Development of a Low-Latency, High-Precision, Beam-Based Feedback System Based on Cavity BPMs at the KEK ATF2

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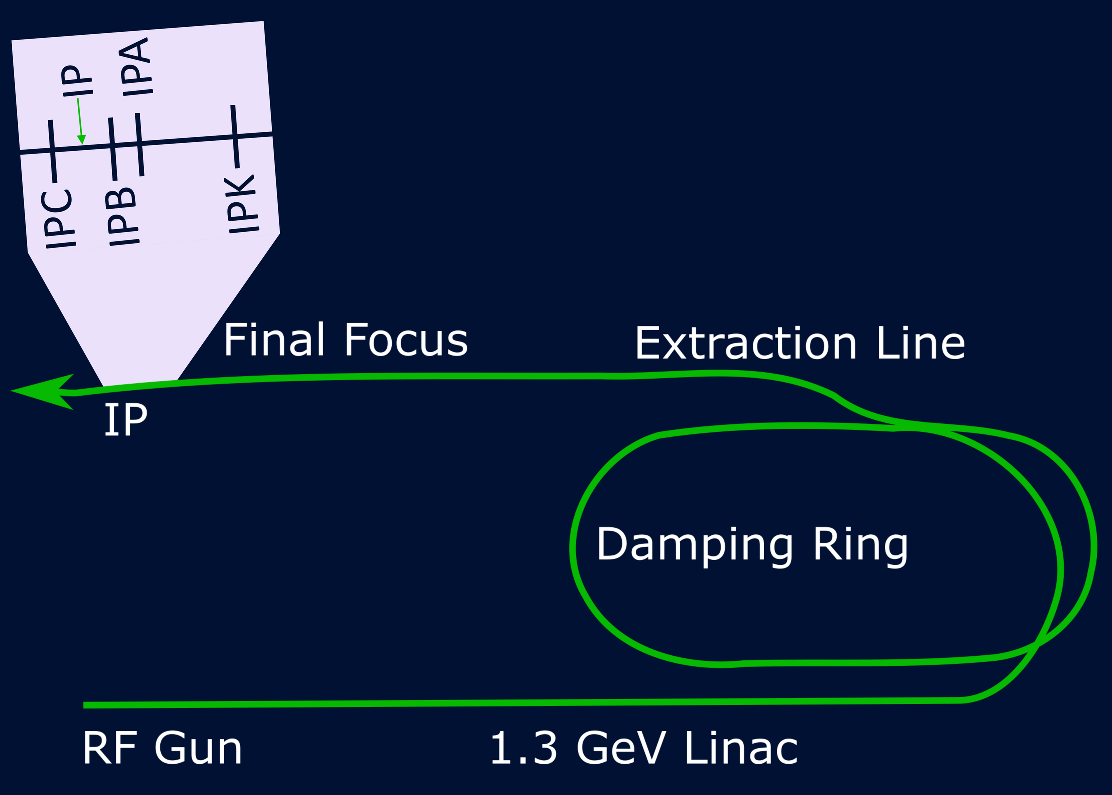
Abstract

A low-latency, intra-train feedback system employing cavity beam position monitors (BPMs) has been developed and tested at the Accelerator Test Facility (ATF2) at KEK. The feedback system can be operated with either position information from a single BPM to provide local beam stabilisation, or by using position information from two BPMs to stabilise the beam at an intermediate location. The correction is implemented using a stripline kicker and a custom power amplifier, with the feedback calculations being performed on a digital board built around a Field Programmable Gate Array (FPGA). The addition of indium sealing to the BPMs to increase the cavities' Q-values has led to improvements to the BPM system resolution, with current measurements of the resolution of order 20 nm. The feedback performance was tested with beam trains of two bunches, separated by 280 ns and with a charge of ~1 nC. For single- (two-)BPM feedback, stabilisation of the beam has been demonstrated to below 50 nm (41 nm). Ongoing work to improve the feedback performance further will be discussed.

Introduction

The Accelerator Test Facility (ATF2), KEK, is a test-bed for the ILC, with a prototype for the ILC final focus [1].

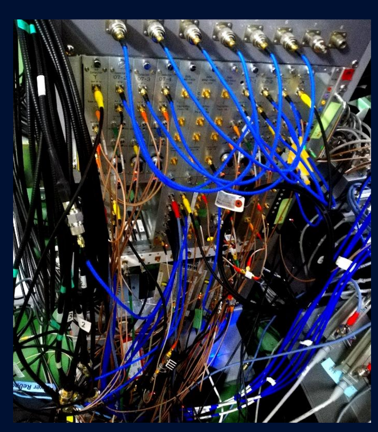


At the ATF2, the FONT (Feedback On Nanosecond Timescales) IP feedback system uses C-band cavity beam position monitors (BPMS), IPA, IPB and IPC to measure the beam orbit, and a stripline kicker, IPK, to implement the feedback correction. The system acts on a two-bunch train with 280 ns bunch separation, stabilising bunch-2 based on position measurements of bunch-1, thus 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 235 ns has been demonstrated.

Cavity BPMs

The IP feedback system has three dipole cavity BPMs and one reference (monopole) cavity BPM. The signals from these BPMs are processed with a two-stage system and used by a FONT5A digital board to compute a correction signal [2].

Cavity BPMs

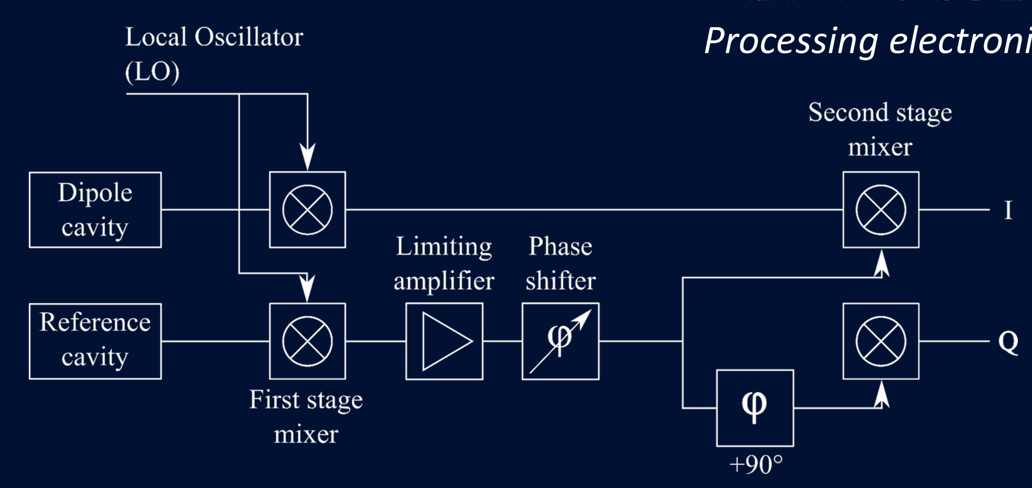


Processing electronics

Signal Processing

First stage: 6.4 GHz monopole and dipole modes are down-mixed using a common 5.7 GHz Local Oscillator (LO) signal to 714 MHz, thus, retaining their relative phases.

Second stage: the monopole and dipole modes are mixed both in-phase and in-quadrature to produce orthogonal baseband signals I and Q.



Two-stage BPM signal processing (simplified diagram) [2]

FONT5A Board

FONT5A Board

The I and Q signals are digitised at 357 MHz and the bunch correction, V, is computed from these signals on a Field Programmable Gate Array (FPGA):

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

where k is the calibration constant between BPM response and position, θ_{IQ} is the IQ phase angle, and M is the calibration constant converting a position measurement to a feedback correction in DAC counts. The gain, G, is set to 1 for a beam with 100% bunch-to-bunch correlation and, otherwise, scaled accordingly.

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:

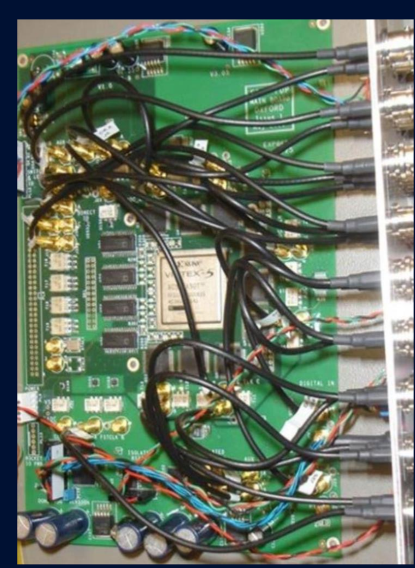
$$Y_2 = y_2 - y_1 + c$$

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:

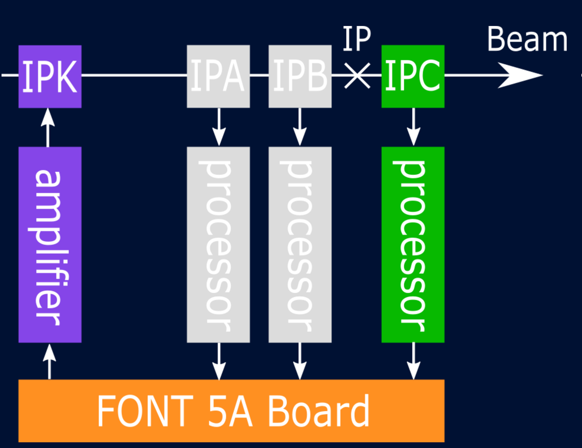
$$\sigma_{Y2}^2 = \sigma_{y1}^2 + \sigma_{y2}^2 - 2\sigma_{y1}\sigma_{y2}\rho_{12}$$

where ρ_{12} is the bunch-to-bunch correlation and σ_{Y_2}, σ_{y_1} and σ_{y_2} represent the jitters on positions Y_2, y_1 and y_2 respectively. The best performance is achieved for ρ_{12}=1 and $\sigma_{y_1} = \sigma_{y_2}$.

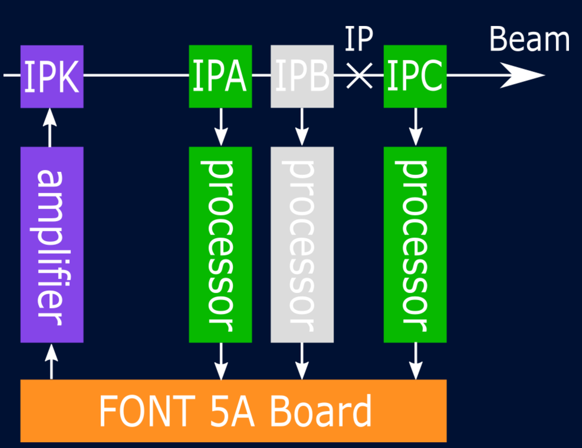


FONT5A digital board

1-BPM & 2-BPM Feedback Configuration



1-BPM feedback: beam position measurement and stabilisation at IPC.



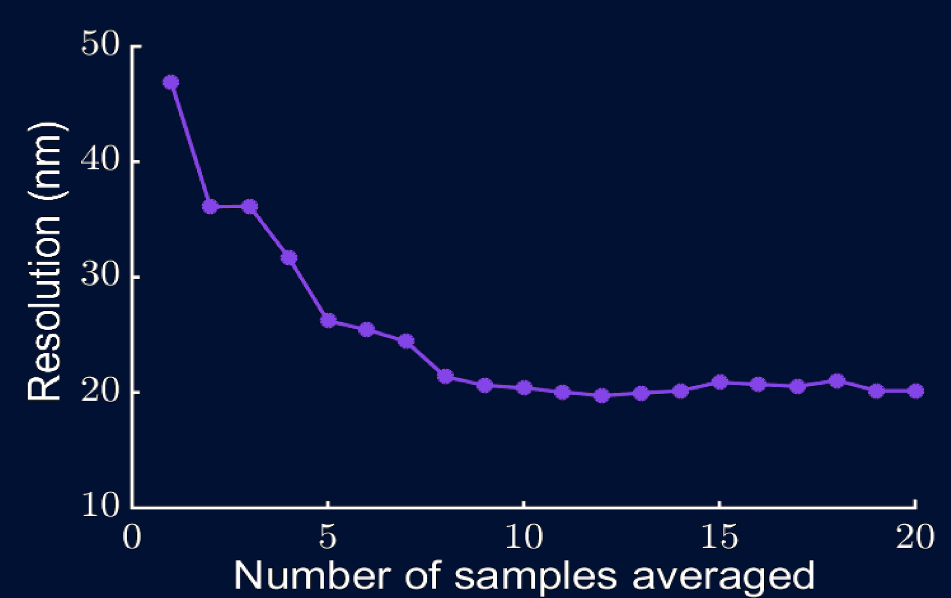
2-BPM feedback: IPA and IPC position measurements interpolated to stabilise at IPB.

For 2-BPM feedback, the resolution of the interpolated measurement is determined from the resolution of the feedback BPMs, σ_{BPM}, and their distance from the location of stabilisation. For stabilisation at IPB, the feedback BPMs IPA and IPC contribute in a ratio 32:64, so that the interpolated resolution is:

$$\sigma_{\mathrm{interp.}} = \sqrt{0.32^2\sigma_{\mathrm{BPM}}^2 + 0.64^2\sigma_{\mathrm{BPM}}^2} = 0.75\sigma_{\mathrm{BPM}}$$

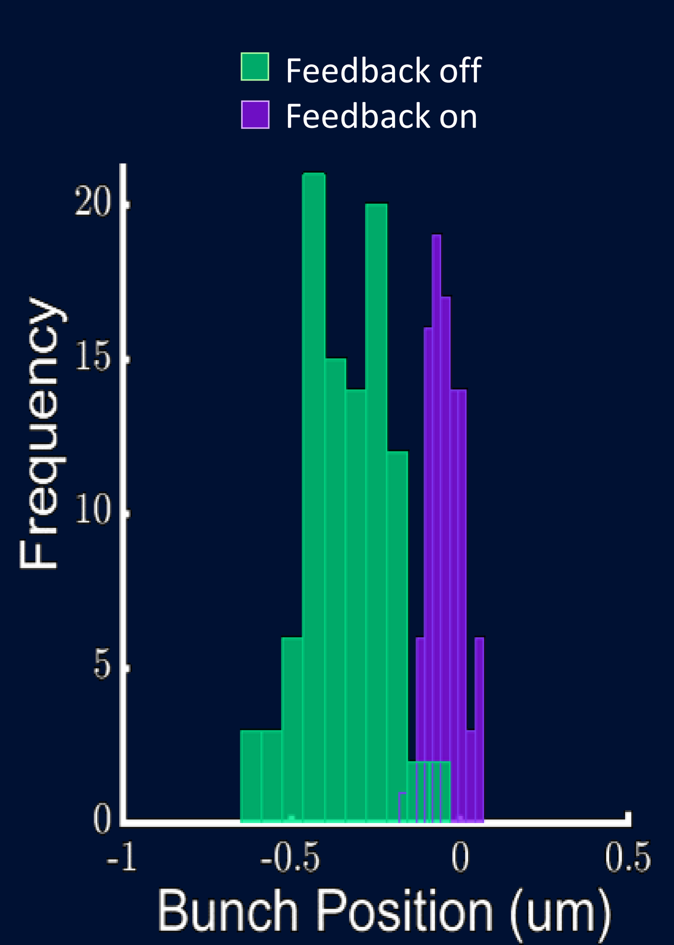
Multi-Sample Feedback

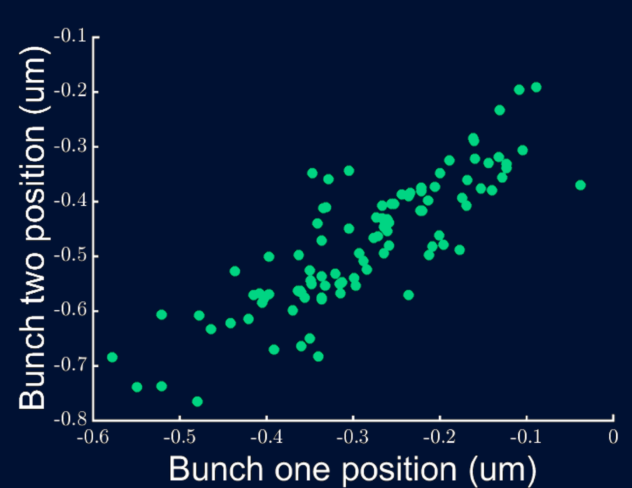
Recent improvements to the firmware mean multiple I and Q samples (within the latency constraint) can be integrated during the feedback calculation. This has been demonstrated to improve the signal-to-noise ratio and, thus, the resolution (see right). A resolution of **20 nm** has been demonstrated by integrating over 12 samples [3].

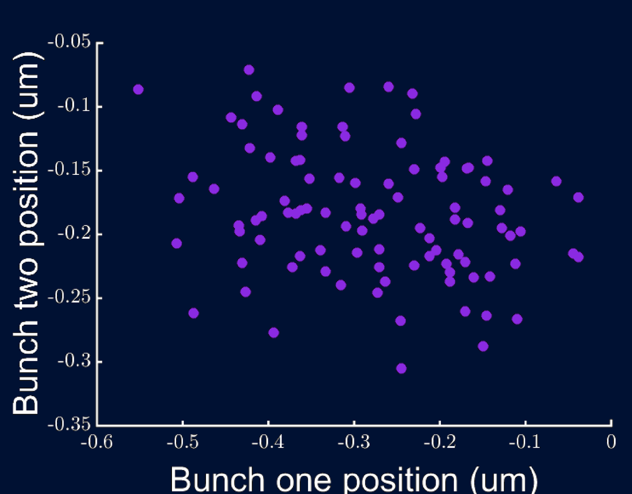


1-BPM Feedback Results

Beam stabilisation to **50 nm** was demonstrated with 1-BPM feedback at IPC, by integrating over 10 samples. Given the incoming bunch jitter and bunch-to-bunch correlation, the expected stabilisation was 65 nm. The feedback exceeds the prediction, suggesting the measured incoming correlation is considerably lower than the true correlation.



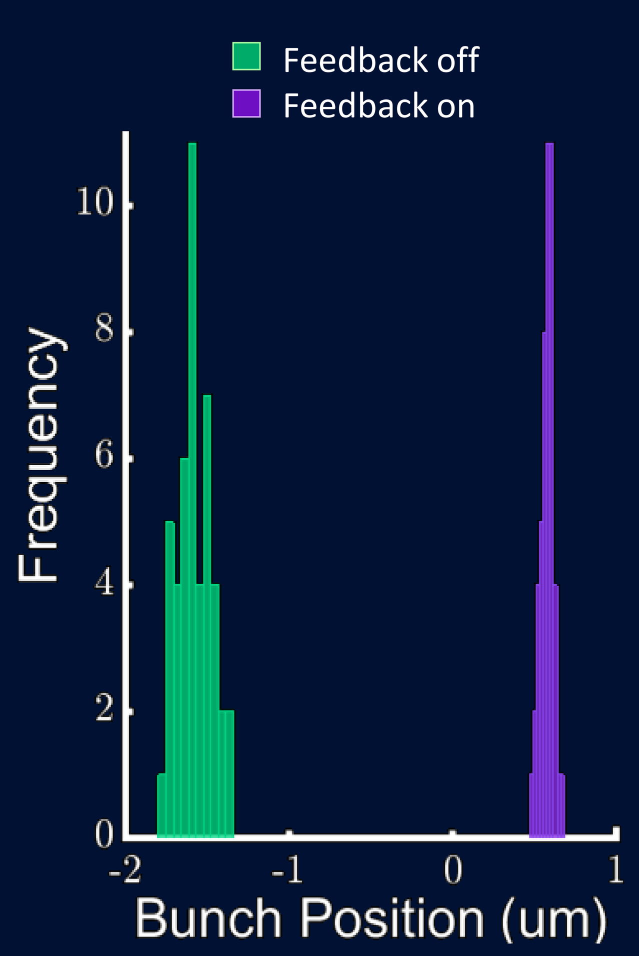


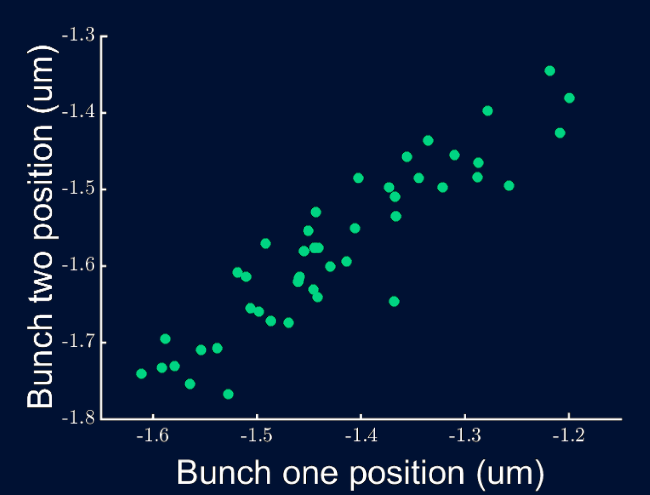


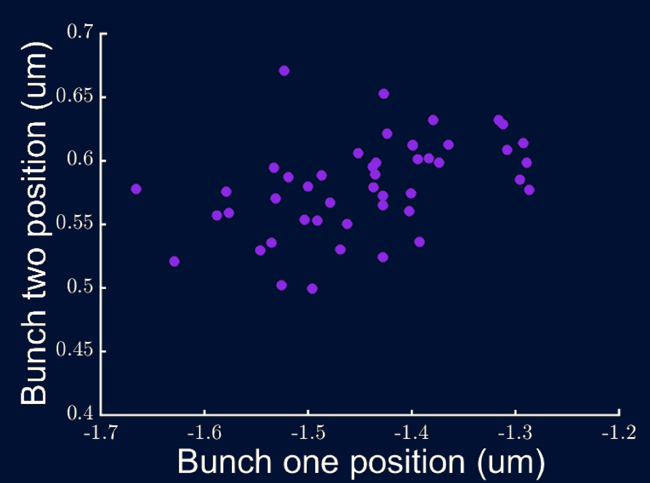
Feedback	Position jitter (nm)		Correlation (%)
	Bunch-1	Bunch-2	
Off	109 ± 11	119 ± 12	$84.0^{+2.5}_{-3.5}$
On	118 ± 12	**50 ± 5**	$-26.0^{+9.8}_{-8.8}$

2-BPM Feedback Results

Beam stabilisation to **41 nm** was demonstrated at IPB with 2-BPM feedback, by integrating over 5 samples. Given the incoming bunch jitter and bunch-to-bunch correlation, the predicted stabilisation was 40 nm, in excellent agreement with the measurement. The correlation has not been fully removed, suggesting the feedback gain, G, was set too low.







Feedback	Position jitter (nm)		Correlation (%)
	Bunch-1	Bunch-2	
Off	106 ± 11	96 ± 10	$91.6^{+1.9}_{-3.2}$
On	106 ± 11	**41 ± 4**	$41.3^{+9.1}_{-12.3}$

Outlook

For future studies we will focus on minimising the pitch of the BPMs with respect to the beam and on optimising the phase of the I and Q components; previous studies have suggested this may improve the system resolution.

For the 2-BPM feedback study, the charge of bunch-2 was ~25% lower than bunch-1 and the resolution was correspondingly poorer. For future studies, we would ideally have a similar charge for both bunches, so as to optimise the resolution for both bunches simultaneously [2].

References

[1] P. Bambade, et al., Phys. Rev. ST Accel. Beams 13 (2010) 042801.
[2] N. Blaskovic Kraljevic, DPhil. Thesis, University of Oxford (2015).
[3] T. Bromwich et al., in Proc. IPAC'18, paper TUZGBD5.

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