eQuS

ARC CENTRE OF EXCELLENCE FOR
ENGINEERED **QU**ANTUM **S**YSTEMS

ANNUAL REPORT 2011

Science is about understanding nature, understanding what is.

By contrast, engineering is synthetic; it is about creating what has never been.

—Theodore von Kármán, 1902

'I heard a fly buzz' by Xanthe Croot (EQuS PhD Student)
Close up of a fly wing, on top a blue printed circuit board

eQus

ARC CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS

Australian Government
Australian Research Council

This Centre of Excellence is a collaboration involving four leading Australian Universities with highly productive and world-renowned efforts in Quantum Science

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

MAILING ADDRESS
ARC COE for Engineered Quantum Systems
School of Mathematics & Physics
The University of Queensland
QLD 4072
PHYSICAL ADDRESS
Parnell Building
The University of Queensland
TELEPHONE (07) 3365 3272
FACSIMILE (07) 3365 3328
EMAIL chris.shannon@uq.edu.au

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

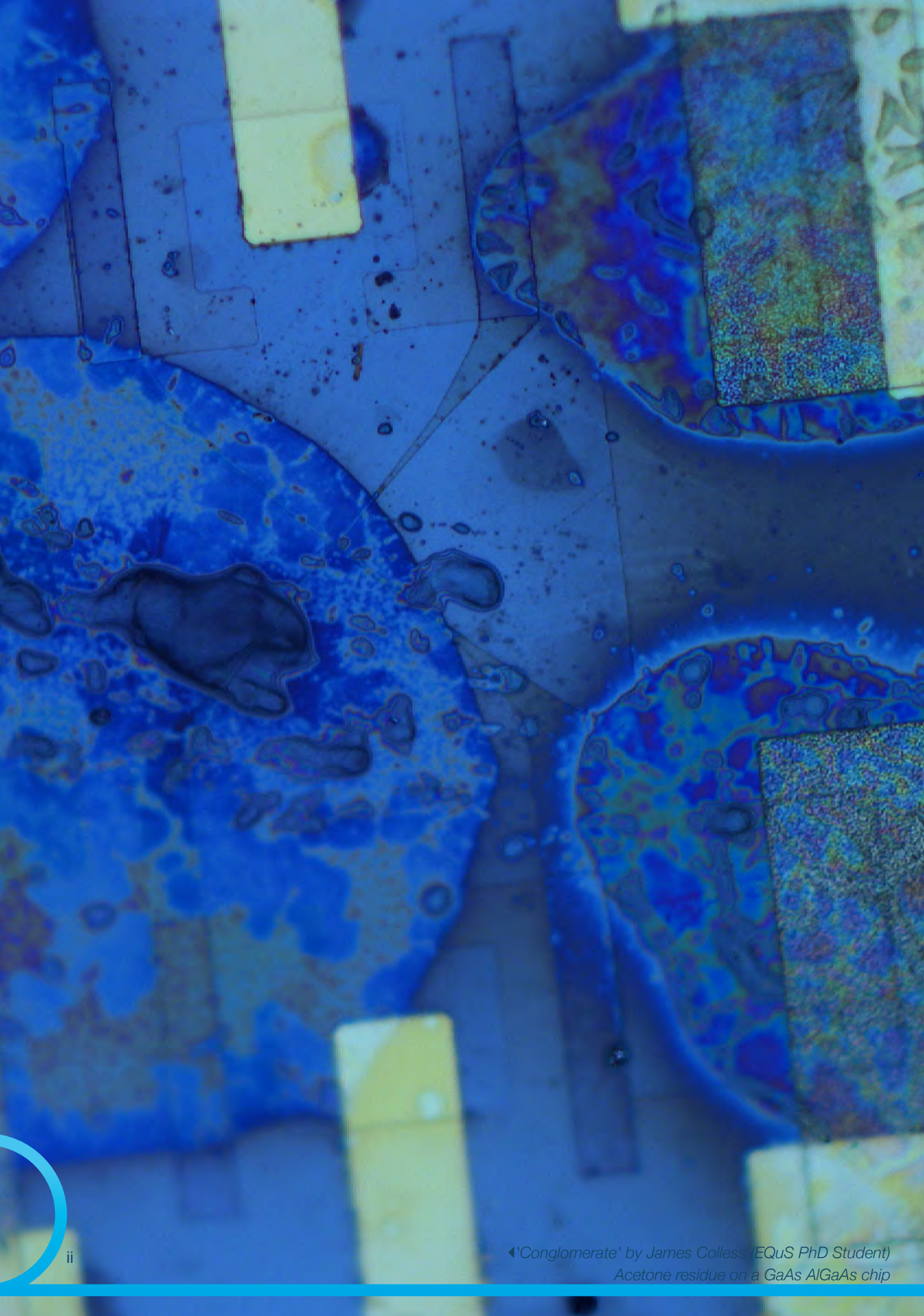
MAILING ADDRESS
ARC COE for Engineered Quantum Systems
School of Physics
The University of Western Australia
Crawley WA 6009
PHYSICAL ADDRESS
Building M013
The University of Western Australia
TELEPHONE (08) 6488 2740
FACSIMILE (08) 6488 7364
EMAIL jay.jay@uwa.edu.au

THE UNIVERSITY OF SYDNEY

MAILING ADDRESS
ARC COE for Engineered Quantum Systems
School of Physics
The University of Sydney
NSW 2006
PHYSICAL ADDRESS
Building A28 Physics Road
The University of Sydney
TELEPHONE (02) 9351 5972
FACSIMILE (02) 9351 7726
EMAIL leanne.price@sydney.edu.au

MACQUARIE UNIVERSITY

MAILING ADDRESS
ARC COE for Engineered Quantum Systems
Department of Physics and Astronomy
Macquarie Univesity
NSW 2109
PHYSICAL ADDRESS
Building C5C 369
Macquarie University
TELEPHONE (02) 9850 8939
FACSIMILE (02) 9850 4868
EMAIL lynne.cousins@mq.edu.au



'Conglomerate' by James Colless (EQuS PhD Student)
Acetone residue on a GaAs AlGaAs chip

Table of Contents

EQuS is dedicated to moving beyond understanding what the quantum world is, to controlling it and “creating what has never been".

Quantum Science

The quantum world was first discovered in atomic systems, where it continues to predict phenomenon with breath-taking precision. But the theory itself is universal, applying on all scales. We are now developing the tools to make even macroscopic systems show quantum phenomenon that would be impossible in the classical physics of Newton and Maxwell.

Quantum mechanics has captured our imagination more than any other physical theory because of the intrinsic strangeness of many of its principles—particles as waves, light as particles, hidden correlations between systems separated by huge distances. These phenomena, however, are not manifested in our daily existence and have largely been inaccessible due to the barrier between the classical and quantum worlds.

A new discipline—Quantum Science—is opening a door between our world and that of the quantum, allowing classical systems access to the most exotic quantum mechanical phenomena. The past two decades have seen an explosion in the number of systems that have been able to provide entry to the quantum realm: from superconducting circuits and semiconductor nanostructures, to trapped atoms and single-photon optics.

Quantum coherent devices are real and accessible to scientists today, but building quantum technologies—exploiting the strangest quantum effects—will take a new kind of effort. It will require systems engineering in the quantum regime.

Message from the Director

Professor Gerard Milburn

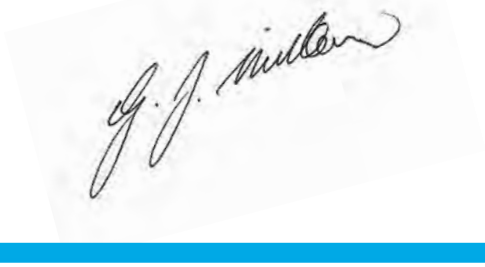
The great aerospace engineer, von Kármán, described his discipline thus: “Science is about understanding nature, understanding what is. By contrast, engineering is synthetic; it is about creating what has never been". The overarching goal of EQuS is to pioneer a future quantum technology engendered by our rapidly growing capability to control the world at is most fundamental level.

We chose the word 'engineered' in the title of our Centre to emphasize a different attitude to quantum physics. We wish to move beyond developing experiments to reveal ever more puzzling quantum phenomenon, to engineering quantum systems *de novo*; to move beyond a view which sees quantum physics as the domain of the atomic realm, to engineer coherent quantum systems of any scale, from atomic dimensions to metres and beyond. This will require the development of new tools for the control of complex hybrid quantum systems.

In our first year of operation we have made some important first steps to realise this vision, described in more detail in this document. Experiments at The University of Queensland have shown how to control the motion of macroscopic silica mechanical resonators with light. EQuS CIs at Macquarie University, in collaboration with our Partner investigators in Germany, have shown how to exploit the quantum properties of defects in diamond to engineer a new kind of magnetometer. Theoretical work involving collaborations across the Centre have pointed the way to a new form of quantum matter capable of processing information.

When Maxwell wrote down a set of partial differential equations just over 150 years ago he opened a door to a new world of engineering capability harnessing the physical realm of electromagnetism: before Maxwell, the technological world was dominated by dinosaurs of steam and mechanics, a clockwork world of levers, cogs and gears. After Maxwell came international telegraphy, wireless communication, radar, computers and CAT scanners, lasers, optical communication systems and microwave mobile phone networks.

In 1926 Schrödinger wrote down another partial differential equation, opening a door to new quantum world. After decades of scientific and technological development, Schrödinger's partial differential equation is only now offering a similar technological promise to that offered by Maxwell. The world indicated by the quantum theory is strange and wonderful. EQuS is dedicated to moving beyond the wonder to build a new technology; from understanding what the quantum world is, to controlling it and “creating what has never been".



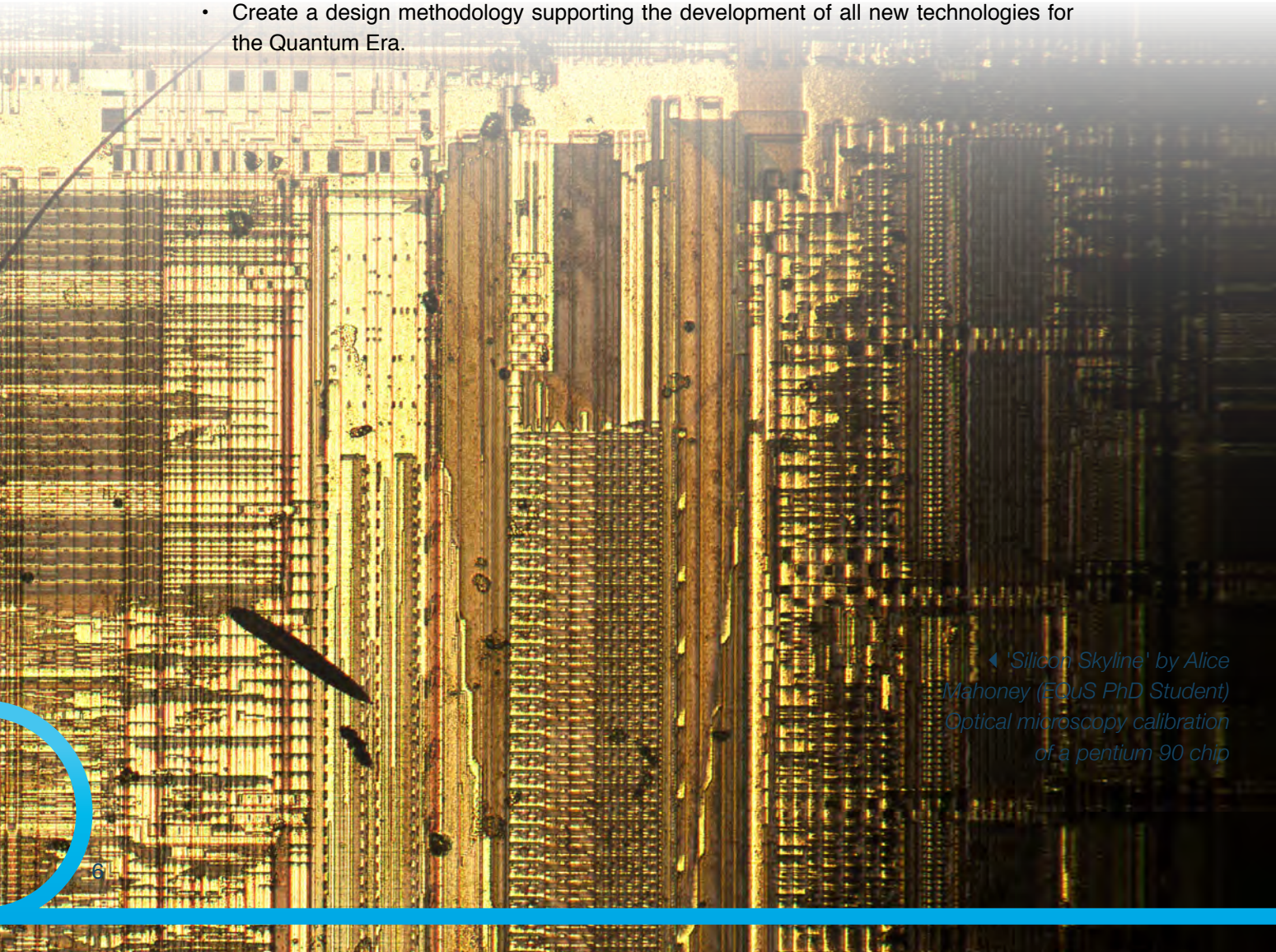
Building the Quantum Future

Our Mission

This Centre of Excellence seeks to initiate the Quantum Era in the 21st century by engineering designer quantum systems. Through focussed and visionary research we will deliver new scientific insights and fundamentally new technical capabilities across a range of disciplines. Impacts of this work will improve the lives of Australians and people all over the world by producing breakthroughs in physics, engineering, chemistry, biology and medicine.

The primary goals of EQuS are to

- Establish a world-leading research community driving the development of quantum technologies, with Australia as the focus of international efforts.
- Stimulate the Australian scientific and engineering communities to exploit quantum devices and quantum coherence in next-generation technologies.
- Train a generation of young scientists with the skills needed to lead the future of technology development.
- Demonstrate the potential and capabilities of engineered quantum technologies by realizing technological breakthroughs in novel and useful engineered quantum coherent systems.
- Create a design methodology supporting the development of all new technologies for the Quantum Era.



'Silicon Skyline' by Alice Mahoney (EQuS PhD Student) Optical microscopy calibration of a pentium 90 chip

EQuS Research Program

The Centre of Excellence for Engineered Quantum Systems seeks to move from Quantum Science to Quantum Engineering—building and crafting new quantum technologies unlike anything the world has seen before.

EQuS provides the world's first focussed research program on systems engineering in the quantum regime, laying the groundwork for our quantum future.

We address fundamental questions about the benefits and limits of quantum technologies, develop strategies for producing novel quantum-enhanced devices, and explore new emergent physical phenomena that arise only in the presence of complex, integrated quantum systems.

Our diverse range of experimental programs and leading theoretical work provides us with unique opportunities on the world stage.

EQuS Core Research Areas

Research efforts are organised around three program 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.

Quantum Science constitutes a new frontier in research that aims to understand, control, and exploit quantum phenomena to create revolutionary new science and technology.

The EQuS Team

Chief Investigators

Gerard Milburn

Andrew White

Jason Twamley

Stephen Bartlett

Michael Tobar

Michael Biercuk

Gavin Brennan

Warwick Bowen

Andrew Doherty

Alexei Gilchrist

Ian McCulloch

Gabriel Molina-Terriza

David Reilly

Halina Rubinsztein-Dunlop

Tom Stace

Business Staff

Lynne Cousins

Danielle Faccer

Ruth Forrest

Gay Holister

Emma Linnell

We are leading theorists and experimentalists, scientists and engineers, and business professionals working across disciplines to produce revolutionary outcomes for Australia and the world.

Postdoctoral Researchers

Uzma Akram
Sylvain Blanvillain
Cyril Branciard
Stefania Castelletto
Robin Cole
Marcelo De Almeida
Alessandro Fedrizzi
Torsten Gaebel
Mathieu Juan
Ivan Kassal
Joachim Knittel
Casey Myers
Aroon O'Brien
Andres Reynoso
Peter Rohde
Suhkbinder Singh
Till Weinhold
Ke Yu Xia

PhD Students

Romain Bara
Sahar Basiri Esfahani
Devon Biggerstaff
Andrew Bolt
Jeremy Bourhill
Carlo Bradac
George Brawley
Courtney Brell
Aharon Brodutch
Matthew Broome
Simon Burton
Janani Chander
Mauro Cirio
James Colless
Daniel Creedon
Andrew Darmawan
Michael Delanty
Tommaso Demarie
Tony Downes
Bixuan Fan
Warwick Farr
Ivan Fernandez-Corbaton
Adil Gangat
Geoffrey Gillett
Glen Harris
Phien Ho
John Hornibrook
Faraz Inam
Lauri Lehman
Trond Linjordet
Terry McRae
Charles Meaney
Matthew Palmer
Gerardo Paz Silva
Robert Pfeifer
Ewa Rej
Yarema Reshitnyk
Andrew Rigby
Andrew Ringsmuth
Ressa Said
Jana Say
Johann-Heinrich Schoefeldt
Alexandr Sergeevich
Devin Smith
William Soo
Alexander Szorkovszky
Maki Takahashi
Michael Taylor
Joel Wallman
Matthew Wardrop

Eric Pham

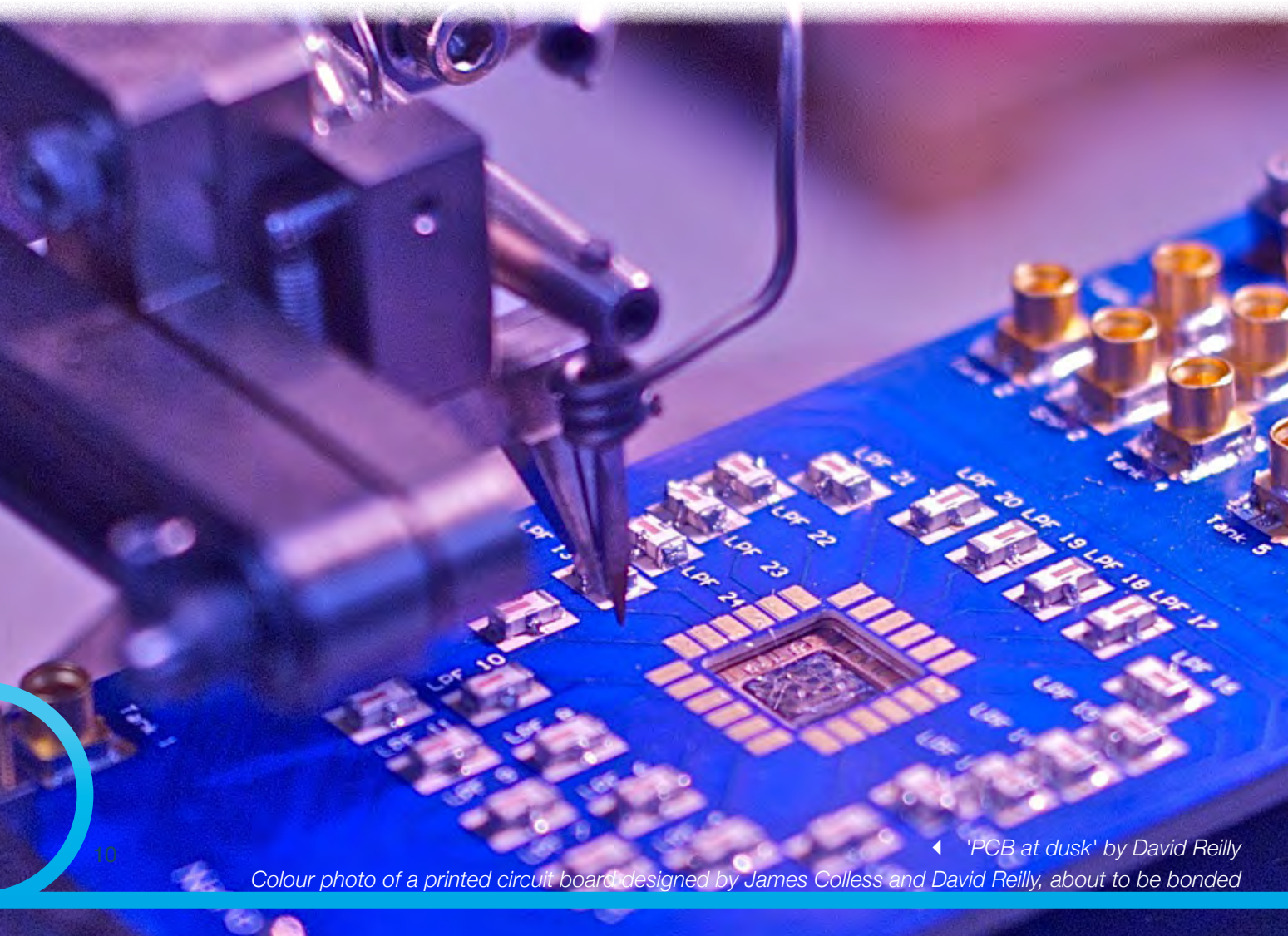
Leanne Price

Lynelle Ross

Quantum Measurement and Control

Precision measurement technology underpins scientific discovery and is an enabler of new technologies. From Galileo's discoveries of pendulum clocks, to the global positioning system (GPS) readily available in our cars and smart phones, the human race has long tried to measure and keep track of time. Improving accuracy for the measurement of time lies at the heart of our modern world and is central to the work EQuS undertakes. However no advanced measurement technology can function without fast and effective control circuits to mitigate the effects of noise and error. To date, control engineering has enabled every major advance in technology.

Our ability to engineer artificial quantum systems is predicated on an ability to understand and control the effects of quantum noise. Error correction in information processing is an example of how measurement and control can mitigate the effects of noise. Were it not for the discovery of quantum error correction by Shor and Steane, quantum computing would have remained a footnote to the quantum theory.



'*PCB at dusk*' by David Reilly

Colour photo of a printed circuit board designed by James Colless and David Reilly, about to be bonded

Quantum errors, and the effects of noise in quantum systems, have long been identified as a major challenge for the development of quantum technologies.

CI Michael Biercuk is leading an international effort aimed at developing techniques to suppress the effects of error in quantum systems. His work is based on a set of techniques know as Dynamic Error Suppression, in which an appropriately crafted control protocol can time-reverse the accumulation of errors in quantum systems.

In collaboration with CI Andrew Doherty and international partner Uys (CSIR, South Africa), the team developed a formal correspondence between the phenomenon of decoherence and linear control theory, as used throughout the classical engineering community.

Through this work, they were able to analyse the efficacy and construction of dynamical error suppression strategies as a problem in filter-design, introducing a straightforward means to compare the performance of different sequences.

CI Michael Biercuk, in collaboration with researchers at the Joint Quantum Institute at the University of Maryland and Dartmouth College developed a unifying mathematical framework for the construction of digital dynamical error suppression sequences.

These sequences permit a system designer to efficiently incorporate dynamical error suppression strategies as a form of Quantum Firmware underlying higher-level system functionality. Further, the sequences developed by this team provide optimal performance as measured against the complexity of control sequencing—a major consideration for large-scale quantum systems.

Quantum engineering can be applied to mechanical systems, advancing fundamental science and technologies

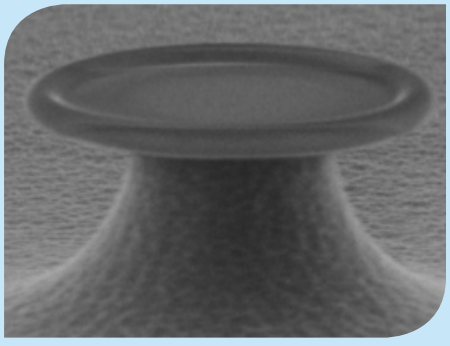
In the optomechanics laboratory of CI Warwick Bowen, the team have developed tools to measure and control the quantum motion of mechanical resonators.

The disk shaped resonators, less than a tenth of a millimetre in diameter, confine light around their perimeter. Vibrations of the disk are imprinted on the light emitted from the structure. This allows the disk diameter to be determined with exquisite precision, at the level of a billionth of a billionth of a metre.

This is one of the most rapidly developing areas of modern physics, with potential applications such as inertial sensing, magnetometry, single molecule detection and quantum computing.

Since opto-mechanical systems have the advantage of very high sensitivity position measurement, EQuS are concentrating on the application of feedback control techniques that are an integral part of all current technologies. Feedback control of quantum systems is different to classical control, in that measurements on quantum systems inevitably disturb the system in some uncontrollable way due to an effect known as "measurement backaction".

Quantum mechanics tells us that mechanical systems continue to vibrate even when cooled to absolute zero. This imposes quantum zero-point motion noise on measurements and sensors. In a collaboration with CI Andrew Doherty, we have shown that quantum feedback control allows the zero point noise to be suppressed, preparing states known as "squeezed" states of motion. This approach appears to be more robust to experimental imperfections than competing approaches, and could have an impact on a broad range of experiments and quantum limited sensors.



Disk shaped resonators

In the Quantum Nanoplasmonics laboratory of CI Gabriel Molina-Terriza, EQuS is testing the fundamental properties of small metallic nanostructures. Most of our technology today is based on metallic conductors that transport electric currents. In order to have smaller and faster devices, one novel approach uses smaller metallic nanostructures.

The optical properties of these metals are very different from other materials, allowing for new physical effects such as extreme field confinement, or enhancement of local fields via the so-called plasmonic resonances of metals. This enables exploiting the optical properties of metals to the maximum level and using these nanoplasmonic devices in several applications.

At the extreme end of minimisation, CI Stephen Bartlett's lab aims to manipulate single electron and nuclear spins, extending the lifetime of their quantum coherence via control techniques like feedback. The program has demonstrated control of a single electron charged qubit using microwaves.

In a collaboration with CI Tom Stace and CI Andrew Doherty we have developed a framework for understanding how a single quantum coherent electron interacts with phonons. We have also tackled several key engineering challenges that have bottlenecked the control of multiple spins, a requirement for establishing entanglement between spins in semiconductors. With the group of CI Michael Tobar we have constructed a first generation cryogenic amplifier that will enable ultra-low noise quantum measurement.

Quantum-Enabled Sensors and Metrology

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.

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.

Single crystals of diamond have a number of natural defects including nitrogen impurities.

The nitrogen atom creates a vacancy nearby, a missing carbon atom, and this vacancy creates a small trap for bound electrons, six in fact. The resulting electronic state has a small magnetic moment inherited from the spin of each electron.

Such nitrogen vacancy centres (NV) represent a quantum nano-magnet and a major focus of research in EQuS is to control and measure the electron spins in NV diamond.

The measurement and control of NV spins is made possible by the discovery that the control and measurement could be done using both magnetic fields and the electric field of a laser.

In a collaboration between EQuS researchers (PhD student Said, and CI Jason Twamley), and the research teams of EQuS PI Jelezko (University of Ulm, Germany), and Prof Wrachtrup (University of Stuttgart, Germany and Max Planck Institute for Solid State Research – Stuttgart, Germany), we have developed and experimentally demonstrated a new type of sensing protocol using quantum control and feedback on a single NV in diamond.

This new protocol achieves high precision sensing of the local magnetic fields, with the very practical advantage of a greatly expanded dynamic range. This allows the sensor to achieve high precision over a very large range of magnetic field strengths, with the ability to provide useful high precision magnetic mapping at atomic resolutions.

The Diamond Nanoscience group recently reduced the size of high-quality, high-pressure, high-temperature NV-defect-enhanced nanodiamonds to below 10nm. This result has been obtained by air-oxidation of irradiated and acid-cleaned initially 35 nm nanodiamonds containing more than 5 NV/nanodiamond defects on average. The work on air-oxidation of non-irradiated nanodiamonds has been obtained as a collaboration with Prof Phil Hemmer at Electrical and Computer Engineering, Texas A&M University, an internationally leading scientist in the field of diamond-based experimental magnetometry.

An alternative approach is the collaboration between the laboratories of CI Warwick Bowen and CI Halina Rubinsztein-Dunlop at UQ, a novel optomechanical magnetometer is being developed. A first experiment has demonstrated microscale magnetometry with nano-Telsa sensitivity at room temperature. Sub-picoTelsa sensitivity is predicted to be possible with improved designs. The high sensitivity, room temperature operation, and potential for integration offer the potential for broad applications, ranging from magnetic resonance imaging (MRI) of the brain to measurements of nuclear spin noise in condensed matter systems.

One of the primary quantum sensor research programs is based on a collaboration between the Quantum Nanoscience Lab at Sydney and the EQuS Node at Macquarie to use nanoparticles of diamond for biosensing. Our ambitious goal is to use nanodiamond, a material already shown to be non-toxic and largely bio-compatible, as a bio-probe for both in-vivo optical tracking and large-scale imaging with Magnetic Resonance Imaging (MRI). These revolutionary applications rest on a foundation of materials research and strong characterisation capabilities both at Sydney and Macquarie. In the last year, NMR measurements at Sydney have demonstrated that nanodiamond is well-placed as a unique contrast agent in MRI, opening the possibility of harnessing an engineered quantum system for the early diagnosis of cancer.

Two approaches for ultra-precise measurements are being developed within EQuS. The Tobar group at UWA have developed a design for Klystron Cavities for precision displacement measurements with sub micro-metre gaps. Results of simulations with Finite Element Analysis shows that the sensitivity increases with smaller gap spacing. We have shown good agreement with experiment and modelling in a prototype experiment. A paper is under preparation, and in 2012 we will design a low temperature superconducting parametric transducer coupled to a mechanical oscillator.

In the Quantum Nanoplasmonics laboratory at Macquarie, we are studying the quantum properties of simple nanostructures, like nanoholes drilled in gold layers. We are studying their properties when excited with quantum states of light in order to use them as quantum sensors and achieve very high sensitivity measurements of their position. We have already given some important steps toward this direction, by calculating the optical modes propagated through the nanohole.

◂ *Under the microscope, CVD diamond synthesis at Macquarie University*

Synthetic Quantum Systems and Simulation

In a quantum world, more of the same is not the same at all. We are just beginning to appreciate the ocean of possibilities for new quantum materials and devices. Our computational tools are simply too limited to enable us to get much beyond the classical shoreline in exploring these possibilities. Quantum computers might get us out into the open sea, but they are decades away. Fortunately there is another way: We can engineer physical hybrid quantum systems to enable hard-wired emulations of existing complex materials, to synthesize new materials and provide completely new insights into the range of quantum materials that are possible.

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 behavior.

The research groups of CI Stephen Bartlett and CI Gavin Brennen are actively collaborating on a theoretical project to investigate the quantum computational power of quantum matter.

While solid-state devices offer naturally reliable hardware for modern classical computers, thus far quantum information processors are 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.

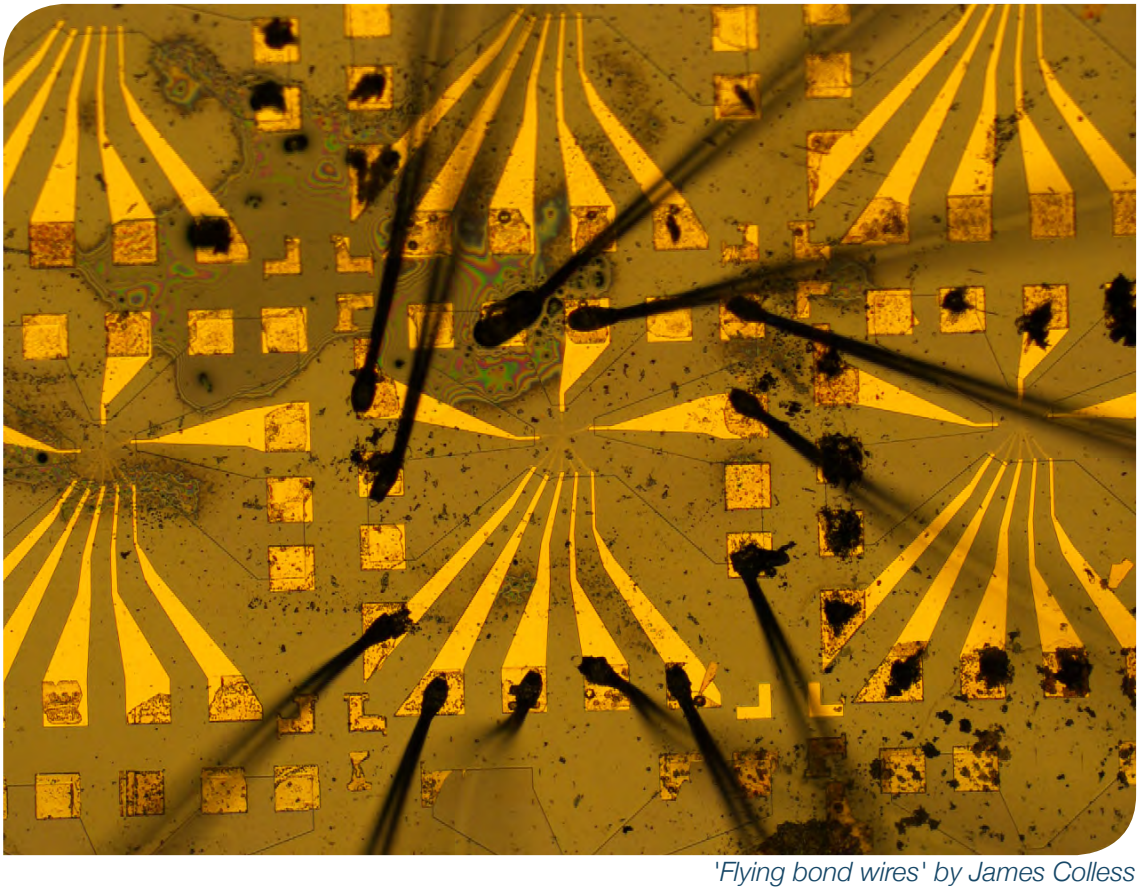
In a joint preprint involving CIs Stephen Bartlett and CI Gavin Brennen, as well as collaborators Akimasa Miyake (Perimeter Institute for Theoretical Physics, Canada) and Joseph Renes (TU Darmstadt, Germany), we have presented a new architecture for quantum computation. The computational power of this quantum matter is robust - in fact, completely insensitive - to fluctuations and perturbations that respect the rotational symmetry of this model. Another result, by PhD Candidate Andrew Darmawan, CI Gavin Brennen and CI Stephen Bartlett, demonstrates a similar robustness for a two-dimensional phase of quantum computational matter based on antiferromagnetic spin lattices. We expect these could be engineered in two-dimensional solid state devices such as quantum dot arrays or AMO systems such as trapped atoms/polar molecules in optical lattices.

This new phase of matter has been dubbed quantum matter, and is the meta-material from which we can build new quantum technologies. Quantum Matter is a new research direction in physics.

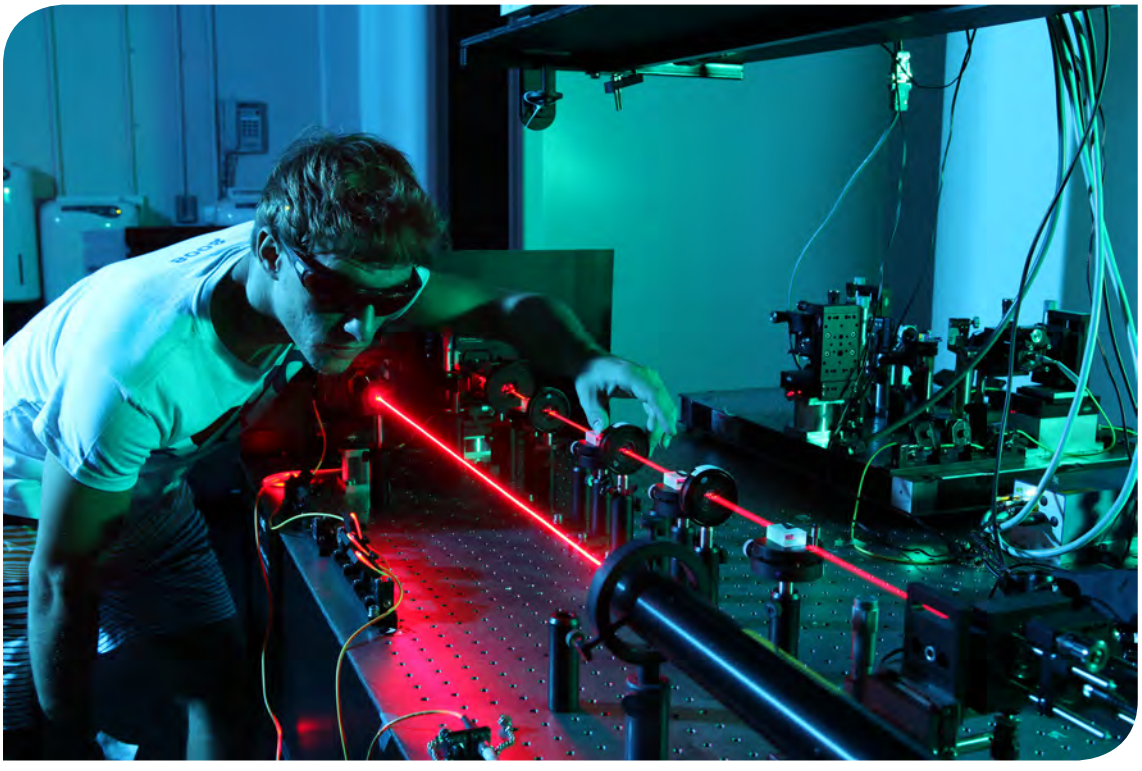
The research projects in this theme are tightly integrated theory-experiment efforts to engineer large, extendable quantum systems with tunable interactions through the combination of elementary building blocks at the microscopic level in a variety of architectures. A key outcome of this project is the simulation of complex condensed-matter and materials systems, and the realization of future quantum technologies for computation and communications.

CI Gavin Brennen is investigating the behaviour of emergent particles in quantum matter both in and out of equilibrium. The primary goal of the research direction is to probe new physics of particles called anyons which are emergent excitations of engineered quantum matter. These particles do not naturally exist in nature but are an emergent property of engineered strongly correlated systems in two dimensions. Certain types of anyons have been shown to be able to perform universal quantum computation in an intrinsically low error way but the collective behaviour of interacting anyons is a largely unexplored area.

The study of the quantum phenomena arising in multi-component quantum systems has long been the subject of intense study and research. One such phenomenon was discovered by Robert Dicke in 1954, and is known as “Superradiance". It is the process whereby the intensity of light emitted from a collection of atoms is greatly enhanced due to collective quantum interference. EQuS proposed to study optical superradiance in a superconducting quantum system where one fabricates a small number of superconducting artificial atoms and couples them to a superconducting coplanar microwave cavity. Using superconducting systems one has very precise quantum control over each and every “atom" and we predict that this system should display all the characteristics of Dicke's superradiance. In addition, by driving this system we predict that the system is capable of being driven into a steady state that is like a Schrödinger cat but with more that two distinct macroscopic states – a phenomena known as phase multistability. We are currently collaborating with researchers in Europe to experimentally demonstrate our predictions.



'Flying bond wires' by James Colless
Bond wires on a gated chip of GaAs AlGaAs heterostructure



PhD Student Matthew Broome conducts a quantum walk

The Quantum Technology laboratory at The University of Queensland is investigating photonic approaches to emulating complex quantum systems. Computer modelling of complex systems has contributed greatly to modern science owing to sophisticated approximation methods and steadily increasing computational power. However, classical simulation methods are ultimately impractical for modelling even moderately sized quantum systems due to an exponentially increasing state space.

Integrated optics provides an ideal testbed for quantum emulation via continuous-time quantum walks, an extension of the classical random walk into the quantum world. A milestone for our program in EQuS is to emulate energy transfer in photosynthesis or light-harvesting, which will require a 3D continuous walk. In 2011 we studied the evolution of two-photon states in a 3D test structure—an elliptic array of waveguides written into a glass —and found distinct differences between temporally indistinguishable and distinguishable two-photon inputs. Our technique is both accurate and noise robust, thus removing a key roadblock to the development and scaling of quantum technologies.

In 2011, we made considerable progress in developing quantum photonic technology, engineering the most efficient entangled-photon source ever demonstrated—62%, more than twice the previous published record of 29%—and demonstrating a simple technique to suppress multi-photon terms from downconversion sources. We also presented the first experimental test of information complementarity—a more complete description of complementarity than the traditional approach based on observables—highlighting the strange and subtle properties of even the simplest quantum systems, e.g. entanglement can be increased by reducing the correlations between two subsystems. Tests such as Bell's inequality and Hardy's paradox show that joint probabilities and correlations between distant particles in quantum mechanics are inconsistent with local realistic theories. We performed the first temporal versions of these tests, showing that Hardy's paradox is much stronger in time, and demonstrating that all quantum states—even fully mixed states—maximally violate the temporal Bell inequality, which allows an exponential saving in memory resources in quantum communication.

Research Infrastructure

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

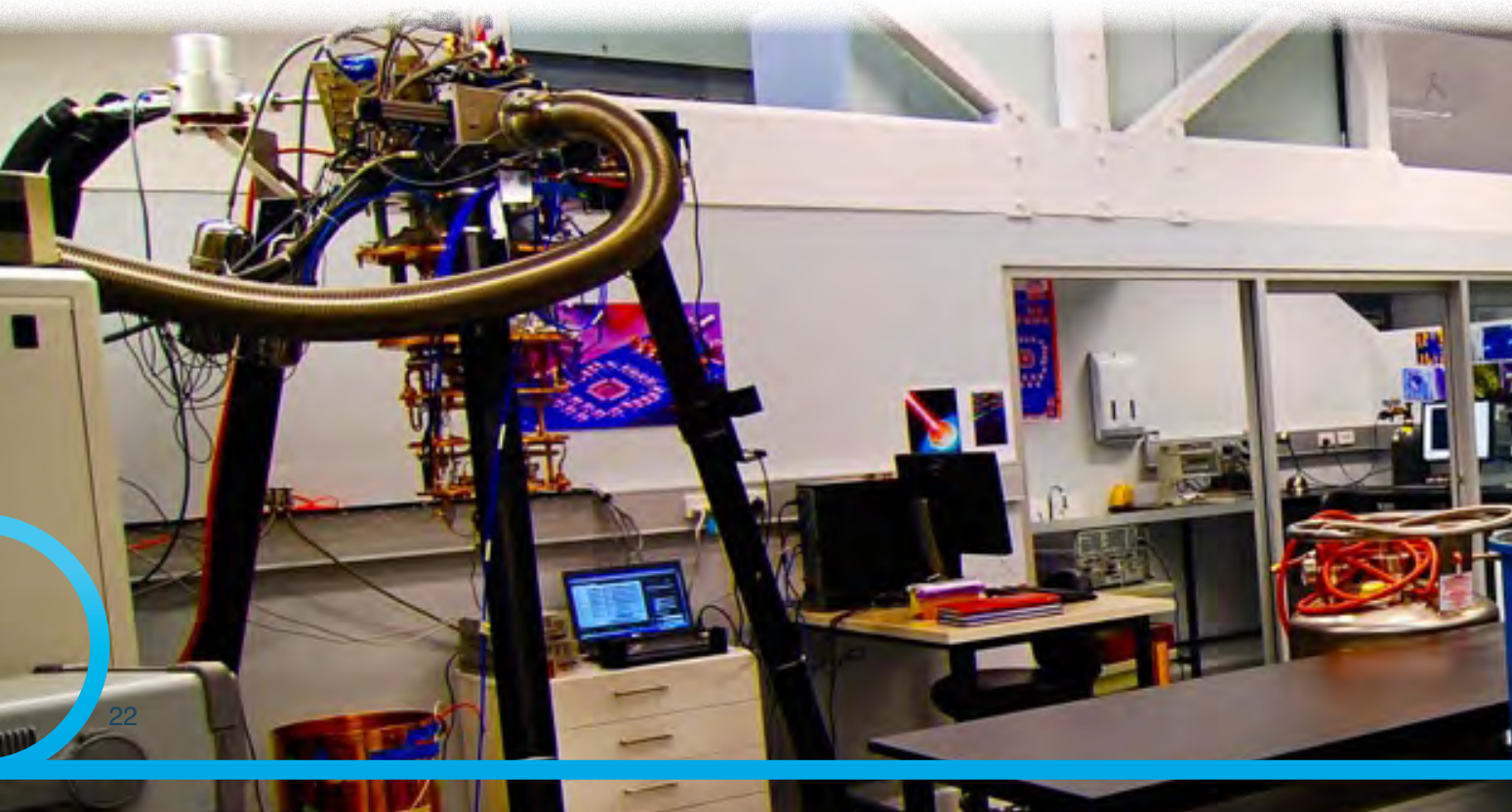
The Quantum Control Laboratory – The University of Sydney

The Quantum Control Laboratory is run by CI Michael J. Biercuk. Opened in 2011, this research lab provides access to trapped atomic ions—one of the leading quantum technologies worldwide. Using a combination of custom ultra-high-vacuum systems, precision stabilized lasers, high-stability radiofrequency oscillators, and flexible microwave control systems; this laboratory allows detailed measurements of quantum systems.

John Hooke CBE, Foundation Council at The University of Sydney declares the Quantum Nanoscience Lab open

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 Technology Laboratory – The University of Queensland

The Quantum Technology Laboratory is focussed 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 Superconducting Quantum Devices Laboratory – The University of Queensland

The School of Mathematics and Physics at The University of Queensland established, in 2009, a new low temperature lab for investigating superconducting quantum circuits based on Josephson junctions. This was initially funded by MIlburn's Federation Fellowship grant and established by Senior Lecturer Dr Tim Duty. The lab 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 CI Tim Duty's replacement, Dr Federov.

The Queensland Quantum Optics Laboratory – The University of Queensland

The Queensland Quantum Optics Laboratory does research into both fundamental tests of quantum mechanics and quantum technologies with future applications in metrology, communication, and computation. This research is primarily based around optical architectures integrated onto silicon chips and compatible with current-day fibre optic systems. These architectures provide a test-bed from which we can study a wide range of processes including quantum backaction, quantum enabled and sensing and metrology, and quantum control.

The Quantum Nanoscience Laboratory at The University of Sydney

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 Frequency Metrology Laboratory – The University of Western Australia

The Frequency Metrology Laboratory is run by CI Michael Tobar. This laboratory develops instruments with world-class precision and performance that are used to make measurements of high value and interest to fundamental physics and more practical applications. The lab offers access to two 4 K pulsed-tube cryogenic systems, one Blue-Fors 10 mK cryogen free dilution refrigerator and many sophisticated microwave diagnostic technologies such as network analyser, synthesizers and spectrum analysers from the RF to millimetre wave frequencies.

The QIRON Lab

The QIRON lab experimentally combines 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.

The Diamond Nanoscience Laboratory - Macquarie University

This laboratory is focussed on cross-disciplinary research activities, including the growth and post-processing of nanometer-sized diamonds, for use in the emerging fields of quantum technology, single particle probing, magnetic nanosensors and microscopy. The laboratory has the capability, via three confocal microscopes, to identify single fluorescent defects in diamond and related materials. An atomic force microscope (AFM), integrated with one confocal system, enables the correlation of confocal maps with of the size of the nanoparticles. In addition to the laser used for excitation, diamond samples can also be probed using microwave signals that can modify the electron spin of the investigated defects.

Chemical vapour deposition system (Seki AX5250) installed and running at Macquarie University

Ewa has been facinated in magnets from a young age so her progression to studying physics was an obvious choice.

“I have always been intrigued by magnets and their uses. My work at EQuS contributes to the quantum-enhanced sensing EQuS goals regarding biomedical imaging," explains Ewa.

“So an MRI machine works by imaging the hydrogen concentration within your body (that being the water), and different tissues have different water concentrations. I'm trying to extend the use of MRI to other molecules, in particular the carbon from nanodiamonds."

Nanodiamonds have no background signal when imaged in our bodies, so their locations would light up. It is believed that if we were to attach a cancer-binding molecule then we could use MRI for cancer diagnosis. But imaging such a molecule is very hard because it has a very tiny signal.

Ewa is working on trying to use hyperpolarization techniques to increase signal strengths so that such a molecule can be imaged.

When Ewa isn't working with magnets she can be found rockclimbing, playing soccer, or relaxing with a good book.

EQuS Postgraduate Candidate, Ewa Rej, with a high-field, superconducting magnet

Education, Outreach and Training

EQuS Education and Training

To ensure Australian graduates are well-prepared to participate in the second quantum revolution, EQuS is committed to raising awareness of quantum physics amongst students currently in high school and in undergraduate courses. Most undergraduate quantum courses are taught at a level that the field reached many decades ago, and even postgraduate courses in Australia rarely reach the level required to join research programs in Engineered Quantum Systems of the kind we propose.

EQuS is in the planning stages of a winter school to run annually to attract undergraduate and honours students for a two week intensive scholarly program. The winter school will begin in 2013.

Students undertaking study in EQuS are given the opportunity to learn in an open environment and encourage to develop their understanding and knowledge in this field. They have opportunities to undertake outreach and communication opportunities, present at world-class conferences, and most importantly learn from leaders in the field, both internally and from the visitors that

The Formulae Lounge – Macquarie University

This is a dedicated space for discussing concepts relating to the theoretical science of EQuS at the Macquarie University node. This consists of a large open plan area with comfortable couches and a very large white board and serves as a focal point for visitors, CIs and students to come and discuss problems, understand new theoretical concepts and share knowledge.

The Formulae Lounge in action during a visit from Sir Professor Anthony Leggett

Graduate Intake

NAME	NODE	SUPERVISOR
PHD STUDENTS		
Romain Bara	UWA	CI Michael Tobar
Sahar Basiri Esfahani	UQ	CI Gerard Milburn
Andrew Bolt	UQ	CI Tom Stace
Jeremy Bourhill	UWA	CI Michael Tobar
George Brawley	UQ	CI Warwick Bowen and Postdoc Joachim Knittel
Simon Burton	USYD	CI Stephen Bartlett
Ivan Fernandez Corbaton	MQ	CI Jason Twamley
Tommaso Demarie	MQ	CI Gavin Brennan
John Hornibrook	USYD	CI David Reilly
Matthew Wardrop	USYD	CI Andrew Doherty

Graduated Students

NAME	NODE	SUPERVISOR
HONOURS STUDENTS		
Xanthe Croot	USYD	CI David Reilly
Hannah Edwards	USYD	CI David Reilly
Dominic Else	USYD	CI Stephen Bartlett
Todd Green	USYD	CI Michael Biercuk
Siva Prashant Kumar	USYD	CI Andrew Doherty
Alice Mahoney	USYD	CI David Reilly
Naea Zaki	USYD	CI Michael Biercuk

NAME	NODE	SUPERVISOR
PHD STUDENTS		
Tony Downes	UQ	CI Gerard Milburn
Charles Meaney	UQ	CI Gerard Milburn
Gerardo Paz-Silva	MQ	CI Jason Twamley
Robert Pfeifer	UQ	CI Ian McCulloch
Ressa Said	MQ	CI Jason Twamley
Johann-Heinrich Schoefeldt	MQ	CI Jason Twamley

EQuS Outreach Program

In 2011 EQuS ran outreach ranging from in-house activities such as the Siemens Science Day at UQ, to school science days in remote parts of the country. This activity was coordinated by PhD Student, Matthew Broome. In addition to our school student outreach program there are plans in place to run science teacher workshops around Australia, ensuring that they too have the most up-to-date knowledge of exciting developments in this field.

UWA has provided $3K towards outreach to be match by EQuS, giving UWA a budget of $6K to further develop their outreach.

Events 2011

Educational Outreach Program provided to Moggil Scout Troop on 4 April 2011 by PhD Candidates, Matthew Broom, Glen Harris and Andrew Stephen. Three workshops were conducted: i) Solids, liquids and gasses, ii) Light and laser, iii) Weather.

Educational Outreach Program provided at Brisbane Extreme Science day run by the ATSE on 5 May 2011.

ABC "Speed-Meet-a-Scientist", Ultimo Science Festival. 27 August 2011.

Educational Outreach Program provided to State Schools in North Western QLD to Mt Isa, Dajarra, and Cloncurry in October 2011 by PhD Candidates, Matthew Broom and Andrew Stephenson. Demo Troup show. Workshops on colour of light and light polarization. Laser light and white light.

Educational Outreach Program provided to Charlleville School of Distance Education in Roma by PhD Candidates, Matthew Broome and Andrew Bolt. Optics workshop: Polarisation of light and the colour of light. Waves: Sound and light. 100+ Students.

Demonstrating polarisation to students at Longreach State High School

On the 29 October, CI Jason Twamley hosted a Physics & Astronomy Open Night at Macquarie University.

August - December 2011, CI Jason Twamley ran a high level undergraduate Program for students at Macquarie University.

CI Gavin Brennan undertook 6 Summer Scholarship Programs for undergraduate students at Macquarie University.

Media Releases

7 March 2011 - Coldest Place to Produce Hotest Science

7 March 2011 - Quantum Engineers remove roadblock in developing next-generation technologies

10 October 2011 - Twinkle Twinkle Little Diamond

18 October 2011 - Quantum Researchers Measuring up

14 November 2011 - Quantum physicist earns innovation nomination

16 November 2011 - Mining with Quantum Physics

19 December 2011 - A new spin in diamonds for quantum technologies

Newspaper or Magazine Articles

7 March 2011 "Coldest place in Western Australia" (www.oneperth.com.au/2011/03/07/super-fridge-coldest-place-in-wa/)

1 June 2011 "Quantum Computing: The power of Discord" Nature Vol 474, Pages 24-26 (2011)

1 November 2011 "Probing Quantum States" Nature Photonics Vol 5, Page 644

12 November 2011 "Michael Biercuk: Force detector" Australian Innovation Challenge final (www.theaustralian.com.au/innovationchallenge/michael-biercuk-force-detector/story-fn9dkrp5-1226192995574)

2 December 2011 "New nanoscience lab targets 'quantum weirdness' Cosmos Magazine

Publication Covers

Cover of Nanotechnology in Australia. Showcase of early career research, Bradac, C edited by D Kane, A Micolich, JR Rabeau,

Cover of Department of innovation industry, science and research, Bradac, C Nanotechnology - Australian capability report, fourth edition, 2011, Commonwealth of Australia, ISBN 978-0-642-72628-5

Online Coverage

7 March 2011 “Coldest place to produce hottest science" (www.noodls.com/viewNoodl/9220633/university-of-western-australia/coldest-place-to-produce-hottest-science) CI Michael Tobar

7 March 2011 “The worlds coolest physics" (www.industrysearch.com.au/Features/The-worlds-coolest-physics-study-6902) CI Michael Tobar

8 March 2011 "Quantum engineers remove roadblock in developing next-generation technologies" (phys.org/news/2011-03-quantum-roadblock-next-generation-technologies.html)

8 March 2011 "Quantum engineers remove roadblock in developing next-generation technologies" (www.myscience.cc/wire/quantum_engineers_remove_roadblock_in_developing_next_generation_technologies-2011-princeton)

8 March 2011 "Quantum engineers clear a roadblock in developing new technologies" (www.tgdaily.com/general-science-brief/54538-quantum-engineers-clear-a-roadblock-in-developing-new-technologies)

9 March 2011 “The Worlds Coolest Research at UWA" (http://au.news.yahoo.com/thewest/a/-/wa/8976834/worlds-coolest-research-at-uwa) CI Michael Tobar

11 April 2011 “Tiny good or tiny bad: Nanotechnology and you" The Conversation, CI Michael Biercuk.

21 April 2011 “Forget what you've read, science can't prove a thing" The Conversation, CI Michael Biercuk

4 May 2011 "Oz boffins in quantum computing breakthrough" (http://www.theregister.co.uk/2011/05/04/qubit_characterization_breakthrough/) 15 May 2011 “How quantum was your day?" The Conversation, CI Michael Biercuk.

24 May 2011 Physicist achieves measurement milestone down to the yoctonewton level (www.nanowerk.com/news/newsid=21460.php) CI Michael Biercuk.

1 September 2011 “Don't count on industry to save manufacturing," ABC Science Online CI Michael Biercuk

22 November 2011 “No Such Thing as Empty Space" (au.ibtimes.com/articles/253622/20111122/thing-space-au-ibtimes-com-ibtimesau.htm) CI Tim Duty

6 December 2011 “Young Einstein is a Modern Myth," ABC Science Online CI Michael Biercuk

“ABC Science Online: Scientists use light to flick nanoswitch." CI David Reilly

Awards and Recognition

CI Andrew White was presented the 2010 Pawsey Medal—recognising outstanding research in physics by a scientist 40 years or younger—by the Australian Academy of Science at "Science at the Shine Dome 2011". In April he was awarded a University of Queensland Vice-Chancellor's Senior Research Fellowship commencing it in mid-December.

CI Andrew White

CI Halina Rubinsztein-Dunlop

CI Halina Rubinsztein-Dunlop was made a Fellow of SPIE, the international society for optics and photonics, for achievements in the optical manipulation of atoms and microscopic particles.

Collaborator Matthew Davis from The University of Queensland was awarded a 2011 Queensland Tall Poppies Award for his work on ultra cold quantum gases.

CI Michael Biercuk, of the School of Physics Quantum Science Group, was awarded the National Measurement Institute Prize for Excellence in Measurement Techniques by a scientist under 35. “This award recognises Dr Biercuk's contribution to research in the most sensitive measurement of force to date - the yoctonewton," said Innovation Minister Senator Kim Carr, on announcing the Award. Michael achieved this milestone in collaboration with the Ion Storage Group at the US National Institute of Standards and Technology.

CI Michael Biercuk

CI James Rabeau won the prestigious Macquarie University Research Award in Excellence in Research- Science and Engineering for demonstrating that nano-diamonds, 5000 times smaller than a human hair, can be isolated and made to emit light. This breakthrough has made strong impacts worldwide due to the current rush to design and implement new technologies in quantum and biological science that rely on the use of small diamonds.

CI James Rabeau

Industry and Community Engagement

Google Australia

In an invited talk on quantum firmware to Google Australia, CI Michael Biercuk initiated a relationship with technical staff. In his seminar, he described the basics of quantum computation, the role of error in quantum systems, and EQuS activities designed to address the problem of error suppression in quantum systems from an engineering perspective.

HRL Laboratories

CIs David Reilly and Michael Biercuk gave invited technical seminars to HRL Laboratories, in Malibu, CA. Reilly focussed on high-frequency engineering for spin qubits and Biercuk talked about resource efficient approaches to quantum error suppression. These talks support HRL research interests in semiconductor spin qubits.

Nanoparticle Research Symposium

On 21 October 2011, CI David Reilly, in collaboration with Prof Nicholas King (Pathology, Sydney) organised a symposium and discussion on Nanoparticle Research. The Symposium brought together leading researchers interested in developing and deploying nanoparticles for a wide range of biomedical applications. Reilly spoke on quantum engineered nano particles as MRI contrast agents.

Australian Academy of Science

CI David Reilly was invited by the Australian Academy of Science to join a discipline group on Nanoelectronics and Nanomagnetics. With funding from DIISR, this group aims to develop a national nanotechnology research strategy for Australia.

The Coogee 2012 Quantum Information Theory Workshop

The Coogee 2012 Quantum Information Theory Workshop, jointly organised by University of Sydney, with sponsorship from EQuS, brought together leading and up-and-coming international and Australian researchers and research students in quantum information theory. The program will consisted of a limited number of invited talks with participation from PhD students and postdocs. The topics covered were

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

Future Perspectives

CI Tom Stace was invited to give a “Future Perspectives" talk to a conference of bankers and other financiers at TradingArchitecture2011 in Hong Kong, outlining where quantum enabled devices and communication will take industry over the coming decades. This industry puts a premium on communication speed and security, and want to keep abreast of the future prospects of academic research in quantum systems.

Research Community

Our domestic research program is complemented by collaboration with five formal Partner Investigators.

- Harvard University
- Imperial College, London
- The University of Innsbruck
- The University of Ulm
- The University of Vienna

Our research program is further complemented by a number of national and international collaborators.

- Dartmouth College, USA
- National Institute of Standards and Technology, USA
- The Quantum Engineering Laboratory at Chalmers University of Technology, Sweden
- The Center for Quantum Information and Control at The University of New Mexico, USA
- University of California Santa Barbara, USA
- NIST Boulder, USA
- US Government (IARPA) funded initiative.

New Collaborators

EQuS in 2011 has developed relationships with the following organisations.

- CEA-Saclay Gif-sur-Yvette, France
- Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
- ´Department de Physique, Universit ´e de Sherbrooke, Sherbrooke, Qu ´ebec, Canada, J1K 2R1
- IQC, University of Singapore

Multi-qubit Coherent Operations Program

EQuS is strongly connected to the US Government program Multi-qubit Coherent Operations Program, a major quantum research initiative funded by the Intelligence Advanced Research Project Activity (IARPA). CIs Stephen Bartlett, Michael Biercuk, Andrew Doherty, and David Reilly are investigators with membership in this program that aims to scale-up quantum systems.

IARPA Icebreaker Session hosted by EQuS CI David Reilly & Director Gerard Milburn (UQ)

In January, EQuS Hosted the 2012 IARPA MQCO Spin Qubits Annual Program meeting at The Sebel Walsh Bay. The meeting was attended by the leading researchers in this field from around the world including, EQuS Partner Investigator Charles Marcus (Harvard/ Neils Bohr Inst), Amir Yacoby (Harvard), Bert Halperin (Harvard), Sankar Das Sarma (Maryland), Siego Tarucha (Tokyo), Daniel Loss (Basel) and Leiven Vandersypen (TU Delft). EQuS sponsored a social event on an evening of the conference to bring this high profile international community together. The event was such a success that plans have been altered to ensure all annual meetings are now hosted by the Sydney Node of EQuS.

Visitors

Jim Butler

Jim Butler (formally of the Naval Research Laboratory, Washington DC) visited the diamond nanoscience group in Sydney. Butler is known due to his extensive research in the field of CVD diamond growth (at the last count 7352 citations and a h-index of 47) and his frequent role in acting as a voice for the worldwide diamond scientific community in popular media.

During his visit, Butler helped in setting up EQuSs new CVD system (Seki AX5250) and has been involved in many informative discussions regarding future experiments. He has also held two seminars and two master-classes, all of which were very well attended

Per Delsing

Per Delsing, Head of the Quantum Engineering Laboratory at Chalmers University, visited The University of Queensland node in November 2011 to discuss new experiments planned for 2012. Part of the work is based on assessing the feasibility for single microwave photon detectors using transmon junction devices. The theory for this scheme is being developed at The University of Queensland node by PhD student Bixuan Fan and is a key component of our quantum measurement and control program.

Per Delsing also gave a talk on their recent experimental demonstration of the Dynamical Casimir effect published in Nature in 2011, and co authored by Future EQuS CI Tim Duty, at the soon to be added University of New South Wales node.

Carlton Caves

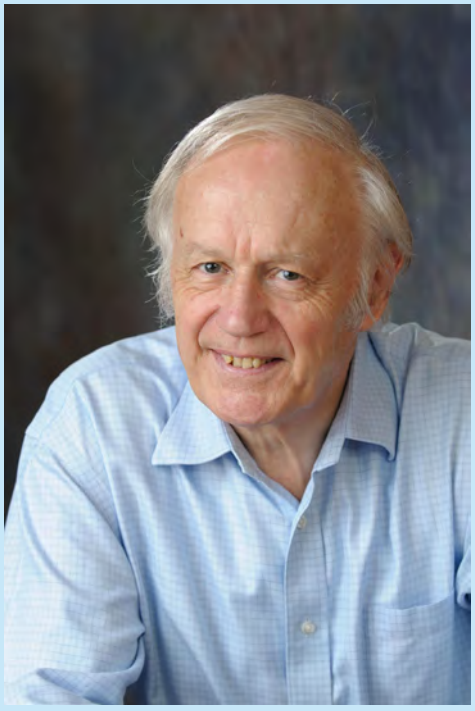
Carlton Caves spent three months at The University of Queensland node in 2011, the first of three visits planned for the term of his Visiting Professor appointment in the Centre. Carl Caves is a pioneer of quantum measurement and the Director of the Center for Quantum Information and Control at The University of New Mexico.

Maxim Goryachev

Maxim Goryachev's visit to UWA brought new technology (Bulk Acoustic Wave Resonators) to the Centre, this allowed measurement of mechanical Qs in excess of one billion, with a Qf product of four orders of magnitude better than previous. Maxim Goryachev is at the FEMTO-ST Institute in Bescancon, France.

Other Visitors

Antonio Acin
Miguel Aguado
Markus Aspelmeyer
David Bacon
Sean Barrett
Robin Blume-Kohout
Mick Bremner
Ben Brown
Dan Browne
Paul Busch
Howard Carmichael
Charles Clark
Mark Dignam
Demosthenes Ellinas
Anton Fisk Kockum
Steve Flammia
Andrew Hilliard
Bei-Lok Hu
Jaesuk Hwang
Sofyan Iblisdir
Ingo Kamleitner
Angela Karanjai
Myungshik Kim
Pieter Kok
Lawrence Krauss
Andrew Landahl
Andre Luiten
Nick Menicucci
Spiros Michalakis
Akimasa Miyake
Yoko Miyamoto
Kavan Modi
Tyler Neely
Jay (Stephan) Olson
Karl Petersson
David Poulin
Joseph Renes
Terry Rudolph
Barry Sanders
Deborah Santamore
Norbert Schuch
Gael Sentis
Mathew Shaw
John Teufel
Stephanie Wehner
Chris Wilson



Professor Sir Anthony James Leggett

Nobel Laureate Tony Leggett visited the Macquarie Node for a week in February to discuss the quantum engineering of macroscopic quantum states of matter.

Professor Leggett won his Nobel Prize in 2003 for his pioneering work on the theory of superfluidity and is internationally renowned for his research in the theoretical physics of low temperature phenomena. Since 2007 he has held a position at the University of Waterloo Canada. Professor Leggett spends at least two months a year on campus at the Institute for Quantum Computing.

Professor Leggett currently serves as the chief scientist at the Institute for Condensed Matter Theory, a research institute hosted by the University of Illinois at Urbana-Champaign.

He has received numerous hours: the Eugene Feenberg Memorial Medal (1999); the 2002/2003 Wolf Foundation Prize for research on condensed forms of matter, with B. I. Halperin; and in 2004, was knighted (KBE) by Queen Elizabeth II in 2004 “for services to physics". He is a Fellow of the Royal Society; an Honorary Fellow of the Institute of Physics (U.K.); in 1997, was elected as the Foreign Associate of the National Academy of Sciences; and, in 2011, was elected as a Foreign Fellow of the Indian National Science Academy.

His research focuses on cuprate superconductivity, conceptual issues in the foundations of quantum mechanics, superfluidity in highly degenerate atomic gases, low temperature properties of amorphous solids and topological quantum computation.

EQuS Summary 2012

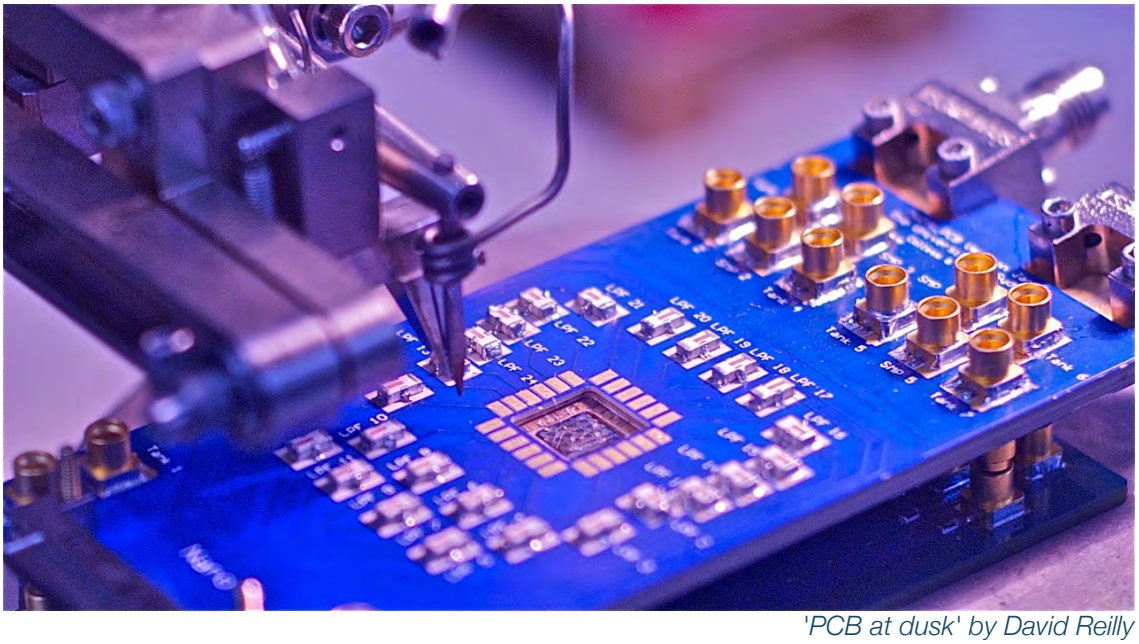
Publications, Key Performance Indicators and financial data will be found in Appendices. However a number of numbers are worth noting.

In the first year of our operation the original 17 CIs were complemented by 19 new hires at the postdoctoral level. More new hires will occur in 2012 especially with the start up of the superconducting labs at our new Partner Institution of The University of New South Wales and the new CI starting at UQ.

Despite our late start, the Centre has a very impressive publication record. In 2011 we published 39 papers in international referred journals of which 95% were in high impact journals such as Nature, Nature Physics, Physical Review Letters, Applied Physics Letters, Proceedings of the National Academy of Science, Optics Express and Optics Letters.

The international competitiveness of the science being done in EQuS is reflected in the high number of invited talks at major international meetings by EQuS CIs: 42 in 2011. Furthermore, the Centre hosted 67 international visiting scientists in 2011 across all our research programs.

The Centre has made a very good start, with a high number of new PhD students: 12 in 2011. These are the vanguard of a new generation of researchers in the frontier area of quantum engineered systems.



'PCB at dusk' by David Reilly
Colour photo of a printed circuit board designed by James Colless and David Reilly, about to be bonded

The Year Ahead

New Collaborating Institution

In early 2012, EQuS welcomes a new collaborating institution, The University of New South Wales. Our latest CI, Tim Duty, has established a new laboratory for the study of superconducting quantum circuits and related physics: The Superconducting Quantum Devices Laboratory.

This laboratory will provide a capability for precision microwave measurements of quantum phenomena in superconducting devices at milli-Kelvin temperatures, and will take advantage of the local SNF and ANFF fabrication facilities that include a Raith 150-II e-beam writer, a dedicated Aluminium evaporator for making Al-AlOx Josephson junctions, and tools for optical lithography and deposition of other metal films.

Quantum Measurement and Control

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

CI David Reilly will complete work on photon-phonon mediated coupling in GaAs single electron quantum dots. This is a collaboration between the experimental group of CI David Reilly, CI Tom Stace, CI Andrew Doherty and PI Barrett of Imperial College, London. He will also undertake new experiments on quantum Hall microwave resonators. These represent an entirely new approach to coupling microwave photons to quantum Hall fluids, single electron charges and spins. They will also complete NMR characterisation of nano diamond and begin dynamic nuclear polarisation studies, in collaboration with Macquarie University.

CI Michael Biercuk will begin the development of novel laser systems for control of Beryllium and Ytterbium qubits in Penning and Paul traps and commence the implementation of high-fidelity single-qubit control operations using a novel quasi-optical microwave system at 12.6GHz. He will also undertake a theoretical study of approaches to maintaining quantum states for long times using dynamical error suppression, and optimized dynamical error suppression strategies designed to protect quantum states during control operations.

CI Andrew Doherty will complete a proposal for exchange based CPHASE gates in singlet-triplet semiconductor qubits that uses magnetic field gradients to overcome leakage error and develop a theory of quantum limits to quantum capacitance read out of the state of singlet triplet qubits. He will initiate a study of an analog of optical parametric oscillation involving microwave photon pair creation in experiments on voltage biased Josephson junctions in the dynamical Coulomb blockade regime.

At UWA, CI Michael Tobar will demonstrate low noise microwave tools for quantum limited actuation and transduction of mechanical systems together with strong coupling between microwave photons in Circuit-QED and a “macroscopic" atomic ensemble. A new measurement of materials at low temperature, with magnetic fields, will be completed in 2012.

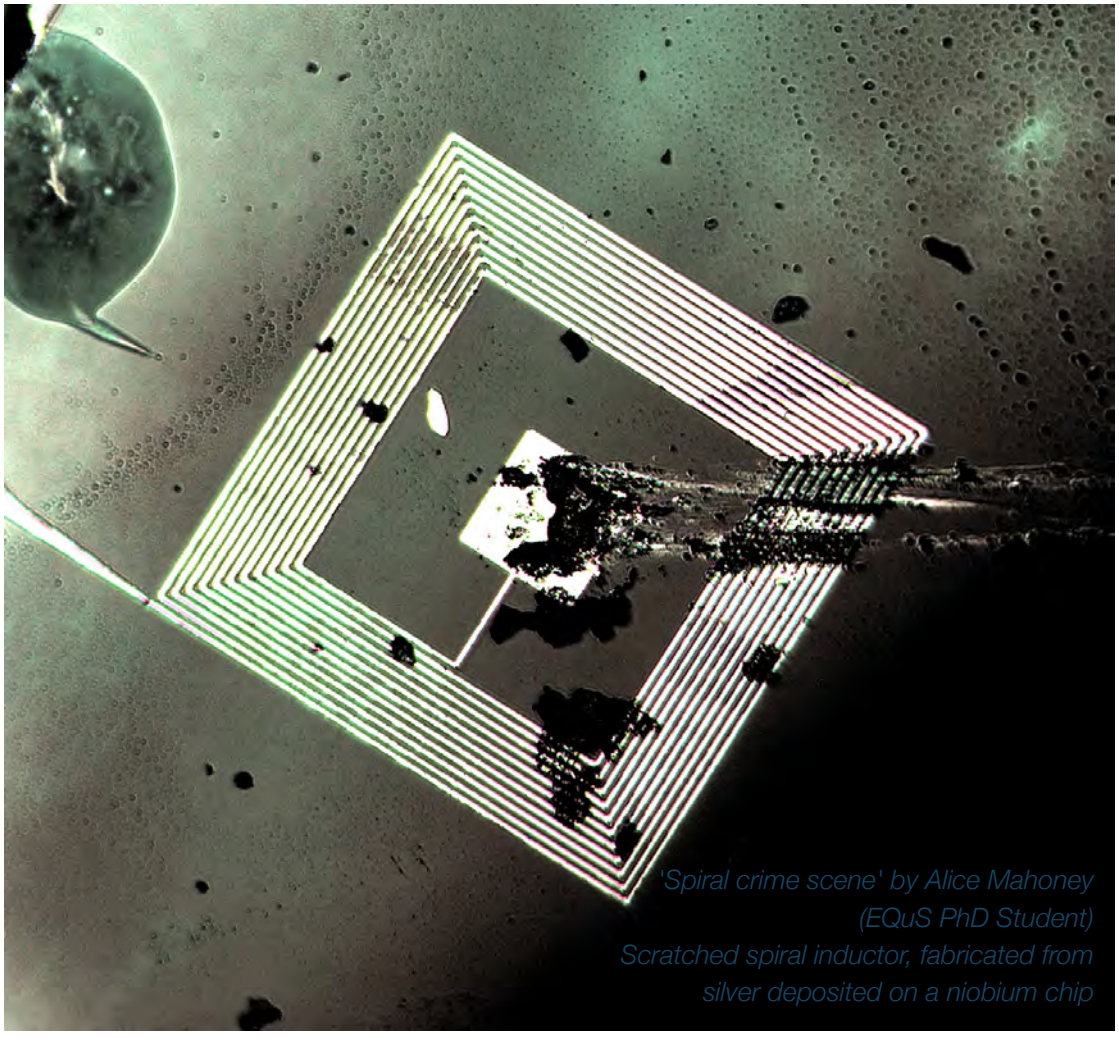
CI Tom Stace and CI Garard Milburn will continue an investigation of the feasibility for single microwave photon detection using superconducting junction devices in a transmission. CI Gerard Milburn is pursuing an interface based on a hybrid superconducting microwave ion trap system.

Both CI Gerard Milburn and CI Jason Twamley are independently developing schemes to implement a two-way microwave/optical interface. This is a much sought after goal as it will enable hybrid solid state and optical quantum systems.

CI Gerard Milburn and co workers in Italy recently developed a scheme for such a system using a mechanical resonator interface, but this requires cooling of the mechanical resonator to very low temperatures.

CI Jason Twamley is developing a scheme for a photon interface between optical/microwave photons at the quantum level using superconducting systems coupled to solid state atomic ensembles: this will allow broadband optical interface between photonic pulses in optical fibre with a superconducting circuit.

CI Jason Twamley will also develop a scheme for deterministic solid-state based integrated optical photon wave-packet generation for use in hybrid quantum systems and also seek ways to give an ultra-large enhancement of opto-mechanical couplings in hybrid quantum systems.



'Spiral crime scene' by Alice Mahoney (EQuS PhD Student)
Scratched spiral inductor, fabricated from silver deposited on a niobium chip

Quantum-Enabled Sensors and Metrology

The past year saw significant development of new optomechanics capabilities. This included the development of capabilities to strongly control mechanical nonlinearities using electrical fields, the implementation of radiation pressure induced nonlinearities in on-chip devices, feedback control techniques to suppress unwanted nonlinear behaviour, and theoretical models for optimal control of nonlinear mechanical systems. This positions the program ideally for the coming year.

By using electrically induced mechanical nonlinearities and optimal control we expect to demonstrate enhanced mechanical squeezing and, when starting at ground state temperatures, zero-point motion resolving measurement. By operating within a cryogenic environment, in future years, we aim to reach the non-classical regime of these measurements.

CI Gabriel Molina-Terriza at Macquarie will begin imaging and nanotracking of nanoparticles and develop quantum metrology methods for nanophotonics together with coupling single photons to plasmonic structures.

CI Michael Tobar's research program in this theme will;

- create a quantum memory from spins in sapphire
- work towards strong coupling of spins in high-Q cavities
- work towards obtaining ground state cooling of mechanical oscillators of order a milligram and above.
- use klystron cavities to sense mechanical displacement of high-Q mechanical oscillators
- couple qubits to high-Q 3D electromagnetic cavities
- build low noise low temperature readout systems (in collaboration with CI David Reilly at USyd)

Synthetic Quantum Systems and Simulations

In the Synthetic Quantum Systems and Simulations, EQuS aims to produce novel states of light and matter exhibiting strong quantum mechanical correlations that enable simulations of complex interacting quantum systems.

CI Michael Biercuk will continue the study of engineered 2D Ising interactions with Bollinger, US NIST with the objective of realizing controllable quantum simulation at a classically computationally intractable scale. The collaboration will involve the numerical study of ground-state configurations of interacting spins on a triangular lattice with long-range interactions.

In 2012, CI Stephen Bartlett and CI Gavin Brennen aim to produce a Ground-state QC stability and a complete theoretical classification of the computational properties of quantum matter, based on symmetry properties of phases.

CI Gavin Brennan will extend the work on anyon quantum walks to include disorder. By varying the number of anyons that are distributed in the islands of a ladder geometry we obtain an effective random potential of topological origin which has dramatically different effects for Abelian vs. non-Abelian anyons.

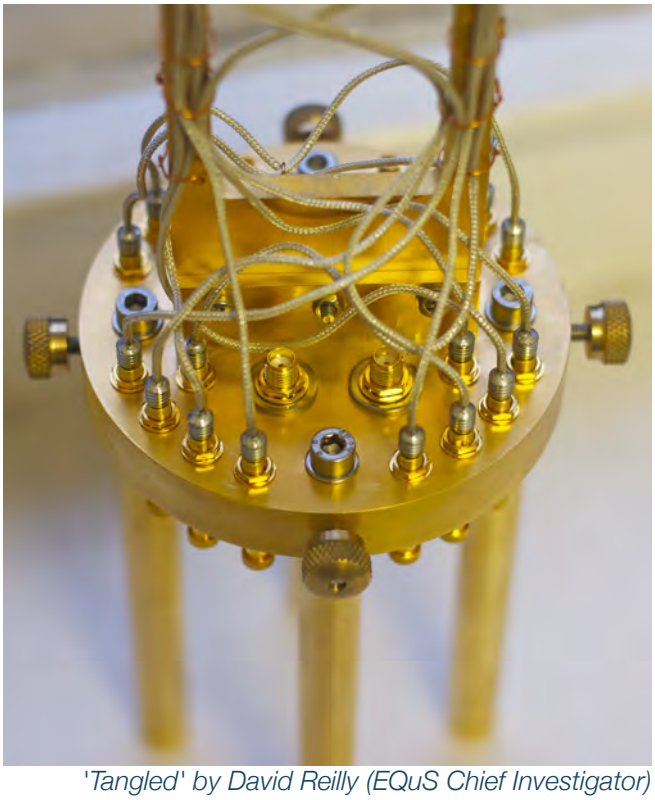
CI Alexei Gilchrist will study extended models of quantum random walks including multiple walkers on arbitrary graphs in higher dimensions, walkers with memory and the characterisation of quantum walk devices.

CI Ian McCulloch will present a calculation of time evolution in 2D tensor network and Steady-state conductance in a 1D dissipative system.

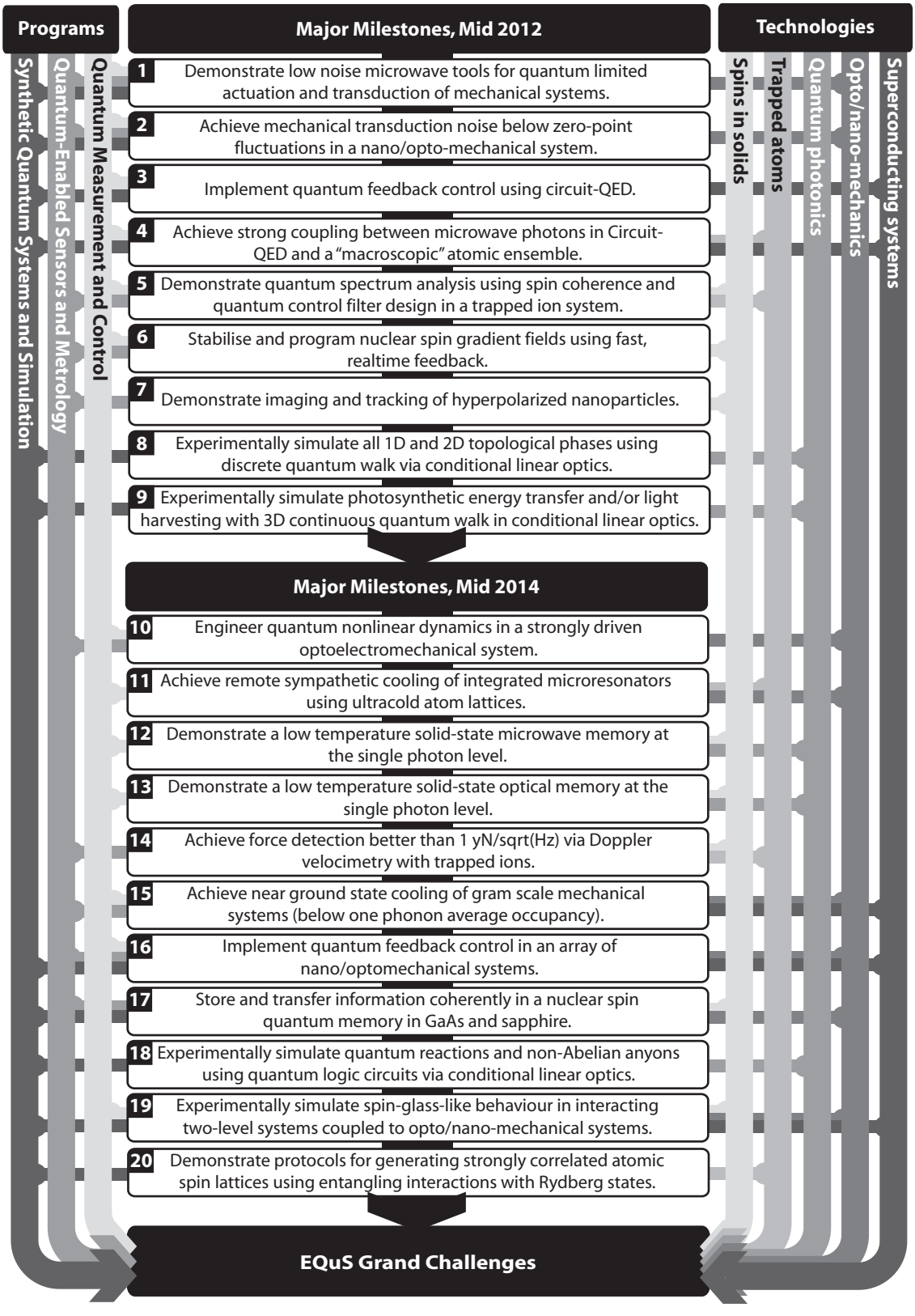
CI Andrew White will continue with the Experimental simulation of 1D and 2D topological phases using discrete quantum walk via conditional linear optics and also the experimental simulation of photosynthetic energy transfer and/or light harvesting with 3D continuous quantum walk in conditional linear optics.

The Atom Optics Laboratory will develop a research project for Quantum Simulations with Flexible Micro-Arrays of Cold Atoms, with both experimental and theoretical goals.

On the experimental side, we will begin the construction of a new experimental apparatus for two-species (Rb + K) ultra-cold atom experiment with Bosonic or Fermionic systems. We hope to achieve the new Magneto-optical Trap by January 2013.



'Tangled' by David Reilly (EQuS Chief Investigator)
Semi-rigid cables on the top of a cold finger- designed to be mounted at the bottom of a cryo-free dilution refrigerator


Programs
Synthetic Quantum Systems and Simulation
Quantum-Enabled Sensors and Metrology
Quantum Measurement and Control
Major Milestones, Mid 2012
1 Demonstrate low noise microwave tools for quantum limited actuation and transduction of mechanical systems.
2 Achieve mechanical transduction noise below zero-point fluctuations in a nano/opto-mechanical system.
3 Implement quantum feedback control using circuit-QED.
4 Achieve strong coupling between microwave photons in Circuit-QED and a "macroscopic" atomic ensemble.
5 Demonstrate quantum spectrum analysis using spin coherence and quantum control filter design in a trapped ion system.
6 Stabilise and program nuclear spin gradient fields using fast, realtime feedback.
7 Demonstrate imaging and tracking of hyperpolarized nanoparticles.
8 Experimentally simulate all 1D and 2D topological phases using discrete quantum walk via conditional linear optics.
9 Experimentally simulate photosynthetic energy transfer and/or light harvesting with 3D continuous quantum walk in conditional linear optics.
Major Milestones, Mid 2014
10 Engineer quantum nonlinear dynamics in a strongly driven optoelectromechanical system.
11 Achieve remote sympathetic cooling of integrated microresonators using ultracold atom lattices.
12 Demonstrate a low temperature solid-state microwave memory at the single photon level.
13 Demonstrate a low temperature solid-state optical memory at the single photon level.
14 Achieve force detection better than 1 yN/sqrt(Hz) via Doppler velocimetry with trapped ions.
15 Achieve near ground state cooling of gram scale mechanical systems (below one phonon average occupancy).
16 Implement quantum feedback control in an array of nano/optomechanical systems.
17 Store and transfer information coherently in a nuclear spin quantum memory in GaAs and sapphire.
18 Experimentally simulate quantum reactions and non-Abelian anyons using quantum logic circuits via conditional linear optics.
19 Experimentally simulate spin-glass-like behaviour in interacting two-level systems coupled to opto/nano-mechanical systems.
20 Demonstrate protocols for generating strongly correlated atomic spin lattices using entangling interactions with Rydberg states.
EQuS Grand Challenges
Technologies
Spins in solids
Trapped atoms
Quantum photonics
Opto/nano-mechanics
Superconducting systems

EQuS Governance and Management

Centre Governance is overseen by two Committees: the Scientific Advisory Committee (SAC) and the Advisory Committee (AC).

The Scientific Advisory Committee

The Scientific Advisory Committee (SAC) is made up by world leaders in quantum physics and chaired by Professor Sir Peter Knight, FRS.

The other members of the SAC are

- Professor Rainer Blatt, University of Innsbruck
- Professor John Clarke, University of California at Berkeley
- Professor Mikhail Lukin of Harvard University.

The SAC meets and reports annually to the CD and the Advisory Committee. Its primary task is to review the progress of the Centre in advancing research on engineered quantum systems and ensuring that EQuS research remains internationally competitive.

The Advisory Committee

The Advisory Committee (AC) 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.

It is Chaired by Rowan Gilmore D.Sc., Adjunct Professor, The University of Queensland, and CEO and Managing Director at EM Solutions Pty Ltd, Australia. The other AC members are

- Rick Wilkinson (Australian Petroleum Production & Exploration)
- David Pulford, (Defence Science and Technology Organisation)
- Peter Russo (Australian Science Teachers Association)
- Ben Greene from (EOS Electrooptic Systems)
- Representative of DVCRs at The University of Queensland, The University of Sydney, Macquarie University, and The University of Western Australia.

Due to the late start of the Centre, neither the Advisory Committee nor the Scientific Advisory Committee met in 2011. The SAC met on January 20, 2012 and the AC met on April 4, 2012.

Chief Investigator Quarterly Meetings.

We hold quarterly meetings of all the CIs (and some PIs) to monitor and refine scientific programs and to review budgets and reports. This is especially relevant for this CoE, which involves highly integrated intellectual contributions from each CI to our scientific goals, and where each CI has equal responsibility in research leadership.

Professor Sir Peter Knight is Principal of the Kavli Royal Society International Centre.
He was an elected member of Council of the Royal Society from 2005 to 2007 and is a member of the Audit Committee and deputy chair of the URF Ai Panel. In 2010 he was awarded the Royal Medal for his pioneering research and international leadership in the field of quantum optics and quantum information science.
Sir Peter was knighted in the Queen's Birthday Honours List in 2005 for his work in optical physics. He was Head of the Physics Department, Imperial College London from 2001 to 2005, and from 2006 to 2008 was Principal of the Faculty of Natural Sciences at Imperial. Peter Knight is a Past-President of the Optical Society of America and was for 7 years a member of their Board of Directors. He is a Director of the OSA Foundation.
He was coordinator of the SERC Nonlinear Optics Initiative, past-chair of the EPS Quantum Electronics and Optics Division and Editor of the Journal of Modern Optics from 1987 to 2006. He is Editor of Contemporary Physics and serves on a number of other Editorial Boards. He is a Thomson-ISI "Highly Cited Author."
Sir Peter is chair of the Defence Scientific Advisory Council at the UK Ministry of Defence and is a Council member of the Science and Technology Facilities Council. Sir Peter was also Chief Scientific Advisor at the UK National Physical Laboratory until the end of 2005.

Day to Day Management

The Day to day management of the Centre is the responsibility of the Chief Operating Officer (COO). The COO manages the operations of the Centre and supports the Director in setting the strategic direction of the Centre. This position oversees all non-academic activities of the Centre across all the nodes of the collaborating organisations. The COO liaises directly with members of the Advisory Board and the Scientific Advisory Committee in order to affect the proper governance of the Centre and achieve its key performance indicators in this category. In 2011 the COO was Mrs Danielle Faccer. The position is currently vacant and a new COO will be appointed in 2012.

Commercialisation and Technology Transfer

The Centre will proactively protect IP utilising the existing commercialisation infrastructure of the participating Organisations and the Centre IP Committee. The Centre's Collaborative Research Agreement (CRA) formalises its IP arrangements. In particular the Centre IP Committee sees all draft publications and conference abstracts which must be submitted to the IP Committee at least 2 Business Days prior to the date upon which a draft of the Publication is intended to be submitted for publication. If the Publishing Party has not received a response from the IP Committee within 2 Business Days the Publishing Party is entitled to assume consent has been granted to publish the draft in the form in which the Publication was submitted for review.

Appendix 1: Publications

B. Book Chapters

Nitrogen-Vacancy Colour Centres in Diamond: Theory, Characterisation, and Applications, in Nanotechnology in Australia, C Bradac, T Gaebel, JR Rabeau, AS Barnard, Chapter 4 in Nanotechnology in Australia, edited by D Kane, A Micolich, JR Rabeau, ISBN 9789814310024

Chapter II: Experimental control of the Orbital Angular Momentum of single and entangled photons, Molina-Terriza G. and Zeilinger A.; in J. P. Torres and L. Torner (Eds.) Twisted Photons, Applications of Light with Orbital Angular Momentum,(Wiley-VCH Verlag GmbH,Weinhelm, 2011).

C1 - Journal article – articles in scholarly and refereed journals

Engineering chromium-related single photon emitters in single crystal diamonds, I. Aharonovich, S. Castelletto, B.C. Johnson, J.C. McCallum, and S. Prawer, New J. Phys., 13, 045015 (2011).

Entangling optical and microwave cavity modes by means of a nanomechanical resonator, Sh. Barzanjeh, D. Vitalis, P. Tombesi, G.J. Milburn, Phys. Rev. A, 84, 042342 (2011).

Phenomenological study of decoherence in solid-state spin qubits due to nuclear spin diffusion, M.J. Biercuk and H. Bluhm. Phys. Rev. B 83, 235316 (2011).

Dynamical decoupling sequence construction as a filter design problem, M.J. Biercuk, A.C. Doherty, and H. Uys. J. Phys., B 44, 154002 (2011).

Toric codes and quantum doubles from two-body Hamiltonians, C.G. Brell, S.T. Flammia, S.D. Bartlett, and A.C. Doherty. New J. Phys., 13, 053039 (2011).

Reducing multi-photon rates in pulsed down-conversion by temporal multiplexing, M. A. Broome, M. P. Almeida, A. Fedrizzi and A. G. White, Optics Express, 19, 22698 (2011).

Efficient generation of Bessel beam arrays by means of an SLM, R. Bowman, N. Muller, X. Zambrana-Puyalto, O. Jedrkiewicz, P. Di Trapani and M. J. Padgett, European Physical Journal. Special Topics, 199, 159, (2011).

High Q-factor sapphire whispering gallery mode microwave resonator at single photon energies and millikelvin temperatures, D.L. Creedon, Y. Reshitnyk, W. Farr, J.M. Martinis, T.L. Duty, and M.E. Tobar, App. Phys. Lett., 98, 222903 (2011).

High-Resolution Flicker-Noise-Free Frequency Measurements of Weak Microwave Signals, D.L. Creedon, M.E. Tobar, E. N. Ivanov, and J.G. Hartnett, IEEE Transactions on Microwave Theory and Techniques, 59, (2011).

Radiative and non-radiative decay rates in chromium-related centres in nanodiamonds, S. Castelletto, and A Boretti, Optics Letters, 36, 4224, (2011).

Diamond-based structures to collect and guide light, S. Castelletto, J.P. Harrison, L. Marseglia, A.C. Stanley-Clarke, B.C. Gibson, B.A. Fairchild, J.P. Hadden, Y-L.D. Ho, M.P. Hiscocks, K.Ganesan, S.T. Huntington, F. Ladouceur, A.D. Greentree, S. Prawer, J.L. O'Brien and J.G. Rarity, New J. Phys., 13 02502 (2011).

Superradiance and phase multistability in circuit quantum electrodynamics, M. Delanty, S. Rebic, J. Twamley, New J. Phys 13, 053032 (2011).

A time-dependent Tsirelson's bound from limits on the rate of information gain in quantum systems, A.C. Doherty and S. Wehner. New J. Phys., 13, 073033 (2011).

Hardy's paradox and violation of a state-independent Bell inequality in time, A. Fedrizzi, M. P. Almeida, M. A. Broome, A. G. White, and M. Barbieri, Phys. Rev. Lett., 106, 200402 (2011).

Experimental information complementarity of two-qubit states, A. Fedrizzi, B. Skerlak, T. Paterek, M. P. de Almeida and A. G. White, New J. Phys., 13,053038 (2011).

Scattering in multilayered structures: Diffraction from a nanohole, I. Fernandez-Corbaton, N. Tischler, and G. Molina-Terriza, Phys. Rev. A 84, 053821 (2011).

Size-reduction of nanodiamonds via air oxidation, Diamond and Related materials, T. Gaebel, C. Bradac, J. Chen, J.M. Say, L. Brown, P. Hemmer, J.R. Rabeau, Diamond and Related Materials, 21, 28 (2011).

Phonon number quantum jumps in an optomechanical system, A.A.Gangat, T.M. Stace and G.J. Milburn, New J. Physics, 13 043024 (2011).

Reducing sequencing complexity in dynamical quantum error suppression by Walsh modulation, D.L. Hayes, K. Khodjasteh, L. Viola and M.J. Biercuk. Phys. Rev. A 84, 062323 (2011).

Modification of spontaneous emission from nanodiamond colour centres on a structured surface, F. A. Inam, T. Gaebel, C. Bradac, L. Stewart, M. J. Withford, J. M. Dawes, J. R. Rabeau, M. J. Steel, New J. Phys., 13, (2011).

Electromagnetic properties of polycrystalline diamond from 35 K to room temperature and microwave to terahertz frequencies, J.-M. le Floch, R. Bara, J. G. Hartnett, M. E. Tobar, D. Mouneyrac, D. Passereiux, D. Cros, J. Krupka, P. Goy, and S. Caroopen, J. of App. Phys. 109, 094103 (2011).

Quantum Walks with Non-Abelian Anyons, L. Lehman, V. Zatloukan, G.K. Brennen, J.K. Pachos, and Z. Wang, Phys. Rev. Lett., 106, 230404 (2011).

Efficient quantum computing using coherent photon conversion, N. K. Langford, S. Ramelow, R. Prevedel, W. J. Munro, G. J. Milburn, A. Zeilinger, Nature, 478, 360 (2011).

Quantum entanglement between a nonlinear nanomechanical resonator and a microwave field, C.P. Meaney, R.H. McKenzie, G.J. Milburn, Phys Rev. E 83, 056202 (2011).

Wide-range Electrical Tunability of Single-photon Emission from Chromium-based Colour Centres in Diamond, T. Muller, I. Aharonovich, L. Lombez, Y. Alaverdyan, A. N. Vamivakas, S. Castelletto, F. Jelezko, J. Wrachtrup, S. Prawer, M. Atatüre, New J. Phys., 13 075001 (2011).

Circuit QED with a nonlinear resonator: ac-Stark shift and dephasing, F. R. Ong, M. Boissonneault, F. Mallet, A. Palacios-Laloy, A. Dewes, A. C. Doherty, A. Blais, P. Bertet, D. Vion, and D. Esteve. Phys. Rev. Lett., 106, 167002 (2011).

Two-photon quantum walks in an elliptical direct-write waveguide array, J. O. Owens, M. A. Broome, D. N. Biggerstaff, M. E. Goggin, A. Fedrizzi, T. Linjordet, M. Ams, G. D. Marshall, J. Twamley, M. J. Withford, and A. G. White, New J. Phys. 13, 075003 (2011).

Bulk fault-tolerant quantum information processing with boundary addressability, G. A. Paz-Silva, G.K. Brennen and J. Twamley, New J. Phys., 13, 013011 (2011).

Time-resolved detection and mode-mismatch in linear optics quantum gates, P. P. Rohde, T. C. Ralph, New J. Phys. 13, 053036 (2011).

Nanoscale magnetometry using a single-spin system in diamond, R. Said, D.W. Berry, J. Twamley, Phys. Rev. B 83, 125410 (2011).

Characterization of a qubit Hamiltonian using adaptive measurements in a fixed basis, A. Sergeevich; A. Chandran, J. Combes, S.D. Bartlett and H.M. Wiseman. Phys. Rev. A 84, 5 (2011).

Efficient measurement of quantum dynamics via compressive sensing, A. Shabani, R. L. Kosut, M. Mohseni, H. Rabitz, M. A. Broome, M. P. Almeida, A. Fedrizzi, and A. G. White, Phys. Rev. Lett., 106, 100401 (2011).

Tensor network states and algorithms in the presence of a global U(1) symmetry, S. Singh, R. N.C. Pfeifer, G. Vidal, Phys. Rev. B 83, 115125 (2011).

Detection limits in whispering gallery biosensors with plasmonic enhancement, Jon D. Swaim, Joachim Knittel, Warwick P. Bowen, App. Phys. Lett., 99, 243109 (2011).

Mechanical squeezing via parametric amplification and weak measurement, A. Szorkovszky, A.C. Doherty, G.I. Harris, W.P. Bowen. Phys. Rev. Lett., 107, 213603 (2011).

Twisting of light around rotating black holes, F. Tamburini, B. Thide, G. Molina-Terriza, and G. Anzolin, Nature Physics, 7, 195 (2011).

Pulsed Quantum Optomechanics, M.R. Vanner, I Pikovski, M.S.Kim, C. Brukner,K.Hammerer, G.J. Milburn, M. Aspelmeyer, Proceedings of the National Academy of Sciences, 108, 16182, (2011).

C2 - Journal article – other contribution to refereed journals

Solid-state spins survive, M. J. Biercuk and D. J. Reilly. Nature Nanotechnology 6, 9 (2011)

Quantum measurement: a quantum spectrum analyser, M. J. Biercuk. Nature Physics 7, 525 (2011).

"Editorial: Special issue on orbital angular momentum." Molina-Terriza, G., Padgett, M. (overseas); Journal of Optics, 13, 060201 (2011), Formerly known as Journal of Optics A.

D - Major review

Diamond-based single-photon emitters, I. Aharonovich, S. Castelletto, D. A. Simpson, A.D. Greentree, S. Prawer, Reports on Progress in Physics , 74, 076501 (2011).

Luminescent nanodiamonds for biomedical applications, J. M. Say, C. van Vreden, D. J Reilly, L. J Brown, J. R. Rabeau, N.J.C King, Biophysical Reviews, 3, 171 (2011).

E1 - Conference – full written paper-refereed proceedings

Nanoscopic Localisation And Characterisation Of Nanoparticle Embedded, Photonic Materials, B. Kouskousis, Xiangping Li, S. A. Castelletto, Min Gu, IQEC/CLEO Pacific Rim Conference 2011

Non-reciprocity in Coupled Linear Waveguide Arrays Using the Technique of Adiabatic Light Trapping, Keyu Xia and Mohammad Al-Amri and M. Suhail Zubairy, The 2011 TAMU-Princeton Summer school.

Precision Metrology at the University of Western Australia, Michael E. Tobar, Eugene. N. Ivanov, Daniel L. Creedon, Jean-Michel le Floch, Karim Benmessai, Yaohui Fan, Warrick Farr, Yarema Reshitnyk, Timothy L. Duty, and John M. Martinis, APMC Conf, Melbourne, 7 December (2011).

Precision Noise Measurements and Oscillator Frequency Stabilization, E.N. Ivanov, and M.E. Tobar, URSI Conf, Istanbul, 16 August (2011).

Spontaneous Emission from Nanodiamond NV Color Centers on Structured Surfaces, Inam, F, CLEO 2011—IEEE/OSA Conference for Lasers and Electro-Optics, (Baltimore) (2011).

Towards hybrid diamond optical devices, 2011 13th International Conference on Transparent Optical Networks, B. C. Gibson, S. Castelletto, T.J. Karle, S. Tomljenovic-Hanic, I. Aharonovich, B.C. Johnson, J. Orwa, M.R. Henderson, H. Ebendorff-Heidepriem, K. Kuan, V.S. Afshar, T.M. Monro, A.D. Greentree, and S. Prawer. Pages: 4 pp. DOI: 10.1109/ICTON.2011.5970886 (2011).

Characterization of the influence of crystal size and dipole orientation on the spontaneous emission lifetime of diamond NV colour centers, Paper Number: 1011.00, Inam, F, IQEC/CLEO Pacific RIM 2011, (Sydney) (2011).

Quantum discord in quantum computation, A.Brodutch, A.Gilchrist, D.R.Terno, C.J.Wood; J. Phys.: Conf. Ser. 306 012030 (2011).

E3 - Conference – extract of paper

Dynamical Decoupling Experiments with Ions in Penning Traps, J.J. Bollinger, M.J. Biercuk, H. Uys, J.W. Britton, W.M. Itano and N. Shiga. 41st Winter School on the Physics of Quantum Electronics (2011).

E4 - Conference – unpublished presentations

Sapphire Whispering Gallery Mode Resonators at Milli-Kelvin Temperature, Daniel L. Creedon, Yarema Reshitnyk, Jean-Michel le Floch, Warrick Farr, John M. Martinis, Tim L. Duty, and Michael E. Tobar, IQEC/CLEO Conf, Sydney, 28 August (2011)

Study of Fe3+- Sapphire Maser above 4K, Karim Benmessai, Mohamad Mrad, Daniel L. Creedon, Jean-Michel le Floch, Michael E. Tobar, Pierre-Yves Bourgeois, Yann Kersale, Vincent Giordano, IFCS Conf, San Francisco, 30 August (2011)

Tailoring the photoluminescence of NV centres in nanodiamonds for superresolution imaging, B. Kouskousis, S. A. Castelletto, X.Li, M. Gu,SPIE Conference 8204 SPIE Smart Nano-Micro Materials and Devices, Paper 8204-103 (2011).

Imaging nano-diamonds using a far-field plasmonic lens, P. Venugopalan, X. Li, S. Castelletto, M. Gu, Paper 8204-64, SPIE Conference 8204 SPIE Smart Nano-Micro Materials and Devices (2011).

Conference Presentations

January 2-7, 2011 - Tom Stace, “Scalable quantum computing with atomic ensembles" Invited Talk. Physics of Quantum Electronics 2011. (www.pqeconference.com)

January 9-15, 2011 - Courtney Brell, “Toric codes and quantum doubles from two-body Hamiltonians" Poster Presentation. QIP 2011.

January 9-15, 2011 - Andrew Darmawan, “Prospects for measurement based quantum computation in a 2D phase around the AKLT point' Poster Presentation. QIP 2011.

January 9-15, 2011 - Graham White, “Efficient topological codes for quantum error correction" Presentation. QIP 2011.

January 22-27, 2011 - Gabriel Molina-Terrizza, Invited Talk. OPTO program of Photonics West (San Francisco).

Febuary 1-4, 2011 - Gerard Milburn, “Engineered Quantum Systems' Invited Talk. 35th Annual Condensed Matter and Materials Meeting, Charles Sturt University, Wagga Wagga, NSW.

Febuary 2-12, 2011 - Gavin Brennan, Invited Talk. PRISM Mitre Series at Princeton University.

Febuary 14-17, 2011 - Jason Twamley, “Lecture Series in the International School on Quantum Information Processing and Application: Superconducting Quantum Optics" Invited Talk. Harish Chandra Research Institute in India.

Febuary 18-20, 2011 - Jason Twamley, “Lecture Series in the International School on Quantum Information Processing and Application: Nonlinear Quantum Optic" Invited Talk. Harish Chandra Research Institute in India.

Febuary 28, 2011 - Andrew White, “Quantum Biology, Chemistry, Maths & Physics" Invited Talk. Quantum Simulation, Benasque, Spain.

March 7-11, 2011 - Gerard Milburn, invited talk "Estimating metrics with quantum fields" , Workshop on relativistic quantum information” University fo Kwa Zulu Natal, Durban, South Africa.

March 21-25, 2011 - Alessandro Fedrizzi, “Hardy's paradox and a violation of a state-independent Bell inequality in time" Presentation. American Physical Society (APS) March Meeting (www.aps.org/meetings/meeting.cfm?name=MAR11).

March 28, 2011 - Andrew White, “ Quantum Biology, Chemistry, Maths & Physics" Invited Talk. 241st National Meeting of the American Chemical Society, Anaheim, USA.

April 10-13, 2011 - Jason Twamley, “Integrated Quantum Photonics" Invited Talk. QUANTIP Annual Meeting, University of Nice, France.

April 25-30, 2011 - James Rabeau, Invited Talk. MRS Spring Meeting, San Francisco, California, USA.

April 28, 2011 - Warwick Bowen , “Quantum control of opto-mechanical systems' Invited Talk. EQuS quarterly meeting.

May 1-5, 2011 - Michael Tobar, “Study of Fe3+-Sapphire Maser above 4 Kelvin"
Invited Talk. 2011 Joint IEEE International Frequency Control Symposium (IFCS) and European Frequency and Time Forum (EFTF).

May 1-5, 2011 - Romain Bara, Invited Talk. IFCS Conf in San Francisco.

May 9-12, 2011 - Cyril Branciard, “Simulation of multipartite quantum correlations with classical communication' Poster Presentation. Conceptual Foundations and Foils for Quantum Information Processing, Waterloo (Canada).

May 16, 2011 - James Rabeau, Invited Talk. New Diamond and nano Carbon (NDNC 2011), Sendai, Japan.

May 22-26, 2011 - Alessandro Fedrizzi, “Observation of topologically protected bound states in photonic quantum walks" Presentation. CLEO Europe and European Quantum Electronics Conference (EQEC) 2011.

May 30, 2011 - Andrew White, “Quantum Biology, Chemistry, Maths & Physics" Invited Talk. The 20th International Conference on Laser Spectroscopy (ICOLS 2011), Aerzen, Germany.

June 6-8, 2011 - Stephen Bartlett, " Benchmarking of Spin Qubits", Invited Talk. IARPA Program Review Austin Texas USA.

June 6-8, 2011 - David Reilly, Invited Talk. IARPA Program Review Austin Texas USA.

June 6-8, 2011 - Tom Stace, “Loss Tolerance in Topological Quantum Codes" Presentation. ICQI 2011 (www.osa.org/meetings/topical_meetings/icqi/default.aspx).

June 6-8, 2011 - Gerard Milburn, "Quantum optical control and measurement in optomechanics", Invited talk. International Conference on Quantum Information, University of Ottawa.

June 28, 2011 - Marcelo Almeida, “Exponentially faster measurements of quantum dynamics via compressive sensing" Invited Talk. Single Photon Workshop 2011 (www.spw2011.ptb.de/spw2011/spw2011-conference-program.html).

July 6, 2011 - Andrew White, “Quantum Biology, Chemistry, Maths & Physics" Invited Talk. Summer School: Introductory Course on Quantum Information, University of Innsbruck, Austria.

July 7-31, 2011 - Gavin Brennan, “Towards Quantum Computational Phases of Matter" Invited Talk. University of Leeds.

July 10, 2011 - Andrew White, “Simulating Quantum Systems in Biology, Chemistry and Physics" Invited Talk. Sonderforschungsbereich meeting, University of Innsbruck, Austria.

July 11-15, 2011 - Alex Szorkovszky, “Optomechanics With Electromechanical Parametric Amplification" Presentation. Laser Physics Workshop LPHYS'11 (www.lasphys.com/workshops/lasphys11/lphys11.htm).

July 11-15, 2011 - Glen Harris, “Feedback stabilization of an optomechanical system experiencing parametric instability" Presentation. Laser Physics Workshop LPHYS'11(www.lasphys.com/workshops/lasphys11/lphys11.htm).

July 24-28, 2011 - Alex Szorkovszky, “Mechanical Squeezing Using Parametric Amplification and Weak Measurement" Poster Presentation. Quantum Optics of Micro- and Nanomechanical Systems, Monte Verita (qomns-monteverita.epfl.ch/)

July 24-28, 2011 - Glen Harris, “Surpassing the Sensitivity Barrier Set by Parametric Instability With Active Feedback in Optomechanical Systems" Poster Presentation. Quantum Optics of Micro- and Nanomechanical Systems, Monte Verita (qomns-monteverita.epfl.ch/).

July 24-28, 2011 - Stefan Forstner, “Optomechanical magnetometer with nano-Tesla sensitivity" Poster Presentation. Quantum Optics of Micro- and Nanomechanical Systems, Monte Verita (qomns-monteverita.epfl.ch/).

July 25, 2011 - Andrew White, “Simulating Quantum Systems in Biology, Chemistry and Physics" Invited Talk. Frontiers of Quantum and Mesoscopic Thermodynamics, Prague, Czech Republic.

25-30 July 2011 - Matthew Broome, " Observation of Topological Phases in photonic quantum walk" Presentation, Frontiers of Quantum and Mesoscopic Thermodynamics.

July 31 - August 5, 2011 - Gerard Milburn, “Quantum measurement and control" Invited Talk. Summer School in Quantum Information and Coherence, University of Strathclyde, Glasgow, UK.

August 7-13, 2011 - Michael Biercuk, Invited Talk. NSA Program Review, Denver USA.

August 8-12, 2011 - Alexandr Sergeevich, “Adaptive qubit Hamiltonian parameter estimation applied to double quantum dots" Poster Presentation. CQIQC 2011.

August 13-20, 2011 - Eugene Ivanov, “Precision Noise Measurements and Oscillator Frequency Stabilization" Invited Talk. URSI General Assembly and Scientific Symposium of International Union of Radio Science.

August 13-20, 2011 - Michael Tobar, “Precision Noise Measurements and Oscillator Frequency Stabilization" Invited Talk. URSI General Assembly and Scientific Symposium of International Union of Radio Science.

August 14-18, 2011 - Tom Stace, “Multiscale Photosynthetic Excitation Energy Transfer" Invited Talk. Towards Global Artificial Photosynthesis (energy.anu.edu.au/event/2011/mar/18/towards-global-artificial-photosynthesis).

August 14-18, 2011 - Gerard Milburn, “Does photosynthesis exploit the quantum?" Invited Talk. Towards Global Artifical Photosynthesis: Energy, Nanochemistry & Governance.

August 19, 2011 - Andrew White, “Simulating Quantum Systems in Biology, Chemistry and Physics" Invited Talk. Centre for Quantum Information and Quantum Computing Colloquium, Toronto.

August 27, 2011 - Andrew White, “Quantum optics: The zombie science?" Invited Talk. Workshop on Quantum Optics in 25 years, Canberra.

August 28, 2011 - Andrew White, “Quantum computing: What is it? Why do it?" Invited Panel Discussion member. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Andrew Doherty, “Microwave Bistability in Circuit QED" Invited Talk. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - George Brawley, “Improved Detection of Nanomechanical Motion Using a Coupled Microtoroid-Interferometer System" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Michael Taylor, “Regenerative Amplification in Microtoroids by Electrical Actuation" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Adil Gangat, “Phonon Number Quantum Jumps in an Optomechanical System" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Gaebel Torsten, “Size Reduction of Nanodiamonds Hosting NV Centres via Air Oxidation" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Bixan Fan, “A practical photon-number-resolving detector in the microwave regime" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Michael Tobar, “Sapphire Whispering Gallery Mode Resonators at Milli-Kelvin Temperature" Poster Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Stefan Forstner, “All-optical magnetometer based on microtoroids" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Terry McRae, “Radiation Pressure Driven Optomechanical Amplifier" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Joachim Knittel, “Nanoparticle detection and characterization using optical micro resonators" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Alex Szorkovszky, “Optomechanics With Electromechanical Parametric Amplification" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Glen Harris, “Feedback Enhanced Sensitivity in Optomechanics: Surpassing the Parametric Instability Barrier" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Philip Light, “High Resolution Optical Spectroscopy in Hollow Core Fibre for Use in Atomic Clocks" CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Alessandro Fedrizzi, “Observation of topologically protected bound states in photonic quantum walks" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Alexandr Sergeevich, “Bayesian approach to adaptive Hamiltonian parameter estimation and measurement in double quantum dots" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Carlo Bradac, “Nitrogen-vacancy centres in nanodiamond: effects of size, surface and surroundings environment on luminescence" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Devon Biggerstaff, “Quantum Walks with Two-Photon Inputs" Presentation. CLEO Pacific Rim, Sydney.

August 28 - September 1, 2011 - Till Weinhold, “Creating Narrowband Single Photon Sources Suitable For Gradient Echo Quantum Memories" Presentation. CLEO Pacific Rim, Sydney.

August 29 - September 2 - Gerard Milburn, “Quantum feedback control" Invited Talk. FASTQUAST, Oxford University.

September 4-8, 2011 - Carlo Bradac, “The effects of size and surface on nitrogen-vacancy in nanodiamond" Presentation. Diamond 2011 Conference.

September 5-9, 2011 - Ian McCulloch, “Density Matrix Renormalization Group and Matrix Product States" Invited Talk. Summer School for Numerical Methods in Condensed Matter Physics, national Centre for Theoretical Sciences, Hsin Chu.

September 5-9, 2011 - Ian McCulloch, “Matrix Product States and DMRG" Invited Talk. Summer School for Numerical Methods in Condensed Matter Physics, national Centre for Theoretical Sciences, Hsin Chu.

September 5-9, 2011 - Ian McCulloch, “Matrix Product States and DMRG: Applications" Invited Talk. Summer School for Numerical Methods in Condensed Matter Physics, national Centre for Theoretical Sciences, Hsin Chu.

September 6-9, 2011 - Tom Stace, “Academic Insights into future technologies" Invited Talk. Trading Architecture ASIA 2011.

September 7-10 - Ewa Rej, “Towards Hyperpolarized Nanodiamonds for MRI" Poster Presentation. Third International Symposium on Dynamic Nuclear Polarization.

September 12-16, 2011 - Cyril Branciard, “One-sided Device Independent Quantum Key Distribution: Security and feasibility" Poster Presentation. 1st Annual Conference on Quantum Cryptography (QCRYPT 2011), Zurich (Switzerland).

September 16, 2011 - Janani Chander, “Finite Temperature algorithms using Tensor Network" Invited Poster Presentation. Poster Day at the School of Mathematics and Physics, The University of Queensland.

September 16, 2011 - Phien Ho, “Faster convergence in tensor network algorithms by recycling the environment", Invited Poster Presentation. Poster Day at the School of Mathematics and Physics, The University of Queensland.

September 16, 2011 - Devin Biggerstaff, “Quantum Walks with Two-Photon Inputs", Invited Poster Presentation. Poster Day at the School of Mathematics and Physics, The University of Queensland.

October 3-7, 2011 - Gerard Milburn, “Quantum control of optomechanical systems" Invited Talk. Rank Prize meeting on Optical Implementation of Quantum Information Grassmere, UK.

October 3-6, 2011 - Cyril Branciard, “Optical tests of quantum foundations" Presentation. Rank Prize Funds Symposium on Optical Implementation of Quantum Information, Grasmere (United Kingdom).

October 16-24, 2011 - Michael Biercuk, "Quantum Firmware" Invited Talk, Tsinghua Dept of Physics.

October 16-24, 2011 - Michael Biercuk, "Quantum Firmware" Invited Talk, Institute of Physics, Chinese Academy of Sciences.

October 16-20, 2011 - Warwick Bowen, “Near threshold optomechanical backaction amplifier" Presentation. Frontiers in Optics, San Jose.

October 16-20, 2011 - Warwick Bowen, “Cavity opto-electromechanical regenerative amplification" Presentation. Frontiers in Optics, San Jose.

October 16-20, 2011 - Jon Swaim, “Cavity optomechanical magnetometer" Presentation. Frontiers in Optics, San Jose.

October 16-20, 2011 - Warwick Bowen, “Mechanical squeezing via parametric amplification and weak measurement" Presentation. Frontiers in Optics, San Jose.

October 16-20, 2011 - Warwick Bowen, “Feedback enhanced sensitivity in cavity optomechanics: Surpassing the parametric instability barrier" Presentation. Frontiers in Optics, San Jose.

October 17, 2011 - James Rabeau, Invited Talk. Carbon Based Nanomaterials, Suzhou, China.

October 17, 2011 - James Rabeau, Invited Talk. Quantum Manipulation of Atoms and Photons, Shanghai, China.

October 18-21, 2011 - Courtney Brell, “Toric codes and quantum doubles from two-body Hamiltonians" Poster Presentation. Quantum Information in Quantum Many-body Physics.

October 18-21, 2011 - Andrew Darmawan, “Prospects for measurement based quantum computation in a 2D phase around the AKLT point" Poster Presentation. Quantum Information in Quantum Many-body Physics.

October 26, 2011 - Andrew White, “Quantum correlations & correlators in space-time: now & then†is weirder than here & there" Invited Talk. Foundations of Quantum Theory: measurement, the quantum to classical transition, and the flow of time, Stellenbosch, South Africa.

October 30 - November 3, 2011 - Warwick Bowen, “Towards non-classical mechanical states in optomechanical WGM resonators" Invited Talk. 492. WE-Heraeus-Seminar on Micro & macro-cavities in classical and non-classical light.

November 5, 2011 - Gerard Milburn, “Hybrid quantum systems" Invited Talk. National Institute of Informatics Shonan workshop on QIT, Shonan, Japan.

November 26 - December 10, 2011 - Courtney Brell, Invited Talk. USC Conference 2011.

November 28-30, 2011 - Warwick Bowen, “How can we answer fundamental questions in quantum mechanics?" Invited Talk. ACQAO Kioloa Workshop.

November 28-30, 2011 - Tom Stace, “Quantum Thermometry" Invited Talk. ACQAO Kioloa Workshop.

December 2011 - Andrew Doherty, “Mechanical Squeezing using Parametric Amplification and Feedback Control" Invited Talk. PRACQSYS 2011.

December 4-19, 2011 - Jason Twamley, Invited Talk. Second International Conference on Quantum Error Correction, Univ. Southern California, Los Angeles, USA.

December 5-9, 2011 - Michael Biercuk, “Quantum Firmware: Engineering error resistance at the physical level" Invited Talk. QEC11.

December 5-8, 2011 - Michael Tobar, “Precision Metrology at the University of Western Australia" Invited Talk. Asia Pacific Microwave Conference.

December 8, 2011 - Michael Biercuk, Invited Talk. HRL Laboratories Industrial Research Lab California USA.

December 12-16, 2011 - Stephen Bartlett, Invited Talk. QIP 2011.

December 12-16, 2011 - Devin Smith, Poster Presentation. Quantum Information Processing 2012.

December 12-16, 2011 - Courtney Brell, "A Perturbative Approach to PEPS parent Hamiltonians," Poster Presentation, Quantum Information Processing 2012", Poster Presentation. QIP 2011.

December 12-16, 2011 - Dominic Else, "Measurement-based quantum computation with the custer state is robest to symmetric perturbations in the parent Hamiltonian," Poster Presentation, Quantum Information Processing 2012.

December 12-16, 2011 - Prashant Kumar, "A Class of Quantum Double Subsystem Codes," Poster Presentation, Quantum Information Processing 2012.

Public Talks

March 23, 2011 - James Rabeau, Latrobe University, Department of Physics colloquium.

April 16, 2011 - David Reilly, Stanford University California USA.

April 4, 2011 - Andrew White, University of Melbourne, School of Physics Colloquium.

May 5, 2011 - Andrew White, Australian Academy of Science, Canberra.

May 7-15, 2011 - Gerard Milburn, Institute of Physics, University of Campinas, Brazil.

June 9-10 - Stephen Bartlett, Caltech California USA.

June 11-17, 2011 - Gerard Milburn, National Taiwan University, Taipei.

June 22-24, 2011 - Gaebel Torsten, ANU.

July 1-7, 2011 - Stephen Bartlett, Imperial College UK.

October 3-14, 2011 - Stephen Bartlett, Perimeter Institute Canada.

December 14, 2011 - Marcelo Almeida, Federal University of Rio de Janeiro (UFRJ).

December 16, 2011 - Marcelo Almeida, Federal Fluminense University.

Appendix 2: Financial Statements

Income

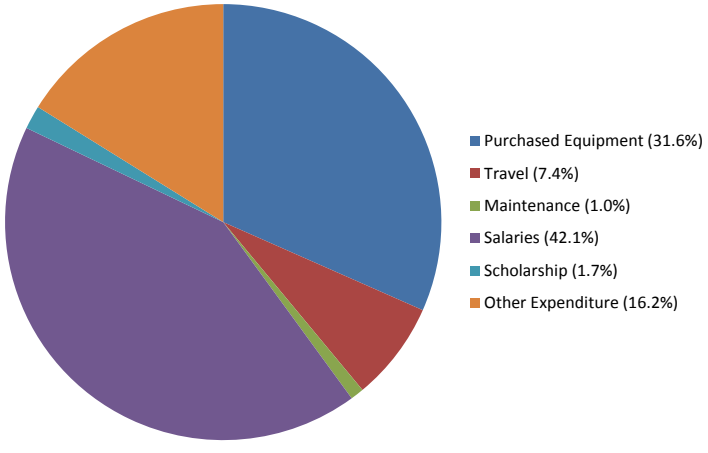
	UQ	USYD	UMQ	UWA	TOTAL
ARC	1,731,190	772,797	783,639	267,500	3,555,126
Institution Support	600,000	200,000	250,538	93,625	1,144,163
Overseas Government Organisations.		718,978			718,978
Total	**2,331,190**	**1,691,775**	**1,034,177**	**361,125**	**5,418,267**

Expenditure

	UQ	USYD	UMQ	UWA	TOTAL
Purchased Equipment	114,180	374,143	114,649	252,371	855,343
Travel	114,470	49,121	13,637	21,938	199,216
Maintenance (IT and Lab)	23,448	3,063	423		26,934
Salaries	580,409	216,873	248,027	94,471	1,139,781
Scholarship - top up/Summer/ Living Allowance/Other type	24,369	22,144		650	47,163
Other expenditure	64,964	291,089	53,963	26,930	436,947
TOTAL	**921,841**	**956,434**	**430,749**	**396,360**	**2,705,385**

Macquarie University cash input included an amount of $160,000 for PhD scholarships. As no scholarships were awarded in 2011 the funding remains available for allocation in 2012.

2011 Expediture by Category



Appendix 3: Key Performance Indicators

Research Findings

PERFORMANCE MEASURE	TARGET	OUTCOME 2011
Number of research outputs in international peer review journals	70	41
Quality of research outputs	90% in A*/A tier journals 14% in A* tier journals	95% (37 of 39) 42% (12 of 39)
Number of invited talks/papers/ keynote lectures given at major international meetings	20	42
Number and nature of commentaries about the centre's achievements	20	21
Citation data for publications	At review	

Research Training and Professional Education

PERFORMANCE MEASURE	TARGET	OUTCOME 2011
Number of attended professional training courses for staff and postgraduate students	6	6
Number of centre attendees at all professional training courses	35	35
Number of new postgraduate students working on core research and supervised by centre staff	17	9
Number of new postdoctoral researchers recruited to the centre working on core centre research	15	19
Number of new honours students working on core centre research and supervised by centre staff	10	7
Number of postgraduate completions and completion times by students working on core centre research and supervised by centre staff	5	6
Number of Research Higher Degree Students		50 PhD 1 Masters
Number of early career researchers working on core centre research	15	19
Number of students mentored	20	30
Number of mentoring programs	2	2

International, National and Regional Links and Networks

PERFORMANCE MEASURE	TARGET	OUTCOME 2011
Number of international visitors and visiting fellows	34	53
Number of national and international workshops held/ organised by the centre	1	4
Number of visits to overseas laboratories and facilties	80	81
Examples of relevant interdisciplinary research supported by the centre		

End User Links

PERFORMANCE MEASURE	TARGET	OUTCOME 2011
Number of government, industry and business community briefings	6	6
Number and nature of public awareness programs	12 school visits	7
	3 science teacher workshops	1
Currency of information on the centres website	6 revisions	8
Number of unique website hits	800 annually	253/mth
Number of public talks given by centre staff	8	16

Organisational Support

PERFORMANCE MEASURE	TARGET	OUTCOME 2011
Annual Cash contributions from collaborating organisations	UQ: $600,000	UQ: $600,000
	MQ: $410,000	MQ: $490,000
	USYD: $200,000	USYD: $200,000
	UWA: $87,500	UWA: $93,625
Annual in-kind contributions from collaborating organisations	UQ: $1,597,065	UQ: $2,323,640
	MQ: $1,036,431	MQ: $2,993,340
	USYD: $2,183,583	USYD: $3,566,700
	UWA: $1,329,111	USYD and National Measurement Institute: $1,824,000
		UWA: $4,976,166
Other research income secured by centre staff	$900,000	$718,978
Number of new organisations collaborating with, or involved in, the centre	2	5
Level and quality of infrastructure provided to the centre	At review	

In-kind support for 2011 was augmented by subsantial office and laboratory refurbishment undertaken at each node in 2011

CIs and students at the Annual EQuS Workshop

Acknowledgements

EQuS would like to thank the following units and people

- The School of Mathematics and Physics at The University of Queensland
- The School of Physics at The University of Sydney
- The Department of Physics and Astronomy at Macquarie University
- The School of Physics at The University of Western Australia
- Members of our Partner Institutes
- Members of the EQuS Scientific Advisory Committee
- Members of the EQuS Advisory Committee
- The DVCR, Professor Max Lu, The University of Queensland
- Executive Dean of Science, Professor Stephen Walker, The University of Queensland
- Kathy Avent from Kathalyst
- Nicole Thompson from The University of Queensland

A special thank you to the Chief Investigators, Staff and Students of EQuS for maintaining vision, enthusiasm, and dedication during our first year of operation.