Sapph measurement also gave a much higher background noise level of over 2000 counts/s, which would increase when the laser was on by approximatively a factor 100. In this case the dynamic range was limited to 10^4, highlighting the importance of isolating the detector from any scattered photons. Hence to improve this, the light was collimated prior to measuring the IRF using the laser diode, and the recorded noise of 1 counts/s was then mainly due to the dark current of the MCP-PMT.

Observation of the full trace of the IRF with the laser diode (Fig. 4) reveals three different after-pulses from the MCP-PMT. The first one, a fast rising pulse 8 ns after the main pulse and five orders of magnitude smaller, decays 10 ns exponentially; the second one, a Gaussian pulse, 1.6 ns width, centered 45 ns after the main pulse and also five orders of magnitude smaller; and finally, a slow rising and decaying pulse, starting 100 ns after the main pulse, extending more than 200 ns, six orders of magnitude smaller. These pulses limit the performance of the system. For Diamond, a spurious bunch in the fourth bucket (8 ns) will not be seen with better than 10^5 dynamic resolution.

The measurement using the synchrotron light sources similarly highlighted the importance of preventing any scattered radiation. As observed at SLS, the dynamic range is mainly limited by SR which is scattered along the optical system and arrives at some later time. A similar effect has been observed during our measurement at SRS. Two ghost reflections (0.5%) at 800 ps and 1 ns after the main single pulse, show the level of the system sensitivity.

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[1] http://www.srs.ac.uk/srs/.

[2] http://sls.web.psi.ch/view.php/about/index.html.

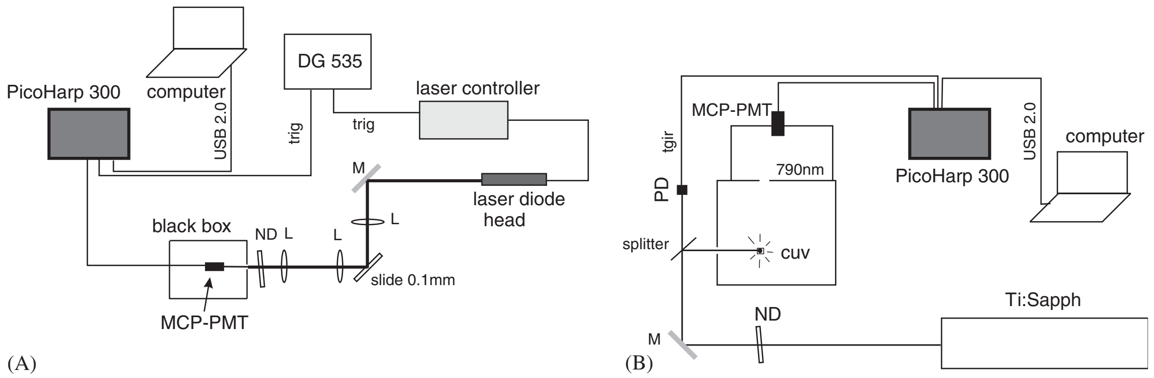

Fig. 1. Experimental setups for the measurement of the IRF, with the red laser diode, setup (A), and with the Ti:Sapph laser, setup (B). With the laser diode, the light is collimated through a small aperture in the black box where the detector is, using mirrors (M) and lenses (L) and attenuated with neutral density filters (ND). We use the DG 535, Stanford Research Systems, to trigger the laser diode and the PicoHarp 300. With the Ti:Sapph laser, the light is attenuated (ND), and then sent through a small aperture to a small cuvette (cuv). The PicoHarp 300 is triggered with the signal of a diode.

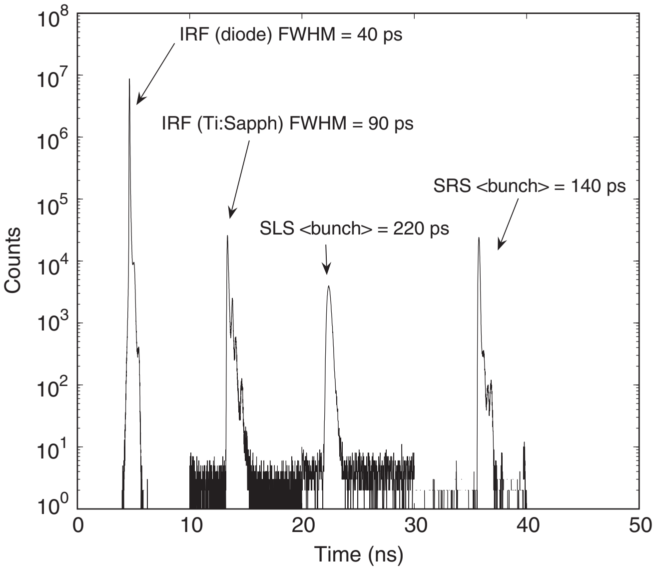

Fig. 2. Instrument response function of our TCSPC measurement system, with two different sources: 120 fs Ti:Sapph laser, 35 ps laser diode; and measurements at SLS with cam-shaft operation mode (80% uniform filling with single bunch(es) in the gap) (2.4 GeV), and at SRS in single bunch mode at 600 MeV.

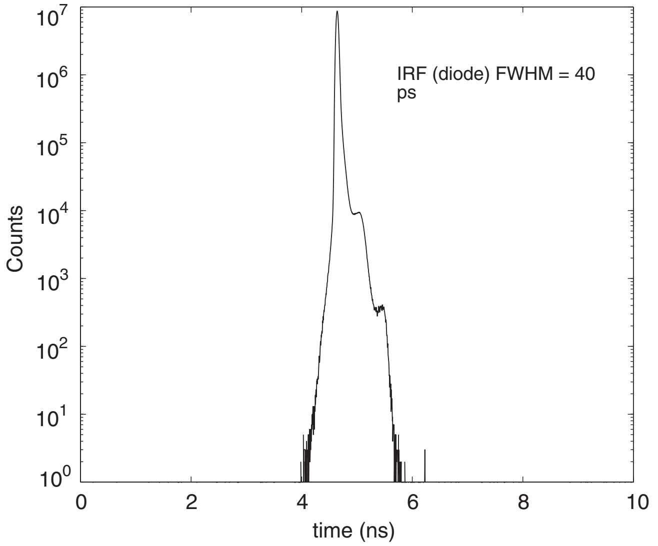

Fig. 3. Instrument response function of our TCSPC measurement system, with a 35 ps laser diode; The noise is of the order of 1 count/s. It is mainly due to the dark current of the MCP-PMT as a result of a good collimation and the measurement performed in a dark room.

3. Measurements with synchrotron radiation

To test the system in conditions similar to Diamond, we performed experiments with the PicoHarp 300 at SRS and at SLS. The main RF of these two rings is at 500 MHz, which is the same as Diamond, so that the electron bunches are separated by 2 ns. Fig. 5 shows the single bunch mode pattern from SRS. A main single bunch can be observed at 20 ns, together with a series of secondary so-called spurious bunches before and after the main one. In addition, at 29 and 65 ns, two signals not originating directly from the electron beam can be seen. As commented above, these two signals are part of the MCP-PMT response signal.

Details of the single bunch at SRS can be seen in Fig. 2. Two reflections coming from the vacuum exit window and the lead glass can be seen at 0.8 and 1 ns, respectively. The resolution of the instrument allows measurements of the bunch length (140 ps FWHM)—the jitter due to the synchrotron oscillations and the electronic jitter contributes to the measurement and cannot be separated although this measurement is close to what has been measured by other means [10]. The resolution of the instrument is not however sufficient to measure the 10 ps rms bunch length at Diamond.

The measurement at SLS provided further insight into the performance of the PicoHarp 300 (see Fig. 6). At 4.5×10^6 count/s the fill pattern is recorded in 5 s. In Fig. 7, a zoom of the fill pattern shows the individual bunches separated by 2 ns. Therefore, it is possible to measure the entire bunch train in a short time and with sufficient resolution to access details of individual bunches.

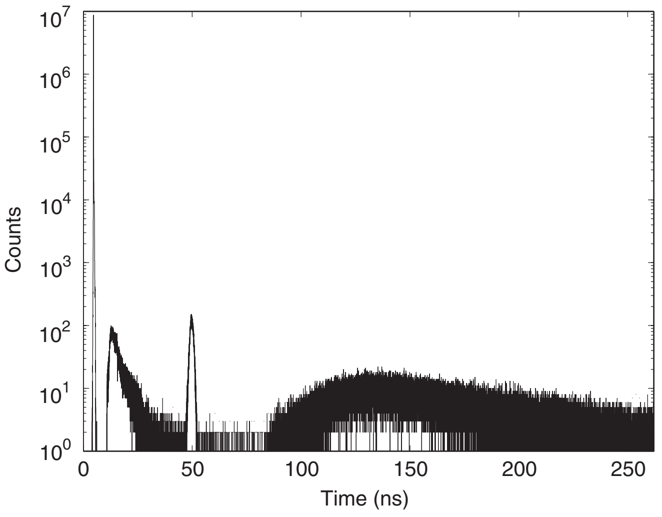

Fig. 4. Full scale of the IRF recorded with the 35 ps diode, with approximatively 1 count/s noise.

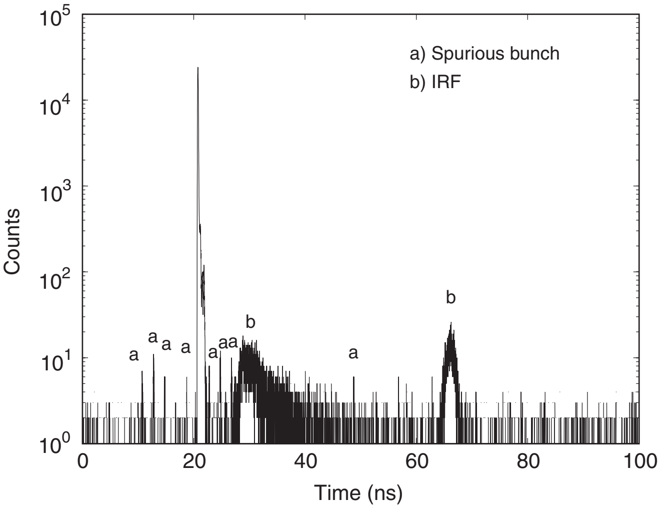

Fig. 5. SRS single bunch mode pattern at 600 MeV. Due to a small current (4 mA) the count rate is only 3000 and the background is 100 counts/s. Spurious bunches (a) can be seen in the adjacent buckets of the main bunch, and the after-pulses of the MCP-PMT (b) as observed in the IRF.

As previously highlighted, the signal-to-noise ratio determines the dynamic resolution of the measurement. The noise observed here was generated by all the uncorrelated photons reaching the MCP-PMT. As seen in Figs. 2 and 5, the detector is highly sensitive to single photons. Every single photon scattered into the measurement chamber has a high probability to be detected, hence contributing to the noise. During the measurement at SRS and at SLS, the detector was in a chamber where the dark current—generated by the MCP-PMT—was the only source of noise. But with the attenuated SR one could notice an important increase of the background level, by a factor 100–1000, thus limiting the dynamic resolution. In these two cases, the scattered SR along the transport beamline is the source for increasing the background level.

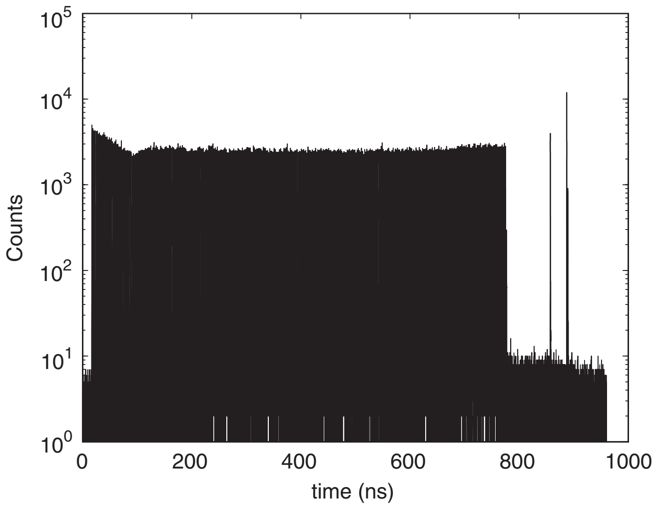

Fig. 6. SLS fill pattern. The count rate is 4.5×10^6 counts/s, so that the histogram has been recorded in 5 s.

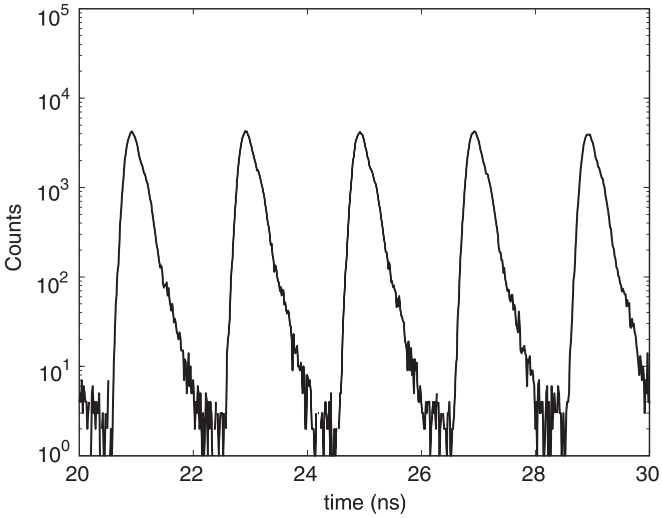

Fig. 7. Detail of SLS fill pattern.

It shows that careful precautions have to be taken to avoid scattering of photons in the optical transfer system through reflections in the beamline and that one should work with a set-up using intermediate focii and apertures to avoid the transport of scattered light through the system.

It is important to comment on the pulse pile-up effect visible in Fig. 6. The number of electrons is nearly the same in the bunches of the train, but the measurement shows a decreasing number in the first bunches, down to a minimum value, followed by a flat top for the rest of the bunches.

This effect is due to a too high count rate of 4.5×10^6 counts/s. At this rate, a photon arrives every 220 ns on average: this is comparable to the dead time of the PicoHarp 300 (95 ns). As a result the probability of a photon from one of the first pulses to be detected is significantly larger than for the rest of the train (as after the gap of 200 ns the TCSPC electronics are always ready to count received photons). A reduction down to 10^6 counts/s, performed on our test-bench, was sufficient to remove the pile-up effect. With such a count rate, we estimate we can measure the Diamond $\frac{2}{3}$ fill mode in about 10 min (624 buckets filled at 10^6 counts/s), and the single bunch mode in several seconds, with a dynamic range of 10^6 in both cases.

4. Concluding remarks

We have successfully tested the PicoHarp 300 TCSPC module combined with the fastest available MCP-PMT to evaluate the possibility of measuring accurately and in a short time the electron beam fill pattern at Diamond. The PicoHarp 300, with 16-bit histogram capability, 4 ps resolution, and 10^7 counts/s acquisition rate appears to be an excellent instrument adapted for our beam quality measurement. By using short and ultra-short pulse lasers, it has been shown that the IRF can be as short as 40 ps which decays to zero in less than 2 ns. The 32 ps times 16 bit histogram ensures the possibility to measure a complete 1872 ns fill pattern at once. The speed of acquisition, up to 10^7 counts/s, allows short-time measurements from several seconds to several minutes. The tests performed with synchrotron radiation demonstrated the performance of the measurement system. The system can detect as fast as 10^6 counts/s without showing any pulse pile-up effect, which would lead to several minutes for a measurement of the $\frac{2}{3}$ fill pattern of Diamond, and several seconds for a single bunch mode. The sensitivity of the detector requires a very good collimation of the synchrotron light, with no scattering so that the only limitation to the dynamic resolution is the dark current noise.

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