MEASURING THE LONGITUDINAL BUNCH PROFILE AT CTF3

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Abstract

The CLIC Test Facility 3 (CTF3) is being built and commissioned by an international collaboration in order to test the feasibility of the proposed Compact Linear Collider (CLIC) two-beam acceleration scheme. The monitoring and control of the bunch length throughout the CTF3 complex is important since this affects the efficiency and the stability of the final RF power production process. Bunch length diagnostics therefore form an essential component of the beam instrumentation at CTF3. This paper presents longitudinal profile measurements based on Streak camera and non-destructive RF power and microwave spectrometry techniques.

INTRODUCTION

The feasibility of the proposed Compact Linear Collider (CLIC) drive beam concept and two beam acceleration scheme [1] is being tested at the 3rd CLIC Test Facility (CTF3)[2] by an international collaboration. Inherent in this scheme, is the use of transverse deflectors to produce a 12 GHz, 140 ns long beam pulse, from a 1.2 μs long train train of 1.5 GHz bunches. The combined beam is used in the CLIC experimental (CLEX) area, where the beam is decelerated in resonant 12 GHz cavities and the power produced is used to perform two-beam acceleration experiments [3, 4].

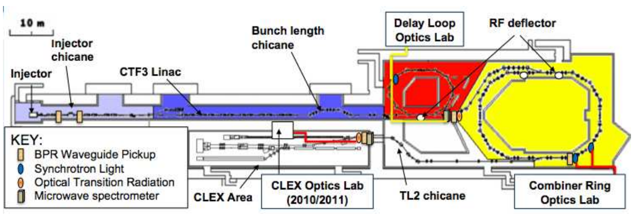

Figure 1: Layout of the CTF3 complex and the diagnostics used for longitudinal profile measurements

The monitoring and control of the bunch length throughout the CTF3 complex, see Fig. 1, is important since this affects the beam combination efficiency and the proficiency and stability of the final RF power production process. Hence, time resolved bunch length diagnostics form an essential component of the beam instrumentation at CTF3.

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This paper presents the longitudinal profile measurements based on Streak camera and non-destructive integrated RF power and microwave spectrometry techniques.

LONGITUDINAL BUNCH PROFILE

The measured single bunch longitudinal spectrum at CTF3 is best described by

$$f_{bunch}\left(t\right) = \frac{1}{\sqrt{2\pi}\sigma_b} e^{-\frac{(t-\tau_i)^2}{2\sigma_b^2(1+\alpha \mathrm{sgn}(t))}}, \quad (1)$$

where $\sigma_b^2 = (\sigma_+^2 + \sigma_-^2)/2$ and $\alpha = \frac{\sigma_+^2 - \sigma_-^2}{\sigma_+^2 + \sigma_-^2}$ where $\sigma_+(\sigma_-)$ describe the width of the left (right) hand side of the fitted skew Gaussian distribution, as shown by the Streak camera measurement in Fig. 2 (a).

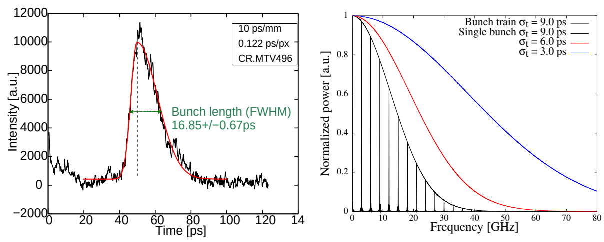

Figure 2: (a) Example of the CTF3 single bunch spectrum measured with the Streak Camera. (b) Power spectrum for a train of Gaussian bunches, with r.m.s. bunch length $\sigma_t = 9$ ps and separated by $\tau_i = 333.3$ ps (black) and the single bunch envelope for $\sigma_t = 9$ ps (black), $\sigma_t = 6$ ps (red) and $\sigma_t = 3$ ps (blue).

From the distribution in Equation 1, the power spectrum for a train of N electron bunches can be expressed as follows

$$P(f,t) \propto I^2\left(t\right)\left(\frac{\sigma_- e^{-2\pi^2\sigma_-^2 f^2} + \sigma_+ e^{-2\pi^2\sigma_+^2 f^2}}{\sigma_+ + \sigma_-}\right)^2$$
$$\times \left[\left(\sum_{i=1}^{N}\cos\left(2\pi\tau_i f\right)\right)^2 + \left(\sum_{i=1}^{N}\sin\left(2\pi\tau_i f\right)\right)^2\right], \quad (2)$$

where the normalized frequency dependent power spectrum induced by a train of identical gaussian ($\alpha = 0$) bunches, bunched at 3 GHz is shown in Fig. 2 (b). The envelope of this spectral distribution corresponds to the width of the single bunch distribution as in Equation 1. Hence, by measuring the power spectrum in the frequency domain, and knowing the response function of the detection system the bunch length can be reconstructed.

LONGITUDINAL PROFILE MONITORS

Monitoring the longitudinal bunch profile using both RF and Optical techniques is complementary, with the Streak camera providing a single shot bunch length measurement within a 140 ps time window of the beam pulse, and the RF techniques acquiring single shot measurements of the bunch frequency envelope along the full pulse train. The transverse RF deflectors, coupled to an OTR screen are also used to measure the average bunch length along the pulse train. This can provide sub-picosecond time resolution and has been presented in detail previously [5], and will not be discussed further in this paper.

Streak Camera

Light emitted as either synchrotron radiation, produced in the arcs of the delay loop and combiner ring dipole magnets, or as Optical Transition Radiation (OTR) produced at the end of the drive beam linac, is guided over long distances [6] to optics laboratories outside the radiation environment of the machine, see Fig. 1. An adjustable picosecond timing delay ($\Delta_t = 10$ ps), from the CTF3 fast timing distribution, with an intrinsic jitter of less than 1 ps, allows for a precise calibration of the Streak camera and the flexibility to measure individual bunches along the full pulse train. A sweep speed of 10 ps/mm is used for single bunch length measurements, with a corresponding measured calibration of 0.122 ± 004 ps/pixel.

RF-pickup – "BPRW"

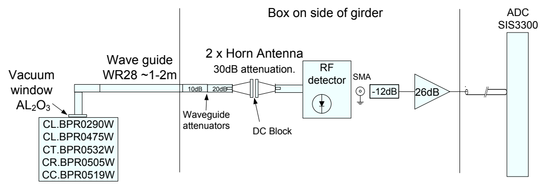

Figure 3: Schematic of the BPR waveguide pickup electronics

The BPRW waveguide hardware, consists of a single WR28 waveguide pickup, attached to the beam pipe separated by a thin vacuum window, see Fig. 3. The beam induced fields flow to the detector box placed on the girder of the machine where they are emitted via a pyramidal horn antenna. The emitting and receiving antenna are insulated from one another, and their separation carefully calibrated for the required attenuation. The power is detected by a fast schottky barrier detector, sensitive in 26.5-40 GHz. The output voltage is amplified and digitized with a 12 bit resolution ADC card sampling at 96 MHz. There are 5 detectors installed, see Fig. 1, to provide a real-time monitoring of the variation of the bunch length along the pulse train, before and after the bunch manipulation chicanes.

RF-pickup – "Microwave spectrometer"

The RF pickup microwave spectrometer uses a series of down mixing techniques, with specific reference local oscillators, to measure the power of selected lines of interested in the power spectrum of the pulse train in Fig. 2 (b), in that way being a more sensitive system than the BPR waveguide detector which is based on a single broadband diode. The system evolved from an earlier detector used in CTF2 [7] and, like the BPRW, is based on on a single RF pickup waveguide. The system measures beam harmonics in four different frequency bands: 30-39 GHz, 45-69 GHz, 78-90 GHz and 157-171 GHz and is described in detail in [8]. Based on this high frequency reach, the detector is sensitive to bunch lengths down to 300 fs. The time resolved down-mixed signals from the RF pickup detector are digitized with a 8 bit, 2 G sample/s Acqiris PCI card.

BEAM BASED MEASUREMENTS

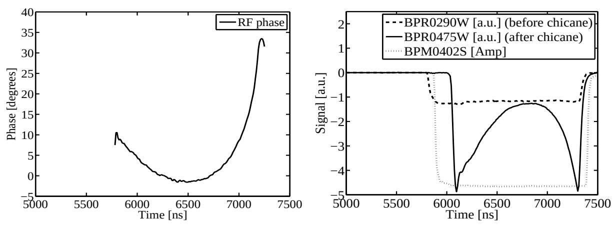

Figure 4: (a) Phase sag along input RF pulse to the pair of accelerating structures before the injector chicane. (b) The effect of the phase sag, as seen on the BPRW signals before and after the chicane for a uniform current.

Calibration Conditions

A bunch length variation along the pulse train in the linac was introduced in order to cross calibrate the RF based bunch length detectors with the Streak camera. This was done by introducing a larger than nominal ($< 10^\circ$) phase variation of about 30° over the input RF pulse, see Fig. 4 (a), to the first accelerating structures in the CTF3 injector, before the injector bunch compression chicane. In CTF3, this phase modulation is done, by manipulating the control of the phase modulator program at the input of the klystrons [9]. The RF phase variation introduces a small single bunch energy variation along the pulse train. The non-zero R_{56} of the injector chicane, results in a variable bunch length spectrum along the pulse train. This effect is seen by comparing the BPRW signal before and after the chicane, for a uniform pulse current, see Fig. 4 (b).

The Streak camera measurements were used as a bunch length reference with which to compare other instruments. The calibration measurements presented here were performed using a 2.99855 GHz beam and the synchrotron light from a dipole magnet in the combiner ring. A blue wavelength filter was used with all measurements, and the jitter, spot size in focus, calibration factor and goodness of the fit was taken into account in the analysis. The bunch length variation along the pulse train, for this special day of instrumentation cross-calibration, is shown in Fig. 5. The Streak camera sampled the pulse in 50 ns time intervals over a period of about 2 hrs.

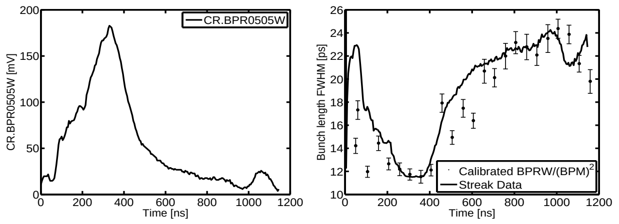

Figure 5: (a) Analog single shot response from BPRW in the combiner ring. (b) Bunch Length measurement comparing calibrated BPRW and the Streak Camera.

At the same location as the Streak camera measurement, the BPRW waveguide pickup signal was measured, see Fig. 5 (a). Using a simple quadratic function, which was sufficient given the sampling of the Streak data and the bunch length range, the BPRW signal was calibrated to the measured Streak data. After applying the calibration, Fig. 5 (b) shows the agreement between the Streak and the BPRW measurement. The BPRW signal can hence be used as an online, calibrated signal for the monitoring of the bunch length along the pulse train.

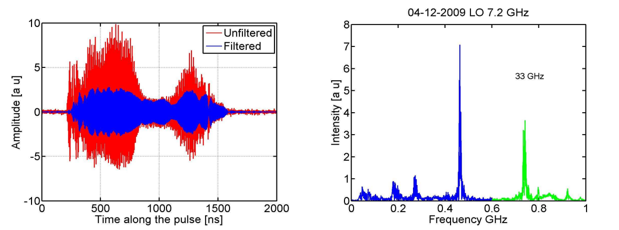

Figure 6: (a)An example of the time domain output of the RF pickup detector (red), with the 33 GHz beam component filtered (blue). (b) The time averaged FFT of the red output signal shown in 6 (a).

An example of the output of the K-band detector of the microwave spectrometer, which is the most sensitive of the detectors in this bunch length range, is shown in Fig. 6 (a). The corresponding average Fast Fourier Transform (FFT) is shown in Fig. 6 (b), where given the choice local oscillator setting of of 7.2 GHz, the second peak corresponds to the average power along the pulse train for the 33 GHz component of the beam signal. This signal is digitally filtered and can provide a time resolved power analysis of the beam harmonic of interest along the pulse train. The time resolved power was cross calibrated with the Streak data, as shown in Fig. 7 (a). This procedure was repeated for all measured beam harmonics, enabling the RF pickup to be used as a calibrated bunch length online monitoring tool.

Nominal Beam Conditions

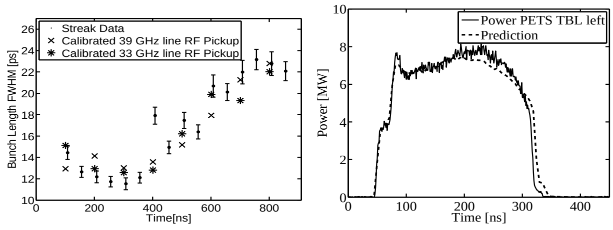

Figure 7: (a) Examples of calibrated 33 and 39 GHz RF pickup signal compared to Streak Data. (b) Power produced by the PETS and compared to the prediction based on the current measured and an assumed form factor of 0.85

The form factor of the beam can also be deduced based on the measured RF power characteristics from the 12 GHz constant impedance power extraction structures (PETS) [10], installed in the CLEX area. The measured power by one side of the the PETS in the Test Beam Line (TBL) [4] is shown in Fig. 7 (b). The predicted power generation in the PETS depends on the beam intensity I and the form-factor, $F(\lambda)$ as $P \propto I^2 F^2(\lambda)$. Hence, based on the measured power and the current in the beam position monitor, the bunch form factor can be deduced. For the measurement in Fig. 7 (b), a uniform form factor of 0.85 at 12 GHz (FWHM 17.8 ps) was deduced along the full pulse train.

OUTLOOK

The Streak camera has been used to calibrate the RF based bunch length detectors that provide single-shot monitoring of the bunch length along the pulse train. The RF power measurement extracted from the PETS structure provides an indirect measurement of the bunch form factor in CLEX. In the near future, dedicated longitudinal diagnostics will be installed in CLEX, based on Streak Camera measurements, RF diodes measuring harmonics of the combined 12 GHz beam and high frequency down mixing techniques, which can provide both bunch length and phase information of the combined beam.

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