Status of FONT IP Feedback

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ATF2 Project Meeting 2018, LAL, Orsay

Thursday, 22rd March 2018

Outline

FONT IP Feedback System and Recent Results

- FONT system and cavity BPM signal processing.
- Previous FONT IP feedback results and recent modifications to the FONT system.
- Recent beam stabilisation results: (ATF2 shifts - December 2017)
  - 1-BPM feedback,
  - 2-BPM feedback.
- Plans for future work.

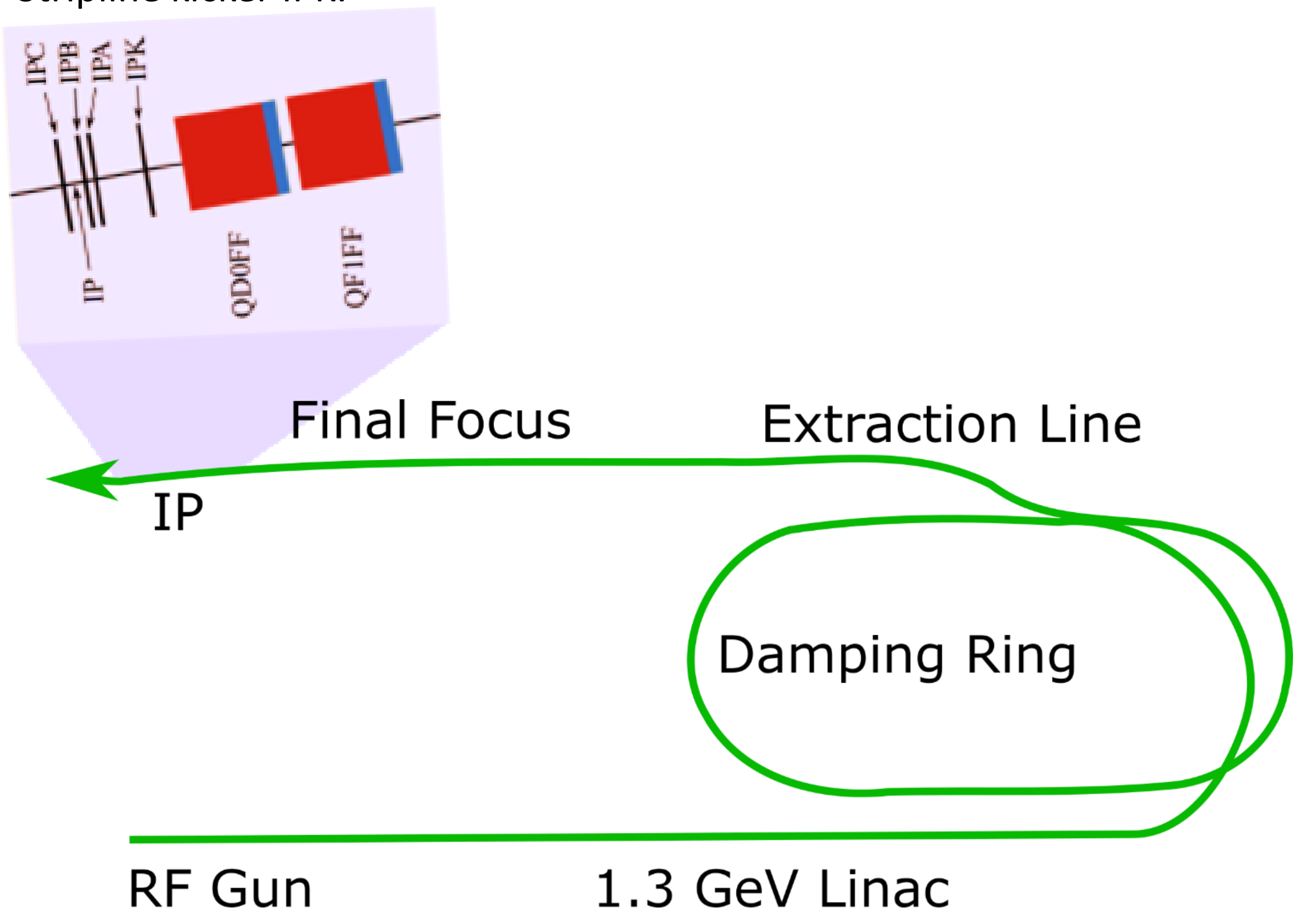
FONT IP Feedback System

Beam Stabilisation at the IP

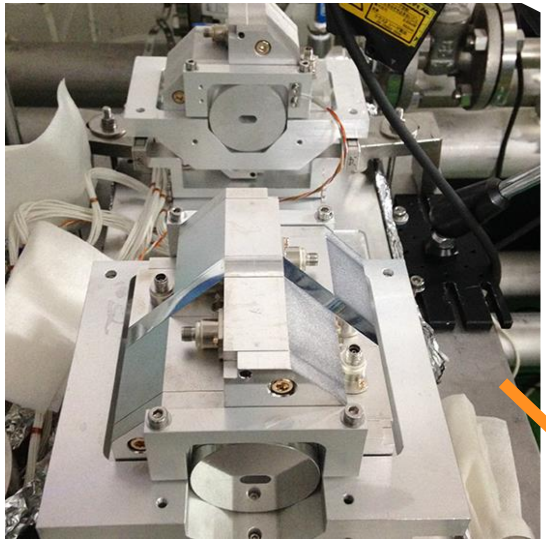
- Feedback system used to measure position offset of the first bunch in the bunch train to provide stabilisation for the second bunch.
- Position measurements made with BPMs and the feedback computation is performed on a specially designed FONT 5A digital board.
- Corrections applied by stripline kicker.
- Typically bunch trains of two bunches with bunch spacing of 280 ns.

Stripline kicker IPK.

Three BPMs around IP:
IPA, IPB and IPC.

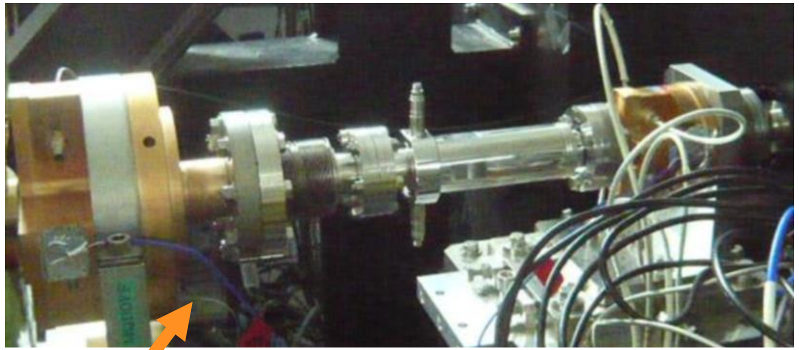


FONT IP Feedback System

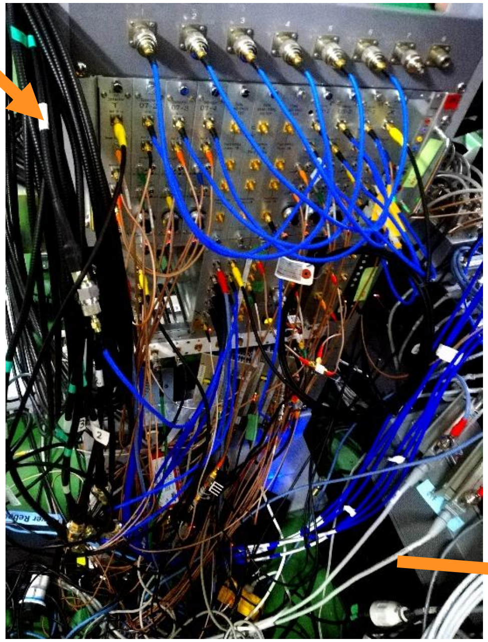


- Cavity Beam Position Monitors - IPA, IPB and IPC.
- We are now able to attenuate the three BPMs individually, allowing us to use all three BPMs while working in nominal optics.

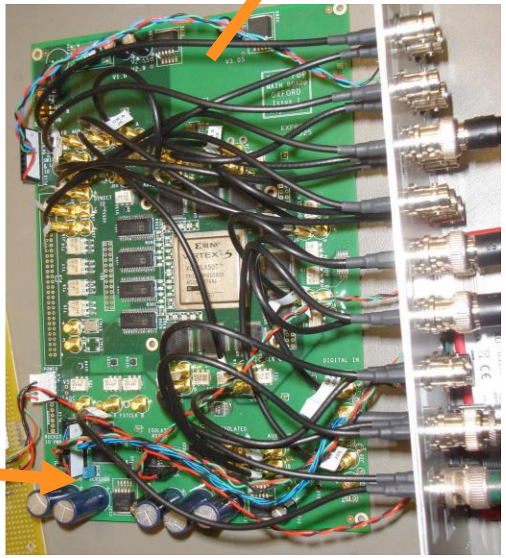
- Strip-line kicker and specialised amplifier used to provide correction.



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

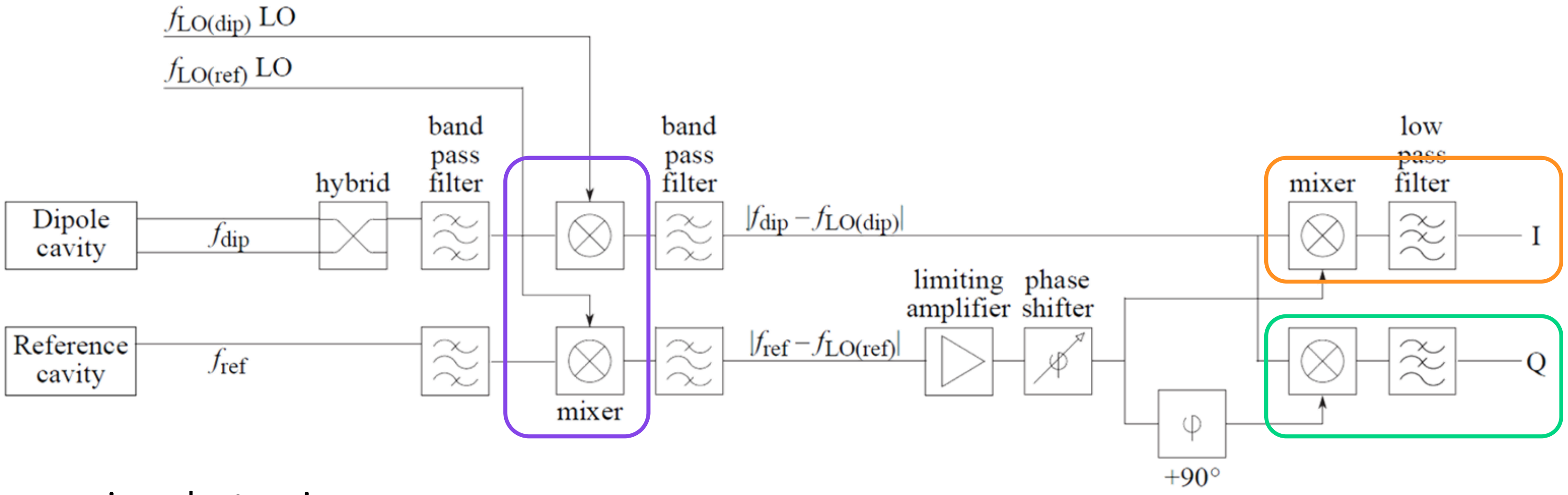


- The signals output from the processing electronics are sampled by the ADCs and used to calculate a bunch position.



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

BPM Signal Processing



First stage processing electronics

Dipole cavity signal: high-frequency signal dependent on position and charge, is down-mixed using $LO_{dip.}$

Reference cavity signal: charge dependent, high-frequency signal down-mixed using $LO_{ref.}$

Second stage processing electronics

Down-mixed dipole and reference signals are mixed in-phase to produce the I signal.

They are mixed in-quadrature to produce the Q signal.

These I and Q signals are used by the FONT 5A board to determine a bunch position: $y = \frac{1}{k}\left(\frac{I}{q}\cos\theta_{IQ} + \frac{Q}{q}\sin\theta_{IQ}\right).$

Where k and θ_{IQ} are determined through position calibration.

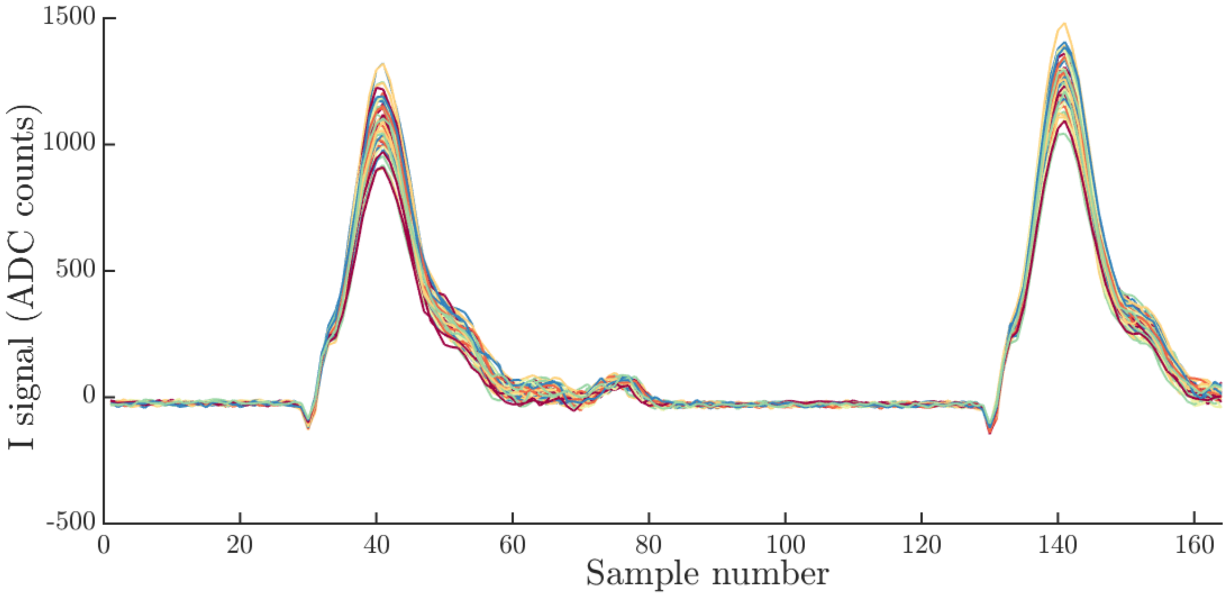
Figure from N. Blaskovic, DPhil. thesis

Terminology

Single sample vs. integrated sample

- **Single sample**: only single samples of the BPMs *I* and *Q* waveforms are used. Susceptible to thermal fluctuations.
- **Integrated sample**: integration over a multi-sample window is used (up to 15 samples), this can improve the signal-to-noise ratio of the position measurement and consequently, the resolution.

Developments to the FONT system allow for feedback using **multiple samples of the BPM waveforms**.

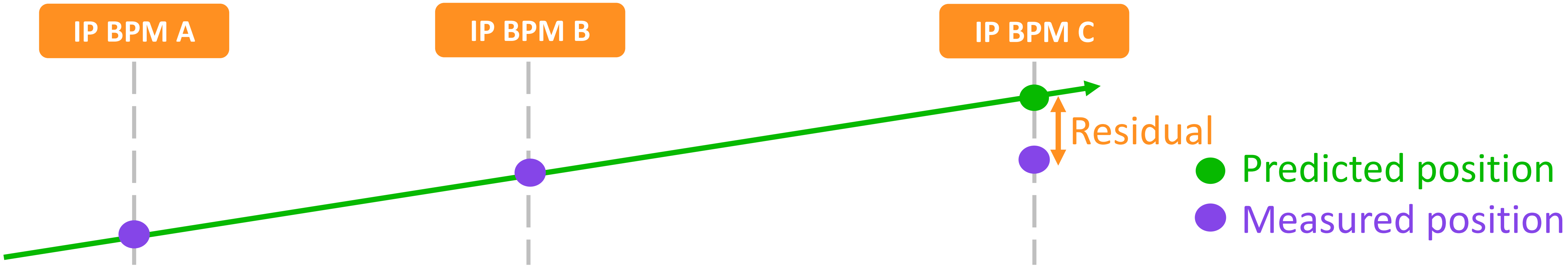


Example I signal waveform, in two bunch operation.

Calculating the Resolution

- Recent focus has been on improving the **useable resolution** of the system. The useable resolution represents the position measurements that can be made in real-time for feedback within the latency limits, set by the bunch spacing.
- We can achieve better resolution measurements in off-line analysis by **fitting** for the bunch position.
- The resolution which is relevant for feedback is the **geometric resolution** – determined using the distances between the BPMs.

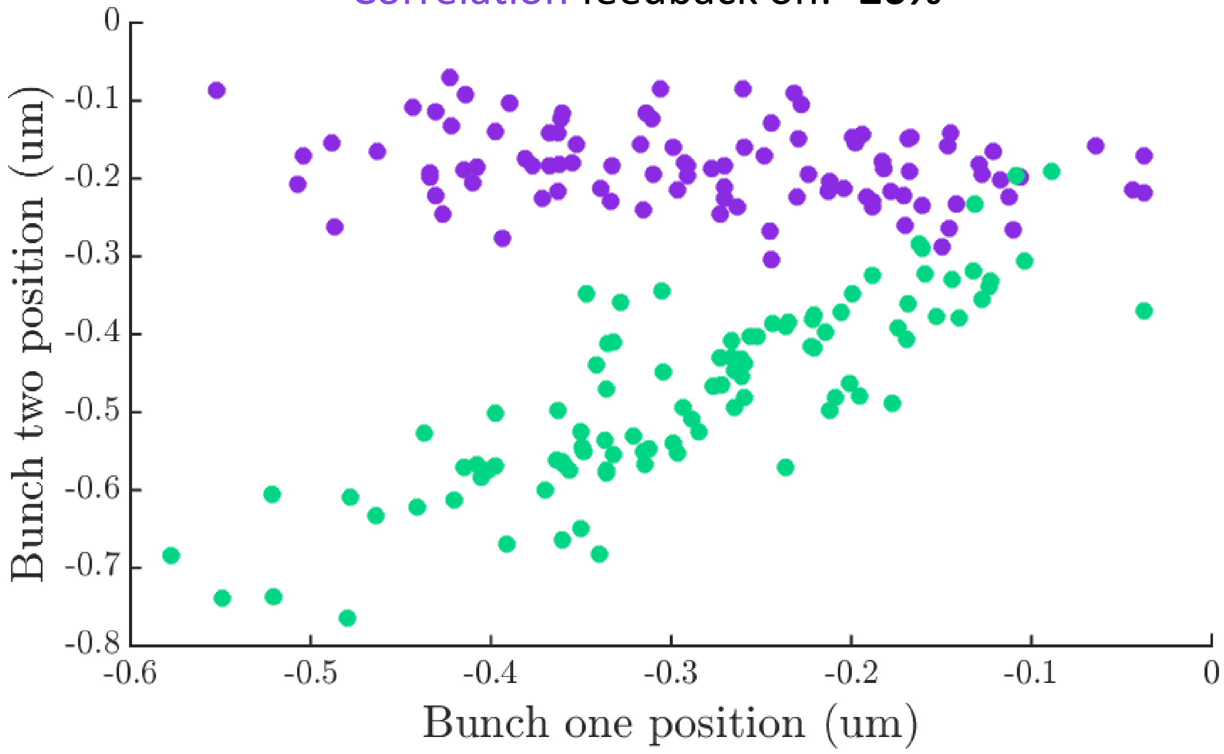
$$\text{residual} = y_{\text{pred}} - y_{\text{meas}}$$
$$\text{resolution} = \ \text{std}(\text{residual})$$



Optimising the Setup for Feedback

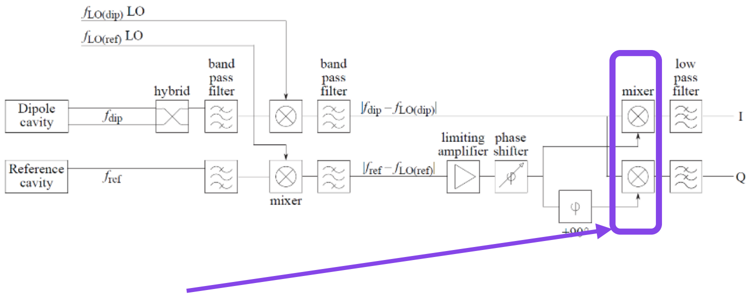
- For the best feedback performance, the ideal setup is where:
  - Bunch 1 and bunch 2 have equal position jitters.
  - Bunch 1 and bunch 2 positions are 100% correlated.
  - Resolution is optimised – align BPMs, sample window optimisation, increasing the bunch charge.
- For an imperfect bunch-to-bunch correlation, the feedback gains should be scaled.
- Both bunches should have similar charges so as to optimise the resolution for both bunches simultaneously.

Correlation feedback off: **84%**
Correlation feedback on: **-26%**

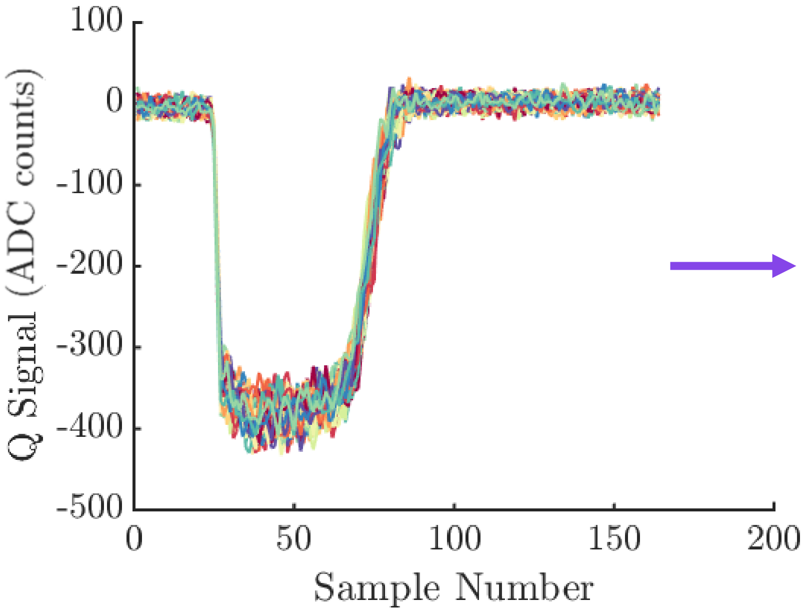


Bunch 1 position plotted against bunch 2 position to show the correlation between the two.

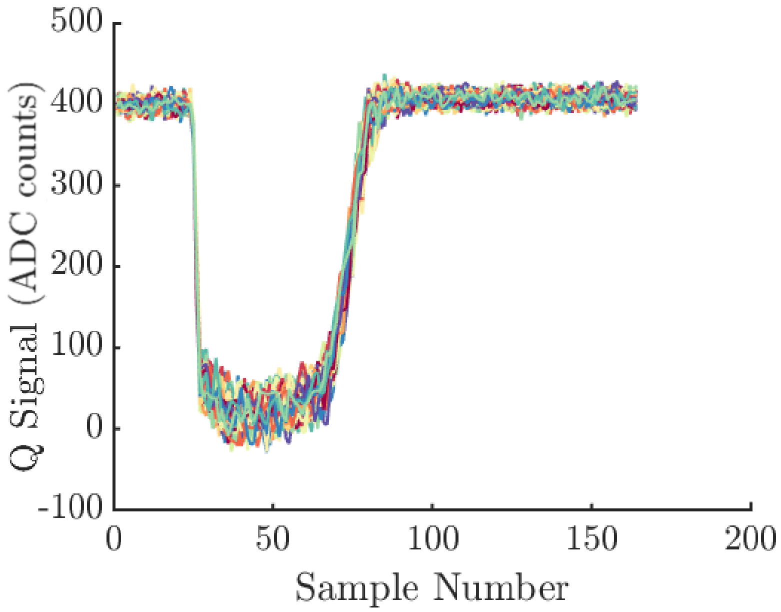
Removal of the I and Q Baseline



- The IQ mixer introduces an unwanted baseline signal which has no dependence on the bunch position.
- The baseline can be determined by heavily attenuating (70 dB) the dipole signal and measuring the remaining BPM waveforms.
- Modifications to the feedback algorithm in the firmware allow for this baseline to be subtracted from the samples used while performing feedback.



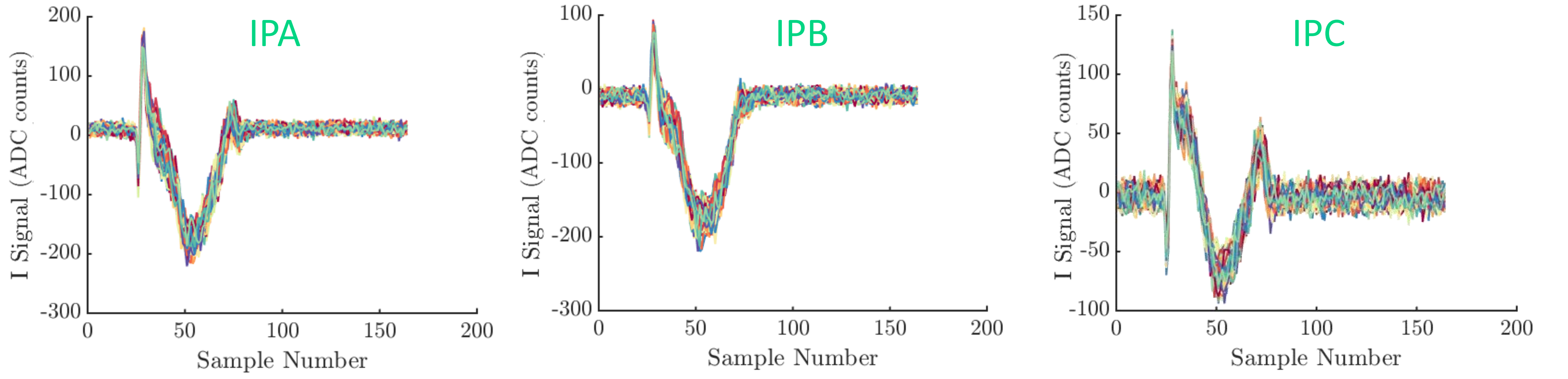
1-bunch IPA Q signal waveform with heavily attenuated (70 dB) position signal. Remaining signal is non position-dependent.

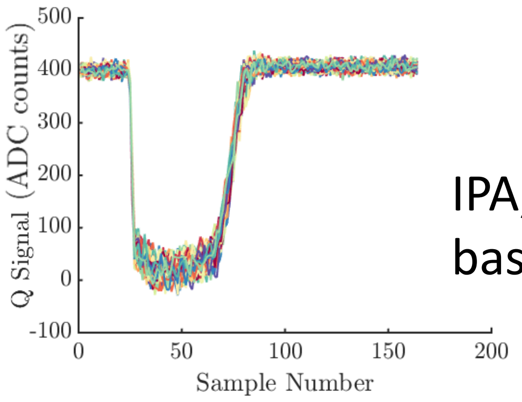


IPA Q waveform with baseline subtracted, so as to zero the samples to be used for feedback (samples 33 to 40) when no position signal is applied.

Non-Position-Dependent Baseline Signal

I signal baselines





IPA, Q signal baseline

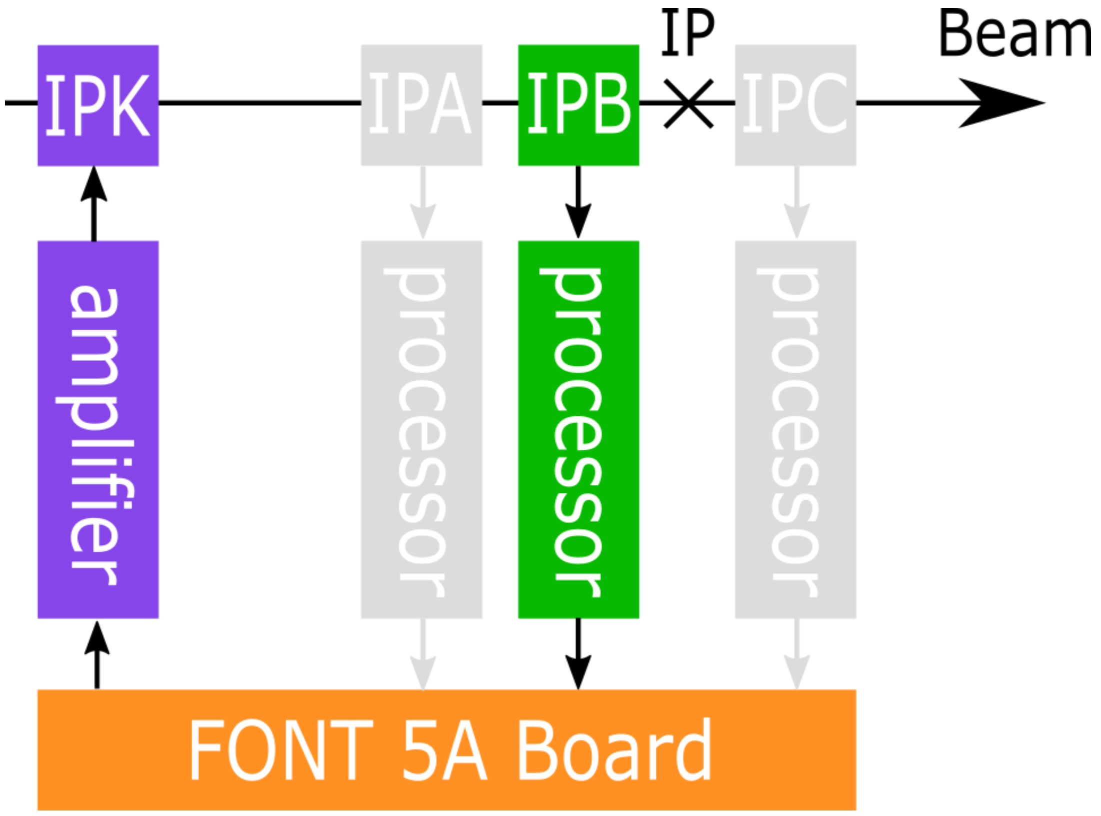
- The baseline signals introduced while mixing the dipole and reference signals are expected to be step functions.
- This is the case for the Q signal baselines (example shown left), but not the case for the I signal baseline (IPA, IPB, IPC shown above).
- Manually phase θ_{IQ} such that the position signal is in Q.

1-BPM Feedback Results

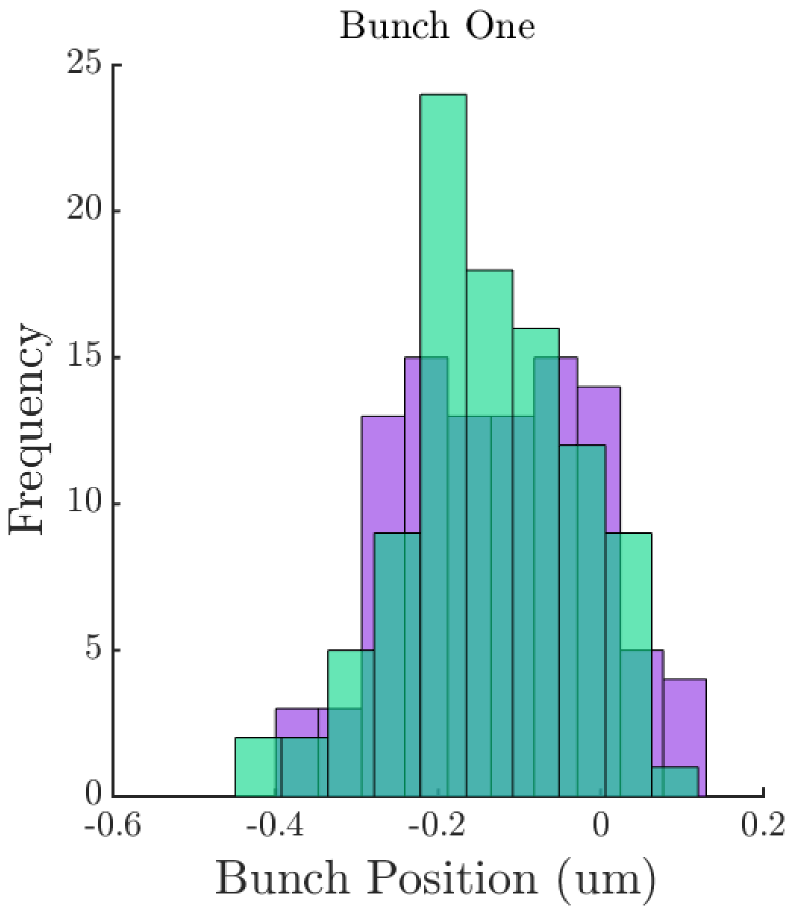
Dec 2017 – ATF2

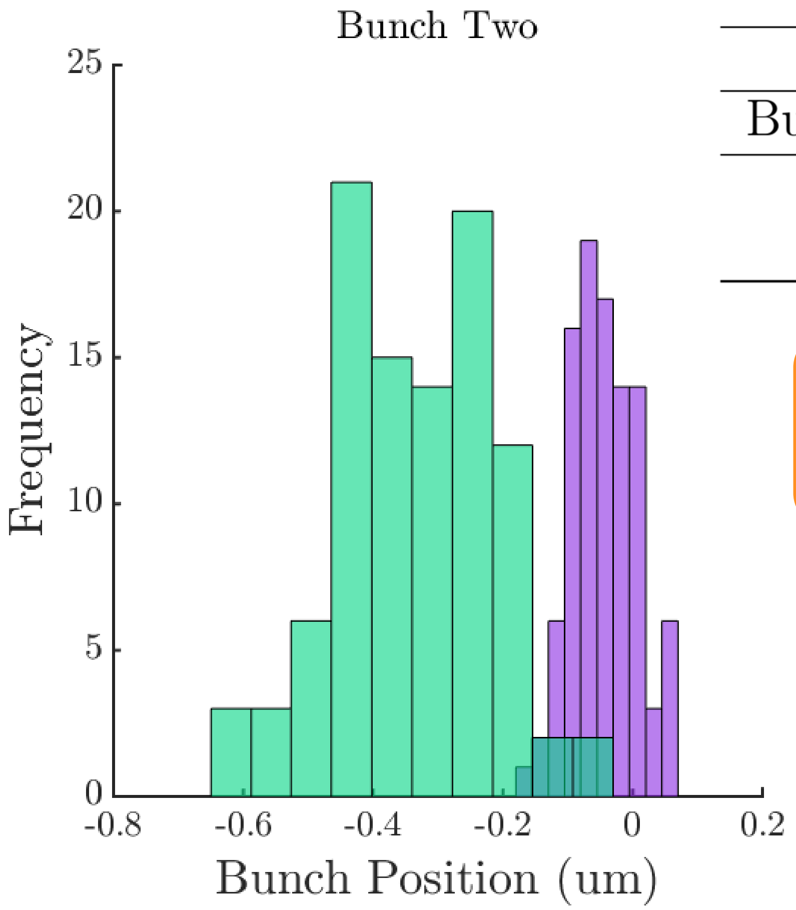
IP Feedback Results – 1-BPM Mode

- Position measurements at one BPM are used to stabilise the beam locally.
- Limit to feedback performance $=\sqrt{2} \times \sigma_{res}$, so it is clearly important to improve the resolution during feedback.
- Previous best stabilisation performance in single-sample 1-BPM mode = **74 nm**. This is consistent with a single sample resolution of approximately 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%**

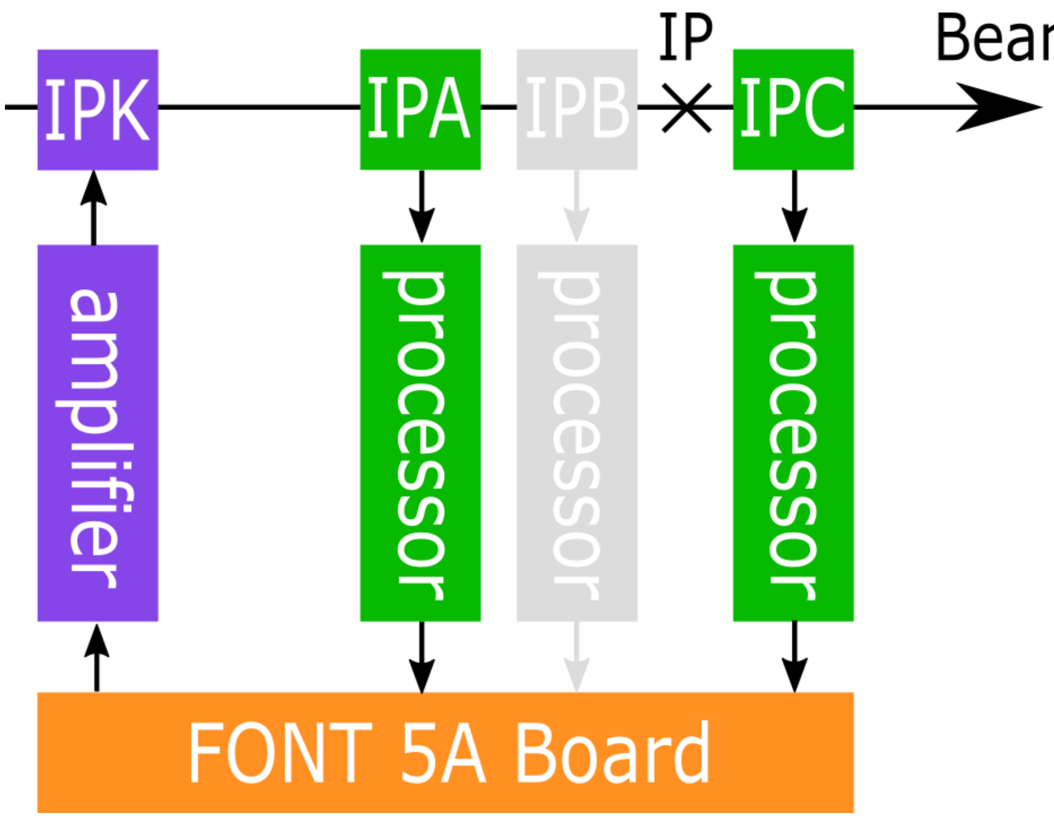
- 10 samples integrated.
- Stabilisation below 55 nm was repeatable.

2-BPM Feedback Results

Dec 2017 – ATF2

IP Feedback Results – 2-BPM Mode

- Beam position measurements made at two BPMs are used to stabilise the beam at an intermediate location.
- Bunch position at IPB is interpolated from measurements at IPA and IPC.
- Previous best 2-BPM single-sample feedback performance = **68 nm**.
- Limit to feedback performance in 2-BPM mode = $1.25 \times \sigma_{res}$.
- Single sample feedback performance is consistent with a resolution of < 54 nm.



Sample Integration and Resolution

- In 2-BPM feedback mode we could perform as well as stabilisation to: $1.25 \times \sigma_{res}$. With a resolution of 20 nm we could stabilise to: 1.25 x 20 = **25 nm**. With a resolution of 47 nm we could stabilise to: 1.25 x 47 = **59 nm**.
- We have been so far unable to reproduce such good resolution while performing feedback.

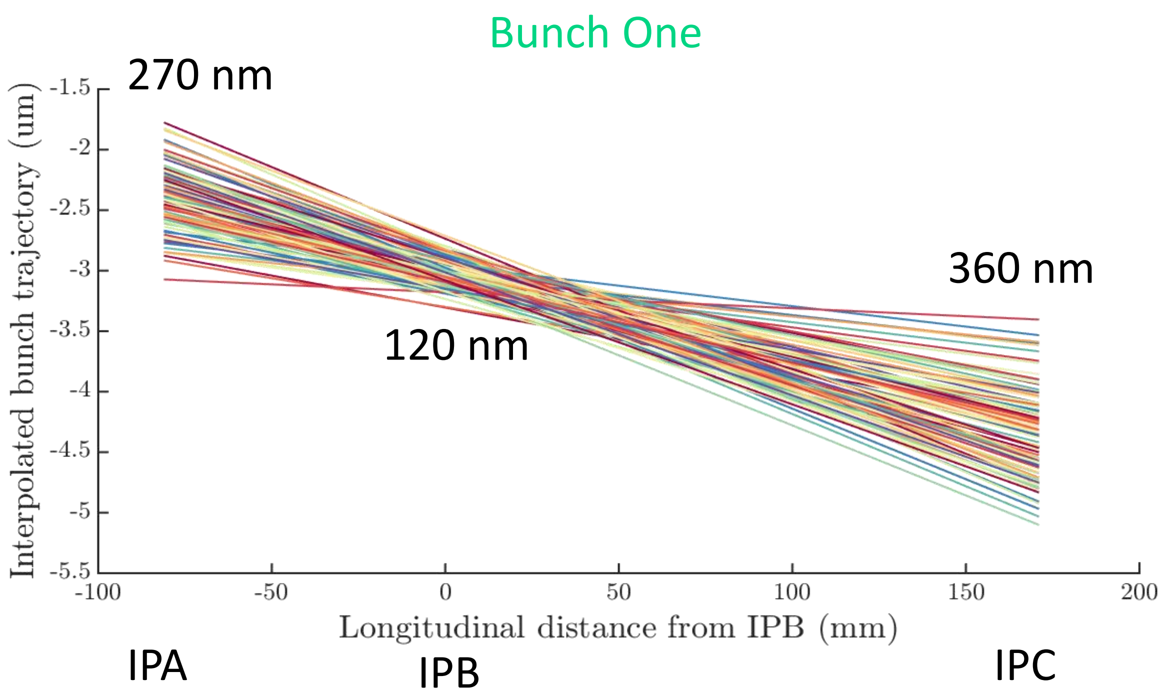
Geometric resolution – single sample (nm)	Geometric resolution – integrated (nm)
47	20

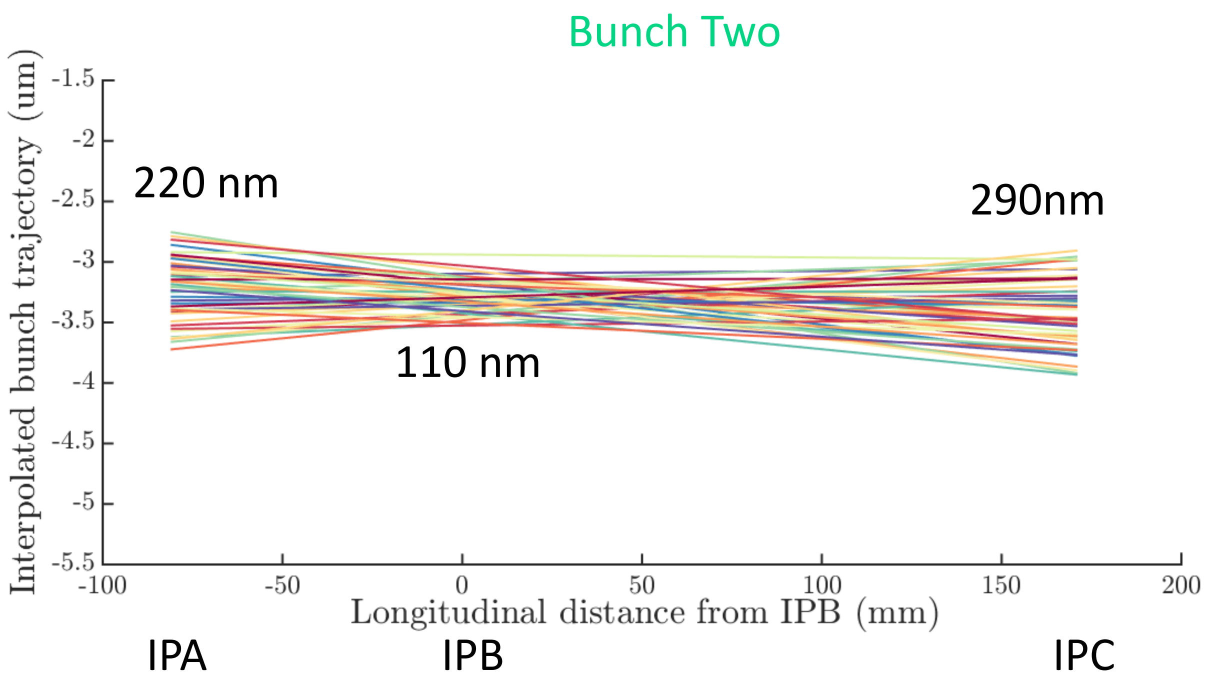
BPM	Fitting resolution – single sample (nm)	Fitting resolution – integrated (nm)
IPA	47	20
IPB	47	20
IPC	62	21

Data with thanks to T. Bromwich

High beta optics

- High beta optics (1000 times the nominal values of β_y^*).
- Data labels show position jitter at the three BPMs. Similar jitters for both bunches – as required for optimal feedback.
- Similar trajectories for both bunches, useful when dealing with the limited BPM dynamic ranges.
- Remaining waist placed near to IPB, the witness BPM in the feedback loop.
- Bunch trajectory shown is interpolated from measurements at IPA and IPC.

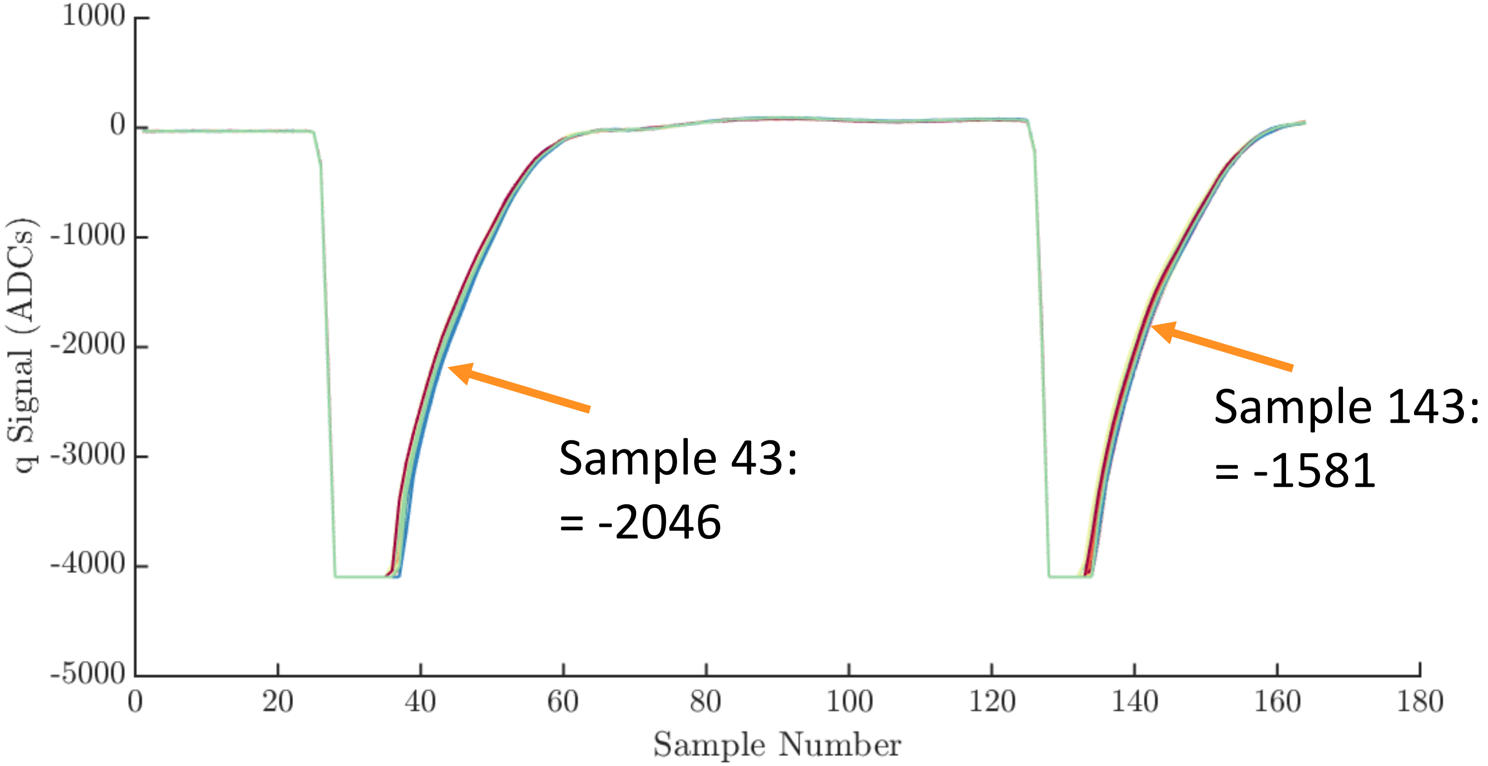




Resolution for December Shifts

- Bunch charge at reference samples used for feedback (43 and 143):
  - Bunch 1: -2046 ADCs
  - Bunch 2: -1581 ADCs
- Geometric resolution:
  - Bunch 1: 31 nm
  - Bunch 2: 39 nm
- Resolution scales **inversely** with charge: bunch two with a lower bunch charge has a correspondingly poorer resolution.
- Best achievable 2-BPM feedback performance with such a resolution is

  → $1.25 \times 31 = 39$ nm.
- Potential limitations when measuring feedback performance as the resolution of bunch 2 is similar to the potential level of stabilisation.



Best stabilisation vs. Expected stabilisation

- **Resolution limited** feedback performance = $1.25 \times \sigma_{res}$, achievable only with equal bunch-1 and bunch-2 jitters and 100% bunch-to-bunch position correlation. It is the best feedback performance achievable for a given resolution.

  The resolution limited feedback performance for this data set was 1.25 x 31 nm = 39 nm.

- **Expected feedback performance:** also taking into account the bunch-1 and bunch-2 jitters and the bunch-to-bunch position correlation.

$$\sigma_{Y_2}^2 = \sigma_{y_1}^2 + \sigma_{y_2}^2 - 2\sigma_{y_1}\sigma_{y_2}\rho_{12}$$

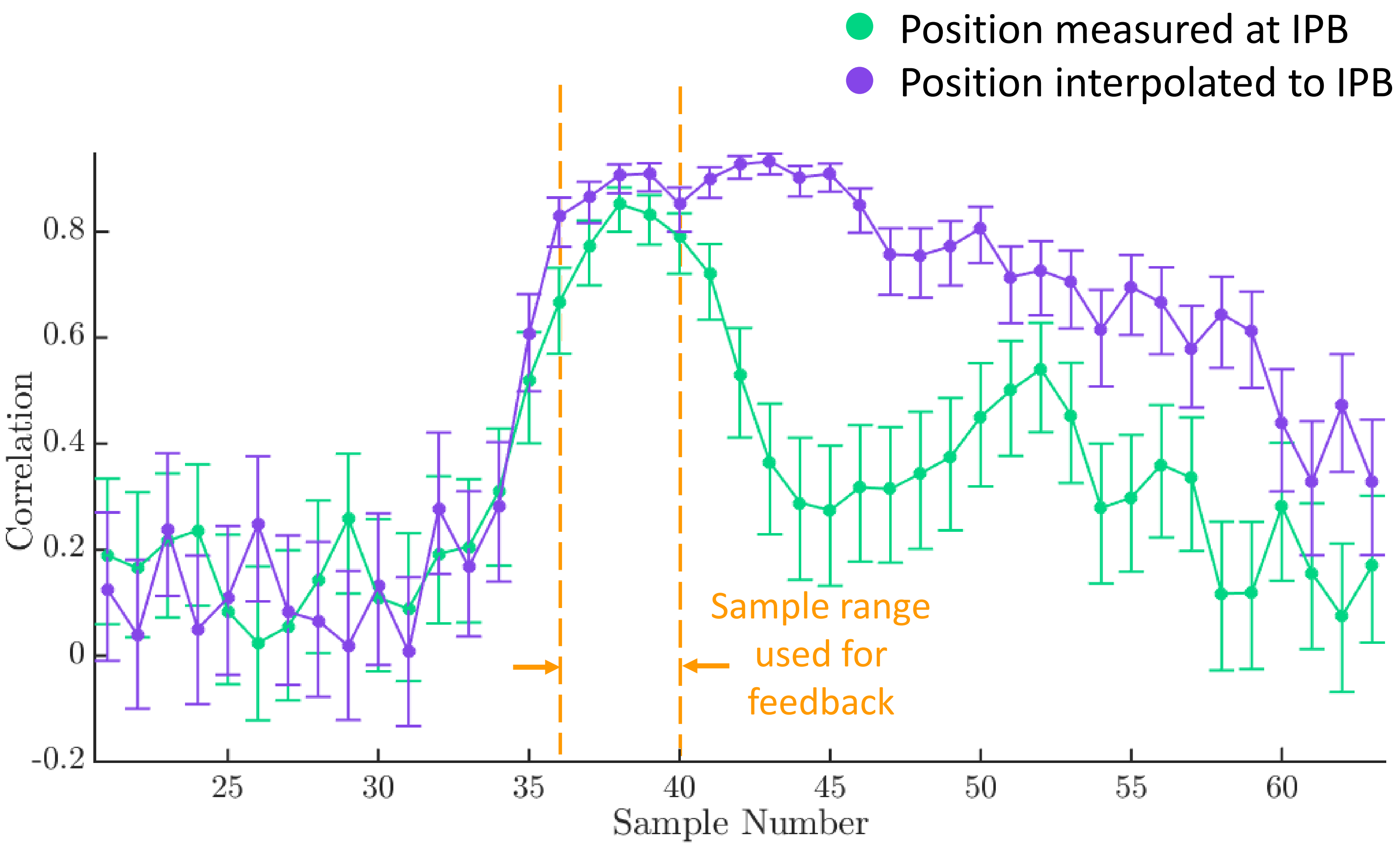
- σ_{Y_2} = jitter of corrected bunches
- $\sigma_{y_{1,2}}$= uncorrected jitter of bunch 1,2
- ρ_{12}= bunch-to-bunch correlation

Expected Feedback Performance

- It is useful to compare the beam stabilisation achieved with that expected, taking into account the imperfect correlation and the differences in bunch 1 and bunch 2 jitters.
- If the bunch-to-bunch position correlation was 100% and the bunch-1 and bunch-2 jitters were equal then the expected performance should equal the best possible performance of $1.25 \times \sigma_{res.}$
- Integration significantly improves the predicted performance. This is an effect of the better resolution improving the jitter measurement and the estimation of the bunch-to-bunch correlation.

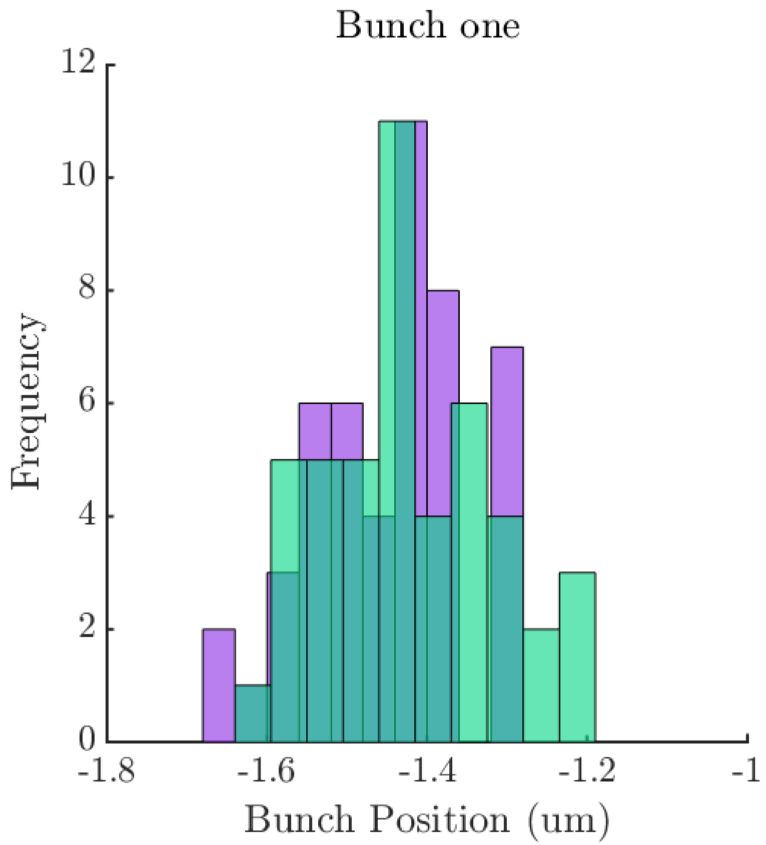
Window width	Res. (nm)	Pred. performance (nm)	Sample window
1	40.8 ± 2.9	62.4 ± 5.2	38
2	37.9 ± 2.7	58.0 ± 5.4	38 to 39
3	33.1 ± 2.3	48.2 ± 5.2	37 to 39
4	31.9 ± 2.3	40.4 ± 5.3	36 to 39
5	31.2 ± 2.2	40.1 ± 5.5	36 to 40
6	31.2 ± 2.2	40.4 ± 5.2	35 to 40
7	32.3 ± 2.3	42.4 ± 5.3	35 to 41
8	36.2 ± 2.6	53.4 ± 5.1	35 to 42
9	41.0 ± 2.9	67.9 ± 8.7	35 to 43
10	46.1 ± 3.3	82.5 ± 9.0	35 to 44

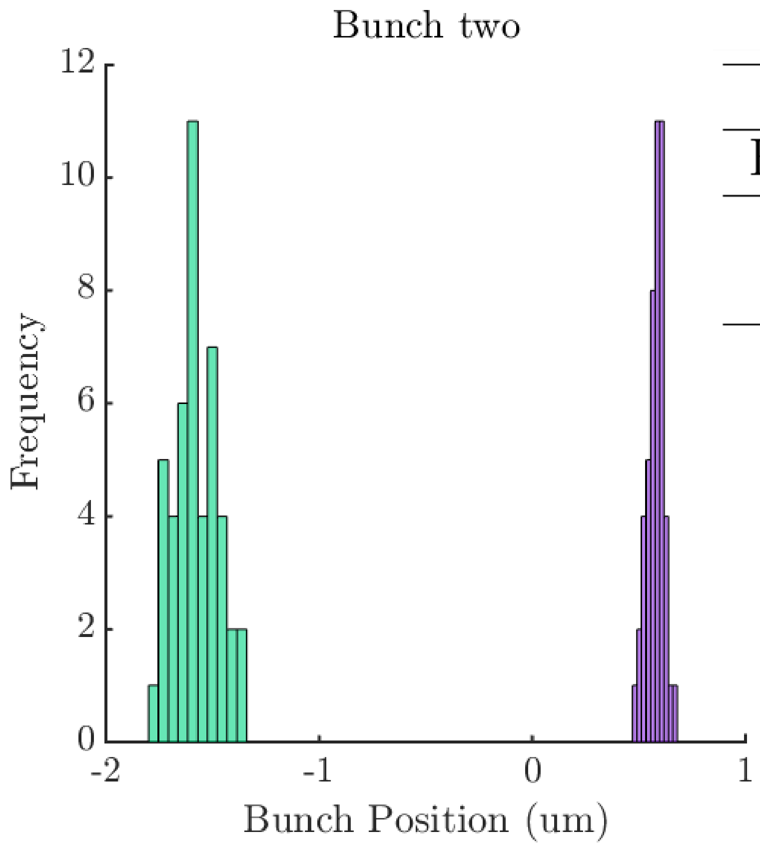
Optimising the Correlation



- Select a sample window which maximises correlation, while also optimising the resolution for measurements at IPB.
- Window used for feedback: samples **36 to 40**.
- Integrated correlation measured at IPB for sample window used: **91.6%.**

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%

Inconsistencies between resolution and feedback performance

- There are inconsistencies between the measured jitter and the resolution. We would expect the true jitter and the resolution to add in quadrature to give the measured jitter ($\boldsymbol{jit_{meas}^2 = jit_{true}^2 + resolution^2}$). However, the resolution and the measured jitter are very similar.

- Bunch one resolution: 31 nm, bunch two resolution: 39 nm,
- Bunch two jitter with feedback: 41 nm (96 nm without feedback),
- Best possible stabilisation given bunch one resolution: 39 nm,
- Predicted stabilisation given imperfect correlation and jitters: 40 nm,
- If $jit_{meas}^2 = jit_{true}^2 + resolution^2$, then this suggests the true jitter is tiny, even though we don't predict we should be able to stabilise to such a level.

  → $41^2 - 39^2 = true\ jitter^2 = \mathbf{13}^2$ << 40 nm.

Summary

- In May 2017, resolution of **20 nm** was demonstrated for geometric and fitting resolution using multiple sample integration. We have been unable to reproduce this while performing feedback but with such a resolution we could potentially correct down to ~ 25 nm beam stabilisation.
- Developments to the feedback firmware allow for the use of an integrated period of the BPM waveform. Integration is shown to improve the useable BPM resolution and consequently feedback performance.
- This was tested with two different feedback modes in December:
    - 1-BPM feedback showed stabilisation down to **50 ± 4 nm**.
    - 2-BPM feedback showed stabilisation down to **41 ± 4 nm.**
- Both of these results show a significant improvement over the best feedback performance in single sample mode.

Future Work

- For these 2-BPM feedback studies, high-beta optics were used to help with BPM alignment. We aim to test 2-BPM feedback also with nominal optics, to better represent the condition of a real linear collider.
- We have previously measured as good as 20 nm resolution, but we have been unable to reproduce this while performing feedback. Hopefully, with fully operational BPM movers we will be able to access this 20 nm resolution again and perform feedback while in that set up.
- We will try adjusting the IQ phase so that we have more position signal in the Q signal, as the baseline for this mixer is better understood.
- If we have fully operational movers we would try adjusting the pitch of the BPMs so as to minimise the angular component of the signal, as in the past this has coupled jitter on the phase angle into our position signal.

Thank you for listening