\documentclass[%

reprint,

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amsmath,

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prl,

]{revtex4-1}

\usepackage{graphicx}% Include figure files

\usepackage{dcolumn}% Align table columns on decimal point

\usepackage{bm}% bold math

\begin{document}

\title{Stabilisation of the Arrival Time of a Relativistic Electron Beam to

the 50~fs Level}

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\date{\today}

\begin{abstract}

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

\(0.2^\circ\)~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 ??? MUST BE CONSISTENT 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

\(0.92\pm0.04^\circ\) to \(0.20\pm0.01^\circ\).

\end{abstract}

\maketitle

%%

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 ~\cite{CLICCDR} 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~\cite{CLIC-Higgs} and the top quark, and provide sensitivity to beyond-SM phenomena at mass scales of up to 10-100 TeV in some cases~\cite{CLIC-staging}.

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. 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~\cite{Gerber2015}. 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. A laser-based optical synchronisation scheme in this context was reported in~\cite{flashPRL}. Here we describe a beam-based, low-latency feed-forward system designed to stabilise the arrival time of a relativistic electron beam to the 50~fs level required for CLIC.

The CLIC drive-beam concept is shown schematically in Fig.~\ref{fig:CLICLayout}; 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. 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^\circ\) phase stability at 12~GHz RF. In the CLIC design the incoming drive-beam phase stability cannot be guaranteed to be better than \(2^\circ\)~\cite{CLICCDR}. 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~\cite{Gerber2015}.

%Higher frequency errors are filtered as a consequence of the

%drive beam recombination process, and by the accelerating structures

%\cite{Gerber2015}.

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. The correction is provided by electromagnetic kickers in a series of 50 4-bend chicanes: 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. The system (Fig.~\ref{fig:pffLayout}) 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~\(\mathrm{\mu s}\) and a pulse repetition rate of 0.8~Hz \cite{CLICCDR}.

The incoming beam phase is measured in two phase monitors. 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 a four-bend, dog-leg shaped chicane.

through the chicane..

A downstream phase monitor 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 380~ns (TRUE?). The total cable delay for the PFF correction signals

is shorter, around 250~ns (see Fig.~\ref{fig:pffLayout}). 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.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/ctfpffLayout}% Here is

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\caption{\label{fig:pffLayout}Schematic of the PFF prototype at CTF3,

showing the phase monitors (\(\phi\_1\) ,

\(\phi\_2\) and \(\phi\_3\)) 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.

}

\end{figure}

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.

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.~\ref{fig:pffLayout}). 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 are also required.

Table~\ref{tab:pffspecs} 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 \cite{CLICCDR}).

\begin{table}

\caption{\label{tab:pffspecs}

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 \*.}

\begin{ruledtabular}

\begin{tabular}{lccc}

& CLIC & CTF3 \\

\hline

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 & \(\pm94\) &

\(\pm560\)^\* & \(~\mathrm{\mu rad}\) \\

Correction Range & \(\pm 10\) & \(\pm 6\)^\* & \(^\circ\) \\

Correction Bandwidth & \(>17.5\) & \(>23\)^\* & MHz \\

Phase Monitor Resolution & \(< 0.14\) & \(0.12\) & \(^\circ\) \\

Initial Phase Jitter & \(2.0\) & \(0.9\) & \(^\circ\) \\

Corrected Phase Jitter & \(0.2\) & \(0.2\)^\* & \(^\circ\) \\

\end{tabular}

\end{ruledtabular}

\end{table}

The CTF3 PFF experiment has been designed and constructed by a collaboration

between CERN, the John Adams Institute/Oxford University, and INFN Frascati.

The phase monitors~\cite{phMonEuCard} 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. WHAT ABOUT CHARGE

NORMALISATION? A linear response to input beam phase was measured over the range

\(\pm70^\circ\). By comparing the signals from the two adjacent upstream

monitors (Fig.~\ref{fig:pffLayout}) we have measured~\cite{RobertsThesis} a phase resolution of

\(0.12^\circ\), i.e. about 30~fs. .

by comparing the measurements of the two adjacent upstream

monitors (see Fig.~\ref{fig:pffLayout}).

The

phase signals are digitised in the feedforward controller (FC) board~\cite{RobertsThesis}, 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 a

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~\cite{RobertsThesis} 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; an input voltage range of \(\pm2\)~V corresponds to an output range of

\(\pm700\)~V. The response is linear to within 3\% for input voltages between

\(\pm1.2\)~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~\cite{kickerIPAC11} (Fig.~\ref{fig:pffLayout}) are based on the

DAFNE design \cite{dafnePAC09}. 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, and to give high kick efficiency WHAT DOES THIS MEAN?. The

strips have tapered ends to reduce beam coupling impedance.

A voltage magnitude of 700~V applied between the

strips at the downstream end yields a horizontal deflection of

560~$\mu$rad 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

\cite{RobertsThesis}.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/corrRange}

\caption{\label{fig:corrRange}Measured downstream beam phase vs. kicker amplifier

input voltage. Standard errors are shown.}

\end{figure}

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 UNITS?

\cite{RobertsThesis} the expected maximum path length change for operation of

the PFF system, corresponding to the

maximum deflection of \(\pm560\)~$\mu$rad from each kicker,

is \(\pm400~\mathrm{\mu m}\), equivalent to \(\pm6^\circ\)., considering the

maximum deflection of \(\pm0.56\)~mrad from the kickers.

The measured phase shift through the chicane versus the amplifier input voltage is

shown in Fig.~\ref{fig:corrRange}, and agrees with this expectation.

In addition, ideally 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~\cite{RobertsThesis}.

A further challenge to operation of the PFF was

obtaining a high correlation between the upstream and

uncorrected downstream phases measured at $\phi\_1$ and $\phi\_3$ respectively.

A correlation coefficient of at least 97\% is required to reduce a typical incoming

phase jitter of \(0.8^\circ\) to the target of \(0.2^\circ\)

\cite{RobertsThesis}.

The maximum measurablecorrelation depends on both the phase monitor resolution and any

additional phase jitter introduced in the beamlines between $\phi\_1$ and $\phi\_3$. The monitor resolution of \(0.12^\circ\)

limits the maximum upstream-downstream phase correlation to

\(98\%\) in typical conditions, and places a theoretical limit of

\(0.17^\circ\) 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.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/r56Scan}

\caption{\label{fig:r56Scan}Measured downstream (red) and upstream (blue) phase

jitter vs. TL1\(R\_{56}\) value. Standard errors are shown.

}

\end{figure}

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 pptimal 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.~\ref{fig:r56Scan}). With \(R\_{56}\) = 10~cm the

downstream phase jitter is reduced to the same level as the upstream jitter.

However, a large second-order phase-energy dependence remained uncorrected and drifts in beam energy did lead to a degradation in upstream-downstream phase correlation~\cite{RobertsThesis}.

The performance of the PFF correction is controlled by a ‘gain’ parameter. DO WE NEED AN EQUATION? 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.~\ref{fig:gScan}); the optimal gain was typically found to be near unity., For beam conditions in which there is a 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

\cite{RobertsThesis}.

. Also shown in Fig.~\ref{fig:gScan} is a theoretical calculation of the phase jitter taking the measured incoming beam phase at $\phi\_1$ and propagating it to $\phi\_3$ using a detailed beam transport simulation model; the simulation reproduces the data.

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 \cite{RobertsThesis}.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/gScan}

\caption{\label{fig:gScan}Measured corrected beam phase jitter at $\phi\_3$ vs.

PFF gain; standard error are shown (points). The theoretically-achieveable performance is shown by the red shaded region (see text).}

\end{figure}

In order to meet CLIC requirements (Table~\ref{tab:pffspecs}) 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~\(\mathrm{\mu s}\) CTF3 beam pulse (Fig.~\ref{fig:shape}). It is an operational feature at CTF3 that there is a roughly parabolic phase sag of \(40^\circ\) peak-to-peak,

resulting from the upstream RF pulse compression scheme~\cite{CLICCDR}. Hence approximately a 440~ns portion of the pulse is within the \(\pm 6^\circ\) dynamic range of the PFF system and can be corrected to zero nominal phase. NOW I AM CONFUSED AS YOU SAY THIS IS +-6 DEGREES BUT IT’S CLEARLY ONLY +-3 DEGREES. This time duration for the full correction exceeds the CLIC drive-beam pulse length of 240ns and in any case the design avoids such a large phase sag~\cite{CLICCDR}. 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 \(0.960\pm0.003^\circ\) with

the PFF system off, to \(0.285\pm0.004^\circ\) with the system on.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/shape}

\caption{\label{fig:shape}Phase vs. time within the central portion of the CTF3 beam pulse. The traces show the incoming phase measured in $\phi\_1$ (green) and the downstream phase measured in $\phi\_3$ with PFF off (blue) and PFF on (red). WHAT IS PLOTTED? THE AVERAGE OVER N PULSES? The data were taken in ‘inter-leaved’ mode whereby alternate beam pulses had the PFF on and off. The vertical dashed lines mark the time interval corresponding to the PFF dynamic range. }

\end{figure}

Fig.~\ref{fig:shape} 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 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.

\begin{figure}

\includegraphics[width=\columnwidth]{figs/fft}

\caption{\label{fig:fft}Amplitude of phase errors at different frequencies

(\(f\)) with the PFF system off (blue) and on (red).}

\end{figure}

\begin{figure}

\includegraphics[width=\columnwidth]{figs/fft}

\caption{\label{fig:fft}Amplitude of phase errors at different frequencies

(\(f\)) with the PFF system off (blue) and on (red).}

\end{figure}

A Fourier-Transform (FFT) method was used to characterise the PFF on/off datasets WHICH PULSE TIME RANGE IS THIS FOR? THE SAME 440NS OR THE WHOLE PULSE?. The FFT amplitude is shown vs. frequency in Fig.~\ref{fig:fft}. It can be seen that phase errors are corrected by up to a factor of 5 for frequencies up to approximately 25~MHz, above which no phase errors are measurable. This is consistent with a system

bandwidth above 30~MHz. WE ARE A BIT SLOPPY HERE. WHAT CAN WE REALLY SAY? YOU HAVE PUT 23 IN TABLE 1!

The PFF system performance in terms of

correction of the mean phase along the beam pulse is , 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

The

mean phase was calculated for the 440~ns window in the

central portion of the pulse (Fig.~\ref{fig:shape})

\begin{figure}

\includegraphics[width=\columnwidth]{figs/meanJit}

\caption{\label{fig:meanJit}Distribution of the mean downstream phase with

the

PFF system off (blue) and on (red).}

\end{figure}

This is illustrated in Fig.~\ref{fig:meanJit}, which shows the pulse-to-pulse

stability for a dataset of around ten minutes’ duration. The mean phase jitter is reduced from \(0.92\pm0.04^\circ\) to \(0.20\pm0.01^\circ\) by the PFF

correction. For this dataset the correlation between the incoming upstream and corrected downstream phase jitters is

reduced from

\(96\pm2\%\) to \(0\pm7\%\). Given the incoming upstream phase jitter and measured upstream-downstream correlation, this performance is consistent with the

Theoretically-predicted correction of (\(0.26\pm0.06^\circ\).

\begin{figure}

\includegraphics[width=\columnwidth]{figs/meanJit}

\caption{\label{fig:meanJit}Distribution of the mean downstream phase with

the

PFF system off (blue) and on (red).}

\end{figure}

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 \(0.30^\circ\) 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 \(3^\circ\); such a variation is roughly 50% larger than that envisaged in the CLIC design (Table~\_. This is illustrated in (ig.~\ref{fig:wiggle}). The system removed the induced phase variations

and achieved more than a factor-5 reduction in the downstream phase jitter, correcting from

\(1.71\pm0.07^\circ\) to \(0.32\pm0.01^\circ\).

\begin{figure}

\includegraphics[width=\columnwidth]{figs/wiggle}

\caption{\label{fig:wiggle}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).}

\end{figure}

%%%%%%%%%%%%

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 \(0.12^\circ\) = 30fs. The overall system latency, including the hardware and

signal transit times, was measured to be approx. 350~ns. Therefore, the feedforward

phase correction was directly downstream to the same beam bunches initially measured upstream.

%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 was used to stabilise the pulse-to-pulse

phase jitter to \(0.20\pm0.01^\circ\) = 50 fs. It has also used

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.

\begin{acknowledgments}

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\bibliography{pff\_short}

\end{document}