22nd ATF2 Project Meeting
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FONT

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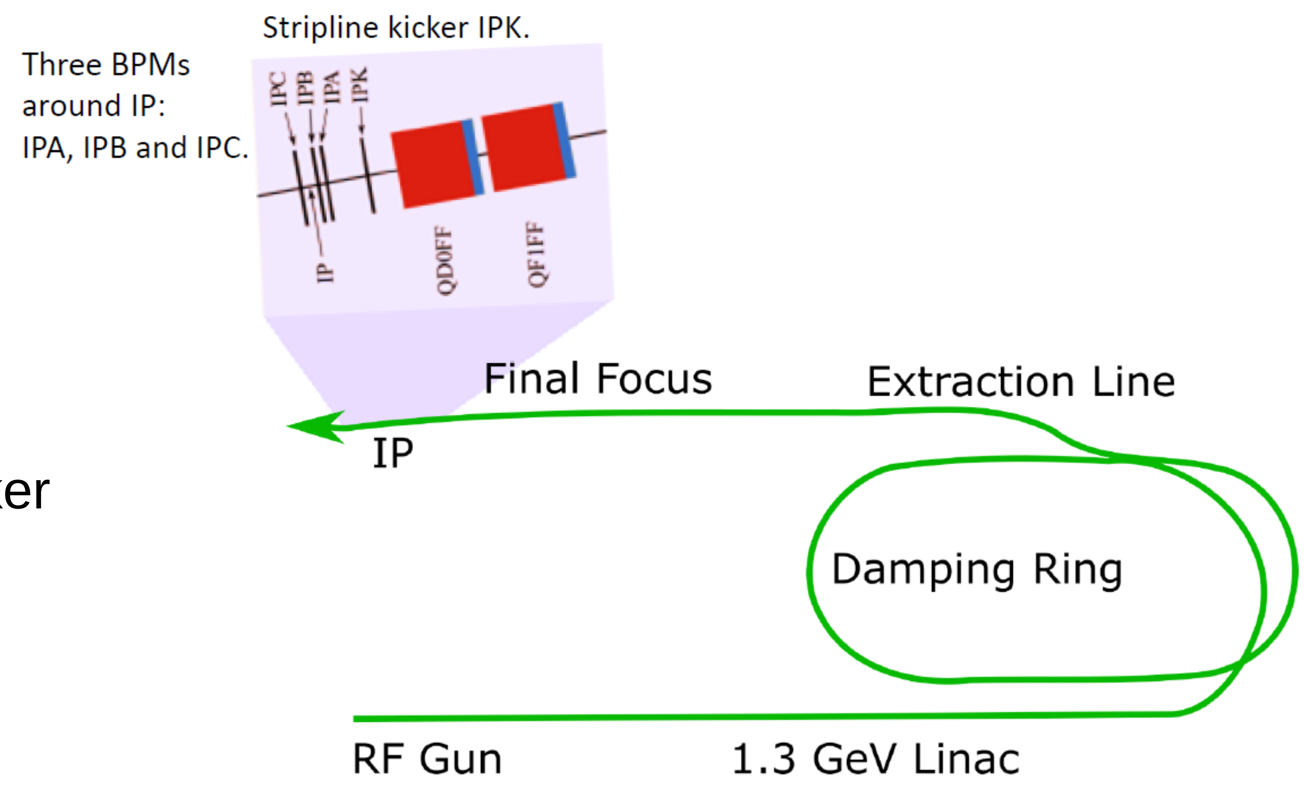
Contents

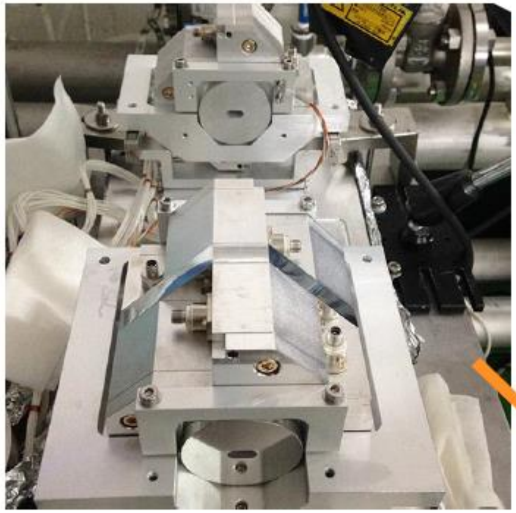
- FONT system and cavity BPM signal processing
- Recent beam stabilisation results
  - 1-BPM feedback
  - 2-BPM feedback
- Diode processor
- Latest studies: upstream feedback performance

Beam stabilisation at the IP

- Feedback system used to measure position offset of first bunch in train to provide stabilisation for second bunch
- Waveforms from low-Q cavity BPMs processed by custom FONT5A digital board to give position from which correction can be calculated
- Beam deflection applied by stripline kicker
- Uses bunch trains of two bunches with bunch spacing of ~280 ns

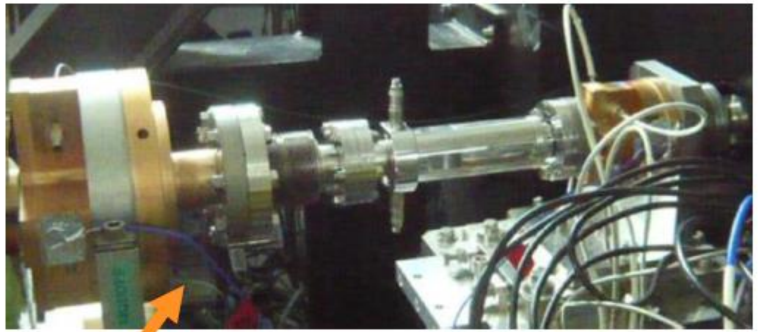


FONT IP feedback system

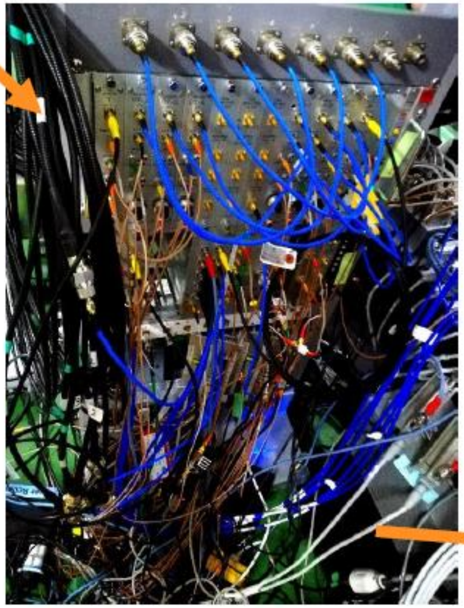


- Cavity Beam Position Monitors - IPA, IPB and IPC.
- We are now able to attenuate the three BPMs individually, allowing us to use all three BPMs while working in nominal optics.

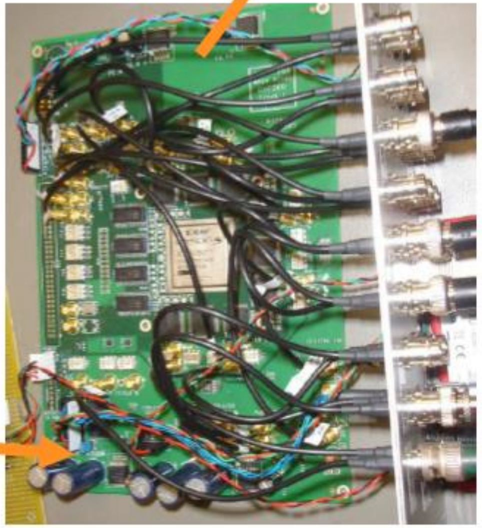
- Strip-line kicker and specialised amplifier used to provide correction.



- Two-stage processing electronics: down-mix and process cavity signals.

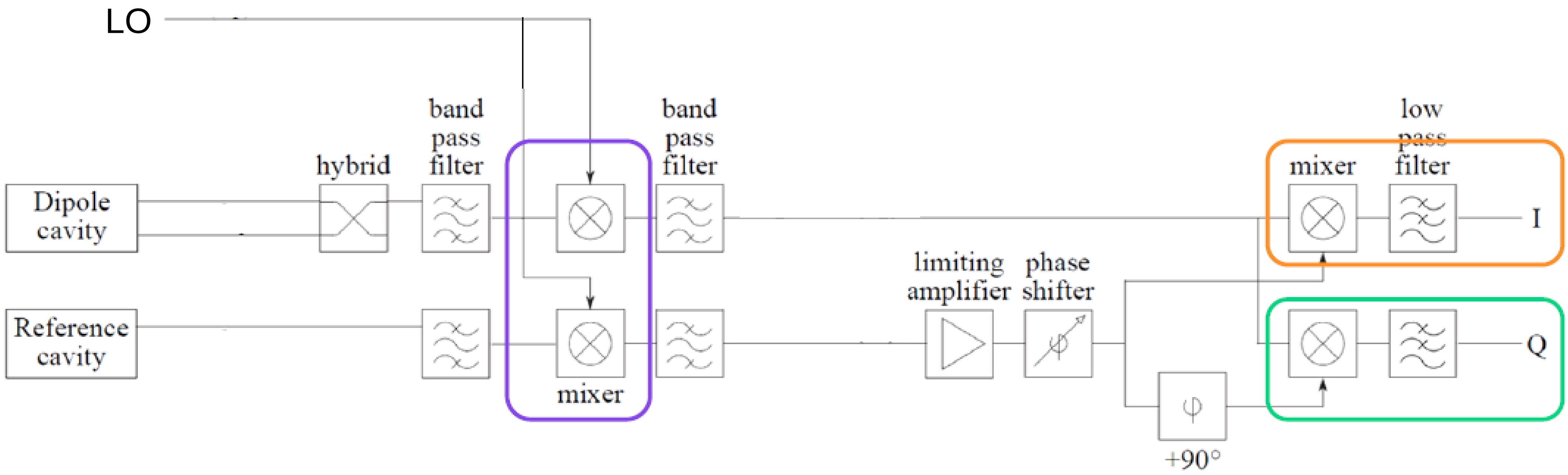


- The signals output from the processing electronics are sampled by the ADCs and used to calculate a bunch position.



- FONT 5A digital board.
- ADC inputs, DAC outputs.
- Contains a Field Programmable Gate Array (FPGA).

Cavity BPM signal processing



First stage (converter): dipole signals (position and charge dependent) and reference signal (charge dependent) down-mixed using a frequency-multiplied version of the DR LO

Second stage (detector): dipole signal down-mixed by the reference signal to form the I and by the reference signal with a 90° phase shift to form the Q

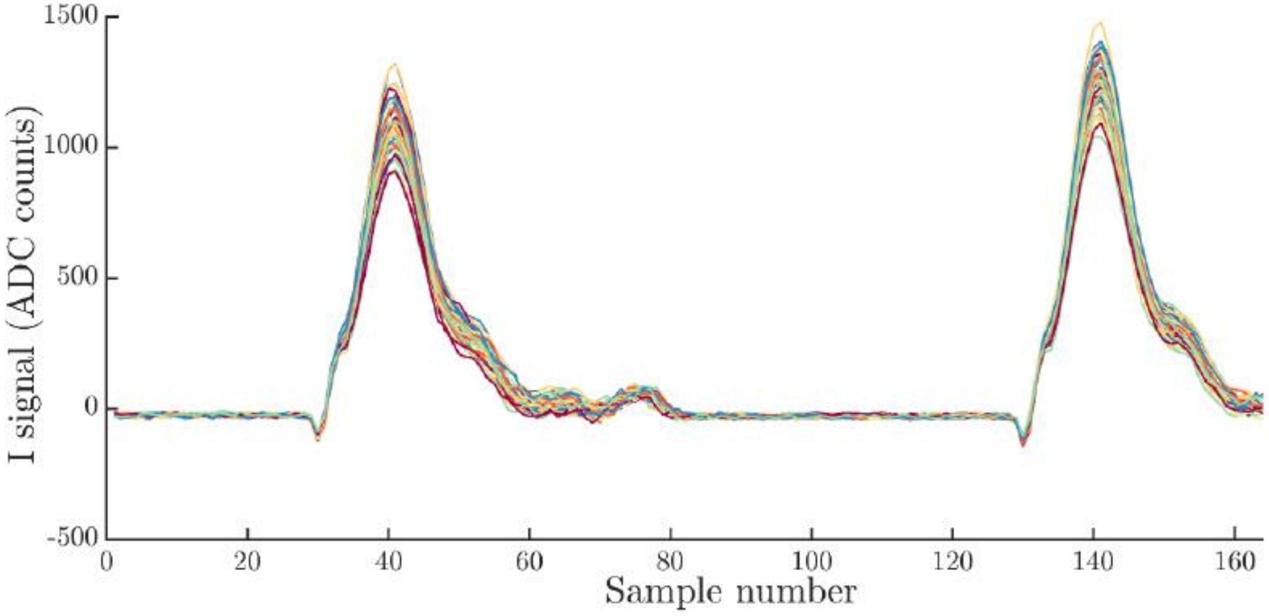
Bunch position given by $y = \frac{1}{k}(\frac{I}{q}\cos\theta + \frac{Q}{q}\sin\theta)$ where θ, k are calibration parameters

Measuring I and Q

Single sample vs. sample integration

- **Single sample:** I, Q and q values for a given bunch obtained from a single sample of the waveform.
- **Sample integration:** I and Q values obtained by integrating the waveform over a range of samples. This can improve the signal-to-noise ratio (and hence the resolution) of the position measurement.

Recent modifications to the FONT5A board firmware allow **feedback to be performed using sample integration** to calculate the position.

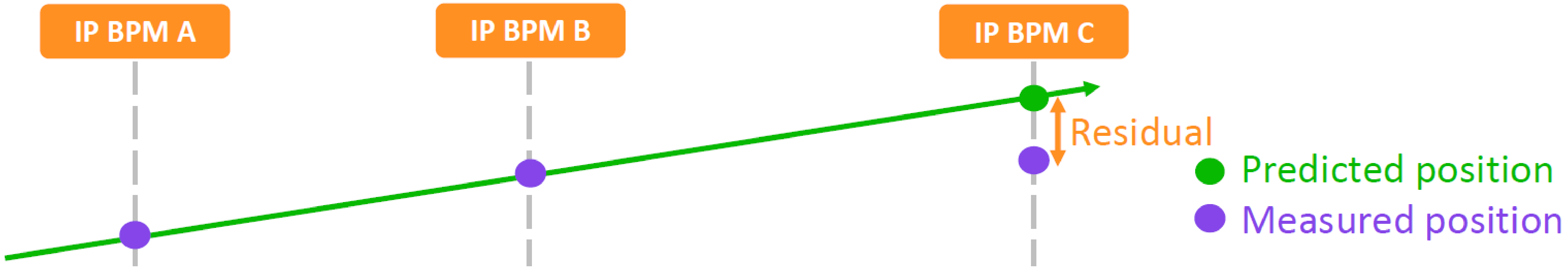


Example I signal waveform, in two bunch operation.

Calculating the resolution

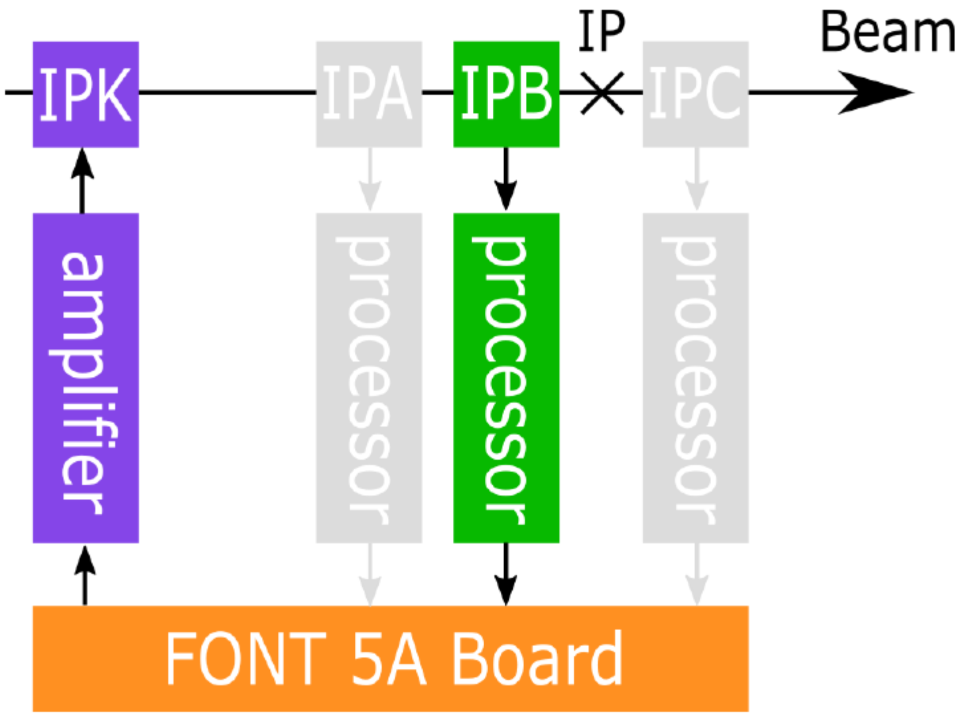
- Recent focus has been on improving the **usable resolution** of the system. The usable resolution applies to real-time position measurements used for feedback.
- Higher resolution can be achieved in off-line analysis by fitting bunch position as a function of additional parameters.

$$\text{residual} = y_{\text{pred}} - y_{\text{meas}}$$
$$\text{resolution} = \text{std}(\text{residual}) \text{ / geometric parameter}$$

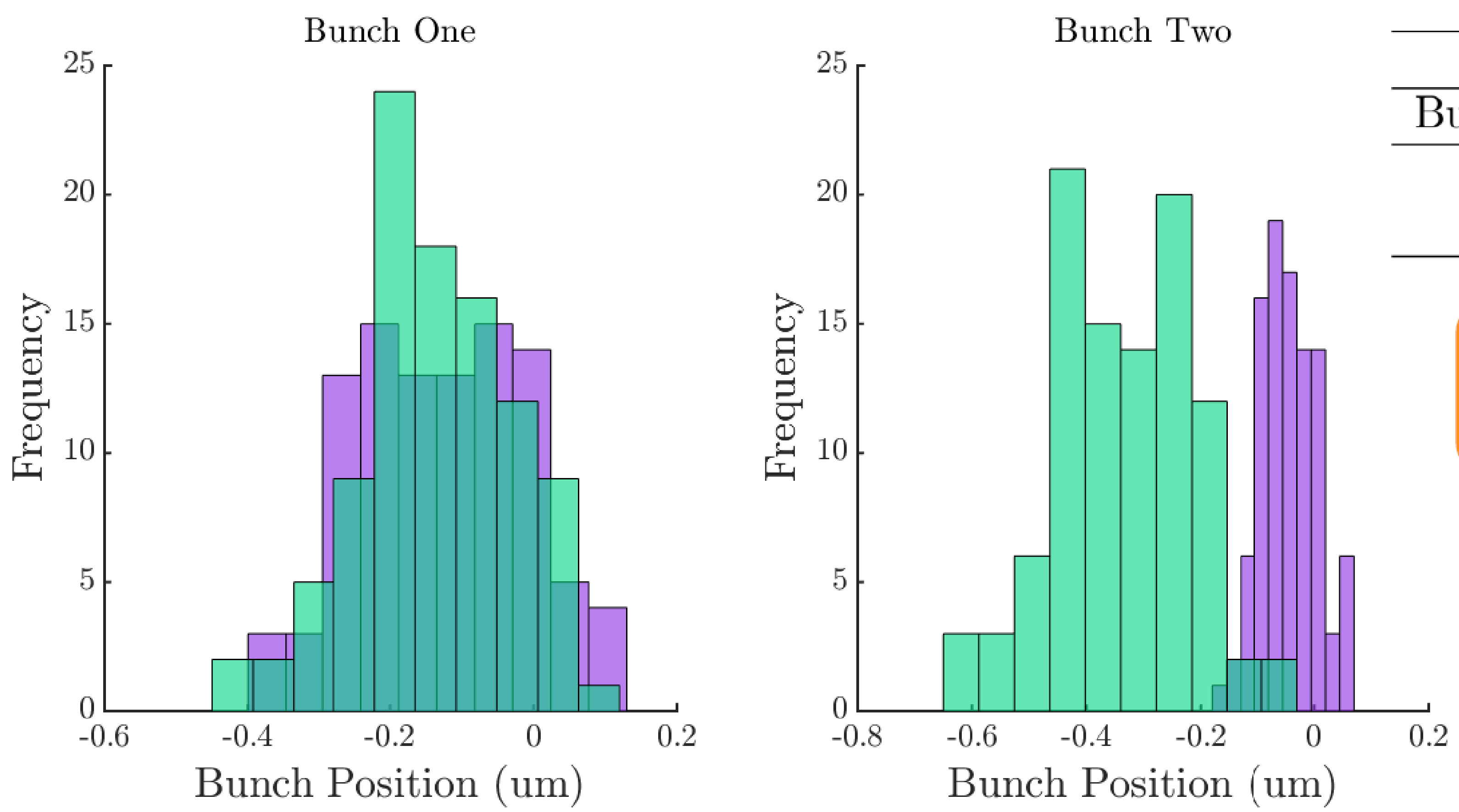


IP feedback results: 1-BPM mode

- Position measurements at one BPM are used to stabilise the beam locally
- Limit to feedback performance = $\sqrt{2} \times \sigma_{res}$
- Previous best stabilisation in single-sample 1-BPM mode = **74 nm**
- Consistent with a resolution of ~50 nm



1-BPM feedback results



	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4

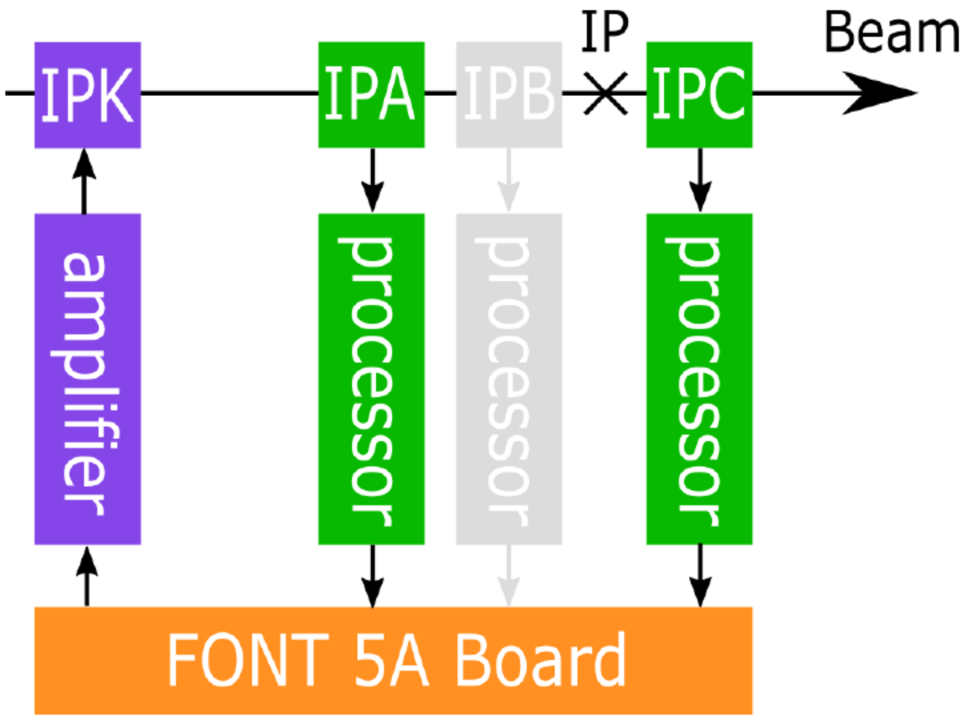
Feedback stabilising to:
50 ± 4 nm.

Feedback off correlation: **84%**
Feedback on correlation: **−26%**

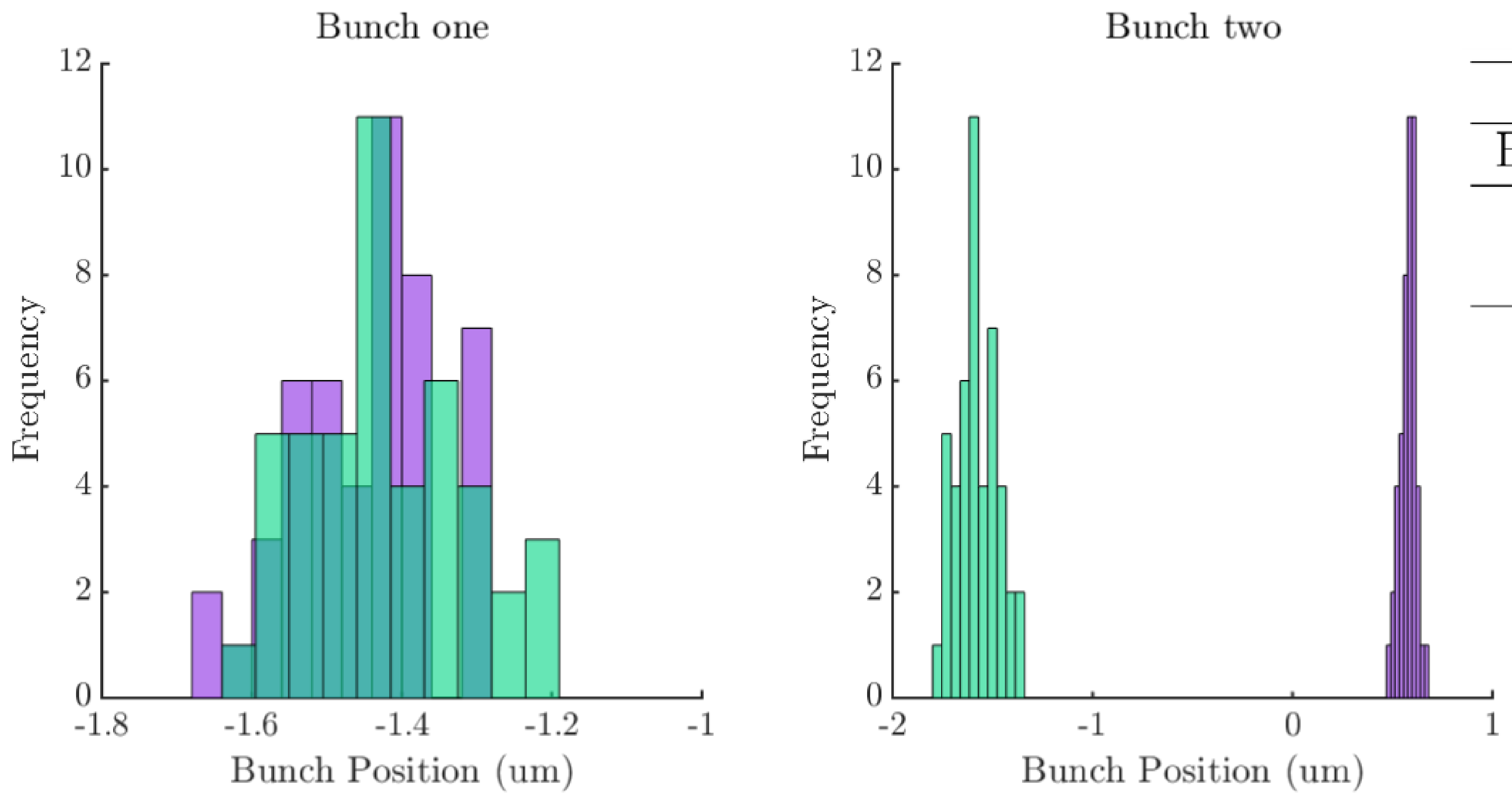
- 10 samples integrated.
- Stabilisation below 55 nm was repeatable.

IP feedback results: 2-BPM mode

- Beam position measurements at two BPMs are used to stabilise the beam at an intermediate location: in this case, bunch position at IPB interpolated from measurements at IPA and IPC
- Limit to feedback performance = $1.25 \times \sigma_{res}$
- Previous best stabilisation performance in single-sample 2-BPM mode = **68 nm**
- Consistent with a resolution of < 54 nm



2-BPM feedback results



	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	106 ± 16
2	96 ± 10	41 ± 4

Feedback stabilising to:
41 ± 4 nm.

Feedback off correlation:
91.6%

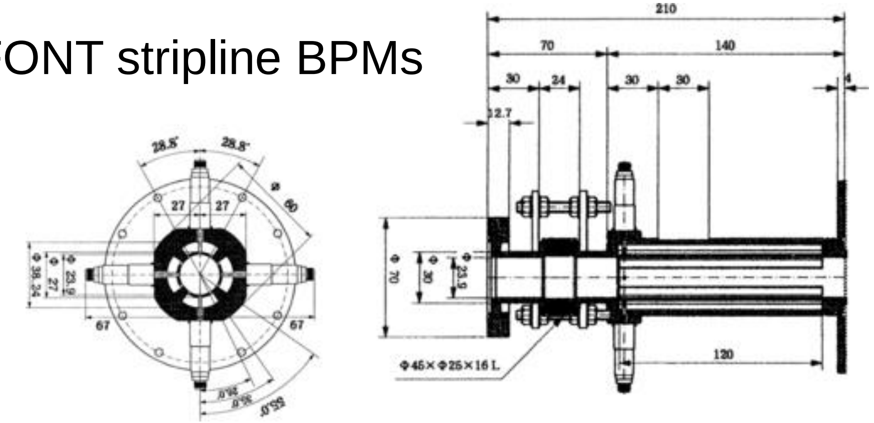
Feedback on correlation:
41.3%

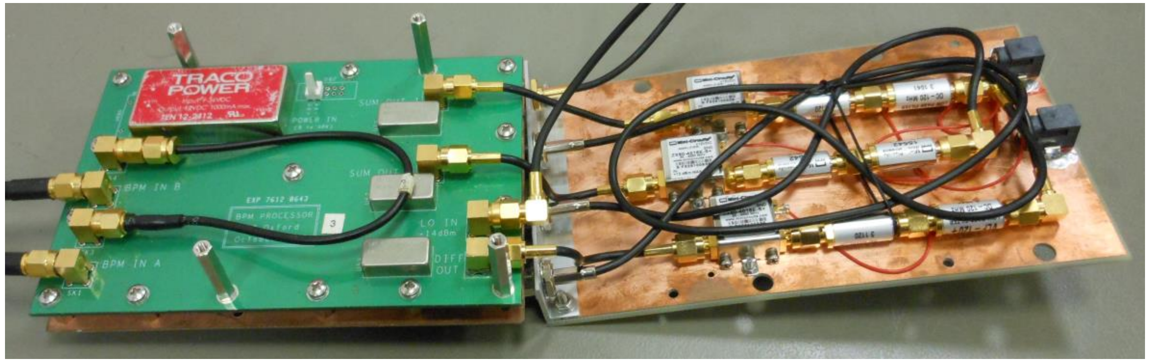
Beam stabilisation: summary

- 1-BPM mode
  - Previous best single-sample feedback:
    jitter of corrected bunch = **74 nm**
  - Reduced to **50 nm** (integrating 10 samples)
- 2-BPM mode
  - Previous best single-sample feedback:
    jitter of corrected bunch = **68 nm**
  - Reduced to **41 nm** (integrating 5 samples)

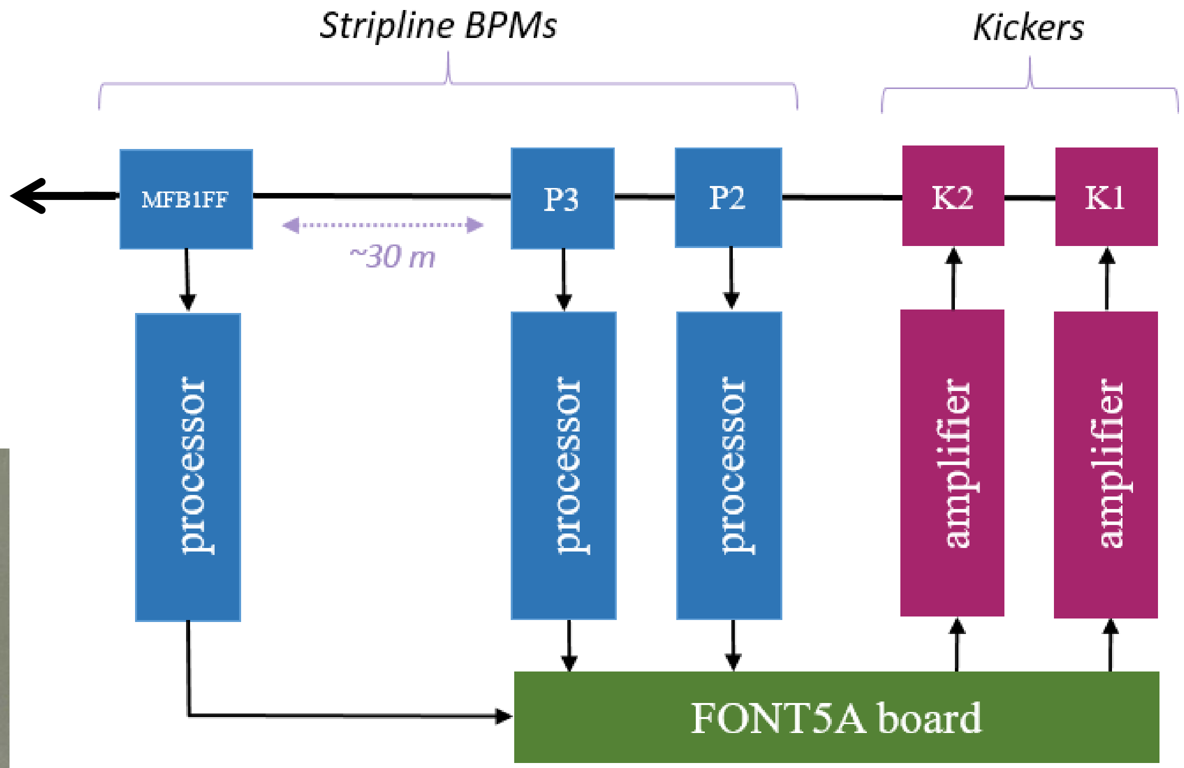
Upstream system: 2-BPM, 2-kicker

FONT stripline BPMs





FONT stripline BPM processors



Diode processor

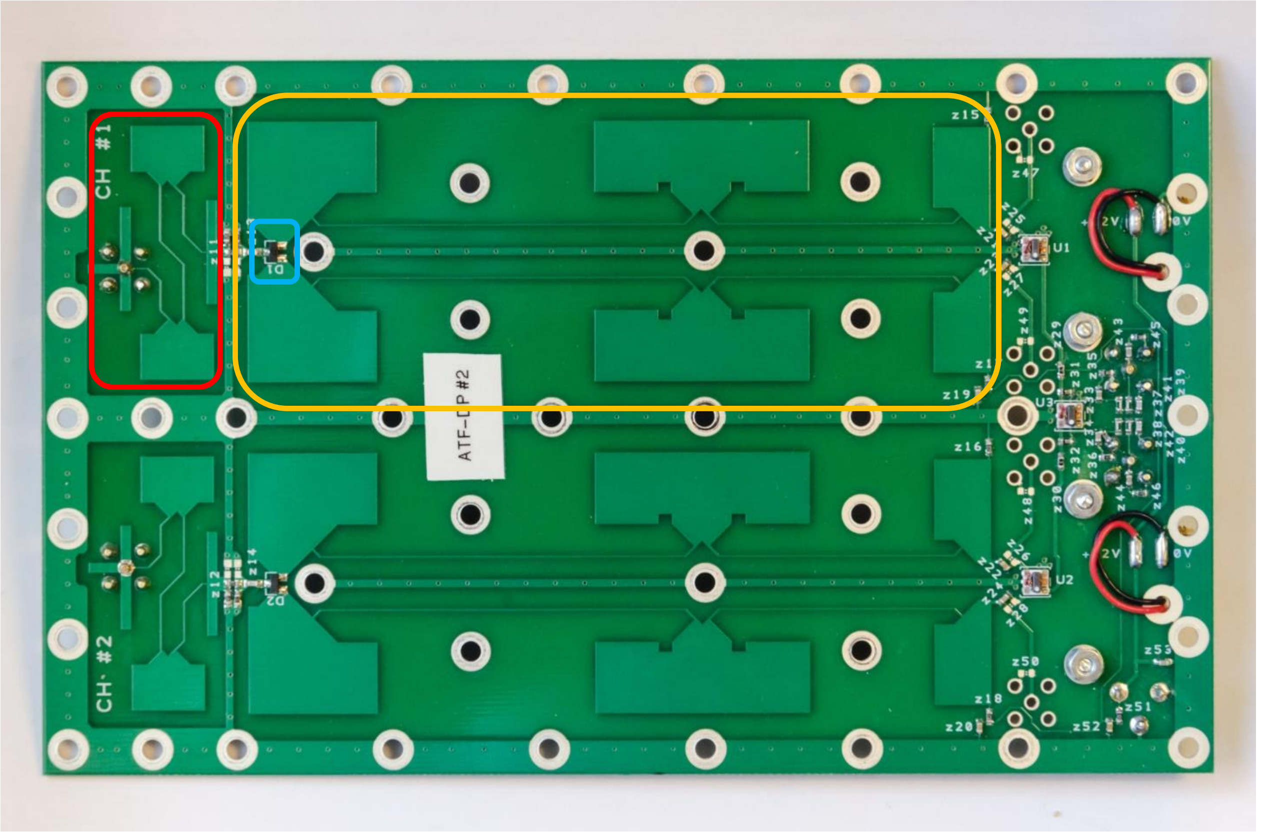
Motivation

- The Compact Linear Collider (CLIC) will require a beam position feedback system at the interaction point (IP)
- This will require a beam position monitor (BPM) with the following characteristics:
  - Low latency, simple, reliable, rad-hard, tolerant of high magnetic field (no ferrites!)
- These requirements are met by a stripline BPM used with the simplest possible processor: a diode detector on each strip

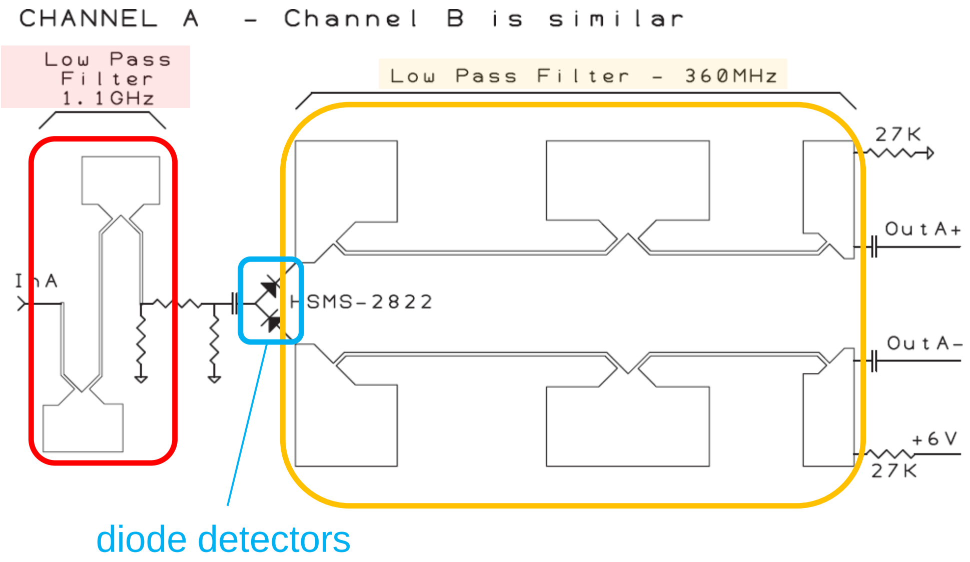
Design

- A prototype was constructed for testing at the KEK Accelerator Test Facility (ATF)
- Processor designed to scale up in frequency
- At CLIC processor outputs would be input to differential amplifiers
  - FONT5 digitizer at ATF unable to handle pulses this narrow due to 357 MHz ADCs, so supplement diode processor with an additional stage to condition signals

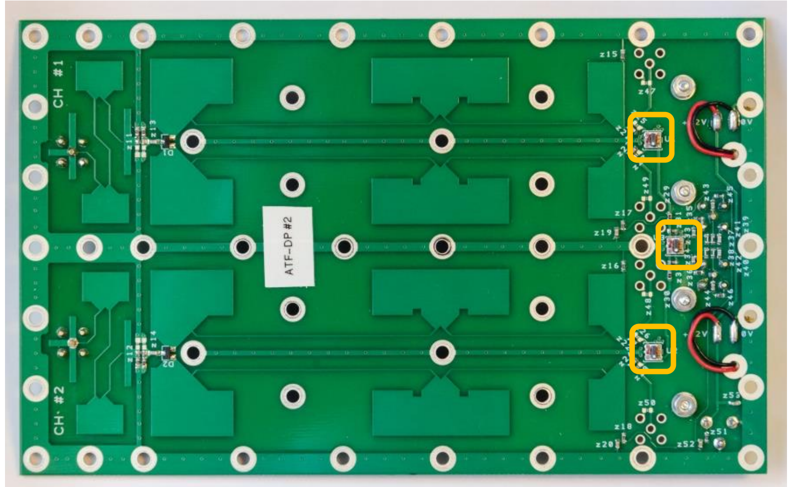
Diode processor schematic



- First microstrip LPF (1.1 GHz)
- Diode detectors
- Second microstrip LPF (360 MHz)

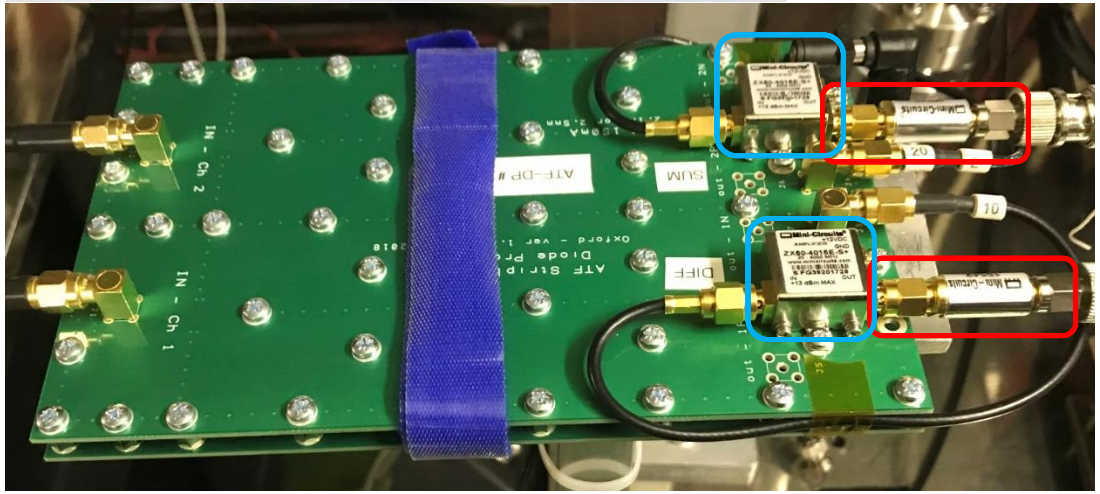


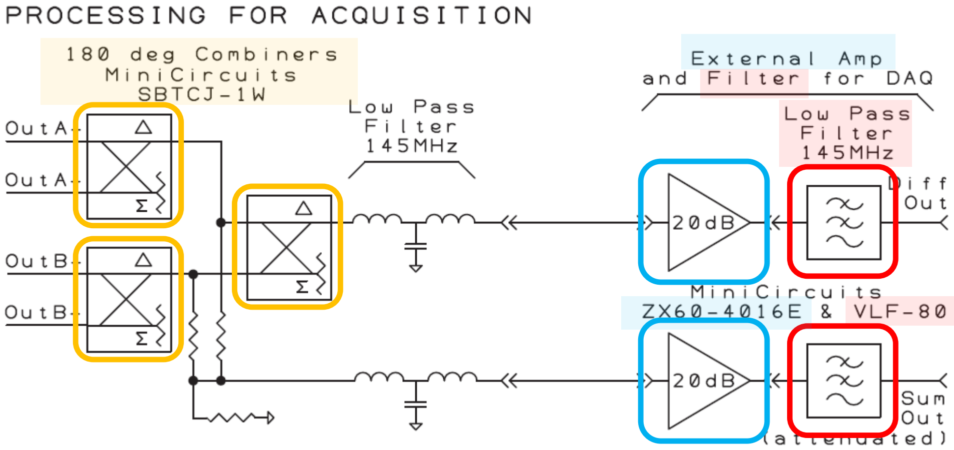
Supplemental stage schematic



- 180° combiners to form the difference of the two inputs
- Narrow LPF (145 MHz) to broaden the pulse
- External amplifier to suit digitizer sensitivity
- External LPF (145 MHz) to reduce amplifier noise

Reduced bandwidth widens output pulse but should not otherwise improve performance (for single bunch case at ATF)

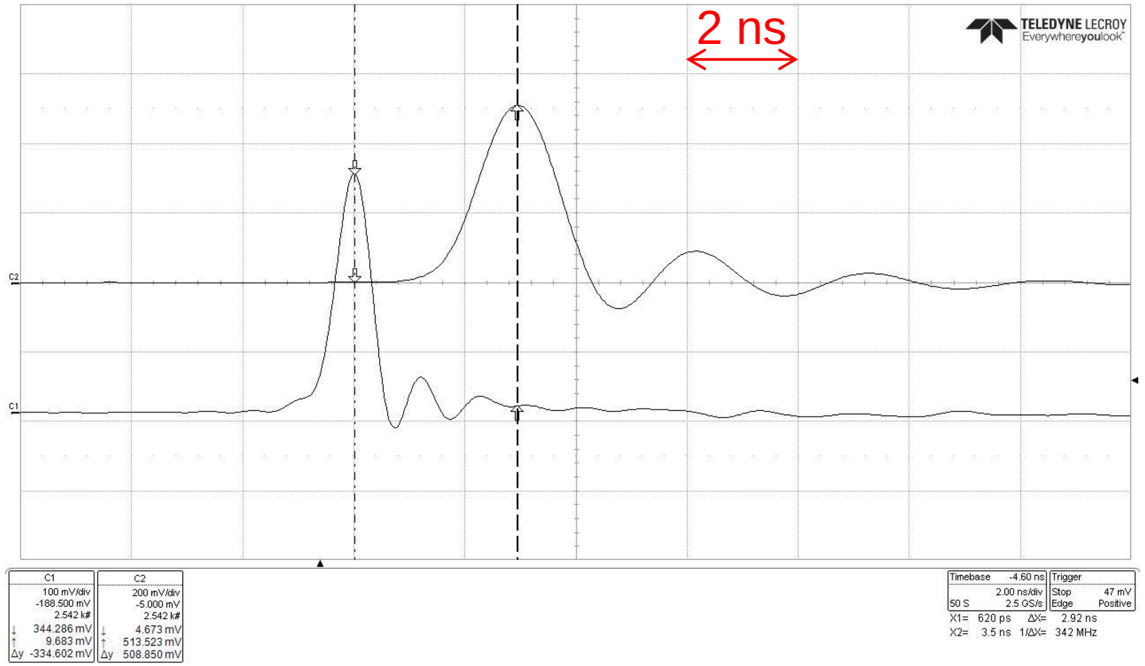




Diode processor latency

Extra processing adds a lot of latency

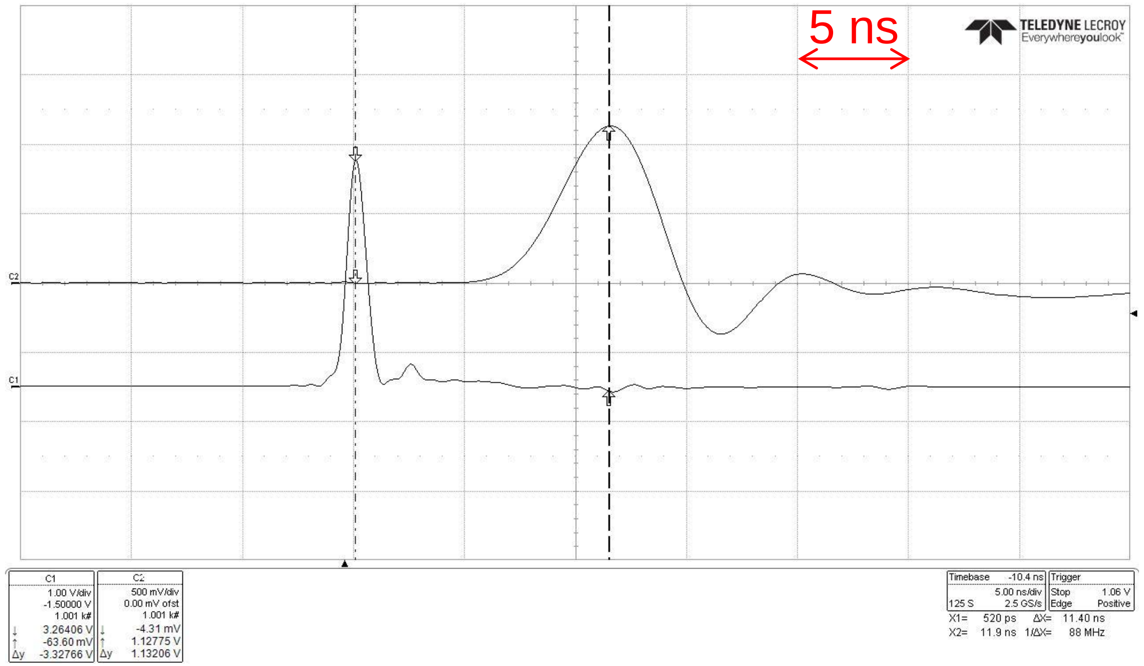
Pulse response after **diode processor**



Measured latency: **2.9 ns**

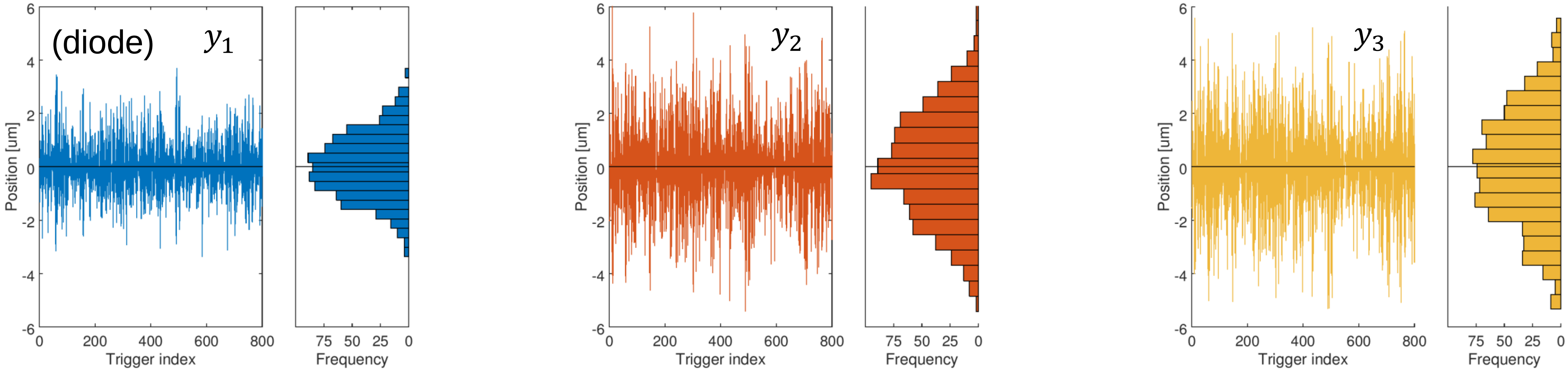
(would scale to ~1.0 ns for CLIC)

Pulse response after **supplemental stage**



Measured latency: **10.4 ns**

Diode processor resolution



- Define residual position at P1: $y_{res} = y_1 - (C_{12}y_2 + C_{13}y_3)$ (where C_{12}, C_{13} are geometric coefficients)
- Variance of residual given by weighted sum in quadrature of BPM resolutions: $\sigma_{res}^2 = \delta_1^2 + C_{12}^2\delta_2^2 + C_{13}^2\delta_3^2$
- Assume conventional processors have equal resolution ~ 200 nm* at relevant beam charge (0.65×10^{10})
- Estimated resolution of diode processor (with supplemental stage) is then ~325 nm

FONT stripline BPM resolution* (N. Blaskovic) ATF Operation Meeting **2 Dec 2016

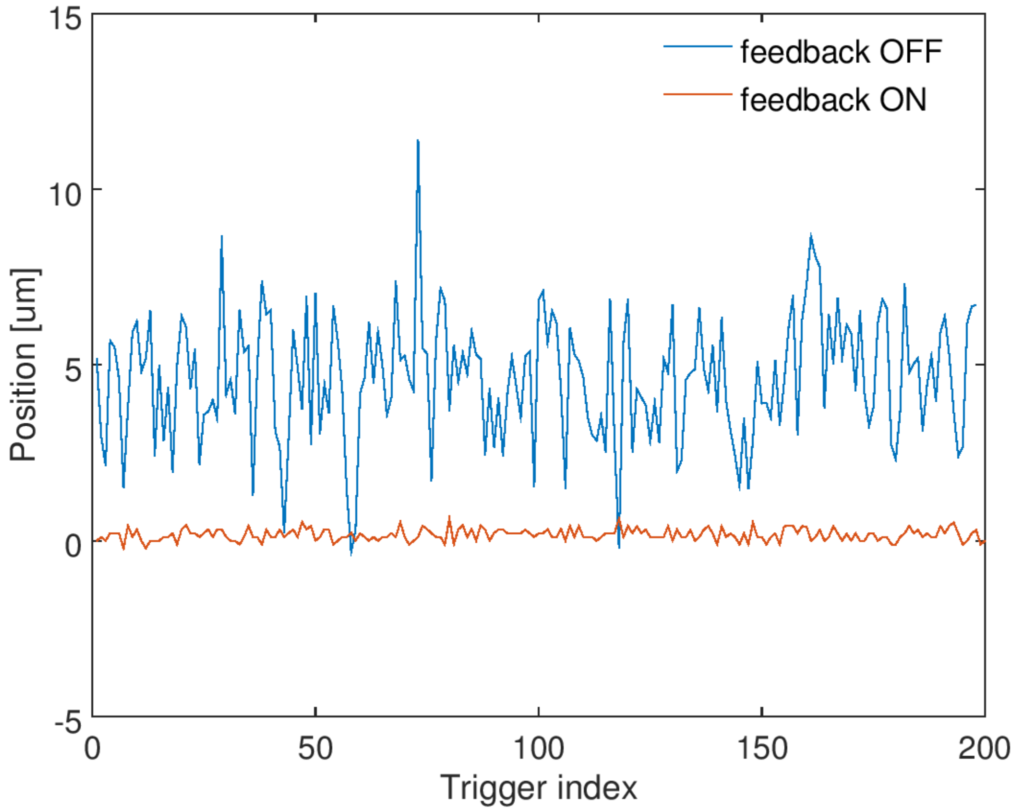
FONT studies: November 2018

- Nominal optics
  - Can IP system be aligned for second bunch with **upstream feedback** on?

- High-β optics
  - Does reducing phase jitter injected by the limiter improve resolution?
  - Resolution as a function of position and angle offset of BPM
  - Bunch to bunch correlation as a function of QD0FF current

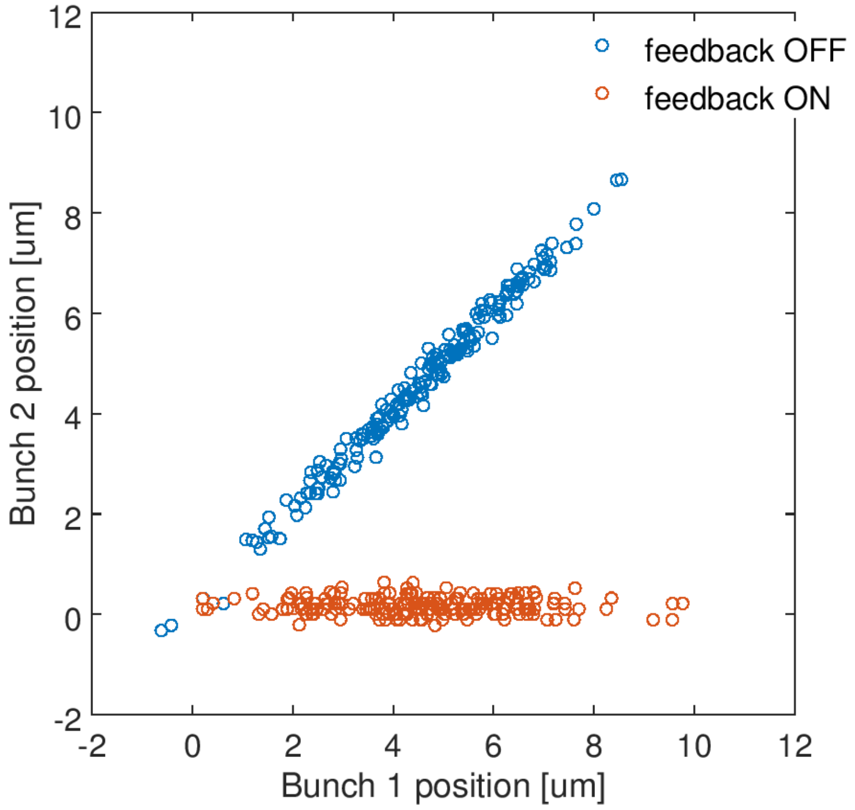
fbRun3, 07-Nov-18
interleaved feedback

Upstream feedback: P2



Position jitter of bunch 2
1.78 µm (feedback off)
0.17 µm (feedback on)

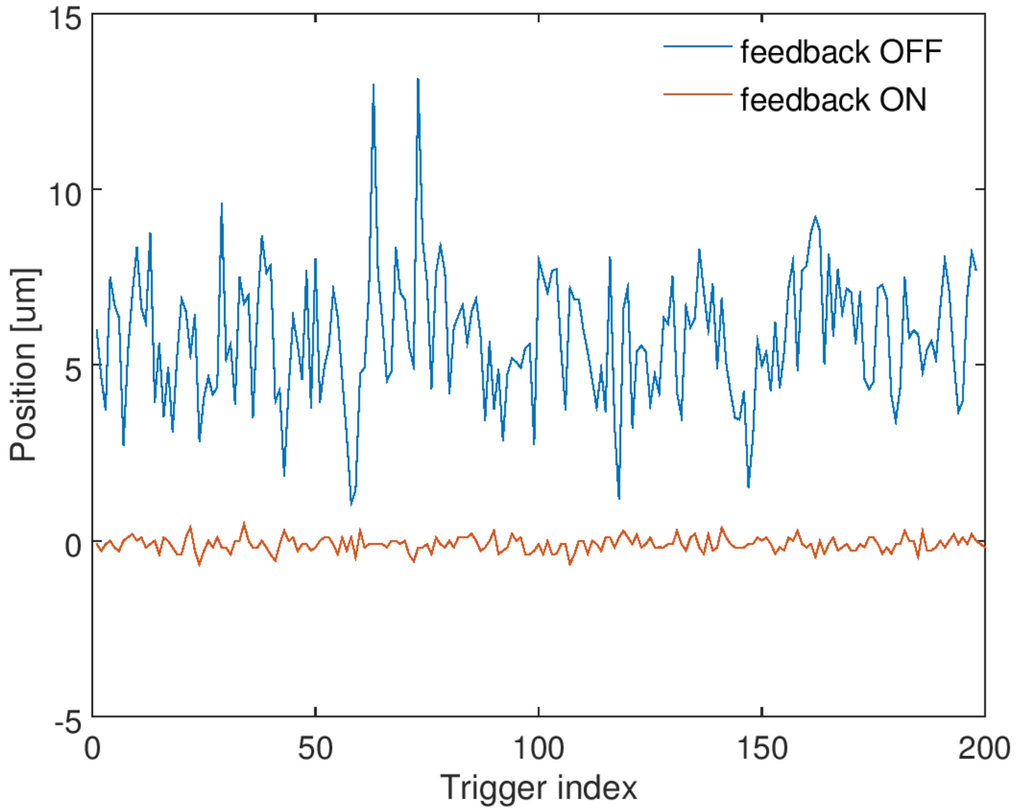
Reduction factor
= 10.5



Bunch-bunch correlation
0.994 (feedback off)
-0.035 (feedback on)

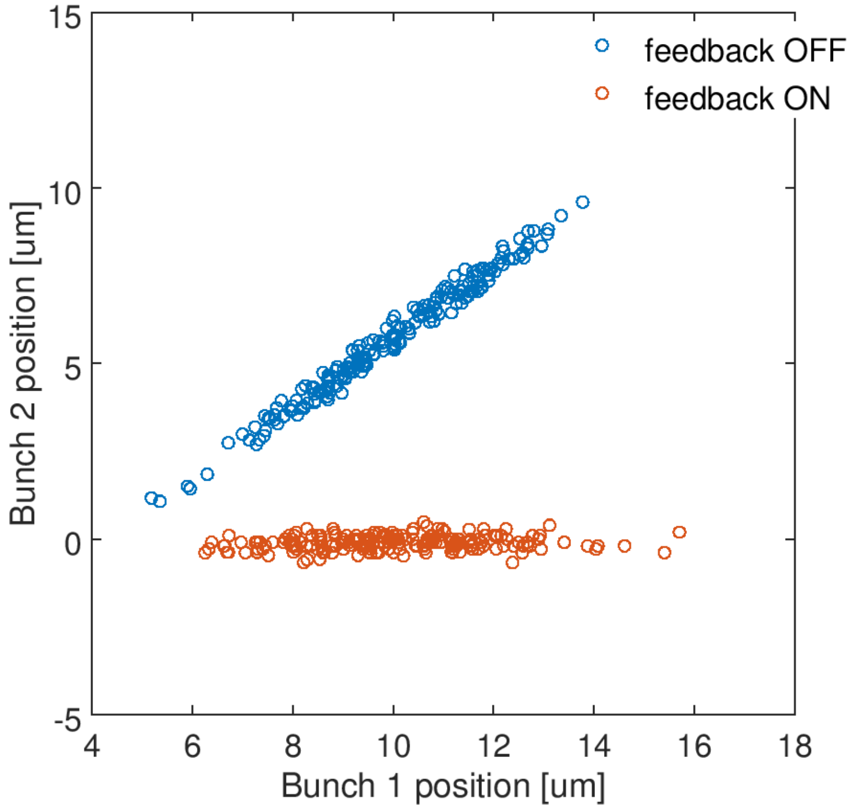
fbRun3, 07-Nov-18
interleaved feedback

Upstream feedback: P3



Position jitter of bunch 2
1.85 μm (feedback off)
0.20 μm (feedback on)

Reduction factor
= 9.1



Bunch-bunch correlation
0.992 (feedback off)
0.163 (feedback on)

Summary

- Implementing **sample integration** in the FONT5A firmware **improved performance** of the IP feedback system
  - Jitter of the corrected bunch reduced to **50 nm** (1-BPM)
41 nm (2-BPM)

- Proof-of-concept **diode processor** deployed at ATF and achieved:
  - Latency = **2.9 ns** (measured in the lab)
  - Resolution = **325 nm** (used with supplemental stage and existing FONT hardware)

- Recent measurements of the performance of the **upstream system** indicate that, for an extremely **high charge** and **well-tuned** beam,
  jitter at P2 and P3 can be reduced to **<200 nm** (**best ever result**)