A NEW FREQUENCY-DOMAIN METHOD FOR BUNCH LENGTH MEASUREMENT

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Abstract

A new method for bunch length measurement has been developed at ELETTRA. It is based on a spectral observation of the synchrotron radiation light pulses. The single pulse spectrum is shaped by means of an optical process which gives the method an increased sensitivity compared to the usual spectral observations.
Some simulations have been carried out to check the method in non-ideal conditions. The results of the first measurements are also presented.

1 INTRODUCTION

ELETTRA is a third generation synchrotron light source in operation in Trieste since 1993. In the ELETTRA storage ring electrons with energies from 1 GeV to 2 GeV are routinely accumulated, both in Multi Bunch (MB) and in Single Bunch (SB) mode.

The length of the electron bunches in Storage Rings is an important parameter to measure, both for machine Physicists and for Synchrotron Light Users. In fact, the bunch length vs. current curve is necessary when the broadband impedance of the vacuum chamber is evaluated [1]. Similarly, when Users are doing fast time dependent experiments, they need to know the bunch length in order to have an indication of the time resolution of their experiment [2].

2 METHOD DESCRIPTION

2.1 Bunch Length measurements

In third generation synchrotrons, the measurement of the bunch length is not a straightforward task due to the extremely short stored bunches (in the mm range).

For these measurements, optical methods [3] have many advantages over purely electrical ones, particularly in Storage Rings. In these machines, the temporal profile of the intensity of the synchrotron radiation from a bending magnet is an exact replica of the electron longitudinal distribution within the bunch. This train of very short light pulses can be optically transported up to the acquisition point without appreciable distorsion. As a direct consequence, the length of the cable connecting the sensor to the acquisition instrument is reduced to a minimum and so is the Rise Time of the system. At ELETTRA, the synchrotron light of a storage ring bending magnet, already used for other diagnostic purposes [4] [5], has been therefore chosen as the source point for this measurement. The work and the results here reported are part of an Electronic Engineering degree thesis [6] at the Trieste University.

2.2 Method general features

This new method thoroughly exploits the information buried in the short light pulse without using dedicated instruments, like the Streak Camera; it has been developed under the assumption of gaussian light pulses.

This new technique is based on the Frequency-Domain analysis of a fast photodiode response to an optically processed version of the beam produced light pulse. This technique, which makes use of standard laboratory instrumentation, like the Spectrum Analyser (SA), offers an enhanced resolution if compared to usual spectral observations (see next paragraph).

Using a SA for the acquisition, this method does not provide a Single Shot measurement of the bunch length. This feature is not of big concern when dealing with stable beams and triggers. At ELETTRA, this operating condition has been recently checked out in SB mode [7].

Moreover, the input extended dynamic range of the SA [8] could eliminate the need for an amplifier: this is also a major advantage as any element between the source and the acquisition point deteriorates the measurement quality.

2.3 The optical signal processing

The optical signal processing used in this method creates a delayed replica of the original pulse. It is obtained by means of multiple reflections between parallel mirrors. A similar optical arrangement has been used at CERN, by E. Rossa, to perform “Real Time Slice Tomography” [9]. The original pulse, along with its delayed replica, are summed up by means of an ultra-fast photodiode [10], [11]; the output from the photodiode is then sent to the SA.

This “slice and sum” technique generates a modified version of the original pulse spectrum, the modification depending on the introduced optical delay. As a consequence, the SA is not used for an absolute amplitude measurement of the spectral lines, but rather it is used to find a threshold, defined in par. 3, by means of a relative measurement on the whole spectrum envelope. This threshold is searched by varying the optical delay. The bunch length is then computed from the value of the introduced optical delay. This, in turn, can be either directly measured (time observation of the processed signal) or estimated (from the mirror distance).

3 THEORY AND SIMULATIONS

3.1 Theoretical background

The spectrum (see Fig. 1) of the sum of two gaussian time-delayed pulses is given by:

$$H(\omega) = \left| \cos\left(\frac{\omega d}{2}\right) \right| e^{-\frac{\omega^2 \sigma^2}{2}}$$

where:

- $H(\omega)$ normalised amplitude of $F(\omega)$
- σ variance of a single gaussian pulse
- d delay between pulses
- $F(\omega)$ Fourier transform of the sum of two pulses

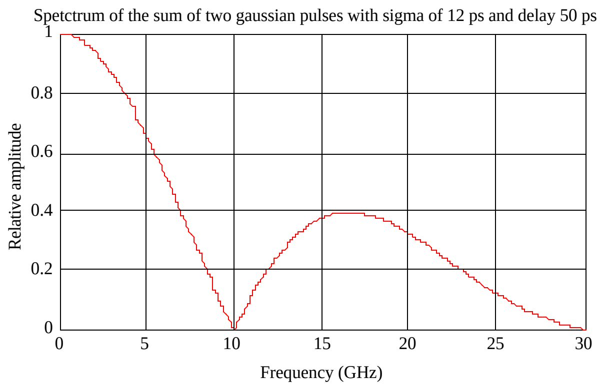

Figure : 1 Theoretical spectrum of the sum of two delayed gaussian pulses (σ=12 ps) with a delay of 50 ps.

The left-hand factor of $H(\omega)$ depends both on frequency and on the delay; it does not depend on σ. The right-hand factor of $H(\omega)$ is the spectrum of a single gaussian pulse; it is independent on the delay. Therefore, by varying the delay *d*, the second peak of the spectrum moves along the spectrum of the single gaussian pulse.

It has been computed a maximum of sensitivity for $d = 0.4428*\sigma$; in that situation the second maximum of the envelope is 43.27% of H(0).

3.2 Simulation set-up overview

Since the stored beam generates a pulse train whose periodicity reflects the machine circumference and its filling mode, simulations have been carried out to evaluate the perfomance of the method when applied to a not purely gaussian pulse.

At first, a model of the MB (80% filling) time structure, normally used at ELETTRA, has been created and its spectrum computed (see fig.2) by means of an FFT algorithm [12].

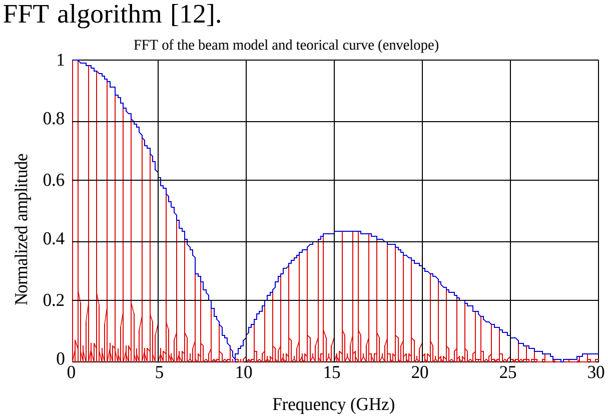

Figure : 2 Comparison between theoretical pulse and MB periodic structure pulses spectra.

Then, distorsions which can be found in real beams, have been introduced into the model, like pulse-to-pulse amplitude and σ variations, longitudinal oscillations, single pulse waveform distorsions from purely gaussian (ringing, tails). The effects of these distorsions on the computed spectrum amplitudes and, therefore, the errors introduced in the bunch length evaluation, were found to be of few percent.

Simulations have also been performed to estimate the spectrum distorsion introduced when using the actual photodiode [11]. A delayed and summed up gaussian pulse has been convoluted with the pulse response of the photodetector. By doing so, the waveform available at the Spectrum Analyser input has been simulated. Then, the spectrum has been computed and the threshold condition searched. The σ obtained in this way has been compared to the σ of the original gaussian pulse. A maximum error of 11 % has been found out, for a range of σ from 12 to 70 ps.

4 FIRST MEASUREMENTS

4.1 Measurement set-up

As already mentioned, the optical delay line has been implemented by means of two square mirrors (see Fig. 3). The first one has been mounted on a motorised translation stage and reflects backwards half of the beam radiation. The second mirror, placed at a fixed location, reflects forwards the radiation from the first mirror. As a result, two parallel beams are created and summed up by the photodiode. The delay between the two pulses is proportional to the distance between the mirrors and can be varied in steps much smaller than a pico-second (Δt=13.3 fs for a 2 μm stepping motor).

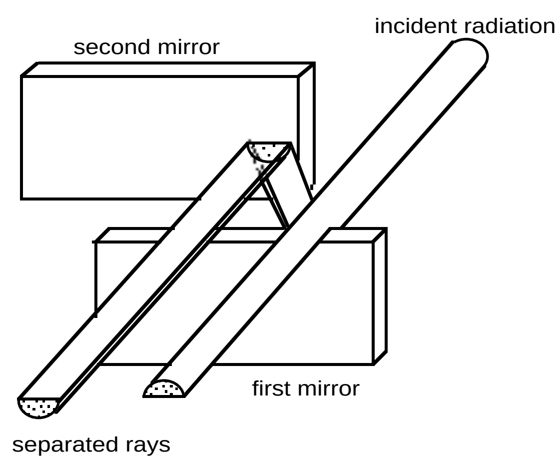

Figure : 3 Schematic of the double mirrors assembly.

A grin lens is used to focus both rays on the active area of the photodiode (25<D<400 μm). The signal from the photo-diode is sent to the Spectrum Analyser with no amplifier in between.

4.2 First results: time-domain observation

Some preliminary observations have been carried out with a 1.5 GHz bandwidth photodiode [10]. The correctness of the method and its practical feasibility have been checked with this component.

The set-up of the optical delay line has been carried out observing in time-domain the photodiode output signal. A Tektronix TDR 7S12 sampling scope, equipped with a 12.4 GHz sampling head, has beeen used. In order to achieve two pulses (see Fig. 4) of the same amplitude the photodiode has been carefully aligned. The 2-ns period of our MB filling is visible as well as the introduced 650 ps delay between pulses.

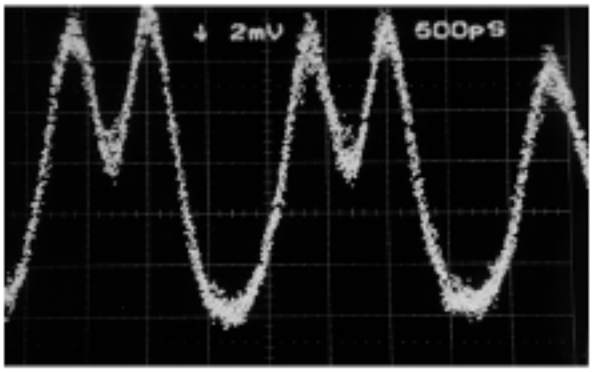

Figure : 4 original pulse and delayed replica relative to two MB pulses (delay 650 ps).

The 650 ps delay is compatible with the slow pulse response of the photodiode (bandwidth limited to 1.5 GHz). To allow an easier time-domain observation the photodiode signal has been amplified by means of an in-house made amplifier with a cut-off frequency of 2 GHz (MAR7 monolitic amplifier from Minicircuit).

4.3 Frequency-domain observations

Some preliminary spectral observations have been performed matching the photodetector directly to a Rhode & Schwarz Spectrum Analyser (model FSMS). The spectral lines from 500 MHz to 3.5 GHz have been measured.

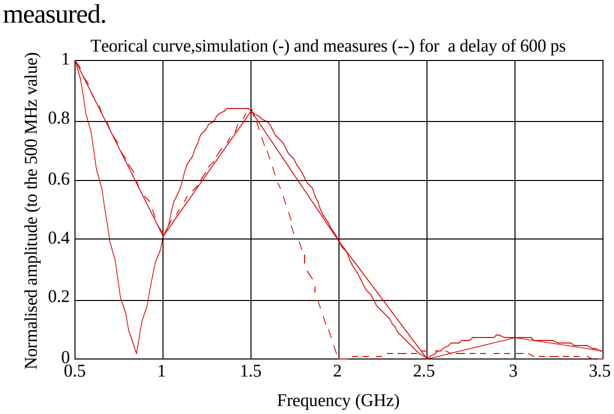

Figure : 5 Comparison between theoretical, simulated and measured spectral line amplitudes.

In Figure 5 these values are compared both with the values obtained in the previously described beam simulation and with the values of the theoretical spectrum of two gaussian pulses. In this simulation, the pulses have been considered gaussian, matching in duration the photodiode pulse response which has been measured with the sampling scope. In the theoretical computation two gaussian pulses with the same σ and delay as in the simulation have been used. The comparison has been made normalising the data to the 500 MHz peak value: a good agreement with the theoretical and calculated values within the band of the photodiode. At 2 GHz the photodiode cut-off is dominant.

5 CONCLUSIONS

A new method for bunch length measurement has been studied at ELETTRA. The theoretical studies have been checked with an extended numerical simulation to analyse the effects on the method due to the actual acquired signal. Preliminary tests has been carried out with a 1.5 GHz photodiode: the results are in good agreement both with the theory and the numerical model.

One major advantage of this method consists in that it uses ordinary laboratory instrumentation, like the Spectrum Analyser.

Future work include extended tests with a wide bandwidth photo-diode to perform a true bunch length measurement in order to fully confirm the validity of the method.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] J. A. Clarke et al., “Revised SRS Impedance Estimates” in EPAC ‘94 London, June 1994

[2] G. Margaritondo, "Synchrotron Light and Free-Electron Lasers", Il nuovo cimento, 1995

[3] E. Rossa, "Picosecond Diagnostics", Optical Engineering, August 1995, Vol.34 No. 8, pp.2353-2360

[4] M. Ferianis et al., "The Optics of the ELETTRA Transverse Profile Monitor” in EPAC ‘94 London, June 1994

[5] M. Ferianis et al., "An Optical System for the observation of Transverse Beam Motion” in EPAC ‘96 Barcelona, June 1996

[6] M. Pros, ”Misura del Profilo Longitudinale del Fascio di Elettroni di ELETTRA”, Degree Thesis at:”Universita’ degli Studi di Trieste”, 1996

[7] M. Ferianis et al., ”Bunch Length Measurements at ELETTRA” Sincrotrone Trieste Technical Note, April 1997

[8] “FSMS Spectrum Analyser”, Rohde & Schwarz

[9] E. Rossa at al., "Real Time Measurement of Bunch Instabilities in LEP in three Dimensions using Streak Camera", EPAC ‘92 Nice 1992

[10] “S 4753, High-speed PIN silicon Photodiode, Technical Data, Hamamatsu Photonics

[11] “High speed Photodetectors”, New Focus inc.

[12] “MATLAB User Manual”, The Mathworks inc.