BUNCH LENGTH MEASUREMENT FROM POWER FLUCTUATION AT DIAMOND

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Abstract

Bunch length can be measured using the visible light power fluctuation statistics of an individual bunch. This method developed at ALS has been implemented at Diamond with further improvement on the detection method and the speed of the measurement. In this paper, we firstly report on the development and implementation of the method. We will show the performance of several detector diodes used and the limits of the method. Validation of the method will be demonstrated against streak camera measurement with picosecond long bunches. Before concluding, we will discuss about the strengths and weaknesses of the method.

INTRODUCTION

Bunch length is becoming an important parameter of modern synchrotron light sources as time resolved experiments demand the bunch to be as short 1 ps or less. Non destructive measurements of such short bunches pulses are difficult and not very many techniques have been developed so far. Mainly, all the techniques rely on the measurement of the synchrotron radiation pulse envelop, which for very short pulses carries the additional difficulty that these pulses have very weak intensity [1]. Well established streak camera measurements are limited to 1-2 ps range [2][3], however it constitutes a benchmark for the recently developed techniques. For example, cross-correlation technique using second harmonic generation in a frequency doubling crystal, which is a non-linear process and requires high intensity pulses to work, has been developed and applied at SPEAR III for the measurement of r.m.s 2.4 ps bunches [4]. The technique, being well established for high intensity laser pulses, is proven to work but needs many minutes to perform a measurement. Therefore, any jitter due to synchrotron oscillations will be integrated in the measurement. At the same time, another technique has been developed at APS [5]. It is based on the statistical properties of the pulse intensity with a coherence length much smaller than the pulse envelope. Following this original work, we have been investigating and developing this technique at Diamond. In this paper we will firstly recall the principle on which the method is based. Then we will comment on the choice of the detector and express the precision and accuracy required in the measurement. Finally, and before concluding, we will present a measurement of the bunch length varied as function of the RF cavity voltage in the range 10 ps to 20 ps.

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BUNCH LENGTH FROM INTENSITY FLUCTUATION

The method described here and explained in more detail in [5] is based on the measurement of the statistics of the pulse intensity fluctuations. If the pulse satisfies the following conditions, then the pulse width σ_τ can be measured: the pulse spectral bandwidth, σ_w is large enough so that the pulse coherence is very small, i.e. $\sigma_\tau\sigma_w > 1/2$. Also the angular spread and the source size are assumed to be small compared to the bandwidth, satisfying the following relation: $\sigma_w \ll c/\sigma_s\sigma_\theta$, with c the speed of light in vacuum, σ_s the source size, and σ_θ the angular spread of the beam. The last assumption is that all distributions, i.e. the pulse envelope and the spectrum are Gaussian. Then the relative intensity fluctuation δ is given by the following expression:

$$\delta^2 = \frac{\sigma_I^2}{< I >^2} = \frac{1}{\sqrt{(1 + 4\sigma_w^2\sigma_\tau^2)T}} \quad (1)$$

with σ_I the standard deviation of the pulse intensity, $\langle I \rangle$ the mean pulse intensity, $k = \frac{2\pi}{\lambda}$, $\sigma_{x,y}$ the source size, and $T = (1+(4k\sigma_{\theta_x}\sigma_x)^2)(1+(4k\sigma_{\theta_y}\sigma_y)^2)$ takes into account the fluctuation due to the beam transverse coherence.

From equation 1, one can see that the bunch length, represented by the synchrotron radiation pulse can be measured, by measuring statistical intensity fluctuation of a narrow spectral bandwidth pulse.

Measurement Precision and Accuracy

The measurement of the pulse intensity can be done using a photodiode or an avalanche photodiode (APD) which will provide a larger signal to noise ratio. In order to measure δ, two noise contributions from the photodiode need to be properly characterised. One is the broadband noise produced by the diode (including amplifier, scope). It can be measured directly with no pulse signal. This noise needs to be very small because it will influence the precision of the measurement. The other characteristic of the diode is the excess noise factor. This is the statistical fluctuation of a constant intensity measured signal. The excess noise factor plays an important role in the accuracy of the measurement.

The measured statistics of the pulse intensity can be expressed as follow:

$$\delta^2 = \delta_M^2 - f(\zeta, \langle I \rangle) = \frac{\sigma^2 - \sigma_0^2}{(\langle I \rangle - \langle I_0 \rangle)^2} - \frac{\alpha\zeta^2}{\langle I \rangle - \langle I_0 \rangle} \quad (2)$$

where δ_M is the measured pulse intensity standard deviation over mean squared, $f(\zeta, \langle I \rangle)$ is the excess noise, σ_0

and $\langle I_0 \rangle$ are the standard deviation and the mean intensity of the broadband noise of the diode, ζ is the excess noise factor and α a proportionality constant factor.

The pulse width is given by equation 1:

$$\sigma_\tau = \frac{1}{2\sigma_w}\sqrt{\frac{\delta^{-4}}{T} - 1} \quad (3)$$

The relative uncertainty in the measurement of σ_τ is given from differentiation of 3:

$$\frac{\Delta\sigma_\tau}{\sigma_\tau} \simeq \frac{\Delta\sigma_w}{\sigma_w} + \frac{2\Delta\delta}{\delta} + \frac{\Delta T}{2T} \quad (4)$$

The bandwidth σ_w and the transverse mode fluctuation T are constant and can both be calculated or measured with good accuracy. For δ, the uncertainty on δ_M can be reduced with a large number of measurement as $\Delta\delta_M/\delta_M \simeq 1/N$. However, depending on $f(\zeta, \langle I \rangle)$, the relative uncertainty is limited by $\frac{\Delta\left(\delta_M^2 - f(\zeta,\langle I \rangle)\right)}{\delta_M^2 - f(\zeta,\langle I \rangle)}$, the signal difference being the limiting factor as the fraction may never converge. As discussed in [5], for an expected accuracy in the measurement, a sufficiently large number of photons in the detector is required so that $f(\zeta, \langle I \rangle)$ becomes small enough compared to δ_M^2, allowing the measurement to be done.

Detector Selection

The photodiode performance can by specified from equation 2, together with the pulse intensity to measure. In brief, the photodiode should have a very low noise and a sufficiently large gain in order to measure δ_M with high precision. We have been testing a number of photodetectors, and here we show only a few as examples. Table 1 presents the evaluation of the pulse peak power that equals the noise level of the detector. The calculation is based on the manufacturers specification. We compared the noise power of the photo-detector to the detected synchrotron radiation power in a narrow bandwidth produced by a 0.1 mA stored electron bunch and transmitted by the Diagnostics beamline. The Newfocus 1 GHz bandwidth 1601 diode shows a signal to noise not so large compared to the power of the pulse to be measured. The Newfocus photodiodes show a very small signal to noise ratio and attempt to perform a measurement with larger bunch current was not successful because the measurement was dominated by the excess noise. The Perkin Elmer APDs show a very large signal to noise. The C30902S was used in [5], here we used the C30902S-DTC which shows a larger signal to noise because it is temperature cooled. However, a careful characterisation of the excess noise is required to perform an accurate measurement of the bunch length. In the next section, we will present the experimental setup and the preliminary required characterisation of the photodetector before bunch length measurements are possible.

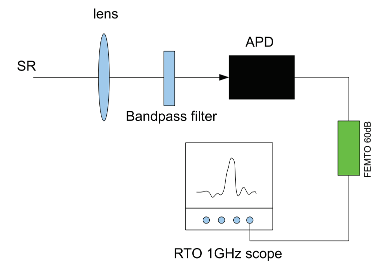

Figure 1: Experimental setup. The filtered synchrotron radiation is focussed onto Perkin Elmer C30302S-DTC APD. Then the APD signal is amplified by a FEMTO 60 dB amplifier before being recorded by Rohde & Schwarz RTO scope.

MEASUREMENT SETUP

For the measurement we chose the APD C30902S-DTC from Perkin Elmer which has been integrated in an EMC box. The EMC ensured that no parasitic signal was coupled to the measurement. The diode chip is mounted on a Peltier element which has been combined with a PID controller to operate the APD at a fixed temperature of -20 deg. C. The control of the temperature is essential, because it stabilises the gain together with the excess noise factor of the APD. Also operating at low temperature enhances the signal-to-noise. For the acquisition of the pulse intensity we used a recently released oscilloscope, the RTO Scope from Rohde & Schwarz, which has the capability to perform measurement and histogram over 10^6 recorded traces per second. This ensured a very high precision of our measurement since all the 533520 pulses per second (revolution frequency of Diamond storage ring) are captured for the intensity histogram. In addition to the cooled APD, the use of this scope constitutes a real (technical) improvement from the original method described in [5], since one measurement takes 1 s, providing a precision of $\simeq 0.2\%$. A schematic of the experimental setup is shown in Fig. 1. The synchrotron light from the Diagnostics beamline was simply focussed with a standard lens. The pulse power spectrum was selected using bandpass filters with the choice of several mean wavelengths between 400 nm and 632 nm and FWHM from 3 nm to 25 nm.

BUNCH LENGTH

In order to measure the bunch length, it is necessary to characterise precisely the excess noise, including the bandpass filter, together with the transverse coherence of the pulses. In our case, the coherence is very close to 1, and we evaluate $T \simeq 1.2$ (see [5]). The excess noise, as shown in Fig. 2, is given by the slope of δ_M vs. $1/(\langle I \rangle - \langle I_0 \rangle)$. Fits of the curves in Fig 2 show small variation of the slopes of the order of 5%.

Using the measured value of the excess noise, correction

Table 1: Noise Comparison for Several Diodes. The noise equivalent power (NEP) is extracted from manufacturer data sheets from which we calculate the noise power for 1 GHz bandwidth pulse signal. It is compared with the signal produced by a the bandwidth limited (FWHM 10 nm) synchrotron pulse power reduced to 1 GHz bandwidth, at 0.1mA current, $\approx 1\ \mu$W.

	APD C30902S	APD C30902S-DTC	NewFocus 1601 - 1 GHz	NewFocus 1437 - 25 GHz
NEP (pW/$\sqrt{Hz}$)	0.010	0.001	40	30
Signal/Noise	$3\ 10^3$	$30\ 10^3$	0.8	1

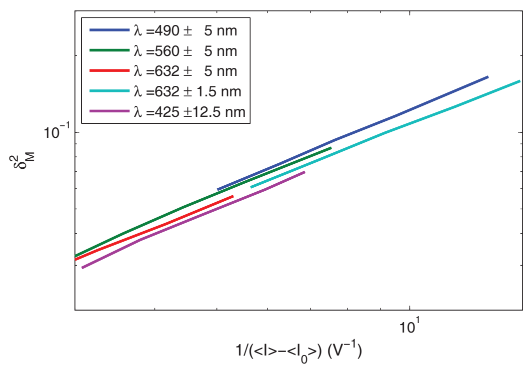

Figure 2: Excess noise measured for several filters.

to δ_M gives δ and the corresponding bunch length using Equation 3. In order to verify the method, we measured the bunch length while varying the RF cavity voltage, using this new method and bench-marked the measurements with our streak camera in the same experimental conditions. Results from the two methods can be seen in Fig. 3. The error bars in both measurements are the standard deviation of the total number of measurements - 30 and 1020[1] for the intensity fluctuation and streak camera respectively. The agreement between the two methods is very good, however, the variation observed by the intensity fluctuation is quite large compared to the streak camera measurements.

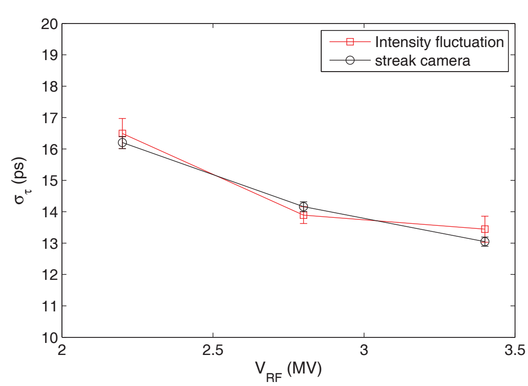

Figure 3: Bunch length as function of the RF cavity voltage, measured with the intensity fluctuation using a 632 ± 5 nm filter (FWHM bandwidth).

[1]For the streak camera, 10 images have been acquired in which 102 profiles give 102 bunch length measurements.

CONCLUDING REMARKS

We have been developing and perform preliminary measurement of the bunch length using the pulse intensity fluctuation properties. The results seem to be in a good agreement with the streak camera measurements, and thereby validate the method. However, some more systematic characterisation of the instrument still need to be done. This would allow to verify the reliability of the instrument. For instance, the method is dominated by the excess noise which needs to be very accurately measured, but also one needs to verify that the measurement is always the same over time, external temperature, etc. Also we have observed nonlinearities in the scope ADCs, which have been addressed by adding a numerical filter to the sample traces, limiting the bandwidth of the signal to 500 MHz. Some further improvement of the method will be investigated with the implementation of a multi-channel analyser (MCA). The MCA is expected to have a better ADC linearity than the scope, so it should combine more precision and accuracy in the measurement. Finally, the method has been implemented in view of performing measurements in low-alpha mode beyond the streak camera limit. As said above, the ability to perform such a measurement will be determined by the excess noise since the low alpha pulses carry very small intensity.

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