FERMILAB-SLIDES-24-0249-SQMS

Demonstrating the Potential of Adaptive LMS Filtering on FPGA-Based Qubit Control Platforms for Improved Qubit Readout in 2D and 3D Quantum Processing Units

IEEE Quantum Week 2024: QCE24 Submission 416

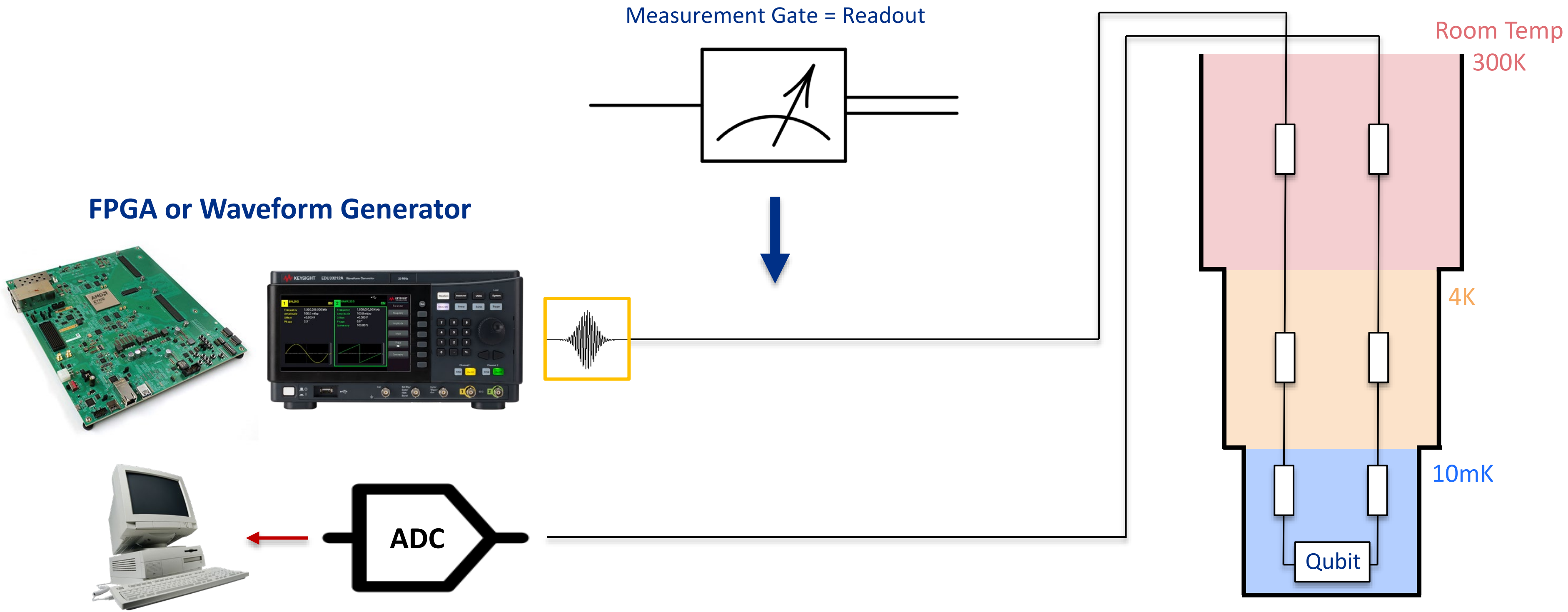
Presenter: Hans Johnson

Authors: Hans Johnson, Nicholas Bornman, Taeyoon Kim, David Van Zanten, Silvia Zorzetti, Jafar Saniie

Introduction

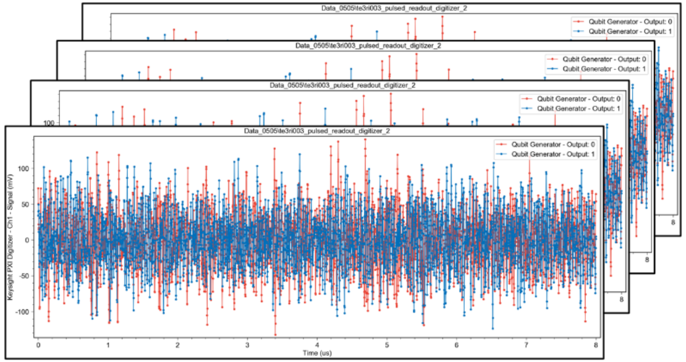
(**L**east **M**eans **S**quared)

- Goal: **Improving Qubit Readout Through Adaptive LMS Filtering!**



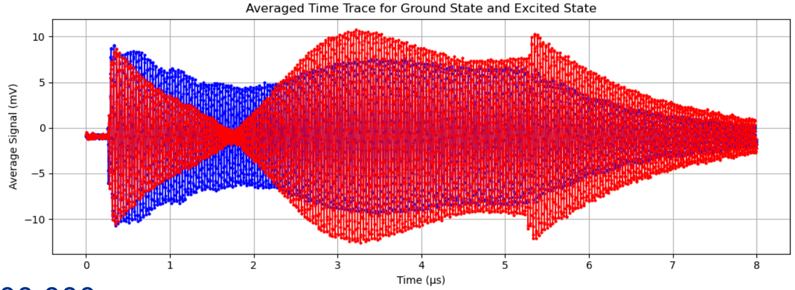
Current Methodology

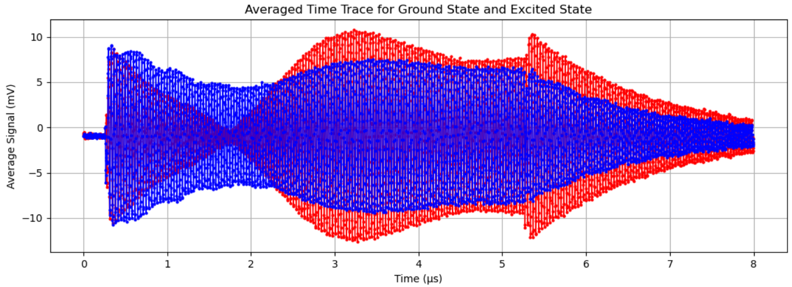
- **Readout pulses are very noisy!**
- The current method to average readout pulses in post processing for qubit readout works for smaller systems. **However, this has limitations as qubit systems scale up.**



Phase Sweep @ ~6.3 GHz for single-shot time trace readout

100,000 averages

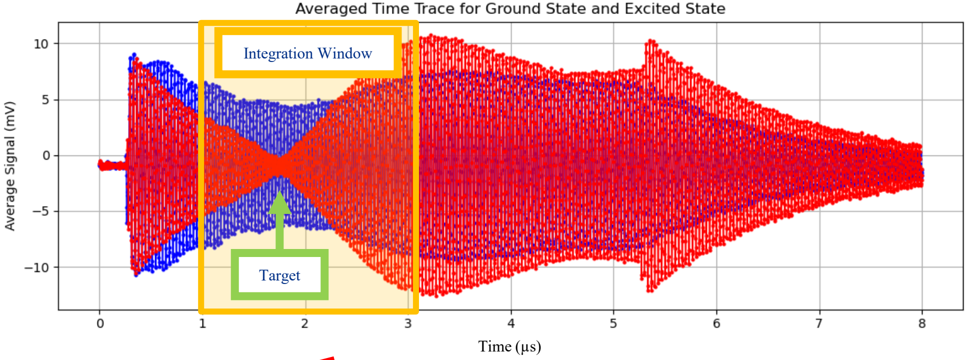




Ground State

Excited State

Qubit Calibration



Ground State

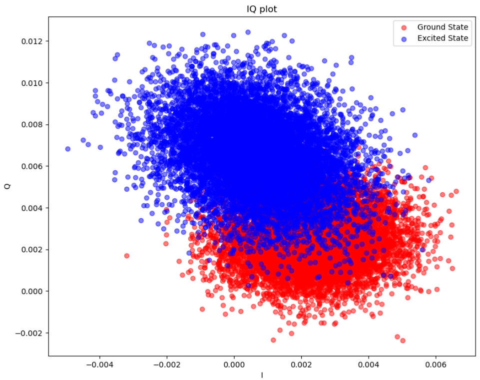
Excited State

Extract I,Q from signal

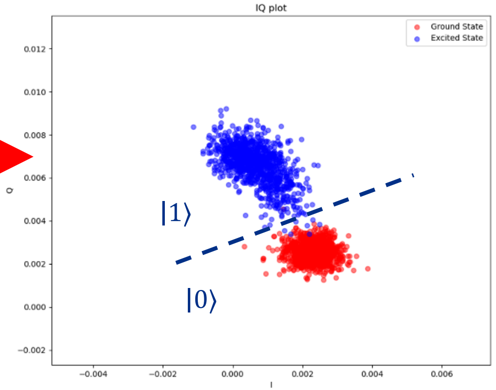
Input signal from digitizer : $s[n] = A\cos(\Omega_{IF} n + \phi)$
Qubit state information is encoded in A, ϕ.
We need to extract A, ϕ (equivalently $I = A\cos(\phi)$, $Q = A\sin(\phi)$)

$$\sum_n s[n]\, e^{-i\,\Omega_{IF} n} = \sum_n A\cos(\Omega_{IF} n + \phi)\ (\cos(\Omega_{IF} n) - i\sin(\Omega_{IF} n))$$
$$= I + i\,Q + (averaged\ to\ zero)$$

1 dot = 10 traces



1 dot = 100 traces



Why Filter Readout Signals?

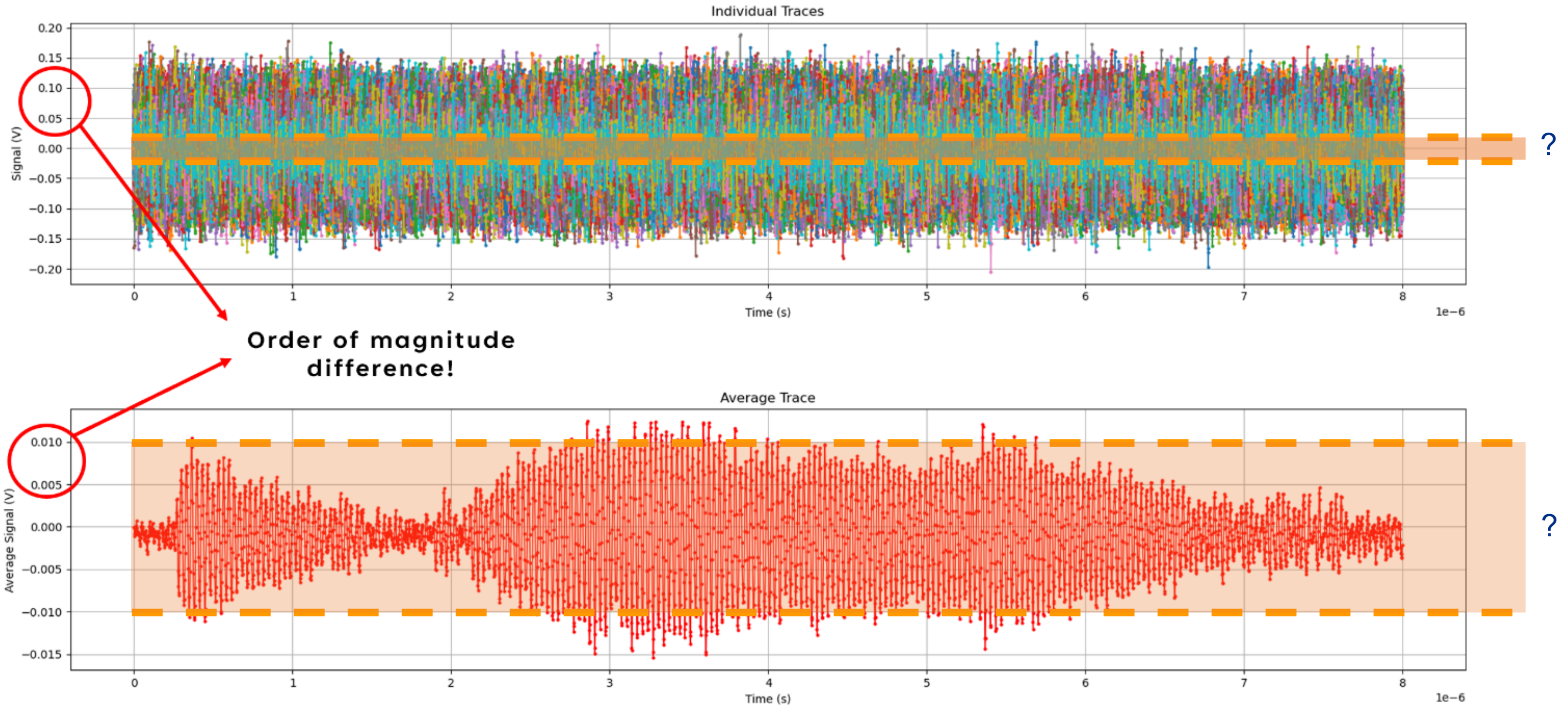
1. Filtered signals = faster convergence to the **center of mass** for the IQ plots.
   - By filtering readout signals on a pulse-by-pulse basis, we reduce the noise in each individual trace before averaging.
   - We can achieve the same level of discrimination with fewer traces or achieve better readout fidelity with the same number of traces.

Larger qubit systems = frequency-multiplexing = increased readout crosstalk…

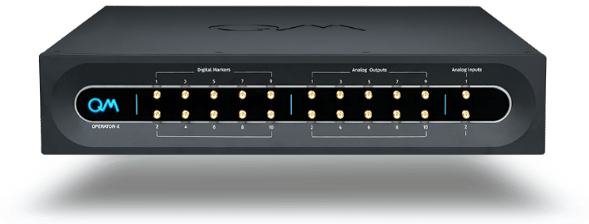
Therefore, faster calibrations are important for larger qubit systems

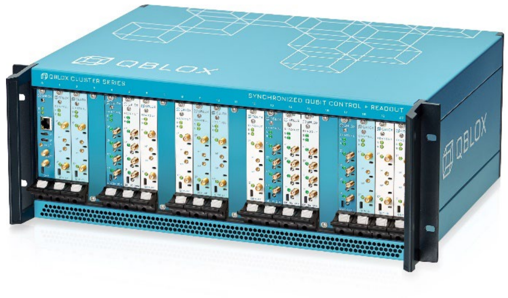
2. Enables us to have a new diagnostic tool for quantum system environment and noise monitoring.
   - Result of using an adaptive filter… more on this later!

Why an LMS Filter?



Commercial Solutions





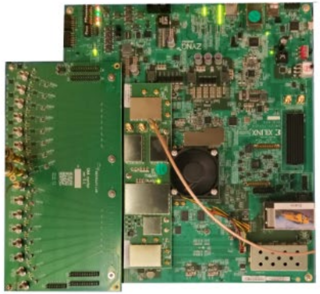
QUANTUM MACHINES

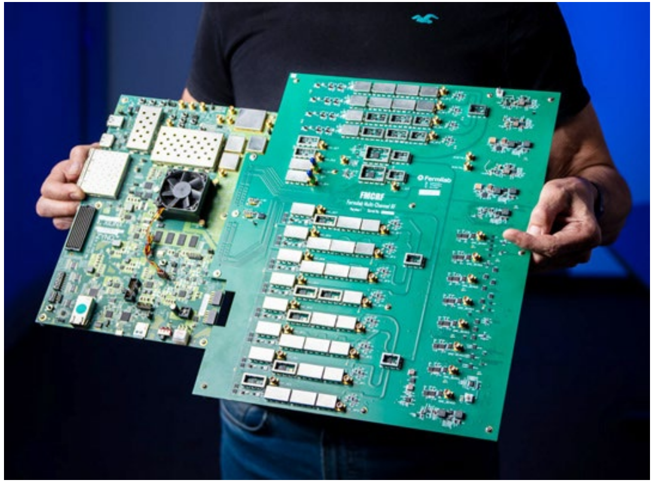
QBLOX

KEYSIGHT TECHNOLOGIES

Open-Source Solutions on FPGA

Lawrence Berkeley National Lab's QubiC



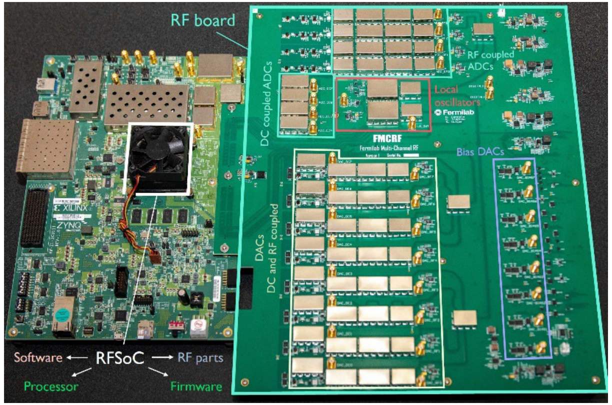


Fermilab's

QICK

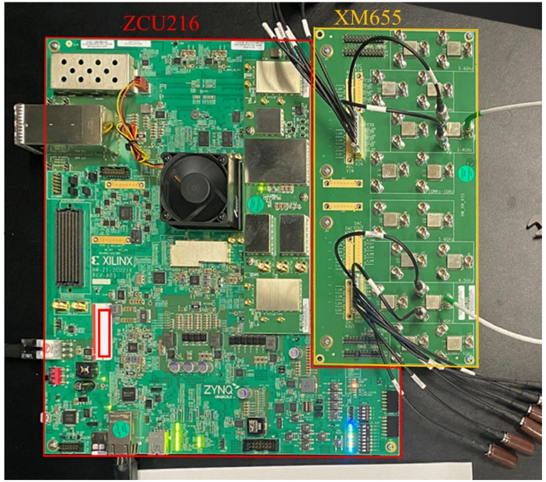
FPGA Quantum Controller

ZCU111



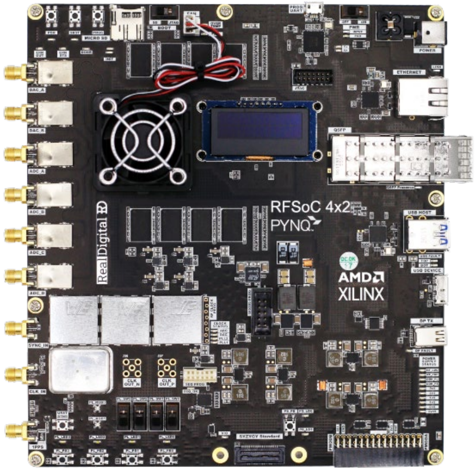
- Gen 1
- Max Control Pulse carrier frequency = 6 GHz
- Eight 14-bit DACs @ 6.5 GSPS
- Eight 12-bit ADCs @ 4.096 GSPS

ZCU216



- Gen 3
- Max Control Pulse carrier frequency = 10 GHz
  - Can push to 12-13 GHz
- Sixteen 14-bit DACs @ 9.85 GSPS
- Sixteen 14-bit ADCs @ 2.5 GSPS
  - Can be combined for 5.0 GSPS

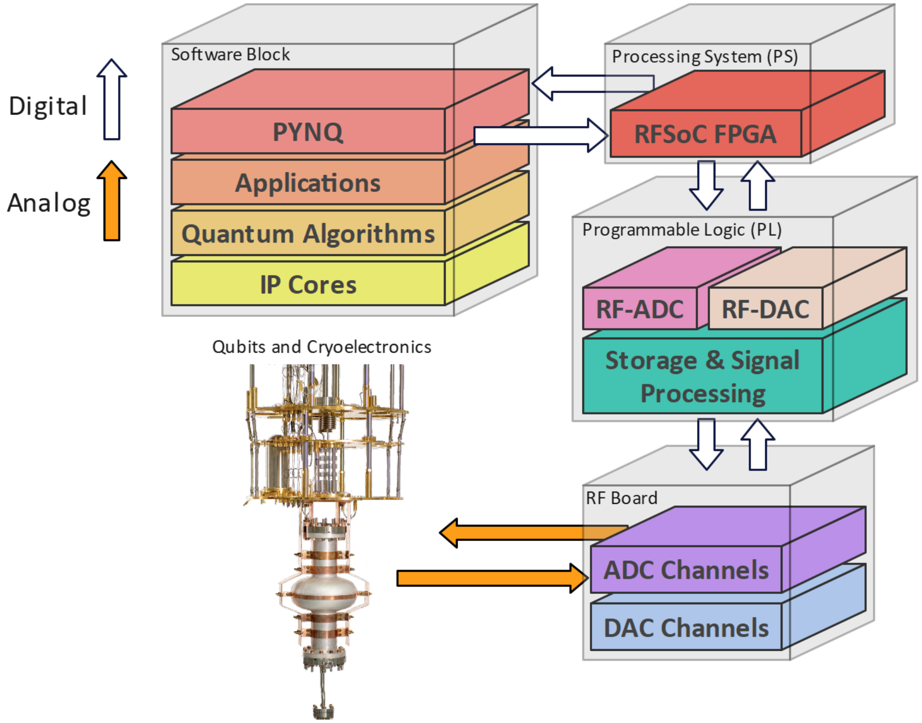
RFSoC 4x2



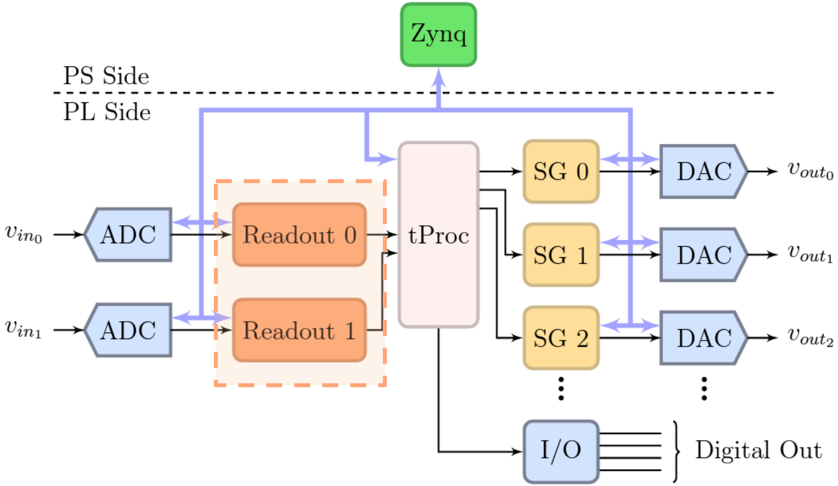
- Gen 3
- Max Control Pulse carrier frequency = 10 GHz
  - Can push to 12-13 GHz
- Two 14-bit DACs @ 9.85 GSPS
- Four 14-bit ADCs @ 5.0 GSPS

Firmware and Readout Chain Overview

Block Diagram of System



Block Diagram of QICK Firmware



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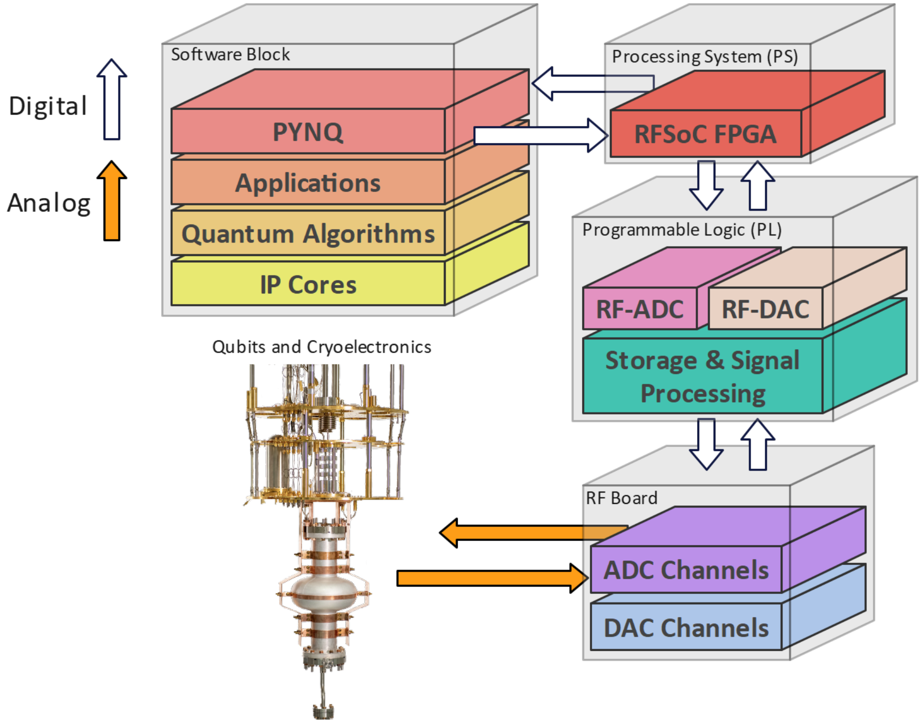
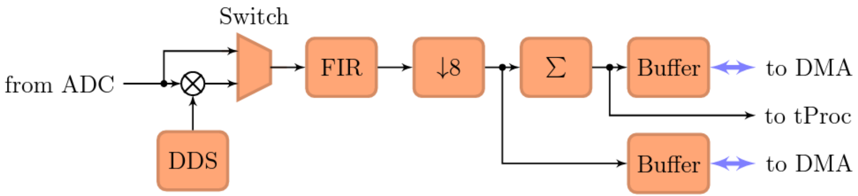
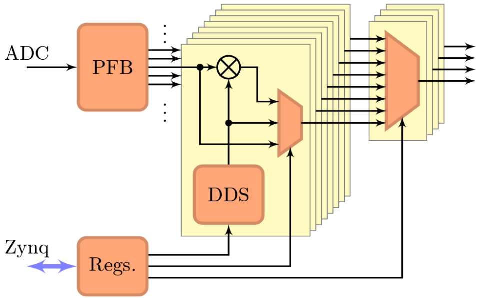


QICK Readout Chain (v1)

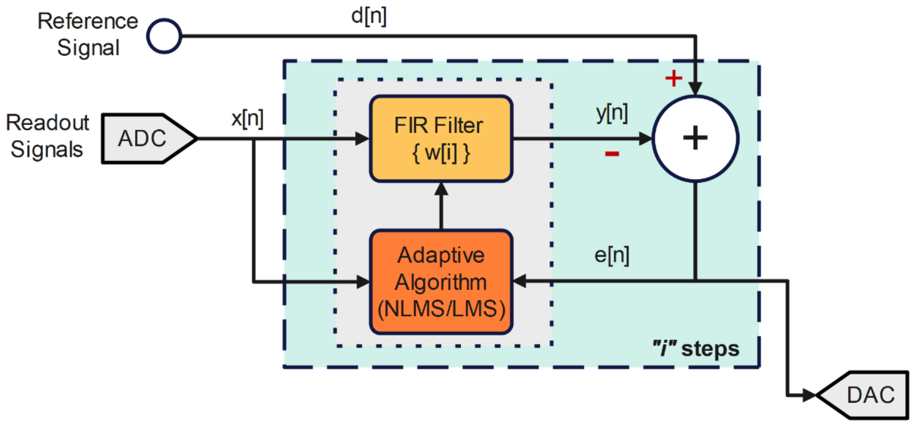


QICK Readout Chain (v2 = multiplexed)



SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

LMS Filter



- n: Sample index
- i: Tap index within the filter's impulse response
- x[n]: Noisy input signal
- d[n]: Desired/reference signal
- w[i]: Weights = adjustable weights of LMS
- y[n]: Output signal (estimated signal or noise estimation) at time index [n]
- e[n]: error signal (difference between desired and output signals) at time index [n]
- μ: Learning rate of LMS algorithm
- N: number of taps in the filter, dictating the number of past input samples used by the filter

$$w[i+1] = w[i] + \mu * e[n] * x[n-i] \quad (1)$$

$$y[n] = \sum_{i=0}^{N-1} w[i] * x[n-i] \quad (2)$$

$$e[n] = d[n] - y[n] \quad (3)$$

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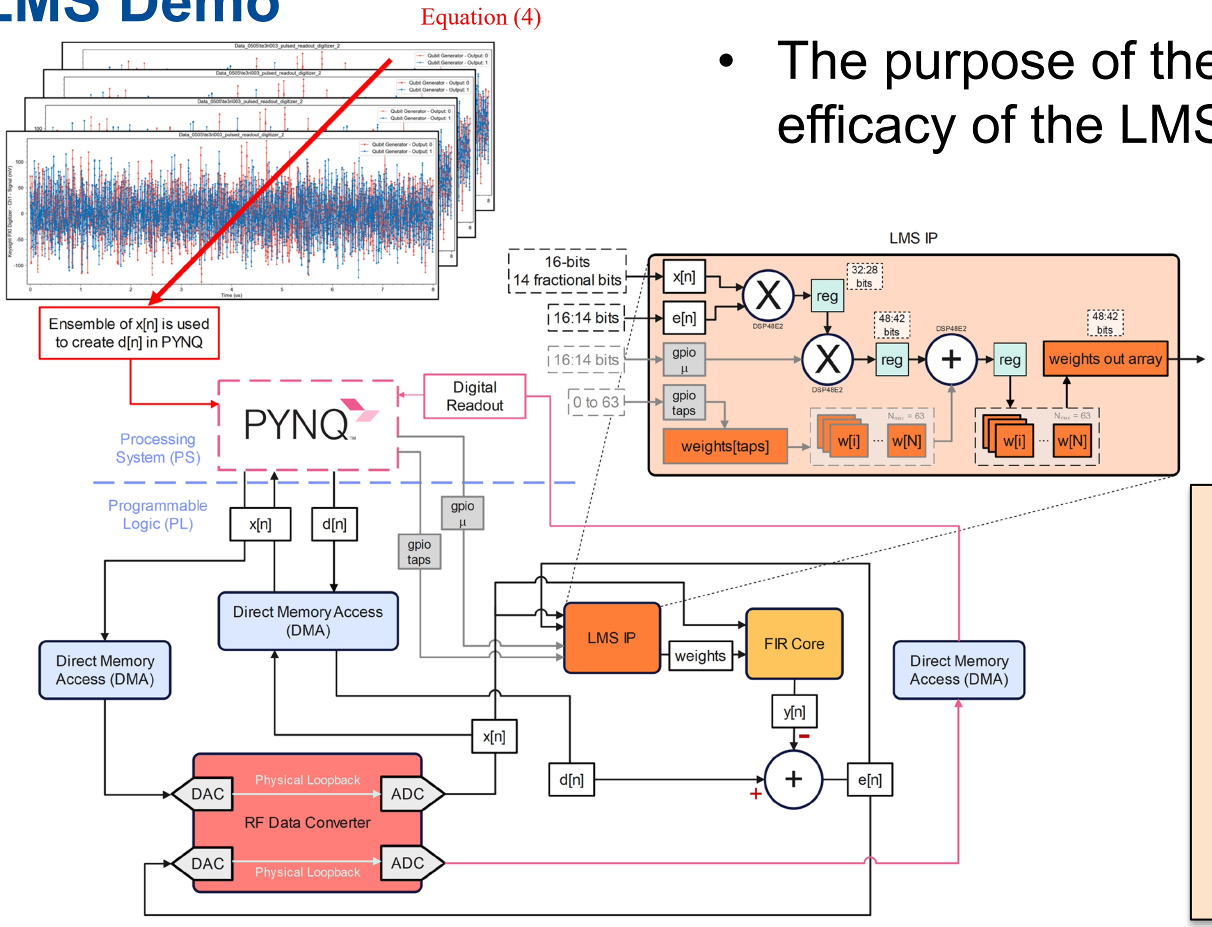
LMS Demo

- The purpose of the demo was to prove the efficacy of the LMS algorithm on FPGA.



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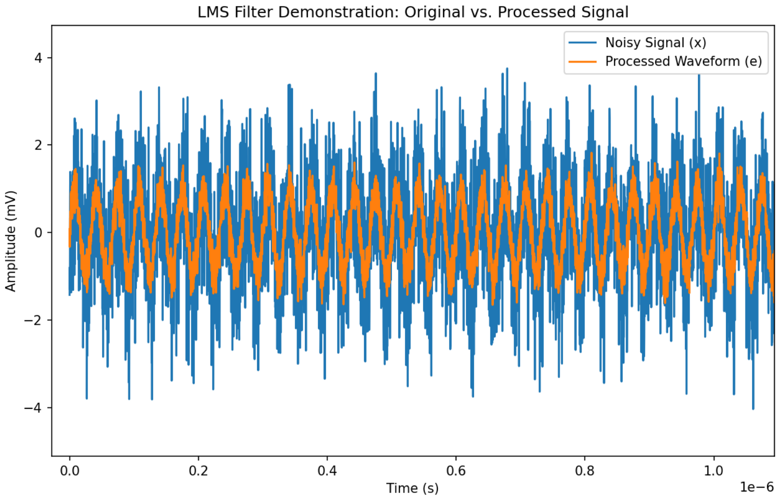
$$e[n] = d[n] - y[n] \quad (3)$$

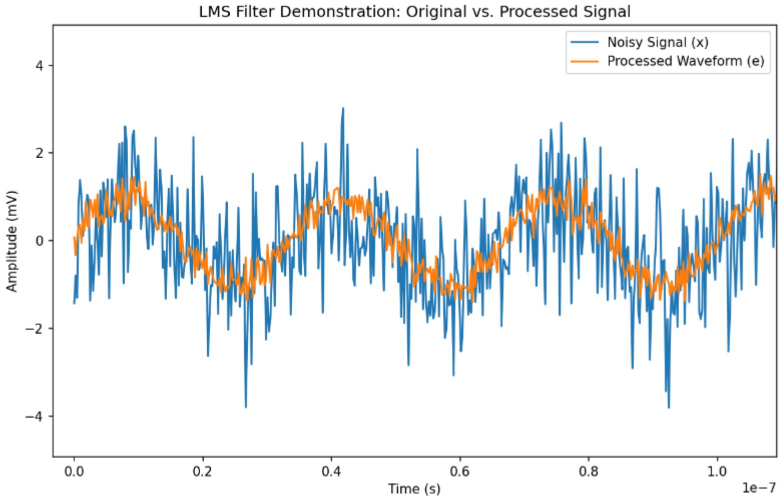
$$d_{new}[n] = \frac{(d_{old}[n] * i) + x_{new}[n]}{i+1} \quad (4)$$

Results: LMS Filter Demonstration on FPGA

- 30 MHz, 8 μs pulse with white-noise standard deviation of 1
- Learning rate = 0.0006
- Taps = 64
- Filter was allowed to execute over 10 pulses
- 10^{th} pulse/iteration for both ‘x’ and ‘e’ are shown



1 μs window



0.1 μs window

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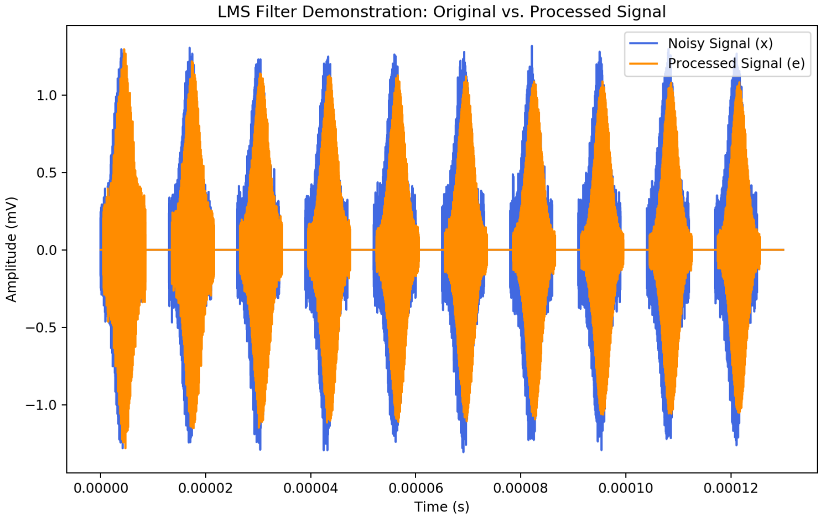
Results: LMS Filter Demonstration on FPGA

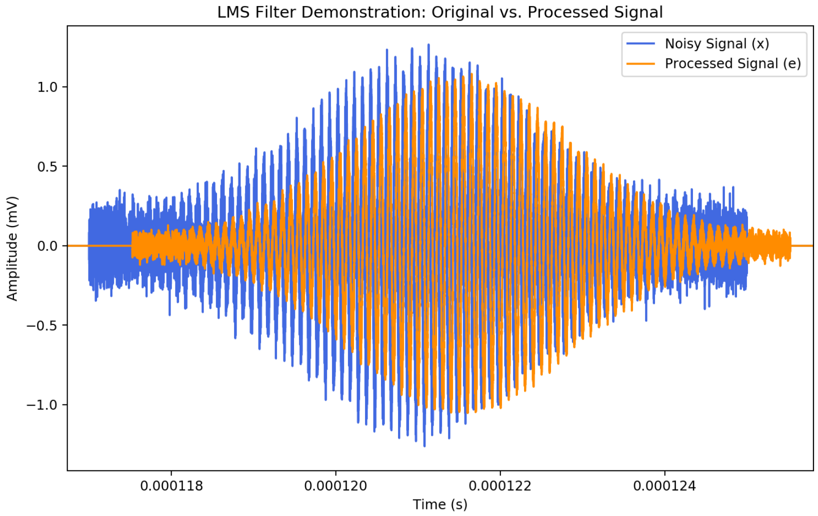
- 30 MHz, 8 µs gaussian chirp with white-noise standard deviation of 1, 5 µs in between pulses
- Learning rate = 0.0006
- Taps = 64
- Filter was allowed to execute over 10 pulses

Latency = 527.66 ns*

Took 15-20 minutes to load



130 µs window



13 µs window (pulse 10)

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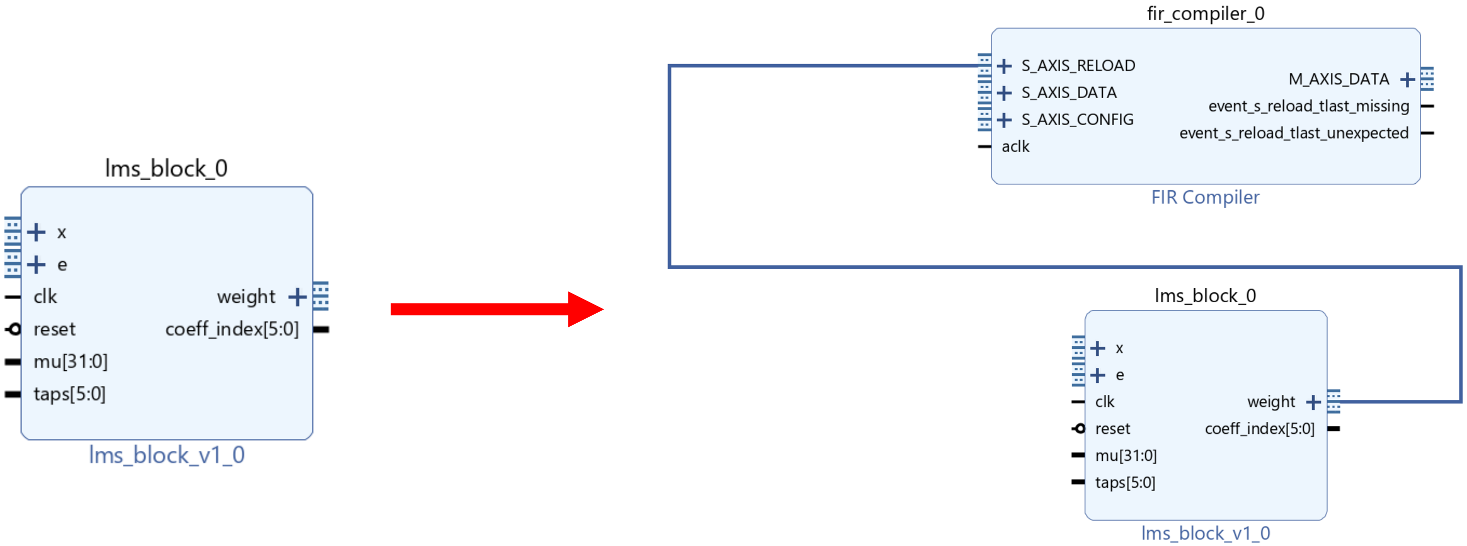
Packaged Logic Blocks



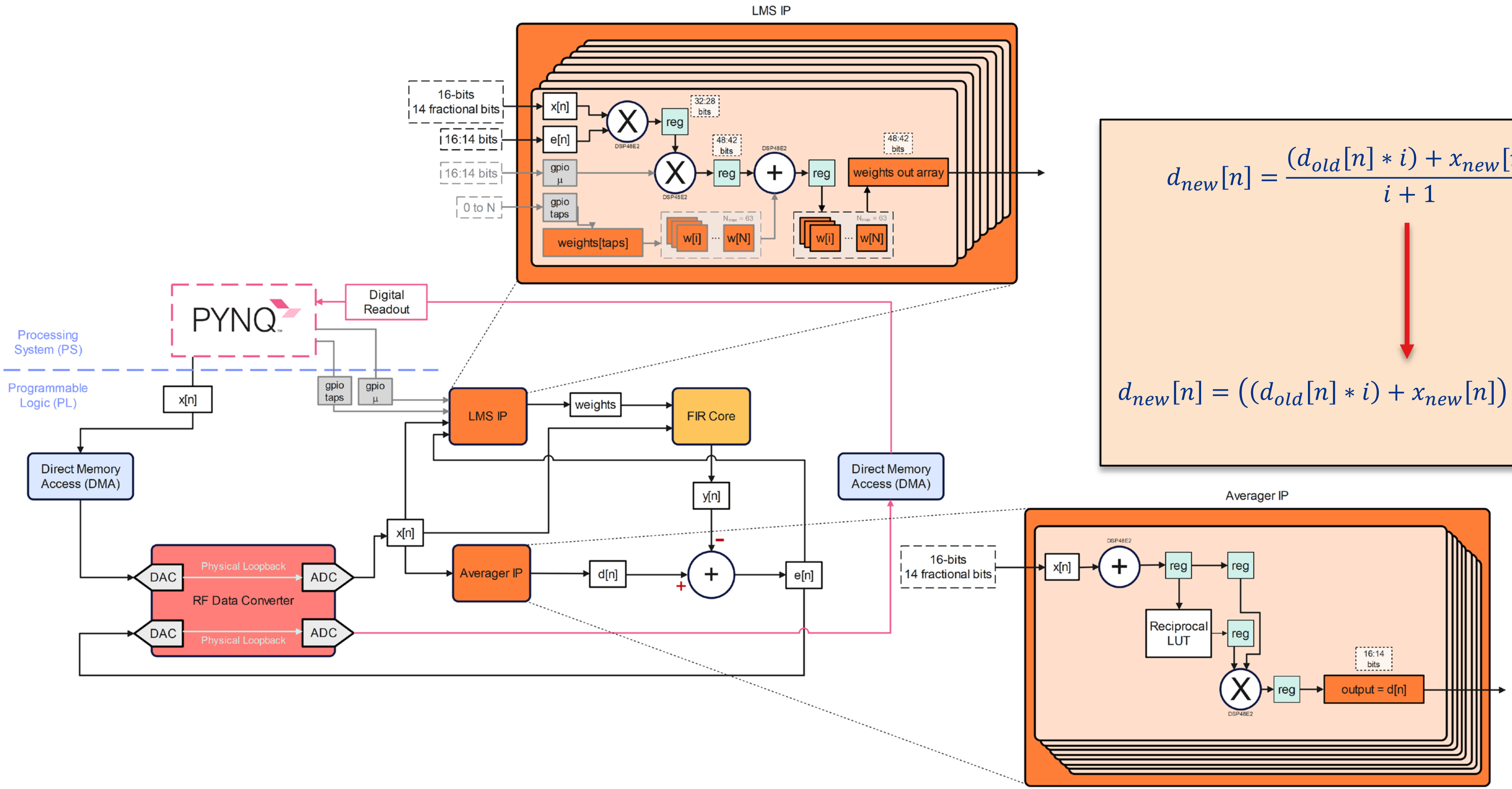
- Packaged logic block containing weight update LMS algorithm
- LMS logic block sends updated weights to FIR compiler

LMS Demo Hardware Resources

TABLE 3.1: RESOURCE UTILIZAITON FOR LMS DEMO ON RFSOC 4X2

Resource	Utilization	Available	Utilization (%)
LUT	21,964	425,280	**5.16%**
LUTRAM	3,529	213,600	**1.65%**
FF	33,992	850,560	**4.00%**
BRAM	133	1080	**12.31%**
DSP	10	42,732	**0.23%**
BUFG	7	696	**1.01%**
MMCM	1	8	**12.5%**

LMS Demo: Current Work



$$d_{new}[n] = \frac{(d_{old}[n] * i) + x_{new}[n]}{i+1} \quad (4)$$

$$d_{new}[n] = \left((d_{old}[n] * i) + x_{new}[n]\right) * \left(\frac{1}{i+1}\right) \quad (5)$$

Research Objectives & Future Work

1. **Develop an Adaptive LMS Filter**: Implement an adaptive Least Mean Squares (LMS) filter on an RFSoC FPGA-based control board to dynamically fine-tune the readout signals of qubits.

2. **Integrate and Tune the Filter with the QICK Platform**: Deploy the adaptive filter onto the open-source Quantum Instrumentation Control Kit (QICK) platform to enhance its capabilities for quantum experiments.

3. **Evaluate and Enhance Qubit Readout Fidelity**: Evaluate the performance of the adaptive filter in comparison to the current methodology of ensemble averaging and timing to demonstrate its efficiency and effectiveness in improving readout signal clarity.

4. **Characterize the Noise Profile**: Utilize the adaptive LMS filter to conduct a detailed analysis and characterization of the noise affecting readout signals in both 2D and 3D QPU experiments.

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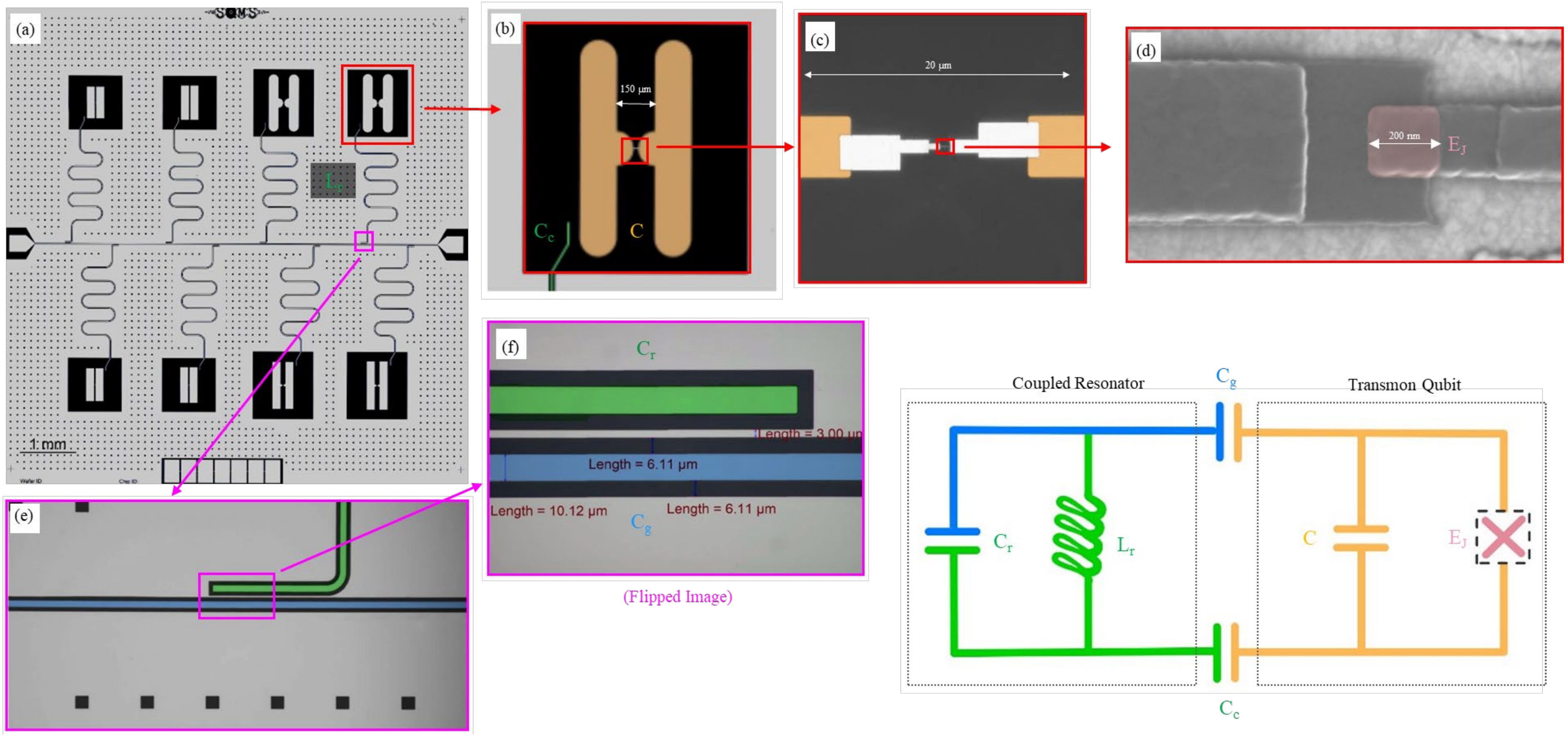
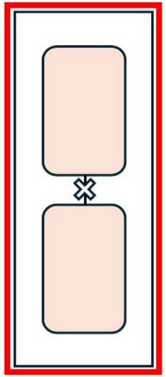
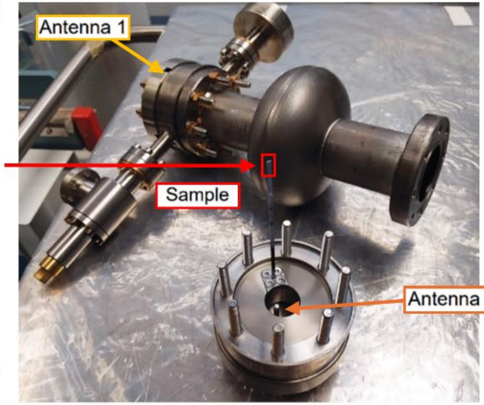
2D QPU Platform

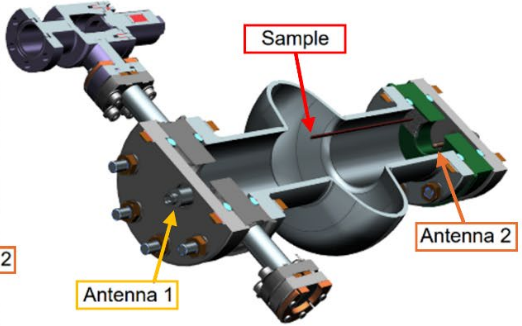


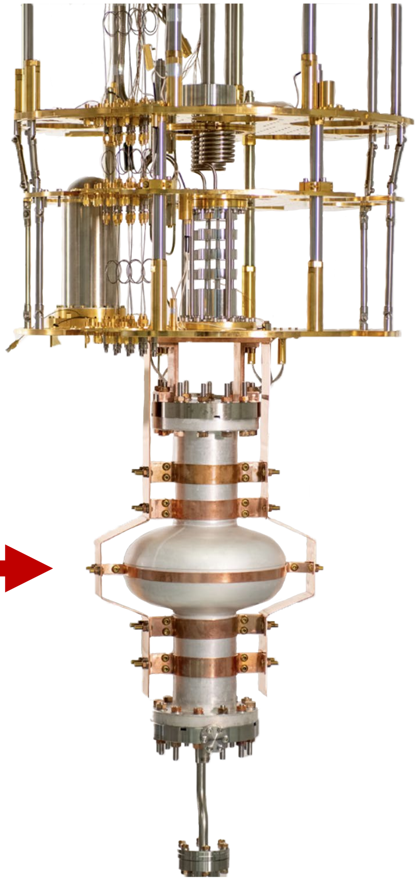
3D QPU Platform

- **3D QPU** = Superconducting qubits with SRF Cavities









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Characteristic Equations of Noise

- These equations are general equations for the noise power spectral density derived to fit the context of readout signals
- As the main effect of this research is to improve the Signal-to-Noise Ratio (SNR), the equations for SNR can give us insight as to what the sources of noise are

Fourier Transform

$$S(\omega) = 2 \int_{-\infty}^{+\infty} d(t - t') \frac{e^{i(\omega-\omega')(t-t')}}{2\pi} [\langle I(t)I(t')\rangle - \langle I(t)\rangle\langle I(t')\rangle] \quad (6)$$

Contribution from all time differences

Autocorrelation function

$$SNR(\omega) = \frac{P_{signal}(\omega)}{S(\omega)} \quad (7)$$

$$SNR(t) = \frac{I_{signal}^2(t)}{\sigma_I^2(t)} \quad (8)$$

$$P_{signal}(\omega) = \left|F\{I_{signal}(t)\}\right|^2 \quad (9)$$

$$P_{signal}(t) = I_{signal}^2(t) \quad (10)$$

Conclusion

- Foundational work is complete, implementation is underway
- Results will be significantly contributing to multi-qubit experiments when complete
    - Latency needs to be measured properly for new LMS filter on hardware, and new design needs more tests before integrating with QICK!

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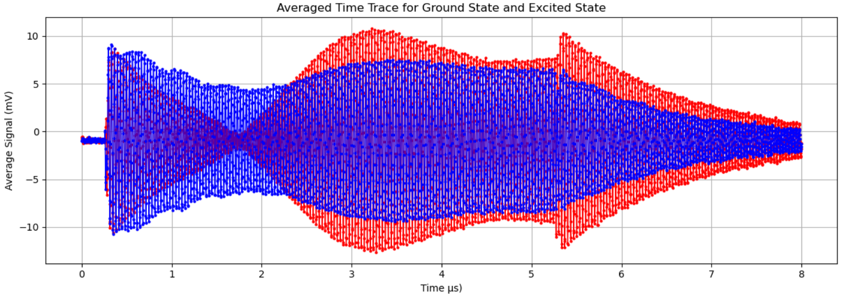
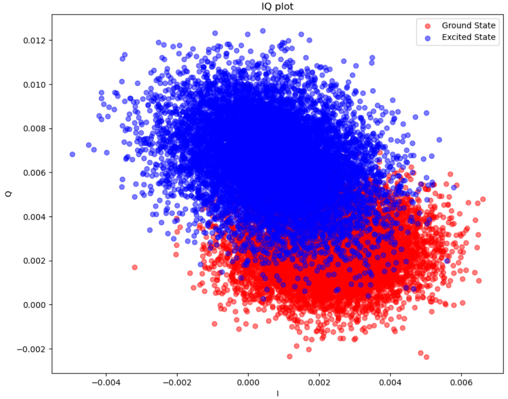
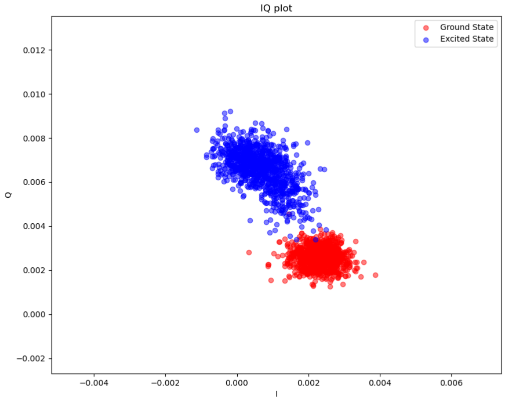
Effect of LMS Filter on Readout calibration



Get this result in
<100,000 traces

Achieve this in the same
number of averages!





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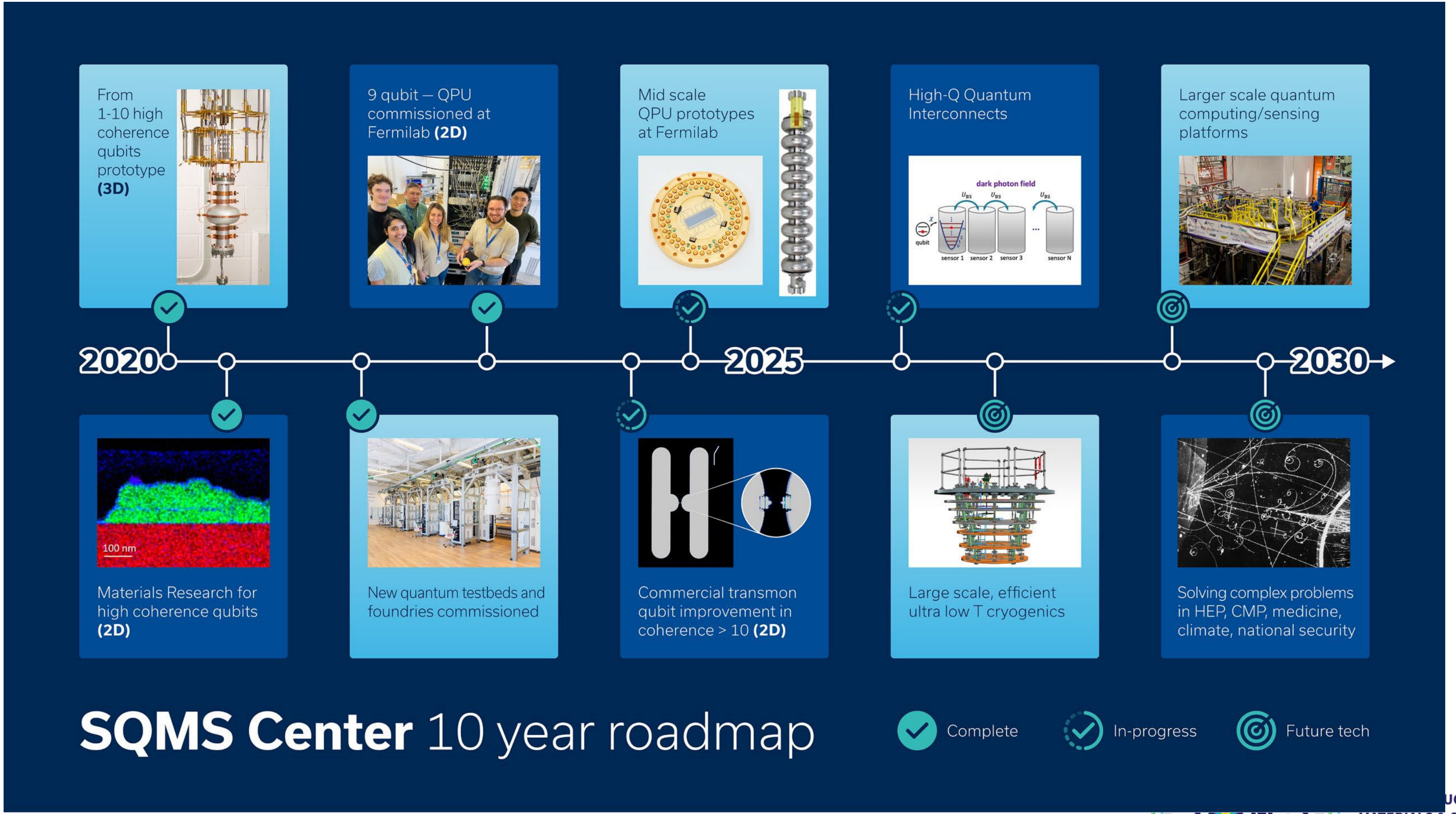
Best Superconducting Coherence Times

TABLE 2.1: BEST 2D SINGLE QUBIT COHERENCE TIMES

Group	*T_1 (µs)*	*Freq. (GHz)*	*Substrate*	*Primary Material*	*Year*	*Ref.*
SQMS/Rigetti	**~600**	**4 – 6**	**Sapphire**	**Ta/Nb, dry etch**	**2024**	**[4]**
SQMS	451	4.5 – 5	Sapphire	Ta/Nb, dry etch	2023	[4] (preprint)
Yu (China)	503	3.8 – 4.7	Sapphire	Ta, dry etch	2022	[58]
IBM	340	~ 4	Silicon	Nb, wet etch	2021	[87]
Houck/Princeton	360	3.1 – 5.5	Sapphire	Ta, wet etch	2021	[57]
IBM	234	3.808	Silicon	Al, dry etch	2021	[88]
Schuster	126	4.749	Sapphire	Nb, Fl etch	2021	[89]
Rigetti	133	3.8 – 4.2	Silicon	Nb	2019	[90]

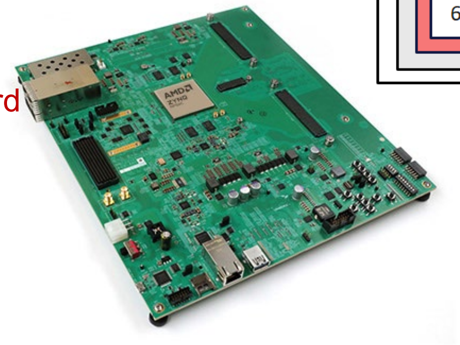
Transmon Qubit Timeline - SQMS

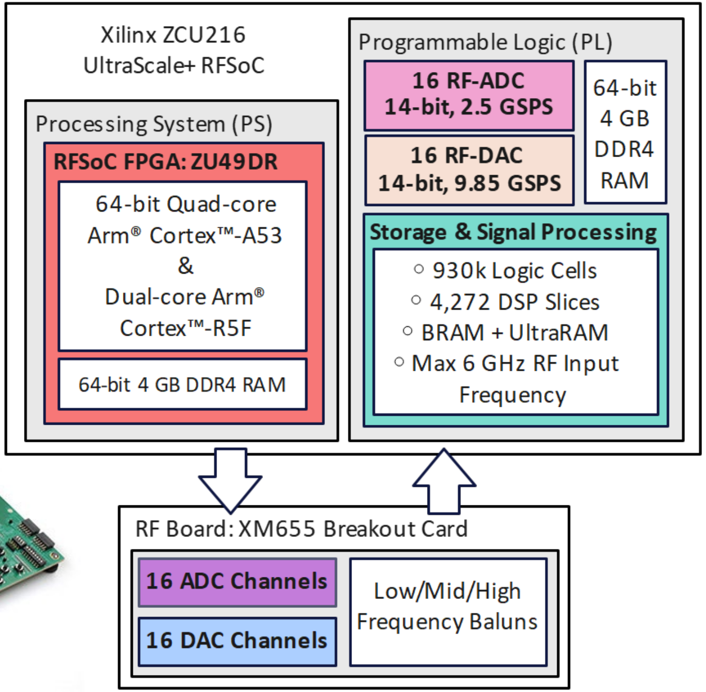


FPGA Controls

- Single RFSoC FPGA is used for controller of 2D qubits.
- 3D QPU uses benchtop control stack for now due to power limitations on ZCU216

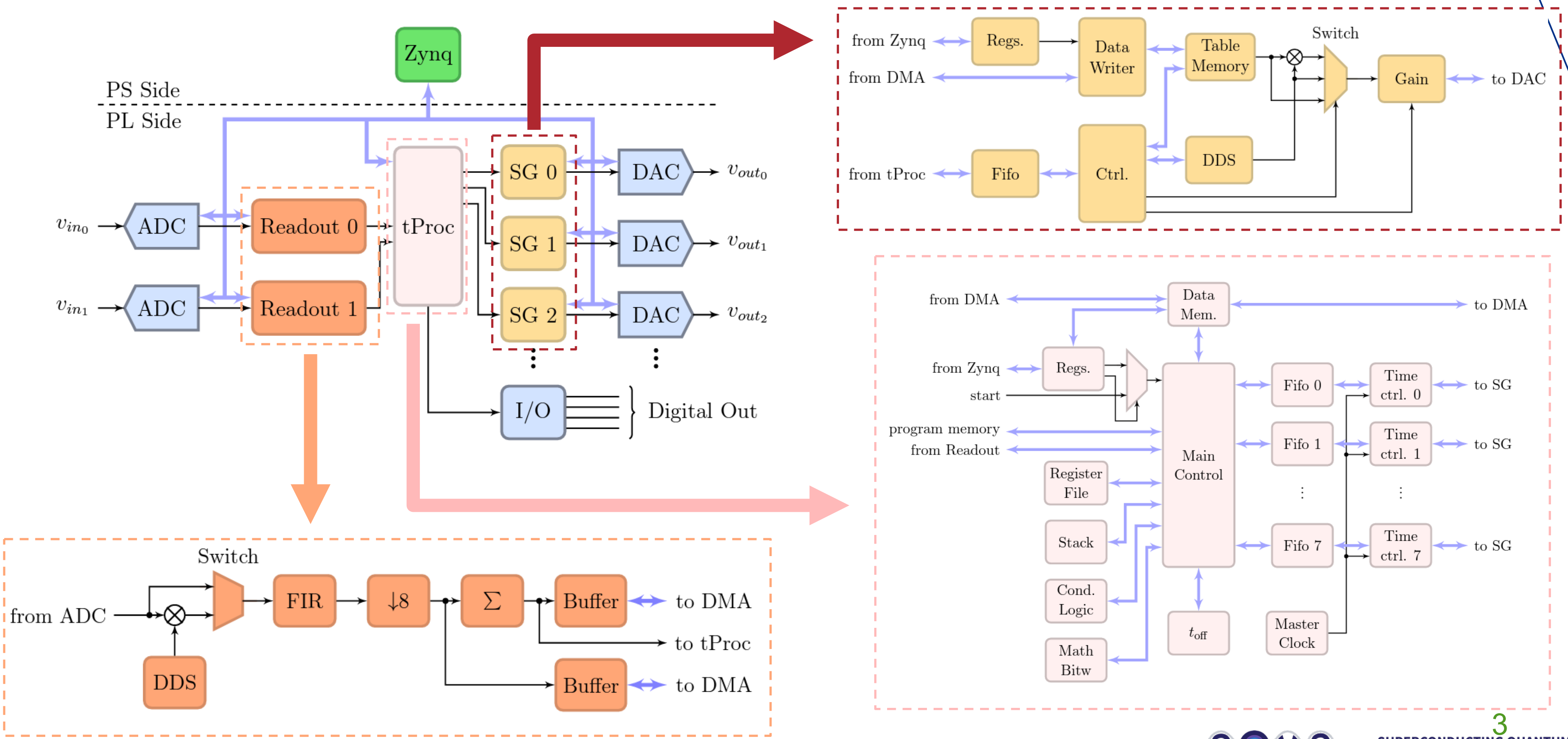
1. Xilinx ZCU111 RFSoC UltraScale+ FPGA (*Gen 1*)
2. Xilinx RFSoC 4x2 UltraScale + FPGA (*Gen 3*)
3. **Xilinx ZCU216 RFSoC UltraScale+ FPGA** (*Gen 3*)
    - XM655 Breakout Card or custom card
    - 16 RF-ADC: 14-bit, 2.5 GSa/s (interleaved)
    - 16 RF-DAC: 14-bit, 9.85 GSa/s



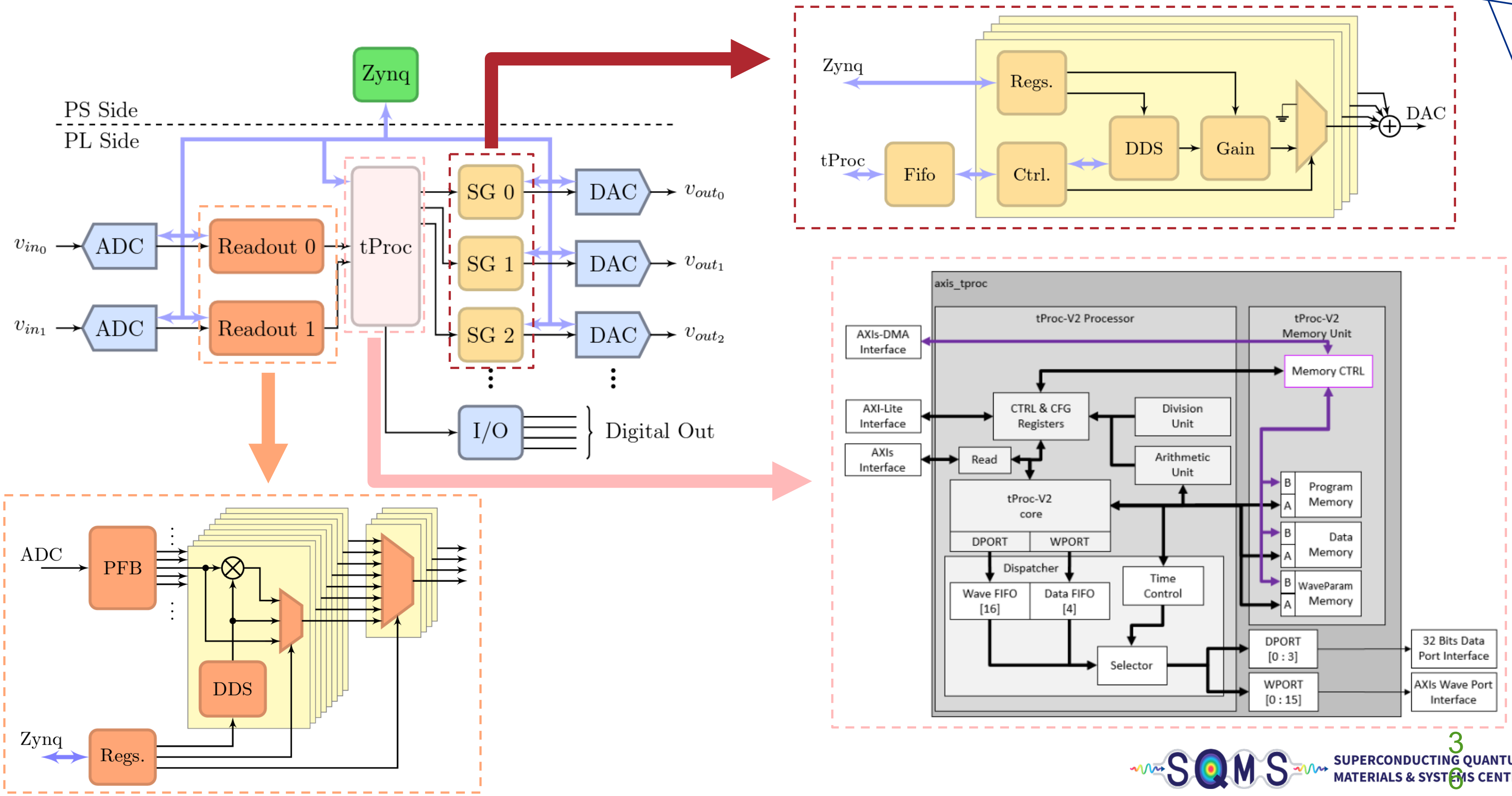


- Quantum Instru ... Control Kit (**QICK**)

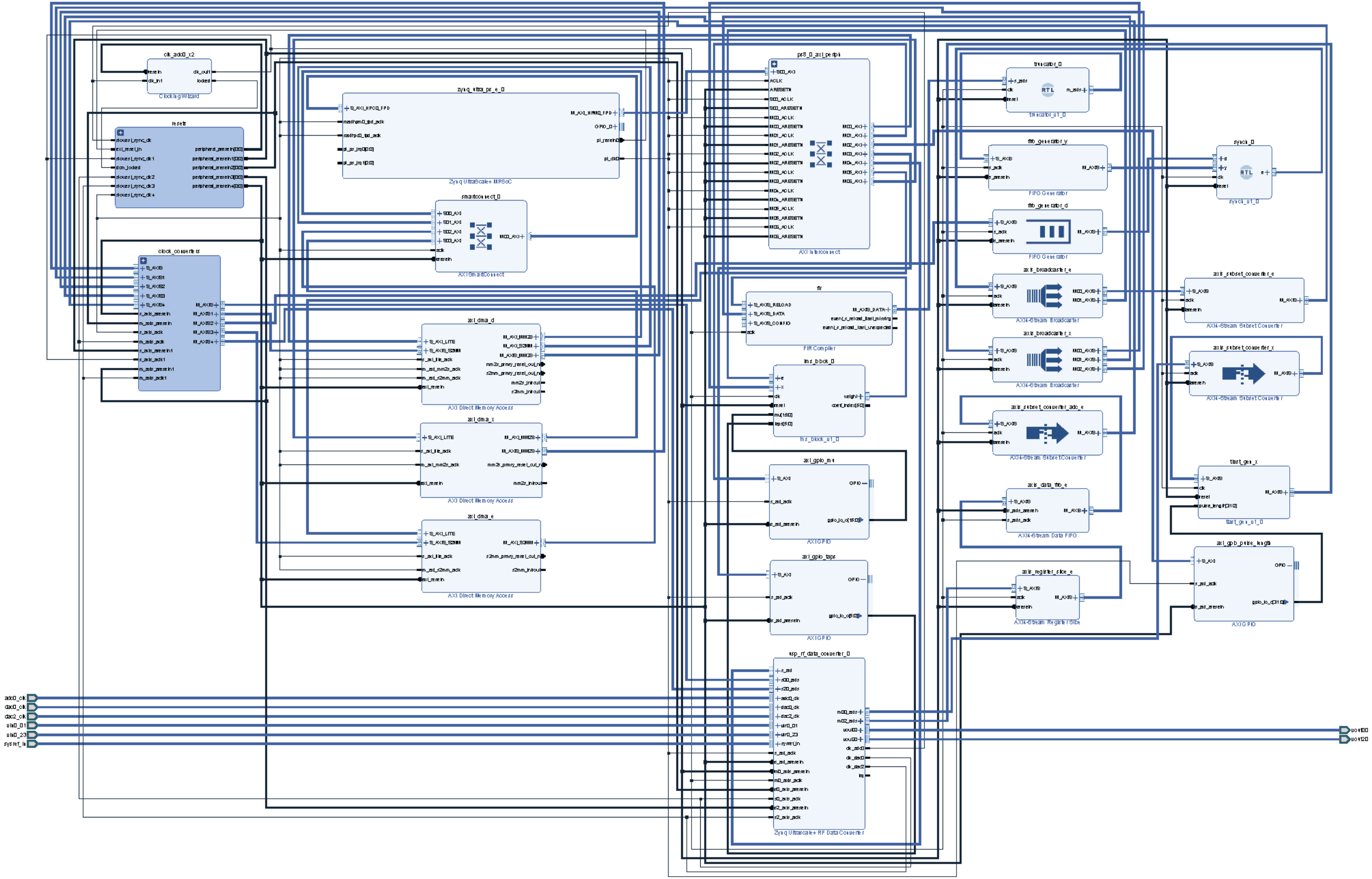
QICK Firmware v1



QICK Firmware v2

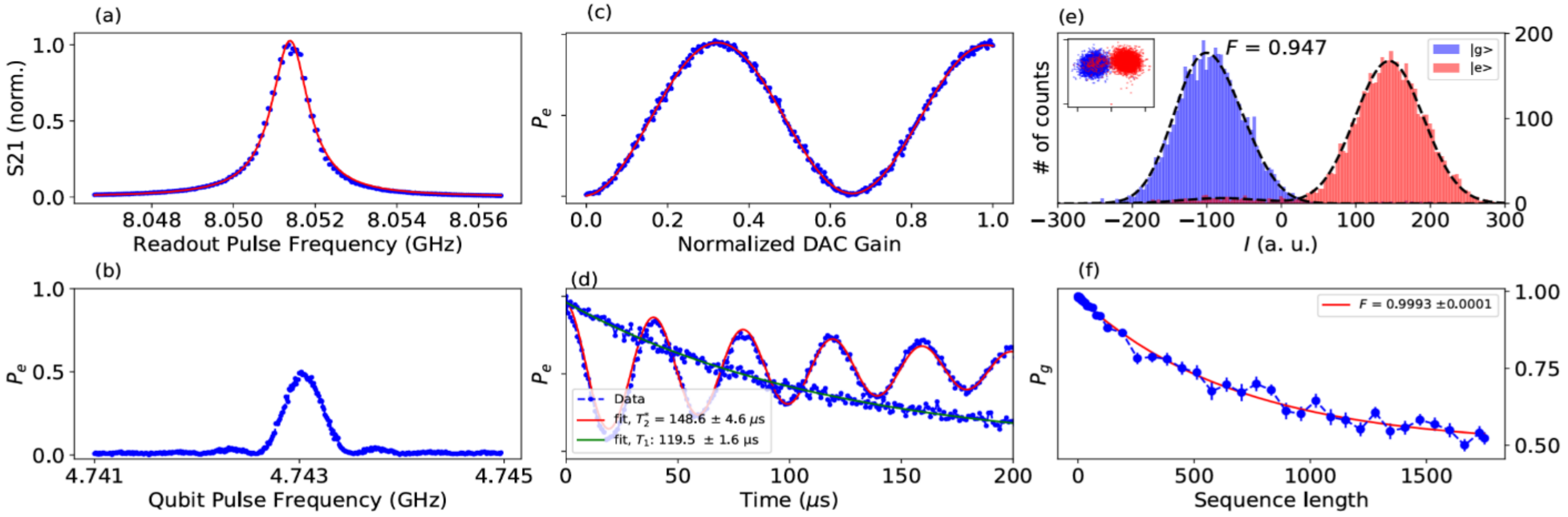


LMS Demo Block Design



Qubit Characterization Experiment

- Qubit calibration and measurement on QICK
- This is a standard process for determining the ground/excited state for a qubit, and then determining T_1 and T_2 measurements for a qubit
- The goal is to do this with the LMS filter active and then compare results!



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