Latest FONT
Resolution and IP Feedback Results

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Outline

Background

- Introduction to ATF2
- FONT system and cavity BPM signal processing.
- Recent modifications to the FONT system.

Results of resolution studies

- Best BPM resolution results (April 2018).
- Work towards achieving consistent resolution results (April 2018).

Results of feedback studies

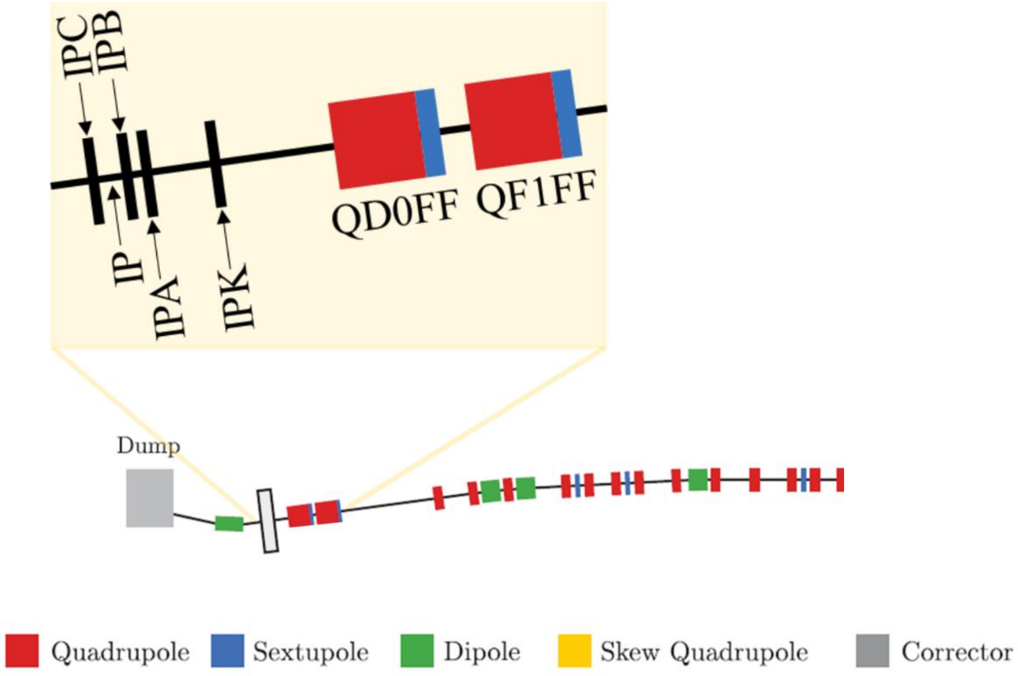
- Beam stabilisation results: (December 2017)
    - 1-BPM feedback,
    - 2-BPM feedback.

Plans for future work

FONT IP Feedback System

FONT IP Feedback Region of ATF2

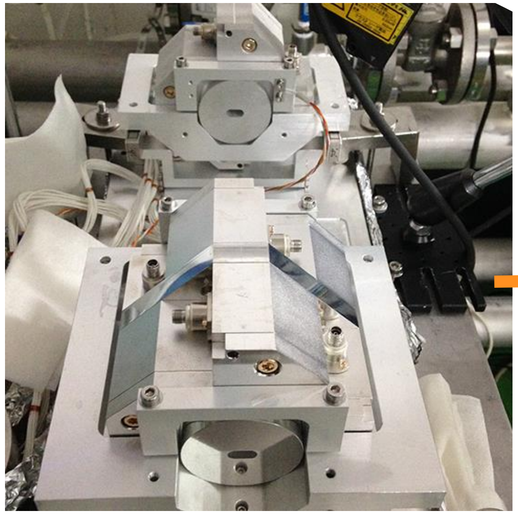
- The FONT (Feedback On Nanosecond Timescales) IP feedback system contains:
  - C-band cavity beam position monitors (BPMs), IPA, IPB and IPC to measure the beam orbit,
  - a digital board (FONT 5A) to compute the feedback correction,
  - a stripline kicker, IPK, to implement the correction.
- The system acts on a two-bunch train with 280 ns bunch separation, stabilising bunch-2 based on position measurements of bunch-1, requiring a high bunch-to-bunch correlation.
- The latency of the system must be less than the bunch separation, requiring fast signal processing; for the system described here, a latency of 232.4 ns has been demonstrated.



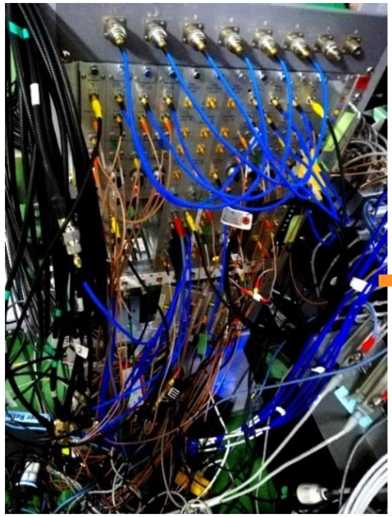
FONT IP feedback system with kicker IPK, cavity BPMs: IPA, IPB and IPC, and final focus quadrupoles QD0FF and QF1FF.

G. White *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 112, p.034802, (2014)

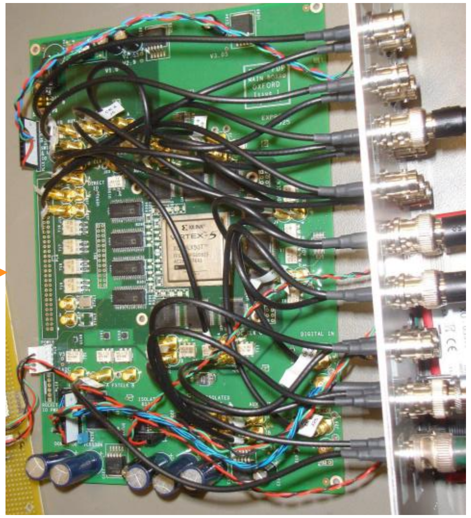
FONT IP Feedback System



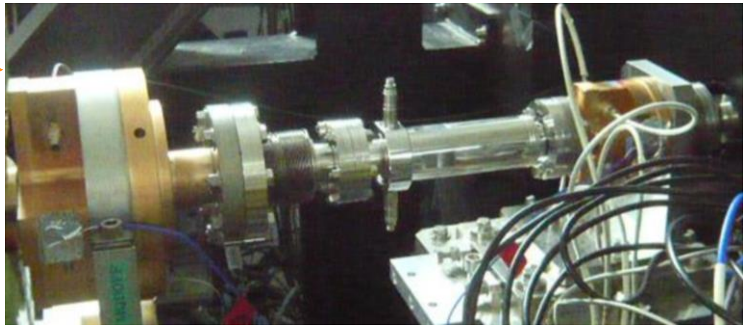
- C-band cavity Beam Position Monitors - IPA, IPB and IPC.
- All with decay times between 20 and 25 ns.
- Mounted on piezo-mover systems to allow for alignment of BPMs with beam in *x*, *y* and also to adjust the pitch.



- Two-stage processing electronics: down-mix and process cavity signals.
- Produces two signals at baseband: I and Q which contain beam position and angle information.

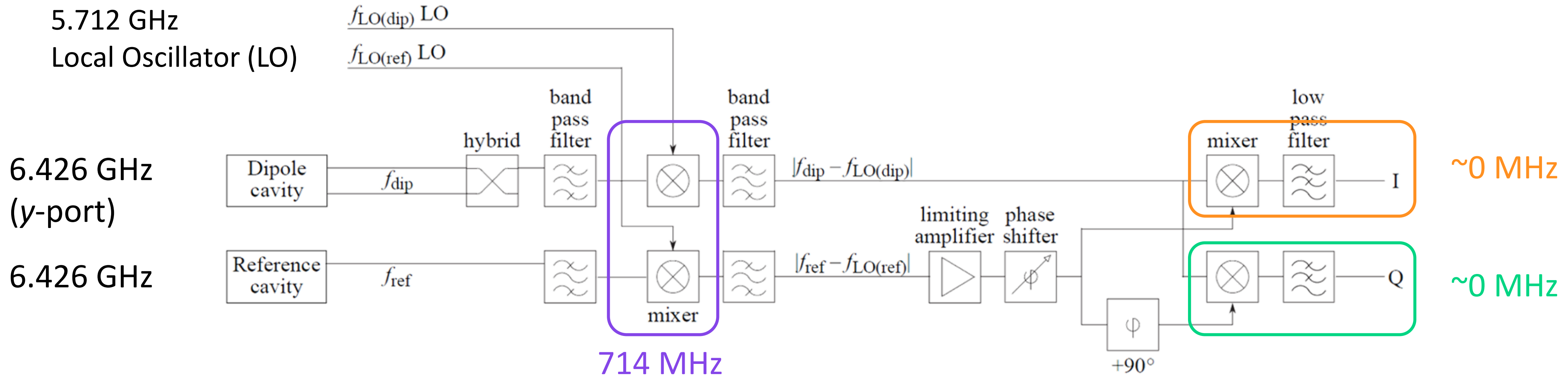


- FONT 5A digital board with Virtex-5 Field Programmable Gate Array (FPGA).
- ADCs to digitise I and Q waveforms at 357 MHz.
- DACs to provide analogue output to drive kicker.



- Stripline kicker and specialised amplifier (provided by TMD Technologies) used to provide feedback correction.
- Amplifier provides ±30 A of current to drive the kicker, with a fast rise time of 35 ns to reach 90% of peak output.

BPM Signal Processing



First stage processing electronics – downmix to 714 MHz

Dipole cavity signal: 6.4 GHz signal dependent on vertical position and charge, is frequency down-mixed using an LO at 5.7 GHz.

Reference cavity signal*:* charge dependent, 6.4 GHz signal is frequency down-mixed using the same LO at 5.7 GHz.

Second stage processing electronics – downmix to baseband

Down-mixed dipole and reference signals at 714 MHz are mixed in-phase to produce the baseband **I signal**.

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

Figure from N. Blaskovic, DPhil. thesis

Digitisation of the BPM Waveform

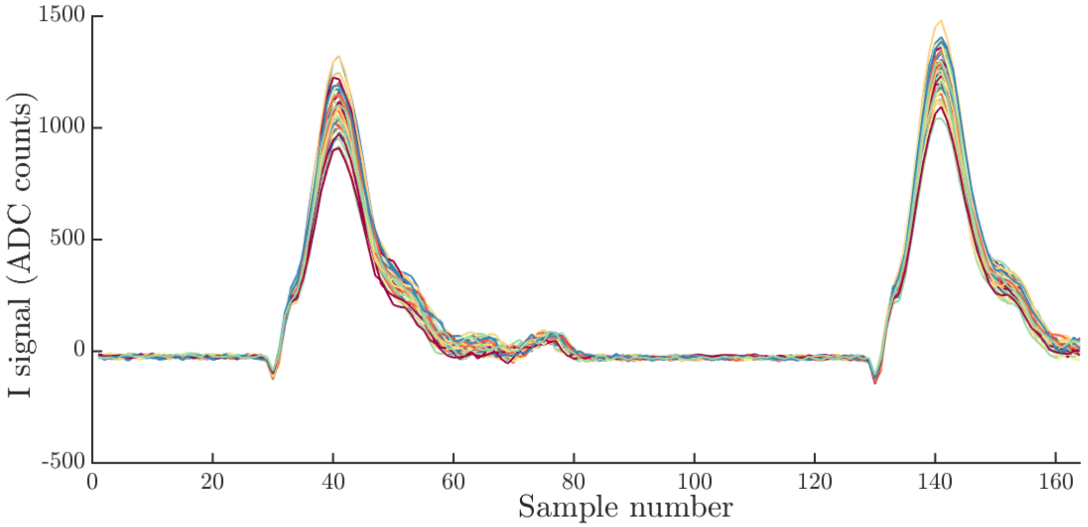
- The waveforms I and Q are digitised at 357 MHz by ADCs on the FONT 5A board; these digitised samples are used to compute a bunch position:

$$y = \frac{1}{k}\left(\frac{I}{q}\cos\theta_{IQ} + \frac{Q}{q}\sin\theta_{IQ}\right),$$

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

Single sample vs. integrated sample

- **Single sample**: only a single sample of each of the *I* and *Q* waveforms are used, resolution in this mode typically ~50 nm.
- **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. Resolution achieved in this mode of 20 nm.
- Improvements to the FONT system allow for feedback using multiple samples of the BPM waveforms.



Example I signal waveform, in two bunch operation with 280 ns bunch spacing. Consecutive samples are separated by 2.8 ns.

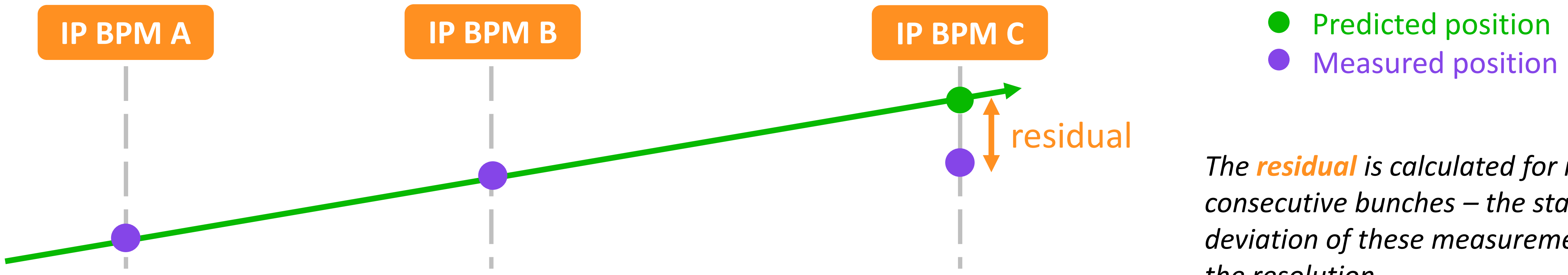
Resolution Studies

April 2018

Calculating the Resolution

- Only two BPMs are required to characterise the straight-line bunch trajectory, so we are able to use the third BPM to estimate the resolution of the measurement.
- The resolution which is relevant for feedback is the **geometric resolution** – determined using the longitudinal separation of the BPMs. We can achieve better resolution measurements in off-line analysis by using **least squares fitting** for the bunch position but this is not possible within the latency required for feedback

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



*The **residual** is calculated for many consecutive bunches – the standard deviation of these measurements is the resolution.*

Resolution Results

- Resolution results from April 2018: we were able to achieve resolution of ~20 nm, and we were able to reproduce this performance consistently across ten repeat data sets, with all ten data sets having sub-25 nm resolution.
- There is very little improvement to the resolution from using fitting to position or charge, suggesting the calibration and charge normalisation were performed successfully.
- These data were analysed using an integration window of 15 samples. Single sample resolutions were measured between 40-45 nm.

Resolution results from a data set collected 19th April 2018 as part of 10 repeat resolution measurements.

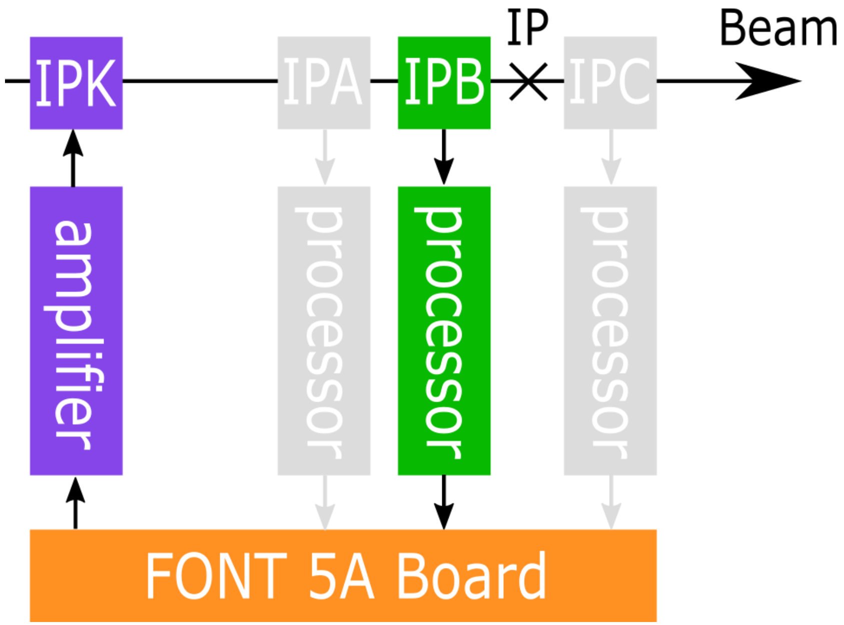
Resolution	IPA (nm)	IPB (nm)	IPC (nm)	Comments
Geometric	20.6 ± 1.0	20.6 ± 1.0	20.6 ± 1.0	Resolution achievable for feedback
Fitting position	20.4 ± 1.0	20.5 ± 0.8	20.3 ± 0.8	Fit out inaccuracies in calibration
Fitting position and charge	19.9 ± 0.9	19.9 ± 0.8	19.7 ± 0.9	Fit out inaccuracies in calibration and position-charge correlation (from imperfect charge normalisation)

1-BPM Feedback Results

Dec 2017

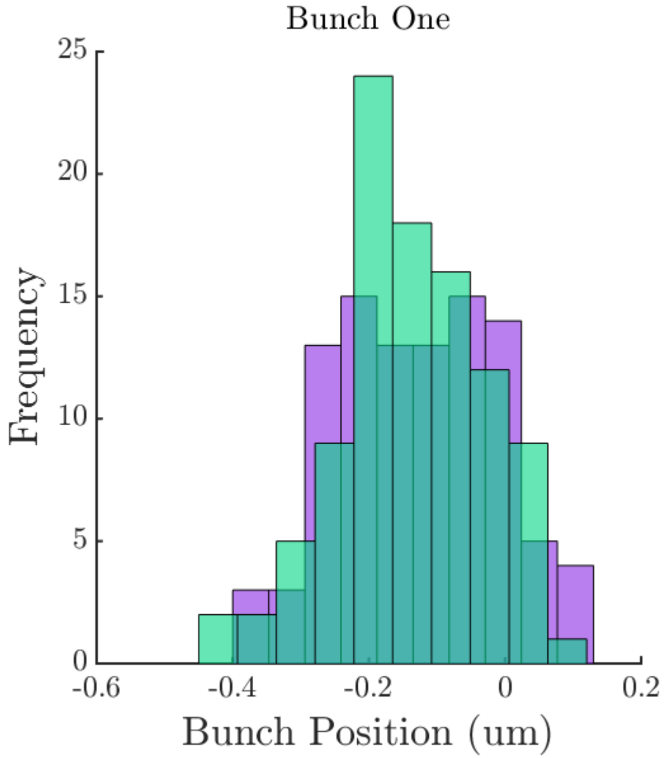
IP Feedback Results – 1-BPM Mode

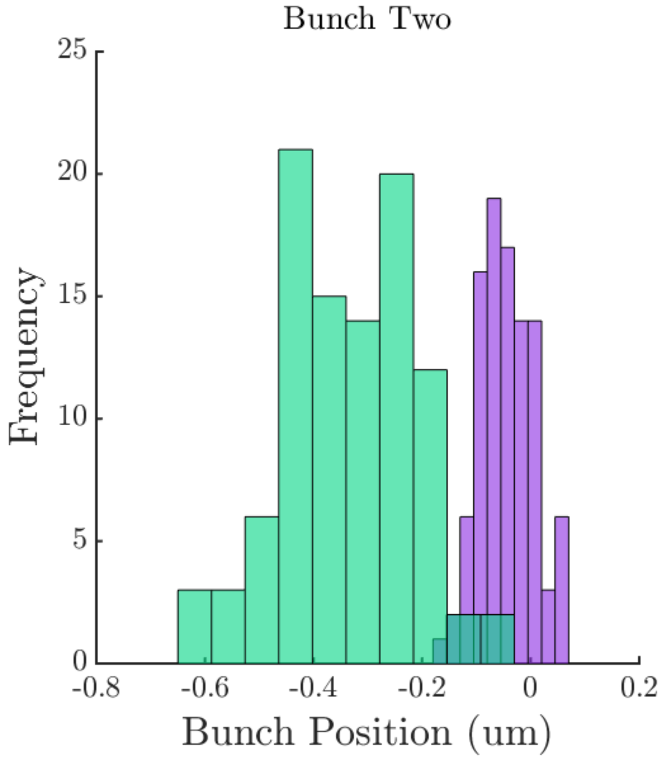
- In 1-BPM feedback mode, position measurements at one BPM are used to stabilise the beam locally.
- Limit to 1-BPM feedback performance = $\sqrt{2} \times \sigma_{res}$, so it is clearly important to improve the resolution accessible in real-time during feedback.
- Previous best stabilisation performance in single-sample 1-BPM mode = 74 nm. This is consistent with a single sample resolution of approximately 50 nm.



1-BPM Feedback Results – With Integration

Best results demonstrated for 1-BPM feedback mode with stabilisation at IPC.





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

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

- 10 samples integrated for feedback - optimised empirically.
- Feedback gain: G = 0.95.
- Predicted stabilisation: 65 nm, suggests the measured correlation was lower than the true correlation – typically due to the resolution introducing a random component to the position measurement.
- Stabilisation below 55 nm was reproducible.

2-BPM Feedback Results

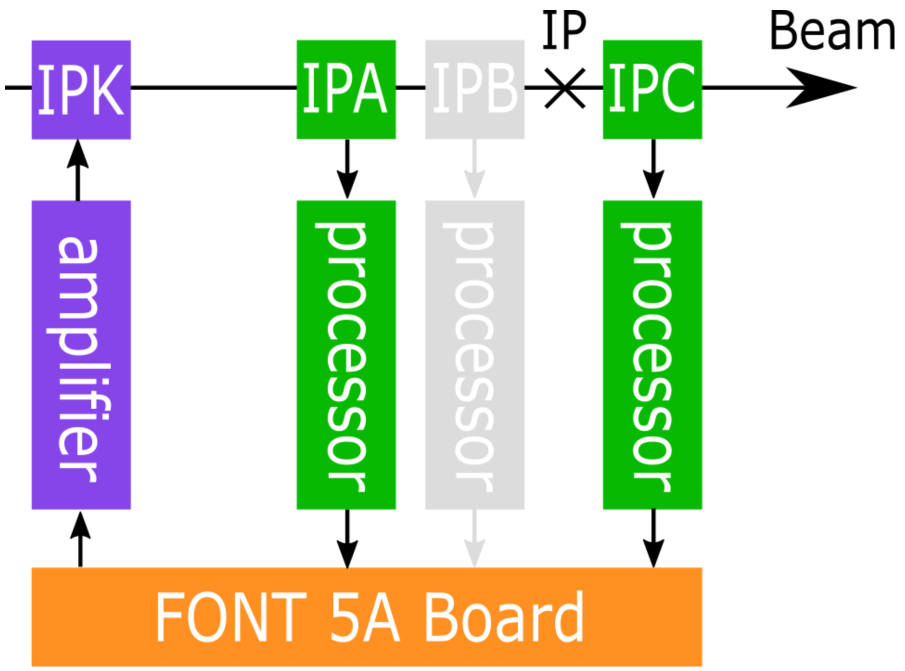
Dec 2017

IP Feedback Results – 2-BPM Mode

- Beam position measurements at IPA and IPC are interpolated and used to stabilise the beam at an intermediate location, for this study, at IPB.
- For stabilisation at IPB, the feedback BPMs IPA and IPC contribute in a ratio 32:68, so that the interpolated resolution is:

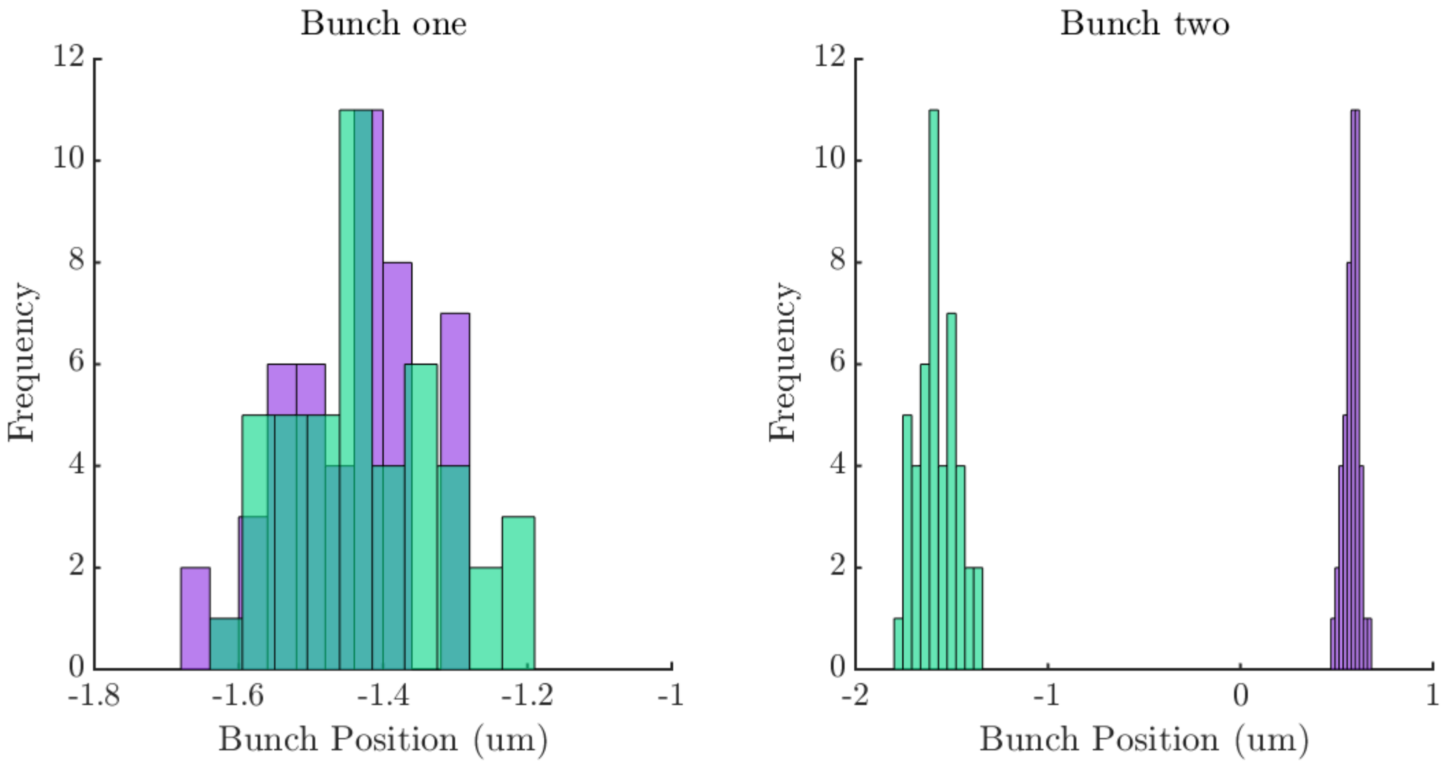
$$\sigma_{\mathrm{interp.}} = \sqrt{0.32^2\sigma_{\mathrm{BPM}}^2 + 0.68^2\sigma_{\mathrm{BPM}}^2}$$
$$= 0.75\sigma_{\mathrm{BPM}}$$

- Previous best 2-BPM single-sample feedback performance = 68 nm (consistent with a resolution of < 55 nm).
- Limit to feedback performance in 2-BPM mode = $1.25 \times \sigma_{res}$, so it is important to improve the resolution by using integration.



2-BPM Feedback Results

Best results demonstrated for 2-BPM feedback mode, with stabilisation at IPB.



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

- Five-sample integration window, empirically optimised to improve both the measured correlation and resolution.
- Feedback stabilising to: **41 ± 4 nm,** shows excellent agreement with predicted stabilisation of 40 nm.
- Feedback gain: G= 0.8.

Feedback off correlation: **92%**
Feedback on correlation: **41%**

The correlation is not fully removed, suggesting feedback gains were set too low; higher gains may offer better performance.

Summary

- While performing resolution studies in April 2018, we were able to reproducibly achieve resolution better than 25 nm; with best results of 20 nm resolution.
- Improvements 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 2017:
  - 1-BPM feedback showed stabilisation to **50 ± 4 nm**.
  - 2-BPM feedback showed stabilisation to **41 ± 4 nm**.

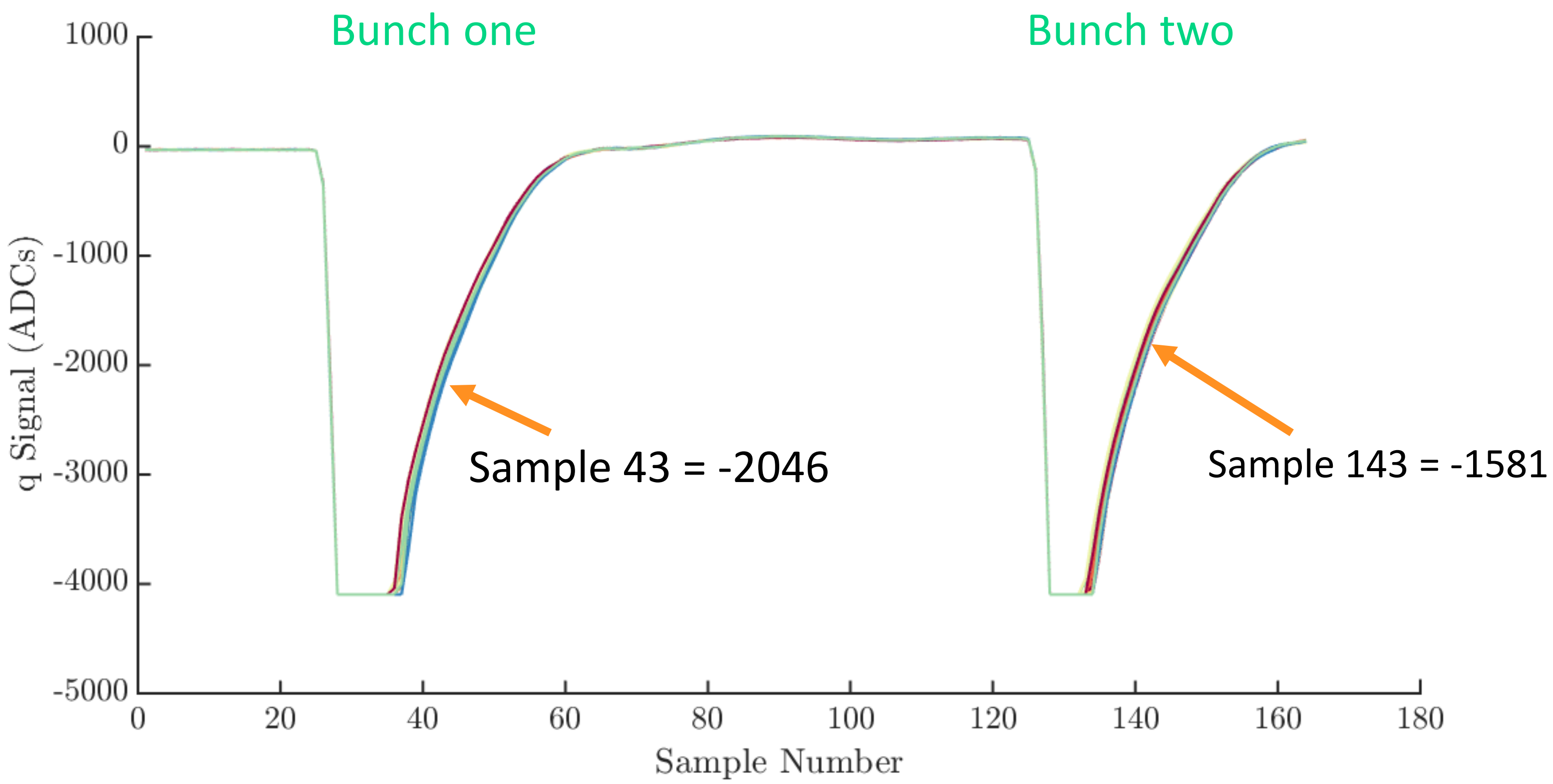
  Both of these results show a significant improvement over the best feedback performance in single sample mode.

Thank you for listening

Extra slides

BPM Resolution (Bunch 1 & 2)

- Bunch charge at reference samples used for feedback (43 and 143):
  - Bunch-1: -2046 ADCs
  - Bunch-2: -1581 ADCs
- Resolution scales **inversely** with charge: bunch-2 with a lower bunch charge has a correspondingly poorer resolution.
- Geometric resolution:
  - Bunch-1: 31 nm
  - Bunch-2: **39 nm**
- Potential limitations when measuring feedback performance as the resolution of bunch-2 is similar to the expected level of stabilisation.



Charge signal, with samples used for charge normalisation during feedback highlighted.

Expected Stabilisation

- The position of the corrected bunch, Y_2, in terms of the uncorrected bunch-1 and bunch-2 positions, y_1 and y_2 is:

$$Y_2 = y_2 - y_1 + c$$

where c is a constant offset which may be applied in order to shift arbitrarily the mean position of the stabilised bunches.

- Taking the variance of this equation gives the predicted level of beam stabilisation:

$$\sigma_{Y2}^2 = \sigma_{y1}^2 + \sigma_{y2}^2 - 2\sigma_{y1}\sigma_{y2}\rho_{12}$$

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

- The best performance is achieved for ρ_{12} = 1 and $\sigma_{y_1} = \sigma_{y_2}$, in this situation the level of stabilisation then just depends on the resolution of the position measurement (for 2-BPM feedback this is 1.25 x σ_{res}.).

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.
- 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