Towards Quantum Feedback using Field Programmable Gate Arrays

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Motivation

- Real-time tracking of the evolution of a quantum state
- Stabilization of a quantum system using feedback protocols

Hardware Requirements

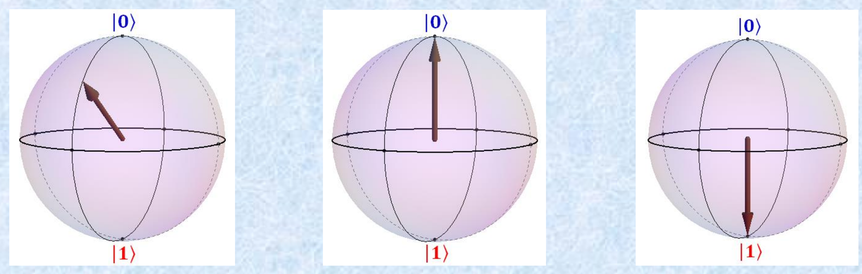
- Typical relaxation time of a qubit in cQED: 10 - 30 μs
- Capability of real-time Digital Signal Processing: FPGA

Quantum Measurements: Strong vs. Weak

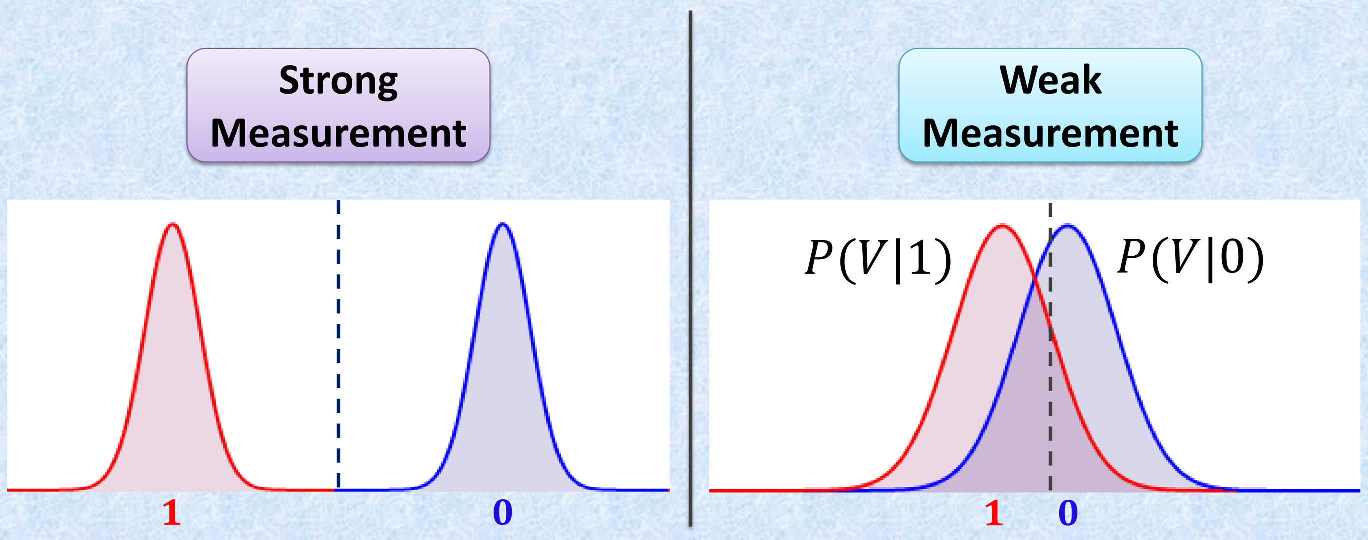
- Two levels system:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

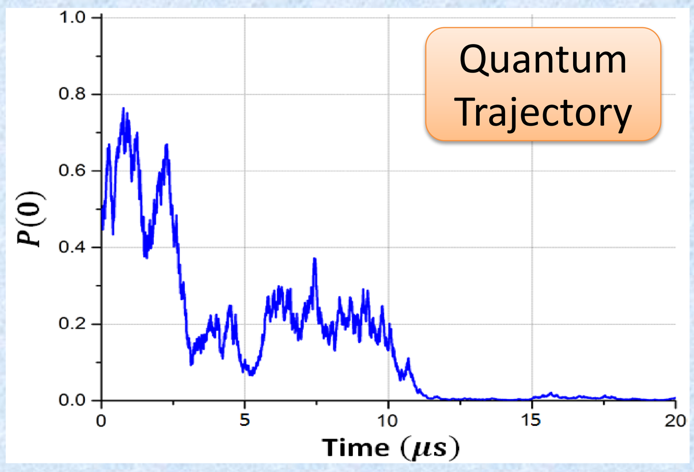


$P(0) \propto |\alpha|^2$ $\quad$ $P(1) \propto |\beta|^2$

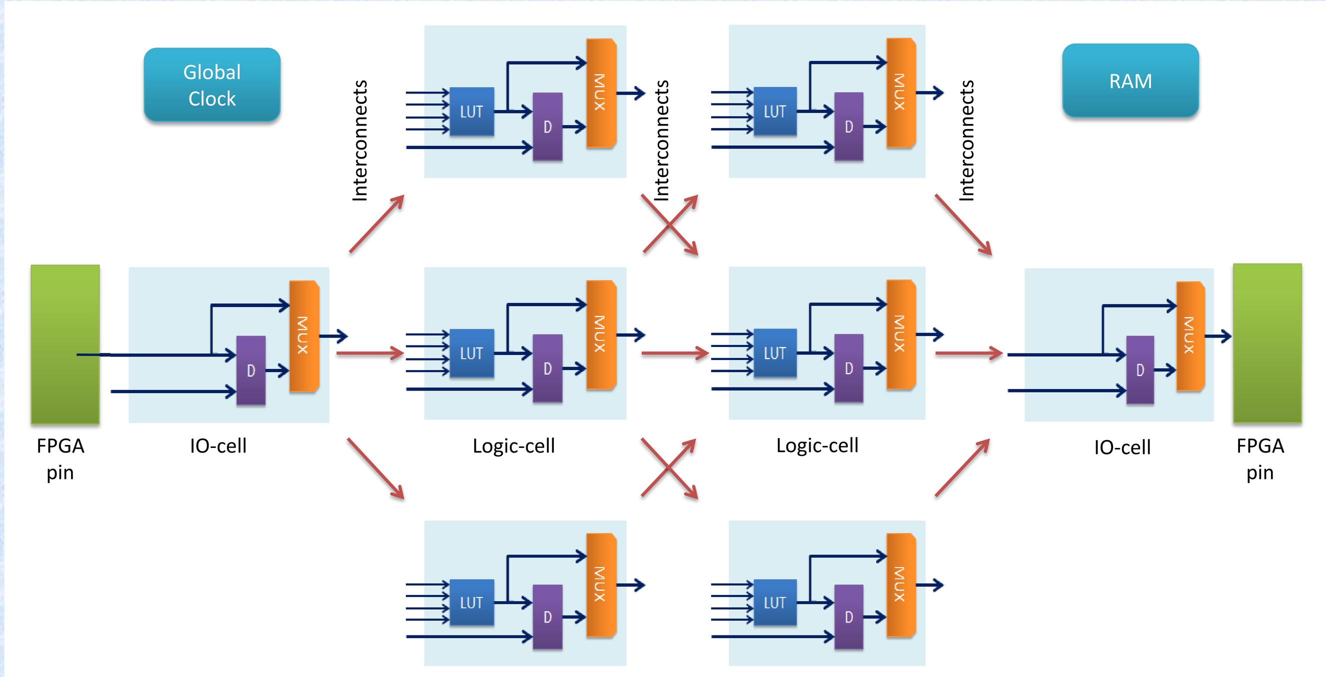


Bayes' Theorem:
$$P(0|V) = \frac{P(0)P(V|0)}{P(V)}$$

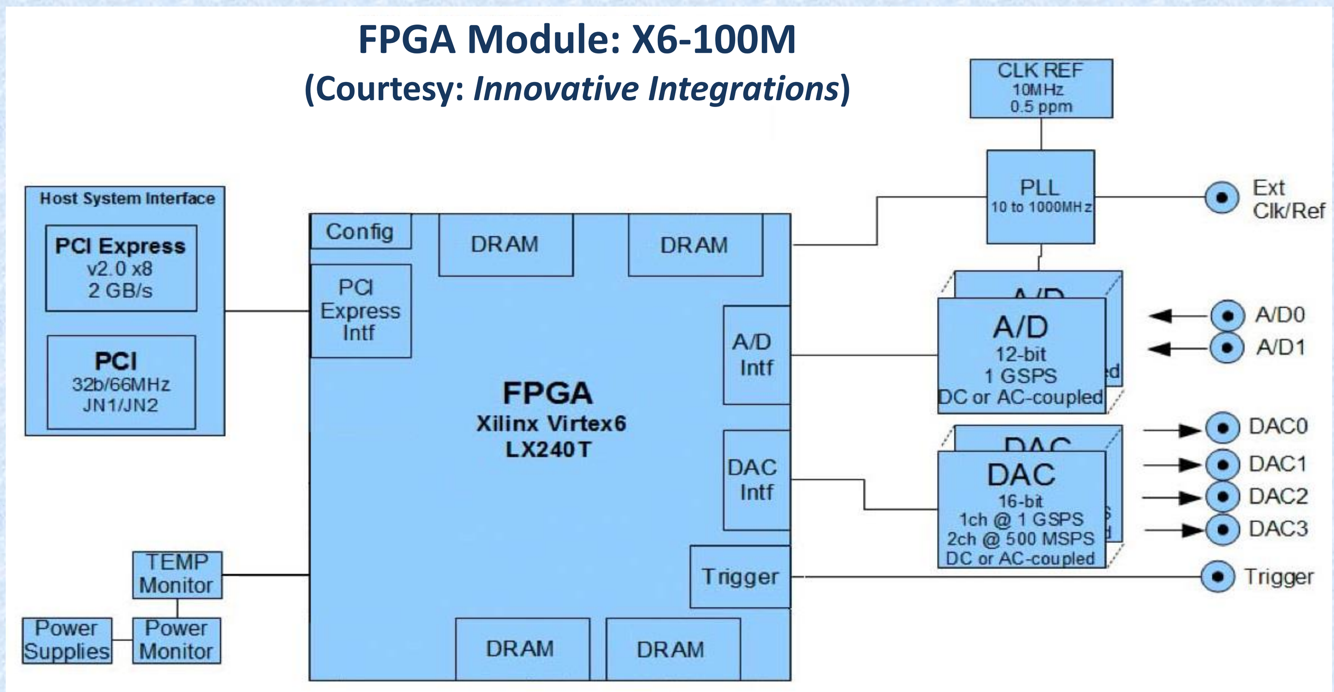
- Each weak measurement causes random perturbation to the system and reveals partial information
- Perfect reconstruction of the new state is possible if there is no loss of signal
- The state is constantly updated [1] by performing repeated measurements to obtain the Quantum Trajectory
- A sequence of weak measurements is equivalent to a strong measurement

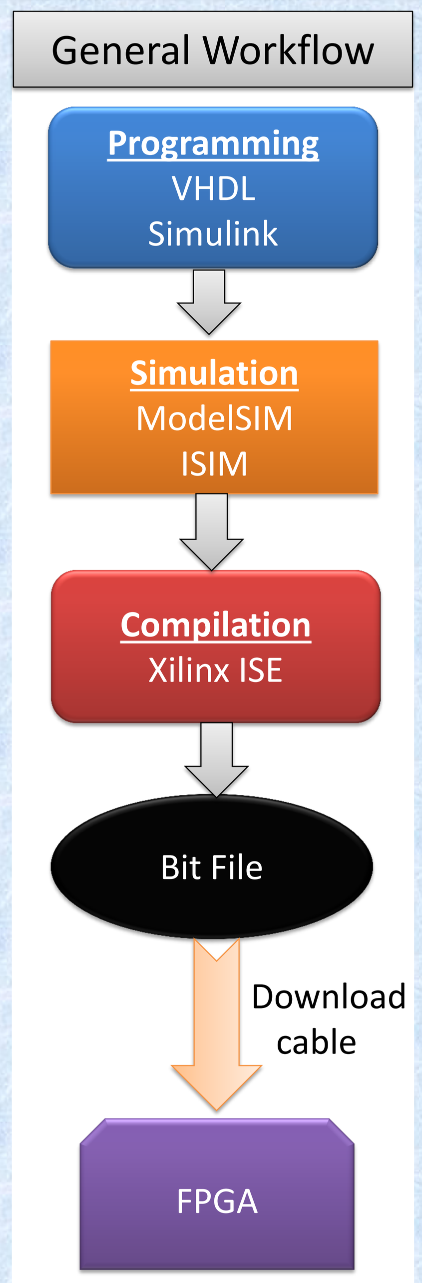


Field Programmable Gate Arrays



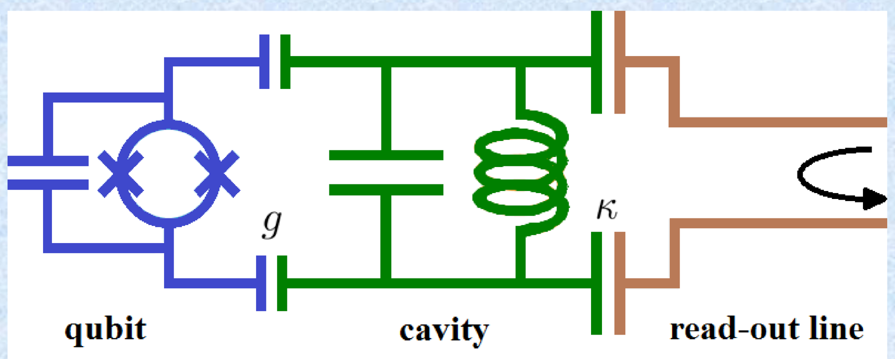
- Reconfigurable any number of times each time with a different logic
- Once programmed, runs at hardware speed without any interruption





- 241,142 Logic cells
- 200 MHz clock
- 720 user I/O pins
- 14,976 Kb Block RAM

Circuit-QED Architecture and Measurement Scheme



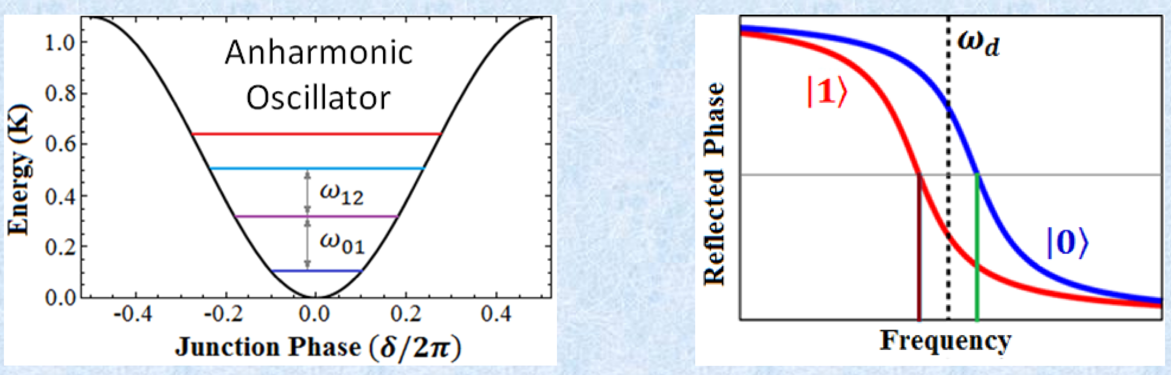
- Jaynes-Cummings Hamiltonian [2]

$$H_{JC} = \frac{1}{2}\hbar\omega_{01}\hat{\sigma}_z + \hbar\omega_{\rm cav}\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) + \hbar g\left(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-\right)$$

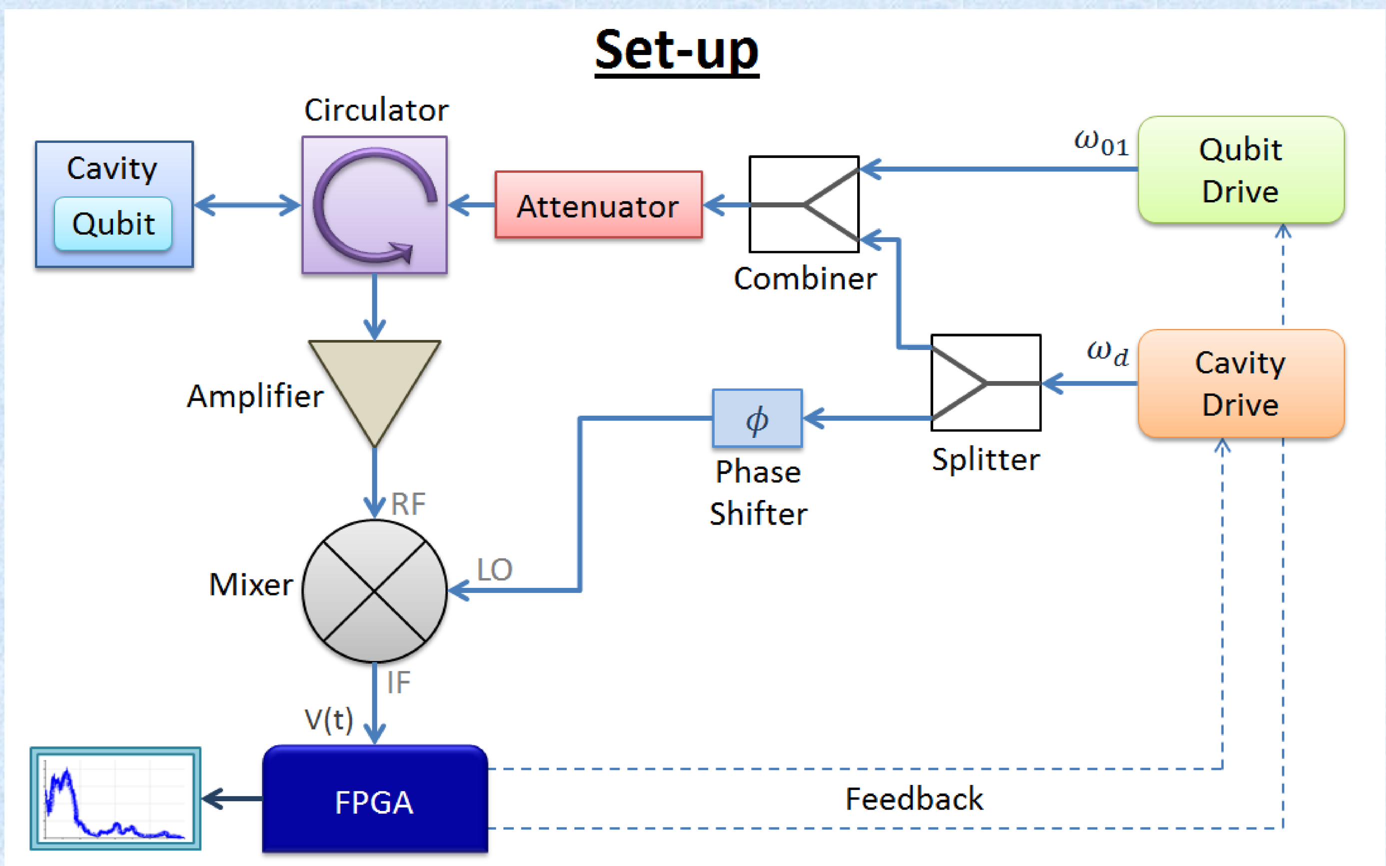
- Dispersive limit: $\Delta = \omega_{01} - \omega_{\rm cav} \gg g, \;\; \chi \sim g^2/\Delta$

$$H_{\rm disp} = \frac{1}{2}\hbar\omega_{01}\sigma_z + \hbar(\omega_{\rm cav} + \chi\sigma_z)\left(a^\dagger a + \frac{1}{2}\right)$$

- Operating condition: $\hbar\omega_{\rm cav} \gg k_B T \sim 10$ mK



Set-up



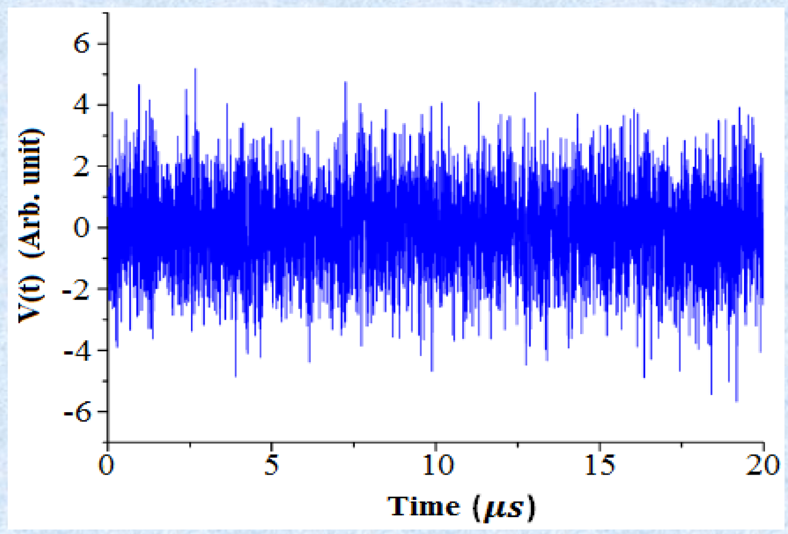
Simulation of Quantum State Tracking

- $V(t)$ is drawn from $P(V)$

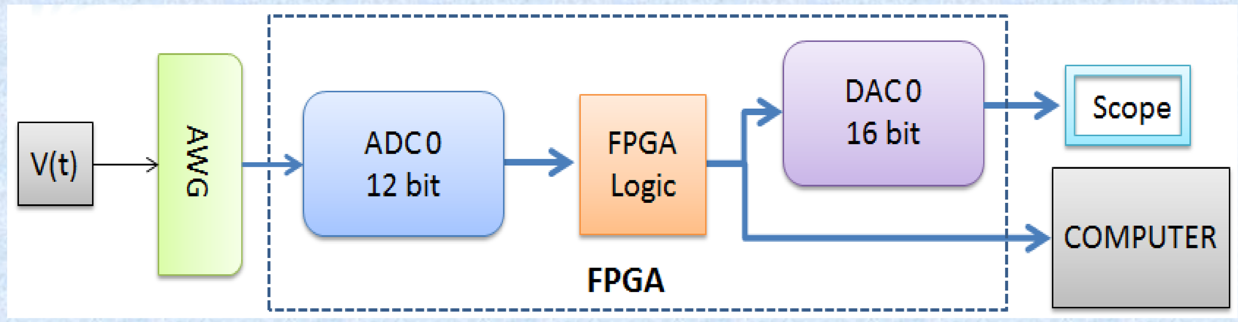
$$P(V|0) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[\frac{(V-V_0)^2}{2\sigma^2}\right];$$

$$P(V|1) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[\frac{(V-V_1)^2}{2\sigma^2}\right];$$

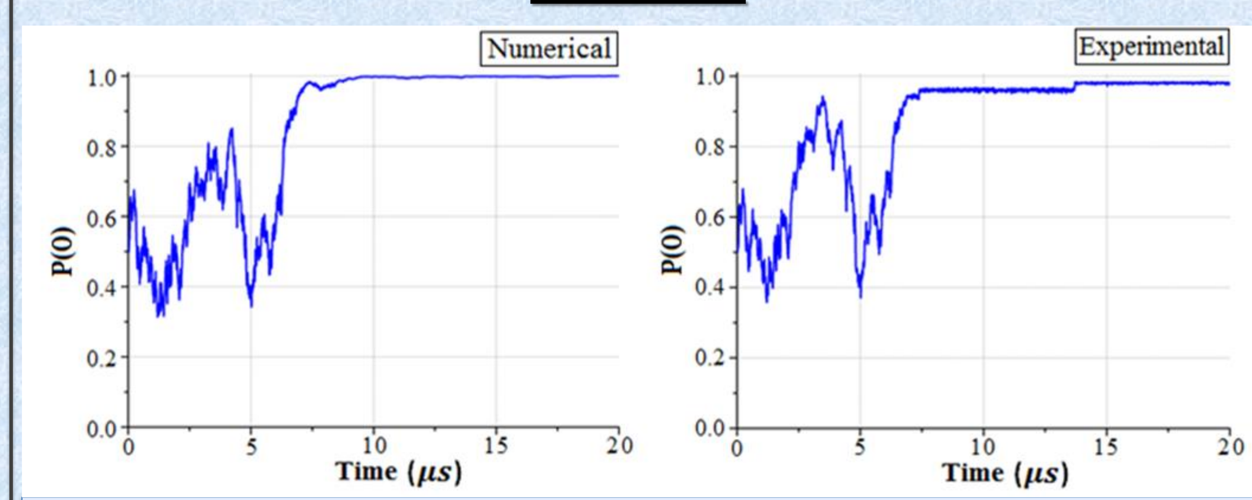
$$P(V) = P(0)P(V|0) + P(1)P(V|1)$$



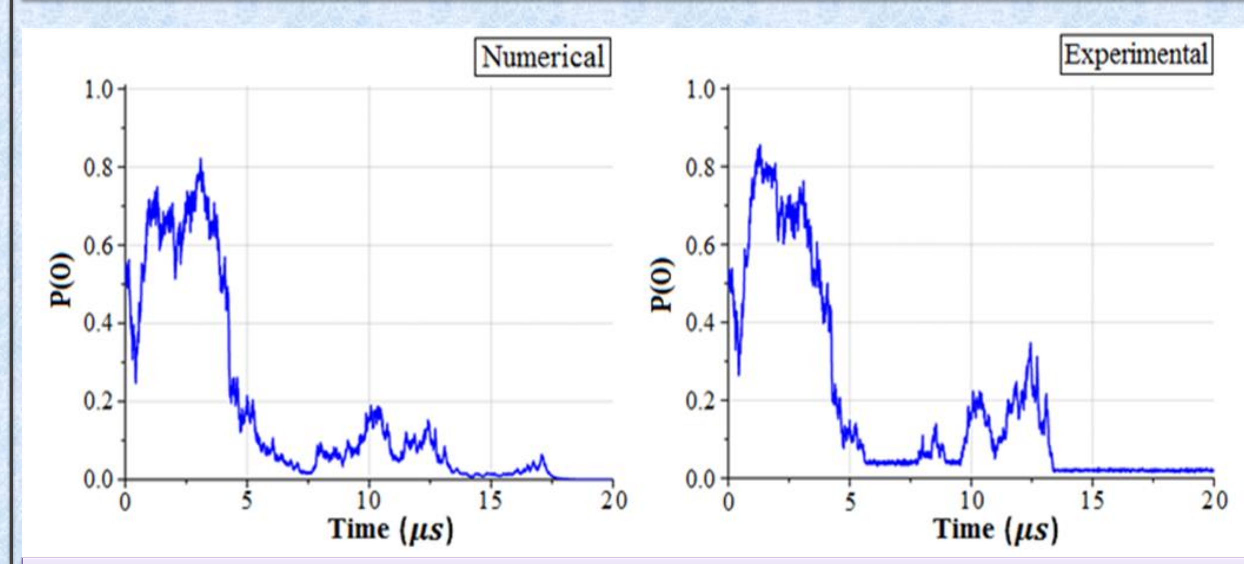
- Arbitrary Waveform Generator generates analog voltage corresponding to $V(t)$
- AWG simulates the measurement signal from a real qubit
- FPGA calculates the trajectory and stores in the host computer



RESULTS



Trajectory ending up in the ground state



Trajectory ending up in the excited state

Conclusions and Future Directions

- Quantum state tracking with an FPGA using simulated measurement signal
- FPGA based tracking of a qubit in cQED architecture
- Implementation of feedback control algorithms using FPGA

Acknowledgements: Vadiraj A. M., Meghan Patankar, Nicolas Roch and Innovative Integrations

References: [1] K. W. Murch, S. J. Weber, C. Macklin, and I. Siddiqi, *Nature* **502**, 211-214.

[2] A. Blais, R. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *Phys. Rev. A* **69**, 062320 (2004).