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Drive beam stabilisation in the CLIC Test Facility 3

L. Malina [a,b,*], R. Corsini [a], T. Persson [a], P.K. Skowroński [a], E. Adli [b]

[a] CERN, Geneva 23, Switzerland
[b] University of Oslo, 0316 Oslo, Norway

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ABSTRACT

The proposed Compact Linear Collider (CLIC) uses a high intensity, low energy drive beam to produce the RF power needed to accelerate a lower intensity main beam with 100 MV/m gradient. This scheme puts stringent requirements on drive beam stability in terms of phase, energy and current. The consequent experimental work was carried out in CLIC Test Facility CTF3. In this paper, we present a novel analysis technique in accelerator physics to find beam drifts and their sources in the vast amount of the continuously gathered signals. The instability sources are identified and adequately mitigated either by hardware improvements or by implementation and commissioning of various feedbacks, mostly beam-based. The resulting drive beam stability is of 0.2°@ 3 GHz in phase, 0.08% in relative beam energy and about 0.2% beam current. Finally, we propose a stabilisation concept for CLIC to guarantee the main beam stability.

1. Introduction

The compact linear collider (CLIC) [1] is a proposed particle accelerator, which will possibly take over from Large Hadron Collider (LHC) at the high energy physics frontier after its planned shut down around 2035. CLIC is a linear e^+e^- collider with a centre of mass energy up to 3 TeV. To reach this energy, it will employ a two-beam acceleration scheme [1]. CLIC Test Facility CTF3 [2] is a test facility, which aims to demonstrate the feasibility of CLIC technology by generation of the high current drive beam used for two-beam acceleration and to develop a variety of different CLIC specific equipment.

The two-beam acceleration concept imposes strict requirements on the drive beam stability, in terms of current, energy and phase. The drive beam current stability impacts the stability of the main beam and it is critical for the integrated luminosity. The beam stability goals are defined as the values yielding 1% luminosity loss. The CLIC drive beam stability goals (phase translated to CTF3 machine independent of RF-frequency) are following [3]:

- beam phase of 0.2° at 3 GHz before phase-feed-forward (PFF)
- relative beam energy stability of 1×10^{-3}
- drive beam current stability of 7.5×10^{-4}.

The layout of CTF3 is shown in Fig. 1. A thermionic gun produces 1.3 μs long pulses of a 5 A continuous electron beam. The injector consists of 3 Sub-Harmonic-Bunching cavities (SHB) operating at 1.5 GHz, 3 GHz pre-buncher, buncher and 2 accelerating structures. The bunch frequency can either be 1.5 GHz or 3 GHz if the SHBs are disabled. It is one of the parameters defining the mode of operation: full factor 8 beam recombination is possible only with a 1.5 GHz beam, while 3 GHz allows only for factor 4. The bunched beam then passes through a magnetic chicane and about 4.3 A is accelerated in the 70 m long linac to the energy of 135 MeV. The acceleration of the beam is done with 3 GHz RF. The power is generated by klystrons delivering 5.5 μs and 40 MW pulses. Pulse compressors are employed to provide a flat-top of 80 MW and 1.4 μs. There are 16 accelerating structures operated in fully loaded mode [4]. This gives a high RF to beam efficiency, however, it introduces a strong correlation between the beam current and beam energy. In the delay loop, the beam pulse is converted to four 140 ns pulses of double intensity and bunch spacing by interleaving bunches using transverse RF deflectors. The four pulses are combined into a single one in the combiner ring. The beam is transported towards the experimental area CLEX [2], where it can be sent in the Test Beam Line (TBL), which investigates the effect of deceleration of the drive beam, or in the Two Beam Module (TBM), which experimentally verifies the concept of the two-beam acceleration.

In order to achieve the stringent stability levels needed for present and future machines, complex feed-back systems are usually required [5–9]. In Section 2 we describe the tools and algorithms that allow identification and study of the sources of drifts and jitters during machine operation. Section 3 describes a novel statistical analysis that

* Corresponding author at: CERN, Geneva 23, Switzerland.
E-mail address: lukas.malina@cern.ch (L. Malina).

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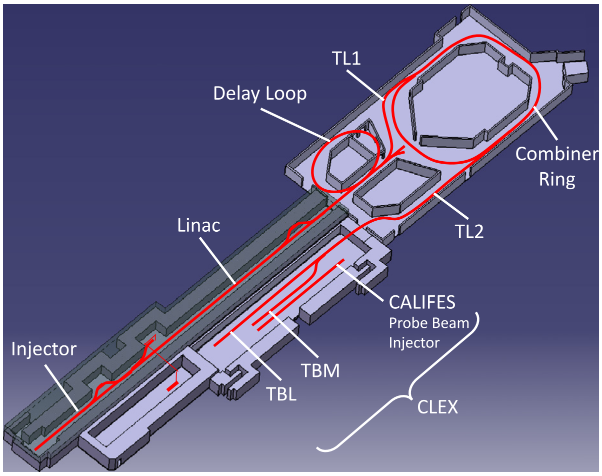

Fig. 1. Layout of CTF3.

allows identification of all relevant drifts within the very large amount of data recorded from hundreds of devices. The analysis leads typically to one of the following outcomes: identification of a particular hardware failure, which needs to be fixed, or to improved understanding of principles governing how to better stabilise the beam using a feedback system. The feedback systems developed for the CTF3 machine are described in detail in Section 4. In Section 5 the resulting beam stability is shown and discussed.

2. Monitoring and operational tools

In this section, we describe the monitoring and operational tools used in the CTF3 machine to identify failures and machine settings changes. In a single beam-pass machine, a change of the initial beam parameters affects all downstream beam parameters. It is therefore crucial to have precise control of the source and injector parameters. As an example, in CTF3 the phase and amplitude of the RF power in structures of the injector are one of the most critical parameters. Any change of these two parameters alters capture efficiency and therefore bunch charge. This also translates into a phase error after the magnetic chicane. Phase and charge differences modify the final bunch energy and length. This leads to different orbit and beam losses. Finally, the RF power produced by power extraction structures [10] has different amplitudes and phases.

In general, any observed drift at the end of a beam line can be caused by any of a vast amount of upstream signals, and the specific source is normally difficult to determine. In order to follow the evolution of all the signals and to provide input for the stability analysis of such complex system, two dedicated monitoring applications have been developed for machine operation.

The first one is called ReferenceMonitor and it is fully described in [11]. It shows in real time most of the beam related signals acquired along the beam pulse (hereafter referred to as "traces") together with earlier captured reference signals. Additionally, it displays the time evolution of their values averaged over the beam pulse and the χ^2 with respect to the reference. More importantly, it saves all beam related signals for further analysis. Since saving all traces for every pulse is not possible due to large amount of data, it saves the mean and χ^2 values instead. Full traces are saved periodically every 10 to 20 min.

For beam stabilisation in a given working point (the set of beam conditions along the machine), a change of the working point must be first effectively identified. An online watchdog application has been developed to quantify and determine the sources of the drifts. It compares the machine settings and the beam measurements to reference values. It shows the largest deviations measured by χ^2 in continuously updating fixed-displays. The signals are grouped by their type and are sorted according to their location along the machine layout. For clarity, only the locations with a beam presence are shown. This allows for quick identification of the origin of a drift, or at least its approximate location, by pointing out the most upstream signal that is diverging. The signal and its time evolution can be then verified in detail using the ReferenceMonitor. This makes these applications crucial for stabilisation of the machine since operators can more quickly identify a problem, determine the origin and react appropriately.

3. Drift and correlation analysis

Due to the large amount of recorded signals, drifts and jitters are analysed offline to identify the source and quantify the effect. This in turn defines the requirements for an appropriate feedback, specifically: required accuracy of signal acquisition, averaging time and gain. A dedicated algorithm has been developed to study drifts and jitters using the sample correlations between signals in a sliding time window of chosen length (depending on which time scale correlated signals are to be found). Let r be the correlation coefficient of pairs of normally distributed observables x and y:

$$r = \frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2}}, \tag{1}$$

where n is a sample size, $\bar{x} = \sum_{i=1}^{n} x_i$ and $\bar{y} = \sum_{i=1}^{n} y_i$. The sample correlation coefficient r lies in the interval $(-1;1)$. In order to easily work with significance levels, Fisher z-transform [12] is performed to obtain corresponding normally distributed quantity z and its uncertainty se:

$$z = \tanh^{-1} r = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$
$$se = \sqrt{\frac{1}{n-3}}$$

The confidence interval $\left(r_-;r_+\right)$ for r (asymmetric in general) is obtained by back-transforming $z \pm se$. Nevertheless, this procedure would be biased, where n is small or r is close to ± 1, because a finite sample of normal distribution follows the student t-distribution. The latter case is not important for drift detection since the resolution for high correlations is not needed. A correction for small sample size (given the requested confidence level) follows:

$$z \pm \sqrt{\frac{1}{n-3}} \cdot f\left(1-\alpha, n-2\right),$$

where f is inverse of cumulative student t-distribution function, given the confidence level α. We treat the correlation as non-significant if zero is within the back-transformed $\left(r_-;r_+\right)$ interval. It is practical to define a measure $R^2_{non\text{-}zero}$, which is similar to the coefficient of determination R^2:

$$R^2_{non\text{-}zero} = sgn\left(r_+\right) \cdot sgn\left(r_-\right) \cdot \min\left(r_+^2, r_-^2\right), \tag{2}$$

which is positive only if the correlation coefficient is statistically inconsistent with zero at the chosen confidence level. R^2 quantifies the fraction of a signal B variation that can be explained by another signal A change. If $R^2_{non\text{-}zero}$ is positive, it directly implies lower estimate on a fraction of signal B variation explainable by signal A. This represents a robust measure, which can be used to filter a large amount of signal pairs in long data samples. This is especially important for a large-scale machine, such as CLIC. Typically the beam passes through periods of drift (signals strongly correlated with time) and periods of relative stability (the signal variations are dominated by noise). It is convenient to study the correlations at various fixed time scales, typically a few minutes to several hours. A drifting signal together with calculated sample correlation coefficients (with time) and respective $R^2_{non\text{-}zero}$ is shown in Fig. 2. We introduce a "movie" of a visualised matrix (devices vs devices) of $R^2_{non-zero}$s over a sliding time interval. Sample frame of the matrix of lower limits on coefficients of determination is shown in Fig. 3.