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FAST FEEDBACK USING ELECTRON BEAM STEERING TO MAINTAIN THE X-RAY BEAM POSITION AT A MONOCHROMATIC X-RAY DIAGNOSTIC AT DIAMOND LIGHT SOURCE

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Abstract

A new feedback system is being developed at Diamond Light Source, applying a modulation to the position of the electron beam to keep the synchrotron X-ray beam fixed at a beamline X-ray diagnostic. Beamline detectors operating in the 100 - 1000 Hz regime are becoming common, and the X-ray beam stability demanded by beamlines is thus of comparable bandwidths. In this paper we present a feedback system operating at these bandwidths, using a diagnostic instrument permanently installed in the X-ray beam path to measure the error in beam position close to the sample point, and fast air-cored magnets to apply a small modulation to the electron beam to compensate. Four magnets are used to generate electron beam bumps through an insertion device straight. This modulation of the beam away from the nominal orbit is small, less than 10 microns, but should be sufficient to compensate for the bulk of the X-ray motion observed. It is small enough that the impact on the machine will be negligible. This system aims to maintain X-ray beam stability to within 3 % of a beam size, at bandwidths of up to 500 Hz.

INTRODUCTION

Beamlines are demanding greater positional stability of X-ray beams and at greater bandwidths than ever before. To meet this need a new system has been developed to improve the positional stability of a focussed X-ray beam. The system achieves this using a fast feedback scheme which monitors the X-ray beam position downstream of the monochromator, and makes small, fast adjustments to the X-ray beam source point. This system can reduce the X-ray beam motion at bandwidths of up to ~ 1 kHz. Presented in this paper are an outline of this system, Source Feedback From X-rays (SOFFOX), and the initial results.

The increases in stability requirements and increases in bandwidths are being driven by sub-micron sized synchrotron beams, and kHz detector rates [1–3]. It is extremely difficult for beamlines to correct beam motion at frequencies > 100 Hz with 'conventional' beamline feedback using optical components (monochromator crystals, mirrors, etc) to steer the X-ray beam. These components are difficult to move and manipulate at high enough frequencies to effectively counter beam motion. However, it is feasible to manipulate the electron beam at these bandwidths.

The I14 beamline at Diamond Light Source was chosen as the testbed for SOFFOX due to the extremely small X-ray beam sizes that it will employ, and due to the long length of the beamline: 30m between the source and the monochromator, and 155m between the monochromator and the sample point [4]. There is the potential for even small position errors at the source point to result in large X-ray beam motion at the sample point.

Figure 1 presents an overview of the beamline and source point. SOFFOX uses four dedicated fast corrector magnets in the insertion device (ID) straight, capable of applying a horizontal magnetic field transverse to the electron beam path. Each is supplied with a high precision bipolar current supply. The corrector magnets are a simple air-cored Helmholtz coil design. The four magnets generate a closed bump in the electron beam orbit, inducing vertical steers of the electron beam through the source point without affecting the remainder of the orbit. The system is only designed to operate on the vertical component of the beam motion, and horizontal coupling should be minimised.

On the beamline, a single-crystal diamond X-ray beam position monitor (XBPM) [5] is used as the monitor. The XBPM signals are acquired into a custom μTCA board at a rate of 100 kHz. An FPGA calculates the new feedback setpoint from the measured beam position, and transmits this new setpoint to the magnet power supplies. The μTCA board and the magnet power supplies are linked by a low-latency, small form-factor pluggable (SFP) fibre optic network connection. The feedback is ultimately designed to operate only on the AC component of the X-ray beam motion, leaving the synchrotron fast orbit feedback (FOFB) and the beamline optics to correct DC errors.

This feedback system is agnostic to the source of the X-ray beam motion, reducing the impact of all disturbances, whether originating with the electron beam, or originating on the beamline. Similar feedback schemes, steering the electron beam to compensate for observed X-ray beam motion, have been implemented in the past [6]. However, to the best of the author's knowledge, this is the first time such a scheme has been implemented using a monitor located downstream of the monochromator and operating at these bandwidths on a 3rd generation light source.

A great emphasis has traditionally been placed upon keeping the electron beam position stable during synchrotron operation. The decision to intentionally modulate the electron beam trajectory in order to improve the X-ray beam stability at the sample point is potentially quite heretical! However the authors hope to demonstrate that it is worthwhile to sacrifice the ideal of 'a stable electron beam', at least over some timescales, for the improved X-ray beam stability that this system provides.

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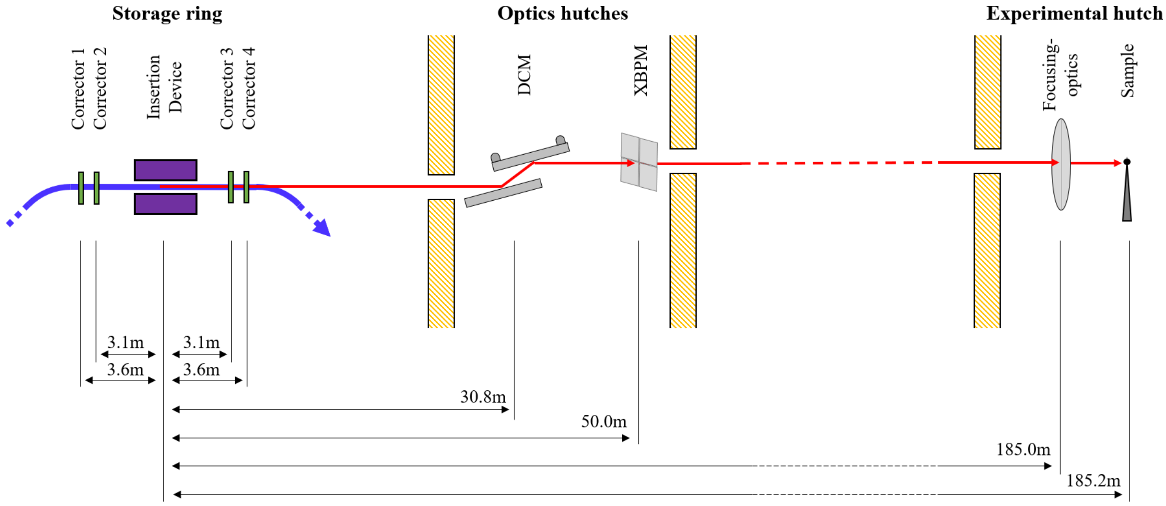

Figure 1: A sketch (not to scale) showing the layout of the I14 beamline and the location of the four SOFFOX chicane magnets.

MAGNETIC FIELD STRENGTHS AND BANDWIDTHS

Each of the four air-cored magnets consists of a pair of 100-turn loops, with a diameter of 125mm. The DC resistance of each pair of coils is measured to be 1.2 Ω, and the inductance measured to be 3.7 mH. The magnets are installed outside of the vacuum chamber, with each pair of loops transversely separated by 95mm (the external width of the vessel). In this configuration the DC magnetic field strength at the centre of the loops is calculated to be 1.0 mT per Ampere current. In reality, an AC magnetic field generated by the coils will be attenuated by the 2 mm stainless steel vacuum vessel, particularly at higher frequencies.

The coil pairs were installed symmetrically either side of the insertion device (ID), as shown in Figures 1 and 2. In this way electron beam bumps can be induced through the ID that are transparent to the rest of the machine orbit.

The magnet currents were supplied by fast, commercially available power supply units (PSUs) located outside of the tunnel in the control instrumentation area.

The power supply scaling required to form a closed bump using the four chicane magnets has been found empirically. A 100Hz AC current was applied to all four magnets simultaneously, and the amplitude of the AC current on each of magnets was varied until the electron beam disturbance observed around the remainder of the synchrotron was minimised. These four power supply scale factors, referred to

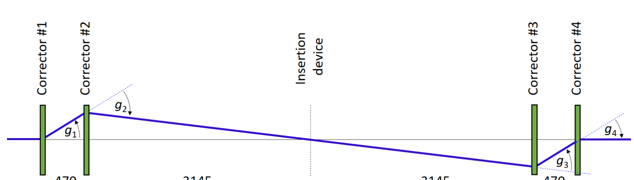

Figure 2: A sketch (not to scale) showing the magnet configuration used to produce a closed bump through the ID straight. Distances given are in millimetres.

as $g_{1,2,3,4}$, were found to be +1.00; -1.15; +1.20; and -1.00 respectively. Figure 2 gives a sketch of the closed bump produced.

In practice, the four magnets are capable of generating an angular steer through the ID of 0.87 µrad per Ampere current on the first corrector magnet, with the currents on the remaining three corrector magnets being scaled by g_2, g_3, and g_4 respectively. The magnitude of this steer of the electron beam through the ID straight (and thus the X-ray beam) has been measured using both front end white beam XBPMs, and by observing the offsets produced on the electron beam position monitors (EBPMs) adjacent to the ID straight.

To determine the bandwidth of the electron beam modulations that the coils can produce, an AC current of known amplitude was requested from one of the PSUs and applied to the first corrector magnet. The effect on the synchrotron orbit was observed. The magnitude of the observed modulation represents the effective bandwidth of the PSU, corrector magnet, and vacuum vessel together as a single system. Figure 3 shows the measured electron beam excitation ampli-

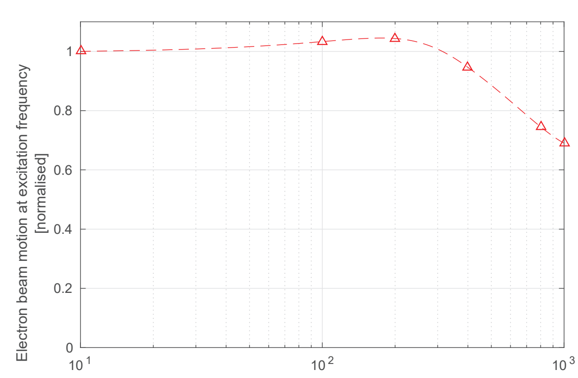

Figure 3: The measured electron beam motion as a function of corrector magnet excitation frequency in open-loop.

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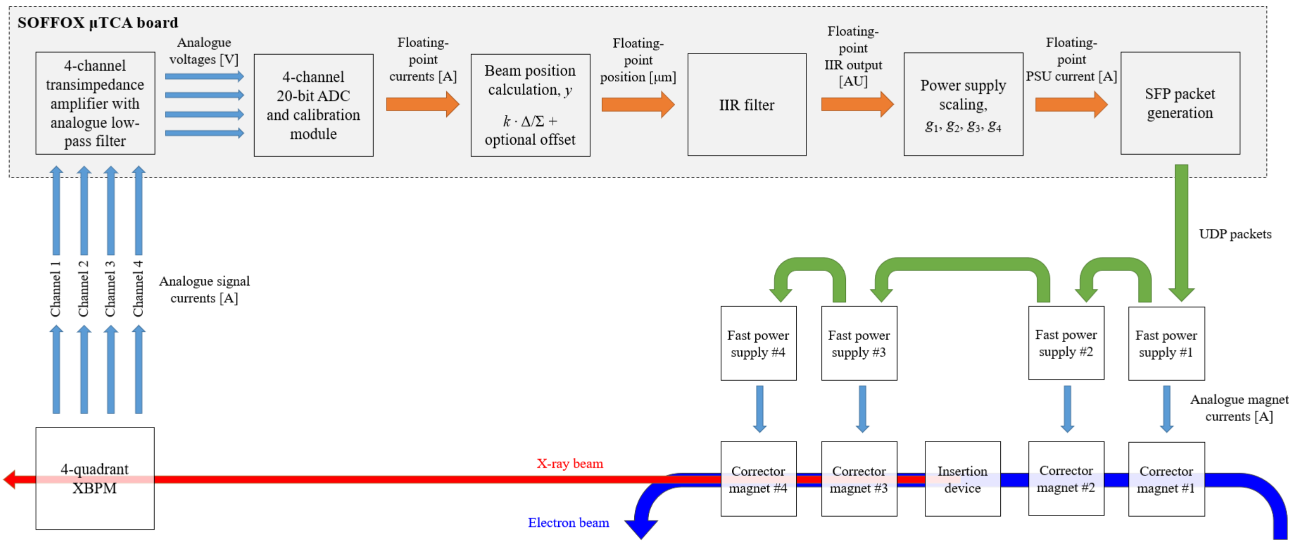

Figure 4: A block diagram showing the processes involved in the SOFFOX feedback scheme.

tude at the EBPM immediately downstream of the modulated corrector magnet as the excitation frequency is swept from 10 Hz to 1 kHz. At higher frequencies the effectiveness of the corrector magnets begins to drop, but even at 1 kHz the magnet is still capable of inducing a beam deflection with a magnitude of 66 % of the deflection induced at 100 Hz.

FEEDBACK PROCESSES

Presented in Figure 4 is a block diagram showing the processes involved. The SOFFOX µTCA board uses a 4-channel 20-bit, 1 MSample / s ADC to record the XBPM signals. Each channel averages 10 samples to provide a 100 kSample / s datastream. An FPGA calculates the Δ/Σ X-ray beam position error from these signal currents, applying a scale factor, k, to convert the dimensionless Δ/Σ into a real beam position in micrometres.

The X-ray beam position error is passed to an infinite impulse response (IIR) filter which generates the coil current set point for the fast power supply. The use of an IIR structure allows flexible discrete time controllers to be investigated including conventional PI and PID structures, Internal Model controllers, band-pass rate feedback controllers and combined state observer/controllers. The initial phase of SOFFOX focussed on the use of proportional (P-only) control implemented on the IIR filter as a proof-of-principal demonstration.

The output from the IIR is a single number which is scaled by the four power supply gains, $g_{1,2,3,4}$, to produce a closed orbit bump that contains the necessary angular component. These four corrector magnet currents are sent as SFP packets over the fibre-optic network connection back to the four daisy-chained PSUs. The PSUs drive currents through the four magnets in order to steer the electron beam, steering the X-ray beam back to the centre of the XBPM. This completes the loop.

The latency of the system as a whole is of crucial importance to successful feedback operation. It will be impossible to make kHz bandwidth corrections if the delay between measurement observation and magnet correction is too great. To ensure successful performance, the latency of the system was measured on the laboratory bench before installation on the synchrotron. A signal generator was used to supply an AC current into one channel of the SOFFOX transimpedance stage. A 'test' mode allows the Δ/Σ calculation to be altered to simply forward the channel signal current as the beam position, y. This is fed into the IIR filter, which was configured so as to pass the beam position straight through to the power supply scaling process.[1] The PSU setpoint is then transmitted to the power supplies, which in turn output a current. Both the input from the signal generator and the output from the PSU, via a resistive load simulating the magnet coils, were acquiring using an oscilloscope. A whole system round trip latency of 120 µs was measured.

FEEDBACK TO AN XBPM DOWNSTREAM OF THE MONOCHROMATOR

An XBPM is installed on the I14 beamline downstream of the monochromator, at a distance of 50 m from the source. The SOFFOX µTCA board was installed on the beamline next to the XBPM in order to reduce the cable distance that the analogue signals must travel from the monitor to the SOFFOX transimpedance input stage. The SFP fibre optic network path between the µTCA board and the PSUs was approximately 250 m in length.

To test that the magnets could induce sufficient X-ray beam motion, visible at the XBPM, a simple 10 Hz square-wave modulation of the electron beam was requested from the four PSUs. The results of this are shown in Figure 5. Although the beam steers should be vertical only, a small amount of horizontal coupling is measured by the XBPM. This is measured by observing the horizontal beam motion, and measuring the amplitude of the induced 10 Hz compo-

[1] a_0=1, b_0=1, a_1=0, b_1=0, ..., all other IIR parameters are zero.

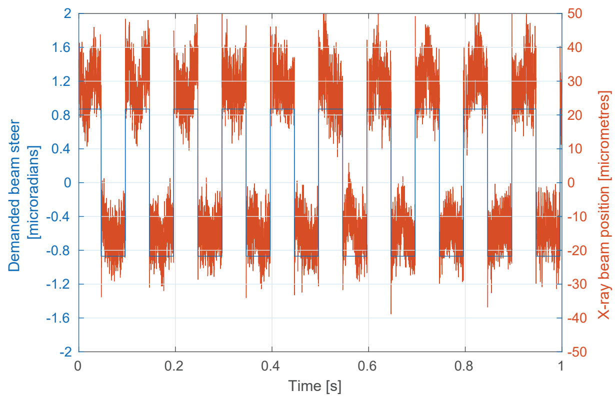

Figure 5: A plot showing the requested electron beam steer alongside the measured X-ray beam position.

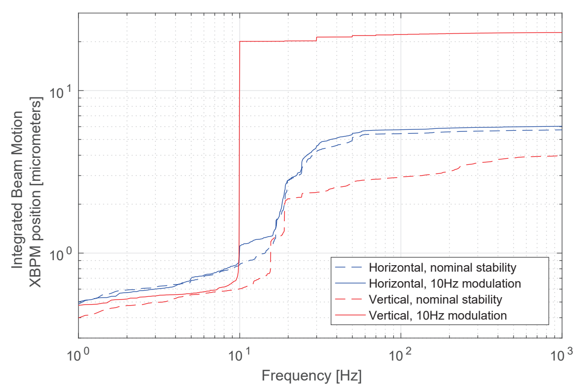

Figure 6: There is a small additional 10 Hz component visible in the horizontal beam motion whilst the system is applying a vertical 10 Hz modulation to the X-ray beam.

nent. These results showing the X, Y coupling are presented in Figure 6, demonstrating that the coupling is only ~ 1 %.

Following this, a very simple proportional-gain feedback was implemented. The IIR filter was set to forward only the error term with a pre-determined gain, P. The X-ray beam motion recorded at the XBPM under the following conditions was recorded: no electron beam feedback at all; fast orbit feedback (FOFB) running (nominal user conditions); SOFFOX feedback turned on and slowly increasing the proportional gain, P. The integrated beam motion under these conditions is given in Figure 7. These results demonstrate that even with a 'simple' proportional gain controller the beam stability can be improved at kHz bandwidths.

Eventually, the feedback gain is sufficiently high that the system becomes unstable. Uncontrolled oscillations start to be introduced at 1.49 kHz, and once the proportional gain P reaches ~ 15 the overall beam motion is worse than with no feedback. The beam stability at bandwidths below these oscillations continues to improve however. For some beamline conditions, where the acquisition rates are ≪ 1.49 kHz, the introduction of more high frequency beam motion could be considered a reasonable compromise in order to obtain better low-frequency beam stability. However, future work

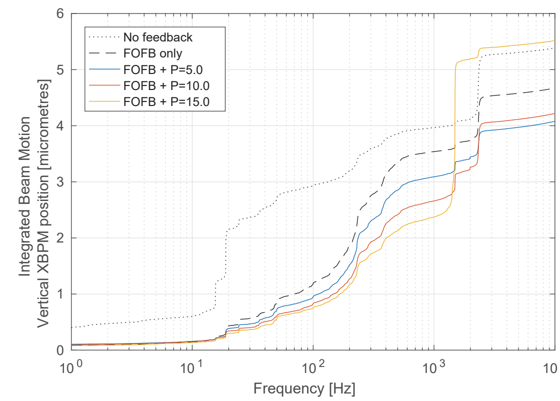

Figure 7: The measured integrated X-ray beam motion as the SOFFOX proportional gain is increased. The nominal stability of the X-ray beam with FOFB running is shown by the dashed black line.

will concentrate on better feedback design that should be able to adress these 1.49 kHz oscillations.

CONCLUSIONS

A fast X-ray beam position feedback system utilising four fast corrector magnets installed in an insertion device straight to modulate the source point has been demonstrated at Diamond Light Source.

The system has been shown to improve X-ray beam stability as measured by X-ray beam position monitor located 50 m from the sample point, downstream of the beamline monochromator. The system can provide an improvement in beam stability at bandwidths of > 1 kHz.

The 10-tap IIR filter implemented on the SOFFOX µTCA board opens up the possibility of implementing more advanced feedback schemes. Future activity will include investigating how best to achieve optimum control using the available hardware, using system identification tools to fit a discrete time state space model to the complete system.

Careful consideration must be given before a 'sample point' feedback can be implemented, as there are numerous possible complications that can arise. However, the manipulation of the electron beam is currently the only feasible solution for 'fast' X-ray beam feedback operating at bandwidths of ~ 1 kHz, so further investigation is warranted.

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REFERENCES

[1] G. Ice, J.D. Budai, and J.W.L. Pang, "The Race to X-ray Microbeam and Nanobeam Science", *Science*, vol. 334, pp. 1234-1239, Dec. 2011. doi:10.1126/science.1202366

[2] A. Casanas *et al*, "EIGER detector: Application in macromolecular crystallography", *Acta Crystallographica Section*

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D: Structural Biology, vol. 72, pp. 1036-1048, Sep. 2016. doi:10.1107/S2059798316012304

[3] Y. Gao *et al*, "High-speed raster-scanning synchrotron serial microcrystallography with a high-precision piezo-scanner", *Journal of Synchrotron Radiation*, vol. 25, pp. 1362-1370, Sep. 2018. doi:10.1107/S1600577518010354

[4] P. Quinn, J. Parker, F. Cacho-Nerin, M. Walker, and P. Howes, "The Hard X-ray Nanoprobe Beamline at Diamond - Current Status", *Microscopy and Microanalysis*, vol. 24, pp. 242-243, Aug. 2018. doi:10.1017/S1431927618013569

[5] C. Bloomer and G. Rehm, "The use of single-crystal CVD diamond X-ray beam diagnostics for synchrotron beamline commissioning and operation at Diamond Light Source Ltd", in *Proceedings of the IEEE Nuclear Science Symposium*, Strasbourg, Oct. 2016, pp. 1-7. doi:10.1109/NSSMIC.2016.8069893

[6] B. Hettel, "Beam Steering at the Stanford Synchrotron Radiation Laboratory", *IEEE Transactions on Nuclear Science*, vol. 30, pp. 2228-2230, Aug. 1983. doi:10.1109/TNS.1983.4332770