Novel RF Readout Architectures for Enhanced performance in Quantum Technologies

Alberto Arcusa Puente (aarcusa@ita.es)
Directores: Ana Arauzo y Javier Galindo
Instituto Tecnológico de Aragón (ITA), Zaragoza, Spain

INTRODUCTION

Quantum technologies have advanced dramatically over the last decade. Superconducting qubits, cryogenic detectors (SQUIDs, MKIDs, TES) and quantum sensors are now approaching the fundamental sensitivity limits set by quantum mechanics [I], with applications ranging from quantum computing to searches for dark matter, axions and high-frequency gravitational waves [II].

However, as the quantum devices themselves improve, the **readout and control chain** has become the limiting factor. It directly determines measurement fidelity, effective coherence time and SNR [III], and it is one of the primary sources of decoherence through phase noise, crosstalk and electromagnetic interference.
Current readout architectures compound the problem: proprietary systems offer little reconfigurability, scale poorly to multichannel setups [IV], and are rarely designed with EMC engineering integrated from the ground up, a critical gap when EMI from the readout hardware itself degrades quantum coherence.

Open RF-SoC platforms such as **QICK** (Fermilab) [V] represent a promising path forward, enabling firmware-level customization, real-time DSP and low-latency control in a single reconfigurable unit. This thesis explores how to extend that approach into robust, low-noise, EMI-hardened readout architectures for both quantum computing and fundamental physics detectors.

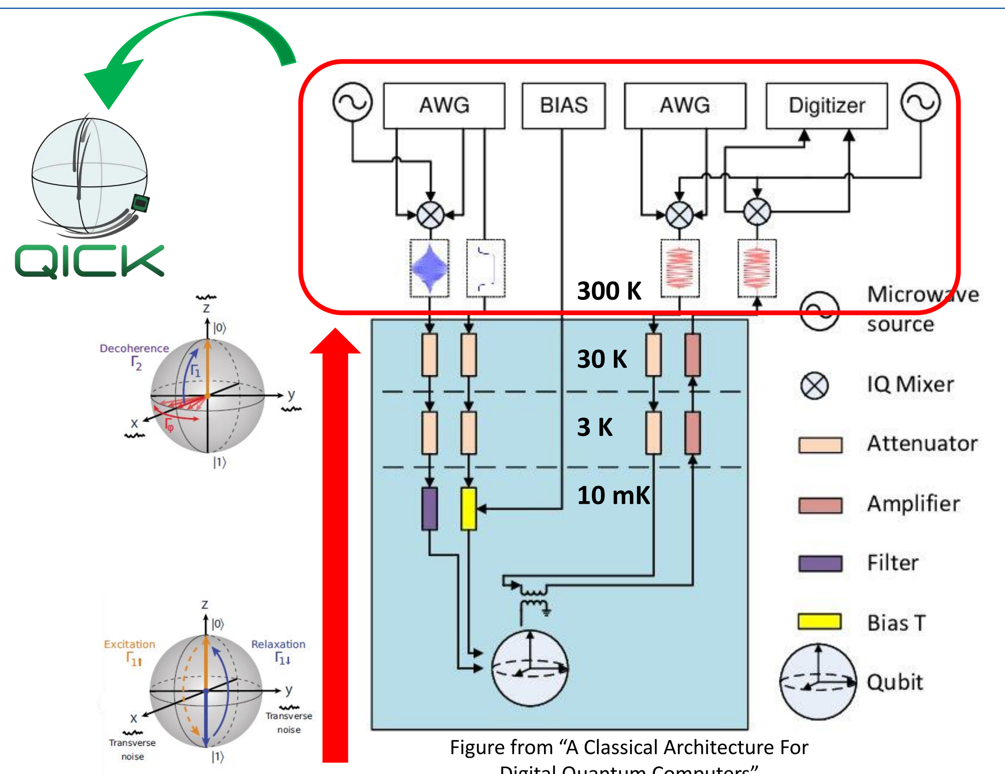


Figure from "A Classical Architecture For Digital Quantum Computers"

MOTIVATION

RF-SoC TECHNOLOGY

RF-SoC technology has reached the performance threshold required for quantum readout

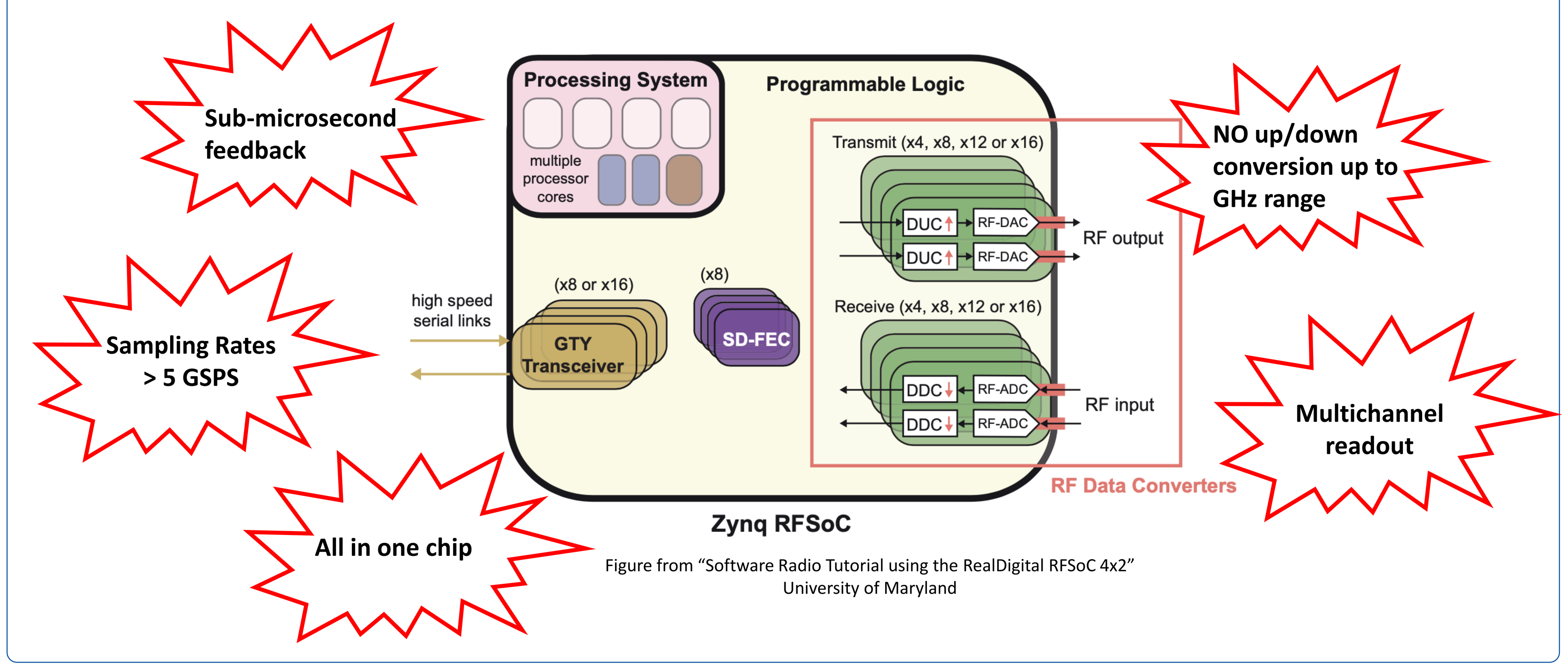


Figure from "Software Radio Tutorial using the RealDigital RFSoC 4x2" University of Maryland

QICK PLATFORM

QICK (Quantum Instrumentation Control Kit) platform is an open RF-SoC architecture that integrates **RF generation**, **digital downconversion**, real-time **DSP** and **low-latency control** in a single reconfigurable unit.

This architecture **scales** naturally to **multichannel configurations**, addressing one of the most pressing demands of next-generation quantum systems.

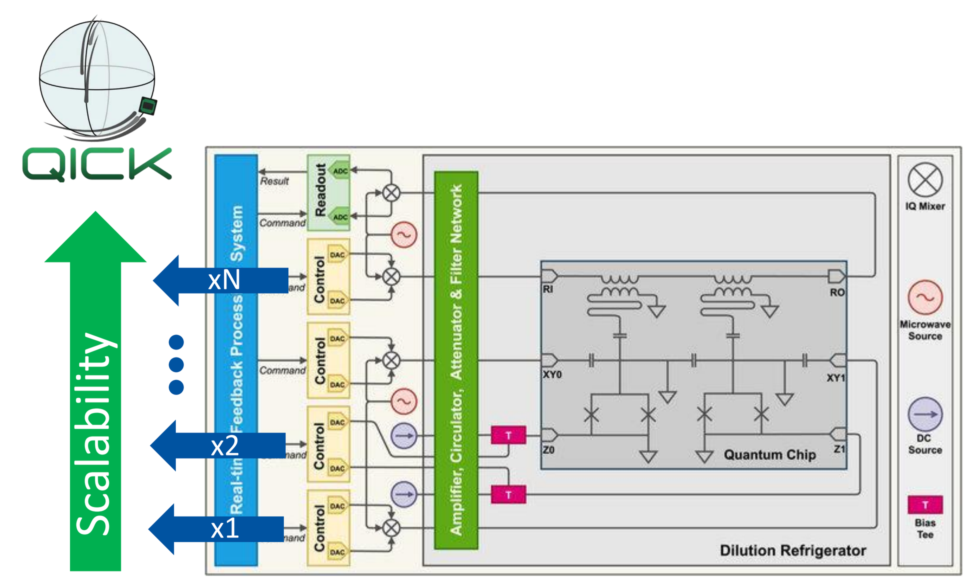


Figure from "Low-latency readout electronics for Dynamic superconducting quantum computing"

QUANTUM PHYSICS DETECTORS

Quantum technologies are gaining strategic relevance in particle physics, enabling access to experimental regions unreachable with conventional detectors.

Particularly in **dark matter** searches (axions, ultralight candidates), high-frequency **gravitational waves** and **Beyond-Standard-Model** phenomena.

Yet exploiting that potential demands readout architectures where **electromagnetic robustness** and **noise floor** minimization are primary design drivers.

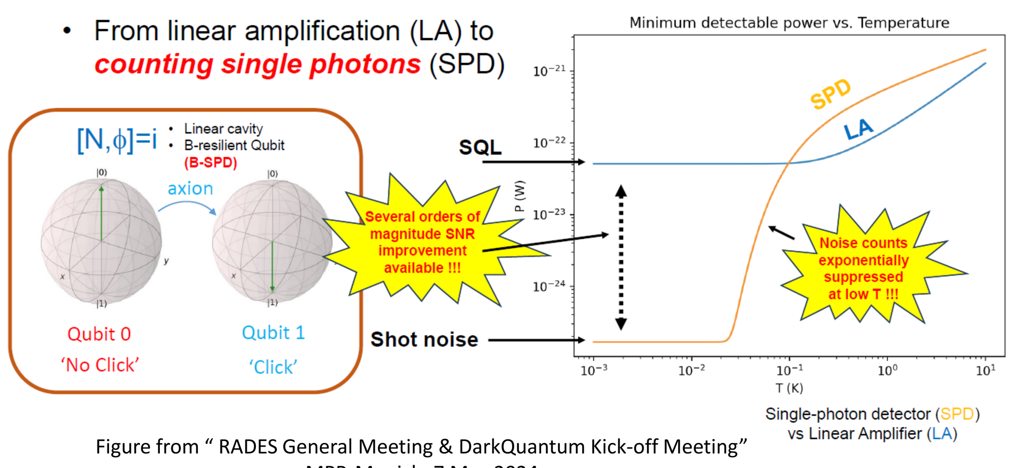
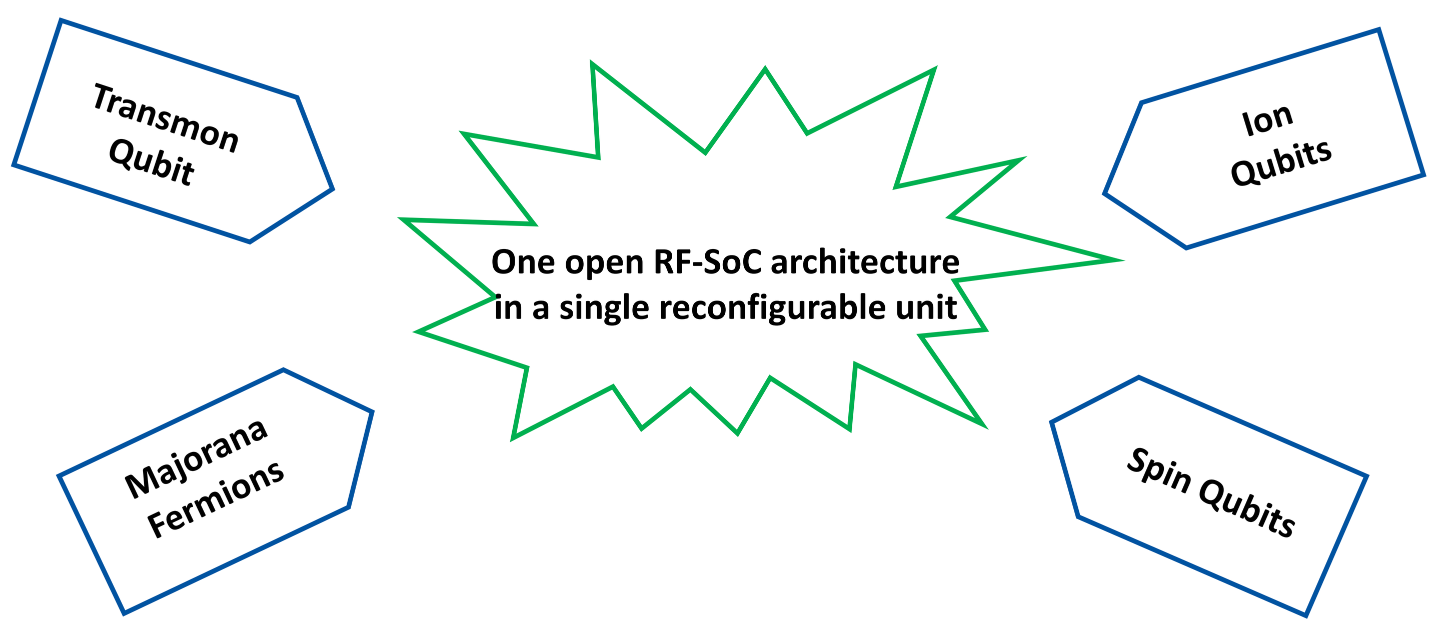


Figure from " RADES General Meeting & DarkQuantum Kick-off Meeting" MPP, Munich, 7 May 2024

QUBIT PLATFORM DIVERSITY

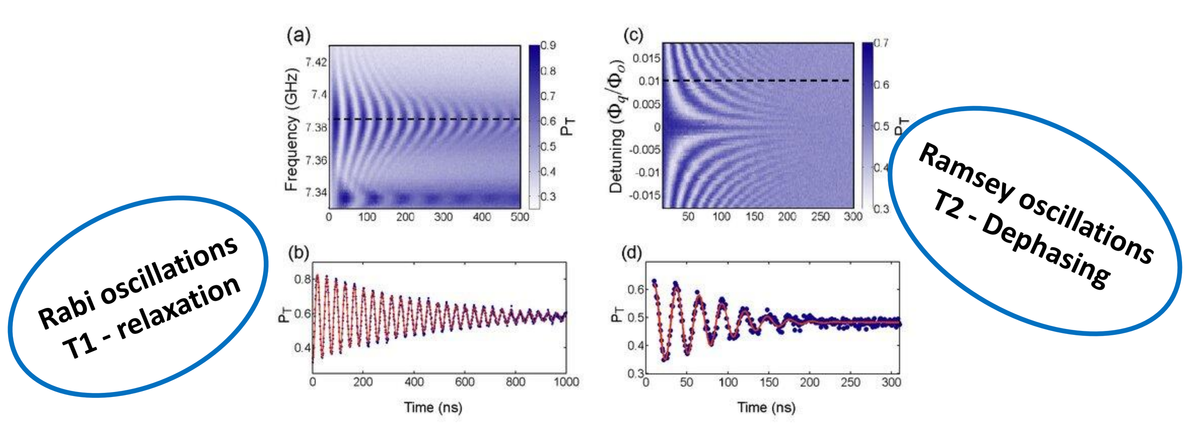
Each application imposes **different requirements** on pulse shape, timing precision and noise floor, but all share a **common vulnerability**: any imperfection in the readout tone or control signal directly compromises qubit coherence and gate fidelity.



OBJECTIVE

CHARACTERIZE

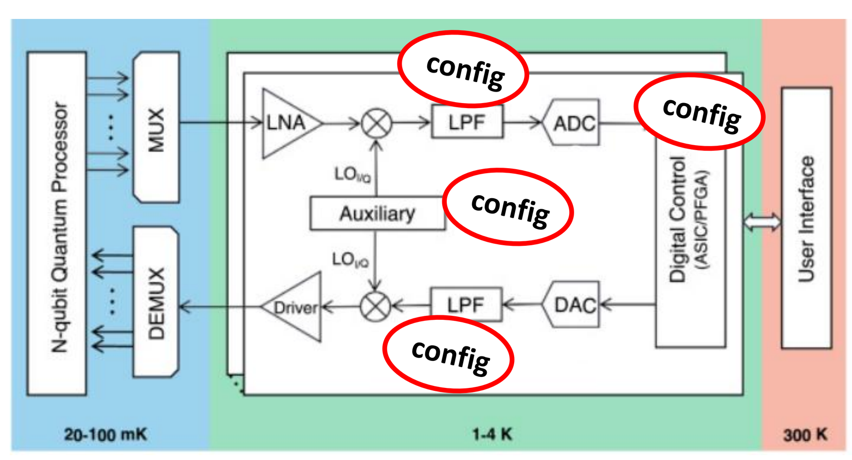
Understanding the **physical** and **electronic mechanisms** through which the RF readout introduces **decoherence**: phase noise, electromagnetic interference, crosstalk between channels and timing imprecision



Figures from "Tunable-Cavity QED with Phase Qubits"

ENGINEER

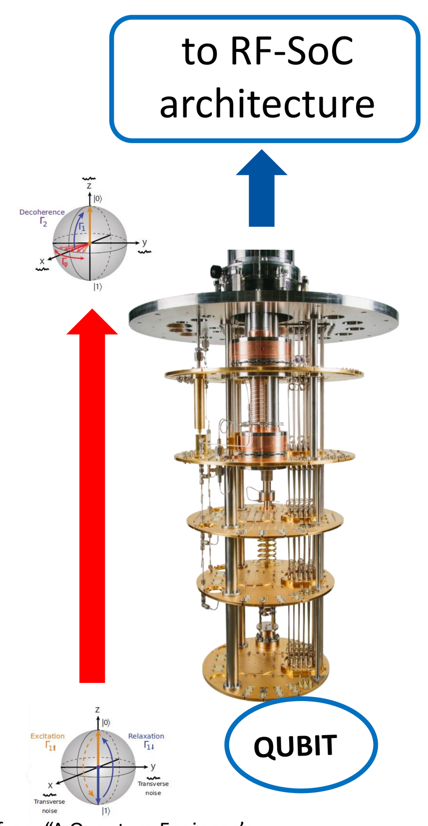
Proposing a **configurable** RF **readout & control** architecture integrating EMI hardening, low-noise signal conditioning and precise **timing synchronization** across hardware, firmware and software to preserve **quantum coherence**



Figures from "Cryo-CMOS modeling and a 600 MHz cryogenic clock generator for quantum computing applications"

VALIDATION

The architecture will be validated through **real-world experiments**—superconducting qubit processors and fundamental physics detectors—by evaluating **coherence stability**, signal-to-noise ratio, and **detection sensitivity**, with real-time adaptation serving as the primary performance metric.



Figures from "A Quantum Engineer's Guide to Superconducting Qubits"

[I] P. Krantz et al. — A quantum engineer's guide to superconducting qubits — Appl. Phys. Rev. 6 (2), 021318, 2019
[II] D. D. Awschalom et al. — Challenges and opportunities for quantum information hardware — Science 390, 1004-1010, 2025
[III] Untangling the challenges of quantum computing — Nat. Electronics 9, 237, 2026
[IV] M. A. Nielsen & I. L. Chuang — Quantum Computation and Quantum Information — Cambridge University Press, 2010
[V] L. Stefanazzi et al. — The QICK: Readout and control for qubits and detectors — Rev. Sci. Instrum. 93 (4), 044709, 2022

Ayuda RED2024-153684-T financiada por MICIU/AEI/10.13039/501100011033

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN

Esta publicación es parte del proyecto de I+D+i BABYIAXO cuya referencia es PID2022-137268NB-C54 financiado por MICIU/AEI/10.13039/501100011033