Quantum Testbed Stakeholder Workshop

Hosted by the Advanced Scientific Computing Research Program

Lawrence Livermore National Lab

Quantum Computing Capabilities and Interests

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LLNL Capabilities and Interests Summary Slide

Primary Expertise & Interest Areas

- Design, fabrication and testing of quantum coherent superconducting devices with special focus on development *from algorithm to device* of novel, hardware efficient, quantum emulation platforms.
- Superconducting device physics and materials science (including first principles material simulation and experimental efforts) focused on identifying and ameliorating materials sources of noise in physical quantum hardware.
- Feedback control and classical FPGA based control hardware.
- Expertise in general quantum many-body theory and classical HPC simulation of many-body quantum systems including open quantum system dynamics.

Most Differentiating Factor

Integrated theory / experiment effort in materials and superconducting quantum hardware based emulation platforms.

Near term focus on short time dynamics in continuous variable open quantum systems.

Main Contribution/Role

- **Testbed development / co-design:** Providing expertise in architecture development, superconducting device design, fabrication and operation of quantum testbeds.
- **Algorithm and Application development:** Leveraging expertise in classical HPC algorithms and applications for simulation of quantum many-body systems for development of new algorithmic approaches and identification of problems of interest for a quantum testbed.
- **V&V:** Employing state-of-the-art experimental facilities for characterization of superconducting quantum circuit testbeds. Complementary capabilities in HPC scale simulation of open quantum systems, statistical analysis and uncertainty quantification.
- **Materials:** Providing experimental and computational condensed matter physics / materials science expertise for understanding and ameliorating microscopic sources of noise and decoherence in superconducting and ion based quantum computing platforms. Collaboration in development of new fabrication processes and materials frameworks.

Quantum Computing Hardware Capabilities

- **Current capability to deliver interconnected and operational qubits**
  - Able to design and deliver interconnected superconducting qubits (fab is in partnership with UCSD and U. Wisconsin).
  - Able to design and deliver complex integrated qubit + cavity systems for continuous variable quantum emulation

- **Experience with design, fabrication, and characterization of qubit devices**
  - LLNL team has collectively ~20 years experience with design, fabrication and characterization of qubit devices.
  - Onsite capability for characterization is complete and operational with expanding throughput.
  - Onsite capability for full fabrication process is in progress.
    - Fully outfitted onsite wafer scale multilayer optical processing for large features.
    - Wafer scale Ebeam writer planned for FY18 (currently have Nabity (NPGS) enabled SEM) for patterning small Josephson junctions,
    - Dedicated ebeam evaporator in late FY17 (currently have multiple shared used deposition systems) for shadow evaporation of Josephson junctions.

Quantum Computer Science Capabilities

- **Algorithm and application development:** Extensive expertise in conventional simulation of quantum many body systems (e.g. path integral, auxiliary field and diffusion Monte Carlo Methods) with applications ranging from quantum chemistry and condensed matter physics to to high energy density materials to lattice QCD.
- **Architectures:** Ongoing study under LDRD-16-SI-004 of hardware efficient architectures for quantum emulation of short time many-body dynamics and quantum graph traversal problems.
- **Software, compilers, etc. :** Dedicated control software / feedback and measurement code under development under LDRD-16-SI-004 and LDRD 17-ERD-006
- **Validation and verification:** Ongoing effort under LDRD-ER to translate microscopic noise models and physical parameters into realistic Hamiltonians + Lindblad terms to complement /replace RB and GST approaches for superconducting and ion trap based systems. Full qubit characterization capability of single qubit and two qubit gate fidelities, T1 and T2 times etc for superconducting systems.
- **Classical simulations to support quantum computing hardware development:** Expertise with open quantum system master equation simulation software for pulse optimization, bath engineering, characterization via Hamiltonian fitting etc.
- **Error correction and gate fidelity:** Focus under LDRD 17-ERD-006 on weak measurement and active feedback control. Focus under LDRD-16-SI-004 on passive error correction in the form of bath engineering for stabilization of states and manifolds.

Fabrication and Characterization Capabilities

- **Tools and capability to manufacture and characterize interconnected qubit devices to increase understanding of their performance limitations**
  - Onsite as well as university and industry partnerships capable of wafer scale multilayer fabrication of superconducting qubits
  - Onsite expertise in conventional and additively manufactured high Q superconducting resonance cavities.
  - Extensive staff experience and fully outfitted lab capability for characterization and performance analysis of interconnected superconducting qubit devices.

- **Fabrication capabilities relevant to manufacturing and characterizing possible future qubit implementations based on, for example, new materials**
  - Onsite as well as university and industry partnerships for development and testing of new materials processes
  - Internally funded combined theory experiment effort focused on identifying sources of noise in superconducting devices and developing new materials processes for higher fidelity qubits.

Capabilities in Engineering and Supporting Technology

- **Expertise in areas of engineering that will be important for advancing quantum computing technology**
  - Microwave electronics
  - FPGA programming and development of High throughput digital acquisition systems
  - Fabrication process development
  - Expertise in feedback and control
  - Statistical analysis and uncertainty quantification
  - Systems engineering

- **Expertise in ancillary technology that will be needed to build and maintain a functioning quantum testbed**
  - Materials engineering and characterization
  - Cryogenics, vacuum, precision machining
  - Laser / optical engineering for interconnects etc.

- **Capabilities for back-end data warehousing and data analysis**
  - HPC center with high end long term storage, “green data oasis”, etc.

Applications to Domain Science

- **What research efforts at the lab are in a position to benefit from quantum computing in the short, medium, and long-term?**

Near term: Core technology (coupled long lived coherent quantum states) is directly applicable to multiple sensing applications. For example, superconducting detectors are currently used in a wide variety of high energy resolution spectroscopic applications. Reducing noise floors and increasing the ability to perform correlated coherent measurements can radically enhance the utility of these systems.

Medium term: Simulation / emulation of quantum dynamics in systems of direct relevance to DOE/NNSA mission space such as; charge transfer dynamics in energy capture and conversion systems, dynamics of nuclear interactions, energy dissipation in mixed quantum classical environments such as stopping power, direct probes of renormalization flows associated with emergence of classical behavior from complex quantum systems, new understanding (through direct simulation) of quantum field theories, etc.

Long term: Complete understanding of nuclear and chemical processes from atoms to proteins. Exact determination of ground state, finite temperature and dynamics of complex materials systems. Large scale, low power, simulation of multiscale networks. Potential for broad applications in "cognitive" computing ranging from categorization, associative memory, graph traversal etc.

Investments in Quantum Computing Technology

- **Integrated, directly relevant LDRD investments in QC technologies**
  - 12-ERD-020, V. Lordi, *"First-Principles Materials Characterization and Optimization for Ultralow-Noise Superconducting Qubits"* ~ $300k / year for 3 years
  - 15-ERD-051, V. Lordi, *"Integrated Physics-Based Noise Modeling of Qubit Devices"* ~ $500k /year for 3 years
  - 16-SI-004, J. DuBois, *"Enhanced Coherence for Quantum Sensing and Simulation"* ~ $2.1M /year for 3 years
  - 17-ERD-006, L. Poyneer, *"Control of Superconducting Quantum Circuits"* ~ $400k/year for 3 years
- **Motivation and lab priorities behind LDRD investments**

  To build theoretical and experimental expertise and capabilities to address anticipated DOE program needs in quantum sensing and quantum emulation platforms.
- **Expertise developed and lessons learned**
  - Growing expertise in and appreciation of the potential for quantum emulation and sensing platforms across the lab.
  - Established low noise cryogenic characterization facility.
  - Established expertise through recruitment and training in design, fabrication and characterization of superconducting quantum devices.
  - Developing synergies with existing science and engineering core competencies – e.g. leveraging work on adaptive optics for quantum feedback and control

Facility Management Experience

- **What facilities are managed by the lab that have aspects that could be adapted for a quantum testbed facility? / Lab infrastructure to support research facilities that support external users**

- Livermore Computing: http://hpc.llnl.gov/portal
  - Supports large international user community
  - Web presence with online training, help
  - User hotline, incident tracking etc.
- Livermore Valley open campus: https://lvoc.org/
  - Open access facility with meeting space, support staff, connectivity etc.
- Multiple large scale, long term experimental facilities with a variety of user and support models

External Partnerships

- Partnerships / Collaborations in current Quantum effort
  - U. Wisconsin : Fabrication (Qubit samples), Characterization, Exp. design
  - UC San Diego : Fabrication (Ebeam, wafer processing)
  - Tulane : Theory (passive error correction)
  - UT El Paso : Fabrication (Additive manufacturing)
  - UC Berkeley : Theory, Qubit samples, fabrication and testing of 3D cavities, Characterization
  - STAR Cryoelectronics: Superconducting system fabrication

- Experience working with industry, including IP protection and technology transition
  - Like most of the DOE labs, Livermore has decades of expertise around developing strong industry collaborations on advanced computing technologies for HPC. Our largest advanced computing systems require 3-5 years of collaboration between industry and the lab prior to the platform being delivered. During this period, Livermore provides R&D/NRE (non-recoverable engineering) funding towards system design and enhancements that would be beneficial to DOE. LLNL has managed R&D contracts for many systems including ASCI White, ASCI Purple, Blue Gene/L, Sequoia, NNSA PathForward, DOE FastForward and PathForward, and ASC Sierra/CORAL.
  - Vendor IP is protected via NDA agreement(s) between the two (or more) parties. The NRE efforts are a shared-cost model and thus require significant vendor contributions towards the research. Due to this large industry investment, the NRE partners can request an IP waiver from DOE. This allows the vendors to fully own any IP that is generated as part of the NRE/R&D efforts. Most NDA(s) involve IP information flowing from the industry partner to LLNL, but no LLNL IP to the industry partner. LLNL may wish to share lab IP or cooperate with an industry partner to potentially develop IP. The sharing of IP would involve the LLNL technology transfer office and a cooperative R&D effort would involve a CRADA.