L. E. Ardila-Perez[1], D. Crovo[1], L. P. Ferreyro[2,1], M. Fuchs[1], M. E. García Redondo[2,1], R. Gartmann[1], M. R. Hampel[2], T. Muscheid[1], M. Platino[2], J. M. Salum[2,1], O. Sander[1], L. Scheller[1], and F. Simon[1]

1 Institute for Data Processing and Electronics (IPE), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany.
2 Instituto de Tecnologías en Detección y Astropartículas (ITeDA), Comisión Nacional de Energía Atómica (CNEA), Argentina.

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Scalable Readout Architecture for Large-Scale Quantum Sensor Arrays in Fundamental Physics

New Physics: Beyond the Standard Model

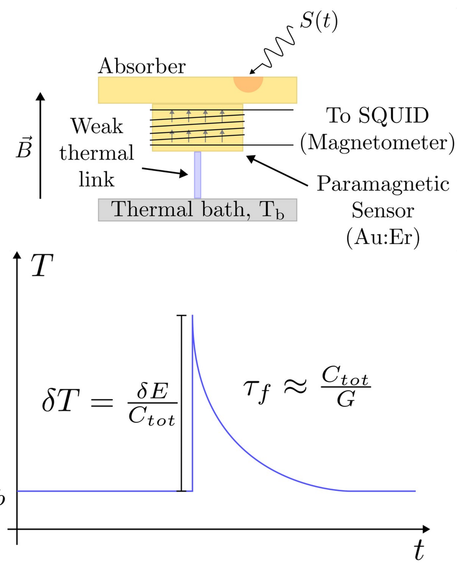
The potential to measure small energy transfers with very high energy resolutions motivated the development of cryogenic detectors to search for dark matter in the universe, the neutrino mass, neutrinoless double beta decay, and new phenomena in astrophysics. Cryogenic detectors operate at temperatures below 1 Kelvin, where thermal noise is suppressed and the physical response of the sensor is maximized.

Metallic Magnetic Calorimeters (MMC)

MMCs use a paramagnetic material embedded in a magnetic field. A particle interaction raises the temperature of the sensor, changing its magnetization. This is detected via a SQUID loop coupled to a pickup coil.

- High energy resolution
- No dissipation during signal generation
- Excellent linearity and low noise

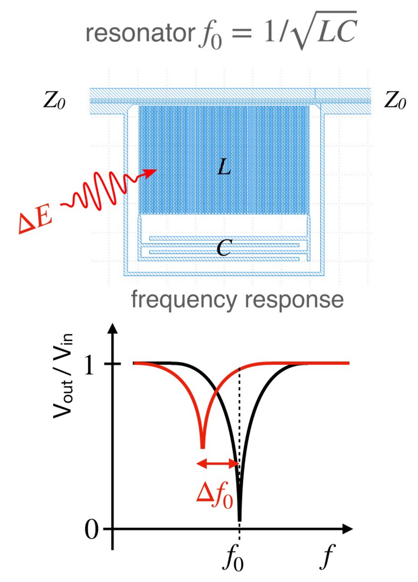
$$\delta M = \frac{\partial M}{\partial T}\,\delta T$$



Kinetic Inductance Detectors (KID)

KIDs rely on superconducting resonators whose resonant frequency shifts when quasiparticles are generated by particle interactions. These frequency shifts are monitored with a probe tone using microwave electronics.

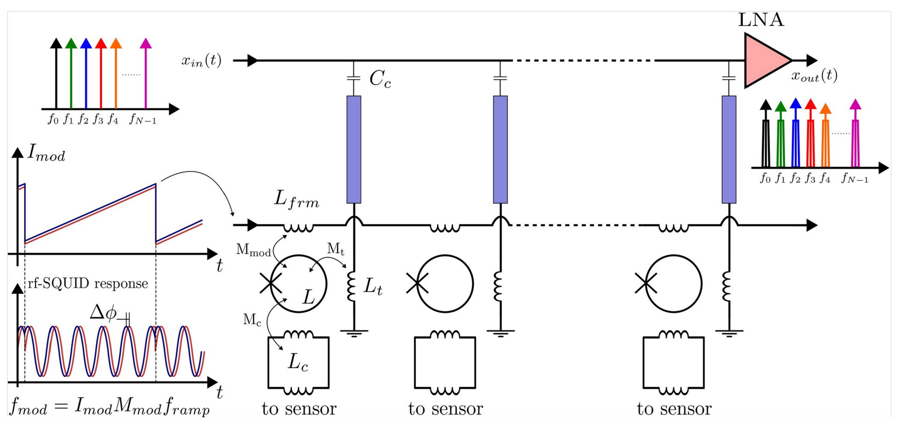
- Natural multiplexing in frequency domain
- High-speed response
- Suitable for large-format arrays



Microwave SQUID Multiplexing (µMUX)

As cryogenic detector arrays scale to thousands of pixels, traditional readout schemes become impractical due to thermal and wiring constraints. Microwave SQUID Multiplexing (µMUX) is a state-of-the-art readout technique that enables the efficient, low-noise readout of large arrays of superconducting detectors like TESs and MMCs.

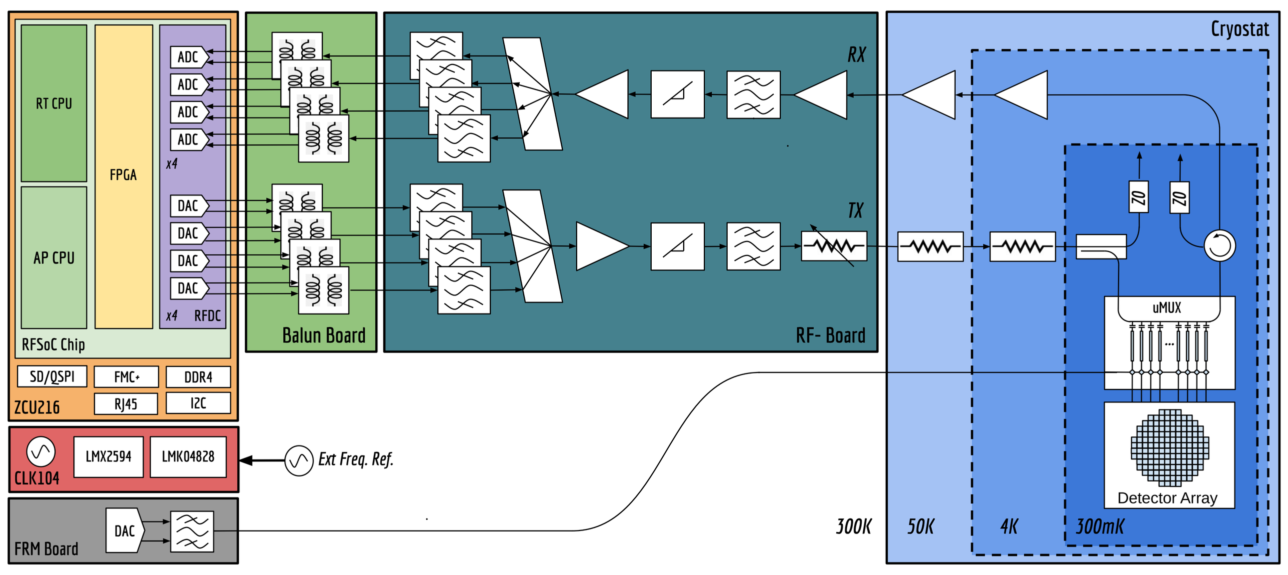
- Each detector (TES or MMC) is inductively coupled to an RF-SQUID, which transduces the current from the detector into a frequency shift.
- The RF-SQUID modulates the inductance of a superconducting microwave resonator.
- Each resonator is tuned to a unique frequency in the GHz range.



Quantum Interface Controller (QIC)

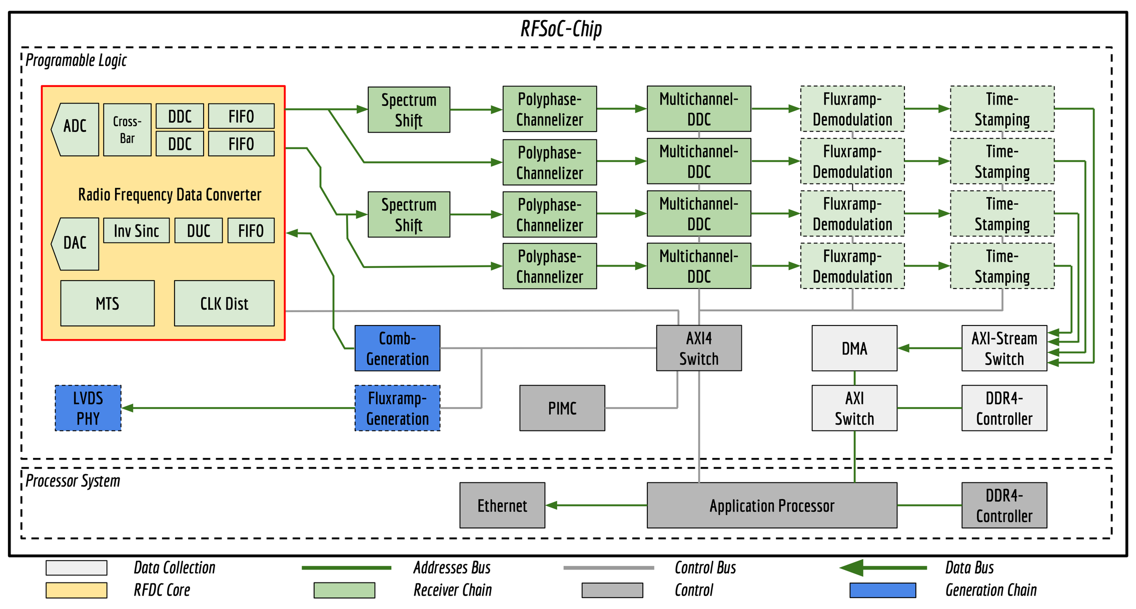
Cryogenic detectors require precise and scalable readout in the microwave domain. To meet these needs, a software-defined radio (SDR) platform called Quantum Interface Controller (QIC) has been developed using Xilinx Zynq UltraScale+ MPSoC and RFSoC devices. These platforms integrate high-speed ADCs/DACs, programmable logic (FPGA), and multicore ARM processors, providing a flexible and high-performance solution for detector readout, by utilizing differnet analog front-ends we can target different bands of interest like the 4 to 8 GHz range or 0.4 to 1.2 GHz.

- Up to thousands of tones per system, supporting large detector arrays
- Overall system architecture depicted for SQUID multiplexed detectors but similar for others.



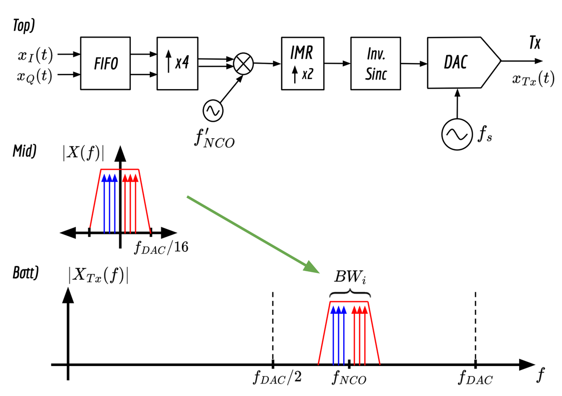
Real-Time Signal Generation and Processing

A modular firmware architecture has been developed, enabling flexible deployment across multiple experiments with minimal reconfiguration. Several firmware modules are reconfigurable at build time and others are setable at run-time.



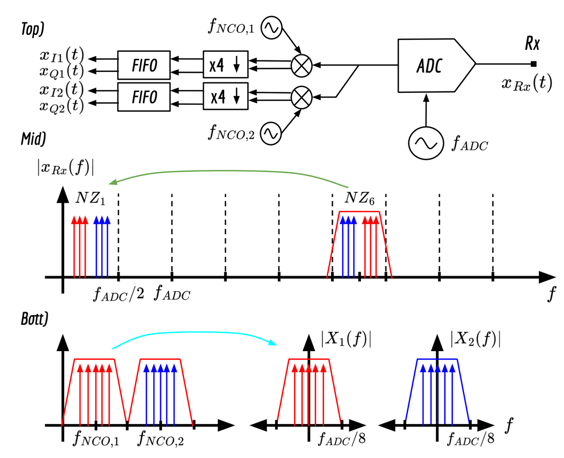
Transmission

DirectRF signal generation is performed in the second Nyquist zone using a Mixed-Mode reconstructor and with Digital-to-Analog Coverters (DACs) operating at fDAC=8 GHz. A Numerically Controlled Oscillator (NCO) sets the center frequency of the desired sub-band.



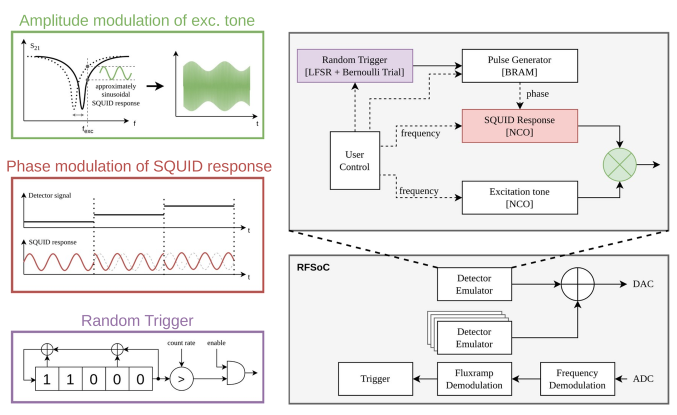
Reception

Band-pass sampling is performed in higher-order Nyquist zones using Analog-to-Digital Converters (ADCs) operating at fADC=2 GHz. Each sub-band is divided into two using Digital Down Converters (DDCs) for subsequent processing.



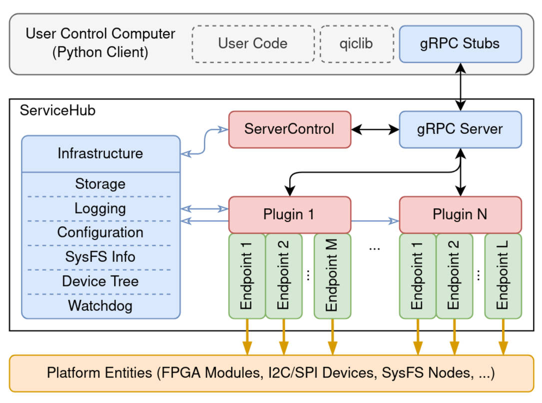
Cryogenic Detector Emulator (CryoDE)

A digital CryoDE was created for the verification of the DAQ electronics without the need for a cryogenic sample. Runtime controllable parameters are the pulse count rate, shape, amplitude, time constant and resonant frequency.



Software Stack

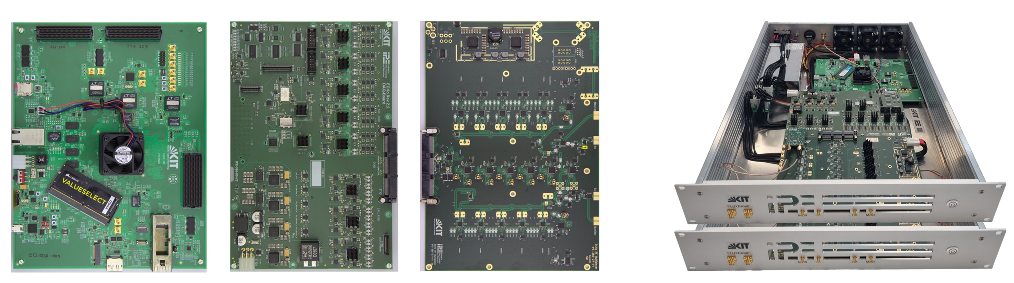
A unified software stack is used across all projects to simplify development, integration, and deployment. Based on the Linux operating system, the stack uses gRPC over Ethernet for efficient and language-independent communication between distributed components. Each physical endpoint has its own dedicated driver. All interfaces are managed centrally by the *servicehub*.



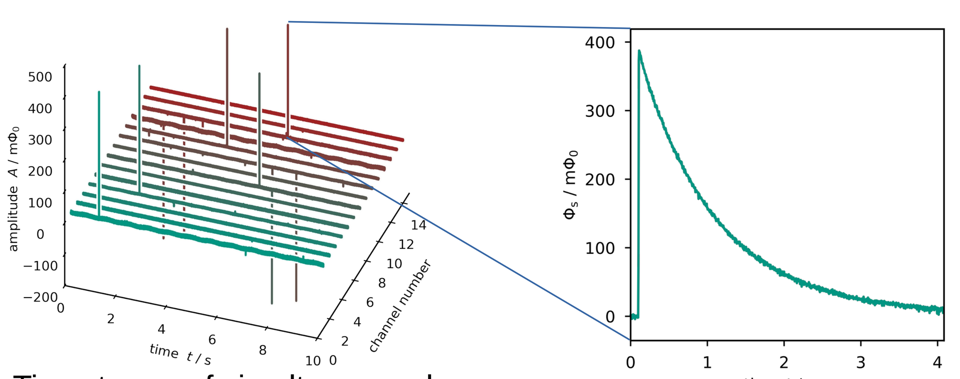
ECHo – Neutrino Mass Experiment

The ECHo experiment (Electron Capture in Holmium-163) aims to determine the effective mass of the electron neutrino by performing high-precision spectroscopy of the electron capture decay of Holmium-163. Using arrays of ultra-sensitive cryogenic microcalorimeters

- Three Custom Boards; Digital MPSoC-based, Analog conversion and Heterodyne Mixer plus power merging/splitting
- 15 systems delivered to Heidelberg University
- Total Bandwidth: 4 to 8 GHz



DTS100G | AD/DA | Mixer | QIC – ECHo

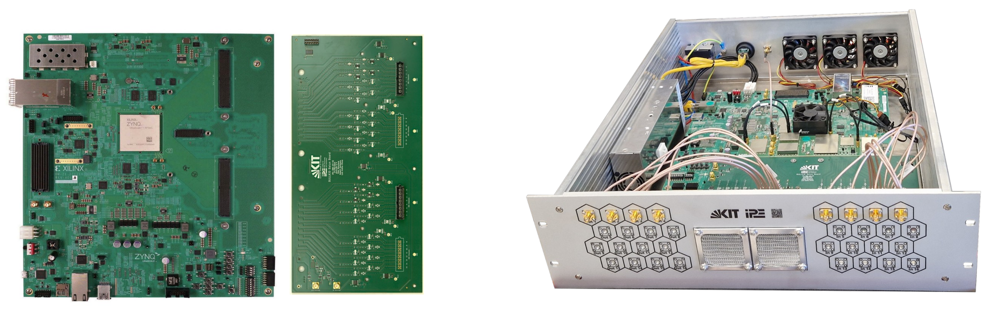


Timestream of simultaneausly operated channels | Single detector signal

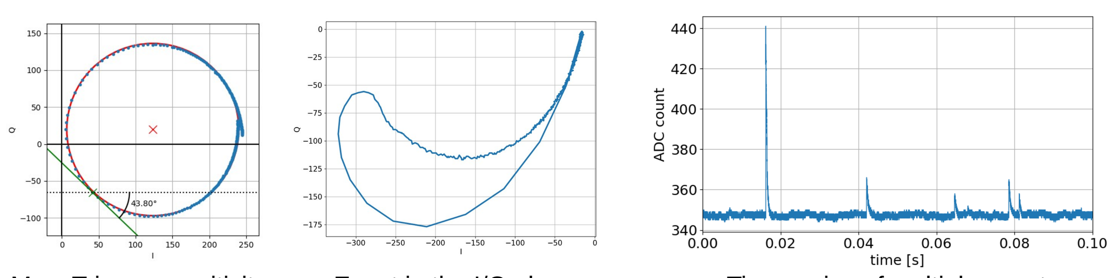
BULLKID-DM – Dark Matter Experiment

Focused on the direct detection of light dark matter using large arrays of Kinetic Inductance Detectors (KIDs) operated at cryogenic temperatures at the very-low background environment of the Gran Sasso Laboratory.

- One Custom Board for analog signal conditioning and the RFSoC evaluation board with 16 DACs and 16 ADCs with 14 bit
- Four systems being commissioned at INFN (Rome, Pisa, LNGS) and Insitut NEEL



ZCU216 | Front-End | QIC – BULLKID-DM



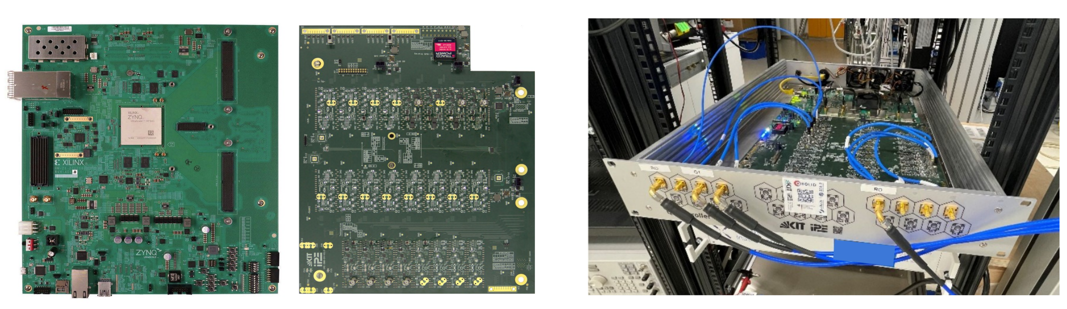
Max. Trigger sensitivity by rotating circle | Event in the I/Q plane | Time series of multiple events

VNA sweep → Setup comb → Resonator circles → Calibrate trigger → Energy calibration

QBRIQS – Building blocks of cryogenic quantum tech.

Dedicated to developing the essential hardware infrastructure needed for the scalable characterization and control of superconducting qubit systems. While the primary focus is on enabling superconducting qubit platforms, the technologies developed within QBRIQS are broadly applicable to quantum sensing, low-temperature detectors, and metrology.

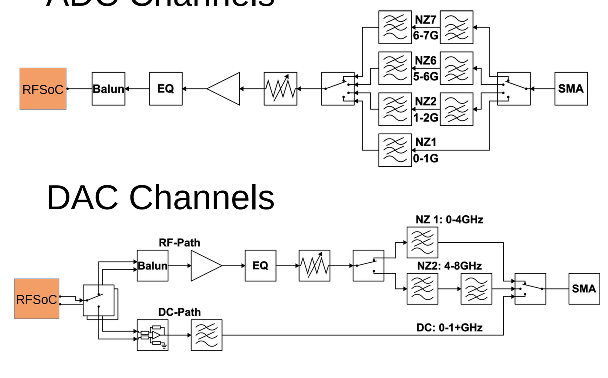
- One Custom Board for microwave analog signal conditioning with runtime selectable filter banks and the RFSoC evaluation board

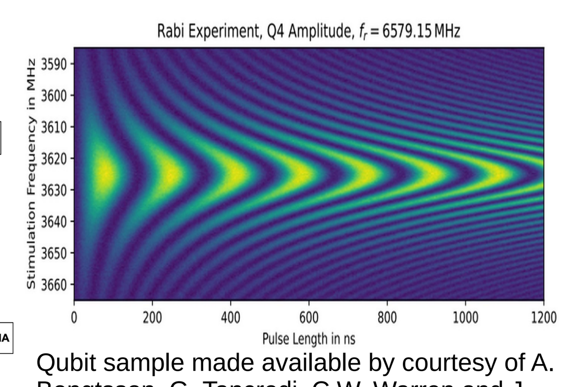


ZCU216 | DirectRF | QIC – SC Qubit

ADC Channels

DAC Channels

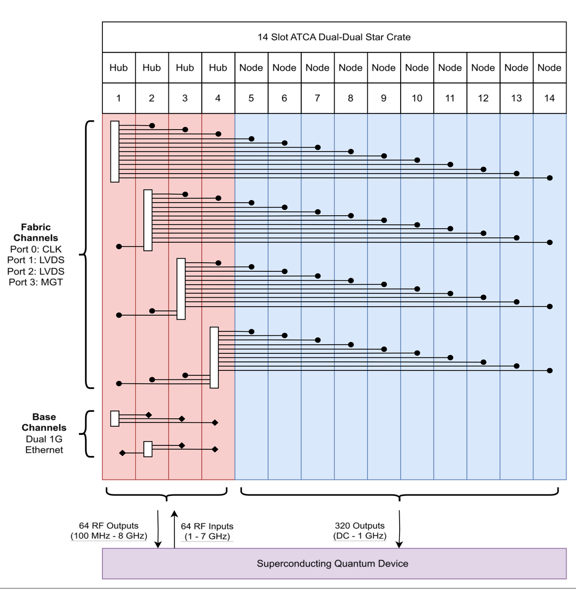




Qubit sample made available by courtesy of A. Bengtsson, G. Tancredi, C.W. Warren and J. Bylander at Chalmers University.

Scalable Readout Architecture

Utilizing the ATCA dual-dual backplane, a system has been developed, initially targeting quantum computing, where four identical RFSoC HUBs are interconnected with ten FLUX NODEs to interface with up to 40 superconducting qubits. The same backplane connectivity can also be applied to other experiments that require multiple synchronized RFSoC boards.



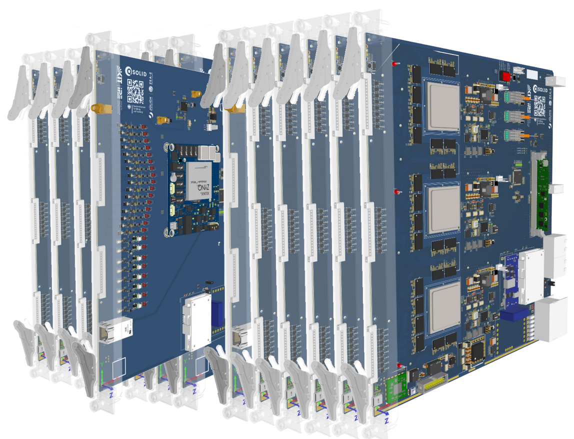


Illustration showing two different types of ATCA boards positioned side by side as they are inserted into a crate.

19-inch rack-mountable ATCA crate with 14 available vertical slots.

Rack for mounting multiple crates.

Conclusions

- The QIC system has proven highly effective for early-stage detector development, where rapid iteration and configurability are crucial. It is already in use across several diverse experimental platforms.
- In its scalable form, the QIC can support hundreds to thousands of synchronized channels, making it a key enabler for next-generation large-scale experiments.
- Its ability to perform DirectRF synthesis in the microwave spectrum leverages technological advancements in telecommunications, future device generations would unlock even higher multiplexing factors at other frequency bands.

References

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