

TEST OF NEW DIAGNOSTICS FOR BUNCH LENGTH MEASUREMENT

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Abstract

Two new diagnostics for bunch length measurements have been recently tested at the ESRF. The first one is based on the spectral analysis of the visible light beam produced by a dipole. The beam is collimated at the input of a photodiode whose output is connected to a spectrum analyzer. The frequency signature is then equivalent to the longitudinal spectrum of the beam. The second device is based on two HF cavities, tuned at two different frequencies, and coupled to the beam wake fields. Their response to the beam passage gives the component of the beam spectrum at the two specified frequencies, from which the beam profile may be reconstructed. Results for these two devices will be presented and compared to measurements made with a streak camera in order to evaluate them. In particular, the reconstruction of the time profile from the information on frequency will be discussed.

INTRODUCTION

For three years, an effort has been made at the ESRF to obtain the bunch length as an operational parameter. For this purpose, a streak camera is already available, and gives precise and reproducible results [1]. However, for reasons of risk of damage to the streak-Tube it is not feasible to operate the streak Camera in an un-manned and permanent mode.

The initial measurement bench is based on the time domain analysis of the visible light produced by a point like source located in a bending magnet [2]. It has shown to be a very practical diagnostic for wide large bunches and is already operational. Nonetheless, due to the reduced bandwidth (5 GHz) of this device, it is not meant to be operated for short bunches of the order of 15 to 20ps RMS.

We will present the test carried out on two new devices, one also using visible light but processing is done in the frequency domain using a 25GHz spectrum analyser, enabling measurements at low bunch currents, as well as for large bunches. The other diagnostic is based on two HF cavities measuring the components of the longitudinal beam spectrum at 10 and 16GHz. Bunch length can then be deduced assuming a Gaussian bunch shape. This device is only relevant for low current per bunch. Both diagnostics obtain information in the frequency domain, and the accuracy of the time domain reconstruction is an important issue, which will be discussed in detail.

SET UP FOR MEASUREMENTS USING THE SPECTRUM ANALYSER.

For this measurement, the visible light beam is focused on the input of a 25GHz photodiode. The size of the active surface of the diode being rather small ($25 \times 25 \mu\text{m}$), a lens with a short focusing length is used in order to get an

image of the source point as small as possible. The output of the photodiode is then directly plugged into a 20GHz 18dB RF amplifier. The amplified signal is processed by a 25GHz spectrum analyser. The resulting spectrum is corrected by the impulse response of the measurement chain. The impulse response drawn on figure 2 has been measured using a femto-second laser emitting at 980nm with a repetition rate of 80Mhz.

The schematic set up of the system is basic, care should be taken to avoid cables because of the high frequencies involved. In addition, the use of optical fiber is dangerous because of the chromatic dispersion they induce. It is possible to use them but the light beam should be filtered, resulting in a loss of input power. This was done for the measurements presented in [2], where input power was not an issue, but this is not the case for the spectrum method. The focusing of the visible light beam had to be done directly on the photodiode, without the help of optical fibers, making the focusing of the image on the optical sensor even more delicate. The set up is pictured on figure 1.

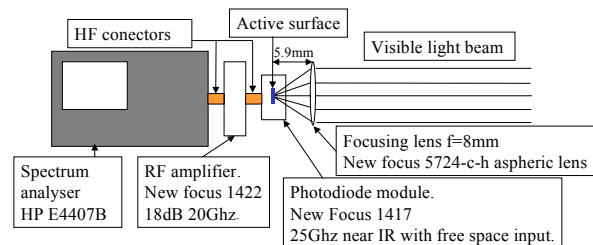


Figure 1: Experimental set up and component references.

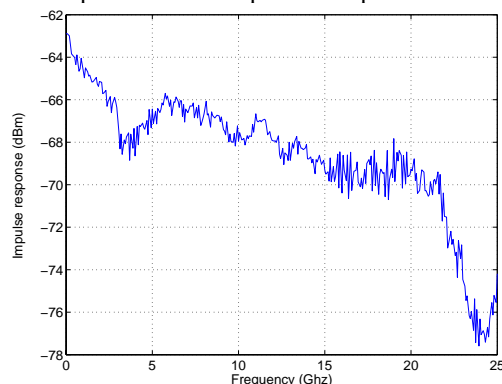


Figure 2: Spectrum of the impulse response of the measurement chain.

If the bunch has a Gaussian longitudinal profile with a standard deviation σ_t , the envelope of the spectrum also is a Gaussian with $\sigma_\omega = 1/\sigma_t$. To obtain the bunch length, a Gaussian fit of the spectrum envelope is performed, giving σ_ω . A simple inversion then gives the RMS bunch length σ_t .

This analysis is made assuming a perfect Gaussian shape for the bunch, which is true for an electron bunch at

zero current. It is however well known that, under the influence of longitudinal impedance, the shape of the bunch is distorted and for high current bunches, the Gaussian approximation is no longer acceptable. An estimation of the induced error has been performed.

Concerning the sensitivity of the set up, in order to obtain a signal to noise ratio of 10 at zero frequency (where the signal is maximum), 20mA should be injected in the machine. It is estimated that above 30 mA the sensitivity is good enough. Thus, the device can cover all operational filling patterns at the ESRF as the current is always in-between 40 (4 bunch mode) and 200mA (uniform).

GAUSSIAN APPROXIMATION.

Evaluating the error done by considering a Gaussian bunch is of importance. Indeed, both diagnostics give an amplitude spectrum in the frequency domain, but the phase information is missing. The inversion is made considering a zero phase for the entire spectrum, which is true for a symmetric bunch, but false as soon as the bunch distorts in a non-symmetric manner. A non-symmetric distortion is the signature of resistive longitudinal impedance.

The error has been evaluated by comparing results of streak camera profiles processed in two different ways. First a usual FWHM is derived and divided by 2.37 in order to get an equivalent RMS bunch length.

The second bunch length estimation is obtained by doing a Gaussian fit of the Fourier transform of a streak camera profile. Comparing both methods will give the error induced by the Gaussian assumption. On figure 3, It becomes obvious that the error induced by considering a Gaussian shape in frequency is significant even for quiet low current per bunches. The two curves converge, as expected, at zero current, but already at 1mA/bunch, we get an error of more than 10%.

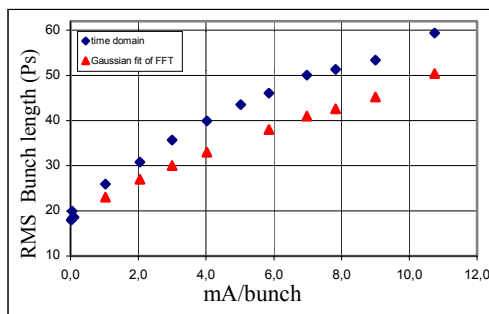


Figure 3: RMS bunch length derived by streak camera time profile (blue squares) and Gaussian fit of the FFT of the same profile (red triangles).

RESULTS USING THE SPECTRUM ANALYZER

Zero current measurements

At zero current, the equilibrium bunch profile is a Gaussian, whose width can be calculated. It is the result of the equilibrium between the focussing RF field and the spread in energy induced by the quantum fluctuation of

photon emission. All measurements were done with an RF voltage of 8MV leading to a theoretical bunch length of 16ps RMS. As the Gaussian approximation holds in this case, it is possible to compare results for the two new devices with streak camera results in the time domain. Measurements were done at low current (10 to 40mA) uniformly distributed in the 992 RF buckets of the ESRF.

Streak camera gives an RMS bunch length of 18.7 ± 1 ps. The Gaussian fit of the frequency spectrum leads to 16.3 ± 3 ps for the RMS width of the bunch, corresponding exactly with the theory. The comparison with streak camera measurements shows a relatively good agreement as both values are only separated by 2.4ps. This comparison validates the viability of the new diagnostic for the low current measurements. Nevertheless, the agreement is not perfect. Figure 3 shows the comparison between the recorded spectrum and the FFT of a streak camera profile. There is obviously divergent behaviour of the two diagnostics at low frequency ($f < 8$ GHz).

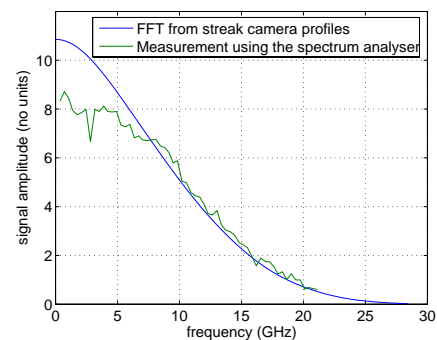


Figure 4: Comparison of the FFT of a streak camera profile (blue) and the recorded spectrum (green). Both measurements are made for $I_{\text{bunch}} < 0.04$ mA.

High current per bunch

As already stated, at high current, the reconstruction of the time profile from the spectral measurement is no longer possible, because the information about the phase of the Fourier components is missing. In order to evaluate the quality of the new diagnostic, the FWHM of the recorded spectrum will be compared with the FWHM of the FFT of streak camera profiles. Figure 5 shows this comparison for different currents per bunch.

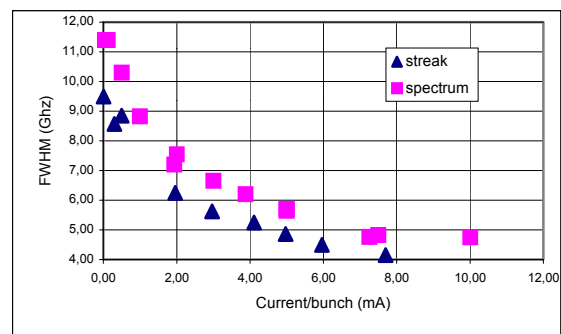


Figure 5: FWHM of frequency spectrums based on streak camera measurements (blue triangle) compared to the measurement using the spectrum analyser (pink squares).

Both curves show the same evolution with current, which is again an encouraging result, but there is a general discrepancy of about 20% between the two curves. Compared to the streak camera spectrums, we already saw that at low frequency, the spectrum tends to underestimate the signal, leading to a smaller maximum and a larger FWHM. As shown on figure 6, it is also valid for large current per bunches. No clear explanation could be found for this behaviour at low frequency, it may be due to an overestimation of the impulse response of the system at these frequencies, which would lead to an underestimation of the signal.

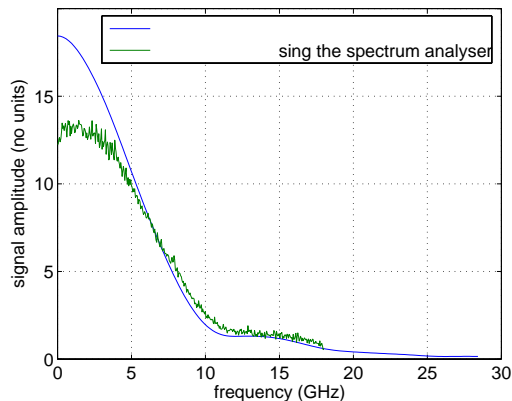


Figure 6: Same as figure 4 but for $I_{\text{bunch}}=3\text{mA}$.

MEASUREMENT USING MICROWAVE CAVITY PICKUPS

When the current per bunch is low enough, we can assume that the bunch current pulse shape is Gaussian. In this regime, it is possible to derive the bunch length from the measurement of only two points of the current spectrum, providing the frequencies of these points are far enough from each other to allow an accurate fit of the Gaussian shape of the spectrum. The measurement of a third point in the spectrum will help to assess if the bunch shape is Gaussian or not. Such a measurement was easy to implement for us since we have installed in 2001 on the ESRF storage ring two sets of narrow bandwidth microwave cavities, loosely coupled to the beam; these cavities are used as the pick ups of a general purpose diagnostics for the study of single bunch phenomena [3]. Their central frequencies are equal to $29 \times f_{\text{RF}} = 10.213\text{GHz}$ and $46 \times f_{\text{RF}} = 16.2\text{GHz}$, with $f_{\text{RF}} = 352.2\text{MHz}$, the frequency of our RF system. Their bandwidth is 100MHz. These cavities are equipped with RF front ends implemented in the storage ring tunnel, which down convert the signals excited by the beam from $29 \times f_{\text{RF}}$ and $46 \times f_{\text{RF}}$ down to an intermediate frequency equal to f_{RF} . The amplitude of these intermediate frequency signals is proportional to the beam spectrum level at 10.213GHz and 16.2GHz and can be detected with any narrow bandwidth detector (RF spectrum analyser or dedicated electronics). The third frequency in the spectrum is 0Hz, given by the average current value. Compared to the full spectrum measurement of the photo diode signal, the measurement of the ratio of the

amplitudes of the two cavities signals versus the RF current is much faster; it takes less than one second when a full 0 to 18GHz spectrum measurement takes several minutes. The accuracy of the beam signal detection is also better: because the cavities have a bandwidth of only 100 MHz, the ratio of the peak value versus the average value of the cavity signals is moderate resulting in a high signal to noise ratio. In parallel with the measurement of the photo diode spectrum, we have measured the variation of amplitudes of the signals of the 10GHz and 16 GHz cavities for various values of the current per bunch. Since the sensitivity of the detection of the cavity signals is not precisely known, we have first calibrated the gain of the amplitude detection of the 10 GHz and 16GHz signals using a streak camera measurement of the bunch length as a reference; we did this calibration with 1mA per bunch. Then using this reference measurement we have derived the value of the bunch length down to .1mA per bunch. The σ value that we derived at .1mA per bunch was 17ps when the value predicted by the theory is 16ps. So this method could also allow an easy and accurate monitoring of the bunch length at low current per bunch without requiring the permanent use of a microwave spectrum analyser.

CONCLUSION

Two new diagnostics for bunch length measurements have been tested by comparing them to streak camera results. In the low current per bunch regime, both devices show promising results as the theoretical value for zero current bunch length could be reproduced. In this regime, the microwave cavity offers a faster acquisition time.

Unfortunately, for high current bunches, time reconstruction is no longer possible for both devices, because the Gaussian approximation is no longer valid. The spectrum method accurately describes, the evolution of the longitudinal spectrum with current, but absolute values differ by about 20% from the streak camera measurements.

Nevertheless, it's simplicity, as far as both hardware and software is concerned, make it a good candidate to be routinely operated. A simple calibration using streak camera results would be sufficient to derive time domain values for high current bunches.

REFERENCES

- [1]K.Scheidt, 'Dual Sweep Streak Camera at the ESRF', EPAC-96, Barcelona, Spain, June 1996.
- [2]G.Naylor, 'Fast DSP Using FPGAs and DSOs for Machine Diagnostics', DIPAC 2003, Mainz, Germany, May 2003.
- [3]E. Plouviez, 'Microwave Pickups for the Observation of Multi GHz Signals' Induced by the ESRF Storage Ring Electron Bunches, DIPAC 2001, Grenoble, France, June 2001.