Measuring the bunch frequency multiplication at the 3rd CLIC Test Facility

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Measuring the bunch frequency multiplication at the 3rd CLIC Test Facility

A.E. Dabrowski,[a] S. Bettoni,[a] E. Bravin,[a] R. Corsini,[a] S. Doebert,[a] T. Lefevre,[a] A. Rabiller,[a] L. Soby,[a] P.K. Skowronski,[a] F. Tecker,[a] D. Egger,[a] A. Ferrari[b] and C.P. Welsch[c,d,1]

[a] *CERN, European Organization of Nuclear Research, 1211 Genève 23, Switzerland*
[b] *Department of Physics and Astronomy, Uppsala University, Box 516, 751 20, Uppsala, Sweden*
[c] *Cockcroft Institute, Daresbury Science and Innovation Campus, 4 Keckwick Lane, WA4 4AD Warrington, U.K.*
[d] *Department of Physics, University of Liverpool, L69 7ZE Liverpool, U.K.*

E-mail: cwelsch@web.de

ABSTRACT: The CLIC Test Facility 3 (CTF3) is being built and commissioned by an international collaboration to test the feasibility of the proposed Compact Linear Collider (CLIC) drive beam generation scheme. Central to this scheme is the use of RF deflectors to inject bunches into a delay loop and a combiner ring, in order to transform the initial bunch frequency of 1.5 GHz from the linac to a final bunch frequency of 12 GHz. To do so, the machine's transverse optics must be tuned to ensure beam isochronicity and each ring's length can finally be adjusted with wiggler magnets to a sub millimeter path length accuracy. Diagnostics based on optical streak camera and RF power measurements, in particular frequency bands, have been designed to measure the longitudinal behaviour of the beam during the combination. This paper presents the diagnostics and recent commissioning measurements.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Instrumentation for synchrotron radiation accelerators

[1] Corresponding author.

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Contents

1 Introduction

The CLIC Test Facility 3 (CTF3) [1] is being built and commissioned by an international collaboration to test the feasibility of the CLIC drive beam generation scheme [2]. The generation scheme of the high current (28 A), 12 GHz drive beam in CTF3 is depicted in figure 1. In the present CTF3 nominal scheme, a 1.2 μs train of 2.3 nC bunches, originating from the CTF3 linac with a bunch spacing of 20 cm is phase coded in sub-trains of 140 ns each. Each subsequent sub-train differs by 180 degrees of a 1.5 GHz cycle originating from the phase switching of the sub-harmonic bunching system in the CTF3 injector [3], as shown schematically in figure 1. This 1.2 μs train from the linac is converted into an eight times shorter train of 140 ns with a 2.5 cm bunch spacing. This is achieved by first exploiting the presence of this phase coding, and utilising a 1.5 GHz transverse RF deflecting cavity in the delay loop (DL) [4] to inject only "even buckets" into an isochronous, single turn, delay loop, see figure 1. This produces a series of 140 ns sub-trains of 3 GHz beam separated by a 140 ns gap. Thereafter, two 3.0 GHz transverse deflecting cavities in the combiner ring (CR) [5, 6] are used to interleave bunches, see schematically figure 1, to provide the full combination factor of eight in current (28 Amps) and frequency (12 GHz) after the first sub-train has made a 4^{th} turn in the isochronous combiner ring.

A full demonstration of the combiner ring scheme was already verified in the CTF3 preliminary phase [7], but with a lower bunch charge (0.1 nC) and a shorter pulse length (6.6 ns) than for the CTF3 nominal phase. For the CTF3 nominal phase, the challenge is to use both the delay loop and the combiner ring simultaneously with a higher bunch charge and a longer train length. The delay loop scheme was tested in 2006 [8] and the combiner ring scheme in 2008 [9]. The two rings, working together, were tested for the first time in 2009, where a factor of eight combination in current was achieved [10]. Recent studies have commenced to verify that the combined beam has the bunch structure of a 12 GHz beam, with minimal phase errors. This paper is an extension

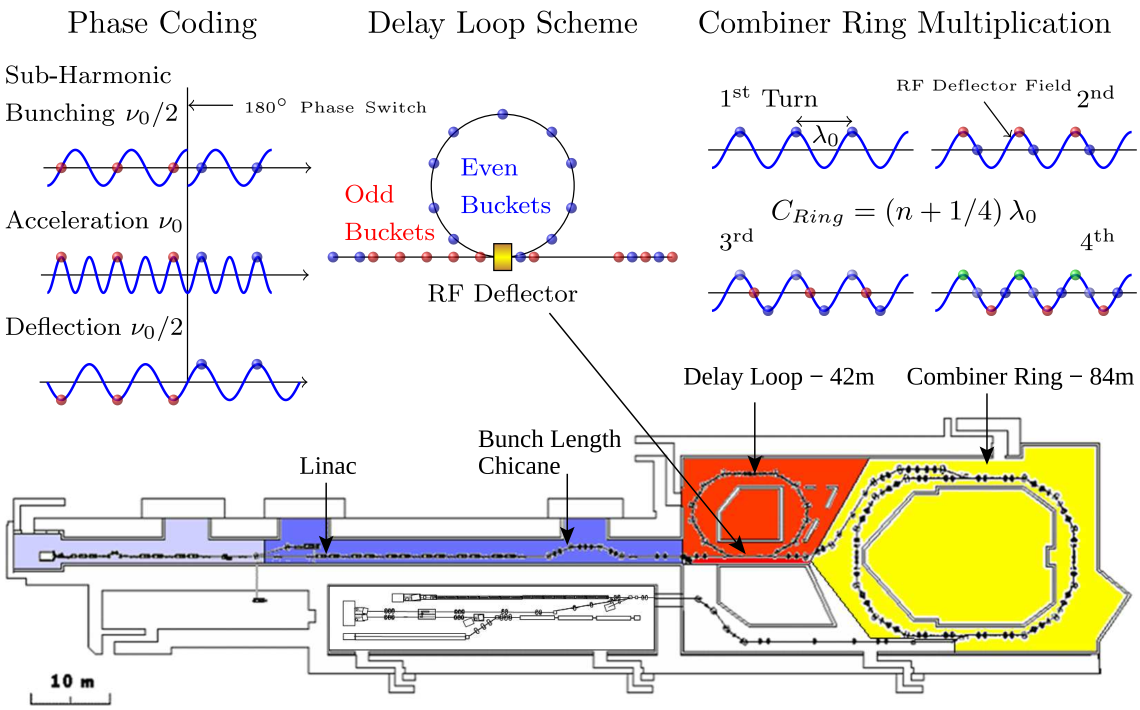


Figure 1. CTF3 complex and drive beam generation scheme.

of the work presented at the IPAC2010 conference [11] and introduces the diagnostics necessary to monitor the bunch frequency multiplication process and first measurement results.

2 Bunch frequency monitors and supporting diagnostics

To optimise the bunch combination scheme, optical diagnostics based on a streak camera and RF diagnostics based on frequency dependent power measurements using the phase monitor have been developed. These diagnostics are located in and after the delay loop and in the combiner ring, see figure 2, in order to monitor the beam during the combination process. The two types of diagnostics are complementary and are both based on a single shot measurement. The streak camera provides a phase measurement within a 200 ps - 10 ns time window of the beam pulse train, while the phase monitor provides a time resolved measurement along the 1.2 μs pulse train, with a 10.4 ns time resolution, limited by the sampling rate of the ADC. In addition to these two diagnostics for bunch frequency monitoring, two other diagnostics were needed for normalisation purposes. The first is an average measurement of the beam power spectrum, and hence bunch length measurement. This is provided by a wave guide pickup (“BPRW”) and wide bandwidth high frequency diode. The second is a beam current measurement which is provided by a beam position monitor (BPM). The diagnostics systems will be described in more detail in the following section.

2.1 Streak camera

Light used for diagnostics purposes is emitted as either synchrotron radiation, produced in the arcs of the delay loop (DL.MTV0361) and combiner ring (CR.MTV0451 and CR.MTV0496) dipole

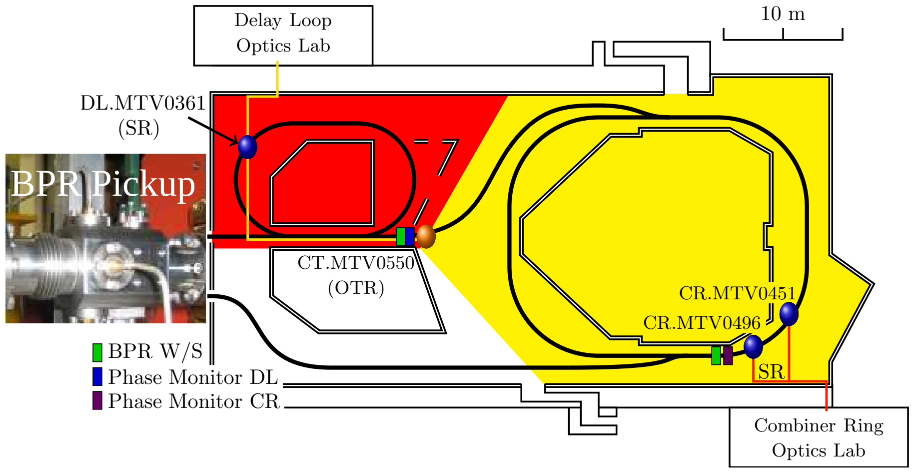


Figure 2. Layout of the diagnostics used for the bunch combination measurements.

magnets, or as Optical Transition Radiation (OTR) produced at the end of the drive beam linac (CT.MTV0550) which is instrumented with a movable thin Si screen, see figure 2. The light is guided over long distances [12], [13] to one of two optics laboratories outside the radiation environment of the machine, see figure 2. The light is then focused onto the streak camera slit, to a spot size of about 350 μm, and used for longitudinal bunch diagnostics studies. The streak camera has been re-calibrated before this measurement campaign using the position of a bunch from a 2.99855 GHz electron beam and a trigger with an adjustable ($\tau_{\min}$ = 10 ps) timing delay. The calibration factor was measured to a precision of 3% for a sweep speed of 10 ps/mm, which is most suitable for bunch length measurements, and to a precision of $<$ 1% for 20 ps/mm and 50 ps/mm sweep speeds which are most suitable for bunch spacing measurements.

The shape of the single bunch distribution was studied with the streak camera, see figure 3, and is best described as

$$f_{\text{bunch}}(t) = \frac{1}{\sqrt{2\pi}\sigma_b} e^{-\frac{(t-\tau_i)^2}{2\sigma_b^2(1+\alpha sgn(t-\tau_i))}}, \tag{2.1}$$

where $\sigma_b^2 = \left(\sigma_+^2 + \sigma_-^2\right)/2$ and $\alpha = \frac{\left(\sigma_+^2 - \sigma_-^2\right)}{\left(\sigma_+^2 + \sigma_-^2\right)}$ where σ_+ (σ_-) describe the width of the left (right) hand side of the fitted skew Gaussian distribution. A blue wavelength filter was used with all streak camera measurements in order to select a narrow frequency band of optical photons. This reduces effects due to longitudinal dispersion in the long optical line which can effect the temporal resolution of the measurement. The narrow frequency band of optical photons also ensures a uniform response on the streak camera photo cathode, thus optimising the temporal streak camera resolution. The resolution smearing due to shot to shot jitter and the small transverse spot size of the beam in focus was measured. These effects where taken into account in the longitudinal measurement. The errors due to the calibration factor measured for the streak camera and goodness of the fit of the streak profile, using the function in equation (2.1), were also taken into account in the bunch length and bunch spacing analysis and corresponding error estimation.

2012 JINST 7 P01005

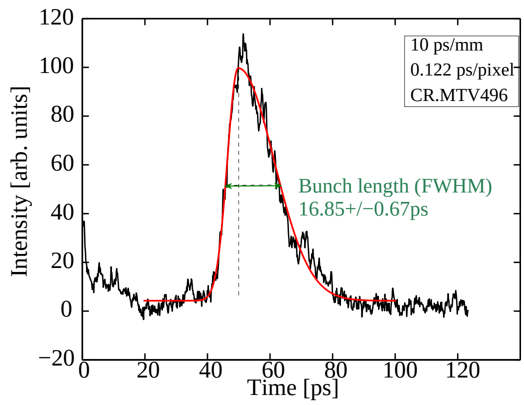


Figure 3. Example of the CTF3 single bunch spectrum measured with the Streak Camera.

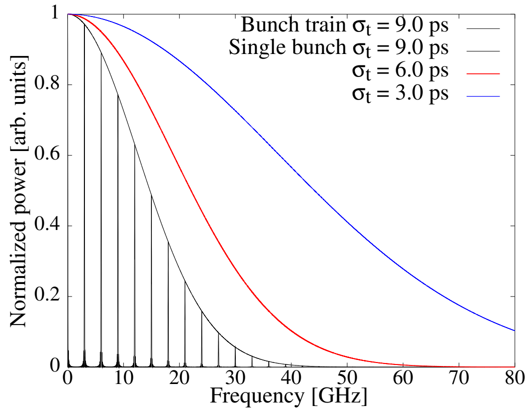


Figure 4. Power spectrum for a train of Gaussian bunches, with r.m.s. bunch length σ_t = 9 ps and separated by τ_i = 333.3 ps (black) and the single bunch envelope for σ_t = 9 ps (black), σ_t = 6 ps (red) and σ_t = 3 ps (blue).

2.2 Phase monitor

Given a skew Gaussian bunch shape measured with the streak camera, the expected power spectrum, in the frequency domain, of a train of N electron bunches can be expressed as follows

$$P(f,t) \propto I^2(t)\left(\frac{\sigma_- e^{-2\pi^2\sigma_-^2 f^2} + \sigma_+ e^{-2\pi^2\sigma_+^2 f^2}}{\sigma_+ + \sigma-}\right)^2 \times \left[\left(\sum_{i=1}^{N}\cos(2\pi\tau_i f)\right)^2 + \left(\sum_{i=1}^{N}\sin(2\pi\tau_i f)\right)^2\right], \tag{2.2}$$

where τ_i indicates the position in time of bunch i in the train. The normalized frequency dependent power spectrum induced by a train of identical Gaussian ($\alpha = 0$) bunches, bunched at 3 GHz is shown in figure 4. The envelope of this spectral distribution corresponds to the width of the single bunch distribution as in equation (2.1).

The phase monitors are designed to measure the magnitude of the beam power spectrum (see equation (2.2)) within selected frequency bands sensitive to the spacing during bunch frequency combination (τ_i), based on the principle outlined in [14]. The monitor is made of four symmetric

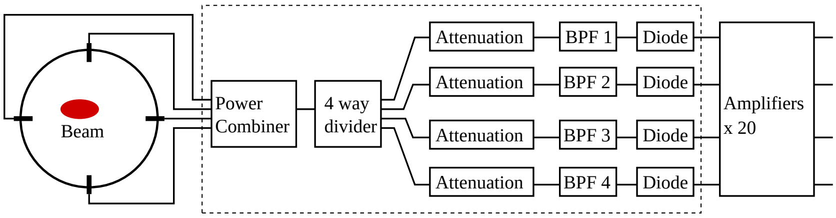
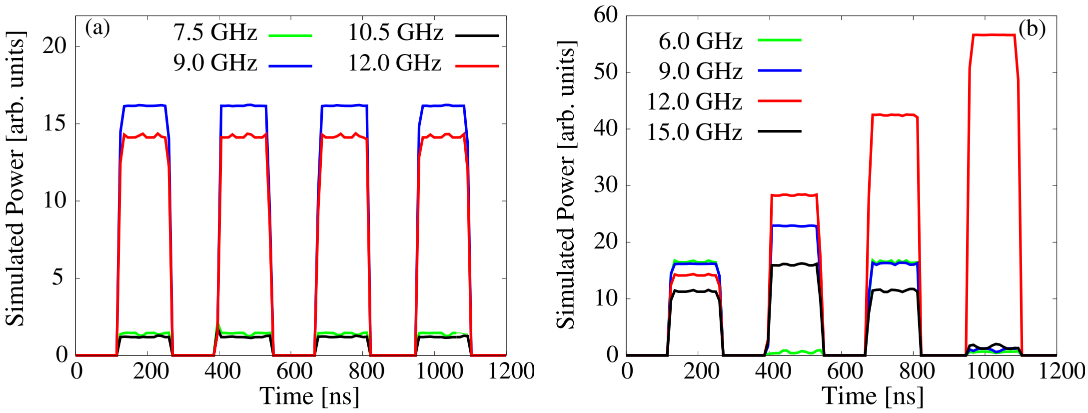


Figure 5. Schematic of the phase monitor electronics.



(a) after DL $\sigma_b = 15$ ps

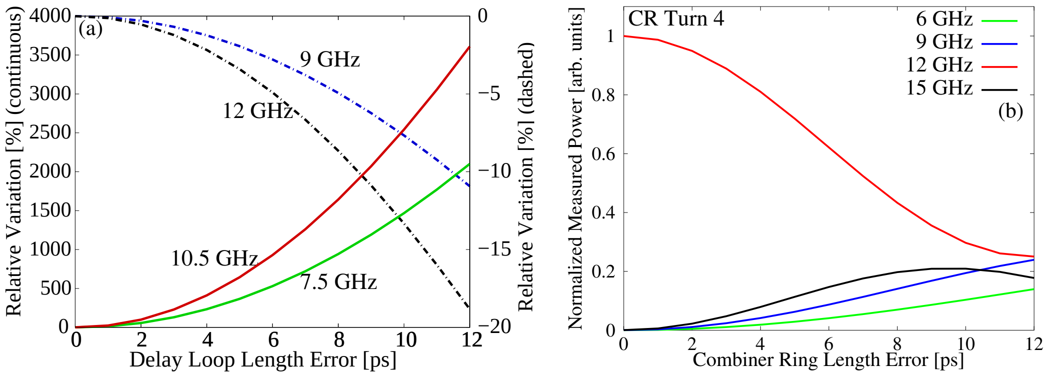
(b) in CR $\sigma_b = 15$ ps

Figure 6. Simulation of the expected phase monitor signals for a perfectly combined beam with a uniform bunch length σ_b along the train.

button antennas around the beam pipe, see the photograph of BPR Pickup in figure 2, to pick up the beam induced RF signal. There are two such devices in CTF3, one after the delay loop and the other in the straight section after the second arc of the combiner ring, see figure 2. The picked up power is combined, to be position insensitive, and redivided into four channels where attenuation is applied where needed. The signals are then band pass filtered ($\Delta f \approx 100$ MHz), measured with a diode, see figure 5, and digitised with a 12 bit ADC, proving power variations less than 10^{-3} to be measured. The ADC is sampled at 96 MHz. The phase monitor in the delay loop monitors the beam power at central frequencies of 7.5, 9.0, 10.5 and 12.0 GHz to be sensitive to residual 1.5 GHz spacing errors in the combined 3 GHz beam. The one in the combiner ring monitors the frequency bands around 6.0, 9.0, 12.0 and 15.0 GHz where after a perfect 12.0 GHz combination, the 12.0 GHz component should increase to a maximum in the 4^{th} turn, whilst the other signals are suppressed.

Figure 6 shows a simulation of the expected phase monitor signals measured in the delay loop and the combiner ring for a combination without phase errors and a uniform bunch length of 15 ps, σ_b, along the bunch train.

The change in the ideal phase monitor signals of figure 6 are shown as a function of a phase error in each of the two effective ring lengths respectively in picoseconds in figure 7. Figure 7(a) shows the relative change in the amplitudes of the signals in figure 6(a) based on an effective ring length error coming from the delay loop. While, figure 7, as an example, focuses on the 4^{th} turn of



(a) Delay loop

(b) Combiner ring

Figure 7. Sensitivity of the phase monitors to path length errors in the delay loop (a) and in the combiner ring 4$^{\text{th}}$ turn (b), for different detection frequencies.

the combiner ring. It shows the change expected in a signal corresponding to a perfect combination, as shown in figure 6(b), as a function of an effective ring length error in the combiner ring. Based on the high dynamic range ADC, and a linear relationship between the diode detector and incoming power, the phase monitor should be sensitive to phase variations less than 2 ps. To be most sensitive to the bunch spacing, as shown in eq. 2, the phase monitor signals are normalised to the current as measured by a BPM and the bunch length, as measured by either a calibrated K-band RF pickup (BPRW), as described in the following section, or by the streak camera.

The rationale for using the phase monitor during CTF3 commissioning is two fold. Firstly, for the adjustments of the delay loop ring length, the 1.5 GHz harmonics measured by the phase monitor located after the delay loop (normalised to current and bunch length variations) are minimised and the corresponding 3.0 GHz harmonics are maximised as a function of the current from the wiggler. For the first adjustment of the combiner ring length there are two main tuning signal that are used from the phase monitor signals in combiner ring. The 6 GHz component (normalised to current and bunch length variations) is suppressed in the 2nd turn of the combiner ring, as a function of the current in the combiner ring wiggler, and the 12 GHz power measurement (normalised to current and bunch length variations) is maximised during the 4th turn. Secondly, the phase monitor signals are saved as references for a good combination condition as measured by the streak camera. In this way, only relative changes from this reference are calculated, and the beam conditions are adjusted in order to fall back onto that reference. This is convenient for the operations, since the phase monitor can then be used as an online single shot monitoring system, for the full pulse train, while the streak camera is an expert measurement, limited to a narrow window within the beam pulse train.

2.3 BPR wave-guide pickup (BPRW)

The BPR wave-guide pickup (BPRW), as shown by the green wave-guide port of the BPR photograph in figure 2, provides a measurement of the beam power spectrum in the K-band frequency range, and is hence sensitive to the bunch length as shown in figure 4. The schematic of the hardware is shown in figure 8. It consists of a single WR28 wave-guide pickup, attached to the beam

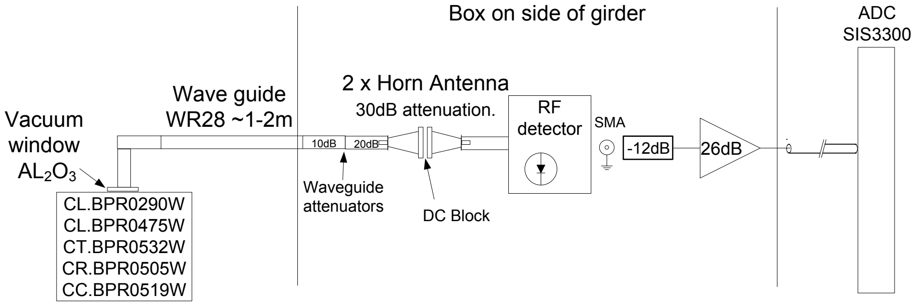


Figure 8. Schematic of the BPRW RF-pickup electronics.

pipe separated by a thin vacuum window. 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 digitised with a 12 bit resolution ADC card sampling at 96 MHz. BPRW detectors are installed at the same location as the phase monitors, see figure 2, for a bunch length normalisation measurement.

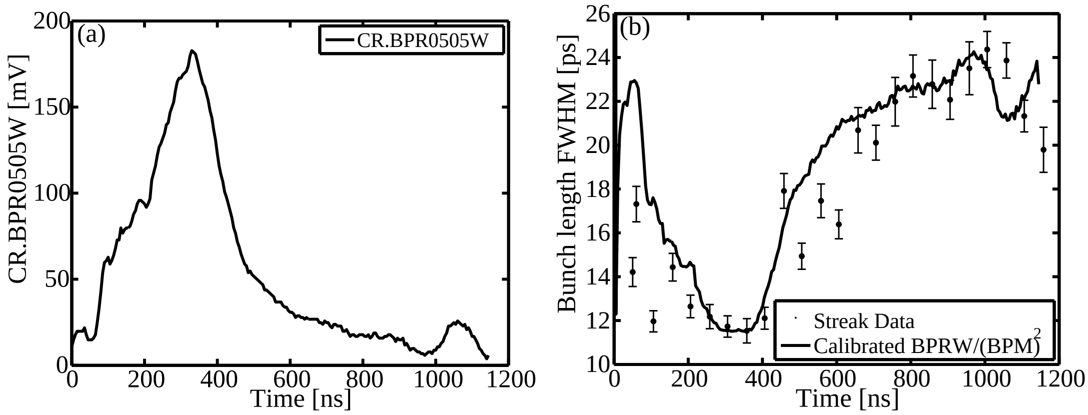
2.3.1 BPRW calibration

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 special beam for instrumentation calibration and the synchrotron light from a dipole magnet in the combiner ring. This beam was special, because it had a larger than nominal bunch length variation along the pulse train, so that a wide range of bunch lengths could be calibrated, within a single train. The bunch length variation along the pulse train, for this dedicated instrumentation cross-calibration, is shown in figure 9. The streak camera sampled the pulse in 50 ns time intervals over a period of about 2 hours.

At the same location as the streak camera measurement in the combiner ring, the BPRW signal was measured, see figure 9(a). Using a quadratic function, which was sufficient given the sampling of the streak camera measurement along the pulse train and the bunch length range, the BPRW signal was calibrated to the measured streak camera data, see figure 9(b). The calibrated BPRW signal can hence be used as an online monitoring of the bunch length along the pulse train and a normalisation for the bunch length dependency in the phase monitor measurement.

2.4 Beam current and position monitors

A circular aperture inductive pickup in the linac (BPM) [15] and an elliptical aperture inductive pickup (BPI) [16], compatible with vacuum chamber in the rings, are used for current and position measurements. The resolution of the position measurement is better than 100 μm, and with a frequency bandwidth ranging from 1 kHz up to 200 MHz, making it sensitive to fast signal fluctuations along the 1.2 μs pulse without any signal droop in position or intensity.



(a) An example of a raw BPRW signal.

(b) The calibrated BPRW signal compared to streak camera measurement.

Figure 9. The analog single shot response from BPRW in the combiner ring (a), and a bunch length measurement comparing the calibrated BPRW to the streak camera measurement (b).

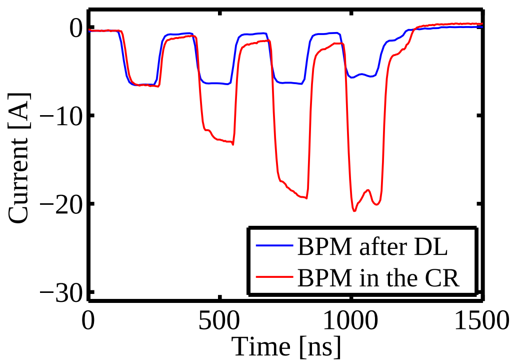
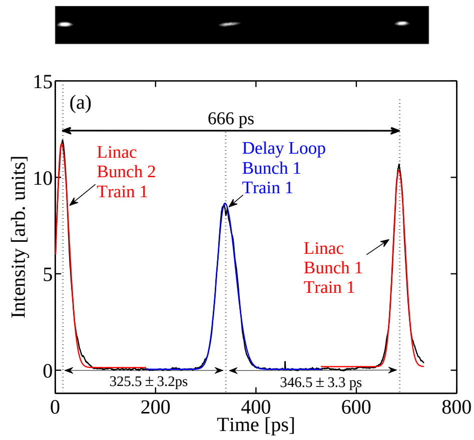


Figure 10. Intensity measurements after the delay loop (blue) and inside the combiner ring (red).

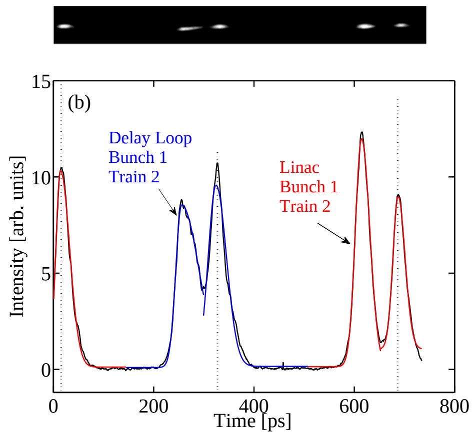
3 Measurement with beams

In the autumn 2009 CTF3 commissioning, a factor of eight combination in beam current was commissioned [10], and since then beam studies have been focused optimising the factor of eight combination in beam frequency. Although the longitudinal beam profile was not fully characterized in the linac and the phase measurements presented in the following were done in conditions where losses developed in the 4^{th} turn and an imperfect combination is measured, see figure 10, this data is still useful to demonstrate the commissioning of the instruments. It is however not sufficient to characterize the evolution of the beam dynamics in detail, and this will be presented in a separate paper.

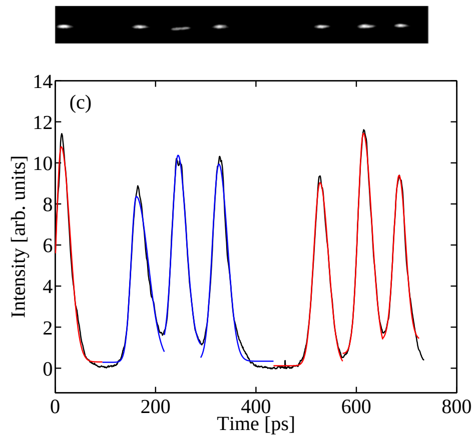
Streak camera measurements of the first turn of the combiner ring, reveal that the time of flight for particles in the delay loop, which should be 140 ns, is rather 13 ps too long, see table 1 and figure 11(a). Subsequent trains are similarly late by about 25 ps, 32 ps and 17 ps respectively, see table 1 and figure 11(b)-(d).



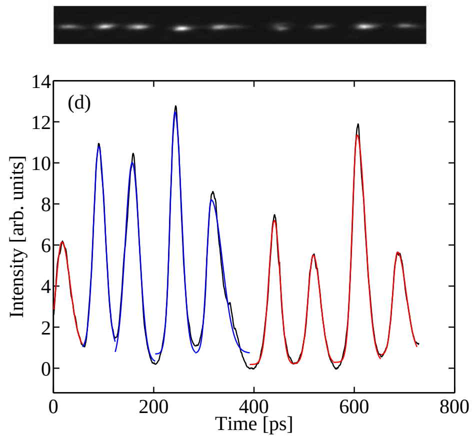
(a) Turn 1, 50 ps/mm



(b) Turn 2, 50 ps/mm



(c) Turn 3, 50 ps/mm



(d) Turn 4, 50 ps/mm

Figure 11. Streak camera bunch spacing measurement for subsequent turns in the combiner ring.

Train	Bunch Spacing error (ps)	Bunch Length (FWHM) Turn 1	
		DL(ps)	Linac (ps)
1	13.0 ± 3.3	30.6 ± 3.2	15.0 ± 1.0
2	25.3 ± 3.4	22.7 ± 2.6	16.3 ± 1.8
3	32.4 ± 3.5	17.4 ± 0.6	17.4 ± 0.6
4	16.9 ± 3.4	–	

Table 1. Measured bunch spacing error w.r.t. 333.3 ps (sweep 50 ps/mm) and the bunch length (sweep 10 ps/mm) during the first turn of each train from either the delay loop or directly from the linac

2012 JINST 7 P01005

The delay loop path length has been measured correctly on other occasions [12]. The observed bunch spacing error is related to a non-zero dispersion at the measurement point [7]. A residual dispersion error in the delay loop enhances the effect and makes the dispersion in the combiner ring irregular, due to the difference in the dispersion for bunches that pass through the delay loop compared to those that by-pass the delay loop. There also seems to be a non-zero R56 in the delay loop optics, reflected by a larger bunch length measured for those bunches that pass through the delay loop compared to those that by-pass the delay loop, see table I. Due to the phase error and the elongation of the bunches, the bunches probably acquire a transverse kick as a consequence of being on the wrong phase with respect to the RF in the deflectors of the combiner ring, which could cause the losses measured for subsequent turns, see figure 10. The difference in the measured effective ring length from turn to turn, has its origin in amplitude and phase modulations along the RF pulses in the linac, originating from the RF pulse compression system used in CTF3 [17]. These modulations, result in a residual non uniform energy profile along the beam pulse of the order of (1-2)% ΔE/E. Since both the magnetic chicane in the injector and at the end of the linac, have a nonzero R56, this can cause a bunch length and phase drift along the pulse train, which is then reflected in the combined beam. A scheme to minimise this effect on the beam is being implemented based on an amplitude and phase compensation scheme by subsequent klystrons in the linac, thereby negating the effect of one klystron by a subsequent one. For example, the RF pulse to the injector buncher and the RF pulse feeding the first accelerating structure in the injector, both contain a residual second order modulation of the amplitude inherent to the pulse compression system. The waveform in the pulse compression system can be programmed so as to result in an opposite curvature between the RF pulse to the buncher and the first accelerating structure. This allows the effect induced by one klystron, to cancel the effect of the following. This will then ensure a flatter energy profile before entering the bunch compression chicane in the injector and as a consequence a uniform longitudinal bunch profile along the pulse train, up to third order. In addition a temperature feedback [18] to compensate for slow variations in the amplitude and phase of the klystron is also being implemented and this will improve the overall stability of the machine and the combination process.

An example of the power measured for the phase monitor, normalized to current and bunch length, is shown in figure 12. As expected, the 12 GHz power measurement dominates for the combination. However, due to the poor combination, there is a residual signal from the other frequency components. These unwanted harmonics should be suppressed in the phase monitor measurement during a better combination. A simulation of the expected phase monitor signal for 12 GHz is shown on figure 12 to compare to the data. This is calculated using the current measured with the BPM along the pulse, the bunch length along the pulse as measured with the calibrated BPRW and a phase error as measured by the streak coming from the delay loop, as listed in table I for turns 1, 2 and 4. For turn 3, an arrival time error from the delay loop of 27 ps was used in the simulation because it better matched the data, compared to the 32 ps as obtained by the streak measurement. This difference may be attributed to a drift in the machine conditions between the time taken to make the streak measurement and the logging of the phase monitor signals (a few minutes). Alternately the difference could be due to the limited sampling window of the streak camera, where the 1 ns time window measured is not fully representative of the average delay loop ring length error for the full 140 ns during of train 3. The remaining difference between the data

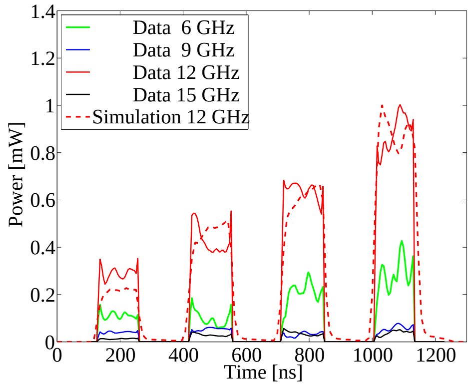


Figure 12. Normalised phase monitor measurement in the combiner ring and a simulation of the corresponding 12 GHz phase monitor signal, based on streak data phase measurements, the intensity data from the BPM and bunch length measured with the BPRW.

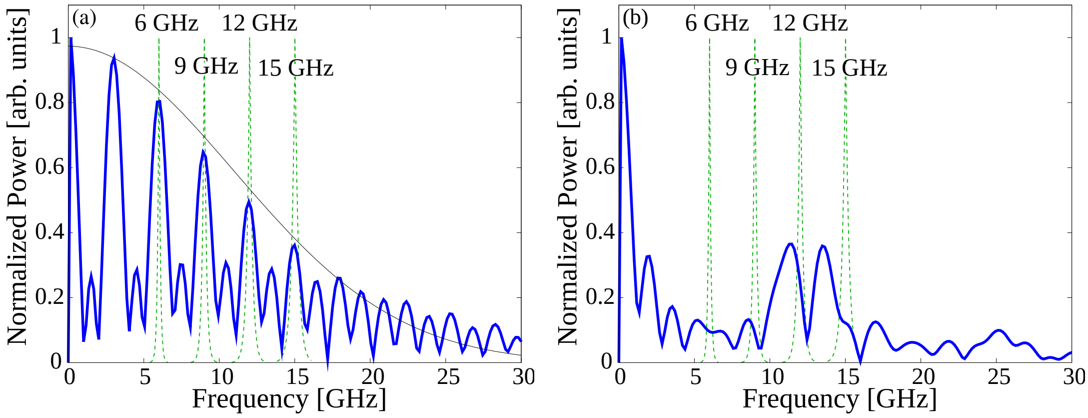
and the simulation might be attributed to differential losses or bunch length variations, that are faster than the 10.4 ns sampling of the BPRW and BPMs. Such differential losses will be studied in the future, based on bunch by bunch light intensity measurements with the streak camera, over a wide time window of the bunch train, turn by turn.

The phase errors as measured by the streak camera can also be visualised in the frequency domain. By performing a fast Fourier transform (FFT) of the streak camera data from figure 11(a) and figure 11(d) the corresponding beam frequency spectrums are shown in figure 13(a) and figure 13(b) respectively. The dominant 3.0 GHz beam harmonics and some residual 1.5 GHz harmonics, caused by the arrival time error from the bunches in the delay loop, are seen in the first turn of the combiner ring, see figure 13(a). The residual non-12 GHz components are seen in the FFT of the data from the 4^{th} turn of the combiner ring, see figure 13(b). The poor resolution of the FFT, as shown by the width of the peaks in figure 13(a) and figure 13(b) is due to the small time window of 750 ps, as sampled by the streak camera for a single shot measurement using a 50 ps/mm sweep speed. The bandpass of the filters in the combiner ring phase monitor are superimposed onto the plots of figure 13, to illustrate the sensitive frequency bands in the phase monitor of the combiner ring, defined by the band pass filters (BPF), see figure 5.

The variation in the bunch length in the combined beam, see table 1 and figure 11, adds an additional complication for the normalisation of the phase monitor signals. This will be addressed in the next CTF3 runs, where a strong focus will be the setting up of the RF pulses in the linac to compensate for phase and amplitude variations in the RF system with subsequent klystrons, and the commissioning of the RF amplitude and phase feedback system [18] and an operation of the CTF3 injector with shorter bunches.

With an expected better control of the longitudinal dynamics, the final step in the adjustment of the combination process will be the fine tuning of the effective ring lengths with the wiggler magnet.

2012 JINST 7 P01005



(a) FFT Streak Data Turn 1

(b) FFT Streak Data Turn 4

Figure 13. A FFT of the streak camera data presented in figure 11(a) and a FFT of the streak camera data presented in figure 11(d). The width of the phase monitor band-pass filters is shown in green.

4 Outlook

The diagnostics to measure the bunch frequency multiplication in CTF3 are being commissioned and already provide feedback for the operators to tune the bunch combination process and complement the BPM intensity measurements. Beam based measurements and CTF3 commissioning are continuing, and a strong focus in the next run will be a better control of the longitudinal beam dynamics along the pulse train. An improved setting up of the RF pulses in phase and amplitude along the pulse train and the setting up of the CTF3 injector for shorter bunches have been identified as areas needing special attention in order to achieve a good combination. The goal of tuning an isochronous ring, and minimising the phase errors during combination will be the focus of the next commissioning phase. Calibration and systematic studies of the instrumentation performance will continue in parallel with beam measurements. In order to be less sensitive to the systematic effects due to the bunch length variation along the pulse train, instrumentation is being considered that functions at lower frequencies [19].

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