Performance of an intra-train dual-phase feedback system at KEK ATF2

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Abstract

A beam orbit correction system has been developed for the extraction line of the Accelerator Test Facility at the High Energy Accelerator Research Organization in Japan. Working with trains of two bunches, the feedback system uses the measured position of the first bunch at two beam position monitors (BPMs) to drive a pair of corrective kicks at two upstream kickers, thus correcting both position and trajectory angle offsets of the second bunch of the train in the vertical axis. The feedback system is shown to be capable of stabilizing the beam offset at the feedback BPMs to within 300 nm and the trajectory angle to within 140 nrad. The quality of the correction has been verified using a witness BPM located 25 m downstream of the kickers as well as a pair of independent BPMs located near the final focus point of the machine. Measurements from these BPMs are in good agreement with the results of simulating the propagation of the bunch measured at the feedback BPMs.

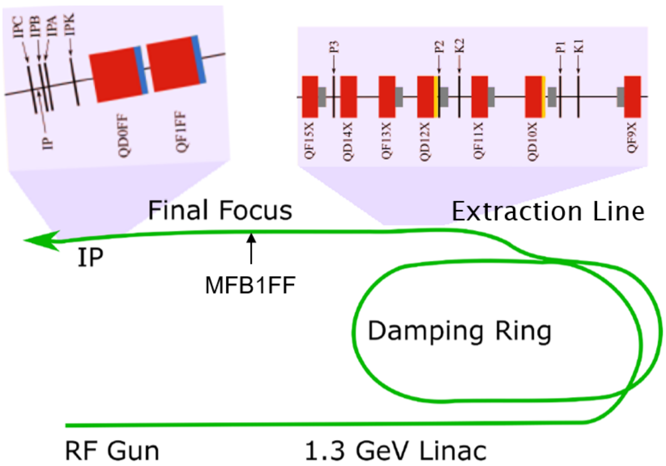

Figure 1: Layout of the ATF. The label “IP” refers to the final focus point of the machine.

1. Introduction

The ATF (Fig.1) is a 1.3 GeV electron test accelerator with a repetition rate of 3.12 Hz. It is intended to facilitate the development of some of the technology and techniques that would be required for a future linear electron-positron collider. The ATF2 Collaboration has two goals: to produce a 37 nm vertical beam spot size at the final focus point and to stabilize the vertical beam position at the same location to the nanometer level.

In service of the beam stabilization goal the Feedback On Nanosecond Timescales (FONT) group at the University of Oxford has developed a beam position stabilization system. This feedback system is capable of stabilizing both the beam position and trajectory angle in the vertical plane. The corrections are applied in the extraction line so that a stable beam is delivered at the entrance to the final focus line.

This section could be expanded upon to include the Japanese wakefield studies with the Shintake monitor as a movitation for reducing the angular jitter..

2. Experimental Setup

2.1. Feedback system

The main components of the system are depicted in Fig. 2. P2 and P3 are beam position monitors (BPMs) of the stripline type. The voltage pulses induced on the top and bottom striplines by the passage of the bunch are processed using custom analogue electronics modules to produce a difference signal (Δ) containing the vertical position information and a sum signal (Σ) for charge normalization purposes. The position of the bunch is proportional to the ratio Δ/Σ. The stripline BPMs and associated processing electronics are the subject of a previously published paper [1]; here it is noted that an upgrade to the stripline phase shifters (used to match the lengths of the signal paths from the top and bottom terminals of the BPM to the inputs of the processor modules) resulted in an improvement in the position resolution to ∼200 nm.

The processed BPM signals are then input to the digital feedback board (“FONT5”). This board features a Field-Programmable Gate Array (FPGA) along with nine analogue-to-digital converters and a pair of digital-to-analogue converters. The feedback algorithm runs on the FPGA and is able to calculate the appropriate kicker drive signals

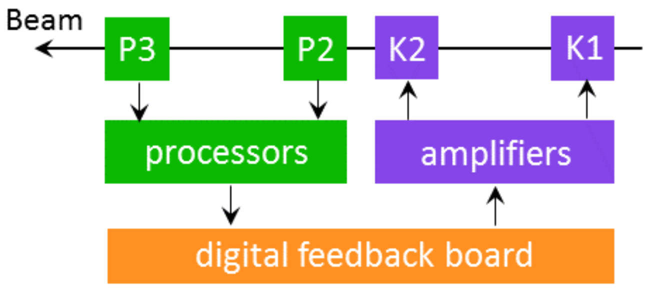

Figure 2: Schematic of the coupled-loop feedback system using BPMs P2 and P3 and kickers K1 and K2.

from the digitized BPM signals. The kicker drive signals are then amplified externally and applied to the stripline kickers K1 and K2. More detail on the digital feedback board and the kicker amplifiers can be found in a second previously published paper [2] which also includes some results of the system operating in "single-loop" mode (a single BPM driving a single kicker).

Here we consider the system operating in "coupled-loop" mode. In this case the position of the bunch at both P2 and P3 is used to calculate a pair of kicks, one at K1 and one at K2. By design each pair of BPM and kicker are situated in the lattice at sufficiently different values of the betatron phase advance that the measurements and corrections are non-degenerate and the offset in both position and trajectory angle can be removed on a train-to-train basis.

2.2. Feedback algorithm

The feedback algorithm converts the measured position of the first bunch at the feedback BPMs P2 and P3 into a pair of kicks to be applied at the kickers K1 and K2. The corrected position of the second bunch at P2, Y_2'', can be expressed as:

$$Y_2'' = y_2'' + H_{12}v_1 + H_{22}v_2 \tag{1}$$

that is, as the sum of three terms: the first, y_2'', represents the position of bunch 2 at that BPM in the absence of any kicks. The second and third terms correspond to the change in position caused by kicks at K1 and K2 respectively. v_i represents the magnitude of the kick at Ki and H_{ij} is the kicker sensitivity constant that describes how a kick at Ki is converted into a position offset at Pj. A similar expression is obtained for the corrected position of the second bunch at P3 and the two can be expressed together in a single matrix equation:

$$\begin{pmatrix} Y_2'' \\ Y_3'' \end{pmatrix} = \begin{pmatrix} y_2'' \\ y_3'' \end{pmatrix} + \begin{bmatrix} H_{12} & H_{22} \\ H_{13} & H_{23} \end{bmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \tag{2}$$

The goal of the feedback system is to stabilize the position of the second bunch at both BPMs ($Y_2'' = Y_3'' = 0$). It is also assumed that the two bunches are highly correlated such that the uncorrected position of the second bunch is identical to the uncorrected position of the first bunch ($y_j'' = y_j'$). Imposing these conditions leads to the following expression for the kicks:

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = -\begin{bmatrix} H_{12} & H_{22} \\ H_{13} & H_{23} \end{bmatrix}^{-1} \begin{pmatrix} y_2' \\ y_3' \end{pmatrix} \tag{3}$$

This algorithm is implemented in the firmware of the FONT5 digital processor module in the form:

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{bmatrix} G_{21} & G_{31} \\ G_{22} & G_{32} \end{bmatrix} \begin{pmatrix} y_2' \\ y_3' \end{pmatrix} + \begin{pmatrix} \delta v_1 \\ \delta v_2 \end{pmatrix} \tag{4}$$

The feedback parameters G_{ji} represent the extent to which the measured offset at Pj contributes to the kick to be delivered at Ki. They are calculated from the measured kicker sensitivity constants and are constant for a given set of beam optics. The δv_i term is a constant offset that can be applied to each kick. This allows the mean position of the corrected bunch to be shifted without affecting the reduction in position jitter that can be achieved.

2.3. Witness BPMs

To verify that the reduction in both position and angle jitter observed at the feedback BPMs survives to the final focus line, a third stripline BPM designated MFB1FF is used as a witness to the correction. This BPM is located about 25 m downstream of the other components (Table 1). It is instrumented with the same model of processor module used by P2 and P3 and connected to the same digital feedback board that performs the correction.

To provide a fully independent confirmation of the performance achieved by the feedback system, two additional BPMs located close to the final focus point are also used. These BPMs, designated IPA and IPB, are of the cavity type and are instrumented with a completely distinct set of processing electronics, the outputs of which are monitored by a second digital feedback board used purely as a digitizer. A complete description of the BPM electronics can be found in [3].

Here it is noted that the passage of the bunch induces an oscillation of the electric field within the cavity. The first mode of oscillation is proportional to the beam charge while the second mode is proportional to both the beam charge and the transverse position of the beam. The dipole signals from IPA and IPB, along with the monopole signal from a separate reference cavity, are down-mixed to 714 MHz using a frequency-multiplied version of the master RF signal of the ATF damping ring. Each 714 MHz dipole signal is then split with one half down-mixed with the 714 MHz reference signal to form a baseband signal denoted I and the other half down-mixed with a 90° phase-shifted version of the 714 MHz reference to form a second baseband signal denoted Q. The position of the bunch is proportional to $I\cos\theta + Q\sin\theta$, where θ is a constant to be determined from calibration.

Variable attenuators on the cavity outputs allow the system to operate for a wide range of beam conditions. Increasing the attenuation increases the dynamic range of the BPMs but makes the resolution worse. Typically the BPMs are operated with a resolution of approximately 50 nm and a dynamic range of several microns.

3. Feedback results

The feedback study was performed using trains of two bunches with a bunch spacing of 187.6 ns. The mean position of the first bunch measured at P2 and P3 was set close to zero by translating those BPMs relative to the beam using the BPM movers. A similar procedure was performed for IPA and IPB which are mounted on a single block that can be both tilted and translated. MFB1FF is not equipped with a mover, resulting in a large offset at that location.

As indicated in Table 1, the nominal location of the focal point of the machine is approximately 90 mm downstream of IPB. For this study, the focal point was shifted to be between IPA and IPB by increasing the current of the final focus quadrupole QD0FF. This resulted in jitters of comparable magnitude at the two BPMs which made them easier to align.

Figures 3-7 show the beam distributions recorded at each BPM for a pair of acquisitions, each of which lasted approximately two minutes. The blue and red histograms correspond to feedback off and feedback on respectively. The feedback on data at P2 and P3 shows that the feedback system is actually kicking the second bunch away from the zero point of those BPMs. This is deliberate and was achieved by using the kick offset terms described in Eq. 4 to try and keep the second bunch within the dynamic range of MFB1FF.

The performance of the feedback system can be measured in a number of ways. Table 2 shows the measured beam position jitter at each BPM. The jitter achieved at the feedback BPMs themselves is a function of their resolution. The results are consistent with P2 and P3 having an average resolution better than 200 nm. The jitter measured at the witness BPMs is more difficult to interpret.

Table 1: Table indicating the location of selected beamline components in the lattice (relative to the start of the extraction line).

Name	Distance [m]
K1	26.672
K2	29.598
P2	30.123
P3	33.025
MFB1FF	58.534
IPA	89.125
IPB	89.212
IP	89.299

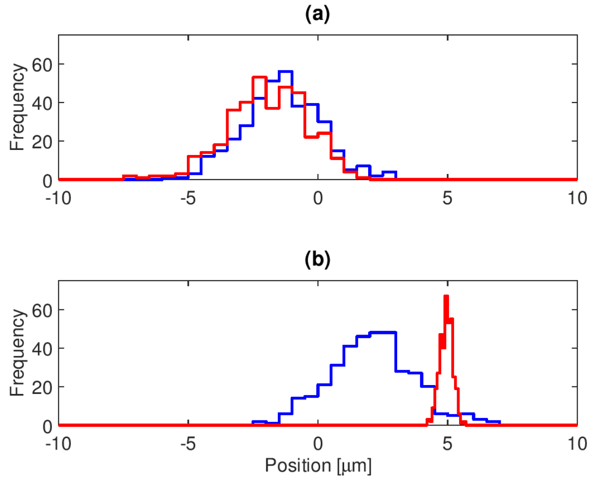

Figure 3: Distribution of beam positions measured at P2 with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. Note that a bin width of 100 nm is used for the case of the second bunch with feedback on, compared to 500 nm for the other cases.

Clearly the jitter is reduced by a much larger factor at the feedback BPMs (6.5 at P2 and 5.5 at P3) than at the witness BPMs (1.9, 1.8 and 1.6 at MFB1FF, IPA and IPB respectively).

As a dual-phase system, it is important to also consider the effect of the feedback on the angular jitter of the beam. The angular jitter is not measured directly but can be inferred using the position measured at two locations and knowledge of how the beam is expected to propagate from one location to the other. The distribution of angles calculated at P3 using the transfer matrix from P2 to P3 calculated using the ATF MAD model is shown in Figure 8. The data suggests the angular jitter at this location is reduced from 1.21 ± 0.04 μrad down to 0.14 ± 0.01 μrad. The angular jitter calculated in the IP region using the position at IPA and IPB is shown in Figure 9. Here the angular jitter is reduced from 19.0 ± 0.7 down to 10.9 ± 0.4 μrad. Similarly to the position jitter, the angular jitter is reduced by a much larger factor upstream than in the IP region (1.7).

Table 3 shows the calculated correlation between the position of the first bunch and the position of the second bunch at each BPM. It can be seen that a significant amount of correlation remains at the witness BPMs despite the large reduction in correlation achieved at the feedback BPMs.

It is instructive to compare the measured beam distributions at the witness BPMs with those predicted from the P2 and P3 data and the linear transfer matrices calculated from the ATF MAD model. These are presented in Table 4. The two sets of numbers are not in exact agreement. The estimated jitter at MFB1FF is on average 15% larger than the measurements and the equivalent figure for IPA is close to 30%. Conversely, at IPB the estimated

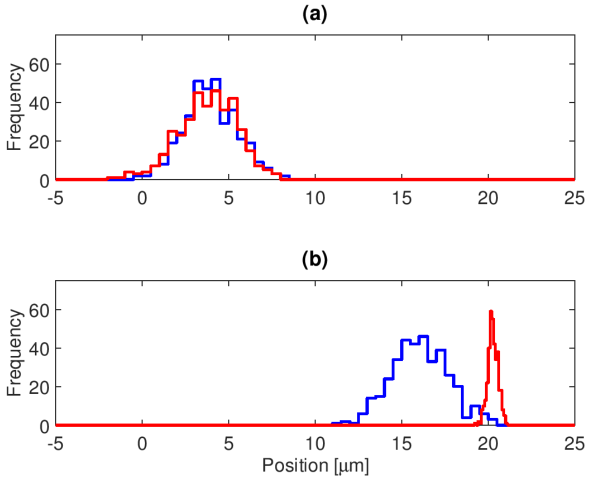

Figure 4: Distribution of beam positions measured at P3 with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. Note that a bin width of 100 nm is used for the case of the second bunch with feedback on, compared to 500 nm for the other cases.

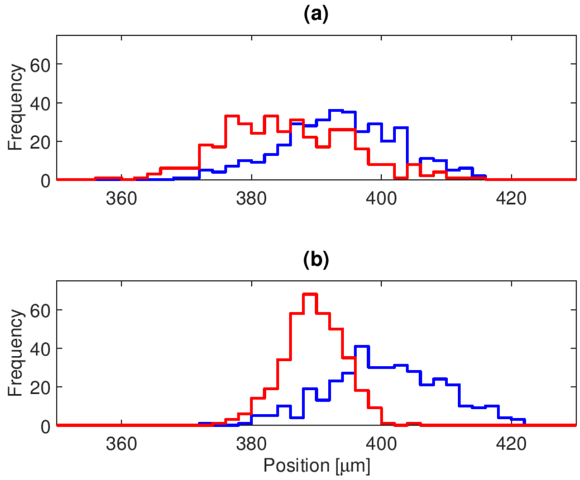

Figure 5: Distribution of beam positions measured at MFB1FF with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. The bin width is 2 µm.

jitter is on average 10% smaller than the measured value. Nevertheless, comparison of the feedback off and feedback on data sets indicates that the measured reduction in jitter at P2 and P3 is only expected to translate into a factor two reduction of the jitter at each of the witness BPMs, close to what is achieved.

For the feedback off run, the P2 and P3 data predict a position jitter of 16 nm at the focal point of the beam, which lies about 2/3 of the distance from IPA to IPB. With feedback operational, the equivalent value at the point of minimum jitter is 2.3 nm.

4. Conclusions

An intra-train position and angle feedback system has been developed for the KEK ATF to achieve the beam stability goal of the ATF2 collaboration.

5. Acknowledgments

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We thank the KEK ATF staff for their outstanding logistical support and for providing the beam time and the necessary stable operating conditions for this research. In addition, we thank our colleagues from the ATF2 collaboration for their help and support. In particular, we thank the IFIC group from the University of Valencia for providing the BPM mover system. We acknowledge financial support for this research from the United Kingdom Science and Technology Facilities Council via the John Adams Institute, University of Oxford, and CERN, CLIC-UK Collaboration, Contract No. KE1869/DG/CLIC. The research leading to these results has received funding from the European Commission under the Horizon 2020/Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) project E-JADE, Grant Agreement No. 645479.

[1] R. J. Apsimon, D. R. Bett, N. B. Kraljevic, P. N. Burrows, G. B. Christian, C. I. Clarke, B. D. Constance, H. D. Khah, M. R. Davis, C. Perry, J. R. López, C. J. Swinson, Design and performance of a high resolution, low latency stripline beam position monitor system, Phys. Rev. ST Accel. Beams 18, 032803.
[2] R. J. Apsimon, D. R. Bett, N. B. Kraljevic, R. M. Bodenstein, T. Bromwich, P. N. Burrows, G. B. Christian, B. D. Constance, M. R. Davis, C. Perry, R. Ramjiawan, Design and operation of a prototype interaction point beam collision feedback system for the international linear collider, Phys. Rev. Accel. Beams 21, 122802.
[3] Y. Inoue, H. Hayano, Y. Honda, T. Takatomi, T. Tauchi, J. Urakawa, S. Komamiya, T. Nakamura, T. Sanuki, E. S. Kim, S. H. Shin, V. Vogel, Development of a high-resolution cavity-beam position monitor, Phys. Rev. ST Accel. Beams 11, 062801.

Table 2: Measured beam jitter for both bunches for feedback off and feedback on.

Name	Bunch 1 [μm]		Bunch 2 [μm]	
	off	on	off	on
P2	1.49 ± 0.05	1.55 ± 0.06	1.63 ± 0.06	0.25 ± 0.01
P3	1.54 ± 0.06	1.69 ± 0.06	1.65 ± 0.06	0.30 ± 0.01
MFB1FF	8.93 ± 0.33	9.75 ± 0.36	8.78 ± 0.32	4.65 ± 0.17
IPA	1.02 ± 0.04	1.16 ± 0.04	0.98 ± 0.04	0.56 ± 0.02
IPB	0.70 ± 0.03	0.80 ± 0.03	0.69 ± 0.03	0.42 ± 0.02

Table 3: Measured bunch-to-bunch correlation coefficient for feedback off and feedback on.

Name	Feedback off	Feedback on
P2	0.99 ± 0.01	0.21 ± 0.05
P3	0.98 ± 0.01	0.06 ± 0.05
MFB1FF	0.98 ± 0.01	0.39 ± 0.05
IPA	0.98 ± 0.01	0.41 ± 0.05
IPB	0.98 ± 0.01	0.48 ± 0.05

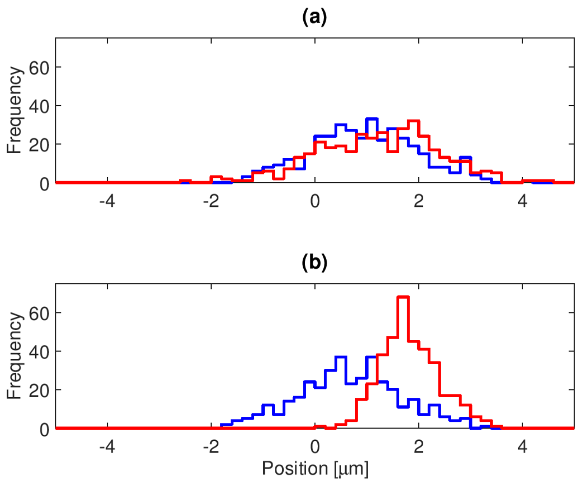

Figure 6: Distribution of beam positions measured at IPA with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. The bin width is 200 nm.

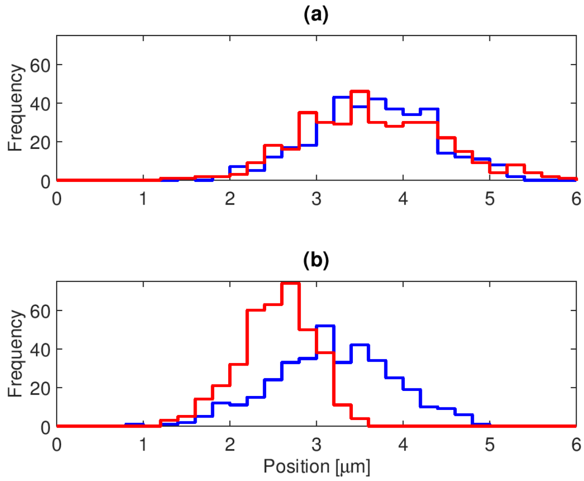

Figure 7: Distribution of beam positions measured at IPB with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. The bin width is 200 nm.

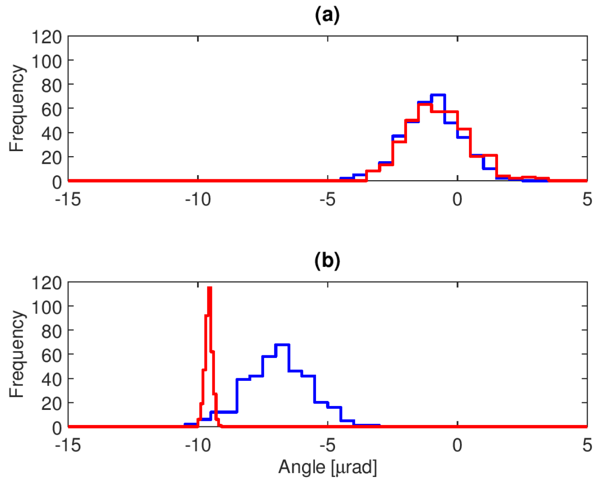

Figure 8: Distribution of beam angles inferred at P3 with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. Note that a bin width of 100 nrad is used for the case of the second bunch with feedback on, compared to 500 nrad for the other cases.

Table 4: Tracked beam jitter for both bunches for feedback off and feedback on.

Name	Bunch 1 [µm]		Bunch 2 [µm]	
	off	on	off	on
MFB1FF	9.90 ± 0.36	10.12 ± 0.37	10.68 ± 0.39	5.37 ± 0.20
IPA	1.31 ± 0.05	1.33 ± 0.05	1.41 ± 0.05	0.70 ± 0.03
IPB	0.64 ± 0.02	0.65 ± 0.02	0.69 ± 0.03	0.35 ± 0.01

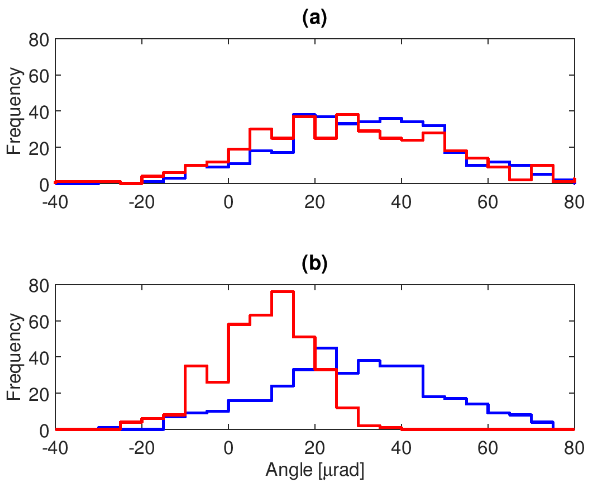

Figure 9: Distribution of beam angles inferred at IPB with feedback off (blue) and feedback on (red) for (a) the first bunch; (b) the second bunch. The bin width is 5 µrad.