Summary of FONT nanometre-level beam stabilisation results at KEK ATF2

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Outline

Background

- Introduction to the ATF2
- (Feedback On Nanosecond Timescales) FONT system

Intra-train, dual-phase upstream feedback system

- Performance of a stripline BPM feedback system

Results of IP BPM resolution studies

- Method of resolution estimation
- Best BPM resolution results

Results of feedback studies

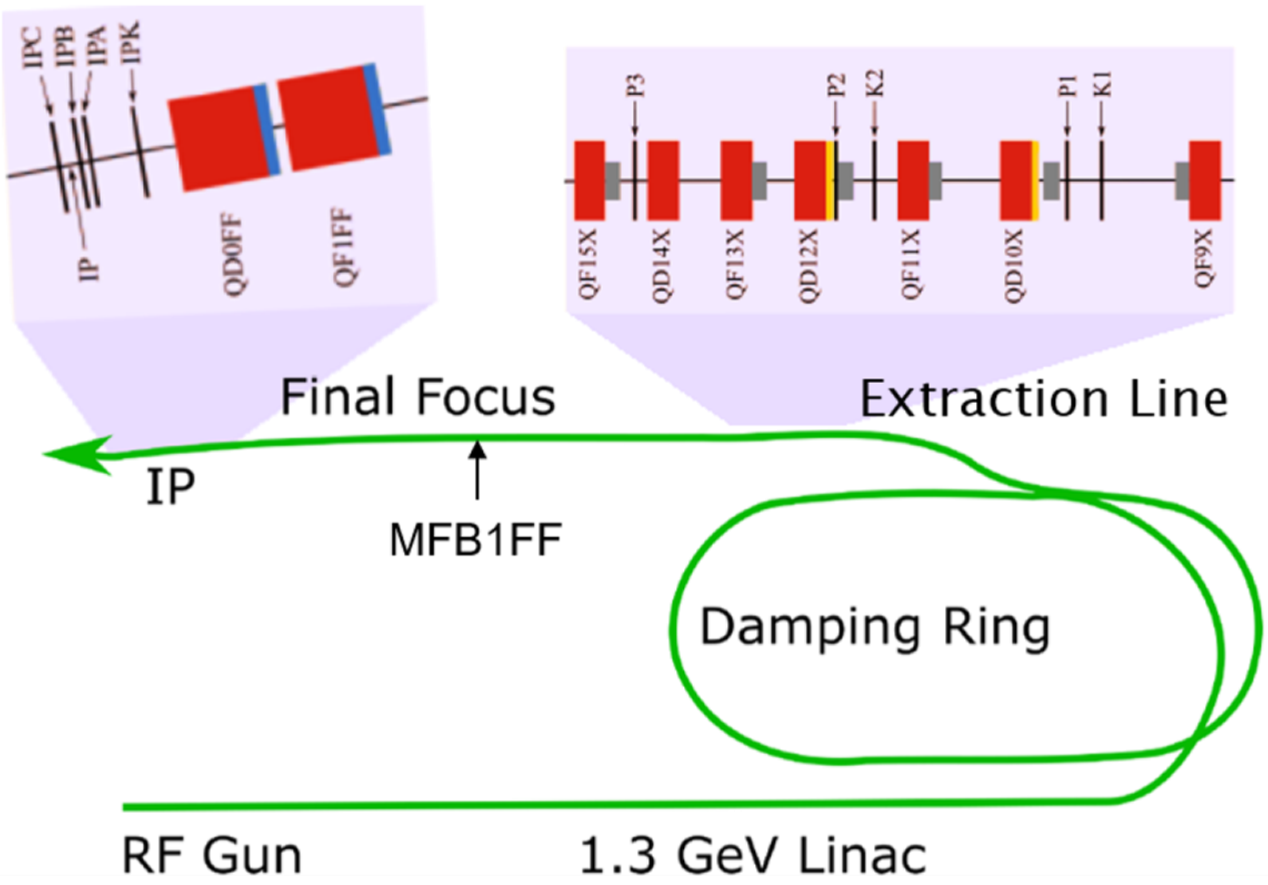
- 1-BPM feedback
- 2-BPM feedback

Summary

Accelerator Test Facility

Accelerator Test Facility

- The Accelerator Test Facility (ATF2) at KEK develops technology and techniques needed for future linear colliders.
- The ATF2 has a low emittance beam and a final focus which is a prototype for the ILC and CLIC. The facility has two primary goals:
  - **Goal 1: Small beam size** (37 nm)
  - **Goal 2: Beam stabilisation** (nm-level)
- Typically configured for trains of two bunches with 280 ns separation as this gives high bunch-to-bunch position correlation.
- FONT have extraction line and IP feedback systems.

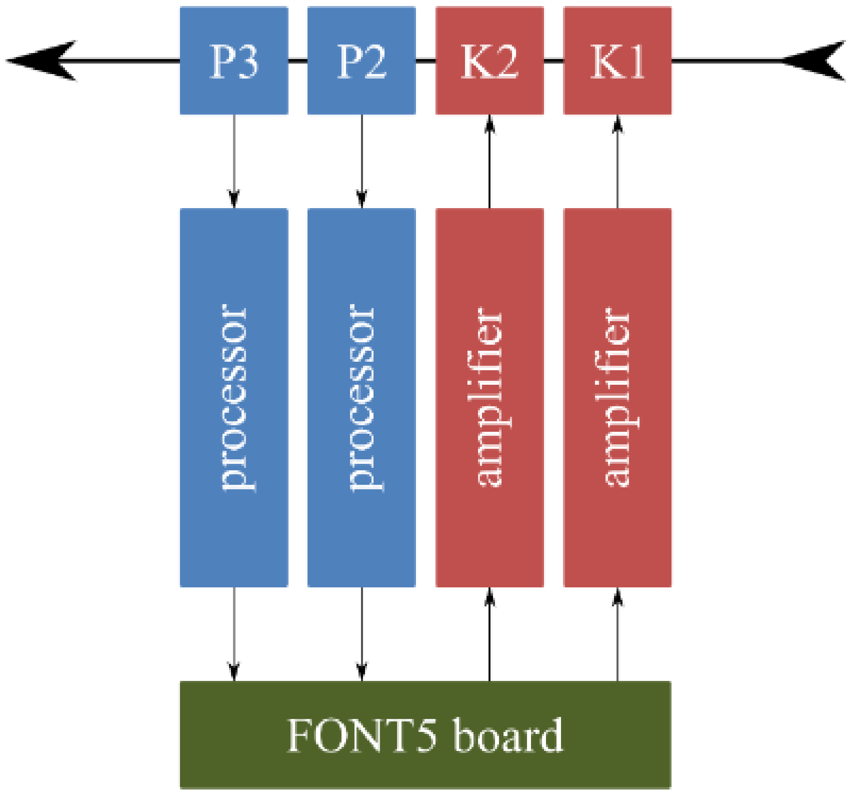


G. White *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 112, p.034802, (2014)

Extraction-line feedback system

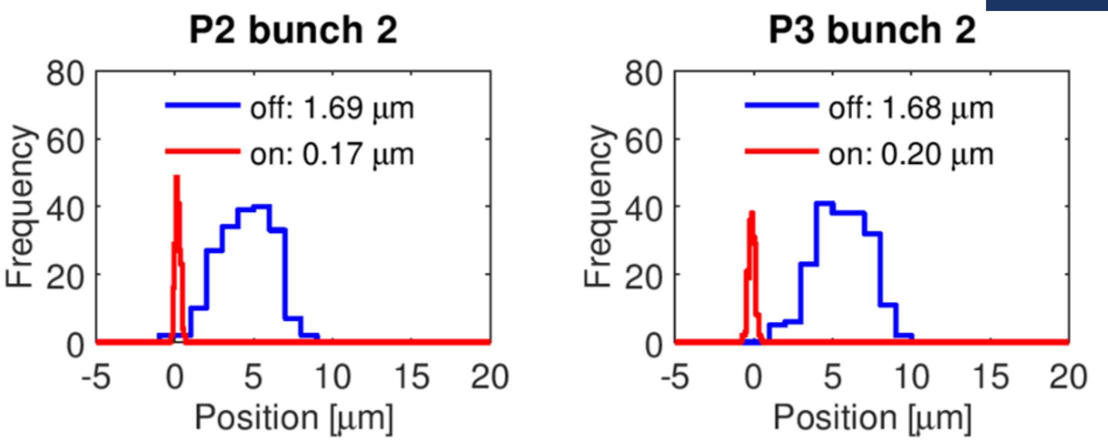
Extraction-line feedback system

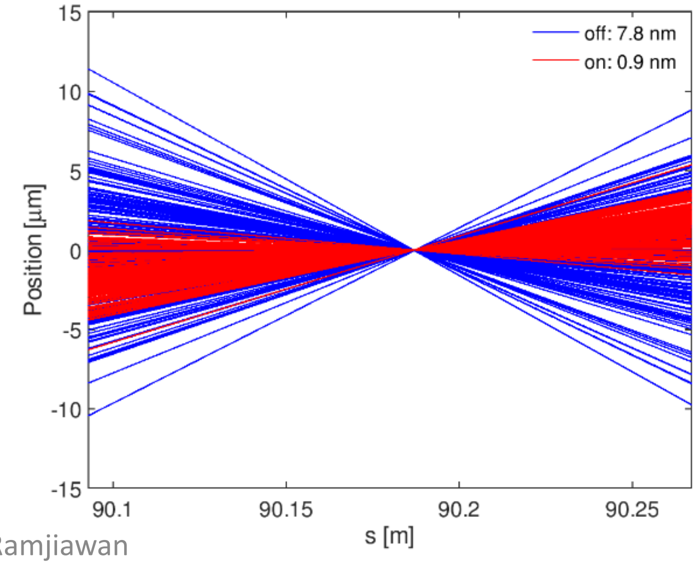
- The beam position is measured using two 12 cm stripline BPMs (P2 and P3).
- Low-latency processing electronics allow for a bunch calculation to be determined on the timescale of the bunch spacing (150 – 300 ns).
- Difference (Δ) and sum (Σ) signals are combined to produce signal $\frac{\Delta}{\Sigma}$, which is proportional to the transverse bunch offset.
- The bunch position correction is then applied by stripline kickers K1 and K2.
- Recent upgrades to the BPMs have increased the single-shot, real-time position resolution of the system to ~150 nm for a beam charge of 1.3 nC.



Feedback results

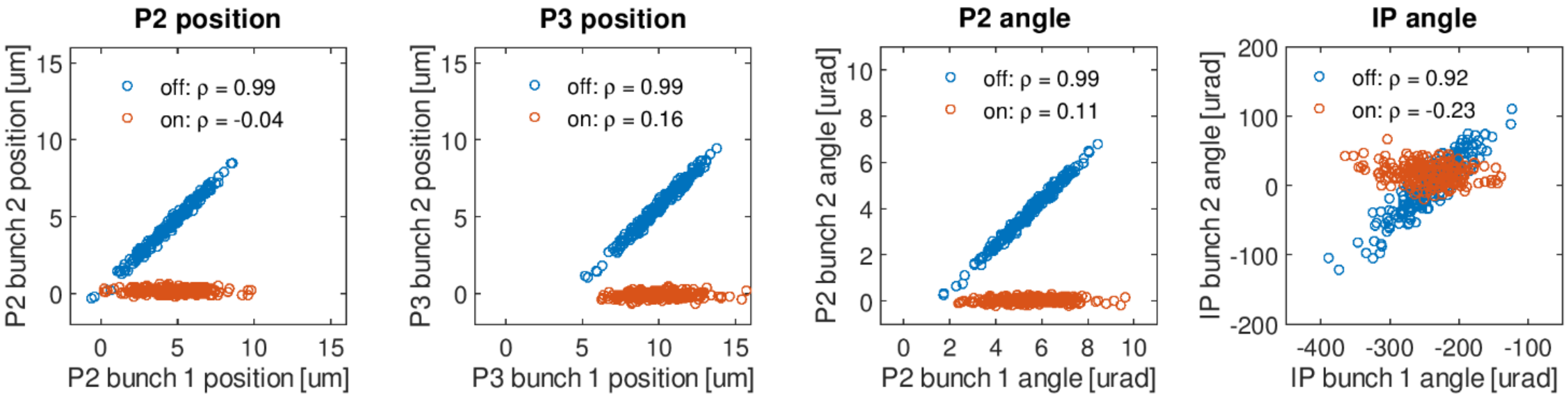
- Intra-train feedback was performed on trains of two bunches separated by 274.4 ns.
- Feedback was operated in an interleaved mode to allow for a direct comparison between feedback *off* and *on*.
- Feedback achieved **position** stabilisation from:
  - $1.69 \pm 0.09\ \mu\mathrm{m}$ to $\mathbf{165 \pm 8\ nm}$ at P2.
  - $1.68 \pm 0.08\ \mu\mathrm{m}$ to $\mathbf{200 \pm 10\ nm}$ at P3.
- Using a model of the ATF2 beamline, transfer matrices can be calculated in order to infer the stabilisation at the IP of:
  - $7.8 \pm 0.4\ \mathrm{nm}$ to $\mathbf{0.86 \pm 0.04\ nm}$
  - Reduction in the angle jitter of $\mathbf{40.7 \pm 2.1\ \mu rad}$ to $\mathbf{14.6 \pm 0.7\ \mu rad}$ when propagated to the IP.





Bunch positions propagated to the IP.

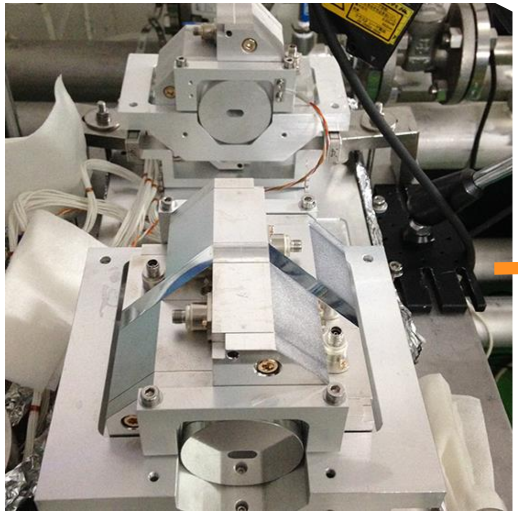
Bunch-to-bunch position correlation

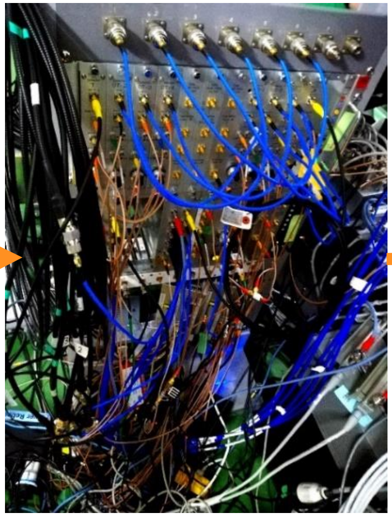


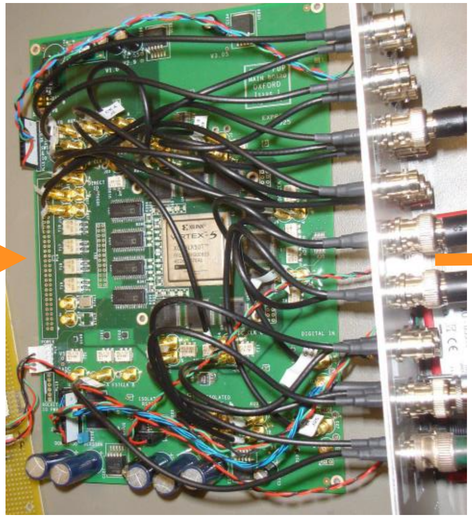
- The plots above show the bunch-2 positions plotted against the bunch-1 positions with feedback off and on, demonstrating a reduction in the correlation from ~99% to close to 0%.
- The feedback system also achieved **angle** stabilisation between P2 and P3 from:
  - 1.26 ± 0.06 µrad to **107 ± 5 nrad**.

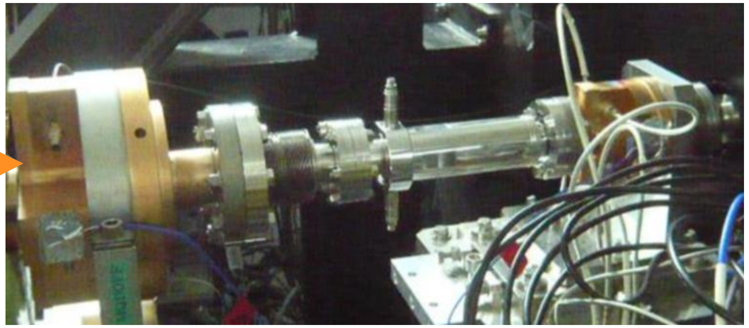
IP feedback system

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.

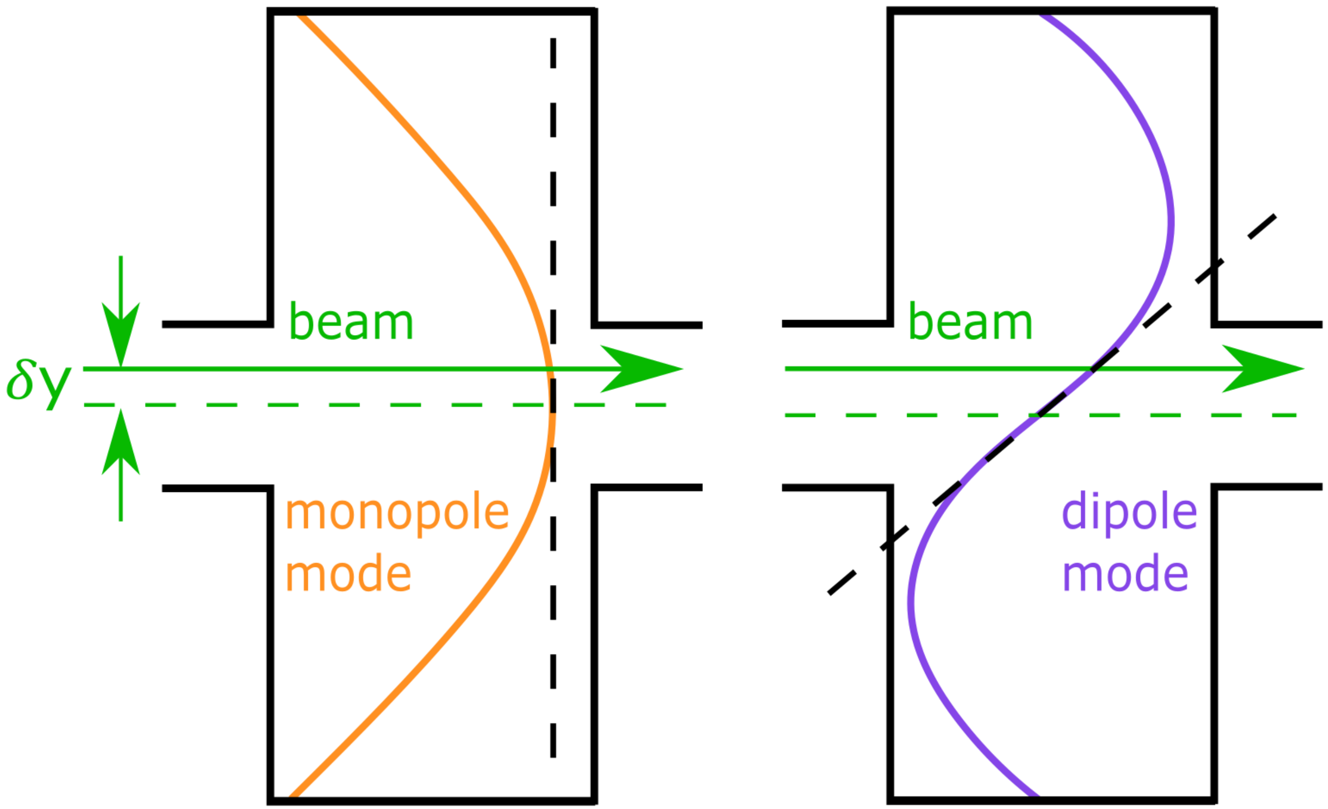
- Two-stage processing electronics: down-mix and process cavity signals.
- Produces two signals at baseband: I and Q which contain beam position and angle information.

- 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.

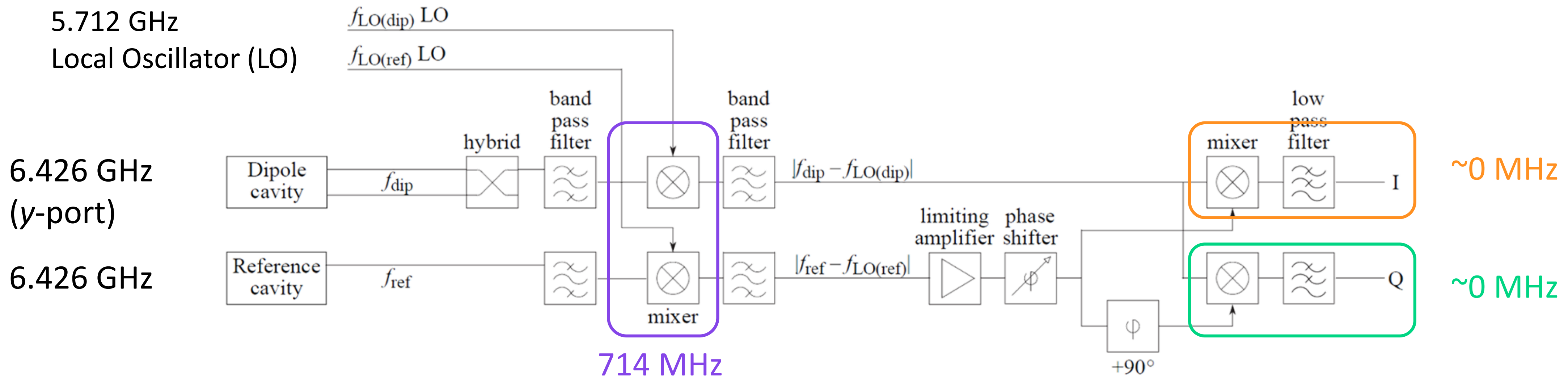
- Stripline kicker and specialised amplifier (provided by TMD Technologies Ltd) used to provide feedback correction.
- Amplifier provides ±30 A of current to drive the kicker, with a fast rise time of 35 ns to reach 90% of peak output.

BPM Signal Processing

- Separate cavities for the extraction of the monopole and dipole modes.
- The extracted monopole mode has to first order only charge dependence.
- The extracted dipole mode has charge and position dependence.
- These high-frequency signals need down-mixing and mixing to produce a baseband signal proportional to only the bunch offset.



BPM Signal Processing



1st 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.

2nd 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**.

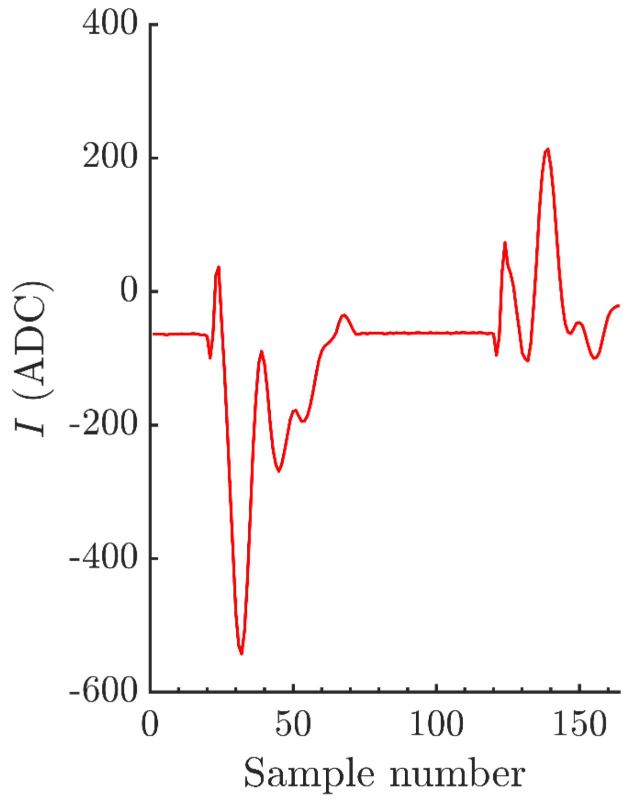
Figure from N. Blaskovic, DPhil. thesis

Sample integration

- **Single sample**: only a single sample of each of the *I* and *Q* waveforms are used.
- **Sample integration**: integration over a multi-sample window is used (up to 15 samples).
- System latency of **230 ns** when integrating 15 samples.
- The *I* and *Q* signals are charge normalised and combined to produce a position signal:

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

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



Example I signal waveform, in two bunch operation.

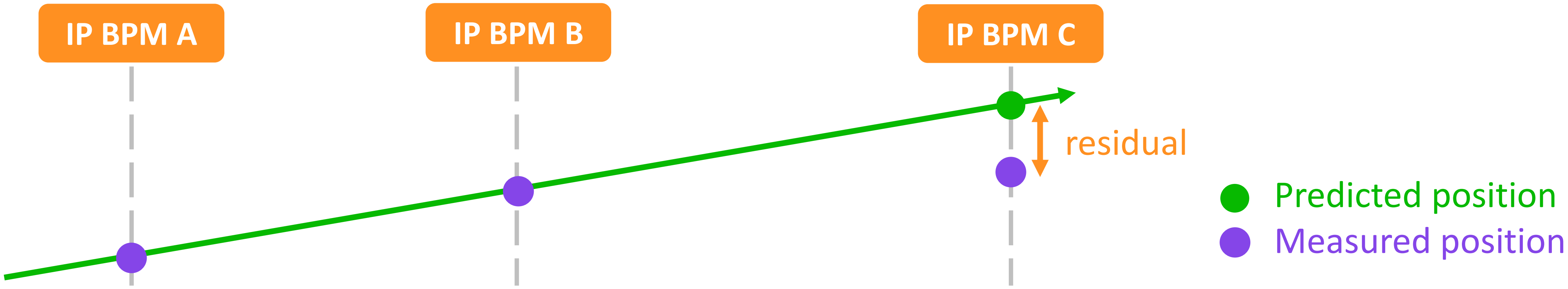
BPM Resolution

Calculating the Resolution

- The known beam transport through the three BPMs means the position at any BPM can be **predicted** using the positions of the beam at the other two BPMs.
- Bunch position is both **predicted** and **measured** at a BPM, the difference between the two is the residual which is calculated for many consecutive triggers. The resolution is defined as the standard deviation of the residuals.

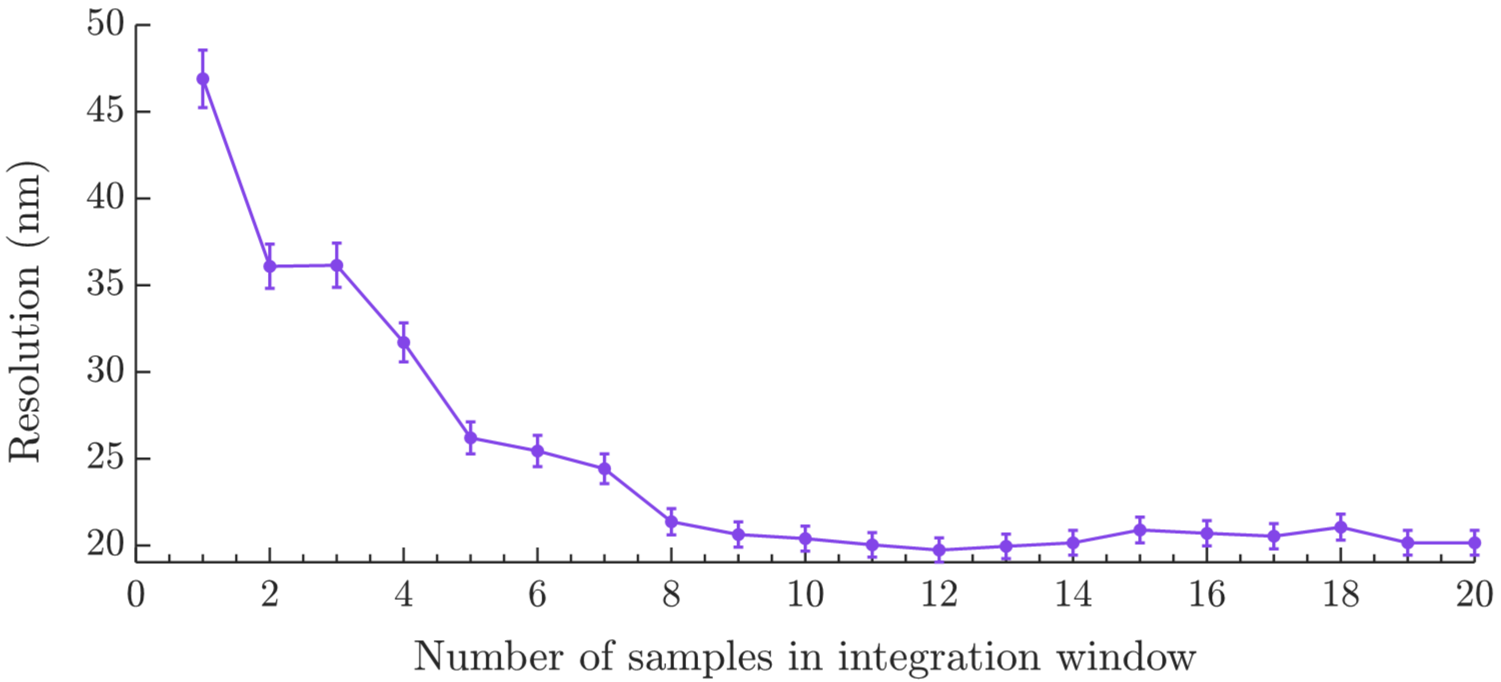
$$\text{residual} = y_{\text{pred}} - y_{\text{meas}}$$

$$\text{resolution} = \text{std}(\text{residual})$$



BPM resolution

- Resolution improves by more than a factor of two using sample integration.
- Estimations of the resolution with sample integration are more stable and consistent between data sets as single-sample fluctuations are averaged over.
- Resolution of ~20 nm can be reproducibly achieved with integration.

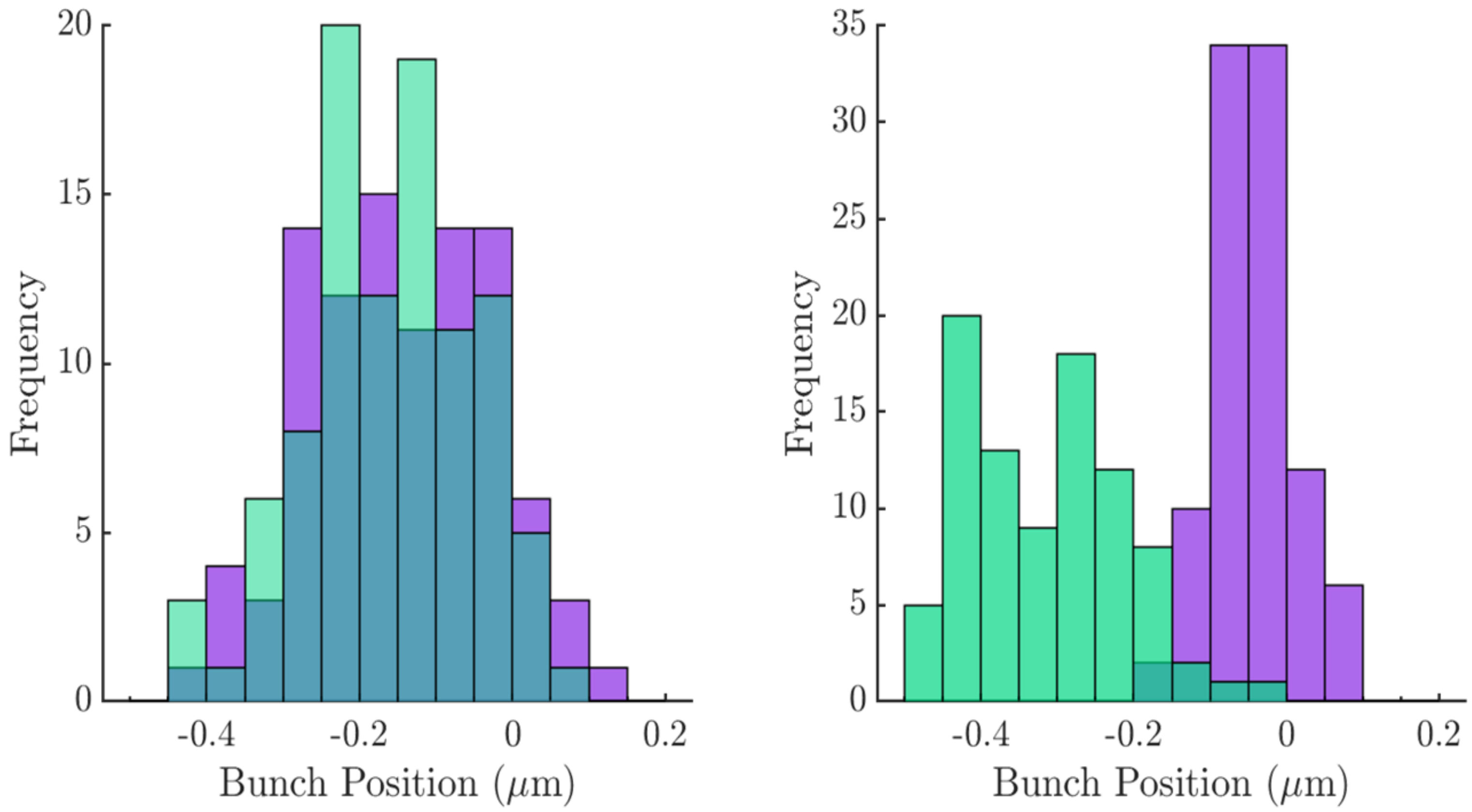


	Single-sample	11-sample
Resolution	46.9 ± 1.7 nm	19.0 ± 0.4 nm

Feedback results

1-BPM Feedback Results

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

Ten-sample integration window.

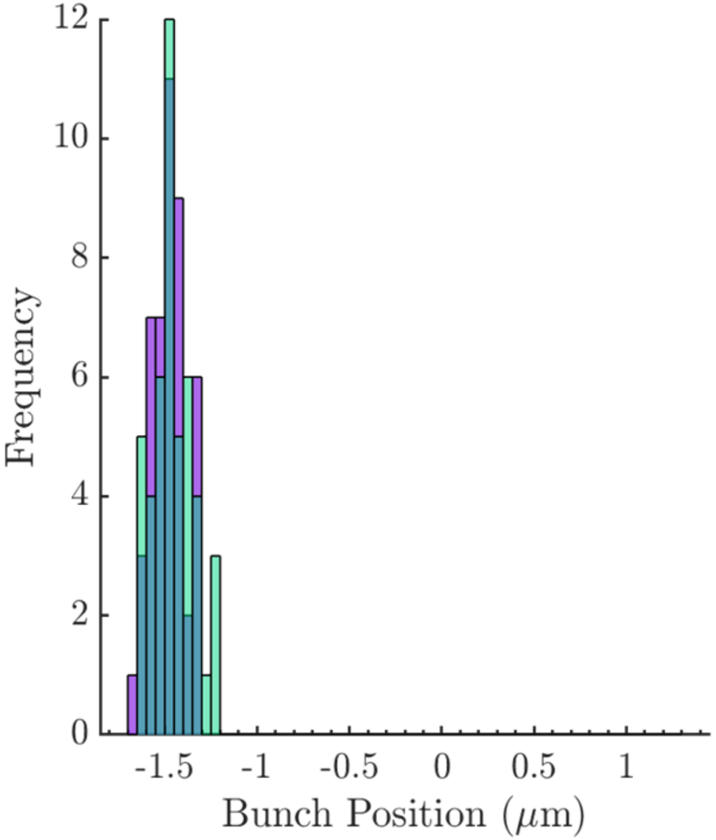
- Feedback **off** correlation: **84%**
- Feedback **on** correlation: **−26%**

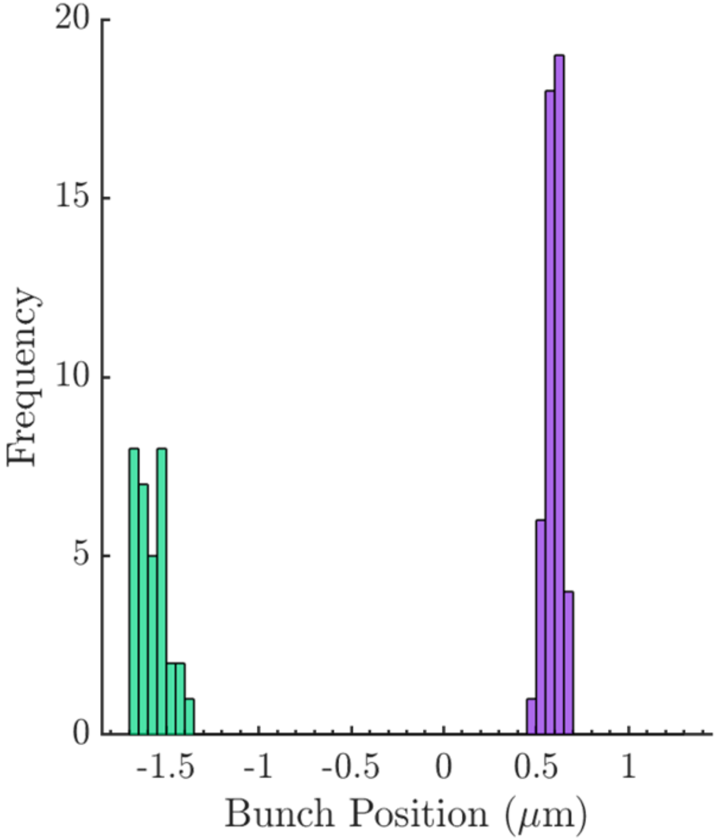
Stabilisation below 55 nm was reproducible.

Shows significant improvement over single-sample performance: 74 nm.

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.

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

The correlation is not fully removed - feedback gain set too low; higher gain may offer better performance (up to **25 nm**).

Shows significant improvement over single-sample performance: 57 nm.

Summary

- Low-latency dual-phase feedback was performed using the upstream system demonstrating local stabilisation to **~200 nm**.
- Improvements to the IP feedback firmware allow for the use of an integrated period of the BPM waveform. Integration is shown to improve the useable BPM resolution from ~**45 nm** to ~**20 nm**.
- This was tested with two different feedback modes:
  - 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 with single-sample operation.

Thank you for listening