

Development of a beam-based phase feed-forward
demonstration at the CLIC Test Facility (CTF3).

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Abstract

This is the abstract TeX for the thesis and the stand-alone abstract.

Dedication.

Acknowledgements

Acknowledgements.

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Glossary

Item1 Description.

Item2 Description.

Item3 Description.

Chapter 1

Introduction

This is the introductory text.

1.1 Particle Physics

1.2 Particle Colliders

1.3 Motivation for Future Linear Colliders

1.4 CLIC

1.5 FONT

1.6 Phase Feedforward for CLIC

1.7 Thesis Overview

Chapter 2

Design of the PFF Prototype at CTF3

This is the introductory text.

2.1 CTF3

2.1.1 Goals of CTF3

CLIC and PFF

2.1.2 Layout of CTF3

2.2 Design of the PFF Prototype at CTF3

2.2.1 Schematic Overview of PFF System

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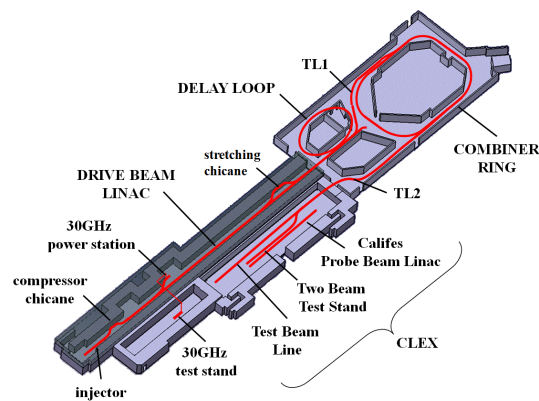


Figure 2.1: CTF3 schematic.

2.2.2 Latency

;

2.3 PFF Hardware

2.3.1 FONT5 Board

2.3.2 Amplifier

2.3.3 Phase Monitors

2.3.4 Kickers

2.4 Differences Between PFF at CTF and CLIC

2.4.1 Phase Sag

2.4.2 Pulse Length

2.5 Feedforward Algorithm

2.5.1 Theoretical Corrected Jitter

2.5.2 Theoretical Optimal Gain

Optics for the PFF Prototype

This is the introductory text.

3.1 Introduction to Optics

transverse focusing, dispersion, twiss etc.

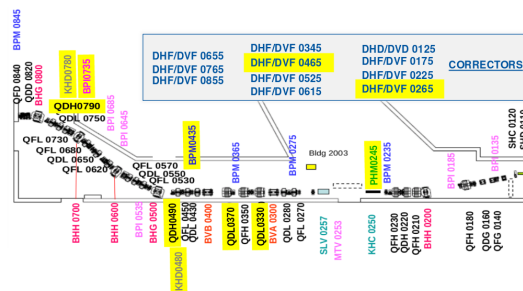


Figure 3.1: New TL2 lattice for PFF. Changes highlighted yellow.

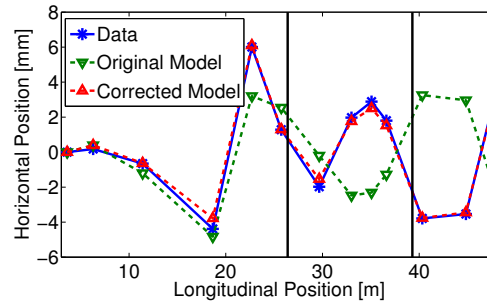


Figure 3.2: Mean phase along.

3.1.1 MADX

3.2 TL2

3.2.1 Lattice

3.2.2 Integration of PFF Hardware

3.2.3 Optics Constraints

Nominal Optics

PFF Optics

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3.3.1 Method

3.3.2 Results

3.3.3 Sources of Errors in MADX Model

Dipole Edge Focusing

Quadrupole Strengths

3.3.4 Corrections to MADX Model

3.4 Matched TL2 Optics

3.4.1 MADX Optics Matching

3.4.2 Nominal Optics

3.4.3 PFF Optics

Chapter 4

Phase Monitor Performance

This is the introductory text.

4.1 Phase Monitor Electronics

4.2 Signal Response Measurements

4.2.1 Experimental Setup

4.2.2 Saturation

4.2.3 Cross-Talk

4.3 Calibrations

4.3.1 Procedure

4.3.2 Single Sample Results

4.3.3 Multi-Sample Results

4.4 Digitiser Noise

4.4.1 On FONT5 Board

4.4.2 On SiS Digitiser

4.5 Phase Shifter Noise

4.5.1 Digital Phase Shifters

4.5.2 Mechanical Phase Shifters

4.6 Resolution

Single sample.

(Multi-sample)

Sample averaging.

Impact for phase correlations.

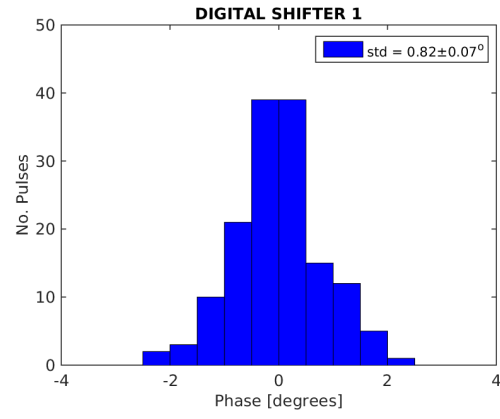


Figure 4.1: Dig shifter 1.

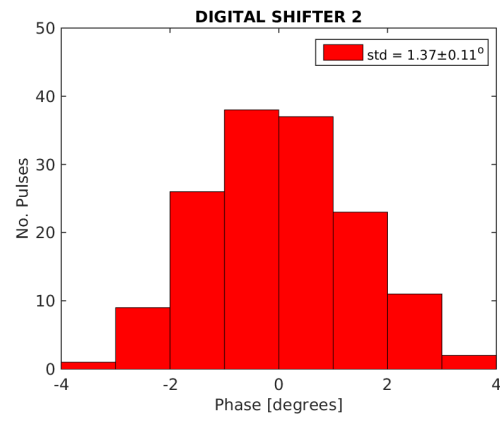


Figure 4.2: Dig shifter 2.

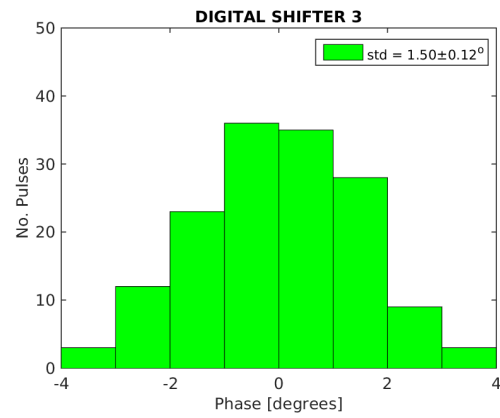


Figure 4.3: Dig shifter 3.

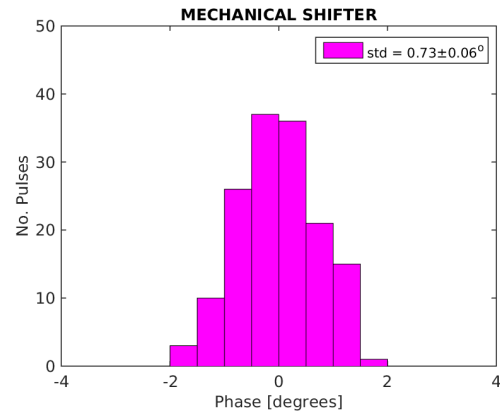


Figure 4.4: Mech shifter.

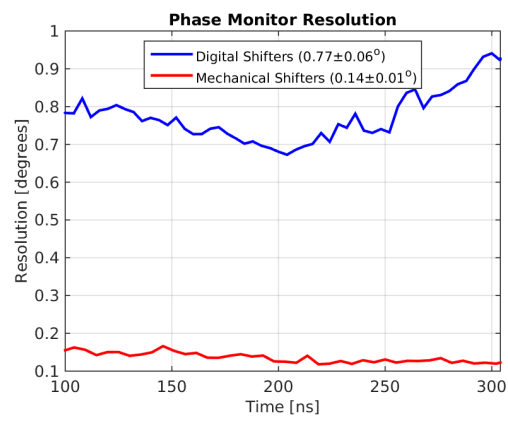


Figure 4.5: Resolution.

4.7 Linearity

4.8 Bandwidth

4.9 Dependence on Position

Chapter 5

Phase Propagation

This is the introductory text.

5.1 Characteristics of Uncorrected Phase Jitter

Injector feedbacks etc.

Definitions of different types of phase jitter.

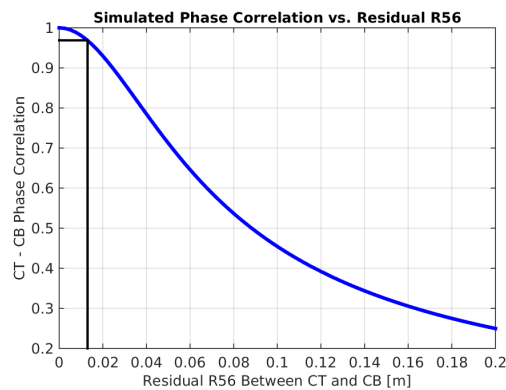


Figure 5.1: Phase correlation vs. residual R56 between monitors.

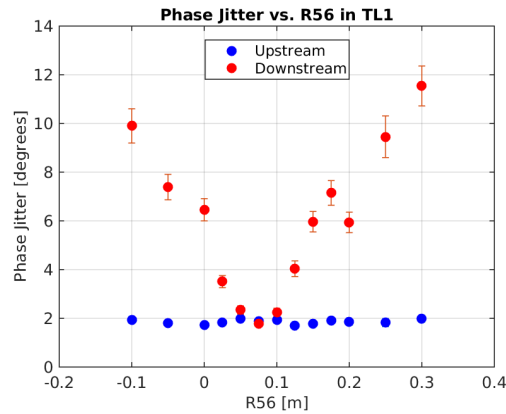


Figure 5.2: Phase jitter for different R56 whilst wiggling gun current.

5.2 First Order Energy Dependencies

5.2.1 Correlation between Phase and Energy

5.2.2 Expected Dependence due to Optics

5.3 Mitigation of First Order Energy Dependence

5.3.1 TL1

5.3.2 Matched Optics for TL1

5.3.3 Scans of R56 in TL1

5.4 Higher Order Energy Dependencies

5.4.1 Expected Dependence due to Optics

5.4.2 Energy Variation Along the Pulse

5.4.3 R56 Scans whilst Varying Beam Energy

5.4.4 Effect on PFF Operation

5.5 Other Sources of Phase Jitter

5.5.1 Combiner Ring Septum

5.5.2 TL1 & Combiner Ring Bends

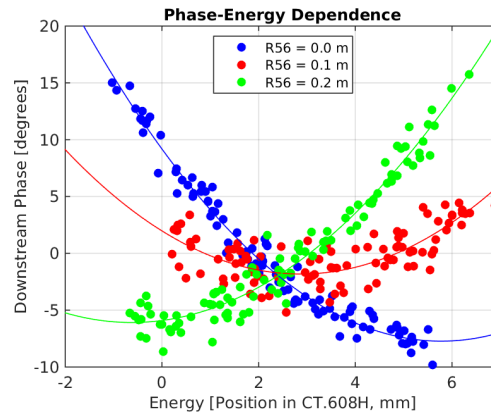


Figure 5.3: Phase vs. energy for different R56 in TL1.

CR Septum

TL1/CR Bends

5.6 Long Term Propagation Stability

Chapter 6

Setup and Commissioning of the PFF System

This is the introductory text.

6.1 Experimental Setup

6.1.1 Implementation of PFF Algorithm in Firmware

6.1.2 FONT5 and Amplifier Setup

Gain conversion

6.1.3 SiS and CERN Control System Setup

6.2 ADC Droop Correction

The droop in the response of the FONT5 ADCs, as most clearly seen in the output of the diode channel in Figure 6.1 (although it also effects the mixer channel), is not an issue for the work the FONT group does at ATF2 where the signals are well approximated by delta functions separated by ~ 100 ns. Although the droop has been seen previously, its significance for the continuous microsecond length pulse at CTF3 had not been considered because of this.

The droop emerges as a result of the use of AC coupling on the ADC input transformers for electrical isolation. This involves using a capacitor, the current across which is dependent on dV/dt (V being voltage and t time), to remove the DC component from a signal. In particular for the diode channel, which should be a square wave, the output is increasingly well described by a DC signal on the flat top as you move away from the leading edge of the pulse, with the capacitor causing droop in the response as a result.

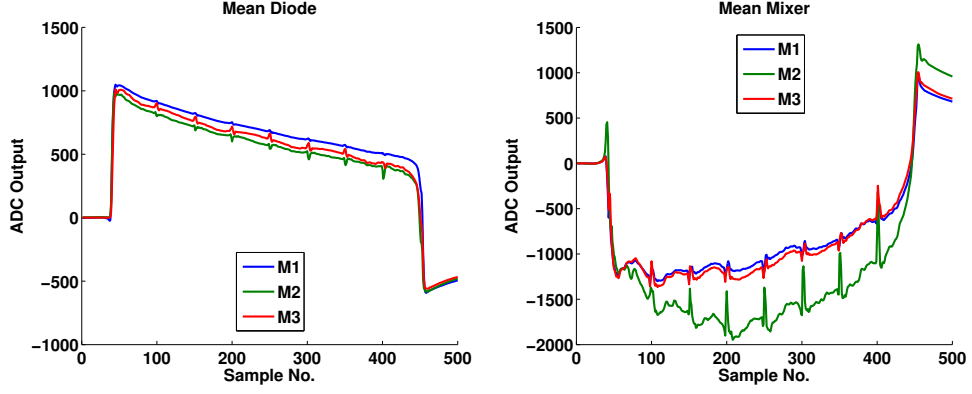


Figure 6.1: Mean diode and mixer output with no filter.

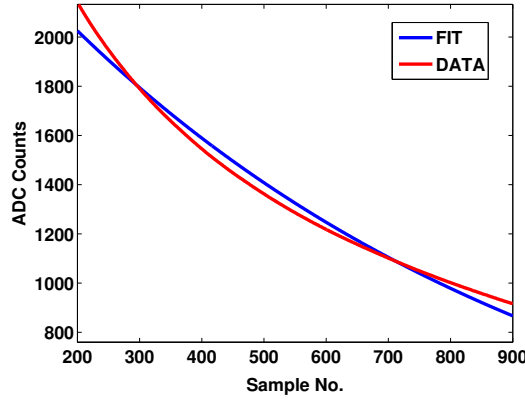


Figure 6.2: Attempted exponential fit to the ADC droop.

In the simplest case the droop should be well described by an exponential decay of the form $A \exp(-t/T)$. The droop makes it difficult to perform calibrations and measurements on the data and one way in which it could be removed in offline analysis is by determining the decay constants, T , for each of the ADCs on the FONT5 board. To avoid the influence of beam effects tests were done in Oxford using a generated $10 \mu\text{s}$ DC pulse.

Unfortunately, as can be seen in Figure 6.2 which shows an example of an exponential fit for one ADC, although the fits return good R^2 values it is clear that the slope of the exponential curve is not a good match for the slope of the data. This is perhaps not unexpected as the ferrite cores used in the transformers have many non-linear properties. In fact, by using a fit with two exponential terms it is possible to obtain a perfect match to the data but at this point the complexity of the fit would make any attempt to remove the droop in real beam data in this way spurious.

Instead, changes will be made to the currently in development FONT5a board hardware and firmware to greatly reduce the scale of the droop. Different transformers will be used to reduce the droop rate by up to a factor of fifty and in addition digital filtering will be implemented in firmware to smooth out and reduce the remaining droop component even further. It is expected that after these changes the droop will be small enough to not have a detrimental effect on the performance of the phase feedforward system.

6.3 Time Alignment of Signals

6.4 Kicker and Optics Performance Verification

6.4.1 Correction Range

Scan and comparison to expectation from optics.

Effect on correction.

6.4.2 Linearity

6.4.3 Orbit Closure

6.4.4 Shape

Shape of FF kick on BPMs vs. shape of upstream phase

6.5 Absolute Kicker Timing

6.5.1 Latency

6.5.2 Using Beam Pickup

6.5.3 Using BPMs

6.6 Relative Kicker Timing

6.7 Definition of Zero Phase

6.8 Correction Bandwidth

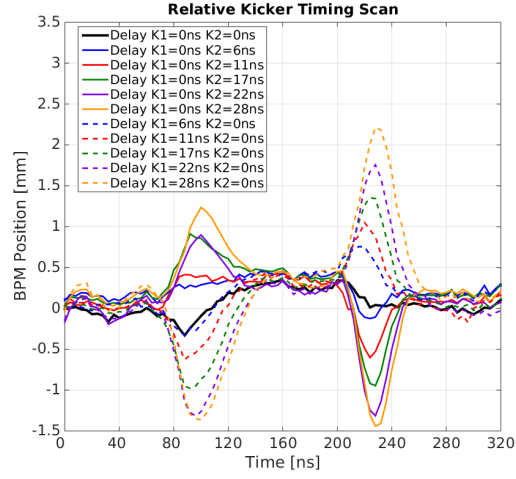


Figure 6.3: Traces relative timing scan.

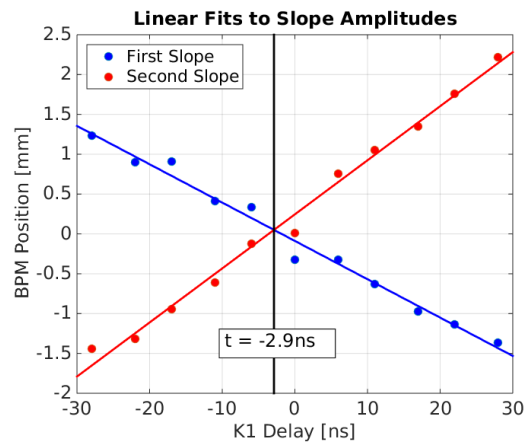


Figure 6.4: Relative timing scan - fit to rising/falling edge.

Chapter 7

Feedforward Results

This is the introductory text.

7.1 Gain Scans

7.2 Lowest Achieved Phase Jitter

The results presented in this section show the best downstream phase jitter currently achieved at CTF3 with the PFF correction. The dataset was taken on Friday 20th November 2015 at 15:38 as one of a sequence of short measurements fine-tuning the gain around the optimal value. Results from the other datasets in this sequence are discussed in the following section to demonstrate the phase stability achieved a longer time scales. The 15:38 dataset shown here comprises 150 pulses taken in interleaved mode, with the correction applied to the 75 odd indexed pulses and no correction applied to the remaining 75 even indexed pulses. The used gain in FONT5a units was 800, corresponding to a real applied correction of 1.13 times the upstream phase using the conversion factor calculated in 6.1.2.

Naturally, this dataset was taken during the best beam conditions currently achieved at CTF3 in terms of phase propagation, taken just after a series of R56 and beam energy optimisations using the same methods discussed in Chapter 5.

Distribution of points at around 0.5 degrees downstream.

Residual uncorrelated phase (mean and along pulse).

Correction Status	Upstream Jitter	Downstream Jitter	Correlation
FF Off	$0.69 \pm 0.06^\circ$	$0.74 \pm 0.06^\circ$	0.93 ± 0.04
FF On	$0.57 \pm 0.05^\circ$	$0.28 \pm 0.02^\circ$	0.19 ± 0.12
FF Simulated	$0.69 \pm 0.06^\circ$	$0.27 \pm 0.02^\circ$	0.06 ± 0.12

Table 7.1: Best PFF results.

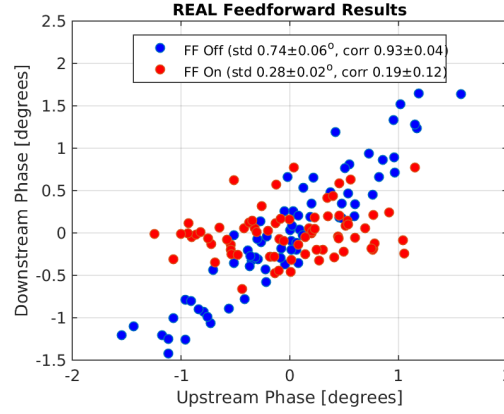


Figure 7.1: Mean phase.

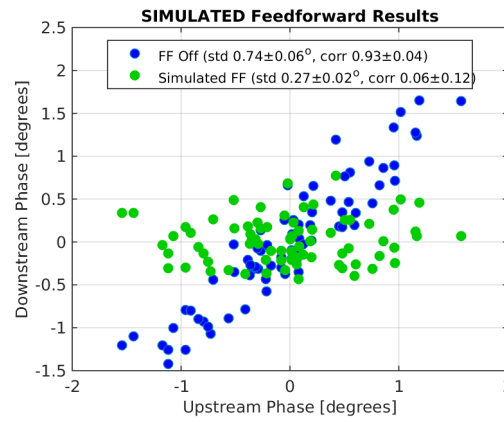


Figure 7.2: Simulated PFF.

Jitter along pulse

7.3 Correction on Longer Time Scales

At CLIC 0.2 degrees phase stability would clearly have to be maintained for much longer time scales than a few minutes. This section therefore discusses the status of the correction across longer time scales, using data from around 15:30 to 18:00 on the 20th November 2015, the same day as the record result previously shown which was taken during this period at 15:38. The PFF system was not operated continuously throughout this two and a half hour window but 15 individual datasets of a few hundred pulses each were taken and these results have been combined to create a large sample of 3083 interleaved pulses (1541 with the correction on and 1542 with the correction off).

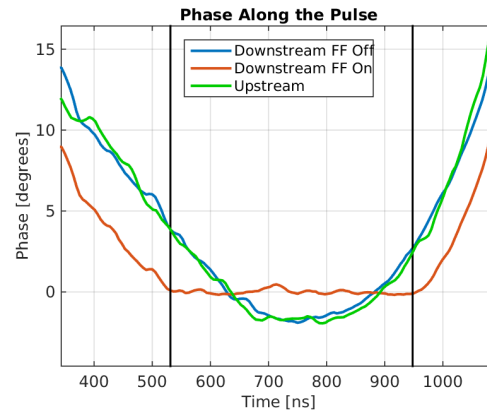


Figure 7.3: Mean phase along.

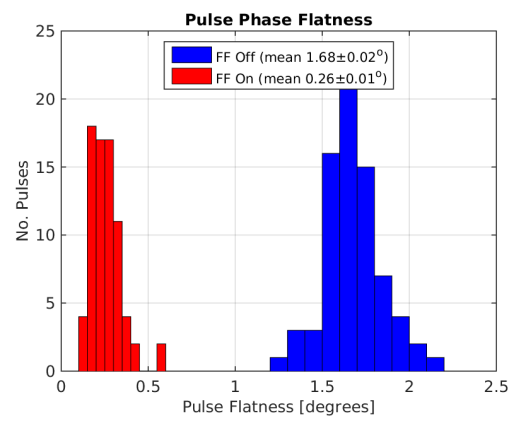


Figure 7.4: Flatness.

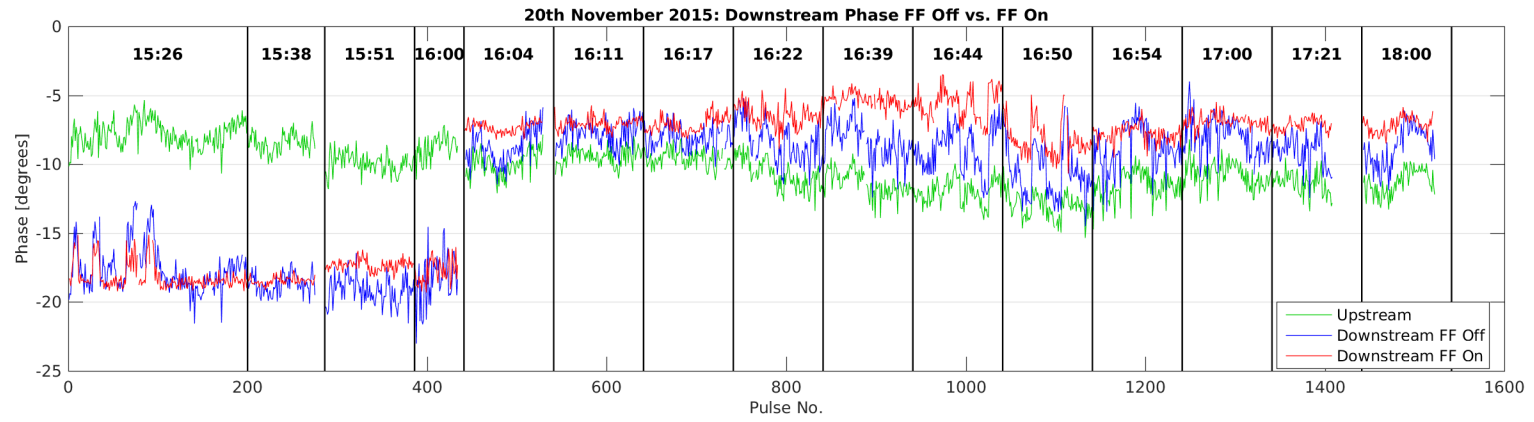


Figure 7.5: History of mean phase across datasets.

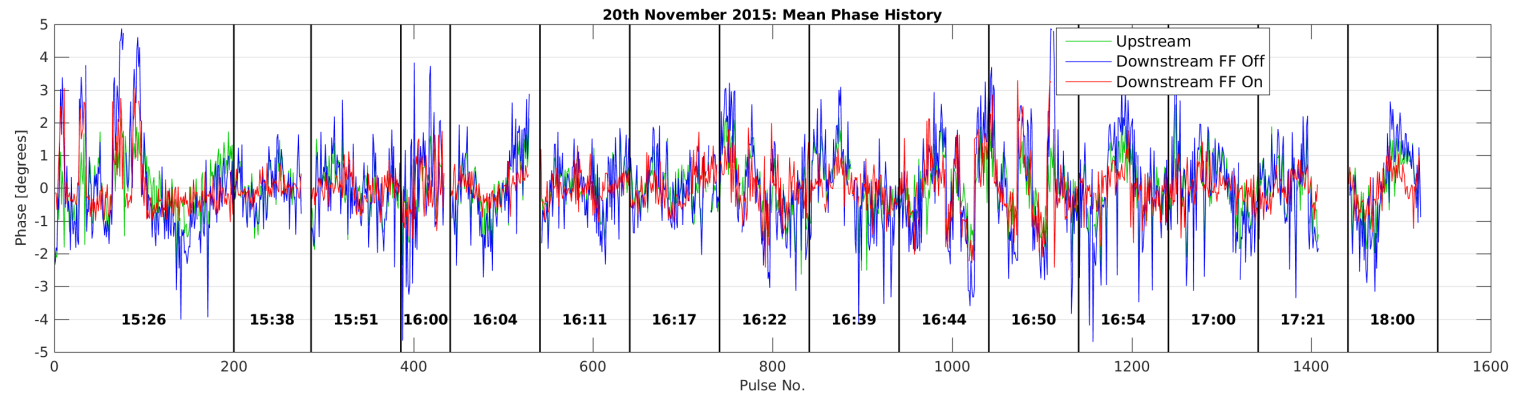


Figure 7.6: History of mean phase across datasets, with mean subtraction.

The raw history of the mean phases upstream and downstream with the correction on and off in the combined data are shown in Figure 7.5. The time span of each individual dataset is marked by vertical black lines and the times displayed on the plot represent the start time of each dataset.

Over the course of the afternoon the mean upstream phase, in green, varies by ten degrees peak-to-peak or $1.75 \pm 0.02^\circ$ in terms of jitter. Small drifts of up to a few degrees in the upstream phase are not an issue for the performance of the PFF correction providing the correlation between the upstream and downstream phase is not degraded. In some cases upstream phase drifts may lead to a loss in correlation, this could be the case if the source of the drift is a variation in beam energy due to the issues discussed in Chapter 5, for example. The variation of the correlation between datasets is discussed later in this section.

Larger changes in the upstream phase such as the ten degree fluctuation seen here will impact the PFF performance purely via the limited correction range of $\pm 6^\circ$ combined with the phase sag along the CTF pulse. Indeed the PFF prototype's main purpose is not to remove any large, slow phase drifts but rather the faster pulse-to-pulse jitter and high frequency variations along the pulse. The phase offset applied by the PFF correction at each sample along the downstream phase, $\Delta\phi_d(t)$, is given by:

$$\Delta\phi_d(t) = \begin{cases} -6^\circ, & \text{if } g\phi_u(t) \geq +6^\circ. \\ +6^\circ, & \text{if } g\phi_u(t) \leq -6^\circ. \\ -g\phi_u(t), & \text{otherwise.} \end{cases} \quad (7.1)$$

Where $\phi_u(t)$ is the upstream phase at each sample point and g is the gain factor used. As the optimal gain (Section 2.5.2) for the correction is typically larger than one due to the slight amplification in the downstream phase jitter with respect to the upstream jitter the range of the PFF system in terms of the upstream phase is less than $\pm 6^\circ$ (for example $\pm 5.3^\circ$ for the 15:38 jitter record dataset with a gain of 1.13). Any point along the upstream phase with $|g\phi_u(t)| > 6^\circ$ receives the maximum 6° phase shift downstream but can not corrected to zero, with this remaining residual degrading the corrected phase jitter that can be achieved.

Figure 7.7 shows the fraction of pulses for which the optimal correction (upstream phase multiplied by the optimal gain) is within the correction range. In the PFF firmware on the FONT5a board it is possible to add an offset to the ADC output corresponding to the upstream phase. If on the FONT5a board this offset has been set up to zero the apparent measured upstream phase (so that the mean voltage sent to the kickers across the afternoon is zero) the effects of limited correction range are small, as the full $\pm 6^\circ$ range can be used to remove phase jitter rather than any static phase offsets. In this case the ideal correction across a 310 ns portion of the pulse is within the $\pm 6^\circ$ range 96% of the time.

However, as to date this offset has been set up manually small deviations from the ideal case are possible. Figure 7.7 also shows the fraction of pulses within the correction range if there is a static two degree offset in the upstream phase. In this case as many as 39% of pulses are outside the correction range. To mitigate these effects and to get the largest reduction in jitter possible the centring of the upstream phase in the correction range on

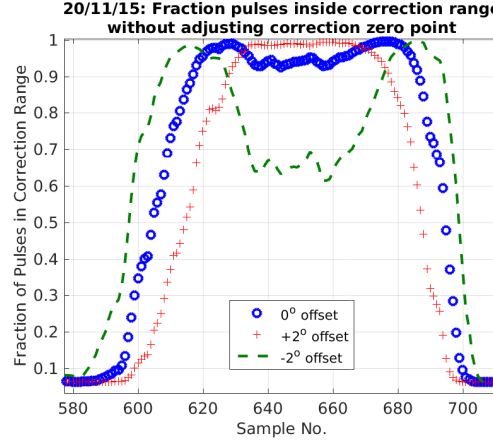


Figure 7.7: Fraction of pulses outside the correction range along the pulse.

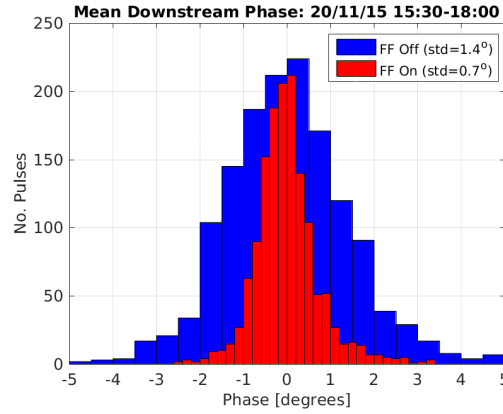


Figure 7.8: Histogram showing overall distribution of downstream phase with FF off and on.

the FONT5a board is normally adjusted between datasets. As a consequence of this slow drifts in the upstream phase between datasets are not removed in the corrected downstream phase.

7.4 Correction with Additional Jitter Source

At CLIC the PFF system will be required to reduce the initial phase jitter by an order of magnitude, from 2 degrees to 0.2 degrees [REF]. With the initial phase jitter of typically 0.8 degrees at CTF3 it is not possible to demonstrate more than a factor 4 reduction in the jitter using the PFF prototype due to hardware limitations, more specifically due to the achieved phase monitor resolution of 0.14 degrees which limits the theoretical best possible correction to 0.2 degrees (Section 4.6). A secondary goal of the PFF prototype in addition to achieving the baseline goal of 0.2 degrees phase jitter is to demonstrate the factor 10 reduction in jitter relevant to CLIC. In order to do this additional sources of phase jitter must be added.

Clearly, the additional source must be prior to the upstream phase monitor in order to add an additional jitter component that is present in both the upstream and downstream monitors. The correlation between the resulting upstream and downstream phase must be

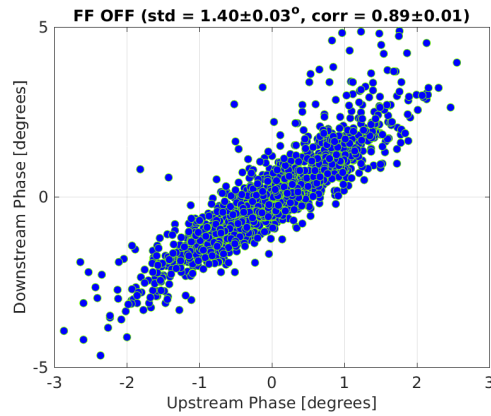


Figure 7.9: Downstream phase vs. upstream phase with FF off.

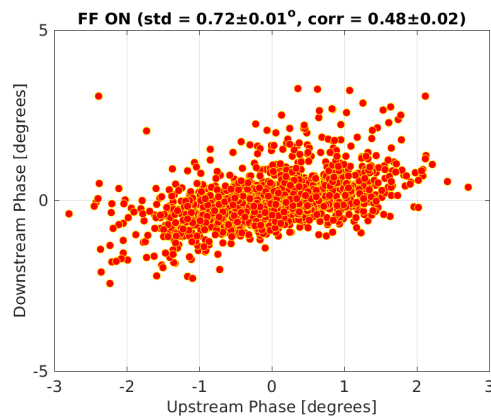


Figure 7.10: Downstream phase vs. upstream phase with FF on.

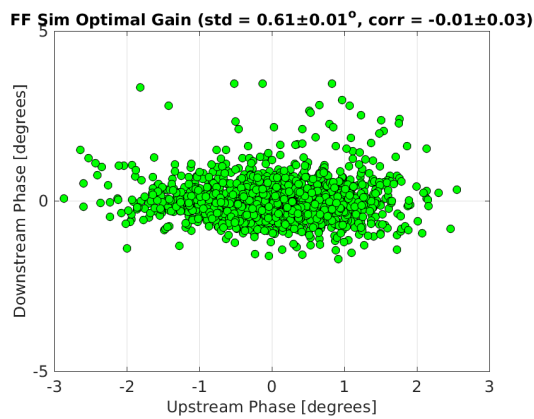


Figure 7.11: Downstream phase vs. upstream phase with FF simulated at optimal gain.

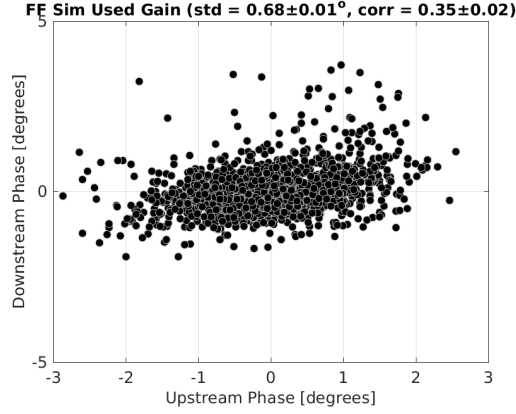


Figure 7.12: Downstream phase vs. upstream phase with FF simulated with actual gain used.

Correction Status	Upstream Jitter	Downstream Jitter	Correlation
FF Off	$0.88 \pm 0.02^\circ$	$1.40 \pm 0.03^\circ$	0.89 ± 0.01
FF On	$0.86 \pm 0.02^\circ$	$0.72 \pm 0.01^\circ$	0.48 ± 0.02
FF Sim Opt Gain	$0.88 \pm 0.02^\circ$	$0.61 \pm 0.01^\circ$	-0.01 ± 0.03
FF Sim Real Gain	$0.88 \pm 0.02^\circ$	$0.68 \pm 0.01^\circ$	0.35 ± 0.02
FF Sim Offset	$0.88 \pm 0.02^\circ$	$0.69 \pm 0.01^\circ$	0.36 ± 0.02
FF Sim 90% Real Gain	$0.88 \pm 0.02^\circ$	$0.72 \pm 0.01^\circ$	0.46 ± 0.02

Table 7.2: Feedforward results using combined data from 20th November 2015.

99.5% in order for a factor 10 reduction in jitter to be possible (see Section 2.5.1). Two different methods to achieve this have been attempted — firstly by varying the phases of all the klystrons in the injector and secondly by using the non-zero R56 stretching chicane (see Figure 2.1) at the end of the CTF linac in order to intentionally add an energy component to the upstream phase (which propagates downstream).

7.5 Slow Correction

As the PFF system has only a small range of $\pm 6^\circ$, a secondary “slow phase feedback” or “slow correction” has also been implemented at CTF3 to be able to remove larger drifts or static offsets in the downstream phase. In principle this slow correction can be used in conjunction with the PFF system to maximise its performance by keeping the mean uncorrected phase well-centred (zeroed) within its $\pm 6^\circ$ range so that the full power of the PFF amplifiers can be used to correct the fast pulse-to-pulse and intra-pulse phase jitter. If the beam phase were to drift away by 15° , for example, the calculated PFF correction would saturate the amplifier across the full pulse length to give the maximal shift of 6° . In this case the drift would be partially removed downstream but the PFF system would no longer have any effect on the phase jitter (as the output voltage to the kickers is constant in saturation rather than varying with the phase).

The design and results from the slow correction are discussed in this section. To date its main use has been to verify the ability to shift the beam phase in the TL2 chicane in early-2014 prior to the kicker amplifiers being available to commission the PFF system itself. The slow phase feedback has not yet been used in parallel with the PFF system apart from preliminary tests thus the results shown here are primarily a proof of principle. As PFF attempts have so far been predominantly taken in short datasets of up to a few hundred pulses any large drifts that arise can be manually removed between datasets, either by changing the correction setup (e.g. by changing the phase monitor phase shifters to re-zero the phase) or by re-establishing the previous beam conditions. The slow correction will however be an important tool for future attempts to demonstrate CLIC-level phase stability on time scales longer than a few minutes at CTF3.

7.5.1 Implementation

Ratio of corrector strengths for orbit closure.

7.5.2 Results

Chapter 8

Conclusions

This is the introductory text.

8.1 Summary

8.2 Future Work