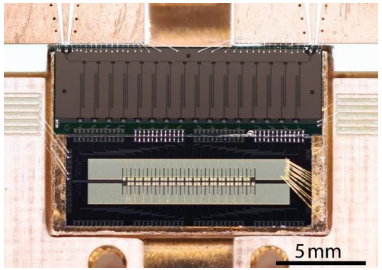
Karlsruher Institut für Technologie

RFSoC Used as a Readout for Cryogenic Superconducting Circuits

Luis Ardila

Cryogenic Superconducting Circuits

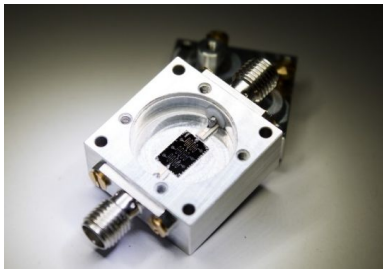


Andreas Fleischmann (U. Heidelberg)

Metallic Magnetic Calorimeters

Highly precise, single particle detectors (1.6 eV at 6 keV)

Multiplexed with microwave resonators


Alexander Stehli (KIT)

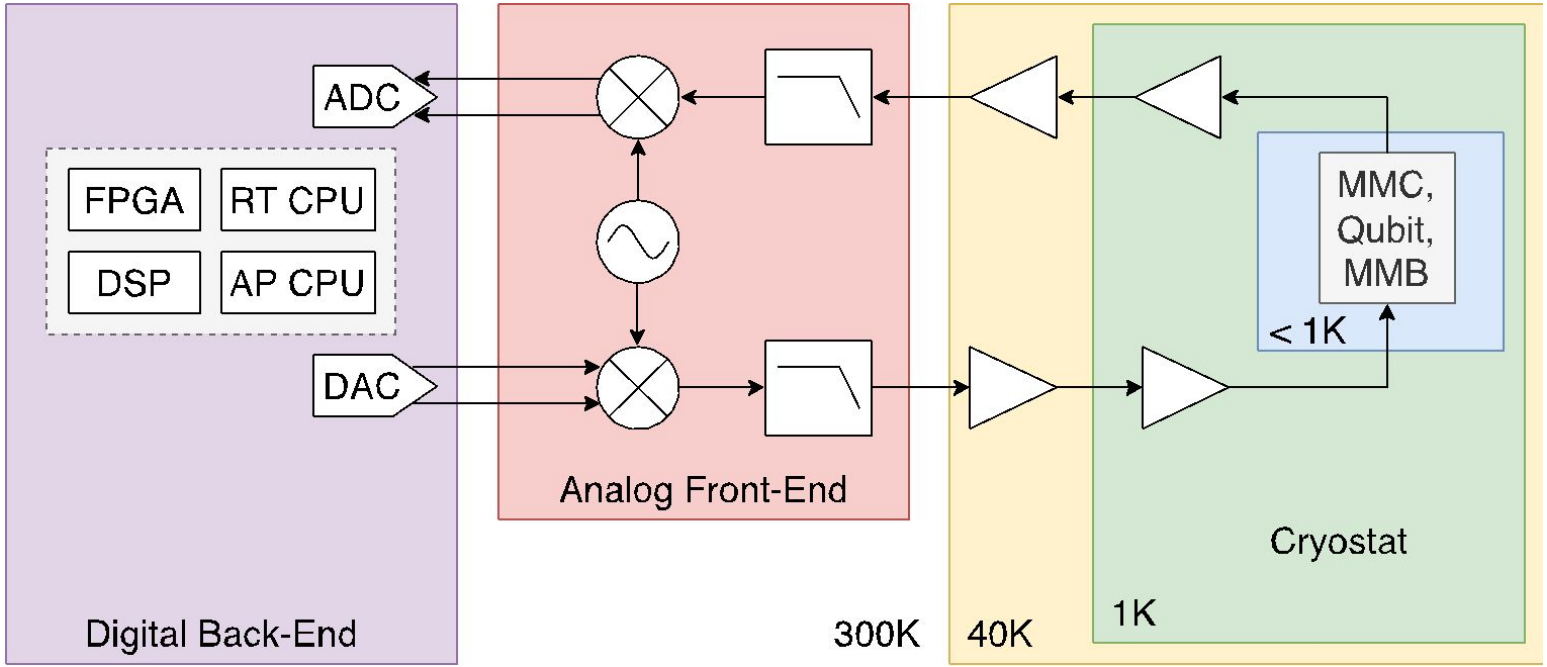
Superconducting Quantum Bits

Building block for quantum computing

Key Requirements

- Operated at very low temperature (<100 mK)
- Interfaced with microwave signals 2 – 12 GHz
- Large signal bandwidth requirements < 500 MHz

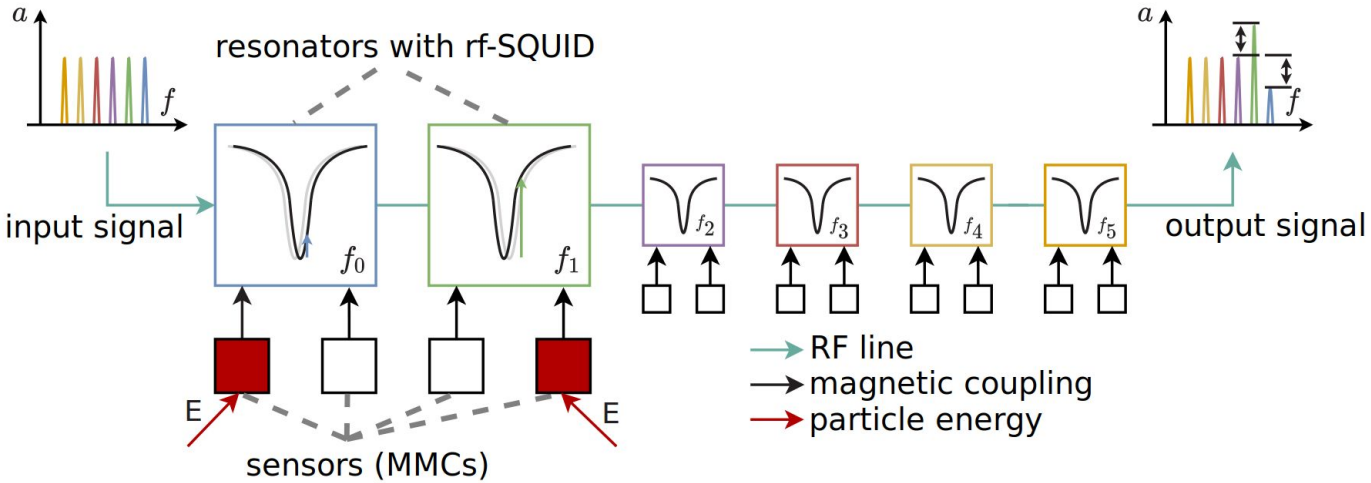
Software Defined Radio (SDR) System Arch.



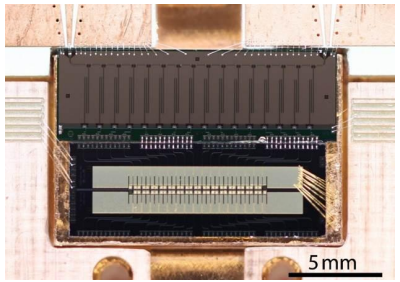
ECHo Experiment

The Electron Capture ^{163}Holmium experiment (ECHo)

- Investigates the upper limit of the **electron neutrino mass**
- Analyzes the energy spectrum in the electron capture process of ^{163}Ho
- Uses metallic magnetic calorimeters (MMCs)
- Parallel readout of **12.000 sensors** using microwave **SQUID** multiplexing approach
- 400 channels per readout line with resonances between **4-8 GHz**

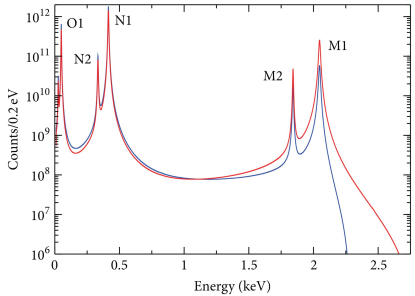


ECHo detector + μMUX:



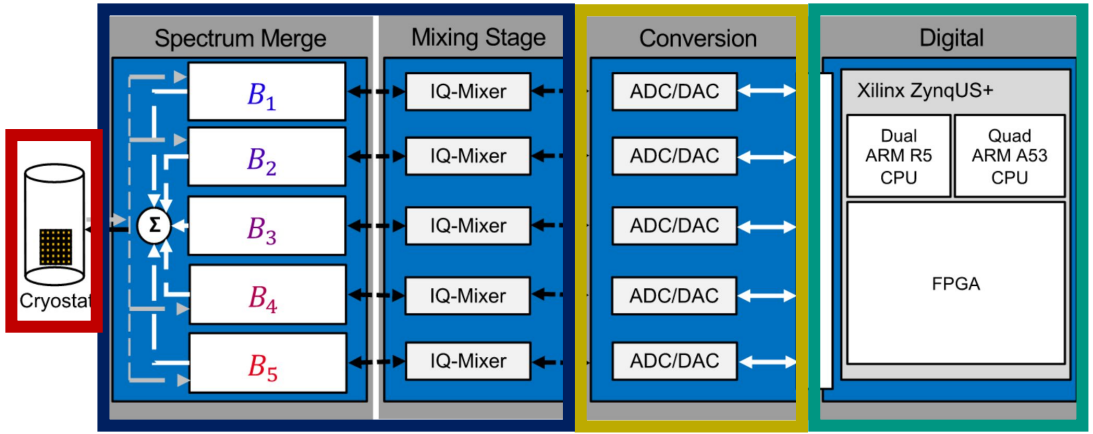
Andreas Fleischmann (U. Heidelberg)

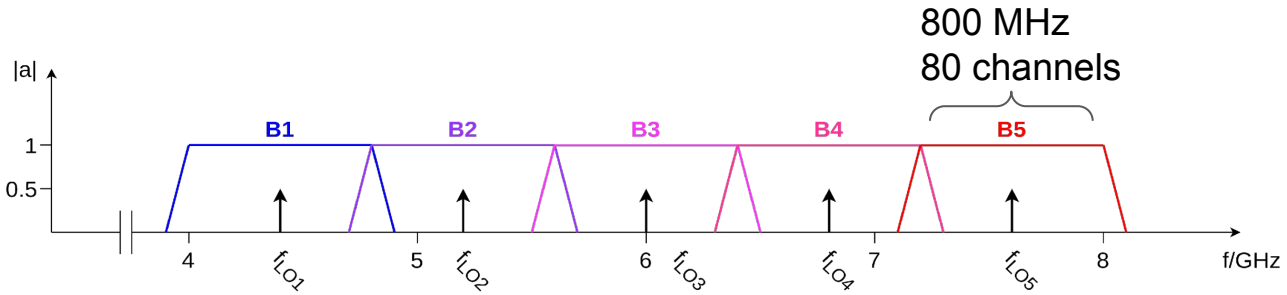
Ho^{163} spectrum:



ECHo Readout Concept

- *Comb generation*
- DAC — *Analog conversion*
- RF TX — *Mixing to RF*
- μMUX — *Cryogenic domain*
- RF RX — *Mixing to baseband*
- ADC — *Digital conversion*
- *Channelization*
- FRD — *Fluxramp demodulation*
- *Event detection*





Gartmann et al., J Low Temp Phys (2022)

Karcher et al., J Low Temp Phys (2022)

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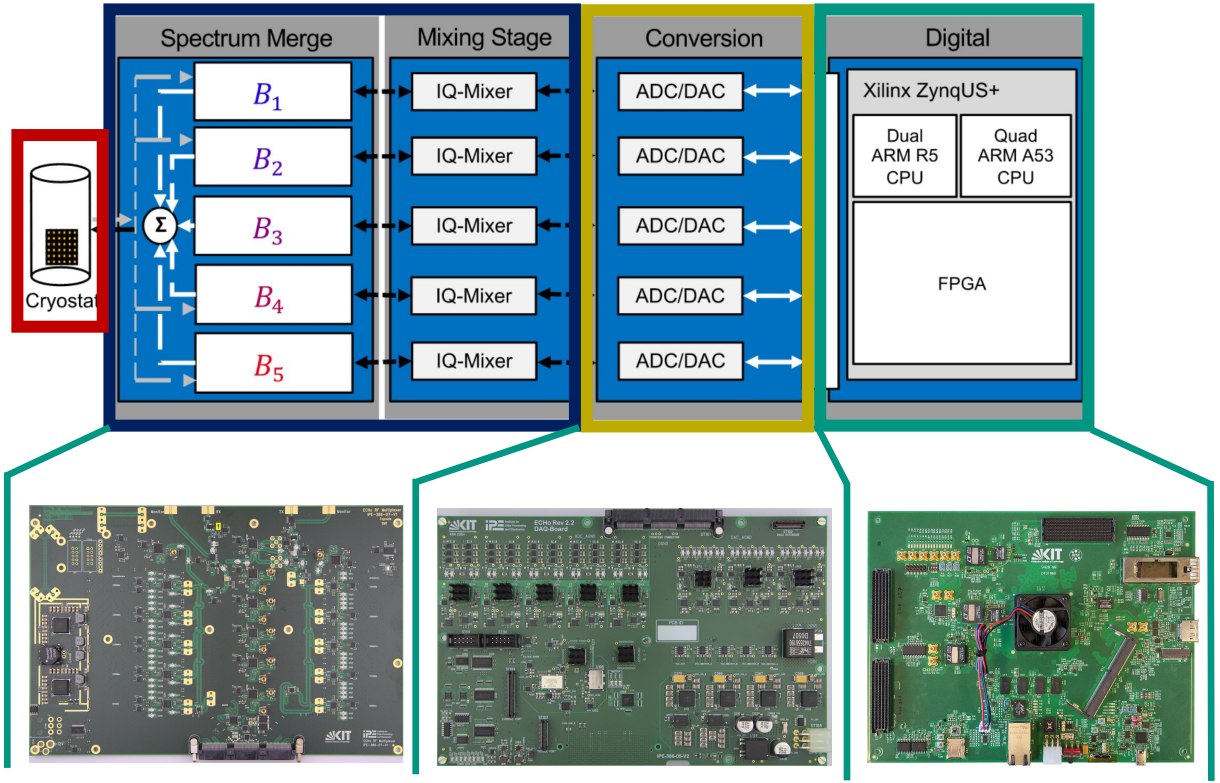

ECHo Readout Concept

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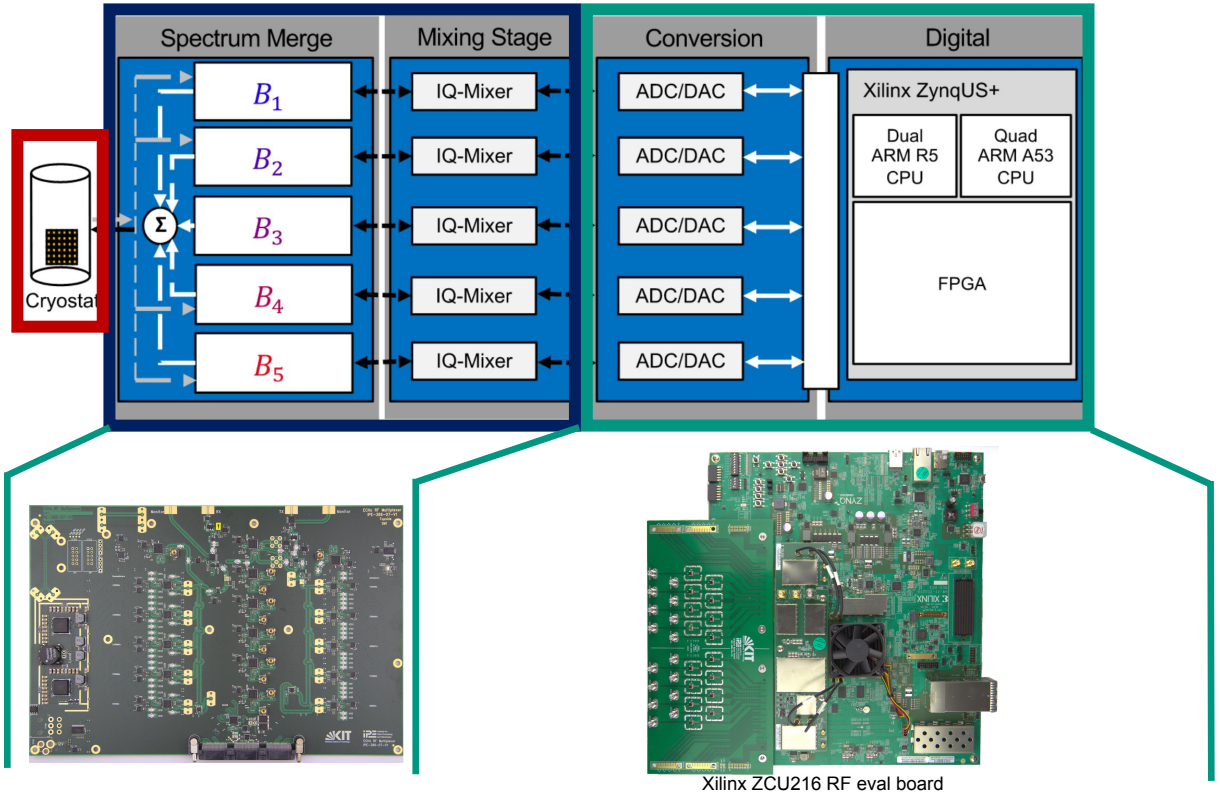
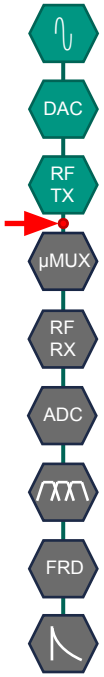
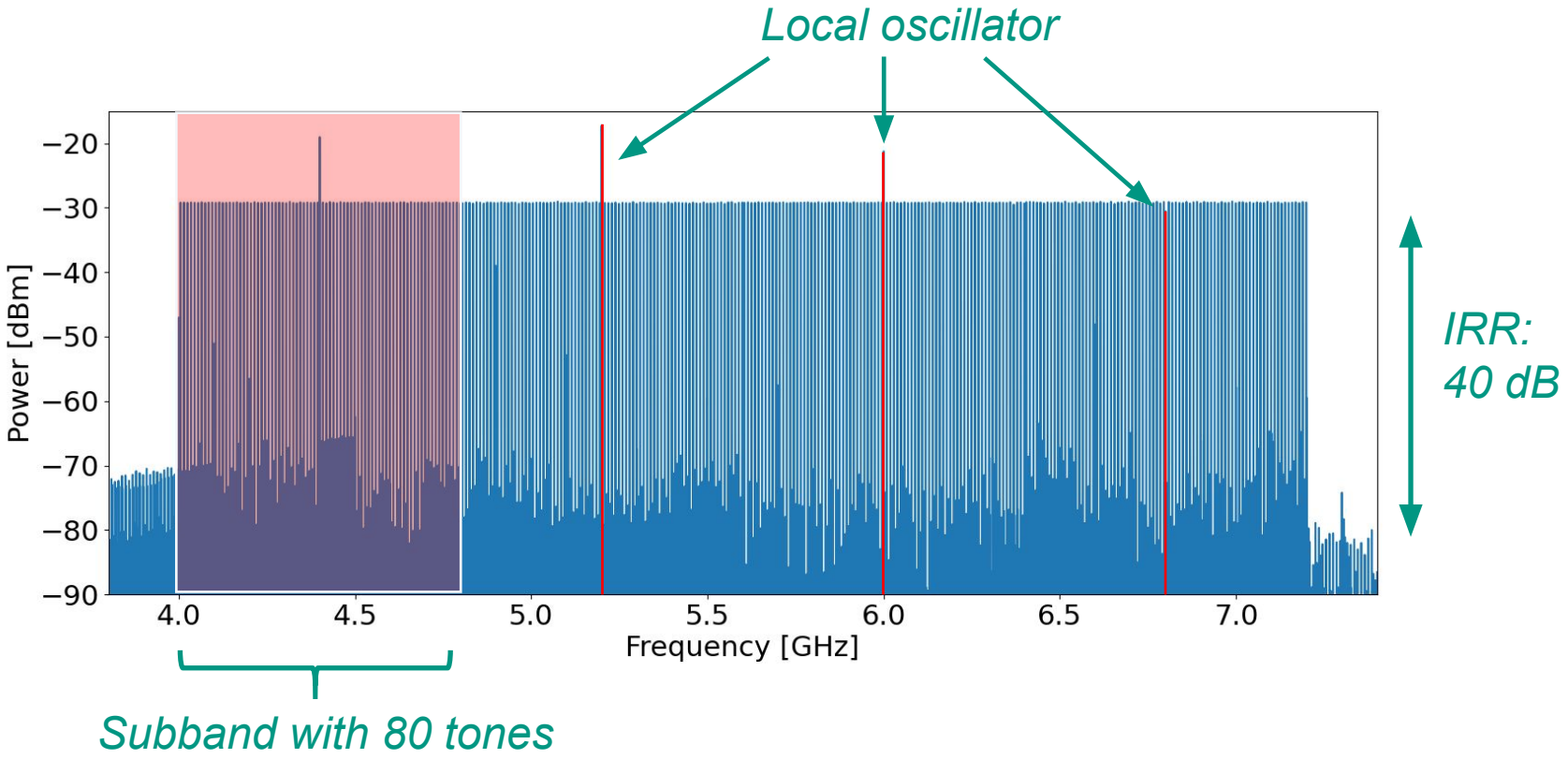


Xilinx ZCU216 RF eval board

Frequency comb





Digital Signal Processing

Digitalization of frequency comb

ADC with internal DDC

Tone separation into TDM-Scheme

Channelization stage

Recovery of raw sensor signal

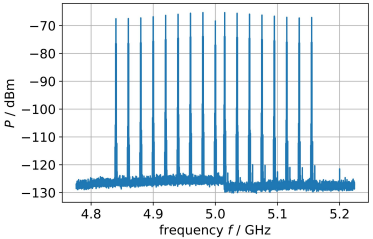
Fluxramp Demodulation

Extraction of relevant samples

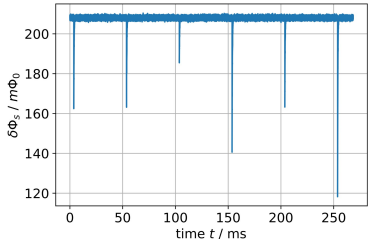
Event Detection

Data rates:

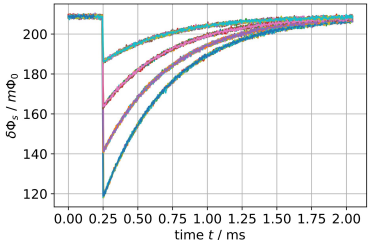
10 parallel data streams
à 500 MSPS (20 GB/s)



20 parallel TDM streams
à 32 x 15.625 MSPS (40 GB/s)



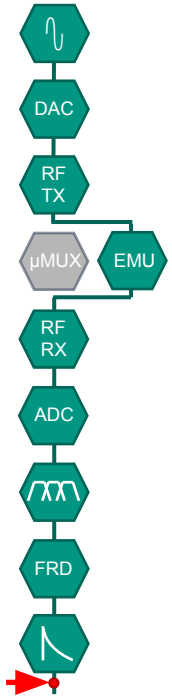
20 parallel TDM streams
à 32 x 1.953 MSPS (10 GB/s)

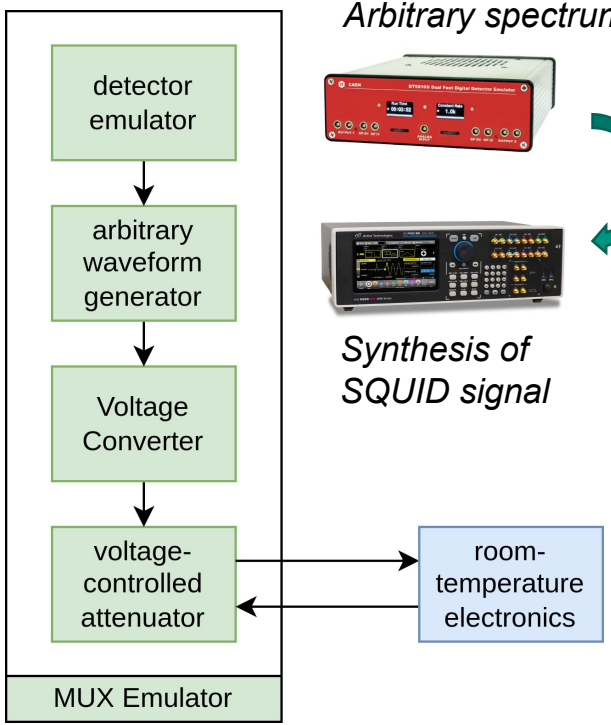


Single data stream
with 8 MSPS (32 MB/s)

Karcher et al., J Low Temp Phys (2022)

Room-temperature emulation

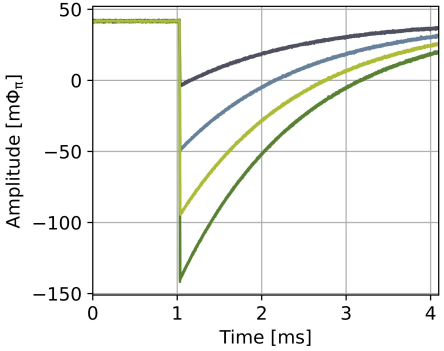


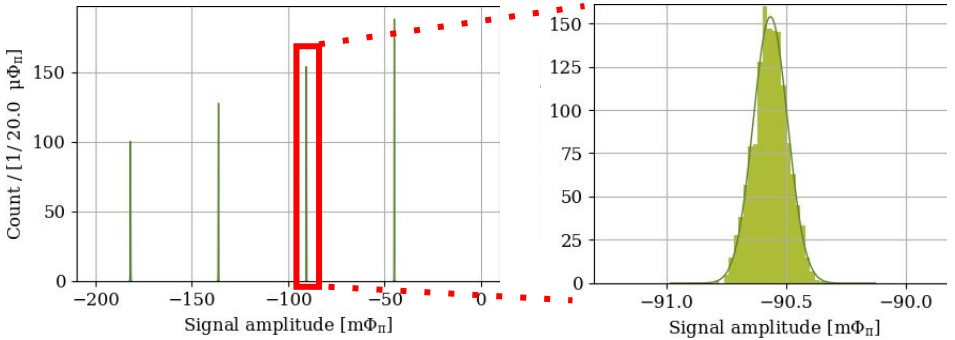


Arbitrary spectrum

Phase modulation

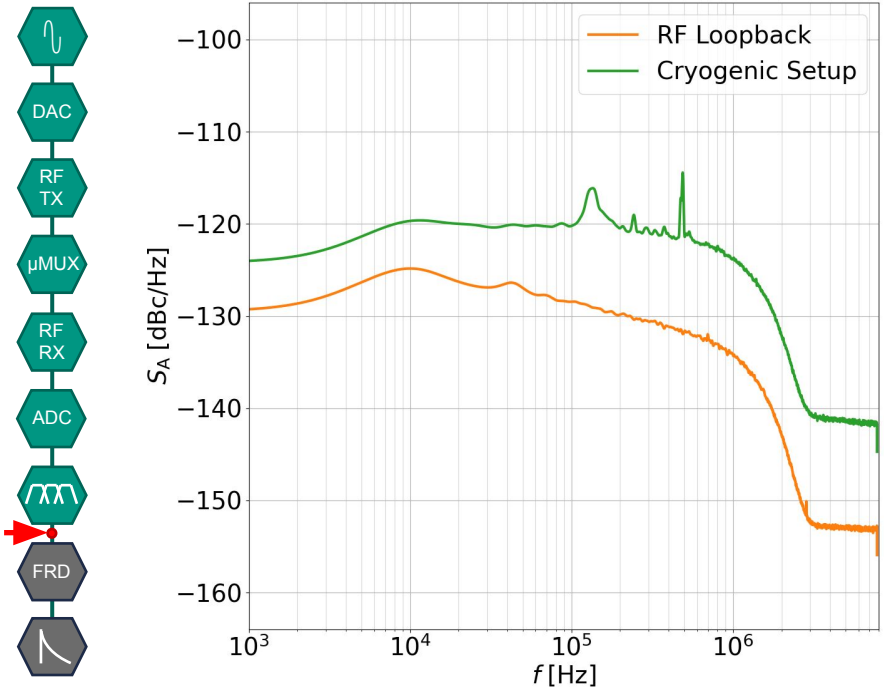
Synthesis of SQUID signal





Preliminary FWHM: 6.28 eV @ 3.35 keV

Amplitude Noise



Measurement procedure:

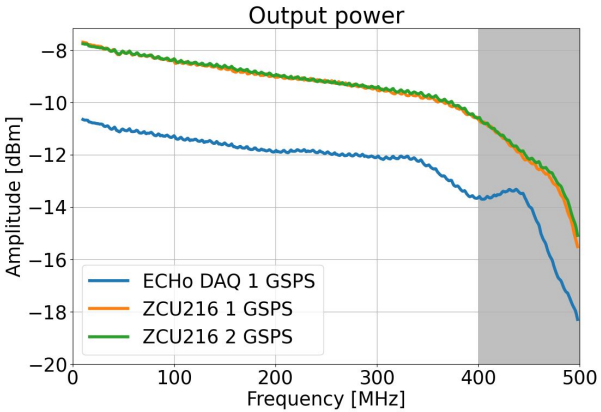
- Generation of a single tone
- Downconversion of carrier signal
- Signal PSD of noise

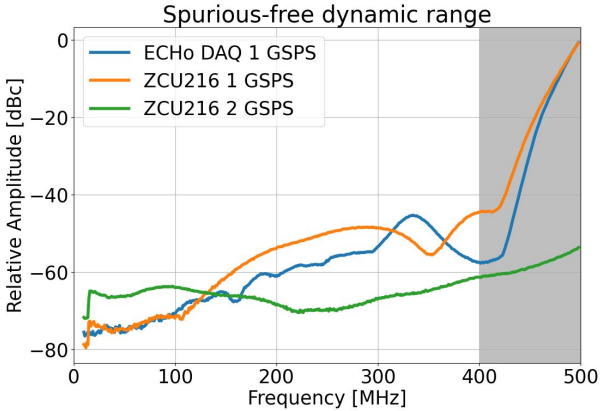
Results:

- room-temperature loopback shows lower noise than with cryogenic interface
- **SDR is not the limiting factor**

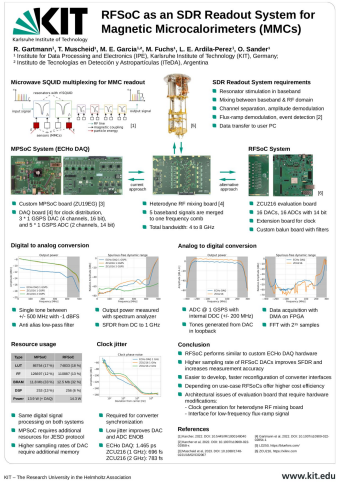
Advantages of RFSoC

- Higher sampling rates of DACs
  - Filtering images close to fs/2 is possible with lowpass-filters
- Simplified interface to converters (AXI-Stream)
- Less resource consumption (no JESD or other protocol required)
- Converters are reconfigurable at runtime



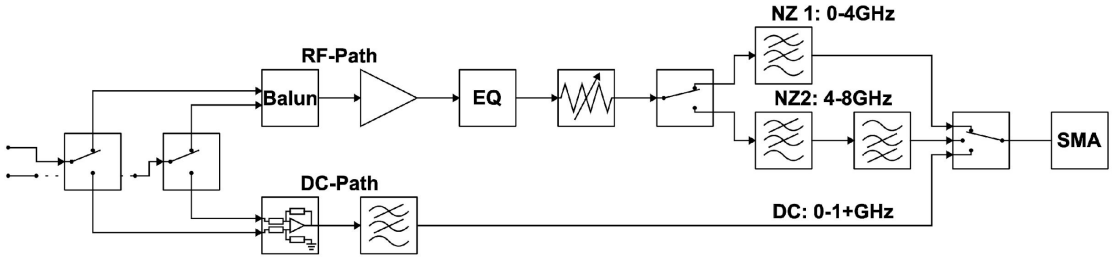


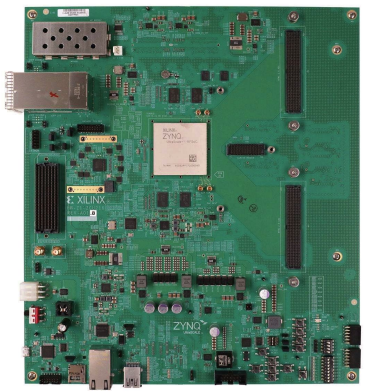
Poster on Thursday by R. Gartmann: [Evaluating the RFSoC as a Software-Defined Radio Readout System for Magnetic Microcalorimeters]



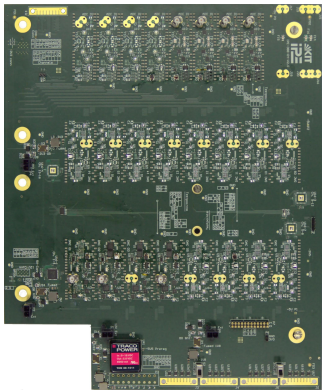
Future SDR - DirectRF Architecture

- With increased bandwidth, analog mixing is no longer required
- Just some filtering is needed
- By using upper Nyquist zones, even higher frequencies can be reached



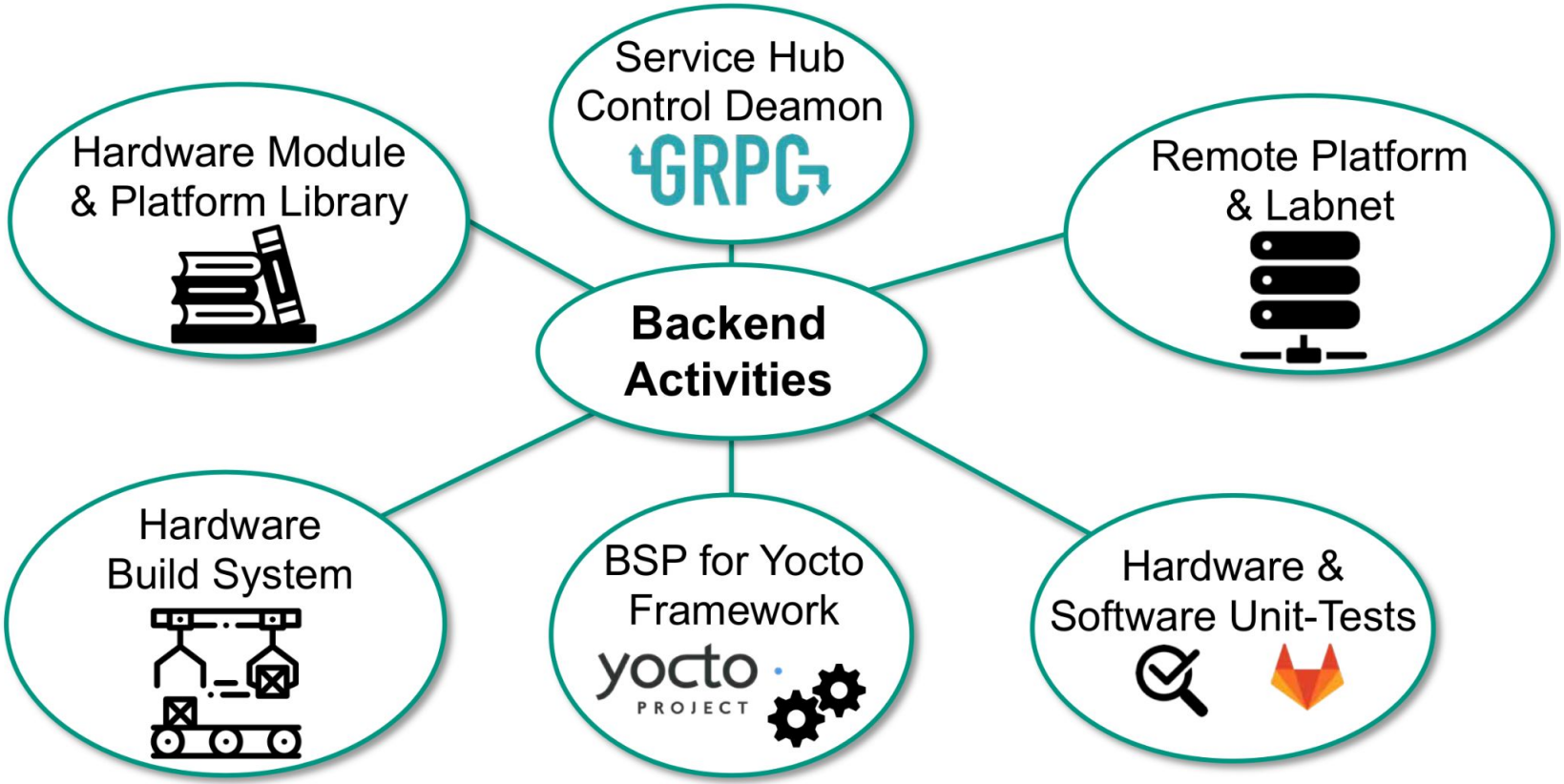


Xilinx ZCU216 RF eval board



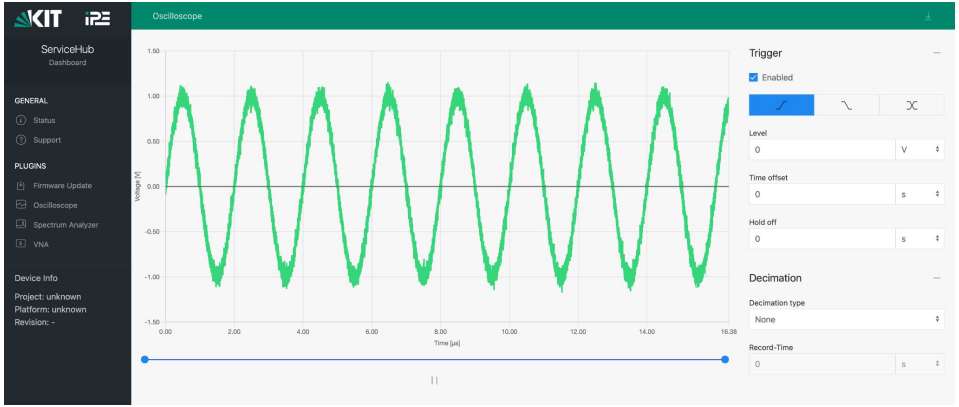
V. Stümpert and R. Gartmann

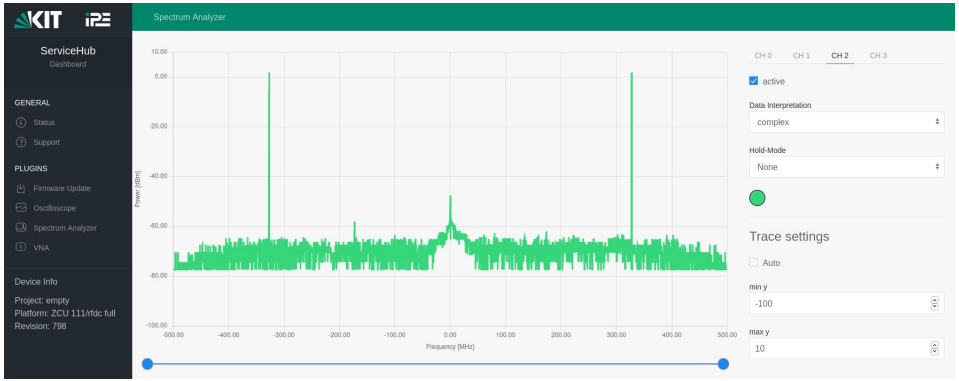
IPE tooling environment for ZynqMP & RFSoC



All-in-One system for quantum sensor readout

- Include VNA, Oscilloscope and Spectrum Analyzer
- Automated resonance search with VNA
- IQ-Imbalance correction of frequency comb
- Dynamic tone generation with crest factor reduction
- Self-calibration and system configuration
- Monitoring of signal quality





Conclusion

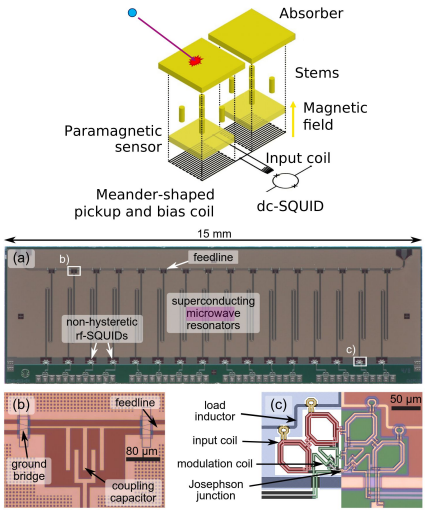
- FPGAs have evolved into very complex heterogeneous devices
  - Zynq US+: FPGA + **CPU & Peripherals**
  - RFSoC: FPGA + CPU + **DACs & ADCs**
- Enables high **functional integration** (including control, calibration, and test software)
- Giant leaps in **tooling required** to leverage the full potential
- RFSoCs are much easier to operate vs. discrete DACs/ADCs (JESD, clocks, synchronization)
- RFSoC performs similar to custom ECHo DAQ hardware
- Higher sampling rate of RFSoC DACs improves SFDR and increases measurement accuracy
- For ECHo, the noise level of DAQ is below cryogenic signal path

Acknowledgments to the IPE-SDR group

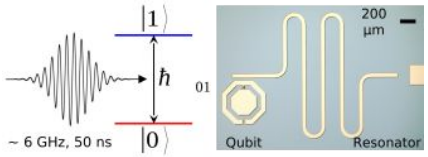
Research Interest: Next-Gen DAQ Systems

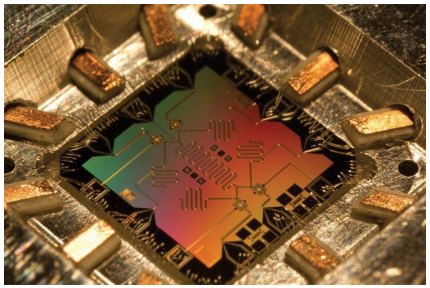
Karlsruher Institut für Technologie

Microwave SQUID multiplexer based readout system



Quantum computing and Qubits characterization platform



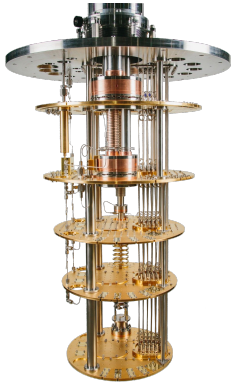


Tools and Methods for Modular and Scalable Next-Gen DAQ systems

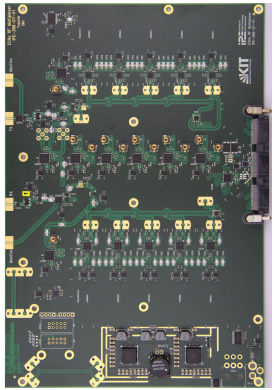
ECHo readout electronics

(Muscheid, et. al. JINST 2022)

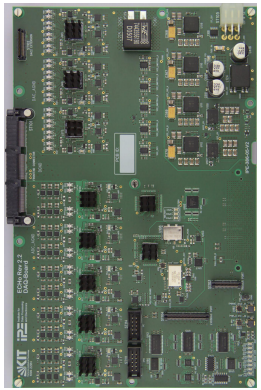
160 Gb/s raw data rate



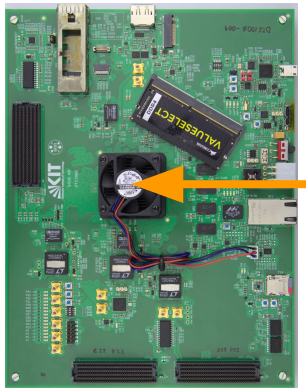
MMCs



RF Board

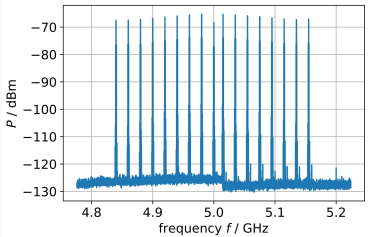


DAC & ADC

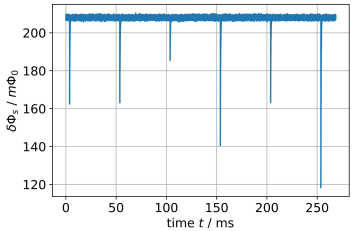


ZynqUS+ Board (DTS-100G)

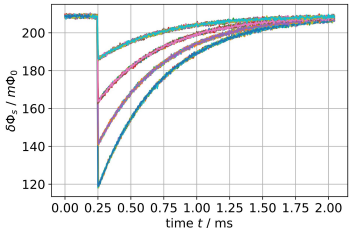
30 Mb/s processed data rate



Input HF signal



Demodulated detector signal

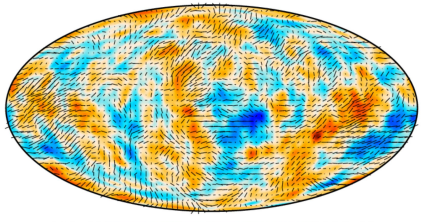


Extracted pulses

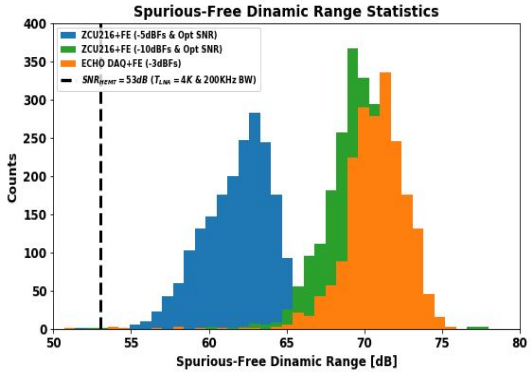
Current effort on characterizing the full-stack to validate and fabricate 15x

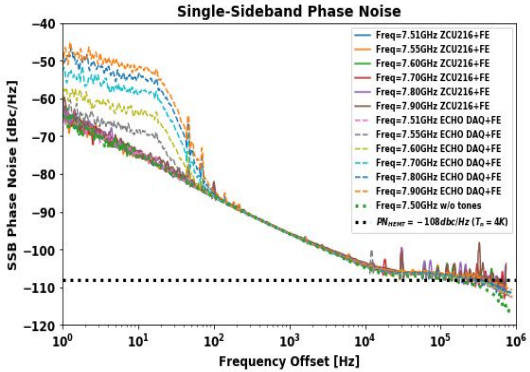
Qubic Experiment

Goal: Measurement of the B-mode polarization of the Cosmic Microwave Background (**CMB**) radiation



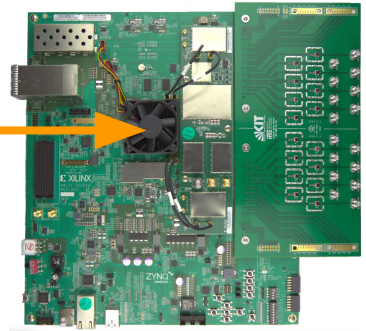
(ESA Planck et. al. 2018)



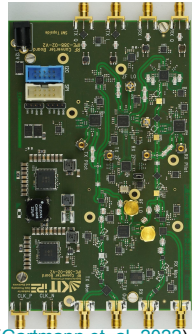


(Garcia Redondo 2022)

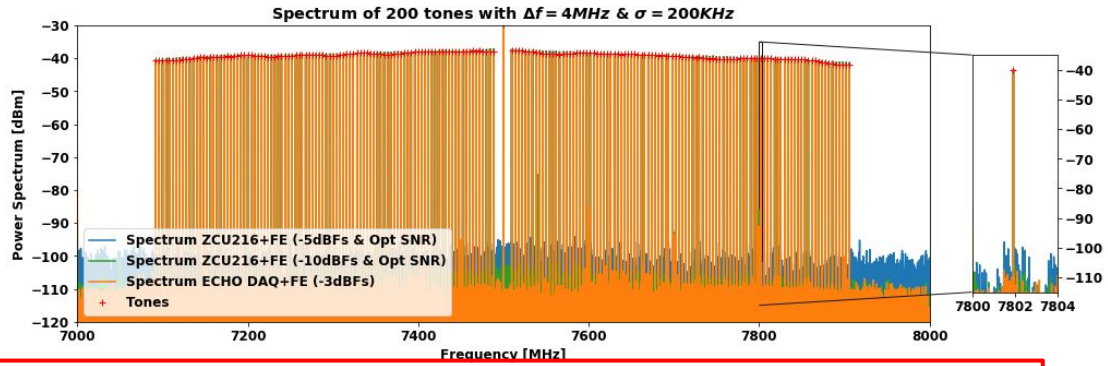
ZYNQ RFSoC



Xilinx ZCU216 RF eva board



(Gartmann et. al. 2022)



ECHo electronics is suitable for QUBIC. However, evaluation of Gen3 RFSoC devices is interesting and ongoing

QiController - System Architecture

Karlsruher Institut für Technologie

Qiskit qKT

User PC

Python Driver

Network

RFSoC

Processors

ServiceHub [2]

Taskrunner [4]

Bus

Programmable Logic

Synchronization

Digital

DACs and ADCs

Digital Unit Cell

Digital Unit Cell

Digital Unit Cell [3]

Analog

HF Board [1]

Digitale Pulse

HF

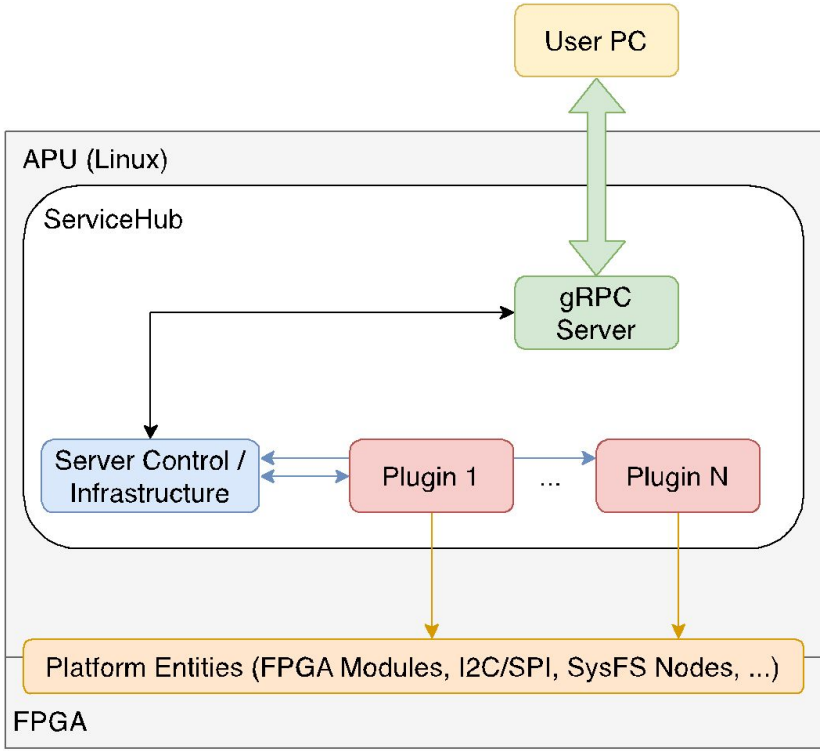
Frequency Multiplexing

Cryostat with Qubit Chip

Qubit characterization, full-stack ownership, defining the classical-quantum interface.

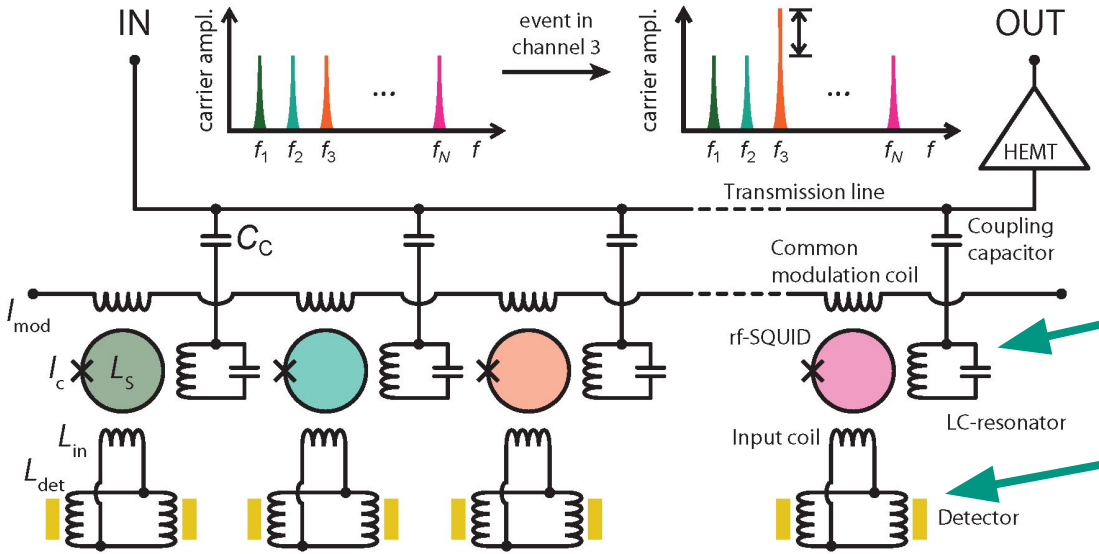
ServiceHub

- Plugin based
  - Modular
  - Load at runtime
- gRPC communication
- Infrastructure
  - Logging
  - Devicetree access
- Platform Entities
  - PL modules e.g. Digital Unit Cell
  - PS modules e.g. DMA



Karcher, Gebauer et al., IEEE TNS, 2021

Microwave-SQUID-Multiplexer



Resonator bandwidth:
1.6 MHz

Ho^{163} decay rate:
10 Bq per pixel

400 channels with resonances between 4 – 8 GHz

15 Multiplexer needed for
12.000 sensors!

Acknowledgments to the IPE-SDR group

Group Leader

- Oliver Sander

Postdocs

- Luis Ardila

Doctoral Students

- Luciano Ferreiro
- Marvin Fuchs
- Manuel Garcia
- Robert Gartmann
- Torben Mehner
- Timo Muscheid
- Juan Salum
- Lukas Scheller

Master & Bachelor Students