Phase Feedforward at CTF3: First Experimental Results

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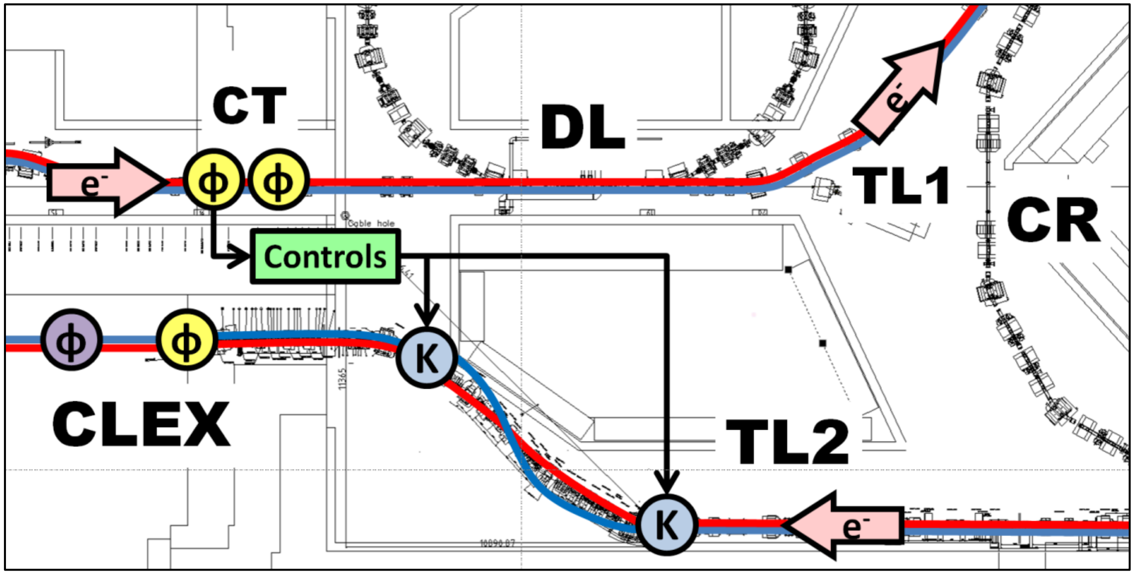
PFF Layout at CTF3

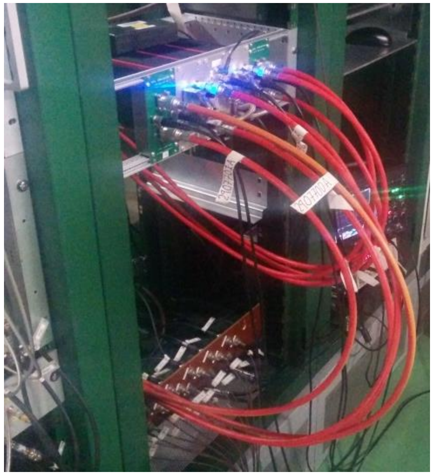
- PFF prototype at CTF3: nominal bandwidth with 65kW amplifiers
- Correction in the pre-existing four bend dog leg chicane in TL2.
  - 3 dedicated phase monitors (INFN Frascati)
  - 2 kickers (INFN Frascati)
  - Amplifiers and digital processor (JAI Oxford)
- Beam time of flight from first monitor to first kicker: 380ns
- First tests of the whole system November-December 2014.



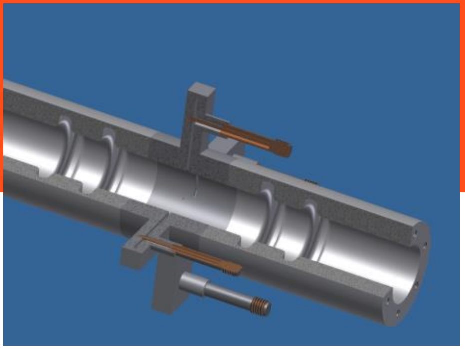
Amplifier (JAI, Oxford University)

- It is a major challenge: >50 MHz bandwidth (although slew rate limited) and 65kW peak power.
- Designed for operation over full 1.2 μs uncombined pulse, full performance guaranteed over ~400 ns portion

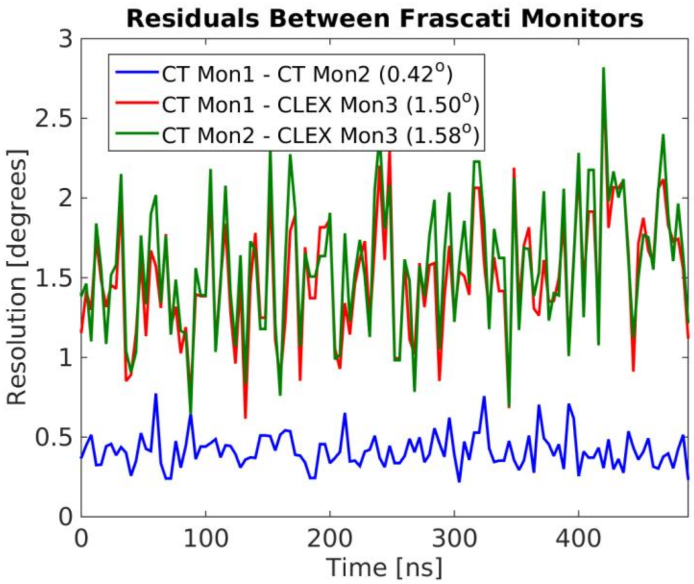
- First amplifier module available for feedforward tests: 16kW, 345 V output.
- Eventual design output of each module will be 600 V (additional FETs will be added). 600 V amplifier should be available by mid-2015.
- Full 1.2 kV from four modules combined. Late 2015.

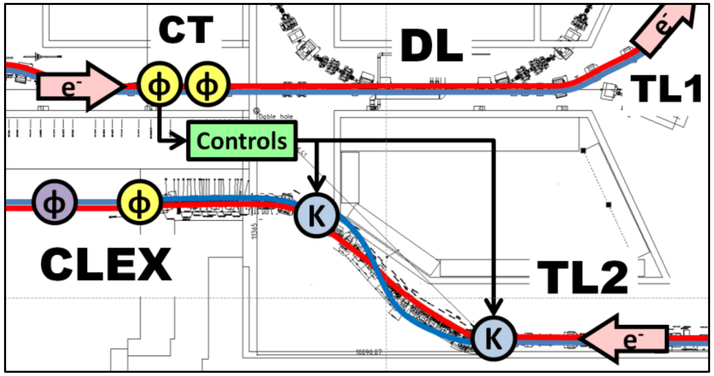


Phase Monitors (INFN Frascati)



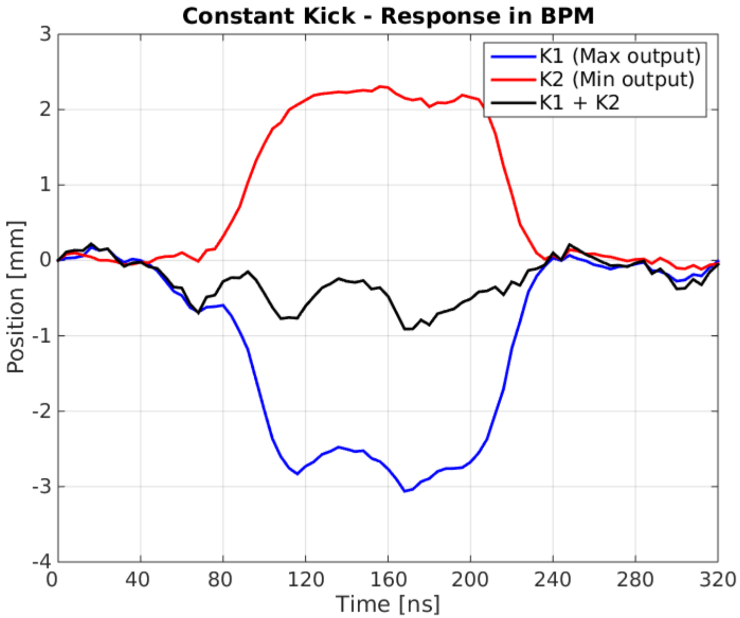
- 12 GHz RF pickups using a choke mode cavity, 30 MHz bandwidth, 0.1° resolution.
- Three monitors installed late 2012 but two damaged. Two new monitors with revised design installed during 2014 summer shutdown.
- Phase monitors used for feedforward tests:
  - **CT Mon1:** Old design monitor, well understood performance. Provides input phase to feedforward system.
  - **CT Mon2:** New design monitor, shows degraded resolution due to electronics issues that will be resolved before the next run.
  - **CLEX Mon3:** New design monitor, used to measure effect of correction.
  - **CLEX PETS:** PETS phase measurement, cross-check results from Mon3.





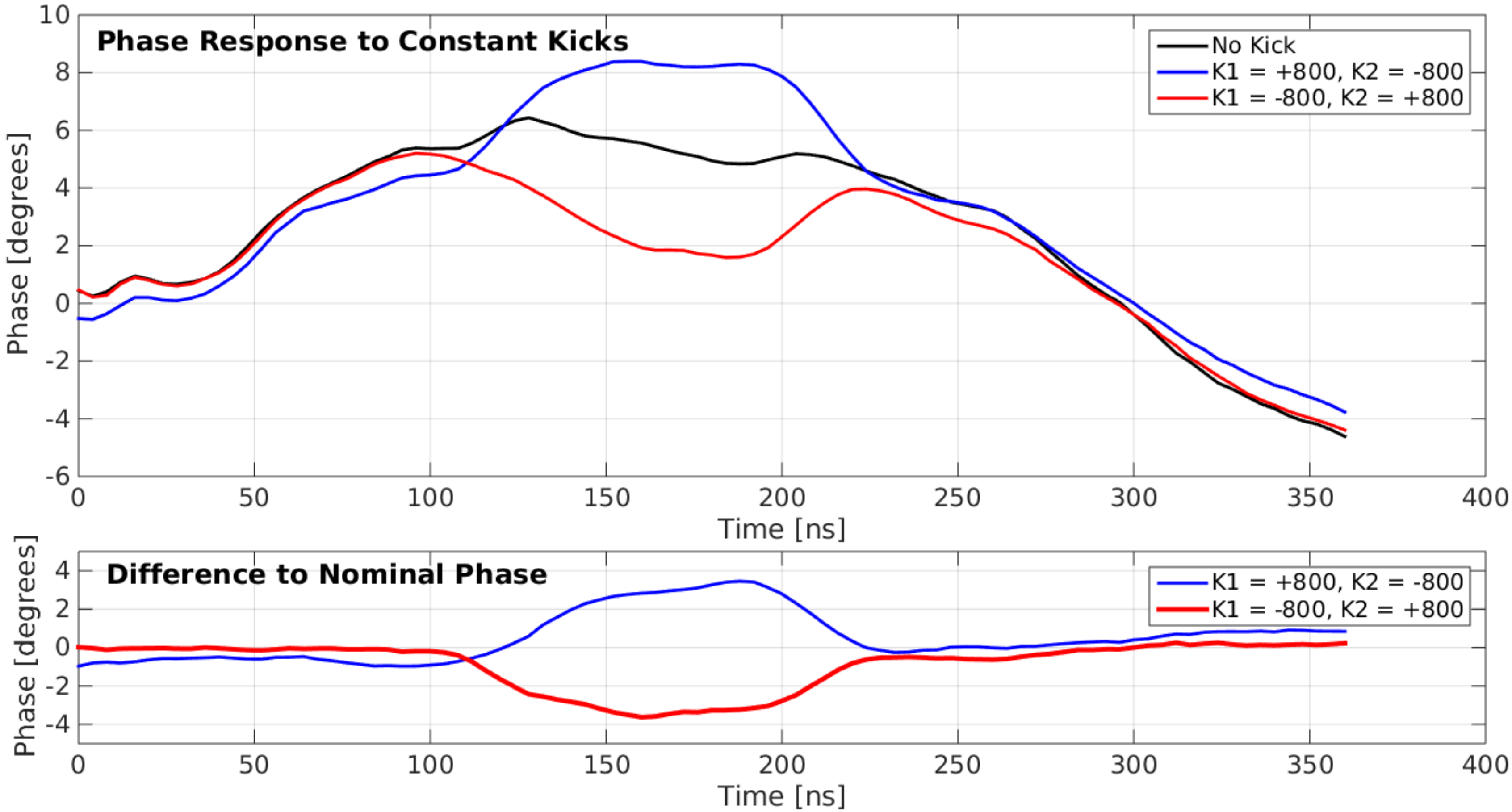
Constant Kicks, BPMs

- Before starting feedforward tests, commissioning to check performance of processor, amplifier and kickers.
- Clearly observe response to each kicker in the BPMs.
- Rise time ~30ns, ~12MHz bandwidth (slew rate limited, bandwidth much higher for smaller variations).



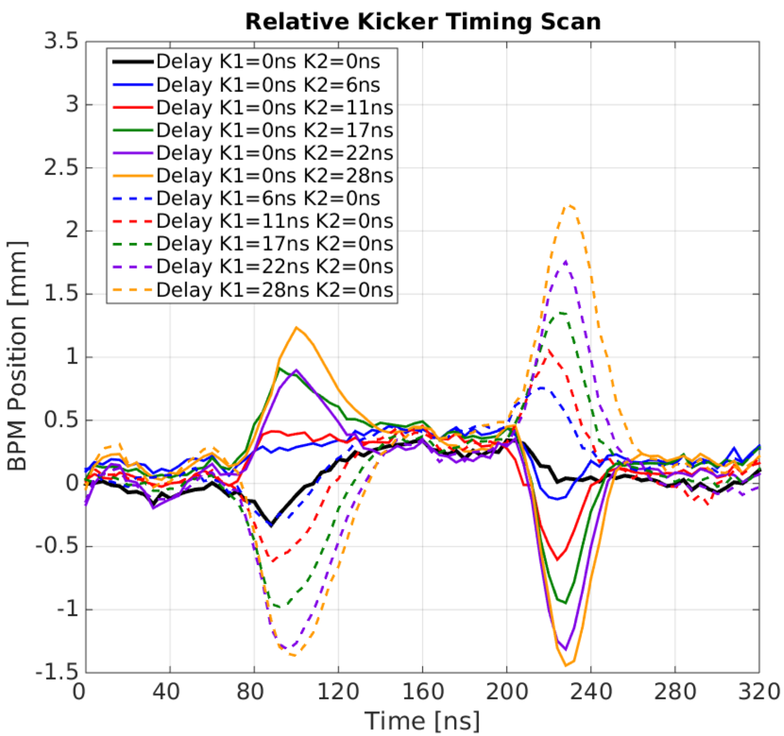
Constant Kicks, Phase

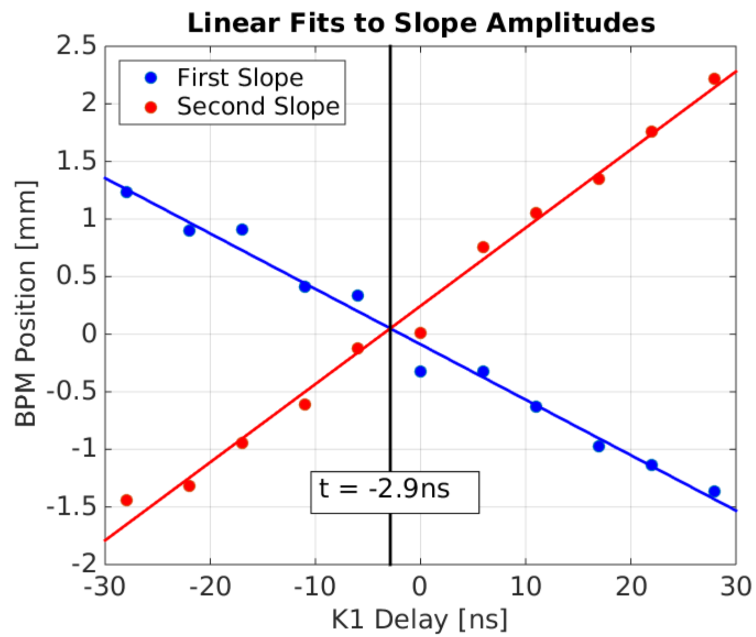
- With full amplifier power expect range +/-10 degrees from optics, with current amplifier power expect ~+/-3 degrees.
- Measured range a bit larger, +/- 3.5 degrees.



Relative Kicker Timing Scan

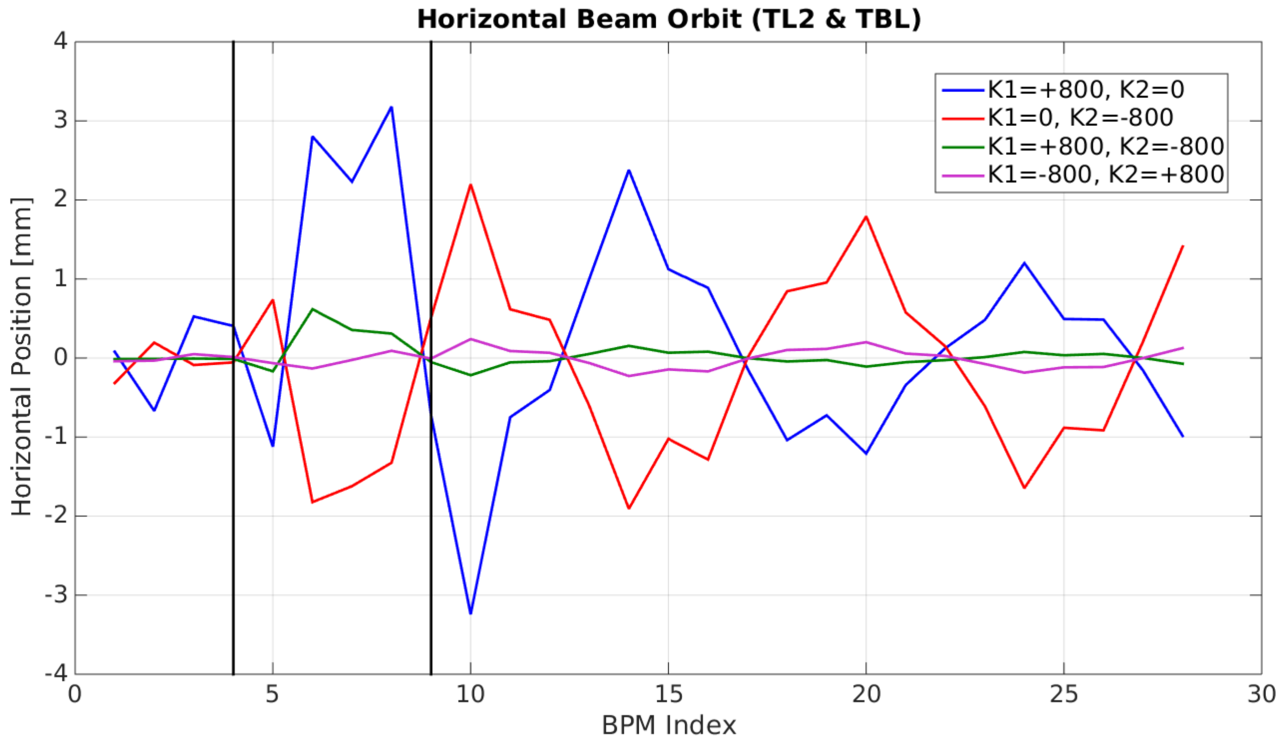
- Both kickers must act on same portion of pulse.
- 35ns beam TOF between 1st and 2nd kicker.
- Cables for 2nd kicker ~6.5m longer to compensate for this.
- Fine tuning by delaying output to 1st/2nd kicker using processor.
- K2 output should be delayed by ~3ns.





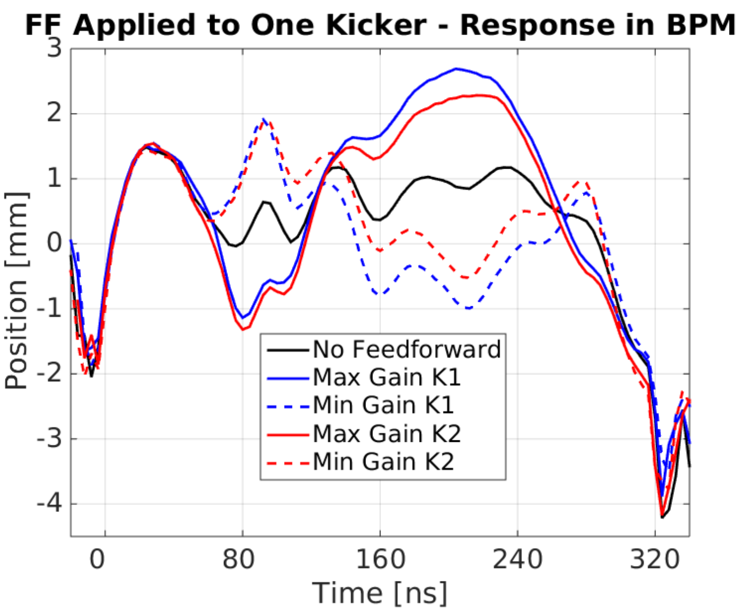
Constant Kicks, Orbit Closure

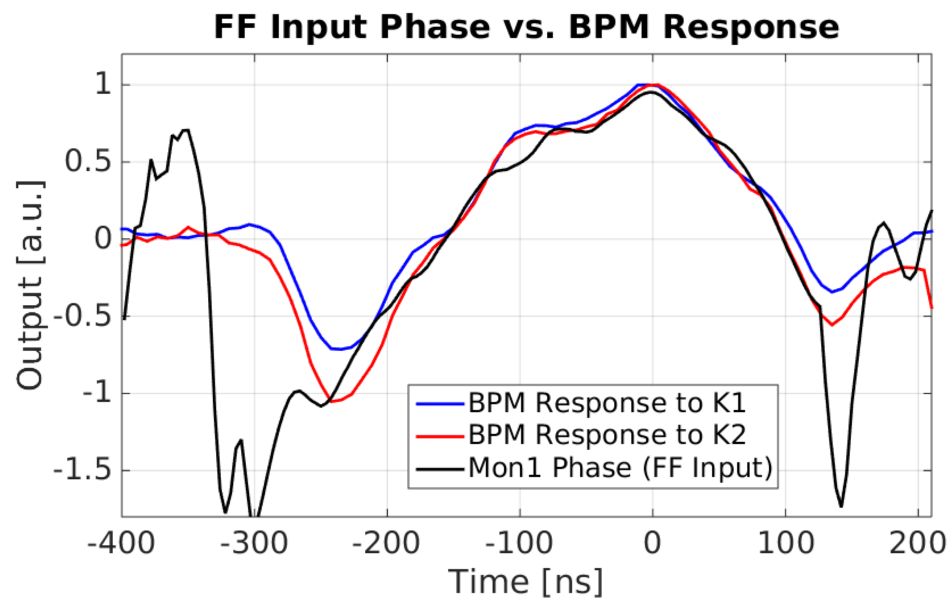
- PFF system should not change orbit downstream of chicane.
- Optics should close orbit with equal and opposite kicks from the kickers.
- Orbit closure is quite good but slight deviation after chicane (from BPM 10) will require fine tuning.



Feedforward Kick, BPMs

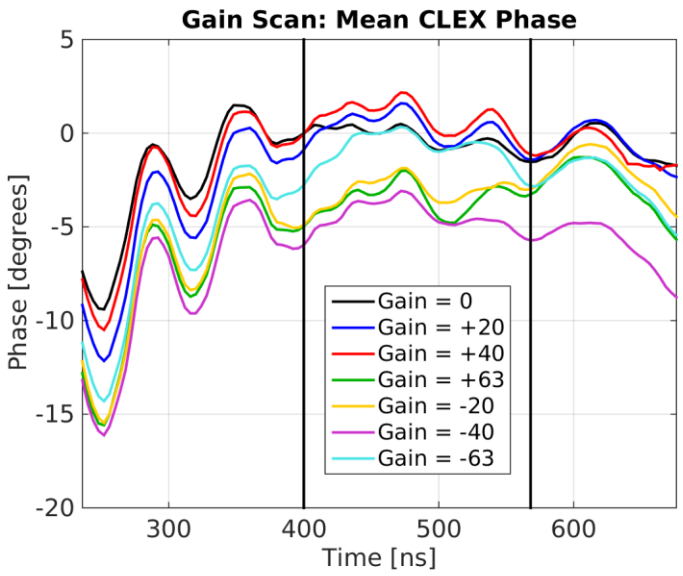
- Applied FF to one kicker at a time to verify performance of FF algorithm, amplifier and kickers.
  - Allows response to be seen in BPMs (less clear in CLEX phase monitors).
- Response in BPM matches FF input phase.

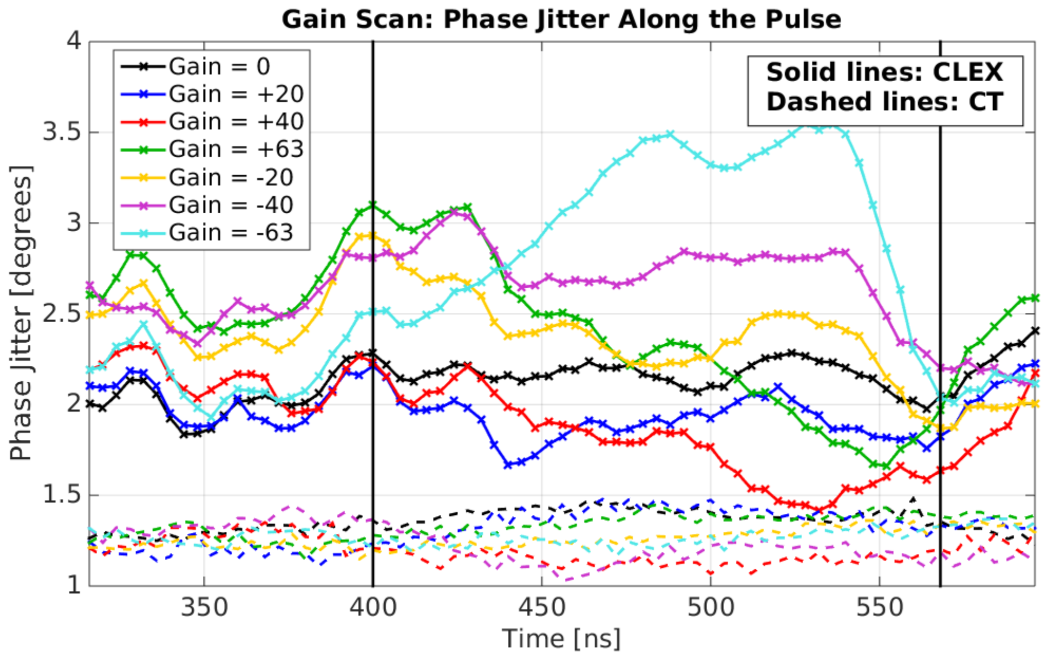




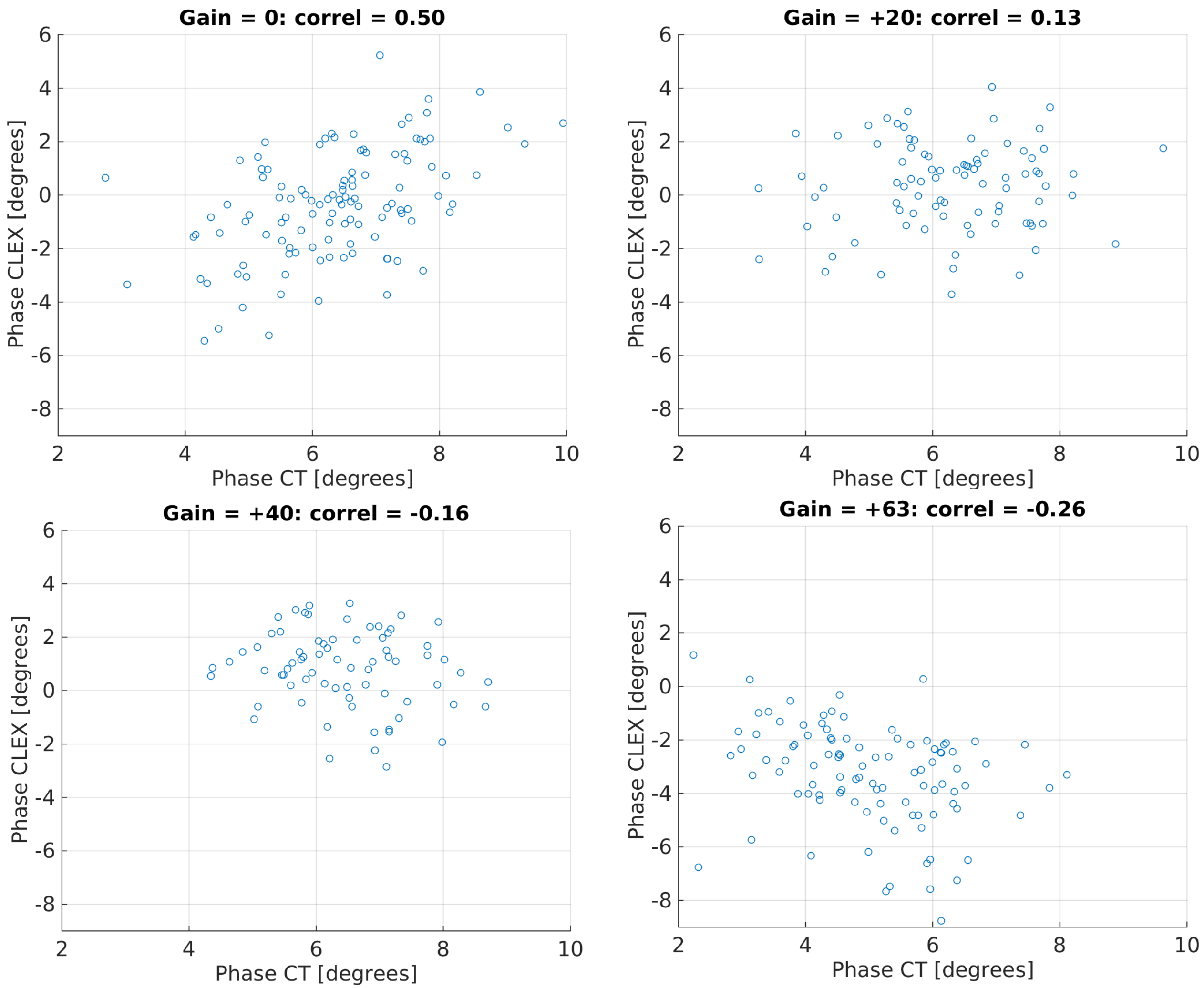
Feedforward Gain Scan

- Correction enabled in the region marked with black vertical lines.
  - Note the drifts outside this region.
- Phase Jitter:
  - Negative gain – phase jitter increases.
  - Positive gain – phase jitter decreases up to +40, then increases.
- Response not so clear in mean phase.



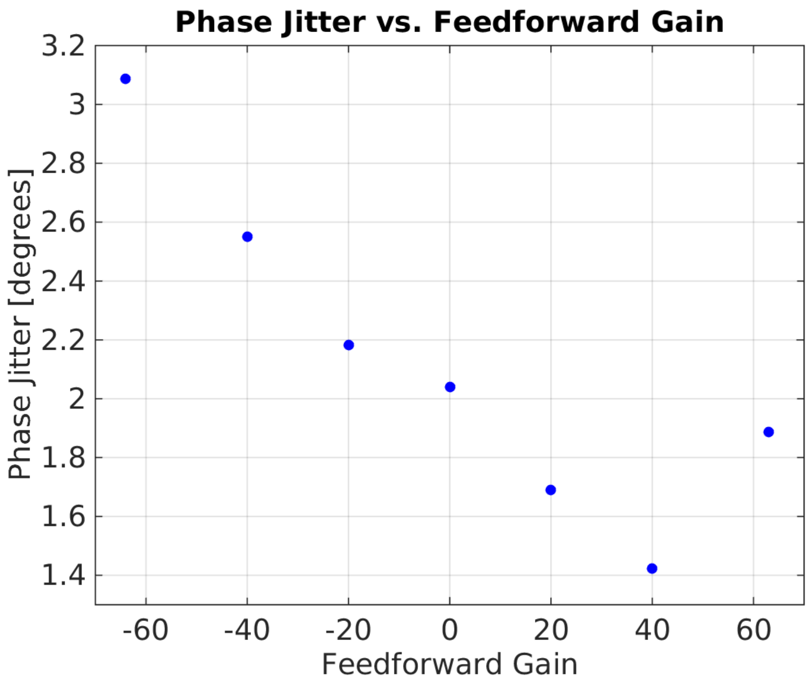


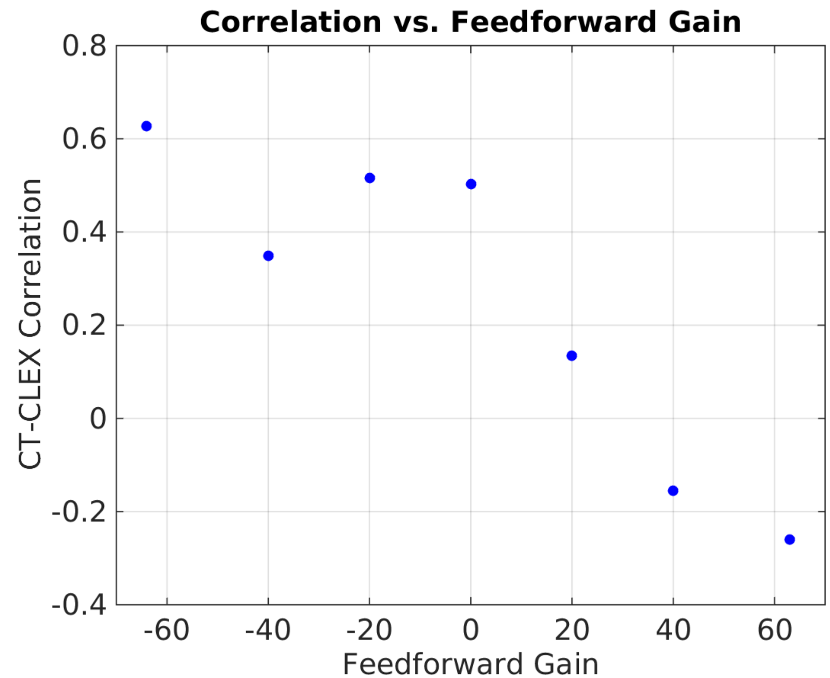
Feedforward Gain Scan: Correlation



- Feedforward with positive gain removes correlation between CT and CLEX phase.

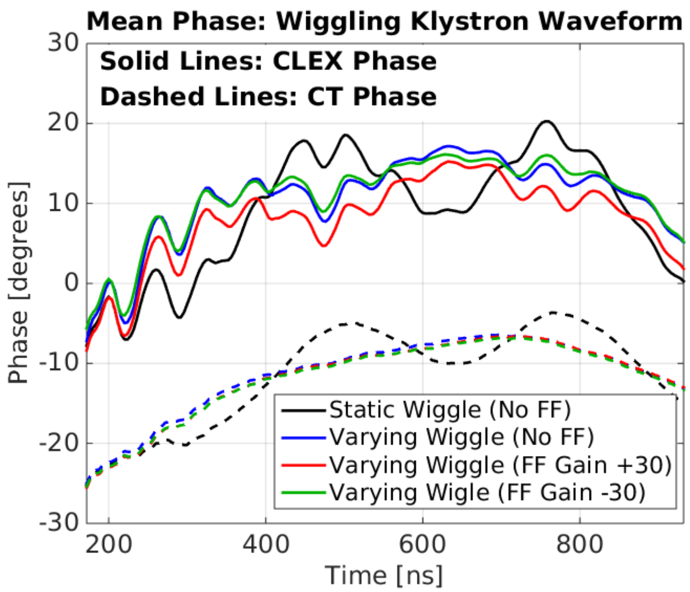
Feedforward Gain Scan: Summary



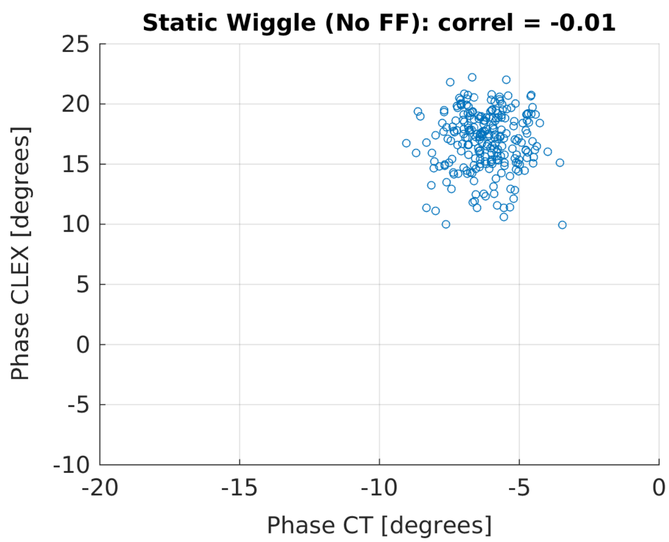


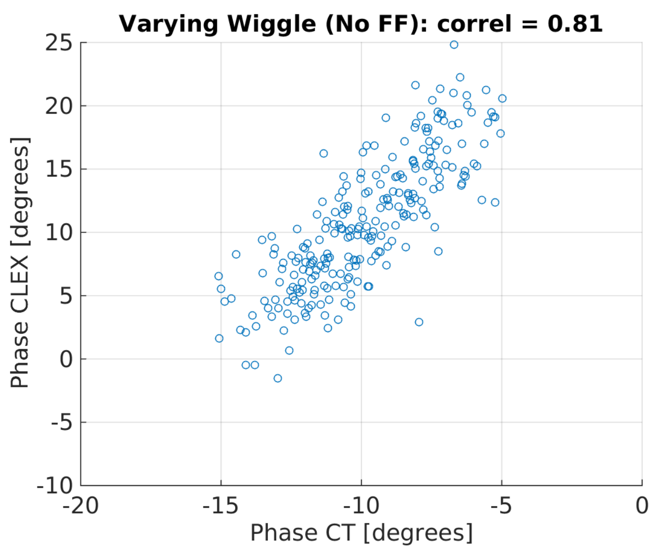
- Very promising results considering the low correlation.
  - Phase jitter reduced from 2.0 degrees to 1.4 degrees with gain of +40 (30% reduction).
  - Phase jitter increased from 2.0 degrees to 3.1 degrees with gain of -63 (55% increase).
  - Flip sign of correlation with feedforward system, optimal gain should remove all correlation (~gain 30).

Varying Klystron Phase

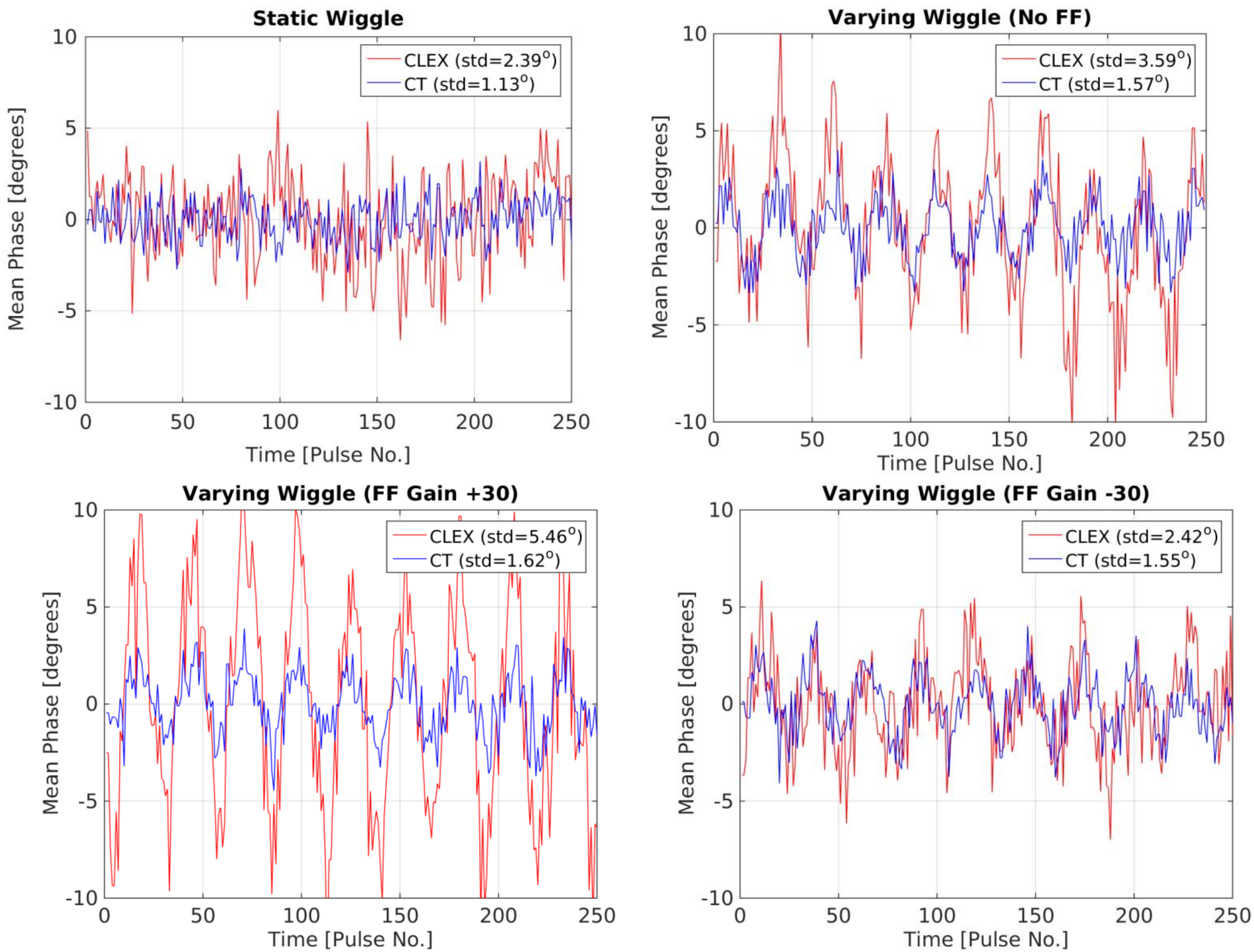


- Induce additional phase jitter by varying the waveform of MKS03.
  - Hope to increase correlation.
- Saw tooth with amplitude varying in time.
- Correlation increased from 0 to 0.8.



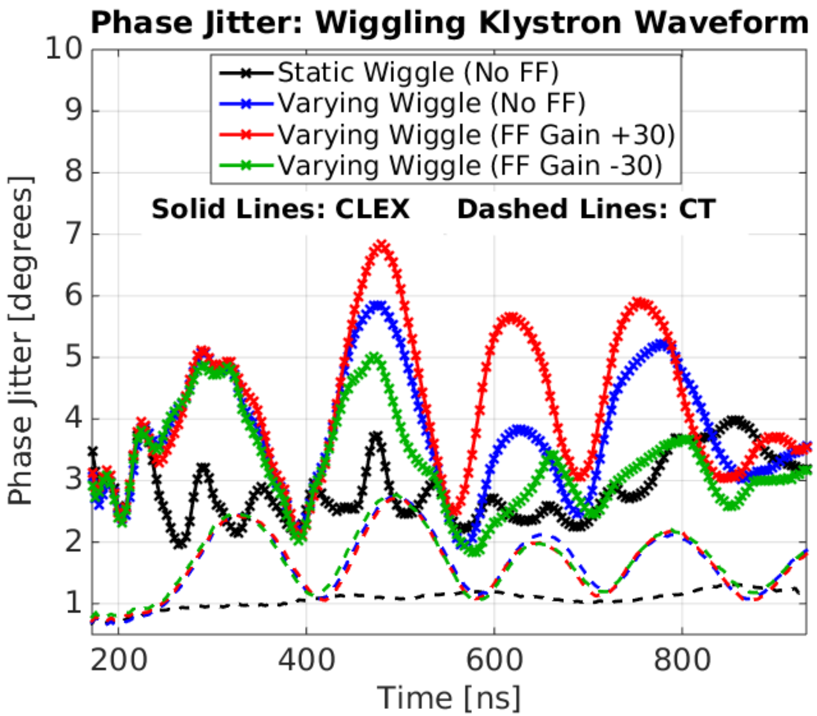


Feedforward with Klystron Phase Variation
MEAN PHASE DURING FEEDFORWARD RUN



Feedforward with Klystron Phase Variation

PHASE JITTER ALONG THE PULSE

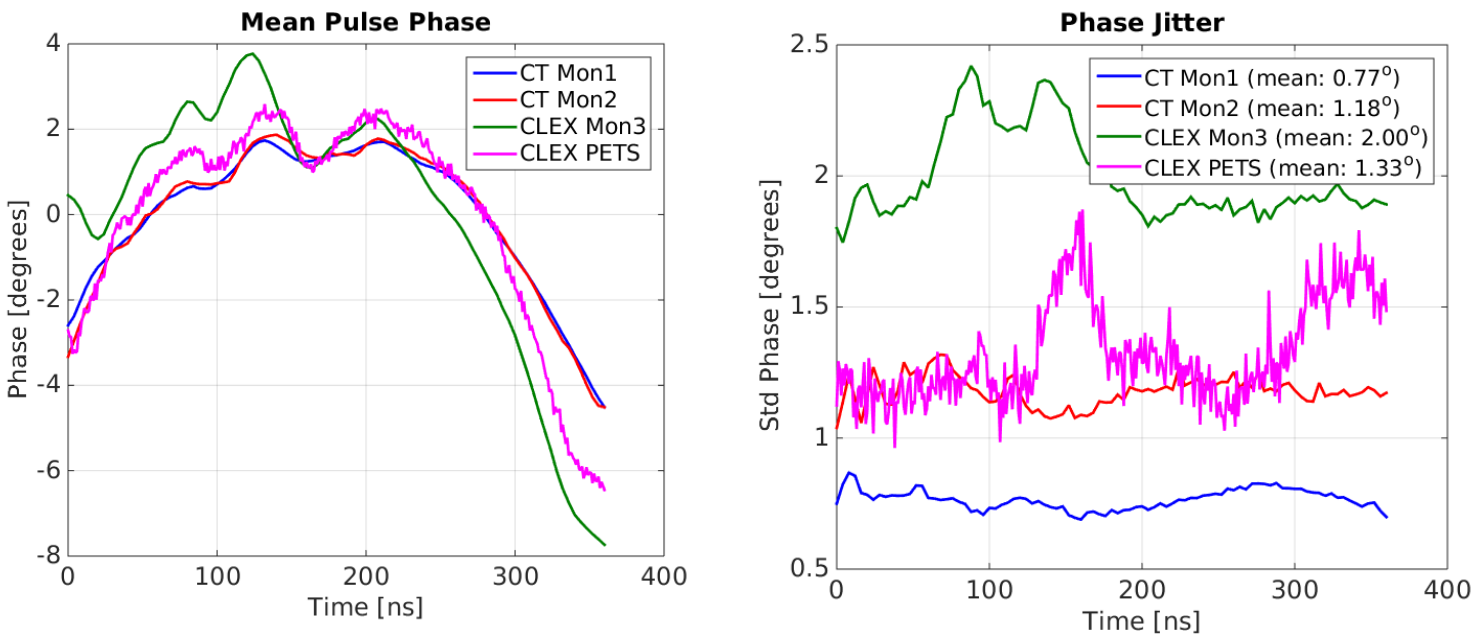


- Able to reduce the phase jitter in CLEX down to the level it was prior to increasing it by varying the klystron waveform.
- Can't correct the whole phase as the induced phase variation goes outside the current range of the feedforward system
  - Should be able to correct it with increased power from the amplifier.

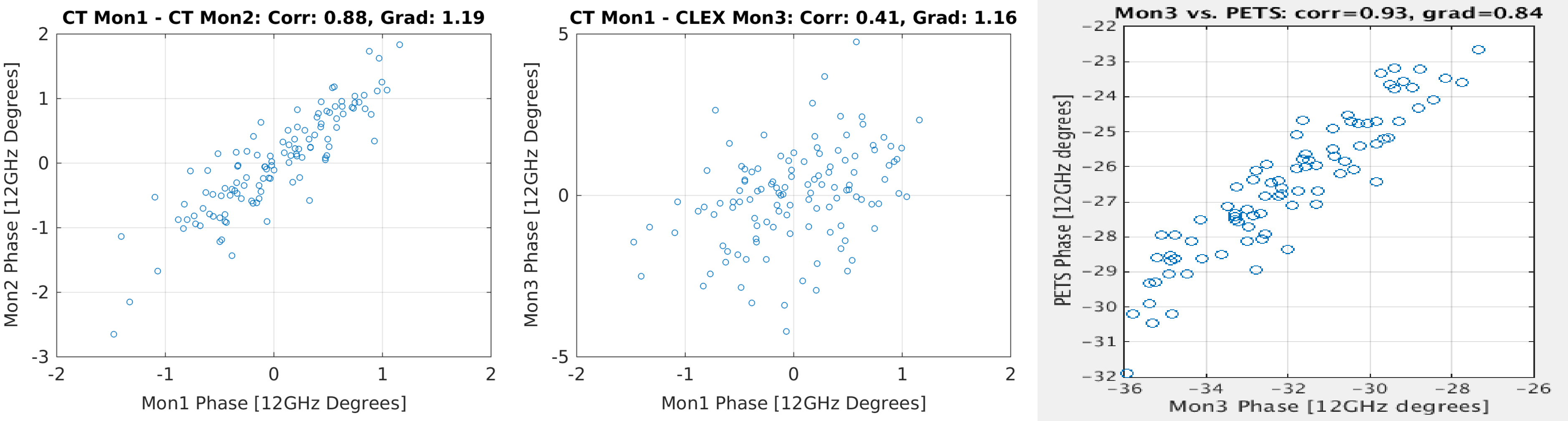
Phase Propagation

- Low correlation between the phase measured in the first monitor (CT Mon1, FF input) and the correction chicane is currently limiting the performance of the feedforward system.

- Differences in the mean phase and phase jitter measured in the phase monitors in CT and CLEX are clearly visible.



Phase Propagation



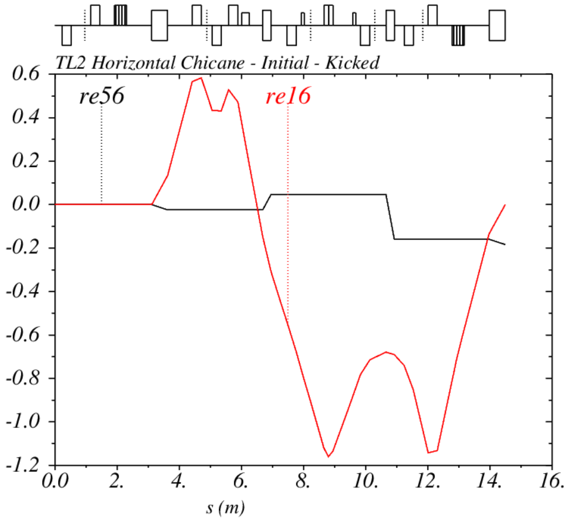
- Typical correlations:
  - CT Mon1 – CT Mon2: ~90%.
  - CT Mon1 – CLEX Mon3: ~30-60%, sometimes less.
  - CLEX Mon3 – CLEX PETS: ~90%.

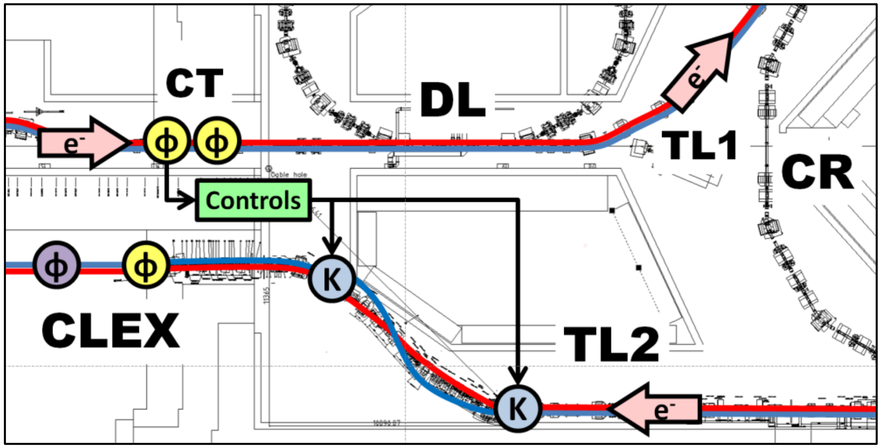
- Two Monitors in CT and CLEX correlate well with each other – real effect of the beam phase not a monitor issue.

- Source?

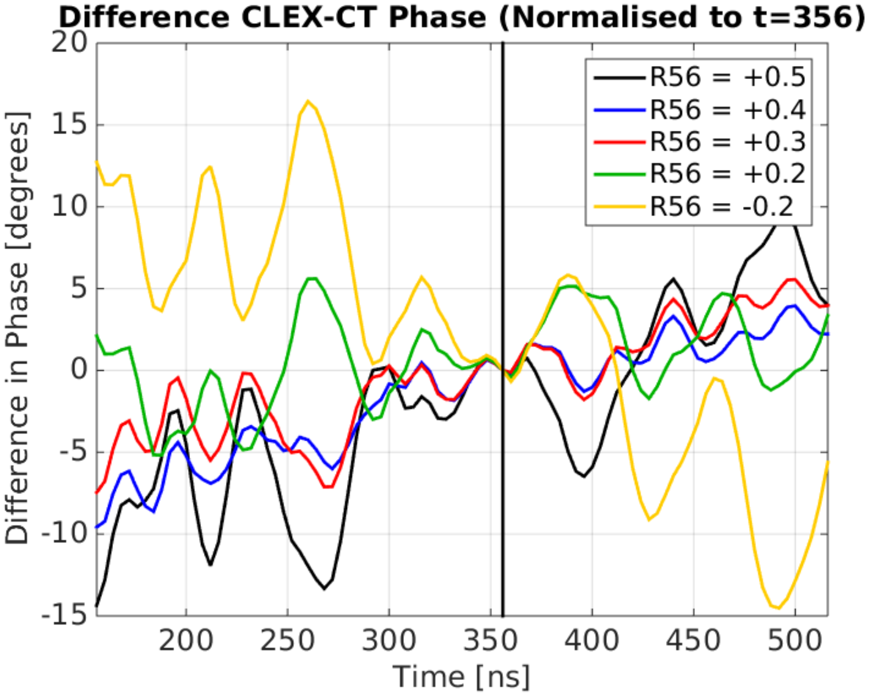
R56

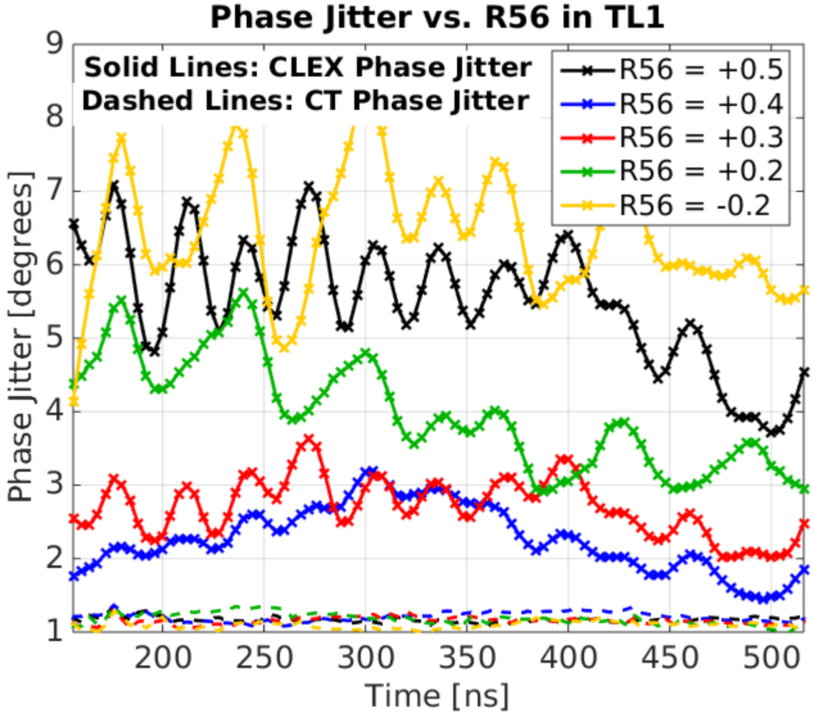
- Phase feedforward optics has non-zero R56 in the correction chicane.
  - Dependence of phase on Energy in the correction chicane.
  - Uncorrelated with FF input phase.
- Compensate negative R56 in TL2 with positive R56 in TL1. Expect R56 around +0.3 to give best results (-0.2 from TL2, -0.1 from other sources).





Scan of R56 in TL1





- Matched optics with R56 = +0.5, +0.4, +0.3, +0.2 and -0.2 in TL1.
- Sign of slope in mean phase differences changes with R56.
- Jitter in CLEX reduced with positive R56 up to +0.4, then amplified with +0.5 (over compensate).
- Large oscillations in phase for large R56 values are energy variations resulting from imperfect gun pulse flattening.
- However, the correlation remains around between CLEX and CT remains around 0.4 -> Must be other sources in addition to energy.

Summary

- All the phase feedforward hardware has now been installed and commissioned in CTF3.

- Demonstrated a clear reduction of 30% in the phase jitter using the phase feedforward system.

- To reduce the jitter further we need to improve the phase propagation between the phase in CT and CLEX:
  - By using optics with positive R56 in TL1 to compensate for negative R56 in TL2 the phase and phase jitter in CLEX is improved.
  - However, the correlation remains quite low so sources other than energy must be identified.
  - The correlation can be increased by varying klystron phases to induce an additional source of phase jitter. However, additional amplifier power is needed to correct it fully (will be possible this year).

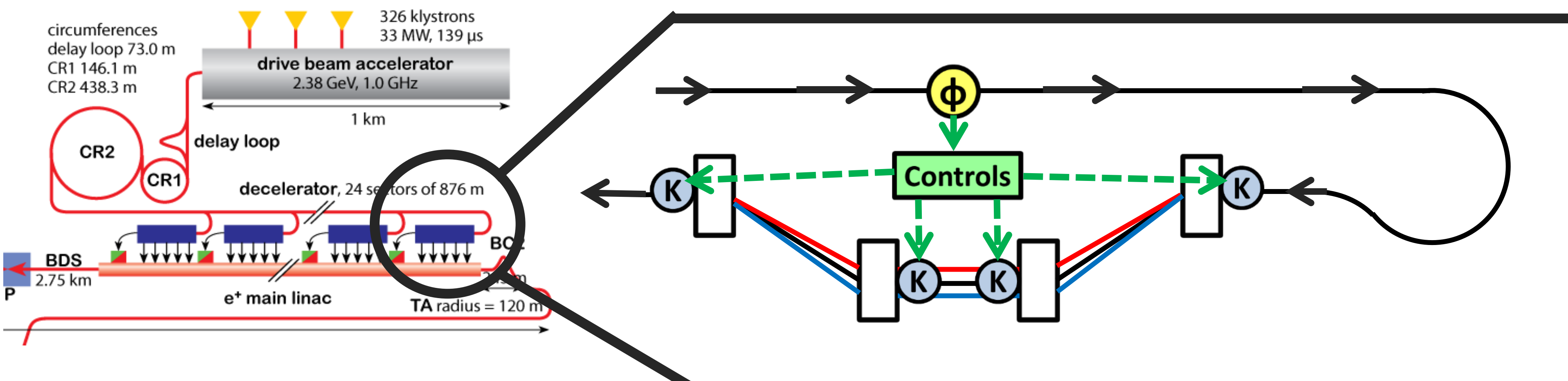
Any questions?

- Links to phase feedforward contributions at conferences/workshops in 2014 for more information:
  - CLIC Workshop 2014 (CERN, February)
  - LINAC14 (Geneva, August)
  - LCWS14 (Belgrade, October)

Backup

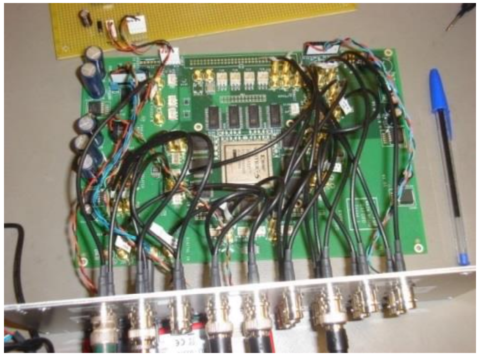
Phase Feedforward System Overview

- The phase synchronisation between the CLIC drive beam and main beam must be within 0.2^{o} of 12 GHz (50 fs rms).
- To achieve this, CLIC requires a drive beam "phase feedforward system" (PFF):
  - Measure the phase (time) of bunches along the drive beam pulse.
  - Drive kickers that alter the beam trajectory in a chicane, adjusting the time of flight and correcting the measured phase offset.
- Significant hardware challenge:
  - 30 MHz bandwidth
  - 500kW peak amplifier power.



Processor (JAI, Oxford University)

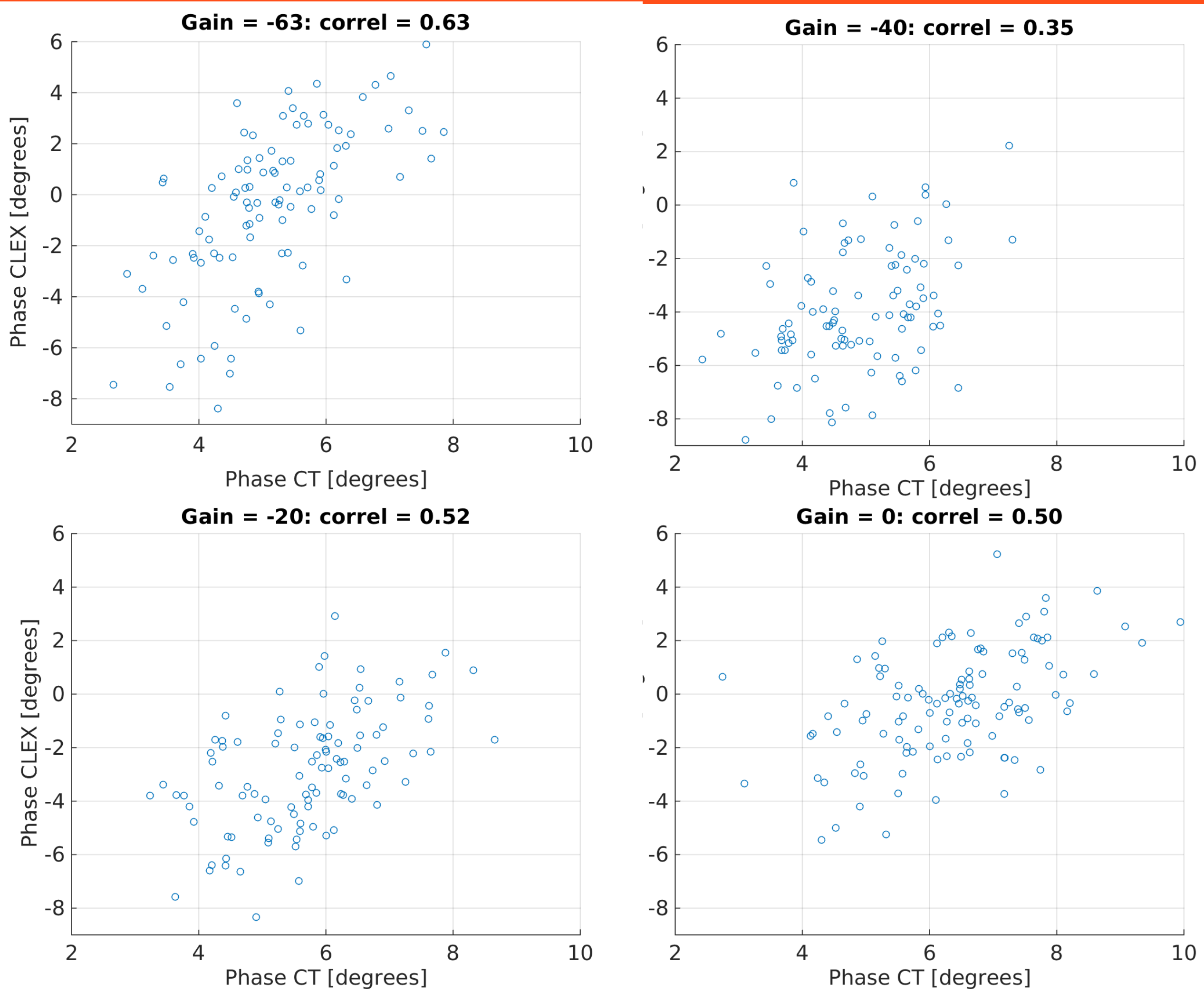
- The brain of the system:
  - Digitises the phase monitor signals.
  - Calculates necessary correction.
  - Drives kicker amplifiers.



- A custom digitiser and feed-forward controller based around a Xilinx Virtex-5 FPGA.
  - 9 analogue input channels.
  - Digitisation using 14-bit 400 MS/s ADCs.
  - 4 analogue output channels, using 14-bit 210 MHz DACs.

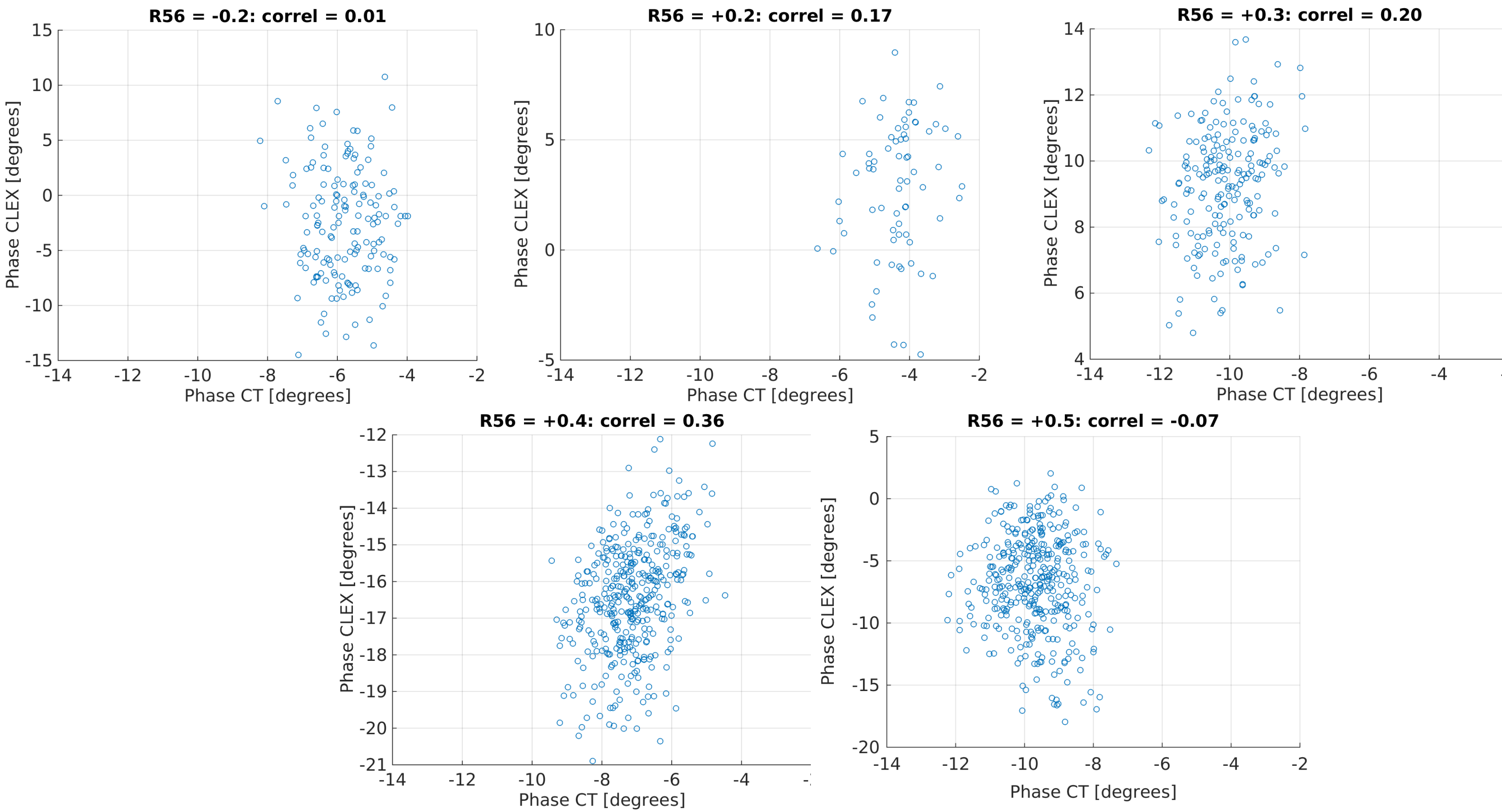
- Several changes implemented based on experience at CTF3:
  - Implemented IIR filters on ADCs and DACs to remove droop in response.
  - Firmware changes to allow additional feedforward gain.
  - Need to implement communication with the CERN control system.

Feedforward Gain Scan: Correlation



- Feedforward with negative gain amplifies correlation between CT and CLEX phase.

Scan of R56 in TL1: Correlation



- Correlation increases when R56 compensated.
  - But correlation is still low – must be sources other than energy.
- Used R56=+0.3 or R56=+0.4 in TL1 for FF tests.