Arrival Time Stabilisation of a Relativistic Electron Beam at the 50 fs Level

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CLIC, a proposed future linear electron-positron collider, and other machines such as XFELs, place tight tolerances on the phase stabilities of their beams. CLIC proposes the use of a novel, high bandwidth and low latency, 'phase feedforward' system required to achieve a phase stability of 0.2° at 12 GHz, or about 50 fs. This work documents the results from operation of a prototype phase feedforward system at the CLIC test facility CTF3, with > 23 MHz bandwidth and a total hardware latency of 100 ns. New phase monitors with 30 fs resolution, 20 kW amplifiers with 47 MHz bandwidth, and electromagnetic kickers have been designed and installed for the system. The system utilises a dog-leg chicane in the beamline, for which a dedicated optics have been created and commissioned. The prototype has demonstrated CLIC-level phase stability, reducing an initial rms phase variation of $0.92 \pm 0.04°$ to $0.20 \pm 0.01°$.

The Compact Linear Collider, CLIC, [1] is a proposal for a future linear electron–positron collider. It uses a novel two beam acceleration concept to achieve a high accelerating gradient of 100 MV/m and a collision energy of up to 3 TeV. In this concept the 12 GHz RF power used to accelerate each high energy colliding beam is extracted and transferred from a high intensity drive beam in 24 decelerator sectors. The drive beams are generated by compressing an initial 140 μs beam pulse bunched at 0.5 GHz into 24 shorter 240 ns beam pulses bunched at 12 GHz, in a bunch recombination process using a sequence of combiner rings and delay loops [REF].

CLIC's luminosity quickly drops if the drive beam phase, or arrival time, jitters with respect to the colliding beams, causing energy errors and subsequent beam size growth at the interaction point. The drive beam phase stability must be 0.2° at 12 GHz (around 50 fs) rms or better to limit the luminosity loss to below 1% [1]. However, the drive beam phase stability cannot be guaranteed to be better than 2° at 12 GHz [REF]. A mechanism to improve the drive beam phase stability by an order of magnitude is therefore required. The correction must be applied to the full drive beam pulse length and have a bandwidth exceeding 17.5 MHz to achieve this [2]. Higher frequency errors are filtered as a consequence of the drive beam recombination process, and by the accelerating structures [2].

Other machines, such as XFELs, have similar beam phase stability requirements to CLIC. At FLASH, DESY, these requirements have been met using an RF phase and power feedback based on the measurement of electro-optic beam arrival time monitors [3]. However, the CLIC drive beam presents a different set of challenges. In particular, FLASH has 1 MHz bunch spacing and a 500 ms beam pulse, whereas the CLIC drive beam has 12 GHz bunch spacing and 240 ns pulse length. A feedback with a latency of several microseconds is therefore not suitable for CLIC.

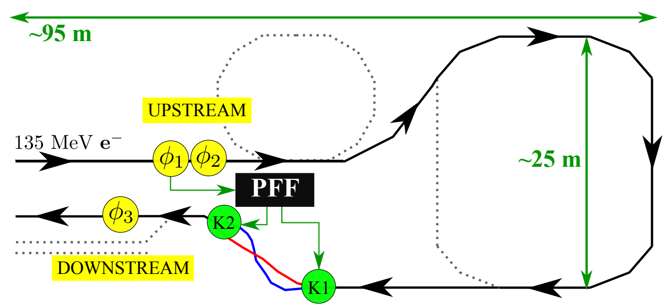

FIG. 1. Schematic of the PFF prototype at CTF3, showing the phase monitors (ϕ_1 , ϕ_2 and ϕ_3) and kickers (K1 and K2). The black box PFF represents the calculation and output of the correction, including the phase monitor electronics, feedforward controller and kicker amplifiers. Dashed lines indicate beam lines that are not used during PFF operation.

CLIC instead proposes a drive beam "phase feedforward" (PFF) system. A prototype PFF system has been designed, commissioned and operated at the CLIC test facility CTF3, at CERN, to prove its feasibility. The prototype system follows the same concept as the CLIC scheme. CTF3 provides a 135 MeV electron beam bunched at 3 GHz with a pulse length of 1.2 μs and a pulse repetition rate of 0.8 Hz [REF]. All phases quoted in the paper are given in degrees at 12 GHz, as relevant for CLIC.

A schematic of the prototype PFF system is shown in Fig. 1. The system corrects the phase using two electromagnetic kickers installed before the first and last dipole in a four bend, dog-leg shaped chicane. The beam's path length through the chicane depends on the voltage applied to the kickers. Bunches arriving early at the upstream phase monitor are deflected on to longer trajectories in the chicane, and bunches arriving late on to shorter trajectories. Downstream of the chicane another phase monitor is placed to measure the effects of the correction.

TABLE I. Overview of parameters, requirements and achievements for the prototype PFF system at CTF3, and how they compare to the proposed CLIC scheme.

	CLIC	CTF3
Drive Beam Energy	2.4 GeV	135 MeV
No. Systems	48	1
Kickers per Chicane	16	2
Power of Kicker Amplifiers	500 kW	20 kW
Angular Deflection per Kicker	± 94 μrad	± 560 μrad
Correction Range	$\pm 10^\circ$	$\pm 6^\circ$
Correction Bandwidth	> 17.5 MHz	> 23 MHz
Phase Monitor Resolution	$< 0.14^\circ$	0.12°
Initial Phase Jitter	2.0°	0.9°
Corrected Phase Jitter	0.2°	0.2°

The beam time of flight between the upstream phase monitor and the first kicker in the chicane is 380 ns. The total cable length for the PFF correction signals is shorter, around 250 ns (see Fig. 1). The PFF correction in the chicane can therefore be applied to the same bunch initially measured at the phase monitor, providing the total system hardware latency is less than 130 ns.

The PFF system presents a significant hardware challenge, in particular in terms of the power, latency and bandwidth requirements for the kicker amplifiers, and the resolution and bandwidth of the phase monitors. A low latency digitiser and feedforward controller is also required. Table I compares the requirements of the CLIC system and their corresponding values at CTF3. The main differences result from the different drive beam energies, and scales of the two facilities. Higher power amplifiers (500 kW rather than 20 kW) are required at CLIC, which may be achieved by combining the output of multiple modules similar to the CTF3 design [REF]. CLIC also requires the synchronisation of multiple PFF systems distributed along the 50 km facility, which is not addressed by the CTF3 prototype (proposals can be found in [REF]).

The three phase monitors used at CTF3 [4] are designed and constructed by INFN Frascati, with the associated electronics built by CERN. The phase monitors are cylindrical cavities with an aperture of 23 mm and a length of 19 cm. Notch filters, small ridges, in the cavity create a resonating volume at 12 GHz, whilst also reflecting stray fields. The fields induced by the beam traversing the cavity contain a position independent monopole mode and a position dependent dipole mode. The induced fields are extracted in an opposing pair of feedthroughs on the top and bottom of the cavity. The unwanted position dependence is then removed by summing the output from each feedthrough in a hybrid. To extract the phase dependence of the beam signal the output from the hybrids is mixed with a 12 GHz reference signal, derived from a 3 GHz source time-locked to CTF3 and common to all three phase monitors. In the electronics for each phase monitor the beam and reference signals are split between eight separate mixers, with the output from each combined to give the final phase dependent outputs. This has allowed a resolution of 0.12°, or about 30 fs, to be achieved whilst maintaining linearity between $\pm 70^\circ$ [REF]. The quoted resolution is determined by comparing the measurements of the two adjacent upstream monitors (see Fig. 1).

The kicker amplifiers [5] have been designed and constructed by the John Adams Institute/Oxford University. They have a modular design, consisting of a central control module, and two drive and terminator modules (one per kicker). The control module distributes power and input signals to the drive modules. The 20 kW drive modules consist of low voltage Si FETs driving high voltage SiC FETs, and for an input voltage of ± 2 V give an output of up to ± 700 V. The output is linear within 3% for input voltages between ± 1.2 V, and has a bandwidth of 47 MHz for small signal variations up to 20% max output. For larger signal variations the bandwidth is slew rate limited.

The two electromagnetic stripline kickers [6] were also designed and built by INFN Frascati, and are based on the DAFNE design [REF]. Each kicker is approximately 1 m in length, and has an internal diameter of 40 mm between the two strips placed along the horizontal walls of the device. The kickers are designed to give a fast response of a few ns to the input signal, and to give high kick efficiency. The strips have tapered ends to reduce beam coupling impedance. A voltage of 700 V, the maximum output of the amplifiers, applied to the downstream ends of the kicker strips yields a horizontal deflection of 0.56 mrad for the 135 MeV CTF3 beam.

The Feedforward digitiser and controller (FONT5a board) [5] was also designed and built by John Adams Institute/Oxford University. This digitises the processed phase monitor signals and then calculates and outputs the appropriate amplifier input voltage. The FONT5a board also controls the correction timing. It consists of a Virtex-5 field programmable gate array (FPGA), nine 14-bit analogue to digital converters (ADCs) clocked at 357 MHz, and four digital to analogue converters (DACs). The combined hardware and firmware latency for the PFF system is approximately 100 ns. The output from the FONT5a board is delayed by 30 ns to synchronise the correction at the kicker with the beam [5].

As well as the hardware challenges, the PFF system places additional constraints on the optics of the correction chicane, and also on the beam lines between the upstream phase monitor and the chicane.

The optics transfer matrix coefficient R_{52} between the kickers relates the change in path length through the chicane per unit deflection at the first kicker. With an R_{52} value of 0.74 m in the chicane optics at CTF3 [5] the expected correction range (path length change) of the PFF system is ± 400 μm, or $\pm 6^\circ$, considering the max-

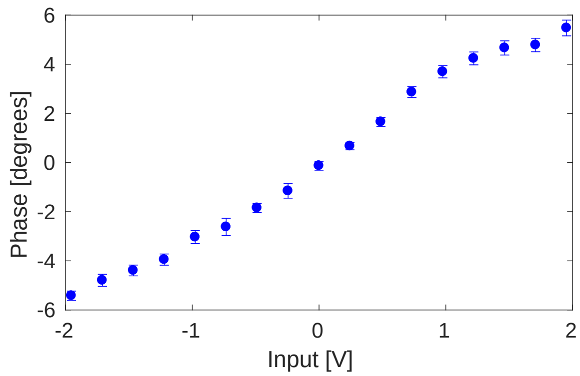

FIG. 2. Downstream phase vs. the kicker amplifier input voltage. Standard errors on the measured phase are shown.

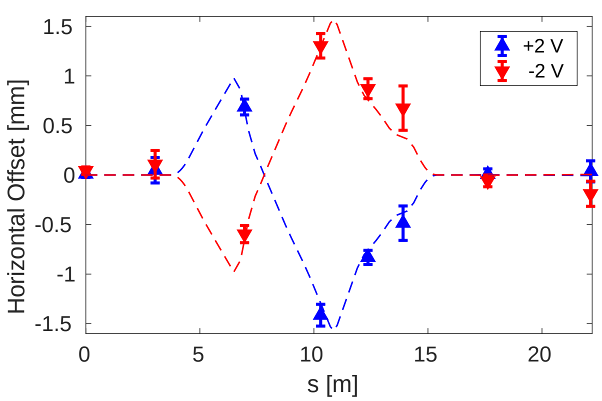

FIG. 3. Horizontal orbit in and around the TL2 chicane at maximum (blue) and minimum (red) input to the kicker amplifiers. Markers show the measured position in beam position monitors, and dashed lines the predicted orbit using the CTF3 MADX model and hardware parameters.

imum deflection of ±0.56 mrad from the kickers. The measured phase shift in the chicane versus the amplifier input voltage is shown in Fig. 2, and agrees with the expected range.

The PFF system also should not change the beam orbit after the chicane. The chicane optics are designed so that the second kicker closes the orbit bump created by the first kicker. Fig. 3 shows the horizontal beam orbit in the region of the chicane for the maximum and minimum kick. The closure in the BPMs following the chicane is better than 0.1 mm, compared to a maximum offset of 1.5 mm inside the chicane.

One of the key challenges in operating the PFF prototype at CTF3 has been obtaining high correlation between the initial, uncorrected, upstream and downstream phase. The theoretical limit on the corrected downstream phase jitter is given by $\sigma_{\mathrm{PFF}} = \sigma_d \sqrt{1-\rho_{ud}^2}$, where ϕ_{PFF} is the corrected downstream phase, σ_u and σ_d are the initial upstream and downstream phase jitter respectively,

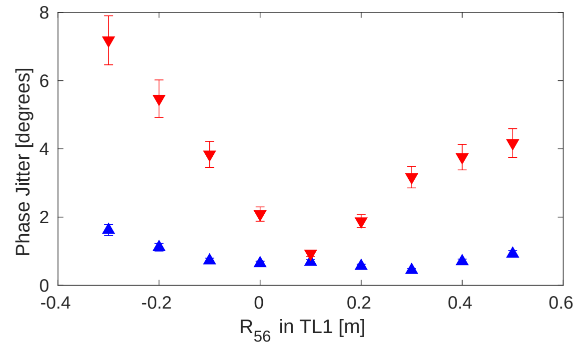

FIG. 4. Downstream (red points) and upstream (blue points) phase jitter vs. the R_{56} value in the set TL1 optics.

and ρ_{ud} is the correlation between the upstream and downstream phase. A correlation of 97% is required to reduce a typical initial phase jitter of 0.8° at CTF3 to the target of 0.2°.

The achievable correlation depends on the phase monitor resolution and any additional phase jitter introduced in the beam lines between the upstream and downstream phase monitors. The phase monitor resolution of 0.12° limits the maximum upstream-downstream phase correlation to 98% in typical conditions, and places a theoretical limit of 0.17° on the measured corrected downstream phase jitter. Any beam jitter that changes the time of flight of bunches influences the resulting downstream phase stability and upstream-downstream phase correlation. The dominant source of uncorrelated downstream phase jitter at CTF3 is beam energy jitter being transformed in to phase jitter in the transfer lines between the upstream and downstream phase monitors.

The first order phase-energy dependence can be described via the optics transfer matrix coefficient R_{56}: $\phi_d = \phi_u + R_{56}(\Delta p/p)$, where $\Delta p/p$ is the relative beam energy offset, and ϕ_u and ϕ_d are the upstream and downstream phase respectively. Optimal conditions for the PFF system are obtained when the total R_{56} between the upstream and downstream monitors is zero. The correction chicane at CTF3 has non-zero R_{56}, thus to create a total R_{56} of zero between the upstream and downstream phase monitors the optics in one of the other transfer lines at CTF3, TL1, has been tuned. Fig. 4 shows that with an R_{56} of around 10 cm in TL1 the first order phase-energy dependence is removed and the downstream phase jitter is reduced to the same level as the upstream jitter. Previously, with the original $R_{56} = 0$ optics in TL1, there is a factor 3 amplification in the downstream phase jitter with respect to the upstream jitter. The upstream-downstream phase correlation is also increased, from below 40% to above 95%. However, a large second order phase-energy dependence was also identified and this remains uncorrected. This leads to a degradation in upstream-downstream phase correlation

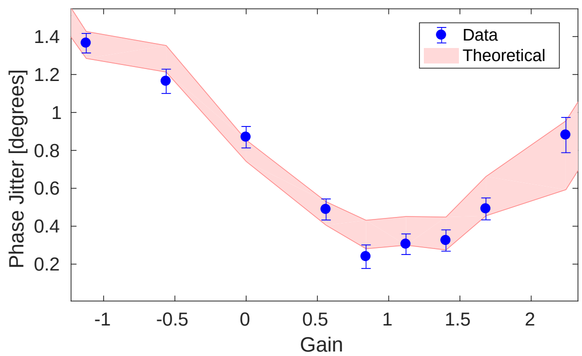

FIG. 5. Downstream phase jitter with the PFF system on at different gains. Markers show the measured phase jitter with standard error bars. The shaded red region shows the expected performance given the initial beam conditions.

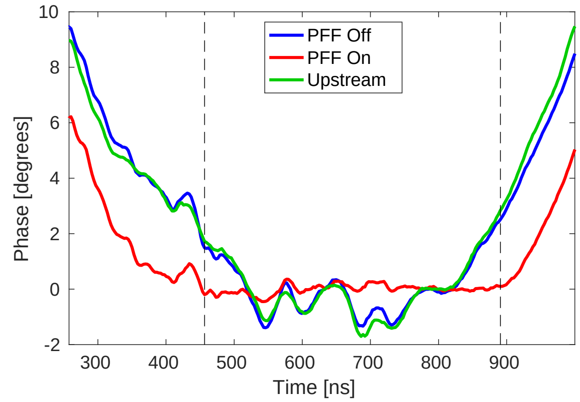

FIG. 6. Effect of the PFF system on intra-pulse phase variations. The pulse shape upstream (green), and downstream with the PFF system off (blue) and on (red) is shown.

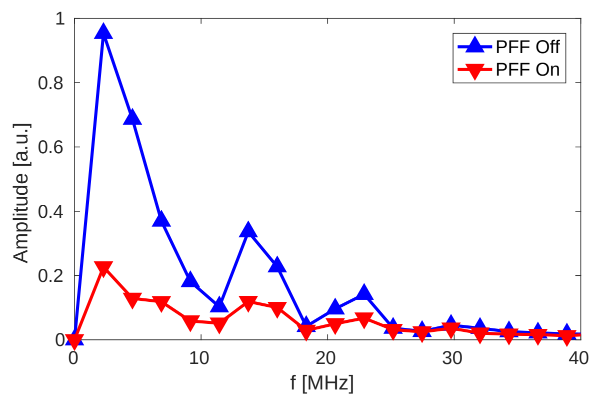

FIG. 7. Amplitude of phase errors at different frequencies (f) with the PFF system off and on.

if there are drifts in beam energy. Energy drifts resulting from klystron trips and RF power drifts at CTF3 have made it difficult to maintain high phase correlations for timescales longer than 10 minutes as a result.

With high upstream-downstream phase correlation the PFF system should be able to achieve a large reduction in the downstream phase jitter. Gain scans have been completed to verify the setup of the system and derive the optimal gain. Fig. 5 shows how the downstream phase jitter depends on the PFF system gain. With stable incoming beam conditions the corrected downstream phase jitter should depend quadratically on the gain [5]. Taking in to account drifts in the initial upstream-downstream phase correlation and downstream phase jitter during the scan, which modify the gain–jitter relationship, the achieved and predicted performance agree within the error at all gains. At CTF3 the optimal system gain is typically in the range 1.0–1.2, being larger than unity when there is a small amplification in the downstream phase jitter with respect to the upstream phase jitter.

The PFF correction is shaped to remove phase variations along the 1.2 μs CTF3 beam pulse. The predominant intra-pulse feature at CTF3 is a roughly parabolic "phase sag" of 40° peak-to-peak, resulting from the use of RF pulse compression [REF]. As this is much larger than the $\pm 6°$ range of the PFF system, only approximately a 400 ns portion of the pulse can be optimally corrected. The phase sag would not be present at CLIC, where in any case the drive beam pulse length is less than 400 ns.

Fig. 6 shows the effect of the PFF system, with the derived optimal gain, on the intra-pulse phase variations. The convention at CTF3 is to operate the PFF system in interleaved mode, with the correction applied to alternating pulses only. This allows a measurement of the initial ('PFF Off') and corrected ('PFF On') downstream phase to be performed concurrently. The upstream (PFF input) phase is also shown for comparison. Vertical dashed lines mark a 440 ns portion of the pulse where the correction is optimal, and this range is used to calculate statistics on the effect of the system.

In this range the PFF system flattens the phase, and almost all variations are removed. Residual offsets in the phase are still present where there are small uncorrelated differences between the shape of the initial upstream and downstream phase. The average rms phase variation within the 440 ns range for each beam pulse in the dataset is reduced from $0.960 \pm 0.003°$ with the PFF system off, to to $0.285 \pm 0.004°$ with the system on.

CLIC requires a PFF correction with a bandwidth in excess of 17.5 MHz. Fig. 7 shows the effect of the PFF system on the amplitude of intra-pulse phase errors at different frequencies. At CTF3 there are typically no measurable phase errors at frequencies above 25 MHz. The PFF system is able to reduce the amplitude of all phase errors up to that frequency, exceeding the CLIC requirements. Considering the specifications of the hardware, the true bandwidth of the CTF3 system is believed to be above 30 MHz.

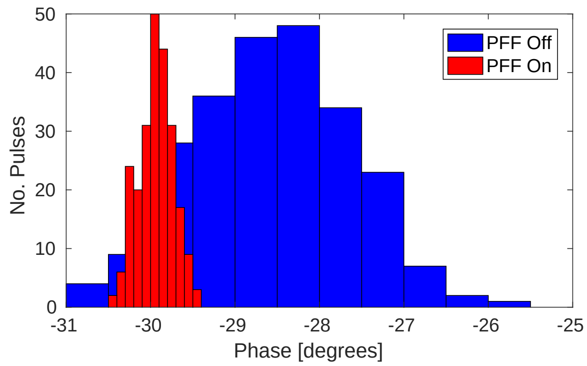

FIG. 8. Distribution of the mean downstream phase with the PFF system off (blue) and on (red).

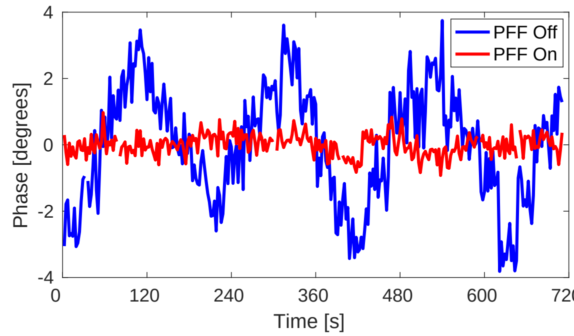

FIG. 9. Mean downstream phase with the PFF system off (blue) and on (red) vs. time, with additional phase variations added to the incoming phase.

As well as removing intra-pulse phase variations the PFF system simultaneously corrects offsets in the overall mean phase, i.e. any pulse-to-pulse jitter. The mean phase of each beam pulse is calculated across the 440 ns range in the central portion of the pulse, as shown before in Fig. 6.

Fig. 8 shows the effect of the PFF system on the pulse-to-pulse stability across a dataset around ten minutes in length. An initial mean downstream phase jitter of $0.92 \pm 0.04°$ is reduced to $0.20 \pm 0.01°$ by the PFF correction. All correlation between the upstream and downstream jitter is removed by the system, from $96 \pm 2\%$ to $0 \pm 7\%$. The achieved stability is consistent with the theoretical prediction (considering the initial correlation and jitter) of $0.26 \pm 0.06°$ within error bars.

This level of stability could not be maintained for longer periods due to CTF3's drifting RF sources, eventually leading to degraded upstream-downstream phase correlation and phase drifts outside the PFF correction range, as previously mentioned. 0.30° phase jitter has been achieved in 20 minute datasets. With suitable feedbacks to keep the phase within the correction range, and a reduction of the higher order phase-energy dependences in the machine optics, the PFF system could achieve CLIC-level phase stability continuously.

The PFF system has also been operated whilst intentionally varying the incoming mean phase, as shown in Fig. 9. It removes the additional phase variations and achieves more than a factor 5 reduction in downstream phase jitter, from $1.71 \pm 0.07°$ to $0.32 \pm 0.01°$. The magnitude of the initial phase jitter is more comparable to the conditions expected at CLIC in this case.

To conclude, CLIC requires a PFF system to reduce the drive beam phase jitter by an order of magnitude, from 2.0° to 0.2° at 12 GHz, or better than 50 fs stability. A prototype of the system has been in operation at the CLIC test facility CTF3, and corrects the beam phase by varying the path length through a chicane using two electromagnetic kickers. As well as the kickers, the system uses newly designed phase monitors with 0.12° resolution, high bandwidth 20 kW amplifiers and a low latency digitiser/feedforward controller. The system latency, including hardware and signal transit times, is less than the 380 ns beam time of flight between the input phase monitor and the correction chicane. Therefore, the feedforward correction can be directly applied to the same bunch initially measured at the monitor. New optics for the correction chicane and other beam lines at CTF3 have been developed to yield the desired phase shifting behaviour and ensure high correlation between the initial upstream and downstream phase.

The prototype system has demonstrated $0.20 \pm 0.01°$ pulse-to-pulse phase jitter on a time scale of ten minutes, verifying the feasibility of the concept. It has also been shown to be able to flatten intra-pulse phase variations up to a frequency of 25 MHz. On longer timescales the performance of the system is limited by changes to the incoming beam conditions, in particular beam energy, which would be better controlled in any future application at CLIC.

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