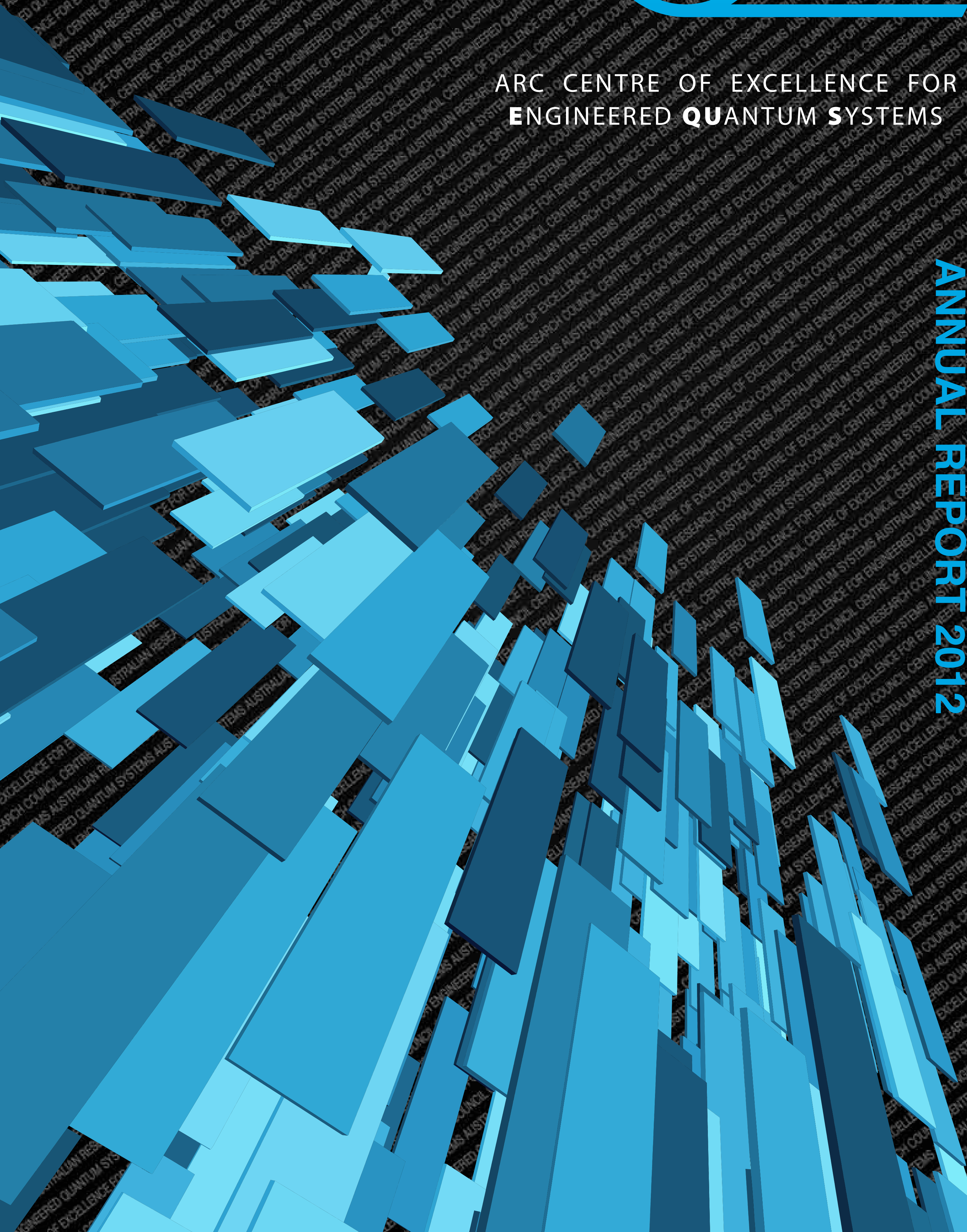
eQus

ARC CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS

ANNUAL REPORT 2012



eQus

ARC CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS

Australian Government
Australian Research Council

EQuS acknowledges the support of the Australian Research Council.

We also acknowledge the financial and in-kind support provided by our participating organisations – The University of Queensland, The University of Sydney, Macquarie University, The University of Western Australia, The University of New South Wales.

THE UNIVERSITY OF QUEENSLAND
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TABLE OF CONTENTS

INTRODUCTION 1
- Overview
- Financial Support

DIRECTOR'S FOREWORD 2

ORGANISATION AND GOVERNANCE 4
- Centre Governance and Management Structure
- Organisational Chart
- Advisory Board
- Program Managers (CI) Committee
- Scientific Advisory Committee

CENTRE PERSONNEL 8
- Chief Investigators
- Management and Administration Personnel
- Researchers
- Research Assistants
- Students – PhD
- Students – Masters

OUR MISSION 17
- Objectives

INFRASTRUCTURE
18

The Quantum Technology Laboratory – The University of Queensland
The Queensland Quantum Optics Laboratory – The University of Queensland
The Atom Optics Laboratory – The University of Queensland
The Superconducting Quantum Devices Laboratory – The University of Queensland
The Superconducting Single-Charge Device Laboratory (SSCDL) – The University of New South Wales
The Diamond Nanoscience Laboratory – Macquarie University
The QIRON Laboratory – Macquarie University
The Quantum Nanoscience Laboratory – The University of Sydney
The Frequency and Quantum Metrology Laboratory – The University of Western Australia

EQUS RESEARCH PROGRAMS
22

Delivering on Grand Challenges
Quantum Measurement and Control
Quantum-Enabled Sensors and Metrology
Synthetic Quantum Systems and Simulation
Achieve new field and force sensing regimes using arrays of quantum controlled mechanical oscillators.
Realise new capabilities through the development of a comprehensive and flexible quantum control toolkit.
Achieve complete control over individual quantum particles in a strongly interacting many-body quantum system with tuneable interactions.
Produce programmable quantum simulators capable of outperforming the best classical technology.

MAJOR RESEARCH PROJECTS IN 2012
31

Semiconductor Quantum Dots
Optomechanics
Atomic Thermometry
Quantum Interfaces
Plasmonics
Hybrid High-Q Oscillators
Noise Filtering in Quantum Control
Quantum Phase Transitions and Simulation
Nanoparticles for sensing and bioimaging
Exotic Quantum Sensors
Entanglement-enabled quantum sensing using trapped ions
Quantum Matter

KEY PERFORMANCE INDICATORS
54

Research Findings
Media Commentaries
Research Training and Professional Education
International, National and Regional Links and Networks
New EQuS-Enabled Collaborations

STRATEGIC DIRECTIONS 2013 87
Quantum measurement and control
Quantum enabled sensors and metrology
Synthetic quantum systems and simulation

APPENDIX 1: PUBLICATIONS 88
Journal Articles

APPENDIX 2: CONFERENCES 92
Conference Proceedings –Refereed
Conference Proceedings – Extract of Paper
Unpublished Presentations

APPENDIX 3: FINANCIAL STATEMENT 96

APPENDIX 4: KEY RESULT AREAS AND STANDARD PERFORMANCE MEASURES 97
Research Findings
International, National and Regional Links and Networks
End-users Links
Organisational Support
Governance
National Benefit

Plasma discharge in a Ytterbium hollow cathode lamp

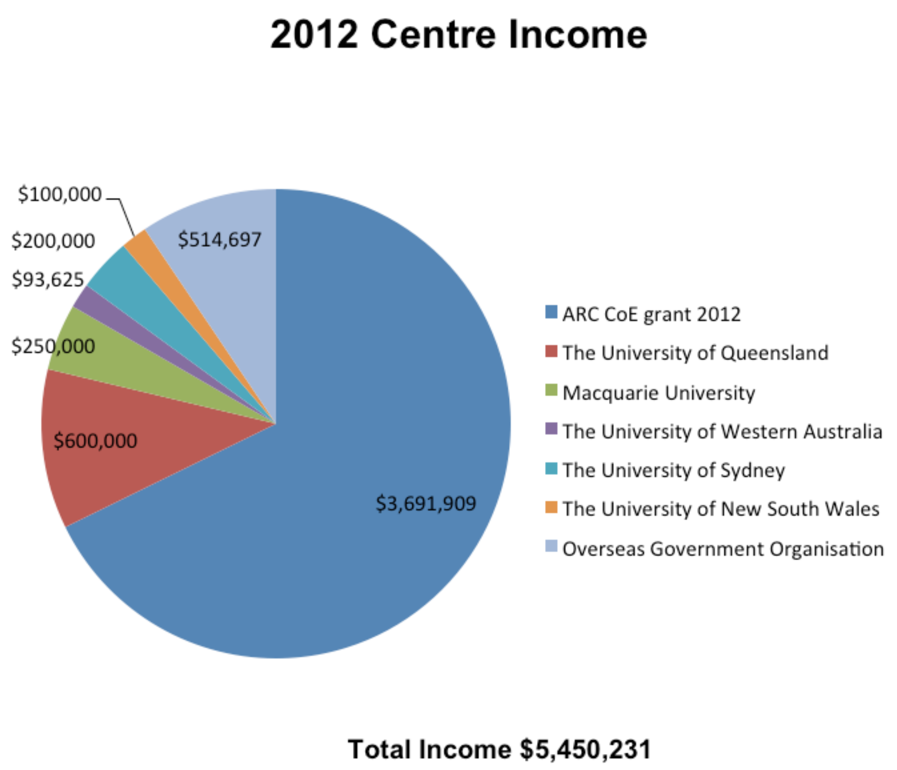
INTRODUCTION

Overview

The ARC Centre of Excellence for Engineered Quantum Systems (EQuS) seeks to move from Quantum Science to Quantum Engineering – building and crafting new quantum technologies. In collaboration with the internationally renowned Physics groups of The Universities of Queensland, Sydney, Western Australia, New South Wales and Macquarie University, EQuS provides the world's first focused research program on systems engineering in the quantum regime. EQuS is addressing fundamental questions about the benefits and limits of quantum technologies, developing strategies for producing novel quantum-enhanced devices, and exploring new emergent physical phenomena that arise only in the presence of complex, integrated quantum systems.

Financial Support

The Centre's main source of funding is the Australian Research Council through the Centres of Excellence program. The ARC provides $3.5 million per annum with the administering institution, The University of Queensland, and the collaborating institutions The University of Sydney, Macquarie University, The University of Western Australia and the University of New South Wales contributing ~$1.2 million in cash contributions per year.



DIRECTOR'S FOREWORD

The year 2012, our second year of operation, was a successful time for the Centre. This was our first full year under contract and our CIs hit the ground running – pushing the frontiers of knowledge with their own research, building an international reputation for our Centre, spinning-off new technologies and forging strong bonds across Centre nodes and around the world.

Our Centre's aims and achievements are exceptionally broad – including scientific and technical accomplishments, but also societal challenges associated with building a skilled workforce for the future. These include

1. Laying the foundation for the quantum future through the generation of new scientific knowledge and techniques
2. Creating a world-recognized community of collaborative researchers
3. Providing world-class training opportunities for young Australian and international researchers
4. Producing new spin-off technologies.

Our science speaks for itself, with major results published in the world's most prestigious scientific journals. We are working on some of the most challenging technical problems in what is perhaps the most active and impactful field of modern physics. For instance, just this year Mike Biercuk and his collaborators at NIST reported an engineered ion crystal of 300 ions trapped in vacuum. This is the first quantum simulator at a computationally relevant scale. Warwick Bowen's laboratory proposed an opto-mechanical sensor for weak magnetic fields that performs as well as superconducting interference devices (SQUIDS) but at room temperature, instead of the cryogenic temperatures required for SQUIDS.

The discipline we are leading has the potential to revolutionize computation, communications, and even our understanding of nature. EQuS research is leading the way, actively solving core problems, and leveraging our knowledge to deliver fundamentally new technical capabilities. We are engineering the quantum future and setting the stage for new technologies as transformational as the modern information revolution.

EQuS had a particularly high profile in the technical community this year, with 40 invited talks given by CIs at conferences, workshops, and seminars around the globe. Our researchers were already recognized leaders of their fields – now they are bringing with them the message of EQuS as a world-player, leading developments for the future of quantum technologies. EQuS CIs and PIs have participated in some of the most prestigious technical programs in the quantum science community, with senior leadership roles, senior invited talks, and steering committee memberships.

Interest in our work is touching the imagination of the general public; EQuS research, in collaboration with teams all over the world, saw extraordinary media attention this year. Feature articles on EQuS research appeared in The Guardian, Sky News, Popular Science, The Australian, The Sydney Morning Herald, ABC, and many other outlets. EQuS CIs were interviewed on ABC News Breakfast, ABC Lateline, SBS World News, and many radio programs. We engaged with school teachers and gave public lectures in the nation's leading science-outreach efforts. Our work is delivering on our promises to engage the community on the importance and excitement surrounding cutting-edge research, and is making EQuS a focus of international interest in the promise of Quantum Science and Engineered Quantum Systems.

However, we are more than just our CIs. In 2012 EQuS comprised of 57 students and 40 postdoctoral researchers across our five nodes. We are providing an unprecedented training ground for Australia's most promising students, building capacity for a highly skilled workforce capable of owning the quantum future. We are attracting world-class researchers to join our Centre and participate in Centre activities, including our annual workshop which this year was attended by 112 staff and students and included research leaders from Physikalisch-Technische Bundesanstalt in Germany, University of California Santa Barbara, and many other organisations. EQuS is a key destination internationally – and our ability to attract high-profile visiting academics and student interns serves our mission of providing the best research-training and educational opportunities in the field.

Finally, our work has already led to the production of novel IP and potential spin-offs, including new research programs derived from core EQuS research and now focused on “classical” technologies including new types of atomic clocks and new classical magnetometers. Our work is delivering near-term benefits in just the way we foreshadowed in our Centre application – necessity is the mother of invention and we are now producing exciting new technological advances derived from our core research path. These successes are recognized by major funding streams coming from, e.g. the US Defence Advanced Research Projects Agency, DARPA.

We trust that the material that follows in our Research Report will explain how our Centre is delivering on our aims, engineering the quantum future, and making Australia the focal point for global efforts in developing tomorrow’s technologies.

Professor Gerard Milburn

Director, ARC Centre of Excellence for Engineered Quantum Systems

'Our CIs hit the ground running – pushing the frontiers of knowledge with their own research, building an international reputation for our Centre, spinning-off new technologies and forging strong bonds across Centre nodes and around the world.'

ORGANISATION AND GOVERNANCE

Centre Governance and Management Structure

In 2011, the Centre was formed as a partnership of the collaborating institutions under a formal Centre Agreement, with The University of Queensland as the administering institution.

Organisational Chart

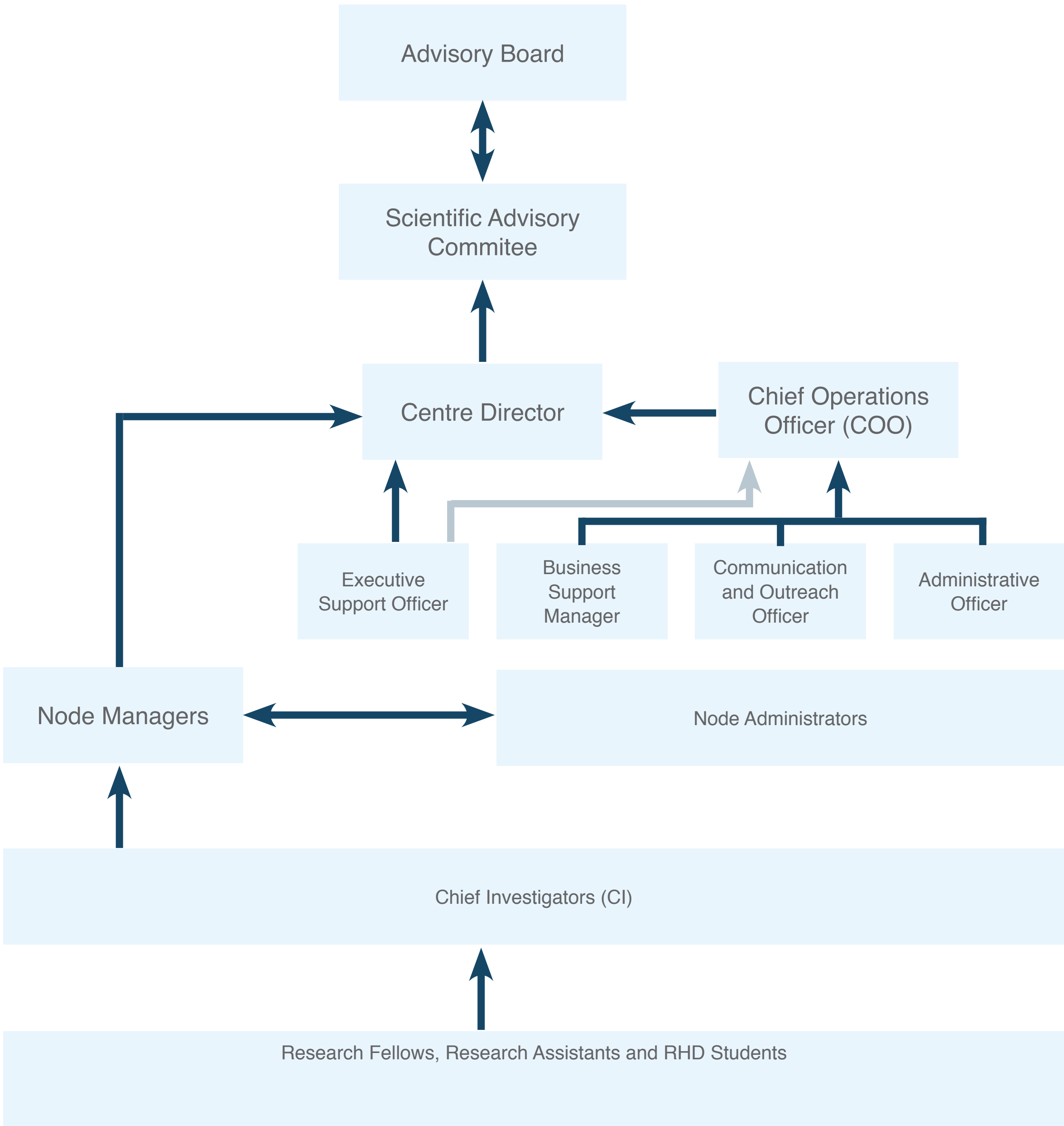


Figure 1 Organisational Chart

Advisory Board

The Advisory Board assists Centre management by contributing to the development of strategies and vision for the future relative to the proposed goals and objectives of the Centre, and by serving as a vehicle for creating better linkages between academia, industry and government.

The Advisory Board met on April 4, 2012.

In 2012, the Centre's Advisory Board comprised:

Dr Rowan Gilmore (Chair)

CEO
EM Solutions Pty Ltd
Brisbane

Dr Ben Greene

Group CEO
Electro Optic Systems (EOS)
Canberra

Professor Alan Lawson

Acting DVC Research
The University of Queensland
Brisbane

Mr Rick Wilkinson

COO – Eastern Region
Aust. Petroleum Production & Exploration Assoc.
Brisbane

Professor Jim Piper

DVC Research
Macquarie University
Sydney

Dr David Pulford

Senior Research Scientist
DSTO
Canberra

Professor Jill Trewhella

DVC Research
The University of Sydney
Sydney

Dr Peter Russo

CEO
Australian Science Teachers Association (ASTA)
Canberra

Professor Robyn Owens

DVC Research
The University of Western Australia
Perth

Professor Les Field

DVC Research
The University of New South Wales
Sydney

Professor Gerard Milburn

EQuS Centre Director (ex officio)
The University of Queensland
Brisbane

Professor Andrew White

EQuS Deputy Director (ex officio)
The University of Queensland
Brisbane

Ms Marianne Johnston

EQuS Chief Operations Officer (ex officio)
The University of Queensland
Brisbane

Program Managers (CI) Committee

The Centre Program Managers or Chief Investigators Committee is responsible for a process of continuous quality assessment of the major programs of the Centre, the provision of feedback to the Advisory Board and Scientific Advisory Committee on the progress being made in the Centre's research programs and against its research objectives and milestones. It works to provide academic leadership and cohesion within the Centre, and oversees continuity of research approach and communication between research nodes.

The Centre Program Managers Committee comprises the Chief Investigators at the participating collaborating organisations (The University of Queensland, The University of Sydney, Macquarie University, The University of Western Australia, and The University of New South Wales) and the Centre Chief Operations Officer, and is chaired by the Centre Director.

The Centre's Program Managers Committee met on the following dates in 2012.

DATE	VENUE
27 April	The University of Sydney
20 July	The University of Queensland
2 November	Macquarie University

Program Managers Meeting The University of Sydney April 2012

Scientific Advisory Committee

The Scientific Advisory Committee (SAC) comprises the Research Director, the Advisory Board Chair, international scientists and experts in quantum science and engineering, and an eminent international researcher, Professor Sir Peter Knight FRS, as an independent chair. The SAC is responsible for advising the Centre Research Director and the Centre Program Managers Committee on the direction of research undertaken within the Centre and providing guidance on emerging international trends and scientific developments as they relate to the major programs of the Centre.

The Centre's Scientific Advisory Committee comprises:

Professor Sir Peter Knight, FRS (Chair)

Kavli Centre
United Kingdom

Professor Mikhail Lukin

Harvard University
United States

Professor Rainer Blatt

University of Innsbruck
Austria

Professor Gerard Milburn

The University of Queensland
Australia

Professor John Clarke

University of California, Berkeley
United States

Dr Rowan Gilmore

EM Solutions Pty Ltd
Australia

CENTRE PERSONNEL

Chief Investigators

Professor Gerard Milburn

THE UNIVERSITY OF QUEENSLAND

Centre Director & Chief Investigator
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Professor Gerard Milburn obtained a PhD in theoretical Physics from the University of Waikato in 1982 for work on squeezed states of light and quantum nondemolition measurements. He is currently an Australian Research Council Federation Fellow at the University of Queensland and the Chair of the Scientific Advisory Committee of the Institute for Quantum Computing in Canada. Professor Milburn is also a Fellow of the Australian Academy of Science and The American Physical Society. He has worked in the fields of quantum optics, quantum measurement and stochastic processes, atom optics, quantum chaos, mesoscopic electronics, quantum information and quantum computation. More recently, he established a new experimental and theoretical research program in quantum nanomechanics and circuit quantum electrodynamics at The University of Queensland.

Professor Andrew White

THE UNIVERSITY OF QUEENSLAND

Deputy Director, UQ Node Manager & Chief Investigator
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Professor Andrew White was raised in a Queensland dairy town, before heading south to the big smoke of Brisbane to study chemistry, maths, physics and, during the World Expo, the effects of alcohol on university students from around the world. Deciding he wanted to know what the cold felt like, he first moved to Canberra, then Germany—completing his PhD in quantum physics—before moving on to Los Alamos National Laboratories in New Mexico where he quickly discovered that there is more than enough snow to hide a cactus, but not nearly enough to prevent amusing your friends when you sit down. Over the years he has conducted research on various topics including shrimp eyes, nuclear physics, optical vortices, and quantum computers. He likes quantum weirdness for its own sake, but his current research aims to explore and exploit the full range of quantum behaviours—notably entanglement—with an eye to engineering new technologies and scientific applications.

Associate Professor Warwick Bowen

THE UNIVERSITY OF QUEENSLAND

Chief Investigator
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Associate Professor Warwick Bowen leads the Queensland Quantum Optics Group at The University of Queensland, and is a program manager in the ARC Centre of Excellence for Engineered Quantum Systems. His group's research is primarily focused on applications of silicon chip based optical microresonators in fundamental science, photonics and sensing. Warwick's research background is in quantum optics and photonics, and particularly in the emerging fields of quantum information science and quantum optomechanics. These fields rely critically on the development of new techniques to generate and control non-classical states of systems such as optical fields, atoms, and micromechanical cantilevers. Warwick has worked on each of these systems, aiming to investigate their quantum behaviour, use it in quantum technologies, and spin off real-world applications.

Dr Arkady Fedorov

THE UNIVERSITY OF QUEENSLAND

Chief Investigator
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Dr Arkady Fedorov completed his PhD studies at Clarkson University, USA in 2005. His research work was primarily on theoretical aspects of quantum information science and decoherence in solid state systems. He was then appointed a postdoctoral fellow at Karlsruhe Institute of Technology, Gemany working on a theory of superconducting quantum circuits in application to quantum computing and quantum optics phenomena. In 2007-2010 he worked in TU Delft, The Netherlands conducting experiments with superconducting flux qubits. Later he became a research scientist in ETH Zurich to continue research in the area of superconducting quantum devices. Starting January 2013 he is a group leader at The University of Queensland. His group studies quantum phenomena in systems consisting of superconducting artificial atoms, microwave resonators and mechanical oscillators.

Professor Halina Rubinsztein-Dunlop

THE UNIVERSITY OF QUEENSLAND

Chief Investigator
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Professor Halina Rubinsztein-Dunlop's research interests are in the fields of atom optics, laser micromanipulation, nano optics, quantum computing and biophotonics. She has long standing experience with lasers, linear and nonlinear high-resolution spectroscopy, laser micromanipulation, and atom cooling and trapping. She was one of the originators of the widely used laser enhanced ionisation spectroscopy technique and is well known for her recent work in laser micromanipulation. She has been also working (Nanotechnology Laboratory, Göteborg, Sweden) in the field of nano- and microfabrication in order to produce the microstructures needed for optically driven micromachines and tips for the scanning force microscopy with optically trapped stylus. Recently she led the team that observed dynamical tunnelling in quantum chaotic system. Additionally Professor Rubinsztein-Dunlop has led the new effort into development of new nano-structured quantum dots for quantum computing and other advanced device related applications.

Dr Ian McCulloch

THE UNIVERSITY OF QUEENSLAND

Chief Investigator
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Dr Ian McCulloch leads the Tensor Network Algorithms group that works in computational tensor network algorithms for one- and two-dimensional quantum systems, and applications to condensed matter, ultra-cold atomic gases and engineered quantum systems. The group has ties to experimental groups at The University of Queensland and other institutions.Ian graduated with a BSc from the University of Tasmania in 1997. After a PhD in condensed matter physics at ANU, he moved overseas, firstly to the Lorentz Institute in Leiden, The Netherlands, and then to RWTH-Aachen University in Germany. In 2007 he moved back to Australia to take up a postdoctoral fellowship, and later a lecturing position, at The University of Queensland. Ian's research interests are numerical techniques for simulating quantum many-body systems, and he is the author of a large suite of software tools that are used by several research groups around the world.

Dr Tom Stace

THE UNIVERSITY OF QUEENSLAND

Chief Investigator
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Dr Tom Stace completed his PhD at the Cavendish Laboratory, University of Cambridge in the UK on quantum computing, followed by postdoctoral research at the Department of Applied Mathematics and Theoretical Physics, also at Cambridge. During this time he was a fellow at Queens' College, known for its eclectic mix of medieval, tudor and victorian architecture. He has been a researcher at The University of Queensland since 2006, firstly on an ARC Postdoctoral Research Fellowship, and latterly with an ARC Research Fellowship. His research has largely focused on applying methods from quantum optics to solid state devices for use in quantum information applications, and more recently on error correction protocols. He also works on high precision measurement in collaboration with experimental colleagues at The University of Western Australia, in a project whose ultimate aim is to contribute to the international definition of Boltzmann's constant, and some biophysics.

Professor Stephen Bartlett

THE UNIVERSITY OF SYDNEY

USYD Node Manager & Chief Investigator
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Professor Stephen Bartlett is a theoretical physicist in the School of Physics at The University of Sydney, and part of the Quantum Information Theory group. He is pursuing fundamental research in quantum physics, his particular focus is on quantum information theory, including the theory of quantum computing, as well as the foundational issues of quantum mechanics.Professor Stephen Bartlett completed his PhD in mathematical physics at the University of Toronto in 2000. Moving to Australia, he directed his research to the theory of quantum computing, first as a Macquarie University Research Fellow and then as an ARC Postdoctoral Research Fellow at the University of Queensland. Since 2005, he has lead a research program in theoretical quantum physics at The University of Sydney, with interests spanning quantum computing, quantum measurement and control, quantum many-body systems, and the foundations of quantum theory.

Dr Michael Biercuk

THE UNIVERSITY OF SYDNEY

Chief Investigator
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Dr Michael Biercuk is an experimental physicist and the Primary Investigator in the Quantum Control Laboratory at The University of Sydney. Michael's specialties include quantum physics, quantum control, quantum error suppression, ion trapping, nanoelectronics, and precision metrology. Michael was educated in the United States, earning his undergraduate degree from the University of Pennsylvania, and his Master's and Doctoral degrees from Harvard University. Today, Michael runs a research group performing cutting-edge experiments using trapped atomic ions as a model quantum system. His expertise has been recognized by numerous technical appointments, awards, and media appearances. He is a regular contributor to both the technical literature and the popular press, providing expert commentary on issues pertaining to science policy and the role of science in society.

Associate Professor Andrew Doherty

THE UNIVERSITY OF SYDNEY

Chief Investigator
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Associate Professor Andrew Doherty is a theoretical physicist and senior lecturer with research interests in quantum control and quantum information at The University of Sydney. He holds an Australian Research Council Future Fellowship in the School of Physics at The University of Sydney. He received a BSc (Hons) in Physics from the University of Canterbury in 1995 and his PhD in quantum optics under the supervision of Professor Dan Walls at The University of Auckland in 2000. From 2000 to 2003 he was a postdoctoral researcher at the California Institute of Technology and from 2003 to 2010 he was at the School of Mathematics and Physics at The University of Queensland.

Associate Professor David Reilly

THE UNIVERSITY OF SYDNEY

Chief Investigator
Phone: +61 2 9351 8167
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Associate Professor David Reilly is the Director of the Quantum Nanoscience Laboratory at the University of Sydney where he leads a Group of 7 PhD students and 3 postdoctoral research fellows. The focus of his research is the development of enabling technology to control condensed matter systems at the quantum level. Reilly's niche is the interface between fundamental quantum science research and technical solutions that typically involve microwave electronics, cryogenics, nanofabrication, and engineering expertise. Before his appointment at Sydney, Associate Professor Reilly was a research fellow in Physics at Harvard University, USA. His PhD is in Physics from the University of New South Wales, Australia.

Professor Jason Twamley

MACQUARIE UNIVERSITY

MQ Node Manager & Chief Investigator
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Professor Jason Twamley is a Professor of Quantum Information Science at the Department of Physics and Astronomy at Macquarie University. He is a theorist who works in quantum science and has worked on topics ranging from the theory of quantum wormholes in quantum cosmology through to the theoretical designs for superconducting quantum devices. Professor Twamley believes that the world is essentially quantum mechanical in nature and we should therefore learn the fascinating properties of this quantum world and use these properties to create new science and technology. He is also Director of the Macquarie University, Quantum Science & Technology (QSciTech).

Associate Professor Gavin Brennen

MACQUARIE UNIVERSITY

Chief Investigator
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Associate Professor Gavin Brennen is an Associate Professor of the Physics & Astronomy Department at Macquarie University. Gavin believes that nature is a wondrous place and an unfinished product. As a result, his main interests are how to use the physical laws we know, particularly quantum mechanics, to probe in ever more exquisite detail the manifestations of nature—from elementary interactions to collective behaviour of complex many particle systems. His more general research interests are quantum information theory, coherent control of atomic/molecular/optical systems, topological order and topological quantum computation.

Associate Professor Alexei Gilchrist

MACQUARIE UNIVERSITY

Chief Investigator
Phone: +61 2 9850 4443
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Associate Professor Alexei Gilchrist is a theoretical physicist in the research areas of quantum optics and quantum information. He received his PhD from Waikato University (New Zealand) in 1997 under the supervision of Professor Crispin Gardiner. Moving to Australia in 2001 as a New Zealand FRST Fellow, he remained in Australia as a research fellow for the ARC COE Centre for Quantum Computer Technology until becoming part of the faculty at Macquarie University in 2007. Associate Professor

Gilchrist was appointed as an EQuS CI in 2011.

Associate Professor Gabriel Molina-Terriza

MACQUARIE UNIVERSITY

Chief Investigator
Phone: +61 2 9850 6371
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Associate Professor Gabriel Molina-Terriza is an Associate Professor of the Physics & Astronomy Department at Macquarie University. At Macquarie University he is the group leader of QIRON (Quantum InteRactiOns with Nanoparticles). Whilst he admits the acronym is rather contrived, he likes being part of a research group based on a mythical centaur who was the master and teacher of several heroes. His research focuses on the spatial properties of light and uses the spatial modes of light as a tool to prove the existence of nanostructures and to store and retrieve quantum information, using engineered quantum states. Further, Associate Professor Molina-Terriza's group is experimentally combining the techniques of quantum optics and new methods available in nanophotonics, in order to study and control the fundamental interactions of light and matter at the nanoscale. For more information about the mythical centaur named QIRON visit en.wikipedia.org/wiki/Chiron

Dr Thomas Volz

MACQUARIE UNIVERSITY

Chief Investigator
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Dr Thomas Volz is a senior lecturer at Macquarie University specializing in solid-state quantum optics and quantum photonics. During his PhD, he carried out experiments on ultra cold atomic and molecular quantum gases in optical lattices in the group of Professor Gerhard Rempe at the Max-Planck Institute of Quantum Optics in Garching (Germany). He was awarded his PhD in 2007 through the Technical University of Munich (Germany). Afterwards Dr Volz changed fields and joined Professor Atac Imamoglu's Quantum Photonics Group at ETH Zurich (Switzerland) where he carried out experiments on semiconductor cavity QED. At Macquarie University, he will continue his research in semiconductor quantum optics, but in addition, will lead the nano-diamond laboratory which specializes in quantum sensing and metrology using nano-diamond. Dr Volz was appointed an EQuS CI in January 2013.

Professor Michael Tobar

THE UNIVERSITY OF WESTERN AUSTRALIA

UWA Node Manager & Chief Investigator
Phone: +61 4 0487 2944
Email: michael.tobar@uwa.edu.au

Professor Michael Tobar is currently an ARC Laureate Fellow with the School of Physics at the University of Western Australia. He received his PhD degree in physics from the University of Western Australia in 1994. His research interests encompass the broad discipline of frequency and quantum metrology, precision measurements, and precision tests of the fundamental of physics. Professor Tobar has had many career highlights since graduating including being elected to the Australian Academy of Science (2012), the award of the Barry Inglis medal (2009), awarded membership of the Australian Academy of Technological Sciences and Engineering (2008), elevated to Fellow of the Institute of Electrical and Electronics Engineers (IEEE) (2007) and receiving the Australian Institute of Physics Boas medal (2006). More recently Professor Tobar received a citation from the Australian Learning and Teaching Council for inspiring research students to reach their full potential and transform to successful research scientists through participation in ground-breaking research.

Professor Tim Duty

THE UNIVERSITY OF NEW SOUTH WALES

UNSW Node Manager & Chief Investigator
Phone: +61 2 9385 4077
Email: t.duty@unsw.edu.au

Professor Tim Duty is a native of Virginia in the USA. He received a BSc degree in physics from Virginia Tech, then a MSc degree and a PhD degree from the University of British Columbia. He has done postdoctoral research at the University of Erlangen-Nuernberg in Germany and Chalmers University of Technology in Gothenburg, Sweden. Following this, Tim Duty took up the position of Research Assistant Professor in the Quantum Device Physics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology before moving to The University of Queensland in Australia. Currently, Tim Duty is based at The University of New South Wales.

Management and Administration Personnel

Ms Marianne Johnston

THE UNIVERSITY OF QUEENSLAND

Chief Operations Officer
Phone: +61 7 3346 9692
Email: m.johnston5@uq.edu.au

Ms Marianne Johnston oversees the day-to-day management of the Centre assuming responsibility for the Centre's reporting requirements, research operations and planning, and the administration of financial, human and physical resources.

Mrs Ruth Forrest

THE UNIVERSITY OF QUEENSLAND

Executive Support Officer
Phone: +61 7 3346 7953
Email: r.forrest@physics.uq.edu.au

Mrs Ruth Forrest provides administrative and secretarial support to the Centre Director and Chief Operations Officer, and secretariat support to the Centre Advisory Board.

Mr Eric Pham

THE UNIVERSITY OF QUEENSLAND

Business Support Manager
Phone: +61 7 3346 6495
Email: eric.pham@uq.edu.au

Mr Eric Pham's primary role is to provide financial management and administrative support to the Centre Director and Chief Operations Officer in managing financial and selected human resource functions of the Centre.

Mrs Emma Linnell

THE UNIVERSITY OF QUEENSLAND

Administration Officer
Phone: +61 7 3346 6495
Email: e.linnell@uq.edu.au

Mrs Emma Linnell provides a high level of customer service and broad administrative support to staff, students and visitors of the EQuS Centre. Emma has a particular focus on Deputy Director Andrew White's research group ensuring it runs efficiently and effectively.

Ms Lynelle Ross

THE UNIVERSITY OF QUEENSLAND

Communication and Outreach Officer
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Email: lynelle.ross@uq.edu.au

Ms Lynelle Ross promotes the Centre through the design, development and implementation of a comphrensive marketing and communication program.

Ms Leanne Price

THE UNIVERSITY OF SYDNEY

USYD Node Administrator
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Email: l.price@physics.usyd.edu.au

Ms Leanne Price provides high level administration and support for HR, finance and events at The University of Sydney node of EQuS (60%) & Reilly's Overseas Government Organisation project (40%).

Mrs Lynne Cousins

MACQUARIE UNIVERSITY

MQ Node Administrator
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Mrs Lynne Cousins provides a high level of customer service and broad administrative support to staff, students and visitors of the EQuS Node at Macquarie University.

Ms Adia Yu

THE UNIVERSITY OF WESTERN AUSTRALIA

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Ms Adia Yu provides a high level of customer service and broad administrative support to staff, students and visitors of the EQuS Node at The University of Western Australia.

Keith Motes, Peter Rohde (MQ) and James Bennett (UQ) at EQuS Annual Dinner December 2012

Researchers

THE UNIVERSITY OF QUEENSLAND

- Uzma Akram
- Cyril Branciard
- Matthew Broome
- Robin Cole
- Gregory Crosswhite
- Matthew Davis
- Marcelo De Almeida
- Alessandro Fedrizzi
- Ivan Kassal
- David McAuslan
- Casey Myers
- Tyler Neely
- Jacopo Sabbatini
- Eoin Sheridan
- Till Weinhold
- Fei Zhan

THE UNIVERSITY OF SYDNEY

- Sylvain Blanvillain
- Carlo Bradac
- Steven Flammia
- Torsten Gaebel
- Stephen Gensemer
- David Hayes
- Michael Lee
- Aroon O'Brien
- Andres Reynoso

THE UNIVERSITY OF NEW SOUTH WALES

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- Jean-Loup Smirr

MACQUARIE UNIVERSITY

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- Andrew Edmonds
- Mathieu Juan
- Peter Rohde
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- Xavier Vidal
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- Devon Biggerstaff
- George Brawley
- Matthew Broome
- Bixuan Fan
- Adil Gangat
- Geoffrey Gillett
- Glen Harris
- Phien Ho
- Marcel Horstmann
- Juan Loredo
- Yarema Reshitnyk
- Martin Ringbauer
- Andrew Ringsmuth
- Javad Shadbad
- Devin Smith
- Jon Swaim
- Alexander Szorkovszky
- Michael Taylor

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- Simon Burton
- James Colless
- Xanthe Croot
- Andrew Darmawan
- Dominic Else
- Todd Green
- John Hornibrook
- Prashant (Siva) Kumar
- Alice Mahoney
- Matthew Palmer
- Ewa Rej
- Alexandr Sergeevich
- William Soo
- Maki Takahashi
- Caryn van Vreden
- David Waddington
- Joel Wallman
- Matthew Wardrop

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- Aharon Brodutch
- Mauro Cirio
- Michael Delanty
- Tommaso Demarie
- Hossein Tavakoli Dinani
- Ivan Fernandez-Corbaton
- Faraz Inam
- Laurie Lehman
- Andrew Rigby
- Nora Tischler
- Xavier Zambrana Puyalto

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- Romain Bara
- Jeremy Bourhill
- Daniel Creedon
- Warrick Farr
- Nitin Nand

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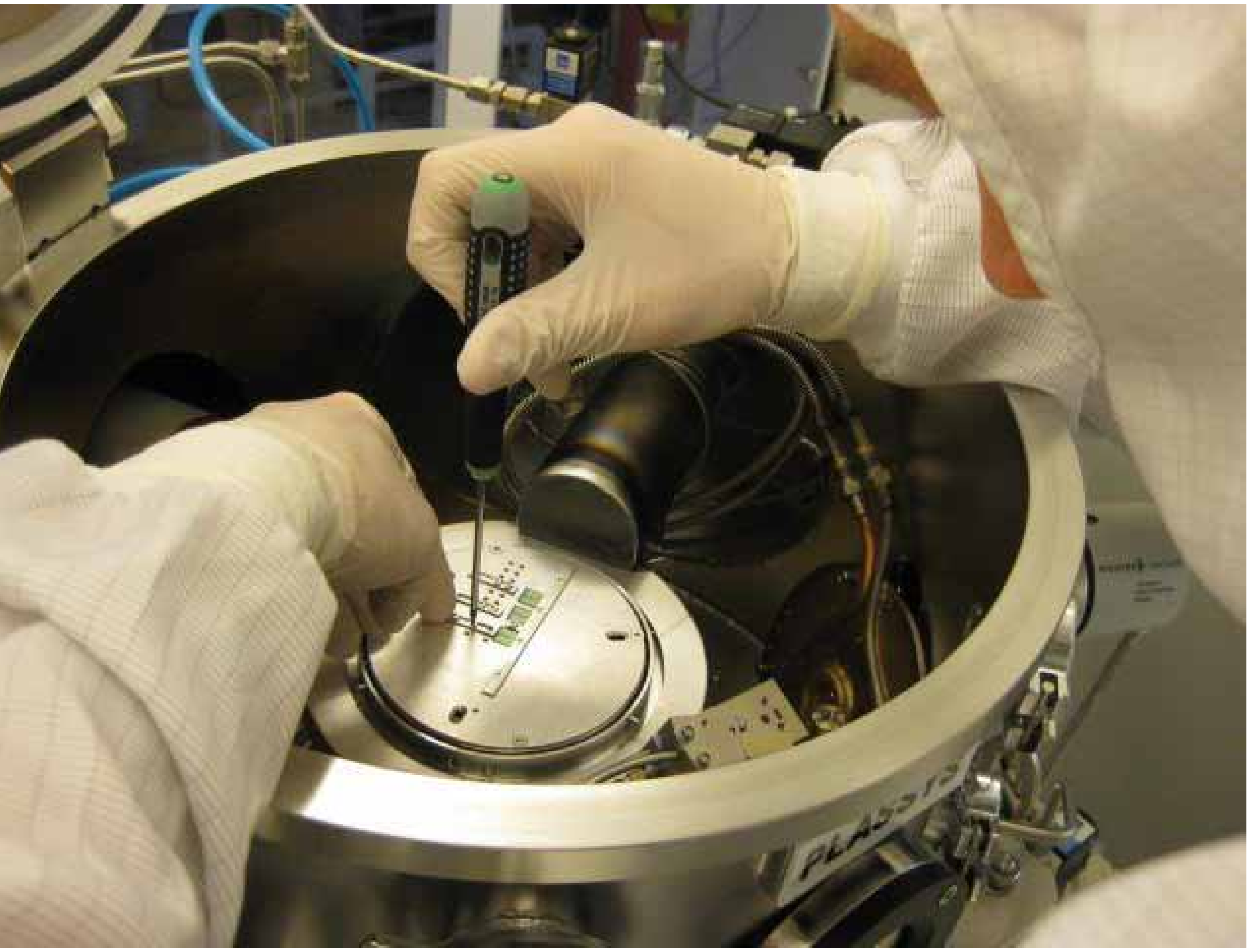
- Trond Linjordet

OUR MISSION

To exploit the vast resources of the quantum realm to produce new capabilities, new technologies, and new science through the creation of designer quantum systems.

Objectives

- To establish a world-leading research community driving the development of quantum technologies, with Australia as the focus of international efforts
- To stimulate the Australian scientific and engineering communities to exploit quantum devices and quantum coherence in next-generation technologies
- To train a generation of young scientists with the skills needed to lead the future of quantum technology development
- To demonstrate the potential and capabilities of engineered quantum technologies by realising technological breakthroughs in novel and useful engineered quantum coherent systems
- To create a design methodology supporting the development of all technologies for the Quantum Era



Loading microchips into a 2 angle aluminium evaporator, Yarema Reshitnyk, UQ, student

INFRASTRUCTURE

Our Centre of Excellence includes world-leading experimental infrastructure focused on a broad spectrum of technologies. Our efforts represent the absolute cutting-edge of capability in quantum control and quantum systems engineering.

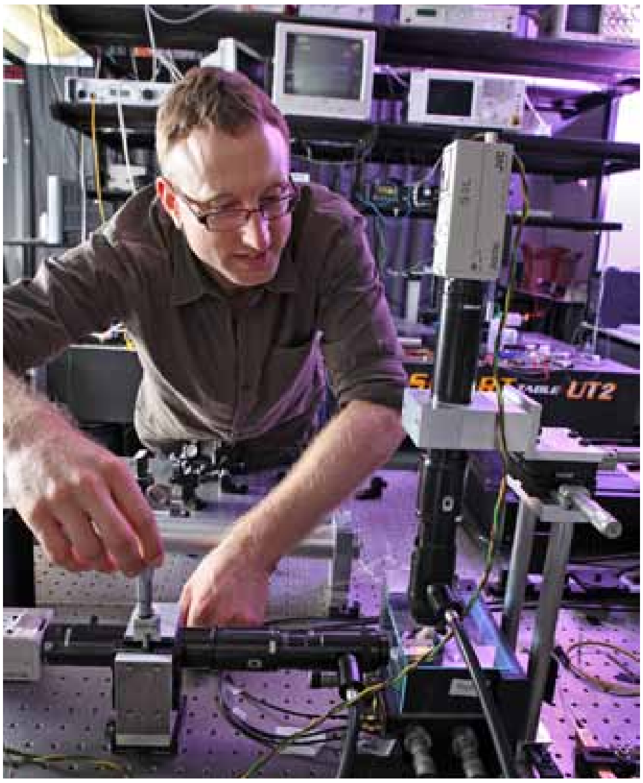
Dr Matt Broome working in the Quantum Technology Laboratory

The Quantum Technology Laboratory – The University of Queensland

The Quantum Technology Laboratory is focused on emulating both natural and engineered quantum systems by using quantum photonics, a proven and flexible architecture for investigating exotic quantum phenomena, to enable new applications from secure communications through to improved metrology. The Laboratory has extensive quantum photonics facilities, including the world's highest-efficiency entangled photon source, integrated photonic circuits, and highly efficient cryogenic calorimeters that can be used to count individual photons.

The Queensland Quantum Optics Laboratory – The University of Queensland

The Queensland Quantum Optics Laboratory undertakes research in the quantum physics of microscale optical devices, with the aims of both testing fundamental physics, and developing quantum technologies with future applications in metrology, communication, and computation. Our research is primarily based around optical architectures integrated onto silicon chips compatible with current-day fibre optic systems. These architectures provide a test-bed from which we can study a wide range of quantum processes including entanglement and non-locality, and quantum optomechanical systems. The robustness and scalability of the systems used offers potential for the investigation of large-scale quantum systems and phenomena. The laboratory has Australia's only fabrication facilities for silicon chip based ultra-high quality optical microcavities, and one of only a few such facilities in the world. The laboratory also has cryogenic facilities allowing operation of quantum devices at temperatures as low as 0.3 K; multiple laser sources; and a range of radio frequency test and measurement systems.



Associate Professor Warwick Bowen at work in The Queensland Quantum Optics Laboratory

The Atom Optics Laboratory – The University of Queensland

The Atom Optics Laboratory provides access to ultra cold atoms and allows for sophisticated quantum atom optics precision measurements to be carried out using custom made ultra-high vacuum chambers, a suite of highly stabilized lasers, custom made electronics and optics with sophisticated imaging technologies.

The Superconducting Quantum Devices Laboratory – The University of Queensland

In 2009, a new low temperature laboratory for investigating superconducting quantum circuits based on Josephson junctions was established at The University of Queensland. This equipment was initially funded by Milburn's Federation Fellowship grant and established by Senior Lecturer Dr Tim Duty. The laboratory enables ultra-low noise electronic measurements at milliKelvin temperatures and contains an Oxford instruments DR200 dilution refrigerator and auxiliary equipment. New equipment will be installed in 2012 upon the appointment of Dr Fedorov.

The Superconducting Single-Charge Device Laboratory (SSCDL) – The University of New South Wales

Superconducting quantum circuits are artificial structures with a possibility to design and engineer their key properties. These unique features have made these engineered systems to be one of the most promising candidates for realizing a quantum computer in solid state, have allowed for exploration of quantum optical phenomena on-chip and have facilitated the implementation of a quantum control of a nanomechanical degree of freedom. Superconducting Quantum Devices Laboratory aims at establishing fabrication and measurement techniques for the next generation of superconducting nanodevices consisting of superconducting qubits or artificial atoms, microwave transmission lines and high quality superconducting resonators. By using strong coupling strength between single microwave photon and a superconducting qubit in these networks, one can realise a plethora of novel light-matter interaction regimes. The results will help to establish a toolbox for future quantum technology based on photons in microwave frequency domain.

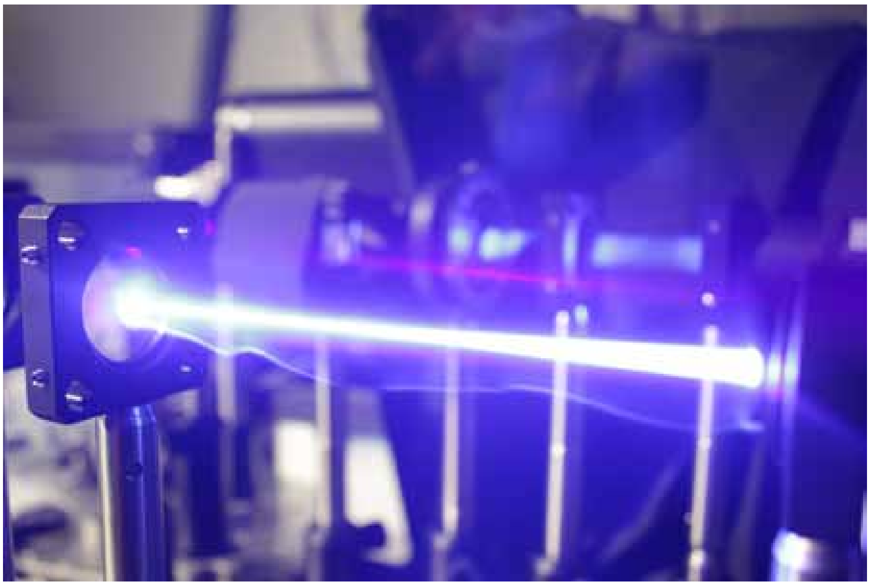
The Diamond Nanoscience Laboratory – Macquarie University

The Diamond Nanoscience Laboratory is based at Macquarie University. It is focused on cross-disciplinary research activities in quantum physics, nanotechnology and material science, including the growth and post-processing of nano-diamonds for use in the emerging fields of quantum technology, single particle probing, magnetic sensing and microscopy. The laboratory has the capability, via two confocal microscopes, to identify single fluorescent defects in diamond and related materials. An atomic force microscope (AFM), integrated with one of the confocal systems, enables the correlation of confocal maps with the size of the nanoparticles. In addition to the laser used for excitation, the samples can also be probed using microwave signals that can modify the electron spin of the investigated defects.

Major achievements of this laboratory in 2012 were the first use of nano-rubies as confocal-microscopy imaging probes in biological samples. Further studies on the blinking properties of NV centres in nano-diamonds were performed. The fundamental properties of the spontaneous emission of NV centres in diamond have been studied by incorporating nano-diamonds in an aerogel composite, determining the quantum efficiency of an NV defect centre in nano-diamond for the first time.

The Diamond Nanoscience Laboratory at Macquarie University

The QIRON Laboratory – Macquarie University



The QIRON Laboratory is based at Macquarie University. The aim of the laboratory is to study and control the properties of the smallest structures that can be fabricated to date. In particular, we are interested in controlling the quantum properties of metallic structures. The fabrication capabilities that exist nowadays allow for realization of a diversity of geometries on the nanoscale, i.e. structures with features with sizes in one part in a million of a millimetre. These particles can confine an electron gas (plasma) in a very small volume, which can then couple very strongly with optical fields forming so called plasmons. In our laboratory we combine the techniques of quantum optics and nanooptics in order to discover new physical phenomena at those scales. In the laboratory we prepare quantum sources of light to interact with very small particles and structures (of the order of one part in one million of a millimetre, i.e. the nanometre). Our quantum sources of light emit optical radiation in a very special state. We take the smallest amount of light that Nature allows, the photon, and engineer states of light with just a few photons which are strongly correlated in their properties: timing, colour, direction, etc. These correlations are much stronger than any classical source of light, like a laser or a bulb, can produce. We use these properties to control and measure with a much higher precision our small structures. The laboratory is equipped with a set of tools which allow us to control the properties of light in a very precise manner. We can control the angular momentum of the light (the amount of torque that light can transfer to material particles) with spatial light modulators, we have laser sources capable of producing very short pulses of light (around 100 femtosecond) and also very stable continuous wave lasers with very small bandwidths.

The Quantum Nanoscience Laboratory – The University of Sydney

The Quantum Nanoscience Laboratory offers extensive measurement capability combining ultra-low temperatures (10 milli-Kelvin) with a suite of radio and microwave frequency electronics and test equipment. These facilities enable a range of nanoscale quantum systems to be investigated at low temperature, high magnetic field, and on short timescales, where exotic quantum phenomena become apparent.

The Quantum Nanoscience Laboratory

Karim Benmessai working in The Frequency and Quantum Metrology Laboratory

The Frequency and Quantum Metrology Laboratory – The University of Western Australia

The Frequency and Quantum Metrology Laboratory, run by CI Michael Tobar, has a long history of research in precision measurement, materials characterisation, ultra-high Q-factor resonators, and the development of frequency stable, low phase noise instruments with world-class precision and performance. One such device, the Cryogenic Sapphire Oscillator, is now found in metrological laboratories around the globe, and has allowed atomic fountain clock technology to reach its ultimate performance, as well as being used in some of the most precise tests of fundamental physics ever performed. The group's research has also led to a number of practical technologies that have been successfully patented and commercialised. The laboratory offers access to two 4 K pulse-tube cryogenic systems, one 30 K system, and a BlueFors cryogen-free dilution refrigerator capable of reaching 10 mK. The laboratory is also well equipped with many sophisticated microwave diagnostic technologies such network analysers, synthesizers, and spectrum analysers from RF to millimetre wave frequencies. The laboratory possesses a hydrogen maser which is distributed as a frequency reference in addition to several Cryogenic Sapphire Oscillators developed in-house that allow microwave signals to be synthesized with frequency stability of better than 1 part in 1000 trillion.

EQuS RESEARCH PROGRAMS

Delivering on Grand Challenges

Our Centre is organized around carefully crafted research programs and individual projects.

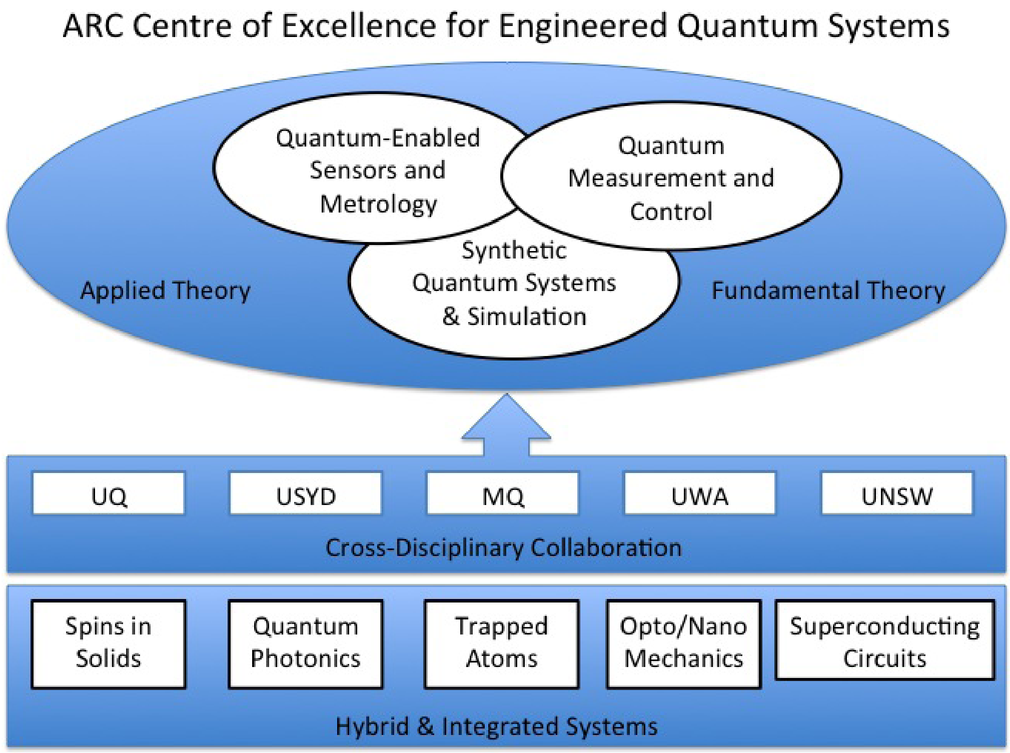


Figure 2 EQuS Research Themes

Quantum Measurement and Control addresses scientific challenges in quantum limited measurement and control, to enable demonstrations of quantum solutions for control engineered problems in each technology platform.

Quantum-Enabled Sensors and Metrology delivers unprecedented levels of sensitivity and precision in applications of quantum systems for sensing, biomedical imaging, and metrology.

Synthetic Quantum Systems and Simulation produces novel states of light and matter exhibiting strong quantum mechanical correlations that enable simulations of complex interacting quantum systems.

All of our investigators, however, share a passion for pushing the limits of quantum technology. This is captured in our creation of EQuS Grand Challenges that lay out our vision of some of the most important – and of course challenging – technical questions in the field.

Quantum Measurement and Control

- Realise new capabilities through the development of a comprehensive and flexible quantum control toolkit. Specific example: Preserve quantum states against decoherence indefinitely using optimised quantum control, quantum feedback, open-loop protocols, weak measurement and projective measurement.
- Realise new and otherwise inaccessible regimes of physics through the construction of hybrid quantum systems. Specific example: achieve macroscopic mechanical entanglement to test the interplay between quantum mechanics and general relativity.
- Develop design principles for robust control of hybrid quantum systems and demonstrate their utility in experimental applications.

Quantum-Enabled Sensors and Metrology

- Realise sub-cellular, in vivo, imaging in real time with microsecond time-resolution using biocompatible nano-particles and spin manipulation.
- Use quantum mechanical coherence to produce enhanced sensing technologies with unrivalled performance. Specific example: use nanoscale diamonds as ultra-sensitive probes of magnetic fields in industrial and biological environments.
- Achieve new field and force sensing regimes using arrays of quantum controlled mechanical oscillators. Specific example: characterize the structure of an uncrystallisable protein using single-molecule MRI with integrated cavity optomechanics.

Synthetic Quantum Systems and Simulation

- Produce programmable quantum simulators capable of outperforming the best classical technology. Specific example: simulate quantum chemistry using conditional linear optics and photosynthesis using electromechanical systems.
- Achieve complete control over individual quantum particles in a strongly interacting many-body system with tunable interactions. Specific example: engineer synthetic quantum system with controllable topological order.
- Address key fundamental theoretical questions. For example: when can one quantum system simulate another? How can one know that a quantum simulation is correct, or even quantum?

All of our research activities tie in to these Grand Challenges, with an aim of progressing towards them by the conclusion of the Centre.

In 2012 our research saw remarkable advances against several of our most ambitious Grand Challenges. The Centre is well positioned to exceed its extraordinary technical objectives and truly lay the groundwork for the future of quantum technology.

AN EQuS SPINOFF

Research performed as part of CI Bowen's program on optomechanical sensors has led to a dramatic new spinoff in the classical domain – ultrasensitive room-temperature magnetometry. EQuS research is making a difference in the long-term and today, by advancing state-of-the-art classical technologies in the quest to exploit quantum effects.

The picoTesla sensitivity achieved surpasses any previous non-cryogenic magnetometer of similar size, and is only a factor of 50 away from the best comparable cryogenic magnetometers. The demonstrated performance in non-cryogenic ultra-low power devices make optomechanical magnetometers attractive for real applications. A prominent example is ultra-low field magnetic resonance imaging (ULF MRI), which is similar to traditional MRI, but replaces the usual requirement of expensive and bulky superconducting coils with ultrasensitive magnetometers operating in the 1-20 kHz frequency range. Superconducting-quantum-interference-device (SQUID)-based ULF MRI has been used, for example, to image the brain while performing magnetoencephalography (MEG), determine the enrichment fraction of uranium, and detect liquid explosives at airports. Cryogen-free operation using cavity optomechanical magnetometers could greatly improve both the range of applications and utility of the technique.

CI Bowen's work in this area has now been funded by the US Defense Advanced Research Projects Agency (DARPA), in a successful EQuS spin-off project.

Achieve new field and force sensing regimes using arrays of quantum controlled mechanical oscillators.

PROGRAM: QUANTUM ENABLED SENSORS & METROLOGY

CHIEF INVESTIGATOR WARWICK P. BOWEN, THE UNIVERSITY OF QUEENSLAND, QUEENSLAND QUANTUM OPTICS LABORATORY

Work in CI Bowen's laboratory in 2012 has shown tremendous strides against this EQuS Grand Challenge.

Micro- and nano-mechanical sensors play an important role in the technology landscape. Fundamentally, they contain a mechanical component that moves or oscillates in response to an external force. This motion is read-out with either electrical currents or light fields. Micro- and nano-electromechanical systems (MEMS/NEMS) with electrical readout are broadly used in applications ranging from pressure sensors in cars, to accelerometers and gyroscopes in portable electronic devices such as cameras and smartphones; and have many more specialised applications such as chemical, gas, and nanoparticle mass sensing. Optically read-out optomechanical systems such as atomic force microscopes (AFMs) and optical tweezers allow microscopy of spin, charge, and surface forces at the single atom level, measurement of picoNewton biological forces, and real-time measurement of intracellular dynamics amongst other applications. Each of the abovementioned applications can be understood through classical physics, without any recourse to quantum mechanics. However, new applications that take advantage of quantum physics are becoming increasingly viable due to the continual miniaturisation of nanomechanical devices. This has led to a burst of activity in the new field of quantum optomechanics, where mechanical oscillators interact with light via the momentum kicks from reflected photons - an effect referred to as radiation pressure.

A central goal of CI Bowen's EQuS program on quantum opto-/nano-mechanics is to develop techniques to control the quantum behaviour of micro- and nano-mechanical sensors. Integrated optical microcavities are a key technology for optomechanical sensing. By allowing light to be manipulated on a silicon chip and concentrated in the region of the mechanical oscillator, they greatly increase the radiation pressure interaction between light and oscillator. Quantum applications require both precision capable of resolving the fundamental quantum zero-point motion of the oscillator, and quantum control techniques capable of engineering the behaviour of the oscillator at the quantum level. CI Bowen's group have developed measurement techniques capable of state-of-the-art precision at the subattometre level, more than a thousand times smaller than the nucleus of a hydrogen atom; and, for the first time, electrical control techniques based both on feedback, and electrical modification of the environment around the oscillator.

Further improvements in precision are required to achieve sensitivity at the level of the zero point motion. However, even with current sensitivity, CI Bowen's EQuS program has demonstrated new classical spin-off applications. This includes both the first demonstration of control enhanced precision in cavity optomechanical sensing; record ultralow power optomechanical amplification of optical signals; and, in collaboration with CI Rubinsztein-Dunlop, the first cavity optomechanical magnetometers.

Realise new capabilities through the development of a comprehensive and flexible quantum control toolkit.

PROGRAM: QUANTUM MEASUREMENT AND CONTROL

CHIEF INVESTIGATOR MICHAEL J. BIERCUK, UNIVERSITY OF SYDNEY, QUANTUM CONTROL LABORATORY

Specific example: Preserve quantum states against decoherence indefinitely, using optimised quantum control, quantum feedback, open-loop protocols, weak measurement and projective measurement.

A major thrust of our research effort focused on the development of new quantum control protocols and techniques that protect quantum states against the deleterious effects of decoherence. These techniques are broadly known as dynamical error suppression, and have been validated through detailed experiments. In short, the simple application of specific quantum control operations can prevent the buildup of error in the system.

Our team has focused on moving beyond the simple approximations used in defining the first dynamical error suppression protocols, extending the field of robust control engineering into the quantum regime, and providing the community with a quantum control toolkit transferable between experimental quantum platforms. We believe that this is a key requirement in order to realize useful quantum technologies.

In particular, in collaboration with Professor Lorenza Viola at Dartmouth we have addressed the problem of designing a practically useful quantum memory through quantum control protocols. While numerous techniques relying on both open- and closed-loop control schemes have been devised in order to address this challenge, quantum error suppression strategies based on dynamical error suppression are emerging as a method of choice for physical-layer decoherence control in non-Markovian open quantum systems

A variety of studies have consistently pointed to dynamical error suppression as a resource-efficient approach to substantially reducing physical error rates. However, they have largely focused on two control regimes: the “coherence-time” regime, where the goal is to extend the characteristic (“1/e” or T2) decay time for coherence as long as possible, and the “high-fidelity” regime, where the goal is to suppress errors as low as possible for storage times short compared to T2 - for instance, during a single quantum gate. Still, these two regimes do not capture the typical operating conditions of any true quantum memory, namely, extremely low error probabilities (e.g. deep below the fault-tolerance threshold) maintained for arbitrarily long storage times. This would be required, for instance, in a quantum repeater or in a quantum computer where some quantum information must be maintained, while large blocks of an algorithm are carried out on other qubits.

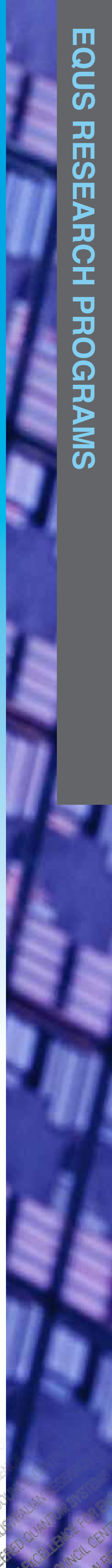
In our work, we showed how dynamical error suppression techniques can be employed to realize a useful quantum memory capable of preserving quantum information for long times with high fidelity, while meeting the practical requirement of a small access latency. Given a variety of technical considerations, we identified the periodic repetition of a high-order dynamical decoupling sequence as an effective strategy for memory applications, and analytically characterized the resulting long-time coherence.

Remarkably, our study revealed that the error in a quantum memory at long times may be rigorously bounded using asymptotic expressions. We identified conditions under which a “coherence plateau” could be engineered, and qubit fidelity guaranteed to a desired level at long storage times – even in the presence of pulse imperfections, realistic noise environments and other practical constraints. The results suggested, for instance, that quantum states could be preserved with error probabilities in the range 10-9 for hours using trapped ion qubits. In certain conditions, we even showed that it would be possible to maintain this error level indefinitely.

These are exciting discoveries that reveal how EQuS research is meeting its Grand Challenges and leading international efforts towards enabling the quantum revolution.

EUREKA!

The Quantum Control Laboratory's research in the area of noise filtering for quantum control – dubbed Quantum Firmware – earned CI Biercuk nomination as a finalist for the 2012 Eureka Prize for Innovation in Computer Science, sponsored by Google.



A MEDIA STORM

EQuS research on Quantum Simulation garnered extraordinary popular media attention at home and abroad with featured news items in *The Guardian, Fox News, Sky News, The Huffington Post, Popular Science, The Australian, The Sydney Morning Herald* and many others.

Dr Biercuk appeared on television and radio describing the research breakthroughs via outlets including *ABC News Breakfast, ABC Lateline, SBS World News, ABC Radio, SBS Radio*, etc.

The work was selected by *BBC FOCUS* magazine as the #8 “World-changing” experiment across all disciplines, and helped to earn CI Biercuk selection as one of Sydney’s 100 most influential people for 2012 by the *Sydney Morning Herald.*

Achieve complete control over individual quantum particles in a strongly interacting many-body quantum system with tuneable interactions.

PROGRAM: SYNTHETIC QUANTUM SYSTEMS AND SIMULATION

CHIEF INVESTIGATOR MICHAEL J. BIERCUK, UNIVERSITY OF SYDNEY, QUANTUM CONTROL LABORATORY

In 2012, the Quantum Control Laboratory, in collaboration with informal partner investigator, NIST, published research detailing achievements towards realization of the first quantum simulator at a computationally relevant scale. With this research, computing technology took a huge leap forward, using a crystal of just 300 atoms suspended in space.

Ever since Nobel Prize winner Richard Feynman highlighted the potential of quantum computing in the 1980s, scientists have been attempting to build quantum computers capable of solving some of the largest and most complex problems. Special-purpose quantum simulators have tremendous potential to solve a variety of challenging problems in materials science, chemistry, and biology, with much greater efficiency than conventional computers.

Quantum Simulation is a process by which a well-controlled quantum system can be used to provide insights into the behaviour of other naturally occurring physical systems. Achieving this is vital, as many properties of natural materials governed by the laws of quantum mechanics are very difficult to model using conventional computational approaches.

Much like studying a scale model of an airplane wing in a wind tunnel to simulate the behaviour of a full-scale aircraft, tremendous insights about difficult and complex quantum systems can be gleaned using a quantum 'scale model'. EQuS is leading international efforts in this research area through its program on Synthetic Quantum Systems and Quantum Simulation.

By engineering precisely controlled interactions and then studying the output of the system, we were effectively able to run a 'program' for the simulation. We exploited new capabilities to “tune” the kind of coupling between particles in order to study interactions of spins in the field of quantum magnetism - a key problem that underlies new discoveries in materials science for energy, biology and medicine.

The experimental device provided exceptional new capabilities that our researchers harnessed to engineer interactions which mimic those found in natural materials. Remarkably, we were even able to realise interactions that are not known to be found in nature, engineering totally new forms of quantum matter.

Our team hopes that, through future research, we will be able to study the spin interactions predicted by models for high-temperature superconductivity - a physical phenomenon that has yet to be explained, but has the potential to revolutionise power distribution and high-speed transport.

The work joins a growing worldwide effort on quantum simulation, but dramatically surpassed previous records in terms of the number of elements working together in a quantum simulator, as well as the “tunability” of the system. The key threshold for the usefulness of a quantum simulator stands at about 40 interacting elements – or qubits. Previous experiments had reached the scale of 16 interacting elements, a major achievement, but still not computationally relevant.

The EQuS result pushed this record to more than 300 interacting qubits. Not only is this far larger than both previous records and the threshold of computational relevance, but it hit an extraordinary level of projected performance for the system. Because of the way that quantum information scales with system size, the computational capacity of this system (equivalent to the memory size that would be required in a classical computer) is an astonishing 80 orders of magnitude greater than any existing supercomputer. In fact, realizing a classical computer with similar capacity would require construction of a machine larger than the size of the universe!

The quantum simulator realized through this research remains at an early stage of development, with much future effort required in order to realize its full capabilities. However, the demonstrations to date point to an exciting research activity for the Centre for years to come. The Quantum Control Laboratory is currently developing advanced new ion trapping technology that will permit next-generation quantum simulation experiments to be conducted within Australia.

JW Britton, BC Sawyer, AC Keith, C-C J Wang, JK Freericks, H Uys, MJ Biercuk, JJ Bollinger (2012) Engineered 2D Ising interactions in a trapped ion quantum simulator with hundreds of spins. *Nature* 484, 489; see also News & Views: Simulating Magnetism, *Nature* 484, 461 (2012).

Produce programmable quantum simulators capable of outperforming the best classical technology.

PROGRAM: SYNTHETIC QUANTUM SYSTEMS AND SIMULATION

CHIEF INVESTIGATOR ANDREW G. WHITE, THE UNIVERSITY OF QUEENSLAND, QUANTUM TECHNOLOGY LABORATORY

Beyond the basic demonstration of large-scale quantum simulators described in the previous section, our Centre has been particularly successful in 2012 in applying useful quantum simulators to challenging problems in physics. Such devices provide a means to probe the bounds of quantum information science and reveal new insights into the nature of computation.

One deep physical problem being studied by CI White using photons relates to the question of when full quantum computers are required for efficient computation. Quantum computers are unnecessary for exponentially efficient computation or simulation if the Extended Church-Turing thesis is correct. The thesis would be strongly contradicted by physical devices that efficiently perform tasks believed to be intractable for classical computers. Such a task is Boson Sampling: sampling the output distributions of n bosons scattered by some linear-optical unitary process.

We characterised the process by inventing a method that, unlike heretofore known methods, neither requires nonclassical resources nor adds to the complexity of the task. Applying this technique, in Science we reported testing the central premise of boson sampling, experimentally verifying that 3- photon scattering amplitudes are given by the permanents of submatrices generated from a unitary describing a 6-mode integrated optical circuit. We found the protocol to be robust, working even with the unavoidable effects of photon loss, non-ideal sources and imperfect detection. Scaling this to large numbers of photons will be a much simpler task than building a universal quantum computer.

In addition to representing a fundamentally new way of performing calculations, these devices and systems have the potential to provide tremendous insight into basic physical processes of interest to biomedical science and industry.

Other exciting work on photonic quantum simulation relates to the notion of topology in physics. Phases of matter have long been characterised by their symmetry properties, with each phase classified according to the symmetries that it possesses. The discovery of the integer and fractional quantum Hall effects in the 1980s has led to a new paradigm, where quantum phases of matter are characterised by the topology of their ground-state wave functions. Since then, topological phases have been identified in physical systems ranging from condensed-matter and high-energy physics, to quantum optics and atomic physics.

We reported in *Nature Communications* simulating one-dimensional topological phases using a discrete time quantum walk, a protocol for controlling the motion of quantum particles on a lattice. We created regions with distinct values of topological invariants and directly imaged the wave function of bound states at the boundary between them. The controllability of our system allowed us to make small changes to the Hamiltonian and demonstrate the robustness of these bound states. Finally, using the quantum walk, we accessed the dynamics of strongly driven systems far from the static or adiabatic regimes to which most previous work on topological phases has been restricted. In this regime, we discovered a topologically protected pair of non-degenerate bound states, a phenomenon that is unique to periodically driven systems

MAJOR RESEARCH PROJECTS IN 2012

EQuS research spans theory and experiment, exploiting an extraordinarily wide range of proven quantum systems for our efforts to Engineer the Quantum Future. In this section we provide highlights of major new discoveries and notable accomplishments across the Centre.

Semiconductor Quantum Dots

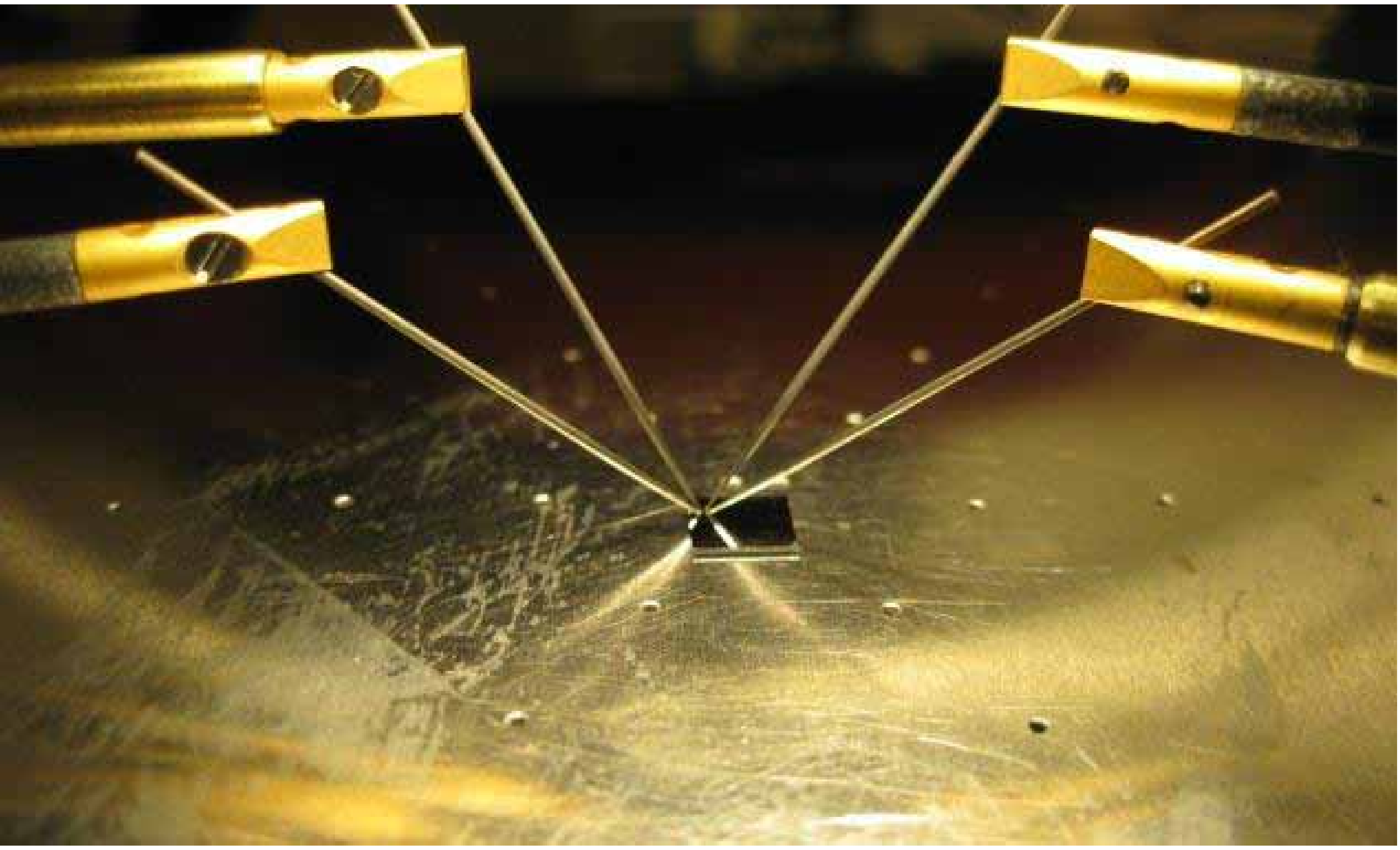
PROGRAM: QUANTUM MEASUREMENT AND CONTROL

CHIEF INVESTIGATORS DAVID J. REILLY & ANDREW C. DOHERTY, THE UNIVERSITY OF SYDNEY

EQuS research on solid-state quantum devices includes a major effort on semiconductor-based quantum systems called quantum dots. These devices allow experimentalists to confine, manipulate, and probe individual electrons in a solid material, in the spirit of the 2012 Nobel Prize in Physics. This effort is led from the Quantum Nanoscience Laboratory (QNL), Directed by CI Reilly at The University of Sydney.

In 2012, the QNL research group made significant progress towards the goals and Grand Challenges of EQuS. Our research is largely focused on controlling nanoscale quantum systems constructed from a range of different material ingredients. A flagship project involves the coherent manipulation of single electron spin-states in ultra-clean gallium arsenide (GaAs) quantum dot structures. Our focus here is the development of new approaches to quantum control and measurement, with the goal of keeping a quantum mechanical system alive indefinitely.

Towards this goal, a recent result published in *Physical Review Letters* combines superconducting microwave resonators with double quantum dots to enable a new quantum measurement technique, termed Dispersive Gate Sensing (DGS). This experiment provided a new method for detecting the location of single electrons in these devices and to read out their spin state, a form of qubit state detection that will enable us to build larger devices involving many more electrons, while retaining the ability to measure and control individual ones. The theory program led by CI Doherty contributed to the understanding of the sensitivity of the measurement characterising both the size of the signal and the intrinsic noise in the measurement. This work was reported in Colless, Mahoney, Hornibrook, Doherty, Reilly, Lu, Gossard, *Physical Review Letters*.



Measuring the resistance of a SQUID using a 4 point probe, Yarema Reshitnyk, UQ, student

Optomechanics

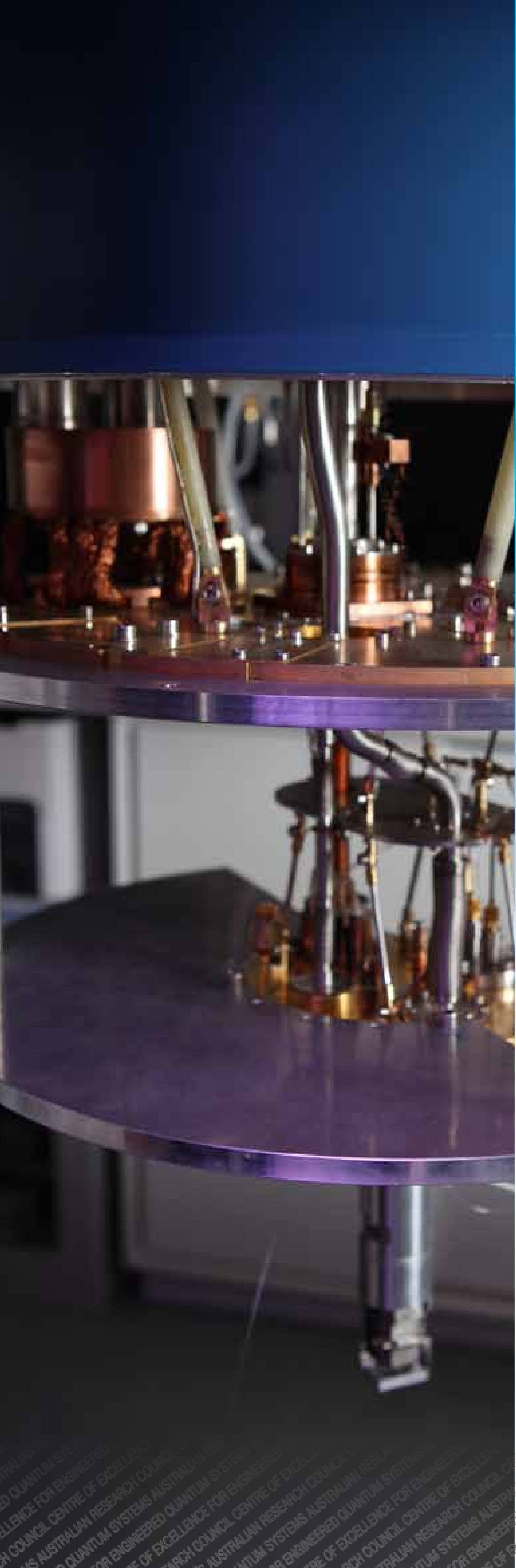
PROGRAMS: QUANTUM CONTROL AND MEASUREMENT & QUANTUM SENSORS

CHIEF INVESTIGATOR WARWICK P. BOWEN, THE UNIVERSITY OF QUEENSLAND

One of the most active areas of research in engineered quantum systems worldwide focuses on the interface between light and mechanical systems – dubbed optomechanics. This research area has the potential to provide deep insights into light matter interactions as well as the limits of quantum theory, but is also already demonstrating major commercial potential for new generations of advanced sensors.

CI Bowen's laboratory has delivered substantial improvements in our ability to observe and control optomechanical systems at the quantum level. Key results include:

- The first demonstration of feedback enhanced force sensing in a cavity optomechanical system. This shows that feedback control, and ultimately quantum feedback control, can meaningfully improve sensing devices. (GI Harris et al. *Physical Review A* (Rapid) 85 061802 (2012))
- The demonstration of an optomechanical backaction amplifier, controlling the radiation pressure interaction between light and matter to perform optical amplification at ultralow microwatt light levels. (TG McRae and WP Bowen, *Applied Physics Letters* 100 201101 (2012))
- Development of new evanescently coupled optomechanical systems with ultrastrong light matter coupling sufficient in principle to allow room temperature measurements surpassing the quantum zero point in precision.
- The first demonstration of cavity optomechanical magnetometry, and with sensitivity surpassing any previous non-cryogenic magnetometer of comparable size. These magnetometers may find applications in medical imaging, explosive detection, geosurvey, and other areas.
- The demonstration of mHz mechanical linewidths in feedback controlled optomechanical systems. This paves the way for new cavity optomechanical mass sensors operating in ambient conditions and with high dynamic range. Such sensors could be used, for example, to detect nanoparticles, monitor important chemical reactions such as photosynthesis, track the growth and movement of bacteria and detect hydrogen gas.
- Demonstrated the first ever use of quantum correlated light to microparticle tracking, and applied the technique to monitor the inner working of living cells. This is the first use of quantum light to improve measurements in biology, and opens the door for many applications in that area.



NEW INDUSTRIAL PARTNERSHIP

The Quantum Nanoscience Laboratory led by CI Reilly at The University of Sydney initiated a new industrial collaboration with Microsoft Research, headquartered in Redmond, Washington USA.

This collaboration involves the development and engineering of bespoke quantum hardware to control large-scale quantum devices, usually at microwave frequencies and in cryogenic environments.

Atomic Thermometry

PROGRAMS: QUANTUM ENABLED SENSORS AND METROLOGY

CHIEF INVESTIGATOR TOM M. STACE, THE UNIVERSITY OF QUEENSLAND

Temperature is surprisingly subtle: it is easily perceived, yet it took 300 years to formalise the concept in operationally useful terms. One of the historical challenges in understanding temperature was the development of primary thermometers capable of measuring the thermodynamic temperature. Indeed, this remains an outstanding issue in modern thermometry, demonstrated by the high relative uncertainty in the CODATA value for Boltzmann's constant, which currently sits at the parts per million level. This uncertainty results in Boltzmann's constant being one of the least precisely known fundamental constants. Further, when, as is currently anticipated, CODATA declares Boltzmann's constant to be a precisely defined quantity, this uncertainty will be simply mapped to the uncertainty in the thermodynamic temperature.

Likewise, thermometry is one of the least precise areas of modern metrology. The community is now moving to improve the availability, foundations and accuracy of the temperature scale by using new techniques to measure thermodynamic quantities from which to extract the temperature. Our work is seeking to overcome these limitations through the development of a novel thermometric technique using the interactions between light and matter in dilute atom gases.

A promising new approach to primary thermometry is based on the absorption spectrum of a dilute gas. The Maxwell-Boltzmann distribution of atomic (or molecular) velocities in a gas gives rise to Doppler shifts for optical transitions resulting in a broadening of the spectral line, whose width depends very simply on the thermodynamic temperature. We will employ a vapour of Cs atoms, which have high optical absorptivity allowing for compact vapour at low pressures with commensurately infrequent inter-atomic collisions. This feature means that collisional perturbations to the spectral line-shape are negligible - in contrast to other approaches for which they are dominant - so the physics of the vapour is sufficiently simple that all of the properties of the absorption line-shape can be calculated from known properties of the basic atomic transition together with the Maxwell-Boltzmann velocity distribution. This is a very powerful fact, since it means that there are no unquantified physical contributions to spectral broadening in an atomic gas.

A fundamental limit to the uncertainty in Doppler thermometry is optical shot noise. Using high laser powers to maximise the signal-to-noise ratio of the measurement can mitigate this. However, because of the high optical cross-section and low collision rates in alkali atoms, even a relatively weak probe laser is sufficient to significantly modify the thermal equilibrium atom populations, leading to small but significant systematic errors. These effects can be overcome either experimentally by extrapolating a sequence of low intensity measurements to zero, or theoretically by calculating corrections to the lineshape associated with this optical pumping, as we have recently done. The latter approach, which we will employ, enables our spectrometer to operate at the optical shot-noise limit without any spurious intensity-dependent biases in the measured temperature.

Existing spectrometers are very far from the atomic shot-noise limit since they fail to probe the vast majority of atoms at any instant. A single narrowband laser scans across the Doppler-broadened spectrum to measure its line-shape. Since the natural linewidth of a typical alkali atom is a small fraction of the Doppler width at room temperature, it follows that only a small fraction of thermodynamically useful atomic velocity classes are interrogated at any given instant. As such, current state-of-the-art Doppler thermometers typically utilise only a tiny fraction, 1 in 10,000, of thermodynamically useful atoms.

The target of this research is to build an optical-shot-noise-limited spectrometer whose performance approaches the atomic shot-noise. This will be achieved by continuously and simultaneously interrogating a substantial fraction of the thermodynamically useful atoms. To do this, the spectrometer will perform continuous optical shot-noise limited absorption spectroscopy of multiple separate, fixed-frequency probe beams, derived from a commercial optical frequency comb. This will lead to an improvement in precision by a factor of several hundred compared to existing Doppler thermometers, resulting in world-record relative thermometric uncertainties (below 1 part per million) in only a few minutes of integration time.

A MEASURE OF SUCCESS

In 2012, CI Stace was awarded a prestigious new NIST Precision Measurement Grant, together with Andre Luiten at the University of Adelaide.

This grant is notable in that Stace's was awarded for the first time outside North America; of 25 applications in 2012, only two were successful (8% success rate); of ~80 awards since the program started in 1972, four awardees have won Nobel prizes.

This funding will support construction of a new form of thermometer - an atomic Doppler thermometer - which we expect will reach world record accuracy for thermometry.

One of the goals of this project is to define Boltzmann's constant as an exact quantity.

Quantum Interfaces

PROGRAMS: QUANTUM CONTROL AND MEASUREMENT

CHIEF INVESTIGATOR GERARD J. MILBURN, THE UNIVERSITY OF QUEENSLAND

The research themes of EQuS move beyond individual quantum systems and touch on the idea of quantum interfaces, whereby multiple quantum systems may be made to interact, perhaps even coherently. Examining these possibilities requires researchers to consider the unusual quantum mechanical effects of backaction and noise in the processes of quantum control and measurement. CI Milburn’s team has led efforts to explore this exciting research topic with substantial success.

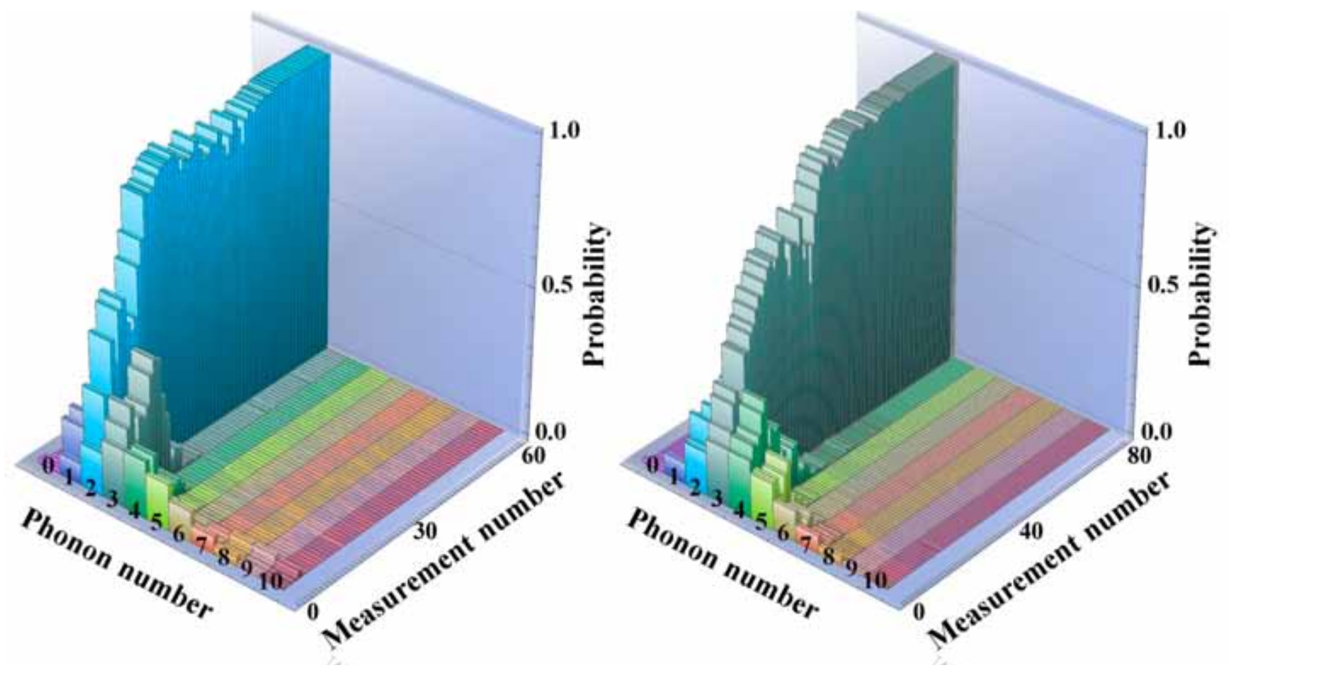
CI Milburn’s team at The University of Queensland has investigated various interfaces in the context of optomechanical systems. A complex engineered quantum system will need various interfaces: classical-quantum, quantum-quantum and quantum-classical. The last of these concerns the issues of quantum measurement and is the subject of many investigations. The classical-quantum interface, however, has received little attention. Largely this is because the ability of classical control quantum systems has been well established. However, in a complex network of quantum systems, we may wish to engineer particular quantum sub-systems to act as a classical controller for future stages. How does one achieve this? We answered this question in GJ Milburn, *Proc Roy Soc A*, 370, 4469 (2012), providing new insights into how one may realize large-scale networks of interacting quantum systems.

We also addressed the issue of quantum-quantum interfaces between very different degrees of freedom, specifically between microwave and optical systems. We proposed two schemes, one based on an ion trap (D Kielpinski, et al., *Phys Rev Lett* 108, 130504 (2012)) and one based on a quantum electromechanical system (Basiri Esfahani et al., *New J Physics*, 14, 085017 (2012)).

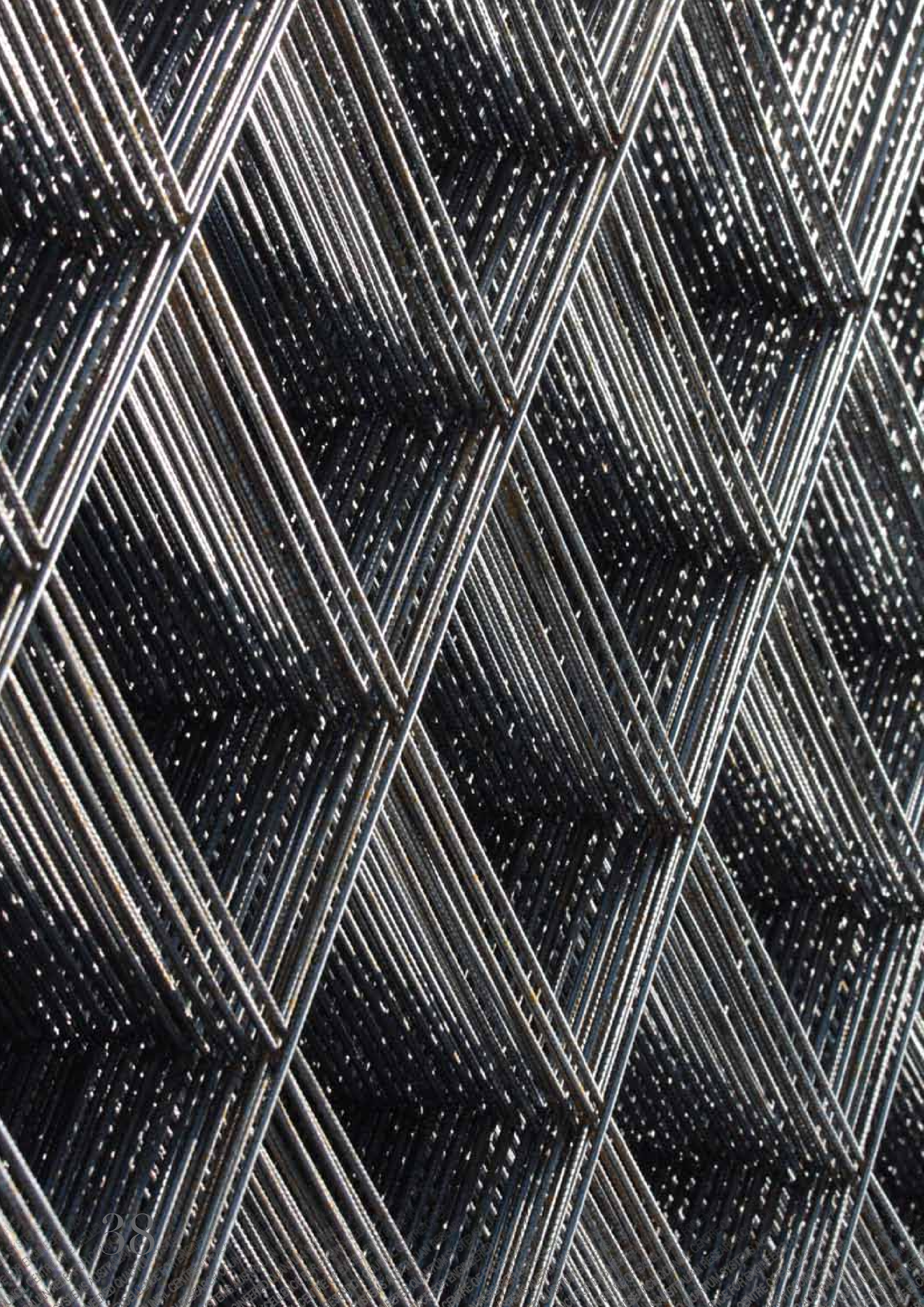
It is well known that arrays of nonlinear oscillators can exhibit synchronisation defined as the self-sustained entrainment of the frequencies of multiple individual oscillators due to their interaction. Synchronisation in networks of non-linear oscillators is the unifying explanation behind diverse phenomenon, from biological systems such as networks of neural cells to engineered systems such as MEMS (micro-electromechanical systems) with particular application to sensing. We have initiated a study of synchronization in quantum electromechancial systems, the first results of which are reported in (Holmes et al., *Phys Rev E* 85, 066203 (2012)). We showed that the mechanism for synchronization in an array of nano-mechanical resonators interacting via a common microwave field mode is very different from the well studied Kuramoto mechanism. This work provides the foundation for an investigation of how quantum noise is manifest in synchronization.

We have continued our work on single photon opto-mechanics. We showed how single photon probes can be sued to gain information about the mechanical state of an opto-mechanical resonator. As successive measurements are made, the conditional state of the mechanics tends to a phonon number state, see figure below,

In Akram et al., *Phys Rev A* 86 042306, (2012), we demonstrated that in a cascaded network of opto-mechanical systems, the mechanical resonators can become entangled. This study will be extended to describe an opto-mechanical distributed memory in 2013.



Phonon number distribution function histograms after successive measurements for the mechanics prepared in a coherent state with amplitude □= 2. As we increase the number of measurements, i.e. inject successive single photon probes, the phonon number distribution evolves from a poissonian distribution into phonon number state distributions (a) n=2 and (b) n=3.



Plasmonics

PROGRAM: QUANTUM MEASUREMENT AND CONTROL

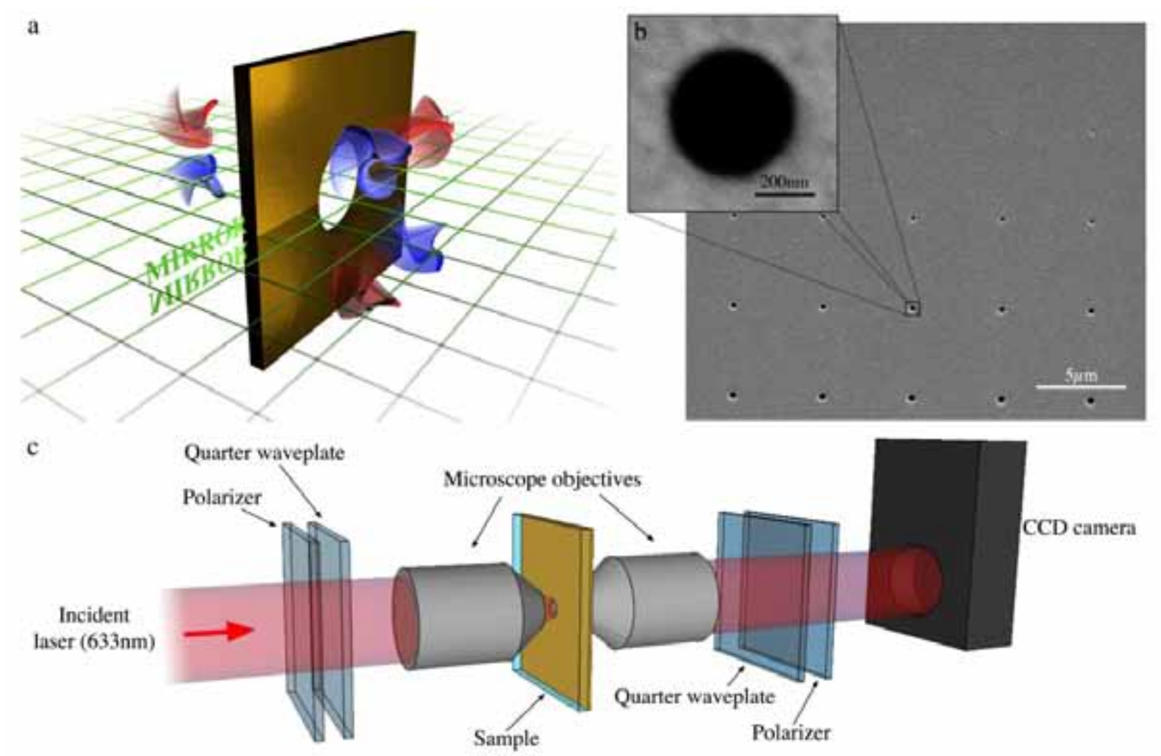
CHIEF INVESTIGATOR GABRIEL MOLINA-TERIZZA, MACQUARIE UNIVERSITY

One of our most ambitious projects within the Centre is the achievement of Quantum Control of metallic nanostructures, such as spheres, holes in metallic surfaces, nanorods, etc. These kinds of structures are becoming more and more important for technology, and they are now being used in sensing applications, as optical transducers, etc. One key property that enables all this range of technologies is that these structures can present localized plasmon resonances. These resonances appear at optical frequencies and happen when the collective oscillations of the electrons in the metallic structure resonate with the driving optical field. One of our aims is to achieve an unprecedented control on the state of those electrons and their resonances, reaching the quantum limit.

In order to achieve this agenda, CI Molina-Terizza's team at Macquarie University has pioneered the study of plasmonic resonances of simple structures such as spheres and holes, with both theoretically and experimental investigations.

One of our key findings last year in this direction has been the discovery that optical helicity plays a very important role in the interaction of light with plasmonic structures. Optical helicity is a concept seldom used in the field of nanophotonics, but is very important in the description of fundamental particles. In particular, it is one of the conserved quantities defining the photon. Optical helicity is intimately related to one of the symmetries of electromagnetism: electromagnetic duality. Duality is the transformation of electromagnetic fields which mixes electric and magnetic fields. In the absence of charges and currents, the electric and magnetic fields are indistinguishable, which means that the electromagnetic fields are symmetric under duality transformations.

Plasmonic structures, on the other hand, typically have a strong electric or magnetic "character", i.e. they react very differently to electric fields than they do to magnetic ones. It is for this reason that optical helicity is a key element in the interaction with these structures and will be a very important feature in order to control the plasmonic resonances at the quantum level.



Hybrid High-Q Oscillators

PROGRAM: QUANTUM MEASUREMENT AND CONTROL

CHIEF INVESTIGATOR MICHAEL E. TOBAR, THE UNIVERSITY OF WESTERN AUSTRALIA

At The University of Western Australia, CI Mike Tobar leads a team seeking to engineer new high-Q mechanical and electrical systems based on low-loss crystalline materials and low temperature superconductors.

Our efforts are broadly classed as relating to (i) quantum-limited cooling of mechanical systems for precision metrology and (ii) controlling impurity spin states in high-Q microwave resonators.

(i) We are investigating known high-Q acoustic and electrical materials such as Sapphire, Niobium and Quartz. Our investigations are targeting systems with the potential for efficient cooling to the quantum mechanical ground state of motion.

The quartz system includes collaboration with FEMTO-ST in Besancon, France. We have cooled Bulk Acoustic Wave (BAW) devices to 20 mK, and we showed that resonant acoustic phonon modes in a BAW quartz resonator demonstrate exceptionally low loss (with Q-factors of order billions) at MHz and even GHz. Given this result, the Q-factor in such devices near the quantum ground state can be four orders of magnitude better than previously attained. Such resonators possess the low losses crucial for electromagnetic cooling to the phonon ground state, and the possibility of long coherence and interaction times of a few seconds, allowing multiple quantum gate operations.

We are also exploring sapphire systems that simultaneously exploit both the intrinsic high-Q electrical and mechanical properties. In the process of developing this experimental platform we have identified a 'fast-light' phenomenon related to pulse shaping in the propagation medium. An ancillary benefit of this discovery is the potential to efficiently engineer modulated waveforms at microwave and optical frequencies. This spin-off development is a major strength of our research program in this area.

In support of this research, the UWA team is engineering the new necessary tools for quantum-limited measurements, including the lowest noise microwave and millimetre wave oscillators ever conceived. One result is the generation of millimetre-wave signals with frequency instability of a few parts in 1016, rivalling primary atomic standards. Similarly, the need for pure amplitude and phase tones motivated by studies of parametrically driven systems has led to new engineering outcomes including the development of a microwave phase modulator with spurious amplitude modulation of the order of 1 ppm, an extraordinary technical achievement.

(ii) In 2012, we made major progress towards our investigation of dilute paramagnetic systems in sapphire at the standard-quantum-limit. Our objective in this effort is to explore novel qubit architectures offering unprecedented coherence times. In particular, we are focusing on electron and nuclear spin systems in Sapphire coupled to high-Q whispering gallery and acoustic resonances. This provides a means for coupling both phonons and photons to isolated spin systems, enabling novel readout and even microwave-mechanical transduction.

During 2012, a majority of the work dealt with investigating spins in sapphire with particular attention to Fe3+. Such ions exhibit an electron spin resonance, which interacts strongly with high-Q whispering gallery modes at microwave frequencies. For the first time, a third-order paramagnetic nonlinear susceptibility was observed, which enabled the first demonstration of four-wave mixing. Using this non-linearity, high-stability frequency conversion was achieved.

Applications of the spins with respect to improving the performance of frequency generation was also investigated in collaboration with FEMTO-ST in Besancon, with papers published this year: M Mrad, PY Bourgeois, ME Tobar, Y Kersale´, V Giordano. Analysis of the whispering gallery mode sapphire Fe3+ maser under magnetic field. *Eur Phys J Appl Phys*, vol 57: 21005, 2012: K Benmessai, DL Creedon, M Mrad, J-M Le Floch, PY Bourgeois, Y Kersale, V Giordano, ME Tobar, Controlling the frequency-temperature sensitivity of a cryogenic sapphire maser frequency standard by manipulating Fe3+ spins in the sapphire lattice. *Phys Rev B*, vol. 85, 075122, 2012.

During 2012, we developed a new technique for spectroscopy using the multimode nature of WG mode resonators. The technique uses traditional Electron Spin Resonance (ESR) combined with the measurement of a large population of electromagnetic Whispering Gallery (WG) modes. This allows the characterization of the physical parameters of paramagnetic impurity ions in the crystal at low temperatures. Two ultra-high purity sapphires cooled close to 20 mK in temperature were characterized using this technique with excellent measurement precision. The high precision revealed anisotropic behaviour of the Zeeman splitting, which has not been previously reported. In both crystals, each Zeeman component demonstrated a different g-factor.

Noise Filtering in Quantum Control

PROGRAM: QUANTUM MEASUREMENT AND CONTROL

CHIEF INVESTIGATOR MICHAEL J. BIERCUK, THE UNIVERSITY OF SYDNEY

Open-loop quantum control techniques have proven themselves extraordinarily effective at suppressing the effects of environmental noise in quantum systems. Over the last few years, CI Biercuk and his team have shown that it is possible not only to suppress error using these techniques – known as dynamical error suppression – but also to accurately predict the resulting errors for complex time-dependent noise. This is a key requirement if one is to accurately bound the performance of quantum systems put to use in quantum information processing.

The predictive power of the methods pioneered by CI Biercuk centre on the notion of studying quantum control techniques as noise filters. One shortcoming of this approach is that traditionally, research has focused almost exclusively on the implementation of quantum memory, and generally incorporates a variety of idealizations that make analytical treatments easier. Foremost among these is the bang-bang limit in which control operations are assumed to occur infinitely fast. While convenient, these approximations are overly constraining and fail to meet the needs of scientists attempting to engineer real quantum systems. It is understood, for instance, that the assumption of bang-bang control is unphysical and that decoherence during the application of control operations can and does produce errors. In fact, a pure dephasing environment will produce depolarization errors in the presence of realistic, bounded control operations.

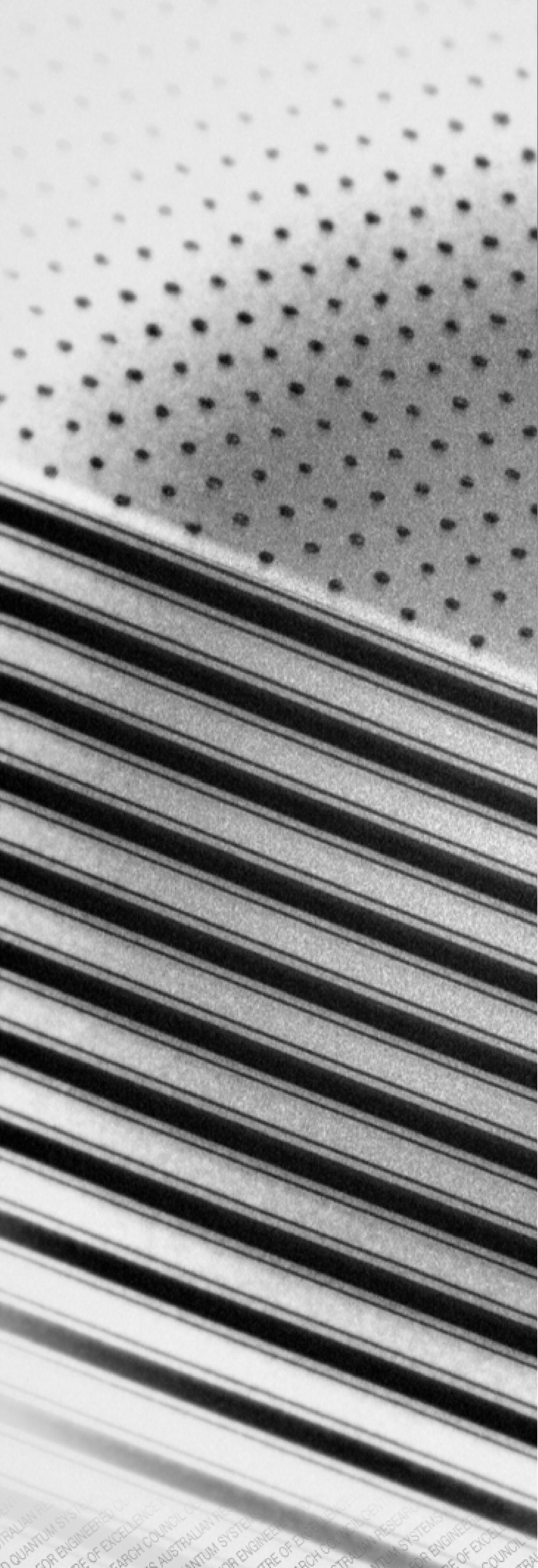
A major development supporting our Centre's progress has been the realization of a robust and broadly applicable theoretical framework for understanding the effects of real noise on quantum systems.

In particular, our theoretical efforts have been aimed at the unification of the perturbative treatment used in the original formulation of protected nontrivial control operations know as dynamically corrected gates (DCGs) with the robust, validated and experimentally accessible filter-design perspective. The group-theoretic construction of Dynamically Corrected Gates (DCGs) has provided a path to consider how such error might be suppressed via appropriate construction of control operators. However, the assumptions underlying DCG construction have not obviously been compatible with the kind of time-dependent classical noise typically observed in realistic laboratory settings. A major aim of this program is to build on this framework and expand its applicability to a variety of experimental settings.

As mentioned above, the filter-design formalism has proven deeply valuable in understanding the performance of dynamical decoupling pulse sequences for the preservation of memory. Through it, we may ascertain the spectral response – a control theoretic concept – of a given quantum control operation. This is a challenging mathematical problem due to the incorporation of time-dependence in capturing the effects of realistic noise environments. However, the Quantum Control Laboratory has developed an effective Hamiltonian formulation that can be used to derive filter functions – the key mathematical description of a given operation – for arbitrary piecewise-constant control sequences to arbitrary order.

Building on this methodology, we have produced the first validation of DCG performance in suppressing errors in the presence of time-dependent noise. We have produced full expressions for the filter function to the first order in the Magnus expansion for previously published DCG constructions, accounting for the dephasing and depolarization effects of a nominally pure dephasing environment during application of a nontrivial control operation.

With this work, we now understand how to evaluate the efficacy of DCG constructions in the presence of classical noise and have verified that similar to the filter-function treatment of dynamical decoupling (DD), it is possible to reduce operational error rates by several orders of magnitude by use of DCGs. This is a significant result demonstrating a path towards error-robust control of quantum systems in real environments.



Patent-Pending

Work by CI Biercuk in collaboration with Professor Lorenza Viola at Dartmouth, has resulted in a pair of provisional patent applications – for resource-efficient dynamical decoupling, and the design of a high-fidelity, low-latency quantum memory.

These are currently being unified into a single, full international patent application.

Quantum Phase Transitions and Simulation

PROGRAM: SYNTHETIC QUANTUM SYSTEMS AND SIMULATION

CHIEF INVESTIGATOR HALINA RUBINZSTEIN-DUNLOP, THE UNIVERSITY OF QUEENSLAND

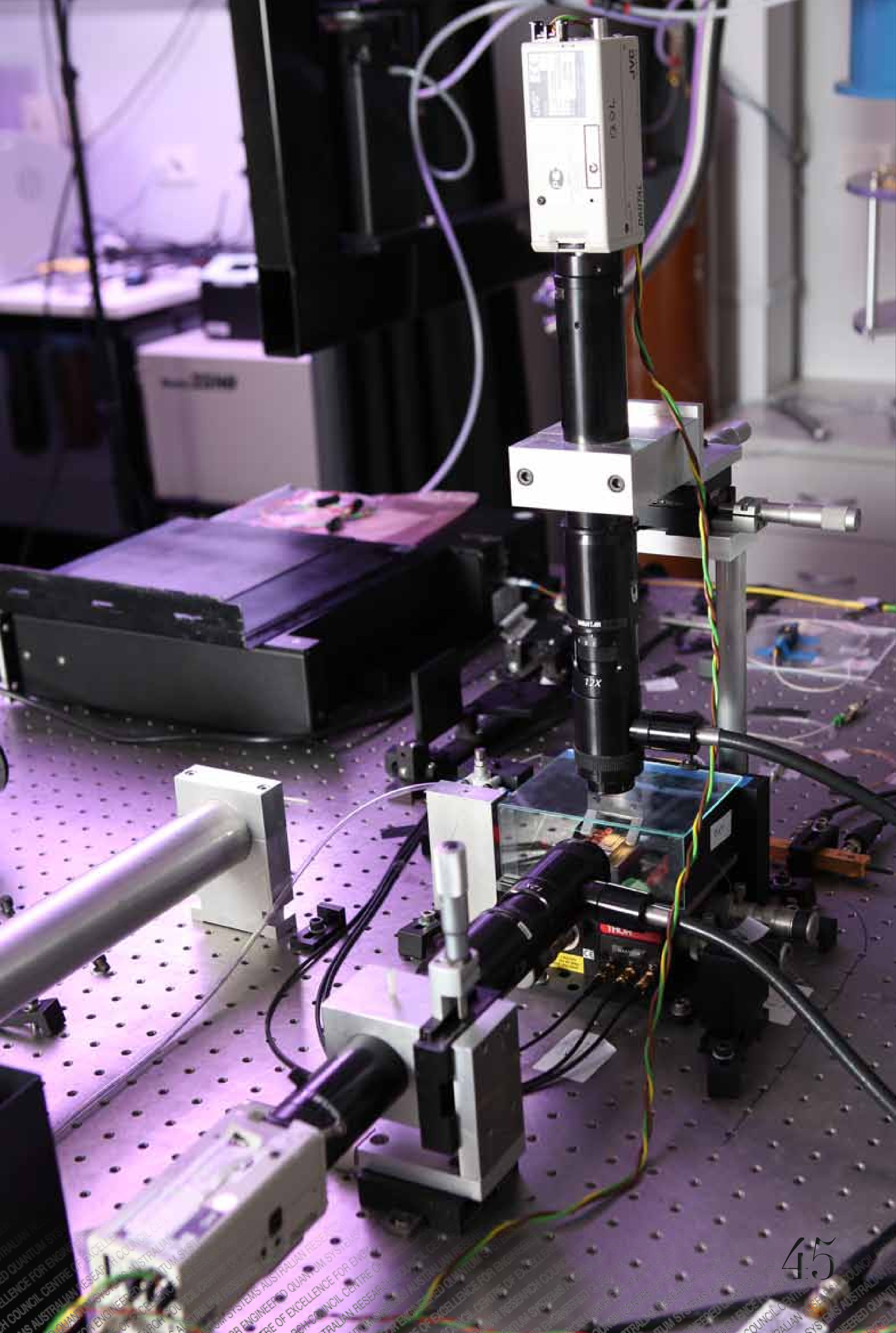
Another major research effort in EQuS is aiming to explore a new regime of quantum simulation using mixtures of cold neutral atoms.

A new experimental platform is being developed to explore the physics of the so-called constrained percolation problem. Percolation theory is well understood in classical settings, but reveals rich physics in the quantum mechanical case. By mapping our physical problem to a system of trapped ultracold atoms, we are able to impose new conservation rules – here the number of atoms in use – but we have another interesting knob; we are able to simultaneously able tune the interactions between two different atoms in the system, 41K and 87Rb. Accordingly, our simulation experiment may be conducted at the edge of a quantum phase transition in an ultra-cold gas.

Quantum phase transitions are known to produce topological defects and several theoretical works in the past two decades provided us with a description of the interplay between the defects and the phase transition. Several experimental attempts to observe and verify these theories have reported encouraging results, but the problem of quantum phase transitions that are constrained by conservation laws, as in our proposed experiment, remains unexplored.

In our setup, we will use the Feshbach resonance to change the interaction constant between and tune the system from a miscible phase to an immiscible one. In the immiscible phase, a lattice site can be filled with atoms from one component only, 41K or 87Rb, and the system can be mapped to a percolation problem. In particular, the mapping consists of labelling a lattice site filled with 41K with a connected edge of the percolation problem, and a site with 87Rb with a disconnected one.

The two species, 41K and 87Rb, will be optically trapped and brought to quantum degeneracy through evaporation. We are also building the capability to use multiple optical beams to form a periodic two-dimensional lattice for holding the two species condensate. By combining this system with a high numerical aperture imaging system we aim to achieve single lattice site resolution. The combination of highly configurable optical potentials, tuneable atom interactions, and capable imaging will provide a flexible system for the initial experiments.



Nanoparticles for sensing and bioimaging

PROGRAM: QUANTUM ENABLED SENSORS & METROLOGY

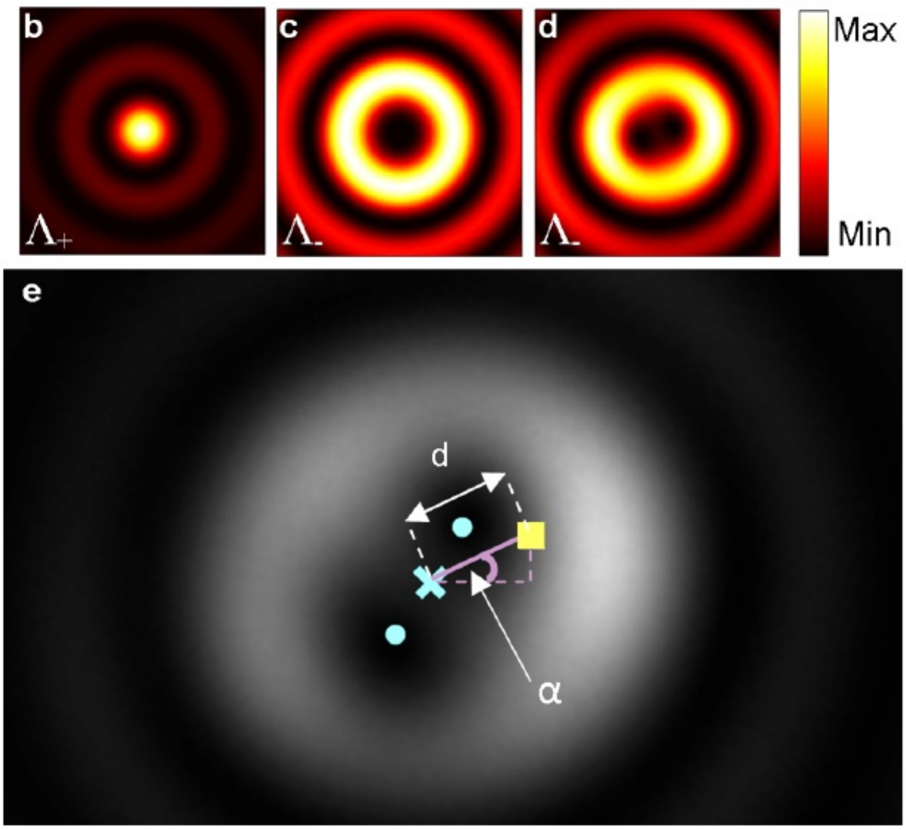
CHIEF INVESTIGATOR GABRIEL MOLINA-TERRIZA, MACQUARIE UNIVERSITY AND CHIEF INVESTIGATOR DAVID J. REILLY, THE UNIVERSITY OF SYDNEY

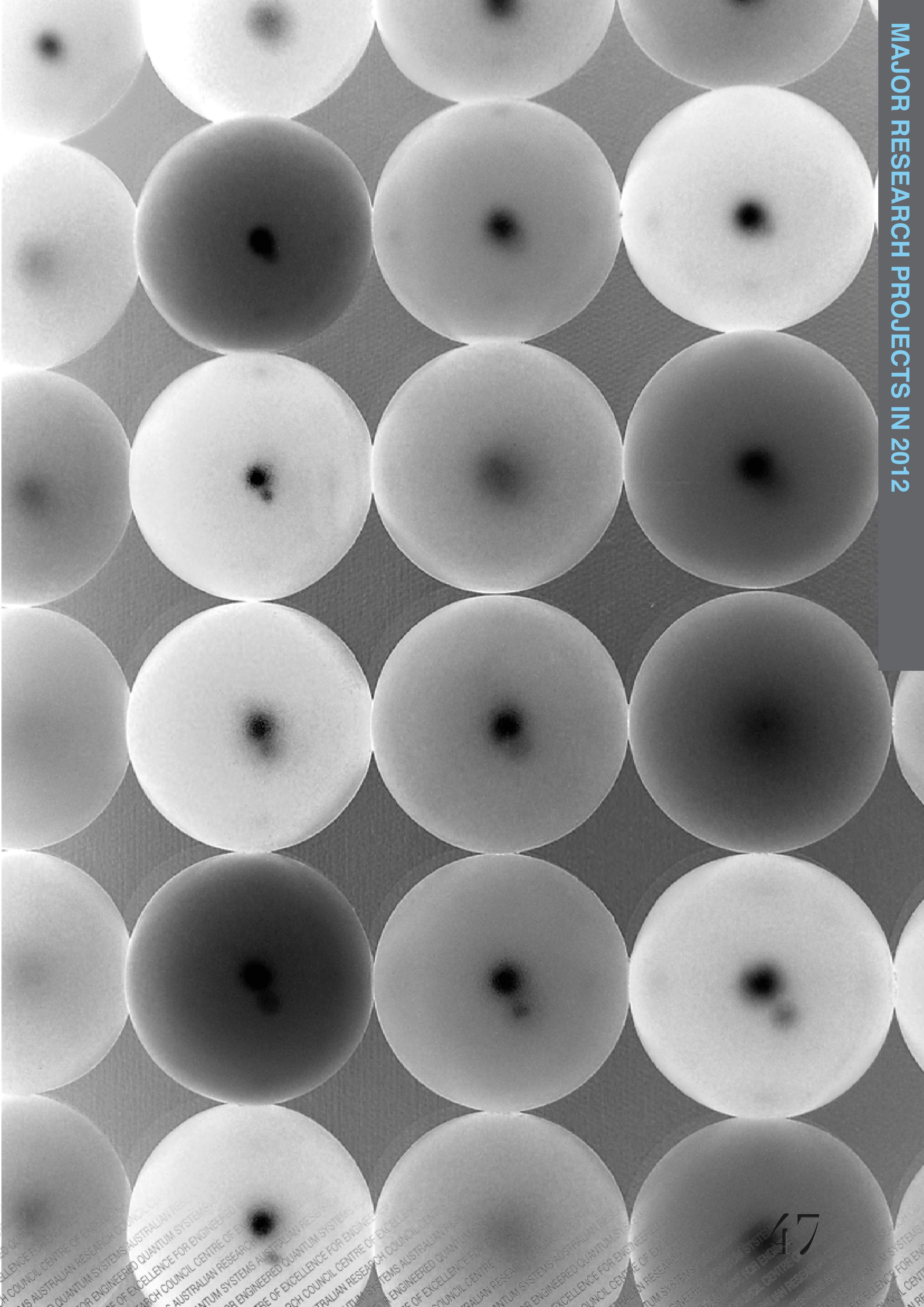
Physical systems that are strongly governed by quantum effects can serve as exquisitely sensitive detectors. The central theme of the EQuS Quantum Enabled Measurement and Metrology program is to harness this capacity towards the development of fundamental quantum technological building blocks. This could lead to breakthroughs in our ability to probe biological and quantum mechanical phenomena in liquids and solids, the noninvasive imaging of proteins and drugs in-vivo, and ultimately the development of a deep understanding of our world at the atomic scale.

Related to our studies of the optical helicity exchange in the interactions with plasmonic structures, CI Molina-Terriza's group at Macquarie University have realized a method to exploit the features of scattered fields to accurately measure positions of nanoparticles. This method has been granted an Australian patent. More importantly, it is closely aligned with one of the 2012 Centre's Milestones: "Demonstrate imaging and tracking of hyperpolarized nanoparticles". Our method has demonstrated imaging and tracking of nanoparticles and it can, in principle, be used for hyperpolarized nanoparticles.

We have demonstrated that we can track the position of nanoparticles with a resolution of around 10nm. This bound to the precision was due to our mechanical system, and it is not a fundamental limit on the precision of our method. More importantly, the whole method is all-optical and our demonstration used a wavelength of 633nm. This means that our method is easy to deploy in different systems and that it operates in a deeply subwavelength regime, i.e. we can achieve resolutions 60 times smaller than the wavelength.

The Quantum Nanoscience Laboratory at The University of Sydney, led by CI Reilly, is developing new types of quantum sensors and bioprobes based on manipulating the spin-states of nanoparticles. To date, we have been focusing on hyperpolarized nanodiamonds as contrast agents for use in magnetic resonance imaging. In 2012, we successfully demonstrated nuclear polarization, using a custom designed and constructed polarizer. Efforts are now underway to understand the relaxation channels for nuclear spins with an eye to enabling long-lived nuclear polarization. This work has strong application in the early detection of diseases such as cancer.





Exotic Quantum Sensors

PROGRAM: QUANTUM ENABLED SENSORS & METROLOGY

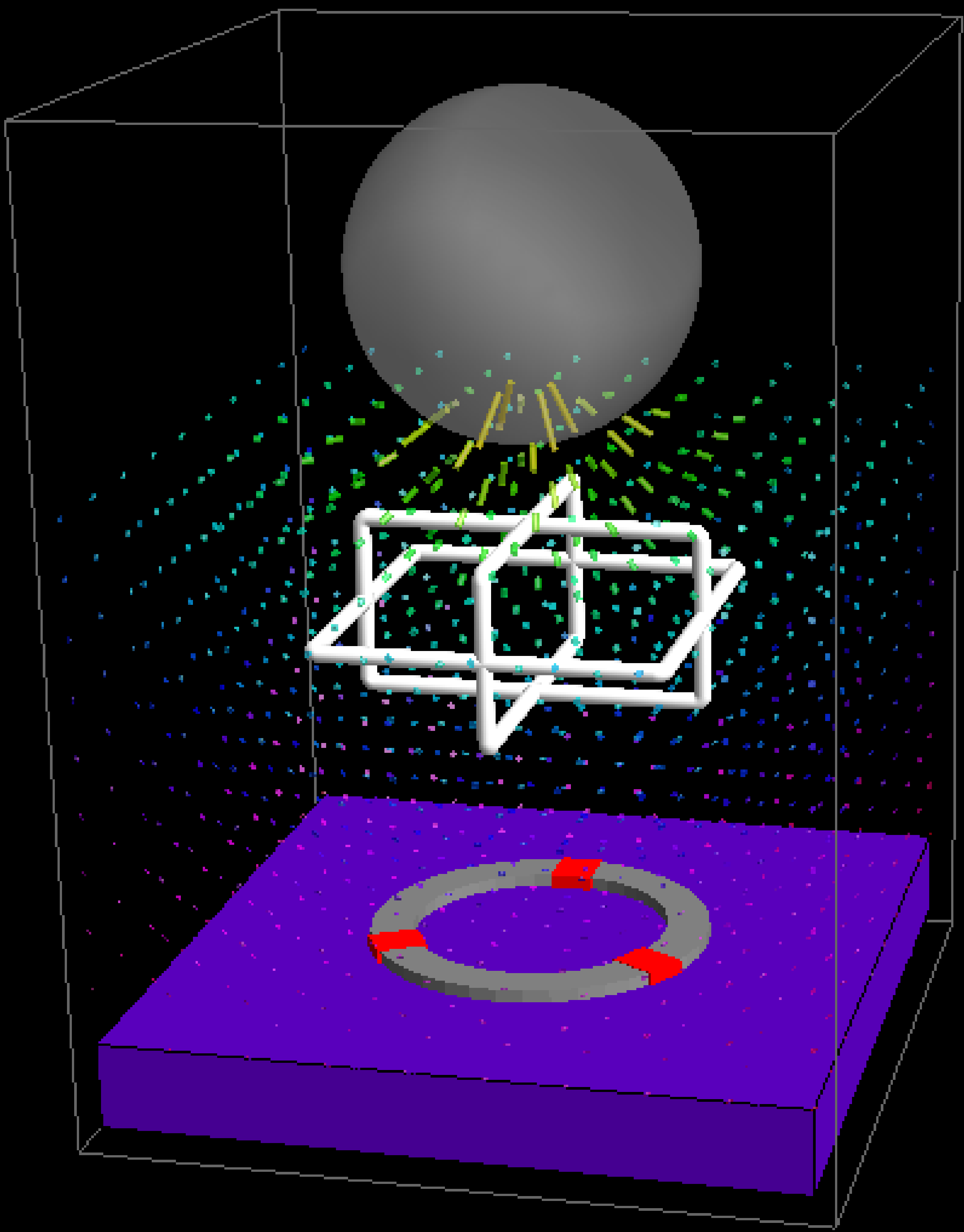
CHIEF INVESTIGATORS GAVIN K. BRENNEN AND JASON TWAMLEY, MACQUARIE UNIVERSITY

Technological advances in the past decade are rapidly bringing quantum enabled sensing into the realm of practical reality. For example, nano-electromechanical systems (NEMS) operating close to the quantum regime offer unprecedented sensitivity to displacement, mass, force and charge; quantum control in solid-state nano-systems now enables the spin of single electrons and nuclei to be imaged; and quantum coherent motion of trapped atomic ions has provided a means to detect forces nearly four orders of magnitude smaller than any comparable technique. The overall landscape suggests that we are now poised to open a vast scientific frontier in quantum sensing and metrology with applications from precision time and frequency standards, to deployable field sensors and bio-imaging.

Quantum systems can be utilized in a variety of ways to perform ultra-precise sensing of various forces. Precision measurement of local gravitational forces is a highly useful tool for geological mapping and oil/mineral exploration. For precision gravity metrology, one requires massive bodies and using massive (almost macroscopic) objects in a quantum assisted force sensing scheme is very challenging, as one needs to be able to generate spatial quantum superposition states of these massive bodies that are long lived.

At Macquarie University, CI Brennen in collaboration with CI Twamley and PhD student Mauro Cirio published a revolutionary new proposal for cooling a mesoscopic superconducting resonator via the Meisner effect. We showed that the resonator can be cooled without being clamped to any other support which frees the system from a significant source of decoherence. We showed how to magnetically levitate a small massive object (three joined loops of superconducting wire), and to cool its centre of mass motion to the quantum motional zero point via magnetic inductive coupling to a nearby superconducting flux qubit. As the levitated mechanical resonator is extremely isolated, it is predicted that the motional quantum state should persist for seconds. The resonator could then potentially be coherently driven into a macroscopic position superposition state, and be used as an extremely sensitive probe for motional forces or even gravitationally induced decoherence. This work was highlighted in *Nature Physics News and Views* (*Nature Physics* 8, 782 (2012)).

Schematic of superconducting levitating resonator (rectangular loops), levitated by the magnetic field (shown as grid of vectors), of a sphere (top), and cooled via inductive coupling to a flux qubit (bottom).



Entanglement-enabled quantum sensing using trapped ions

PROGRAM: QUANTUM ENABLED SENSORS AND METROLOGY

CHIEF INVESTIGATOR MICHAEL J. BIERCUK, THE UNIVERSITY OF SYDNEY; PARTNER INVESTIGATOR JOHN J. BOLLINGER, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) UNITED STATES

Precision metrology focuses on the development of new techniques to perform measurements at the extremes of human technical capability. This research has applications in standards research, but also in physics research. New advances in metrology—for instance quantum-enhanced metrology—are fundamental enabling technologies for new experiments probing the structure of the universe. For instance, the use of so-called squeezed light is permitting access to new regimes of gravitational wave detection at LIGO.

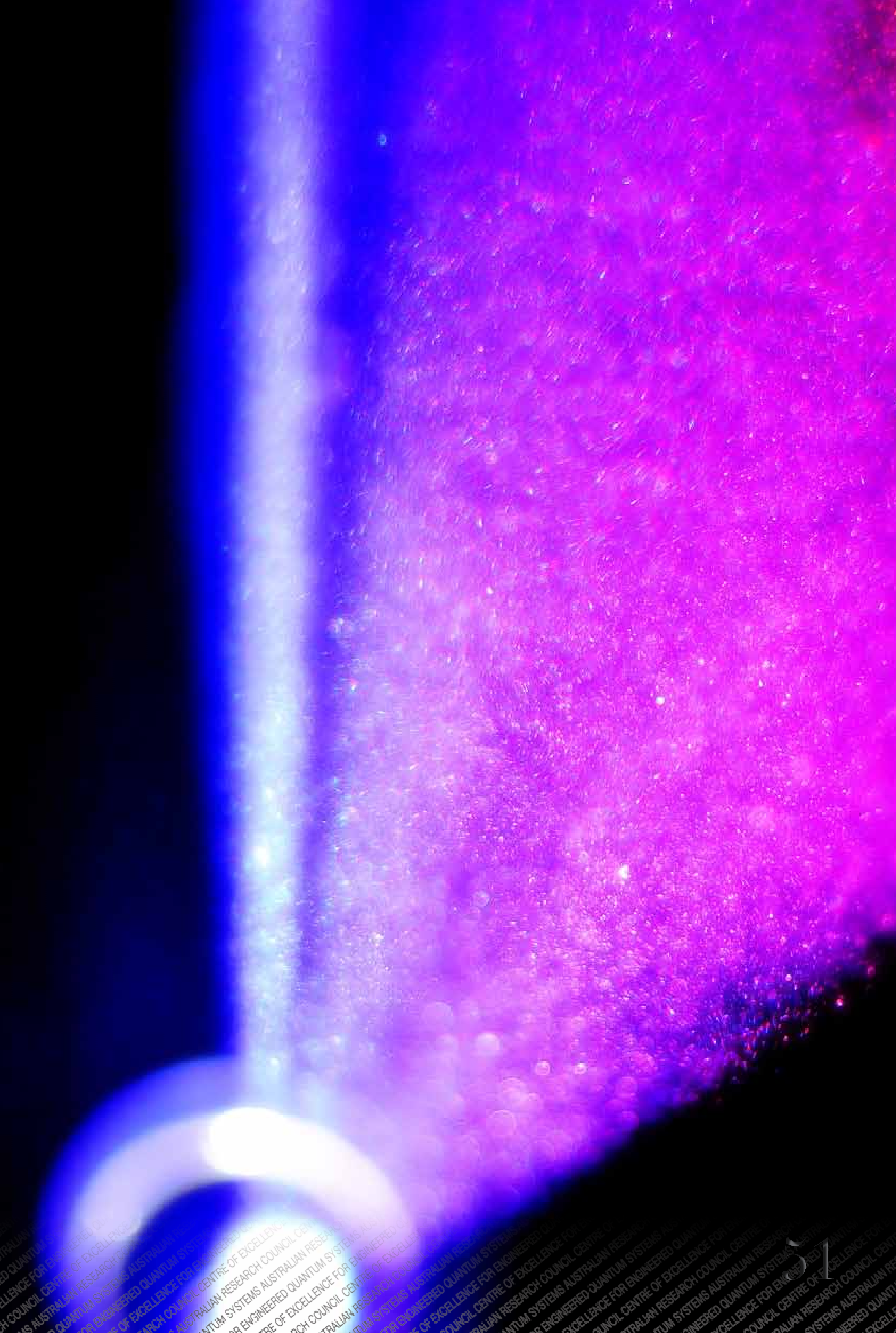
Our research outcomes in quantum-enhanced metrology fall into this category – enabling technology for new physics research. In particular, we developed a technique by which quantum entanglement between the spin and motional degrees of freedom in a large crystal of trapped ions could be used as an extraordinarily sensitive probe of the system's mechanical behaviour.

Motional degrees of freedom have been a tool used in the regime of single-ion experiments for more than a decade, enabling the implementation of quantum logic operations. However, existing techniques for motional-mode spectroscopy fail for large collections of ions – as would be used in large-scale quantum simulators or simple plasma physics experiments. Accessing the wide variety of motional modes that exist in a large atomic sample is a key requirement for advances in these research areas.

Our work used entanglement between the spin degree of freedom of each atom and the collective modes of motion to permit both spectroscopy and thermometry of the entire spectrum of transverse and in-plane motional modes in a two-dimensional ion crystal. We performed these experiments using the Penning trap apparatus at NIST, in which crystals of beryllium ions were formed using laser cooling techniques.

By using entanglement, the sensitivity of the measurement increased dramatically over previous demonstrations. For instance, our record-breaking detection of yoctonewton-scale forces and ion displacements at the scale of tens of nm were shattered using this technique. Signal-to-noise limits suggest sub-yN force-detection sensitivities are achievable and discrimination of motional excursions on the scale of picometers were routinely observed (the cost is generality of the detected force). Additionally, this technique permitted mode thermometry with sensitivity at the scale of microkelvin, and the ability to determine phonon occupation with single-phonon resolution across all accessible modes.

These specific technical achievements pave the way for more advanced studies of precision metrology using the physics of cold atoms.



Quantum Matter

PROGRAM: SYNTHETIC QUANTUM SYSTEMS AND SIMULATION

CHIEF INVESTIGATORS STEPHEN D. BARTLETT AND ANDREW C. DOHERTY, THE UNIVERSITY OF SYDNEY; CHIEF INVESTIGATORS GAVIN K. BRENNEN, MACQUARIE UNIVERSITY

In the Centre, we are working on a variety of optical, atomic, semiconducting and superconducting quantum architectures to the point where we can strongly couple large arrays of microscopic quantum systems in a coherent fashion up to mesoscopic or even macroscopic scales, while maintaining the ability to perform precision measurement and control of the individual quantum constituents. With these capabilities, we can coax the system out of its natural classical state and enter an exotic new regime of large-scale coherent quantum behaviour. But first, we need to understand what we need to engineer!

The central aim of this research program is to develop the theoretical foundations for computing with quantum matter. While solid-state devices offer naturally reliable hardware for modern classical computers, thus far quantum information processors resemble vacuum tube computers in being neither reliable nor scalable. Strongly correlated many body states stabilised in topologically ordered matter offer the possibility of naturally fault tolerant computing, but are both challenging to engineer and coherently control and cannot be easily adapted to different physical platforms. As part of this EQuS research project, we have proposed an architecture which achieves some of the robustness properties of topological models, but with a drastically simpler construction.

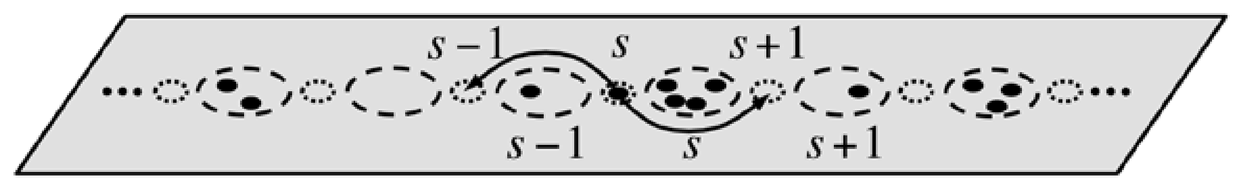
In 2012, we achieved a significant breakthrough in characterising quantum matter and its use for quantum computation. This characterisation relates the quantum computational power of a zero-temperature quantum phase to a phenomenon known as symmetry-protected topological order. This order characterises the way in which hidden long-range entanglement is contained in a system (which gives the phase its quantum computational power), the relation between this entanglement and the presence of gapless edge modes (which form the logical quantum information), and the way in which the entanglement and the edge modes transform under a particular symmetry (which enables the quantum logic gates). We reported a full characterisation of this phenomena in one-dimensional spin chains in Else, Schwarz, Bartlett and Doherty, *Physical Review Letters* (2012) and a subsequent extension to a full quantum computational model in Else, Bartlett, Doherty, *New Journal of Physics* (2012). This work has been accepted as a talk at the Quantum Information Processing workshop in January 2013: the premiere international quantum computing workshop.

Also in 2012, in work by Wallman and Bartlett published in *Physical Review A* (2012), we have completely classified the possible 'classical subtheories' of a single quantum system (qubit or qudit). Within such a subtheory, any quantum state, transformation and measurement can be viewed as a classical probabilistic operation. Full quantum mechanics cannot be described in this fashion, due to the nonclassical properties of Bell nonlocality and contextuality; classifying the classical subtheories allows us to better identify truly quantum resources for quantum computing and other quantum technologies.

CI Brennen's team at Macquarie University has made a number of significant accomplishments in this research area: (i) discovery of localization effects in the transport of anyons in the presence of topological disorder, (ii) simulation of classical Ising models with quantum mechanics.

(i) One of the main focuses of the Brennen research group is to study dynamics of new kinds of particles called anyons that are predicted to emerge in strongly correlated two dimensional states of matter such as in spin lattices, quantum Hall states and topological insulators. The goal is to show how these particles could be measured and how their physics differs from the well understood behaviour of fermions or bosons. In 2011, our group theoretically predicted that out of equilibrium, static anyons act as viscous background slowing down the propagation of one free anyon in a distance independent way. In 2012, together with PhD student Mr Lehman and co-workers in University of Leeds, UK and Czech Technical University in Prague, we extended this work to transport in the presence of random backgrounds of pinned anyons. This work is the first extension of the phenomenon of Anderson localization, predicted over 60 years ago, to the case of anyons in random topological environments. We discovered surprising behaviour that depends on whether the anyonic statistics are Abelian or non-Abelian. Both features have important consequences for the stability of topological quantum computing and offer a robust signature of statistics that may be much easier to implement in the laboratory.

(ii) An important goal for quantum simulators is to make one quantum system that is easily controlled behave like another that is difficult to analyse. However, there is also great potential to use quantum systems to extract information about classical statistics models such as free energy, specific heat and finite temperature phase transitions. In collaboration with coworkers at the University of Barcelona, CI Brennen and PhD student Mauro Cirio created a new way to simulate classical Ising models in two or three dimensions using a relatively simple quantum state overlap experiment. The method is a notable advance since prior work only showed how to do this generically for complex temperature classical systems, whereas our method works for real temperatures. We also identified the computational complexity of certain Ising partition functions in terms of being able to predict the outcome of quantum computations.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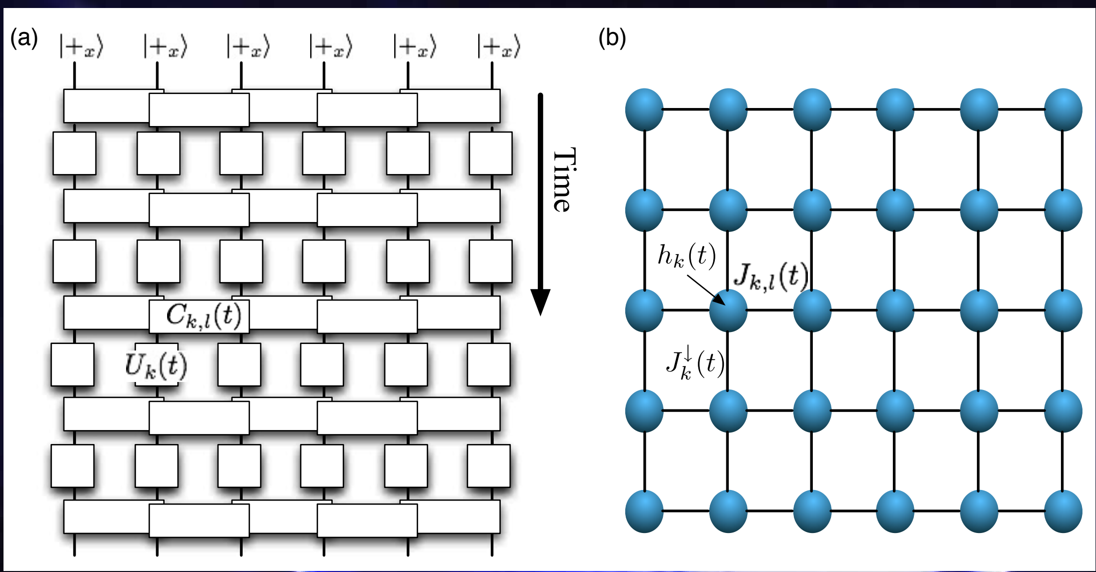
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(b)
$h_k(t)$
$J_{k,l}(t)$
$J_k^{\downarrow}(t)$

KEY PERFORMANCE INDICATORS

Research Findings

Quality of publications

In the Centre's first full year of operation, EQuS researchers have published 74 peer-reviewed publications. Of these papers 87% appeared in journals with an A*/A rating.

In 2012, fundamental research within the Centre into Quantum technology was published in prestigious scientific journals such as *Nature, Nature Physics, Nature Photonics, Nature Communications, Nature Nanotechnology, Science, Physical Review Letters, Applied Physics Letters,* and *Optics Express*.

Details of publications are shown in Appendix 1: Publications

Patents

In 2012, the following provisional patents were filed:

Biercuk, Michael. Long-time low-latency quantum memory by dynamical decoupling. Provisional Patent Application: 2012902541. 18 June 2012

Molina-Terriza, Gabriel. A method and an apparatus for generating information indicative of a position of a round feature Provisional Patent Application: 2012904967. 12 November 2012

Commentaries about the Centre's achievements

EQuS and the node institutions issued 15 media releases about EQuS research during 2012.

MEDIA RELEASES

'Australian-UQ Collaboration leaps ahead in catching spooky light' EQuS Media Release 19 January 2012 http://equs.org/news/australian-us-collaboration-leaps-ahead-catching-spooky-light

'March 2012 Science Research Lecture looks at stars and diamonds' EQuS Media Release 2 March 2012 http://equs.org/news/march-2012-science-research-lecture-looks-stars-and-diamonds

'147 Stand-out Researchers to help evaluation our research strengths', ARC Media Release, 8 March, 2012, http://www.arc.gov.au/media/releases/media_8mar12.htm

'Science Academy elects distinguished new Fellows', Australian Academy of Science Media Release, 22 March 2012, http://www.science.org.au/news/media/26march12.html

'Light Reveals secrets of the Quantum Walker' EQuS Media Release 23 March 2012 http://equs.org/news/light-reveals-secrets-quantum-walker

'Physicists make light matter' EQuS Media Release 7 June 2012 http://equs.org/news/physicists-make-light-matter

'Algae shedding light on Quantum Systems' EQuS Media Release 7 June 2012 http://equs.org/news/algae-shedding-light-quantum-systems

'EQuS Welcomes Maxim Goryachev' EQuS Media Release 9 August 2012 http://equs.org/news/equs-welomes-maxim-goryachev

'EQuS Students successful in Poster Day Competition' EQuS Media Release 21 September 2012 http://equs.org/news/equs-students-successful-poster-day-competition

'EQuS Turns up the heat on thermometer Research' EQuS Media Release 11 October 2012 http://equs.org/news/equs-turns-heat-thermometer-research

'Advancing Scientific Insights into Quantum Systems' EQuS Media Release 11 October 2012 http://equs.org/news/advancing-scientific-insights-quantum-systems

'Joint statement from the University of Western Australia and The University of Queensland: Sean Barrett' UWA, UQ and EQuS Media Release 22 October 2012 equs.org/news/joint-statement-university-western-australia-and-university-queensland-sean-barrett

'Quantum Physics Student Wins Accolades' EQuS Media Release 31 October 2012 http://equs.org/news/quantum-physics-students-wins-accolade

'UWA's Physics Gems Sparkle' EQuS Media Release 22 November 2012 http://www.news.uwa.edu.au/201211225239/awards-and-prizes/uwas-physics-gems-sparkle

'At the solstice: Shining light on quantum computers' EQuS Media Release 21 December 2012 http://equs.org/news/solstice-shining-light-quantum-computers

A number of media commentaries about the Centre, and its Chief Investigators' achievements and activities were published or broadcast in 2012, including the following:

ELECTRONIC

'Australian-UQ Collaboration leaps ahead in catching spooky light' *UQ News*, 11 January, 2012 http://www.uq.edu.au/news/index.html?article=24252

'Australian-UQ Collaboration leaps ahead in catching spooky light', *Jon Baer Blog,* 11 January, 2012 http://jonbaer.com/post/15660694780/australian-us-collaboration-leaps-ahead-in-catching

'Australian-US collaboration leaps ahead in catching spooky light', *Science in Public Media Bulletin,* 19 January, 2012 http://www.scienceinpublic.com.au/bulletins/intelligenceandmore

'Australian-US collaboration leaps ahead in catching spooky light', *Australian Institute of Physics Bulletin*, 1 February, 2012 http://www.aip.org.au/info/?q=article/boas-medal-australia-day-honours-nasa-robots-and-space-junk-%E2%80%93-physics-february

'March 2012 Science research lecture looks at stars and diamonds', *Macquarie University News,* 2 March, 2012, http://www.mq.edu.au/newsroom/2012/03/02/march-2012-science-research-lecture-looks-at-stars-and-diamonds/

'Bill to stop misuse of dangerous technology could hit uni researchers', *The Conversation,* 21 March, 2012 http://theconversation.edu.au/bill-to-stop-misuse-of-dangerous-technology-could-hit-uni-research-5980

'Light Reveals secrets of the Quantum Walker', *Macquarie University News*, 23 March, 2012 http://www.mq.edu.au/newsroom/2012/03/23/light-reveals-secrets-of-the-quantum-walker/

'Physicists benchmark quantum simulator with hundreds of qubits' *PhysOrg*, 25 April 2012, http://phys.org/news/2012-04-physicists-benchmark-quantum-simulator-hundreds.html

'Researchers claim Quantum Computer Breakthrough', *ABC News,* 26 April, 2012 http://www.abc.net.au/news/2012-04-26/super-computer/3972832

'Tiny crystal may hold key to future of computers' *Fox News,* 26 April, 2012 http://www.foxnews.com/tech/2012/04/26/tiny-crystal-may-hold-key-to-future-computers/

'Reseachers claim quantum computer breakthrough' *SBS World News,* 26 April, 2012 http://www.sbs.com.au/news/article/1645619/Researchers-claim-quantum-breakthrough

'Tiny crystal 'revolutionises' computing', *Sky News*, 27 April, 2012 http://news.sky.com/story/13273/tiny-crystal-revolutionises-computing

'NIST's quantum simulator mimics hundreds of qubits interacting' *Australian Popular Science,* 28 April, 2012 http://www.popsci.com.au/science/energy/nist-s-quantum-simulator-mimics-hundreds-of-qubits-interacting

‘300’, *The Quantum Pontiff,* 29 April, 2012 http://dabacon.org/pontiff/?p=6251

‘NIST Physicists Benchmark Quantum Simulator with Hundreds of Qubits’, *NIST Tech Beat,* 25 April, 2012 http://www.nist.gov/pml/div688/qubits-042512.cfm

‘Particles and persecution: why we should care about Iranian physicists’, *The Conversation,* 12 June, 2012, https://theconversation.edu.au/particles-and-persecution-why-we-should-care-about-iranian-physicists-7132

‘Three Eureka Prize Finalists in the Faculty of Science’, *The University of Sydney, Faculty of Science News,* 27 July, 2012, http://sydney.edu.au/news/science/397.html?newsstoryid=9717

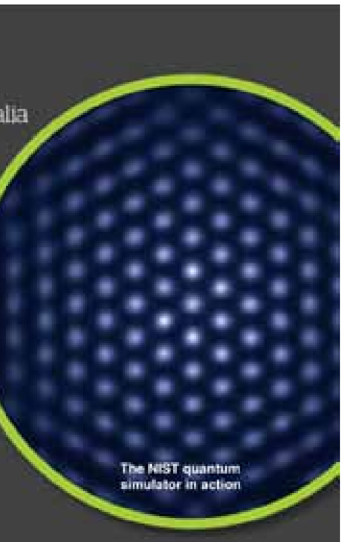
‘Quantum Physics Makes Tomorrow’s Technology’ *Vibewire* 15 August, 2012 http://vibewire.org/2012/08/dr-michael-biercuk-using-quantum-physics-to-make-tomorrows-technologies/

‘Quantum Evolution’ *ABC Science*, 20 September, 2012 http://www.abc.net.au/science/articles/2012/09/20/3593847.htm

‘Tiny particles: quantum leaps’ *Sydney University Alumni Magazine (SAM),* 10 October, 2012 http://sydney.edu.au/alumni/sam/october2012/michael-biercuk.shtml

8 DEVELOPING A PRACTICAL SUPERCONDUCTOR

WHO: University of Sydney, Australia and the USA's National Institute of Standards and Technology (NIST) in Boulder, Colorado
STATUS: First results published in *Nature* in April 2012. Research ongoing
COST: Undisclosed



The NIST quantum simulator in action

Superconductors could be the future of electricity distribution and storage. These materials have zero electrical resistance – a current in a loop of superconducting wire will continue to circulate forever. They could be used to build lossless cables and batteries for power grids, and for a wealth of other energy-saving applications. But there's a problem. All the superconductors we know of today only work at very low temperatures (less than −163°C). So they would have to be actively cooled, thus wiping out any potential savings.

The race is on to find materials that superconduct at higher temperatures. But it's a problem mired in quantum physics – the tricky laws governing the behaviour of subatomic particles. Solving this problem is just too difficult for ordinary computers. But now, in a major breakthrough, researchers at the University of Sydney and NIST in the US have developed a 'quantum simulator' – a computing device that enables researchers to set up and run simulated interactions between quantum particles and simply read off the results of those interactions. If the interactions are carefully chosen so as to be representative of those that take place inside superconductors, then the device becomes a computer capable of solving the problem.

"In our experiments we produce a well-controlled system whose dynamics are governed by the laws of quantum physics," says Dr Michael J Biercuk, a member of the team undertaking the research at the University of Sydney. "Accordingly, we are able to mimic the behaviour of naturally occurring quantum systems."

In a research report published in the journal Nature in April this year, the team described their device, which consists of ions of the metal beryllium arranged in a crystal lattice. They are now investigating how to configure the ions in order to run experiments to mimic processes inside various materials, including superconductors.

‘Influential mentor wins overdue recognition with Nobel Prize in Physics’, *The Conversation,* 10 October, 2012, http://theconversation.edu.au/influential-mentor-wins-overdue-recognition-with-nobel-prize-in-physics-10084

‘UQ Turns up the heat on thermometer Research’ *UQ News,* 11 October, 2012 http://www.uq.edu.au/news/index.html?article=25375

‘Advancing Scientific Insights into Quantum Systems’, *e! Science News,* 11 October,2012, http://esciencenews.com/sources/physorg/2012/10/11/advancing.scientific.insights.quantum.systems

‘Advancing Scientific Insights into Quantum Systems’, *PhysOrg,* 11 October, 2012 http://yah.vn/advancing-scientific-insights-into-quantum-systems-v5OV

‘Advancing Scientific Insights into Quantum Systems’, *Feed my Science,* 11 October, 2012 http://feedmyscience.com/news/Advancing+scientific+insights+into+quantum+systems

‘Advancing scientific insights into quantum systems’ *UQ News,* 11 Octpber, 2012 http://www.uq.edu.au/news/index.html?article=25377

‘A wind tunnel for quantum physics’ *Optics and Photonics Focus*, 22 October, 2012 http://opfocus.org/index.php?topic=story&v=18&s=2

‘Quantum Physics Students Wins Accolades’, *UQ News,* 31 October, 2012 http://www.uq.edu.au/news/index.html?article=25469

‘Quantum Physics Students Wins Accolades’, *SciAnswers.com,* 31 October 2012, http://scianswers.com/topic/quantum-physics-student-wins-accolade-uq-news/

‘UWA's Physics Gems Sparkle’, *UWA University News*, 22 November, 2012 http://www.news.uwa.edu.au/201211225239/awards-and-prizes/uwas-physics-gems-sparkle

‘At the solstice: shining light on quantum computers’ *UQ News,* 21 December, 2012 http://www.uq.edu.au/news/index.html?article=25707

‘At the solstice: shining light on quantum computers’, *e! Science News,* 21 December, 2012 http://esciencenews.com/sources/physorg/2012/12/21/at.solstice.shining.light.quantum.computers

‘At the solstice: Shining light on quantum computers’, *PhysOrg,* 21 December, 2012 http://phys.org/news/2012-12-solstice-quantum.html

TWITTER

Meeting Professor Brian Cox https://twitter.com/COSMOSmagazine/status/266052643183542272/photo/1 07-Nov-12

UWA's Physics Gems Sparkle https://twitter.com/uwanews/status/271513388830564353 21-Nov-12

TELEVISION AND RADIO

'Tiny Super Computer' *AM with Tony Eastly,* ABC News, 26 April 2012 http://www.abc.net.au/news/2012-04-26/tiny-super-computer/3973176

'Researchers tout quantum computer breakthrough' *AM with Tony Eastly*, ABC News 26 April 2012 http://www.abc.net.au/news/2012-04-26/researchers-create-mini-computer-with-crystal/3973208

'Crystal could rival Supercomputers', *SBS World News Radio,* 26 April, 2012, http://www.sbs.com.au/news/radio/episode/213091/Crystal-could-rival-supercomputers

'Tiny Crystal Boosts Computer Power' *SBS World News,* 26 April, 2012, http://www.sbs.com.au/news/video/2227261951/Tiny-crystal-boosts-computer-power

'Microscopic crystal could power supercomputer' *Lateline* ABC News, 26 April, 2012 http://www.abc.net.au/lateline/content/2012/s3489923.htm

'Laws will stifle research claims scientist' *Lateline* ABC News, 31 October, 2012 http://www.abc.net.au/lateline/content/2012/s3623059.htm

NEWSPAPER AND MAGAZINES

'Sweating the (very) small stuff', *COSMOS,* 12 January, 2012 http://www.cosmosmagazine.com/cosmos_online/sweating-very-small-stuff/

'Quantum walk towards new supercomputers', *COSMOS,* 11 April, 2012 http://www.cosmosmagazine.com/node/5505/full

'Sydney scientist helps design tiny super computer' *Sydney Morning Herald,* 26 April, 2012 http://www.smh.com.au/technology/sci-tech/sydney-scientist-helps-design-tiny-super-computer-20120426-1xmik.html

'Link to 'world's most advanced computer' *The Australian,* 26 April, 2012 http://www.theaustralian.com.au/news/nation/link-to-worlds-most-advanced-computer/story-e6frg6nf-1226338312030

'Scientists develop 'most powerful' quantum simulator' *Herald Sun,* 26 April, 2012 http://www.heraldsun.com.au/technology/sci-tech/scientists-develop-most-powerful-quantum-simulator/story-fn5iztw3-1226338514398

'Quantum Computer Breakthrough? 'Ion-Crystal' Points To Vast Increase In Processing Power, Scientists Say', *Huffington Post*, 30 April, 2012 http://www.huffingtonpost.com/2012/04/27/quantum-computer-ion-crystal_n_1459237.html?ref=science

'Device just one-atom thick a quantum leap in technology' *The Canberra Times,* 26 April, 2012 http://www.canberratimes.com.au/technology/sci-tech/sydney-scientist-helps-design-tiny-super-computer-20120426-1xmik.html

'Quantum computers are leaping ahead', *The Guardian,* 6 May, 2012, http://www.guardian.co.uk/science/2012/may/06/quantum-computing-physics-jeff-forshaw

'The 10 world-changing experiments that will shape the future' *BBC Focus,* 12 July, 2012 http://sciencefocus.com/issue/10-experiments

'Defence Bill a Research risk: Academics' *The Australian,* 17 October, 2012 http://www.theaustralian.com.au/higher-education/defence-bill-a-research-risk-academics/story-e6frgcjx-1226497279991

'Top 100 thinkers', *Sydney Morning Herald*, 30 November, 2012 www.smh.com.au/lifestyle/top-100-the-thinkers-20121126-2a37o.html

Developing a comprehensive framework for the training and mentoring of a new generation of quantum scientists and engineers is a major Centre goal. In 2012, the Centre funded 16 top-up scholarships at its host institutions and nodes as well as supporting 38 PhD scholarships funded by UQ and the EQuS nodes. In addition to project-based training and mentoring, Centre RHD students have access to professional development training provided by the Graduate schools of their host institutions. Students participate in a PhD student workshop at the Centre's Annual Conference and are also encouraged to attend national and international Quantum Theory conferences.

The Formulae Lounge – Macquarie University

Macquarie University hosts a dedicated space – The Formulae Lounge for discussing concepts related to the theoretical science of EQuS. It acts as a focal point for MQ EQuS visitors, Chief Investigators and students to meet and discuss problems, understand new theoretical concepts and share knowledge.

Training Courses Attended

COURSE	COUNTRY	DATE/S	CENTRE ATTENDEE
Biosafety and Biohazards Workshop	Australia		Jana Say
ERA: Examiner Training Course	Australia		Michael Tobar
RHD Supervision Enhancement Program	Australia		Stefania Castelletto & Torsten Gaebel
Information Technology training course at the US Department of Commerce	United States of America	June 2012	Eugene Ivanov
Laser Safety	Australia		Tyler Neely
Performing Staff Appraisals	Australia		Thomas Stace
Privacy at UQ	Australia		Jacopo Sabbatini
SPIE Short Course - Fundamentals of Nonlinear Optics			Daniel Creedon
UNSW ANFF Training Sessions on Equipment and Safety	Australia		Alice Mahoney, Torsten Gaebel & Xanthe Croot
Rottnest Island Workshop September 2012	Australia	September 2012	David Reilly, Andrew Doherty, Stephen Bartlett & Michael Biercuk
Tensor Incubator Workshop	Australia		Aroon O'Brien & Jacob Bridgeman
Quantum Walkshop	Australia	10 April - 11 April 2012	William Soo
2012 MQCO Spin Qubit Meeting	Austraila	11 January - 14 January 2012	Leanne Price, Andres Reynoso, Michael Biercuk, Sylvain Blanvillian, James Colless, Xanthe Croot, John Hornibrook, Siva Prashant Kumar, Alice Mahoney & Ewa Rej

COURSE	COUNTRY	DATE/S	CENTRE ATTENDEE
Coogee 2012 Sydney Quantum Information Theory Workshop	Australia	30 January - 1 February 2012	Trond Linjordet, Tommaso Demarie, Lauri Lehman, Andrew Rigby, Aharon Brodutch, Peter Rohde, Gavin Brennen, Sukhi Singh, Mauro Cirio, Jason Twamley, Stephen Bartlett, Courtney Brell, Jacob Bridgeman, Andrew Darmawan, Andrew Doherty, Dominic Else, Dylan Griffith, Aroon O'Brien, Andres Reynoso, Dominic Williamson, Simon Burton, William Soo, Matthew Wardrop, Ian McCulloch, Gregory Crosswhite, & Phien Ho.
ARC CoE CUDOS Workshop	Shoal Bay, Australia	31 January - 3 February 2012	Gabriel Molina-Terriza & Michael Delanty
Introduction to University Teaching Program	Australia	16 February 2012	Ivan Kassal
APS Conference	Boston, United States of America	27 February - 2 March 2012	Stephen Bartlett, Michael Biercuk, Andrew Doherty, James Colless, Xanthe Croot, John Hornibrook, Siva Prashant Kumar, Alice Mahoney, David Reilly, Ewa Rej, & William Soo
Applying for Research Only Academic Promotion	Australia	7 March 2012	Marcelo de Almeida
Session of Student Integrity and Misconduct	Australia	12 March 2012	Andrew White
Quantum Technology Workshop, Australian Government, Department of Defence, Defence Science and Technology	Canberra, Australia	19 April 2012	David Reilly & Gabriel Molina-Terriza
Essential Knowledge for Research Management	Australia	20 April 2012	Marcelo de Almeida
Molecular Imaging Symposium	Sydney, Australia	1 May 2012	David Waddington
TQC Conference	Tokyo, Japan	17 May - 19 May 2012	Stephen Bartlett
Andreev Bound State Workshop	Spain	4 June - 6 June 2012	Andrew Doherty
Quantum Mechanics, Operatory Theory and the Reimann Zeta Function Workshop	Spain	17 June - 23 June 2012	Jason Twamley
AIP Congress	Sydney, Australia	9 December - 13 December 2012	Andrew Doherty, Stephen Bartlett, Dominic Williamson, Aroon O'Brien, Andres Reynoso, Carlo Bradac, Torsten Gaebel, Sylvain Blanvillain, Stephen Gensemer, David Hayes, Michael Lee, Xanthe Croot, James Colless, Alice Mahoney, John Hornibrook, William Soo, Jacob Bridgeman, Joel Wallman, Ewa Rej, David Waddington, Simon Burton, Courtney Brell, Natasha Gabay, Rafael Alexander, Andrew Darmawan

Centre postgraduate recruitments - PhD

THE UNIVERSITY OF QUEENSLAND

Andrew Bolt
Title: Diffusion in Gradient Echo Memories
Supervisors: Tom Stace and Gerard Milburn

Juan Loredo
Title: Holonomies in experimental quantum information processing
Supervisors: Andrew White and Marcelo de Almeida, Alessandro Fedrizzi, Till Weinhold

Marcel Horstmann
Title: Plasmonically-Enhanced Hybrid Optomechanics
Supervisor: Warwick Bowen

Martin Ringbauer
Title: Quantum Simulation and Computation
Supervisor: Andrew White

MACQUARIE UNIVERSITY

Hossein Tavakoli Dinani
Title: Loss-Tolerant Phase Measurement
Supervisor: Jason Twamley

Nora Tischler
Title: Quantum applications for the orbital angular momentum of light.
Supervisors: Gabriel Molina-Terriza and Mathieu Juan

THE UNIVERSITY OF SYDNEY

Xanthe Croot
Title: The Control of GaAs spin qubits.
Supervisors: David Reilly and Stephen Bartlett

Dominic Else
Title: Theoretical research on how to use interacting quantum spin systems for measurement-based quantum computation
Supervisors: Stephen Bartlett and Andrew Doherty

Todd Green
Title: Physical-layer Error Evasion Strategies Through Quantum Control
Supervisors: Michael Biercuk and Andrew Doherty

Prashant (Siva) Kumar
Title: Topological Quantum Technology
Supervisor: David Reilly

Alice Mahoney
Title: Manipulation and control of spin qubits in GaAs
Supervisor: David Reilly

Caryn Van Vreden
Title: In-vivo tracking of hyperpolarized nanoparticles
Supervisor: David Reilly

David Waddington
Title: Hyperpolarisation of nanoparticles for MRI
Supervisor: David Reilly

Centre postgraduate recruitments Honours students

THE UNIVERSITY OF QUEENSLAND

James Bennett
Title: Cavity-Enhanced Hybrid Optomechanics with Cold Atoms
Supervisor: Warwick Bowen

Kiran Khosla
Title: Gravitational decoherence in optomechanics
Supervisor: Warwick Bowen

THE UNIVERSITY OF SYDNEY

Jacob Bridgeman
Title: Gapless Boundary Modes in the Ashkin-Teller Model
Supervisor: Stephen Bartlett

Alexander Soare
Title: Agile microwave system for the control of hyperfine transitions in trapped Ytterbium ions.
Supervisor: Michael Biercuk

Dominic Williamson
Title: Holonomic quantum computing using gapless boundary modes
Supervisor: Stephen Bartlett

Harrison Ball
Title: Development of high-power solid-state laser systems for Be+ ion trapping experiments
Supervisor: Michael Biercuk

Dylan Griffith
Title: Tensor Networks and the Ising Model
Supervisor: Stephen Bartlett

Centre Postgraduate course completions - PhD

MACQUARIE UNIVERSITY

Michael Delanty
Title: Collective effects in circuit QED
Supervisors: Jason Twamley and Gavin Brennen

Carlo Bradac
Title: Magnetic field detection using single spins in diamond
Supervisor: Jason Twamley

Aharon Brodutch
Title: Non-local observables in quantum field theory
Supervisor: Gavin Brennen

THE UNIVERSITY OF SYDNEY

Alexandr Sergeevich
Title: Estimation algorithms of a qubit Hamiltonian parameter
Supervisors: Stephen Bartlett and David Reilly

THE UNIVERSITY OF WESTERN AUSTRALIA

Daniel Creedon
Title: Effects of Electron Spin Resonance in a Cryogenic Sapphire Whispering Gallery Mode Maser
Supervisor: Michael Tobar

International Visitors

EQuS actively encourages visits from Australian and overseas colleagues and peers and is pleased to have hosted the following visitors in 2012.

VISITOR	INSTITUTION	COUNTRY	DATE/S
Aziz Alam	Indian Institute of Science Education Research, Mohali Knowledge City	India	4 January 2011 to 14 January 2012
John Baez	University of California	USA	28 January 2012 to 9 February 2012
Ed Barnes	University of Maryland	USA	11 January 2012 to 17 January 2012
PI Sean Barrett	Imperial College London	United Kingdom	22 January 2012 to 26 January 2012
Brad Blakestad	Laboratory for Physical Sciences of the National Security Agency (LPS/NSA)	USA	15 February 2012 to 15 February 2012
Rainer Blatt	University of Innsbruck	Austria	20 February 2012 to 20 February 2012
Hendrik Bluhm	Harvard University	USA	12 January 2012 to 15 January 2012
Robin Blume Kohout	Sandia Laboratories	USA	26 November 2012 to 5 December 2012
Héctor Bombin	Perimeter Institute	Canada	28 January 2012 to 10 February 2012
Floris Braakman	Delft University of Technology	The Netherlands	11 January 2012 to 15 January 2012
Ben Brown	Imperial College London	United Kingdom	30 January 2012 to 18 February 2012
			18 September 2012 to 29 September 2012
			28 September 2012 to 5 October 2012
Jim Butler	Naval Research Laboratory, USA & consultant to the Smithsonian Institute	USA	28 January 2012
Mark Byrd	Physics Department, Southern Illinois University	USA	2 August 2012 to 31 August 2012
Stefano Chesi	McGill University	Canada	18 August 2012 to 16 September 2012
Jared Cole	RMIT	Australia	11 December 2012 to 12 December 2012
Josh Combes	University of New Mexico	USA	12 March 2012 to 1 June 2012

VISITOR	INSTITUTION	COUNTRY	DATE/S
			6 August 2012 to 10 August 2012
Michael Cuthbert	Oxford Instruments	United Kingdom	10 January 2012 to 15 January 2012
Sankar Das Sarma	University of Maryland	United States	11 January 2012 to 17 January 2012
Paul Lopata	Laboratory for Physical Sciences of the National Security Agency (LPS/NSA)	USA	15 February 2012
Daniel Loss	Universität Basel	Switzerland	10 January 2012 to 15 January 2012
Brendon Lovett	Herriot Watt University	UK	21 January 2012 to 1 February 2012
Robert Mann	Department of Physics, University of Waterloo	Canada	26 November 2012 to 21 December 2012
PI Charles Marcus	Harvard University	USA	10 January 2012 to 15 January 2012
Jim Medford	Harvard University	USA	10 January 2012 to 15 January 2012
Julia Michl	Institute of Physics, University of Stuttgart	Germany	21 October 2012 to 21 November 2012
Clemens Mueller	Université de Sherbrooke	Canada	11 December 2012 to 12 December 2012
Bill Munro	NTT Japan	Japan	19 January 2012 to 31 January 2012
Kae Nemoto	National Institute for Informatics	Japan	19 January 2012 to 31 January 2012
Karim Noui	Laboratoire de Mathématiques et Physique Théorique Parc de Grandmont 37200 Tours	France	26 March 2012 to 14 April 2012
Tobias Osborne	Leibniz Universität Hannover	Germany	29 January 2012 to 2 February 2012
Christian Ospelkaus	University of Hannover	Germany	5 December 2012
Tomohiro Otsuka	The University of Tokyo	Japan	11 January 2012 to 15 January 2012
Jiannis Pachos	University of Leeds	United Kingdom	28 January 2012 to 2 February 2012
Chris Palmstrom	University of California Santa Barbara	USA	10 January 2012 to 15 January 2012
Gerardo Paz Silva	Quantum Computation and Open Quantum Systems, University of Southern California	USA	30 January 2012 to 2 February 2012
			2 February 2012 to 13 February 2012

VISITOR	INSTITUTION	COUNTRY	DATE/S
David Poulin	Université de Sherbrooke	Canada	28 January 2012 to 8 February 2012
Markus Rambach	University of Innsbruck	Austria	20 June 2012 to 22 June 2012
Terry Rudolph	Imperial College London	United Kingdom	3 January 2012 to 22 January 2012
			11 July 2012 to 18 July 2012
Fabio Scardigli	Academia Sinica	Taiwan	1 June 2012 to 1 June 2012
Gerd Elmar Schroeder	Friedrich-Alexander Universitaet Erlangen-Nuernberg	Germany	2 April 2012 to 3 April 2012
Norbert Schuch	Caltech	USA	29 January 2012 to 4 February 2012
Brian Schultz	University of California Santa Barbara	USA	10 January 2012 to 15 January 2012
Javad Shabani	Harvard University	USA	10 January 2012 to 15 January 2012
Qingxiao Shan	National University of Defense Technology	China	8 October 2012 to 7 October 2013
Borzoyeh Shojaei	University of California Santa Barbara	USA	10 January 2012 to 15 January 2012
Vikesh Siddhu	Indian Institute of Science Education Research, Mohali Knowledge City,	India	7 June 2012 to 11 July 2012
Anna Swan	University of Boston	USA	9 July 2012 to 31 December 2012
Alex Tacla	University of New Mexico	USA	1 May 2012 to 27 June 2012
Charles Tahan	Laboratory for Physical Sciences, Maryland	USA	23 February 2012 to 23 February 2012
Seigo Tarucha	The University of Tokyo	Japan	12 January 2012 to 16 January 2012
Bo Thide	Swedish Institute of Space Physics, Upsala	Sweden	30 April 2012 to 8 June 2012
Peter Turner	University of Tokyo	Japan	5 August 2012 to 15 August 2012
Lieven Vandersypen	Delft University of Technology	The Netherlands	11 January 2012 to 15 January 2012
Frank Verstraete	Universität Wien	Austria	30 January 2012 to 2 February 2012
PI Guifre Vidal	Perimeter Institute	Canada	29 January 2012 to 2 February 2012
			4 December 2012 to 31 December 2012

VISITOR	INSTITUTION	COUNTRY	DATE/S
Yingdan Wang	McGill University	Canada	18 August 2012 to 16 September 2012
Stephanie Wehner	National University of Singapore	Singapore	12 May 2012 to 21 May 2012
			2 October 2012 to 9 October 2012
Amir Yacoby	Harvard University	USA	10 January 2012 to 15 January 2012
Jun Yoneda	The University of Tokyo	Japan	5 March 2012 to 20 March 2012
Vaclav Zatloukal	Faculty of Nuclear Sciences & Physical Engineering, Czech Technical University, Prague	Czech Republic	26 January 2012 to 5 February 2012

International Workshops held by the Centre

SYDNEY QUANTUM INFORMATION THEORY WORKSHOP

30 January - 2 February 2012, Coogee, New South Wales

The focus topics of this workshop were:

- quantum computation with spin lattices;
- quantum memories: topological, self-correcting, and related;
- quantum error correction and the renormalization group/emergence.

Speakers (partial list):

- John Baez (CQT, Singapore)
- Sean Barrett (Imperial College London, UK)
- Hector Bombin (Perimeter Institute, Canada)
- Andrew Doherty (Sydney, Australia)
- Guillaume Duclos-Cianci (Université de Sherbrooke, Canada)
- Steve Flammia (Caltech/Washington, USA)
- Jeongwan Haah (Caltech, USA)
- Robert Koenig (IBM, USA)
- Tobias Osborne (Leibniz Universitat Hannover, Germany)
- David Poulin (Université de Sherbrooke, Canada)
- Jiannis Pachos (Leeds, UK)
- Norbert Schuch (Caltech, USA)
- Frank Verstraete (Vienna, Austria)
- Guifre Vidal (Perimeter Institute, Canada)

Scientific organising committee:

- Stephen Bartlett (Sydney) - principal local organiser
- Gavin Brennen (Macquarie)
- Andrew Doherty (Sydney)
- Tom Stace (Queensland)

AUSTRALIAN QUANTUM WALKSHOP

April 10 & 11 2012, Manly, New South Wales

The Centre for Engineered Quantum Systems sponsored the First Australian Quantum Walkshop. The walkshop brought together researchers and students from across Australia to discuss the topic of quantum walks: a new approach to quantum information processing that is being actively researched across the globe.

40 researchers and students from Sydney, Brisbane and Perth attended the walkshop to listen to 10 invited speakers. Talking points included quantum algorithms using quantum walks, experimental progress in the field, and the study of the theory behind quantum walks.

The aim of the walkshop was to provide an open forum to discuss this exciting new field. Rather than listening to monologues, participants were encouraged to participate in the discussion, ask questions and offer input. The walkshop succeeded in creating such a forum, and the discussion was very active. Amongst the speakers were Matthew Broome who provided insight into the experimental progress being made by the group of Professor Andrew White at The University of Queensland. Also Peter Rohde discussed experimental progress that was recently published in Science providing a valuable overview of the field and insights into recent theoretical progress being made by himself and his German collaborators at the University of Paderborn led by Professor Christine Silberhorn, and Jingbo Wang.

Participants were enthralled by all the speakers who introduced this relatively new topic of research to those otherwise unfamiliar with the field. The walkshop, held in Manly, was extremely successful and participants provided enormous positive feedback on the value of the talks. The walkshop stimulated much interest in this flourishing field among the participants and succeeded in networking the entire Australian quantum walk community. The outcomes of the walkshop will lead to further collaborations between the participating Universities.

Participants at the first Australian Quantum Walkshop

INAUGURAL WORKSHOP ON QUANTUM-PHOTONIC HARDWARE

October 22-25 2012, Rottnest Island, Western Australia

The workshop brought together international experimental and theoretical researchers in atom-optics, photonics and quantum science to identify new pathways to develop useful quantum-enabled hardware.

The format was a mixture of invited and contributed talks together with plenty of discussion and recreation on marvellous Rottnest Island, in the Indian Ocean, 18km offshore from Perth.

The organisers were Andre Luiten, Phil Light and James Anstie from the University of Western Australia, and Tom Stace, Till Weinhold, and Andrew White from the University of Queensland.

The workshop was possible due to a UWA-UQ Bilateral Research Collaboration Award and sponsorship from the Australian Research Council Centres of Excellence for Engineered Quantum Systems and Quantum Computation and Communication Technology.

EQUS ANNUAL WORKSHOP

December 5-8, 2012 Wollongong, New South Wales

The Centre hosted its second Annual Workshop from 5-8 December 2012 at the Novotel, Wollongong New South Wales. The event was attended by 112 delegates representing the five nodes of the Centre, Partner Investigators (PIs), overseas collaborators and industry colleagues. Key features of the workshop included:

- A PhD Tutorial hosted by CIs Molina-Terriza, Duty and Milburn

- Presentations from overseas speakers Professor Christian Ospelkuas, Institute of Quantum Optics Leibniz Universitat Hannover, Professor Andrew Cleland University of California Santa Barbara and Professor Kae Nemoto, National Institute of Informatics

In 2013, the venue for the workshop will be the Novotel Twin Waters resort at Mudjimba on the Sunshine Coast, Queensland.

Above: Ruth Forrest (UQ), Emma Linnell (UQ), and Halina Rubinsztein-Dunlop (UQ) at EQuS Annual Dinner December 2012.

Right: Gerard Milburn Opening the 2012 Annual Workshop

Below: Wollongong, New South Wales.

Visits to Laboratories and Facilities

VISITOR	INSTITUTION	COUNTRY	DATES
CI Stephen Bartlett	Harvard University	USA	22 February 2012 to 24 February 2012
	APS Conference, Boston	USA	27 Febuary 2012 to 2 March 2012
	QVCC meeting Washington DC, USA	USA	29 March 2012 to 1 April 2012
	Seigo Turucha Research Group	Japan	21 May 2012 to 23 May 2012
	US Government Organisation Review	USA	23 May 2012 to 25 May 2012
	Niels Bohr Institute	Denmark	30 September 2012 to 30 September 2012
CI Michael Biercuk	APS Conference, Boston	USA	27 Febuary 2012 to 2 March 2012
	Harvard University	USA	2 March 2012
	US Government Organisation Review	USA	22 May 2012 to 25 May 2012
	Washington	USA	15 August 2012
	ETH Zurich	Switzerland	4 September 2012
	University of Innsbruck	Austria	10 September 2012
	Australian-China Workshop on Quantum Control	China	5 November 2012 to 7 November 2012
	Tsinghua	China	6 November 2012
Courtney Brell	Perimeter Institute	Canada	23 January 2012 to 25 January 2012
			7 May 2012 to 23 October 2012
CI Gavin Brennen	University of Tokyo	Japan	17 May 2012 to 19 May 2012
			13 July 2012 to 17 July 2012
	University of Leeds	UK	17 July 2012 to 23 July 2012
	Imperial College	UK	24 July 2012 to 25 July 2012
Stefania Castelletto	Centre for Micro-Photonics	Australia	14 May 2012 to 14 May 2012
Mauro Cirio	University of Ulm	Germany	1 June 2012 to 25 June 2012
James Colless	Harvard University	USA	23 February 2012 to 24 February 2012

VISITOR	INSTITUTION	COUNTRY	DATES
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
Daniel Creedon	National Aeronautics & Space Administration Jet Propulsion Laboratory	United States of America	27 January 2012 to 27 January 2012
	University of California Santa Barbara	United States of America	30 January 2012 to 30 January 2012
	National Institute of Standards and Technology	United States of America	2 February 2012 to 4 February 2012
Xanthe Croot	Harvard University	USA	23 February 2012 to 24 February 2012
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
Gregory Crosswhite	Technical University Dresden, Centro de ciencias de Benasque Pedro	Spain, Germany	6 May 2012 to 2 June 2012
CI Andrew Doherty	Harvard University	USA	23 February 2012 to 24 February 2012
	APS Conference, Boston	USA	27 Febuary 2012 to 2 March 2012
	QVCC meeting Washington DC, USA	USA	30 April 2012 to 1 May 2012
	Université de Sherbrooke	Canada	1 May 2012 to 4 May 2012
	US Government Organisation Review	USA	21 May 2012 to 24 May 2012
	CEA Paris	France	7 June 2012 to 14 June 2012
	Neils Bohr Institute	Denmark	15 June 2012 to 18 June 2012
	University of Bristol	UK	19 June 2012 to 21 June 2012
	Imperial College London	UK	22 June 2012 to 26 June 2012
	Riken	Japan	14 September 2012 to 14 September 2012
	Niels Bohr Institute	Denmark	30 September 2012 to 30 September 2012
	Australian-China Workshop on Quantum Control	China	5 November 2012 to 7 November 2012
CI Alexei Gilchrist	National University of Singapore	Singapore	30 April 2012 to 1 May 2012
Todd Green	Australian-China Workshop on Quantum Control	China	5 November 2012 to 7 November 2012
Phien Ho	Centro de ciencias de Benasque Pedro	Spain	6 May 2012 to 19 May 2012

VISITOR	INSTITUTION	COUNTRY	DATES
John Hornibrook	Harvard University	USA	23 February 2012 to 24 February 2012
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
(Siva) Prashant Kumar	Harvard University	USA	23 February 2012 to 24 February 2012
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
Alice Mahoney	Harvard University	USA	23 February 2012 to 24 February 2012
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
CI Ian McCulloch	National Centre for Theoretical Sciences, Hsinchu	Taiwan	5 September 2012 to 7 September 2012
CI Gerard Milburn	University of Waterloo	UK	16 May 2012 to 18 May 2012
	Oxford	UK	23 May 2012 to 23 May 2012
	Optical Society of America	USA	30 September 2012 to 2 October 2012
CI Gabriel Molina-Terriza	University of Electro-Communication	Japan	7 June 2012 to 8 June 2012
	Tokyo Institute of Technology	Japan	4 July 2012
	Keio University (Tokyo)	Japan	7 July 2012 to 7 July 2012
CI David Reilly	Harvard University	USA	23 February 2012 to 24 February 2012
	APS Conference, Boston	USA	27 Febuary 2012 to 2 March 2012
	HRL Laboratories	USA	3 March 2012 to 3 March 2012
	Meetings at Microsoft Offices California & Washington State.	USA	26 March 2012 to 31 March 2012
	HRL Laboratories, California	USA	1 April 2012 to 1 April 2012
	ANFF - US Air Force Workshop Review	USA	1 May 2012 to 4 May 2012
	HRL Laboratories	USA	5 May 2012 to 5 May 2012
	US Government Organisation Review	USA	22 May 2012 to 25 May 2012
	HRL Laboratories	USA	26 May 2012 to 26 May 2012

VISITOR	INSTITUTION	COUNTRY	DATES
	Meeting Microsoft Station Q	USA	10 July 2012 to 10 July 2012
	Meeting Microsoft Station Q	Denmark	27 September 2012 to 27 September 2012
	US Government Organisation Meeting, Niels Bohr Institute	Denmark	30 September 2012 to 30 September 2012
	HRL Laboratories, California	USA	5 December 2012 to 5 December 2012
	Meeting Microsoft Station Q	USA	6 December 2012 to 12 December 2012
Ewa Rej	Harvard University	USA	22 February 2012 to 24 February 2012
	Massachusetts General Hospital	USA	24 February 2012 to 24 February 2012
	APS conference, Boston	USA	27 Febuary 2012 to 2 March 2012
Andres Reynoso	Niels Bohr Institute	Denmark	30 September 2012 to 30 September 2012
William Soo	APS Conference, Boston	USA	27 Febuary 2012 to 2 March 2012
	Australian-China Workshop on Quantum Control	China	5 November 2012 to 7 November 2012
CI Thomas Stace	Royal Holloway, Imperial College	UK	16 March 2012 to 16 March 2012
	Mainz University	Germany	22 March 2012 to 23 March 2012
	Chalmers University	Sweden	26 March 2012 to 28 March 2012
	NIST	USA	11 June 2012 to 12 June 2012
CI Michael Tobar	National Aeronautics & Space Administration Jet Propulsion Laboratory	United States of America	27 January 2012 to 27 January 2012
	University of California Santa Barbara	United States of America	30 January 2012 to 30 January 2012
	National Institute of Standards and Technology	United States of America	2 February 2012 to 4 February 2012
	FEMTO-ST Univerity of Franche Comte	France	10 June 2012 to 14 June 2012
	Xlim, University of Limoges	France	4 July 2012 to 6 July 2012
	FEMTO-ST Besancon, ENSMM École Nationale Supérieure de Mécanique et des Microtechniques, Besancon	France	25 November 2012 to 28 November 2012

VISITOR	INSTITUTION	COUNTRY	DATES
	FEMTO-ST Besancon, ENSMM École Nationale Supérieure de Mécanique et des Microtechniques, Besancon	France	25 November 2012 to 28 November 2012
	Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe	Germany	28 November 2012 to 1 December 2012
	Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe	Germany	28 November 2012 to 1 December 2012
CI Jason Twamley	University of Stuttgart	Germany	6 March 2012 to 18 May 2012
	University of Ulm	Germany	21 May 2012 to 6 July 2012
	Centro de Ciencias de Benasque, Pedro Pascual	Spain	17 June 2012 to 23 June 2012
	PI3 Institute, University of Stuttgart	Germany	28 November 2012 to 1 December 2012
Matthew Wardrop	Australian-China Workshop on Quantum Control	China	5 November 2012 to 7 November 2012
CI Andrew White	University of Vienna AND Institute for Quantum Optics and Quantum Information	Austria	16 March 2012 to 16 March 2012
KeYu Xia	University of Ulm	Germany	10 June 2012 to 7 July 2012

New EQuS-Enabled Collaborations

A major aspect of our Centre is how collaborative we are across nodes, projects, and research subfields. In addition, EQuS has become a recognized player in the international community, and has facilitated the development of many substantial collaborations with partner investigators and colleagues all over the world. Here we provide some highlights of major collaborative efforts ongoing or started in 2012 between Centre Nodes and with external partners:

COMPUTATIONAL STATES OF MATTER

Program: Synthetic Quantum Systems and Simulation

Partners: Chief Investigators Gavin K. Brennen, Macquarie University; Chief Investigators Stephen D. Bartlett and Andrew C. Doherty, The University of Sydney

In collaboration between Gavin Brennen, Stephen Bartlett and his PhD student Andrew Darmawan (co-supervised by Brennen), we showed how to perform quantum computation in a two dimensional phase of matter. Prior work had proven that it was possible to map a particular ground state of the so-called AKLT model in two dimensions to a resource state that is universal for quantum computation. This method is appealing because the resource state can be prepared relatively simply as the ground state of nearest neighbour interacting spin-3/2 particles on a honeycomb lattice. The major contribution was to demonstrate that this particular ground state is not unique in its abilities. Rather a large class of the ground states in the disordered phase of the model works. This means that even if the interactions were not perfectly engineered in the laboratory, the ground state would still be useable for quantum information processing. This result established for the first time a constructive proof of an entire phase of quantum computational matter.

SUPERCONDUCTING MICROWAVE DETECTORS

Program: Quantum Measurement and Control

Partners: Chief Investigator Andrew C. Doherty, The University of Sydney; Collaborator Daniel Esteve, Université de Sherbrooke, Canada

CI Doherty at The University of Sydney worked with collaborators from the group of Dr Daniel Esteve at the Commissariat à l'énergie atomique et aux énergies alternatives in France and Université de Sherbrooke in Quebec to demonstrate experimentally the use of superconducting Josephson junction qubit devices as sensitive detectors of the quantum fluctuations of microwave sources. This work is a clear demonstration of the use of the new quantum devices to enable measurements that were not previously possible. This work was reported in Ong, Boissoneault, Mallet, Doherty, Blais, Vion, Esteve, Bertet *Physical Review Letters* and in an accompanying paper of theoretical analysis in *Physical Review A.*

ENGINEERED QUANTUM STATES OF MECHANICAL SYSTEMS

Program: Quantum Measurement and Control

Partners: Chief Investigator Andrew C. Doherty, The University of Sydney; CI Warwick P. Bowen, The University of Queensland

CI Andrew Doherty has an ongoing collaboration with the group of CI Warwick Bowen (UQ) to understand how to produce exotic quantum states of motion of very small oscillators using feedback control. One paper was published in 2012 undertaking a detailed analysis of our breakthrough proposal from 2011 to produce highly squeezed states of motion (Szorkovszky, Doherty, Harris, Bowen *New Journal of Physics*) and Bowen's group also completed an experimental demonstration.

EXPLOITING PHONONS IN SEMICONDUCTOR QUANTUM DEVICES

Program: Quantum Measurement and Control

Partners: Chief Investigators David J. Reilly & Andrew C. Doherty, The University of Sydney; Chief Investigator Tom M. Stace, The University of Queensland

The year 2012 saw the Quantum Nanoscience Laboratory collaborating closely with EQuS CI theorists Doherty and Stace to develop new understanding and approaches to coupling microwave photons to electron spins and phonons. The transduction of quantum excitations is a key theme of our EQuS CoE and has been enabled by this close collaboration.

MICROWAVE AMPLIFIERS FOR SEMICONDUCTOR QUANTUM DEVICES

Program: Quantum Measurement and Control

Partners: Chief Investigator David J. Reilly, The University of Sydney; Chief Investigator Michael E. Tobar, The University of Western Australia

In collaboration with CI Tobar, the Quantum Nanoscience Laboratory has begun a new project to design and construct a new kind of cryogenic microwave amplifier that can boost quantum signals in a variety of systems being investigated in EQuS. Quantum limited amplification, in which an amplifier only adds the minimum noise required by quantum mechanics, is a capability that would transform the measurement and control of condensed matter quantum devices and enable new physics and applications. UWA student Romain Bara has spent several months at Sydney developing prototype amplifiers and the stage is now set to begin trying these out with spin-based readout detectors.

COUPLING SUPERCONDUCTING QUBITS TO SAPPHIRE RESONATORS

Program: Quantum Measurement and Control

Partners: Chief Investigators Michael E. Tobar, The University of Western Australia; Chief Investigator Tim Duty, The University of New South Wales; Collaborator Aumentado, NIST US

An important goal of the UWA team is to develop a microwave optomechanical capability, using microwave cavity QED coupling of a Qubit with a sapphire resonator that will become a phonon counting readout to measure the ground state and a variety of Fock states of a mechanical oscillator. We have provided sapphire cavities to two groups working on qubits and will work collaboratively with both groups to achieve these goals in 2013.

a) First with Tim Duty, the EQuS CI from UNSW, who is now manufacturing qubits to couple to these types of resonators.

b) Also, with the group of Jose Aumentado at NIST (Boulder, Colorado), who have a student Adam Sirois working on the project.

ENGINEERED PHOTON INTERACTIONS IN ATOMIC MEMORIES

Program: Quantum Measurement and Control

Partners: Chief Investigator Jason Twamley, Macquarie University; Collaborator Ping Koy Lam, Australian National University/The ARC Centre of Excellence for Quantum Computation & Communication Technology

Large optical nonlinearity at the single-photon level can pave the way for the implementation of universal quantum gates. However, realizing large and noiseless nonlinearity at such low light levels has been a great challenge for scientists in the past decade. EQuS CI Twamley, together with A/Prof S Rebic collaborated with researchers in the ARC Centre of Excellence for Quantum Computation & Communication Technology, Professor PK Lam, Dr B Buchler, Dr M Hosseini and Mr B Sparkes at ANU, to explore a scheme that enables substantial nonlinear interaction between two light fields that are both stored in an atomic memory. We performed semiclassical and quantum simulations to demonstrate the feasibility of achieving large cross-phase modulation (XPM) down to the single-photon level. In addition, we executed a proof of principle experimental demonstration of XPM between two optical pulses: one stored and one freely propagating through the memory medium. The proposed scheme can be used to implement parity gates from which CNOT gates can be constructed. This work has been published in M Hosseini, S Rebic, BM Sparkes, J Twamley, BC Buchler, and PK Lam, Memory-enhanced noiseless cross-phase modulation. *Light, Science & Applications* 1, E40, 10.1038/lsa.2012.40.

Schematic of experimental setup to show proof-of-principle that large optical nonlinearities can be generated for photons in a Gradient Echo Memory [M. Hosseini et al., Light, *Science & Apps* 1, E40 (2012)]

MICROWAVE PHOTON INTERACTIONS IN SUPERCONDUCTING DEVICES

Program: Quantum Measurement and Control

Partners: Chief Investigator Tom M. Stace, The University of Queensland; Chalmers University of Technology, Sweden

In collaboration with experimental efforts at Chalmers University of Technology, Gothenburg, Sweden, CI Stace at The University of Queensland investigated the behaviour of one class of Cooper-pair box, known as a transmon. One of these papers (in review, *Physical Review Letters*) is an experimental characterisation of a transmon in a microwave waveguide, which gives rise to a very strong non-linearity between microwave photons at two different frequencies. The size of this non-linearity is three orders of magnitude larger than the equivalent nonlinearities at optical frequencies. The other work coming out of this collaboration is a theoretical paper, Fan, B, et al. “Breakdown of the cross-Kerr scheme for photon counting”, *Phys. Rev. Lett*, 110:053601 (2013), which demonstrates the surprising result that a certain kind of optical non-linearity known as a cross-Kerr phase shift cannot be realized in a broad class of atom-like systems. This has implications for building optical quantum devices, since it fundamentally precludes strong interactions between photons that are often assumed to exist in various proposals over the years.

QUANTUM ENABLED METROLOGY FOR TESTS OF FUNDAMENTAL PHYSICS

Program: Quantum Measurement and Control

Partners: Chief Investigator Michael E. Tobar, The University of Western Australia; Partner Investigator Markus Aspelmeyer, University of Vienna

CI Tobar's group is integrating EQuS measurement achievements to cool an acoustic oscillator on the gram scale to the ground state of motion and measure at the Standard Quantum Limit (SQL). This goal has extraordinary significance, as it has been shown by others that such large-scale experiments can be used to test aspects of Quantum Gravity. The UWA group has begun collaborating with the group of Markus Aspelmeyer from the Vienna Center for Quantum Science and Technology, sharing details of their proposed experiments. This includes unpublished calculations, with first analysis suggesting the UWA experiments could lead to a significant test of quantum gravity.

New Collaborators

In 2012, EQuS welcomed two major new contributors – a new Node at UNSW and a new high-end research laboratory focused on ion trapping at the University of Sydney.

A NEW NODE AT UNSW

Program: Quantum Measurement and Control

Chief Investigator: Tim Duty, The University of New South Wales

A new node of EQuS was established at The University of New South Wales in 2012 led by Professor Tim Duty, starting with two Level A postdoctoral researchers at the beginning of November 2012: Jean-Loup Smirr and Karin Cedergren. Both Jean-Loup and Karin are currently heavily focused on device fabrication, although Jean-Loup is also conducting measurements. Jean-Loup is concentrating on fabrication of “transmon” style superconducting qubits, which will be coupled to sapphire whispering gallery modes (WGMs) using a sapphire dielectric resonator in collaboration with Mike Tobar's group at UWA. Karin Cedergren comes from Chalmers University of Technology in Sweden and brings significant expertise in nano-fabrication to EQuS. Previously, she has done pioneering work on HTS grainboundary Josephson junctions, as well as microfabrication of graphene layers grown on SiC. Karin is developing new fabrication processes at UNSW for 1) high-quality factor 1D superconducting coplanar chip-based cavities (CPW resonators), and 2) large 1D arrays of Josephson junctions. There were two major events to report for 2012 that are significant for our EQuS program. Firstly, our first BlueFors dilution refrigerator (purchased from UNSW startup funds) was installed and commissioned in September 2012, and by the end of 2012 the UNSW superconducting device laboratory was fully functioning. Secondly, in November 2012, superconducting devices fabricated by Jean-Loup in the UNSW/ANFF cleanrooms were being measured in the new UNSW laboratory. Jean-Loup had spent nearly a year developing the fabrication process for these devices and his groundwork will provide a significant foundation to the UNSW EQuS research program, as well as the program lead by Arkady Fedorov at UQ.

A NEW EQUS LABORATORY

Program: Quantum Measurement and Control, Quantum Enabled Sensors & Metrology

Chief Investigator: Michael J. Biercuk, The University of Sydney

2012 saw the opening of the new Quantum Control Laboratory housed in the Australian Government’s National Measurement Institute. This laboratory provides the base for EQuS research on trapped ions providing infrastructure for advanced microwave quantum control experiments, ultrafast-laser-mediated quantum entangling gates, and optically engineered quantum simulation.

This laboratory houses experiments using Beryllium ions in a Penning trap as well as Ytterbium ions in a Paul trap. These projects benefit from the extraordinary environmental controls provided by laboratories in the NMI, with special vibration isolated concrete slabs and temperatures stable to ~0.2 degrees.

The University of Sydney and EQuS are excited to grow their relationships with the NMI, specifically focused on the development of new quantum control techniques for precision metrology.

The Quantum Control Laboratory at the National Measurement Institute

Collaborating Institutions

Centre staff and students were also collaboratively involved with the following institutions in 2012.

NATIONAL

- Centre for MicroPhotonics (CMP) Swinburne University
- Nanometrology Section, National Measurement Institute, Department of Industry, Innovation, Science, Research and Tertiary Education, Sydney
- Queensland University of Technology
- ARC Centre of Excellence for Quantum Computation and Communication Technology

INTERNATIONAL

- Boston University
- Centre for Quantum Technologies, Singapore
- Chalmers University of Technology
- CSIR South Africa
- Dartmouth University, USA
- Duke University
- East China University of Science and Technology
- FEMTO-ST, University of Franche Comte
- Georgia Tech Research Institute
- Harvard University
- Heriot Watt University
- Imperial College, London
- Karlsruhe Institute of Technology
- Maryland University
- National Institute for Informatics
- Niels Bohr Institute
- National Institute for Standards and Technology
- NTT Laboratories Japan
- Oxford University
- Perimeter Institute
- Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany
- Royal Holloway, University of London
- SELEX Sistemi Integrati SpA,Quantum Optics Laboratory Engineering Directorate
- Université de Sherbrooke
- The Instituto Balseiro
- Universidad de Sevilla
- University of California, Santa Barbara
- University of Copenhagen
- University of Innsbruck
- University of Jena
- University of Limoges
- University of New Mexico
- University of Stuttgart
- University of Toronto
- University of Vienna
- University of Limoge

Membership of Editorial Boards & Committees in Quantum Physics

PROFESSOR GERARD J. MILBURN

- Editor in Chief, *EPJ Quantum Technology*
- Editorial Board, *New Journal of Physics*
- Editorial Board, *Journal of Quantum Computation*
- Chair: Scientific Advisory Board, The Institute for Quantum Computing, Canada.

PROFESSOR ANDREW G. WHITE

- Editorial Board *Journal of Modern Optics*

ASSOCIATE PROFESSOR WARWICK P. BOWEN

- Editorial Board, *Scientific Reports* (broad scope journal of the Nature Publishing Group)

PROFESSOR HALINA RUBINSZTEIN-DUNLOP

- Scientific Advisory Board, NTT Basic Research Laboratories, Japan.
- Board of Directors, Beckman Laser Institute Inc (Non-Profit Corporation)
- Board, Australian Plasma Fusion Research Facility
- Editorial Board, *IOP Journal of Optics*

PROFESSOR JASON TWAMLEY

- Subcommittee, Annual International CLEO conference, FS 2, Quantum Science, Engineering and Technology

DR MICHAEL J. BIERCUK

- Academic editor, *Advances, the American Institute of Physics*

Awards and Recognition

DR MICHAEL J. BIERCUK

- Finalist, 2012 Eureka Prize for Innovation in Computer Science, sponsored by Google
- Rated one of Sydney's most influential people, *Sydney Morning Herald*
- Research rated #8 *BBC Focus* magazine's World Changing Top 10 experiments

DR TOM M. STACE

- 1st non-North American to be awarded National Institute of Standards and Technology (NIST) Precision Measurement Grant

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- Dr Ken Brown, Georgia Tech
- Dr Pavel Bushev, Karlsruhe Institute of Technology
- Chief Scientist Fabio Bovino, SELEX Sistemi Integrati SpA, Quantum Optics Laboratory Engineering Directorate
- Professor Carl Caves, University of New Mexico
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- Dr Hermann Uys, CSIR South Africa
- Dr Gonzalo Usaj, Universidad de Sevilla, Spain
- Dr Kristy Vernon, QUT
- A/Professor Lorenza Viola, Dartmouth College
- Professor Ian Walmsley, Oxford University
- Professor Joerg Wrachtrup, Institute for Theoretical Physics III, University of Stuttgart, Germany
- Professor Amir Yacoby, Harvard University
- A/Professor Andrei Zvyagin

End-user links

Government, industry and business community briefings

The Centre actively promotes its activities and uses government, industry and business community briefings to encourage investment from these agencies. In 2012, briefings included:

- Large Executive Committee of the Quantum Information Topical Group, American Physical Society January 2012 - December 2013 – Andrew Doherty
- National Aeronautics & Space Administration Jet Propulsion Laboratory, 27 January 2012 – Michael Tobar and Daniel Creedon
- Naval Research Laboratory, USA, 9, 10, 17 & 24 Febuary 2012 – James Rabeau
- Senate Committee ACT Canberra, 21 March 2012 – Michael Biercuk
- Senate Committee ACT Canberra 24 March 2012 – Michael Biercuk
- Microsoft Offices Washington State, 26-31 March 2012 – David Reilly
- Microsoft Offices California Santa Barbara USA, 26-31 March 2012 – David Reilly
- Microsoft Station Q, Santa Barbara USA, 27 March 2012 – Michael Biercuk
- DSTO Defence Quantum Technology Workshop - group discussions DSTO, Canberra, 19 April 2012 – David Reilly
- ANFF - US Air Force Workshop Review Washington DC USA 1-4 May 2012 – David Reilly
- Boeing Seminar at AIBN, The University of Queensland, 18 May 2012 – Andrew White
- LPS/DARPA Government Meeting (Bethesda, Washington) May 2012 – Stephen Bartlett and Andrew Doherty.
- HRL Laboratories, USA, August 2012 – Michael Biercuk
- Microsoft Station Q, Denmark, 27 September 2012 – David Reilly
- Overseas Government Organisation Workshop – Denmark, 30 September 2012 –David Reilly and Andrew Doherty

Public Awareness activities

The ARC Centre of Excellence for Engineered Quantum Systems was proud to announce that two of our PhD students based at The University of Queensland were recipients of the ATSE Science Ambassador Awards. These awards assisted our students to undertake several trips to remote and outback parts of Queensland in collaboration with the UQ Physics Demo Troupe. During this time, they visited the following schools, sometimes covering both the Primary and High School students in the towns. Outreach trips included the towns of Cunnamulla, Atherton, Gordonvale, Freshwater, Smithfield, Tully, Cairns, Trinity Bay and Townsville.

There were many on-campus activities throughout the year including the Science Experience, National Youth Science Forum, UQ Experience Science including laboratory tours, and participation in the LEAP Macquarie Mentoring University Experience Program. Local schools

Biercuk and SBS's Lily Serna at Vibewire Fastbreak. Biercuk gave an invited talk on the topic 'Danger' such as NUS High School in Perth, Masada College in Sydney, Moggill Scout Troop and Brisbane State High School in Brisbane hosted EQuS at their schools for a variety of activities that included ‘Speed Date a Scientist’, virtual laboratory tours, science advice evenings and judging a science competition.

In May 2012, Professor Michael Tobar had the honour of presenting his research at the Science at the Shine Dome Lecture Series. His presentation was titled, 'Precision electromagnetic measurements with application to terrestrial and space clocks and the quest for a physical theory of everything'. In June, Professor Tobar presented another public lecture at Scitech Discovery Centre in Perth. This lecture was titled 'It’s about Time'.

As part of the Sydney Ultimo Science Festival, Dr Michael Biercuk presented the Einstein Lecture for 2012. Dr Biercuk’s presentation was entitled, “It’s a small, small world”. Dr Biercuk also presented this lecture again later in the year for Vibewire, an innovative non-profit youth organisation providing media, arts and entrepreneurial opportunities and events for young people.

Following is the full list of public talks given by Centre staff in 2012:

Michael Tobar answers questions after the Alan Walsh Medal Presentation

- Michael Tobar, ‘Precision electromagnetic measurements with application to terrestrial and space clocks and the quest for a physical theory of everything.’ Science at the Shine Dome, 2 May 2012
- Michael Tobar, ‘Precision electromagnetic measurements with application to terrestrial and space clocks and the quest for a physical theory of everything.’ WA Branch: Academy of Science Fellowship Meeting, 24 May 2012
- Matthew Broome, Juan Loredo, Andrew Stephenson, Andrew Bolt, Moggill Scout Troup, 18 June 2012
- Michael Tobar, Public Lecture ‘Its about time’, Scitech, WA Scitech Discovery Centre, Perth 21 June 2012
- Jean-Michel Le Floch, National Science Week – Science Café The University of Western Australia 15 August 2012
- Michael Biercuk, Einstein Lecture 2012: ‘It’s a small, small world’ Ultimo Science Festival 2012 21 August 2012
- Stephen Bartlett, Lecture, The University of Sydney Physics Society, 6 September 2012
- Matthew Broome, ‘Speed Date a Scientist’ Brisbane State High School 21 September 2012
- Gabriel Molina-Terriza, EQuS stand at Astronomy Open Night Macquarie University 20 October 2012
- Gerard Milburn, ‘2012 Nobel Prize in Physics and the coherent control of single quantum systems’ The University of Queensland 29 October 2012
- Jean-Michel Le Floch, Co-organisation WA branch of Australian Institute of Physics - PostGrad Conference Jarrahdale, Western Australia 26-27 September 2012
- Michael Biercuk, Vibewire Fastbreak, 24 August 2012

Michael Biercuk on stage at the Powerhouse Museum, as part of the Ultimo Science Festival, Sydney

School Visits

- Siemens Science Experience UQ 18 January 2012 Matthew Broome, Devon Biggerstaff, Devin Smith
- Physics Outreach Workshop University of Queensland 25 January 2012 Andrew Bolt, Matthew Broome
- EQuS Outreach Workshop University of Queensland 25 January 2012 Andrew Bolt, Matthew Broome
- National Youth Science Forum UQ 17 February 2012 Matthew Broome, Glen Harris, Yarema Reshitnyk
- NUS High School visit University of Western Australia 16 March 2012 Jean-Michel le Floch, Eugene Ivanov, Warrick Farr
- OSA and EQuS Outback Cunnamulla, St George, Warwick, Goodiwindi 16 April 2012 Andrew Stephenson, Glen Harris
- Judge for a School Science Competition (years 8-10) Meriden School in Strathfield 8 May 2012 Stephen Bartlett
- The LEAP Macquarie Mentoring University Experience Program Macquarie University 18 May 2012 Trond Linjordet
- High School Activities at the Masada College Science Evening Masada College 24 May 2012 Gabriel Molina-Terriza
- Experience Science 26 June 2012 Matthew Broome, Glen Harris, Andrew Bolt, Yarema Reshitnyk
- Devin Smith School Campus visit Demo UQ 12 July 2012 Matthew Broome, Glen Harris, George Brawley, Andrew Bolt, Yarema Reshitnyk, Jacques Pienaar, Nathan Walk
- Atherton SHS Visit, Atherton 7 August 2012 Andrew Bolt
- Science School interview The University of Sydney 12 August 2012, Stephen Bartlett
- Australian Academy of Techological Science and Engineering (ATSE) 'Wonders of Science' Gordonvale High School, Freshwater State School 13 August 2012 Andrew Bolt
- Australian Academy of Techological Science and Engineering (ATSE) 'Wonders of Science' Gordonvale Primary School,Freshwater State School 4 September 2012, Andrew Bolt
- Australian Academy of Techological Science and Engineering (ATSE) 'Wonders of Science' Freshwater State School 6 September 2012, Andrew Bolt
- Smithfield State High School Visit 8 September 2012, Andrew Bolt

PhD Student Glen Harris demonstating vorticies to students at St George High

PhD Student Glen Harris presenting to the Goodiwindi State School

Students at The SCOTS PGC College in Warwick learning about vorticies

- Tully State High School Visit Tully 9 September 2012, Andrew Bolt
- Cairns and Trinity Bay State School Visit, Cairns, 10 September 2012, Andrew Bolt
- ATSE Wonders of Science Townsville Presentations 19 September 2012, Andrew Bolt
- School Campus visit The University of Queensland 19 October 2012, Andrew Bolt, Devin Smith, Yarema Reshitnyk
- Beijing Normal University visit - Laboratory Tour University of Western Australia 22 October 2012, Yaohui Fan
- UQ Experience Science University of Queensland 12/13/17/18 July 2012, Matthew Broome
- ATSE Wonders of Science Program Atherton State High School, Glen Harris
- Young Scholars Program UQ, 28 November 2012, Matthew Broome and Robin Cole
- NUS High School and Catholic Junior College, UWA 3 December 2012, Daniel Creedon and Warrick Farr

PhD Student Andrew Bolt demonstrates air pressure with UQ's Science Communicator Andrew Stephenson in Cape York

Science Teacher Workshops

The Centre's involvement with ASTE Wonder of Science program included a presentation to teachers at Townsville 19 September 2012. The Townsville visit sought to bring enthusiasm for science and technology to Queensland's young people and teachers to inspire and develop a love of science.

Website

In July 2012, the Centre launched a new website. The new site uses the Open Source CMS technology, Drupal, that allows finite access control for members. Each Chief Investigator, researcher, and student has an account which they can update independently and which allows them to add content such as new publications, upcoming events, conferences, awards, and research projects. Further functionality has been added to the site since the initial launch including the capability to report on KPIs directly into the website database. This is a secure SQL database located and managed at UQ. The website also has a secure intranet accessible only to members.

The website has integrated social media including Facebook, Twitter, Flickr, YouTube and an RSS feed on the website. These social media tools are linked, meaning that when information is posted on one social media channel it automatically propagates to the other channels.

The site allows for monitoring of the SEO (Search Engine Optimisation) keyword and metadata to ensure that in search results EQuS is found on google and other search engine results pages. In 2012, the site received 3,417 unique website hits averaging 569 per month. The website and our social media channels also have google analytics and google webmaster tools embedded to monitor visitors, visitors' countries of origin, demographics of our visitors, and other useful information used to inform our SEO administration tools, future web developments and Key Performance Indicators.

Vacation Students

In 2012, the Centre hosted 20 vacation students. The students, several from overseas, completed paid practical work experience on projects associated with Quantum physics.

The provision of the internships was made possible through the generous support of CIs Molina-Terriza, Brennen, Reilly and Biercuk, as well as Bartlett.

COUNTRY	NAME	PRINCIPAL SUPERVISOR
India	Aziz Alam	A/Prof Molina-Terriza
Australia	Daniel Lombardo	A/Prof Brennen
India	Vikesh Siddhu	A/Prof Brennen
Australia	Matthew van Breugel	A/Prof Molina Terriza
India	Priya Dwivedi	Dr McCulloch
Australia	Jye Sawtell-Rickson	A/Prof Bowen
Australia	Rafael Alexander	Prof Bartlett
Australia	Harrison Ball	Dr Biercuk
Australia	Christine Beer	A/Prof Reilly
Australia	Hari Bhrugubanda	A/Prof Reilly
Australia	Jacob Bridgeman	Prof Bartlett
Australia	Ian Conway-Lamb	A/Prof Reilly
Australia	Natasha Gabay	Prof Bartlett
Australia	Chris Herron	A/Prof Reilly
Australia	Marie Claire Jarratt	Dr Biercuk
Australia	Shelley Leong	Dr Biercuk
Australia	Cleo Loi	Prof Bartlett
Germany	Christian Marciniak	Dr Biercuk
Australia	Jarrah Sastrawan	Dr Biercuk
Australia	Alexander Soare	Dr Biercuk

Income derived from other sources

The Centre welcomes engagement with organisations that wish to establish new collaborations and/or contract research opportunities in Quantum Physics. In 2012, the Centre was pleased to leverage the following investments:

NODE	SCHEME NAME	FUNDING BODY	CHIEF INVESTIGATOR	TOTAL FUNDING FOR PROJECT
The University of Sydney		Overseas government organisation	Reilly	AUD $2,100,000
The University of Sydney	Industry collaboration	Microsoft Corporation	Reilly	USD $50,000
The University of Sydney	Australia China Science and Research Fund Group Mission	Federal Government Department of Innovation, Industry, Science, Research and Tertiary Education	Biercuk	AUD $37,000
The University of Sydney	Industry collaboration	Lockheed Martin	Biercuk	USD $305,000
Macquarie University	Science Leveraging Fund	New South Wales State Government Trade and Investment	Twamley	AUD $250,000
The University of Western Australia and The University of New South Wales	Research Collaboration Award	The University of Western Australia	Tobar and Duty	AUD $10,000
The University of Western Australia and The University of Queensland	UWA UQ Bilateral Research Collaboration Award	The University of Western Australia and The University of Queensland	Tobar and Bowen	AUD $15,600
The University of Western Australia	Go8 - DAAD German Research Cooperation	German Academic Exchange Service	Tobar	AUD $20,000

STRATEGIC DIRECTIONS 2013

Quantum measurement and control

In 2013, our new super conducting laboratories at UQ and UNSW will come on-line. At UQ, CI Fedorov will establish a state-of-the-art measurement setup that will be used for quantum control and measurement of superconducting quantum circuits. The setup will include real time data processing for efficient characterization of microwave photon field and will use a quantum-limited parametric amplifier for dramatic improvement of signal-to-noise ratio.

In 2013, CI Bowen's group at UQ aims to demonstrate quantum radiation pressure noise for the first time in a room temperature optomechanical system, and use this interaction to control the mechanical quantum state. By incorporating arrays of mechanical oscillators, we aim to condition the joint quantum state to exhibit correlations that can only be explained through quantum mechanics.

Quantum enabled sensors and metrology

At The University of Western Australia laboratory of CI Tobar, we will measure ground state acoustic oscillations in quartz or sapphire crystals and demonstrate strong coupling between rare-earth paramagnetic spins to microwaves in a high-Q cavities.

Synthetic quantum systems and simulation

The team led by Bartlett at The University of Sydney has identified the usefulness of an exotic quantum state of matter, known as symmetry protected topological order, as a mechanism to provide nonclassical processing power in quantum many-body systems. We are now at the cusp of understanding how two-dimensional quantum antiferromagnetics can be understood in terms of this exotic quantum order, and we expect to fully characterise this property in 2013. With such a characterisation, we can design new quantum materials to serve as a substrate for quantum technologies - a new 'semiconductor' for the quantum age. In 2013, CI Brennen's group will show how to measure topological entanglement entropy in continuous variable systems like massive quantum harmonic oscillators or massless optical frequency combs. He will also investigate projective simulations for quantum autonomous agents to study potential quantum speedups for artificial learning.

APPENDIX 1: PUBLICATIONS

Journal Articles

* Represents A*/A tier journals

Akram, U., Munro, W., Nemoto, K., **Milburn, G.J.** (2012) Photon-phonon entanglement in coupled optomechanical arrays. *Physical Review A*, 86, 42306. doi: 10.1103/PhysRevA.86.042306. *

Barzanjeh, S.H., Abdi, M., **Milburn, G.J.**, Vitali, D., and P Tombesi. (2012) Reversible optical-to-microwave quantum interface. *Physical Review Letters*, 109, 130503. doi: 10.1103/PhysRevLett.109.130503. *

Basiri Esfhani, S., **Akram, U.**, **Milburn, G.J.** (2012) Phonon number measurements using single photon opto-mechanics. *New Journal of Physics*, 14, 85017. doi: 10.1088/1367-2630/14/8/085017. *

Benmessai, K., **Creedon, D.L.**, **Le Floch, J-M.**, **Tobar, M.E.**, Mrad, M., Bourgeois, P-Y., Kersale, Y., Giordano, V. (2012) Controlling the frequency-temperature sensitivity of a cryogenic sapphire maser frequency standard by manipulating Fe3+ spins in the sapphire lattice. *Physical Review B*, 85, 075122. Doi: 10.1103/PhysRevB.85.075122. *

Blanvillain, S., **Colless, J.I.**, **Reilly, D.J.**, Lu, H., and Gossard, A.C. (2012) Suppressing on-chip electromagnetic crosstalk for spin qubit devices. *Journal of Applied Physics*, 112, 064315. doi: 10.1063/1.4752863. *

Boissonneault, M., **Doherty, A.C.**, Ong, F.R., Bertet, P., Vion, D., Esteve, D., and Blais, A. (2012) Back-action of a driven nonlinear resonator on a superconducting qubit. *Physical Review A*, 85, 022305. doi: 10.1103/PhysRevA.85.022305. *

Bolech, C.J., Heidrich-Meisner, F., Langer, S., **McCulloch, I.P.**, Orso, G., and Rigol, M. (2012) Long-Time Behavior of the Momentum Distribution During the Sudden Expansion of a Spin-Imbalanced Fermi Gas in One Dimension. *Physical Review Letters*, 109, 110602. doi: 10.1103/PhysRevLett.109.110602.*

Bradac, C., **Gaebel, T.**, Pakes, C.I., Zvyagin, A.V., Rabeau, J.R. (2012) Effect of the nanodiamond host on a nitrogen-vacancy colour-centre emission state. *Small*, 9, 132-139. doi: 10.1002/smll.201200574. *

Britton, J.W., Sawyer, B,C., Keith, A.C., Wang, C-C .J., Freericks, J.K., Uys, H., **Biercuk, M.J.**, and Bollinger, J.J. (2012) Engineered 2D Ising interactions in a trapped ion quantum simulator with hundreds of spins. *Nature*, 484, 489-92. doi: 10.1038/nature10981. *

Broome, M.A., **Fedrizzi, A.**, Rahimi-Keshari, S., Dove, J., Aaronson, S., Ralph, T.C., **White, A.G.** (2012) Photonic Boson Sampling in a Tunable Circuit. *Science*, 339, 794-798. doi: 10.1126/science.1231440. *

Castelletto, S., Li, X., Gu, M. (2012) Frontiers in diffraction unlimited optical methods for spin manipulation, magnetic field sensing and imaging using diamond nitrogen vacancy defects. *Nanophotonics*, 1, 139-153. doi: 10.1515/nanoph-2012-0001.

Castelletto, S., **Edmonds, A.**, **Gaebel, T.**, and Rabeau, J. (2012) Production of multiple diamond-based single photon sources. *Journal of Selected Topics in Quantum Electronics*, 18, 1792 – 1798. doi: 10.1109/JSTQE.2012.2199283. *

Caves, C.M., **Combes, J**., Jiang, Z., and Pandey, S. (2012) Quantum limits on phase-preserving linear amplifiers. *Physical Review A*, 86, 63802. doi: 10.1103/PhysRevA.86.063802. *

Chow, J.H., **Taylor, M.A.**, Lam, T. T-Y., **Knittel, J.**, **Sawtell-Rickson, J.D.**, Shaddock, D.A., Gray, M.B., McClelland, D.E., and **Bowen, W.P.** (2012) Critical coupling control of a microresonator by laser amplitude modulation. *Optics Express*, 20, 12622-12630. doi: 10.1364/OE.20.012622. *

Cirio, M., **Brennen, G.K.**, and **Twamley, J.** (2012) Quantum Magnetomechanics: Ultrahigh -Q-Levitated Mechanical Oscillators. *Physical Review Letters*, 109, 147206. doi: 10.1103/PhysRevLett.109.147206.*

Colless, J.I., and **Reilly, D.J.** (2012) Cryogenic high-frequency readout and control platform for spin qubits. *Review of Scientific Instruments*, 83, 023902-7. doi: 10.1063/1.3681195.

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Darmawan, A.S., **Brennen, G.K.**, and **Bartlett, S.D.** (2012) Measurement-based quantum computation in a two-dimensional phase of matter. *New Journal of Physics*, 14, 013023. doi: 10.1088/1367-2630/14/1/013023. *

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Depenbrock, S., **McCulloch, I.P.**, and Schollwoeck, U. (2012) Nature of the spin-liquid ground state of the S=1/2 Heisenberg model on the kagome lattice. *Physical Review Letters*, 109, 67201. doi: 10.1103/PhysRevLett.109.067201. *

Doherty, A.C., **Szorkovszky, A.**, **Harris, G.I.**, and **Bowen, W.P.** (2012) The quantum trajectory approach to quantum feedback control of an oscillator revisited. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370, 5338-5353. doi: 10.1098/rsta.2011.0531. *

Duan, Z., **Fan, B.** (2012) Coherently slowing light with a coupled optomechanical crystal array. *Europhysics Letters*, 99, 44005. doi: 10.1209/0295-5075/99/44005. *

Else, D.V., **Bartlett, S.D.**, and **Doherty, A.C.** (2012) Symmetry protection of measurement-based quantum computation in ground states. *New Journal of Physics*, 14, 113016. doi: 10.1088/1367-2630/14/11/113016. *

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Harris, G.I., Andersen, U.L., **Knittel, J.**, and **Bowen, W.P.** (2012) Feedback-enhanced sensitivity in optomechanics: Surpassing the parametric instability barrier. *Physical Review A*, 85, 61802. doi: 10.1103/PhysRevA.85.061802. *

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Ivanov, E., **Bourhill, J.**, **Creedon, D.**, Hartnett, J., and **Tobar, M.** (2012) 'Fast light' effect in experiments with cryogenic resonators. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 45, 221001. doi: 10.1088/0953-4075/45/22/221001. *

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Kitagawa, T., **Broome, M.A.**, **Fedrizzi, A.**, Rudner, M.S., Berg, E., **Kassal, I.**, Aspuru-Guzik, A., Demler, E., and **White, A.G.** (2012) Observation of topologically protected bound states in a one dimensional photonic system. *Nature Communications*, 3, 882. doi: 10.1038/ncomms1872. *

Langer, S., Schuetz, M.J.A., **McCulloch, I.P.**, Schollwoeck, U., and Heidrich-Meisner, F. (2012) Expansion velocity of a one-dimensional, two-component Fermi gas during the sudden expansion in the ballistic regime. *Physical Review A*, 85, 043618. doi: 10.1103/PhysRevA.85.043618. *

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Book Chapters

Bertet, P., Ong, F.R., Boissonneault, M., Bolduc, A., Mallet, F., **Doherty, A.C.**, Blais, A., Vion, D., Esteve, D. (2012) Circuit quantum electrodynamics with a nonlinear resonator. *Fluctuating Nonlinear Oscillators*. Ed Mark Dykman, Oxford. ISBN-10: 019969138X I ISBN-13: 978-0199691388.

APPENDIX 2: CONFERENCES

Conference Proceedings –Refereed

Maxim Goryachev, **Daniel L. Creedon**, **Eugene N. Ivanov**, Serge Galliou, Roger Bourquin and **Michael E. Tobar** - Extremely high Q-factor mechanical modes in quartz Bulk Acoustic Wave Reonators at millikelvin temperature, 11th International Conference on Quantum Communication, Measurement and Computing - 1 April 2012

Daniel L. Creedon, Karim Benmessai, Warwick P. Bowen, Michael E. Tobar - Paramagnetic Kerr-type$\chi(3)$ Nonlinearity in a Highly Pure Ultra-Low Loss Cryogenic Sapphire Microwave Whispering Gallery Mode Resonator, 11th International Conference on Quantum Communication, Measurement and Computing - 1 April 2012

K. Xia., G.K. Brennen, D. Ellinas. and **J. Twamley** - Deterministic generation of an on-demand Fock state, American Physical Society: 43rd Annual Meeting - 7 June 2012

Michael E. Tobar, Daniel L. Creedon, Maxim Goryachev, Karim Benmessai, Jean-Michel le Floch, Eugene N. Ivanov - Some Future Applications of Cryogenic High-Q Resonant Cavities 2012, European Frequency and Time Forum – 24 April 2012 to 27 April 2012.

Conference Proceedings – Extract of Paper

E. Rej, and D.J. Reilly - Towards Hyperpolarized Nanodiamonds for Magnetic Resonance Imaging, 2012 Medical Imaging Symposium - 2 May 2012

Unpublished Presentations

Invited Plenary/Keynote

Till Weinhold - Optical Quantum Communication Technology, NI Symposium - 23 February 2012 (Australia)

Gerard Milburn - Quantum optomechanics: an engineered quantum system, Photon 12 - 3 September 2012 to 6 September 2012 (UK)

Invited

Bartlett, Stephen - Quantum logic, tomography, and algorithms, 2012 MQCO Spin Qubits Workshop - 11 January 2012 to 14 January 2012 (Australia)

Bartlett, Stephen - Quantum computational matter, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Bartlett, Stephen - Quantum tomography of spin qubits, LPS workshop on Quantum Characterisation, Verification and Validation - 29 April 2012 to 1 May 2012 (USA)

Benmessai, Karim - The Fe^{3+}:sapphire WHIspering Gallery modes Maser Oscillator, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Biercuk, Michael - Recent highlights from the Quantum Control Laboratory, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Biercuk, Michael - From quantum control to quantum simulation with trapped ion crystals, Invited Talk European Conference on Trapped Ions - 10 September 2012 to 14 September 2012 (Austria)

Bourhill, Jeremy - Towards observing the standard quantum limit in a macroscopic oscillator, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Bowen, Warwick - Optical whispering gallery mode resonators for unlabelled nanoparticle sensing, 3rd Asia Pacific Optical Sensors Conference - 31 January 2012 to 3 February 2012 (Australia)

Bowen, Warwick - Optomechanical Structures for Sensing, OSA 2012 Mesoscale Photonics Incubator Meeting - 21 April 2012 to 28 April 2012 (USA)

Bowen, Warwick - Quantum microrheology; Hot topic talk - Enhancing mechanical squeezing via weak measurements and optimal estimation, 11th Intl Conference on Quantum Communication, Measurement and Computing - 30 July 2012 to 3 August 2012 (Austria)

Bowen, Warwick - Quantum control of optomechanical systems, The 6th International Workshop on Principles and Applications of Control in Quantum Systems (PrACQSys) - 10 September 2012 to 13 September 2012 (Japan)

Bowen, Warwick - Breaking the quantum limits of sensing in optomechanical device, Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Bowen, Warwick - Biological measurement beyond the quantum limit, Quantum Optics IV - 12 November 2012 to 16 November 2012 (Uruguay)

Brennen, Gavin - Braiding interactions of non-Abelian anyons, 2nd International Conference on Theoretical Physics - 1 July 2012 to 6 July 2012 (Russia)

Brennen, Gavin - Quantum Algorithms on Classical and Quantum Statistical Models using Trapped Atoms in Optical Lattices, 10th Asian International Seminar on Atomic and Molecular Physics - 23 October 2012 to 27 October 2012 (Taiwan)

Bridgeman, Jacob - MERA for Lattice Models with Critical Lines, Symposium on Tensor Networks for Engineered Quantum Systems - 28 November 2012 (Australia)

Bridgeman, Jacob - Multiscale entanglement renormalisation anstaz study of spin chains with a line of criticality, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Broome, Matthew - Topological phases in photonics quantum walk, Australian Quantum Walkshop - 6 April 2012 to 11 April 2012 (Australia)

Broome, Matthew - Experimental BosonSampling, Quantum Simulation Workshop - 22 October 2012 to 25 October 2012 (Spain)

Broome, Matthew - Direct Characterisation of a Linear Optical Network, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Castelletto, Stefania - Radiative and Non-radiative Decay Rate of Single Defects in Nanodiamonds for Imaging and Sensing Applications, APMC10 & ICONN 2012 - 5 February 2012 to 9 February 2012 (Australia)

Castelletto, Stefania - Production of multiple diamond-based sources of single photons, Quantum Communications and Quantum Imaging X, SPIE Optical Engineering + Applications - 12 August 2012 to 16 August 2012 (United States of America)

Castelletto, Stefania - Production of multiple diamond-based sources of single photons, International Conference on Diamond and Carbon Materials - 3 September 2012 to 6 September 2012 (Spain)

Castelletto, Stefania - Emission properties of single defects in diamonds for imaging applications, IQIS 2012 - 26 September 2012 to 28 September 2012 (Italy)

Castelletto, Stefania - Room Temperature Single Photon Emission In Silicon Carbide, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Cirio, Mauro - Classical Ising Models Realised on Optical Lattices, American Physical Society March Meeting - 27 February 2012 to 2 March 2012 (USA)

Cole, Robin - Towards non-classical mechanics with optomechanical resonators, International Workshop on Quantum Information - 20 February 2012 to 25 February 2012 (India)

Colless, James - Electron Spin in GaAs, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Colless, James - Readout and Control Technology for Spin Qubits, American Physical Society March Meeting - 27 February 2012 to 2 March 2012 (USA)

Creedon, Daniel - Linear and Nonlinear E ects of Electron Paramagnetic Resonance in High-Q Cryogenic Sapphire Microwave Resonators, SPIE Photonics West - 21 January 2012 to 26 January 2012 (USA)

Creedon, Daniel - Overview of the Effects of Paramagnetic Spins in High-Q Cryogenic Sapphire Microwave Resonators, EQuS Annual Workshop - 5 December 2012 to 8 December 2012 (Australia)

Creedon, Daniel - Extremely High Q-factor Mechanical Modes in Quartz Bulk Acoustic Wave Resonators at Millikelvin Temperature, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Crosswhite, Gregory - The infinite languages spoken by infinite matrix product states, Networking tensor networks: many-body systems and simulations - 19 May 2012 to 29 May 2012 (Spain)

Crosswhite, Gregory - Embracing divergence: an approach to generalizing weighted automata to infinite words with applications in quantum simulation, Weighted Automata: Theory and Applications – 29 May 2012 to 2 June 2012 (Germany)

Darmawan, Andrew - Measurement-based quantum computing in a 2D phase of matter, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

de Almeida, Marcelo - Competing 1H Spin Relaxation Mechanisms in Low-Dimensional, American Physical Society March Meeting - 27 February 2012 to 5 March 2012 (USA)

de Almeida, Marcelo - Conclusive steering with transition-edge sensor, American Physical Society March Meeting - 27 February 2012 to 5 March 2012 (USA)

Doherty, Andrew - Microwave quantum optics and the Dynamical Coulomb Blockade, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Doherty, Andrew - A master equation approach to P(E) theory for the dynamical Coulomb blockade, Andreev Bound States Workshop - 4 June 2012 to 6 June 2012 (Spain)

Doherty, Andrew - A Quantum de Finetti theorem, phase space distributions and quantum state estimation, Principles and Applications of Control in Quantum Systems - 11 September 2012 (Japan)

Doherty, Andrew - Microwave Quantum Optics in the Dynamical Coulomb, Riken, Tokyo - 14 September 2012 (Japan)

Edmonds, Andrew - Production of multiple diamond-based sources of single photons, De Beers Diamond Conference - 9 July 2012 to 12 July 2012 (UK)

Farr, Warrick - WG modes- Fe3+ interaction in Sapphire with DC Magnetic field at mK Temperature, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Farr, Warrick - Behaviour of the Fe3+ Paramagnetic Ion in Sapphire Whispering Gallery Mode Resonator at mK Temperatures Under DC Magnetic Field, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia).

Fedrizzi, Alessandro - Photonic Quantum Engineering, Workshop on Quantum Characterization, Verification, and Validation (QCVV) - 29 April 2012 to 1 May 2012 (USA)

Goryachev, Maxim - Generation of sidebands/frequency comb in a non-linear rutile resonator at 4.2 K, EQuS Annual Workshop - 5 December 2012 to 8 December 2012 (Australia)

Ho, Phien - The infinite languages spoken by infinite matrix product states, Networking tensor networks: many-body systems and simulations - 19 May 2012 to 29 May 2012 (Spain)

Hornibrook, John - Superconducting resonators in parasitic electromagnetic environments, American Physical Society March Meeting - 27 February 2012 to 2 March 2012 (USA)

Ivanov, Eugene - Generation of pure phase and amplitude-modulated signals at microwave frequencies, International Frequency Control Symposium, - 1 May 2012 (USA)

Kassal, Ivan - Conditions for coherence in photosynthesis under incoherent light, Workshop on Quantum Effects in biological systems - 4 June 2012 to 7 June 2012 (USA)

Kassal, Ivan - Environmental-assisted quantum transport in ordered and disordered excitonic systems, International Conference on Excitonic Processes in Condensed Matter, Nanostructures and Molecular materials - 2 July 2012 to 6 July 2012 (Netherlands)

Kassal, Ivan - Modelling photosynthesis with quantum walks, Workshop of Quantum Dynamics and Quantum Walks - 25 November 2012 to 26 November 2012 (Japan)

Le Floch, Jean-Michel - Microwave precision metrology using a cylindrical klystron cavity, Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Le Floch, Jean-Michel - Different approach for quantum measurements of the spin resonances, Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Le Floch, Jean-Michel - Generation of sidebands/frequency comb in a non-linear rutile resonator at 4.2 K, EQuS Annual Workshop - 5 December 2012 to 8 December 2012 (Australia)

McAuslan, David - Vibration Stabilization for Quantum Optomechanics, 20th Australian Institute of Physics Congress - 9 December 2012 to 13 December 2012 (Australia)

Milburn, Gerard - Single Photon Optomechanics, Central European Workshop on Quantum Optics - 29 June 2012 to 7 July 2012 (Romania)

Milburn, Gerard - Hybrid quantum systems, QCMC12 - 30 July 2012 to 3 August 2012 (Austria)

Milburn, Gerard - Engineered Quantum Systems, Forum on Quantum Science - 16 November 2012 (Australia)

Molina-Terriza, Gabriel - Defense Quantum Technology Workshop - 19 April 2012 (Australia)

Molina-Terriza, Gabriel - The role of symmetries in nanophotonics, Tokyo Institute of Technology - 4 July 2012 (Japan)

Molina-Terriza, Gabriel - The role of symmetries in nanophotonics, Topological-Lightwave Synthesis - 5 July 2012 to 6 July 2012 (Japan)

Molina-Terriza, Gabriel - The role of symmetries in nanophotonics, Keio University - 7 July 2012 (Japan)

Nand, Nitin - Generation of sidebands/frequency comb in a non-linear rutile resonator at 4.2 K, EQuS Annual Workshop - 5 December 2012 to 8 December 2012 (Australia)

Reilly, David - Readout and Control and Crosstalk of GaAs Qubits, 2012 MQCO Spin Qubits Workshop - 11 January 2012 to 14 January 2012 (Australia)

Reilly, David - Engineered Spin System, EQuS Annual Workshop - 23 January 2012 to 25 January 2012 (Australia)

Reilly, David - Hybrid Quantum Systems as Nanoscale Sensors, ANFF - US Air Force Workshop Review - 30 April 2012 to 4 May 2012 (USA)

Reilly, David - Quantum Devices Based on GaAs and HgCdTe: Why the Excitement? 2012 International Symposium on Optoelectronic Materials & Devices - 13 July 2012 (USA)

Reilly, David - Fabrication infrastructure for quantum nanoscience, Sydney Nanoscience Strategy Symposium - 10 August 2012 (Australia)

Reilly, David - Quantum Hardware based on spins Presentation Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Rej, Ewa - Nuclear Polarization of Nanodiamond, American Physical Society March Meeting - 27 February 2012 to 2 March 2012 (USA)

Rej, Ewa - Towards Hyperpolarized Nanoparticles for MRI, 2012 Medical Imaging Symposium - 1 May 2012 (Australia)

Rej, Ewa - Hyperpolarized Nanoparticles for Magnetic Resonance Imaging, 2012 International Conference for Nanomedicine - 2 July 2012 to 4 July 2012 (Australia)

Say, Jana M. - Photostable NV Centres in Nanodiamond: Labels for Bioimaging, De Beers Diamond Conference - 9 July 2012 to 12 July 2012 (UK)

Say, Jana M. - Single Molecule Förster Resonance Energy Transfer Between An NV Centre In 15-nm Nanodiamond and A Dye Molecule, International Conference on Diamond and Carbon Materials - 3 September 2012 to 6 September 2012 (Spain)

Sheridan, Eoin - Cavity Optomechanical Magnetometer, Optical Society of America - 24 June 2012 to 28 June 2012 (USA)

Singh, Sukhwinder - Introduction to tensor network algorithms, Frontiers of Quantum Science - 19 March 2012 to 21 March 2012 (India)

Smith, Devin - Quantum Steering: Experiments and Applications, Qcrypt - 10 September 2012 to 14 September 2012 (Singapore)

Stace, Thomas - Observation of Electromagnetically Induced Transparency (EIT) in Rb-filled Hollow-core Fibre, Quantum Information and Measurement (QIM) - 19 March 2012 to 21 March 2012 (Germany)

Stace, Thomas - Multiscale photosynthetic and biomimetic excitation energy transfer, Workshop on Quantum Effects in biological systems - 4 June 2012 to 7 June 2012 (USA)

Taylor, Michael - Quantum-enhanced sensing of biological objects with optical tweezers, SPIE Optics and Photonics - 11 August 2012 to 16 August 2012 (USA)

Tobar, Michael - High Q-Factor Cryogenic Resonators and Applications, European Frequency and Time Forum - 24 April 2012 to 27 April 2012 (Sweden)

Tobar, Michael - High-Q resonator technology at milliKelvin temperatures for quantum measurement applications, Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Tobar, Michael - Low Noise Sapphire Oscillators, 20th Australian Institute of Physics National Congress - 9 December 2012 to 13 December 2012 (Australia)

Twamley, Jason - The Quantum Mellin Transform, Quantum Mechanics, Operator Theory and the Riemann Zeta function - 17 June 2012 to 23 June 2012 (Spain)

Weinhold, Till - Detection loophole free quantum steering with photons, QIM2012 - 12 March 2012 (Germany)

Weinhold, Till - Engineering photons for hybrid systems, Quantum Photonic Hardware Workshop - 22 October 2012 to 25 October 2012 (Australia)

Weinhold, Till - Conclusive Quantum Steering with superconducting transition edge sensors, 20th Australian Institute of Physics Congress - 9 December 2012 to 13 December 2012 (Australia)

White, Andrew - Photonic quantum information: applications & challenges, First NASA Quantum Future Technologies Conference - 17 January 2012 to 21 January 2012 (USA)

White, Andrew - Exploiting the quantum advantage, QIM2012 - 19 March 2012 to 21 March 2012 (Germany)

White, Andrew - Photonic quantum information: applications & challenges, Defence Quantum Technology Workshop - 19 April 2012 (Australia)

White, Andrew - Photonic quantum information: applications & challenges, CLEO 2012: Laser Science to Photonic Applications - 6 May 2012 to 11 May 2012 (USA)

Xia, KeYu - Deterministic and on-demand solid-state generation of photon Fock states, 43rd Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics - 4 June 2012 to 7 June 2012 (USA)

Zambrana-Puyalto, Xavier - Control of optical resonances in dielectric spheres using Laguerre-Gaussian beams, Lasers and Interactions with Particles conference (LIP2012), France - 26 March 2012 to 30 March 2012 (France)

APPENDIX 3: FINANCIAL STATEMENT

INCOME	$	$
Carry Forwards		
The University of Queensland	1,409,348	
Macquarie University	603,104	
The University of Sydney	812,951	
The University of Sydney (Overseas Gov. Org)	-103,824	
The University of Western Australia	-35,238	
Total Carry Forwards		2,686,340
ARC Grants		
Centre Grant 2012 Base Income	3,500,000	
Centre Grant 2012 Indexation on Base Income	191,909	
Total ARC Grants		3,691,909
Overseas Government Organisation		
The University of Sydney	514,697	
Total Overseas Government Organisation		514,697
Participant Institution Cash Contributions		
The University of Queensland	600,000	
Macquarie University *	250,000	
The University of Sydney	200,000	
The University of Western Australia	87,500	
The University of Western Australia ~	6,125	
The University of New South Wales ~~	100,000	
Total Participant Contributions		1,243,625
TOTAL INCOME LESS CARRY FORWARD		***5,450,231***
TOTAL INCOME		8,136,571

EXPENDITURE	$	$
Salaries	2,007,472	
Scholarships	108,021	
Purchased Equipment	727,980	
Maintenance	617,670	
Travel ~*	613,601	
Other Expenditure	293,415	
The University of Sydney (Overseas Gov. Org.)	546,564	
TOTAL EXPENDITURE		4,914,722
Funds Carried Forward to 2013		3,221,849

* MQ contribution excludes $240,000 allocation to PhD Scholarships Program

~ UWA Cash Contribution indexation

~~ Includes $50,000 late receipt of UNSW 2011 cash contribution

~*Includes 2011 travel expenses of $63,354

APPENDIX 4: KEY RESULT AREAS AND STANDARD PERFORMANCE MEASURES

Research Findings

PERFORMANCE MEASURE	TARGET	OUTCOME
Number of research outputs: Papers in International Peer Reviewed Journals	70	Total of 74 Publications See Appendix 1 for details
Quality of Research Outputs: 90% papers in A* or A tier Journals	63	87% in A* or A Journals in 2012 See Appendix 1 for details
Number of Invited talks/papers/ keynote lectures given at major international meetings	20-30	Total of 44 See page 92
Media Releases	10	Total of 15 See page 55
Number and Nature of Commentaries about the Centre's achievements (electronic media, newspapers and magazine articles)	10	Total of 52 See page 55
Citation Data for Publications: Average citations per paper	Target at Review in 2014 2.8 per paper	At March 2013, EQuS has an average of 4.1 citations per paper

International, National and Regional Links and Networks

PERFORMANCE MEASURE	TARGET	OUTCOME
Number of International Visitors and Visiting Fellows	34	Total of 103 See page 62
Number of National and International Workshops held/organised by the Centre	2	Total of 4 See page 66
Number of Visits to Laboratories and Facilities (Overseas Research Collaborative Visits)	80	Total of 105 See page 69
Examples of Relevant Interdisciplinary Research Supported by the Centre	Quantum Effects Biology Biosensors Microwave Electronics and Electrical Engineering	Details of relevant interdisciplinary research supported by the centre can be found on page 22

End-users Links

PERFORMANCE MEASURE	TARGET	OUTCOME
Number of Government, industry and business community briefings	7	Total of 15
Number and Nature of Public Awareness Programs	School Visits Target 12 Science Teacher Workshops Target 3	Schools Visited in 2012 total 29 Science Teachers Workshops total 1 Details of public awareness programs are shown on page 81 Expansion plans for the Centre's Science Teacher Workshops will be guided by ASTA is 2013
Currency of information on the Centre's website: Number of Revisions	6 Revisions per calendar year	In 2012, EQuS website was revised 24 times
Number of Website Hits	900 unique hits per calendar year	3417 unique hits since July 2012 (Data was not available prior to July 2012)
Number of Public Talks given by Centre Staff	10 public Talks	13 Public Talks

Organisational Support

PERFORMANCE MEASURE	TARGET	OUTCOME
Other Research Income secured by Centre Staff (list research from ARC Grants, other Australian Competitive Grants, Grants from the Public Sector Industry, and CRCs and other research income separately)	$500K	Details about other research income is provided on page 86
Number of New Organisations Collaborating with, or involved in, the Centre	2	36 Collaborations See page 77
Level and Quality of Infrastructure provided by the Centre	Target at Review New/Upgraded Laboratories Renovation of Facilities at UQ Nanofabrication USYD will provide key enabling specialised nanfabrication infrastructure, CoE programs at all nodes	See page 18

Governance

PERFORMANCE MEASURE	TARGET	OUTCOME
Breadth, Balance and Experience of the Advisory Committee	Target at Review The Scientific Advisory Committee (SAC) will evaluate progress against the Centre's KPIs, considering the following • Has the Centre succeeded in advancing research on engineered quantum systems? • Have any Centre programs failed to achieve significant progress? • Has the Centre been successful in the recruitment of the highest calibre postdocs and postgraduate students in the field?	No change
Frequency, attendance and value added by Advisory Board Meetings	Target 2 per year 80% membership to attend on average	1 in 2012
Vision and usefulness of the Centre strategic plan	Target at Review 90% of milestones are achieved. 90% of the KPIs in balanced scorecard are achieved Strategic Plan Reviewed Annually	No Change
The adequacy of the Centre's performance measure targets	Target at Review Meet 90% of Targets	> 90% achieved in 2012
Effectiveness of the Centre in bringing Researchers Together to Form an Interactive and Effective Research Team	Targets at Review	Outcomes by 2012
	Number of new collaborations (within CoE)	36 New Collaborations
	Number of Training schools/ workshops undertaken	4 training Schools/Workshops undertaken in 2012
	Transfer of CIs and Postdocs between nodes	
	Number/Percentage of Joint Papers	10% of Joint Papers
	Visits to PI Groups by CIs, staff and students	26 Visits to PI Groups in 2012
	Visits by International PIs to Australian nodes of the Centre	3 PI Visits to Nodes
	Jointly supervised RHD Students	

PERFORMANCE MEASURE	TARGET	OUTCOME
Capacity Building of the Centre through scale and outcomes	Establish major Australian Critical Mass in the Field	
	Attracting new Academic Staff and Students to Australia	2 new overseas CIs and 10 new Research Fellows in 2012
	Extent of new Collaborations formed with parties and stakeholders outside CoE	4 new Funded Collaborations
	Extent of Linkages with other leading-edge Centres Internationally	31 new 'informal' collaborations
	Extent to which the Centre is positioning itself as a National and International Hub for High Calibre Research in the field (including publication quality and formal recognition of it's members by awards, prizes etc.)	11 overseas Partner Investigators
	International benchmarking (where applicable)	

National Benefit

PERFORMANCE MEASURE	TARGET	OUTCOME
Contibution to the National Research Priorities and the National Innovation Priorities % of Papers	70	74
Measures of Expansion of Australia's Capability in the Priority Area(s)	New Research and Academic Staff attracted to Australia	2 new overseas CIs and 10 new Research Fellows in 2012
	New Fabrication and Research Facilities for Engineered Quantum Systems	4 new funded collaborations
	New Funding leveraged from International and National Agencies other than the ARC	
	Addressing the priority to support high-quality research agencies other than ARC	
	Realise the National Research Priority 3: Frontier Technologies for Building and Transforming Australian Industries, Stimulating the growth of world-class Australian Industries using innovative technologies developed from cutting-edge research	

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