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Low-latency beam feedbacks for e+e- colliders

Phil BURROWS, Colin PERRY,

Douglas BETT, Rebecca RAMJIAWAN

University of Oxford

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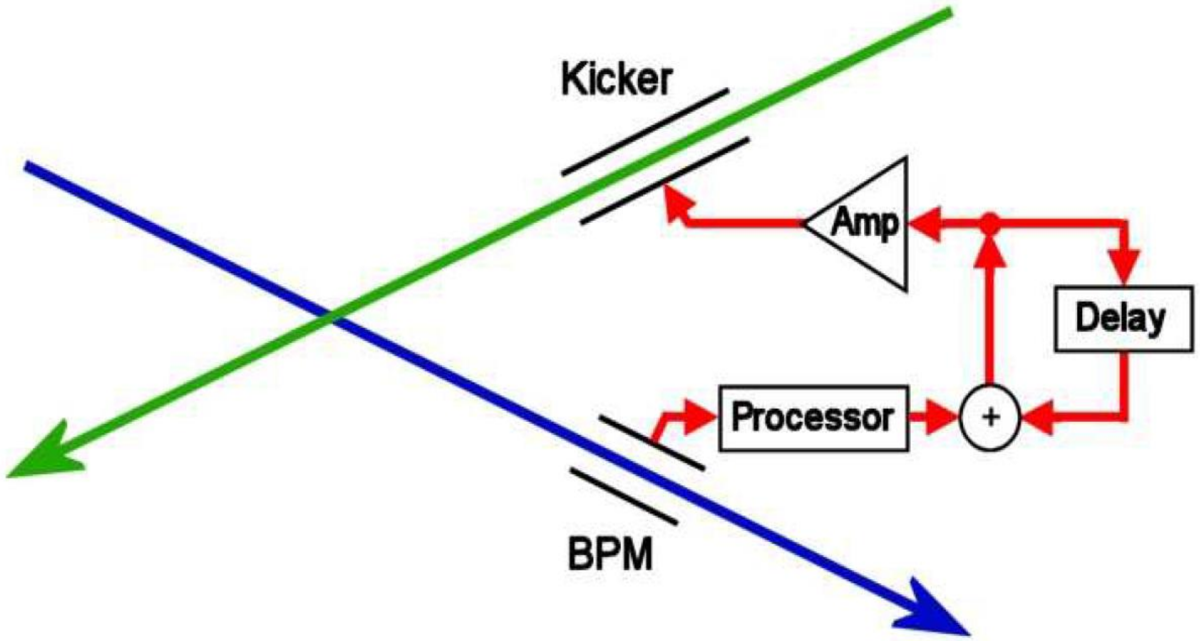
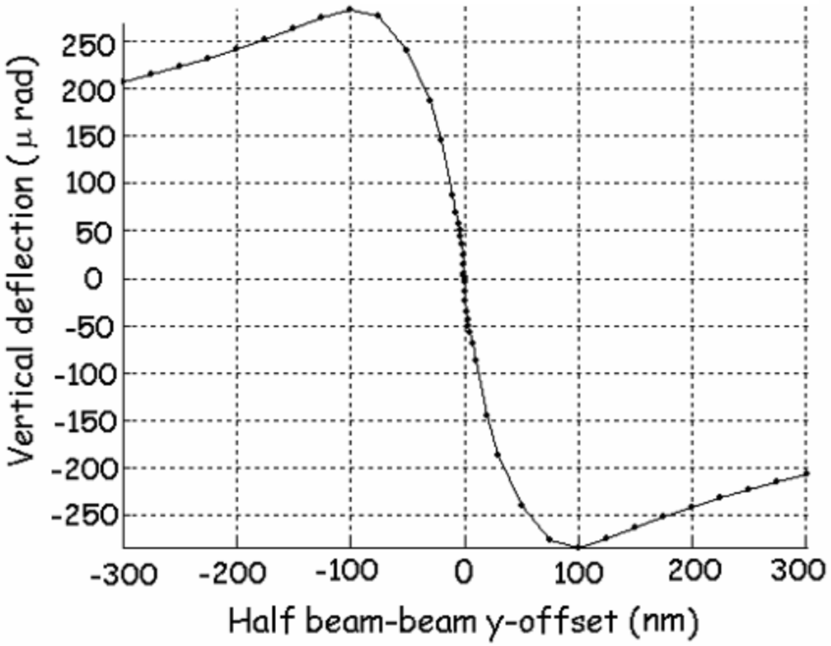
- Introduction to Interaction Point (IP) feedback
- FONT system and cavity BPM signal processing at KEK ATF2
- Recent beam stabilisation results
  - 1-BPM feedback
  - 2-BPM feedback

Interaction Point feedback

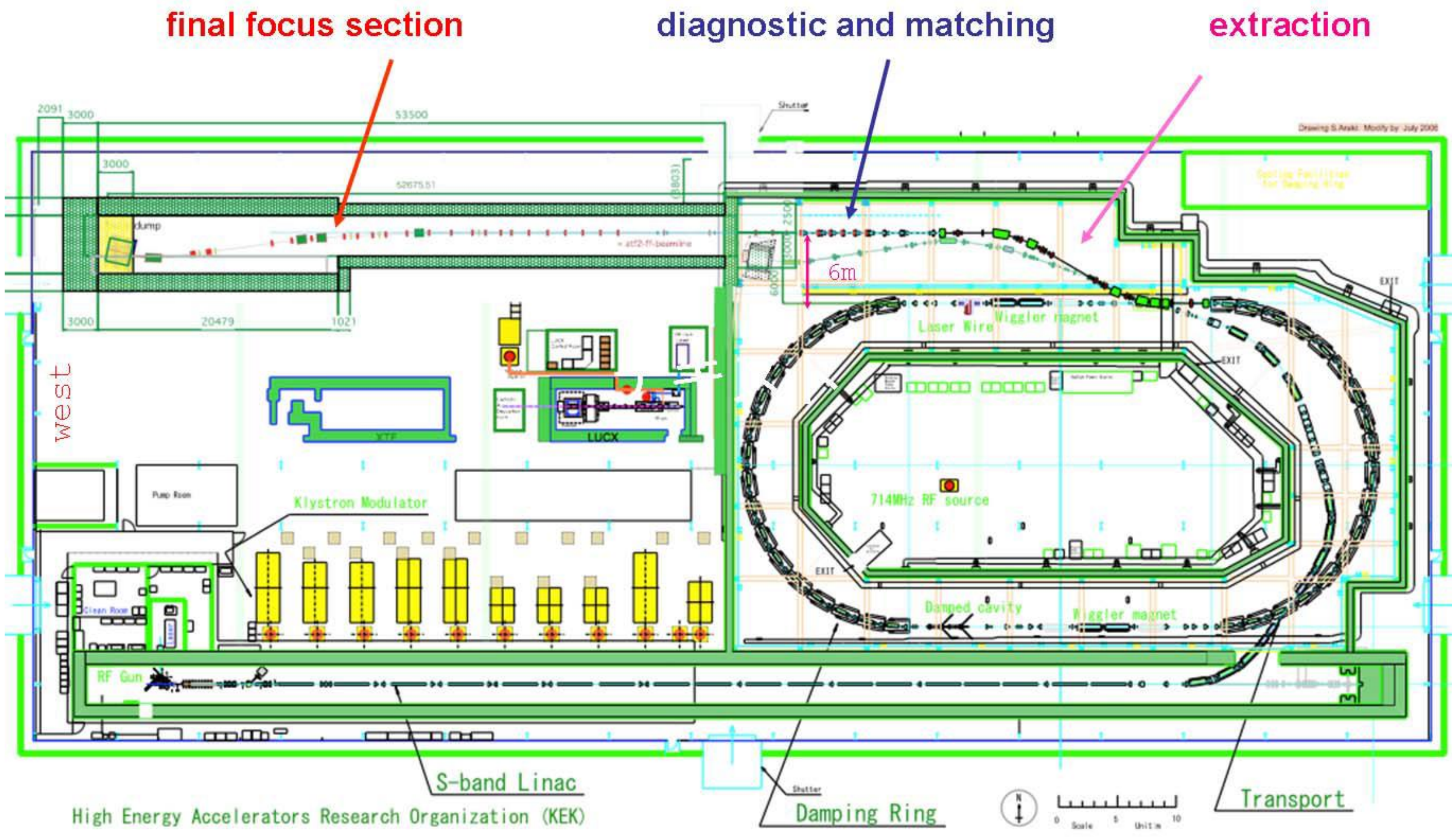
- Offset of bunches at IP inferred from position of first bunch measured at downstream BPM
- Second bunch kicked upstream of IP in other beamline to compensate for this misalignment
- Delay loop preserves correction for subsequent bunches



Beam-beam deflection curve



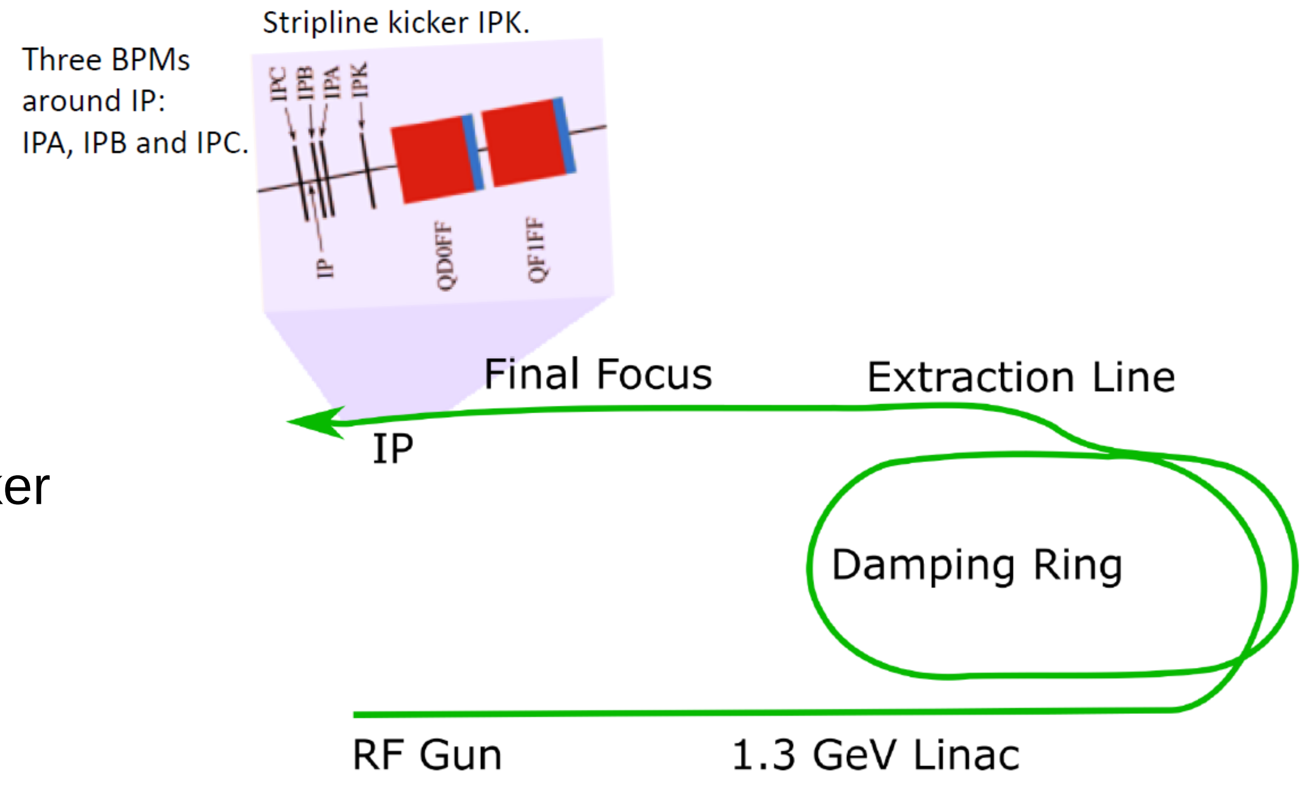
KEK ATF2



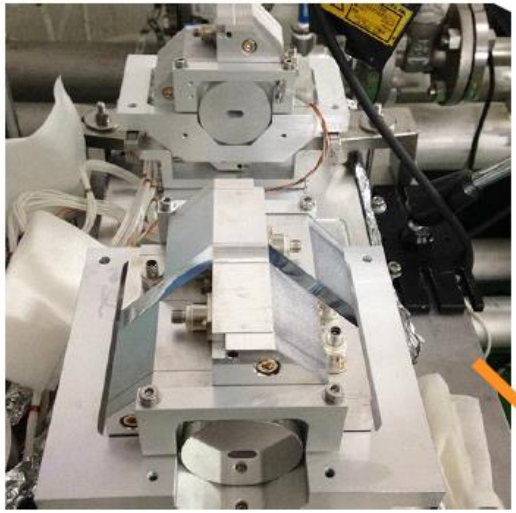
- Test accelerator in Japan using 1.3 GeV electron beam
- Original aim to demonstrate super-low beam emittance required for future e+e- collider achieved 2001
- ATF2 collaboration now has two goals for beam:
  - 37 nm beam size
  - nm level beam stability

Beam stabilisation at ATF2

- Feedback system used to measure position offset of first bunch in train to provide stabilisation for second bunch
- Waveforms from low-Q C-band 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

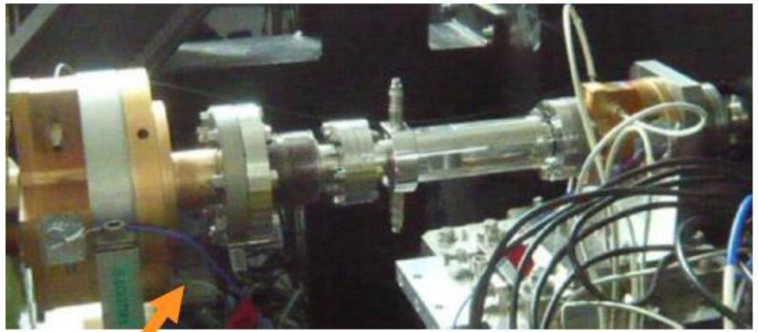


FONT IP feedback system

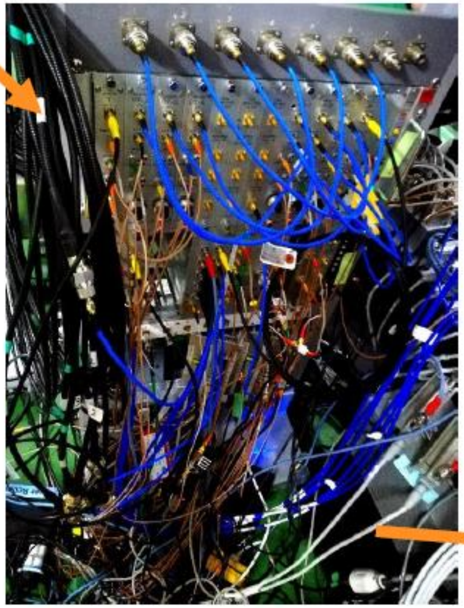


- Cavity Beam Position Monitors - IPA, IPB and IPC.
- We are now able to attenuate the three BPMs individually, allowing us to use all three BPMs while working in nominal optics.

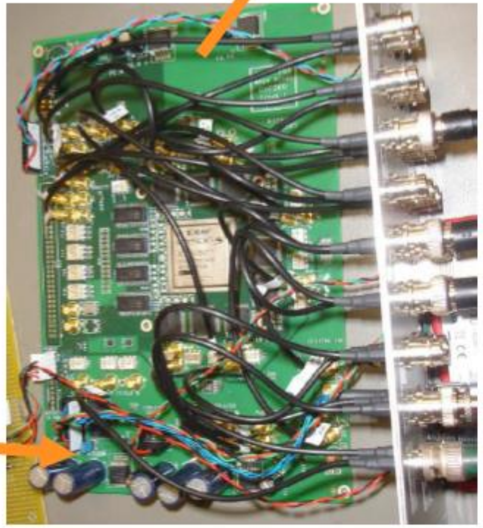
- Strip-line kicker and specialised amplifier used to provide correction.



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

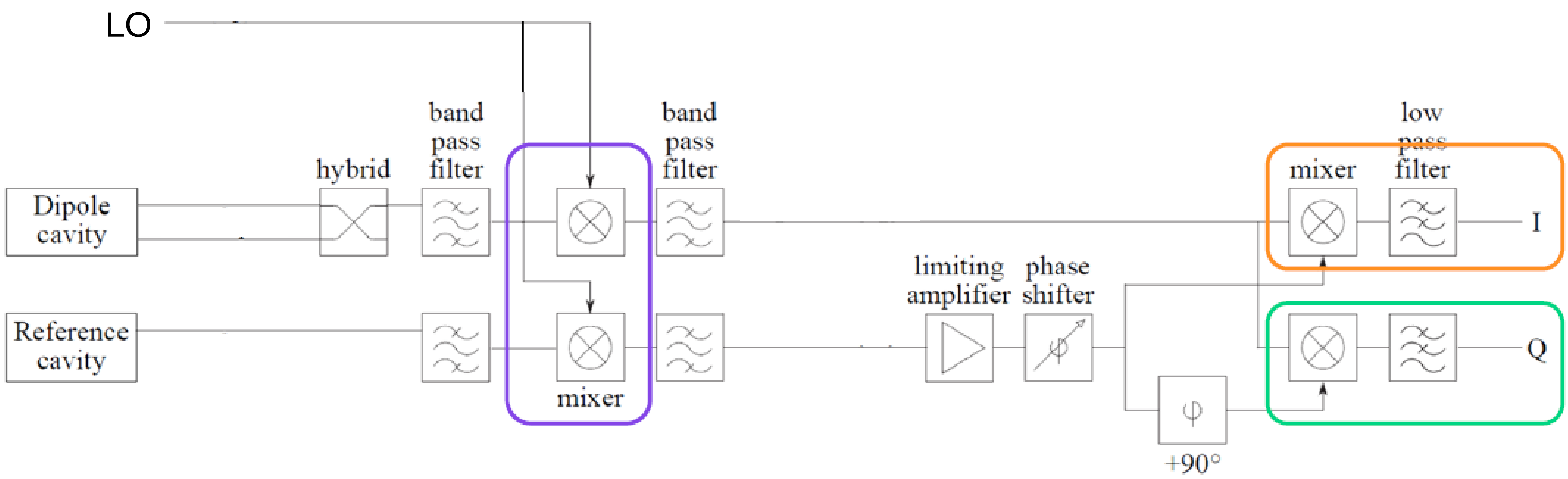


- The signals output from the processing electronics are sampled by the ADCs and used to calculate a bunch position.



- 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

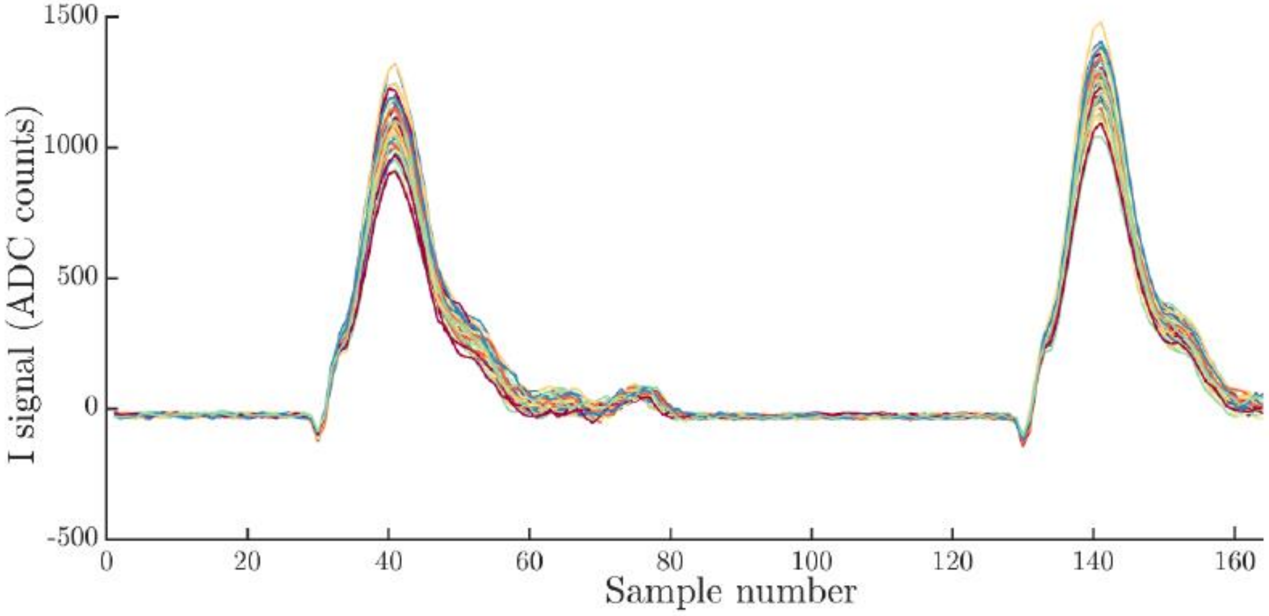
Bunch position given by $y = \frac{1}{k}\left(\frac{I}{q}\cos\theta + \frac{Q}{q}\sin\theta\right)$ where θ, k are calibration parameters

Measuring I and Q

Single sample vs. sample integration

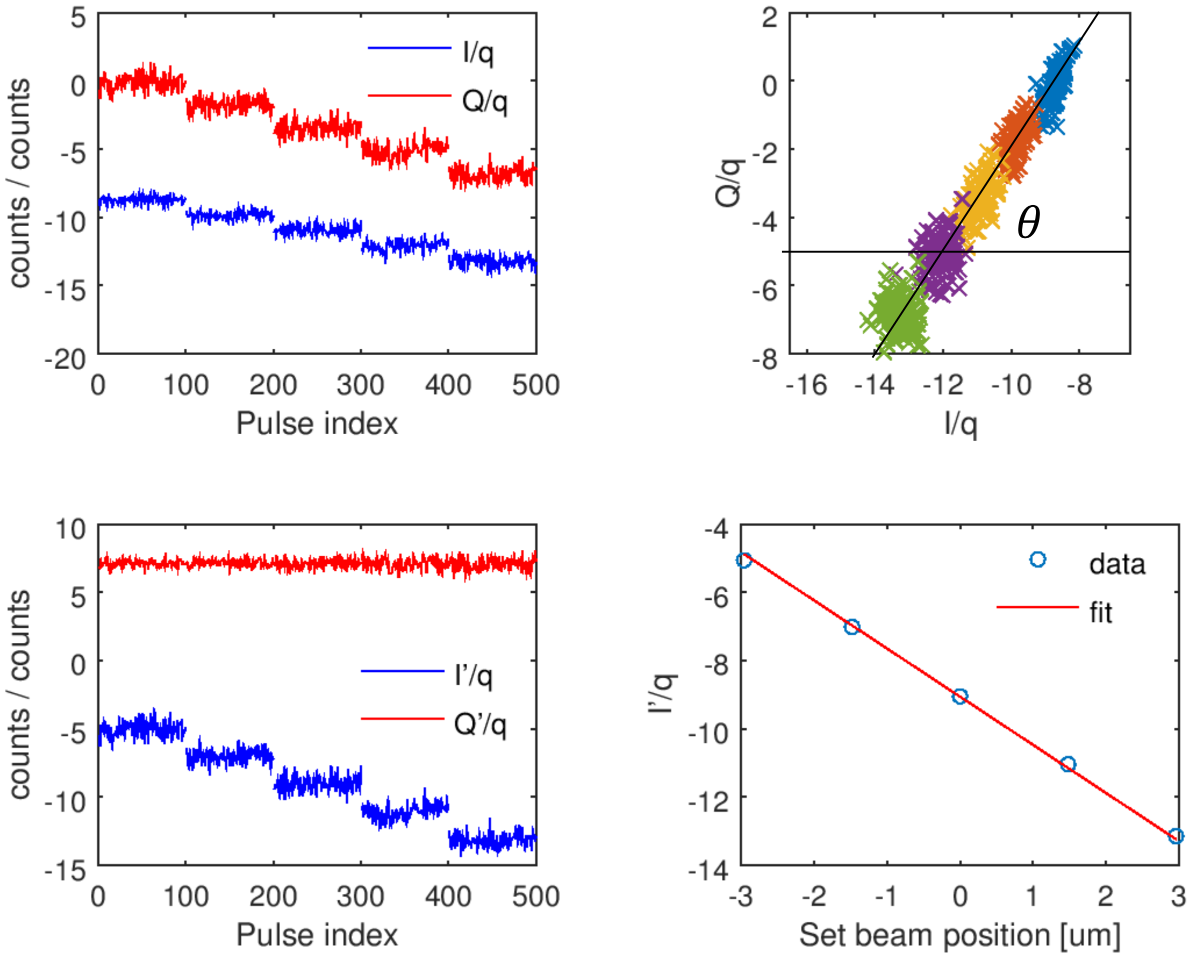
- **Single sample:** I, Q and q values for a given bunch obtained from a single sample of the waveform.
- **Sample integration:** I and Q values obtained by integrating the waveform over a range of samples. This can improve the signal-to-noise ratio (and hence the resolution) of the position measurement.

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.

Example calibration

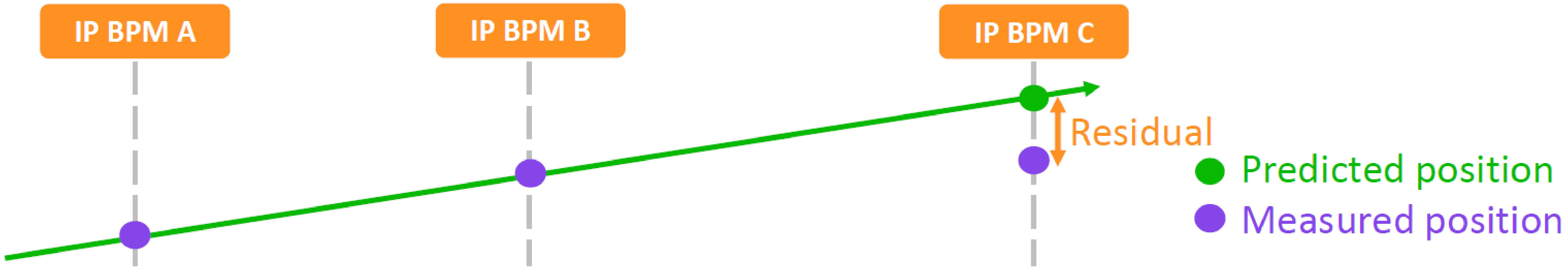


- Beam displaced by known amount relative to BPM using movers
- Both I and Q waveforms change in response
- θ found from plot of I vs. Q
- This enables I' (position) and Q' (tilt) to be calculated
- k found from plot of I' vs. set position

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.

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



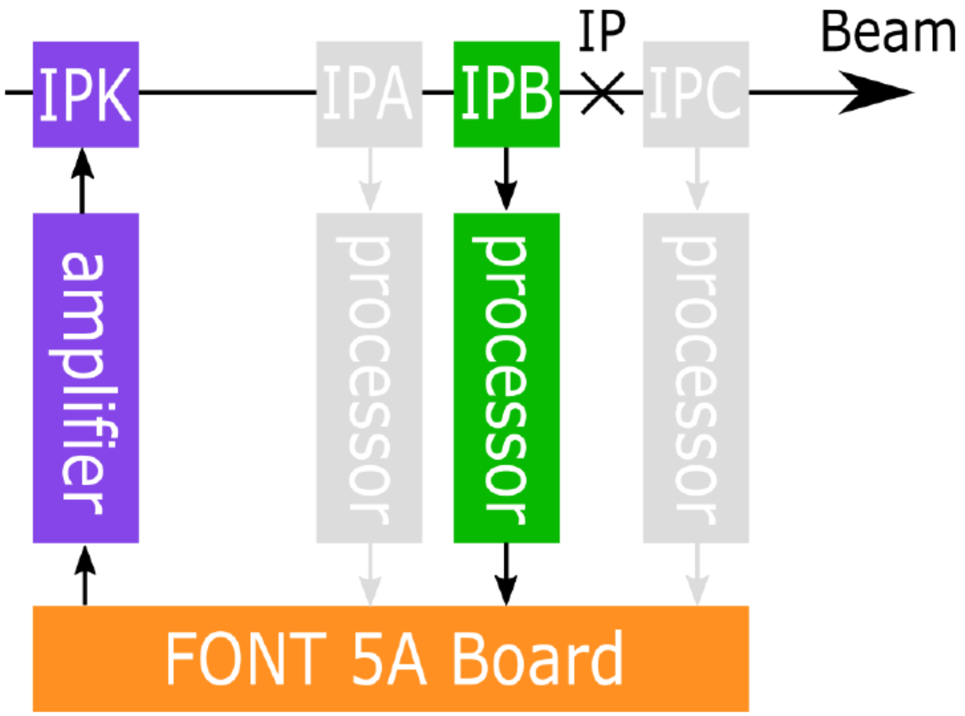
Best Resolution Run (19/04/18)

N = 400
Position jitters (um): IPA 0.45461, IPB 0.28977, IPC 0.35818
Mean position (um): IPA -0.18721, IPB -0.42826, IPC 3.8979

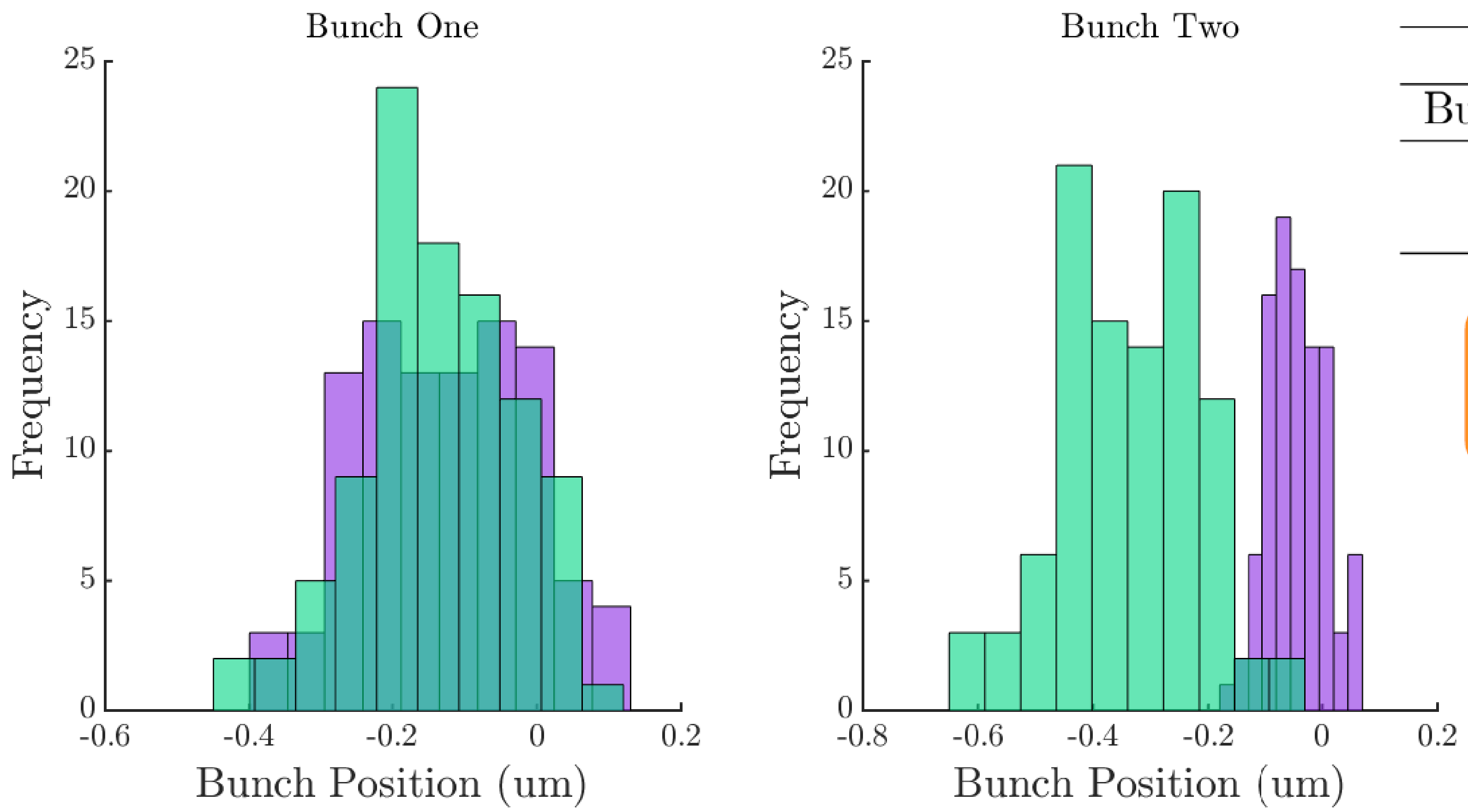
Resolution	IPA (nm)	IPB (nm)	IPC (nm)	Justification
Geometric	20.6 ± 1.0	20.6 ± 1.0	20.6 ± 1.0	-
Fit to position (fit for k)	20.4 ± 1.0	20.5 ± 0.8	20.3 ± 0.8	Fit out error in k
Fit to position and charge	19.9 ± 0.9	19.9 ± 0.8	19.7 ± 0.9	Fit out error in k and position-charge correlation
Fit for k and theta (fit to I and Q)	20.3 ± 1.0	20.3 ± 0.8	20.2 ± 0.9	Fit out error in k and theta.
Fit for k and theta and to charge	19.6 ± 0.9	19.6 ± 0.8	19.6 ± 0.8	Fit out error in k and theta, and position-charge correlation.
Fit for k, theta, charge and self Q'	19.5 ± 0.9	19.6 ± 0.8	19.2 ± 0.8	Fit out all of the above, and also residual position information in Q', or Q' coupling in through phase jitter.

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

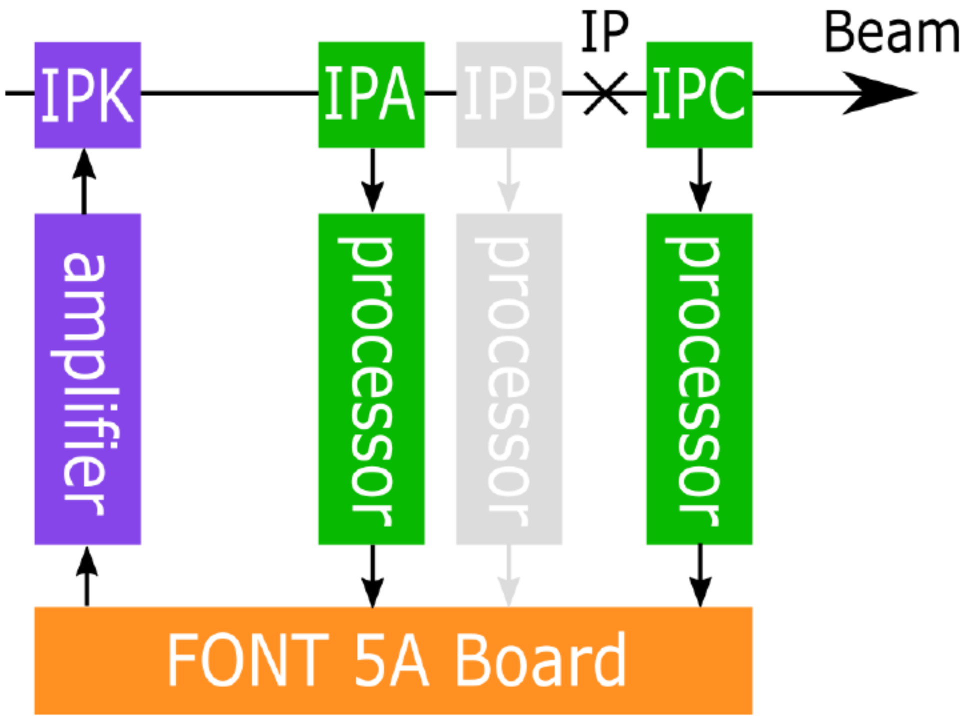
Feedback stabilising to:
50 ± 4 nm.

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

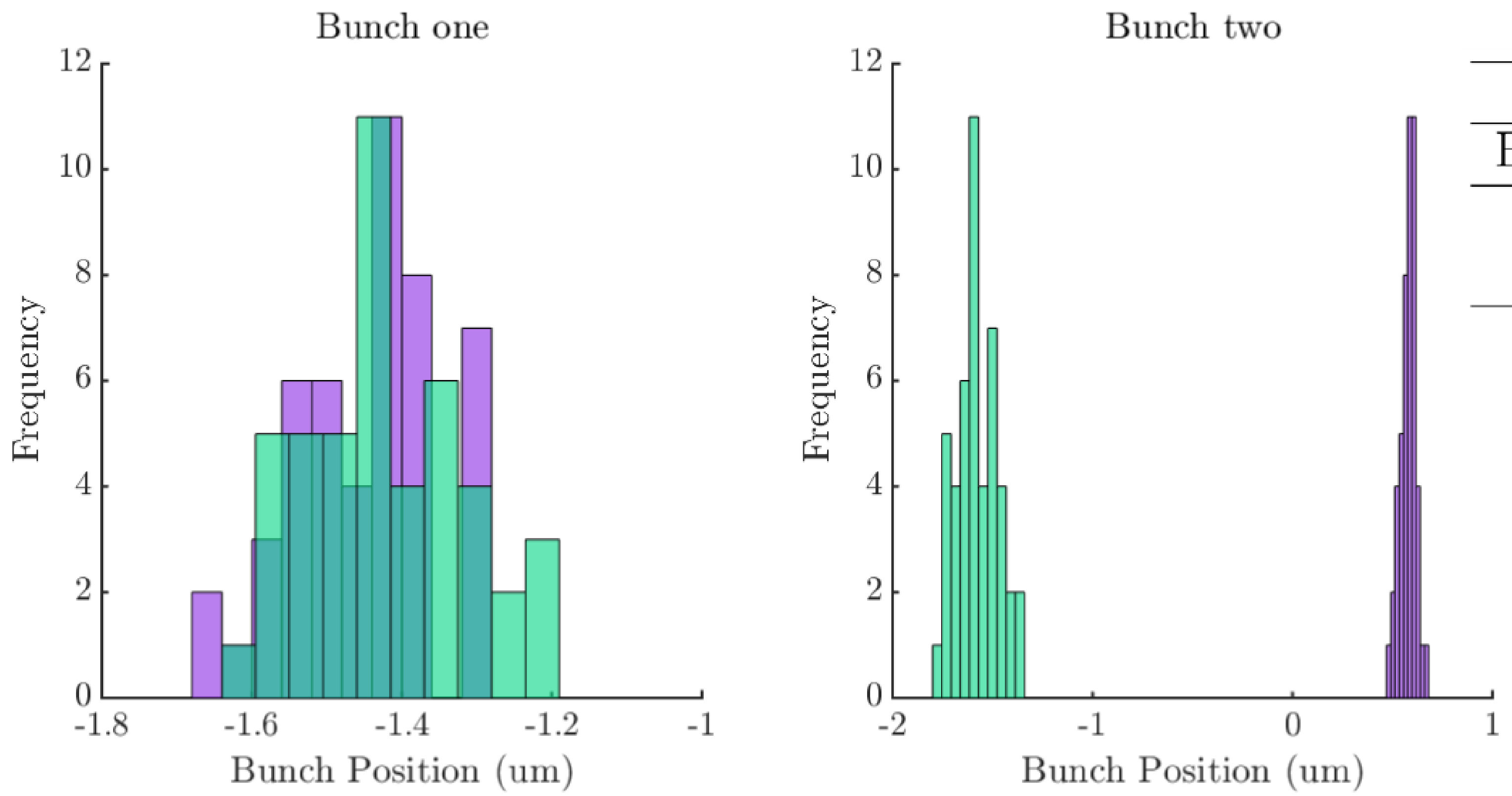
- 10 samples integrated.
- Stabilisation below 55 nm was repeatable.

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%

Summary

- Best resolution ever measured: ~20 nm
- Best feedback performance:
  - 1-BPM mode
    - Previous best single-sample feedback: jitter of corrected bunch = **74 nm**
    - Reduced to **50 nm** by integrating 10 samples
- 2-BPM mode
    - Previous best single-sample feedback: jitter of corrected bunch = **68 nm**
    - Reduced to **41 nm** by integrating 5 samples