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DEMONSTRATION OF CLIC LEVEL PHASE STABILITY USING A HIGH BANDWIDTH, LOW LATENCY DRIVE BEAM PHASE FEEDFORWARD SYSTEM AT THE CLIC TEST FACILITY CTF3

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Abstract

The CLIC acceleration scheme, in which the RF power used to accelerate the main high energy beam is extracted from a second high intensity but low energy beam, places strict requirements on the phase stability of the power producing drive beam. To limit luminosity loss caused by energy jitter leading to emittance growth in the final focus to below 1%, 0.2 degrees of 12 GHz, or 50 fs, drive beam phase stability is needed. A low-latency phase feedforward correction with bandwidth above 17.5 MHz will be used to reduce the drive beam phase jitter to this level. The proposed scheme corrects the phase using fast electromagnetic kickers to vary the path length in a chicane prior to the drive beam power extraction. A prototype of this system has been installed at the CLIC test facility CTF3 to prove its feasibility. The latest results from the system are presented, demonstrating phase stabilisation in agreement with simulations given the beam conditions and power of the kicker amplifiers. Necessary improvements in the phase monitor performance and optics corrections made to remove the phase-energy dependence via R56 in order to achieve this level of stability are also discussed.

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Abstract

The CLIC acceleration scheme, in which the RF power used to accelerate the main high energy beam is extracted from a second high intensity but low energy beam, places strict requirements on the phase stability of the power producing drive beam. To limit luminosity loss caused by energy jitter leading to emittance growth in the final focus to below 1%, 0.2 degrees of 12 GHz, or 50 fs, drive beam phase stability is needed. A low-latency phase feedforward correction with bandwidth above 17.5 MHz will be used to reduce the drive beam phase jitter to this level. The proposed scheme corrects the phase using fast electromagnetic kickers to vary the path length in a chicane prior to the drive beam power extraction. A prototype of this system has been installed at the CLIC test facility CTF3 to prove its feasibility. The latest results from the system are presented, demonstrating phase stabilisation in agreement with simulations given the beam conditions and power of the kicker amplifiers. Necessary improvements in the phase monitor performance and optics corrections made to remove the phase-energy dependence via R56 in order to achieve this level of stability are also discussed.

INTRODUCTION

The RF power used to accelerate the main beam in the proposed linear collider CLIC is extracted from a second ‘drive beam’. To verify the feasibility of this concept a drive beam ‘phase feedforward’ system is required to achieve a timing stability of 50 fs rms, or equivalently a phase stability (jitter) of 0.2 degrees of 12 GHz (the CLIC drive beam bunch spacing) [1–3]. This system poses a significant hardware challenge in terms of the bandwidth, resolution and latency of the components and therefore a prototype of the system has been designed, installed and commissioned at the CLIC test facility CTF3 at CERN. Phase feedforward is hereafter referred to as “PFF".

A schematic of the CTF3 PFF system is shown in Fig. 1. The phase is corrected utilising two kickers placed prior to the first and last dipole in the chicane in the TL2 transfer line. By varying the voltage applied to the kickers the beam can be deflected onto longer or shorter paths through the chicane, thus inducing a phase shift. The goal is to demonstrate a 30 MHz bandwidth phase correction with a resolution approaching the CLIC requirement of 0.2 degrees at 12 GHz. The required hardware consists of three precise phase monitors [4, 5] and two strip line kickers [5] designed and fabricated by INFN/LNF Frascati, and a kicker amplifier and digital processor [6] from the John Adams Institute at Oxford University. More detailed descriptions can be found in [7].

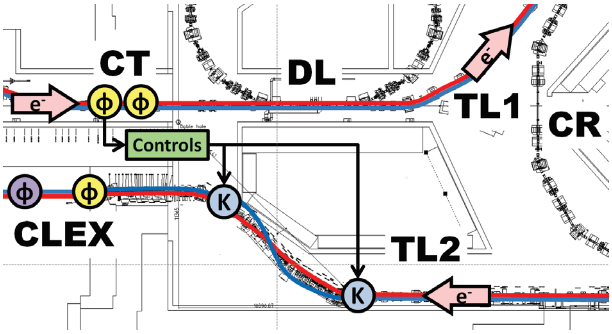

Figure 1: Simplified schematic of the PFF system. Red and blue lines depict orbits for bunches arriving late and early at the first phase monitor, ϕ, respectively. The trajectory through the TL2 chicane is changed using two kickers, K.

The latency of the PFF system, including cable lengths and the latency of each component, is below the 380 ns beam time of flight between the first monitor and the first kicker. This allows the same bunch that was originally measured to be corrected.

The design and commissioning of the PFF system began in 2012. In 2013 the installation of the individual pieces of hardware started as they became available. This included the first tests of the new phase monitors and modifications to the TL2 chicane in order to accommodate the PFF kickers [7]. New optics for the TL2 chicane were created to take in to account the changes and meet the new PFF constraints, namely to create a closed orbit bump between the kickers with the path length between the two dependent on the given kick [8].

The first prototype of the kicker amplifiers became available in mid-2014, allowing the first tests of the PFF system as a whole to begin in late 2014 [9]. This paper will highlight the necessary areas of improvement that were identified after the 2014 attempts, and the work that has been done over the course of 2015 to drive the achieved corrected phase jitter at CTF3 down to close to the CLIC target.

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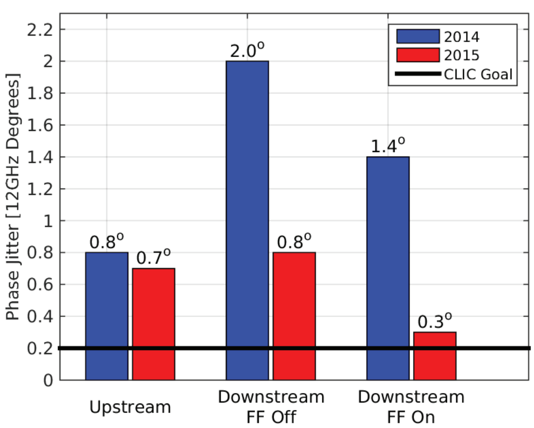

Figure 2: Comparison of achieved phase jitters at the end of 2014 and 2015.

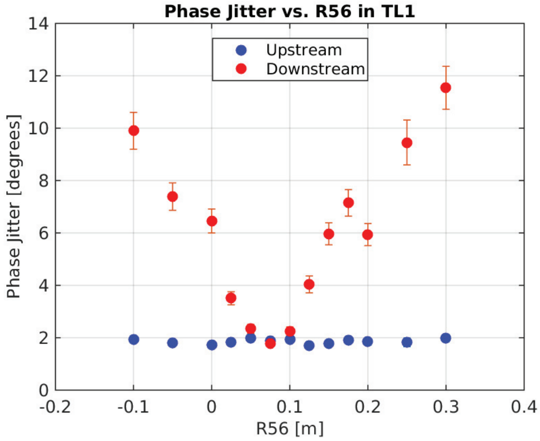

Figure 3: Upstream (blue) and downstream (red) phase jitter for different values of R56 in TL1.

IMPROVEMENTS IN 2015

Figure 2 gives an overview of the achieved phase jitter at CTF3 upstream (at the end of the linac, in the CT line as shown in Figure 1) and downstream (after the TL2 chicane in the CLEX area) with the PFF correction both off and on, at the end of 2014 and 2015. In 2014 the first tests of the complete PFF system demonstrated a modest 30% reduction in downstream phase jitter from an initial 2.0 degrees to 1.4 degrees.

Extensive improvements have been made to both the beam conditions and the PFF hardware and setup during 2015, culminating in the achievement of below 0.3 degrees corrected downstream phase jitter by the end of 2015. Particular areas of significant improvement are the upstream–downstream phase correlation, the phase monitor resolution, the amplifier power and the correction timing. These changes are only summarised below but are presented in more detail in [10].

The most critical limiting factor for the PFF performance in 2014 was the low correlation of only up to 50% between the upstream and downstream phase plus the large amplification in the phase jitter between the upstream and downstream phase, from 0.8 degrees upstream to 2.0 degrees downstream (with the correction off). The theoretical reduction factor in the jitter that the PFF system can achieve is $\sqrt{(1-\rho^2)}$, thus 97% correlation is required to reduce an initial downstream jitter of 0.8 degrees to the CLIC goal of 0.2 degrees, or 99.5% to reduce 2.0 degrees phase jitter to 0.2 degrees.

The PFF prototype utilises the pre-exsiting TL2 chicane at CTF3, with only minor modifications to the lattice possible due to building constraints. As a result it was not possible to match optics for the chicane that met all the desired constraints for the PFF system. In particular, a non-zero value for R56 of -0.2 m had to be accepted. This means that the chicane introduces an additional energy-dependent jitter component to the downstream phase that is not present at the location of the upstream phase monitors. In 2014, the transformation of energy jitter in to phase jitter via R56 was the dominant source of the low upstream-downstream phase correlation and high downstream phase jitter.

In order to compensate for the negative R56 in TL2, new optics for the previous transfer line TL1 (labelled in Figure 1) with positive R56 have been created, so that the overall residual R56 between the upstream and downstream phase monitors is zero. Simulations show that the residual R56 must be controlled at the centimetre level in order to achieve the required correlations of above 97% [9].

By performing a scan of R56 in TL1 it is now possible to reduce the downstream phase jitter to the same level as the upstream phase jitter. This is shown in Figure 3. In combination with the lower downstream phase jitter, the upstream–downstream phase correlation is also increased to up to 96%. Further small improvements to the R56 optimisation process and the energy stability of CTF3 in 2016 should allow the required 97% correlation to be achieved.

The lowest corrected phase jitter that can be achieved in the ideal case of 100% correlation between the real upstream and downstream phase is sqrt(2) times larger than the phase monitor resolution. In 2014 the phase monitor resolution was in excess of 0.2 degrees, therefore making a correction down to the CLIC requirement of 0.2 degrees theoretically impossible. Replacing digital phase shifters in the phase monitor electronics with mechanical shifters to reduce noise and optimising the input power to each set of electronics yielded a resolution of 0.14 degrees, meaning a 0.2 degree correction is now theoretically possible with the PFF prototype.

The first version of the kicker amplifiers used from 2014 until mid-2015 provided an output voltage of up to ±345 V sent to each kicker strip. This voltage determines the correction range of the PFF prototype, which with this output was ±3 degrees. Unfortunately, with this range the calculated correction to apply based on the upstream phase jitter was saturating the amplifier for typically 10% of the beam pulses in each dataset. A new version of the amplifier with additional FETs was designed, built and delivered in 2015,

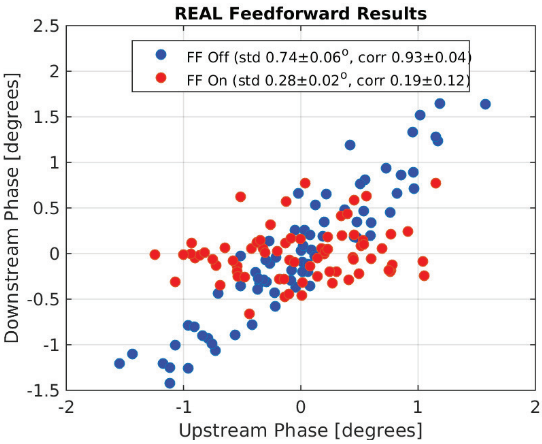

Figure 4: Upstream–downstream mean phase distribution with the real PFF system.

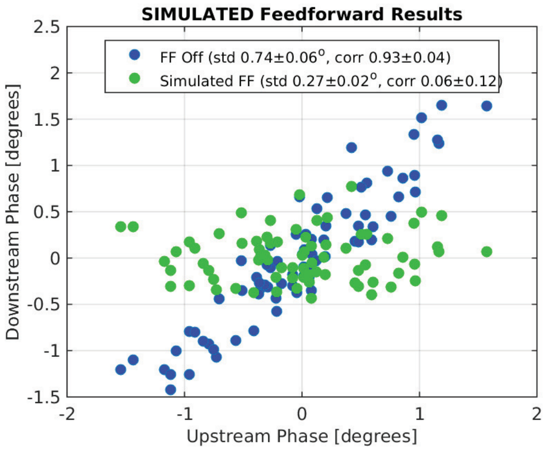

Figure 5: Simulated upstream–downstream mean phase distribution.

giving an output voltage of ±695 V for a correction range of ±6 degrees. With this output a 350 ns portion of the 1.2 μs CTF3 beam pulse can now be optimally corrected. The whole 1.2 μs cannot be corrected due to the large phase sag along the CTF3 pulse seen in Figure 6. However, this is already longer than needed for CLIC, where the relevant pulse length will be 240 ns and the phase sag will not be present.

Finally, in early 2015 it was discovered that the applied amplifier output was arriving at the kickers 25 ns before the beam, so that variations in the phase along the pulse were not being removed by the PFF system. Correcting this in the PFF setup allowed these variations to be perfectly flattened, as seen later in Figure 6.

PHASE FEEDFORWARD RESULTS

With all these improvements in place, Figure 4 shows the lowest downstream phase jitter achieved to date. The data shown is taken with the PFF system operating in interleaved mode, with the correction turned on for the even pulses in the dataset and turned off for the odd pulses. The distribution with the PFF system off (in blue) and on (in red) are therefore taken in exactly the same beam conditions and can be directly compared. With the correction off the upstream–downstream phase correlation is 93 ± 4% with an initial downstream phase jitter of 0.74 degrees. Applying the correction removes all correlation between the upstream and downstream phase, reducing the downstream phase jitter to 0.28 ± 0.02 degrees.

An additional benefit of using interleaved data is that the pulses with the PFF system off can be used to perform a simulation of the expected effect of the correction. This is shown in Figure 5. The simulated downstream phase jitter of 0.27 ± 0.02 degrees agrees perfectly with the jitter achieved using the real system, giving confidence that the setup is well understood and the PFF correction is optimal.

The previous results are for the mean pulse phase, but the high bandwidth PFF system also corrects variations in the phase along the pulse. This is shown in Figure 6. The area bounded by the vertical black lines marks the region in which the amplifier is not being saturated due to the phase sag along the pulse discussed in the previous section. Within this region the PFF system almost perfectly flattens all variations along the pulse, reducing an initial mean deviation of 1.68 ± 0.02 degrees to 0.26 ± 0.01 degrees.

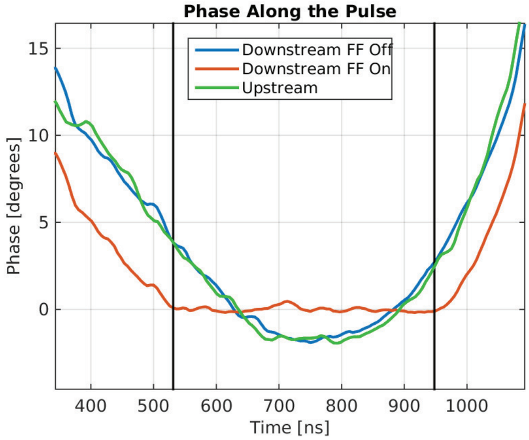

Figure 6: Phase variations along the pulse with the PFF system on and off.

CONCLUSIONS

A prototype of the PFF system needed to reduce the CLIC drive beam phase jitter to 0.2 degrees at 12 GHz has been installed at CTF3. After one year of experience operating this prototype system a phase jitter of 0.28 ± 0.02 has been demonstrated, very close to the CLIC specifications. A wide range of improvements to the R56 control and beam stability at CTF3, optimisations of the phase monitor resolution and doubling the amplifier output voltage have made this possible. With additional fine-tuning in 2016, the final year of operation at CTF3, it will be possible to further reduce the achieved phase jitter and to reproduce it on longer time scales.

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