Karlsruher Institut für Technologie

Readout Systems for HEP and Quantum Circuits

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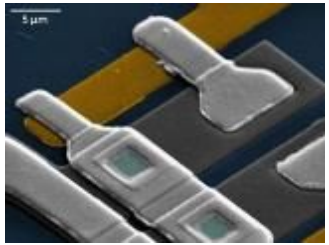
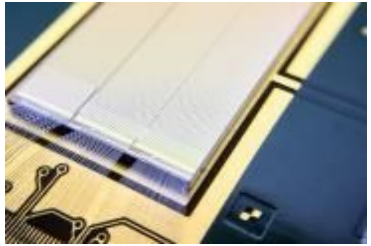
Institute for Data Processing and Electronics (IPE)

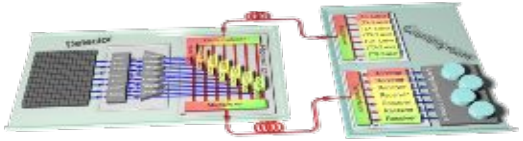


Superconducting sensors MMCs (ECHo)

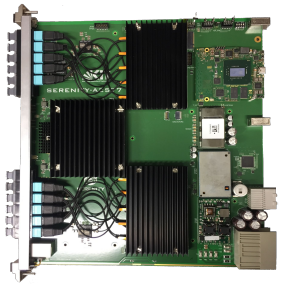


Monolithic CMOS sensor (LHCb)

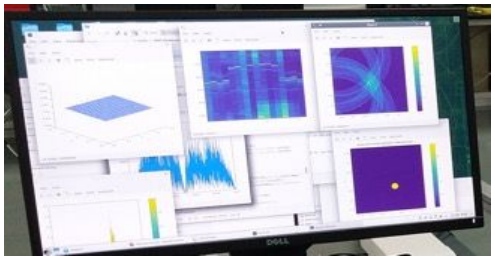
Silicon Tracking System of the CBM experiment (FAIR)



Optical data transmission with Silicon Photonics



Processing high data rates ~50 Terabit/s (CMS)



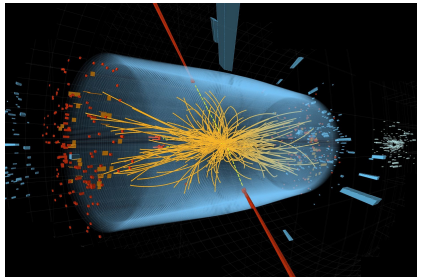
Data visualization (USCT)

IPE has specialist groups in every step of the DAQ chain (from sensor design to data visualization/storage)

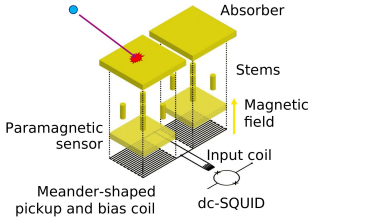
Research Interest: Next-Gen DAQ Systems

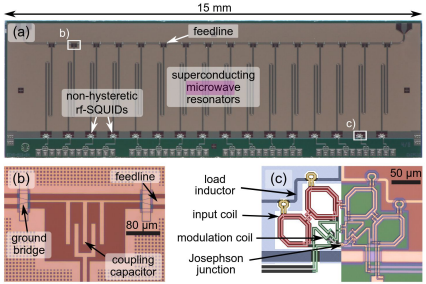
Karlsruher Institut für Technologie

Low-Latency readout and processing electronics for High-Energy Physics

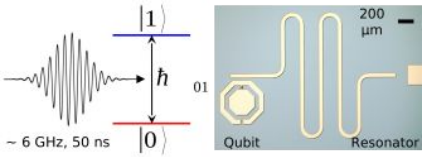


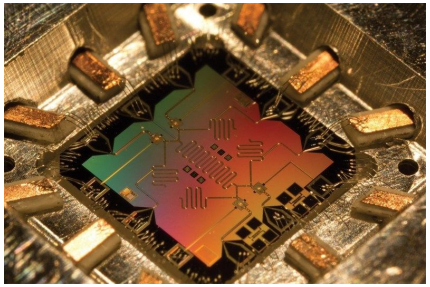
Microwave SQUID multiplexer based readout system





Quantum computing and Qubits characterization platform

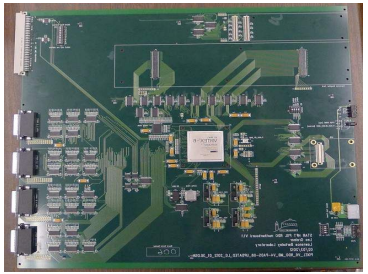


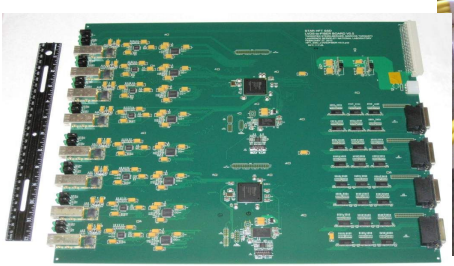


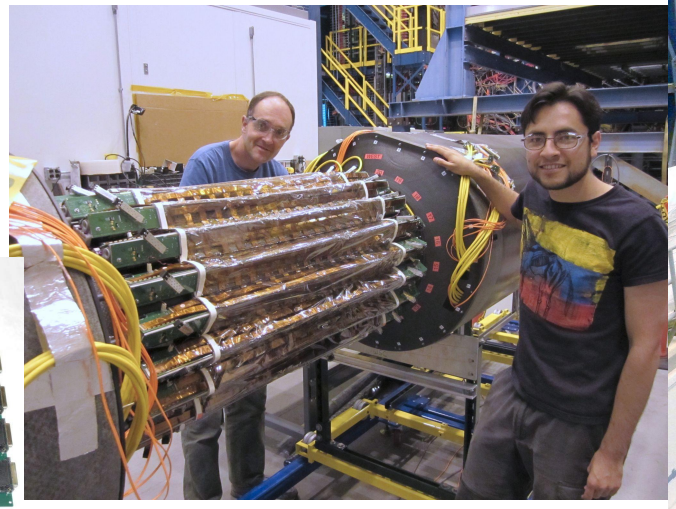
Tools and Methods for Modular and Scalable Next-Gen DAQ systems

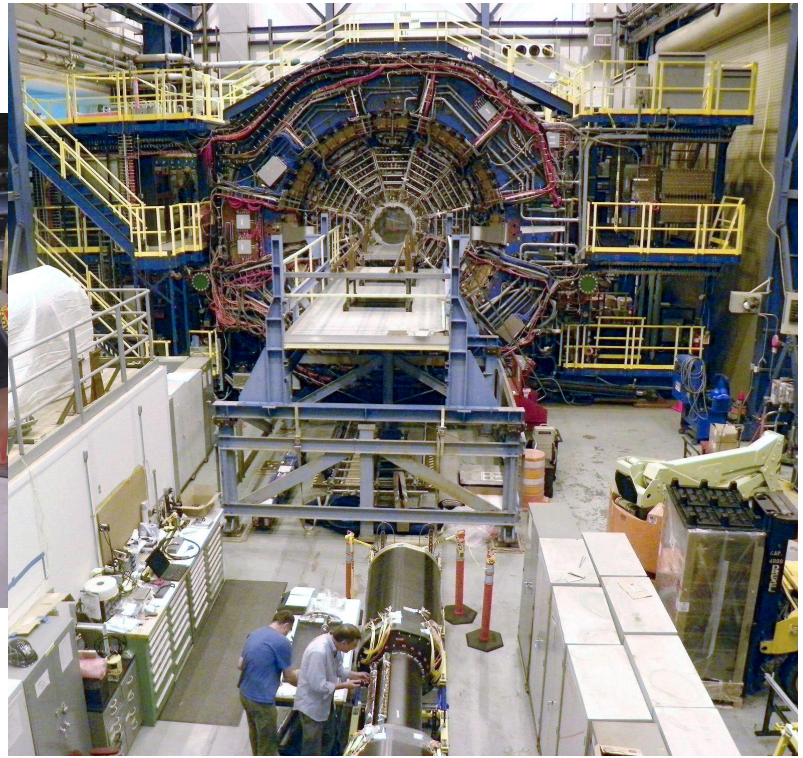
STAR Heavy Flavor Tracker

VME STAR HFT SSD RDO (Virtex-6)





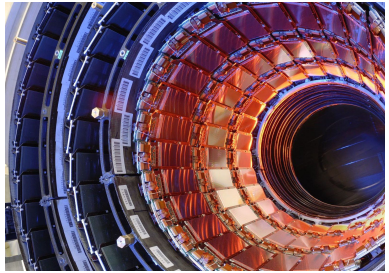




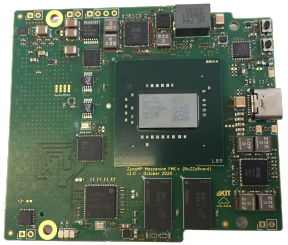
Designed and commissioned the readout system for the Silicon Strip Detector (SSD) at the STAR experiment

CMS Phase-2 L1 Track Finder

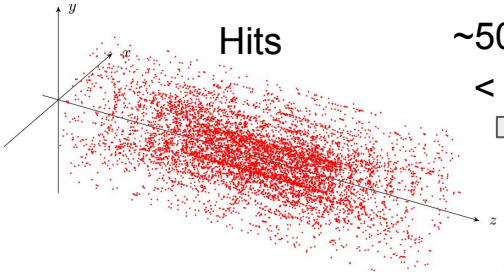
CMS Silicon Tracker



ATCA CMS OT-DTC (Virtex US+)

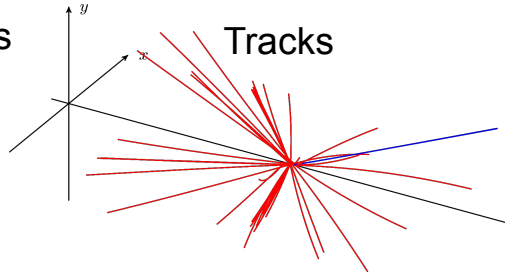


Unified Management Mezzanine (Zynq US+)



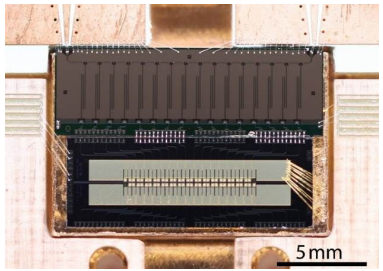
~50 Tb/s

< 4 µs

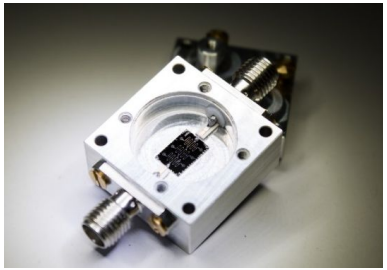


DAQ System for the CMS Phase-2 upgrade to read the Silicon Tracker and perform online data reconstruction

Cryogenic Superconducting Circuits



D. Richter (U. Heidelberg)



Alexander Stehli (KIT)

Metallic Magnetic Calorimeters

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

Microwave SQUID multiplexed

Superconducting Quantum Bits

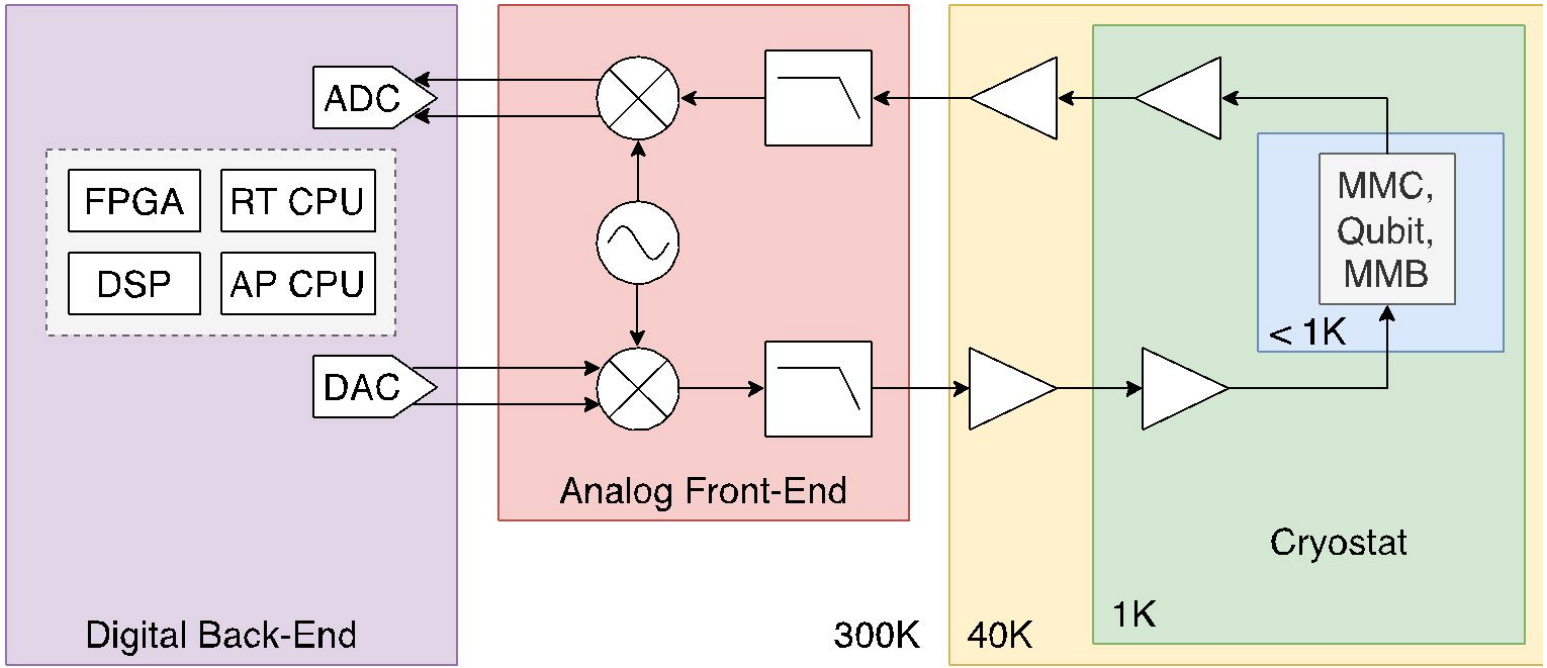
Building block for quantum computing

Key Requirements

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

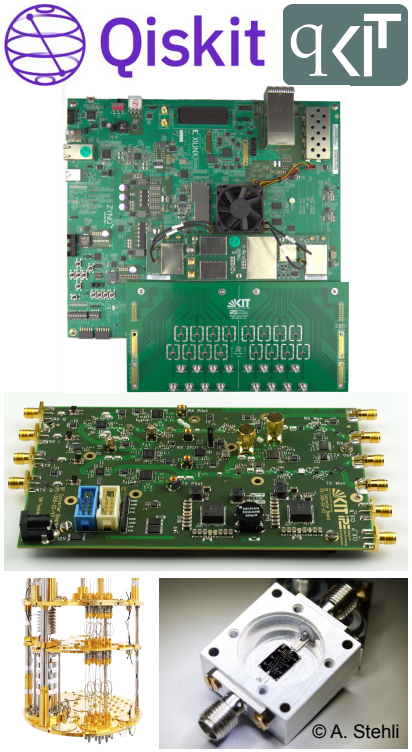
Quantum Circuits require Frequency Division Multiplexing

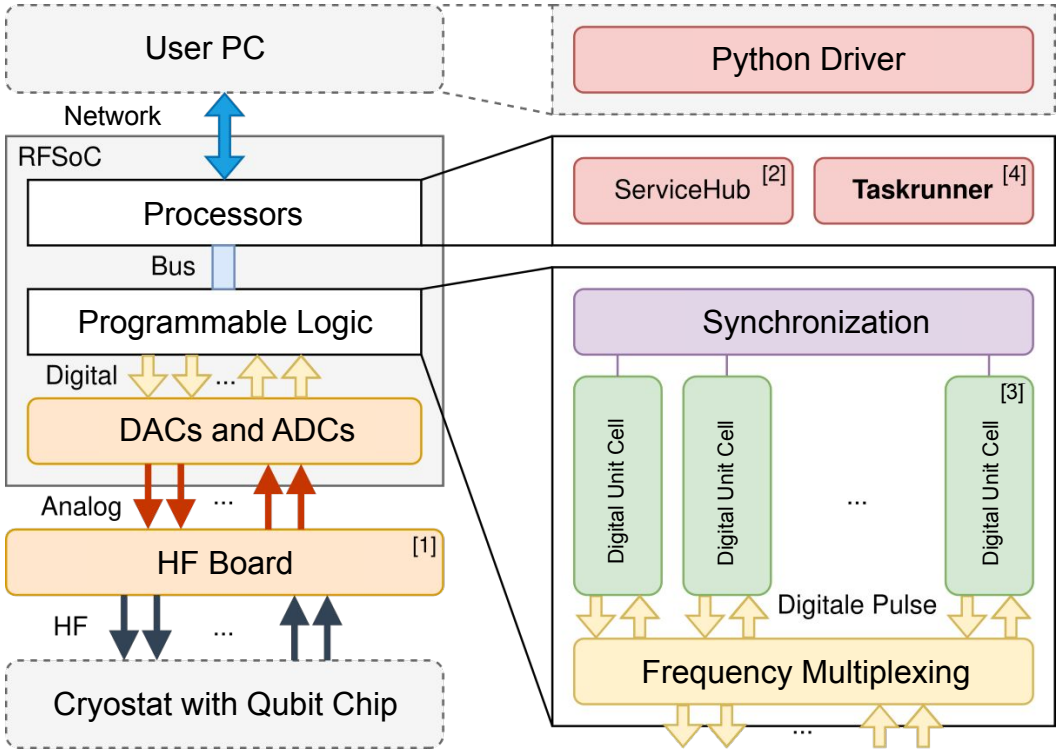
Software Defined Radio (SDR) System Arch.



Software Defined Radio (SDR) DAQ System with a frequency mixing stage

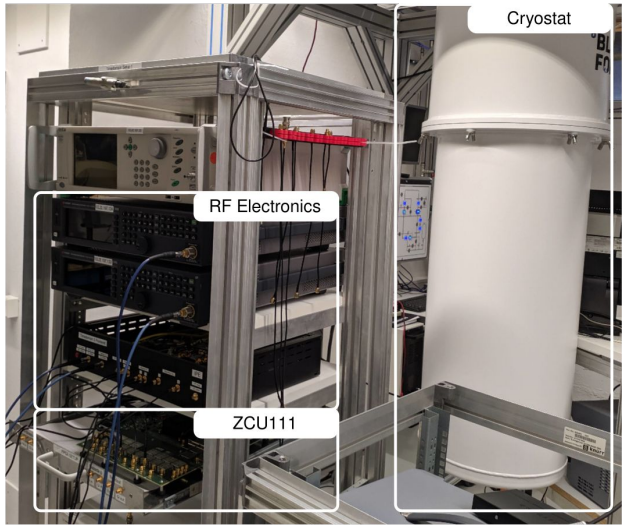
QiController - System Architecture

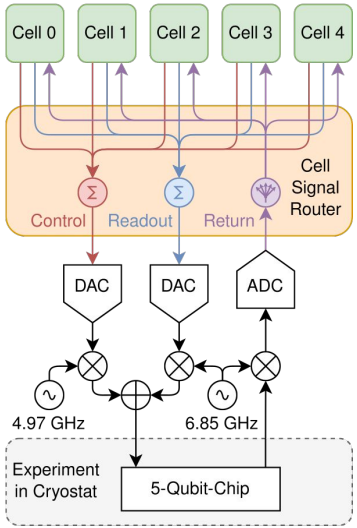


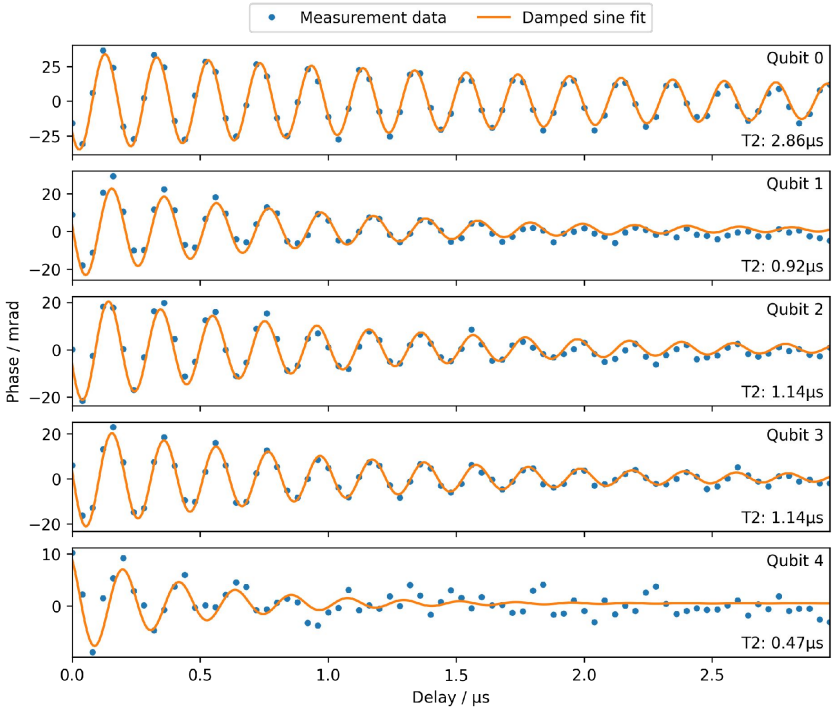


Qubit characterization, full-stack ownership, defining the classical-quantum interface.

Simultaneous Qubit Measurements





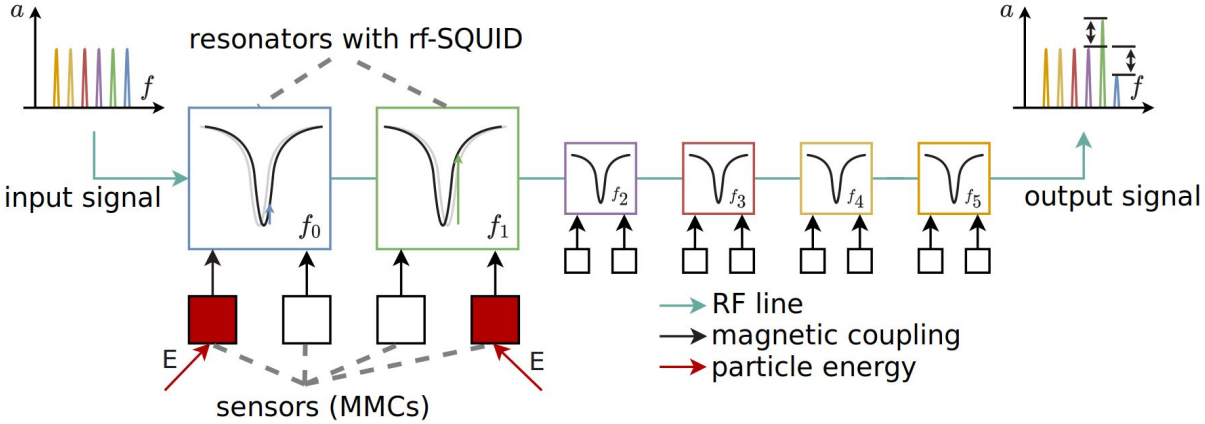


Parallel rabi experiment on a 5-qubit device

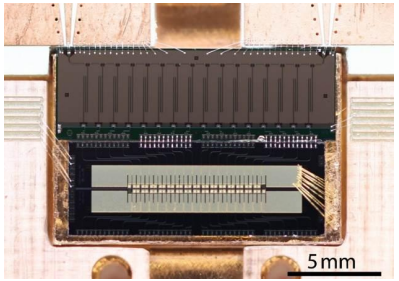
ECHo Experiment

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) **BW > 1 MHz**
- Parallel readout of **12.000 sensors** using microwave **SQUID** multiplexing approach
- 400 channels per readout line with resonances between **4-8 GHz**

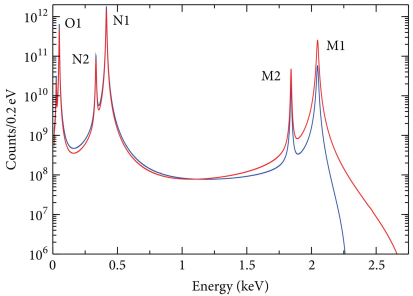


ECHo detector + μMUX:



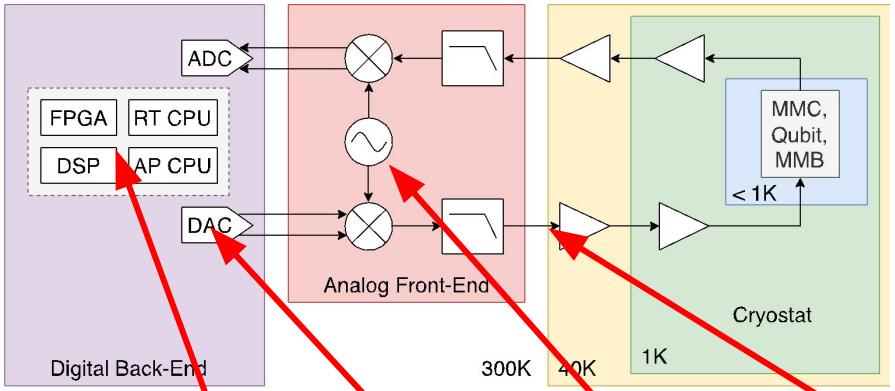
D. Richter (U. Heidelberg)

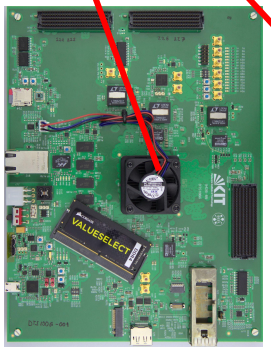
Ho^{163} spectrum:



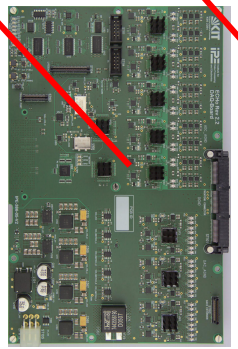
Massively parallel detector array with 400 resonators per readout line

ECHo SDR-DAQ System Arch.

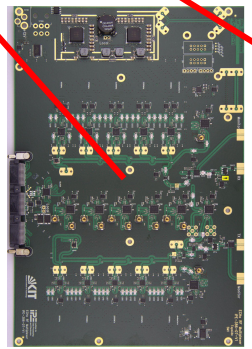




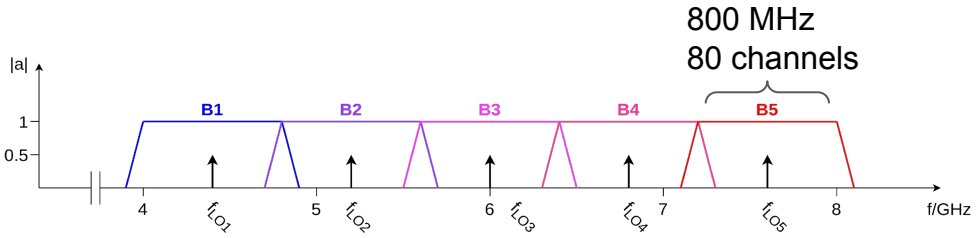
DTS100G



EDCB

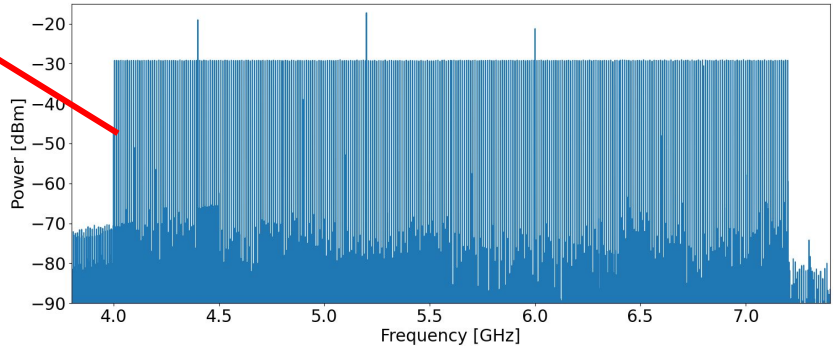


HDM-GS



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

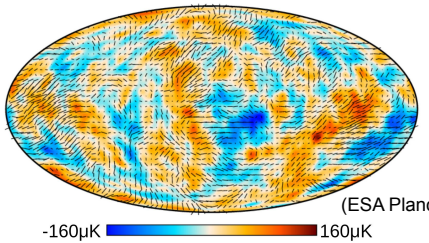
Karcher et al., J Low Temp Phys (2022)



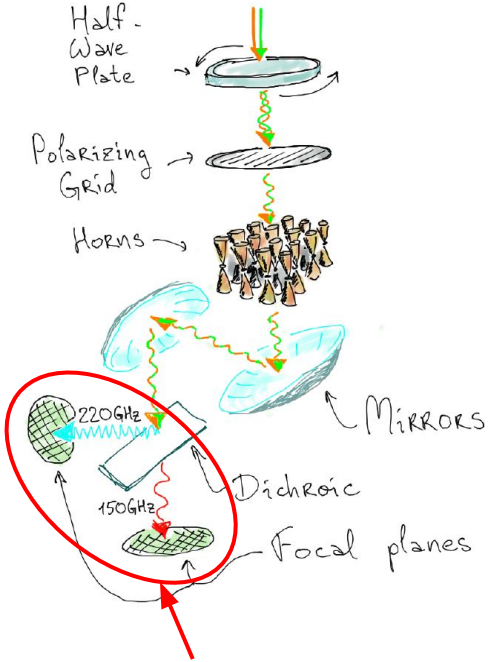
Custom designed electronics with discrete ADCs and DACs and a wideband frequency mixer board

QUBIC Experiment

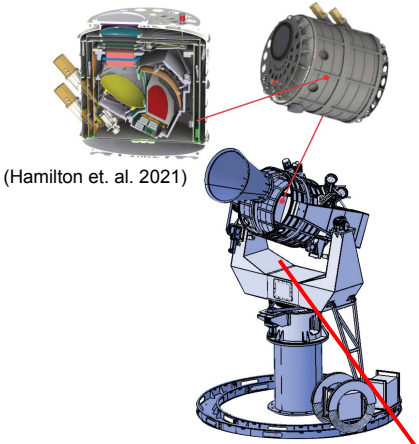
Goal: Measurement of the B-mode polarization of the Cosmic Microwave Background (**CMB**) radiation



(ESA Planck et. al. 2018)



Superconducting sensors

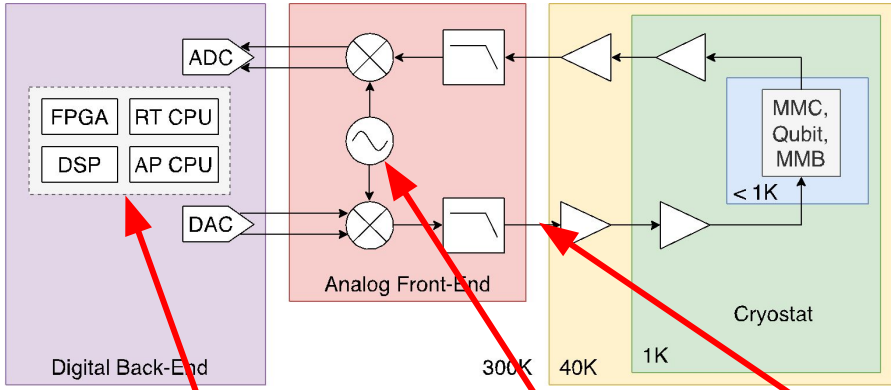


(Hamilton et. al. 2021)

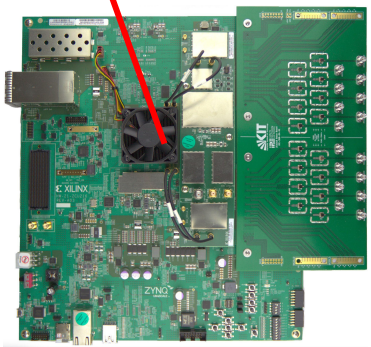
Argentina

QUBIC is a telescope at the northern Argentinian Andes which measures the CMB

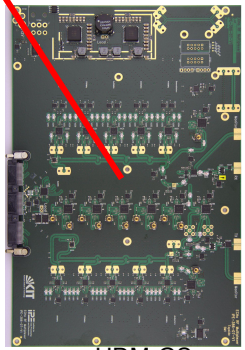
Qubic SDR-DAQ



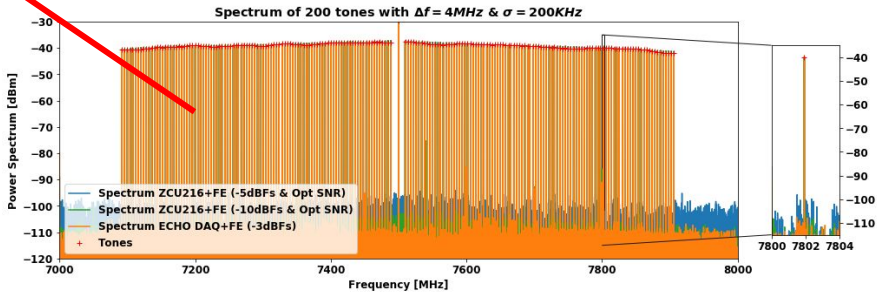
- 200 channels per frequency band with 4 MHz spacing (**~1000 detectors in 4-8 GHz** spectrum)
- **Power spectrum** of the individual tones satisfy the SQUID multiplexer requirements **(-40 dBm)**
- **Spurious free dynamic range comparable to ECHo** electronics when signal attenuated -10 dBFs



ZCU216 SFBB



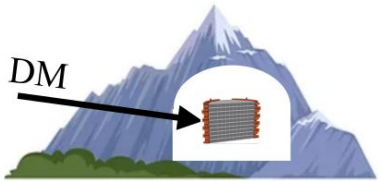
HDM-GS



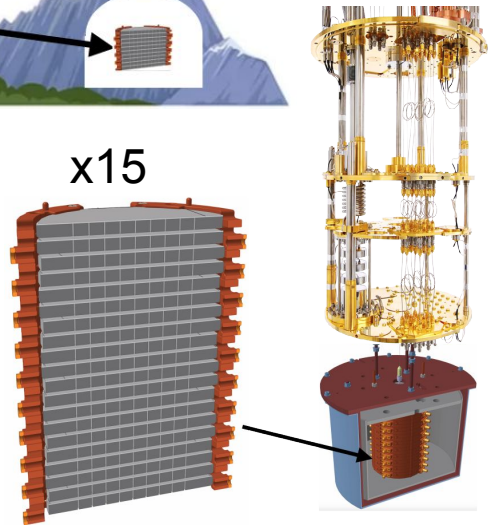
ECHo electronics is suitable for QUBIC. However, Gen3 RFSoC devices offer higher integration factor

BULLKID Experiment

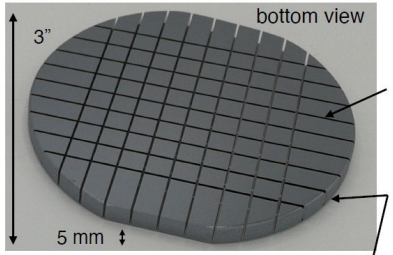
kg-scale, low-threshold and low-background Dark Matter or neutrino scattering experiment



x15



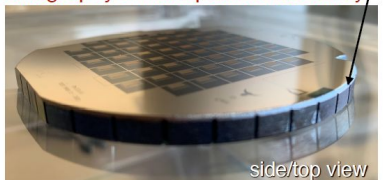
1. carving of dices in a thick silicon wafer



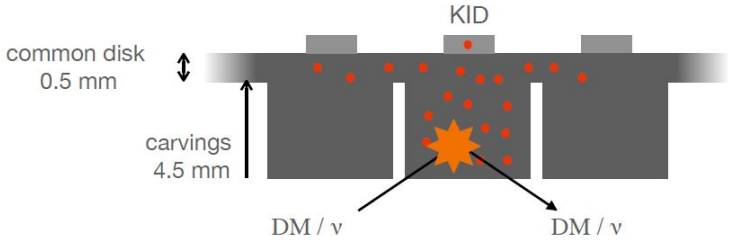
4.5 mm deep grooves
- 6 mm pitch
- chemical etching

0.5 mm thick common disk:
- holds the structure
- hosts the KIDs

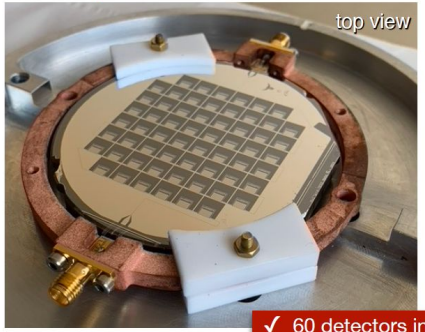
2. lithography of multiplexed KID array



KID array
- 60 nm aluminum film
- 60 KIDs lithography



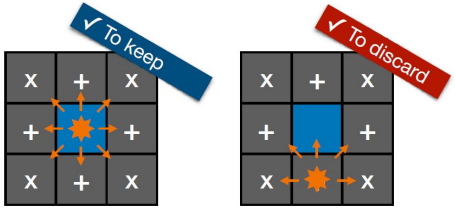
3. assembly



✓ 60 detectors in 1

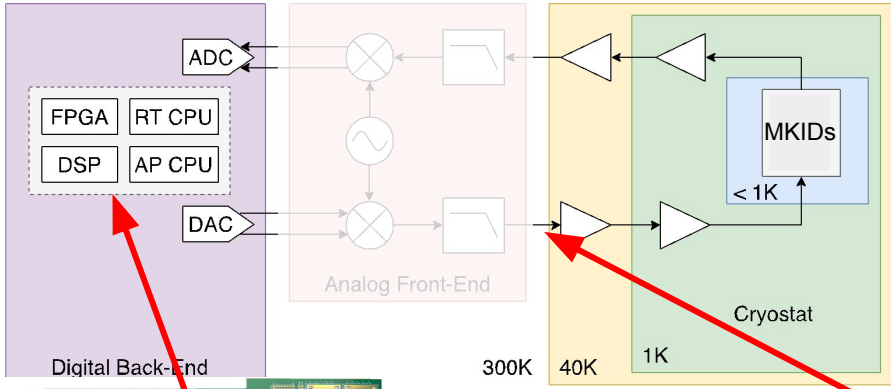
Assembly
- 3D-printed Cu holder
- Aluminum case

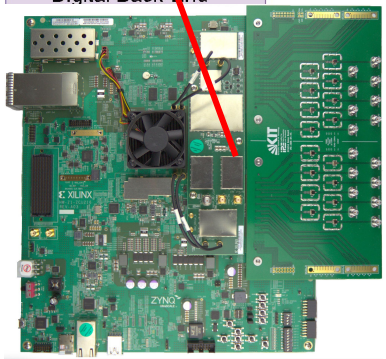
60 dices 0.35 g each
1 readout line



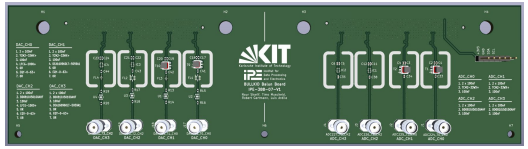
BULLKID requires 15 readout channels each with 60 KIDs and online data processing to trigger on events

BULLKID SDR-DAQ System Arch.

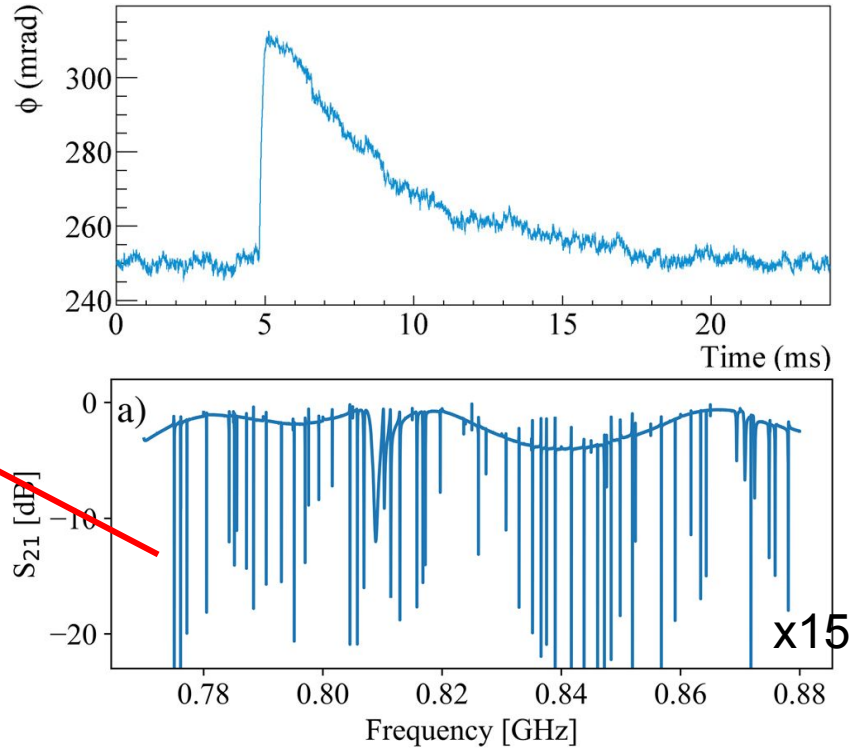




ZCU216

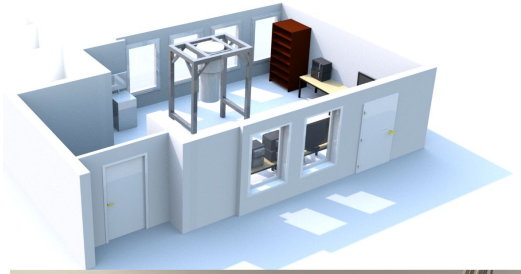


BKSFBB



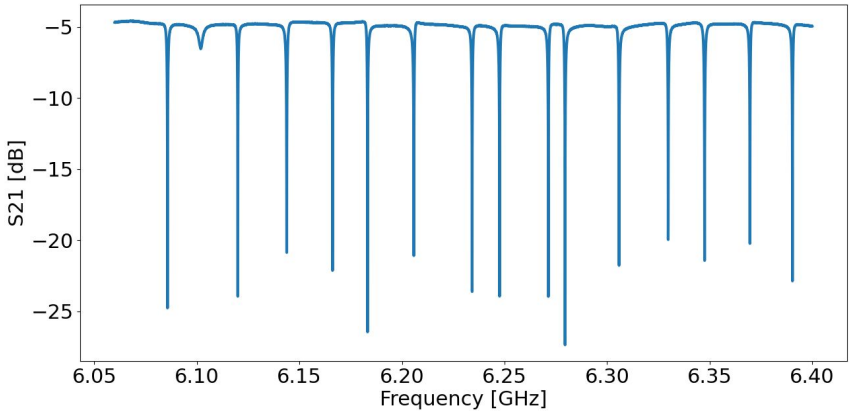
BULLKID Simple Filter Balun Board was designed and fabricated

IPE KryoDAQ Lab



- The **cryogenic DAQ lab** for characterization and development of next generation cryogenic detector DAQ (full chain evaluation)

T. Muscheid, R. Gartmann



Activities and goals at a glance

- Contributing to the definition of the **quantum computing stack** with a special focus on the **cryogenic - room temperature interface** (e.g., ptQube, QBriqs, QSolid)
- Delivering electronics for readout of **>1000** pixelated cryogenic detectors with a special focus on **frequency multiplexed readout** (e.g., ECHo, QUBIC, BULLKID)
- Delivering easy-to-use, scalable, highly integrated, and cost-efficient readout systems for the next generation experiments (e.g., KATRIN++)

Acknowledgments to the IPE-SDR group

Group Leader
- P.D. Dr.-Ing. Oliver Sander

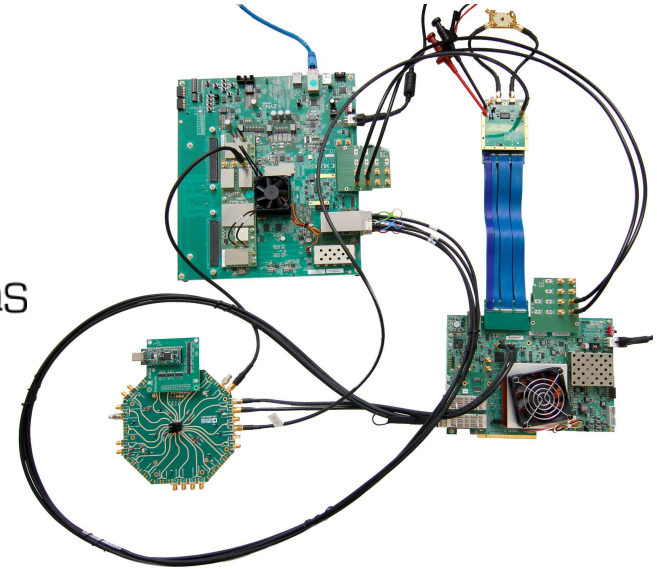
Post-Docs
- Dr.-Ing. Luis Ardila-Perez
- Dr.-Ing. Luciano Ferreyro (USAM-KIT)

Doctoral Students
- Timo Muscheid
- Lukas Scheller
- Marvin Fuchs
- Robert Gartmann
- Torben Mehner
- Manuel Garcia (USAM-KIT)
- Juan Salum (USAM-KIT)

Previous Members
- Dr.rer.nat. Richard Gebauer(*)
- Dr.-Ing. Nick Karcher(*)
- Dr.rer.nat. Francesco Valenti

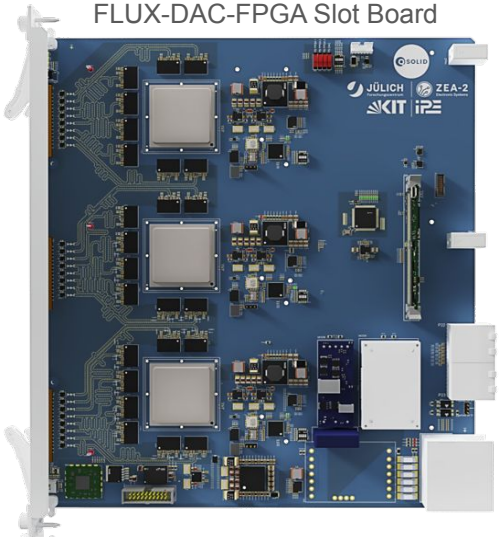
(*) Received Helmholtz Awards 2023 for doctoral thesis.

Quantum Interface Controller (QiC) for 30 Qubits



- All interfaces communicating the different boards are available in a test setup for evaluation of their performance and influence on factors like fidelity

FLUX-DAC-FPGA Slot Board

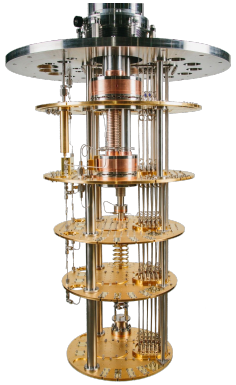


- A modular architecture based on ATCA was defined and it is currently in fabrication by FZJ-ZEA2 to realize a Quantum interface Controller (QiC) capable of scaling up to 100s of qubits.

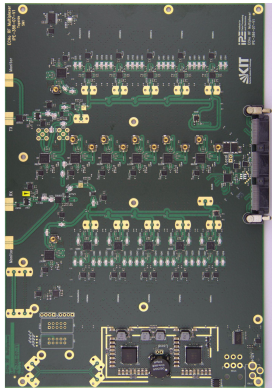
ECHo readout electronics

(Muscheid, et. al. JINST 2022)

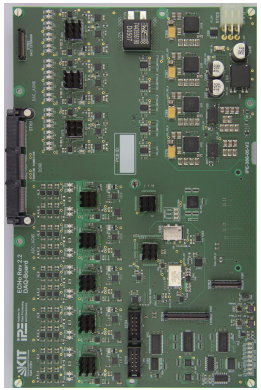
160 Gb/s raw data rate



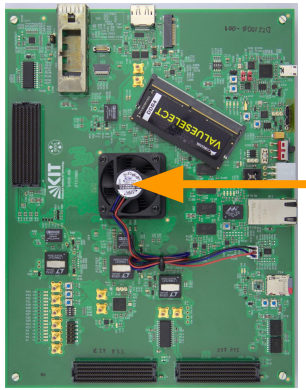
MMCs



RF Board

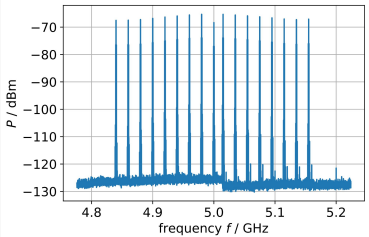


DAC & ADC

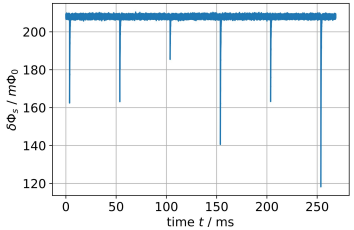


ZynqUS+ Board (DTS-100G)

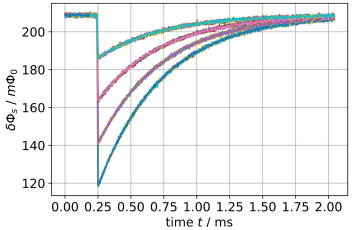
30 Mb/s processed data rate



Input HF signal



Demodulated detector signal



Extracted pulses

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

ECHo Digital Signal Processing

Digitization 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

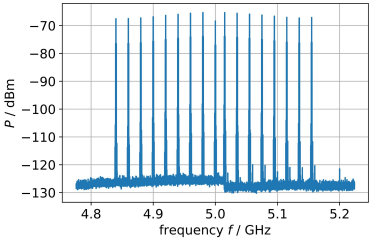
Data rates:

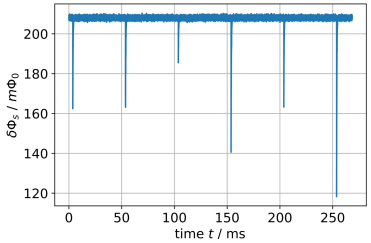
10 parallel data streams
à 500 MSPS (20 GB/s)

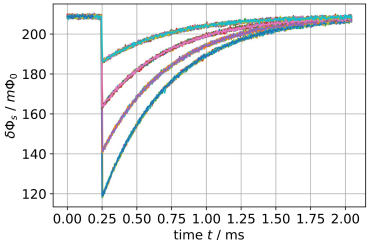
20 parallel TDM streams
à 32 x 15.625 MSPS (40 GB/s)

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)