

# FIRST EXPERIMENTAL RESULTS WITH THE CLIC DRIVE BEAM PHASE FEEDFORWARD PROTOTYPE AT THE CLIC TEST FACILITY CTF3\*

G.B. Christian, P.N. Burrows, C. Perry, JAI, Oxford University, UK  
 J. Roberts, CERN, Geneva, Switzerland; JAI, Oxford, UK  
 A. Andersson, R. Corsini, P.K. Skowroński, CERN, Geneva, Switzerland  
 A. Ghigo, F. Marcellini, INFN/LNF Frascati, Italy

## Abstract

The two-beam acceleration scheme envisaged for CLIC will require a high degree of phase stability between two beams at the drive beam decelerator sections, to allow efficient acceleration of the main beam. There will be up to 48 such decelerator sections for the full 3 TeV design, and each decelerator section will be instrumented with a feed-forward system to correct the drive beam phase to a precision of 0.2 degrees at 12 GHz relative to the main beam, using a kicker system around a four-bend chicane. A prototype system has been developed and tested at the CLIC Test Facility (CTF3) complex, where the beam phase is measured upstream of the combiner ring and corrected with two kickers in a dog-leg chicane just upstream of the CLEX facility, where the resulting phase change is measured. This prototype is designed to demonstrate correction of a portion of the CTF3 bunch train to the level required for CLIC, with a bandwidth of greater than 30 MHz, and within a latency constraint of 380 ns as set by the beam time-of-flight through the combiner ring complex. A description of the hardware will be given and initial results from the first phase of the experiment will be presented.

## INTRODUCTION

The RF power used to accelerate the main beam in the proposed linear collider CLIC is extracted from a second ‘drive beam’. To ensure the efficiency 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.

A schematic of the CTF3 phase feedforward (PFF) system is shown in Fig. 1. The phase is corrected utilising two kickers placed prior to the first and last dipole in the pre-existing 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 of 0.2 degrees of

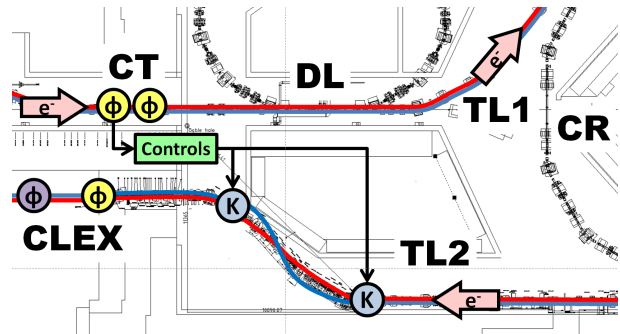


Figure 1: Simplified schematic of the PFF system. Red and blue lines depict orbits for bunches arriving late and early at the first phase monitor,  $\phi$ , respectively. The trajectory through the TL2 chicane is changed using two kickers,  $K$ .

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].

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.

## COMMISSIONING

The complete PFF system became available in October 2014. Previous results from commissioning of the optics and phase monitors are presented in [8, 9].

The first prototype kicker amplifiers used for the tests presented here provide an output voltage of 340 V. They will be upgraded in stages over the course of 2015, ultimately providing the nominal voltage of 1.2 kV. Constant kick tests demonstrated that applying the maximal 340 V to the PFF kickers resulted in a phase shift of  $\pm 3.5^\circ$ , thus verifying the functionality of the amplifiers, kickers and chicane optics (Fig. 2). The 30 ns rising and falling edges of the response to the kick correspond to 12 MHz amplifier bandwidth when rising from zero to maximum output. This is slew-rate limited and the bandwidth is expected to be 50 MHz for smaller variations.

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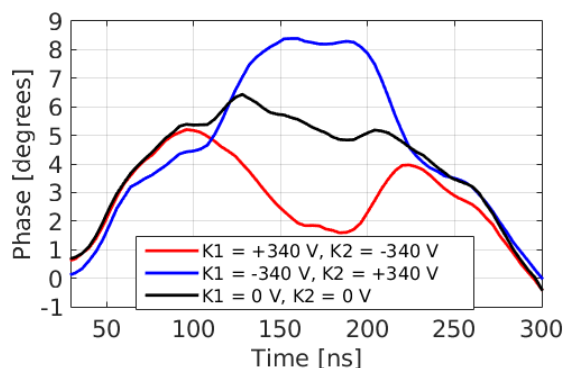


Figure 2: Phase shift resulting from a constant kick applied between 110 ns and 225 ns on the time axis.

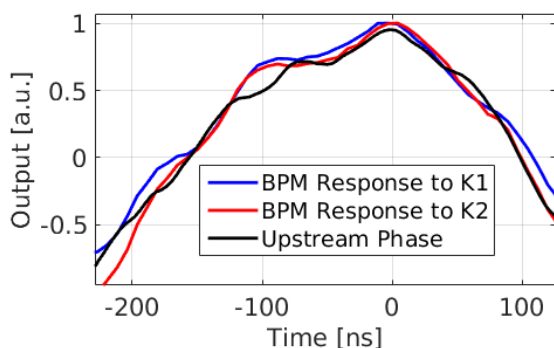


Figure 3: Comparison of the measured downstream position offset and the upstream phase whilst applying the PFF algorithm to one kicker. Note that the phase is normalised to match the sign and amplitude of the position (the actual correction output is the inverse of the input phase).

The PFF algorithm on the digital processor varies the drive signal to the amplifier based on the upstream phase (measured in the CT line, see Fig. 1) in order to correct the downstream phase (after the correction chicane in CLEX) with 30 MHz bandwidth. Its performance was verified by observing the response in a BPM after the correction chicane whilst applying the PFF correction to one kicker at a time. Figure 3 proves that the applied kick has the same shape as the upstream phase.

During the commissioning it was apparent that the upstream phase jitter of up to  $1^\circ$  increased to as much as  $4^\circ$  downstream. The correlation between the upstream and downstream phase was also low, often below 30%.  $R_{56}$ , the transfer matrix coefficient relating phase to energy, is a critical parameter for the PFF system and should be exactly zero between the upstream and downstream phase measurements. Any incoming energy jitter will otherwise be converted in to additional downstream phase jitter. This is the dominant source of the low correlation between the upstream and downstream phase at CTF3.

In order to reduce the energy component in the downstream phase,  $R_{56}$  for the transfer line TL1 (prior to TL2, see Fig. 1) was therefore tuned to compensate for the non-

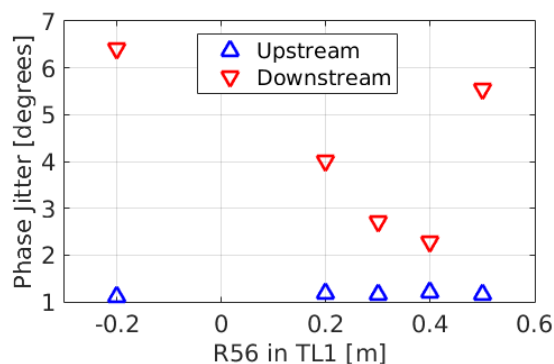


Figure 4: Dependence of phase jitter on  $R_{56}$  set in TL1.

zero  $R_{56}$  in the TL2 chicane. The downstream phase jitter is reduced to around  $2^\circ$  with an  $R_{56}$  of 0.3 m to 0.4 m in TL1 (Fig. 4). Meanwhile, the upstream to downstream phase correlation increased to 40–50%. This improvement in the downstream phase jitter was sufficient to obtain the first PFF results, as shown in the following section. However, further improvements will be needed to reduce the downstream jitter to the CLIC level, as discussed later.

## PHASE FEEDFORWARD RESULTS

The drive beam pulses in CLIC are 240 ns long. 100–200 ns pulses (such as shown in Fig. 2) were used to test the functionality of the PFF system at CTF3. As the amplifiers are upgraded during 2015 the increased power will allow tests to be conducted on the full CLIC pulse length.

In the first PFF tests the gain on the digital processor was varied, including both positive (acting to reduce the phase jitter) and negative (acting to increase the phase jitter) values, in order to determine the optimal gain setting and to verify the performance of the correction. Figure 5 shows the relationship between the mean upstream and downstream phase for different gain values, and the upstream-downstream phase correlation is plotted as a function of the gain in Fig. 6. With the PFF system turned off (zero gain) there is 50% correlation between the upstream and downstream phase with a gradient of 1.0. By using a gain of  $-63$  the gradient and correlation are amplified to 1.8 and 63% respectively. Alternatively, with a gain value of  $+40$  the PFF correction acts to remove almost all correlation between the upstream and downstream phase, in fact slightly over-correcting to give a small negative correlation of  $-0.16$ .

Figure 7 shows the effect of the PFF correction on the downstream phase jitter. The initial downstream phase jitter of  $2^\circ$  degrees is reduced to  $1.4^\circ$  degrees with a gain of  $+40$ , a reduction of 30%. Negative gain values or values above  $+40$  result in the downstream phase being amplified or over-corrected respectively, naturally leading to an increase in jitter.

These results demonstrate a clear improvement in the stability of the mean downstream phase via the PFF correction. However, the goal is to demonstrate not only a correction of

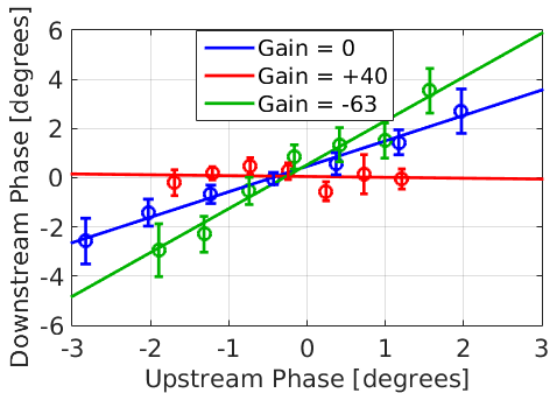


Figure 5: Relationship between the mean upstream and downstream phase for different correction gains.

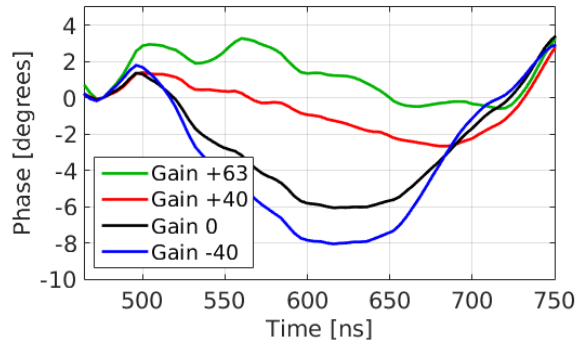


Figure 8: Phase variation along the pulse downstream for different PFF gains. The correction is applied from 510 ns to 710 ns on the time axis.

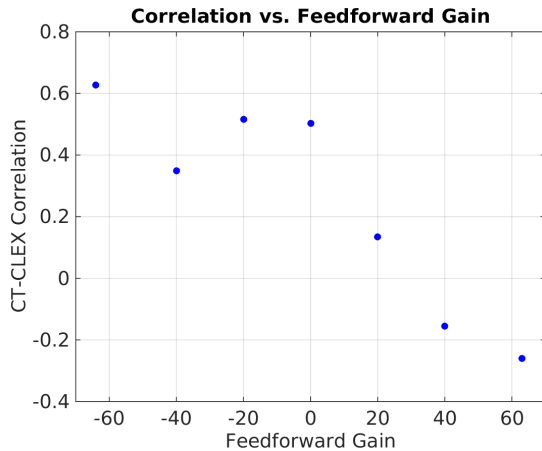


Figure 6: Upstream-to-downstream phase correlation vs feedforward gain.

the mean pulse phase but also flattening of phase variations within the pulse. The effect of the PFF system on the phase within the 200 ns portion of the pulse in which the correction was applied is shown in Fig. 8. With the optimal gain of +40 the phase variation along the pulse is reduced from 7° to 3°. There is a remaining slope in the phase along the pulse as a result of the current limits in correlation and correction range.

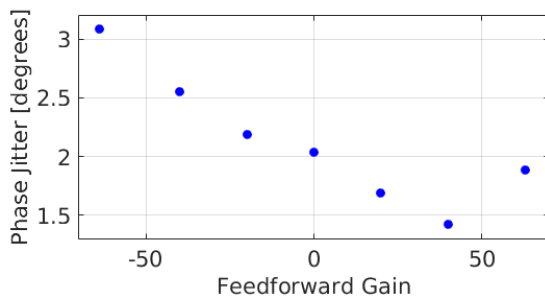


Figure 7: Dependence of the downstream phase jitter on the PFF gain.

### IMPROVING PERFORMANCE

The theoretical minimum phase jitter achievable using the PFF correction with optimal gain is given by  $\sigma_f = \sigma_i \sqrt{1 - \rho^2}$ , where  $\sigma_f$  is the corrected downstream phase jitter,  $\sigma_i$  is the initial downstream phase jitter and  $\rho$  is the correlation between the upstream and downstream phase. A correlation of 97% is therefore required to reduce an initial phase jitter of 0.8° to the CLIC limit of 0.2°. The beam conditions during the first PFF tests were typically 2° phase jitter and 40% correlation, thus important further improvements are needed to achieve this goal.

Despite varying  $R_{56}$  in the TL1 line in order to minimise the total residual  $R_{56}$  as discussed previously, the adjustments were not precise enough and it was proven that energy was still the dominant source of the low phase correlation. To verify this, the correlation of the upstream and downstream phase with a dispersive BPM (used as an energy measurement) was checked. This is shown in Fig. 9. The high 80% correlation between the downstream phase and the energy compared to the low 2% correlation between the upstream phase and energy confirms that energy jitter is being converted into phase jitter via a residual  $R_{56}$  between the upstream and downstream phase monitors.

Simulations have shown that a residual  $R_{56}$  of around 0.1 m is enough to recreate the 40% correlation and 2° phase jitter typical of the observed beam conditions. As the  $R_{56}$  scan in TL1 shown previously was performed in steps of 0.1 m, it is reasonable to expect that the majority of the remaining energy component in the phase can be removed with finer tuning of  $R_{56}$  in TL1. In order to achieve the 97% correlation necessary to correct the downstream phase jitter down to 0.2° the  $R_{56}$  must be controlled to within 1 cm.

Additionally, the signal from a dispersive BPM in the same region as the upstream phase monitors can be connected to the PFF processor. The PFF algorithm will then be adjusted to use a combination of the upstream phase and the energy (measured as position jitter in the BPM), thus increasing the correlation of the PFF input with the downstream phase and therefore the capability of the system.

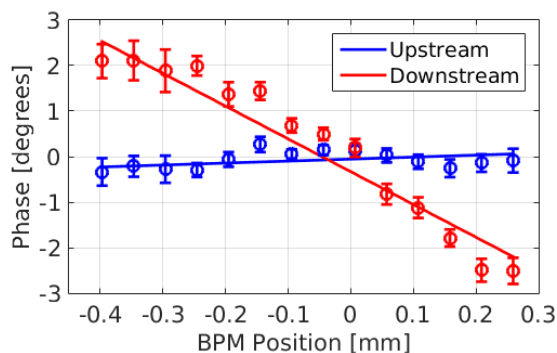


Figure 9: Dependence of the phase on the beam energy (position in a dispersive BPM).

## CONCLUSIONS

CLIC requires a drive beam phase stability of  $0.2^\circ$  degrees, which can only be achieved via the use of a high bandwidth PFF correction. Preliminary running of the prototype of this system at the CLIC test facility CTF3 has so far demonstrated a 30% reduction in the drive beam jitter by using kickers to vary the path length through a magnetic chicane. It was identified that in order to reduce the phase stability to the CLIC level at CTF3 energy effects entering the phase via  $R_{56}$  must be removed in order to improve the correlation between the upstream and downstream phase from 40% to above 95%. During the 2015 run, finer tuning of  $R_{56}$  and including an energy measurement in the PFF algorithm will be tested to achieve this.

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