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DEVELOPMENT AND EVALUATION OF AN RFSoC BASED STRIPLINE BPM READOUT HARDWARE PROTOTYPE

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Abstract

We have developed a Stripline BPM readout device based on an AMD/Xilinx RFSoC chip which integrates multiple ADCs, DACs, a large scale FPGA, and an ARM processor in a single package. The developed device is intended for use at the beam transport line connecting the KEK injector Linac to the SuperKEKB collider rings. SuperKEKB will operate at unprecedented luminosities requiring very high beam currents. To reach and maintain such currents, high injection efficiency is essential which in turn requires precise tuning of the injection process. The RFSoC based BPM will provide a highly flexible platform for beam orbit measurements near the injection point required for the tuning. One objective is to enable the separate resolution of the orbit of both bunches in the two-bunch injection mode, where two bunches are accelerated and injected with 96 ns spacing. Additionally, we plan to utilize resulting measurements as inputs for real-time automated injection tuning and feedback to the upstream steering in the beam transport line. Here, we present the status of the development including results from prototype tests conducted at the KEK injector Linac.

INTRODUCTION

The SuperKEKB collider, while already holding the current luminosity world record of $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, is still aiming for luminosities much beyond this value. To achieve such high luminosities, beam currents on the order of Ampere must be sustained, which due to the short beam life requires high performance (top-up) injection.

While the injection rate is limited at 25 Hz, a *two-bunch injection* mode is available where charge is injected into two 96 ns spaced buckets within the same injection cycle. However, present instrumentation near the injection point is not able to measure the trajectory of both injected bunches separately, complicating injection tuning.

Specifically the readout electronics of the last last Beam Position Monitor (BPM) before the injection point are not able to process signals from both bunches separately. Thus we develop a new readout device based on the highly flexible Radio Frequency System on a Chip (RFSoC) platform [1].

HARDWARE

One main advantage of the RFSoC platform is the simplification of hardware development as high performance ADCs and DACs, an FPGA as well as ARM CPU are contained all in the same package. Further, the ADCs of the 3rd generation RFSoCs are known to be highly performant, providing 9.3 effective bits at 4 GS per second [2].

Thus, for the purpose of our development effort a readily available 3rd generation RFSoC evaluation board (RFSoC4x2 by RealDigital, shown in Fig. 1) already provides most of the required functionality, including clock and trigger inputs.

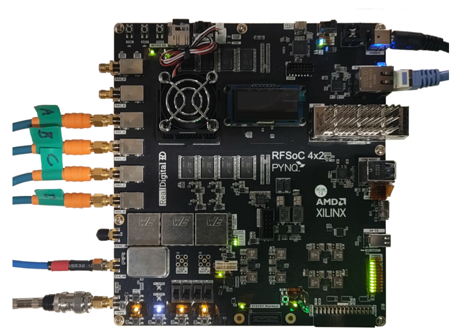

Figure 1: RFSoC4x2 evaluation board used for development.

SuperKEKB INJECTION POINT BPM

The injection point BPMs for the positron and electron rings of SuperKEKB are each located just after the last septum magnet, slighly upstream of the injection point. A simplified model of the injection point BPM chamber (electron ring) is shown in Fig. 2. The injection beam traverses the small chamber attached to the side of the larger storage beam chamber. Four electrodes of stripline type are located on the top and bottom of the small rectangular chamber.

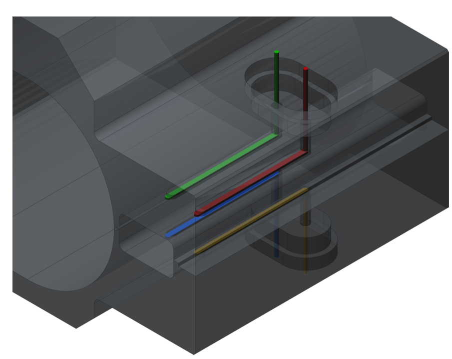

Figure 2: Simplified model of the SuperKEKB injection point BPM chamber (electron ring). The four pickups located on the top and bottom of the chamber are shown in different colors.

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Signal Map Generation Using Boundary Element Method

As no stretched-wire scan was performed for injection point BPM chambers, expected signal strength for each pickup as a function of beam position x, y is determined by simulation using custom boundary element method (BEM) code. An example of the produced maps for the electron ring is shown in Fig. 3. For the positron ring the electrode positions are slightly different (asymmetric).

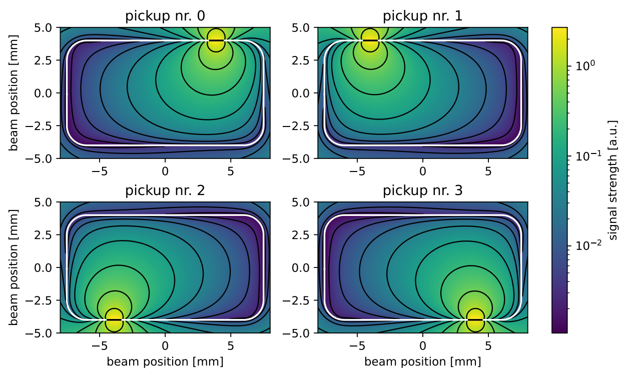

Figure 3: Signal strength maps for each BPM electrode for electron ring chamber geometry. The Chamber boundary is shown in white, the designated pickup section in black.

Position Computation

Due to the rather complex chamber geometry two separate methods for position computation are implemented. Inputs to the calculation are measured signal strengths at each electrode s_i (sum of ADC samples).

The first method uses the differences $\Delta_{ij} = s_i - s_j$ and sums $\Sigma_{ij} = s_i + s_j$ of the measured signals, expressing position using a polynomial defined in Eq. (1). The coefficients A_{mn} and B_{mn} are determined by a fit to the BEM signal map data.

$$x = \sum_{m=0}^{s} \sum_{n=0}^{s} A_{mn} \left(\frac{\Delta_{02}}{\Sigma_{02}}\right)^m \left(\frac{\Delta_{13}}{\Sigma_{13}}\right)^n , \quad (1)$$
$$y = \sum_{m=0}^{s} \sum_{n=0}^{s} B_{mn} \left(\frac{\Delta_{02}}{\Sigma_{02}}\right)^m \left(\frac{\Delta_{13}}{\Sigma_{13}}\right)^n .$$

The second method uses the BEM signal map directly. The position is determined as the coordinates x, y minimizing discrepancy between measured signals and BEM signal map defined in Eq. (2). This method may be useful near the chamber edges where a polynomial fit may fail.

$$f(x, y) = \sum_{i=0}^{3} \left(\frac{s_i^{\text{map}}(x, y)}{\Sigma_{i=0}^{3} s_i^{\text{map}}(x, y)} - \frac{s_i}{\Sigma_{i=0}^{3} s_i} \right)^2 . \quad (2)$$

FIRMWARE AND SOFTWARE

A block diagram of the RFSoC firmware is shown in Fig. 4. The sampling clock of the RF Data Converter (RFDC) is synchronized with the SuperKEKB RF clock (509 MHz).

Data from the RFDCs ADCs is read out continuously and stored in ring buffers implemented in PL. To store waveforms from one injection only around 300 ns are required. A second larger buffer, read out at a lower rate, is included for debugging. The injection waveform buffer is read out on arrival of a injection trigger. Data is transferred from PL to PS via AXI (stream) interfaces and DMA.

Firmware registers can be accessed over a dedicated memory interface. This is also used to set waveforms played back by the DACs, which are mainly employed for debugging purposes (e.g. loop back into ADCs).

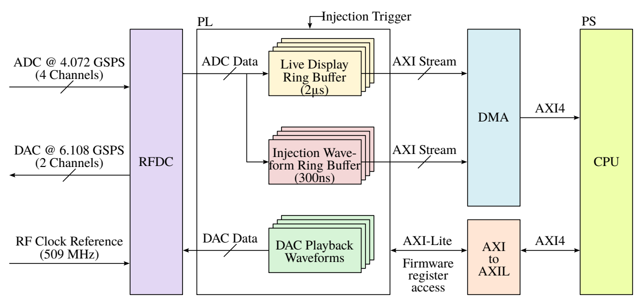

Figure 4: Block diagram of the firmware run on the RFSoC.

On the CPU a TCP bridge is run on top of embedded Linux (build using Yocto, previously Petalinux). As illustrated in Fig. 5, stream and memory interfaces are extended over the local network. Waveform data is transmitted to a rack server where further processing is implemented. The same server is used for setup and control of the RFSoC and attached devices via the memory bridge. It is further possible to attach a GUI for waveform display and easy access to all registers. The firmware and software described here is based on the publicly available *axi-soc-ultra-plus-core* [3] and *rogue* [4] frameworks developed at SLAC.

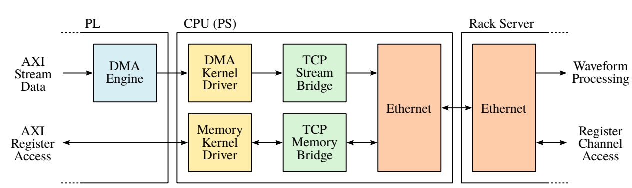

Figure 5: Block diagram of the TCP bridge used for data transfer between the RFSoC board and a rack server running the waveform processing and device control code.

TESTS AT KEK INJECTOR LINAC

During the KEK Injector Linac operation in June 2025 a RFSoC4x2 board was attached to one of the linac BPMs and data was collected in order to judge the achievable resolution. Data from two adjacent (upstream) linac BPMs was used to extrapolate the beam position at the BPM the board was attached to. The difference of extrapolated position and position measured using the RFSoC is used to estimate the resolution.

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To provide some degree of signal shaping (stretching) *Mini-Circuits SLP-450* low-pass filters were employed. While those are not optimal, they were the only ones available during the tests.

The beam was scanned by around 1.5 mm vertically (y direction) over the course of 25 minutes while recording waveforms for every shot. Using this data, the beam position is computed using a polynomial as defined in Eq. (1). The coefficients A_{mn} and B_{mn} in this case were previously determined by stretched-wire scan of the used BPM chamber.

The width of the distribution of difference between measured and extrapolated position is used to estimate the resolution (Fig. 6, left). As the width is also dependent on the resolutions of the linac BPM measurements used as inputs to the extrapolation, their resolution is determined separately, propagated as an uncertainty and eventually subtracted in quadrature. The linac BPM resolution is determined by the ordinary 3-BPM method using the closest three BPMs upstream of the one read out using the RFSoC readout, two of which are those used for extrapolation (Fig. 6, right). The data used is from during the same vertical scan.

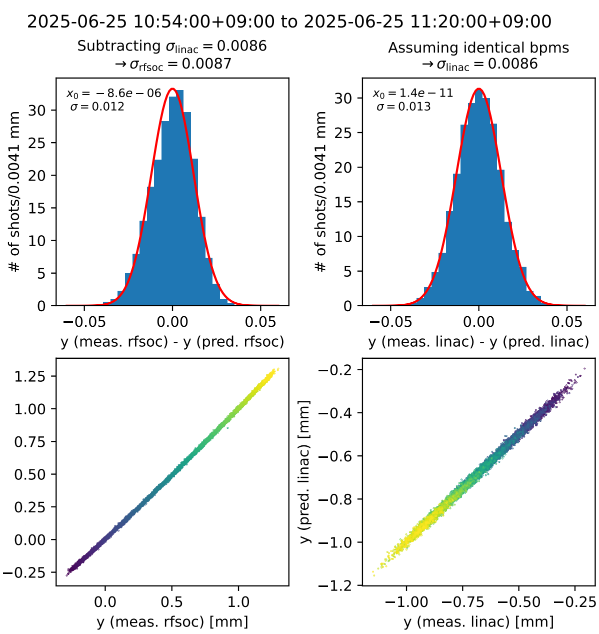

Figure 6: Results of the analysis for resolution estimation. Shown are the residuals (deviation of measured position from predicted position) for RFSoC readout (left) as well as present Linac readout electronics (right).

The resolution using RFSoC based readout was found to be around 9 µm. While for the linac BPMs depending on the operating conditions a resolution of up to 4 µm has been achieved [5], using the data from during the vertical scan we observed again around 9 µm. Thus at least under the operating conditions during the test, the RFSoC readout appears to provide a resolution comparable to the linac BPMs (including their readout electronics).

Data was also collected for the horizontal direction, but as the fit involved in the extrapolation leads to large systematic uncertainties when the range of positions is small, only the vertical direction where the position was scanned is used for the resolution estimation.

Long-Term Stability and Signal Shaping

During the tests at the injector linac it was found that for long measurements on the order of multiple hours, the position readings would tend to drift. This however can be attributed to improper signal shaping. The signal still contained fast rising edges ($\mathcal{O}$ (ns)), the samples on those being extremely sensitive to environmental factors introducing slight signal delays. This mechanism was reproduced in additional lab measurements. Further, the stability of the ADCs was separately verified (using slower signals) and no significant inherent drift was observed over the course of multiple days.

It therefore became obvious that proper signal shaping is mandatory. The exact filter parameters will be selected based on data collected during the next SuperKEKB operation in November 2025. A preliminary study was conducted using a linac BPM waveform (Fig. 7). Evidently a narrow bandpass provides suitable shaping. The signal must not overlap with the one from the second bunch in two-bunch injection mode, which sets a lower limit on the filter's width. Attenuation is not a concern as signals from the stripline pickups in the comparatively small injection point BPM chamber are sufficiently large.

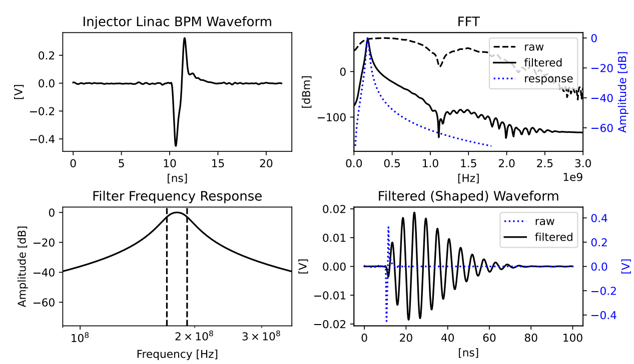

Figure 7: Simulation of a Bessel bandpass filter applied to a BPM signal to shape (stretch) it. Shown are the unfiltered signal, FFTs of filtered and unfiltered signal, filter response as well as filtered signal.

SUMMARY

To reach even higher luminosities, SuperKEKB must sustain high beam currents, which in turn requires high injection performance. This requires careful injection tuning, for which proper measurement of both bunches in two-bunch injection mode is required. To provide such measurements, we develop a new readout device for the injection point BPMs based on the RFSoC platform. First tests demonstrated sufficient resolution. Further improvements are anticipated if signal shaping is optimized.

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