Stabilisation of the Arrival Time of a Relativistic Electron Beam to 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, 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 $0.20 \pm 0.01°$.

High-energy linear electron-positron colliders have been proposed as next-generation particle accelerators for exploring the subatomic world with extreme precision. They will provide sensitivity to new physics processes, beyond those described by the Standard Model (SM) of elementary particle interactions, at mass scales that can exceed the eventual reach of the CERN Large Hadron Collider (LHC) by more than an order of magnitude.

The Compact Linear Collider (CLIC) has been proposed [1] as a particle physics facility for the annihilation of electrons and positrons at centre-of-mass energies of up to 3 TeV. CLIC is the most technologically mature concept of a high-energy lepton collider for enabling direct searches for new physics processes in the multi-TeV energy regime. This energy reach, combined with high-luminosity of the electron-positron collisions, will also enable precise measurements of properties of the Higgs boson [**?**] and the top quark, and provide sensitivity to beyond-SM phenomena at mass scales of up to 10-100 TeV in some cases [**?**].

The CLIC design employs the novel concept of high power generation at radio-frequency (RF) by decelerating an electron drive beam and utilising that power to accelerate the main electron and positron beams to the desired high energies. The CLIC drive-beam concept is shown schematically in Fig. 1; 50 deceleration sections are required for a 3 TeV electron-positron collider. At the decelerators the drive beam comprises a 240 ns-long pulse of 2.4 GeV electrons bunched with a frequency of c. 12 GHz; the pulse repetition rate is 50 Hz.

A major challenge for this drive-beam acceleration concept is the synchronisation of the arrival of the drive and main beams at the power-extraction structures to an exceptional level of temporal accuracy. The arrival times need to be synchronised to better than 50 fs in order to limit the loss of luminosity, resulting from subsequent mis-acceleration of the main beams, to less than 1% of the design value [2]. Other types of novel particle accelerator, for example X-ray free-electron lasers, also demand a high degree of beam arrival-time stability w.r.t. an externally-applied laser beam for the purpose of seeding of X-ray lasing from the electron beam. An RF phase and amplitude stabilisation scheme using electro-optic beam arrival time monitors in this context was reported in [3].

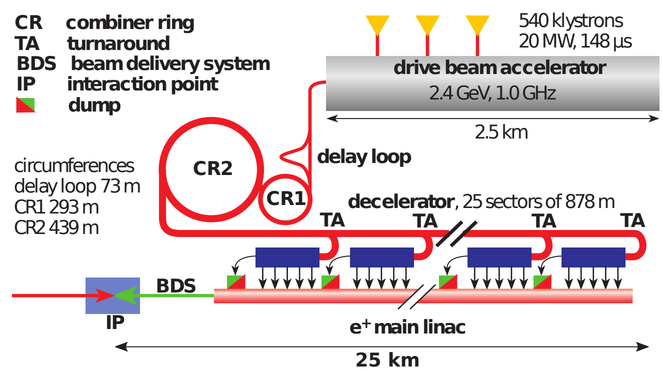

FIG. 1. Schematic of the CLIC two beam acceleration concept.

Throughout this paper we use the equivalent term longitudinal phase to refer to the beam time coordinate; 50 fs temporal stability is equivalent to 0.2° phase stability at 12 GHz RF. In the CLIC design the incoming drive-beam phase stability cannot be guaranteed to be better than 2° [1]. A correction mechanism to improve the phase stability by an order of magnitude is therefore required and must be applied to the full drive beam pulse with a bandwidth exceeding 17.5 MHz [2].

The design calls for a 'phase feed-forward' (PFF) system to measure the incoming beam phase and provide a derived correction to the same beam pulse after it has traversed the turnaround loop (TA in Fig. 1). A PFF system will be installed in each deceleration section. The

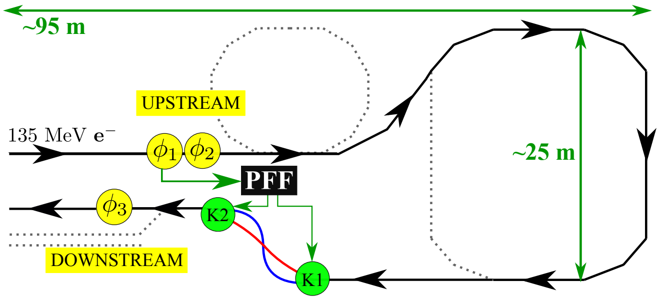

FIG. 2. Schematic of the PFF prototype at CTF3, showing the phase monitors (ϕ_1 , ϕ_2 and ϕ_3) and kickers (K1 and K2). The black box PFF represents the calculation and output of the correction, including the phase monitor signal processing electronics, feedforward controller and kicker amplifiers. Dashed lines indicate beam lines that are not used during PFF operation.

correction is provided by electromagnetic kickers in a 4-bend chicane: bunches arriving early (late) in time have their path through the chicane lengthened (shortened) respectively. A particular challenge is that the PFF latency must be shorter than the beam flight time of XXns around the turnaround loop.

We describe a prototype PFF system that implements this novel concept. It has been designed and constructed by a collaboration between CERN, the John Adams Institute/Oxford University, and INFN Frascati. The system (Fig. 2) was installed, commissioned and operated at the CLIC test facility (CTF3) at CERN. CTF3 provides a 135 MeV electron beam bunched at 3 GHz frequency with a beam-pulse length of 1.2 μs and a pulse repetition rate of 0.8 Hz [1].

The incoming beam phase is measured in two upstream phase monitors (ϕ_1, ϕ_2). While the beam transits the turnaround loop a phase-correction signal is evaluated and fed to fast, high-power amplifiers; these drive electromagnetic kickers which are used to alter the beam transit time in a four-bend, dog-leg shaped chicane. A downstream phase monitor (ϕ_3) is used to measure the effect of the correction.

The beam time of flight between the upstream phase monitor and the first kicker in the chicane is around 380 ns. The total cable delay for the PFF correction signals is shorter, around 250 ns (see Fig. 2). 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 resolution and bandwidth of the phase monitors and of the power, latency and bandwidth requirements for the kicker amplifiers. 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 for CLIC, which may be achieved by combining the output of multiple modules similar to those built for CTF3. CLIC also requires the synchronisation of multiple PFF systems distributed along the 50 km facility, which is not addressed by the CTF3 prototype (see [1]).

TABLE I. Requirements for the proposed CLIC PFF system, and how they compare with the respective CTF3 parameters; performance achieved with the prototype system is indicated by *.

	CLIC	CTF3	
Drive Beam Energy	2400	135	MeV
No. PFF Systems	50	1	
Kickers per PFF Chicane	16	2	
Power of Kicker Amplifiers	500	**20***	kW
Angular Deflection per Kicker	±94	**±560***	μrad
Correction Range	±10	**±6***	°
Correction Bandwidth	> 17.5	> **23***	MHz
Phase Monitor Resolution	< 0.14	**0.12***	°
Initial Phase Jitter	2.0	0.9	°
Corrected Phase Jitter	0.2	**0.2***	°

The phase monitors [4] are cylindrical cavities with an aperture of 23 mm and a length of 19 cm. Small ridges (notch filters) in the cavity create an effective volume with a resonant frequency of 12 GHz. The resonant electromagnetic field induced by the beam traversing the cavity contains a beam-position-independent monopole mode and an unwanted position-dependent dipole mode. The effect of the latter is removed by summing the outputs from an opposing pair of feedthroughs, on the top and bottom of the cavity, via an RF hybrid. To extract the beam phase the output from each hybrid is mixed with a 12 GHz reference signal derived from a 3 GHz source which is time-locked to the CTF3 master oscillator and serves all three phase monitors. For each phase monitor the beam and reference signals are split among an array of eight separate mixers and the outputs are combined to give the final phase-dependent signal. A linear response to input beam phase was measured over the range ±70° [5]. By comparing the signals from the two adjacent upstream monitors (Fig. 2) we have measured [6] a phase resolution of 0.12°, i.e. about 30 fs.

The phase signals are digitised in the feedforward controller (FC) board [6], which is used to calculate and output the appropriate amplifier drive signal. The FC is also used to control the timing of the applied correction. It consists of nine 14-bit analogue to digital converters (ADCs) clocked at 357 MHz, a field programmable gate array (FPGA), and four digital to analogue converters (DACs).

The kicker amplifiers [6] have a modular design, con-

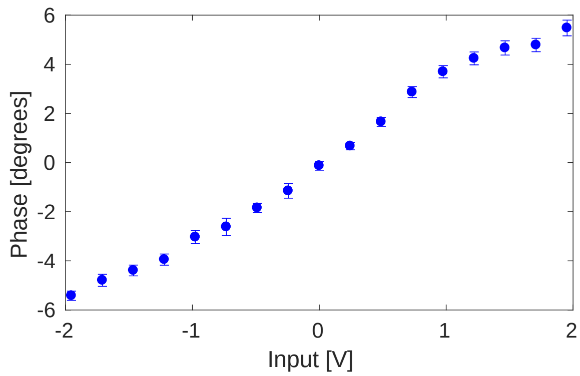

FIG. 3. Measured downstream beam phase vs. kicker amplifier input voltage. Standard errors are shown.

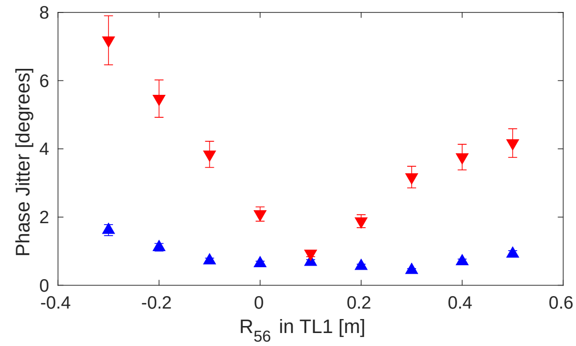

FIG. 4. Measured downstream (red) and upstream (blue) phase jitter vs. TL1R_{56} value. Standard errors are shown.

sisting 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; an input voltage range of ±2 V corresponds to an output range of ±700 V. The response is linear to within 3% for input voltages between ±1.2 V, and the output bandwidth is 47 MHz for small signal variations of up to 20% of the maximum. For larger signal variations the bandwidth is slew-rate limited.

The two electromagnetic stripline kickers [7] are based on the DAFNE design [8]. Each kicker is approximately 1 m in length and has an internal aperture 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. The strips have tapered ends to reduce beam coupling impedance. A voltage magnitude of 700 V applied to the strips at the downstream end yields a horizontal deflection of 560 μrad to the 135 MeV CTF3 beam.

The measured total latency of the phase monitor signal processing, the FC calculation, and amplifier response was approximately 100 ns. Therefore the output from the FC was delayed by an additional 30 ns to synchronise the correction at the kicker with the beam arrival [6].

The operation of the PFF system placed severe constraints on the setting of the magnetic lattice in both the beamline between the upstream phase monitors and the correction chicane and in the chicane itself. The beam transfer matrix coefficient R_{52} between the two kickers characterises the change in path length through the chicane relative to the deflection applied at the first kicker. With an R_{52} value of 0.74 m/rad [6] the expected maximum path length change for operation of the PFF system, corresponding to the maximum deflection of ±560 μrad from each kicker, is about ±400 μm, equivalent to ±6°. The measured phase shift through the chicane versus the amplifier input voltage is shown in Fig. 3, and agrees with this expectation.

In addition, the PFF operation should not change the beam trajectory at the exit of the chicane. Therefore the chicane magnet settings were chosen so that the second kicker cancels the transverse orbit deviation created by the first [6].

A further challenge to operation of the PFF was obtaining a high correlation between the upstream and uncorrected downstream phases measured at ϕ_1 and ϕ_3 respectively. A correlation coefficient of at least 97% is required to reduce a typical incoming phase jitter of 0.8° to the target of 0.2° [6]. The maximum measurable correlation depends on both the phase monitor resolution and any additional phase jitter introduced in the beamlines between ϕ_1 and ϕ_3. The 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 measurable corrected downstream phase jitter. The dominant source of uncorrelated downstream phase jitter arises from beam energy jitter that is transformed into phase jitter.

To first order the phase-energy dependence can be described via the beam transfer matrix coefficient R_{56}: $\phi_3 = \phi_1 + R_{56}(\Delta p/p)$, where $\Delta p/p$ is the relative beam energy offset. The optimal condition is $R_{56} = 0$. This was achieved by tuning the R_{56} value in the 'TL1' transfer line so as to compensate for non-zero R_{56} in the other beamline sections (Fig. 4). With $R_{56} = 10$ cm in TL1 the downstream phase jitter is reduced to the same level as the upstream jitter. However, a large second-order phase-energy dependence remained uncorrected, resulting in a degradation in upstream-downstream phase correlation if there are drifts in beam energy.

The performance of the PFF correction is controlled by a gain parameter. Theoretically the best gain, in appropriate units, should be roughly unity, but in practice the gain can be chosen to achieve optimal performance for real beam conditions. A representative gain scan is shown in Fig. 5; the optimal gain was typically found to be near unity. For beam conditions in which there is a

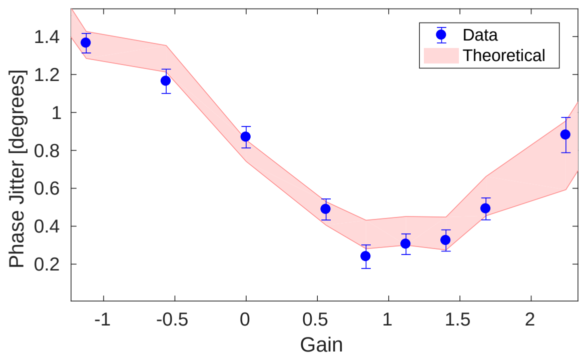

FIG. 5. Measured corrected beam phase jitter at ϕ_3 vs. PFF gain; standard error are shown (points). The theoretically-achieveable performance is shown by the red shaded region (see text).

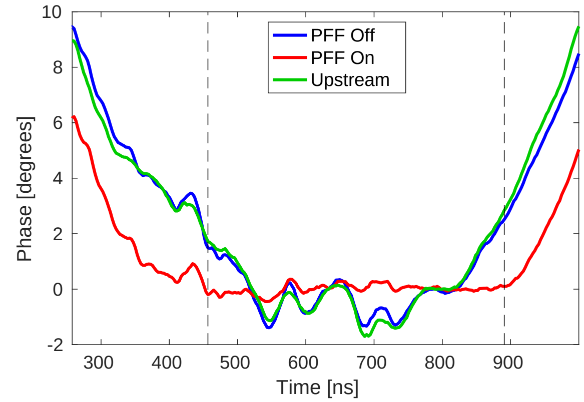

FIG. 6. Phase vs. time within the central portion of the CTF3 beam pulse. The traces show the incoming phase measured in ϕ_1 (green) and the downstream phase measured in ϕ_3 with PFF off (blue) and PFF on (red). Each trace is the average across the 30 minute dataset. The vertical dashed lines mark the time interval corresponding to the PFF dynamic range.

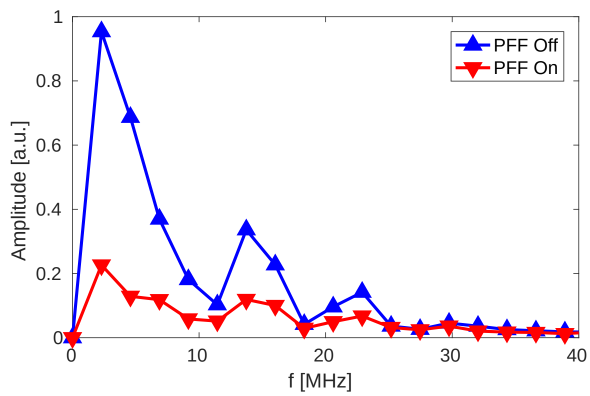

FIG. 7. Amplitude of phase errors at different frequencies (f) with the PFF system off (blue) and on (red).

small amplification in the downstream phase jitter with respect to the upstream phase jitter a gain slightly above unity provides the best achievable phase-jitter reduction [6]. At CTF3 the optimal system gain is typically in the range 1.0–1.2. Also shown in Fig. 5 is a theoretical prediction of the corrected phase jitter considering the initial beam conditions; the phase jitter at ϕ_1 and ϕ_3 and the upstream-downstream phase correlation. The simulation reproduces the data.

In order to meet CLIC requirements (Table I) the PFF correction bandwidth should be at least 17.5 MHz so as to allow correction within the 240ns-long drive-beam pulse. This function was tested with the CTF3 prototype, which was used to remove phase variations within a portion of the 1.2 μs CTF3 beam pulse (Fig. 6). It is an operational feature at CTF3 that there is a roughly parabolic phase sag of 40° peak-to-peak, resulting from the upstream RF pulse compression scheme [1]. Hence approximately a 440 ns portion of the pulse is within the ±6° dynamic range of the PFF system for the duration of a 30 minute dataset, and can be corrected to zero nominal phase. This time duration for the full correction exceeds the CLIC drive-beam pulse length of 240ns and in any case the CLIC design avoids such a large phase sag [1]

Fig. 6 shows the effect of the PFF system 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 the 440 ns portion of the pulse where the correction is optimal, and this range is used in all analyses of the effect of the system.

Within 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 shapes of the incoming upstream and downstream phases. The average rms phase variation within the 440 ns window is reduced from $0.960 \pm 0.003°$ with the PFF system off, to $0.285 \pm 0.004°$ with the system on.

A Fourier-Transform (FFT) method was used to characterise the PFF on/off datasets. The FFT amplitude is shown vs. frequency in Fig. 7. It can be seen that phase errors are corrected by up to a factor of 5 for frequencies up to 23 MHz, above which phase errors are smaller than the monitor resolution and not measurable. This is consistent with an expected system bandwidth of around 30 MHz.

As well as removing intra-pulse phase variations the PFF system simultaneously corrects any pulse-to-pulse jitter. For each beam pulse the mean phase is calculated as the average across the 440 ns window in Fig. 6.

Fig 8 shows the effect of the PFF system on the

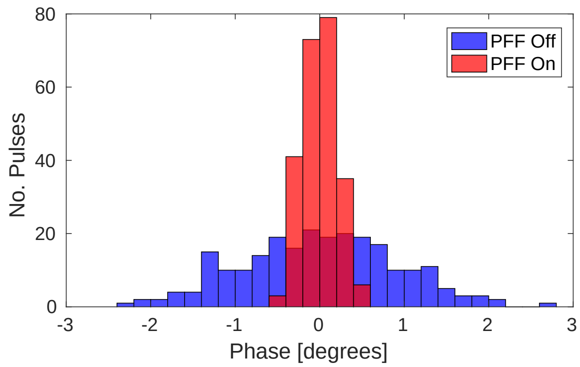

FIG. 8. Distribution of the mean downstream phase with the PFF system off (blue) and on (red).

mean phase stability for a dataset of around ten minutes duration. The pulse-to-pulse phase jitter is reduced from $0.92 \pm 0.04°$ to $0.20 \pm 0.01°$ by the PFF correction, demonstrating CLIC-level phase stability. The PFF system acts to remove all correlation between the upstream and downstream phase, reducing an initial correlation of 96±2% to 0±7% for this dataset. Given the incoming upstream phase jitter and measured upstream-downstream correlation, the performance is consistent with the theoretically predicted correction of $0.26 \pm 0.06°$.

Typically this level of corrected phase stability could not be maintained for longer time periods due to drifts in the operation of the CTF3 RF system, which led to a degradation in the upstream-downstream phase correlation as well as mean phase drifts beyond the PFF correction range. Nevertheless a mean phase stability of 0.30° was achieved in datasets taken over periods as long as 20 minutes. With suitable upstream RF feedbacks to keep the beam phase within the correction range, and a reduction of the higher order phase-energy dependence in the magnetic lattice, the PFF system is capable of achieving CLIC-level phase stability continuously.

The PFF system was further tested by intentionally varying the incoming mean beam phase systematically by up to 3°; such a variation is comparable to the expected conditions in the CLIC design (Table I). This is illustrated in (Fig. 9). The system removed the induced phase variations and achieved more than a factor-5 reduction in the downstream phase jitter, correcting from $1.71 \pm 0.07°$ to $0.32 \pm 0.01°$.

In conclusion, we have built, deployed and tested a prototype drive-beam phase feedforward system for CLIC. The system incorporates high-resolution phase monitors, an advanced signal-processor and feedforward controller, low-latency, high-power, high-bandwidth amplifiers, and state-of-the-art electromagnetic kickers. The phase-monitor resolution was measured to be $0.12° \simeq 30$ fs. The overall system latency, including the hardware and signal transit times, was measured to be approx. 350 ns,

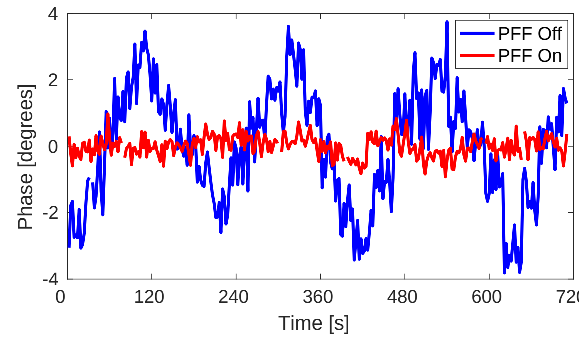

FIG. 9. Mean downstream phase vs. time with the PFF system off (blue) and on (red) subject to large additional phase variations added to the incoming phase (see text).

which is less than beam time of flight between the input phase monitor and the correction chicane. Therefore, the feedforward phase correction was applied downstream to the same beam bunches initially measured upstream.

The prototype system was used to stabilise the pulse-to-pulse phase jitter to $0.20 \pm 0.01° \simeq 50$ fs. It also simultaneously corrected intra-pulse phase variations up to a frequency of 23 MHz.

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