Latest FONT
Resolution and 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

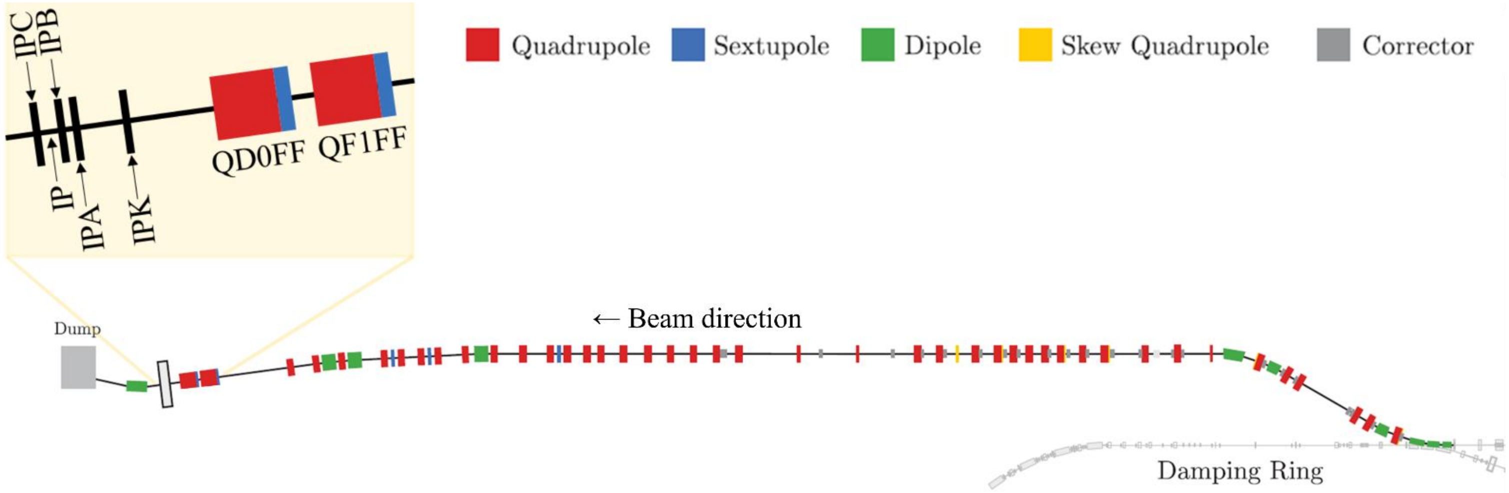
- Beam stabilisation results: (December 2017)
    - 1-BPM feedback,
    - 2-BPM feedback.

Plans for future work

FONT IP Feedback System

Accelerator Test Facility (ATF2)

- The Accelerator Test Facility (ATF2), KEK, is a test-bed for the ILC, with a prototype for the ILC final focus.
- ATF2 goals:
  - Demonstrate 37 nm beam size,
  - Demonstrate nm-level beam stabilisation.

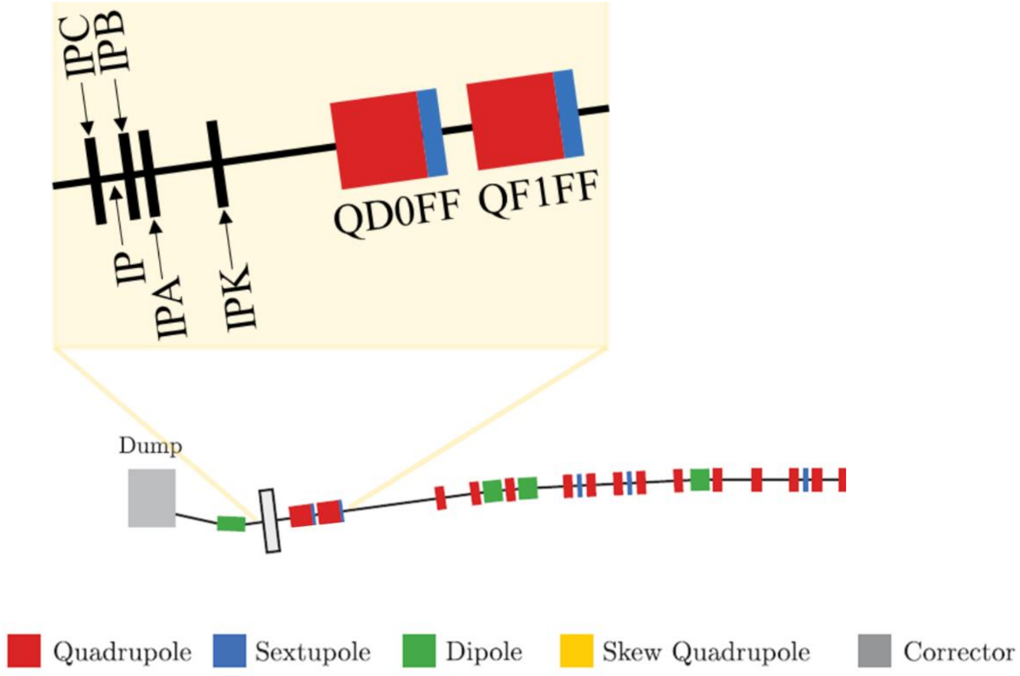


Schematic of the layout of the ATF2 extraction line and final focus, with FONT IP feedback region highlighted, with stripline kicker IPK, cavity BPMs IPA, IPB and IPC, and final focus quadrupoles QD0FF and QF1FF.

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

FONT IP Feedback 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.

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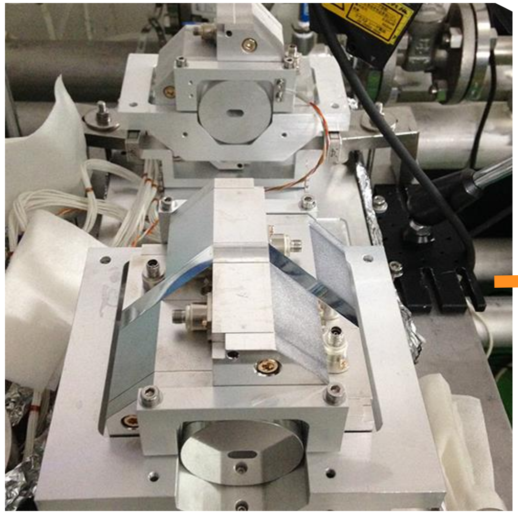
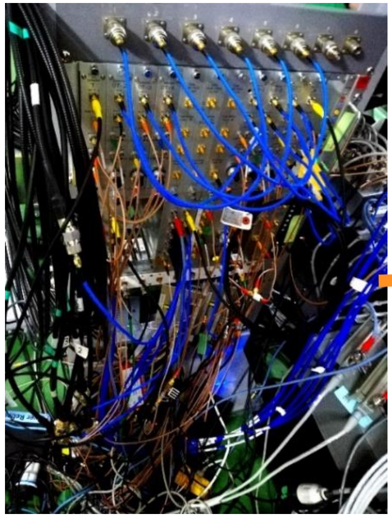
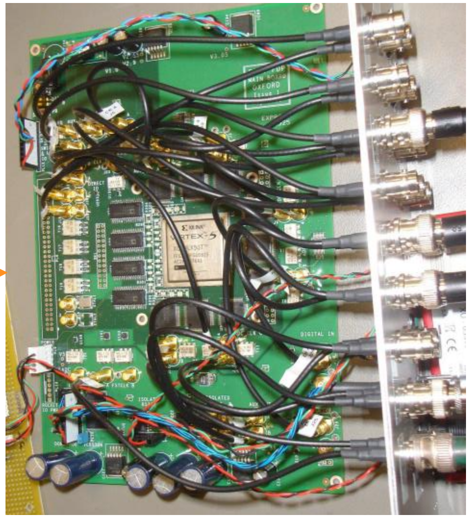
FONT IP Feedback System



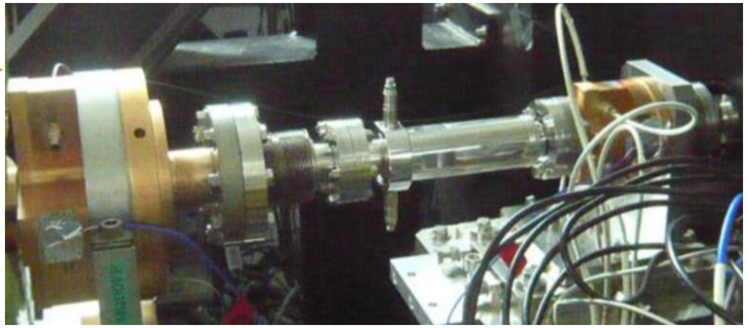
- C-band cavity Beam Position Monitors - IPA, IPB and IPC.
- All with decay times between 20 and 25 ns.
- Mounted on piezo-mover systems to allow for alignment of BPMs with beam in *x*, *y* and also to adjust the pitch.



- 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.

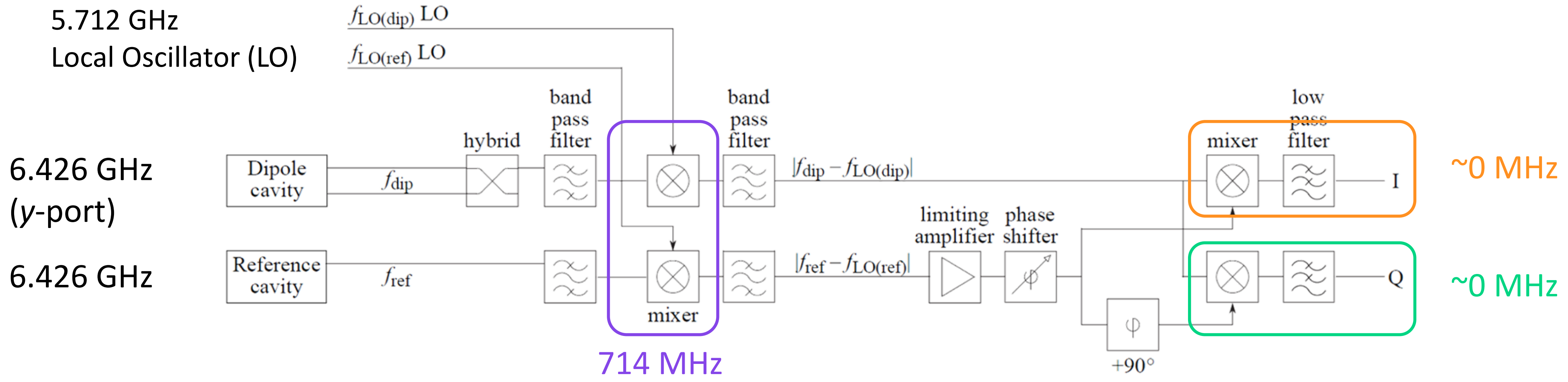


- FONT 5A digital board with Virtex-5 Field Programmable Gate Array (FPGA).
- ADCs to digitise I and Q waveforms at 357 MHz.
- DACs to provide analogue output to drive kicker.



- 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

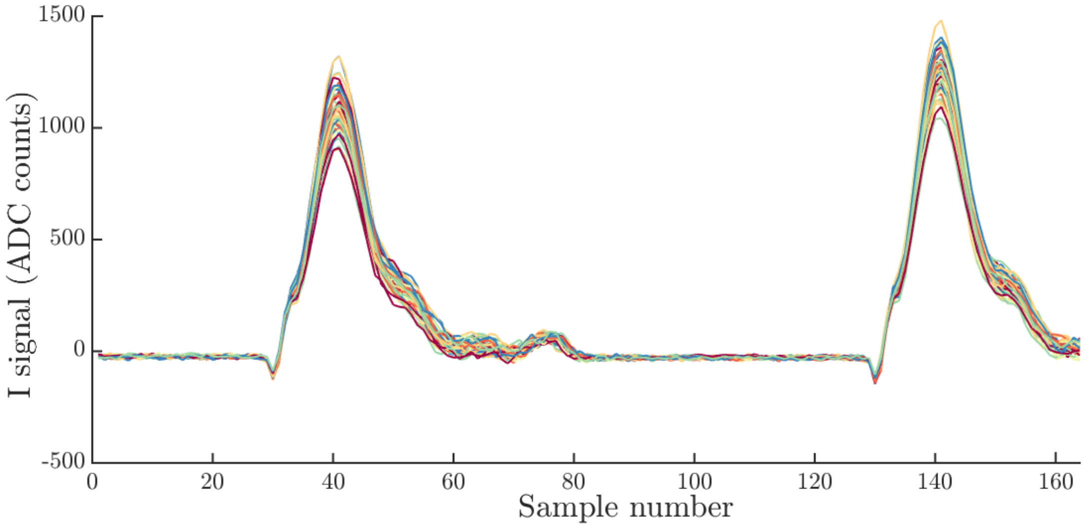
- The waveforms I and Q are digitised at 357 MHz by ADCs on the FONT 5A board; these digitised samples are used to compute a bunch position:

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

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.

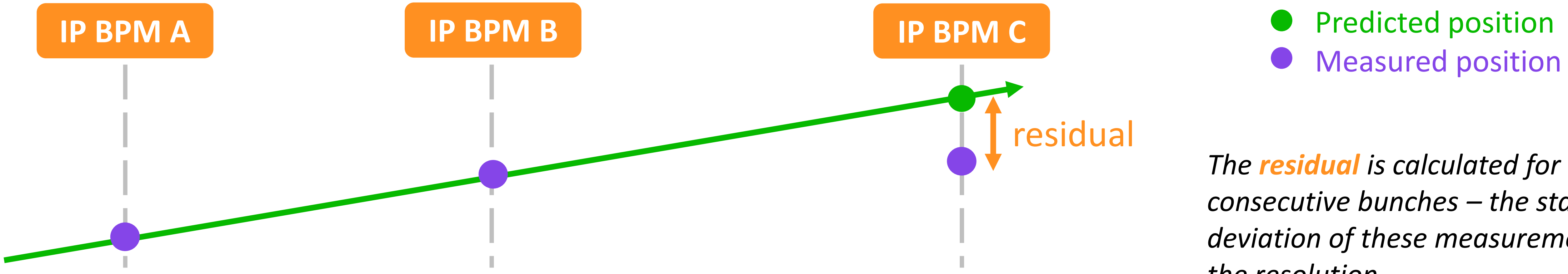


Example I signal waveform, in two bunch operation with 280 ns bunch spacing. Consecutive samples are separated by 2.8 ns.

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.*

Feedback Algorithm

- The feedback correction is computed from the digitised samples of the I and Q signals, using the FPGA on the FONT 5A board as:

$$V = \frac{-Gy}{M} = \frac{-G}{kM}\left(\frac{I}{q}\cos\theta_{IQ} + \frac{Q}{q}\sin\theta_{IQ}\right)$$

where

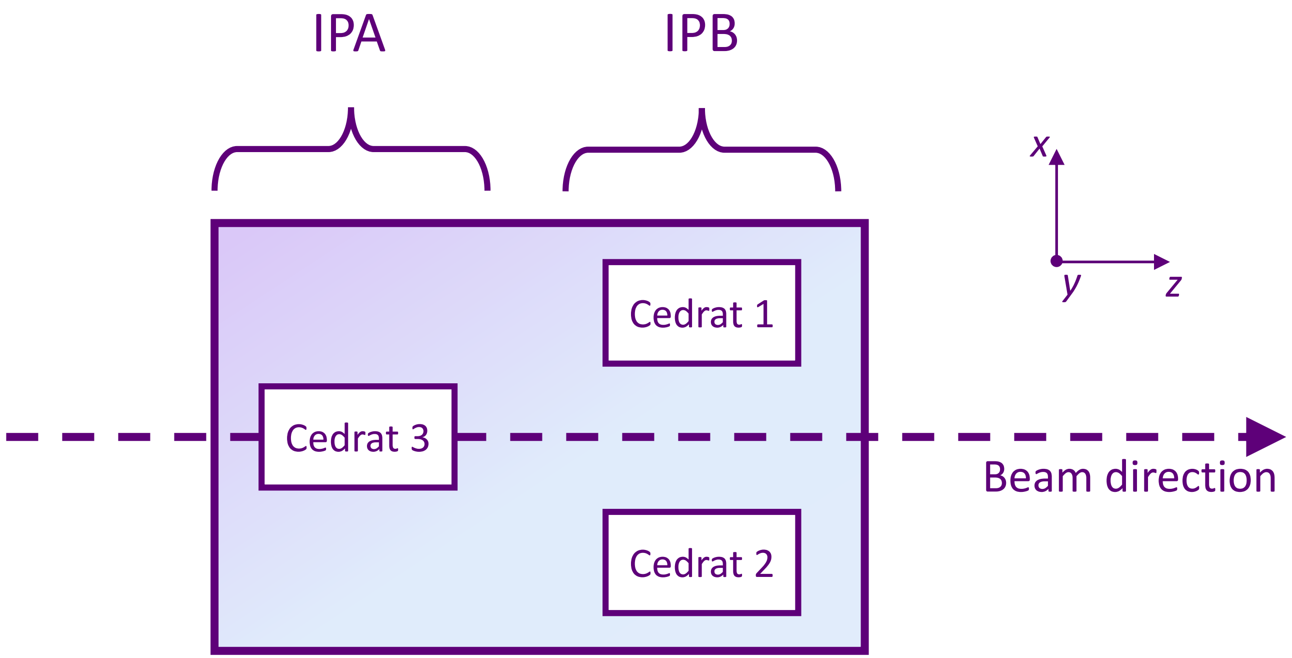
- k is the calibration constant between BPM response and position – determined by moving the BPM with respect to the beam through a known range and measuring the corresponding change in BPM signal.
- θ_{IQ} is the IQ phase angle – determined like k, by position calibration.
- M is the calibration constant converting a position measurement (microns) to a feedback correction in DAC counts – determined by operating the kicker with a range of constant DAC outputs and measuring the corresponding position offsets.
- G, the feedback gain, is set to 1 for a beam with 100% bunch-to-bunch correlation and, otherwise, scaled accordingly.

Resolution Studies

April 2018

Sub-mover fixed – April 2018

- Until early April, sub-mover Cedrat 3 (responsible for vertical adjustment of the block on which IPA and IPB are mounted) was broken and remained at the 0 V setting.
- This made alignment of the IPA and IPB positions and pitches challenging. We typically work with 10 dB attenuation on the dipole cavity signal which gives us 5 µm dynamic range for each BPM.
- Consequently, achieving consistently good resolution results of ~20 nm was not possible.
- Thanks to the work of S. Wallon, S. Araki and the ATF2 staff, we now have fully operational BPM movers.



Recommended sub-mover voltage range:
0.5 to 6 V corresponds to ~170 µm range.

Schematic of locations of vertical sub-movers on IP AB block, and location of BPMs IPA and IPB.

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.

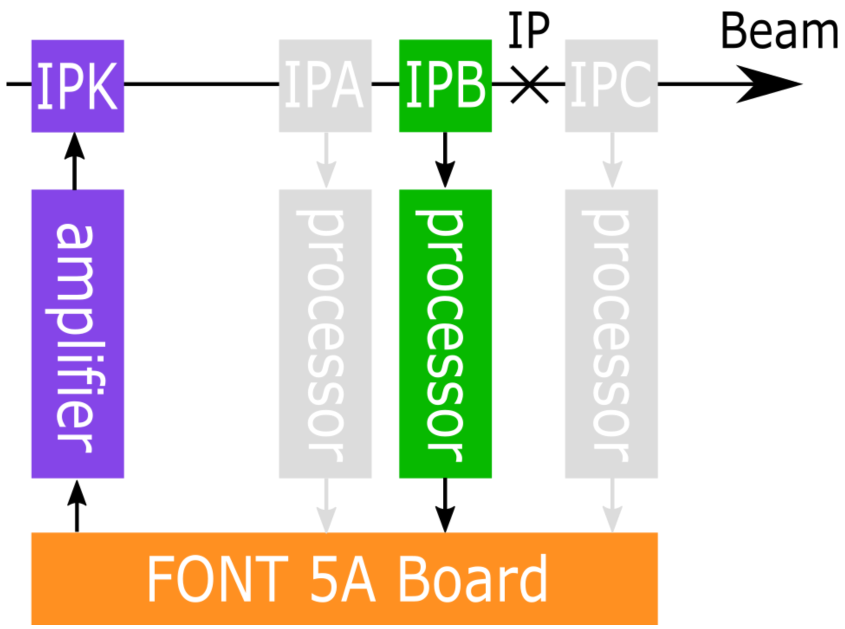
Resolution	IPA (nm)	IPB (nm)	IPC (nm)	Comments
Geometric	20.6 ± 1.0	20.6 ± 1.0	20.6 ± 1.0	Resolution achievable for feedback
Fitting position	20.4 ± 1.0	20.5 ± 0.8	20.3 ± 0.8	Fit out inaccuracies in calibration
Fitting position and charge	19.9 ± 0.9	19.9 ± 0.8	19.7 ± 0.9	Fit out inaccuracies in calibration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

1-BPM Feedback Results

Dec 2017

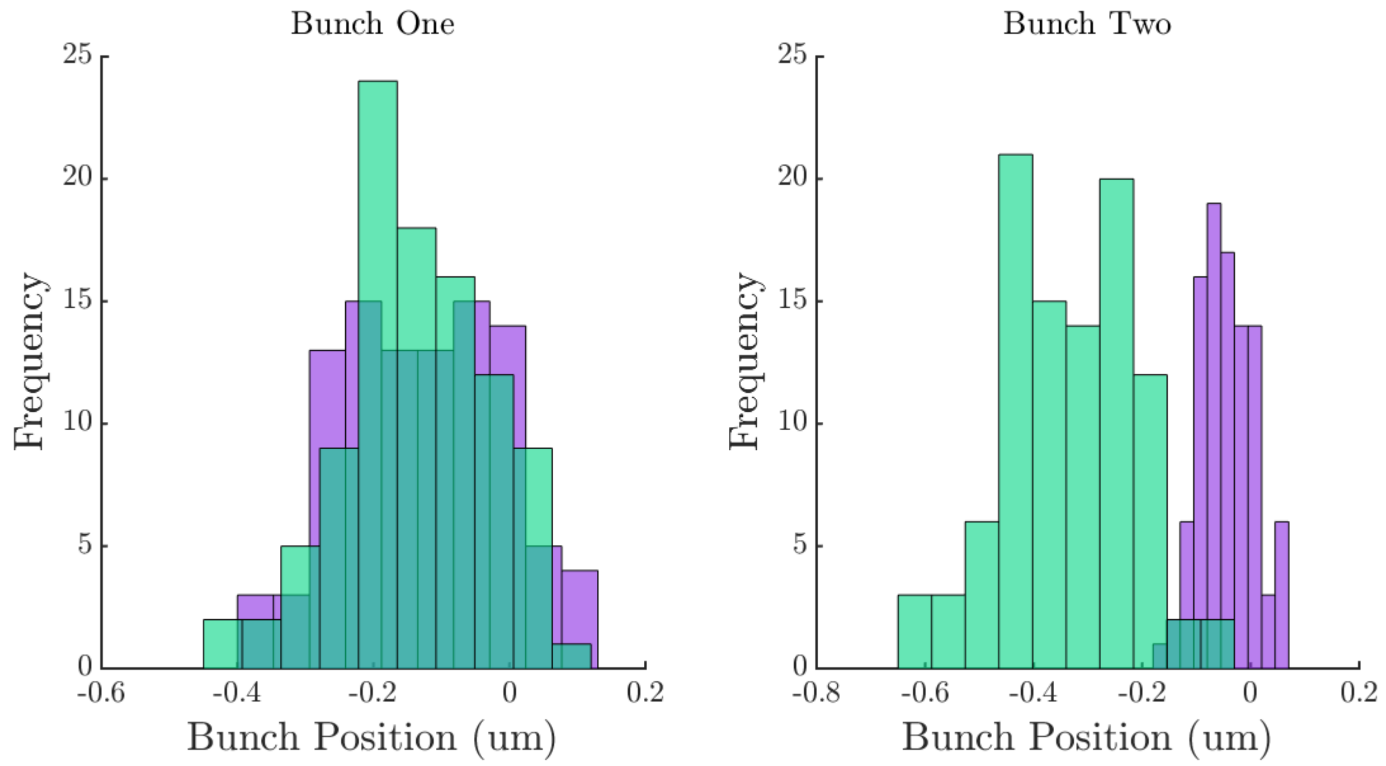
IP Feedback Results – 1-BPM Mode

- 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

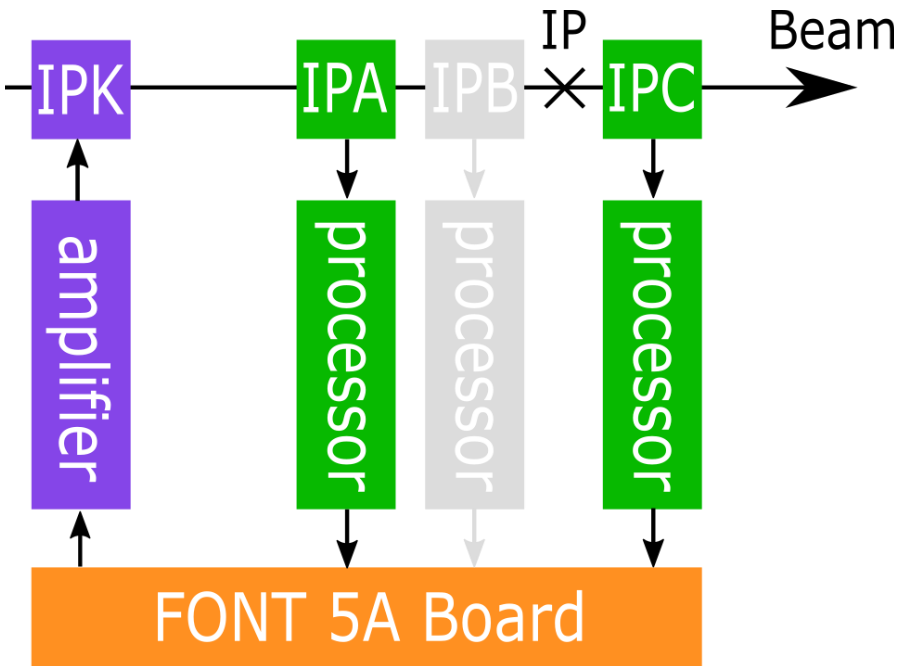
Dec 2017

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:

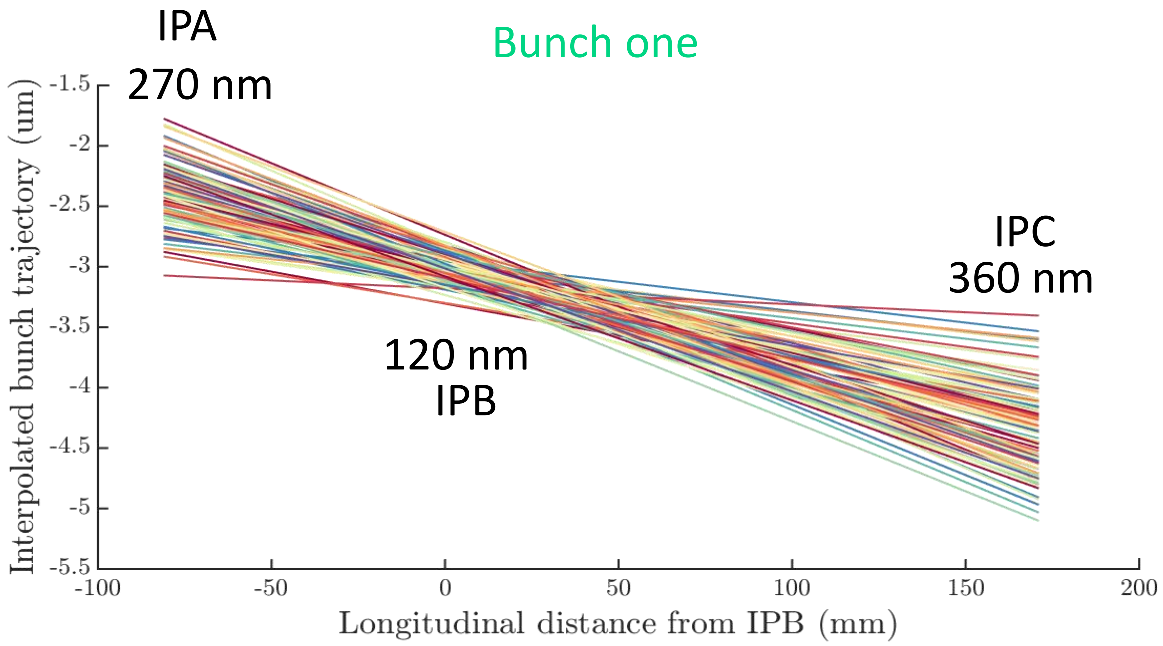
$$\sigma_{\text{interp.}} = \sqrt{0.32^2\sigma_{\text{BPM}}^2 + 0.68^2\sigma_{\text{BPM}}^2}$$
$$= 0.75\sigma_{\text{BPM}}$$

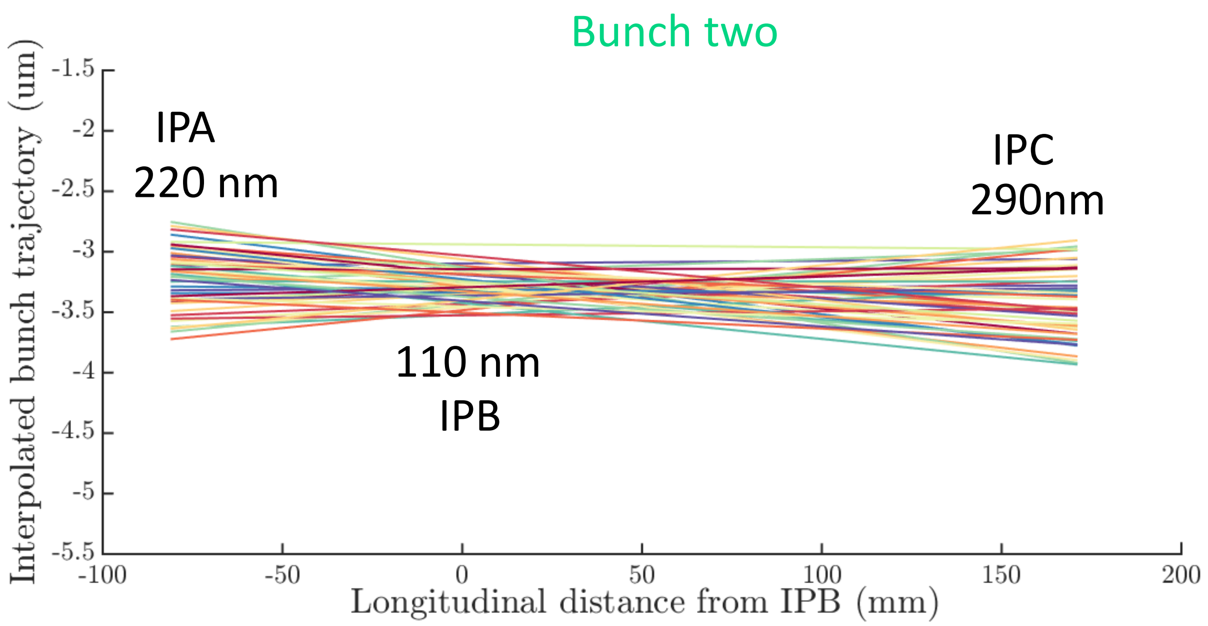
- Previous best 2-BPM single-sample feedback performance = 68 nm (consistent with a resolution of < 55 nm).
- Limit to feedback performance in 2-BPM mode = $1.25 \times \sigma_{res}$, so it is important to improve the resolution by using integration.



High-beta optics

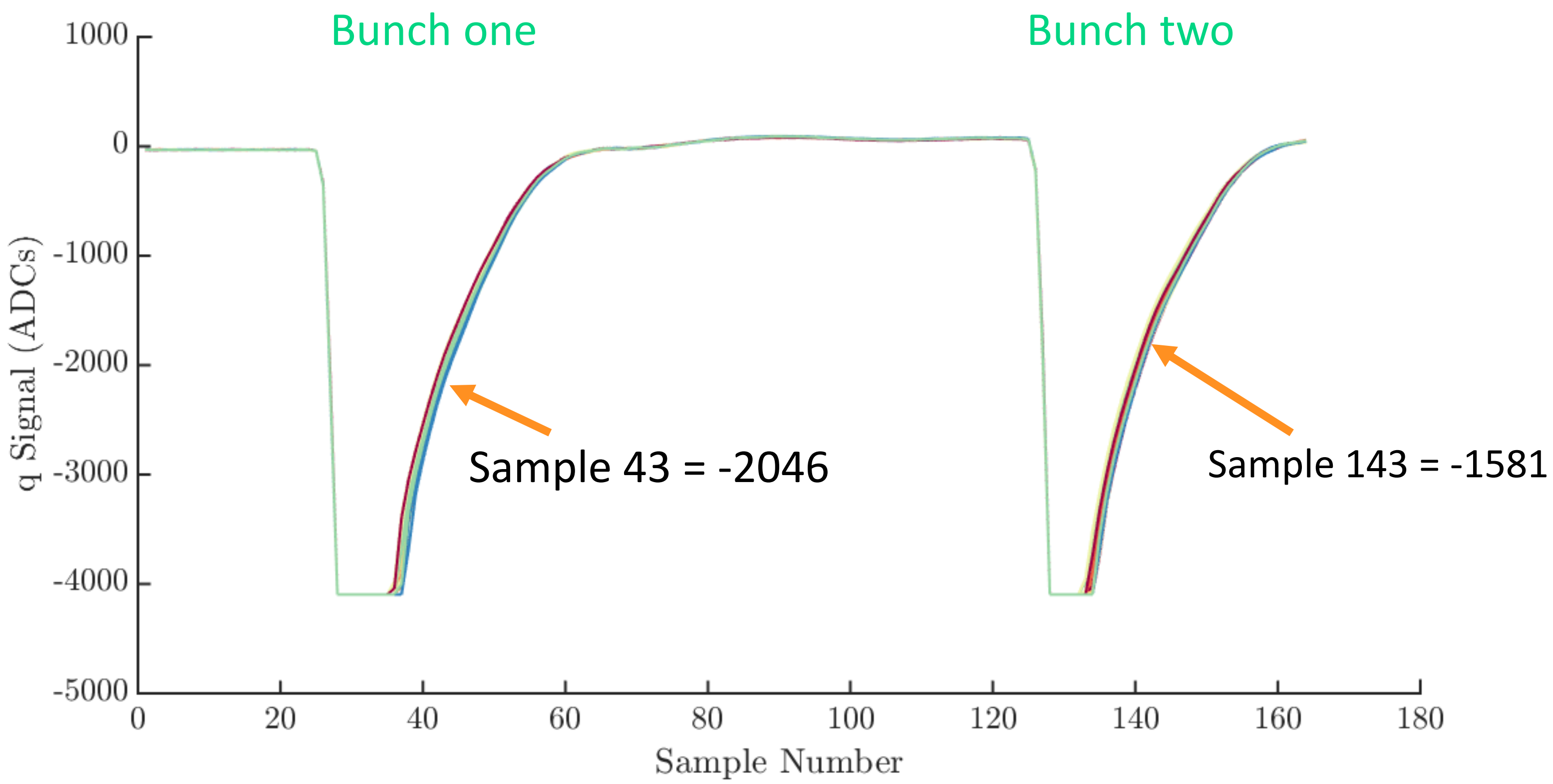
- High-beta optics (1000 times the nominal values of β_y^*).
- Bunch trajectory shown is interpolated from measurements at IPA and IPC.
- Data labels show position jitter measured at the three BPMs. Similar jitters for both bunches - as required for optimal feedback.
- Similar trajectories for both bunches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





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}.).

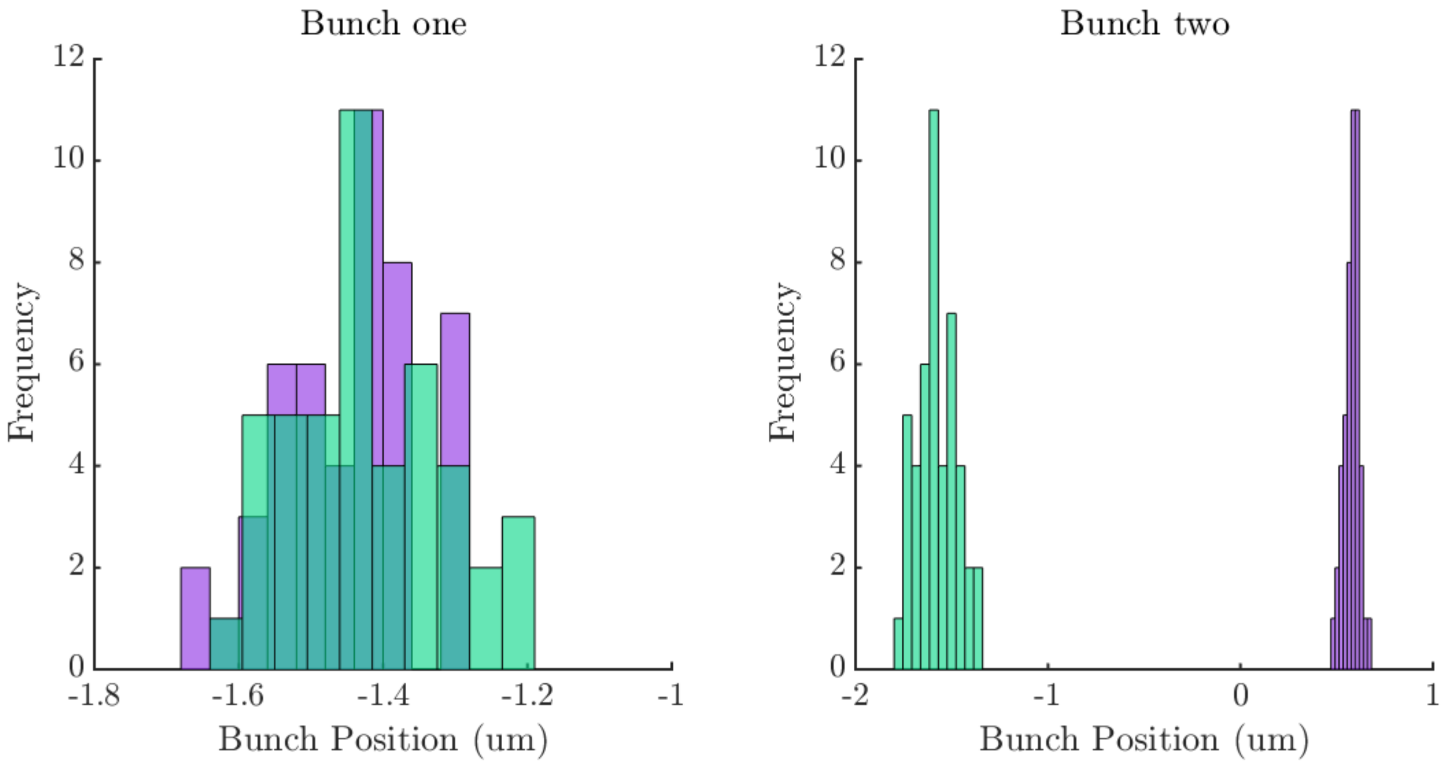
Expected Feedback Performance

- 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

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.

Future Work

- A full analysis of parameters that may have an impact on the BPM resolution is planned for June 2018, including:
  - Jitter on the phase θ_{IQ} introduced by the reference signal limiting amplifier – which could couple into position measurements.
  - Jitter on the bunch phase (bunch arrival time).

Acknowledgments

We would like to thank KEK for providing the beam-time for these experiments and the ATF2 staff for their excellent support and assistance towards achieving these results.

Many thanks also to S. Wallon, S. Araki and our LAL collaborators for their help with the IP BPM mover system, which has been vital in achieving reproducible resolution measurements.

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