MEASURING THE BUNCH FREQUENCY MULTIPLICATION AT CTF3

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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. The optimization procedure relies on several steps. The active length of each ring is carefully adjusted to within less than millimeter accuracy using a wiggler magnet. The transverse optics of the machine must be set up in a way to ensure beam isochronicity. Diagnostics based on optical Streak camera and RF power measurements have been designed to measure the longitudinal behavior of the beam during the combination. This paper presents their performance and recent measurements.

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 production of the high current (28 A), 12 GHz drive beam is depicted in Fig. 1.

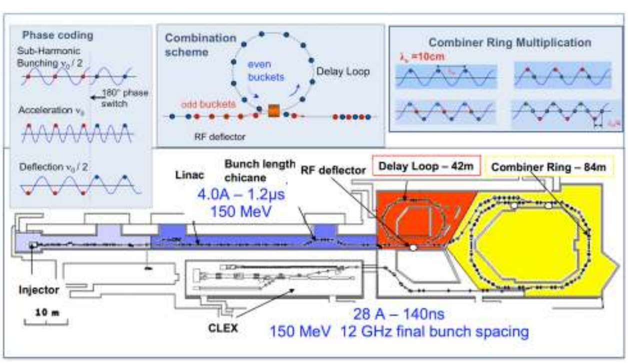


FIGURE 1 – CTF3 complex and drive beam generation scheme

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, are converted into an eight times shorter train of 140 ns and with a 2.5 cm bunch spacing after completing the $4^{\rm th}$ turn inside the combiner ring.

A full demonstration of the combiner ring scheme was already verified in the CTF3 preliminary phase [3], 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 (DL) and the combiner ring (CR) simultaneously with a higher bunch charge and longer train length. The delay loop scheme was tested in 2006 [4] and the combiner ring scheme in 2008 [5]. The two rings, working together, were tested for the first time in 2009, where a successful factor eight combination in current was achieved [6]. This paper introduces the diagnostics necessary to verify the production of the 12 GHz beam without phase errors.

BUNCH FREQUENCY MONITORS

To study and optimize the bunch combination scheme, diagnostics based on Streak camera and RF power measurements using the "Phase monitor" have been developed. The two diagnostics are complementary and both based on a single shot measurement. The Streak camera provides a phase measurement within a 200 ps -10 ns time window and a few picoseconds of resolution, while the Phase monitor provides a time resolved phase measurement of the 1.2 μs pulse train, with a 10 ns time resolution.

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 [7] to optics laboratories outside the radiation environment of the machine. The light is then focused onto the Streak camera, to a spot size of about 350 μm, and used for longitudinal bunch diagnostics studies.

The Streak camera has been re-calibrated, for sweep speeds relevant for the most precise bunch spacing and bunch length measurements, see Table 1, using the position of a bunch from a 3 GHz electron beam and a trigger with an adjustable picosecond timing delay.

TABLE 1 – Streak camera calibration factors

Sweep Speed (ps/mm)	Calibration Factor (2σ) (ps/pixel)
10	0.122 ± 0.004
20	0.312 ± 0.003
50	0.725 ± 0.007

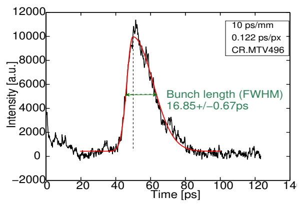


FIGURE 2 – An example of a bunch length measurement with the Streak Camera in the CR

The shape of the single bunch distribution was studied with the Streak camera, see Fig. 2, and is best described as

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

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.

Phase Monitor

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

$$P(f,t) \propto I^2\left(t\right) \left(\frac{\sigma_- e^{-2\pi^2\sigma_-^2 f^2} + \sigma_+ e^{-2\pi^2\sigma_+^2 f^2}}{\sigma_+ + \sigma_-} \right)^2$$

$$\times \left[\left(\sum_{i=1}^{N} \cos\left(2\pi\tau_i f\right) \right)^2 + \left(\sum_{i=1}^{N} \sin\left(2\pi\tau_i f\right) \right)^2 \right], \qquad (2)$$

where τ_i indicates the position in time of bunch_i in the train.

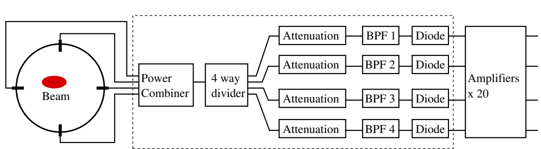
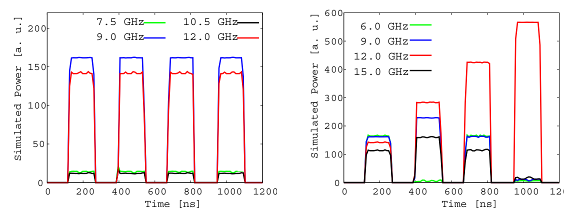


FIGURE 3 – Schematic of the phase monitor electronics

The phase monitors are designed to measure the magnitude of the beam power spectrum (see Eqn. 2) within selected frequency bands sensitive to the spacing during bunch frequency combination (τ_i), based on the principle outlined in [8]. The monitor is made of four button antennas around the beam pipe to pick up the beam induced RF signal in a position independent manner. 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. The picked up power is combined and redivided into four channels and attenuation applied where needed. The signals are then band pass filtered (Δf $\approx$ 100MHz), measured with a diode, see Fig. 3, and digitized with a 12 bit ADC sampling at 96 MS/s. The phase monitor in the delay loop monitors the beam power at 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 others signals are suppressed, see Fig. 4.



(a) after DL $\sigma_b = 15$ps (b) in CR $\sigma_b = 15$ps

FIGURE 4 – Simulation of the phase monitors for a combined beam with uniform bunch length along the train, σ_b

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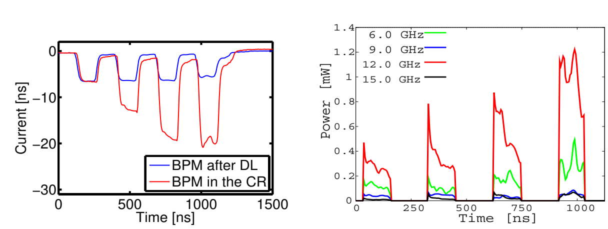
To be most sensitive to the bunch spacing, as shown in Eqn. 2, the phase monitor signals are normalized to the current as measured by a BPM and the bunch length, as measured by a calibrated 30 GHz RF pickup (for an uncombined beam) or the Streak camera.

MEASUREMENT WITH BEAMS

In the autumn 2009 CTF3 commissioning, a factor of eight was commissioned and later routinely operated [6]. Owing to the constraints in the operation schedule, there was limited time dedicated to bunch length and phase studies. The phase measurements presented here were done in conditions where losses developed in the 4^{th} turn, see Fig. 5(a), and an imperfect combination is measured. However, this data is still useful to demonstrate the commissioning of the instruments.

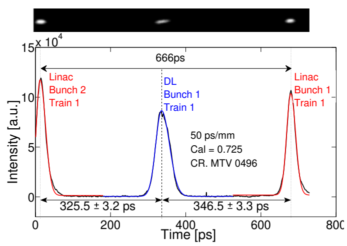
Streak camera measurements, see Fig. 6, show that in the first turn of the combiner ring that the time of flight for particles in the delay loop, which should be 140 ns, is rather 13 ps too long, see Table 2. Subsequent trains are similarly late by about 25 ps, 32 ps and 17 ps respectively. The delay loop path length has been measured correctly on other occasions [7]. The observed bunch spacing error is related to



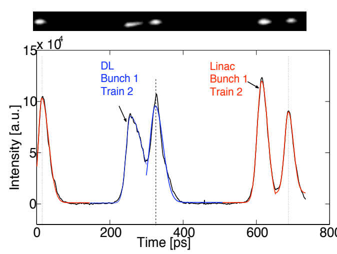
(a) BPM (b) Phase monitor CR

FIGURE 5 – Fig 5(a) Intensity measurements after the DL (blue) and inside the CR (red). Fig 5(b) Phase monitor power measurement, normalised to the intensity in Fig 5(a).

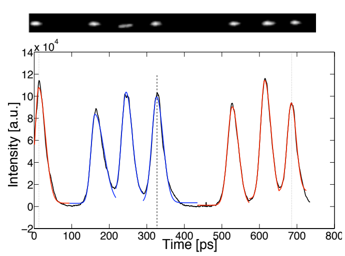
a non-zero dispersion at the measurement point [3]. A residual dispersion error in the delay loop enhances the effect and makes the dispersion in the combiner ring irregular, due to the difference in the dispersion for bunches that pass through the delay loop compared to those that by–pass the delay loop. There also seems to be a non–zero R_{56} 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 2. 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 would cause the losses measured for subsequent turns.



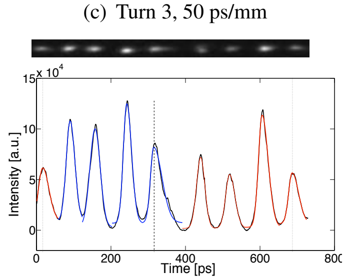
(a) Turn 1, 50 ps/mm



(b) Turn 2, 50 ps/mm



(c) Turn 3, 50 ps/mm



(d) Turn 4, 50 ps/mm

FIGURE 6 – Streak Camera bunch spacing measurement for subsequent turns in the combiner ring

An example of the power measured for the Phase monitor, normalized to current, is shown in Fig 5(b). As expected, the 12 GHz power measurement dominates for the combination. Due to the poor combination, there is residual signal from the other frequency components. These should be suppressed during a better combination. The variation in the bunch length in the combined beam adds an additional complication for the normalization of the Phase monitor signals, and will be addressed in the next CTF3 run.

TABLE 2 – Measured bunch spacing error w.r.t. 333.3 ps (50 ps/mm) and bunch length (10 ps/mm) during the first turn of each train from the DL or the linac

Train	Bunch Spacing error (ps)	Bunch Length Turn 1 DL (ps)	Bunch Length Turn 1 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	-	

OUTLOOK

The diagnostics to measure the bunch frequency multiplication in CTF3 are being commissioned and provide feedback for the operators to tune the bunch combination process and complement the BPM measurements. Beam based measurements will continue when the CTF3 operation resumes in the summer, with the goal of tuning an isochronous ring, and minimizing the phase errors during combination. 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 [9].

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