

STATUS OF THE CLIC PHASE AND AMPLITUDE STABILISATION CONCEPT

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Abstract

In CLIC very tight tolerances exist for the phase and amplitude stability of the main and drive beam. In this paper we present the status of the CLIC beam phase and amplitude stabilisation concept. We specify the resulting tolerances for the beam and technical equipment and compare to measurements.

INTRODUCTION

In CLIC, the main phase tolerances are the relative arrival time of the two main beams at the interaction point and the main to drive beam phase stability. The tolerance on the main beam to main beam timing jitter is $22 \mu\text{m}$ for 1% luminosity loss. This is achieved by stabilising the timing of the main beams coming from the ring to main linac system (RTML) and by a feed-forward on the beam phase at the last turn-around that bends the beam into the main linac. The impact of this feed-forward on the RTML tolerances depends on the design of the distributed timing system. Details of the RTML timing are discussed in [1].

Based on the results of ref. [2], the luminosity loss due to drive beam jitter can be approximated as:

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \approx 0.01 \left[\left(\frac{\sigma_{\phi,coh}}{0.2^\circ} \right)^2 + \left(\frac{\sigma_{\phi,inc}}{0.8^\circ} \right)^2 + \left(\frac{\sigma_{I,coh}}{0.75 \times 10^{-3}I} \right)^2 + \left(\frac{\sigma_{I,inc}}{2.2 \times 10^{-3}I} \right)^2 + \left(\frac{\sigma_{\sigma_z,coh}}{1.1 \times 10^{-2}\sigma_z} \right)^2 + \left(\frac{\sigma_{\sigma_z,inc}}{3.3 \times 10^{-2}\sigma_z} \right)^2 \right]$$

Here, $\sigma_{\phi,coh}$ is the RMS amplitude of the relative phase error between main and drive beam, integrated over the main linac structure fill time, and assuming that the error is the same in each drive beam decelerator. $\sigma_{\phi,inc}$ is assumed to be independent from one decelerator to the next. The errors for the drive beam current and bunch length are similarly defined as $\sigma_{I,coh}$, $\sigma_{\sigma_z,coh}$, $\sigma_{I,inc}$ and $\sigma_{\sigma_z,inc}$.

In the drive beam generation complex, these tolerances are valid for constant errors along the pulse. The tolerances are significantly larger for errors that vary along the pulse [3].

Three main ingredients are used to achieve the tight demands on the drive beam phase, current and bunch length stability:

- The complex has been optimised to increase tolerances by design.
- In the drive beam accelerator feedback is used to stabilise the drive beam properties during the $140 \mu\text{s}$ long pulse. This is very efficient since the combiner rings mix later parts of the drive beam pulse with earlier parts.
- A phase feed-forward is used just before the drive beam decelerator to correct residual phase jitter. This feed-forward requires a distributed timing reference.

DRIVE BEAM PHASE STABILISATION

The main concern is that energy jitter induced in the drive beam accelerator (DBA) would be transformed into beam phase jitter in the bunch compressor (BC). In Fig. 1 the concept of the drive beam layout is shown. The bunches are accelerated to 300 MeV to reduce space charge forces. They are compressed to a length of 1 mm, which is the length they need to have in the PETS, and then accelerated to their final energy of $\approx 2.5 \text{ GeV}$. With this design one can afford having a strong energy chirp, i.e correlation between particle energy and longitudinal position within a bunch, leading to a low R_{56} and thus to a weak coupling of energy jitter to beam phase. In the second stage of the drive beam accelerator (DBA2), the large relative energy spread will be reduced to levels which are acceptable in the drive beam decelerator. To avoid that an energy jitter from DBA2 can turn into beam phase jitter the sum of all R_{56} afterwards has to be zero.

To avoid significant impact of coherent synchrotron radiation, the bunches are uncompressed to 2 mm before they enter the delay loop and re-compressed behind the combiner rings. These steps might be skipped if loop and ring lattices are found which allow the transport of short

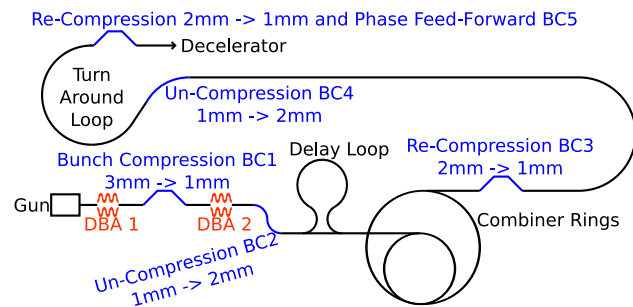


Figure 1: Conceptual layout of the CLIC drive beam showing one of the 24 turn around loops required for each side.

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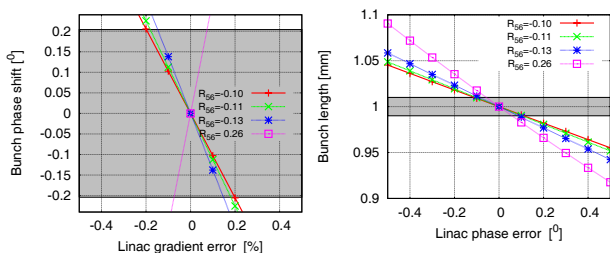


Figure 2: Outgoing bunch phase shift vs. linac gradient (left) and bunch lengthening vs. linac phase error. The gray area marks the acceptable tolerances.

Table 1: RF Tolerances of DBA1

Parameter	Value
RF power error (%)	0.2
Beam current error (%)	0.1
RF phase error (deg)	0.05

bunches. Uncompression and re-compression are transparent for the energy jitter and beam phase and should not lead to any significant beam degradation when properly designed.

In order to further reduce beam phase jitter, also from other sources, it is foreseen to have a phase feed-forward system just in front of the PETS [3]. The beam phase is measured in front of the turn around loop and is corrected afterwards. This requires that the path length can be changed in a controlled manner. The easiest solution is to include a chicane built of four dipoles. Such a chicane acts as a bunch compressor and the bunches need to be uncompressed before to maintain the final bunch length. The correction of the path length is done with fast kickers changing the bunch deflection in the dipoles.

The correction of the path length changes the R_{56} of the chicane which leads to a small bunch length jitter. This will become smaller if the nominal R_{56} becomes larger. A nominal $R_{56} = 0.2$ m was found to allow phase corrections of up to ± 10 deg with kickers of a maximum strength of $375 \mu\text{rad}$. Based on this design we allow an RMS phase jitter of 2.5° ($\sigma_{\Delta z} = 175 \mu\text{m}$) at the end of DBA which the feed-forward should reduce to 0.25° .

The DBA1 RF amplitude and phase tolerances are defined by this limit. Different designs have been developed the first bunch compressor. Tolerance studies showed that phase as well as bunch length errors after the compressor can be the limiting factor. An example is shown in Fig. 2.

The drive beam accelerating structure has been designed [4] to be the same as the final drive beam pulse length in the main linac (240 ns). This maximises the tolerances for high frequency RF errors from the klystrons [3].

CTF3 RESULTS

The pulse-to-pulse stability of beam current and RF phase and amplitude have been measured in CTF3 [5].

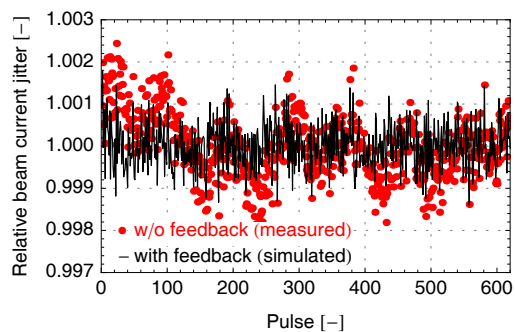


Figure 3: The pulse-to-pulse beam current jitter (\circ). The simulation of an beam current feedback ($-$).

The beam current has been analysed along the CTF3 linac, before the beam recombination. Our observable is the average beam current on the fraction of the beam pulse used for the beam recombination ($1.12 \mu\text{s}$). A typical result is shown in Fig. 3. In a time window of 10 min we observed an RMS relative jitter, of $\sigma/\mu \approx 7.8 \times 10^{-4}$. By analysing the correlation between different BPM readings related to the same beam pulse we can estimate the BPM precision ($< 3 \times 10^{-4}$): the observed jitter is larger than the BPM noise.

Cutting the beam into 113 10 ns-long timeslices we evaluate the coherence of the jitter along the pulse. The coherent variation between the samples is at the level of $\approx 7.7 \times 10^{-4}$ whereas the incoherent component is $\approx 11 \times 10^{-4}$ and does not depend on the time distance between the samples. These two different contributions can be associated to the electron source stability and the BPM noise, respectively.

To further improve the CTF3 performance a pulse-to-pulse feedback on the beam current has been investigated (Fig. 3): the residual simulated RMS jitter is 5.4×10^{-4} . An actual implementation of this system is under study.

One CTF3 klystron was used to measure the short term RF stability. It produces a $5.5 \mu\text{s}$ RF pulse at 3 GHz with the peak power of a 33 MW. We measured 500 consecutive RF pulses (≈ 10 min). The pulse-to-pulse mean phase jitter is 0.035° . The pulse-to-pulse phase jitter for a fixed 10 ns time slice is 0.07° (3 GHz). The relative pulse-to-pulse power jitter (σ/μ) measured along the pulse is $\leq 2.1 \times 10^{-3}$.

In Fig. 4 correlation spectra of the klystron RF phase and power variations along the pulse are illustrated. The correlation of the RF phase variation at high frequencies (20 – 100 MHz) and at ≈ 2 MHz is significant, which indicates the possibility to improve the klystron stability by using a fast phase feedback. The phase variation is uncorrelated after a few μs . The power and the phase variation is weakly correlated at 4 MHz suggesting that it can be eventually cured by the averaging during the drive beam recombination.

The measurements show that the beam current and RF

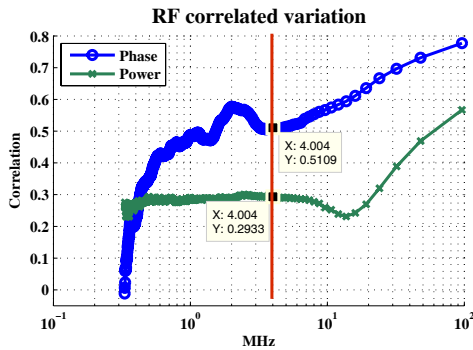


Figure 4: Correlation spectra of the klystron phase and power.

stability of a klystron is close to the CLIC requirements. Measurements of the drive beam bunch length jitter are planned.

TIMING REFERENCE

In order to achieve the required phase stability of 46 fs the measurement used for feed-forward correction must be better than 23 fs and the timing reference must be better than 10 fs. There are two distinct options for the timing reference. The first uses local oscillators at all measurement/correction locations. They are synchronised with the outgoing main beam which constitutes the global reference of the machine. The second option constructs an optical global reference distributed from a central generation point, i.e. a system similar to the X-FEL timing system.

In the first strategy, the main beam is used as the timing reference for the phase jitter correction system. The main-beam is picked up in the outgoing direction, and its timing relative to a stable local oscillator is established. This information is then stored until the arrival of the drive beam, up to 160 μ s later (corresponding to the return trip time for a 24 km linac), and used in the final calculation of timing mismatch between the beams [6]. The required highly stable local oscillators exist, with a minimum integrated time jitter (< 10 fs) over 160 μ s and two have been ordered for beam tests in CTF3. The phase monitors are being developed and will also be tested.

The second strategy has been explored to meet the challenging European X-FEL timing requirements. They have thus developed a centrally generated timing reference, distributed through stabilized laser fibers. Optical synchronisation with < 10 fs resolution has been demonstrated over ~ 300 m at DESY [7].

For the two different timing systems we find the following final beam-beam jitter at the interaction point:

$$\sigma_{BB} \approx \sqrt{2} \left(\sigma_{MB} \oplus \frac{6}{7} [\sigma_{MB \rightarrow LO} \oplus \sigma_{LO \rightarrow RF}] \right) \quad (1)$$

$$\sigma_{BB} \approx \sqrt{2} \left(\frac{1}{7} \sigma_{MB} \oplus \frac{6}{7} [\sigma_{ref} \oplus \sigma_{ref \rightarrow RF}] \right) \quad (2)$$

Equation (1) is valid when using the outgoing main beam as a reference, where σ_{MB} is the timing error of the outgoing main beam, $\sigma_{MB \rightarrow LO}$ the error of the local oscillator with respect to the main beam, and $\sigma_{LO \rightarrow RF}$ the error in correction of the RF phase. Equation (2) is valid for an X-FEL type timing system with σ_{ref} the error between the central timing reference and the one at the final turn-around, and $\sigma_{ref \rightarrow RF}$ the error in correction of the RF phase.

It can be clearly seen that the X-FEL type timing system is less sensitive to errors in timing between the two main beams. The primary challenge is to scale up such a system to CLIC size while maintaining stability below 10 fs of the reference.

In case of beam-based timing, the problem of reference stability is already solved. But the system requires 7 times tighter relative phasing tolerances for the two main beams after the RTML. This tolerance could be relaxed if this error is measured in the central complex before the main beams are sent to the linacs. In this case one could shift the position of the beam waists at collision longitudinally to reduce the luminosity loss. This can be achieved by a feed-forward that either uses fast quadrupoles or changes the beam energy slightly just before the final doublet. The Detector Working Group has indicated their willingness to accept the longitudinal jitter of the collision point [8].

As a CLIC-scale global timing reference seems at the present time to be far from realisation, the beam-based timing system remains attractive, in particular if one develops the ability to feed-forward on the main-beam to main-beam jitter, thus reducing the sensitivity to main-beam generation errors.

CONCLUSION

We have developed a conceptual design of the CLIC drive beam complex in order to achieve the required drive to main beam phase stability. The RF phase stability requirement for this concept compares favorably with the measured performances at CTF3. Also the first measurements of the drive beam current stability in CTF3 are close to the needs.

An important ingredient of this scheme is a distributed timing system. We discussed two different options for such a scheme, which could even be combined.

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