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Evaluating the RFSoC as a Software-Defined Radio Readout System for Magnetic Microcalorimeters

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Arrays of superconducting sensors enable particle spectrum analysis with superior energy resolution. To efficiently acquire data from these sensors, the readout electronics operating at room temperature must perform multiple tasks, such as real-time frequency demodulation. We designed a Software-Defined Radio (SDR) system composed of an MPSoC board, an analog-to-digital conversion stage, and a radio frequency front-end mixing stage to meet the system requirements. Nevertheless, utilizing an Radio Frequency System-on-Chip (RFSoC) could simplify the overall system by integrating the conversion stage and potentially eliminating the mixing stage. This work investigates the applicability of RFSoCs for the aforementioned use case.

Summary (500 words)

The development of high-precision superconducting particle detectors, such as Magnetic Microcalorimeters (MMC) operating at temperatures of a few millikelvins, enables the investigation of fine details in particle interactions. With their inherent high energy resolution, broad energy range, and excellent quantum efficiency, these detectors are ideally suited for precise measurements. To increase the spatial detection area or the number of measurements per time unit, arrays of tens of thousands of these detectors can be operated in parallel. Using a Microwave SQUID Multiplexer (uMUX), multiple sensors can be read out via frequency multiplexing utilizing a single common transmission line. This reduces the number of thermal bridges in the cryogenic environment but increases the complexity of the readout electronics at room temperature, as both the generation and acquisition of a frequency comb at several GHz are required.

A Software-Defined Radio (SDR) has been developed to perform signal generation, demodulation of the frequency comb, and recovery of the raw sensor signals. This SDR comprises a heterogeneous MPSoC platform connected to a conversion stage equipped with several high-speed DACs and ADCs. The converters are in turn connected to another board, designed for mixing the analog signal from baseband to microwave frequencies and vice versa, to meet the requirements of the uMUX. The first application for our SDR system will be at the ECHo-100k experiment, which investigates the electron neutrino mass by detecting the decay spectrum of Ho-163 with more than 10,000 MMCs over a three-year period.

Currently, the room-temperature SDR readout electronics system is based on custom hardware. However, Radio Frequency System-on-Chips (RFSoCs) from AMD Xilinx offer a new possibility for accelerating and simplifying SDR systems for future experiments. In addition to the processing system and the programmable logic, these devices also contain tightly coupled high-speed DACs and ADCs for the transmission and acquisition of analog signals, respectively. The third generation of these RFSoCs provides sufficient converters to be comparable to the system we have developed for the ECHo experiment.

In this work, we evaluate the feasibility of using such an RFSoC device in an SDR system for the readout of superconducting particle detectors. We ported our firmware from a conventional MPSoC to the RFSoC and operated the system on a ZCU216 evaluation board. For the RFSoC to operate comparably to our system, several modifications in the FPGA modules and drivers were necessary due to the differing clock tree structure and converter interfaces on the two platforms.

Through the characterization of both our custom hardware and the ZCU216 under the same conditions, a comparison of the signal quality and measurement accuracy was carried out. The tests were performed within the context of the ECHo experiment, considering the specific requirements of the experiment for the preparation of the measurement setup. The results of our analysis are presented here, as is an assessment of whether the RF-SoC can be used for potential extensions of the ECHo experiment or for the readout of frequency-multiplexed superconducting particle detectors in general.

Primary authors: Dr ARDILA, Luis (KIT-IPE); MUSCHEID, Timo

Presenter: GARTMANN, Robert

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