Large Scale Simulations of Quantum Systems on HPC with Analytics for HEP Algorithms

Adam L. Lyon[1], Yuri Alexeev[2], Eric Holland[1], Jim Kowalkowski[1], Matthew Otten[2]

[1]Fermi National Accelerator Laboratory, [2]Argonne National Laboratory

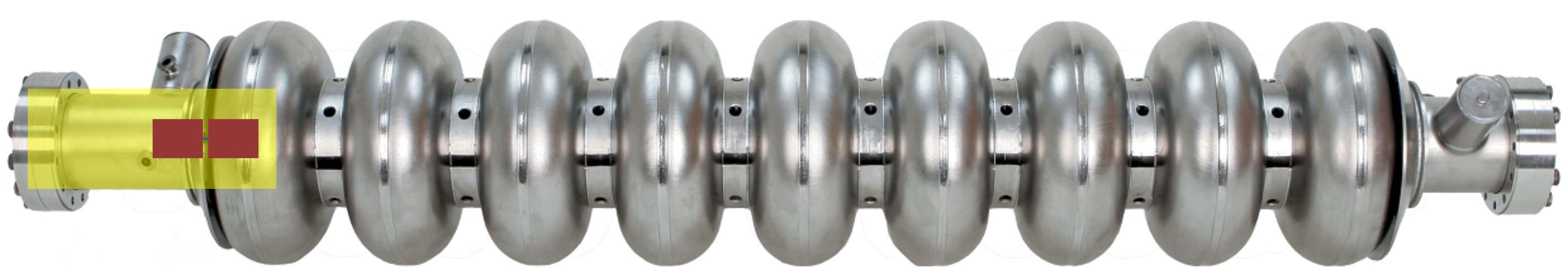
FERMILAB-POSTER-20-039-QIS-SCD

Objective:

Combine HEP simulation experience with HPC quantum systems simulations to provide an environment for executing large-scale experiments with advanced analysis capabilities for studying multi-qubit and multi-level reduced-noise, long coherence time quantum systems such as 3D Superconducting RF (SRF) cavities integrated with transmon qubits.

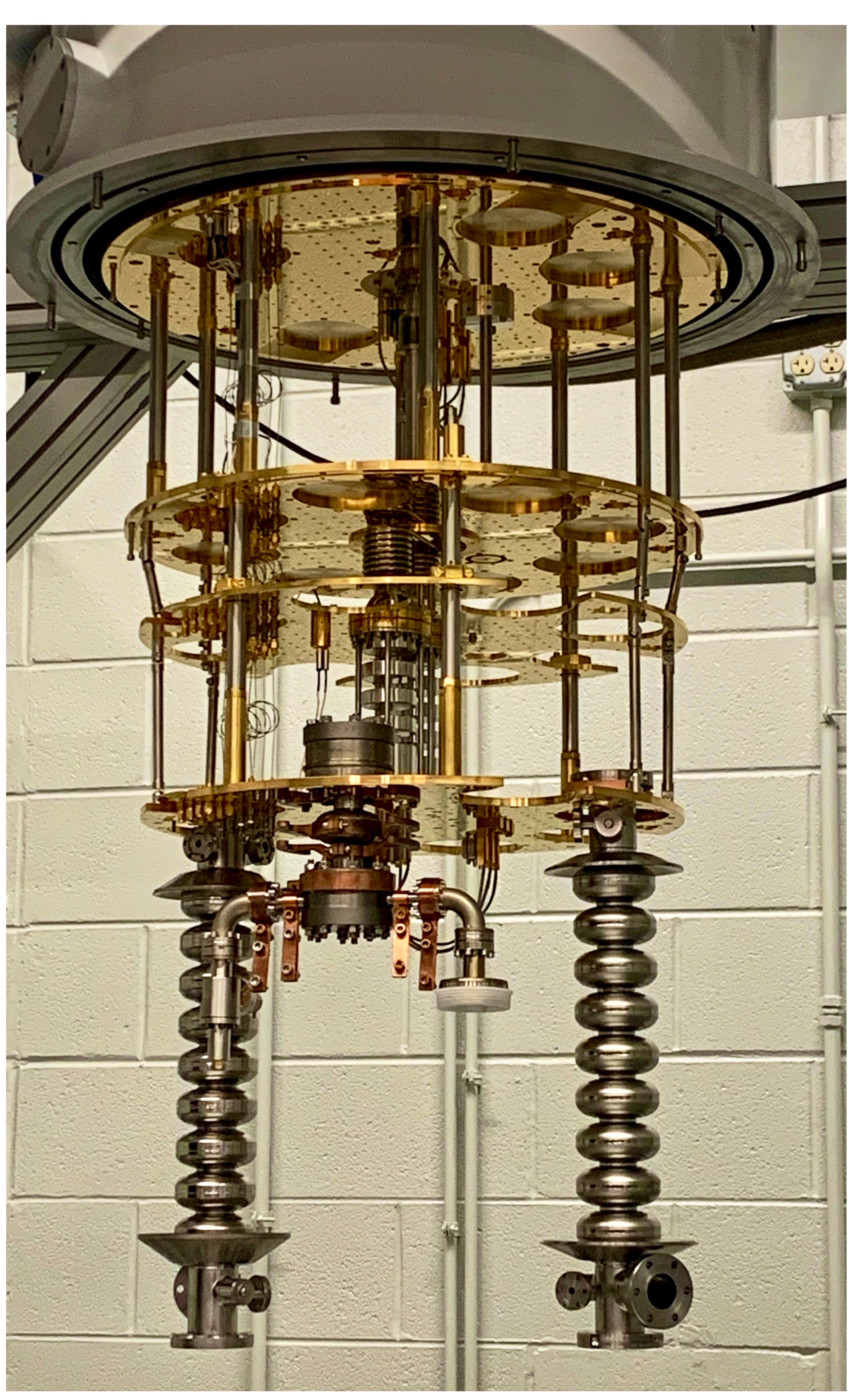
Current studies:

Understand the advantages of **multi-level long coherence time *qudit*** devices (such as 3D SRF cavities) compared to multiple ***qubit*** (two-level) devices.

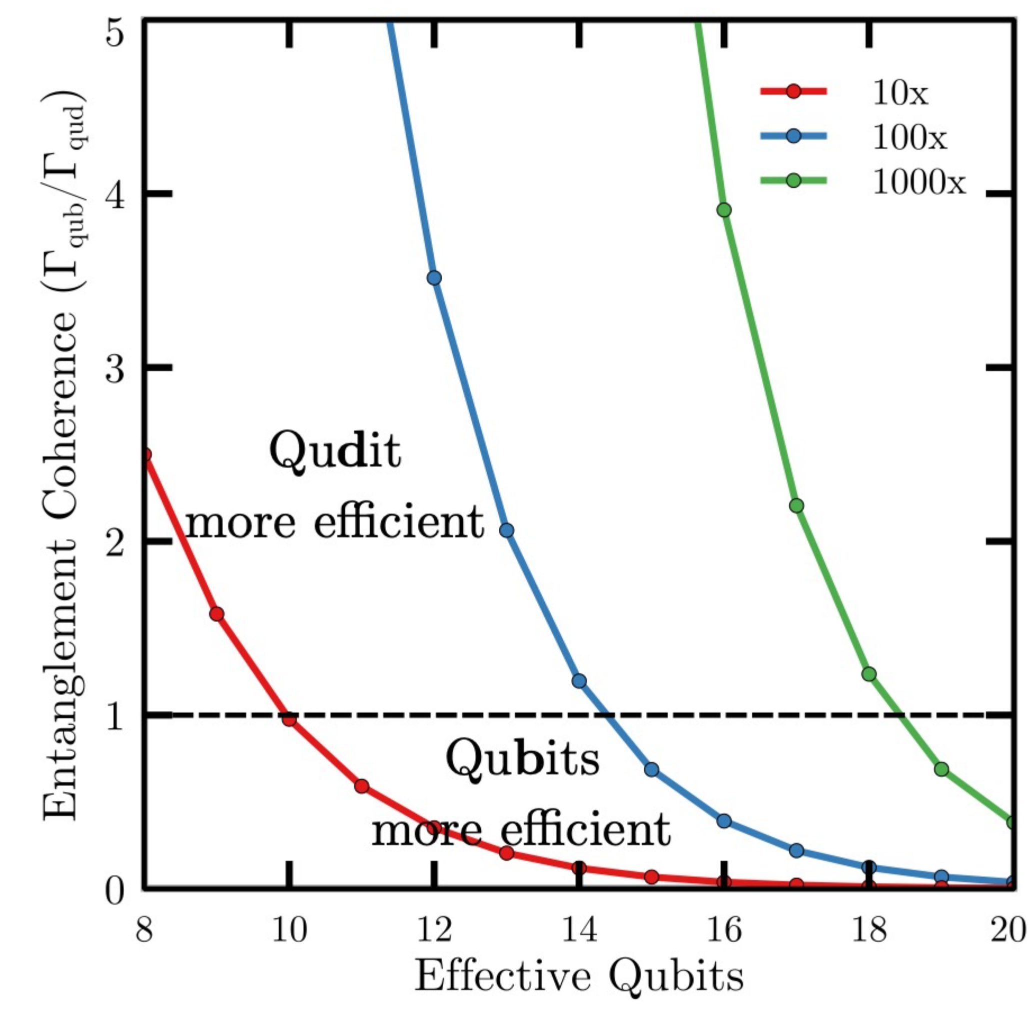


A multi-cell 3D SRF cavity structure driven by an embedded superconducting transmon qubit

Fermilab is conducting experiments on 3D SRF cavity systems with an embedded transmon qubit. We are simulating such systems with the work in this QuantISED project.



The experimental apparatus at Fermilab currently under test with two 3D SRF cavity structures (bottom) in place.



Highly entangled states are preserved in **long coherence time** multi-level 3D SRF cavities (qudits) with potential advantages over qubits shown at left

# of photons = $2^{\#\ \text{effective qubits}} - 1$

e.g. 14 effective qubits correspond to 16383 photons in the cavity

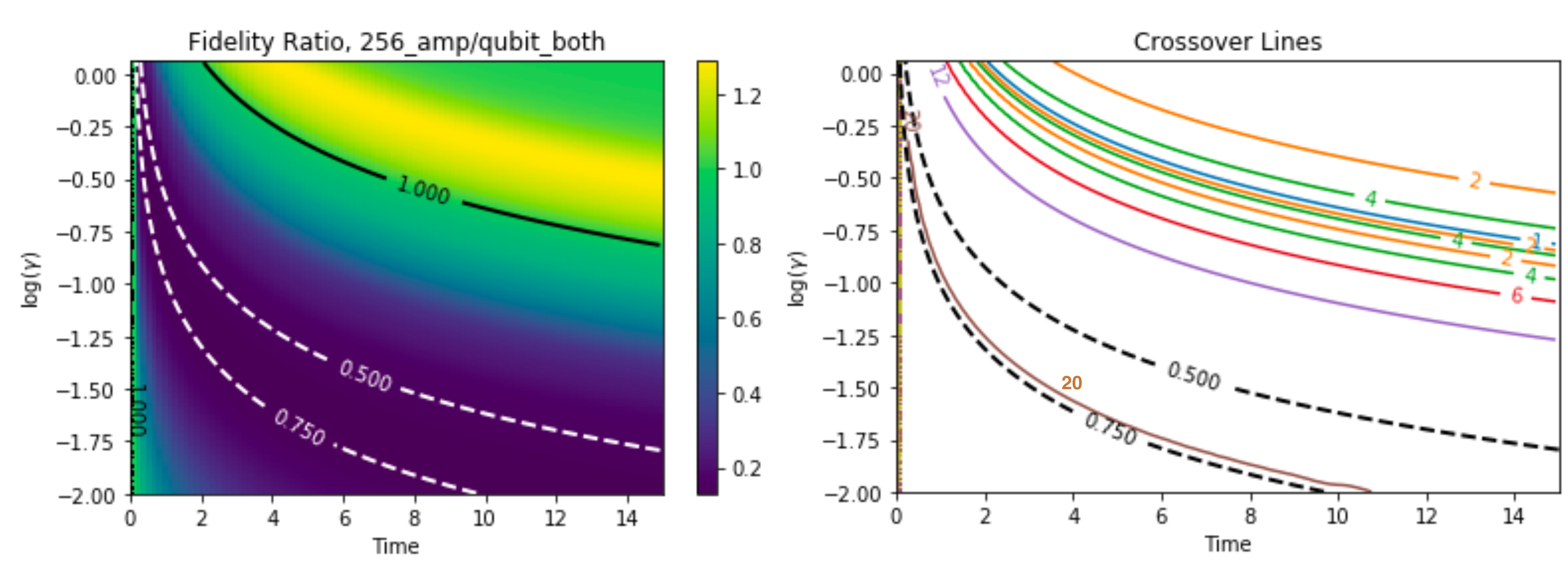
The above was calculated by QuTiP[1] on a laptop. For larger scale studies we need High Performance Computing and parallelized simulation code…

Simulations with QuaC:

QuaC[2] is an open quantum system simulation that takes advantage of High Performance Computing to solve the Linblad master equation for large scale problems

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H + H(t), \rho] + L(C)[\rho]$$

QuaC takes input as low level state information or QASM generated by gate circuit compiling tools such as Qiskit[3]



For an arbitrary state compare state decoherence over time for multi-level qudit vs. multiple qubits. y axis is log(decoherence rate). Dashed contours are the *absolute* fidelity for qubits (do not follow color scale). Lower left of plots is good fidelity region.

Left: Compare 256 level qudit to 8 qubits fidelity (color scale is fidelity ratio). Solid contour is equal fidelity ratio. Decoherence rate is same for qudit & qubit. Qudits are better in upper right, but this is where absolute fidelity is poor.

Right: Like plot at left, but improving the qudit decoherence rate by indicated factor. Contours are where fidelity ratio is 1 (*e.g.* orange line is for qudit 2x better than qubit). At 20x better (brown), qudits improve over qubits in the good absolute fidelity region. Over 20x qudits are always better.

[1]J. R. Johansson, P. D. Nation, and F. Nori: "QuTiP 2: A Python framework for the dynamics of open quantum systems.", Comp. Phys. Comm. **184**, 1234 (2013) [DOI: 10.1016/j.cpc.2012.11.019].

[2]Matthew Otten (ANL), https://github.com/0tt3r/QuaC.

[3]Hector Abraham, et. al., Qiskit: An Open-source Framework for Quantum Computing, 2019, [DOI: 10.5281/zenodo.2562111]

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. We gratefully acknowledge the computing resources provided on Bebop, a high-performance computing cluster operated by the Laboratory Computing Resource Center at Argonne National Laboratory.

Argonne NATIONAL LABORATORY