Demonstration of 50 fs stability of an electron beam at the CLIC Test Facility CTF3

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Here is the abstract.

INTRODUCTION

CLIC is a proposal for a future linear electron positron collider that 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 the high energy colliding beams is extracted from high intensity drive beams.

CLIC's luminosity quickly drops if the RF phase jitters with respect to the main beam, causing energy errors and subsequent beam size growth at the interaction point. The RF phase stability must be 0.2 degrees at 12 GHz (around 50 fs) or better to limit the luminosity loss to below 1%. However, the expected phase stability of the drive beams is 2 degrees at 12 GHz. CLIC therefore requires a "phase feedforward" (PFF) system, which will reduce the drive beam phase jitter (rms) by an order of magnitude. XFELs have similar phase stability requirements [!!!???].

The PFF system poses many challenges, particularly in terms of the hardware bandwidth, power and latency requirements. A prototype PFF system has therefore 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 proposed CLIC scheme, and is the focus of this work.

CTF3: 135 MeV electron beam, 1.2 μs beam pulse, 0.8 Hz.

All phases quoted in the paper are given in degrees at 12 GHz.

SYSTEM DESIGN

A schematic of the 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 chicane (in the TL2 transfer line). The beam's path length through the chicane depends on the magnitude and polarity of the voltage applied to the kickers. The phase is measured using a monitor upstream of the chicane (in the CT beam line), and then corrected by setting the kicker voltage to deflect bunches arriving early at the phase monitor on to longer trajectories in the chicane, and bunches arriving late on to shorter trajectories. Downstream of the chicane, in the TBL line, 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. By bypassing the combiner ring (CR) and TL1 transfer line (see Fig. 1) the total cable length required to transport signals between the monitor and kickers is shorter, approximately 250 ns. 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 system has a bandwidth of around 30 MHz, able to remove phase variations along the 1.2 μs CTF3 beam pulse, as well as any offsets in the overall mean phase.

Hardware

The PFF system uses three phase monitors, two electromagnetic kickers, kicker amplifiers and a digitiser/feedforward controller.

The three phase monitors are designed and built by INFN Frascati, with the associated electronics built by CERN. The monitors are 12 GHz resonating cavities with a dipole and monopole mode present. The output from opposing vertical pairs of feedthroughs are summed in hybrids to create a position independent signal. This signal is split and mixed with a reference 12 GHz signal in eight separate mixers. The output from the eight mix-

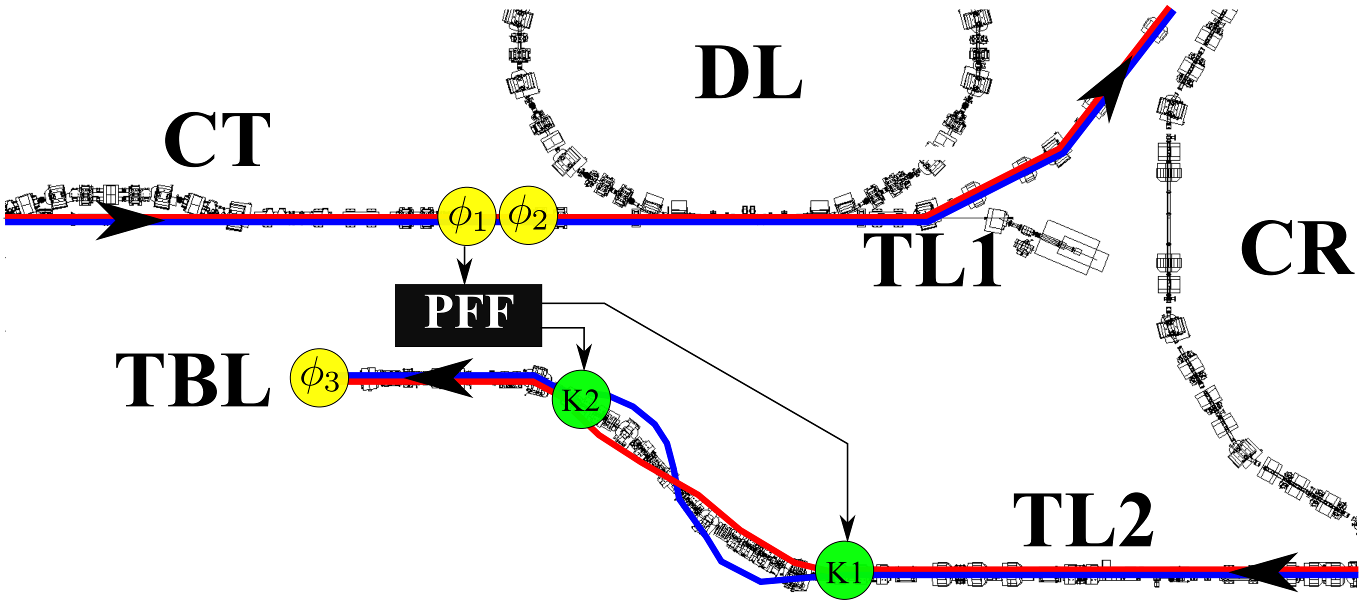

FIG. 1. Schematic of the PFF prototype at CTF3, showing the approximate location of the phase monitors (ϕ_1 , ϕ_2 and ϕ_3) and the kickers (K1 and K2). The black box PFF represents the calculation and output of the correction, including the phase monitor electronics, feedforward controller and kicker amplifiers. A bunch arriving early at ϕ_1 is directed on to a longer path in the TL2 chicane using the kickers (blue trajectory), whereas a bunch arriving late will be directed on to a shorter path (red trajectory). Maybe add upstream/downstream labels to phase monitors

ers is combined, allowing a resolution of 0.126 degrees to be achieved whilst maintaining good linearity. This resolution is determined by comparing the measurements of the two monitors installed in the CT line.

The two electromagnetic kickers were also designed and built by INFN Frascati, and are based on the DAFNE design. A voltage of 1.26 kV applied to the downstream end of the kicker strips yields a horizontal deflection of 1 mrad for the 135 MeV CTF3 beam.

The kicker amplifiers have been designed and built by the John Adams Institue/Oxford University. For an input voltage of 2 V gives an output of up to 700 V. Response linear within 3% for input voltages up to 1.2 V, then starts to saturate. Bandwidth 47 MHz for small signal variations up to 20% max output...

Finally, the Feedforward digitiser and controller (FONT5a board) was also designed and built by John Adams Institute/Oxford University. This takes the processed phase monitor signals then calculates and outputs the appropriate voltage with which to drive the amplifier. 9 ADCs, FPGA, 4 DACs... Digitises output from phase monitor electronics, calculates amplifier output based on set gain values, deals with correction timing...

The total latency of the phase monitor electronics, FONT5a board and amplifier is approximately 100 ns... Mention timing setup.

Chicane Optics

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. These constraints are needed to ensure a linear dependence of the phase on the kicker voltage, to ensure the PFF system does not degrade the beam orbit stability downstream of the chicane, and to ensure there is high correlation between the initial (uncorrected) upstream and downstream phase.

The correction range of the PFF system is defined by the kicker design, the maximum output voltage of the kicker amplifiers, and the optics transfer matrix coefficient R_{52} between the kickers in the chicane. The coefficient R_{52} describes the change in path length through the chicane per unit deflection at the first kicker. The optics at CTF3 have $R_{52} = 0.74$ m and at the maximum amplifier output of ± 700 V the kickers deflect the beam through 0.56 mrad. Together these define a correction range of approximately ± 400 μm, or ± 6 degrees, for the PFF prototype.

The measured phase shift in the chicane versus the amplifier input voltage is shown in Fig. 2, and agrees with the predicted range given the hardware and optics parameters. However, the output of the amplifier is non-linear for input voltages above 1.2 V (with a maximum input of 2 V). The linear range of the PFF system is therefore closer to $\pm 4°$.

MADX units for R52, R56, i.e. conversion between

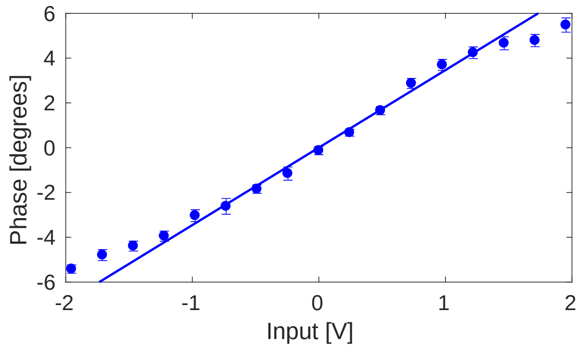

FIG. 2. Correction range.

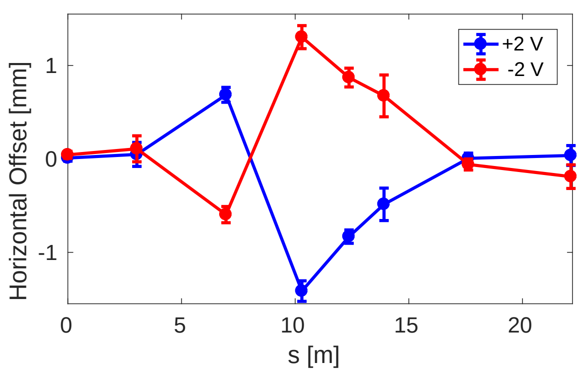

FIG. 3. Orbit closure. Maybe: Replace lines with model prediction, add lines to indicate kicker positions, remove -2 V line

distance and phase.

The PFF system also should not degrade transverse stability of beam after chicane. The purpose of the second kicker is to close the orbit bump created by the first kicker, so that the downstream beam orbit is independent of the kicker voltage. In terms of optics tranfer matrix coefficients this can be achieved by requiring $R_{11} = -1$ and $R_{12} = 0$ between the kickers. Fig. 3 shows the horizontal beam orbit before, in and after the TL2 chicane for the maximum and minimum applied 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.

All this must be achieved whilst keeping dispersion low, matching betas etc. within constraints of pre-existing buildings. Achieved R52 0.74m with max dispersion 1.16m...

Phase Propagation

The PFF system acts to subtract the measured upstream phase (ϕ_u) from the initial downstream phase (ϕ_d) with a gain factor (g): $\phi_{\text{PFF}} = \phi_d - g\phi_u$, where

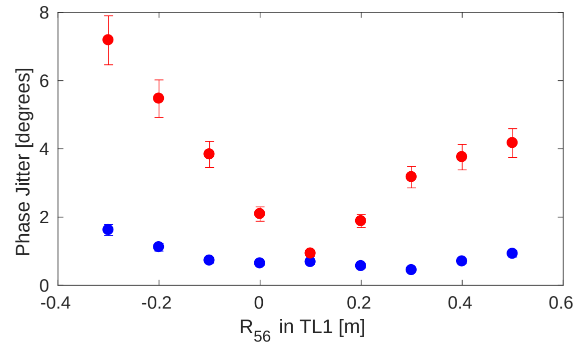

FIG. 4. R56 scan. Maybe remove upstream jitter, or replace with a single value line.

ϕ_{PFF} is the corrected downstream phase. The optimal system gain is given by: $g = \rho_{ud}\sigma_d/\sigma_u$, where σ_u and σ_d are the initial upstream and downstream phase jitter respectively, and ρ_{ud} is the correlation between the upstream and downstream phase. The theoretical limit on the corrected downstream phase jitter (σ_{PFF}) with this gain is given by: $\sigma_{\text{PFF}} = \sigma_d\sqrt{1-\rho_{ud}^2}$.

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. A correlation of 97% is required to reduce a typical initial phase jitter of 0.8 degrees to the target of 0.2 degrees. Early measurements showed below 40% correlation, and typically a factor 3 increase in the downstream phase jitter with respect to the upstream jitter.

The source of low correlation and jitter amplification was discovered to be energy dependent phase jitter introduced between the upstream and downstream phase monitors. This is 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.

Correlation or jitter vs. R56 equation?...

To achieve high upstream-downstream phase correlation the PFF system requires R_{56} to be zero between the upstream and downstream phase monitors.

The phase propagation has therefore been optimised by creating new optics for the transfer line TL1 (see Fig. 1) with R_{56} values ranging between -30 cm and +60 cm in 0.5 cm increments. TL1 can then be used to compensate for the non-zero R_{56} values in other beam lines, with the dominant contribution being from the TL2 chicane. In other words, TL1 is tuned such that $R_{56}(\text{TL1}) = -R_{56}(\text{TL2})$.

Fig. 4 shows the effect of varying the R_{56} value in TL1 on the downstream phase jitter. With an R_{56} of around 10 cm in TL1 the downstream phase jitter is reduced to the same level as the upstream jitter, as desired. The upstream-downstream phase correlation is also increased in these conditions, with correlations above 95% achieved.

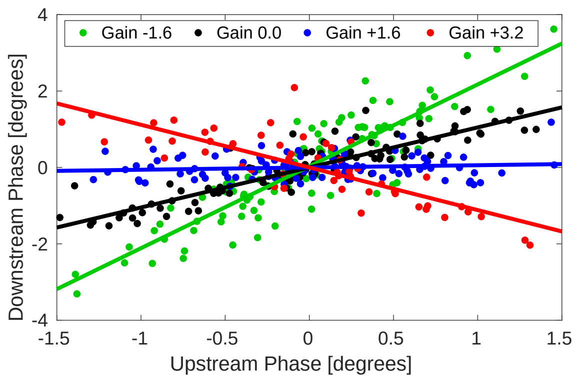

FIG. 5. Gain scan.

In this way the necessary initial conditions for the PFF correction were obtained at CTF3. However, the phase propagation is also sensitive to higher order phase–energy dependencies and therefore beam energy drifts. These lead to apparent drifts in the optimal set point for R_{56} in TL1 and have made it difficult to maintain high correlation between the upstream and downstream phase on long timescales.

RESULTS

Gain Scan

With the optimal gain the PFF correction acts to remove all correlation between the upstream and downstream phase, reducing the downstream phase jitter. If the gain is too small some residual correlation will remain, and if it is too large the correlation will flip sign.

The optimal system gain can be derived empirically by observing the dependence of the downstream phase on the upstream phase with the correction on, as seen in Fig. 5. Optimal gain values for the system are typically in the range 1.0–1.5, being larger than unity when the downstream jitter is larger than upstream as per Equation xxx (but would prefer to leave that equation in-line without a number).

Intra-Pulse Phase Variations

The PFF correction is shaped to remove phase variations along the 1.2 μs CTF3 beam pulse. The predominant intra-pulse feature at is a roughly parabolic "phase sag" of 40° peak-to-peak, resulting from the RF pulse compression system at CTF3. As this is much larger than the ±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.

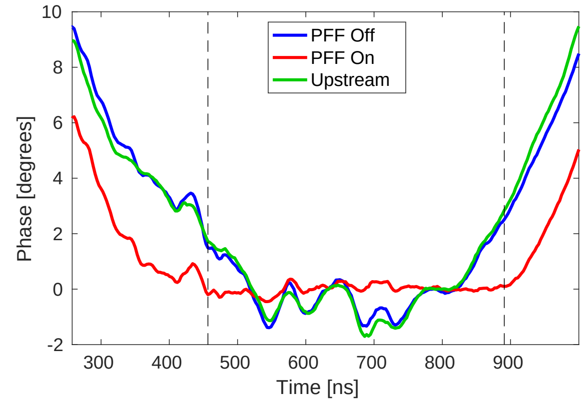

FIG. 6. Correction of pulse shape. NB: 2015 showed larger reduction in flatness, flatter corrected phase, but no wiggles in initial upstream phase.

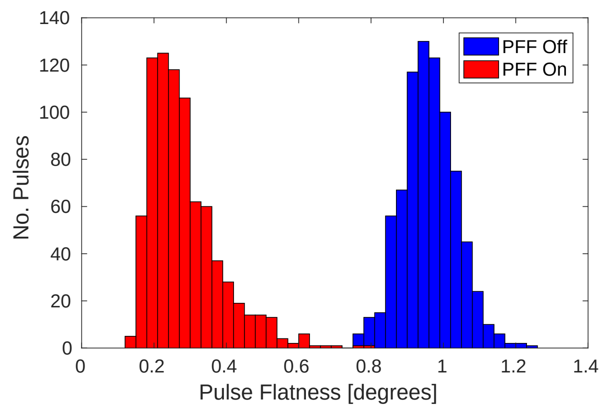

FIG. 7. Pulse flatness.

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 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.

Fig. 7 shows the rms phase variation within the 440 ns range for each beam pulse in the dataset, with the PFF system on and off. The PFF off pulses have an rms of $0.960 \pm 0.003°$ on average, and this is reduced to $0.285 \pm 0.004°$ by the PFF system.

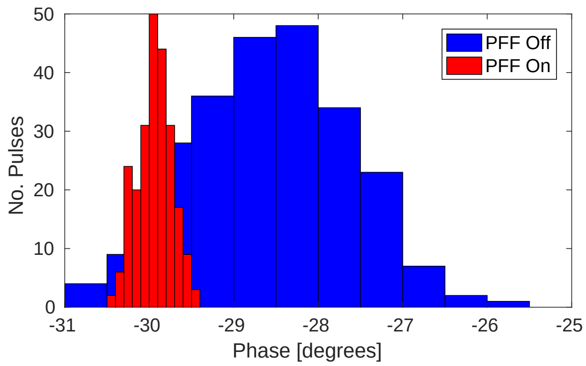

FIG. 8. Best mean phase jitter. 0.92 degrees to 0.20 degrees. The mean is shifted by xxx degrees...

Pulse-to-pulse Jitter

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 (482 pulses). 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, 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.

NB: upstream PFF off is $0.76 \pm 0.03°$, but $0.68 \pm 0.03°$ for PFF on. Helps to explain why achieved is better than predicted.

This represents the longest time period during which the target CLIC phase stability has been achieved with the prototype. 0.30 degrees phase jitter has been achieved in 20 minute datasets.

Mean phase vs. time and result with wiggling?

CONCLUSIONS

CLIC requires a PFF system to reduce the drive beam phase jitter by an order of magnitude, from 2.0 degrees to 0.2 degrees. A prototype of the system has been in operation at the CLIC test facility CTF3.

The prototype has demonstrated $0.20 \pm 0.01°$ pulse-to-pulse phase jitter on a time scale of ten minutes.

Intra-pulse phase variations are also greatly reduced by the PFF system...

Drifts, in particular in beam energy, degrade the correlation between the upstream and downstream phase and prevent this level of stability from being demonstrated on longer time scales at CTF3. A key consideration for any future system should be to design beam lines and optics with zero phase-energy dependence, including non-linear dependencies, to solve this issue.

Try to apply to XFELs/something else.

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