# TIME DOMAIN MEASUREMENTS AT DIAMOND

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*Abstract*

We present a set of four complementary measurements of the synchrotron visible light to characterise the stored electron beam at Diamond in the time domain. The electron bunch profiles and its evolution are measured with picosecond accuracy using a dual sweep streak camera. The beam dynamics are also given by a fast photodiode connected to a fast oscilloscope. The fill pattern is measured using a time correlated single photon counting system which has a high dynamic range for bunch purity measurement, and a fast averaging card which gives the fill structure with high accuracy within a short integration time. We describe our set of instruments, discuss their performance and show first results from measurements at Diamond.

## INTRODUCTION

Diamond is the UK third generation synchrotron light source and has been commissioned in 2006 [1]. During this period many diagnostics for the electron beam have been developed and successfully integrated in the diagnostic control system. This includes a set of diagnostics related to characterising the time domain properties of the stored electron bunches using synchrotron light. To measure the electron beam longitudinal profile and dynamics we use a dual sweep streak camera, a fast 25 GHz bandwidth diode, a photon counting system, and a fast averaging card. These four systems produce a complete picture of the time-domain behaviour of the stored electrons. They all use the visible light from a bending magnet for which the beam line is described in [2]

In this paper we firstly present in detail these four measurements. The streak camera measures the single bunch profile in a single shot. The fast diode gives a complementary picture of the streak camera in the frequency domain. To measure the electron beam fill pattern a single photon counting system is used, and the complementary measurement is performed using a fast averaging card. We will then compare all these measurements in a second section before giving some concluding remarks.

## TIME DOMAIN MEASUREMENTS

### *The dual sweep streak camera*

The dual sweep streak camera (SC) from Optronis converts the time structure of a photon pulse into a linear deflection along one axis of a charged coupled device (CCD). Detailed descriptions of SCs can be found in [3, 4, 5]. Our choice for the streak camera was determined by the resolution of the fast axis of the camera (2 ps), the ability to use a synchroscan sweep at 250 MHz, half the RF cavity frequency (the same frequency would be ideal), and the second sweep covering the entire range sweeping across from several bunches to many thousands of storage ring revolution (1.3 ns to 65 ms). We have been performing beam longitudinal measurements at Diamond with the SC from the early days of commissioning. We have been measuring bunch profiles as short as 16 ps as predicted by the energy spread measurements, the RF cavity voltage readout, and the momentum compaction factor. We expect to measure shorter bunch profile with the installation of our second RF cavity which will bring the voltage to 3.3 MV instead of 2 MV for the latest measurements. In addition, operation with a very small momentum compaction factor should produce electron bunches of 1 ps r.m.s, which will put the SC to its limit.

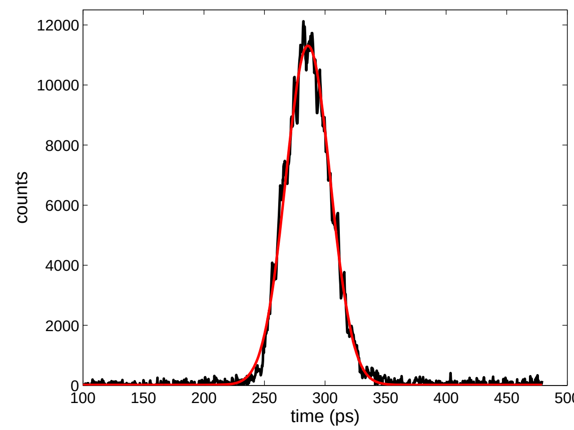


Figure 1: Single bunch profile calculated from SC image. The current is 0.1 mA and the r.m.s bunch length is 16 ps.

**Resolution of the SC** As the SC produces images, the resolution is given by the FWHM of the point spread function. In our case the smallest point spread function is 5.5 pixels FWHM. On the fast axis, the best resolution for the fastest sweep is 0.139 ps/pixel, which makes 0.7 ps FWHM spot size, and the resolution of the streak camera is specified to resolve two pulses spaced by 2 ps. On the slow sweep axis, this resolution varies between 50 ps (9.2 ps/pixel) to 0.38 ms (0.0695 ms/pixel). The detection level of the camera is very low. At Diamond, measurements of single bunch with 0.1 mA (187 pc) current can be done in a single sweep. This corresponds to visible light pulses of 10 mW peak power. Figure 1 shows such a measure-

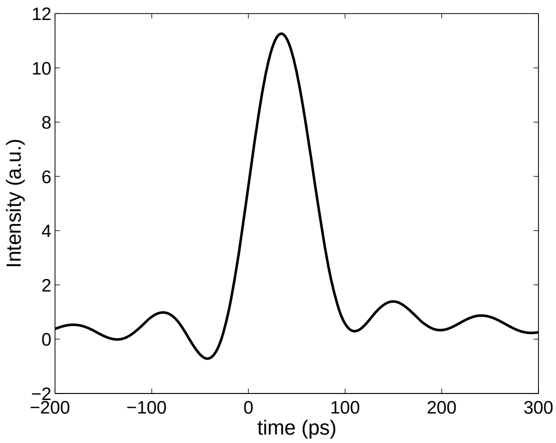


Figure 2: Diode 1481-S-50 response measured with a 10 GHz real time oscilloscope. The input pulse is a 33 ps FWHM laser pulse at 638 nm.

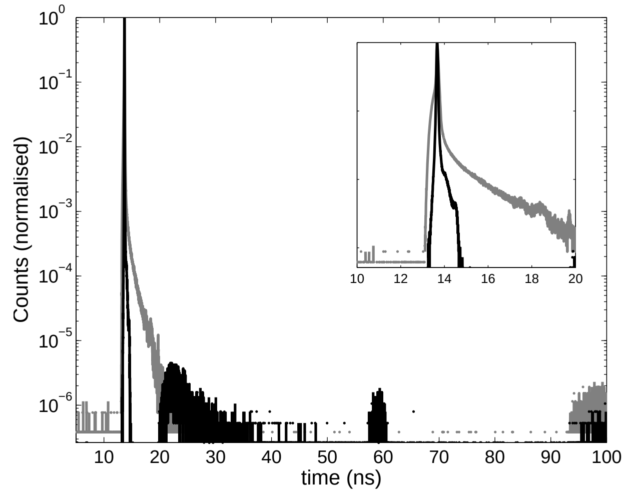


Figure 3: TCSPC IRF with the MCP-PMT (dark line) and with the id-100-20 (gray line).

ment.

For Diamond, the SC is used to measure accurately the bunch profile with a r.m.s length expected to be as short as 10 ps and at low current (typically 0.1 mA). In addition the slow sweep unit permits to measure a train of pulses and study their longitudinal dynamic, from bunch-by-bunch to 35000 turns.

## *The fast diode*

Beam longitudinal dynamics can be studied as well in the frequency domain. For that we use a 25 GHz Bandwidth diode (1481-S-50 from New Focus) either connected to a 10 GHz bandwidth oscilloscope or to a 27 GHz bandwidth spectrum analyser. The resolution of the system in the time domain is shown in figure 2. In this measurement, the FWHM is 67 ps which determined by the bandwidth of the oscilloscope. However, analysing the output of the fast diode on the 27 GHz bandwidth spectrum analyser will allow to investigate longitudinal characteristics by Fourier transform the synchrotron light signal, which covers most of the observable phenomena in the electron beam dynamics. As this fast diode has a sensitivity of only 10 V/W and the peak power of the synchrotron radiation in the visible beam line 18 $\mu$W/mA for a 2/3 fill, the detection level is estimated to be $\approx 100$ mA stored beam.

## *The TCSPC system*

In order to measure the beam fill pattern and the single bunch purity, we use a Time Correlated Single Photon Counting system. It is composed of a fast single photon detector, in our case we use either the MCP-PMT RU380-50 from Hamamatsu or the id100-20 from id-Quantique. To count the photons detected, we use the PicoHarp300 from PicoQuant as a stand alone TCSPC module. Figure 3 shows the instrument response functions (IRF) of the two detectors. It shows the limitations for bunch purity measurements. The MCP-PCT has a very clean signal, rising and decaying by more than 7 orders of magnitude in less than 2 ns. However, the MCP-PMT has a probability of $10^{-5}$ to emit a signal from a detected photon with 9 ns and 45 ns delays [4]. With such a behaviour, the MCP-PMT is the better of the two detectors for bunch purity measurement with single bunch fill pattern, but in an hybrid fill pattern, having 2/3 of the buckets filled and one isolated bunch in the gap, the delayed pulses limit the dynamic resolution to $10^3$. In contrast, the diode has a comparatively long trailing edge, which has decayed 5 orders of magnitude 2 ns after the main pulse. Therefore the diode limits the dynamic resolution to $10^5$ for a bunch purity measurement with single bunch fill. Nevertheless, this allows to measure a hybrid beam fill pattern with 5 orders of dynamic resolution. The minimum power detectable by this system is very low, we can detect as little as 1 pC stored in a bunch. However, in order to achieve a rate of 1 Count per revolution ($533 \cdot 10^3$ counts/s), the average flux needs to be of the order of several nW.

## *The fast averaging system*

The fill pattern of the electron beam is also measured with a 1 GHz bandwidth diode coupled to a fast averaging card (AP200 from Acqiris). This card has a 2 GS/s sampler (clocked at externally supplied quadrupled RF frequency) and facilitates realtime averaging. We can thus produce an average of measurements over 20000 turns consisting of 3744 samples (4 samples per 936 buckets) at an update rate of 13 Hz. This results in a fast measurement of the fill pattern with better than 0.5% resolution on the charge per bucket. Figure 4 compares measurement of the 2/3 fill pattern at 83 mA stored current, with the picoharp300 and the

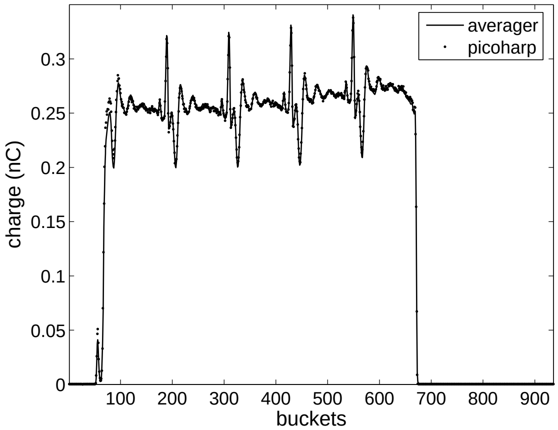


Figure 4: Measurement of the fill pattern with the picoharp300 and the fast averaging card. The traces are normalised using the total stored charge (156 nC). The agreement between the two traces is better than 1 %. The noise floor is $\approx 0.5$ % from the averager and it is $\approx 0.005$ % in the picoharp300 measurement.

AP200. The agreement between the two measurements is very good. We note the noise floor of the averaging card is about 0.5%. It isn't shown in the figure as it has been removed due to the normalisation of the recorded trace. We intend to use this system for top-up operation with fill pattern feedback allowing a re-assessment of the fill pattern after each injector shot at 5 Hz.

## CONCLUDING REMARKS

With this set of 4 measurements, we are able to characterise the longitudinal profile of the stored electron beam. The SC is able to measure real time single pulse profile, with 2 ps resolution. It is able as well to follow the dynamics of the stored bunches from individual bunches to 35000 turns. As a complementary measurement we can use a fast photodiode which to give temporal information on a real time oscilloscope or frequency domain information on a broadband spectrum analyser. The fill pattern is measured with two complementary systems, one is a TCSPC measurement, and the other is averaging a sampled trace. The TCSPC is by far the most accurate, but needs time for acquisition, whereas the averaging system can measure the fill pattern within fractions of a second and reasonable resolution. In addition, single bunch purity can be measured with better than 6 orders of magnitude using the TCSPC system. Table 1 summarises the performance of each of these four measurement systems. A number of future improvements is possible. Firstly, the use of a fast repetitive sampling scope with considerably larger bandwidth (instead of the 10 GHz realtime scope). Secondly, the use of a broadband, low noise amplifier after the fast photo diode should lower the detection limit. Finally, for the TSCPC system, a detector with the same fast decay like the MCP-PMT, but without the observed delayed pulses would be ideal.

## REFERENCES


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Table 1: Comparison of the system performances

| | Streak camera | Fast diode | Photon Counting | Fast Averager |
|---|---|---|---|---|
| Single shot | yes | yes | no | yes |
| IRF (FWHM) (ps) | 2 | 17 | 40 | 1000 |
| temporal quantisation (ps) | 0.139/pixel | 25 [a] | 4 [b] | 500 |
| shortest measurement time | 1 sweep | 1 sweep | - | 1 turn |
| typical measurement time | 1 sweep | < 1 ms | 5 s | 20000 turns |
| Dynamic range (bits) | 16 | 8 | 16 [c] | 8 [d] |
| Detectable charge (pC) | 200 | 30 | <1 | 2 |

[a] with 40Gs/s 10 GHz bandwidth oscilloscope
[b] to cover the full turn of 1,872 ns with the 65536 bins, a 32 ps quantisation has to be selected
[c] the TCSPC system has 16 bits bin depth in hardware. Further counting can be realised in software.
[d] the sampler has 8 bit resolution, averaging over $n$ acquisitions increases the resolution by $\ln(\sqrt{n})/\ln 2$