

Enabling Large-Scale Cryogenic Detector Arrays through Advanced Trigger and DAQ Systems

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[2] Instituto de Tecnologías en Detección y Astropartículas (IteDA), Comisión Nacional de Energía Atómica (CNEA), Argentina.

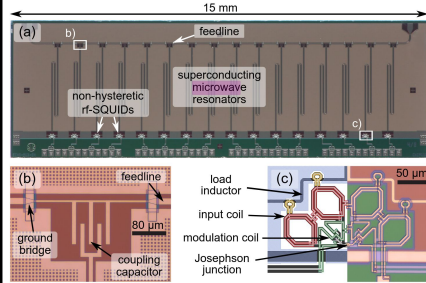
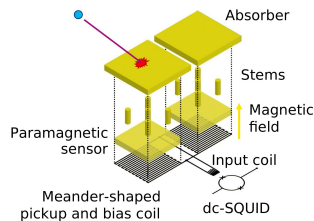
[3] Integrated Computing Architectures (ICA) - Peter Grünberg Institute (PGI-4), Forschungszentrum Jülich GmbH, Germany

Research Interest: Next-Gen TDAQ Systems

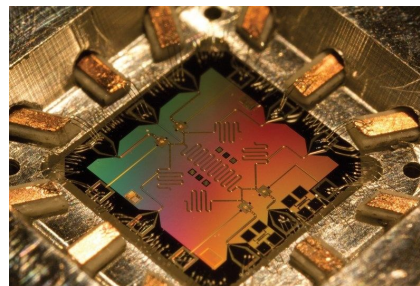
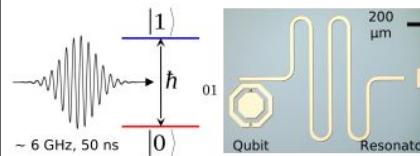
Low-Latency readout
and processing
electronics for
High-Energy Physics



Microwave SQUID
multiplexer
based readout
system



Quantum computing
and Qubits
characterization
platform



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

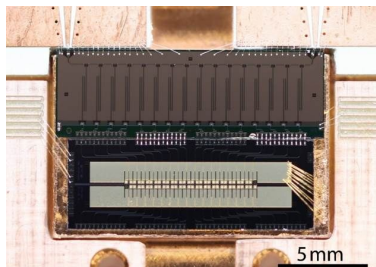


Heterogeneous real-time computing architectures

FPGAs for cost sensitive or mid-range products	• focus on logic/money • limited IO bandwidth	  
High performance FPGAs	• maximum LUTs • maximum DSP slices • maximum internal memory • maximum IO bandwidth (30 Gbps, 58 Gbps)	 
FPGA + HBM	• derived from HP FPGAs • integration of large memories (GB)	 
FPGA + Processor System	• derived from HP FPGAs • multiple processors • memory and caches • peripherals	 
FPGA+Processor+ ADC/DAC	• derived from previous • high performance ADC/DAC	 
		 Versal  Versal-RF

Experience with VirtexUS+, ZynqUS+, RFSocS, targeting Versal and Versal-RF in the future

Cryogenic Superconducting Circuits

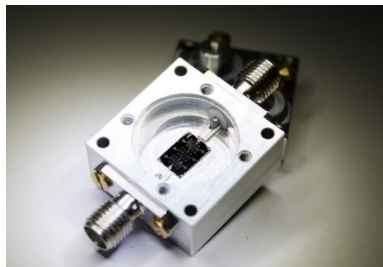


D. Richter (U. Heidelberg)

Metallic Magnetic Calorimeters

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

Microwave SQUID multiplexed



A. Stehli (KIT)

Superconducting Quantum Bits

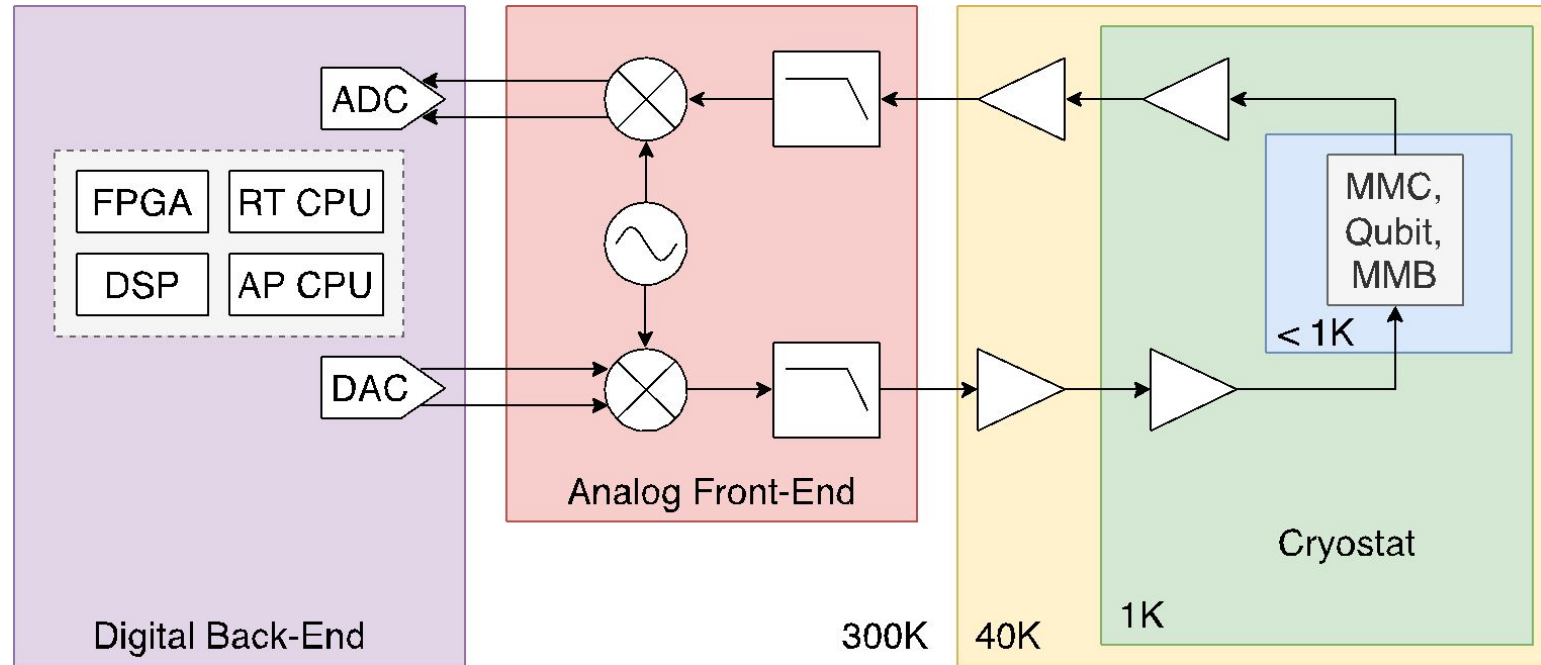
Building block for quantum computing

Key Requirements

- Operated at very low temperature (**<100 mK**)
- Interfaced with **microwave signals** (1-12 GHz)
- Large signal **bandwidth** requirements < 500 MHz

Large arrays of Cryogenic Circuits require Frequency Division Multiplexing

Software Defined Radio (SDR) System Arch.



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

ECHo Experiment

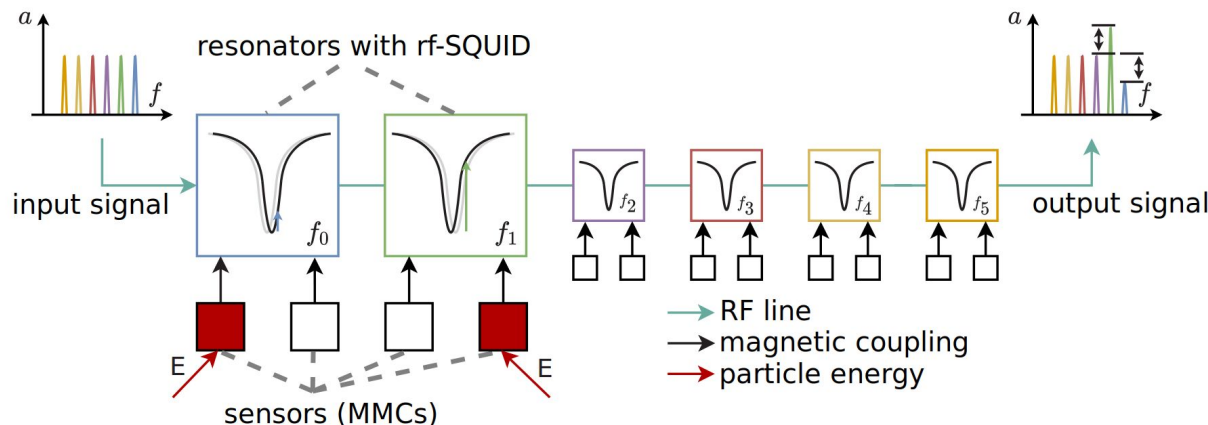


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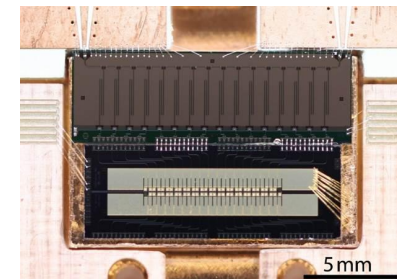


The Electron Capture ^{163}Ho experiment (ECHo)

- 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**

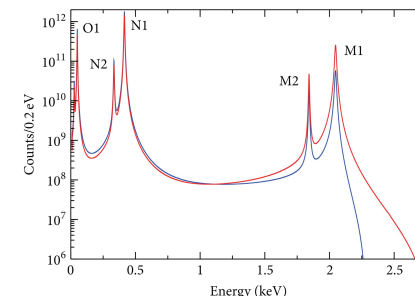


ECHo detector + μMUX :



D. Richter (U. Heidelberg)

Ho^{163} spectrum:

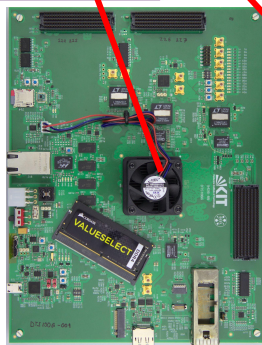
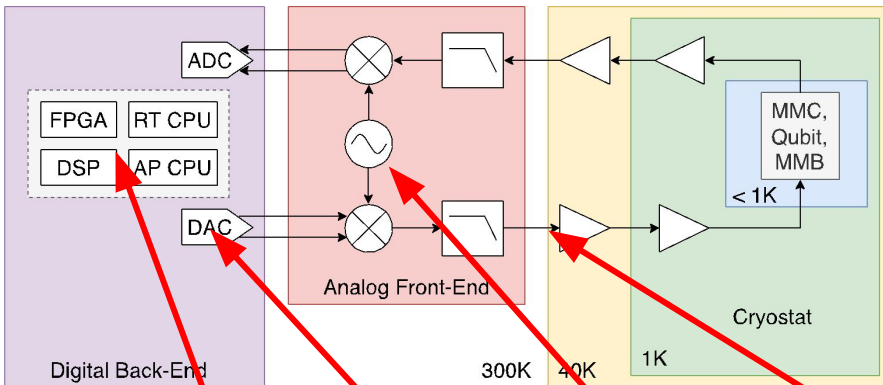


Massively parallel detector array with 400 resonators per readout line

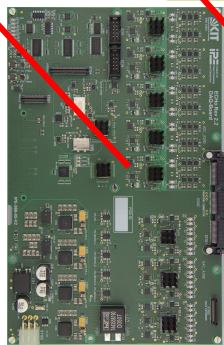
ECHo SDR-DAQ System Arch.



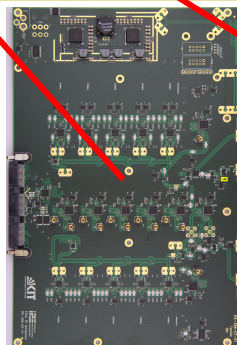
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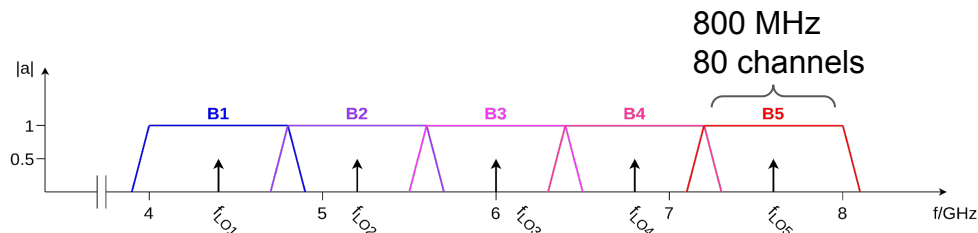
DTS100G



EDCB



HDM-GS

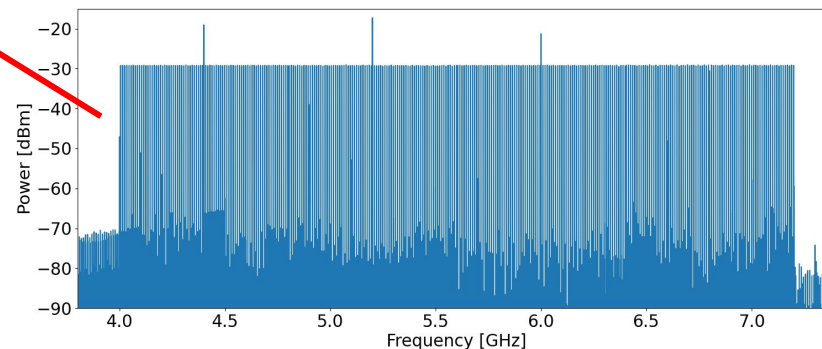


[Gartmann et al., J Low Temp Phys \(2022\)](#)

[Muscheid et al., J Low Temp Phys \(2024\)](#)

[Karcher et al., J Low Temp Phys \(2022\)](#)

[Niedig et al., IEEE TAS preprint \(2025\)](#)



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

ECHo Digital Signal Processing



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*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

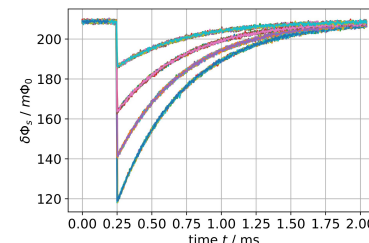
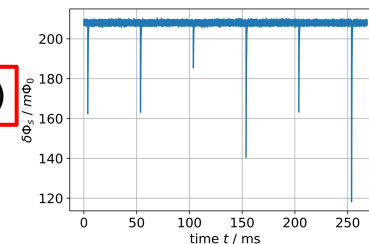
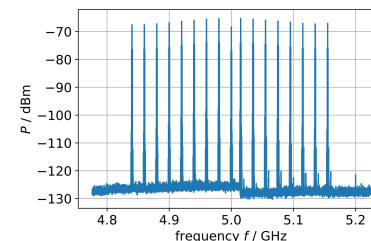
Data rates:

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 \(2022\)](#)

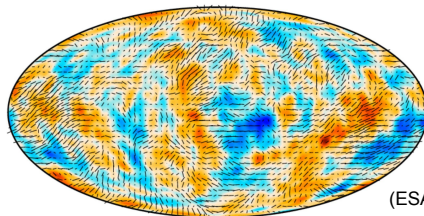
QUBIC Experiment



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SAN MARTÍN

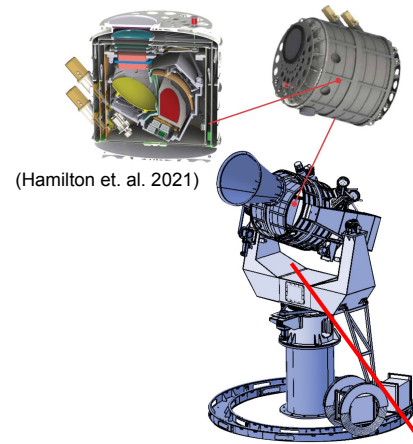
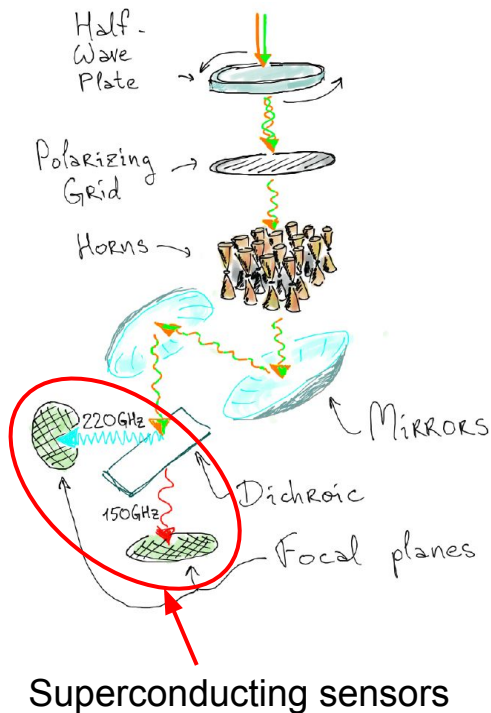
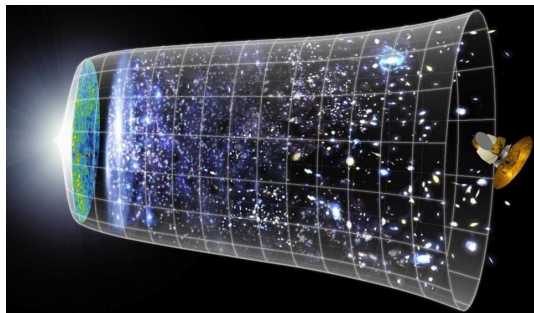


Goal: Measurement of the B-mode polarization of the Cosmic Microwave Background (**CMB**) radiation



(ESA Planck et. al. 2018)

-160 μ K 160 μ K



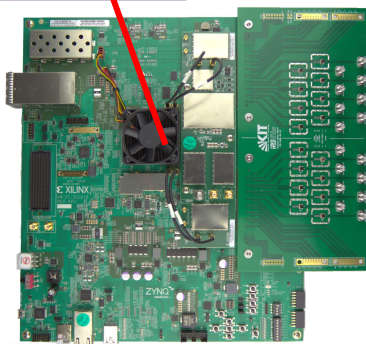
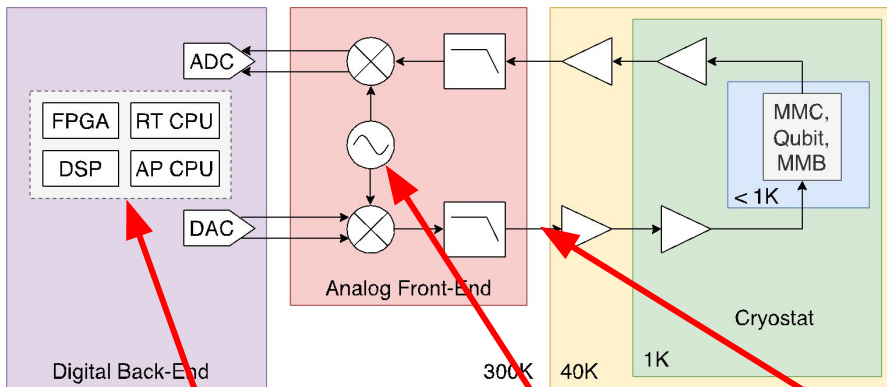
(Hamilton et. al. 2021)

Argentina



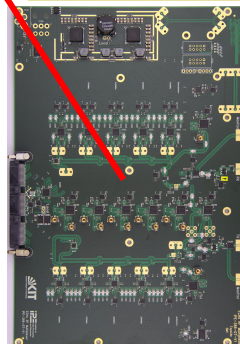
QUBIC is a telescope at the northern Argentinian Andes which measures the CMB

Qubic next-gen SDR-DAQ



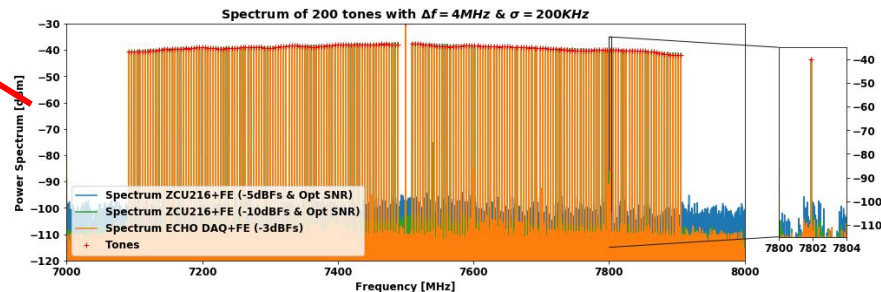
ZCU216

SFBB



HDM-GS

- 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



[Platino et al., J Low Temp Phys \(2024\)](#)

[Ferreiro et al., J Low Temp Phys \(2024\)](#)

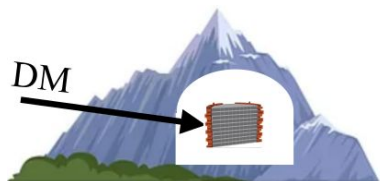
[Salum et al., J Low Temp Phys \(2024\)](#)

[García Redondo et al., J Low Temp Phys \(2024\)](#)

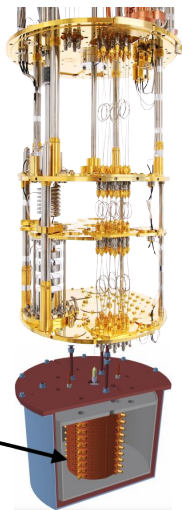
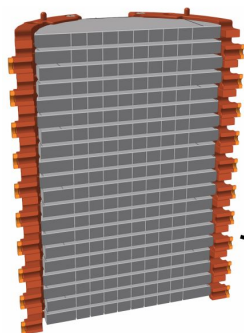
Gen3 RFSoc-based TDAQ with similar firmware modules

BULLKID-DM Experiment

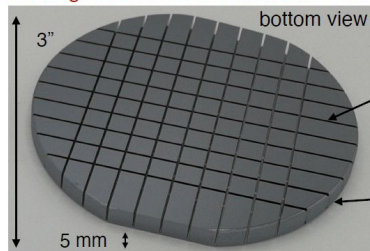
kg-scale, low-threshold and
low-background Dark Matter
(<1 GeV) experiment



x16



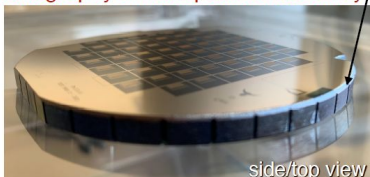
1. carving of dices in a thick silicon wafer



4.5 mm deep grooves
- 6 mm pitch
- chemical etching

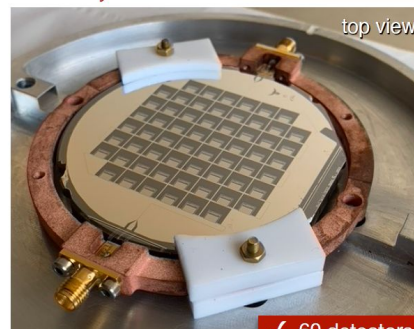
0.5 mm thick common disk:
- holds the structure
- hosts the KIDs

2. lithography of multiplexed KID array



KID array
- 60 nm aluminum film
- 60 KIDs lithography

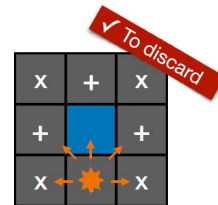
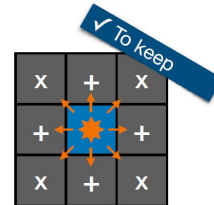
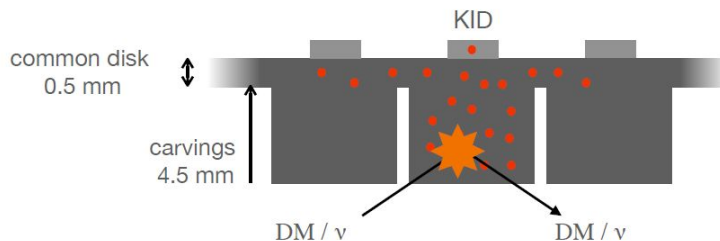
3. assembly



✓ 60 detectors in 1

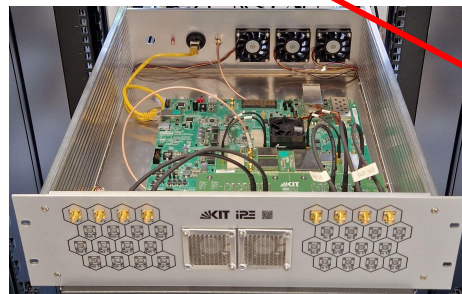
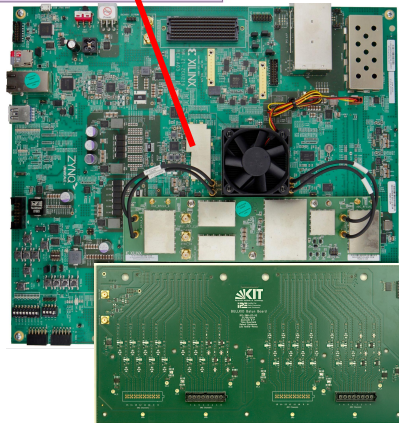
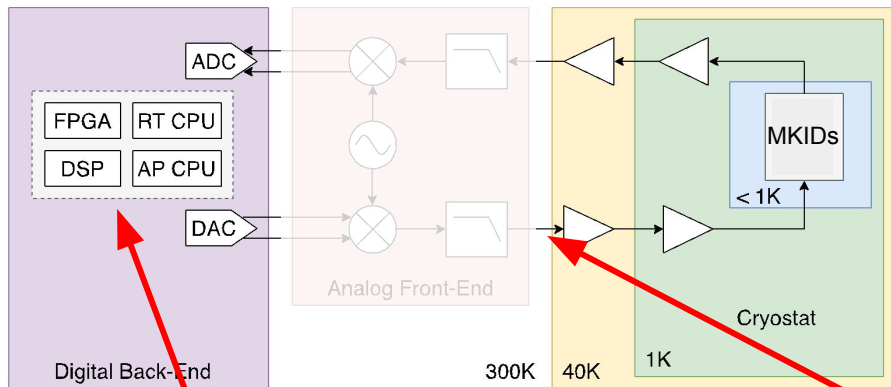
60 dices 0.35 g each
1 readout line

Assembly
- 3D-printed Cu holder
- Aluminum case

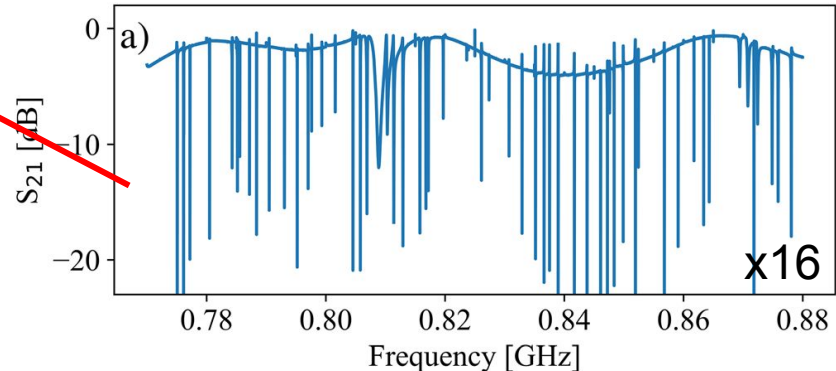
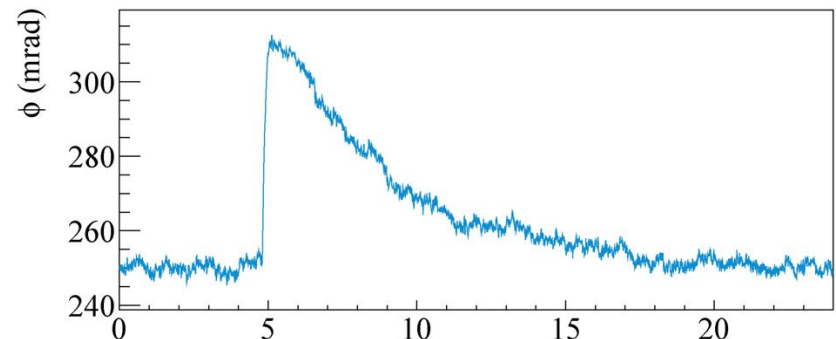


BULLKID-DM requires 16 readout channels each with 145 KIDs and online data processing to trigger on events

BULLKID-DM SDR-DAQ System Arch.



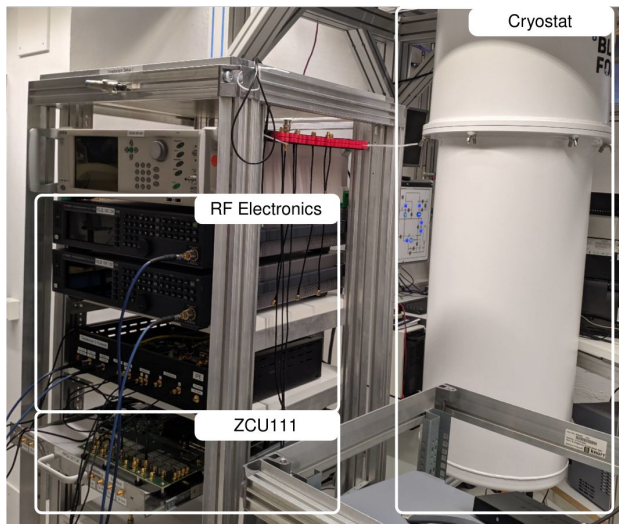
[Muscheid et al., IEEE TAS preprint \(2025\)](#)



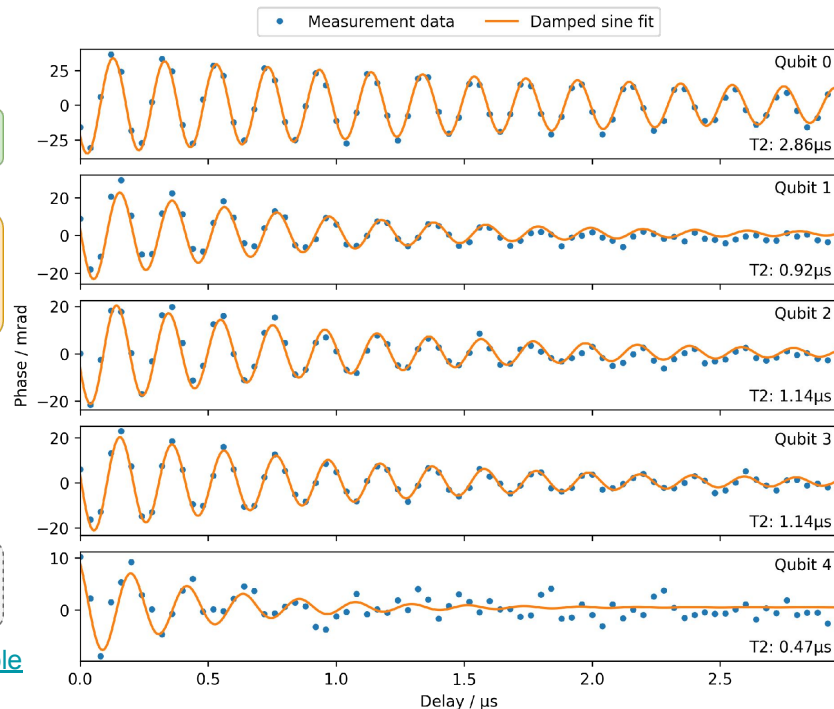
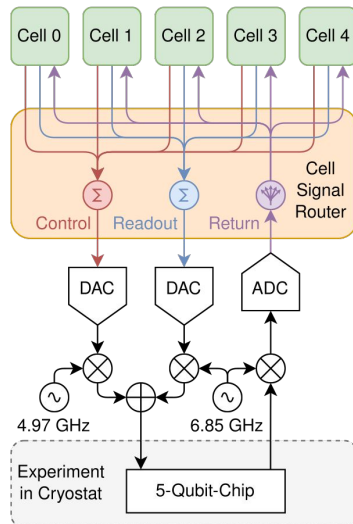
BULLKID-DM DAQ system based on RFSoc Gen3, Analog Mixer not needed

Simultaneous Qubit Measurements

(a)



(b)

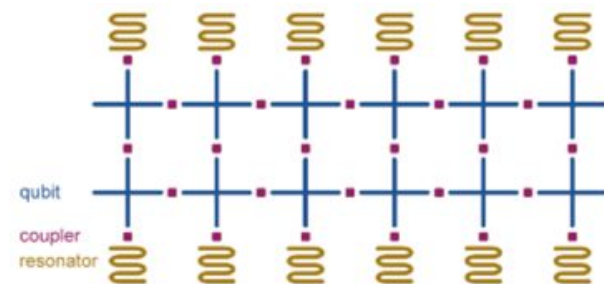
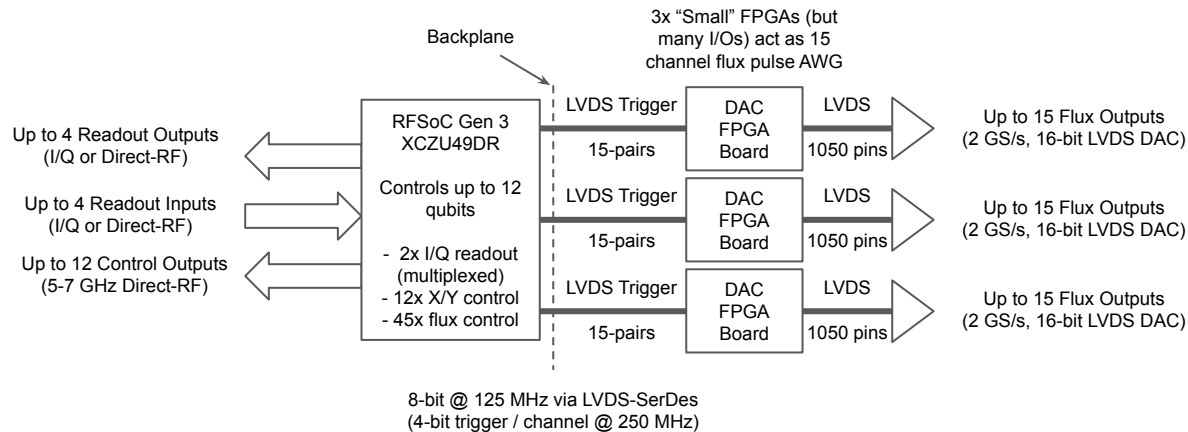


[Gartmann et al., IEEE CS QCE \(2024\)](#)

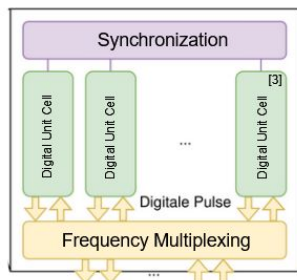
[Gebauer et al., ACM Trans. Reconfigurable Technol. Syst \(2023\)](#)

Parallel rabi experiment on a 5-qubit device

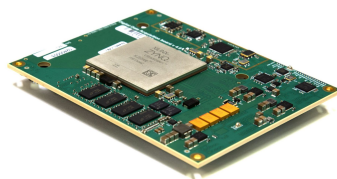
Scalability



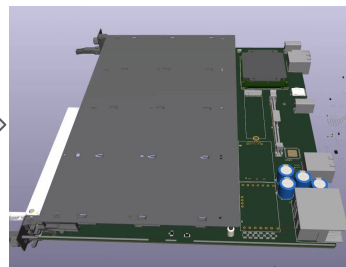
Additionally AXI-C2C for configuration of the DAC FPGAs (via regular SerDes)



Patented QiCell FW



RFSoc Module



ATCA Carrier



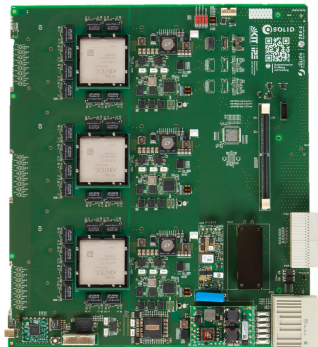
ATCA Crate



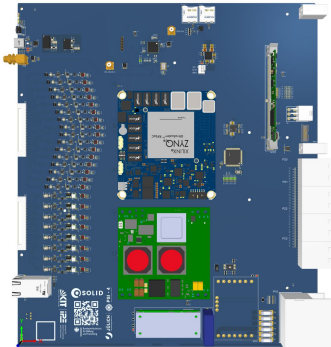
Rack

Modular QiController

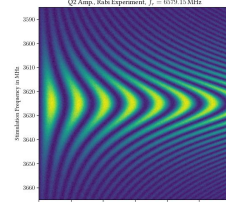
FLUX DAC NODE



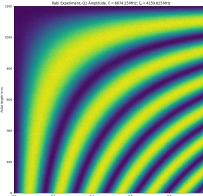
RFSOC HUB



[Gartmann et al., IEEE CS \(2024\)](#)



Time vs
detuning Rabi



Amplitude vs
time Rabi

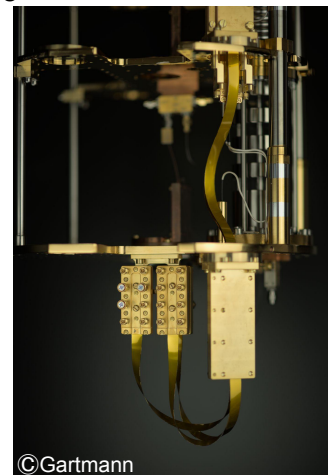
[Ardila-Perez et al., IEEE CS \(2024\)](#)

[Schlösser et al., IEEE CS \(2024\)](#)

QSOLID ATCA boards designed
in collaboration with Jülich ZEA2

- FluxDAC Node
- RFSoc Hub

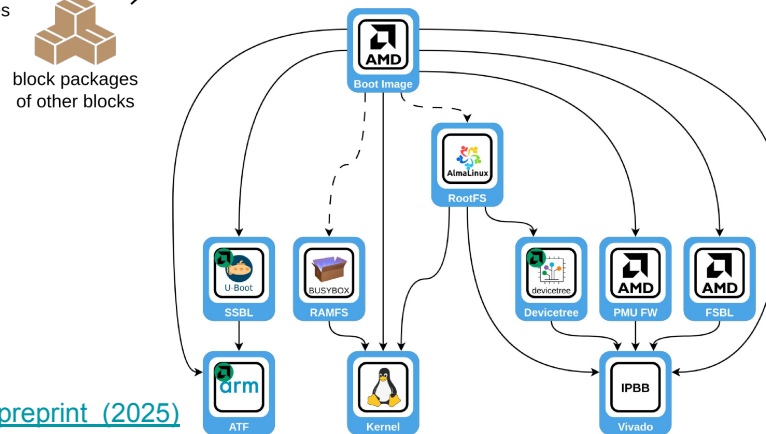
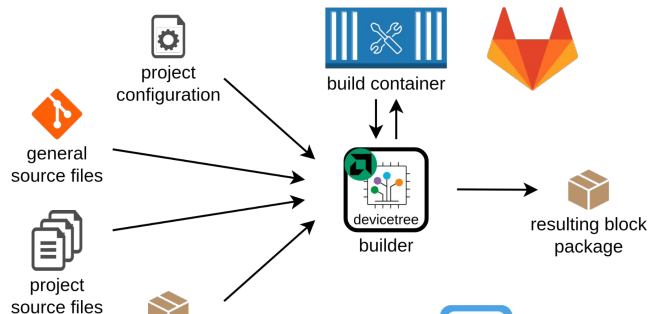
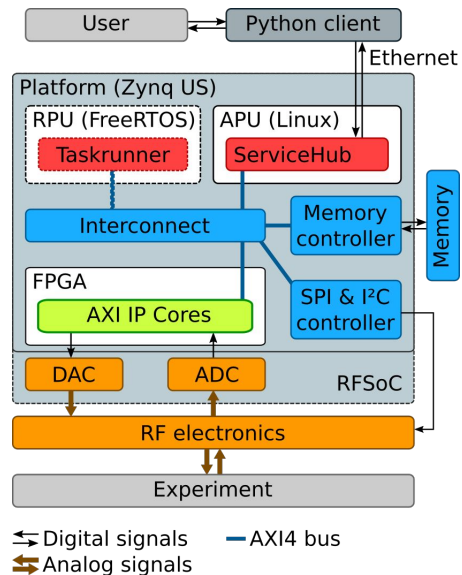
**QIC-10Q commissioned at
Jülich PGI-13 Prof. Barend's lab**
with measurements of a 5-Qubit
device from Chalmers Uni.



©Gartmann

24 channel Delft Circuit flat cables
at IPE's KryoDAQ Lab for "cQED"
project with Prof. Ioan Pop

IPE Tooling for Zynq Ultrascale+



[Karcher et al., IEEE TNS \(2021\)](#)

[Fuchs et al., AMC preprint \(2025\)](#)

Tooling centered around the MPSoc/RFSoc, SoCks and the gRPC protocol

Summary

- Readout electronics for cryogenic detector systems, with emphasis on frequency multiplexing (e.g., ECHo, QUBIC, BULLKID-DM, etc.).
- Key contributions to the quantum computing stack, focusing on bridging the cryogenic-to-room-temperature interface with the QiController (e.g., PtQube, QBriqs, QSolid, etc.).
- Delivering scalable, easy-to-use, and cost-efficient readout solutions for **next-generation experiments** in coordination with DRD5 (Quantum Detectors) and DRD7 (Electronics).



ECHo-100k TDAQ



BULLKID-DM TDAQ



QSolid QiController

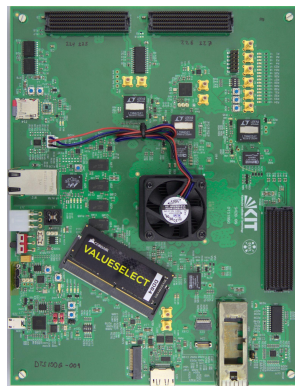
KIT: DAQ for Cryogenic Circuits (Detectors & Qubits)

Experience:

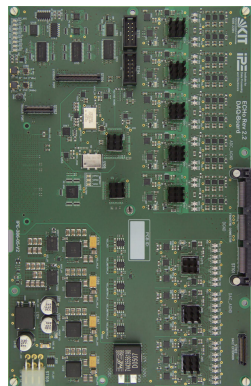
- Full-stack DAQ development for low-temperature Detectors (MMCs, MMBs, KIDs) and Superconducting Qubits using custom designed boards and COTs boards
- Generic radio frequency (RF) analog front-end targeting various applications.
- Tools and methods for building firmware/software for heterogeneous devices (MPSoCs, RFSocS)

Interests:

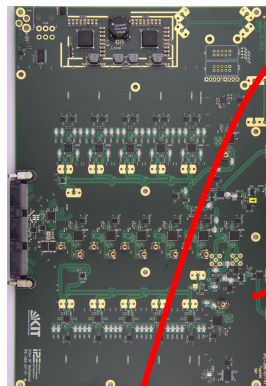
- Develop DAQ systems targeting future large-scale arrays of low-temperature detectors (to be coordinated with DRD5)
- R&D on firmware modules for online data processing specifically for frequency-division multiplexed (FDM) detectors



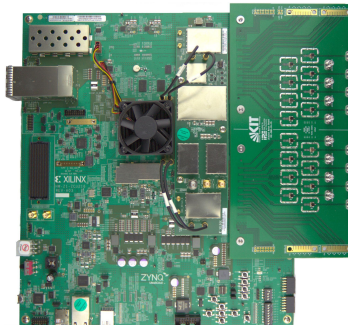
ZynqUS+ Board
(DTS-100G)



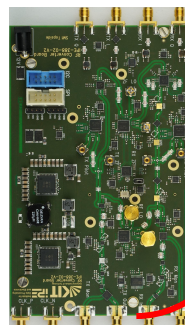
DAC & ADC



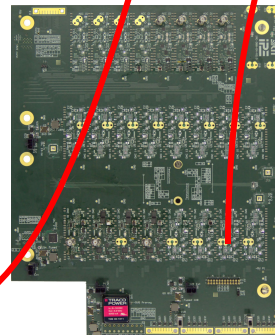
RF Board



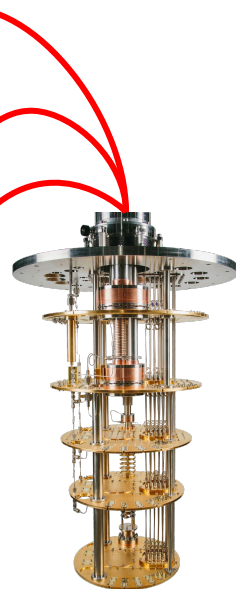
Xilinx ZCU216
RFSoc eva board



HDM RF Board

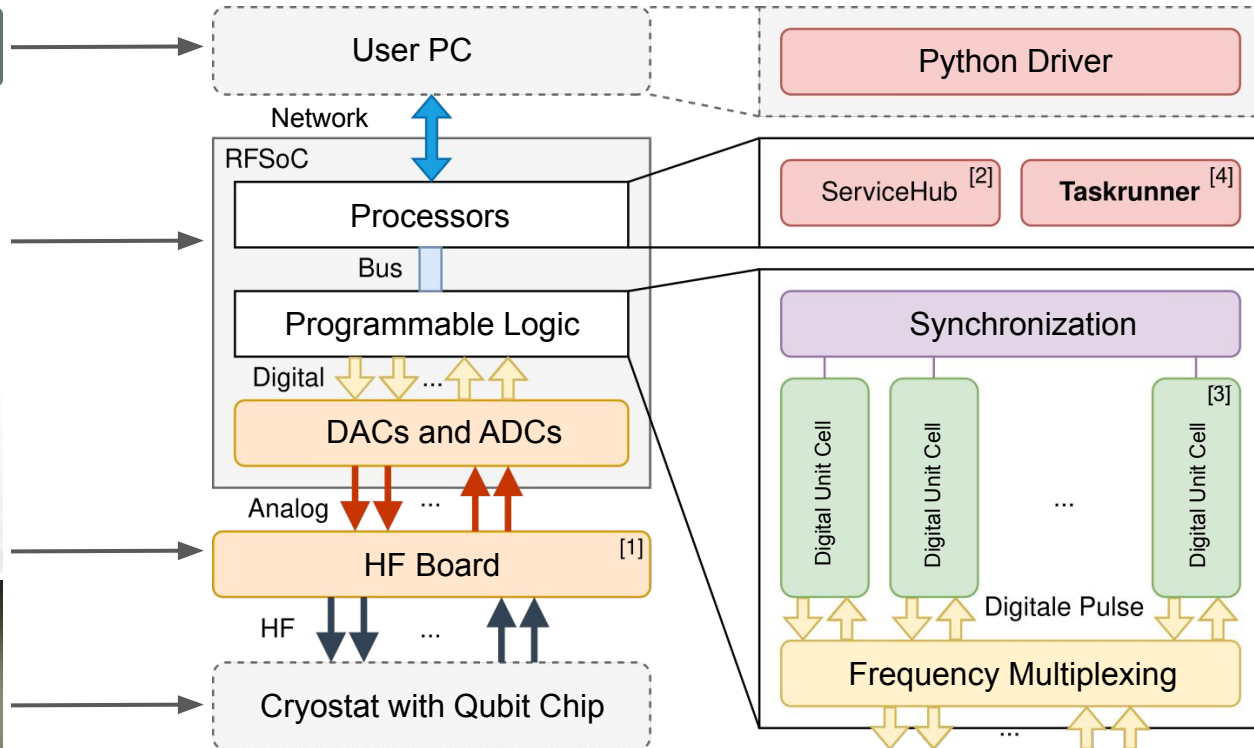
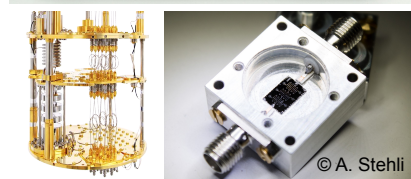
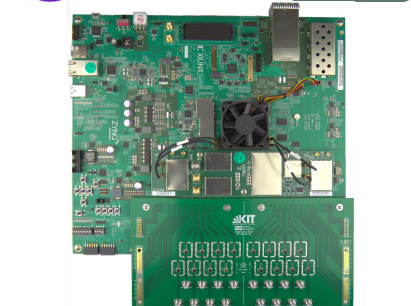


DirectRF Board



MMCs/ KIDs / Qubits
currently installed at
IPE KryoDAQ Lab

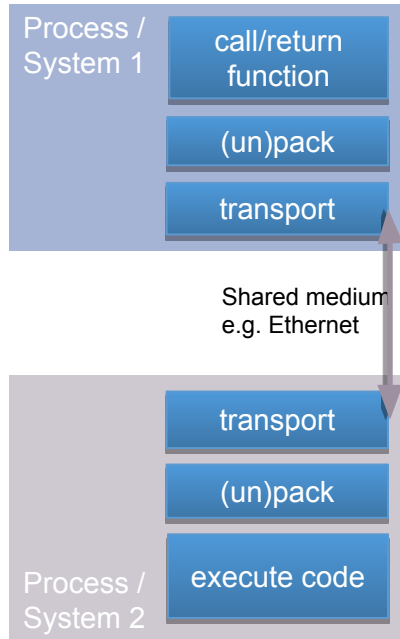
QiController - System Architecture



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

Remote Procedure Calls and the gRPC Library

Calling and called context in different processes or systems



Example Service

```
syntax = "proto3";

package dac;

service DACService {
  rpc SetDACValue(Param) returns (Empty) {}
}

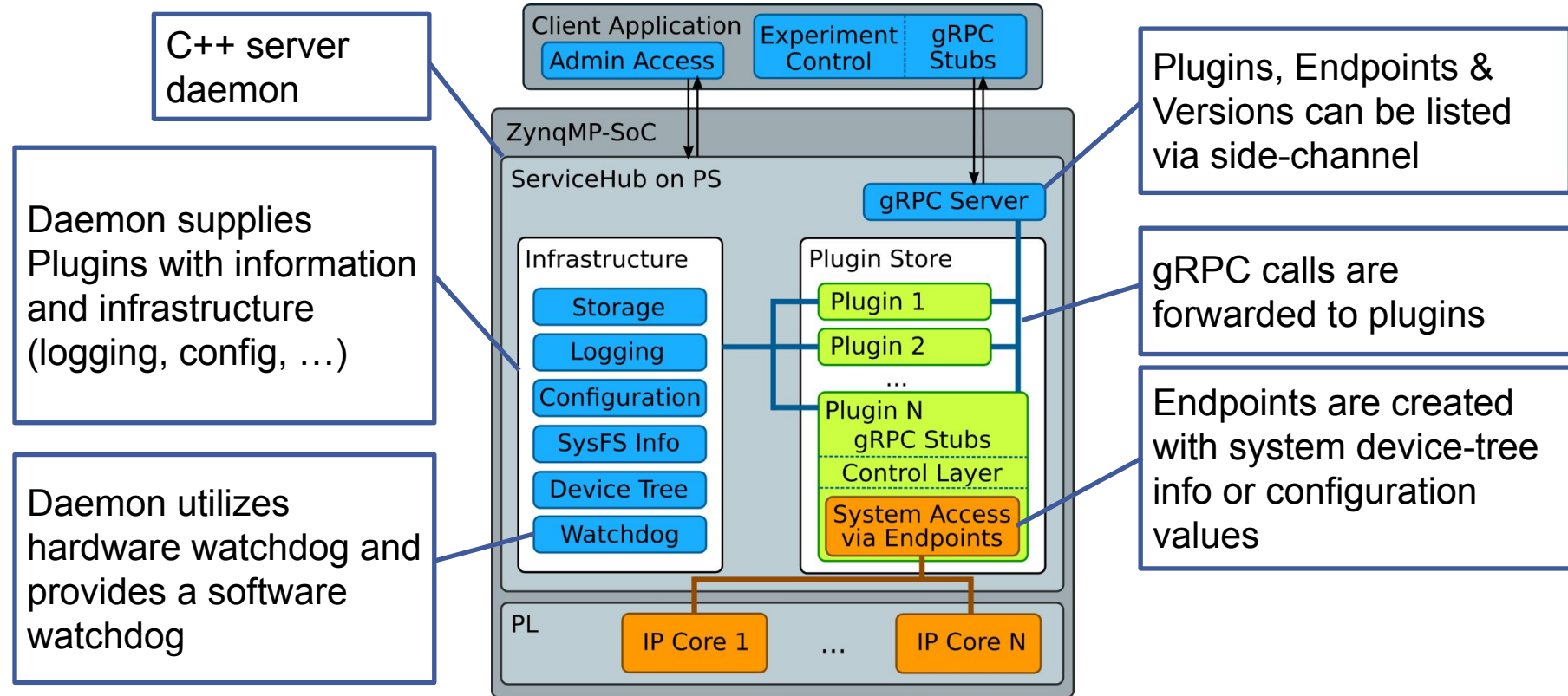
message Empty {}

message Param {
  uint64 value = 1;
  boolean enable = 2;
}
```

- TCP/IP based
- Interface description: protobuf language
- Code generation for various languages (client agnostic)
- Support for data streams



ServiceHub Architecture

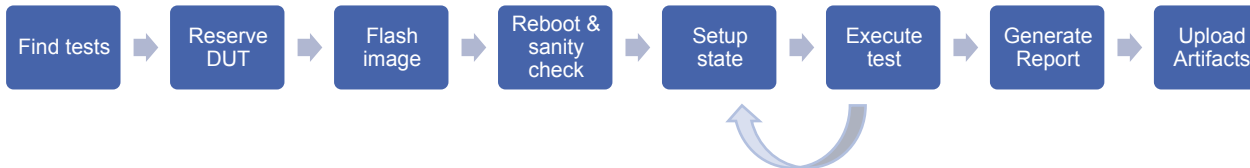


System Test with Remote Rack

Automatic control via gitlab runner process

- Platforms with SSH, gRPC interface, USB/IP
- Remote accessible instruments (e.g. oscilloscope)

```
1 @ipe.Test
2 class check_core_id():
3     def __init__(self, dut):
4         self.run_for_image = {'cap_frm_zcu102_ti', 'cap_zcu102_ti', 'qup_rfsoc_2rec'}
5
6     def setup(self):
7         self.channel = grpc.insecure_channel(f"{dut}:50058")
8         self.stub = pimc_pb2_grpc.PIMCServiceStub(self.channel)
9
10    @ipe.decorators.StartState(states.platformRdy)
11    def run_test(self):
12        coreID = self.stub.GetCoreId(pimc_pb2.Empty())
13
14        ipe.EXPECT_EQ(coreID.chip_id, 65535)
15        ipe.EXPECT_EQ(coreID.chip_version, 2)
```



IPE KryoDAQ Lab

- The **cryogenic DAQ lab** for characterization and development of next generation cryogenic detector trigger and readout electronics TDAQ (full chain evaluation)
- Mobile version **Bluefors LD250 cryostat** (<10mK)

