Q-CTRL’S EXPERTISE & CAPABILITIES

THE WORLD’S LEADING EXPERTS IN QUANTUM CONTROL ENGINEERING
INTRODUCTION

At Q-CTRL we’ve assembled a team comprising many of the world’s leading experts in quantum control engineering, with expertise spanning the dominant quantum computing hardware platforms as well as near-term applications in sensing and metrology.

Our team understands the challenges faced by hardware R&D teams, software architects, and end-users, and has a sustained publication track record demonstrating an ability to drive progress across the field of quantum technology. We solve tough challenges from experimental hardware optimization through to quantum computer architecture analyses, sensor data fusion to improved clock stabilization using machine learning.

Just imagine how much our team can help you achieve.

Explore below for highlights of our capabilities.

SUPERCONDUCTING QUANTUM COMPUTING

Our team members have led the development and operation of superconducting quantum processors, as well as the application of optimal control to these devices. We’ve leveraged these experiences to deliver totally new control solutions for superconducting qubits to our customers and partners.

KEY STAFF

Dr. Mirko Amico
Dr. Harrison Ball
Dr. Yuval Baum
Dr. Per Liebermann

SELECTED PUBLICATIONS

Optimal qubit control using single-flux quantum pulses
Physical Review Applied 6 (2), 024022

Optimized cross-resonance gate for coupled transmon systems
Physical Review A 97 (4), 042348

Tunable quantum entanglement of three qubits in a nonstationary cavity
Physical Review A 96 (3), 032328

Dissipative quantum entanglement dynamics of two and three qubits due to the dynamical Lamb effect
Physical Review A 98 (4), 042325

Dynamical Lamb effect in a superconducting circuit
Physical Review A 100 (1), 013841

Experimental study of Shor’s factoring algorithm using the IBM Q Experience
Physical Review A 100 (1), 012305

Laplace transform approach for the dynamics of N qubits coupled to a resonator
Physics Letters A 383 (6), 487-493

Experimental study of Shor’s factoring algorithm using the IBM Q Experience
Physical Review A 100 (1), 012305

Laplace transform approach for the dynamics of N qubits coupled to a resonator
Physics Letters A 383 (6), 487-493

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Tunable quantum entanglement of three qubits in a nonstationary cavity
Physical Review A 96 (3), 032328
TRAPPED-ION QUANTUM COMPUTING

The Q-CTRL team has extensive experience in trapped-ion quantum logic and experimental hardware. Through our IARPA and ARO sponsored collaborations with the University of Sydney we have demonstrated how Q-CTRL solutions can help identify noise sources and dramatically improve the robustness and speed of Molmer-Sorensen entangling gates.

KEY STAFF
Dr. Harrison Ball
Dr. Chris Bentley
Prof. Michael J. Biercuk
Dr. Andre Carvalho
Ms. Claire Edmunds

SELECTED PUBLICATIONS
Assessing the progress of trapped-ion processors towards fault-tolerant quantum computation
Physical Review X 7 (4), 041061

Engineered two-dimensional Ising interactions in a trapped-ion quantum simulator with hundreds of spins
Nature 484 (7395), 489

Fast gates for ion traps by splitting laser pulses
New Journal of Physics 15 (4), 043006

Site-resolved imaging of beryllium ion crystals in a high-optical-access Penning trap with inbore optomechanics
Review of Scientific Instruments 90 (5), 053103

Near-ground-state transport of trapped-ion qubits through a multidimensional array
Physical Review A 84 (3), 032314

A Study on Fast Gates for Large-Scale Quantum Simulation with Trapped Ions
Scientific Reports 7, 46197

Scaling Trapped Ion Quantum Computers Using Fast Gates and Microtraps
Physical Review Letters 120 (22), 220501

Phase-modulated entangling gates robust against static and time-varying errors
arXiv:1808.10462

QUANTUM CHARACTERIZATION, VERIFICATION, AND VALIDATION

The validation of quantum hardware performance is a critical task in the development and integration of quantum firmware. Our team has focused on moving beyond simplified abstractions to understanding the practical impact of realistic hardware noise environments on the interpretation of QCVV protocols. Our emphasis on gaining actionable information about microscopic noise sources has led to new interpretations of hardware characterization routines.

KEY STAFF
Dr. Harrison Ball
Dr. Yuval Baum
Prof. Michael J Biercuk
Dr. Li Li

SELECTED PUBLICATIONS
Full reconstruction of a 14-qubit state within four hours
New Journal of Physics 18 (8), 083036

Adaptive quantum state tomography via linear regression estimation: Theory and two-qubit experiment
npj Quantum Information 3 (1), 19

Experimental demonstration of real-time adaptive one-qubit quantum-state tomography
Physical Review A 95 (1), 012129

Experimental demonstration of real-time adaptive one-qubit quantum-state tomography
Physical Review A 95 (1), 012129

The effect of noise correlations on randomized benchmarking
Physical Review A 93, 022303

Experimental quantum verification in the presence of temporally correlated noise
npj Quantum information 4 (1), 1-9

Dynamically corrected gates suppressing spatiotemporal error correlations as measured by randomized benchmarking
Physical Review Research 2 (1), 013156

Adaptive scheduling of noise characterization in quantum computers

Convergence analysis for autonomous adaptive learning applied to quantum architectures
NEUTRAL ATOMS FOR QUANTUM COMPUTING AND SENSING

The Q-CTRL Quantum Engineering team has built extraordinary proficiency from working in some of the world’s most advanced atomic devices groups. We have a demonstrated track record of the integration of machine-learning and optimal control into neutral atom experiments to drive major performance enhancement in hardware.

KEY STAFF

Dr. Albert Benseny Cases
Dr. Chris Bentley
Dr. Andre Carvalho
Dr. Michael Hush
Dr. Nick Robins
Dr. Harry Slatyer

SELECTED PUBLICATIONS

- Machine learning for quantum physics
  Science 355 (6325), 580-580

- Approaching the adiabatic timescale with machine learning
  Proceedings of the National Academy of Sciences 115 (52), 13216-13221

- Multiparameter optimisation of a magneto-optical trap using deep learning
  Nature Communications 9 (1), 4360

- Fast machine-learning online optimization of ultra-cold-atom experiments
  Scientific Reports 6, 25890

- Feedback control of an interacting Bose-Einstein condensate using phase-contrast imaging
  Physical Review A 82 (4), 043632

- Continuous measurement feedback control of a Bose-Einstein condensate using phase-contrast imaging
  Physical Review A 80 (1), 013614

- Transferring orbital and spin angular momenta of light to atoms
  New Journal of Physics 12 (8), 083053

- Atomtronics with holes: coherent transport of an empty site in a triple-well potential
  Physical Review A 82 (1), 013604

- Need for relativistic corrections in the analysis of spatial adiabatic passage of matter waves
  Physical Review A 85 (5), 053619

- Transport of ultracold atoms between concentric traps via spatial adiabatic passage
  New Journal of Physics 18 (1), 015010

- Speeding up the spatial adiabatic passage of matter waves in optical microtraps by optimal control
  Quantum information processing 12 (3), 1439-1467

- Non-adiabatic generation of NOON states in a Tonks–Girardeau gas
  New J. Phys. 18, 035012

- Spatial non-adiabatic passage using geometric phases
  EPJ Quantum Technology 4 (1), 3

- Robust boson dispenser: Quantum state preparation in interacting many-particle systems
  Physical Review A 96 (2), 023606

- Interaction-induced effects on Bose-Hubbard parameters
  Physical Review A 96 (6), 063611

- Coherent spectral hole burning and qubit isolation by stimulated Raman adiabatic passage
  Physical Review A 100 (2), 023813

- Fast and robust quantum control based on Pauli blocking
  Physical Review A 96 (4), 043601

- Shaken not stirred: Creating exotic angular momentum states by shaking an optical lattice
  J. Phys. B 49, 215003

- Quantum tunneling dynamics of an interacting Bose-Einstein condensate through a Gaussian barrier

- Observation of a modulational instability in Bose-Einstein condensates

- Highly efficient optical quantum memory with long coherence time in cold atoms
  Optica 3, 1(2016) 100-107
**PRECISION METROLOGY, CLOCKS, AND SENSING**

We are pioneers in the application of quantum control to clocks and sensors for applications in defense and aerospace. Our experiences tackle some of the toughest problems in developing high-performance devices in tight-SWAP settings. We've delivered control solutions to suppress the Dick effect in atomic clocks, narrowband controls to suppress clutter in magnetometers, and novel pulse sequences enabling nanoscale MRI. Moreover, members of our team have led ground-breaking hardware developments in novel quantum-enhanced sensors.

**KEY STAFF**

Prof. Michael J Biercuk  
Dr. Andre Carvalho  
Dr. Michael Hush  
Dr. Viktor Perunicic  
Dr. Nick Robins

**SELECTED PUBLICATIONS**

A faster scaling in acceleration-sensitive atom interferometers  
*Europhysics Letters* 105, 6(2014) 63001

Role of source coherence in atom interferometry  
*Physical Review A: Atomic, Molecular and Optical Physics* 89, 2(2014) 023626

A Bose-condensed, simultaneous dual-species Mach-Zehnder atom interferometer  

Atom lasers: Production, properties and prospects for precision inertial measurement  

A quantum spin-probe molecular microscope  
*Nature Communications* 7, 12667

Detection of atomic spin labels in a lipid bilayer using a single-spin nanodiamond probe  
*Proceedings of the National Academy of Sciences* 110 (27), 10894-10898

Multimode laser cooling and ultra-high sensitivity force sensing with nanowires  
*Nature Communications* 5(2014) 4663-4663

Controlling oscillators  
*US Patent* 9,362,929

Prediction and real-time compensation of qubit decoherence via machine-learning  
*Nature Communications* 8, 14106

Sagnac interferometry with a single atomic clock  
*Physical Review Letters* 115 (16), 163001

Analytically exploiting noise correlations inside the feedback loop to improve locked-oscillator performance  
*Physical Review E* 94, 022204

Towards rotation sensing with a single atomic clock  
*Quantum Optics* 9900, 990007

Simultaneous Precision Gravimetry and Magnetic Gradiometry with a Bose-Einstein Condensate: A High Precision, Quantum Sensor  
APPLIED QUANTUM CONTROL ENGINEERING AND MACHINE LEARNING

Various members of our team have made foundational contributions to quantum control engineering as a discipline. This spans open quantum-system dynamics, open-loop control and dynamic error suppression, feedback control, and input-output theory. We also possess deep expertise in machine learning applied to control engineering with experience spanning robotics and quantum coherent devices.

**KEY PERSONNEL**

- Dr. Harrison Ball
- Prof. Michael J Biercuk
- Dr. Andre Carvalho
- Mr. Sean Howell
- Dr. Michael Hush
- Dr. Li Li
- Dr. Junkai Zeng

**SELECTED PUBLICATIONS, OPEN-LOOP CONTROL**

<table>
<thead>
<tr>
<th>Title</th>
<th>Journal/Media</th>
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<tbody>
<tr>
<td>Optimized dynamical decoupling in a model quantum memory</td>
<td>Nature 458 (7241), 996</td>
</tr>
<tr>
<td>Experimental noise filtering by quantum control</td>
<td>Nature Physics 10, 825-829</td>
</tr>
<tr>
<td>High-order noise filtering in nontrivial quantum logic gates</td>
<td>Physical Review Letters 109, 020501</td>
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<tr>
<td>Dynamical decoupling sequence construction as a filter-design problem</td>
<td>Journal of Physics B: Atomic, Molecular and Optical Physics 44 (15), 154002</td>
</tr>
<tr>
<td>Arbitrary quantum control of qubits in the presence of universal noise</td>
<td>New Journal of Physics 15, 095004</td>
</tr>
<tr>
<td>Robustness of composite pulses to time-dependent control noise</td>
<td>Physical Review A 90, 012316</td>
</tr>
<tr>
<td>Reducing sequencing complexity in dynamical quantum error suppression by Walsh modulation</td>
<td>Physical Review A 84 (6), 062323</td>
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<tr>
<td>Walsh-synthesized noise filters for quantum logic</td>
<td>EPJ Quantum Technology 2 (1), 11</td>
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<td>Fastest pulses that implement dynamically corrected single-qubit phase gates</td>
<td>Physical Review A 98 (1), 012301w</td>
</tr>
<tr>
<td>General solution to inhomogeneous dephasing and smooth pulse dynamical decoupling</td>
<td>New Journal of Physics 20 (3), 033011</td>
</tr>
<tr>
<td>Geometric formalism for constructing arbitrary single-qubit dynamically corrected gates</td>
<td>Physical Review A 99 (5), 052321</td>
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<tr>
<td>Experimental control of the transition from Markovian to non-Markovian dynamics of open quantum systems</td>
<td>Nature Physics 7, 931-934 (2011)</td>
</tr>
<tr>
<td>Canonical form of master equations and characterization of non-Markovianity</td>
<td>Phys. Rev. A 89 042120</td>
</tr>
<tr>
<td>Concepts of quantum non-Markovianity: a hierarchy</td>
<td>Physics Reports 759, 1-51</td>
</tr>
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<td>Experimental control of the transition from Markovian to non-Markovian dynamics of open quantum systems</td>
<td>Nature Physics</td>
</tr>
<tr>
<td>Experimental generation of an eight-photon Greenberger–Horne–Zeilinger state</td>
<td>Nature Communications 2, 546</td>
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<td>Canonical form of master equations and characterization of non-Markovianity</td>
<td>Physical Review A 89 (4), 042120</td>
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<tr>
<td>Experimental validation of quantum steering ellipsoids and tests of volume monogamy relations</td>
<td>Physical Review Letters 122 (7), 070402</td>
</tr>
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### Applied Quantum Control Engineering and Machine Learning

#### Key Personnel
- Dr. Harrison Ball
- Dr. Yuval Baum
- Prof. Michael J Biercuk
- Dr. Andre Carvalho
- Mr. Sean Howell
- Dr. Michael Hush
- Dr. Li Li
- Dr. Junkai Zeng

#### Selected Publications, Closed-Loop Stabilization
- Machine learning for predictive estimation of qubit dynamics subject to dephasing
  Physical Review Applied 9 (6), 064042
- Ignorance is bliss: General and robust cancellation of decoherence via no-knowledge quantum feedback
  Physical Review Letters 113 (2), 020407
- Robustness of system-filter separation for the feedback control of a quantum harmonic oscillator undergoing continuous position measurement
  Physical Review A 87 (1), 013626
- Feedback tracking control of non-Markovian quantum systems
  IEEE Transactions on Control Systems Technology 25 (5), 1552-1563
- Coherently tracking the covariance matrix of an open quantum system
  Physical Review A 92 (1), 012115
- Non-Markovian coherent feedback control of quantum dot systems
  Quantum Science and Technology 2 (1), 014002

#### The Impact of Noise & Control in Quantum Computer Architecture

The interface of quantum control with other layers of the quantum computing stack presents some of the most profound opportunities to advance quantum computing in the NISQ era. Our team has led the exploration of control in the development of quantum computer architectures, from the physical to the logical layers.

#### Key Staff
- Dr. Harrison Ball
- Prof. Michael J Biercuk
- Dr. Andre Carvalho
- Ms Claire Edmunds
- Dr Michael Hush
- Dr Junkai Zeng

#### Selected Publications
- Designing a practical high-fidelity long-time quantum memory
  Nature Communications 4, 2045
- Functional basis for efficient physical layer classical control in quantum processors
  Physical Review Applied 6 (6), 064009
- The role of master clock stability in quantum information processing
  Nature Quantum Information 2, 16033
- Quantum-classical interface based on single flux quantum digital logic
  Quantum science and technology 3 (2), 024004
- Scaling Trapped Ion Quantum Computers Using Fast Gates and Microtraps
  Physical Review Letters 120 (22), 220501
- Near-ground-state transport of trapped-ion qubits through a multidimensional array
  Physical Review A 84 (3), 032314
- Dynamically corrected gates suppress spatio-temporal error correlations as measured by randomized benchmarking
  arXiv:1909.10727
- Adaptive scheduling of noise characterization in quantum computers
  arXiv:1904.07225