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A LOW-LATENCY FEEDBACK SYSTEM FOR THE CONTROL OF HORIZONTAL BETATRON OSCILLATIONS

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Abstract

Reinforcement learning (RL) algorithms are investigated at KIT as an option to control the beam dynamics at storage rings. These methods require specialized hardware to satisfy throughput and latency constraints dictated by the timescale of the relevant phenomena.

The KINGFISHER platform, based on the novel Xilinx Versal Adaptive Compute and Acceleration Platform, is an ideal candidate to deploy RL-on-a-chip thanks to its ability to execute computationally intensive and low latency feedback loops in the order of tens of microseconds. In this publication, we will present the integration of the KINGFISHER system at the Karlsruhe Research Accelerator (KARA), as a proof-of-principle turn-by-turn control feedback loop, to control induced transversal oscillations of an electron beam.

INTRODUCTION

As previously discussed in reference [1], the implementation of low-latency reinforcement learning inference platforms will be fundamental for the next generation of particle accelerator control systems. One possible application of such a system is achieving a high degree of control of the microbunching instability (MBI) in synchrotron light sources. In order to streamline the process of development and deployment of this kind of infrastructure, the KINGFISHER platform was developed. In this work the first test of a closed-loop feedback with such a platform is discussed. A latency-critical task, such as the damping of horizontal betatron oscillations in a synchrotron light source, was chosen. This has the benefit of not needing any invasive modification to the accelerator. Moreover, an additional benefit is that the control problem of these kind of oscillations is well understood, with several commercial options already currently available [2]. In the future, the chosen feedback action will be performed by the low-level radio frequency (LLRF) [2] system, as it was shown to be the only one effectively influencing the MBI [3].

HARDWARE SETUP

Each component will be examined from the accelerator readout to the application of the feedback signal on the accelerator. A schematic drawing is shown in Fig. 1.

Beam Position Signal

The four signals of a 4-button beam position monitor (BPM) are fed into a Dimtel BPMH-20-2G [2] passive RF hybrid that performs the analog computation of the sum and difference signals, thus disentangling the vertical, horizontal, and longitudinal dimensions. This leads to signals whose amplitude is proportional to the position of the beam in each axis. The signal corresponding to the horizontal plane is then split with a Mini-Circuits ZN2PD2-14W-S+ with a bandwidth from 500 to 10 500 MHz. One output is processed with the existing bunch-by-bunch (BBB)[2] feedback system for monitoring, while the other is amplified with a Mini-Circuits ZX60-2534MA-S+.

KAPTURE System

The output from the amplifier is then acquired with the KAPTURE system [4]. A new version of the firmware presented in reference [1] has been developed in order to perform low-latency streaming of the full KAPTURE data, corresponding to a data rate of 38 Gbps. This was achieved by using the Aurora 64b/66b protocol [5] IP released by AMD Xilinx. The specific implementation aggregates four serial channels, each one operating at 10 Gbps, on a Samtec FireFly connector [6]. This allows a standardized connection to other electronic cards, both on copper wire and optical fiber in a completely transparent way for the user. In this way, the system can be easily adapted for long-distance fiber connection, for experiments spanning facility-level dimension, and to smaller scales where copper interconnection between two racks is sufficient. For the test described in this work, a copper wire connection was chosen.

KINGFISHER System

As discussed in the previous subsection, the implementation presented in reference [1] was modified. Thanks to its modular design, it was only necessary to replace the Gigabit Ethernet interface module with Aurora. In order to add Firefly connectivity to the VCK190 evaluation board, the 14 Gbps FireFly™ FMC Development Kit [7] was connected to one of the two FMC+ connectors.

On the Versal AI Engine Array, a single tile was used to implement a 32-coefficient Finite Impulse Response (FIR) filter, operating on the continuous data stream in real time. This specific filter was chosen because it is the same used in the existing BBB feedback system. The filtered output is then applied to a Digilent PMOD-3A digital-to-analog converter (DAC) in order to output the analog feedback signal. The DAC control logic runs in a separate clock domain using a low-voltage transistor-transistor logic reference from the machine timing system, maintaining the synchronization with the accelerator. In a first step for single-bunch feedback, the

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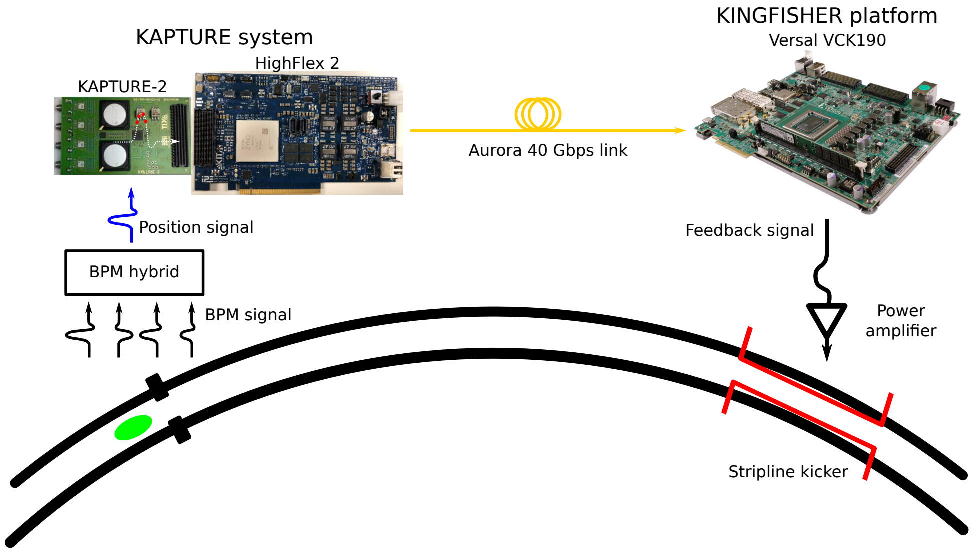

Figure 1: Schematic drawing of the feedback loop implemented at KARA, showing the main electronic boards used.

DAC sample rate corresponding to the revolution frequency of the accelerator was chosen, namely about 2.7 MHz.

An Experimental Physics and Industrial Control System (EPICS) [8] input/output controller (IOC) implemented with the caproto [9] library, executed on the Versal ARM processor, is used to set parameters of the system (e.g. the DAC digital gain, change the FIR coefficients, etc…) and is completely integrated into the accelerator control system. Moreover, it is possible to acquire the streamed signals and store them for later analysis.

Feedback Signal

The feedback signal from KINGFISHER is then transferred to the power amplifier usually utilized by the BBB feedback system and is then fed to a stripline kicker.

LABORATORY TEST

In order to ensure that the Aurora link was working as intended, the eye diagram of each serial channel was measured with the Integrated Bit Error Ratio Tester (IBERT) embedded in the FPGA transceiver. In this way, it could be verified that each serial line did not exhibit any problematic behaviour. An example eye diagram is shown in Fig. 2.

After this, it was possible to test the complete system: a pulse was generated with a signal source and the FIR filter coefficients were set such that it would behave as the identity. The timing difference between the input and output of the feedback system showed a total latency of 2.5 μs, representing approximately a factor of four improvement compared to the previous approach using Gigabit Ethernet, while also allowing a much higher throughput.

BEAM TEST

The first beam test of the system took place at KARA. The machine was operated at injection energy (500 MeV). In order to reduce possible multi-bunch effects due to coupled bunch instabilities, a single-bunch filling pattern was used.

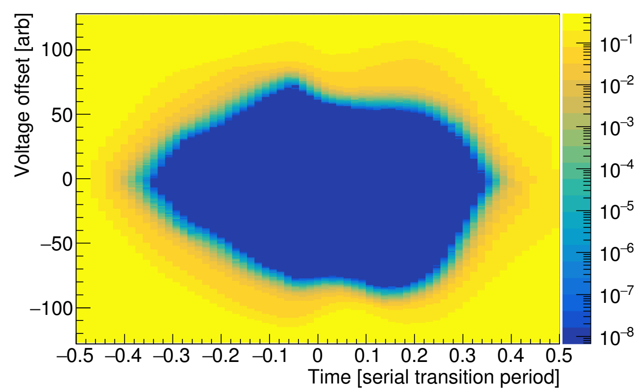

Figure 2: Eye diagram representing the Bit Error Rate (BER) as a function of the time from the zero crossing and Voltage offset as measured on the Xilinx Versal VCK190 Breakout Board with a 14 Gbps FireFly™ FMC Development Kit at 10 Gbps.

Commissioning

The first step was testing whether the readout of the BPM signal was functioning properly. This was achieved by using the injection magnets in order to excite transversal oscillations in the beam position.

The next step was verifying that the KINGFISHER feedback output was being processed properly. A test sinusoidal signal was output from the system, while measuring the output level of the power amplifier, showing that the system could actually drive it to full-scale.

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After these initial tests the feedback loop was closed and the coefficients were set with a sinusoidal shape

$$c[i] = \sin\left(2\pi f \frac{i}{N} + \varphi\right),$$

where $c[i]$ is the i-th FIR coefficient, N is the number of non-zero coefficients, while f and φ can be used to tune the response of the filter. This expression was chosen as the frequency response can be easily computed analytically. Moreover, changing the phase φ allows to change the output phase of the filter while maintaining a similar shape of the response function.

For the first test $N = 5$ and $f = 2$ were chosen, which led to a wide band filter having the maximum gain around the betatron tune. The phase was then modified in order to obtain a stable operating condition: if the beam becomes unstable, usually causing a degraded beam lifetime, it means the feedback system output signal has a phase that is exciting the betatron oscillations. Usually shifting the phase by up to 180° makes the loop stable.

Damping Test

The first way to test that the feedback system is actually working is to verify its capability of dampening the betatron oscillations induced by the injection kicker. As shown in Fig. 3, the behaviour of the system is as one would expect: increasing the feedback system gain leads to stronger damping of the betatron oscillation, leading to a faster decay of the oscillation amplitude.

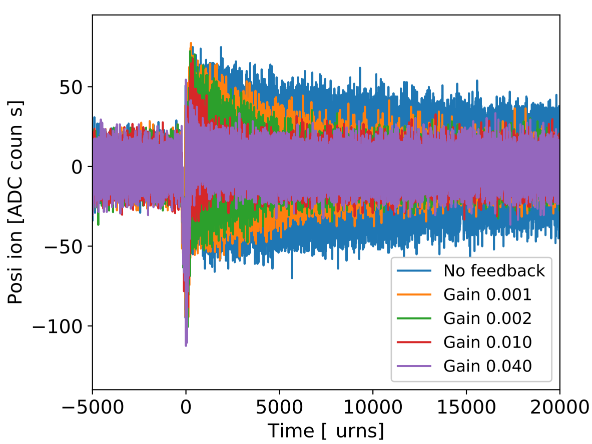

Figure 3: Position measured with the BPMs as a function of time, expressed in turns, for different gains of the feedback system. The injection kick arrives at $t = 0$.

Notch Test

Another characteristic of a functioning feedback system is a notch in the BPM signal power spectra that can be observed when the feedback system is on [10, 11].

This phenomenon can be explained as follows: the noise from the front-end electronics is processed by the FIR filter. In turn, this leads to the frequencies around the betatron frequency to be phase-shifted by approximately 180°. This is then applied to the beam, whose frequency response exhibits a strong resonance in that region and is then sampled again by the front-end electronics, this time with opposite sign to the original noise, which leads to a noise subtraction.

To test that this is indeed the case, Fig. 4 compares the Fast Fourier Transform (FFT) of the BPM signal with the feedback on to the case where there is no beam in the machine. The notch is clearly visible with the beam, while it disappears without it. Moreover, the notch goes below the noise floor of the front-end electronics, as expected from the explanation given.

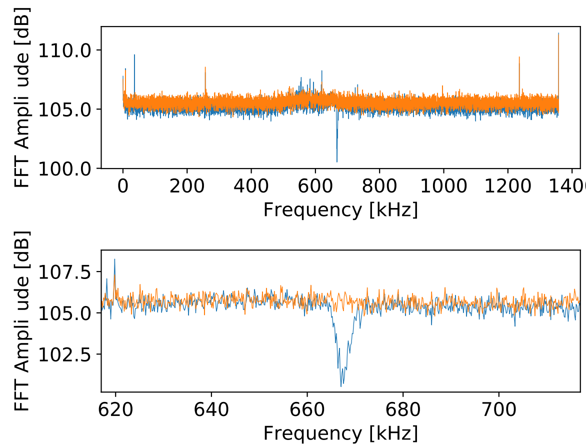

Figure 4: Comparison of BPM signal FFT with the feedback (blue line) and without beam (orange line). The notch produced by the feedback is clearly visible. The lower plot shows a zoom in the notch region. The peak in the 30 kHz region (blue line) is due to synchrotron oscillations.

CONCLUSIONS

In conclusion, an upgraded version of the KINGFISHER platform was presented, allowing continuous feedback on the full data acquired by the KAPTURE detector system. The versatility of the platform allows its connection to different diagnostic detector systems placed in different locations of a facility.

Moreover, the feedback loop was closed, showing its ability to achieve continuous control of the horizontal betatron oscillations at KARA.

In the future, the integration of the system with the latest RL frameworks will be carried out, paving the way to the first feedback tests using RL algorithms. Additionally, the system will be extended to act on the beam through the LLRF system, in this way allowing the first tests of control of the MBI.

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