# **RFSoC-based Readout and Characterization Platform Development at SLAC**

Chao Liu on behalf of SLAC TID&FPD collaborators

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## **RFSoC Platforms Supported at SLAC**



Ref: https://www.xilinx.com/products/silicon-devices/soc/rfsoc.html

# SLAC TID TECHNOLOGY

### **Evaluation Platforms**

Open-source firmware and software and example projects with commercial

evaluation hardware – great for small scale R&D projects

https://github.com/slaclab/Simple-ZCU208-Example and other platforms

- ZCU111 RFSoC GEN 1 XCZU28DR
  - 8x 4.096GSPS ADCs and 8x 6.554GSPS DACs
  - Support GEN1 device based hardware
- ZCU216 RFSoC GEN 3 XCZU49DR

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- 16x 2.5GSPS ADCs and 16x 9.85GSPS DACs
- High channel count applications
- ZCU208 RFSoC GEN 3 XCZU48DR
  - 8x 5GSPS ADCs and 8x 10GSPS DACs
  - High bandwidth applications
- ZCU670 RFSoC DFE XCZU67DR
  - 8x 2.95GSPS ADCs, 2x 5.9GSPS and 8x 10GSPS DACs
  - Applications need higher RF input frequency
- RFSoC 4x2 Kit RFSoC GEN 3 XCZU48DR
  - 4x 5GSPS ADCs, 2x 9.85GSPS DACs
  - Academic applications with low channel count
  - Low cost and low barriers to entry

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## **Science Drives**

#### Microwave SQUID multiplexing (µMUX) for CMB experiments nultiplexe Ŷ resonator flux ramp-SOUID 4 4 m m Ø\_m ☆\_m ₫\_m detector TES array TES biasrouting wafer

McCarrick et al. https://arxiv.org/abs/2106.14797

#### Heterodyne-based radio astronomy receivers



Liu et al. https://ieeexplore.ieee.org/abstract/document/9814190

### LLRF control of Linac



### Axion dark matter experiment

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#### Bartram et al. https://arxiv.org/abs/2010.06183

### Quantum Sensing R&D For Dark Matter



#### Kurinsky @ Aspen23

## SMuRF – µMUX at scale for CMB

### **SLAC Microresonator Radiofrequency Electronics = SMuRF**

- Generate and readback up to 3328 RF carriers in 4-8 GHz bandwidth.
- Unique "tone-tracking" ability sets SMuRF apart from other systems
  - Game changer enables >1000x channel readout/RF line
     C. Yu et al., Rev. Sci. Instrum. 94 (2023)

An integrated 6x SMuRF system – readout for >20,000 TESs



SMuRF readout for 1x 2000 TES CMB wafer

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48x SMuRF systems deploying now on Simons Observatory in Chile



## SMuRF Electronics and SMuRF-RFSoC



#### **Readout System Summary**

- SMuRF electronics
  - Analog mixers
  - Discrete data converters with JESD interface .

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#### SMuRF-RFSoC - upgrade path for SMuRF

- Integrated ADCs and DACs datapath
- NO JESD interface ٠
- NO analog mixer needed for 4-6 GHz ٠
- Lower cost and barriers of entry •
- µmux firmware as example

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- SMuRF firmware ported to RFSoC platform
- Firmware and software are just scaled down or . modified versions for other application
- Performance characterization widely applicable

## **Motivation for Characterization**

### Higher order Nyquist zone / Direct RF sampling

- Reduced complexity of RF front end
  - DAC generating RF signal at 2<sup>nd</sup> Nyquist zone
  - ADC direct sampled and aliased image as signal
- Reduced analog impairments: matching and LO leakage
- Compact size, low cost and low barriers of entry
- Does performance meet HEP requirements???

#### Key performance parameters

- Spurious Free Dynamic Range (SFDR) the overall dynamic range for measurement
- Intermodulation distortion intermod-products can land on other resonators on same RF line
- RF dynamic range measured at a specific offset of the carrier frequency and requirement for µMUX is -100 dBc/Hz at 30 kHz offset to achieve the high channel density

TECHNOLOGY

### Zyng UltraScale+ MPSoc BBF Replaced by Integrated Direct RF Subsystem

Heterodyne to direct RF-sampling

High IF Superheterodyne Receiver to a Direct RF-Sampling Receiver





Ref: https://docs.xilinx.com/v/u/en-US/wp489-rfsampling-solutions

Yu et al. https://arxiv.org/pdf/2208.10523



#### Ref: https://www.rfsocbook.com/

## Single Tone Test Results of Direct RF Sampling

Spectrum of RF signal at 4.25 GHz DAC: 2<sup>nd</sup> order Nyquist zone ADC: 2<sup>nd</sup> order Nyquist zone Spectrum of RF signal at 5.25 GHz DAC: 2<sup>nd</sup> order Nyquist zone ADC: 3<sup>rd</sup> order Nyquist zone



### Test Summary

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- DAC-ADC loop-back
  - SFDR measured
    - 79.6 dB at 4.25 GHz

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- 81.2 dB at 5.25 GHz
- SFDR in Xilinx datasheet with CW power at –10 dBFS
  - 75 dB at 4.9 GHz
  - 74 dB at 5.9 GHz
- Performance at higher order Nyquist zones meet requirements



### Inter-modulation Performance Test in 2<sup>nd</sup> Nyquist Zone

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DAC Two Tone Test in SNR Optimized Mode

DAC Two Tone Test in High Linearity Mode

#### DAC Two Band Test in High Linearity Mode



### **Test Summary**

- RFSoC DACs have two modes use different mechanism to select the unit current cells for decoding the SNR optimized mode and high linearity mode. The **high linearity mode offers 8 dB better IMD performance** than SNR optimized mode.
- The two RF bands directly generated by the integrated DAC have a low level of intermodulation products and leakage to other bands in high linearity mode.

## Loopback RF Dynamic Range Measurements

### RF dynamic range measured at all 4 500MHz bands is mostly below -110 dBc/Hz



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# Full Microwave Multiplexing Readout with RFSoC





### **Test Summary**

 SMuRF-RFSoC to readout a superconducting sensor in the CMB dilution refrigerator

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- Scan of complex transmission through a superconducting resonator
- Tracking the modulation of a SQUID-coupled resonator demonstrates tone tracking
- Recovered 100 mHz sine-wave signal injected into a transitionedge sensor (TES),

demonstrating the successful readout of TES.

# **Jupyter Notebook for Prototyping**

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### System Setup

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# Measurement and readout scripting and data capturing

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# Data processing and visualization

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University and national lab users can prototype rapidly based on example notebook



### Pizza Box for RFSoC based uMux Readout











### RFSoC Chassis Ideal for Small Scale R&D and university project

- 3U module for rack mounting
- Flexible circuit connection
- 10 MHz external sync
- PL and PS Ethernet for data
   stream and remote updating
- Two front panel versions



## **Conclusions and Future Works**

- Direct RF sampling delivered desired performance at higher order Nyquist zones
- Milestones for RFSoC based readout and control system development at SLAC
  - Demonstrating the successful readout of transition-edge sensor for CMB experiment
  - Highly configurable channelizer developed for axion dark matter search
  - LLRF control for Linac demonstrated with extremely low phase noise
- Commercial hardware and open-source firmware and software enable rapid and low-cost (but extremely powerful) R&D readout system prototyping
- Highly flexible system implementation with capability of data streaming at multiple stages of readout – essential for CMB and dark matter search experiments
- Open to collaboration for firmware and software library development

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### **Backups**







### Higher Order Nyquist Zone IMD Evaluation for DACs

### **DAC inter-modulation evaluation circuit**

### Two-tone Signal Loaded to DAC

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#### Motivations

- Intermodulation distortion (IMD) performance for the DAC is critical for frequency division multiplexing with high multiplexing factor
- Exploring the optimum DAC configuration to achieve the best performance with the integrated datapath in RFSoC

# **Integrated Datapath Characterization Test Setup**



### **Setup Summary**

- Single tone test
  - Full loopback
  - Dynamic range
- Comb of tones test
  - Tone power
  - Intermodulation level

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- Phase noise