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HIGH-RESOLUTION, LOW-LATENCY, BUNCH-BY-BUNCH FEEDBACK SYSTEMS FOR NANOBEAM PRODUCTION AND STABILISATION

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Abstract

High-precision intra-bunch-train beam orbit feedback correction systems have been developed and tested in the ATF2 beamline of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. Two systems are presented: 1) The vertical position of the bunch measured at two stripline beam position monitors (BPMs) is used to calculate a pair of kicks which are applied to the next bunch using two upstream kickers, thereby correcting both the vertical position and trajectory angle. This system was optimised so as to stabilize the beam offset at the feedback BPMs to better than 350 nm, yielding a local trajectory angle correction to within 250 nrad. Measurements with a beam size monitor at the focal point (IP) demonstrate that reducing the trajectory jitter of the beam by a factor of 4 also reduces the observed wakefield-induced increase in the measured beam size as a function of beam charge by a factor of c. 1.6. 2) High-resolution cavity BPMs were used to provide local beam stabilization in the IP region. The BPMs were demonstrated to achieve an operational resolution of ~20 nm. With the application of single-BPM and two-BPM feedback, beam stabilization of below 50 nm and 41 nm respectively has been achieved with a closed-loop latency of 232 ns.

INTRODUCTION

A number of in-construction and proposed future particle accelerator designs feature trains of particle bunches with bunch-separation intervals in the ranges of nanoseconds to tens or hundreds of nanoseconds. For example, the International Linear Collider (ILC) design [1] calls for bunch trains comprising thousands of bunches separated in time by around 500 ns with a train repetition frequency of 5 Hz; the Compact Linear Collider (CLIC) design [2] specifies bunch trains comprising several hundred bunches separated in time by around 0.5 ns, with a train repetition frequency of 50 Hz. Free-electron lasers based on similar accelerating technologies as ILC and CLIC, such as the European XFEL [3], have respectively similar bunch-train time structures. Beam control at such facilities calls for beam position monitors (BPMs) that can resolve bunches on an intra-train (ideally bunch-by-bunch) timescale, with submicron position resolution in single-pass mode. The designs of such BPM and feedback systems are presented here.

STRIPLINE BPM SYSTEM AT ATF2

The system was developed by the Feedback on Nanosecond Timescales (FONT) group [4] and it was deployed, commissioned and tested at the Accelerator Test Facility (ATF) [5] at KEK. The layout of the BPMs is shown in more detail in Fig. 1. The design goal for the FONT5 system is to stabilize the vertical beam position to the 1 μm level at the entrance to the final-focus system. This requires BPMs capable of resolving bunches separated in time by around 100 ns, and with a position resolution at the submicron level. For tests of the FONT system the ATF is operated in a mode whereby a train of two or three bunches is extracted from the damping ring and sent down the ATF2 beam line. The bunch separation is determined by the damping ring fill pattern and typically is chosen to be between 140 ns and either 154 ns (3-bunch mode) or 300 ns (2-bunch mode).

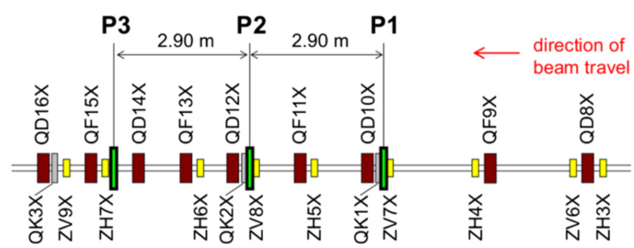

Figure 1: Layout of the FONT BPMs (P1, P2 and P3) in the ATF2 extraction line; quadrupole ("Q") and dipole corrector ('Z') magnets are indicated.

The FONT5 BPM system (Fig. 2) consists of three stripline BPMs (Fig. 3) each of which is instrumented with an analogue processor, and a custom multichannel digitizer. Stripline BPMs were used due to their inherently fast, broadband response and capability to resolve bunches with the required time resolution. In the FONT5 system, only the vertical plane of the BPMs is routinely instrumented.

The FONT5 analogue processors' (Fig. 4) function [6] is to deliver the stripline pickoff-pair difference and sum signals in a form that can be easily recorded by the digitizer for calculation of the position-dependent, beam charge-independent ratio of the two. Ten processors were built and are used in beam operations at ATF2. A single BPM processor can be used to process the beam position data in either the horizontal or vertical plane; from here on only the vertical plane is considered. The BPM processor outputs are digitised by a custom digital feedback processor board (Fig. 5). The board has nine analogue signal input channels digitised using ADCs with a maximum conversion rate of 400 MS/s, and two analogue output channels formed using DACs, which can be clocked at up to 210 MHz. The digital signal processing is based on a Xilinx Virtex5 FPGA. The FPGA is clocked with a 357 MHz source derived from the ATF

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master oscillator and hence locked to the beam. The ADCs are clocked at 357 MHz.

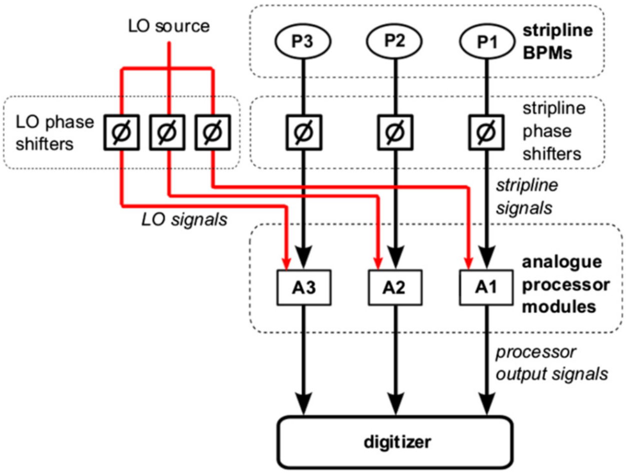

Figure 2: Schematic of the FONT5 BPM system. For each BPM, a phase shifter is used on one of the stripline signals to adjust the relative path lengths of the two input signals at the BPM processor, and another phase shifter is used to adjust the phase of the LO signal at each processor.

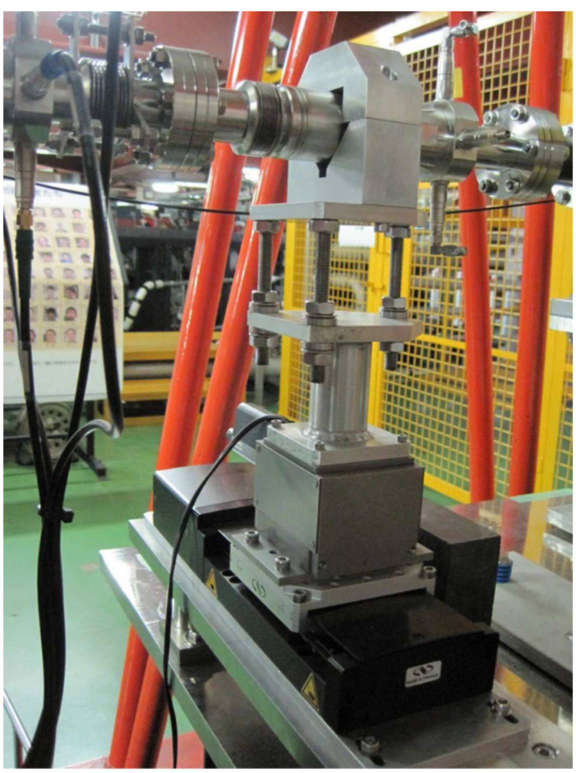

Figure 3: Photograph of FONT5 stripline BPM P3 and its mover in the ATF2 beam line.

The BPM resolution achieved [7, 8] is summarised in Fig. 6. For a bunch charge of 1.3 nC a resolution of c. 157 nm was obtained [8].

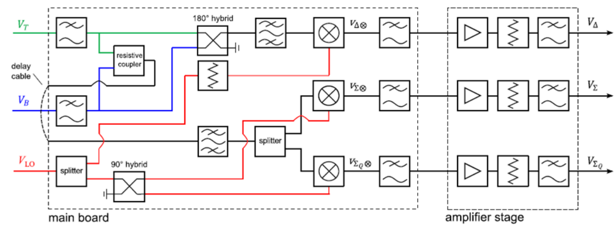

Figure 4: Schematic diagram illustrating the structure of the FONT5 analogue processor.

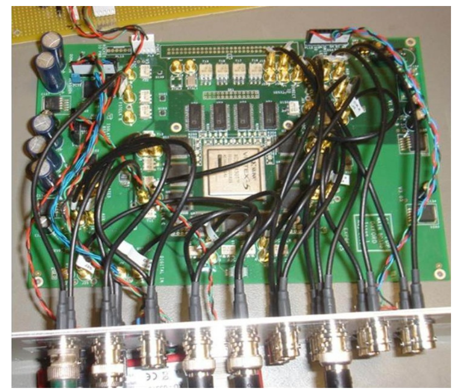

Figure 5: FONT5 digital feedback board.

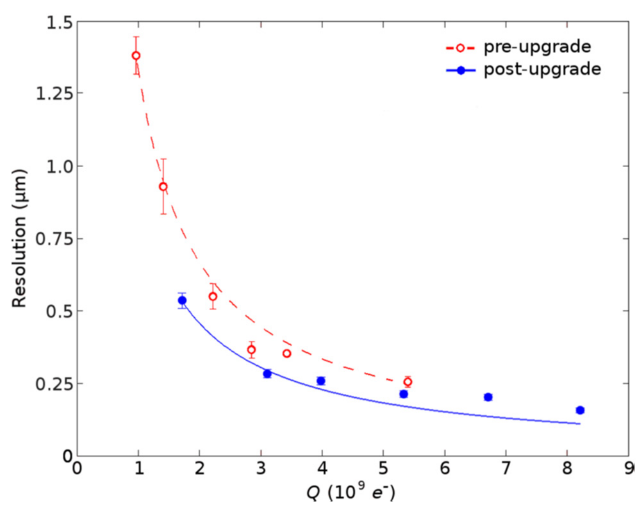

Figure 6: BPM resolution vs. beam bunch charge (Q) [8]. The filled and unfilled data points correspond to measurements with the upgraded and original systems respectively. In each case the line shows the result of extrapolating the lowest-charge data point to higher charges with a $1/Q$ dependence.

ILC IP FEEDBACK SYSTEM

An intra-train position feedback system has been designed to achieve and maintain collisions at the ILC, and a prototype has been developed, commissioned, and tested at the ATF; full details are reported in [9]. The beam position is measured using a stripline BPM with analogue signal-processing electronics as just described. The outputs are processed on the FPGA-based digital

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board used to calculate and deliver a correction signal, which is amplified by a high-current drive amplifier and applied to a stripline kicker. All components have been designed for minimum latency, with an overall feedback latency of 148 ns, allowing bunch-to-bunch feedback at the ILC. The stripline BPM has a position resolution of 291 +- 10 nm and a linear range of 500 µm and satisfies the ILC requirements. The kicker response is linear over a correction range of over 60 µm measured at the feedback BPM which satisfies the ILC requirements. The feedback system has been used to successfully stabilize the second and third bunches in a three-bunch train with 154 ns bunch spacing, where the first bunch is used as a pilot bunch. The propagation of the correction has been verified by using an independent stripline BPM located downstream of the feedback system. The system has been demonstrated to meet the BPM resolution, beam kick, and latency requirements for the ILC [9].

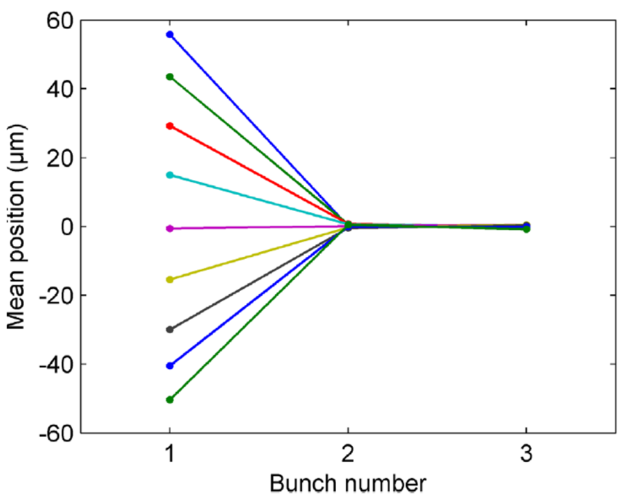

Figure 7: Mean position measured at P3 with feedback on versus the bunch number for nine incoming beam orbit settings (colour coded). Standard errors are given.

The performance is illustrated in Figs. 7-9. In order to assess the feedback operation over a wide correction range, the vertical position of the beam arriving at P3 was swept through a range of approximately 60 µm by varying an upstream corrector magnet. The results show that the mean positions (Fig. 7) of the second and third bunches are zeroed and the spread of positions (Fig. 8) is consistently reduced to around 500 nm, which is limited by the BPM resolution. As an additional test, two vertical steering magnets were used to enhance the incoming beam jitter. The magnets were set up so as to apply a random kick conforming to a predefined distribution with the kick updated successively at the train repetition frequency. The feedback was observed (Fig. 9) to successfully centre and stabilize the beam, even when the full spread of uncorrected positions reaches +-100 µm.

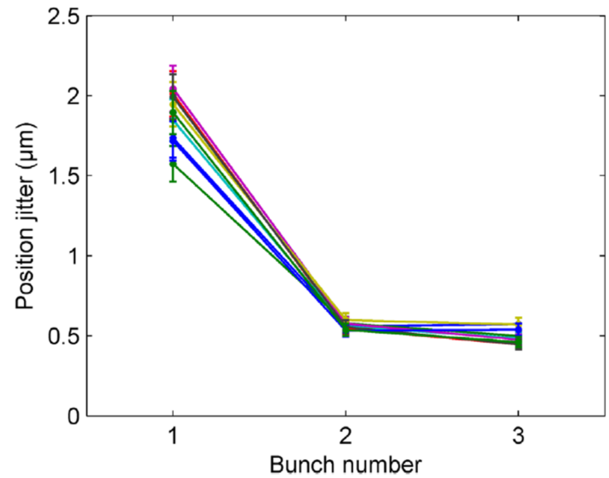

Figure 8: Mean jitter measured at P3 with feedback on versus the bunch number for nine incoming beam orbit settings (colour coded). Standard errors are given.

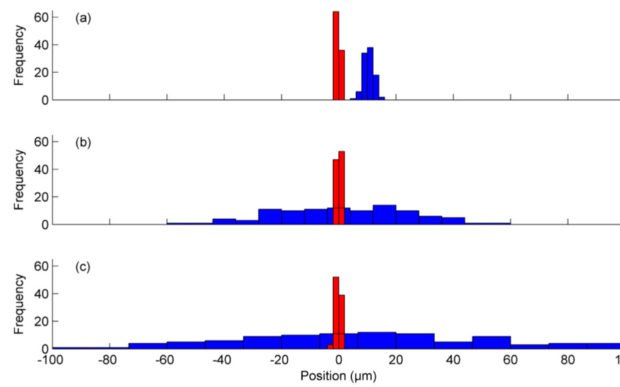

Figure 9: Distributions of positions with feedback off (blue) and feedback on (red) for bunch 2 at P3 with incoming, uncorrected r.m.s position jitters of (a) ~2 µm, (b) ~22 µm, and (c) ~45 µm.

ATF2 Y-Y' FEEDBACK SYSTEM

We report the results of a feedback system based on this technology to stabilize both the beam position and the trajectory angle in the ATF2. The corrections were applied in the vertical plane locally in the early part of the ATF2 beamline so as to deliver a stable beam to the entrance of the final focus system. Figure 10 shows the overall beamline layout of the components used here.

The hardware of the y-y' feedback system is depicted schematically in Fig. 11. P2 and P3 are the stripline BPMs; the upgraded analogue signal processor system (see Fig. 6) was used for the results reported here. For each train of two bunches extracted from the ATF damping ring, the feedback calculation converts the measured position of the first bunch at the feedback BPMs P2 and P3 into a pair of kicker drive signals to be applied to the second bunch at the kickers K1 and K2.

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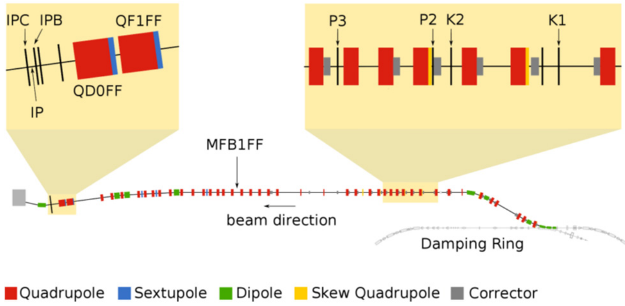

Figure 10: Schematic of the ATF2 beamline showing the layout of components (used here) in the upstream region and at the IP.

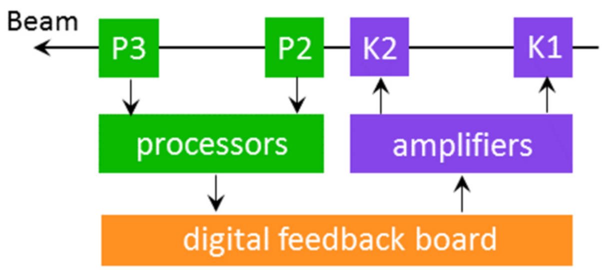

Figure 11: Schematic of the y-y' feedback system using BPMs P2 and P3 and kickers K1 and K2.

The beam stability study was performed using trains of two bunches extracted from the Damping Ring with a bunch spacing of 187.6 ns, a train repetition rate of 1.56 Hz and a bunch population of 0.45×10^{10} electrons. The stripline BPM MFB1FF (Fig. 10) is located about 25m downstream of the feedback system and was instrumented with an analogue processor of the same type as used for P2 and P3. The outputs of this processor were monitored using a second FONT5 board operating purely as a digitizer. The cavity BPMs IPB and IPC (see later) are located either side of the focal point. These BPMs were instrumented with a completely distinct set of processing electronics, the outputs of which were monitored by a third FONT5 board.

Distributions of the vertical beam position recorded at each BPM are shown in Fig. 12 [8] for a typical run comprising 200 beam pulses. The feedback was toggled on and off for alternate beam pulses and the distributions are shown separately for the feedback-off and feedback-on sets of pulses. The feedback BPMs themselves are mounted on translatable mover stages and, at the start of a period of data taking, are normally aligned so as to approximately zero the mean of the readout position of bunch 1. It is clear from the feedback-off data that there is a difference of c. 35 µm in the orbits of the two bunches, suggesting a non-uniformity of the extraction kicker pulse that removed the bunch train from the damping ring. The relative timing of the extraction kicker pulse can be adjusted to ensure that neither bunch is close to the pulse edges, but the goal of this scan is to maximize the bunch-to-bunch correlation rather than match the mean orbits. The higher the correlation between the pulse-by-pulse positions of the two bunches, the more stable the position of the corrected bunch is. Kick offset parameters are available to eliminate the residual offset of the mean position at each BPM.

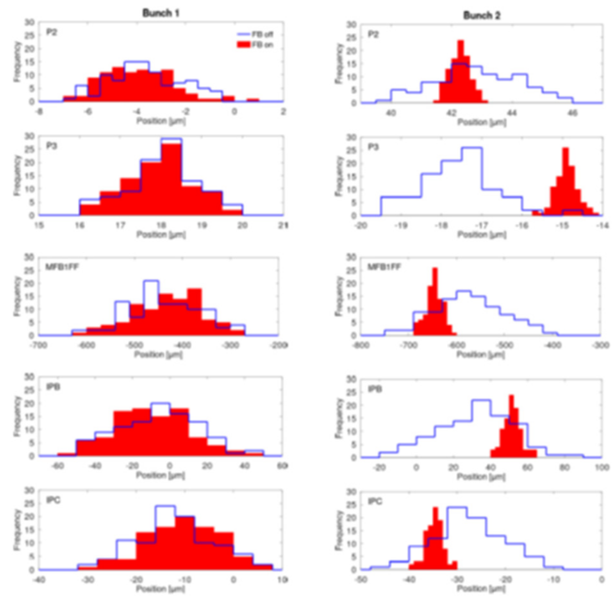

Figure 12: Distribution of position measured at each BPM (rows) for bunch 1 (left column) and bunch 2 (right column) with feedback off (outline) and on (filled). Where necessary a reduced bin width is used to display the feedback-on data so as to limit the maximum frequency of a single bin for display purposes.

The performance of the feedback system in terms of the beam stability is shown in Fig. 12. Bunch 1 provides the feedback input and its position is not corrected. Bunch 2 is well corrected by the feedback as shown by the substantial reduction in the position jitter seen at the two feedback BPMs. The correction is limited by the resolution of BPMs P2 and P3, which was approximately 200 nm for the bunch charge used. The correction factor at all three witness BPMs is consistent with the in-loop correction of roughly a factor of 4. The predictions of a linear beam transport model of theATF2 beamline based on MAD are in good agreement with the direct measurements [8], implying that there are no major sources of additional beam jitter between the feedback kickers and the ATF2 final focus.

As the system is dual-phase, the effect of the feedback on the angular jitter of the beam is also of interest. The angular jitter of the bunch is calculated using the position measured at two BPMs and knowledge of how the beam propagates from one BPM to the other; the MAD model is used for the transfer matrix from P2 to P3. The measured position and angle can then be propagated downstream using additional transfer matrices from the model in order to give the predicted distributions of the beam angle at each witness BPM. In the IP region the

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transfer matrix is trivially obtained as the beam propagates in a ballistic fashion from IPA to IPB to IPC. The angles at P3 and in the IP region are shown in Fig. 13. The results show that the angular jitter of bunch 2 is also corrected by the feedback by about a factor of 4, consistent with the position correction

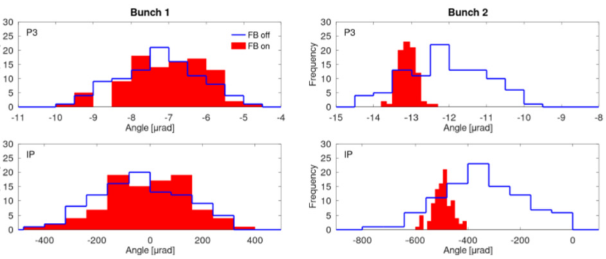

Figure 13: Distribution of angle at P3 (calculated from the position at P2 and P3) and in the IP region (calculated from the position at IPB and IPC) with feedback off (outline) and feedback on (filled). A reduced bin width is used for the feedback on data where necessary to limit the maximum frequency of a single bin for display purposes.

ATF2 is known to be particularly sensitive to wakefields due to the long bunch length and the relatively low beam energy. The primary sources of wakefields in the ATF2 beamline are C-band cavity BPMs, bellows and vacuum flanges. The orbit change caused by wakefields at ATF2 has been reported and several of the cavity BPMs were removed in order to reduce it. As the magnitude of the wakefield kick is proportional to the position offset between bunch and wakefield source (for small offsets), a position feedback that reduces the offset between bunch and wakefield source would be expected to mitigate the increase in beam size due to wakefields.

The ATF was set up to provide trains consisting of two bunches separated by 302.4 ns. Figure 14 shows the measured size of the second bunch as a function of beam charge, both with and without operation of the y-y' feedback. It can be seen that stabilizing the position and angle of the second bunch with the FONT feedback system also reduced the charge dependence of the beam size measured at the IP by a factor of 1.6 +- 0.2, from 27.4 +-1.9 nm/10^9e to 16.9 +- 1.6 nm/10^9e. The magnitude of this reduction is in line with what would be expected from a detailed model of beam transport in the ATF2 beamline including explicitly the known wakefield sources [8]; full details are reported in [10].

ATF2 'IP' FEEDBACK SYSTEM

We report the design and performance of a high-resolution, high-precision, low-latency, beam position feedback system located around the ATF2 IP (Fig. 10), which is aimed at stabilizing directly the IP vertical beam position to the nanometer level. This system incorporates (Fig. 15) five cavity BPMs similar to those reported in [11], but with a much lower `quality factor'. The cavities are fabricated from aluminium and were designed [12] to have ultra-low quality-factor values so as to be suitable for resolving in time individual particle bunches in multi-bunch trains with bunch separation of order 100 ns. The signals from the BPMs are digitised on a `FONT5A' board [9] and the feedback calculation is performed on the FPGA mounted on the board. An analogue correction signal is output from the board, amplified using a custom power amplifier, and used to drive a dedicated stripline kicker, IPK.

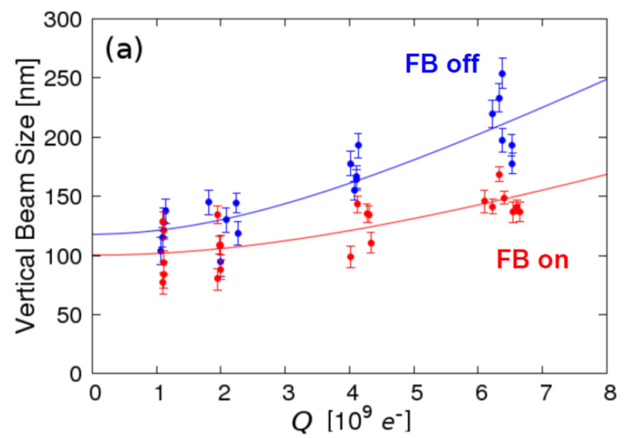

Figure 14: Beam size as a function of beam charge for two-bunch operation with feedback on (unfilled points) and feedback off (filled points). Each point represents a single beam size measurement.

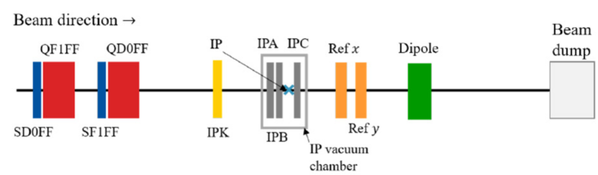

Figure 15: Schematic of the ATF2 IP region, showing the final-focus magnets and the elements of the FONT IP feedback system including dipole cavity BPMs IPA, IPB and IPC, reference cavity BPMs Ref x and Ref y, and the stripline kicker IPK.

The cavity BPM signals undergo two stages of frequency down-mixing (see Fig. 16) so as to produce baseband signals that can be digitized with the FONT5A board. In the first stage, both the reference and dipole cavity signals are down-mixed to an intermediate frequency (IF) centred at 714 MHz using a common Local Oscillator (LO) signal so as to retain the phase relation between the signals. The 5.712 GHz LO signal is derived by frequency up-mixing the DR master oscillator signal and hence is phase-locked to the beam. In the second stage, the reference and dipole signals are mixed in-phase and in-quadrature to produce I and Q signals, respectively. These signals are orthogonal components that together include the full amplitude and phase information of the BPM waveform. Before digitization these signals are amplified so as to reduce the effect of quantization noise.

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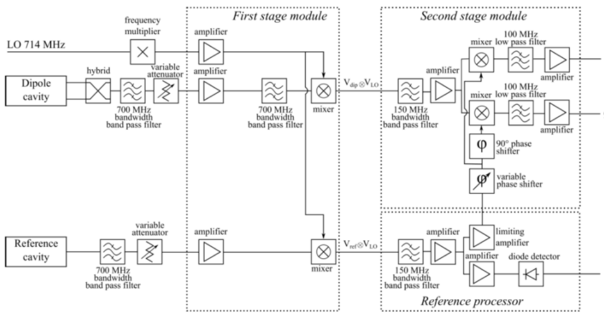

Figure 16: Simplified block diagram of the two-stage down-mixing process of the dipole and reference cavity signals from GHz-level to baseband.

The FONT5A board contains nine 14-bit analogue-to-digital converters (ADCs) grouped into separately-clocked banks of three. Seven ADCs are used to digitize the I and Q waveforms from IPA, IPB and IPC, and the q waveform from the Ref y cavity, at 357 MHz. Representative digitized waveforms for 2-bunch-train operation are shown in Fig. 17. A linear combination of I and Q can be chosen to produce a signal, I', with an amplitude proportional to the bunch position [11]. A signal orthogonal to I' can also be generated, Q', that is proportional to the beam pitch.

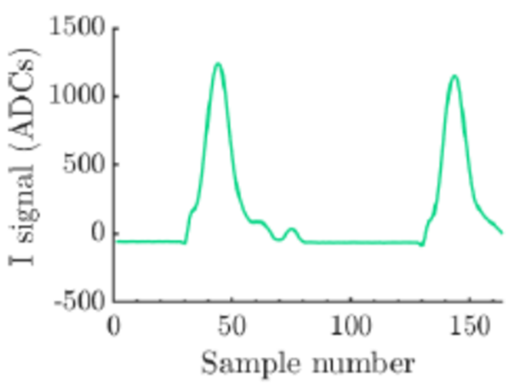

Figure 17: Representative digitized I waveform from IPC, for two-bunch-train operation with a bunch spacing of 280 ns. The waveform was sampled at intervals of 2.8 ns.

Each dipole BPM is calibrated w.r.t. position by vertically scanning the beam across a known range and measuring the corresponding BPM response. For each measured bunch in the beam, the calibration calculation can be performed using either single or multiple samples of the I and Q waveforms. The position resolution can be significantly improved by integrating over multiple samples of the I and Q signals as this both increases the signal level and averages over thermal and electronic noise. The integration range is chosen around the peak of the I and Q signals, as samples significantly in advance of the peak may contain transient effects from unwanted modes and samples late in the waveform have a poorer signal-to-noise ratio. This integration is performed in real time on the FONT5A board.

The resolution of the BPM system was evaluated using measurements of the bunch trajectory at all three dipole BPMs. Since the bunch follows a straight-line trajectory which can be characterized with measurements from only two BPMs, measurements from the third BPM can be used to estimate the resolution of the system. For a representative data set with bunch charge $0.5\text{x}10^{10}$ e, Fig. 18 shows the resolution as a function of the number of I and Q samples integrated in real time for the position calculation. It can be seen that the resolution improves from 41 nm (single sample) to an optimal value of 19 nm with 11 samples. No improvement is seen by integrating additional later samples as the BPM waveforms have decayed and the signal levels are low (see Fig. 17).

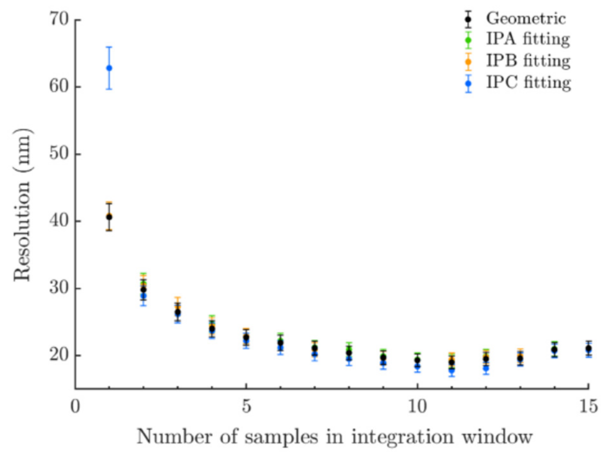

Figure 18: Resolution vs. number of samples integrated. The error bars show the statistical uncertainty.

The high-resolution real-time vertical beam position information from the cavity BPM system was used as input to a closed-loop feedback. In extracted two-bunch trains the position of the first bunch was measured and used to correct the position of the second bunch. Two feedback operating modes were used, represented functionally in Fig. 19. In single-BPM mode the position signal from one BPM was input to the FONT5A board and the derived correction signal was supplied to the kicker IPK such that the vertical beam position was stabilised at the chosen BPM. For this mode the IP was moved longitudinally from the nominal IP to the centre of the chosen BPM so as to stabilise directly the nanobeam vertical position there. In two-BPM mode the IP was placed longitudinally at one BPM; the position signals from the other two BPMs were used to derive a correction signal such that the nanobeam was stabilised vertically at the chosen BPM, which hence served as an independent witness of both the corrected and uncorrected beam positions. For both modes the correction signal to the kicker is output from the FONT5A board via a 14-bit digital-to analogue converter (DAC).

The correction signal from the FONT5A board requires amplifying before it can be used to drive the kicker. The amplifiers are capable of a drive current of +-30 A. The stripline kicker consists of two conducting strips,

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12.5 cm in length and separated by 24 mm. The closed-loop feedback latency is defined as the time interval between bunch 1 passing through the longitudinal centre of IPK and the derived kicker correction pulse (for bunch 2) reaching 90% of its final output value. The latency was measured directly with the beam to be 83 samples, i.e. 232 ns.

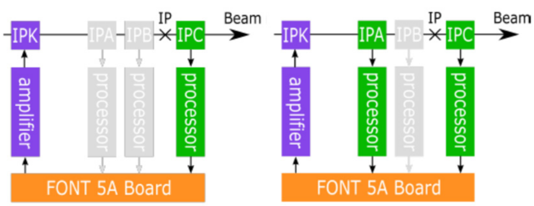

Figure 19: Diagrams of feedback loops showing dipole cavity BPMs (IPA, IPB and IPC) and stripline kicker (IPK). (a) Single-BPM feedback with beam measurement and stabilization illustrated at IPC. (b) Two-BPM feedback, illustrated for position measurements at IPA and IPC with beam stabilization at IPB.

For the operation of the IP bunch-by-bunch feedback system the ATF DR was configured to deliver two-bunch trains to ATF2 with a bunch separation of 280 ns. The train repetition rate was 1.56 Hz. The feedback was operated in the two complementary modes to stabilise the vertical position of the ultra-small beam produced at the focal point of the ATF2. In single-BPM feedback mode, beam stabilization to 50 +- 5 nm was demonstrated. Two-BPM feedback was operated with the IP set at IPB and with IPA and IPC used as inputs to the feedback; hence IPB was used as an independent witness of the feedback performance. The feedback performance is illustrated in Fig. 20. Since bunch-1 provides the input to the feedback its position is unaffected by the correction. By contrast the bunch-2 jitter is substantially reduced, from 96 nm to 41 nm, in good agreement with the predicted value, given the incoming beam conditions, of 40 nm.

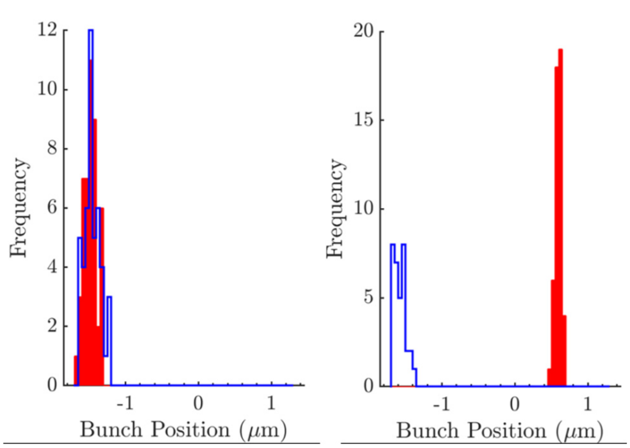

Figure 20: Distributions of bunch-1 (left) and bunch-2 (right) positions measured at IPB, with feedback off (blue) and feedback on (red).

Some margin remains to improve the feedback performance by optimising the gain, as well as by increasing the degree of bunch-to-bunch position correlation in the incoming beam. For the best achieved position resolution to date, and for 100% bunch-to-bunch correlation, an ultimate beam stabilisation to about 24 nm is in principle achievable with the current hardware. Should ATF/ATF2 beam operations resume, this will be the subject of future feedback studies.

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