REAL-TIME BEAM ORBIT STABILISATION TO 200 NANOMETRES IN SINGLE-PASS MODE USING A HIGH-PRECISION DUAL-PHASE FEEDBACK SYSTEM

D. R. Bett, P. Burrows, G. B. Christian, C. Perry, R. Ramjiawan
John Adams Institute, University of Oxford, UK

Abstract

A high-resolution, low-latency, stripline beam position monitor (BPM) system has been developed for use at particle accelerators and beamlines that operate with trains of particle bunches with bunch separations as low as several tens of nanoseconds, such as future linear electron-positron colliders and free-electron lasers. The system consists of fast analogue stripline BPM signal processors input to a custom FPGA-based digital feedback board which drives a pair of kickers local to the BPMs and nominally orthogonal in phase in closed-loop feedback mode, thus achieving both beam position and angle stabilisation. The feedback system was tested with the electron beam in the extraction line of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. 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. We report the latest results which demonstrate the feedback system operating at this resolution limit and a beam stabilisation performance of 200 nm.

INTRODUCTION

The designs for the International Linear Collider (ILC) [1] and the Compact Linear Collider (CLIC) [2] require nanometre-sized beams stabilized in position to the nanometre level at the interaction point (IP). To demonstrate that this degree of position stability is feasible, the Feedback On Nanosecond Timescales (FONT) project [3] operates a position and angle feedback system at the Accelerator Test Facility (ATF) of the High Energy Accelerator Research Organization (KEK) in Japan. The layout of the ATF is shown in Fig. 1. The beam is extracted from the damping ring to the ATF2 beam line which consists of a 52 m long extraction section leading to a 38 m long final focus line. One of the goals of the ATF2 collaboration is to achieve beam position stability of approximately 1 nm at the notional IP (i.e. the focal point) [4]. To achieve this, the FONT feedback system needs to stabilise the position of the beam to within 1 μm at the entrance to the final focus section. This requires a beam position monitor (BPM) system capable of delivering position signals accurate to the sub-micron level on the timescale of the bunch-to-bunch spacing (150-300 ns).

In 2017, the BPM system achieved a resolution of 150 nm for a beam charge of 1.3 nC [5]. This paper presents the feedback system operating under practically ideal conditions, achieving the smallest jitter ever recorded at the feedback BPMs and implying a beam position resolution better than 150 nm for a beam charge of 1 nC.

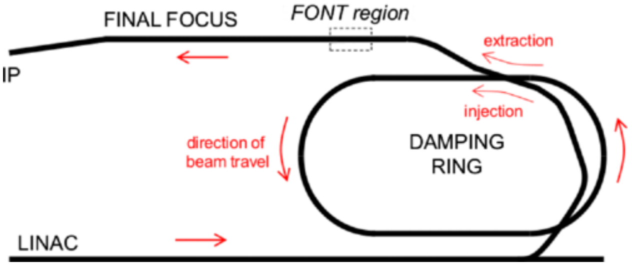

Figure 1: Layout of the ATF showing the location of the FONT feedback system in the ATF2 beam line.

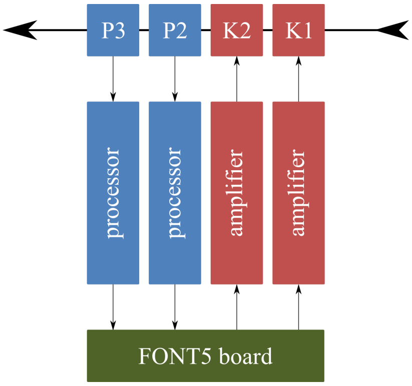

Figure 2: Schematic representation of the FONT feedback system.

EXPERIMENTAL SETUP

The FONT feedback system is depicted schematically in Fig. 2. The position of the first bunch is determined using two BPMs consisting of 12 cm striplines, designated P2 and P3, located in the diagnostics section of the ATF2 extraction line. These stripline BPMs are connected to specially developed analogue processing electronics [6]. Their design is presented in Fig. 3. The top (V_A) and bottom (V_B) stripline signals are subtracted using a 180° hybrid to form the difference (Δ) signal and added using a resistive coupler to form the sum (Σ) signal. The resulting signals are then band-pass filtered and down-mixed with a 714 MHz local oscillator (LO) signal phase-locked to the beam, before being low-pass filtered and amplified using 20 dB low-noise amplifiers. The LO is phased with the stripline signals using a phase shifter on the LO input and the stripline signals are themselves matched in phase using a phase shifter on V_A. The output signals are digitised using analogue-to-digital converters (ADCs), operated with a sample frequency of 357 MHz

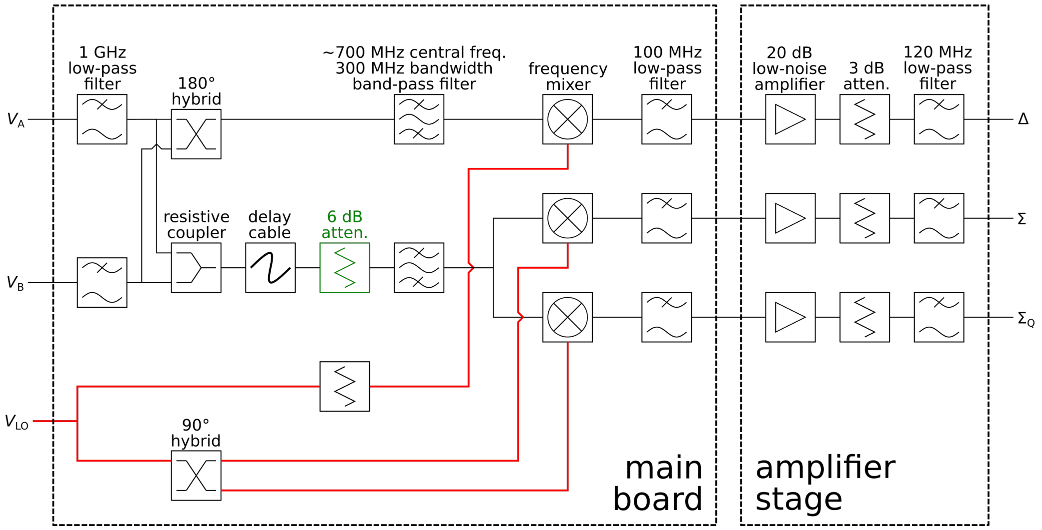

Figure 3: Schematic diagram illustrating the layout of the stripline processor modules. The local oscillator distribution is indicated in red.

and 13-bit resolution, on the custom-made FONT5A digital board [7].

The feedback processor obtains the position in real time from the ratio Δ/Σ and calculates the appropriate kicks to apply at a pair of stripline kickers, designated K1 and K2, located just upstream of the feedback BPMs. The kicker drive signals are generated by the feedback processor and then amplified externally using a pair of bespoke amplifiers with an ultra-fast rise time [8] so that the drive signal has attained the required amplitude before the arrival of the second bunch.

RESULTS

A beam consisting of two bunches separated by 274.4 ns was used with the feedback system operating in 'interleaved' mode where the correction is only applied to every other machine pulse. The resulting distributions of bunch positions at the two feedback BPMs are presented as histograms in Fig. 5. The effect of the feedback system is to reduce the jitter of the second bunch from 1.69 ± 0.09 µm to 165 ± 8 nm at P2 and from 1.68 ± 0.08 µm to 200 ± 10 nm at P3. The same data set is presented in the form of scatter plots in Fig. 7. The feedback system is seen to reduce the almost perfect bunch-to-bunch position correlation observed for the uncorrected beam down to approximately zero.

The transfer matrices calculated from the model of the ATF2 beamline can be used to infer the vertical angle of the beam at P2 and then propagate this distribution of position and angle down through the lattice to the notional interaction point of the machine. Figure 6 shows the distributions of bunch angles both at P2 and in the region downstream of the final quadrupole where the bunch travels along a ballistic trajectory. It is inferred from the measurements at P2 and P3 that the angle jitter of the beam at P2 is reduced from 1.26 ± 0.06 µrad to 107 ± 5 nrad. From this, a reduction in angle jitter at the IP from 40.7 ± 2.1 µrad to 14.6 ± 0.7 µrad is predicted. The angle data is presented in the form of scatter plots in Fig. 8.

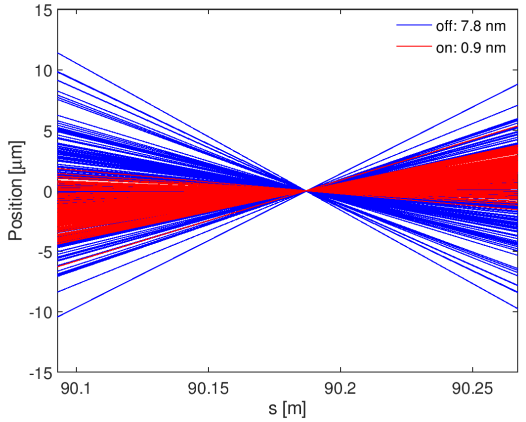

Figure 4: Trajectory of the second bunch in the IP region predicted from the measured positions at P2 and P3 for the feedback off data (blue) and feedback on data (red). Values of the position jitter at the focal point are quoted in each case. The longitudinal coordinate *s* represents distance from the start of the extraction line.

It is also possible to estimate the jitter at the focal point of the lattice, where it is at a minimum. The trajectory of the second bunch in the region of the focal point is plotted in Fig. 4. The estimated jitter of the second bunch at the focal point is 7.8 ± 0.4 nm with no feedback correction applied and this is reduced to 0.86 ± 0.04 nm with feedback. Assuming that the model accurately describes the transport of the beam to the IP, the feedback system is expected to stabilize the beam to the nanometre level as specified in the second goal of the ATF2 collaboration.

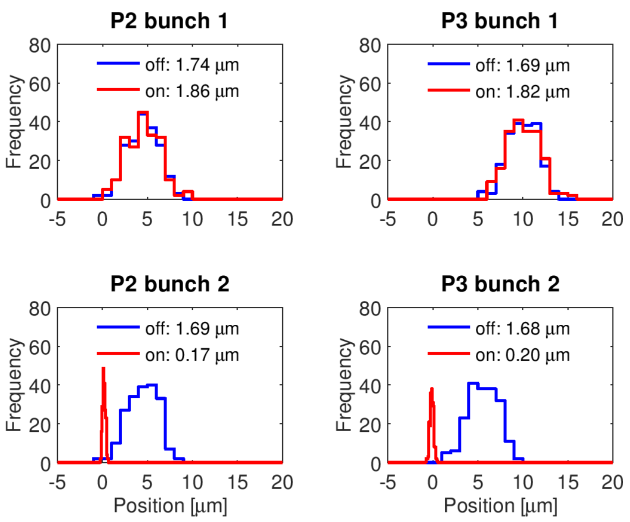

Figure 5: Distribution of the vertical position of bunches 1 and 2 at P2 and P3 with (red) and without (blue) application of the feedback correction. Values of the position jitter are quoted in each case. The bin width is 100 nm for the bunch 2 feedback on case and 1 µm otherwise.

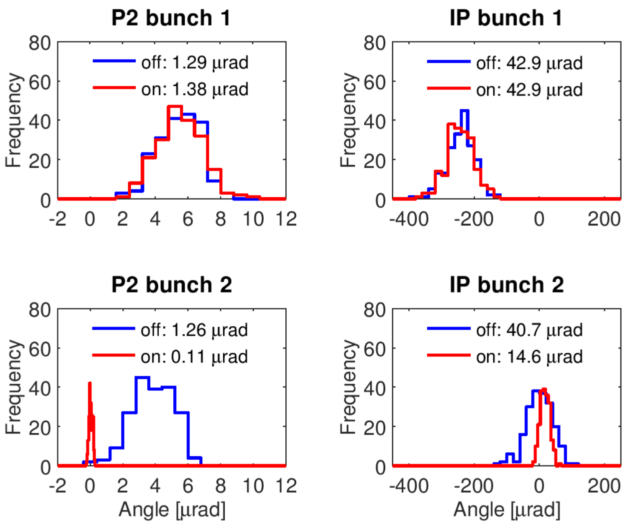

Figure 6: Distribution of the vertical angle of bunches 1 and 2 at P2 and in the IP region with (red) and without (blue) application of the feedback correction. Values of the angle jitter are quoted in each case. For the P2 data, the bin width is 50 nrad for the bunch 2 feedback on case and 0.8 µrad otherwise. For the IP data, the bin width is 8 µrad for the bunch 2 feedback on case and 20 µrad otherwise.

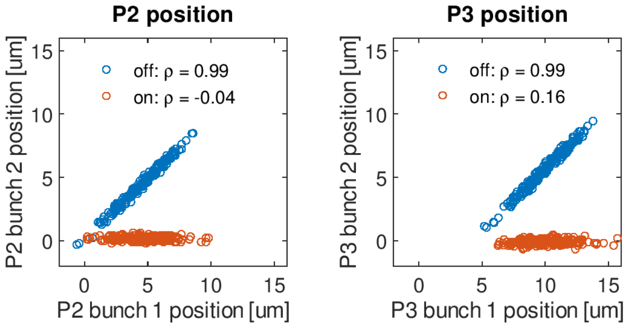

Figure 7: Bunch 2 position vs. bunch 1 position at P2 and P3 with (red) and without (blue) application of the feedback correction. Values of the bunch-to-bunch position correlation are quoted for each BPM.

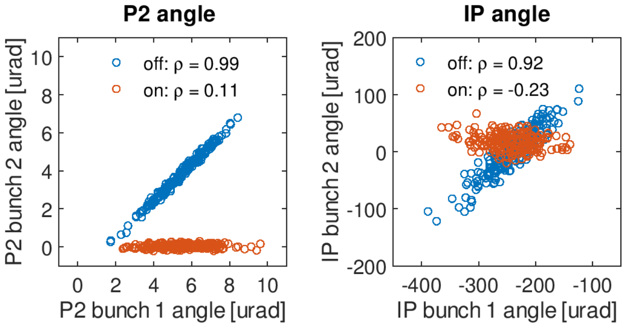

Figure 8: Bunch 2 angle vs. bunch 1 angle at P2 and in the IP region with (red) and without (blue) application of the feedback correction. Values of the bunch-to-bunch angle correlation are quoted for each location.

CONCLUSION

A beam position and angle feedback system using stripline BPMs has been deployed in the ATF2 extraction line. A resolution of ~150 nm for a beam charge of 1.3 nC was previously demonstrated, and vertical beam stabilisation to the 200 nm level has now been achieved at both feedback BPMs. Propagation of this data using a linear transfer model predicts a vertical jitter at the focal point of less than 1 nm, suggesting the system achieved the target set by the ATF2 beam stability goal.

ACKNOWLEDGEMENTS

We thank our ATF2 collaborators for their help and support, in particular the KEK ATF staff for providing the beam time and stable operating conditions for this study. This work was supported by the UK Science and Technology Facilities Council, CERN, and the European Commission's Horizon 2020 Programme through the Marie Skłodowska-Curie RISE project E-JADE, Contract No. 645479.

REFERENCES

[1] C. Adolphsen et al., "The ILC technical design report, volume 3: Accelerator", John Adams Institute, Oxford, UK, Tech. Rep. JAI-2013-00,1 2013.

[2] M. Aicheler et al., "CLIC conceptual design report", CERN, Geneva, Switzerland, Tech. Rep. CERN-2012-007, 2012.

[3] FONT Project. `groups.physics.ox.ac.uk/font`

[4] B. I. Grishanov et al., "ATF2 proposal", vol. 2, KEK Report 2005-9, 2005.

[5] N. Blaskovic Kraljevic *et al.*, "Optimisation of a High-Resolution, Low-Latency Stripline Beam Position Monitor System for Use in Intra-Train Feedback", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen,

Denmark, May 2017, pp. 1979–1982. doi:10.18429/JACoW-IPAC2017-TUPIK110

[6] R. J. Apsimon et al., "Design and performance of a high resolution, low latency stripline beam position monitor system", *Phys. Rev. ST. Accel. Beams*, vol. 18, p. 032803, Mar. 2015.

[7] B. D. Constance, DPhil thesis, University of Oxford, 2011.

[8] R. J. Apsimon et al., "Design and operation of a prototype interaction point beam collision feedback system for the International Linear Collider", *Phys. Rev. Accel. Beams*, vol. 21, p. 122802, Dec. 2018.