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The RFSoc-Based Electronics Readout System for the BULLKID-DM Experiment: Sub-GeV Dark Matter Detection with MKIDs

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The BULLKID-DM experiment targets the detection of sub-GeV WIMP-like dark matter candidates using microwave kinetic inductance detectors (MKIDs). The experiment foresees the use of over 2000 individually instrumented silicon dice distributed across 15 wafers. We present the architecture of the room-temperature DAQ system based on the ZCU216 RFSoc board, including the design of a custom analog front-end board, an FMC+ interface card for the energy calibration system, and the design of the active veto detector. We also present the FPGA firmware for tone generation, frequency demultiplexing, system calibration, and triggering. Preliminary data from the demonstrator system will be presented.

Summary (500 words)

The BULLKID-DM experiment aims to detect WIMP-like particles with masses below $1\text{ GeV}/c^2$, which are potential candidates for Dark Matter. Detecting these low-mass particles poses a significant challenge, as it requires nuclear recoil detectors with both high exposure and energy thresholds below 200 eV —capabilities that exceed those of conventional semiconductor detectors. BULLKID-DM addresses this issue by using cryogenic microwave kinetic inductance detectors (MKIDs), which offer exceptional sensitivity at low energies. The experimental target is composed of approximately 800 g of silicon, segmented into more than 2000 individually instrumented dice, distributed across 16 wafers. Each wafer is read out using a single transmission line through frequency division multiplexing (FDM) with resonators between 800 MHz and 1 GHz , enabling a compact and scalable approach to detector signal acquisition.

In this contribution, we present the design and evaluation of the room-temperature data acquisition system. It is built around the ZCU216 evaluation board, which integrates an AMD-Xilinx RFSoc equipped with high-speed analog-to-digital and digital-to-analog converters. This system is paired with a custom analog front-end for signal conditioning, and the FPGA includes firmware modules developed for real-time signal processing tasks such as tone generation, frequency demultiplexing, and event triggering. To ensure versatility, these firmware modules have been generalized to allow rapid adaptation to new detector configurations—such as those used in the demonstrator system and the final experiment.

The full electronics chain has been tested using a prototype detector system composed of three wafers, each featuring 60 instrumented MKID sensors, totaling 180 channels. For this initial demonstrator, energy calibration was carried out using LANTERN, a novel optical calibration system developed in parallel to the readout electronics. To scale up from the prototype to the full experimental configuration, the system is being extended with a dedicated FMC+ interface board that enables calibration of wafers carrying 145 MKIDs. To suppress background from ambient gamma rays and neutrons in the region of interest ($200\text{ eV} - 2\text{ keV}$), BULLKID-DM is evaluating the use of a cryogenic active veto system based on scintillating crystals also read out with frequency multiplexed MKIDs via the RFSoc. While the final experiment will be installed at the Gran Sasso underground laboratory to benefit from its ultra-low background environment, the current results obtained from the surface-based demonstrator validate the performance of the readout and calibration systems.

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